Weak Interactions and Neutrinos in the LHC Era

- 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

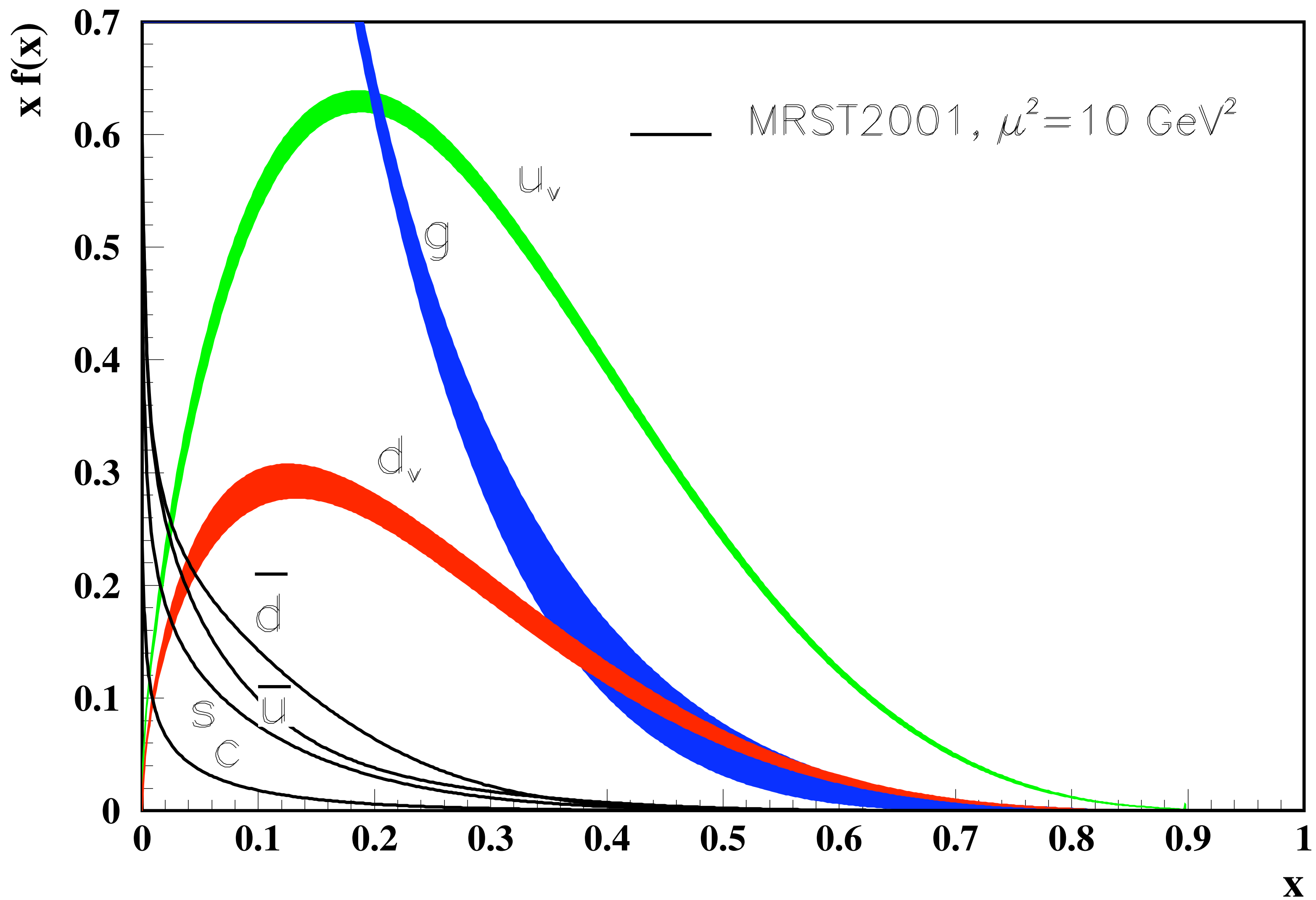
- Complicated, free parameters, fine tunings $\Rightarrow$must be new physics

- 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, $\not{R}_p$)

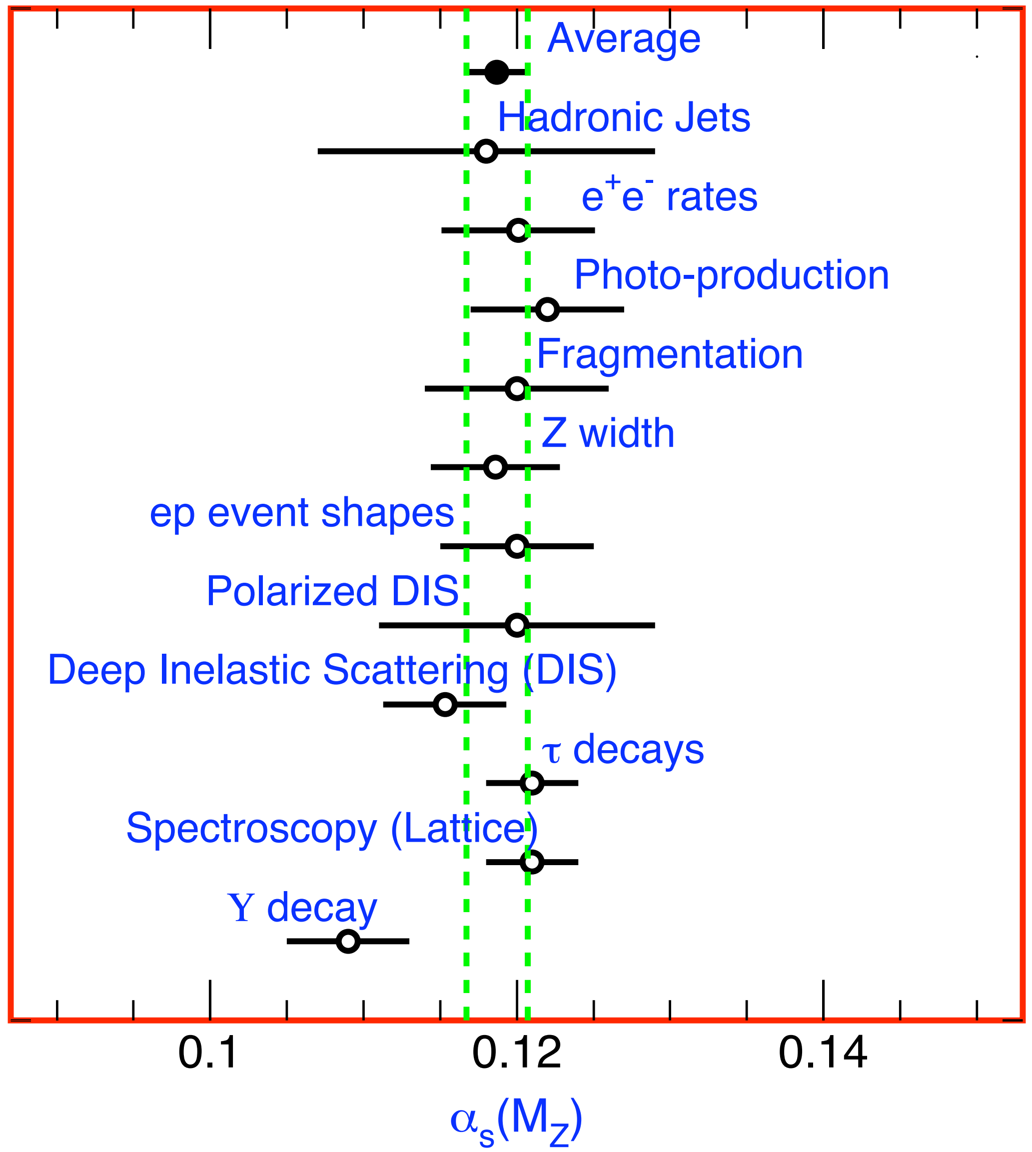
Quantum Chromodynamics (QCD)

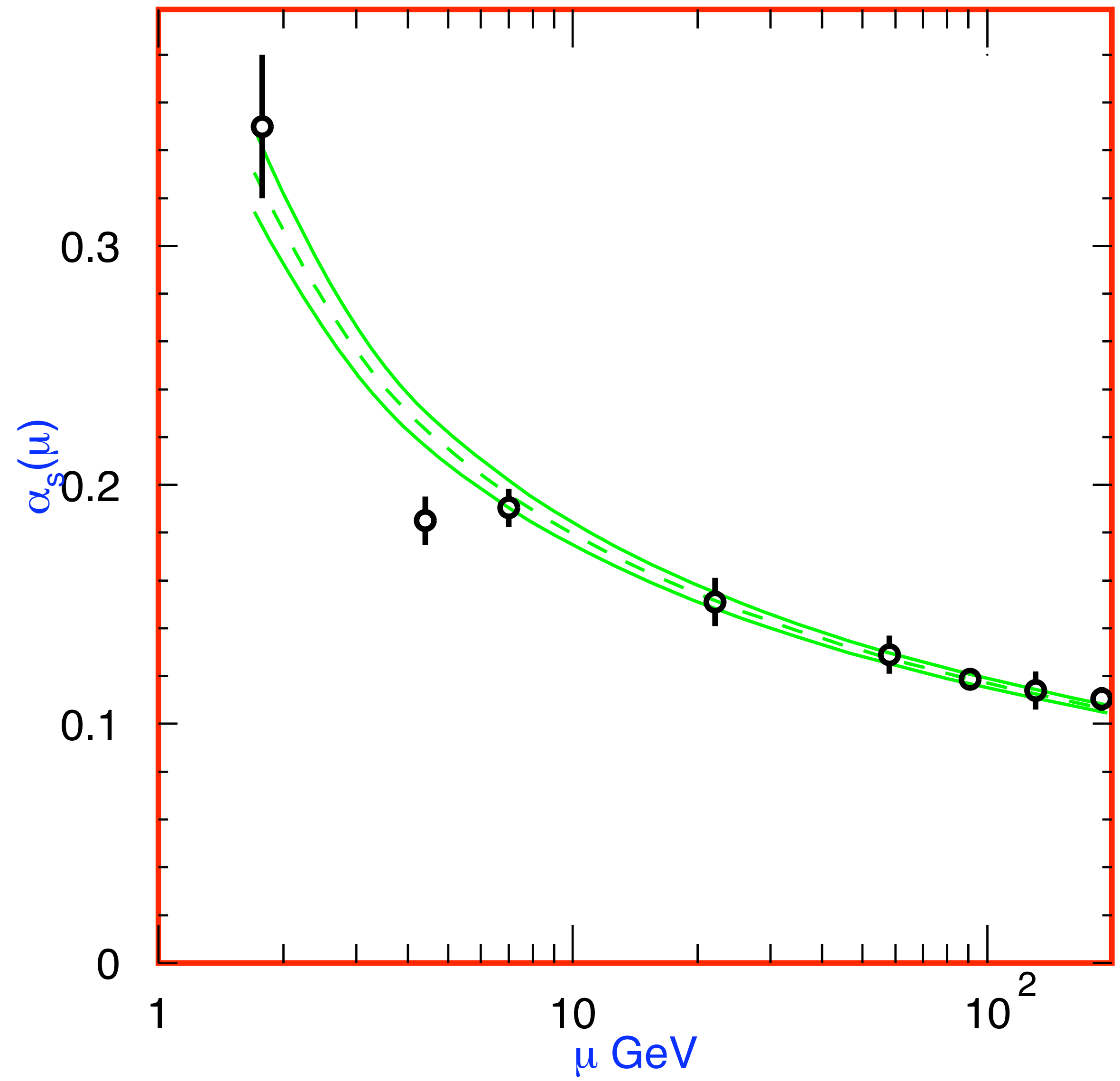
Modern theory of the strong interactions

- Quark model/ color/ confinement
- Low energy symmetries (+ realization, breaking) $(SU(3)_L \times SU(3)_R)$
- Hadronic models: Yukawa, Regge, dual resonance ($\rightarrow$ strings)
- Asymptotic freedom (weak coupling at high energy)



Relation of “running” α_s at different scales



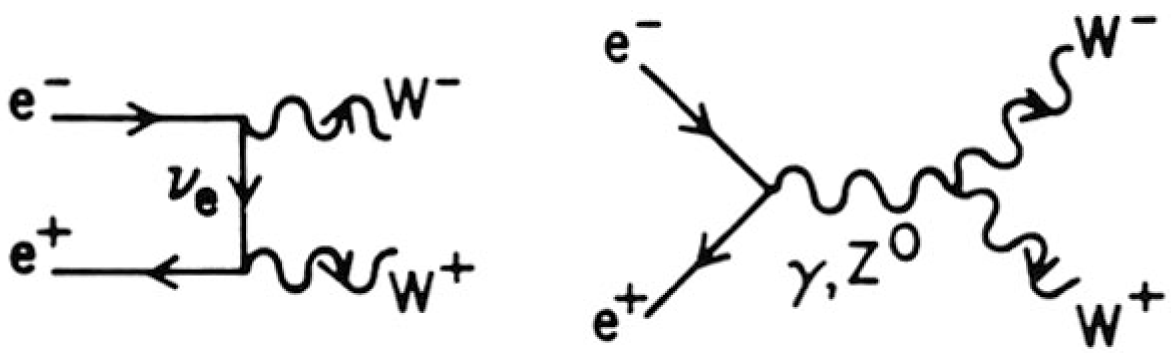


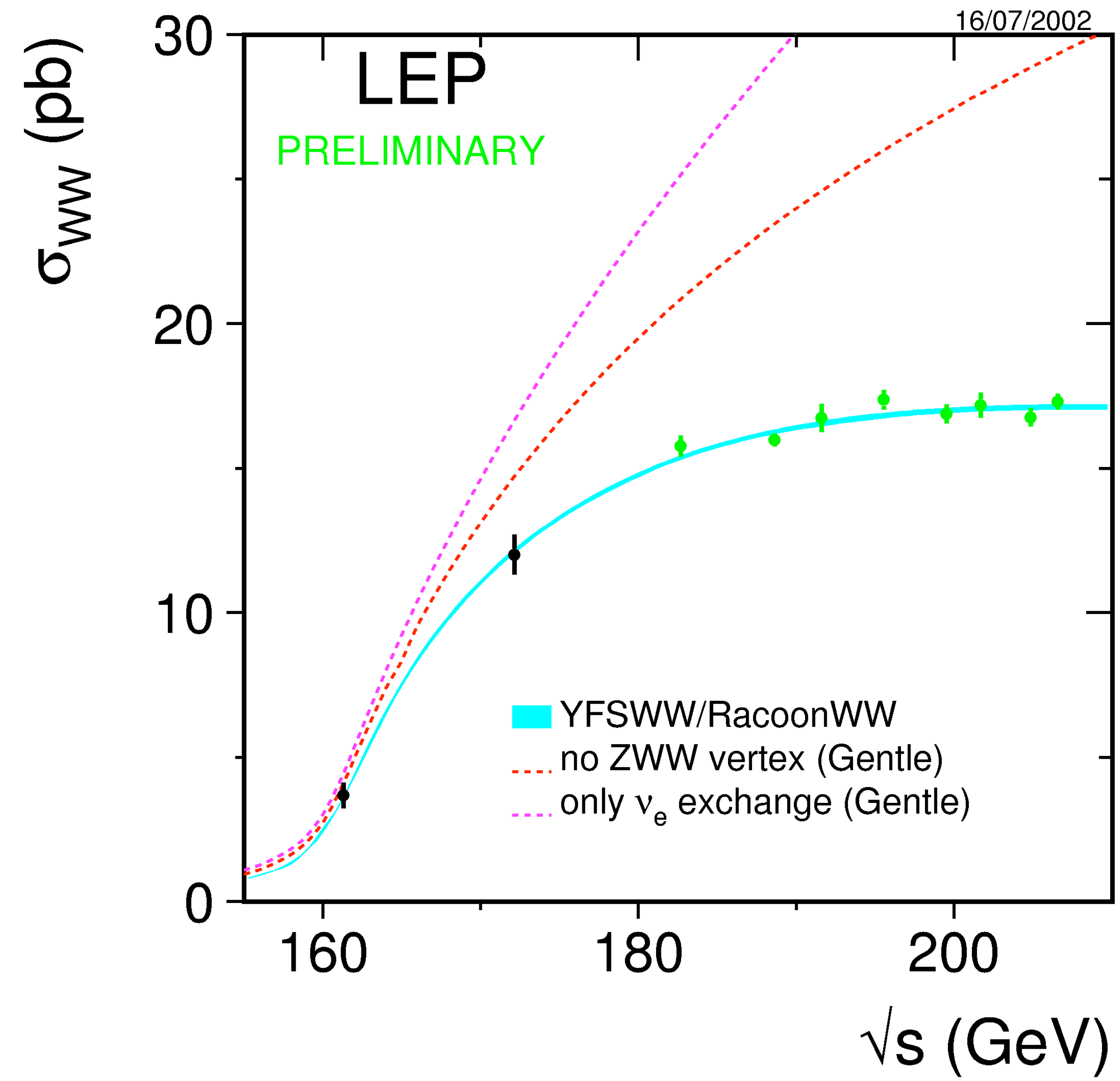
Quantum Electrodynamics

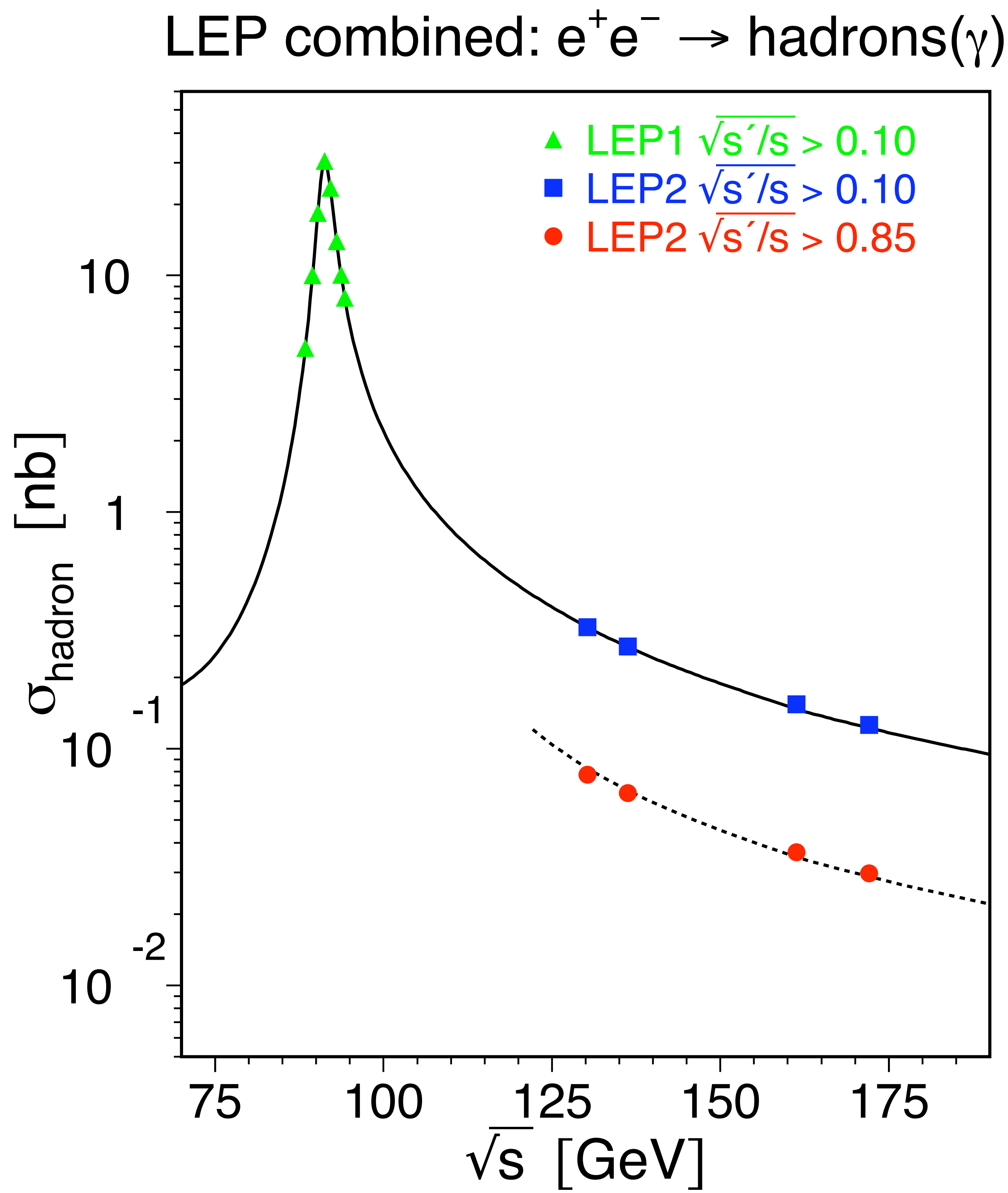
Experiment	Value of α^{-1}		Difference from $\alpha^{-1}(a_e)$
Deviation from gyromagnetic ratio, $a_e = (g-2)/2$ for e^-	$137.035\,999\,58\,(52)$	$[3.8 \times 10^{-9}]$	–
ac Josephson effect	$137.035\,988\,0\,(51)$	$[3.7 \times 10^{-8}]$	$(0.116 \pm 0.051) \times 10^{-4}$
h/m_n (m_n is the neutron mass) 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

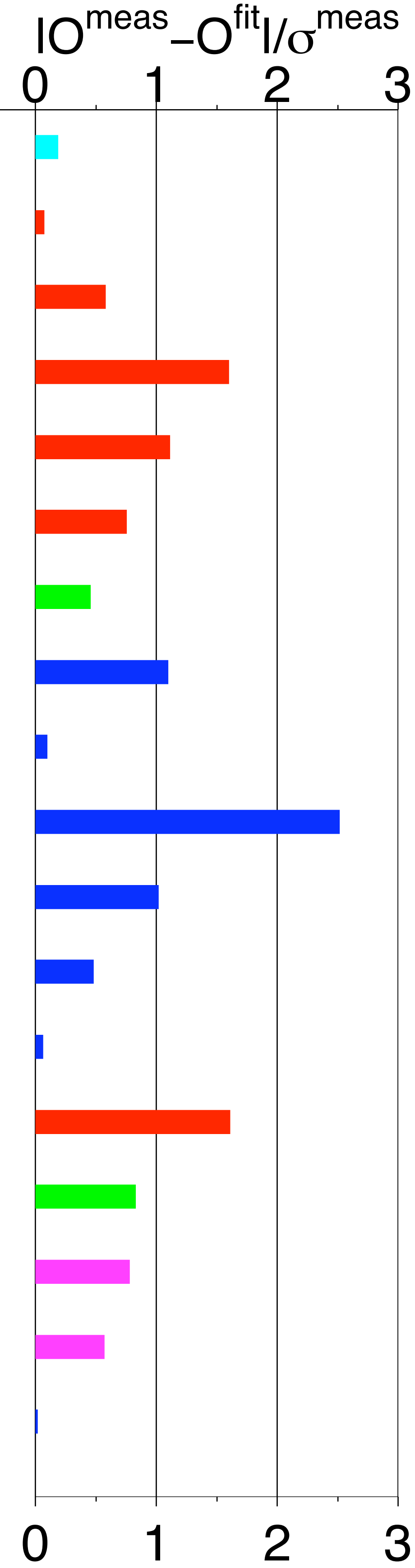
- QED and weak charged current unified
- Weak neutral current predicted
- Stringent tests of wnc, Z-pole and beyond
- Fermion gauge and gauge self interactions

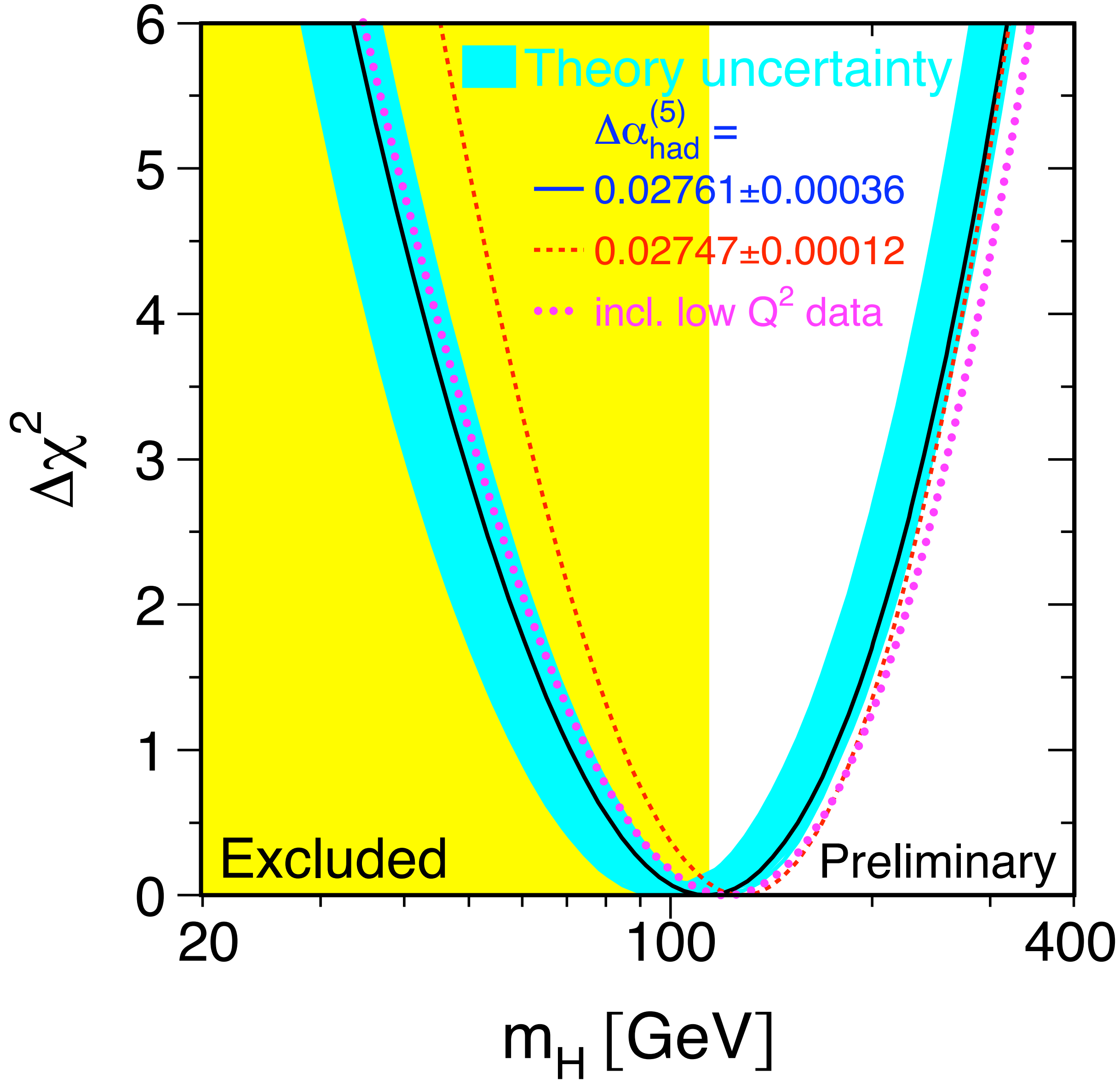





LEP combined: e+e− → hadrons(γ)
LEP1 √s´/s > 0.10
LEP2 √s´/s > 0.10
LEP2 √s´/s > 0.85
σhadron [nb]
10
1
10-1
10-2
75
100
125
150
175
√s [GeV]

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	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]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1





- **SM correct and unique to zeroth approx. (gauge principle, group, representations)**

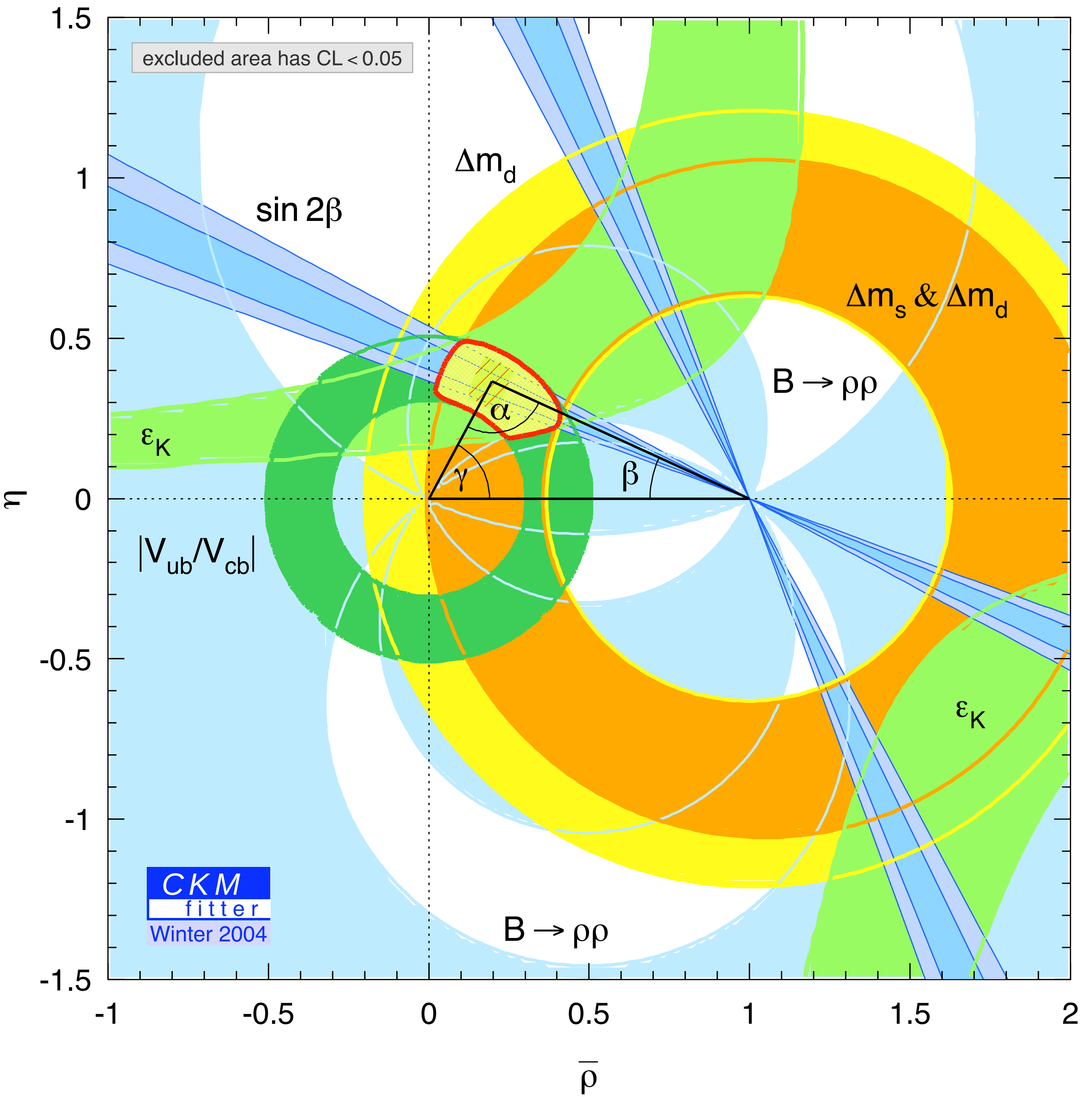
- **SM correct at loop level (renorm gauge theory; m_t, α_s, M_H)**

- **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?**



Problems with the Standard Model

Lagrangian after symmetry breaking:

$$\begin{aligned}\mathcal{L} &= L_{\text{gauge}} + L_{\text{Higgs}} + \sum_i \bar{\psi}_i \left(i \not\partial - m_i - \frac{m_i H}{\nu} \right) \psi_i \\ & -\frac{g}{2\sqrt{2}} \left(J_W^\mu W_\mu^- + J_W^{\mu\dagger} W_\mu^+ \right) - e J_Q^\mu A_\mu - \frac{g}{2\cos\theta_W} J_Z^\mu Z_\mu\end{aligned}$$

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

Mathematically consistent, renormalizable theory

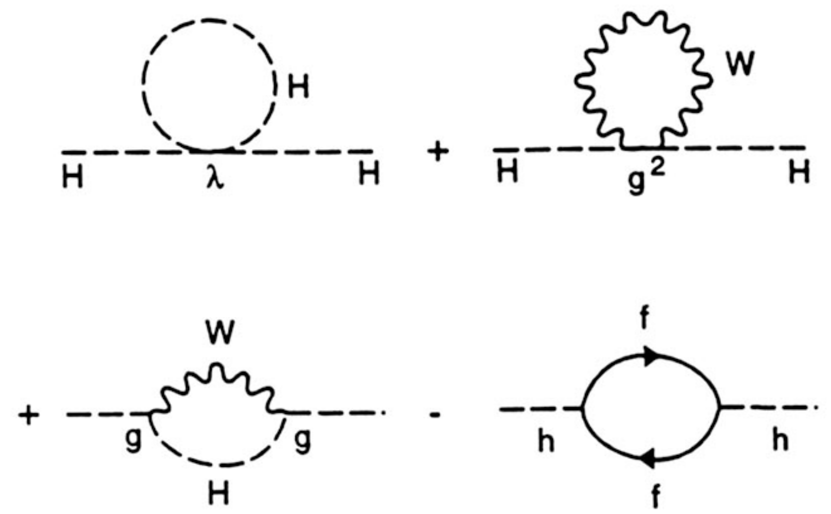
Correct to 10^{-16} cm

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: $\Lambda_{\text{SSB}} = 8\pi G_N \langle V \rangle > 10^{50} \Lambda_{\text{obs}}$ (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 Higgs (0) $\Leftrightarrow$ gauge (1) $\Leftrightarrow$ Graviton (2) ($d > 4$)	10^{19}	Graviton
Grand unification Strong $\Leftrightarrow$ electroweak	10^{14}–10^{19}	Gauge
Supersymmetry/supergravity Fermion $\Leftrightarrow$ boson	10^2–10^{19}	Higgs, graviton

Compositeness

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

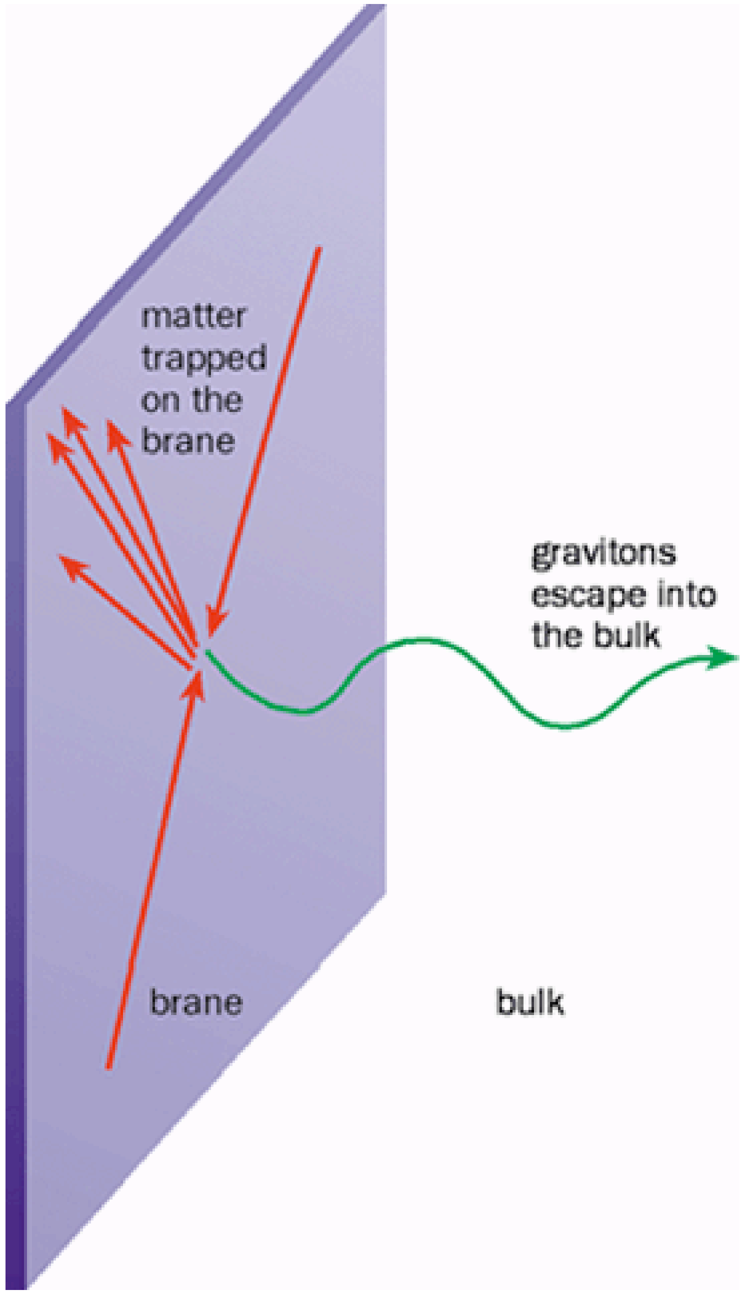
Large extra dimensions (deconstruction, brane worlds)

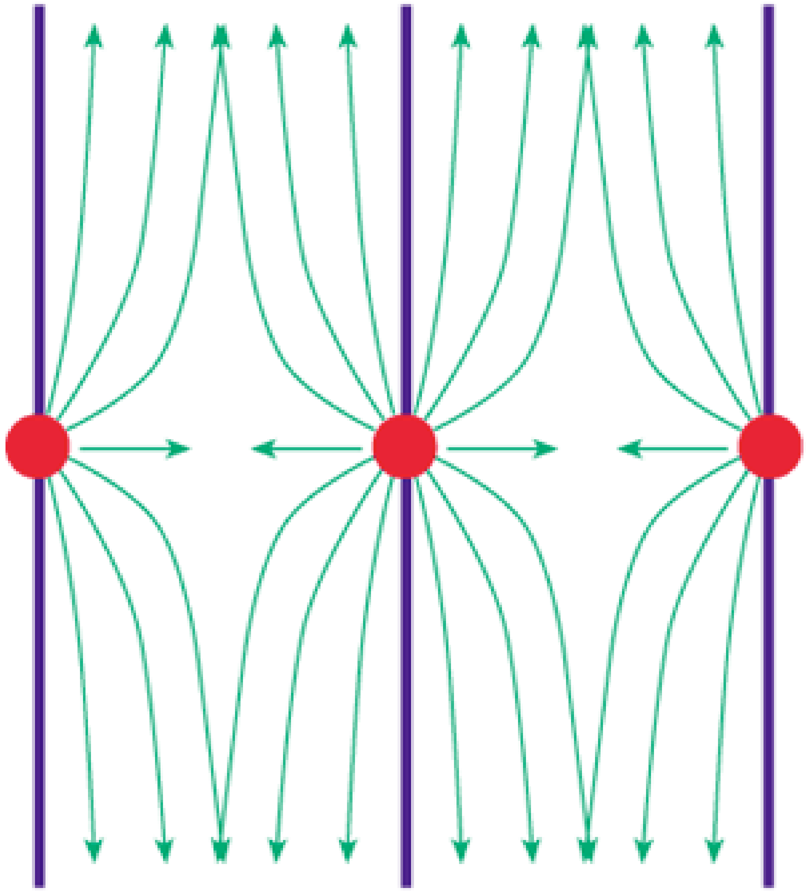
- **Can be motivated by strings, but new dimensions much larger than $M_P^{-1} \sim 10^{-33}$ cm**

- **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 $V_\delta \gg M_F^{-\delta}$**

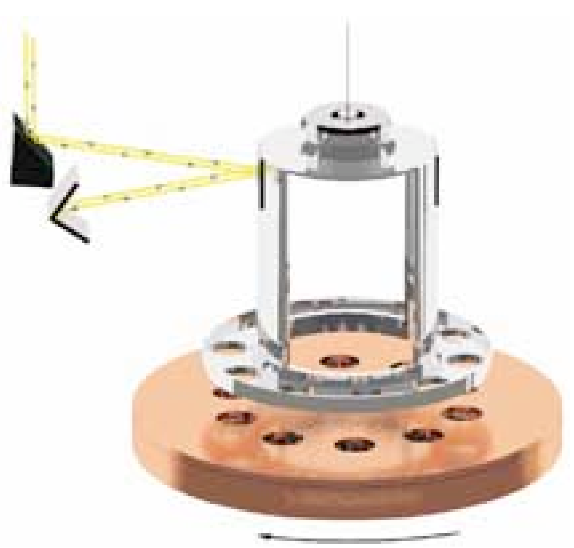
$$\bar{M}_{Pl}^2 = M_F^{2+\delta} V_\delta \gg M_F^2$$

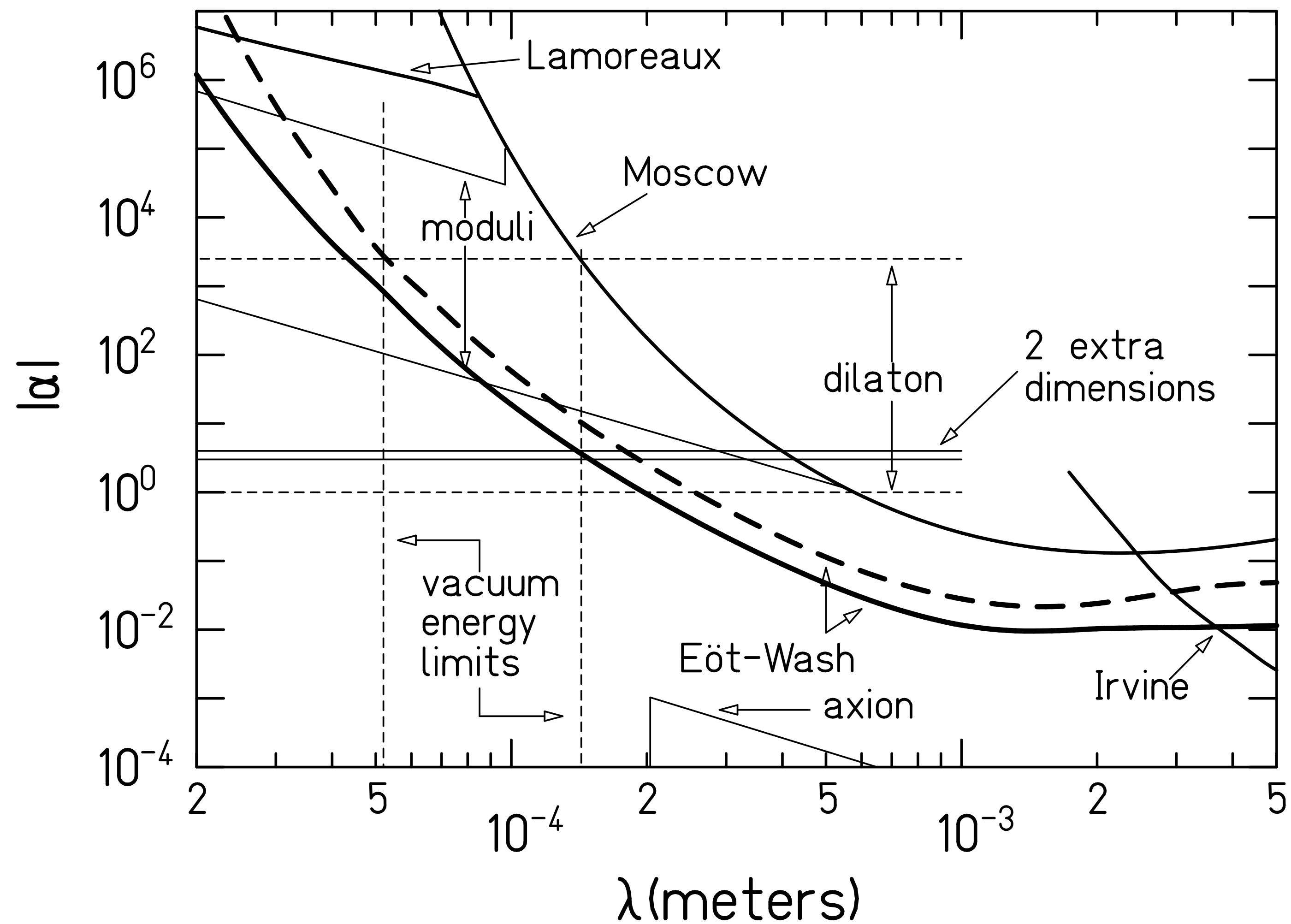
(Introduces new hierarchy problem)





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





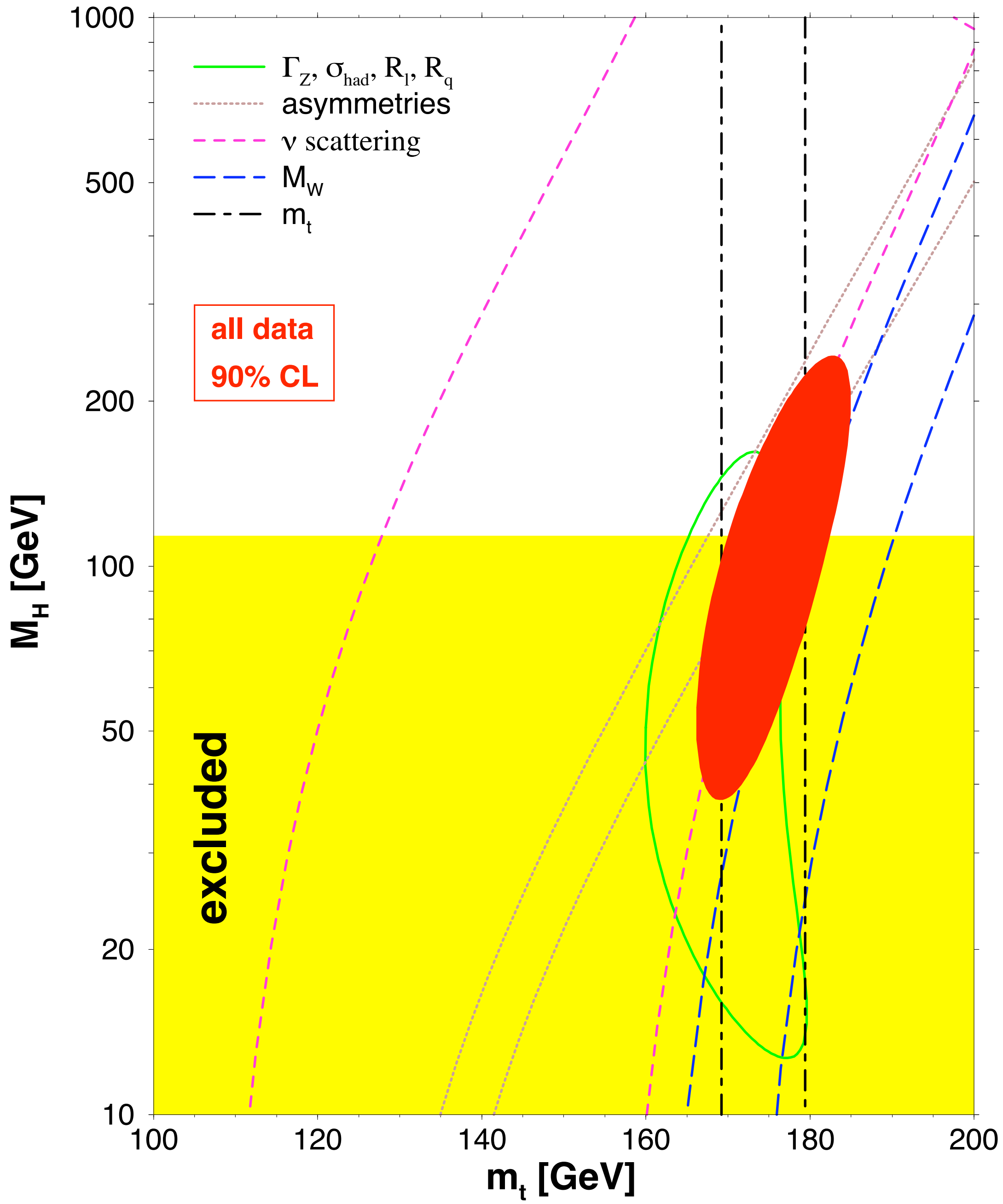
Unification

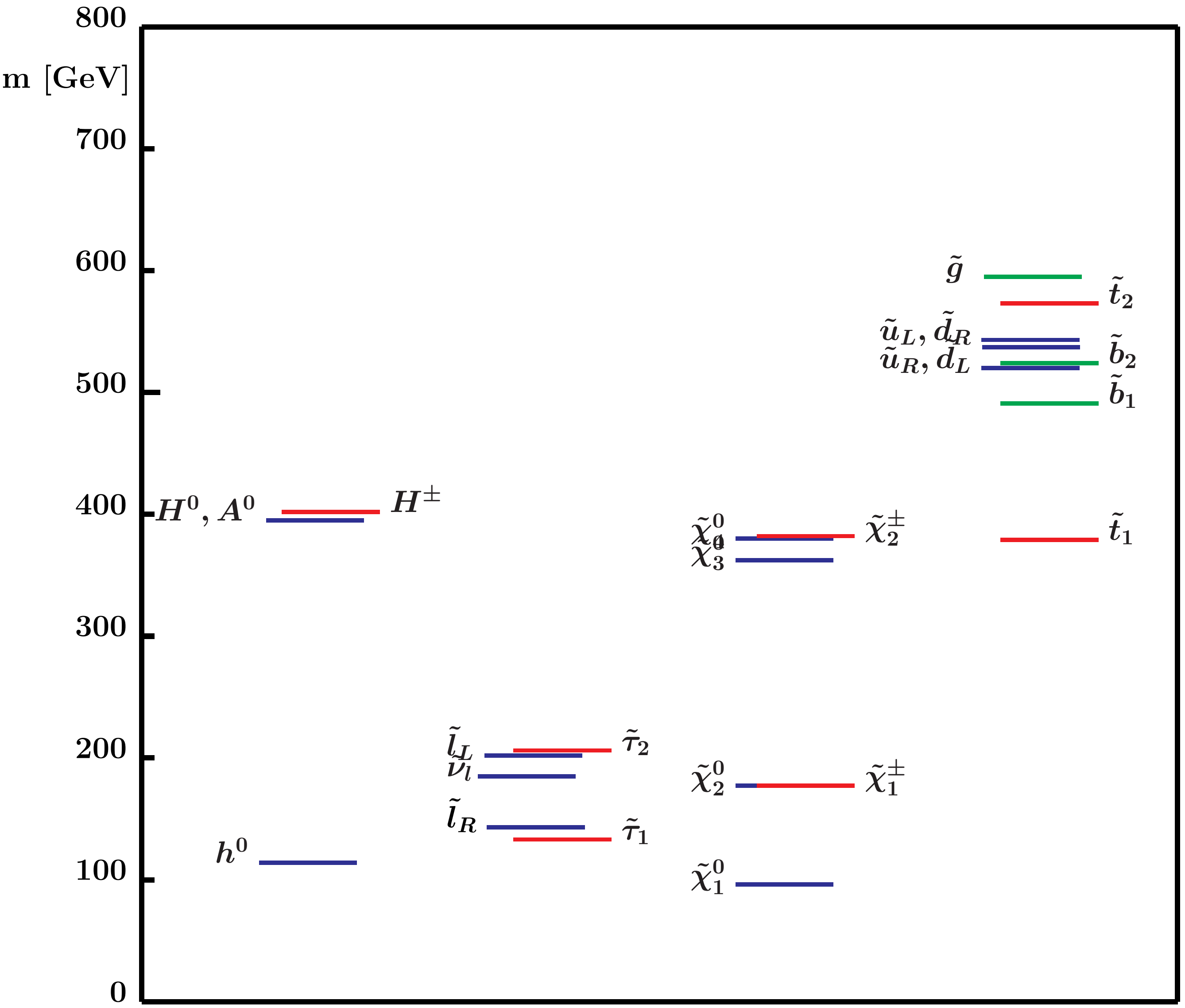
- Unification of interactions
- Grand desert to unification (GUT) or Planck scale
- Elementary Higgs, supersymmetry (SUSY), GUTs, strings
- Possibility of probing to M_P and very early universe

Supersymmetry

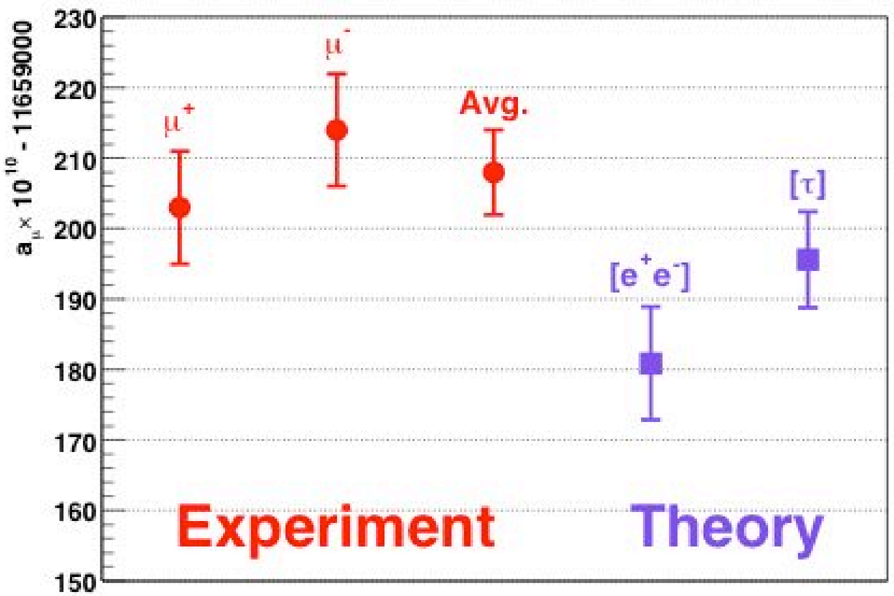
- Fermion $\leftrightarrow$ boson symmetry
- Motivations
  - stabilize weak scale $\Rightarrow M_{SUSY} < O(1$ TeV) (but recent high scale ideas)
  - supergravity (gauged supersymmetry): unification of gravity (non-renormalizable)
  - coupling constants in supersymmetric grand unification
  - decoupling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

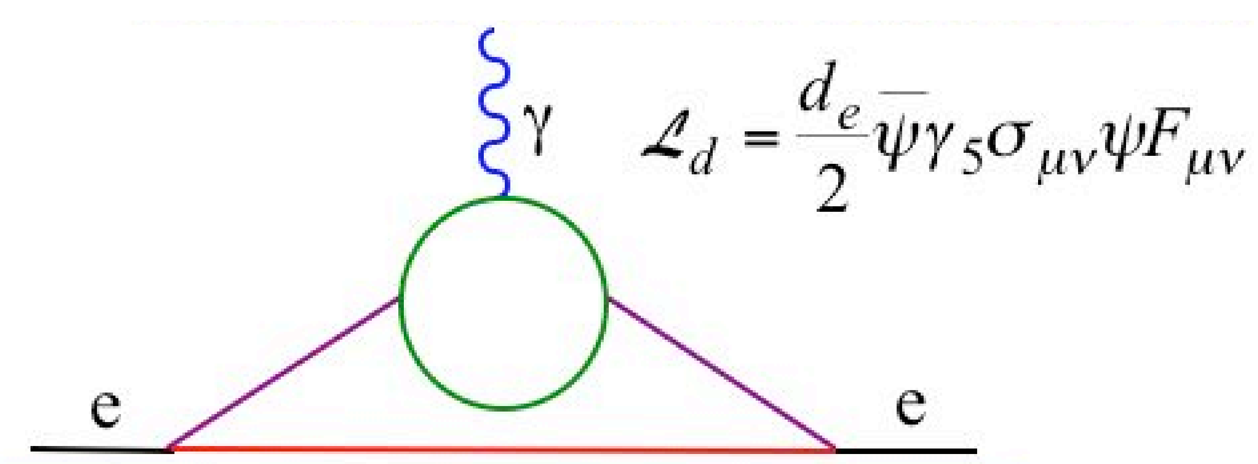
- **Consequences**
  - **additional charged and neutral Higgs particles**
  - $M_{H^0}^2 < \cos^2 2\beta M_Z^2 +$ **H.O.T.** $(O(m_t^4)) < (150$ **GeV**$)^2$, **consistent with LEP**
    - $*$ **cf., standard model:** $M_{H^0} <$ 1000 **GeV**





- **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, $\Delta(g_\mu - 2)$

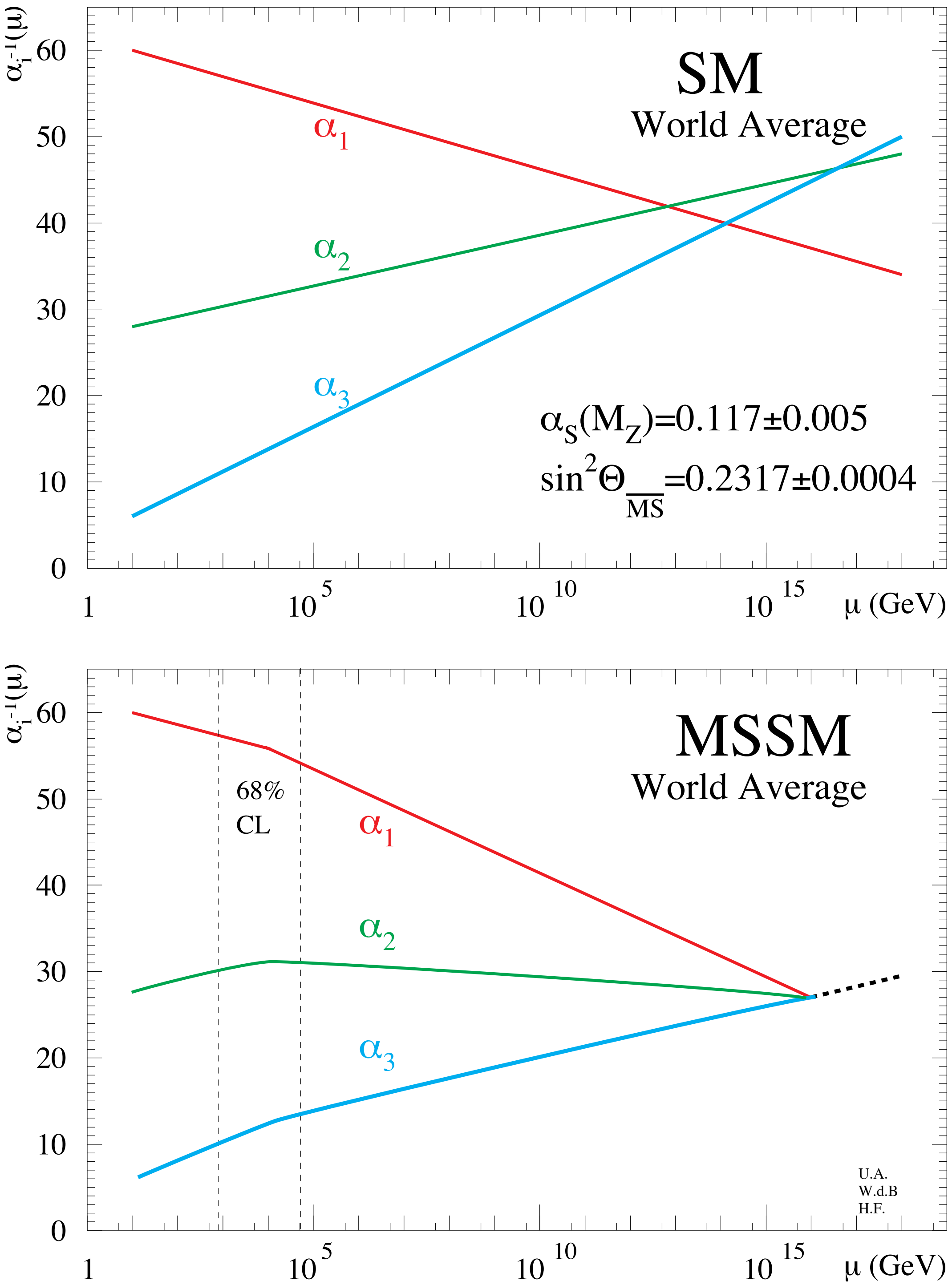




Grand Unification

- **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?)

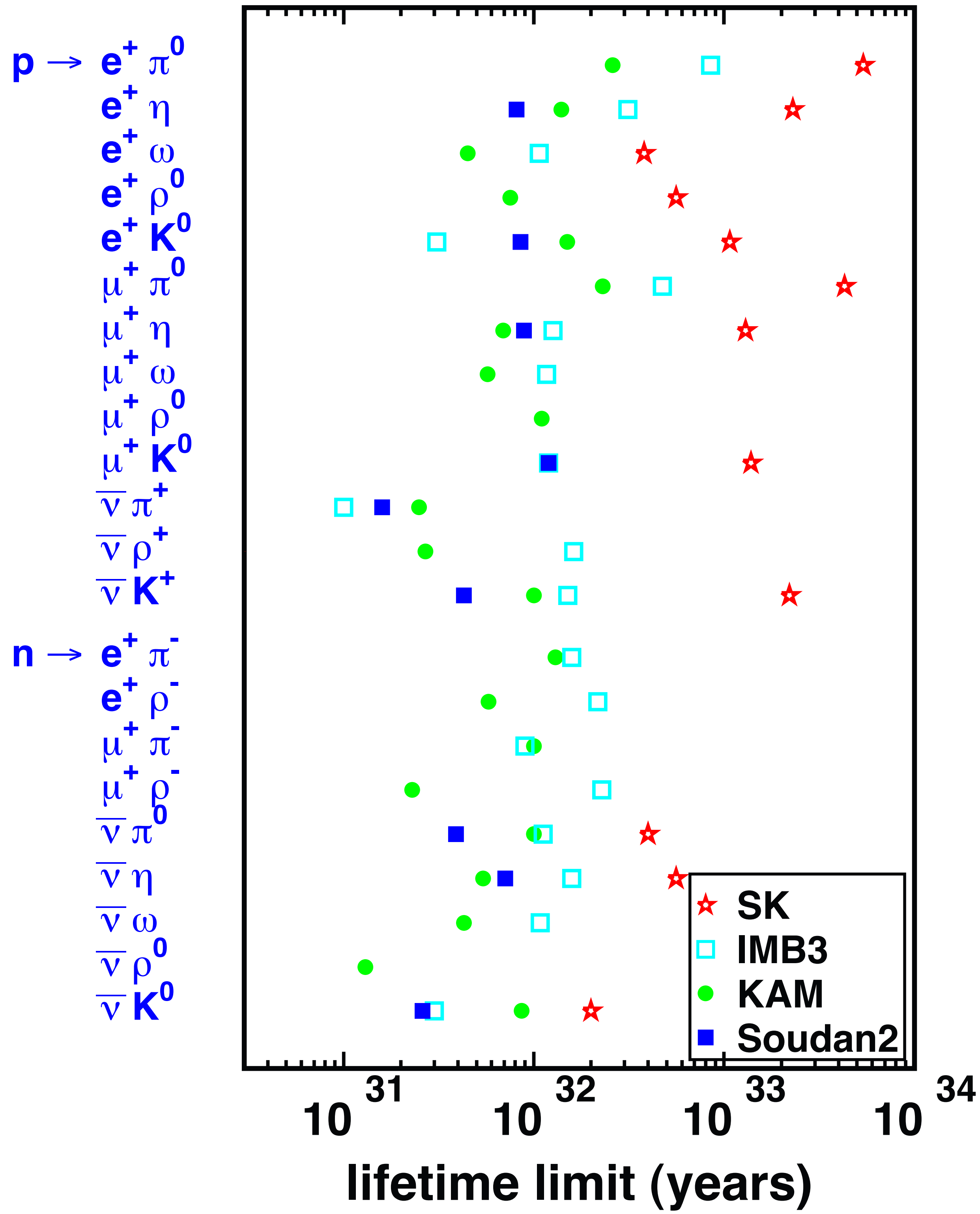
- **Quark-lepton $(q - l)$ unification** ($\Rightarrow$ charge quantization)

- **$q - l$ mass relations** (work only for third family in simplest versions)

- **Proton decay?** (simplest versions excluded)

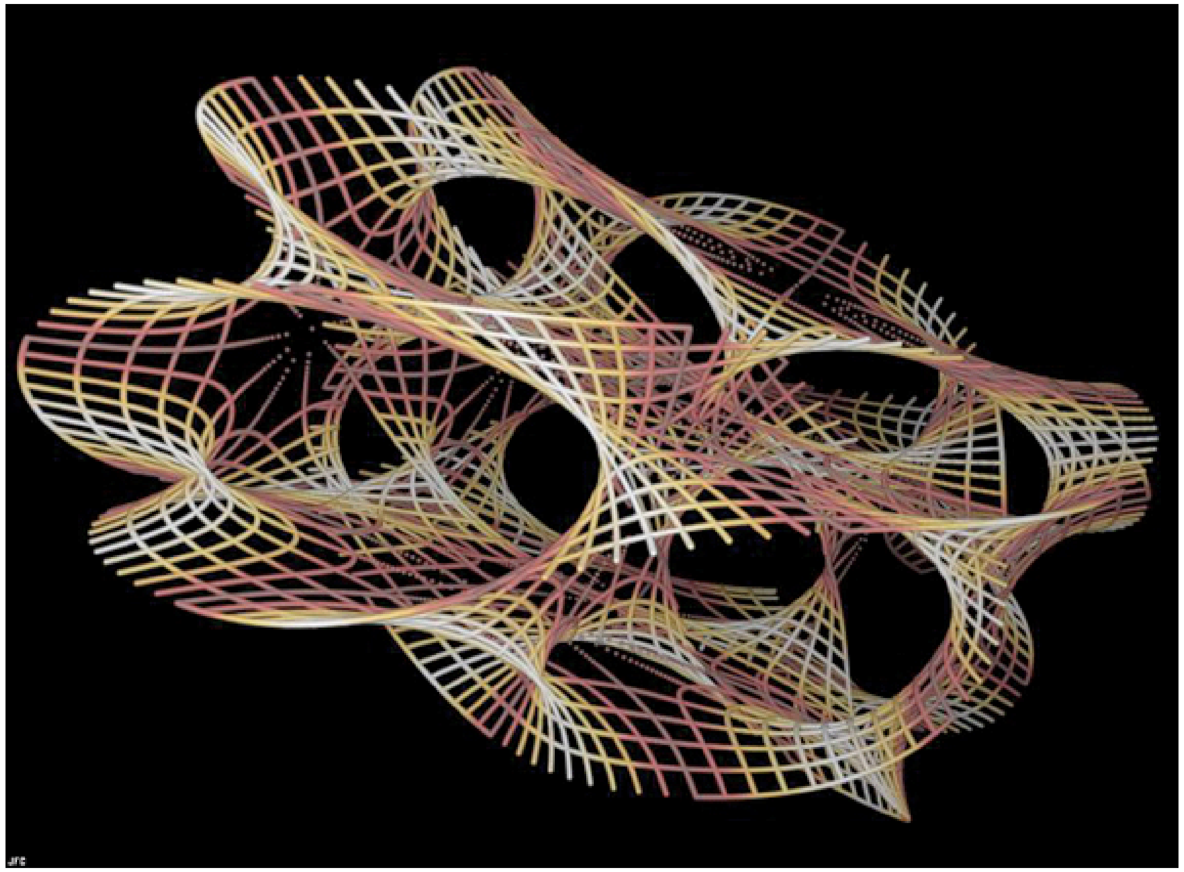
- **Doublet-triplet problem?**

- **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

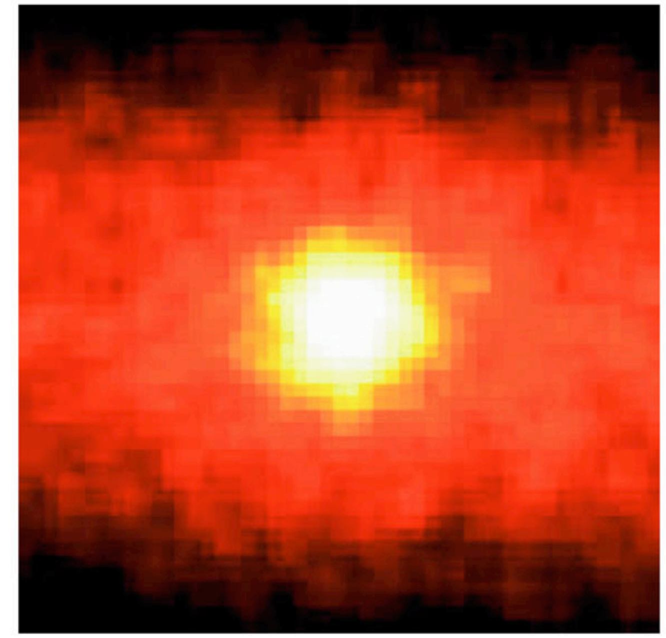
Future/present Experiments

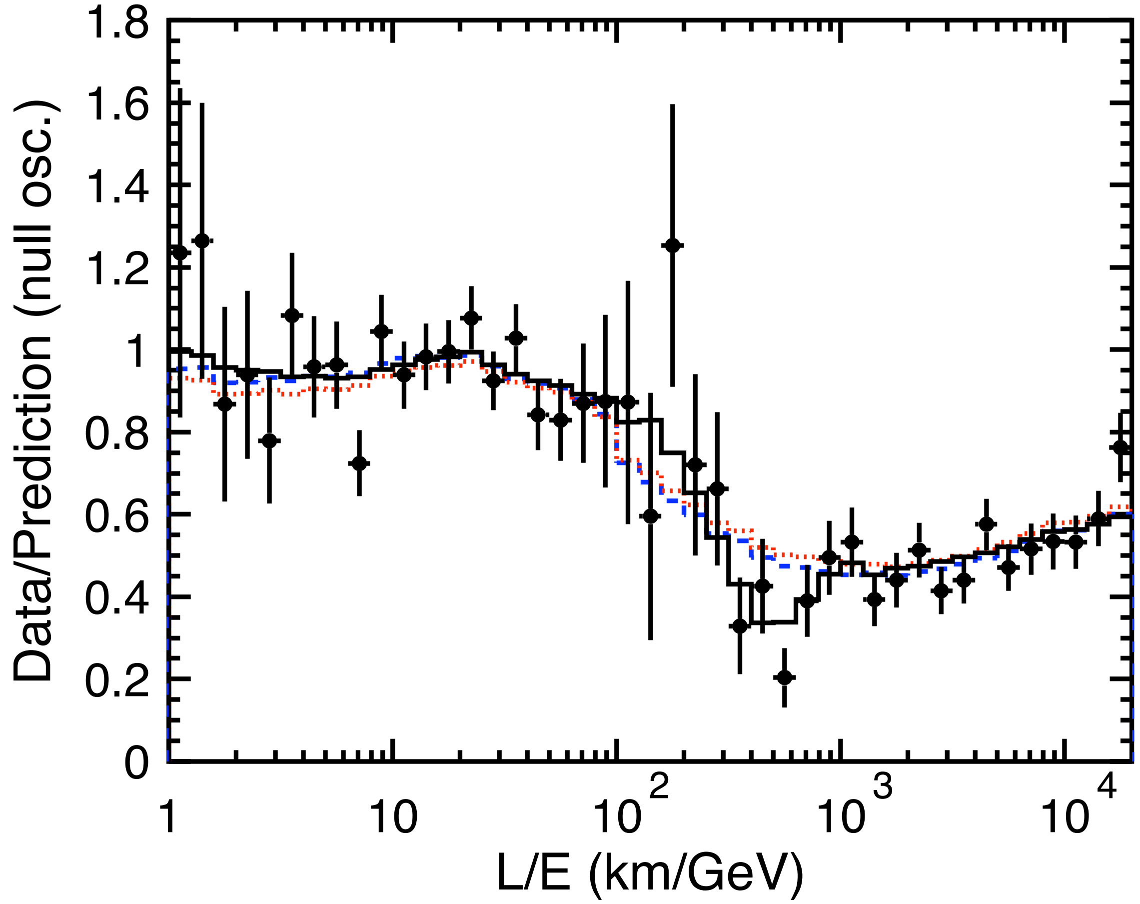
- High energy colliders: the primary tool
  - The TEVATRON; Fermilab, 1.96 TeV $\bar{p}p$, exploration
  - The Large Hadron Collider (LHC); CERN, 14 TeV pp, high luminosity, discovery (Discovery machine for supersymmetry, R_p violation, string remnants (e.g., Z', exotics); or compositeness, dynamical symmetry breaking, Higgless theories, Little Higgs, large extra dimensions, $\cdots$)
  - The 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)
- Also, CP violation (B decays, electric dipole moments), flavor changing neutral currents (e.g., $\mu \to e\gamma$, $\mu N \to eN$, $B \to \phi K_s$), neutrino physics

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

- Particle Physics
  - $\nu N, \mu N, e N$ scattering: existence/ properties of quarks, QCD
  - Weak decays ($n \to p e^- \bar{\nu}_e, \mu^- \to e^- \nu_\mu \bar{\nu}_e$): 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: $m_\nu \sim m_q^2/M_{\mathrm{GUT}}$

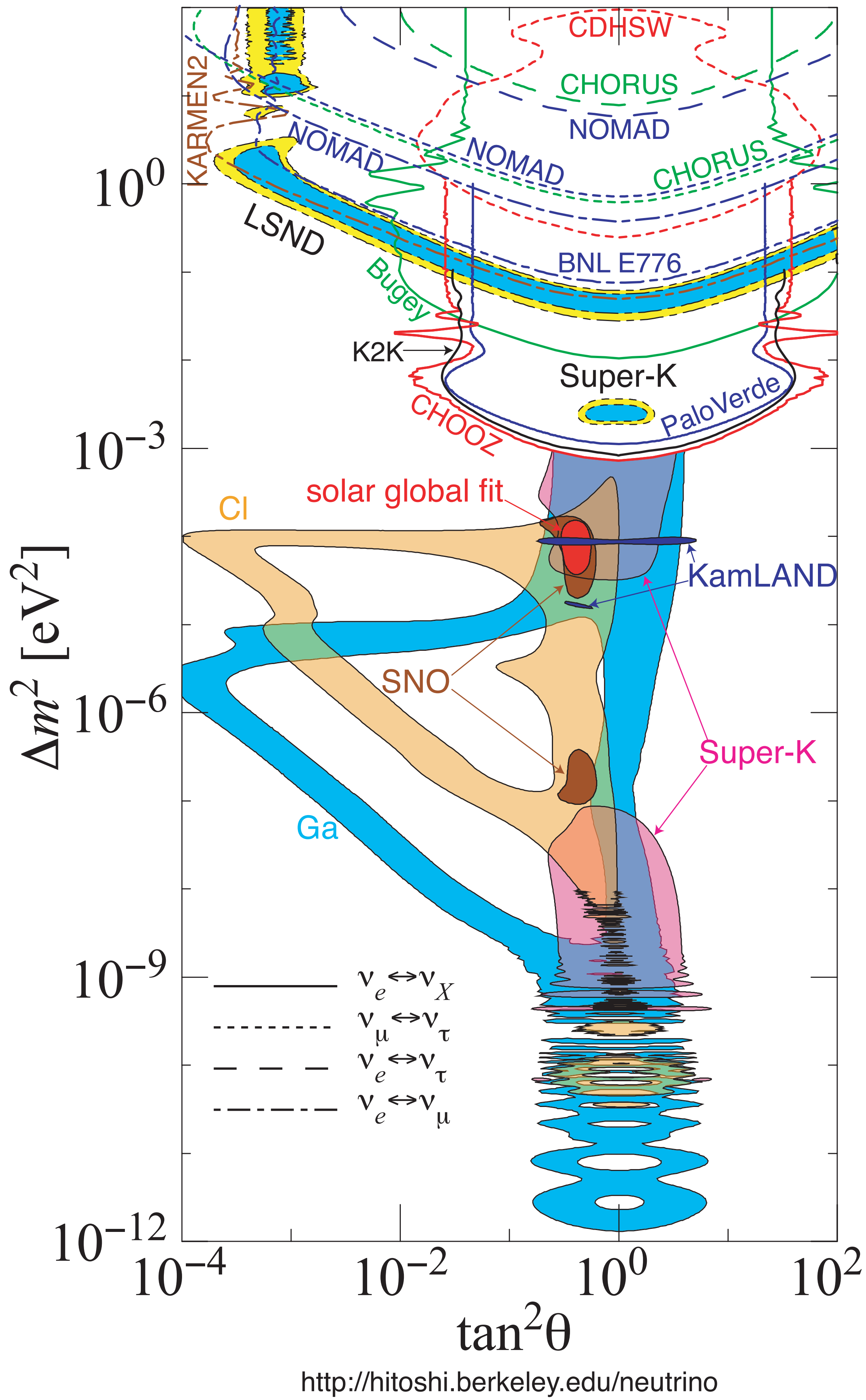
- **Solar/atmospheric neutrino experiments**
  - **Neutrinos have tiny masses (but large mixings)**
  - **Standard Solar model confirmed**
  - **First oscillation dips observed! (QM on large scale)**





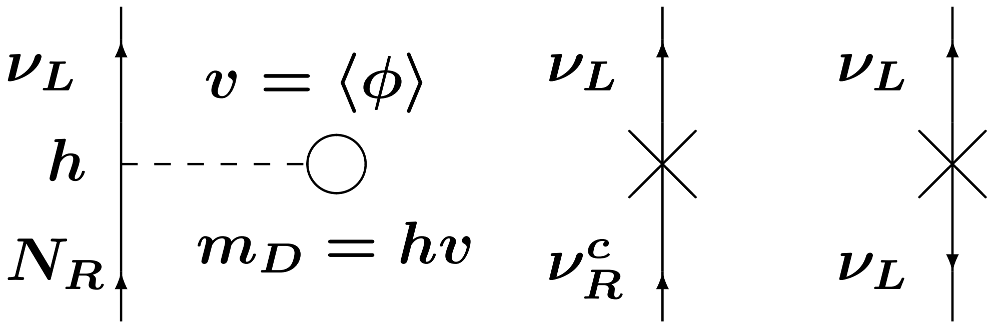
3 ν Patterns

- **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**

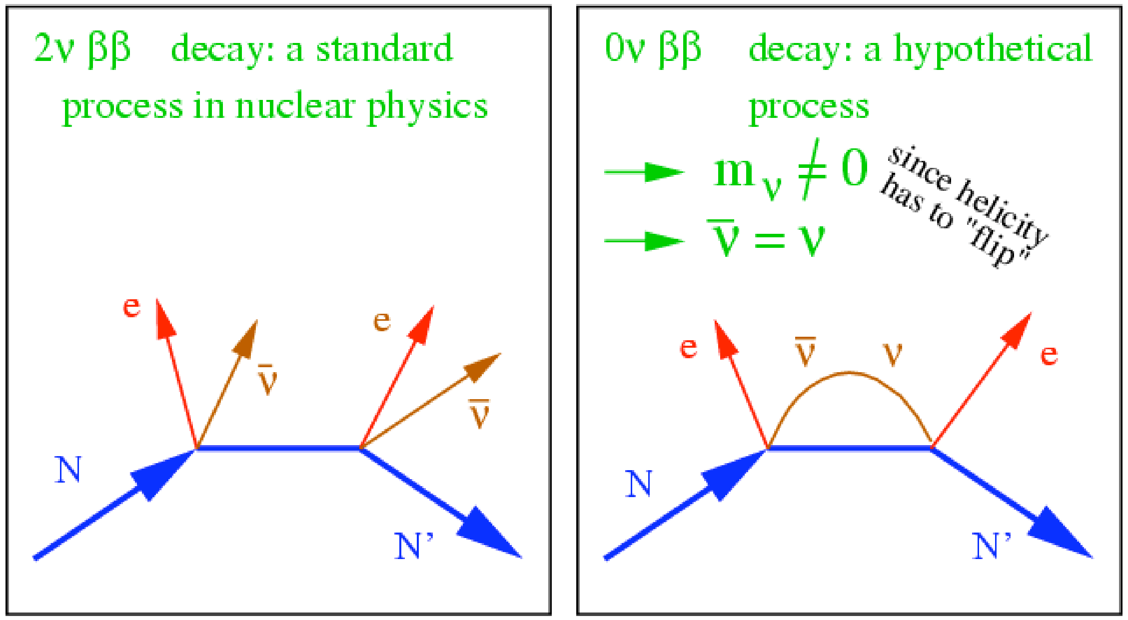


Neutrino Implications/questions

- **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)
- **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)**



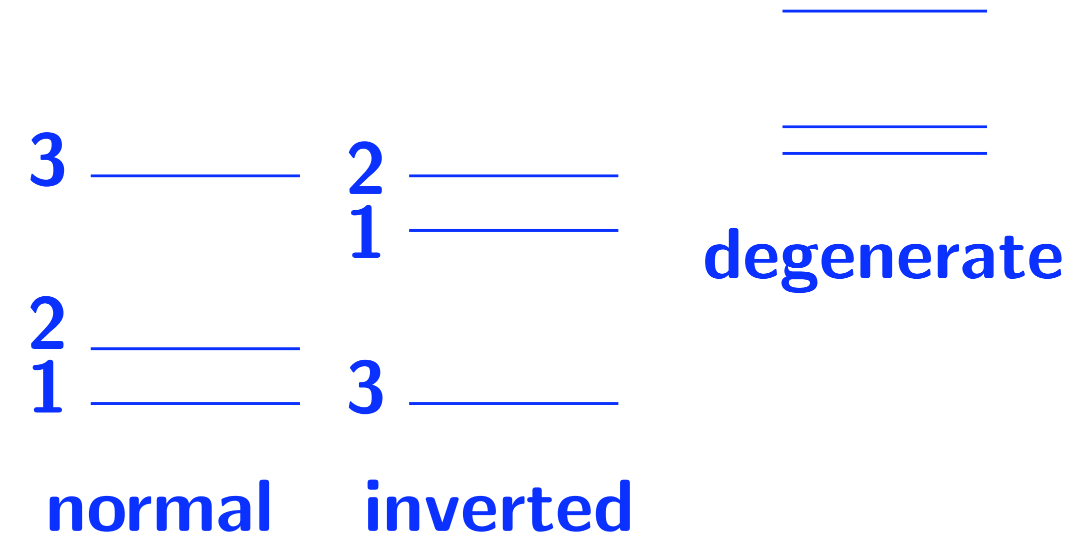
Dirac Majorana

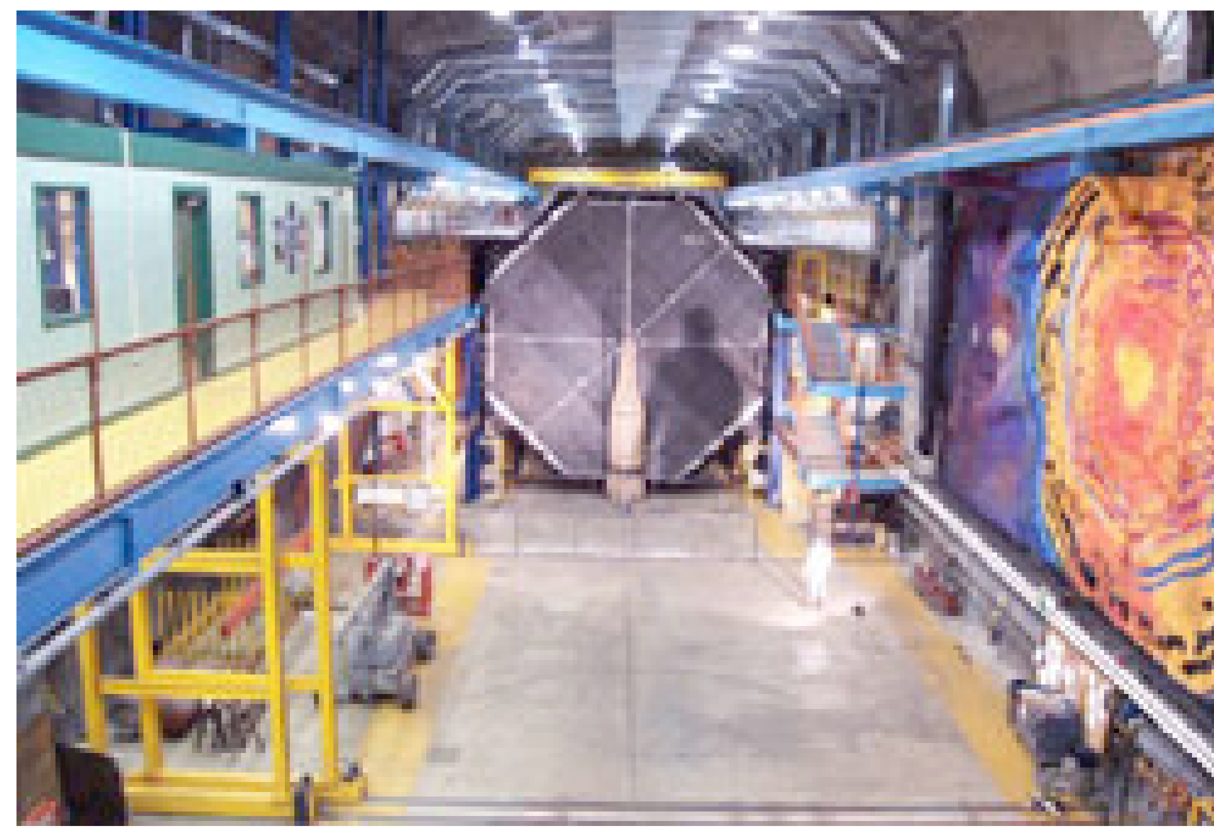


- **What is the spectrum: number, mass scale/pattern, mixings**
  - Scale: β decay (KATRIN), $\beta\beta_{0\nu}$, large scale structure (SDSS)
  - Mixings and CP: reactor, long baseline oscillation experiments, Solar
  - Pattern: long baseline, $\beta\beta_{0\nu}$, supernova
  - Number: LSND? MiniBooNE

- **Leptogenesis?**

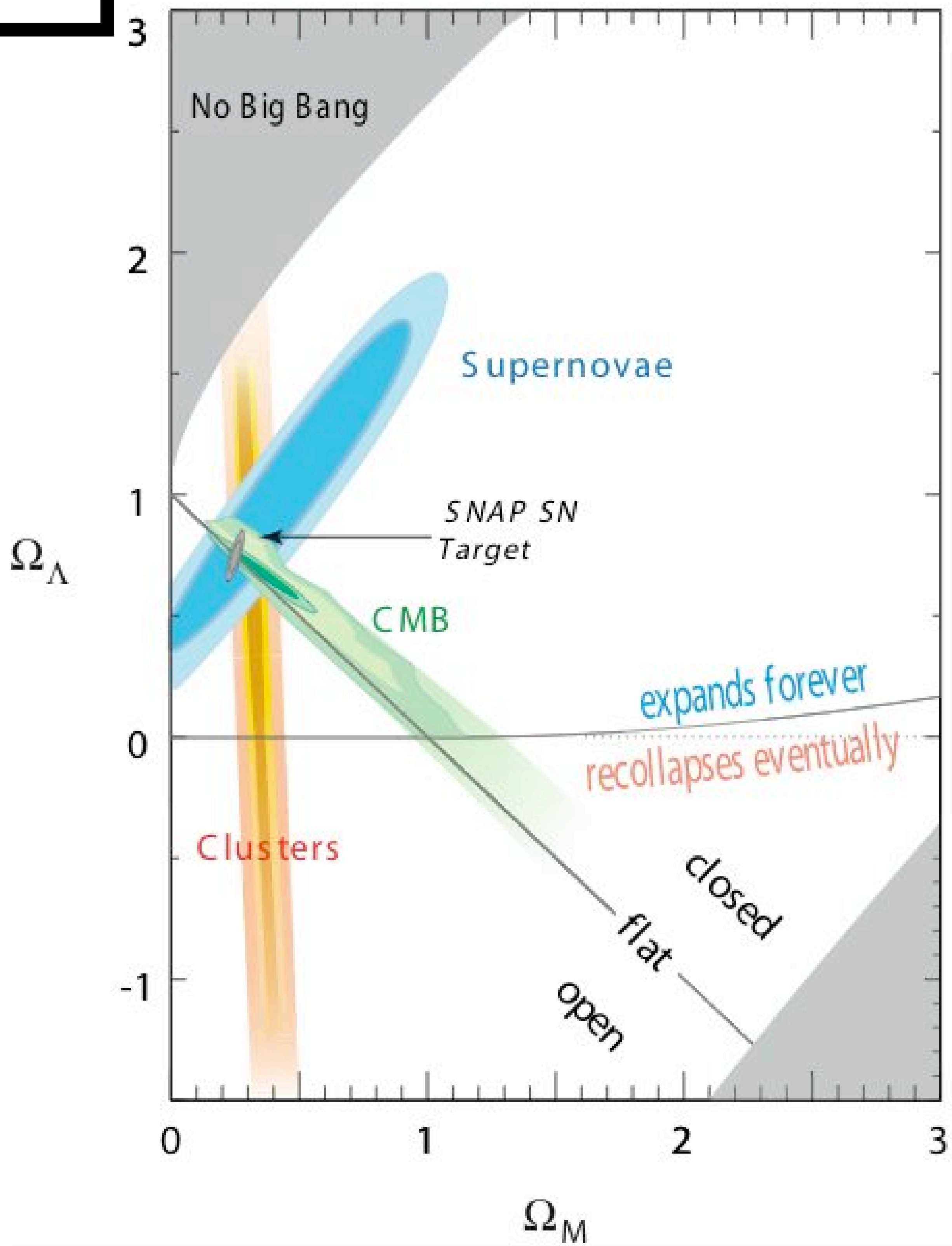
- **Relic neutrinos?**
  - Indirect: Nucleosynthesis, large scale structure. Direct? (Z-burst?)



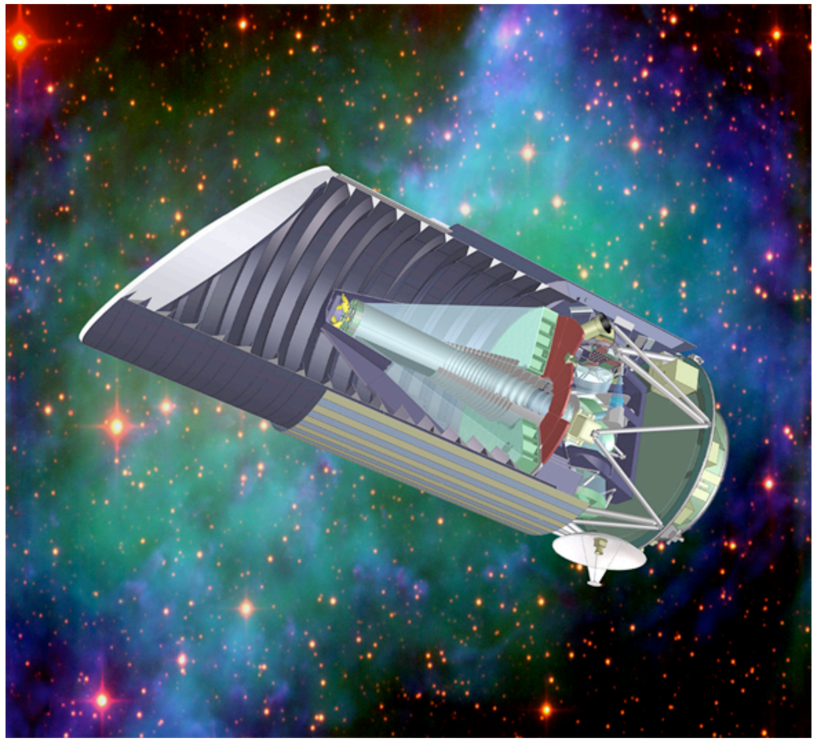


The Universe

- **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))

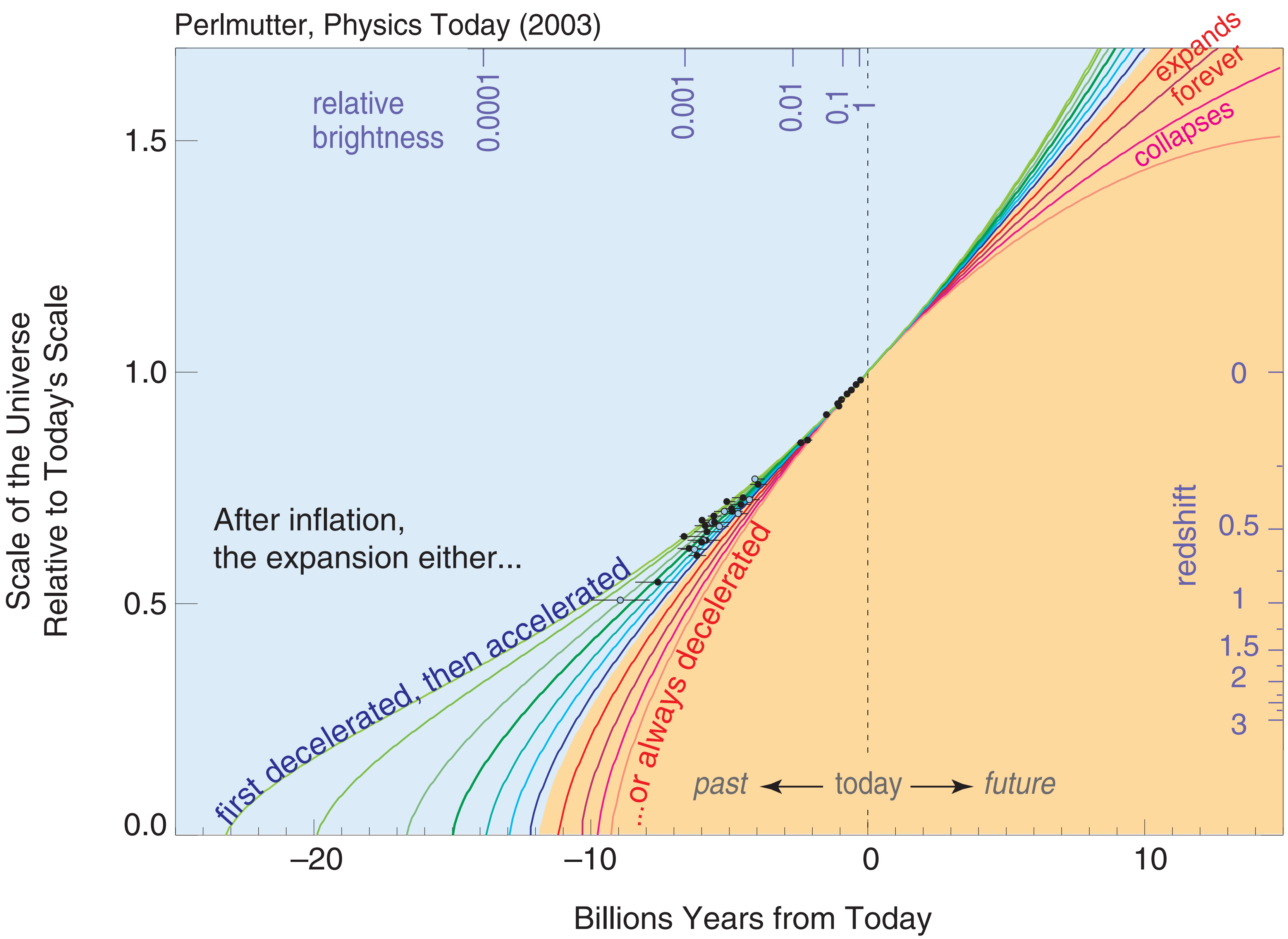


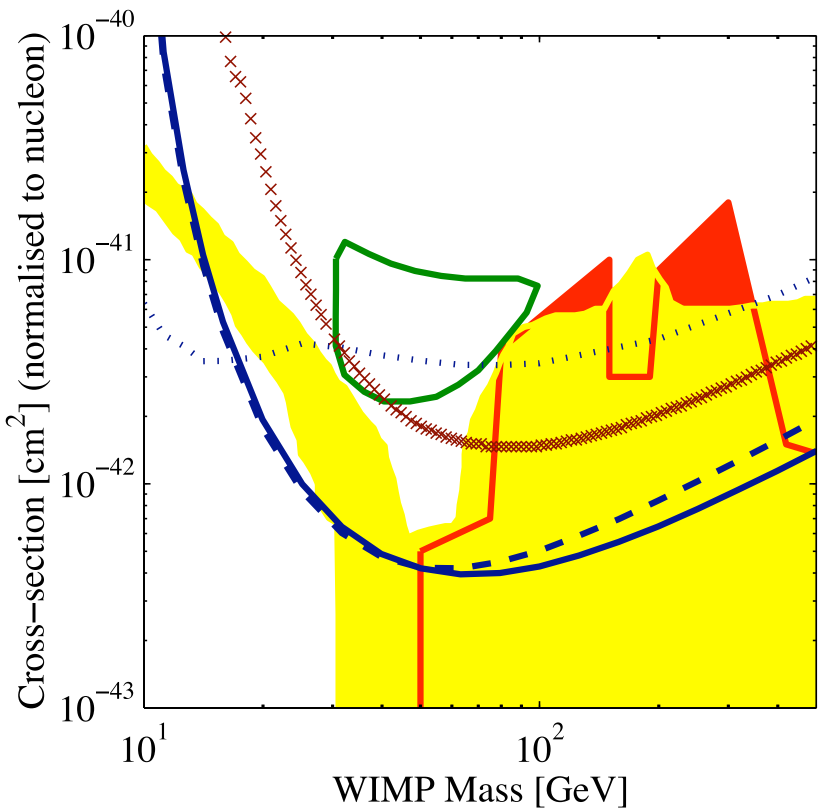
- **What is the dark energy?**
  - **Vacuum energy (cosmological constant); time varying field (quintessence)?**
  - **High precision supernova survey (SNAP); CMB (Planck)**



Expansion History of the Universe

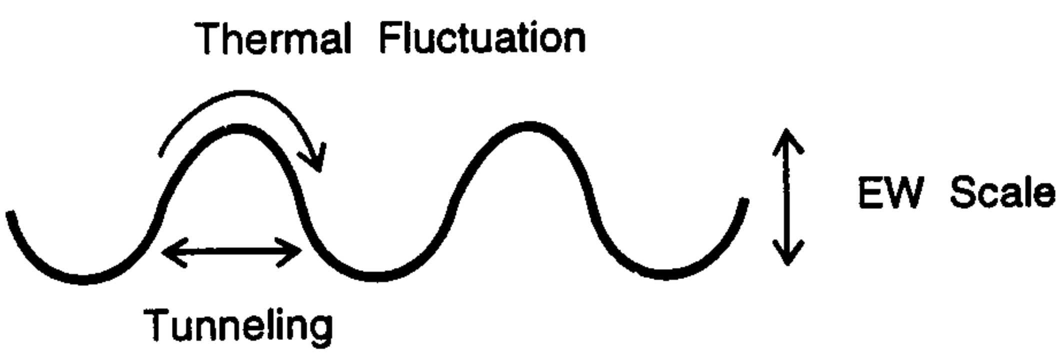
Perlmutter, Physics Today (2003)

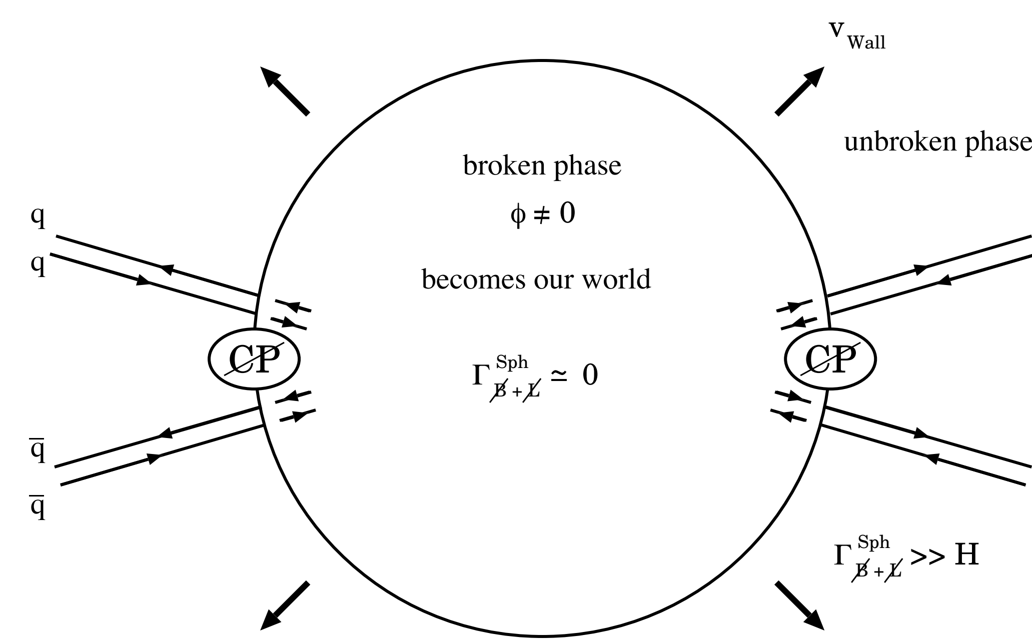




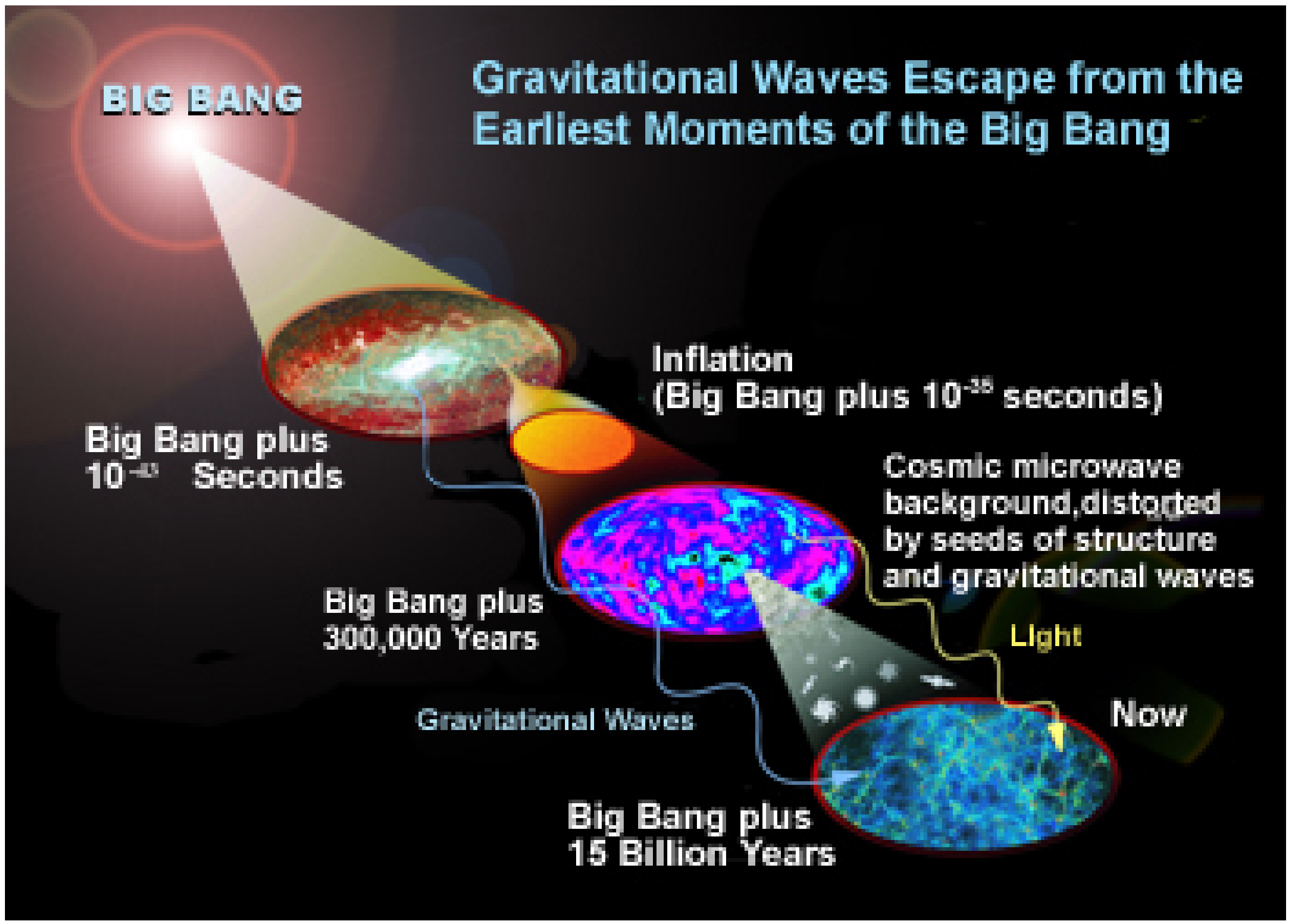
- **What is the dark matter?**
  - **Lightest neutralino in supersymmetry (if R parity conserved)? Axion?**
  - **Direct searches: LHC, ILC; cold dark matter searches; high energy annihilation ν's**
  - **Axion searches (resonant cavities)**
  - **Gravitation lensing (SNAP), CMB (Planck)**

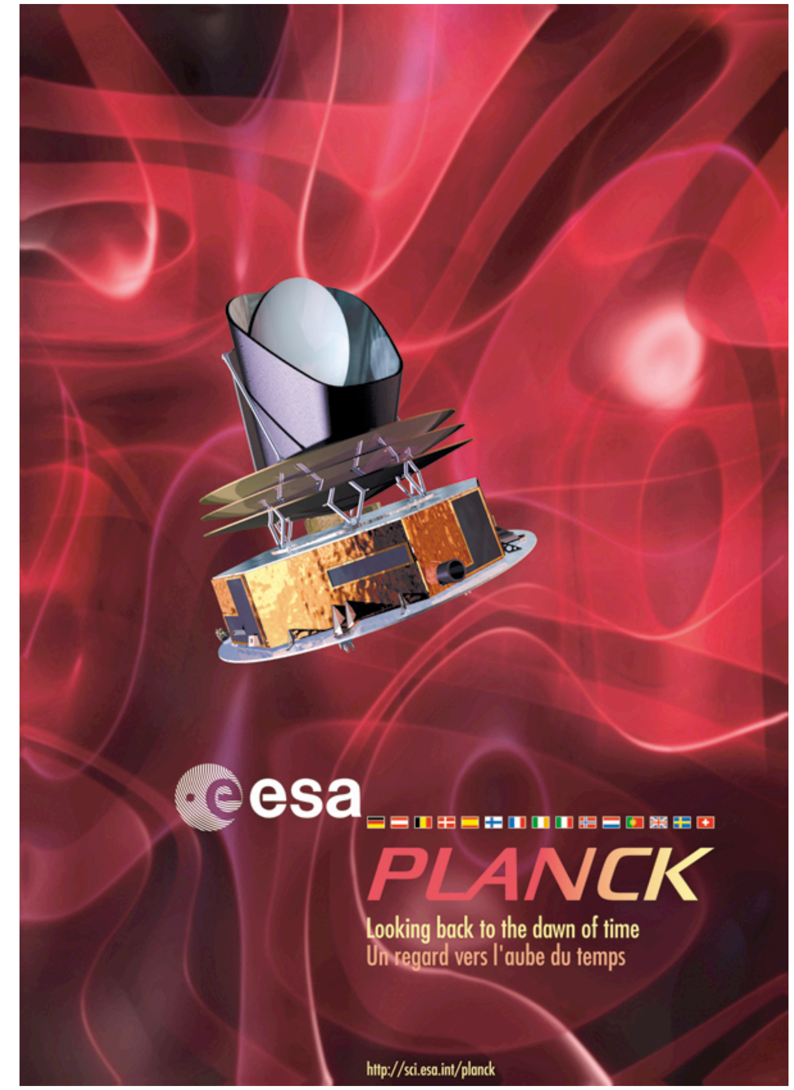
- **Why is there matter and not antimatter?**
  - $n_B/n_\gamma \sim 10^{-10}$, $n_{\bar{B}} \sim 0$
  - Electroweak baryogenesis (extensions of MSSM)? Leptogenesis? Decay of heavy fields? CPT violation?

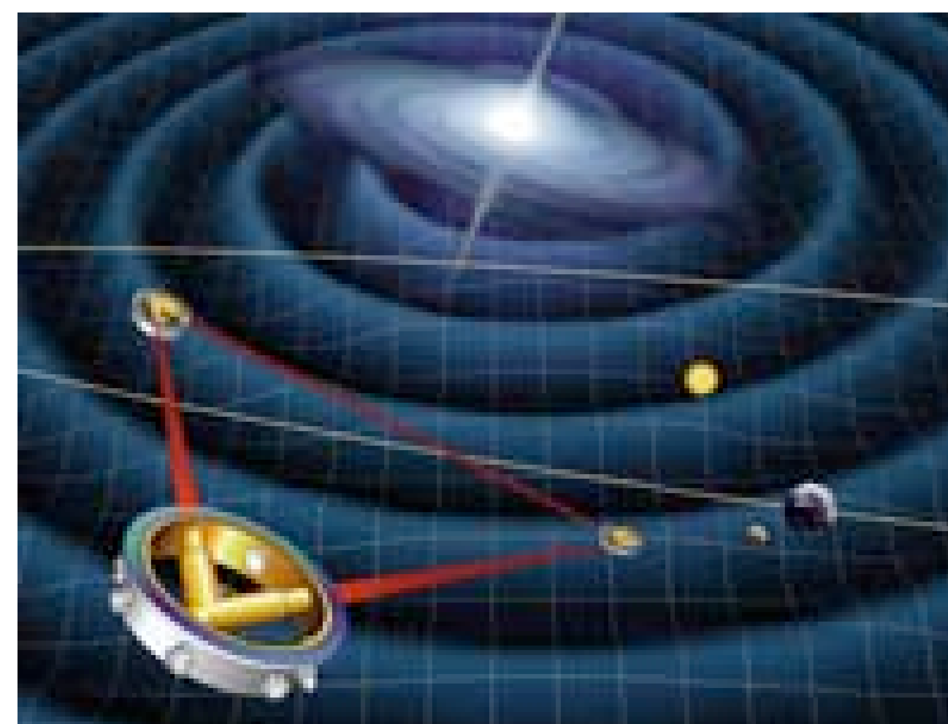




- The very beginning (inflation)
  - Relation to particle physics, strings, Λ?
  - CMB (Planck); gravity waves (LISA)

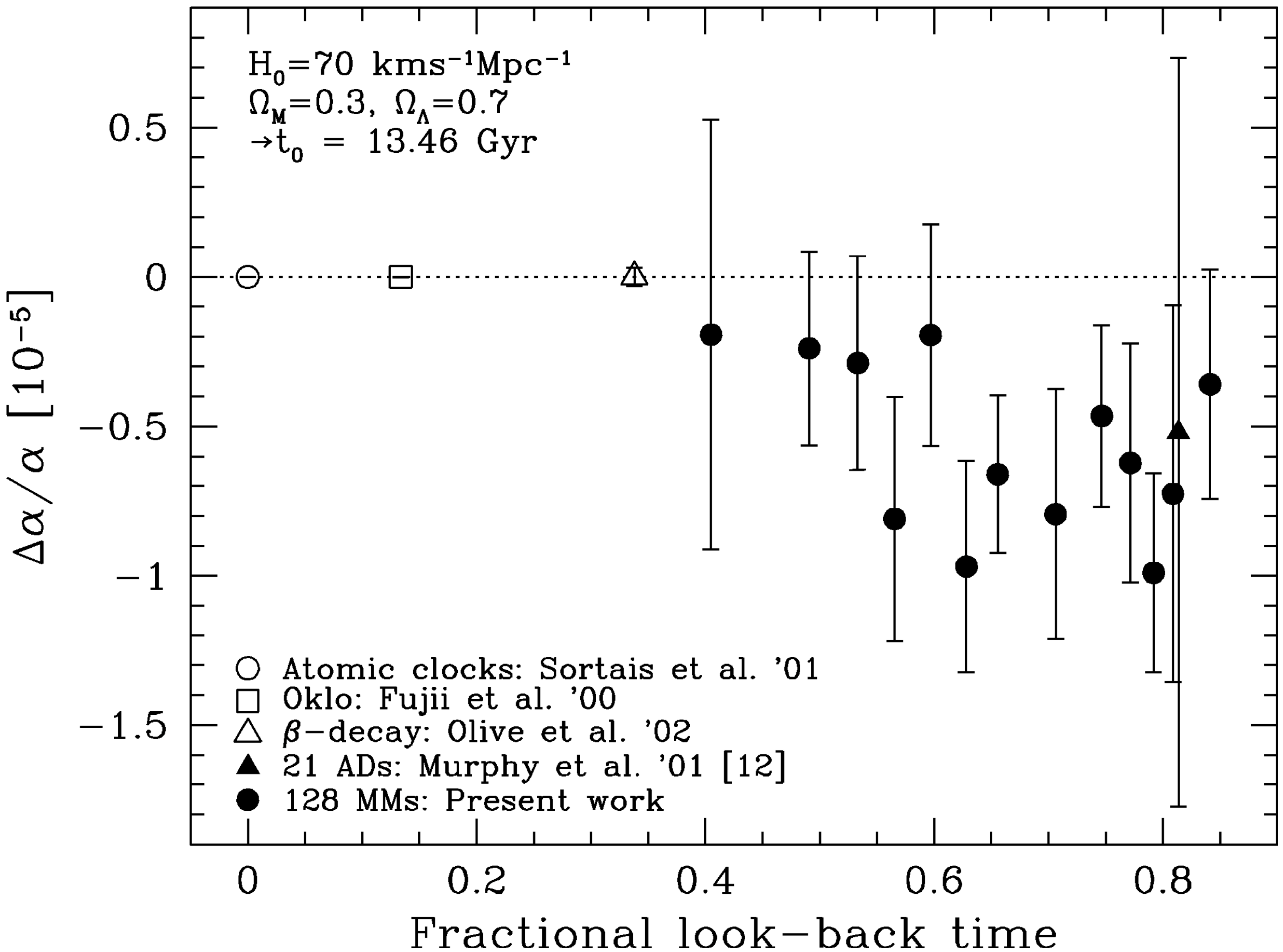






Far-Out Stuff

- **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