The Standard Model and Beyond

- The standard model
- Testing the standard model
- Problems
- Beyond the standard model
- Where are we going?

The *New* Standard Model

- **Standard model, supplemented with neutrino mass (Dirac or Majorana):**

$$SU(3)\times SU(2)\times U(1)\times \text{classical relativity}$$

- **Mathematically consistent field theory of strong, weak, electromagnetic interactions**
- **Gauge interactions correct to first approximation to 10^{-16} cm**
- **Complicated, free parameters, fine tunings $\Rightarrow$must be new physics**

- **Many special features *usually not* maintained in BSM**
  - **$m_\nu = 0$ in *old* standard model** (need to add singlet fermion and/or triplet Higgs and/or higher dimensional operator (HDO))
  - **Yukawa coupling $h \propto gm/M_W \Rightarrow$ flavor conserving and small for light fermions** (partially maintained in MSSM and simple 2HDM)
  - **No FCNC at tree level (Z or h); suppressed at loop level** (SUSY loops; Z' from strings, DSB)
  - **Suppressed off-diagonal $\not{C}P$; highly suppressed diagonal (EDMs)** (SUSY loops, soft parameters, exotics)
  - **B, L conserved perturbatively ($B - L$ non-perturbatively)** (GUT (string) interactions, $\not{R}_p$)

Quantum Chromodynamics (QCD)

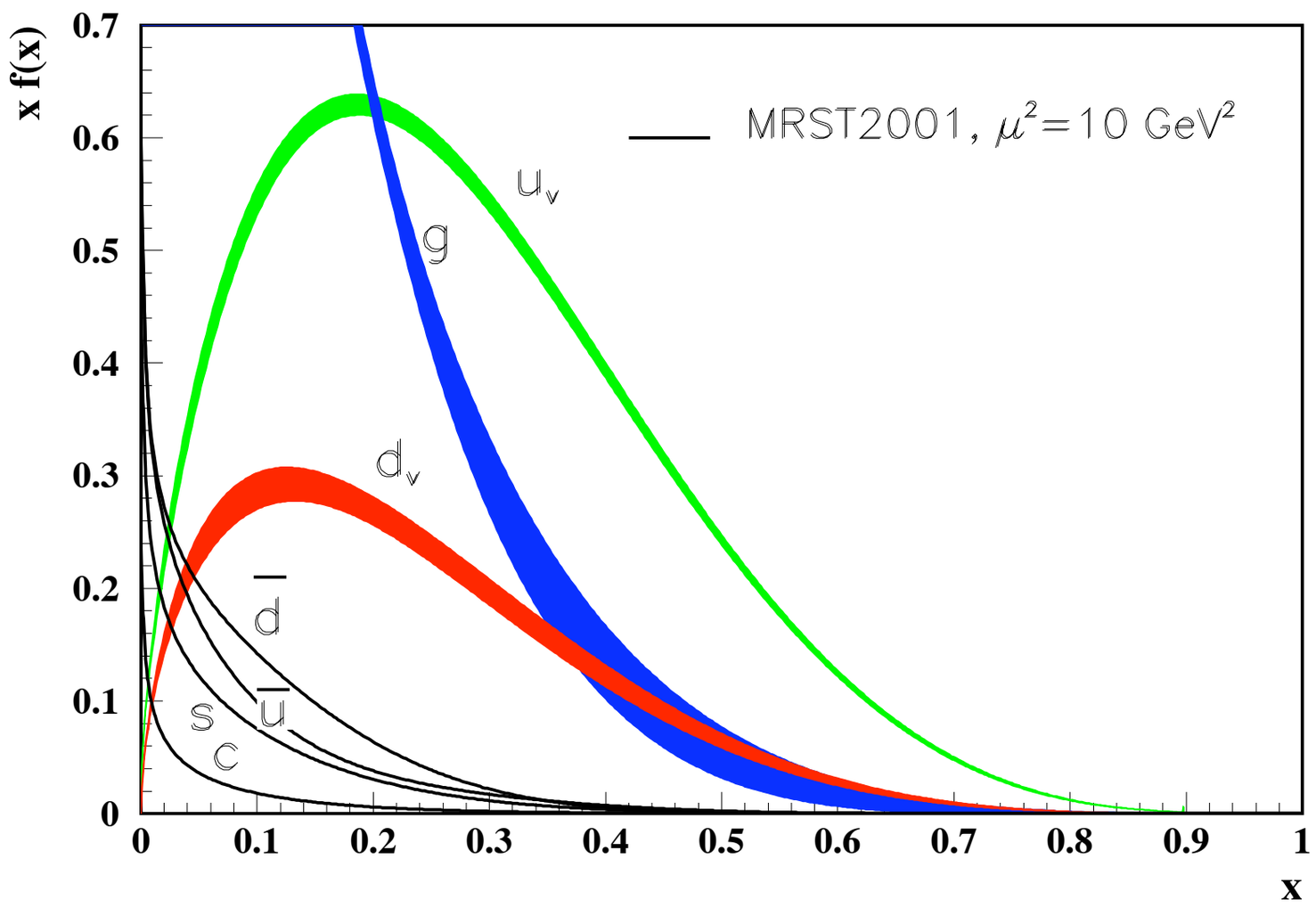
Modern theory of the strong interactions

- Quark model/ color/ confinement

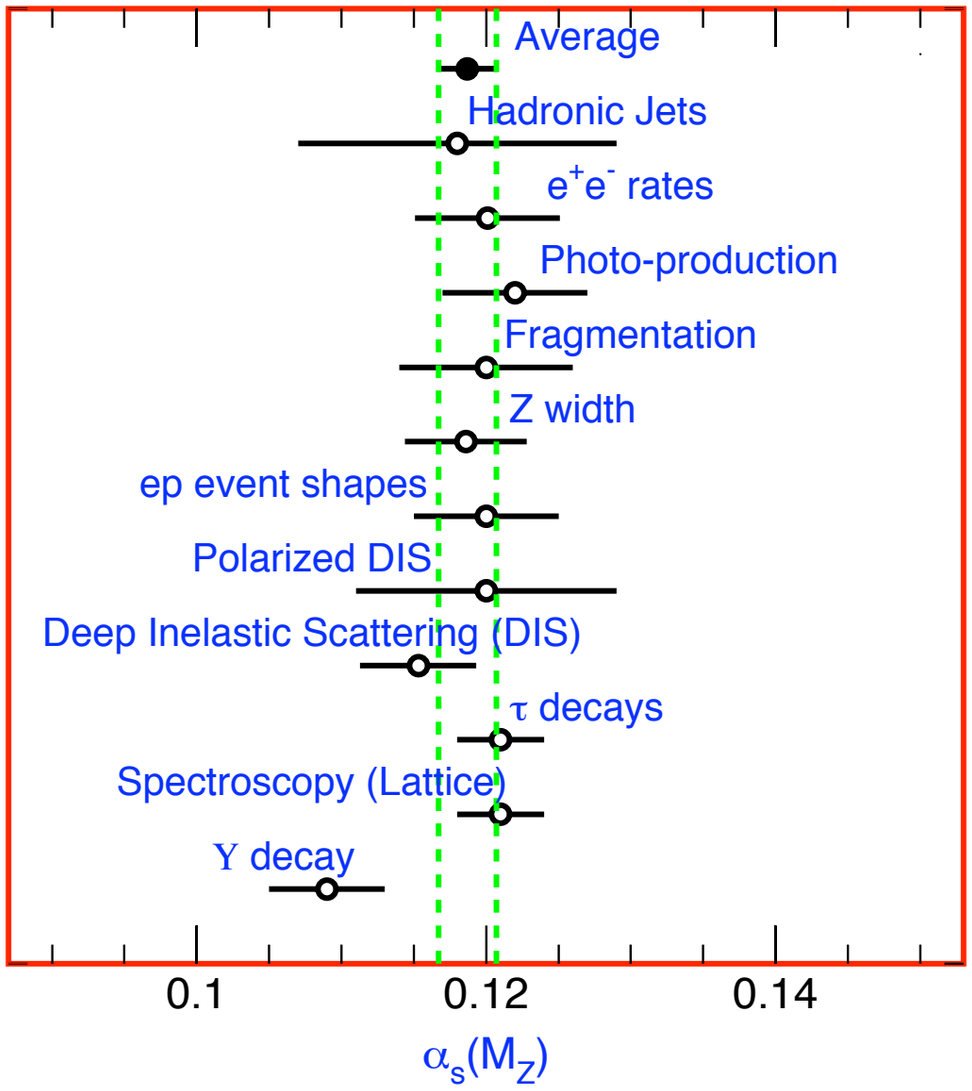
- Low energy symmetries (+ realization, breaking) $(SU(3)_L \times SU(3)_R)$

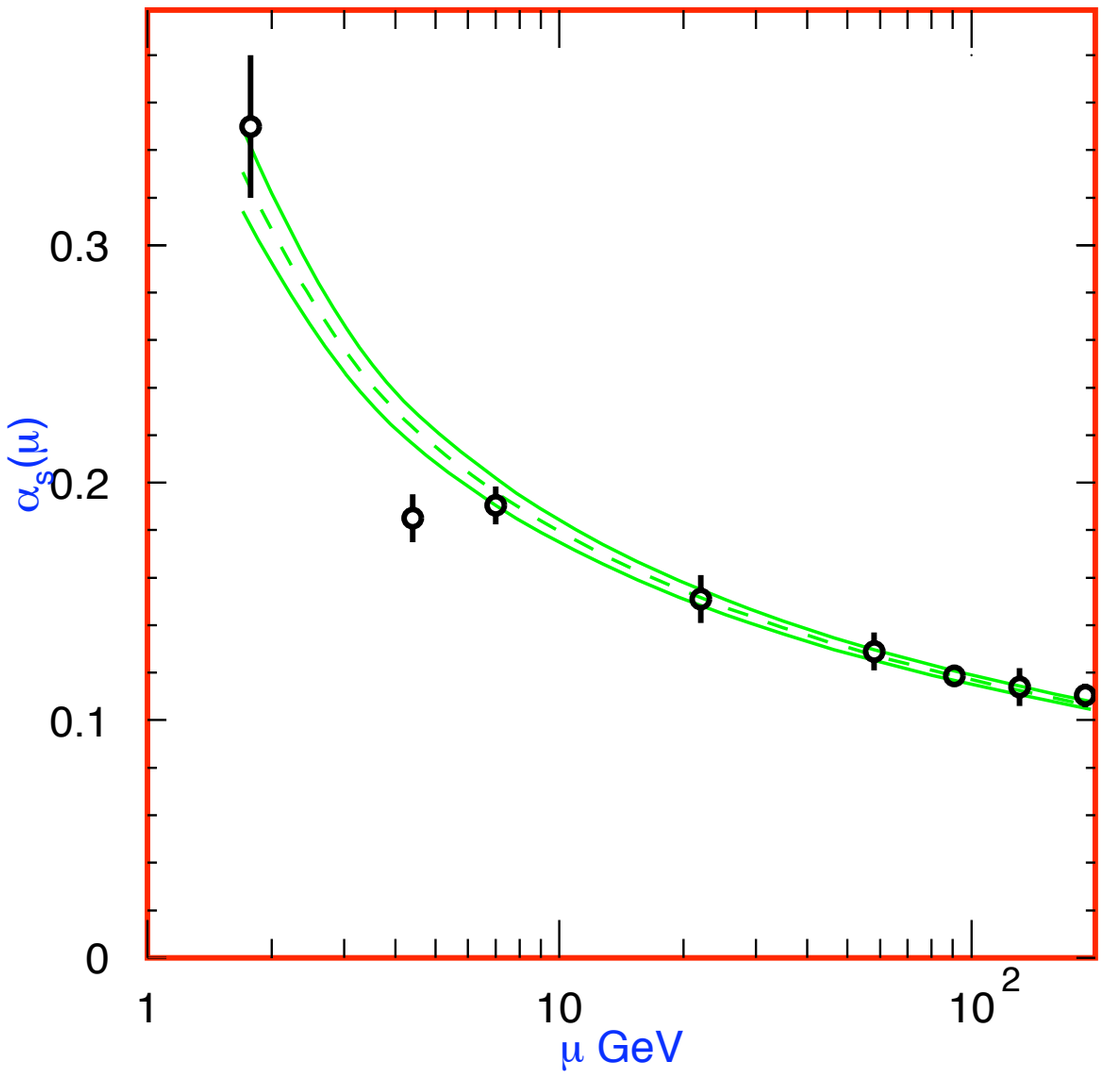
- Hadronic models: Yukawa, Regge, dual resonance (→ strings)

- Asymptotic freedom (weak coupling at high energy)



Relation of "running" α_s at different scales



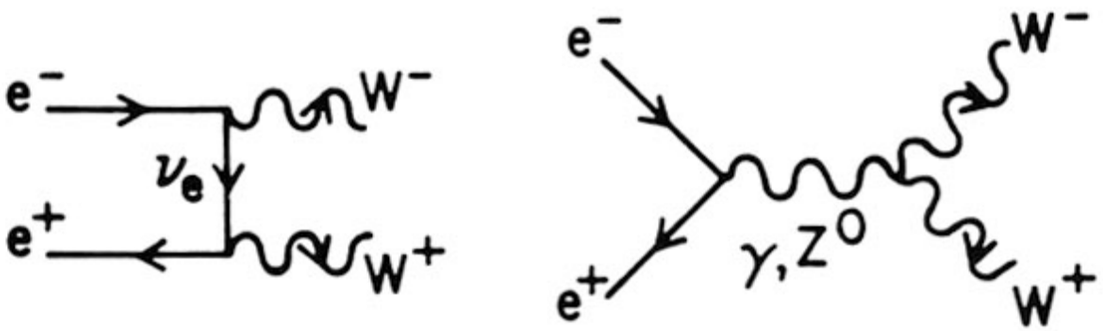


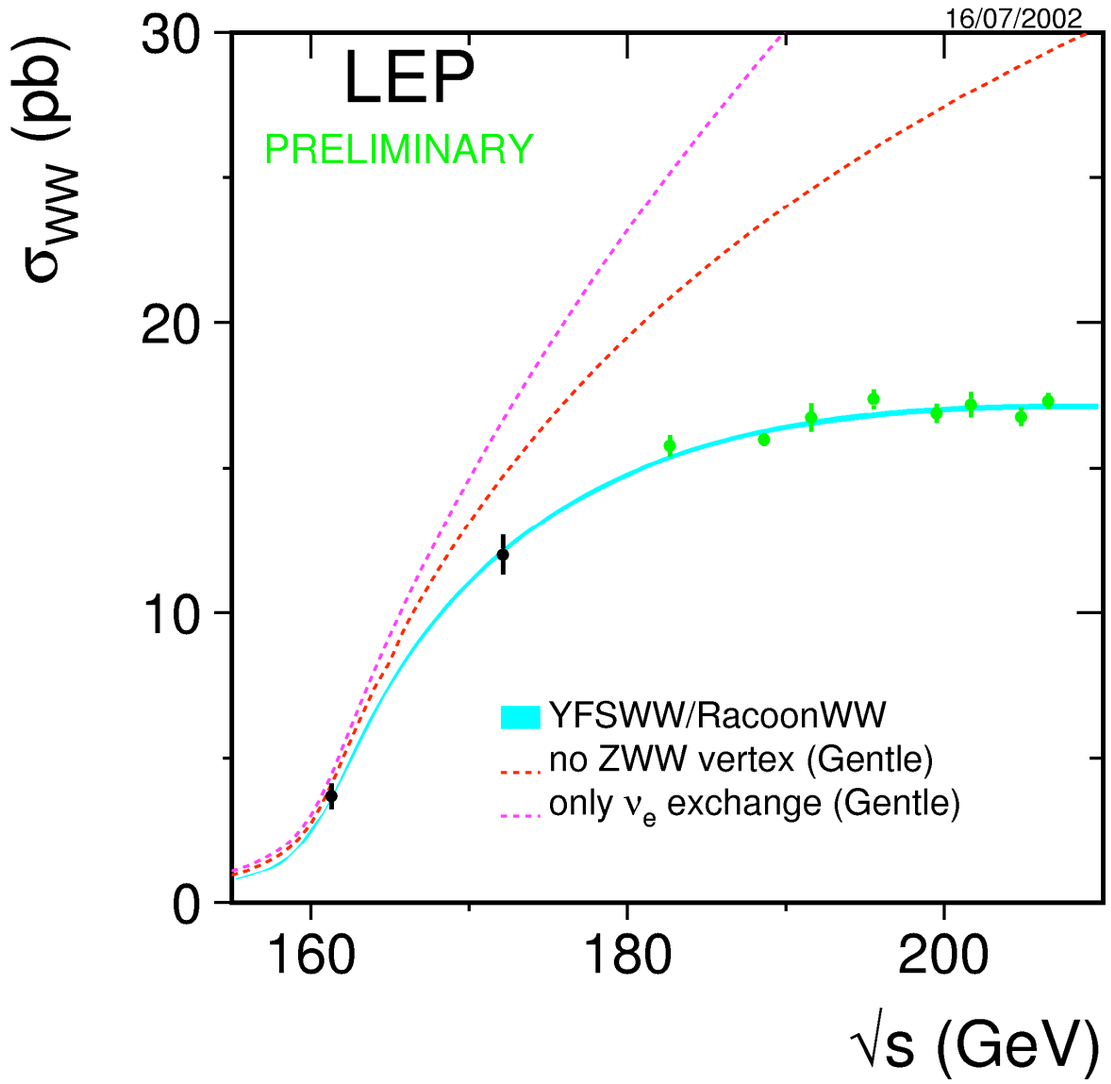
Quantum Electrodynamics

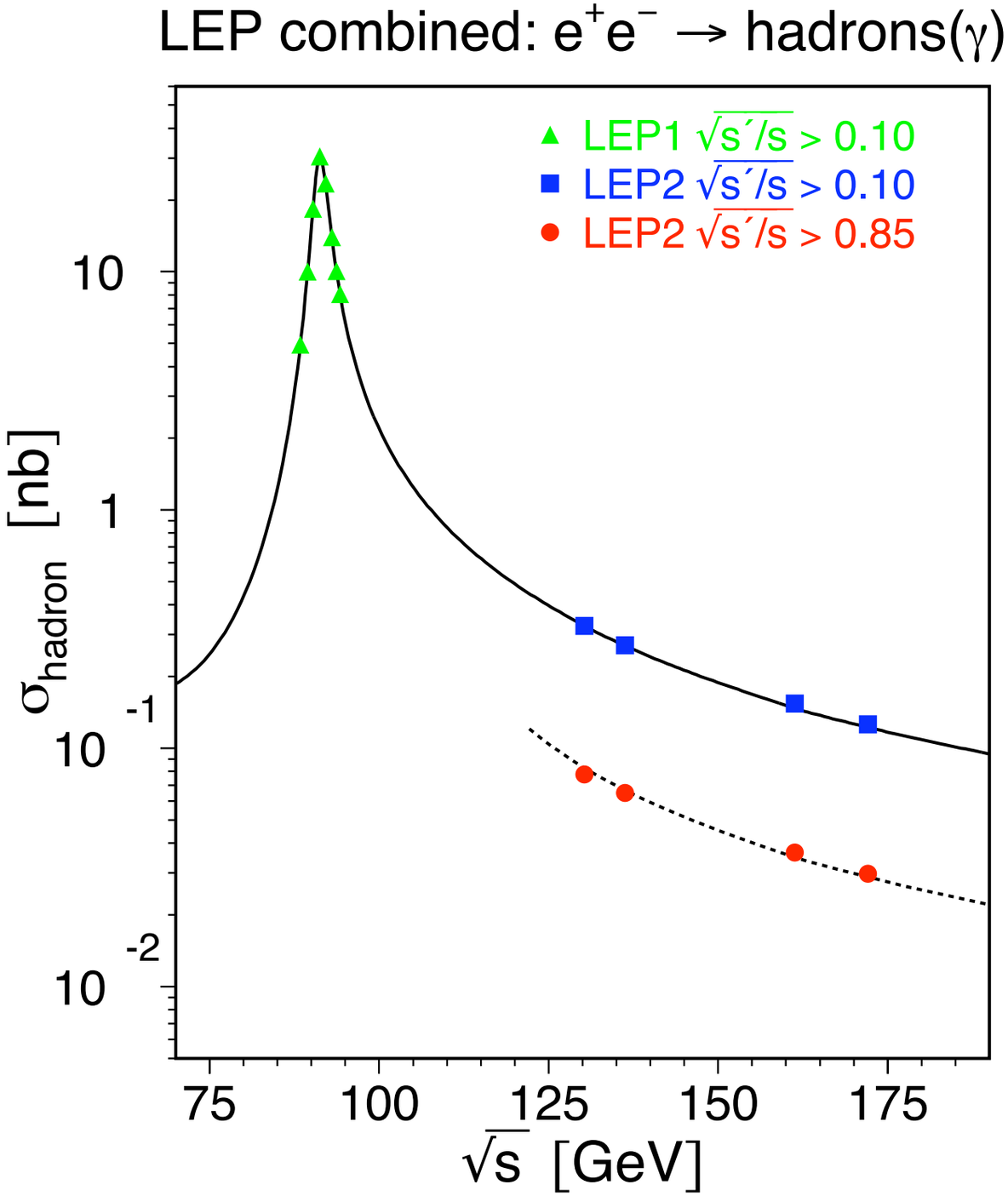
Experiment	Value of α^{-1}		Difference from $\alpha^{-1}(a_e)$
Deviation from gyromagnetic ratio, $a_e = (g-2)/2$ for e^-	$137.035\ 999\ 58\ (52)$	$[3.8 \times 10^{-9}]$	–
ac Josephson effect	$137.035\ 988\ 0\ (51)$	$[3.7 \times 10^{-8}]$	$(0.116 \pm 0.051) \times 10^{-4}$
h/m_n (m_n is the neutron mass) from n beam	$137.036\ 011\ 9\ (51)$	$[3.7 \times 10^{-8}]$	$(-0.123 \pm 0.051) \times 10^{-4}$
Hyperfine structure in muonium, $\mu^+ e^-$	$137.035\ 993\ 2\ (83)$	$[6.0 \times 10^{-8}]$	$(0.064 \pm 0.083) \times 10^{-4}$
Cesium D_1 line	$137.035\ 992\ 4\ (41)$	$[3.0 \times 10^{-8}]$	$(0.072 \pm 0.041) \times 10^{-4}$

The Electroweak Theory

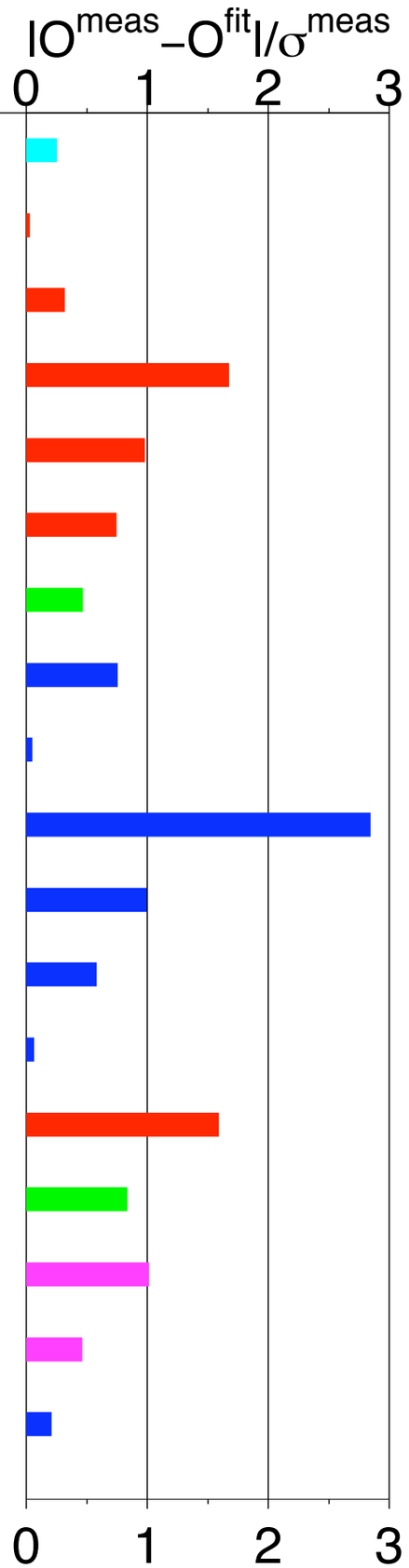
- **QED and weak charged current unified**
- **Weak neutral current predicted**
- **Stringent tests of wnc, Z-pole and beyond**
- **Fermion gauge and gauge self interactions**

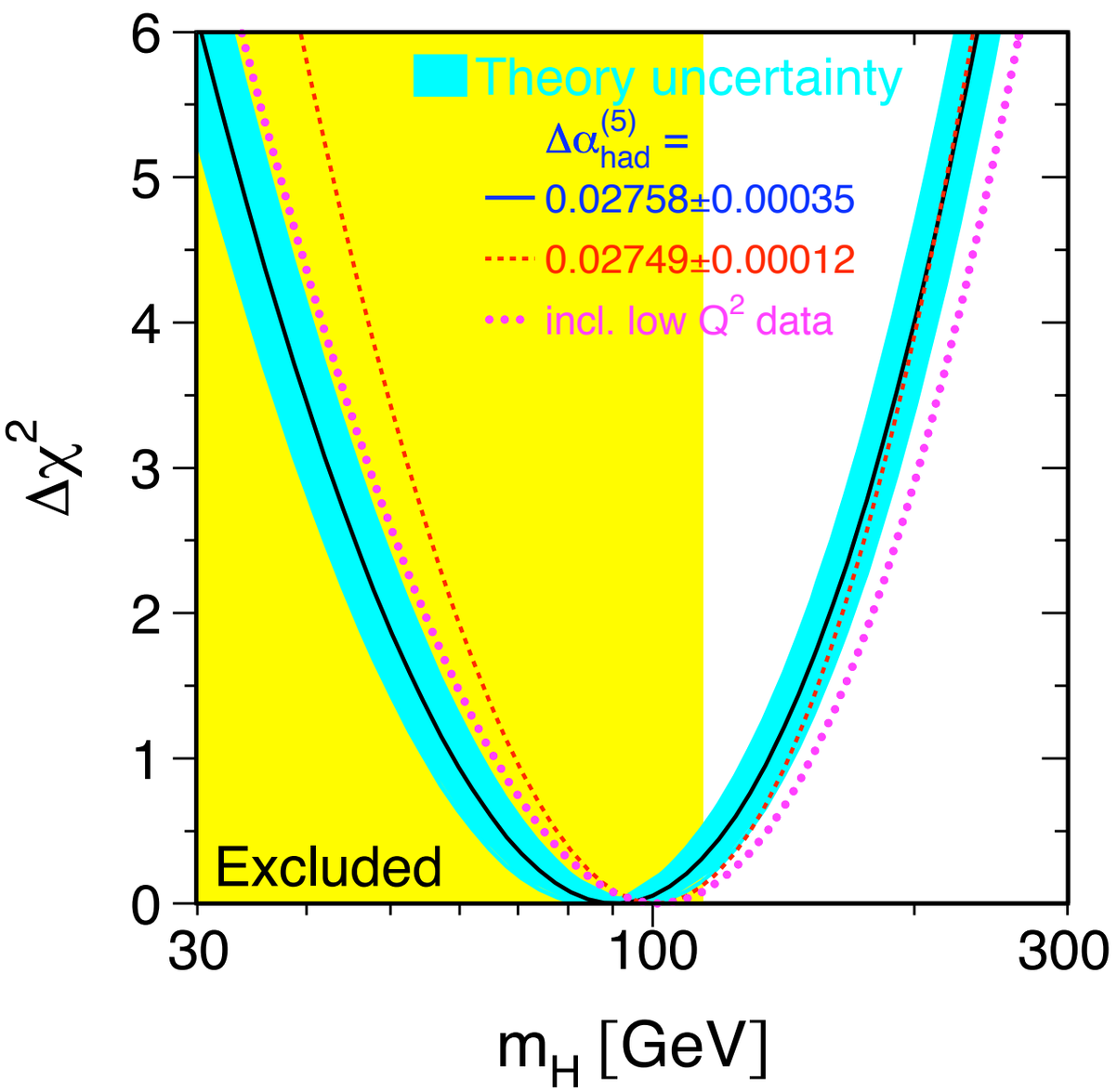





LEP combined: $e^+e^- \to$ hadrons(γ)
LEP1 $\sqrt{s'/s} > 0.10$
LEP2 $\sqrt{s'/s} > 0.10$
LEP2 $\sqrt{s'/s} > 0.85$
σ_{hadron} [nb]
10
1
10^{-1}
10^{-2}
75
100
125
150
175
$\sqrt{s}$ [GeV]

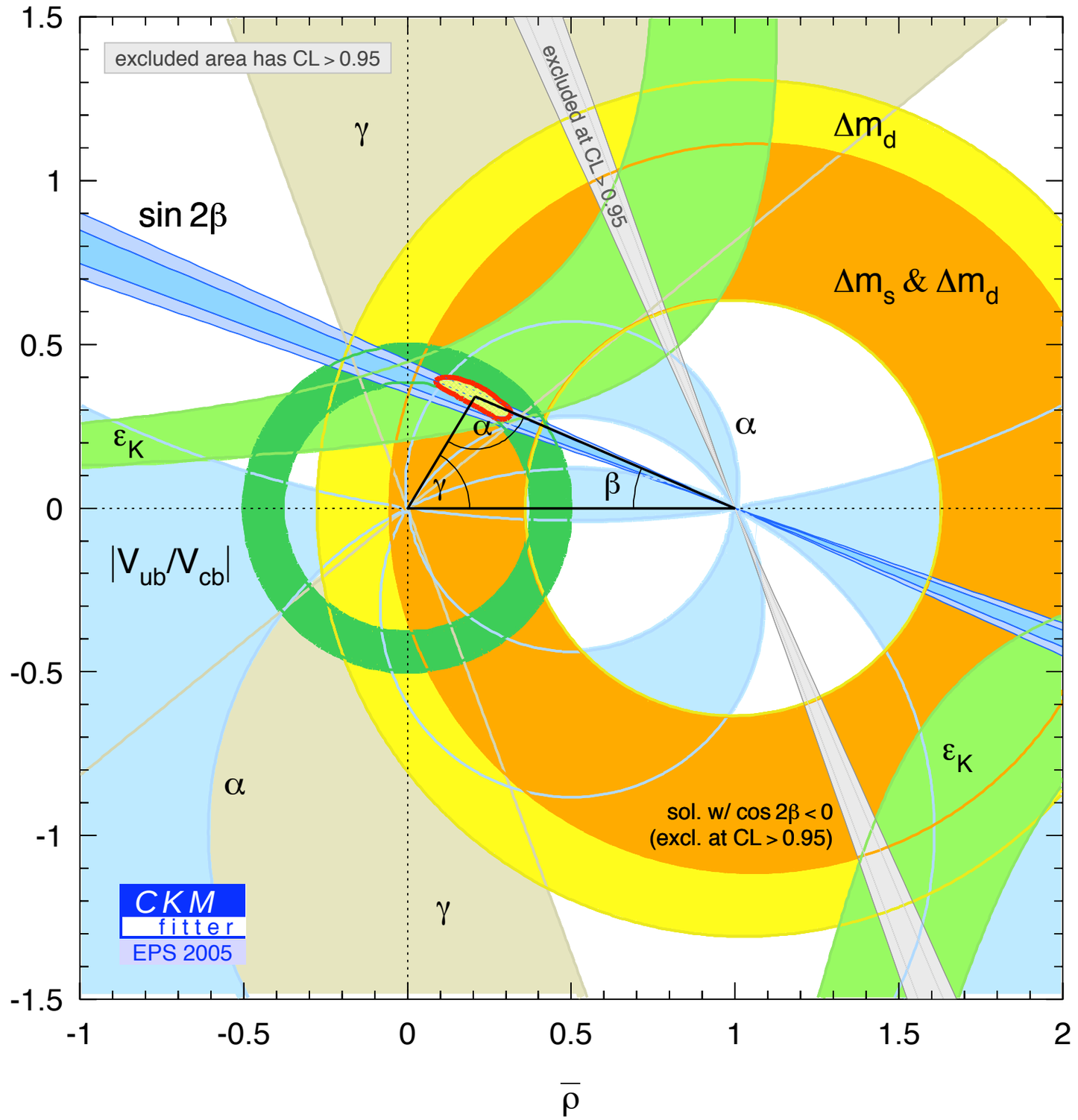
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.410 ± 0.032	80.377
Γ_W [GeV]	2.123 ± 0.067	2.092
m_t [GeV]	172.7 ± 2.9	173.3





- **SM correct and unique to zeroth approx. (gauge principle, group, representations)**
- **SM correct at loop level (renorm gauge theory; m_t, α_s, M_H)**
- **TeV physics severely constrained (unification vs compositeness)**
- **Consistent with light elementary Higgs**
- **Precise gauge couplings (gauge unification)**

- **Heavy B decays and CP violation**
  - **CKM (quark mixing) $\longrightarrow$ CP breaking**
  - **Unitarity triangle**
  - **Search for new physics**
  - **Anomalies in electroweak penguins?**
  - **Baryogenesis?**
- **Universality?**
  - $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$



Problems with the Standard Model

Lagrangian after symmetry breaking:

$$\mathcal{L} = L_{\rm gauge} + L_{\rm Higgs} + \sum_i \bar{\psi}_i \left(i \not{\partial} - m_i - \frac{m_i H}{\nu} \right) \psi_i$$

$$- \frac{g}{2\sqrt{2}} \left(J^\mu_W W^-_\mu + J^{\mu\dagger}_W W^+_\mu \right) - e J^\mu_Q A_\mu - \frac{g}{2\cos\theta_W} J^\mu_Z Z_\mu$$

Standard model: $SU(2)\times U(1)$ (extended to include ν masses) + QCD + general relativity

Mathematically consistent, renormalizable theory

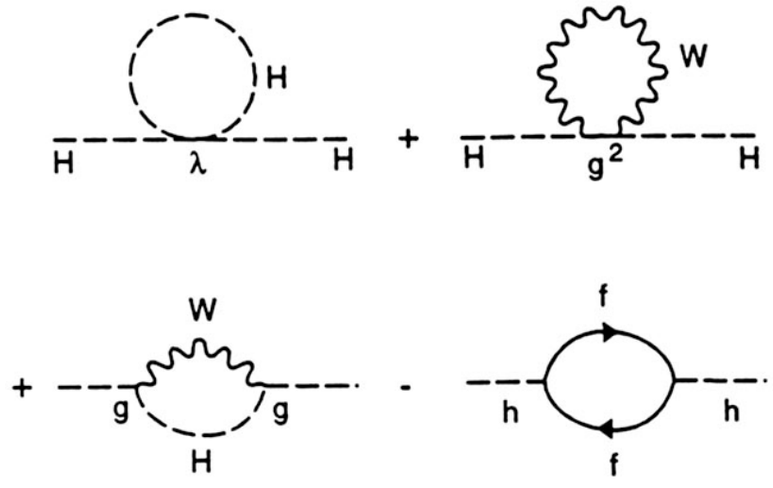
Correct to 10^{-16} cm

However, too much arbitrariness and fine-tuning: $O(27)$ parameters (+ 2 for Majorana ν) and electric charges

- Gauge Problem
  - complicated gauge group with 3 couplings
  - charge quantization ($|q_e| = |q_p|$) unexplained
  - Possible solutions: strings; grand unification; magnetic monopoles (partial); anomaly constraints (partial)

- Fermion problem
  - Fermion masses, mixings, families unexplained
  - Neutrino masses, nature? Probe of Planck/GUT scale?
  - CP violation inadequate to explain baryon asymmetry
  - Possible solutions: strings; brane worlds; family symmetries; compositeness; radiative hierarchies. New sources of CP violation.

- **Higgs/hierarchy problem**
  - **Expect $M_H^2 = O(M_W^2)$**
  - **higher order corrections: $\delta M_H^2/M_W^2 \sim 10^{34}$**



Possible solutions: supersymmetry; dynamical symmetry breaking; large extra dimensions; Little Higgs; anthropically motivated fine-tuning (split supersymmetry) (landscape)

- **Strong CP problem**
  - **Can add $\frac{\theta}{32\pi^2} g_s^2 F\tilde{F}$ to QCD (breaks, P, T, CP)**
  - **$d_N \Rightarrow \theta < 10^{-9}$, but $\delta\theta|_{\rm weak} \sim 10^{-3}$**
  - **Possible solutions: spontaneously broken global $U(1)$ (Peccei-Quinn) $\Rightarrow$ axion; unbroken global $U(1)$ (massless u quark); spontaneously broken CP + other symmetries**

- **Graviton problem**
  - **gravity not unified**
  - **quantum gravity not renormalizable**
  - **cosmological constant:** $\Lambda_{\rm SSB} = 8\pi G_N \langle V \rangle > 10^{50} \Lambda_{\rm obs}$ **(10^{124} for GUTs, strings)**
  - **Possible solutions:**
    - **supergravity and Kaluza Klein unify**
    - **strings yield finite gravity.**
    - **Λ? Anthropically motivated fine-tuning (landscape)?**

- **Necessary new ingredients**
  - **Mechanism for small neutrino masses**
    - **Planck/GUT scale?**
  - **Mechanism for baryon asymmetry?**
    - **Electroweak transition (Z' or extended Higgs?)**
    - **Heavy Majorana neutrino decay (seesaw)?**
    - **Decay of coherent field? CPT violation?**

- What is the dark energy?
  - Cosmological Constant? Quintessence?
  - Related to inflation? Time variation of couplings?
- What is the dark matter?
  - Lightest supersymmetric particle? Axion?
- Suppression of flavor changing neutral currents? Proton decay? Electric dipole moments?
  - *Automatic* in standard model, but not in extensions

Beyond the Standard Model

- **The Whimper: A new layer at the TeV scale**
- **The Hybrid: low fundamental scale/large extra dimensions**
- **The Bang: unification at the Planck scale, $M_P = G_N^{-1/2} \sim 10^{19}$ GeV**

Model	Typical scale (GeV)	Motivation
New Ws, Zs, fermions, Higgs	10^2–10^{19}	Remnant of something else
Family symmetry	10^2–10^{19}	Fermion (No compelling models)
Composite fermions	10^2–10^{19}	Fermion (No compelling models)
Composite Higgs	10^3–10^4	Higgs (No compelling models)
Composite W, Z (G, γ?)	10^3–10^4	Higgs (No compelling models)
Little Higgs	10^3–10^4	Higgs
Large extra dimensions ($d > 4$)	10^3–10^6	Higgs, graviton
New global symmetry	10^8–10^{12}	Strong CP
Kaluza–Klein	10^{19}	Graviton
Higgs (0) $\Leftrightarrow$ gauge (1) $\Leftrightarrow$ Graviton (2) ($d > 4$)		
Grand unification	10^{14}–10^{19}	Gauge
Strong $\Leftrightarrow$ electroweak		
Supersymmetry/supergravity	10^2–10^{19}	Higgs, graviton
Fermion $\Leftrightarrow$ boson		

Compositeness

- Onion-like layers
- Composite fermions, scalars (dynamical sym. breaking)
- Not like to atom $\longrightarrow$ nucleus $+e^- \longrightarrow p + n \longrightarrow$ quark
- Other new TeV layer: Little Higgs
- At most one more layer accessible (Tevatron, LHC, ILC)
- Rare decays (e.g., $K \longrightarrow \mu e$)
- Typically, few % effects at LEP/SLC, WNC (challenge for models)
- anomalous VVV, new particles, future $WW \longrightarrow WW$, FCNC, EDM

Large extra dimensions (deconstruction, brane worlds)

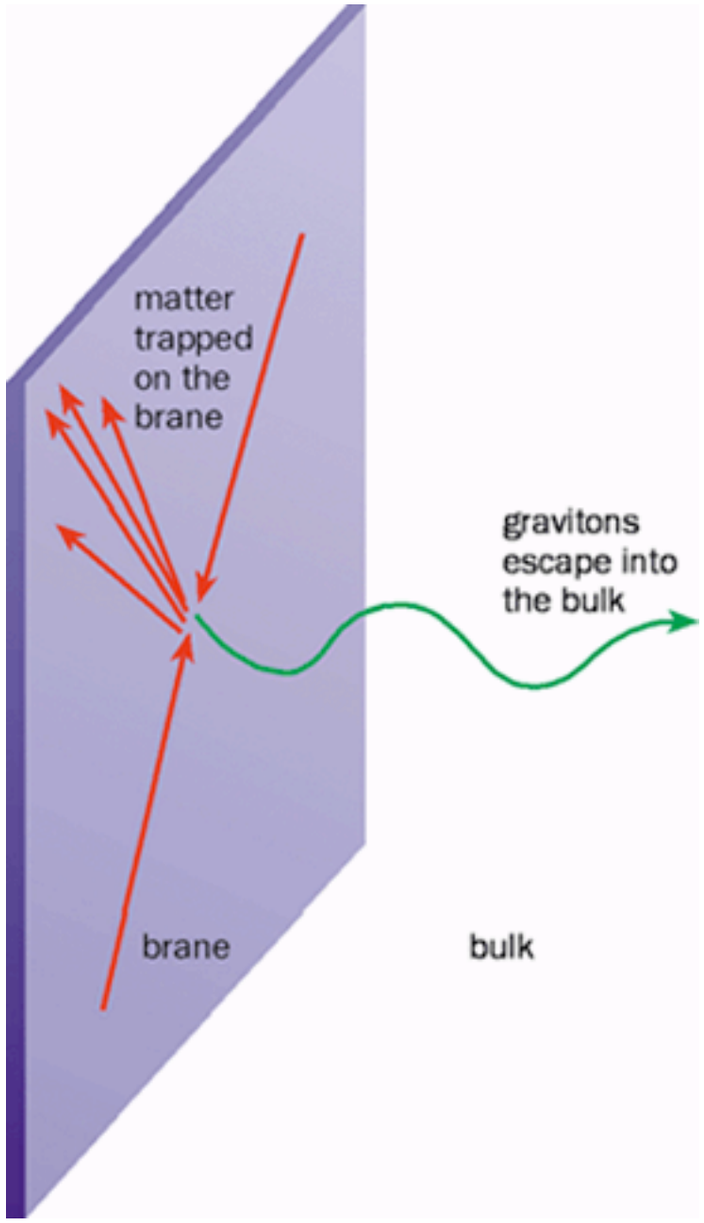
- **Can be motivated by strings, but new dimensions much larger than $M_P^{-1} \sim 10^{-33}$ cm**

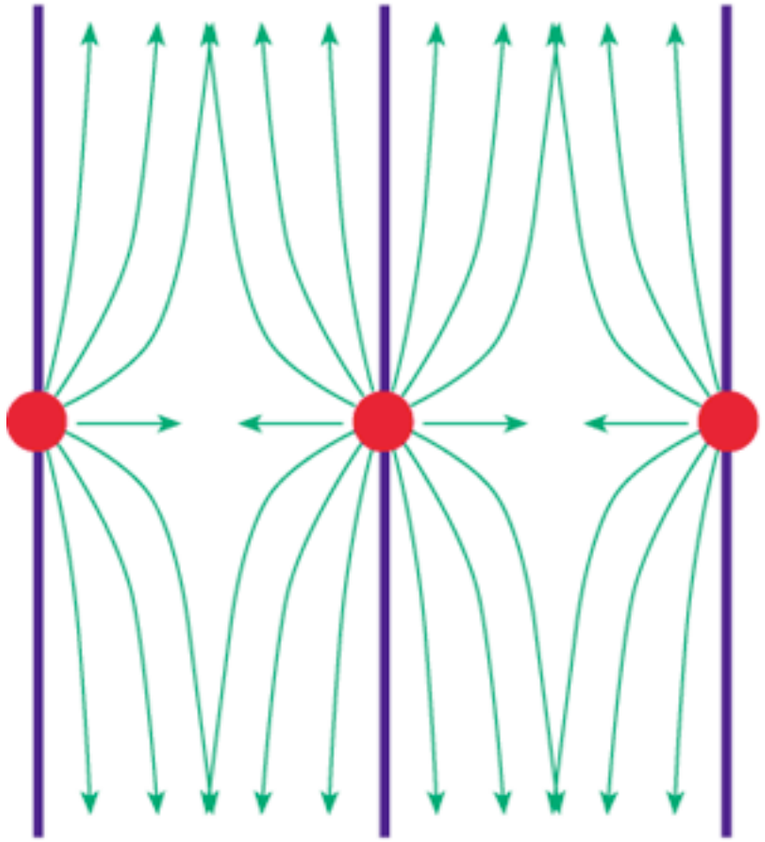
- **Fundamental scale $M_F \sim 1 - 100$ TeV $\ll \bar{M}_{Pl} = 1/\sqrt{8\pi G_N} \sim 2.4 \times 10^{18}$ GeV**

  – **Assume δ extra dimensions with volume $V_\delta \gg M_F^{-\delta}$**

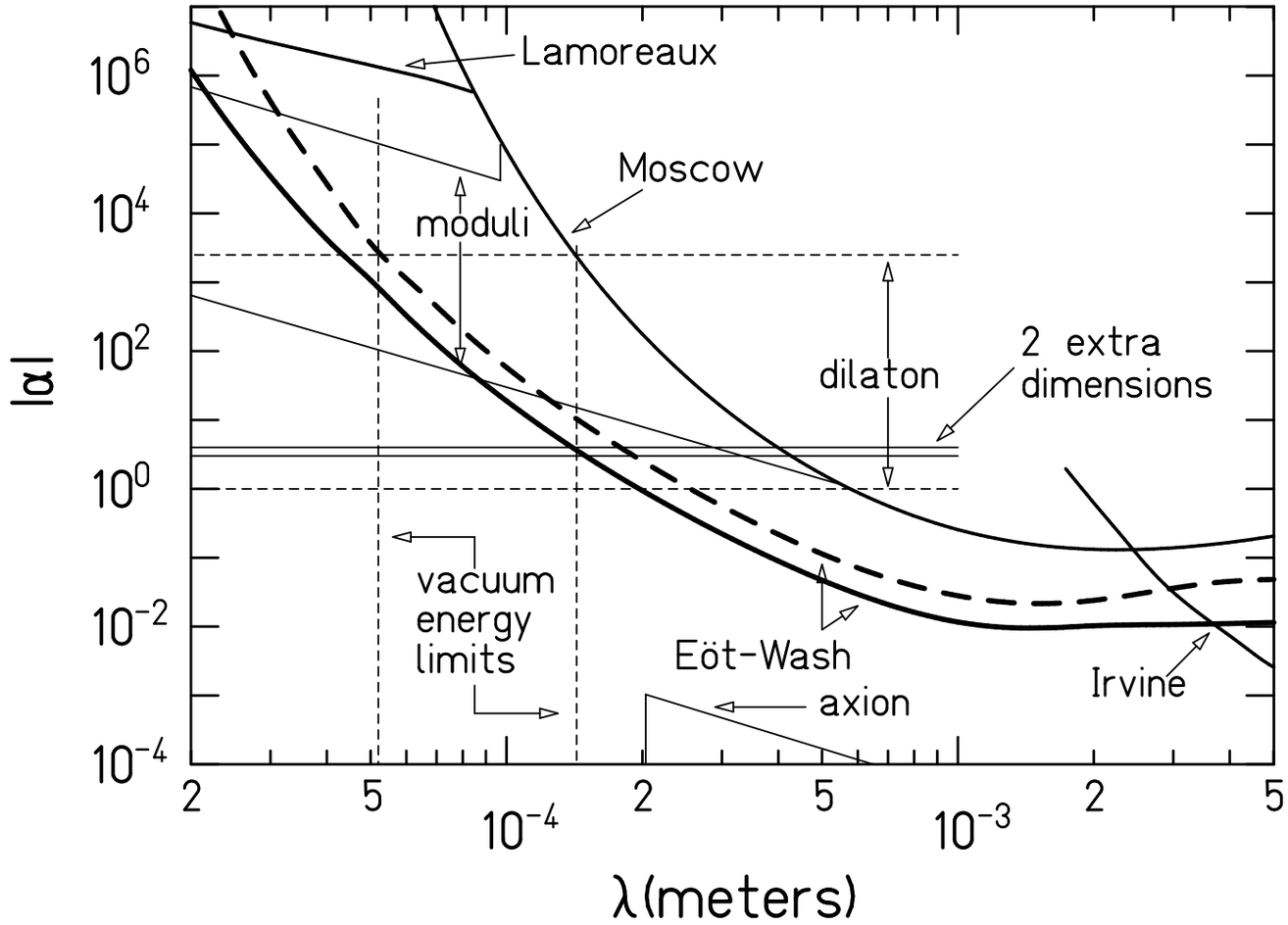
$$\bar{M}_{Pl}^2 = M_F^{2+\delta} V_\delta \gg M_F^2$$

(Introduces new hierarchy problem)





- **Black holes, graviton emission at colliders!**
- **Macroscopic gravity effects**
- **Astrophysics**



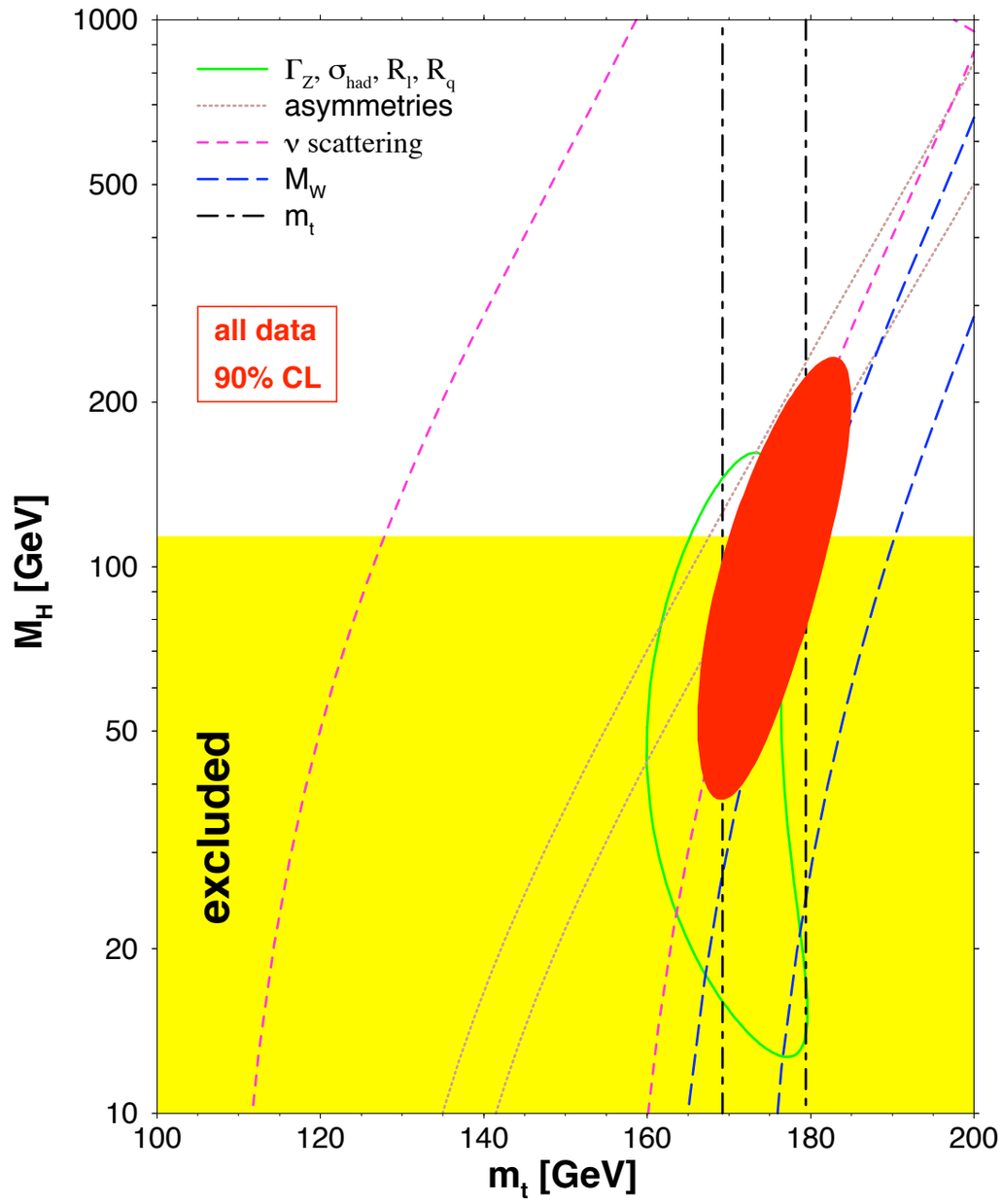
Unification

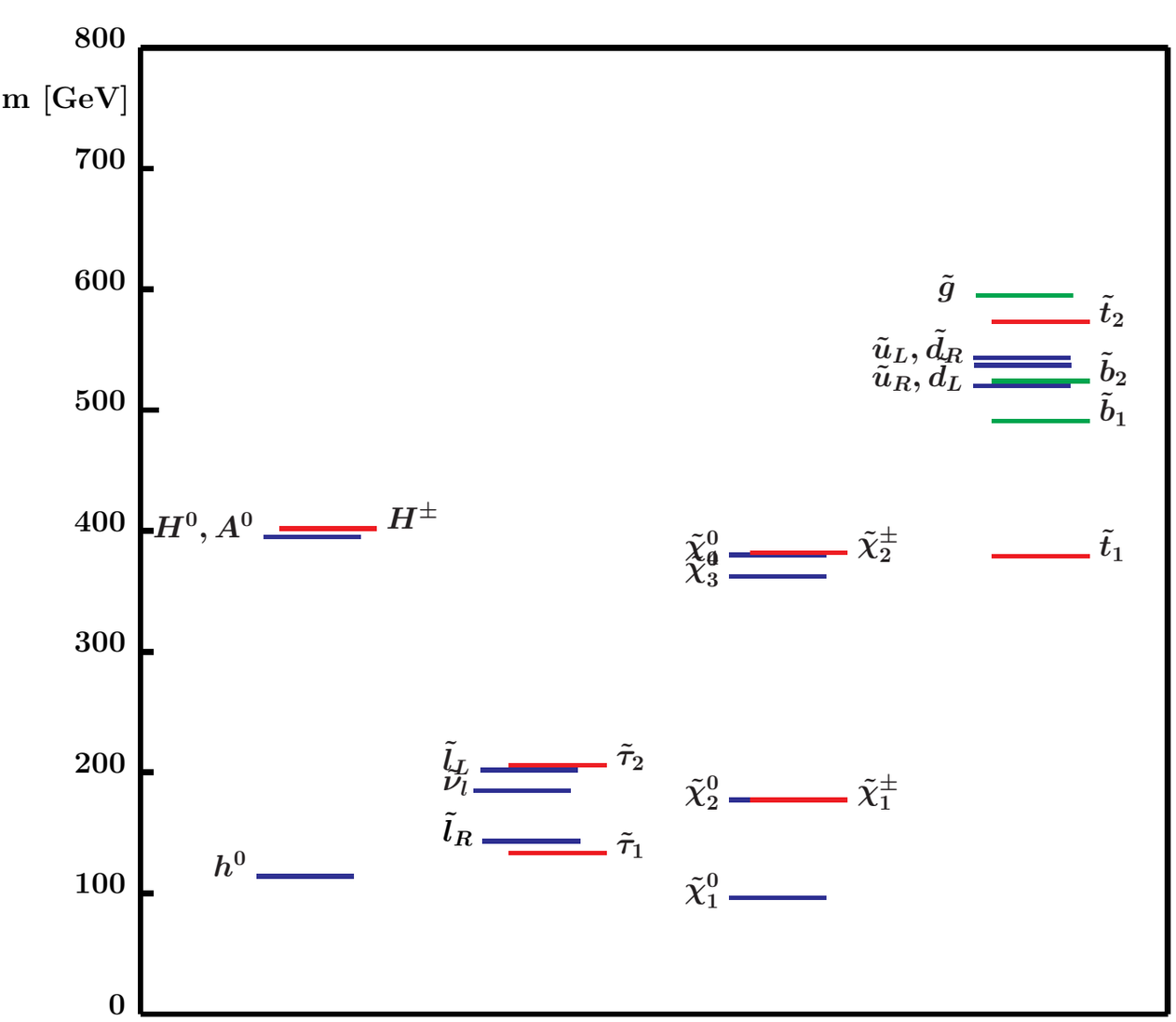
- **Unification of interactions**
- **Grand desert to unification (GUT) or Planck scale**
- **Elementary Higgs, supersymmetry (SUSY), GUTs, strings**
- **Possibility of probing to M_P and very early universe**

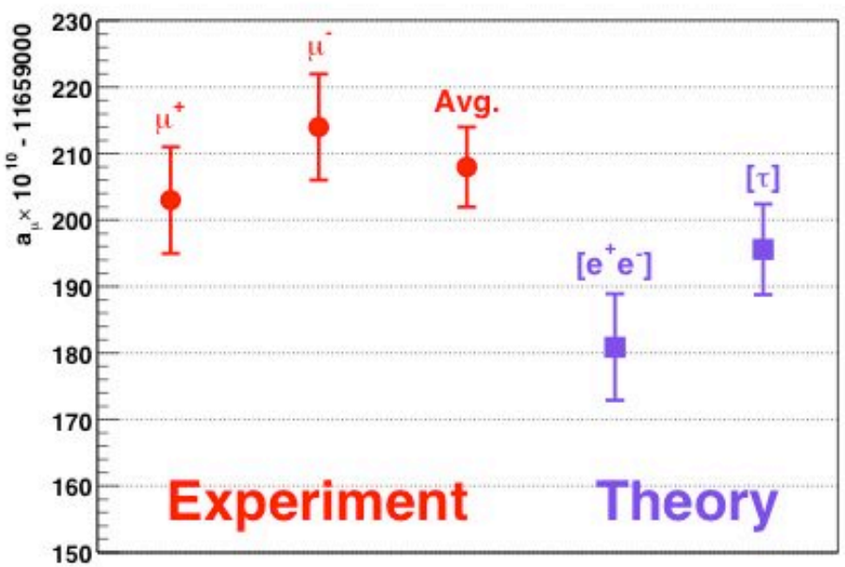
Supersymmetry

- **Fermion $\leftrightarrow$ boson symmetry**
- **Motivations**
  - **stabilize weak scale $\Rightarrow M_{SUSY} < O(1$ TeV)** **(but recent high scale ideas)**
  - **supergravity (gauged supersymmetry): unification of gravity (non-renormalizable)**
  - **coupling constants in supersymmetric grand unification**
  - **decoupling of heavy particles (precision)**

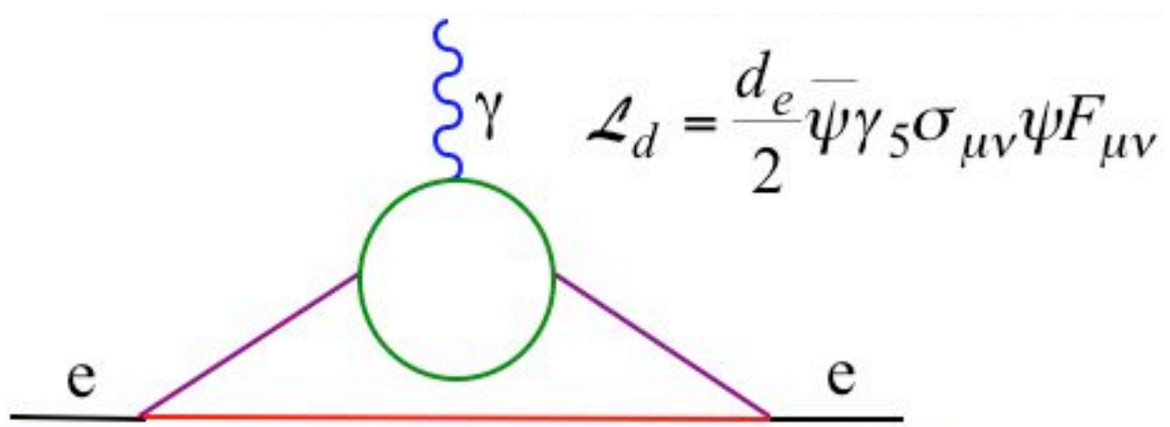
- **Consequences**
  - **additional charged and neutral Higgs particles**
  - $M^2_{H^0} < \cos^2 2\beta M^2_Z +$ **H.O.T.** $(O(m_t^4))$ $<$ **(150 GeV)^2, consistent with LEP**
    - **cf., standard model:** $M_{H^0} <$ **1000 GeV**







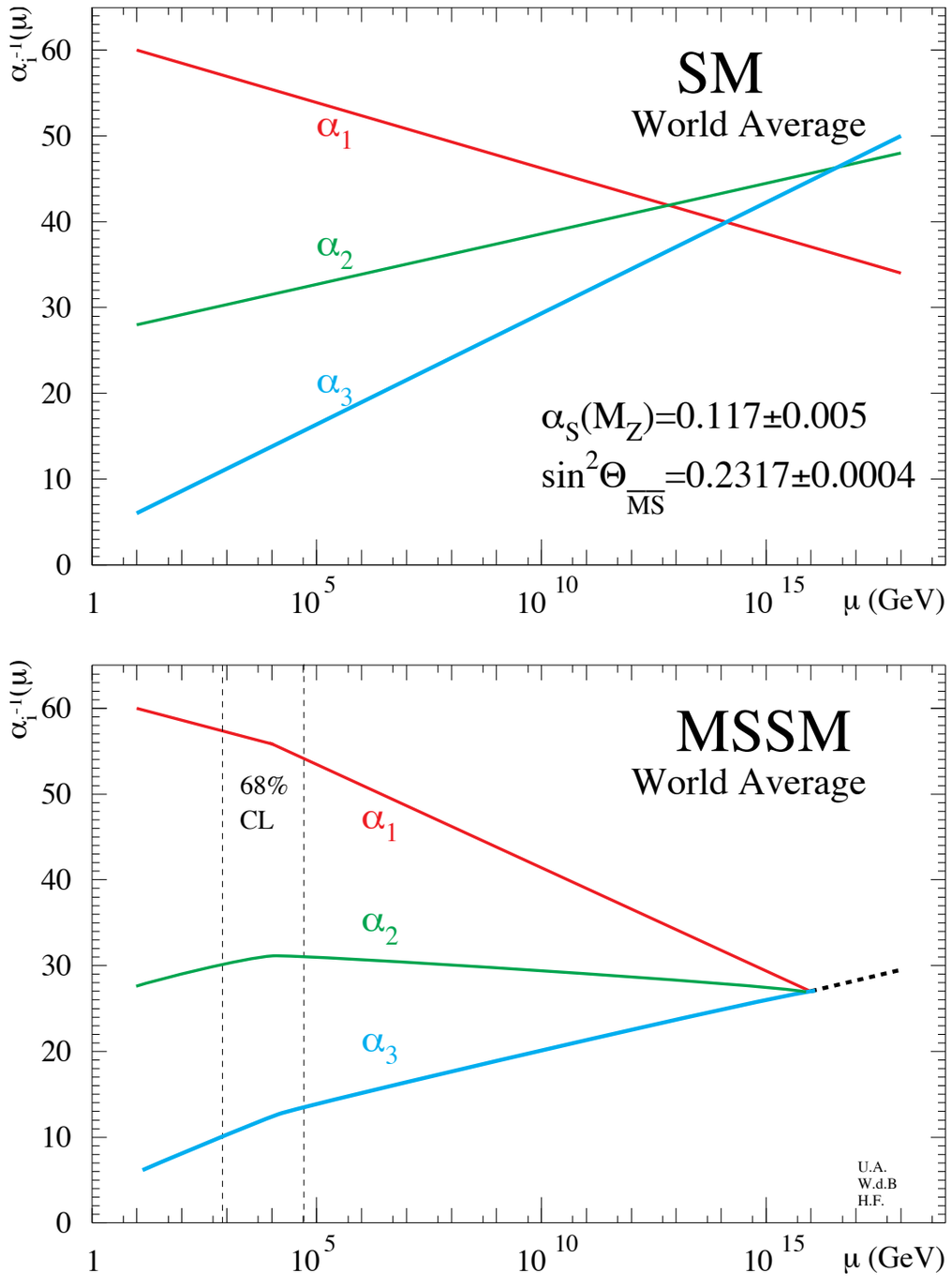
- **Superpartners**
  - $q \Rightarrow \tilde{q}$, **scalar quark**
  - $\ell \Rightarrow \tilde{\ell}$, **scalar lepton**
  - $W \Rightarrow \tilde{w}$, **wino**
  - **typical scale: several hundred GeV**
  - **LSP: cold dark matter candidate**
  - **SUSY breaking $\Leftrightarrow$ large m_t**
  - **May be large FCNC, EDM, $\Delta(g_\mu - 2)$**



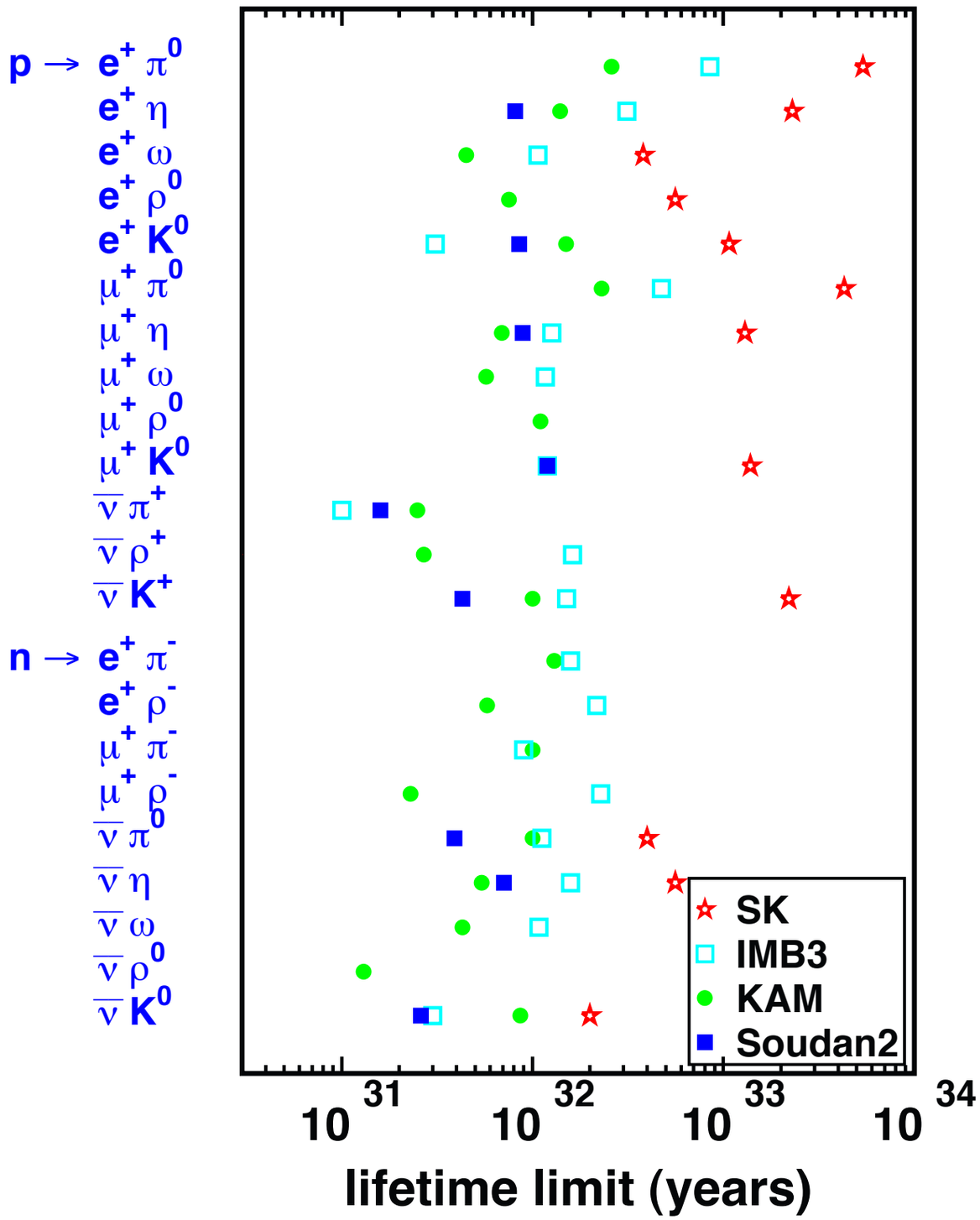
Grand Unification

- **Unify strong $SU(3)$ and electroweak $SU(2)\times U(1)$ in simple group, broken at $\sim 10^{16}$ GeV**

- **Gauge unification (only in supersymmetric version)**

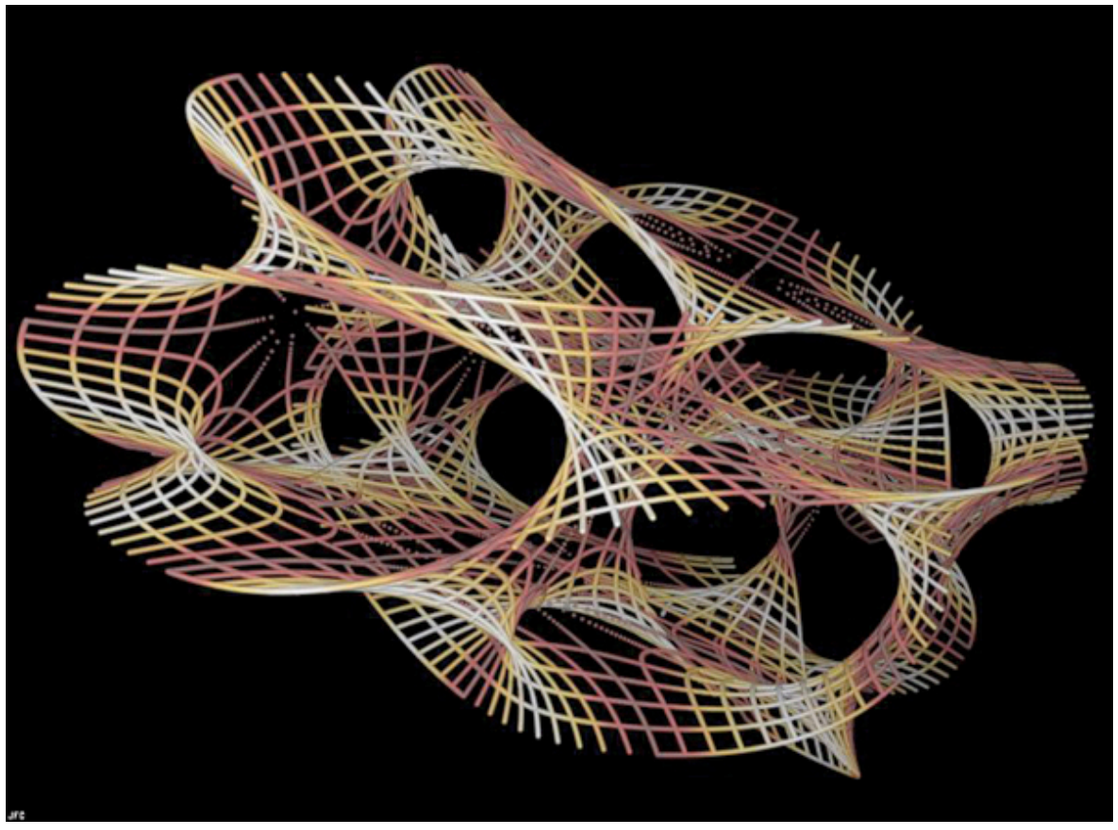


- **Seesaw model for small m_ν** (but why are mixings large?)
- **Quark-lepton $(q-l)$ unification** ($\Rightarrow$ charge quantization)
- **$q-l$ mass relations** (work only for third family in simplest versions)
- **Proton decay?** (simplest versions excluded) **Neutron oscillations?**
- **Doublet-triplet problem?**
- **String embedding?** (breaking, families may be entangled in extra dimensions)



Superstrings

- **Finite, "parameter-free" "theory of everything" (TOE), including quantum gravity**
  - **1-d string-like object**
  - **Appears pointlike for resolution $> M_P^{-1} \sim 10^{-33}$ cm**
  - **Vibrational modes $\longrightarrow$ particles**
  - **Consistent in 10 space-time dimensions $\longrightarrow$ 6 must compactify to scale M_P^{-1}**
  - **4-dim supersymmetric gauge theory below M_P**
  - **May also be solitons (branes), terminating open strings**



- **Problems**
  - **Which compactification manifold?**
  - **Supersymmetry breaking? Cosmological constant?**
  - **Many moduli (vacua). Landscape ideas - is there any predictability left?**
  - **Relation to supersymmetric standard model, GUT?**

- **Need theoretical progress *and* hints from experiment**
  - **TeV scale remnants, such as Z', extended Higgs, exotics**
  - **SUSY breaking patterns**
  - **Need very precise masses and couplings $\rightarrow$International Linear Collider**

Future/present Experiments

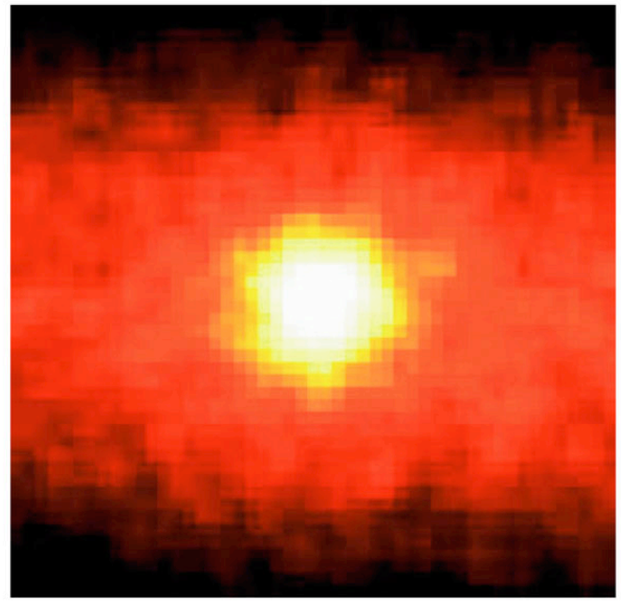
- **High energy colliders: the primary tool**
  - **TEVATRON; Fermilab, 1.96 TeV $\bar{p}p$, exploration**
  - **Large Hadron Collider (LHC); CERN, 14 TeV pp, high luminosity, discovery** (Discovery machine for supersymmetry, R_p violation, string remnants (e.g., Z', exotics, Higgs); or compositeness, dynamical symmetry breaking, Higgless theories, Little Higgs, large extra dimensions, $\cdots$)
  - **International Linear Collider (ILC), in planning; 500 GeV-1 TeV e^+e^-, cold technology, high precision studies** (Precision parameters to map back to string scale)

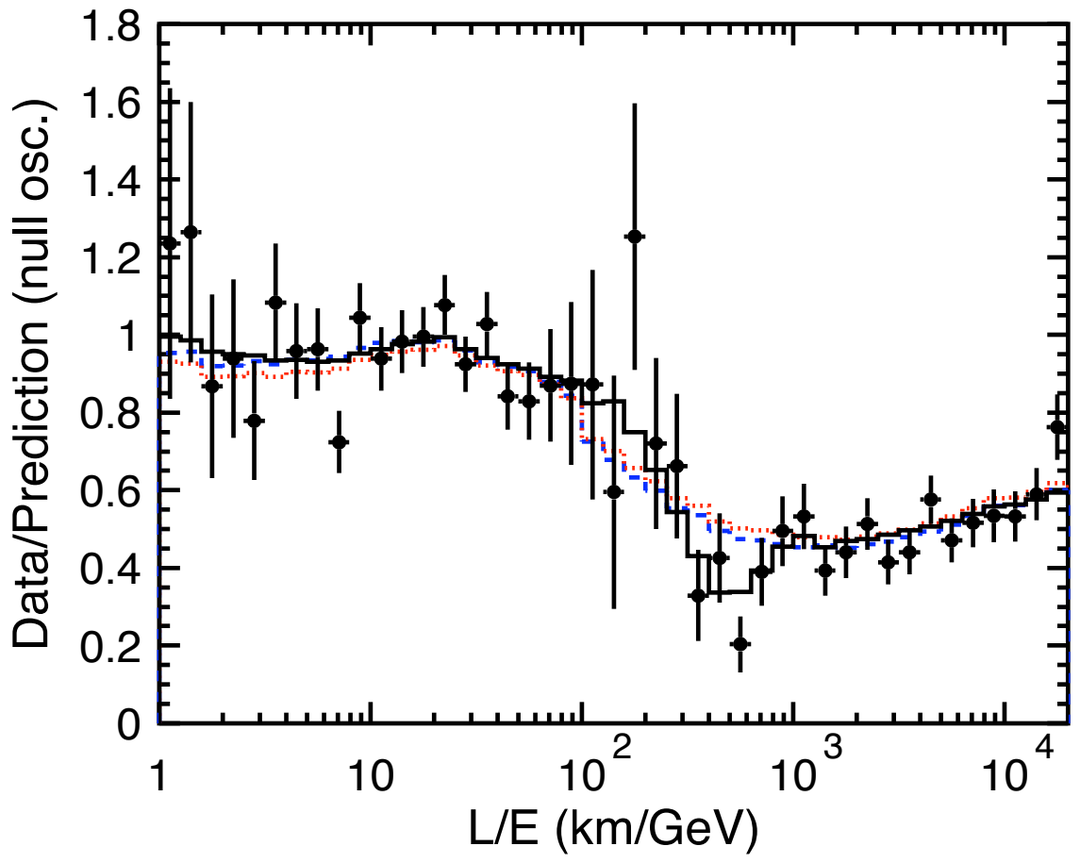
- **CP violation** (B decays, electric dipole moments)**, CKM universality, flavor changing neutral currents** (e.g., $\mu \to e\gamma$, $\mu N \to eN$, $B \to \phi K_s$)**, B violation** (proton decay, $n - \bar{n}$ oscillations)**, neutrino physics**

Neutrinos as a Unique Probe: $10^{-33} - 10^{+28}$ cm

- **Particle Physics**
  - $\nu N, \mu N, eN$ scattering: existence/ properties of quarks, QCD
  - Weak decays ($n \longrightarrow pe^-\bar{\nu}_e, \mu^- \longrightarrow e^-\nu_\mu\bar{\nu}_e$): Fermi theory, parity violation, mixing
  - Neutral current, Z-pole, atomic parity: electroweak unification, field theory, m_t; severe constraint on physics to TeV scale
  - Neutrino mass: constraint on TeV physics, grand unification, superstrings, extra dimensions; seesaw: $m_\nu \sim m_q^2/M_{\rm GUT}$

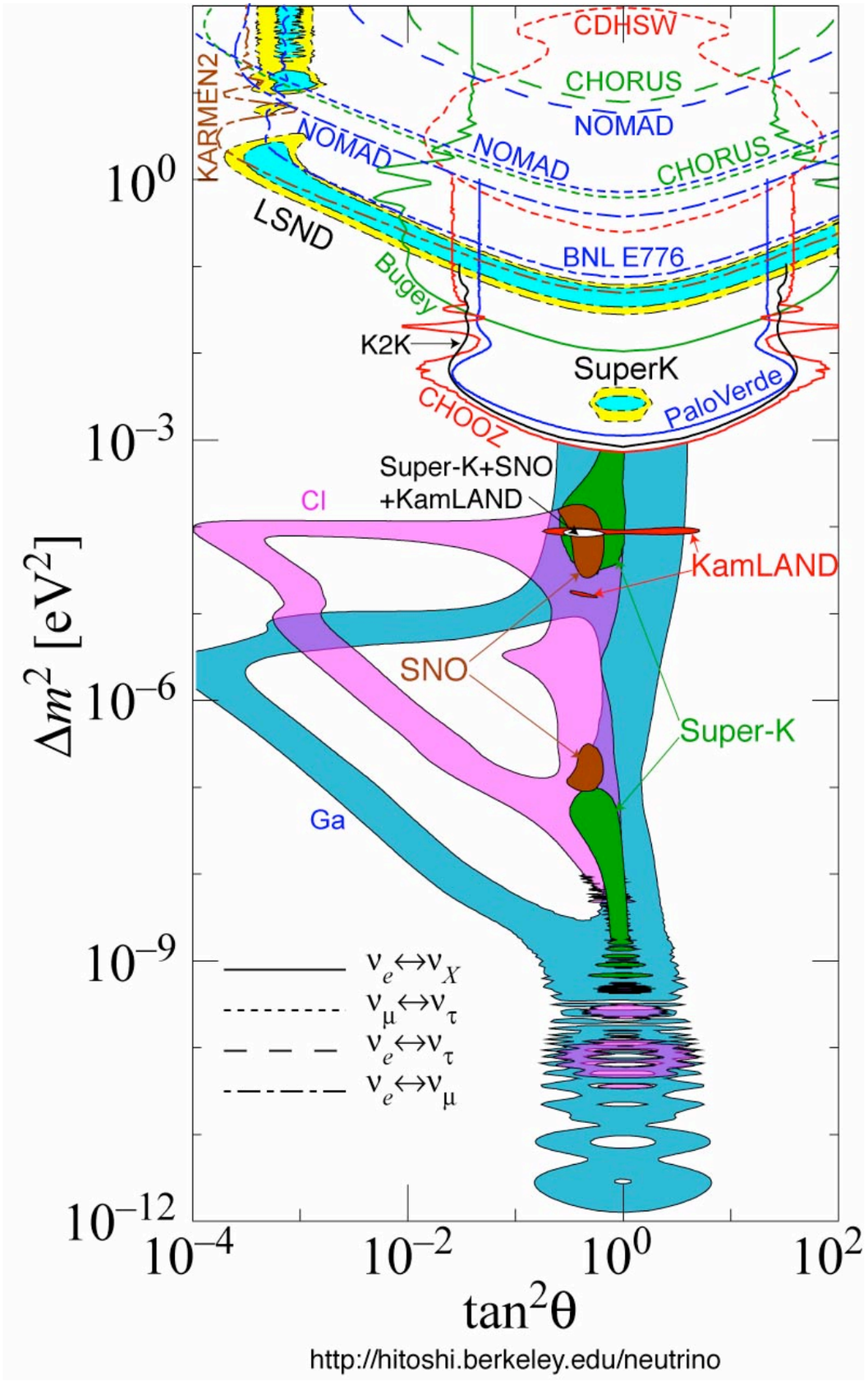
- **Solar/atmospheric neutrino experiments**
  - **Neutrinos have tiny masses (but large mixings)**
  - **Standard Solar model confirmed**
  - **First oscillation dips observed! (QM on large scale)**





3 ν Patterns

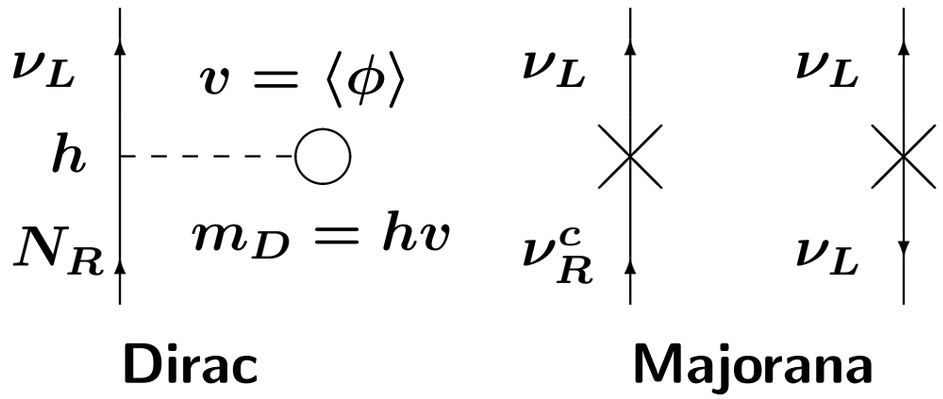
- **Solar: LMA (SNO, KamLAND)**
- **$\Delta m^2_{\odot} \sim 8\times10^{-5}$ eV^2, nonmaximal**
- **Atmospheric: $|\Delta m^2_{\rm Atm}| \sim 2\times10^{-3}$ eV^2, near-maximal mixing**
- **Reactor: U_{e3} small**



Neutrino Implications/questions

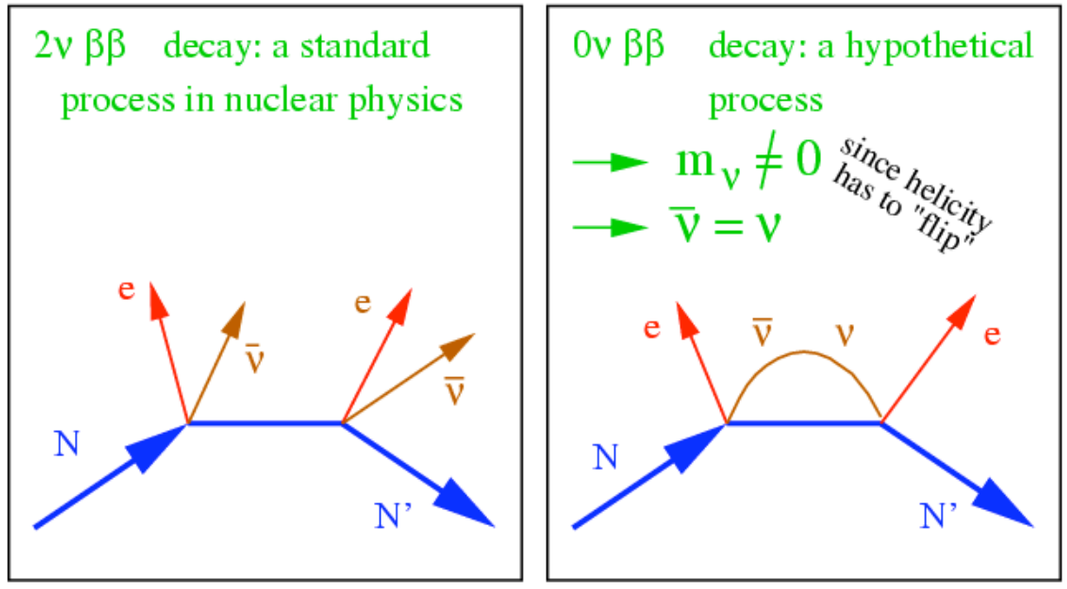
- **Key constituent of the Universe**

- **Why are the masses so small?**
  - **Planck/GUT scale? e.g., seesaw or generalization, $m_\nu \sim m_D^2/M_N$**
    (may not be generic in strings)

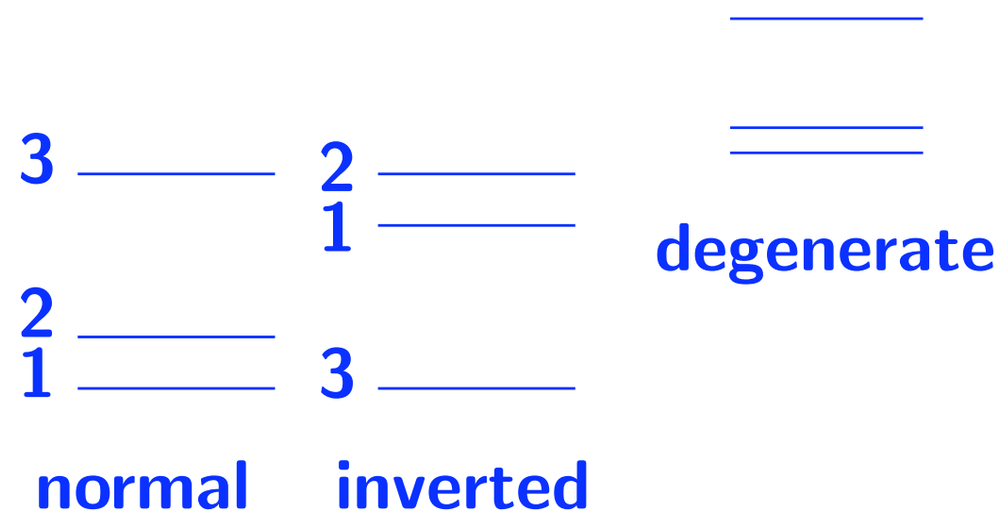


Dirac Majorana

- **Are the neutrinos Dirac or Majorana?**
  - **No SM gauge symmetry forbids Majorana (but string, extended?)**
  - **Neutrinoless double beta decay ($\beta\beta_{0\nu}$) (inverted or degenerate spectra)**

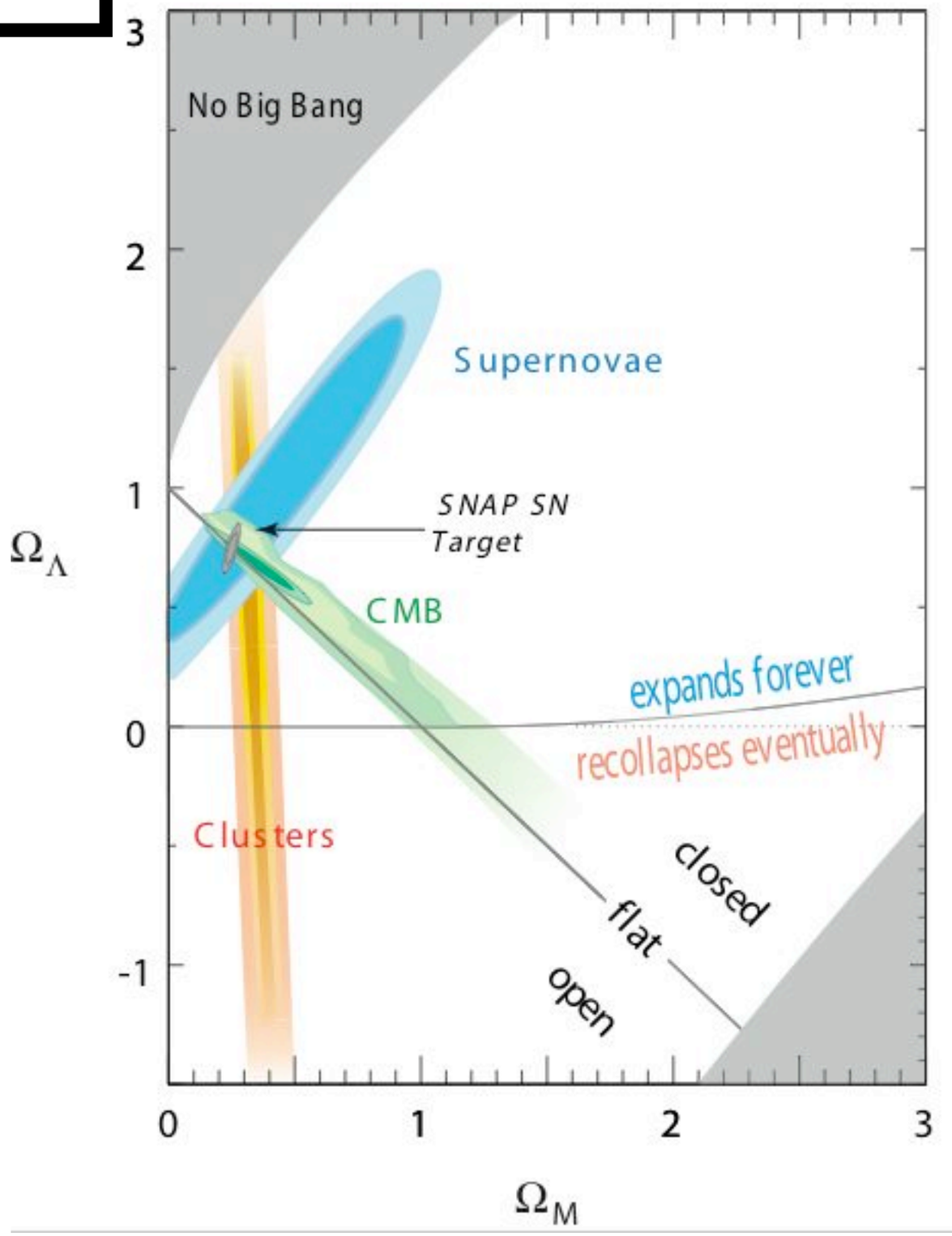


- What is the spectrum: number, mass scale/pattern, mixings
  - Scale: β decay (KATRIN), $\beta\beta_{0\nu}$, large scale structure (SDSS)
  - Mixings and CP: reactor, long baseline oscillation experiments, Solar
  - Pattern: long baseline, $\beta\beta_{0\nu}$, supernova
  - Number: LSND? MiniBooNE
- Leptogenesis?
- Relic neutrinos?
  - Indirect: Nucleosynthesis, large scale structure. Direct? (Z-burst?)

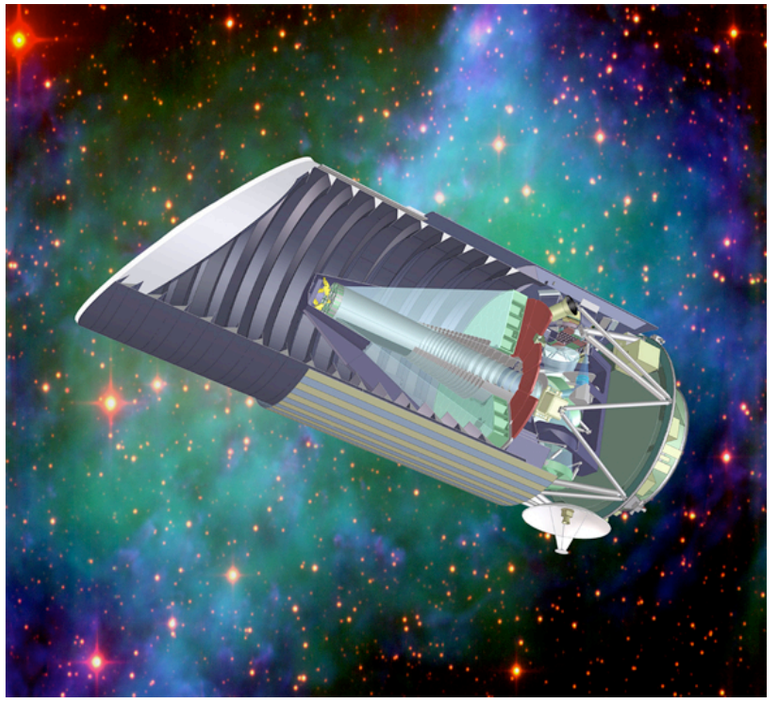


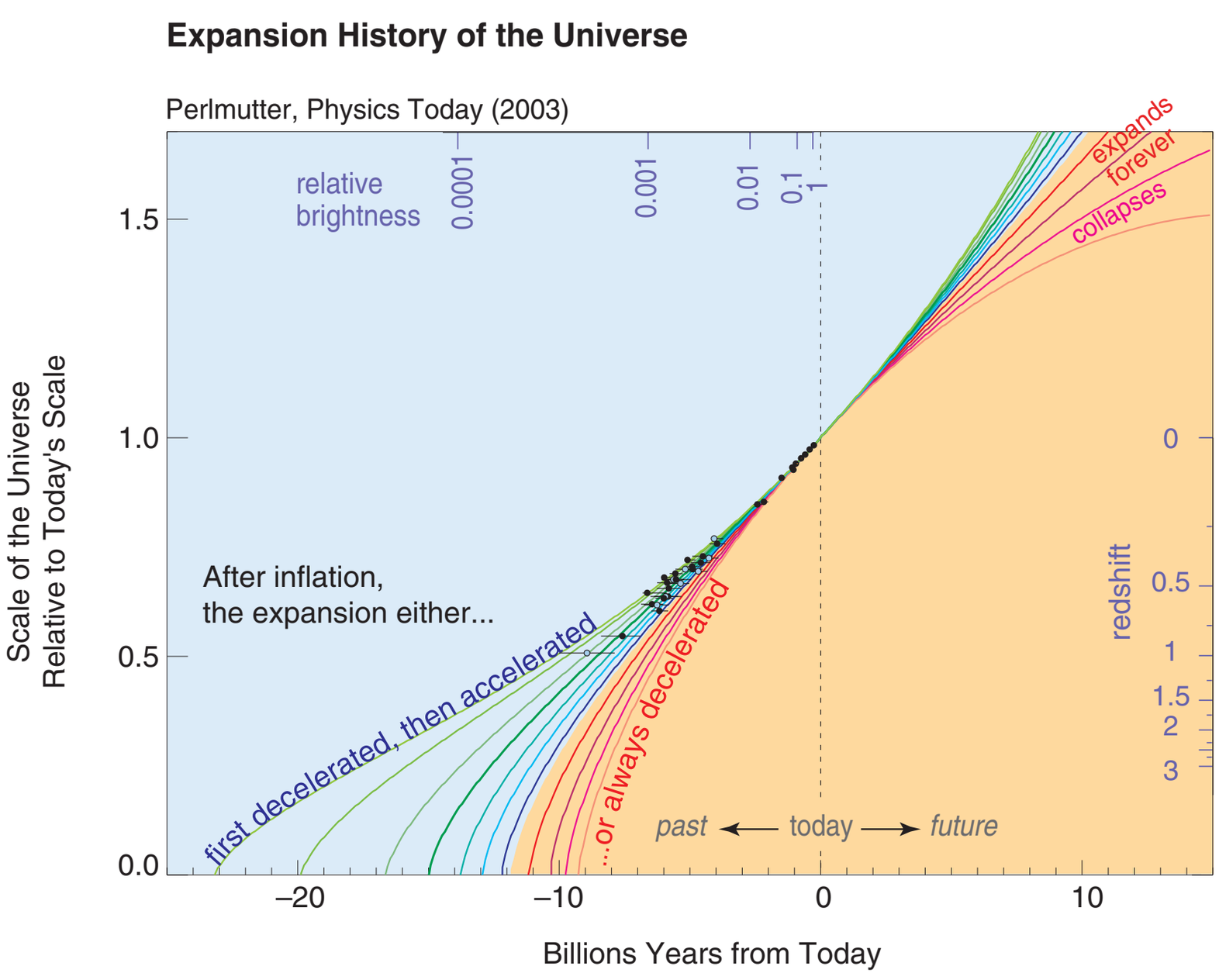
The Universe

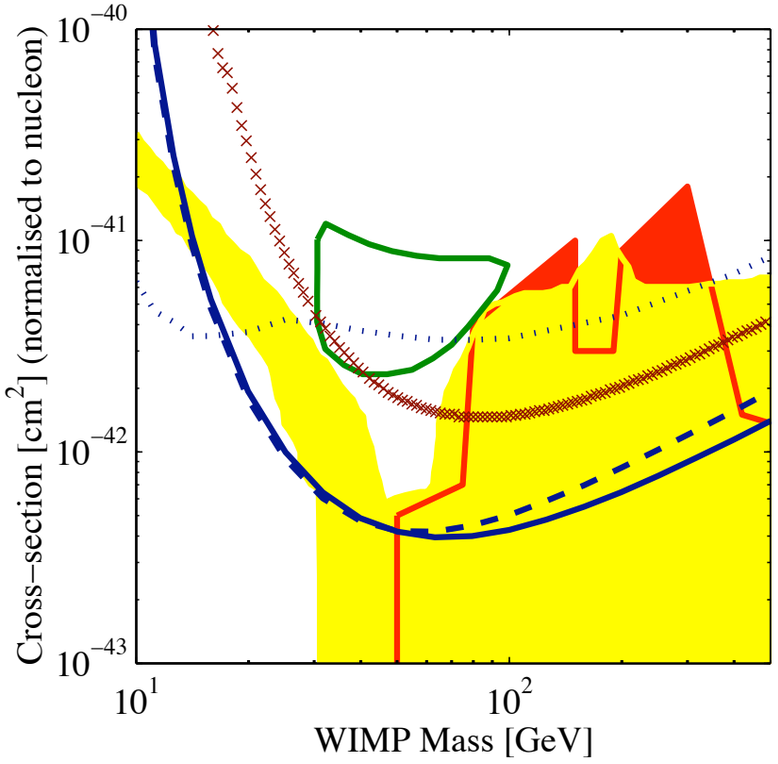
- **The concordance**
  - **5% matter (including dark baryons): CMB, BBN, Lyman α**
  - **25% dark matter (galaxies, clusters, CMB, lensing)**
  - **70% dark energy (Acceleration (Supernovae), CMB (WMAP))**



- **What is the dark energy?**
  - **Vacuum energy (cosmological constant); time varying field (quintessence)?**
  - **High precision supernova survey (SNAP); CMB (Planck)**

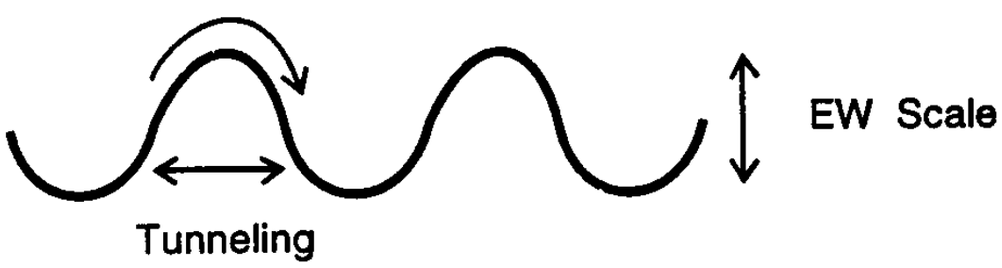


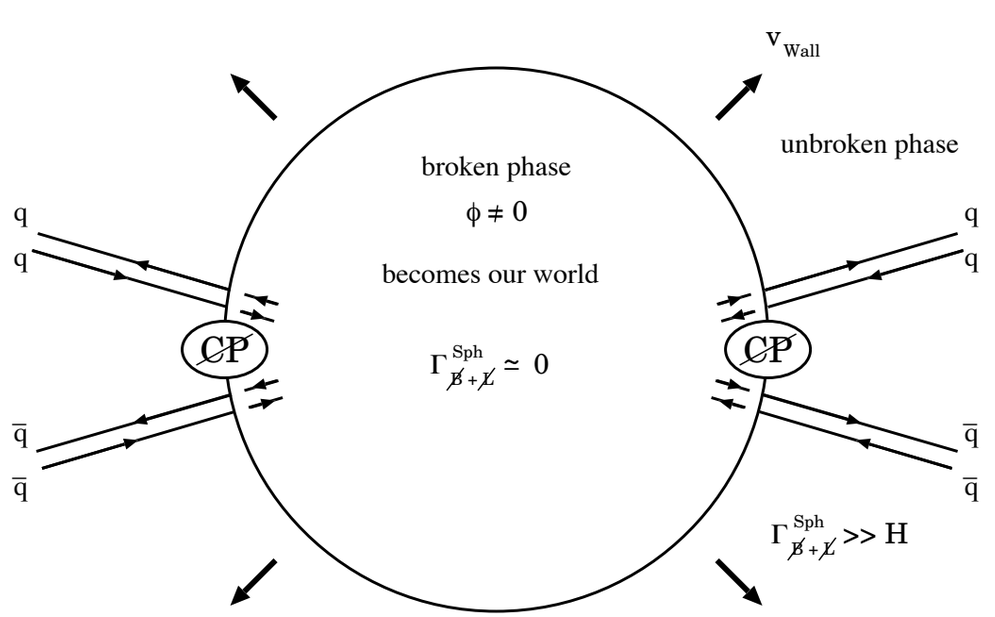




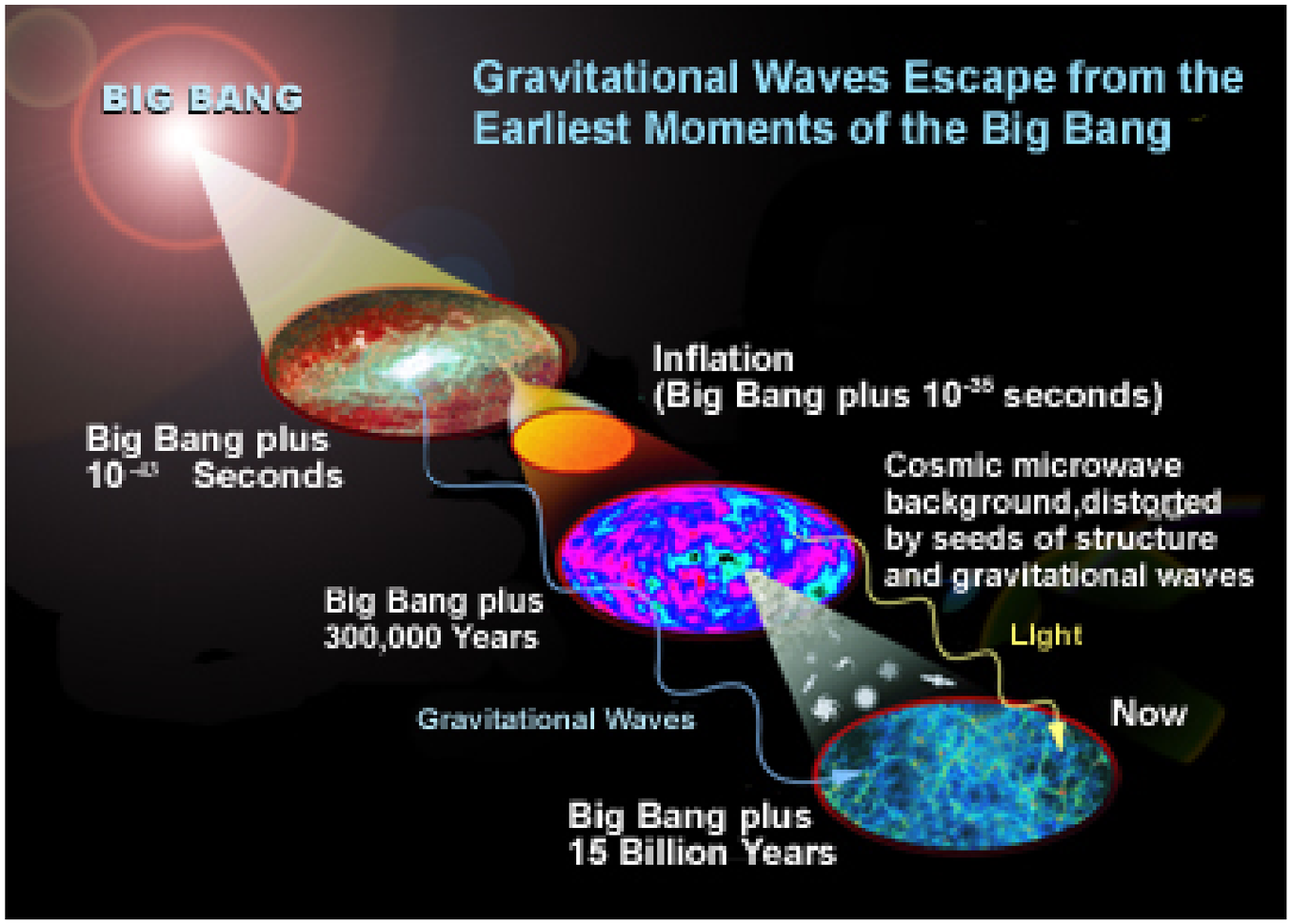
- **What is the dark matter?**
  - **Lightest neutralino in supersymmetry (if R parity conserved)? Axion?**
  - **Direct searches: LHC, ILC; cold dark matter searches; high energy annihilation ν's**
  - **Axion searches (resonant cavities)**
  - **Gravitation lensing (SNAP), CMB (Planck)**

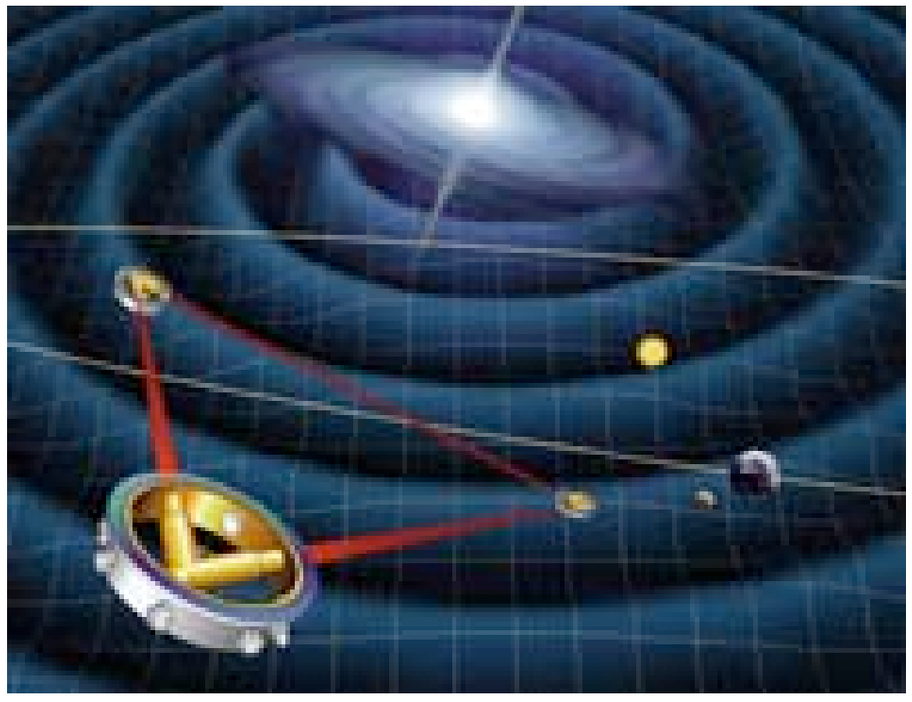
- **Why is there matter and not antimatter?**
  - $n_B/n_\gamma \sim 10^{-10}$, $n_{\bar{B}} \sim 0$
  - **Electroweak baryogenesis (extensions of MSSM)? Leptogenesis? Decay of heavy fields? CPT violation?**





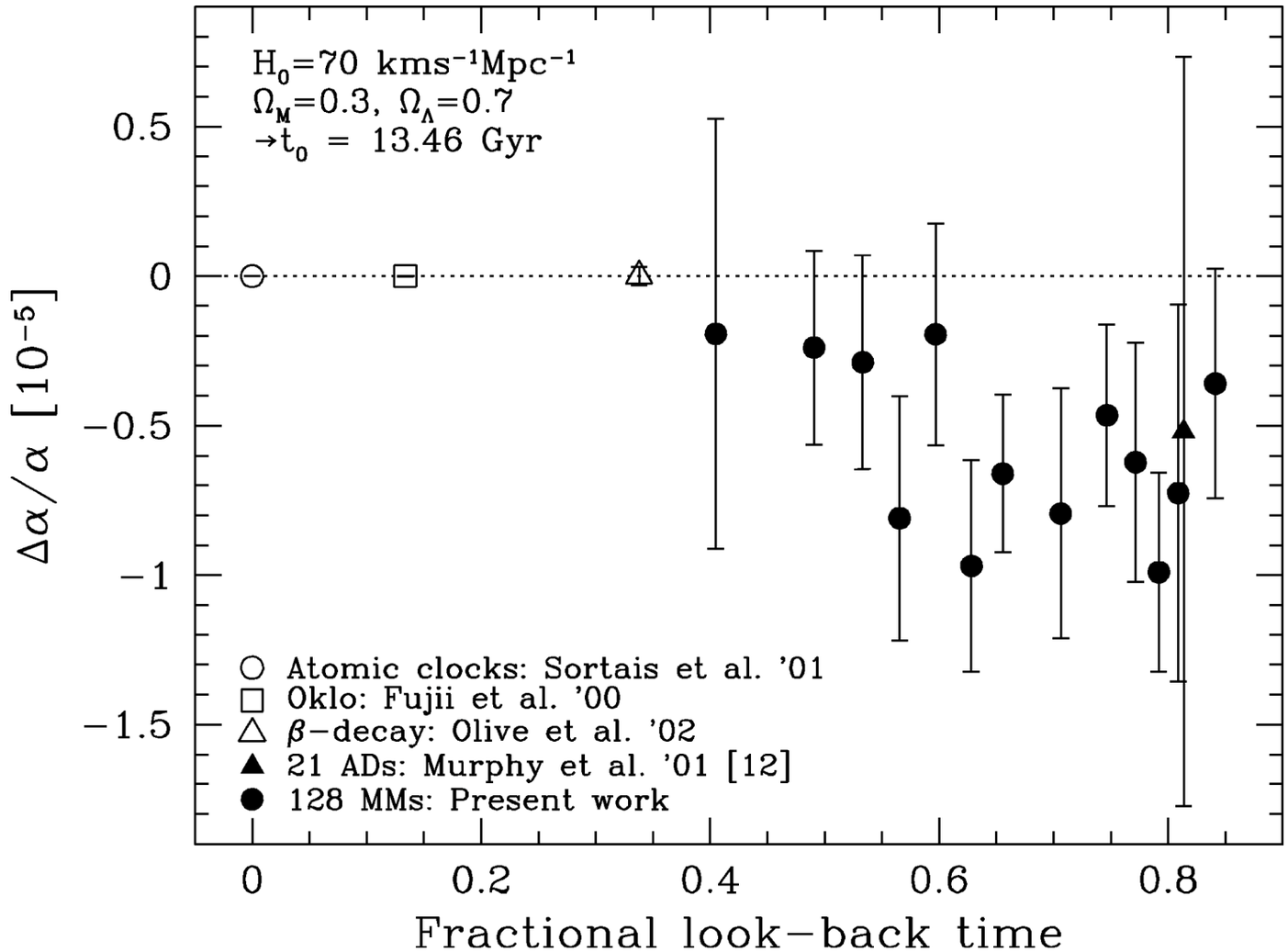
- **The very beginning (inflation)**
  - **Relation to particle physics, strings, Λ?**
  - **CMB (Planck); gravity waves (LISA)**





Far-Out Stuff

- **LIV, VEP** (e.g., maximum speeds, decays, (oscillations) of HE γ, e, gravity waves (ν's))
- **LED, TeV black holes**
- **Time varying couplings**



(Murphy et al, astro-ph/0209488)

Conclusions

- The standard model is the correct description of fermions/gauge bosons down to $\sim 10^{-16}$ cm $\sim \frac{1}{1\ \mathrm{TeV}}$
- EWSB: consistent with light elementary Higgs but not proved
- Standard model is complicated $\longrightarrow$ must be new physics
- Precision tests severely constrain new TeV-scale physics
- Promising theoretical ideas at Planck scale
- Promising experimental program at colliders, accelerators, low energy, cosmology
- Challenge to make contact between theory and experiment