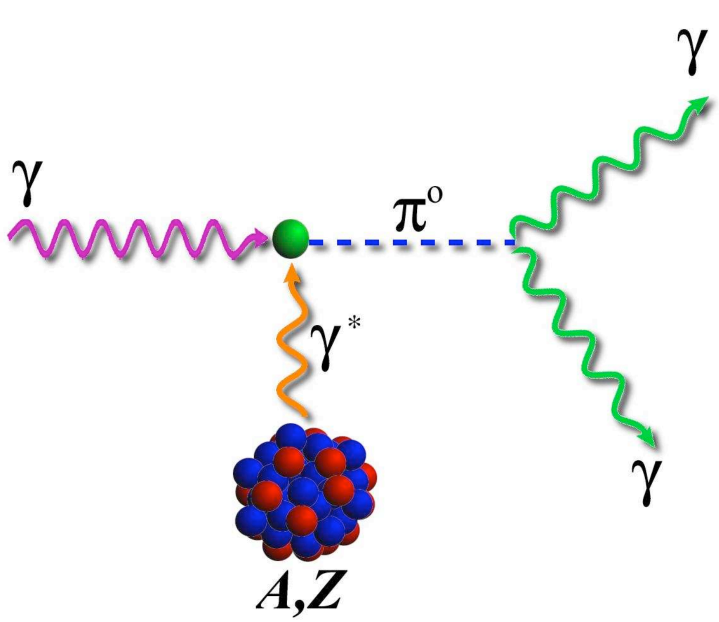


PHYSICAL REVIEW D VOLUME 18, NUMBER 9 1 NOVEMBER 1978

Neutrino-antineutrino oscillations

John N. Bahcall
Institute for Advanced Study, Princeton, New Jersey 08540

Henry Primakoff
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19174
(Received 16 June 1978)

We show that observable neutrino-antineutrino oscillations require not only the nonconservation of lepton number and fermion number and a nonzero mass for the neutrino but also the presence of some right-handed leptonic charged current, and we discuss, very briefly, the prospects for an experimental search.

In the present note we consider the possibility of neutrino-antineutrino oscillations, i.e., of $\bar{\nu}_e \leftrightarrow \nu_e$ or $\bar{\nu}_\mu \leftrightarrow \nu_\mu$ or $\bar{\nu}_\tau \leftrightarrow \nu_\tau$ or $\cdots$ oscillations; such oscillations (as $[A,Z] \to [A,Z+2]+e^- + e^-$ or $K^+ \to \pi^- + \mu^+ + \mu^+$) violate not only lepton-number (l) conservation but also fermion-number (f) conservation. In contrast, $\nu_e \leftrightarrow \nu_\mu$ or $\nu_\mu \leftrightarrow \nu_\tau$ or $\nu_\tau \leftrightarrow \nu_e$ or $\cdots$ oscillations[1] (as $\mu^\pm \to e^\pm + \gamma$ or $\tau^\pm \to \mu^\pm + \gamma$ or $\tau^\pm \to e^\pm + \gamma$ or $\cdots$) violate the conservation of electronic lepton number (l_e), muonic lepton number (l_μ), tauonic lepton number (l_τ), etc., in such a way as to conserve $l = l_e + l_\mu + l_\tau + \cdots$ and f. For the sake of definiteness, and with the possibility of nuclear-reactor experiments in mind, we shall focus our attention on the case of $\bar{\nu}_e \leftrightarrow \nu_e$ oscillations.

To parametrize the situation as simply and as economically as possible we suppose that the $\bar{\nu}_e \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \nu_\mu$ oscillations as well as the $\nu_e \leftrightarrow \nu_\mu$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ oscillations take place between mutually orthogonal neutrino states $|\bar{\nu}_e\rangle, |\nu_e\rangle, |\bar{\nu}_\mu\rangle, |\nu_\mu|$ which can be expressed in terms of the one-particle helicity (h) eigenstates of a Dirac neutrino-antineutrino field, ψ_ν, via[2]

$$
\begin{aligned}
|\bar{\nu}_e\rangle &= \alpha^*|\bar{\nu}_+\rangle + \beta^*|\bar{\nu}_-\rangle , \\
|\nu_e\rangle &= \alpha|\nu_-\rangle + \beta|\nu_+\rangle , \\
|\bar{\nu}_\mu\rangle &= \alpha^*|\nu_+\rangle - \beta^*|\nu_-\rangle , \\
|\nu_\mu\rangle &= \alpha|\bar{\nu}_-\rangle - \beta|\bar{\nu}_+\rangle , \qquad (1 \\
|\alpha|^2 + |\beta|^2 &= 1 , \\
\langle h_{\bar{\nu}_e}\rangle &= -\langle h_{\nu_e}\rangle = \langle h_{\bar{\nu}_\mu}\rangle = -\langle h_{\nu_\mu}\rangle \equiv \langle h_\nu\rangle , \\
\langle h_\nu\rangle &= |\alpha|^2 - |\beta|^2 ,
\end{aligned}
$$

with

$$
\begin{aligned}
m_{\bar{\nu}_e} &= m_{\nu_e} = m_{\bar{\nu}_\mu} = m_{\nu_\mu} \equiv m_\nu , \\
m_\nu &= \langle \nu_\pm | H | \nu_\pm \rangle_{\vec{p}_\nu = 0} = \langle \bar{\nu}_\pm | H | \bar{\nu}_\pm \rangle_{\vec{p}_\nu = 0} , \qquad (2) \\
m_{\bar{\nu}_e} &= \langle \bar{\nu}_e | H | \bar{\nu}_e \rangle_{\vec{p}_\nu = 0} , \text{ etc.},
\end{aligned}
$$

where $H = H_{\text{strong}} + H_{\text{em}} + H_{\text{weak}} + \cdots$ is the world Hamiltonian. Also,

$$\langle h_\nu \rangle = \frac{1-\epsilon^2}{1+\epsilon^2}\left[\frac{|\vec{p}_\nu|}{(|\vec{p}_\nu|^2 + m_\nu{}^2)^{1/2}}\right], \qquad (3)$$

where ϵ specifies the relative amount of right-handed leptonic charged current entering into H_{weak}, i.e.,[3]

$$
\begin{aligned}
\mathcal{J}_\lambda^{\text{leptonic charged current}} &= \psi_e^\dagger \gamma_4 \gamma_\lambda \left[\frac{(1+\gamma_5) + \epsilon(1-\gamma_5)}{(1+\epsilon^2)^{1/2}}\right]\psi_\nu \\
&\quad + \psi_\mu^\dagger \gamma_4 \gamma_\lambda \left[\frac{(1+\gamma_5) - \epsilon(1-\gamma_5)}{(1+\epsilon^2)^{1/2}}\right]\psi_{\bar{\nu}} , \\
\psi_{\bar{\nu}} &= \mathcal{C}\tilde{\psi}_\nu^\dagger , \quad \psi_\nu = \mathcal{C}\psi_{\bar{\nu}}^\dagger . \qquad (4)
\end{aligned}
$$

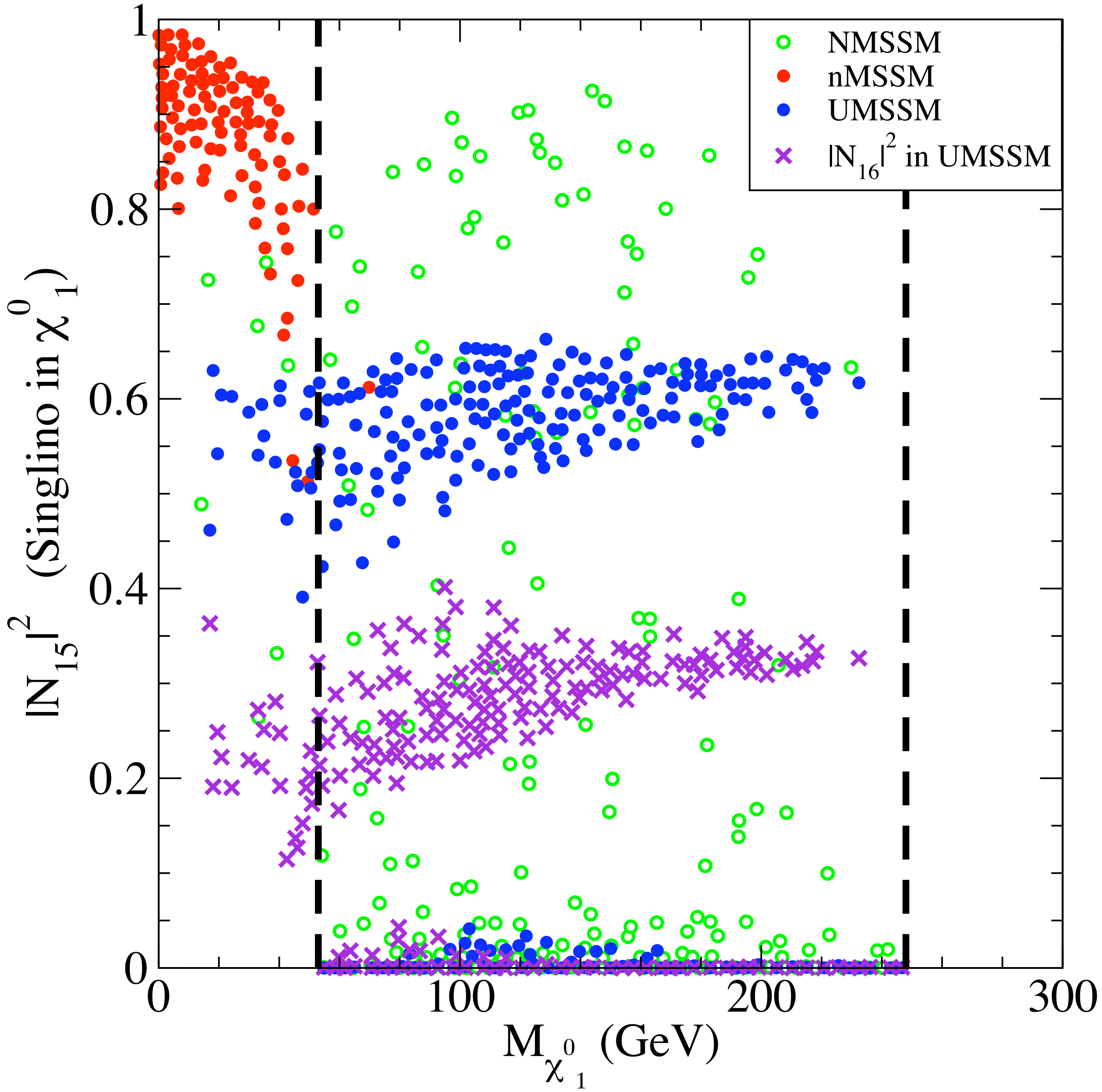
In a similar way, we can suppose that

$$
\begin{aligned}
|\bar{\nu}_\tau\rangle &= \alpha'^*|\bar{\nu}'_+\rangle + \beta'^*|\bar{\nu}'_-\rangle , \\
|\nu_\tau\rangle &= \alpha'|\nu'_-\rangle + \beta'|\nu'_+\rangle , \\
|\bar{\nu}_\sigma\rangle &= \alpha'^*|\nu'_+\rangle - \beta'^*|\nu'_-\rangle , \qquad (5) \\
|\nu_\sigma\rangle &= \alpha'|\bar{\nu}'_-\rangle - \beta'|\bar{\nu}'_+\rangle , \\
|\alpha'|^2 + |\beta'|^2 &= 1 ,
\end{aligned}
$$

where σ is a charged lepton with $m_\sigma > m_\tau$, ν_σ is its associated neutrino (assuming such particles exist), and $|\nu'_\pm\rangle, |\bar{\nu}'_\pm\rangle$ are one-particle helicity eigenstates of another Dirac neutrino-antineutrino field, $\psi_{\nu'}$. It is to be noted that Eqs. (1) and (2) completely segregate $\bar{\nu}_e, \nu_e, \bar{\nu}_\mu, \nu_\mu$ from $\bar{\nu}_\tau, \nu_\tau, \bar{\nu}_\sigma, \nu_\sigma$ but this restriction can be easily removed by postulation of a more complicated relationship between $|\bar{\nu}_e\rangle, |\nu_e\rangle, |\bar{\nu}_\mu\rangle, |\nu_\mu\rangle, |\bar{\nu}_\tau\rangle, |\nu_\tau\rangle, |\bar{\nu}_\sigma\rangle, |\nu_\sigma\rangle$ and $|\bar{\nu}_+\rangle, |\bar{\nu}_-\rangle, |\nu_+\rangle, |\nu_-\rangle, |\bar{\nu}'_+\rangle, |\bar{\nu}'_-\rangle, |\nu'_+\rangle, |\nu'_-\rangle$. It is also to be noted that the states $\alpha^*|\nu_+\rangle - \beta^*|\nu_-\rangle$ and $\alpha|\bar{\nu}_-\rangle - \beta|\bar{\nu}_+\rangle$, which are identified with $|\bar{\nu}_\mu\rangle$ and $|\nu_\mu\rangle$ in Eq. (1), may not have anything to do with the muon and so should be labeled $|\bar{\nu}_\xi\rangle$ and $|\nu_\xi\rangle$ with the question of the participation of ν_ξ together with an appropriate charged lepton ξ in H_{weak} left completely open; in

The Standard Model and Strings - Can They Be Connected?

- **The standard model**
- **Testing the standard model**
- **Problems**
- **Beyond the standard model**
- **New TeV physics suggested by string constructions**
- **Where are we going?**



The *New* Standard Model

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

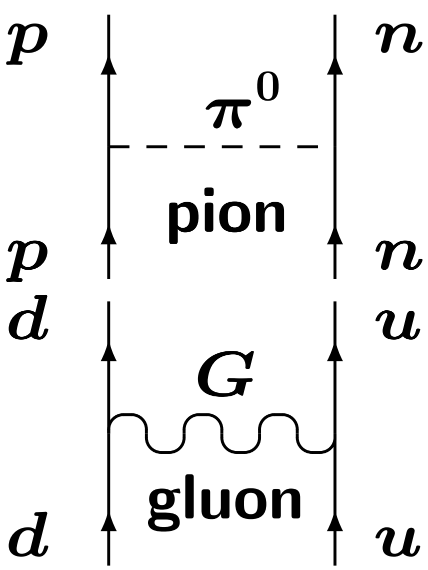
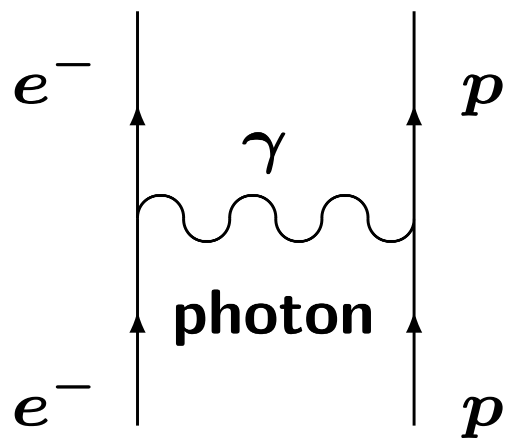
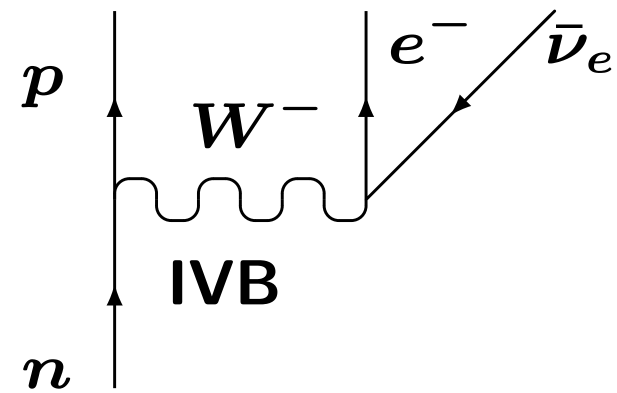
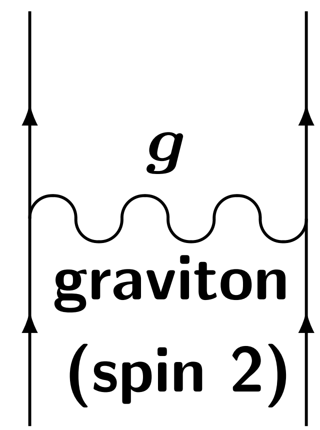
$$SU(3)\times SU(2)\times U(1)\times \text{classical relativity}$$

- 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

The Fundamental Forces

<table>
<tr><th>Strong</th><th>Electromagnetic</th><th>Weak</th><th>Gravity</th></tr>
<tr>
<td>
</td>
<td>
</td>
<td>
</td>
<td>
</td>
</tr>
<tr><td>$V = g_\pi^2 \frac{e^{-m_\pi r}}{r}$</td><td>$\frac{e^2}{r}$</td><td>$g^2 \frac{e^{-M_W r}}{r}$</td><td>$G_N \frac{m_1 m_2}{r}$</td></tr>
<tr><td>strength: $\frac{g_\pi^2}{4\pi} \sim 14$</td><td>$\alpha = \frac{e^2}{4\pi} \sim \frac{1}{137}$</td><td>$\frac{g^2 E^2}{M_W^2} \sim 10^{-11}$
(E = 1 MeV)</td><td>$G_N m_1 m_2 \sim 10^{-38}$
($m_1 = m_2 = 1$ GeV)</td></tr>
<tr><td>range: $\frac{\hbar}{m_\pi c} \sim 10^{-13}$ cm $\equiv$ 1 fm</td><td>∞</td><td>$\frac{\hbar}{M_W c} \sim 10^{-16}$ cm</td><td>∞</td></tr>
</table>

Unification of Forces

Strong	Electromagnetic	Weak	Gravity
hadrons: p, n; pions: $\pi^\pm, \pi^0$; (QCD: quarks, gluons)	charged particles: e^-, μ^-, τ^-; p; $\pi^\pm$	p, n, π; e, μ, τ;, neutrinos: ν_e, ν_μ, ν_τ	all particles (always attractive)
nuclear binding; energy in stars	atoms, crystals, molecules; light; chemical energy	decays: $n \to pe^- \bar{\nu}_e$; element synthesis	weight; binding of solar system, stars, galaxies
	$\leftarrow$ $E + B$ $\rightarrow$ (Maxwell)		
$\leftarrow$ QCD $\rightarrow$	$\leftarrow$ Electroweak $(SU(2) \times U(1))$ $\rightarrow$		
$\leftarrow$ Grand Unification (GUT)? $\rightarrow$			
$\leftarrow$ Theory of Everything (superstring)? $\rightarrow$			

Gauge Theories

- Gauge symmetry requires existence of (apparently) massless spin-1 (vector, gauge) bosons
- Interactions prescribed up to group, representations, gauge coupling
- Analogous to QED ($U(1)$), but gauge self interactions for non-abelian groups
- Standard model: $SU(3)\times SU(2)\times U(1)$
- Application to strong (short range) $\Rightarrow$ confinement
- Application to weak (short range) $\Rightarrow$ spontaneous symmetry breaking (Higgs or dynamical)
- Unique renormalizable field theory for spin-1

The Standard Model

- Gauge group $SU(3) \times SU(2) \times U(1)$; gauge couplings g_s, g, g'

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$$

$$\begin{matrix} u_R & u_R & u_R & \nu_{eR}(?) \\ d_R & d_R & d_R & e_R^- \end{matrix}$$

(L = left-handed, R = right-handed)

- $SU(3)$: $u \leftrightarrow u \leftrightarrow u$, $d \leftrightarrow d \leftrightarrow d$ (gluons)

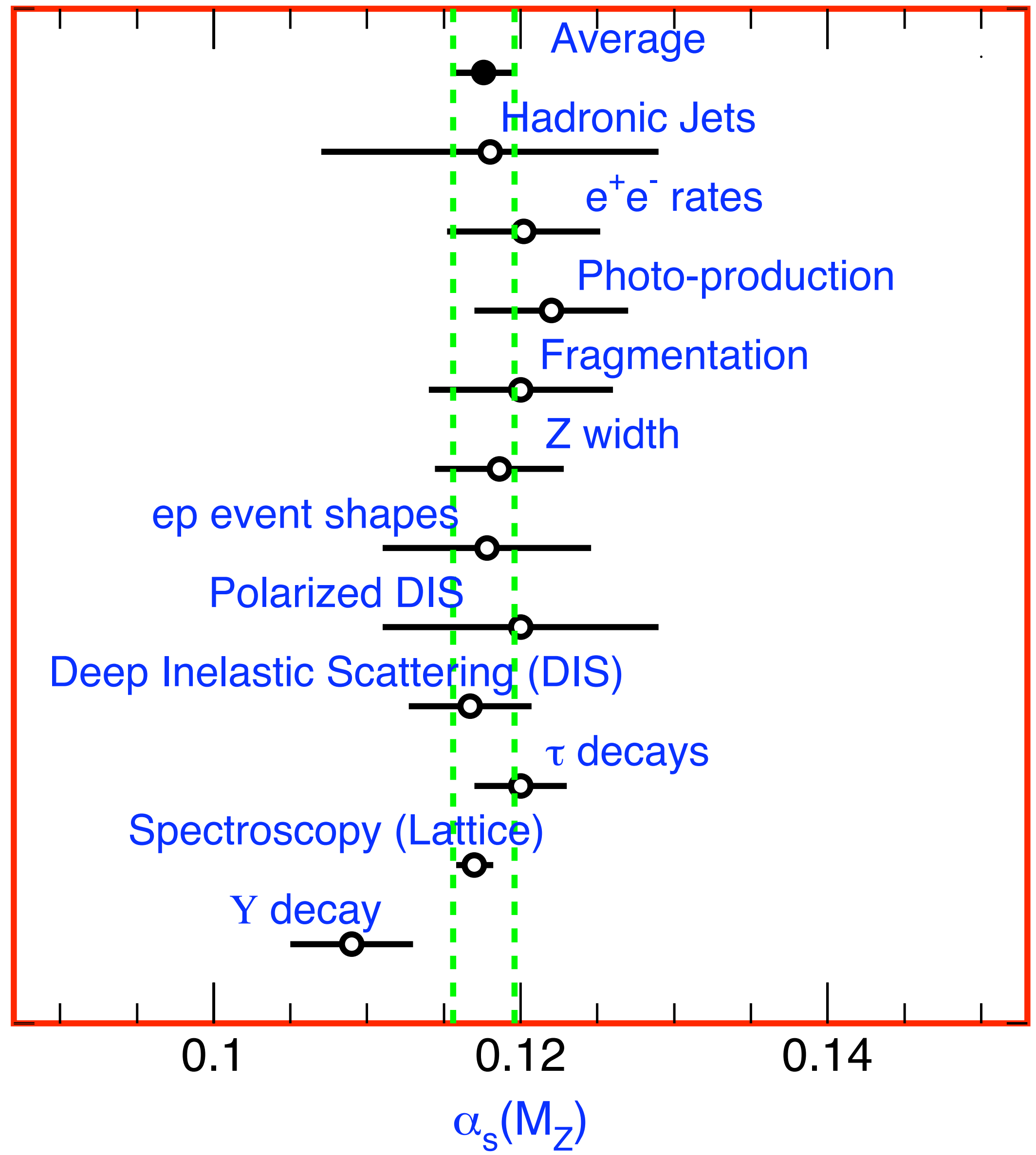
- $SU(2)$: $u_L \leftrightarrow d_L$, $\nu_{eL} \leftrightarrow e_L^-$ $(W^\pm)$; phases (W^0)

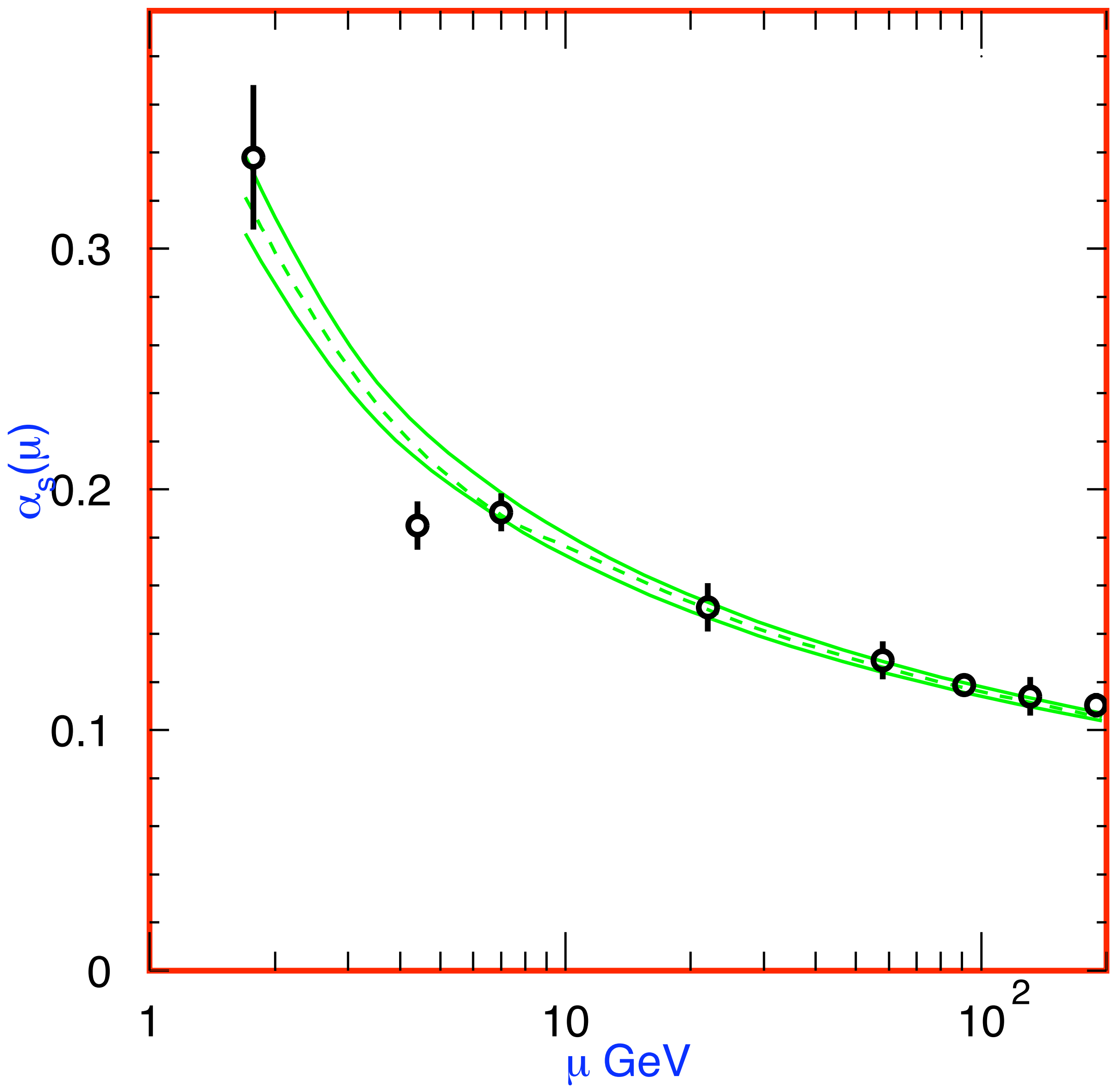
- $U(1)$: phases (B)

- Heavy families (c, s, ν_μ, μ^-), (t, b, ν_τ, τ^-)

Quantum Chromodynamics (QCD)

Modern theory of the strong interactions





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)	$[3.0 \times 10^{-8}]$	$(0.072 \pm 0.041) \times 10^{-4}$

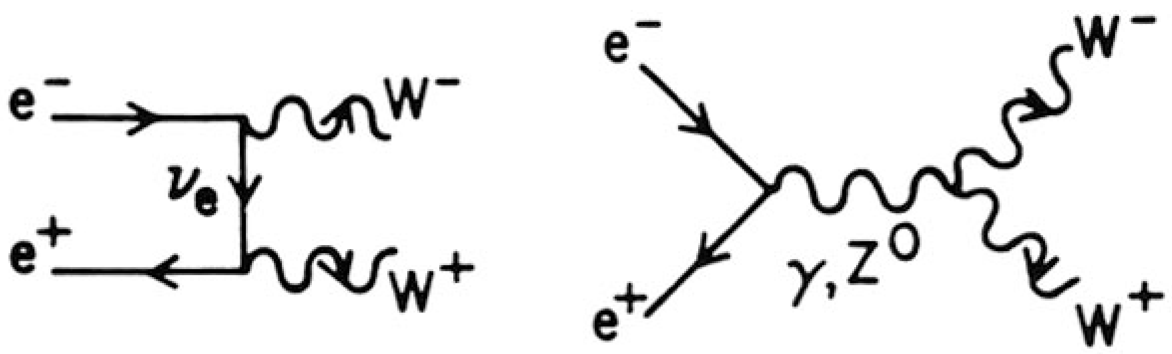
The Electroweak Theory

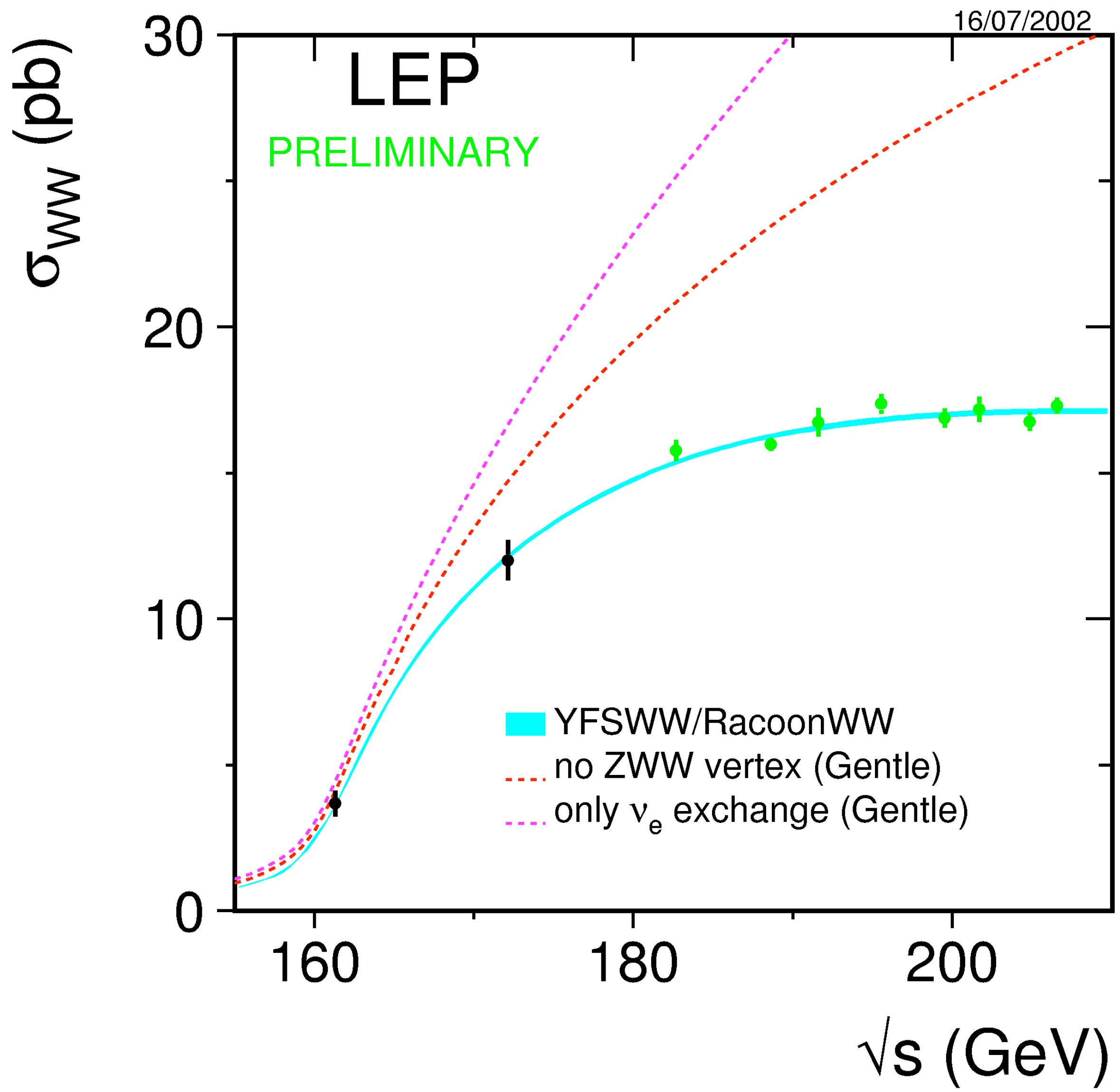
- QED and weak charged current unified

- Weak neutral current (Z) predicted
  ($\nu N \to \nu X$, atomic parity violation)

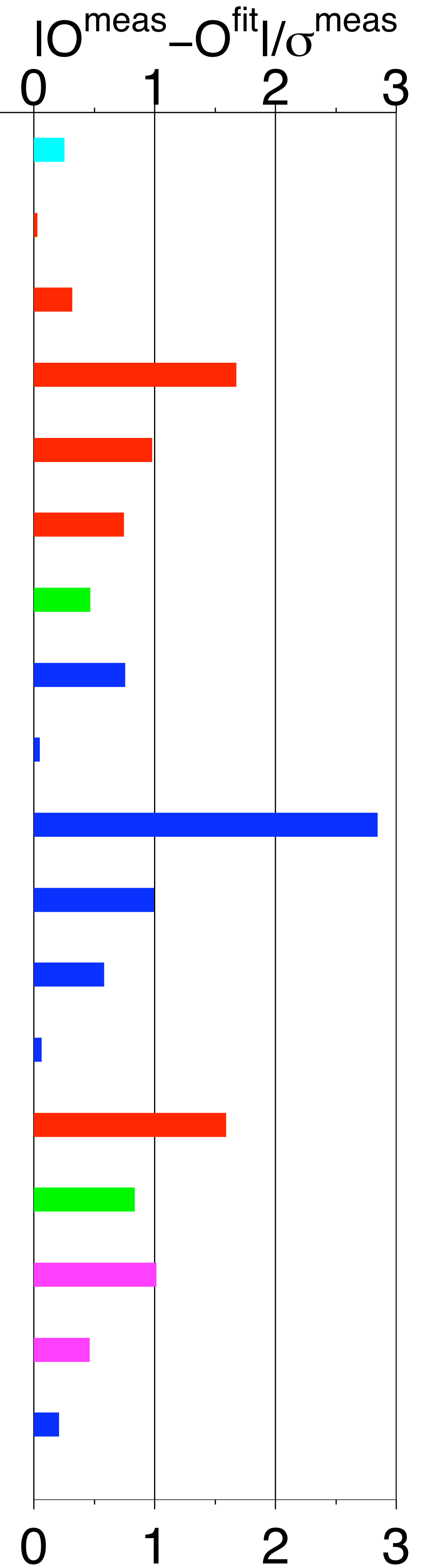
- Stringent tests of wnc, Z-pole and beyond

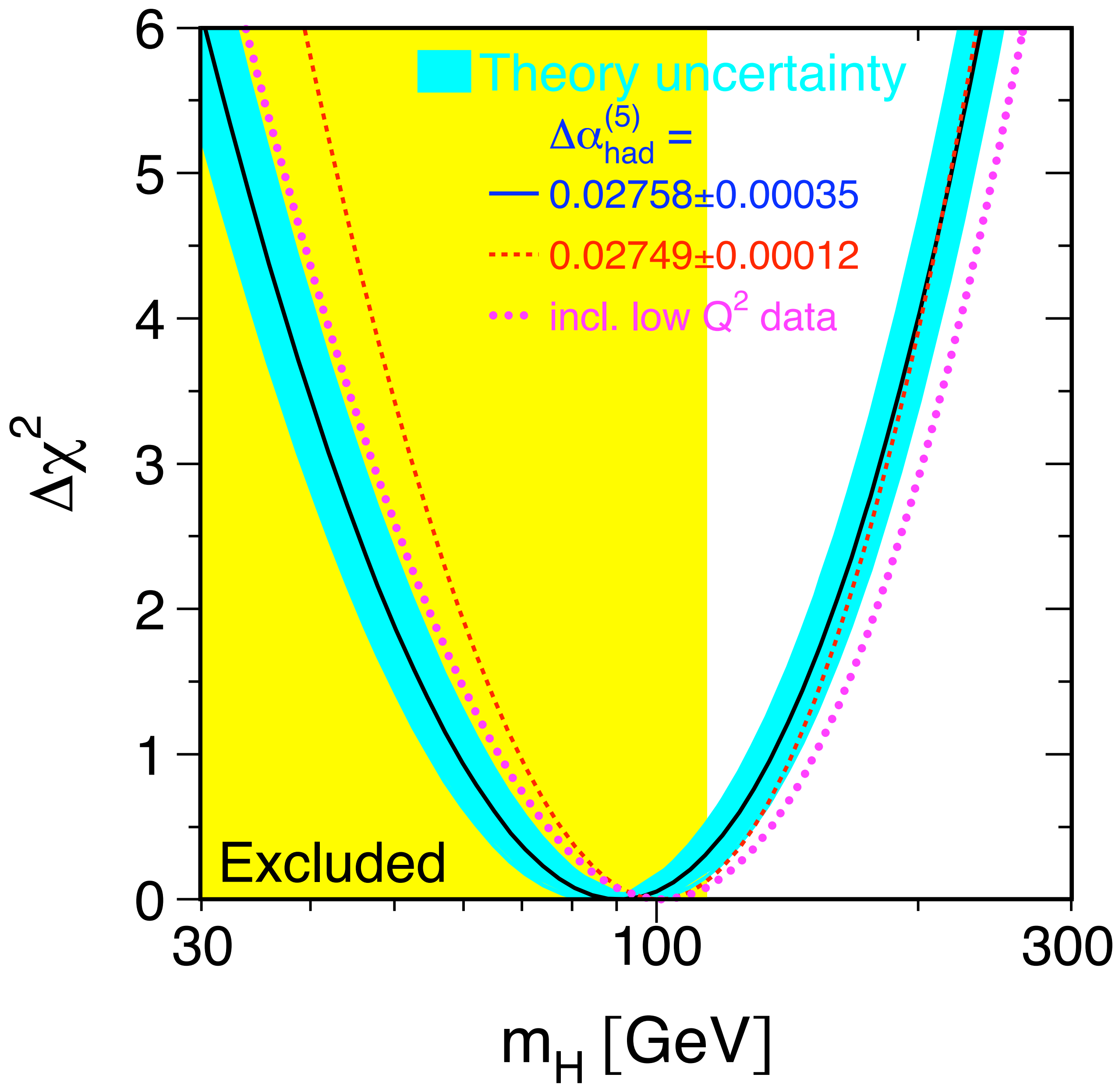
- Fermion gauge and gauge self interactions





	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	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_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	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
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	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
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	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)**

Problems with the Standard Model

Lagrangian after symmetry breaking:

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

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

Mathematically consistent, renormalizable theory

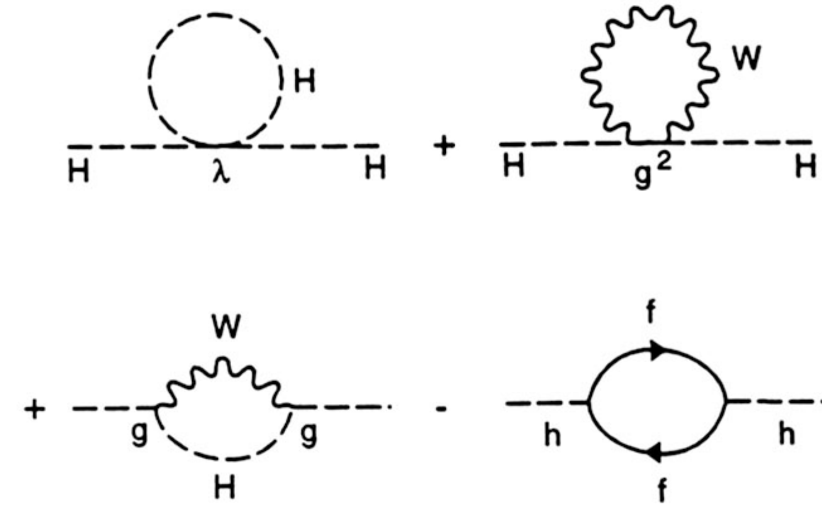
Correct to 10^{-16} cm

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 $\delta\theta|_{\text{weak}} \sim 10^{-3}$
  - 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)?

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**

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

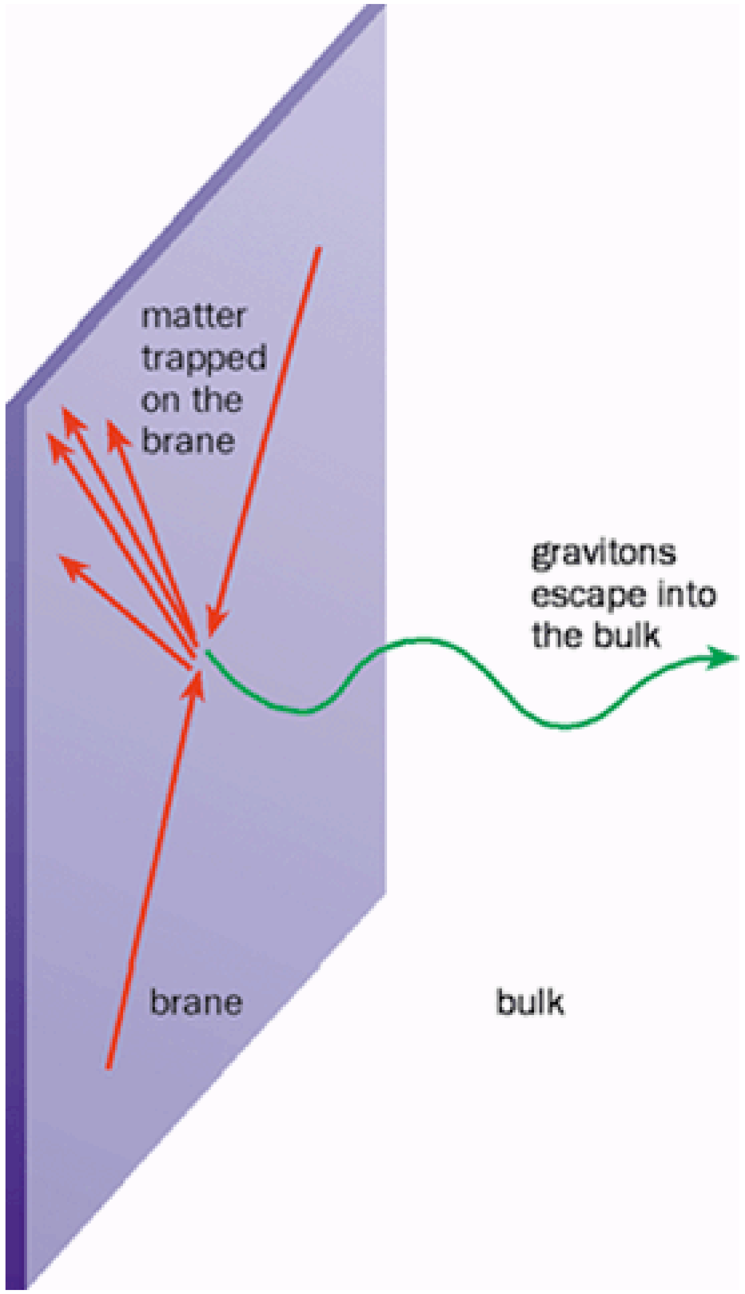
Large extra dimensions (deconstruction, brane worlds)

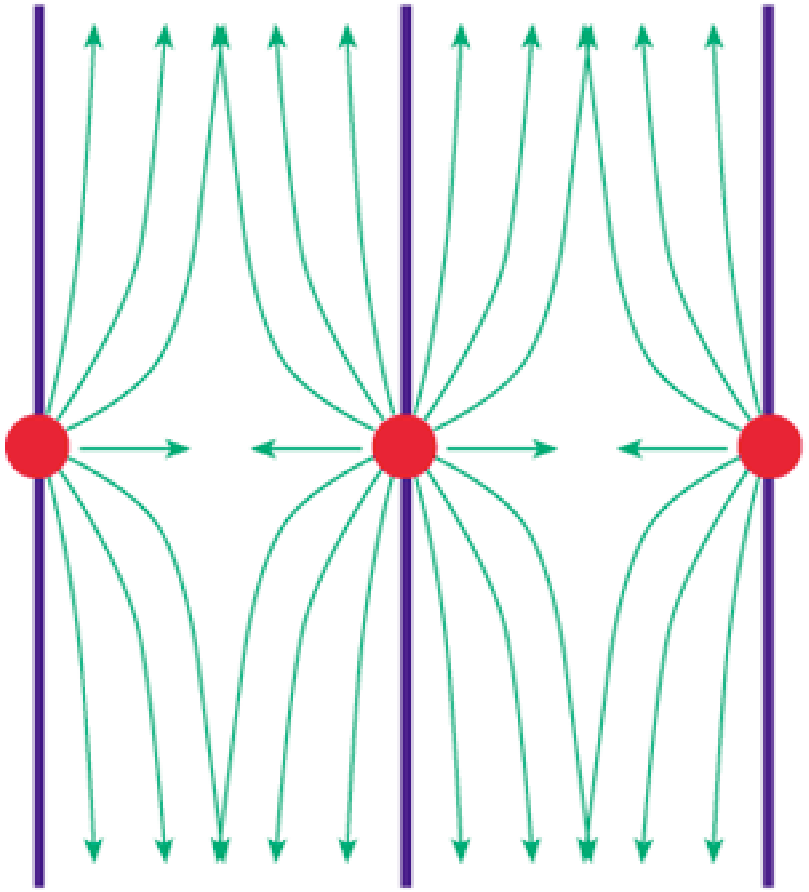
- **Can be motivated by strings, but new dimensions much larger than $M_P^{-1} \sim 10^{-33}$ cm**

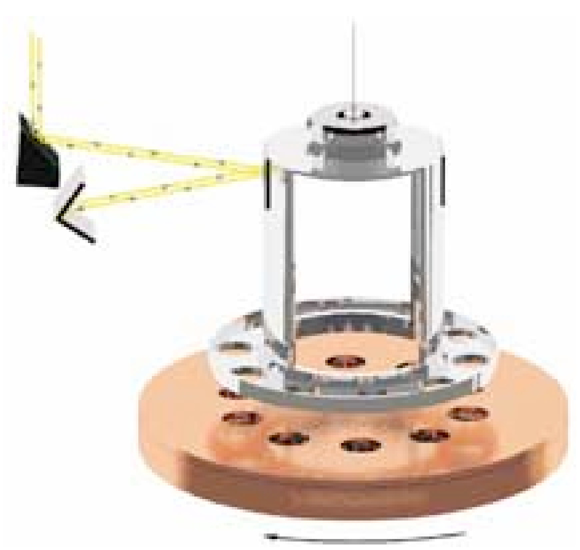
- **Fundamental scale $M_F \sim 1 - 100$ TeV $\ll \bar{M}_{Pl} = 1/\sqrt{8\pi G_N} \sim 2.4 \times 10^{18}$ GeV**
  - **Assume δ extra dimensions with volume $V_\delta \gg M_F^{-\delta}$**

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

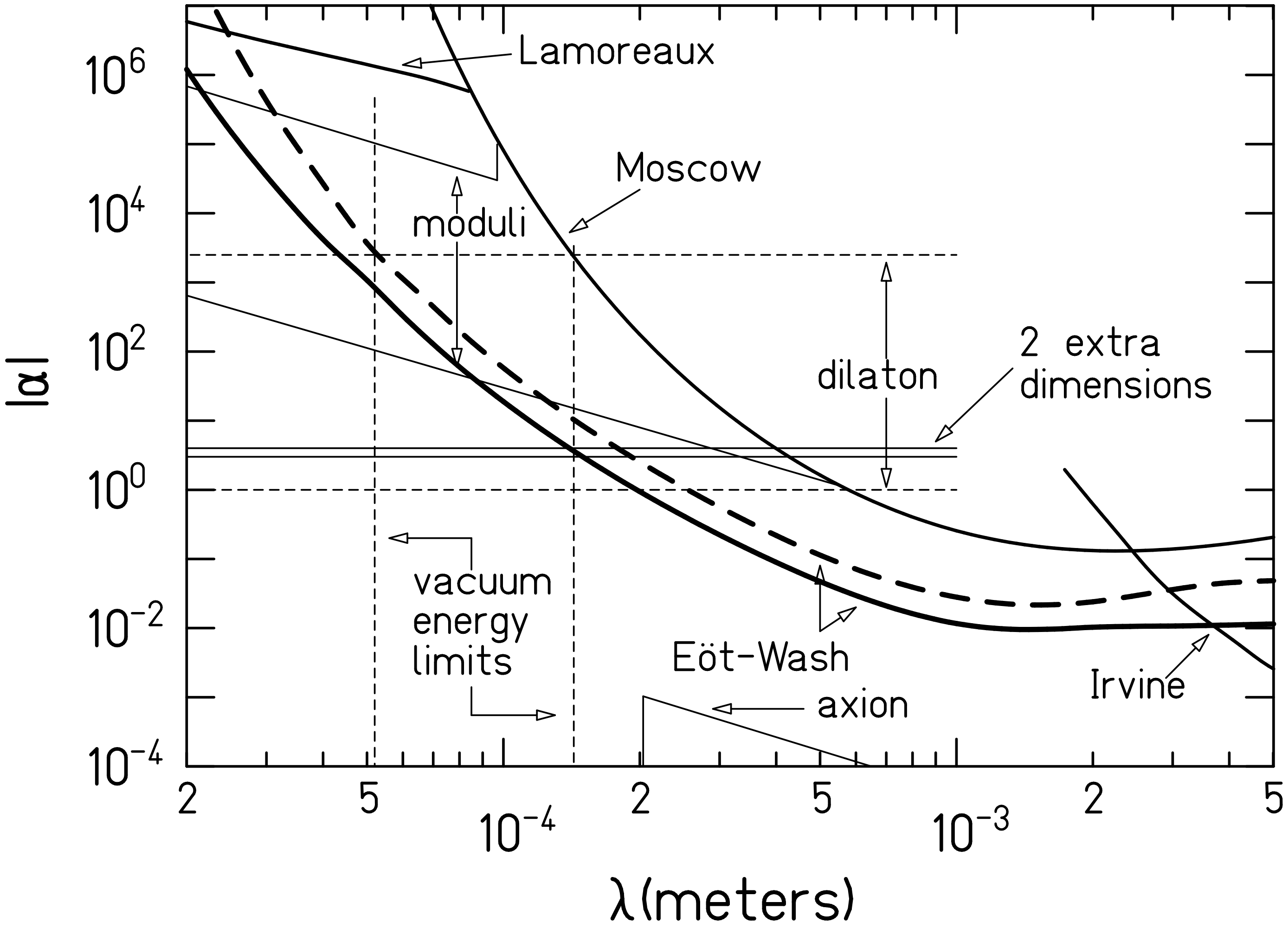
(Introduces new hierarchy problem)







- **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

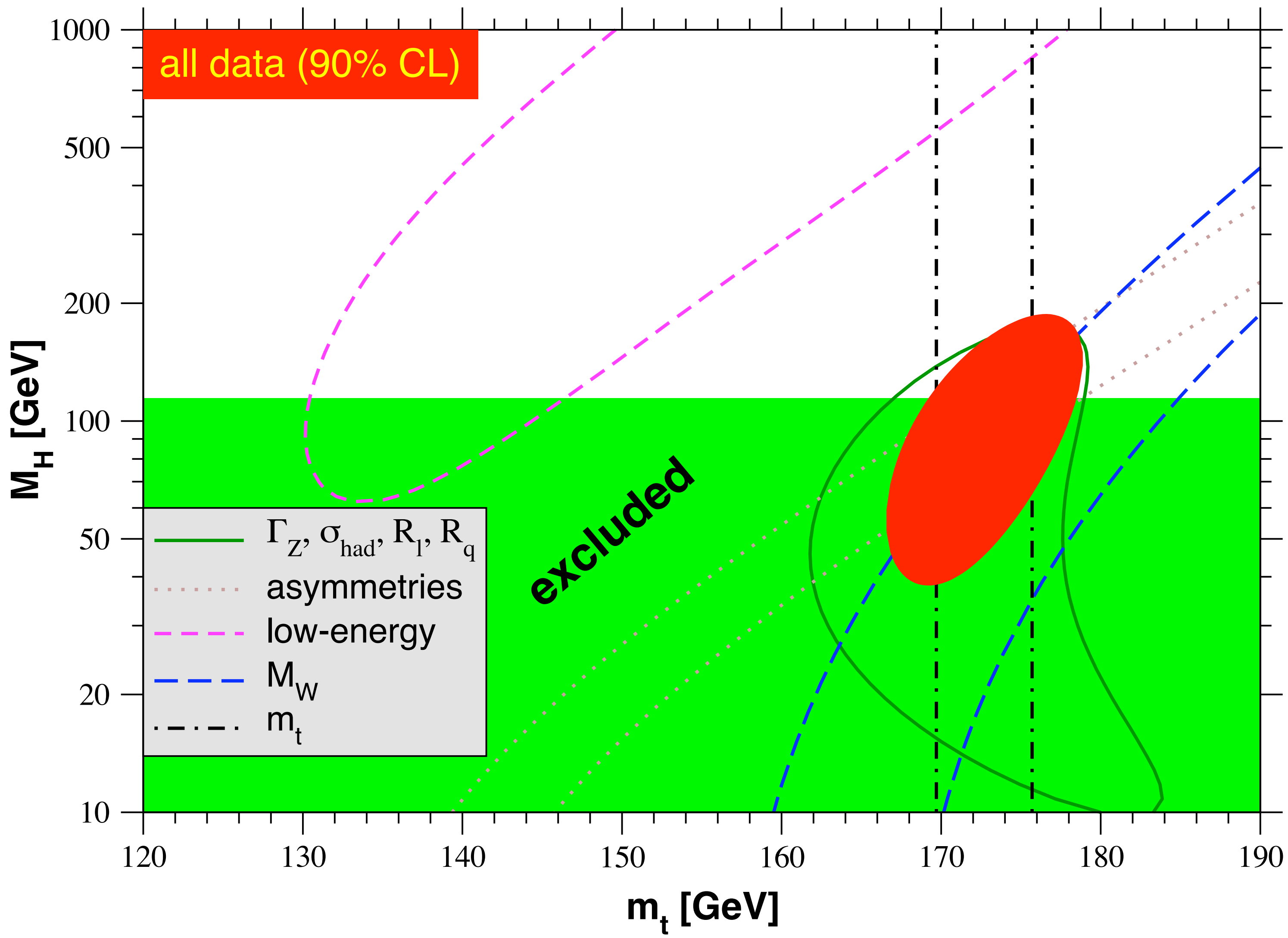
- Possibility of probing to M_P and very early universe

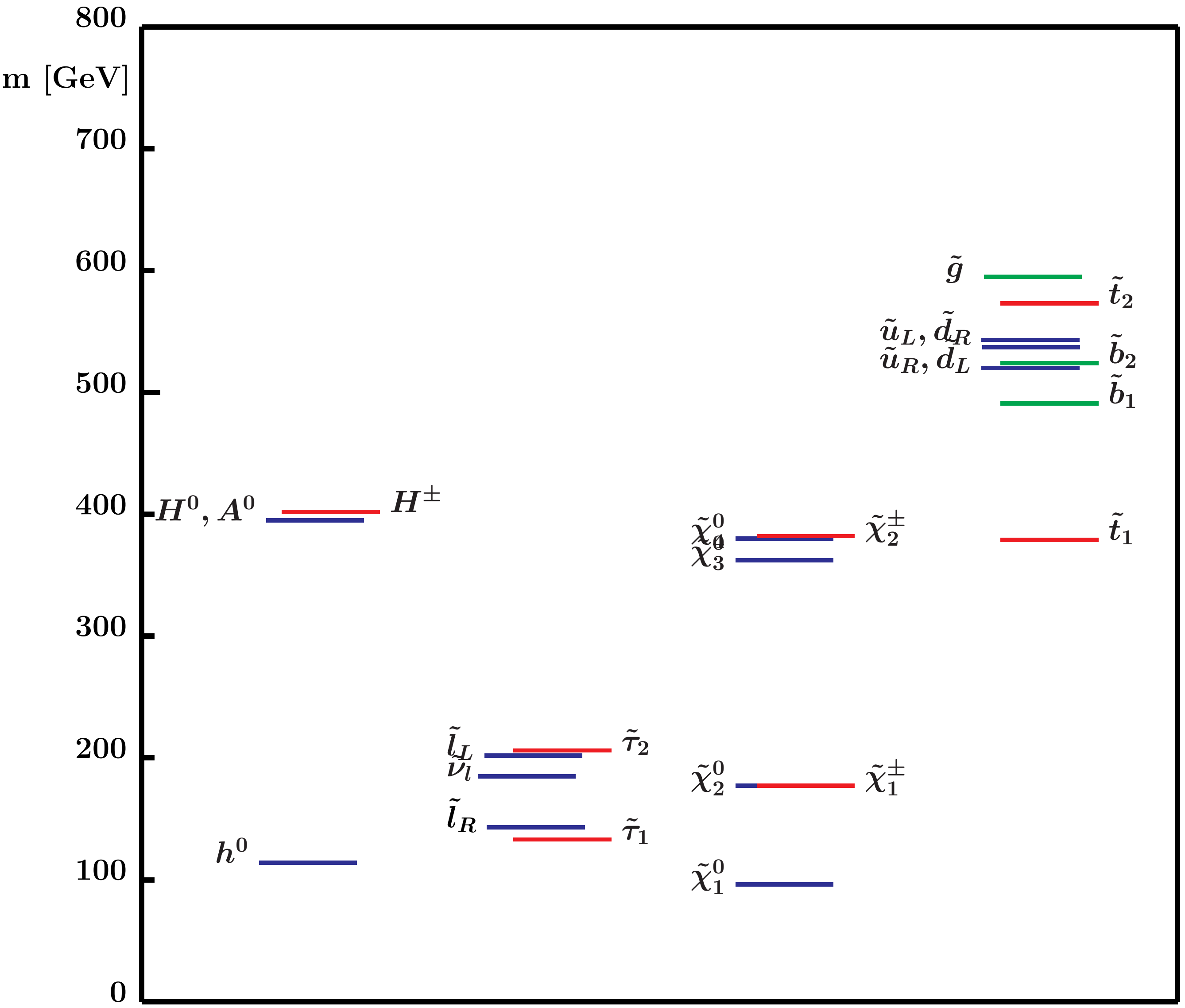
Supersymmetry

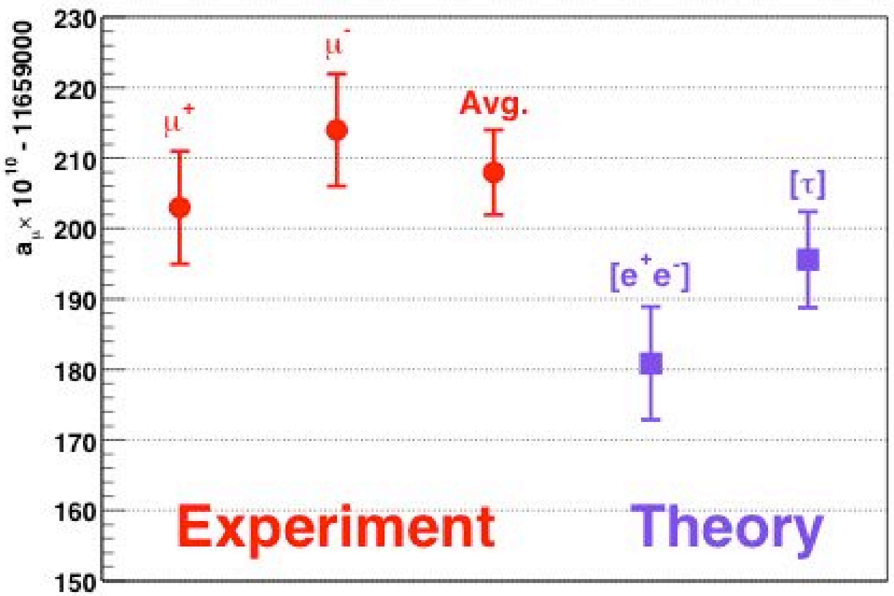
- Fermion $\leftrightarrow$ boson symmetry
- Motivations
  - stabilize weak scale $\Rightarrow M_{SUSY} < O(1$ TeV$)$
    (but recent high scale ideas)
  - supergravity (gauged supersymmetry): unification of gravity (non-renormalizable)
  - coupling constants in supersymmetric grand unification
  - decoupling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

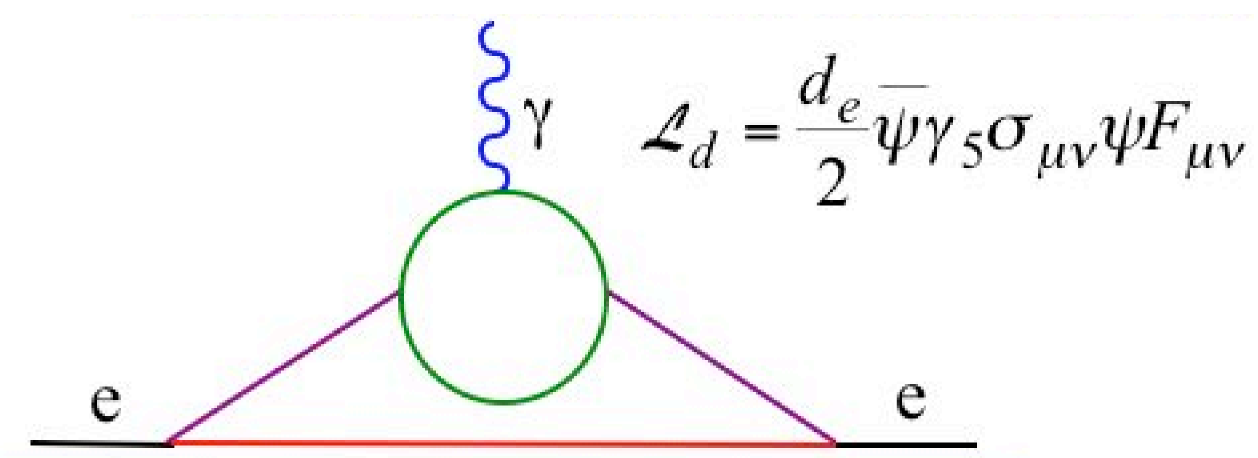
- **Simplest version: supersymmetric contribution to Higgs mass must be of $O(100)$ GeV (not 10^{19})** (μ problem)







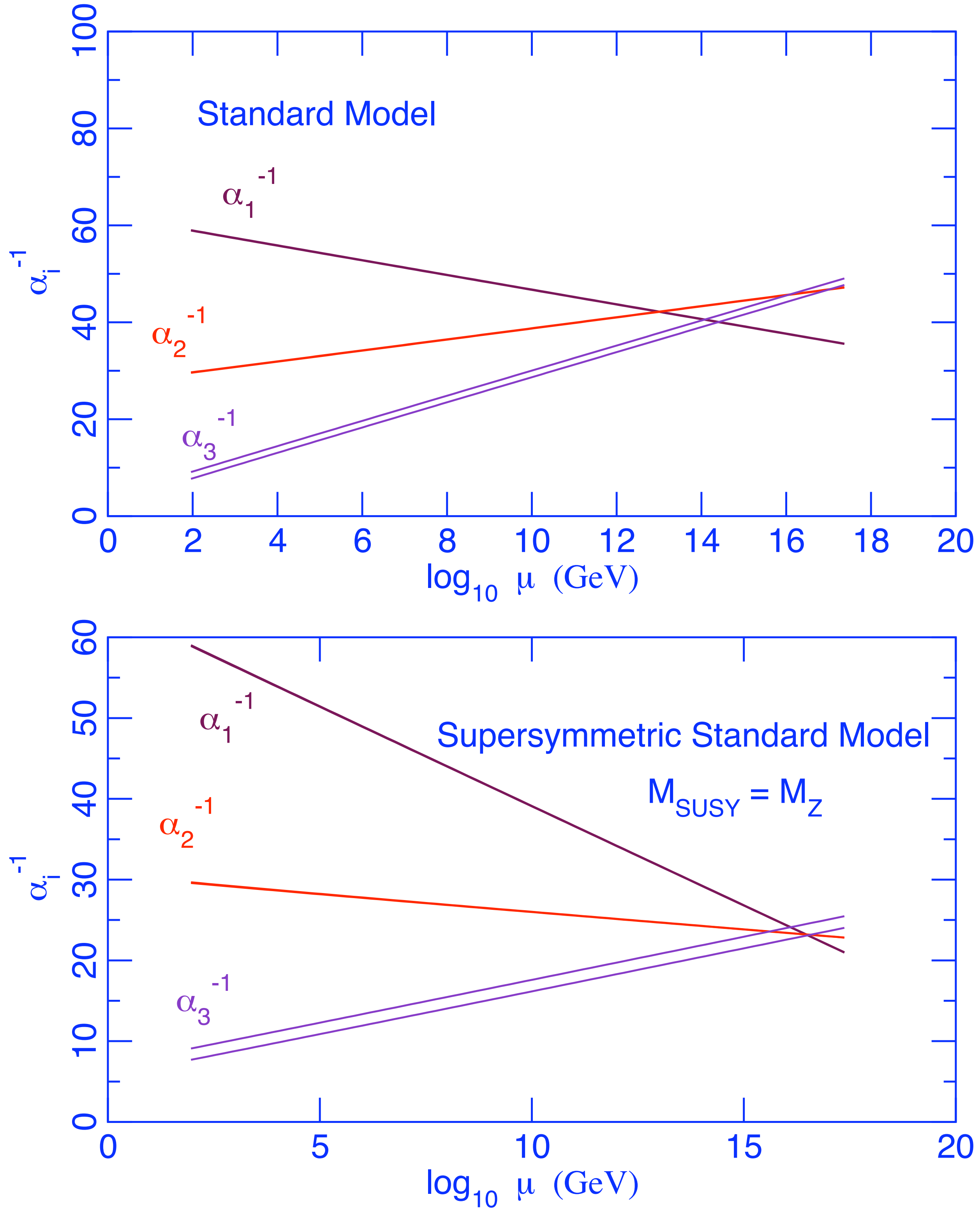
- **Superpartners**
  - $q \Rightarrow \tilde{q}$, scalar quark
  - $\ell \Rightarrow \tilde{\ell}$, scalar lepton
  - $W \Rightarrow \tilde{w}$, wino
  - typical scale: several hundred GeV
  - LSP: cold dark matter candidate
  - SUSY breaking $\Leftrightarrow$ large m_t
  - May be large FCNC, EDM, $\Delta(g_\mu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



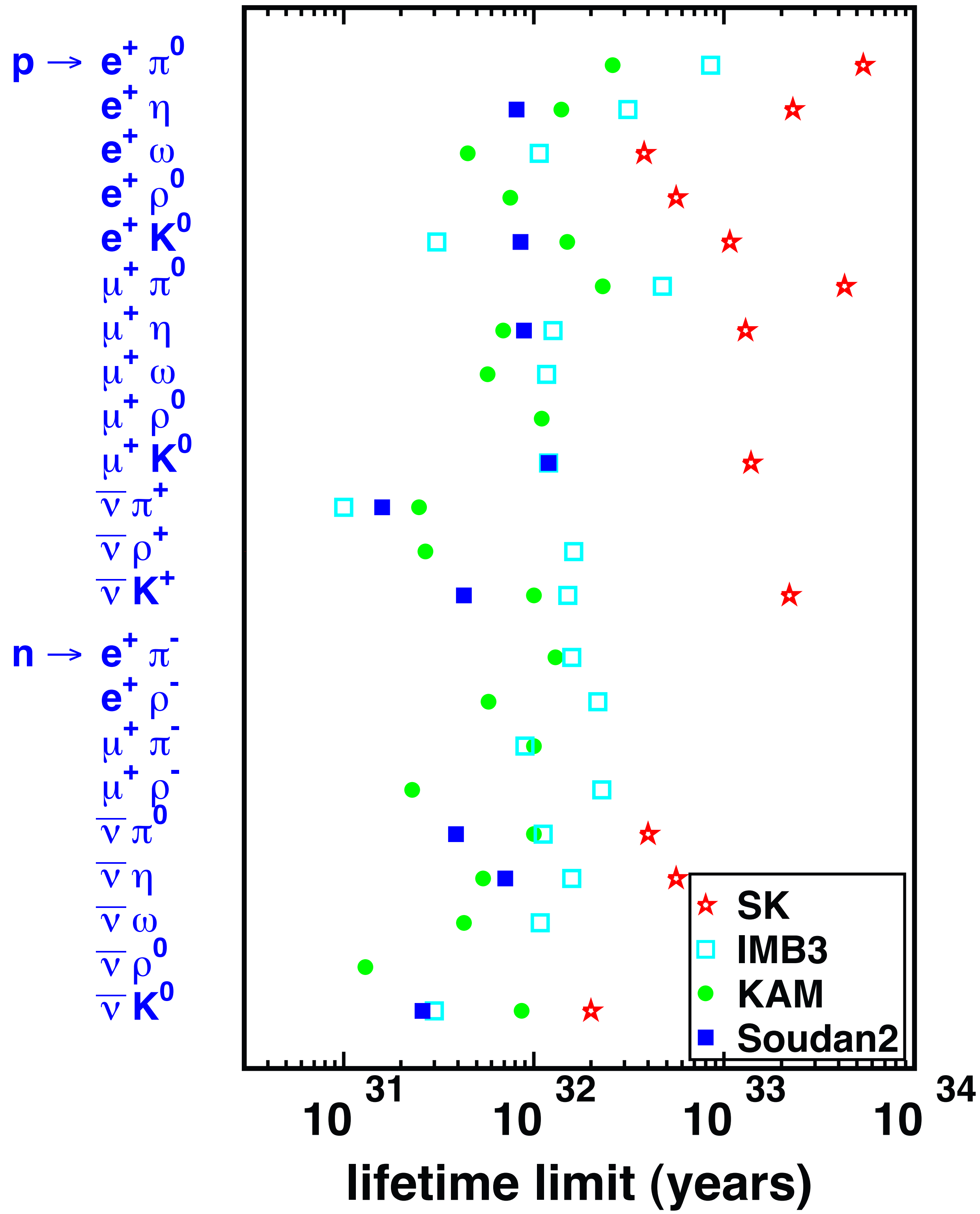
Grand Unification

- **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)**

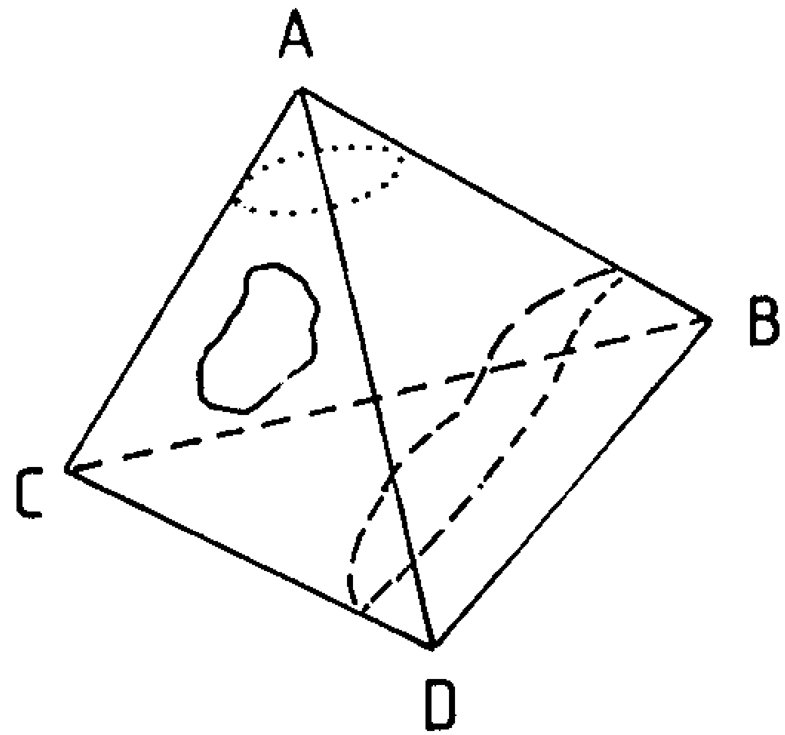


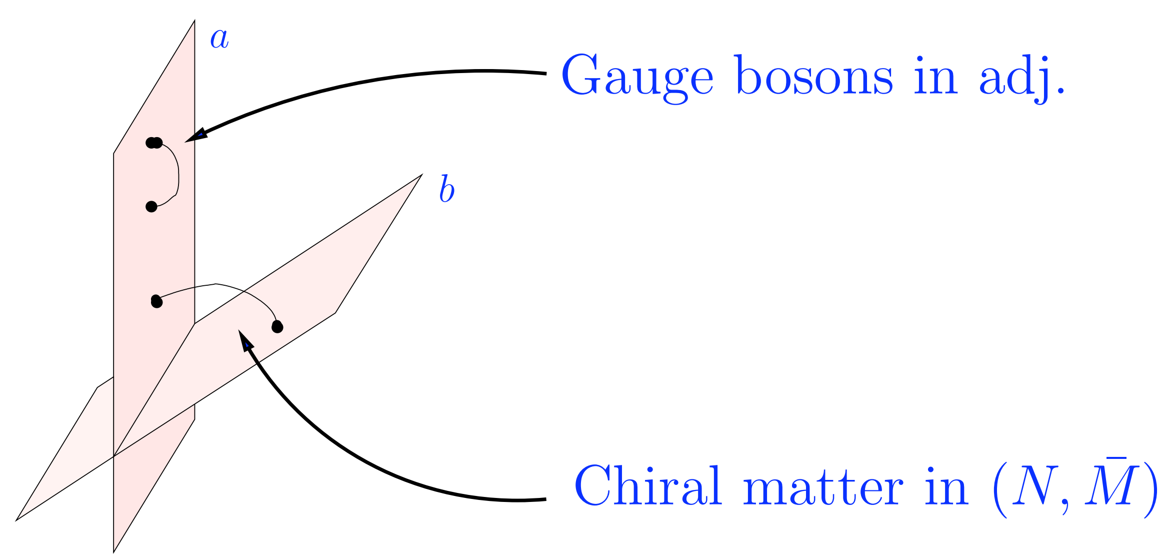
- **Seesaw model for small m_ν** (but why are mixings large?)
- **Quark-lepton $(q-l)$ unification** ($\Rightarrow$ charge quantization)
- **$q-l$ mass relations** (work only for third family in simplest versions)
- **Proton decay?** (simplest versions excluded)
- **Doublet-triplet problem?**
- **String 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 type? Dualities
  - Which compactification manifold?
  - Relation to supersymmetric standard model, GUT?
  - Supersymmetry breaking? Scale? Cosmological constant?
  - Many moduli (vacua). Landscape ideas - any predictability left? (TOE $\longrightarrow$TOA?)

- The great debate: is our physics environmental or selected?
  - Small cosmological constant, weak scale appear needed for life
  - Physics depends on location in multiverse? i.e., $O(10^{500})$ vacua of landscape continually sampled by pockets of eternally inflating multiverse!

Remnant Physics from the Top-Down

- Z' or other gauge
- Extended Higgs/neutralino (doublet, singlet)
- Quasi-Chiral Exotics
- Charge $1/2$ (Confinement?, Stable relic?)
- Quasi-hidden (Strong coupling? SUSY breaking? Composite family?)
- Time varying couplings
- LED (TeV black holes, stringy resonances)
- LIV, VEP (e.g., maximum speeds, decays, (oscillations) of HE γ, e, gravity waves (ν's))

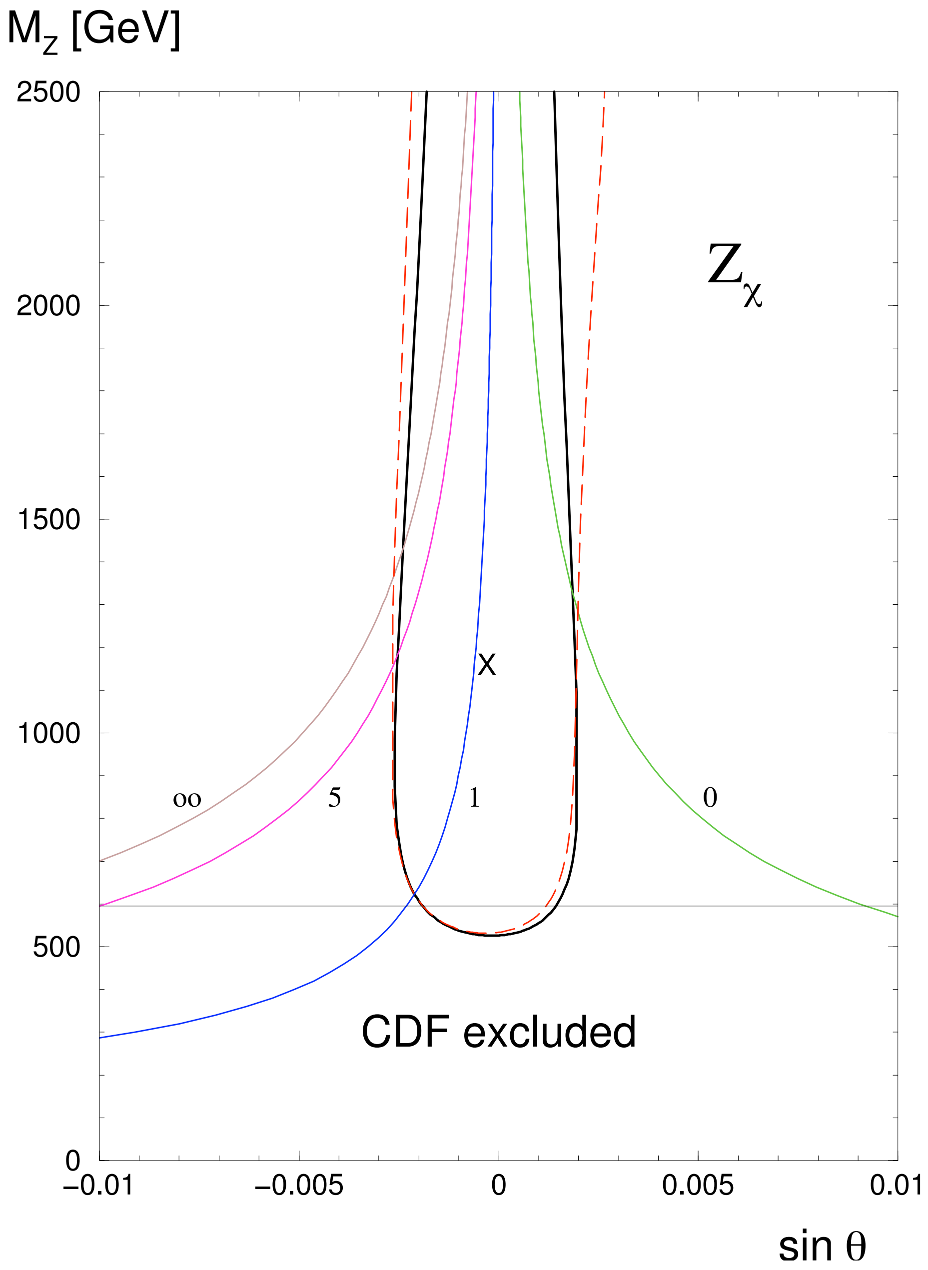
A TeV-Scale Z'

- Strings, grand unified theories, dynamical symmetry breaking, little Higgs, large extra dimensions often involve extra Z'

- Typically $M_{Z'} > 600 - 900$ GeV (Tevatron, LEP 2, WNC), $|\theta_{Z-Z'}| <$ few $\times 10^{-3}$ (Z-pole)

- Discovery to $M_{Z'} \sim 5 - 8$ TeV at LHC, LC, $(pp \rightarrow e^+e^-, \mu^+\mu^-, q\bar{q})$ (depends on couplings, exotics, sparticles)

- Diagnostics to 1-2 TeV (asymmetries, y distributions, associated production, rare decays)

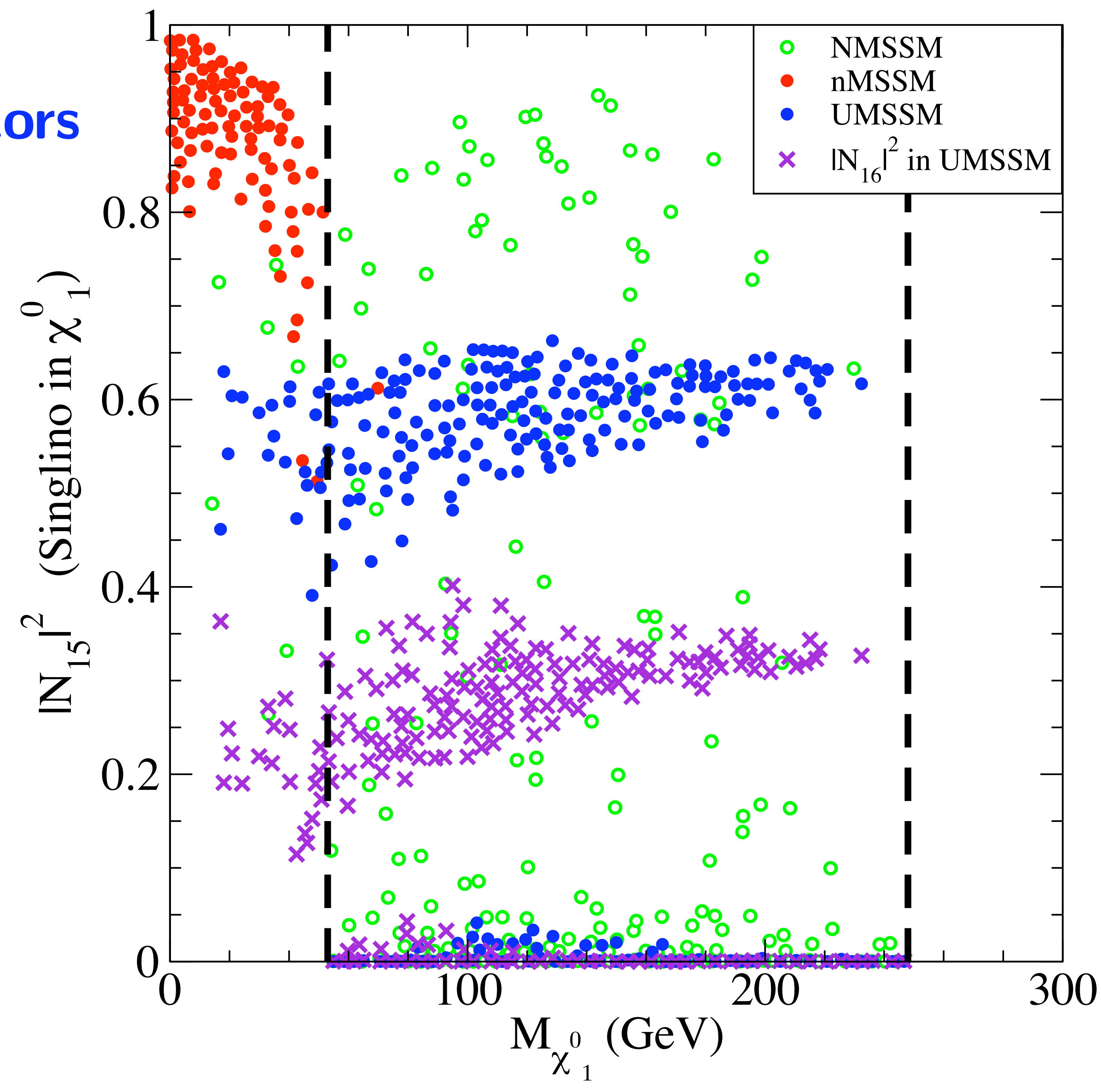


Implications of a TeV-scale Z'

- **Natural Solution to μ problem: supersymmetric contribution to Higgs mass tied to Z' mass**

- **Extended Higgs/neutralino sectors**
  (typical in strings, even w.o. Z')

  - Complicated spectra/decays/cascades at colliders
  - Enhanced possibilities for electroweak baryogenesis
  - Enhanced possibilities for cold dark matter



Quasi-Chiral Exotics

(J. Kang, PL, B. Nelson, in progress)

- Exotic fermions (anomaly-cancellation)
- Examples in 27-plet of E_6
  - $D_L + D_R$ ($SU(2)$ singlets, chiral wrt $U(1)'$)
  - $\begin{pmatrix} E^0 \\ E^- \end{pmatrix}_L + \begin{pmatrix} E^0 \\ E^- \end{pmatrix}_R$ ($SU(2)$ doublets, chiral wrt $U(1)'$)
- Pair produce $D + \bar{D}$ by QCD processes (smaller rate for exotic leptons)
- Lightest may decay by mixing; by diquark or leptoquark coupling; or be quasi-stable

Future/present Experiments

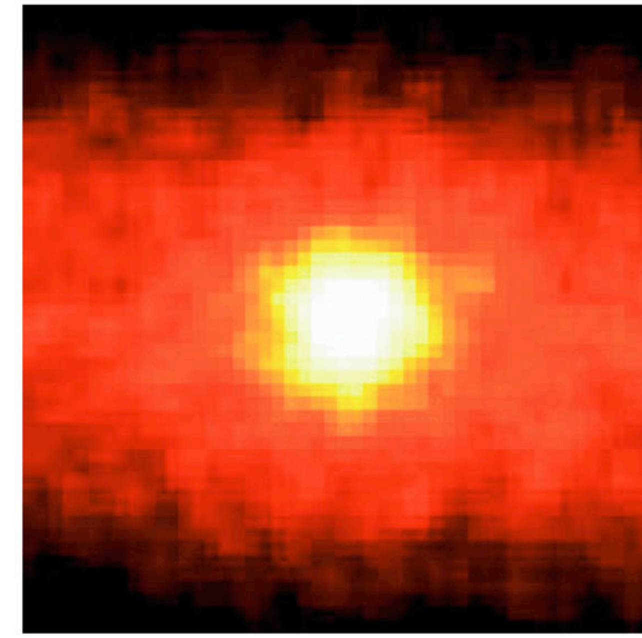
- **High energy colliders: the primary tool**
  - **TEVATRON; Fermilab, 1.96 TeV $\bar{p}p$, exploration**
  - **Large Hadron Collider (LHC); CERN, 14 TeV pp, high luminosity, discovery** (Discovery machine for supersymmetry, R_p violation, string remnants (e.g., Z', exotics, Higgs); or compositeness, 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, e.g., SUSY breaking mechanism)

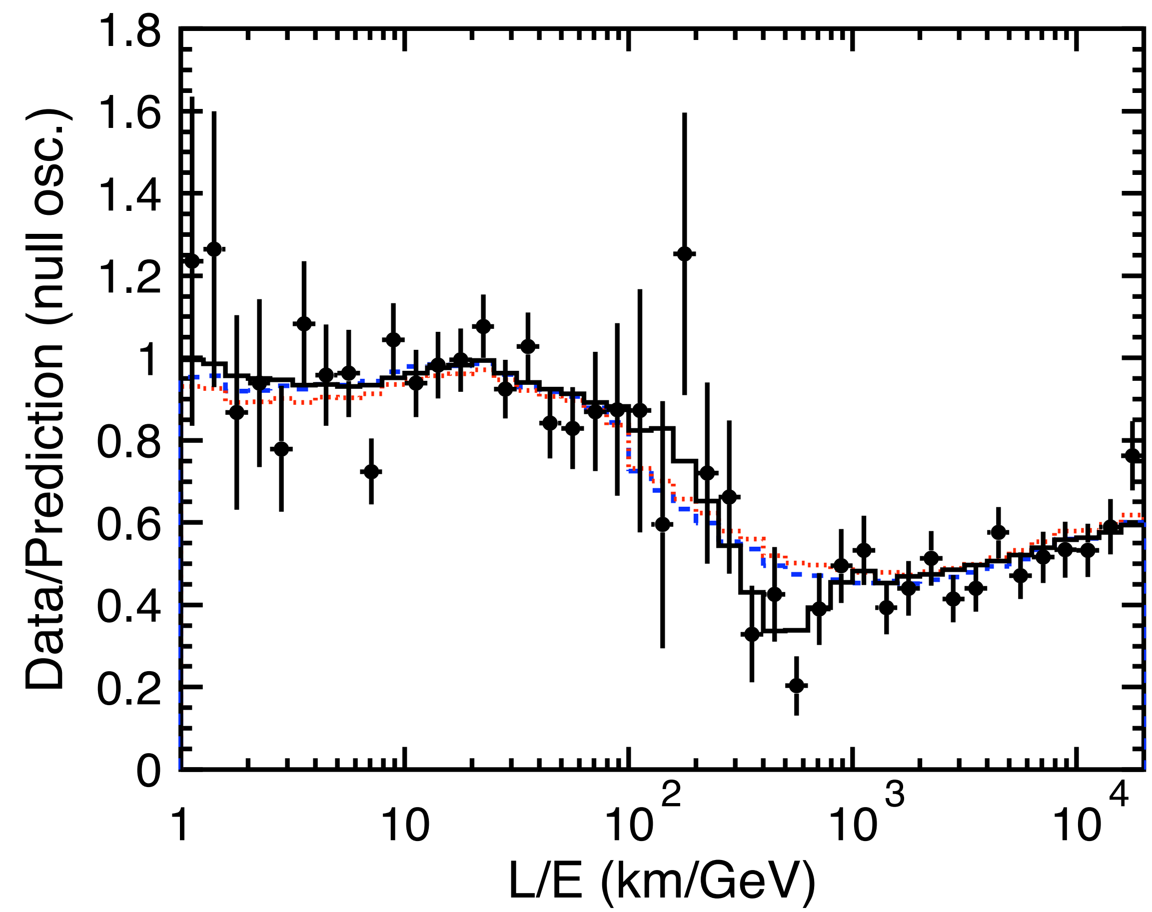
- **CP violation** (B decays, electric dipole moments)**, flavor changing neutral currents** (e.g., $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, $B \rightarrow \phi K_s$)**, neutrino physics**

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 ($n \to p e^- \bar{\nu}_e, \mu^- \to e^- \nu_\mu \bar{\nu}_e$): 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: $m_\nu \sim m_q^2/M_{\rm GUT}$

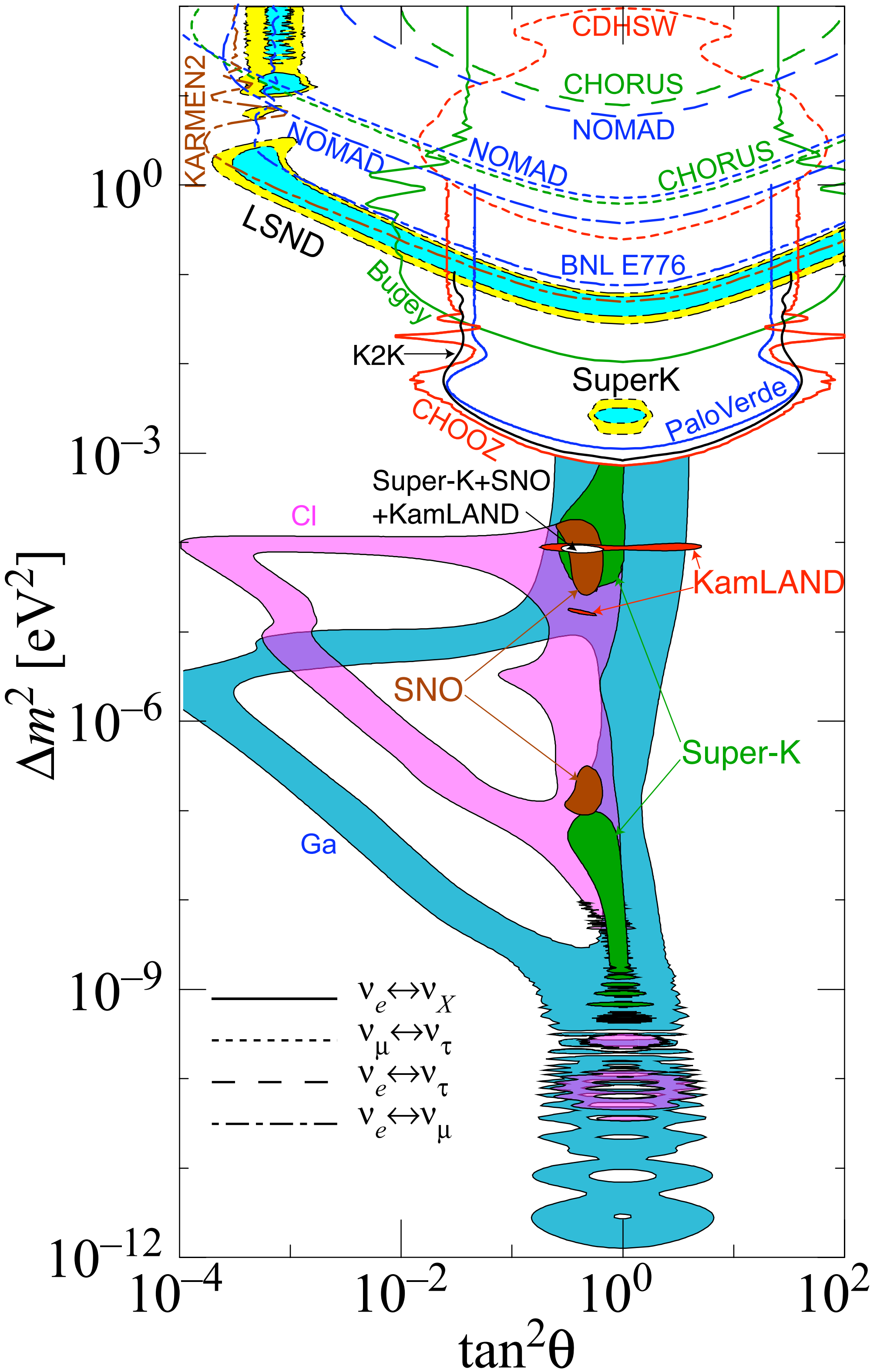
- **Solar/atmospheric neutrino experiments**
  - **Neutrinos have tiny masses (but large mixings)**
  - **Standard Solar model confirmed**
  - **First oscillation dips observed! (QM on large scale)**





3 ν Patterns

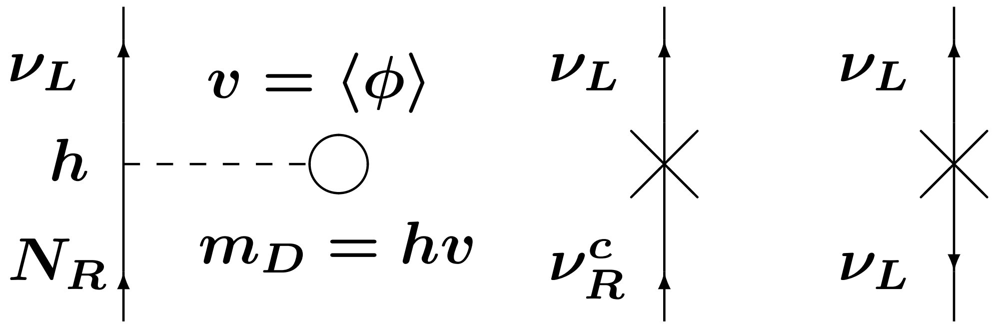
- **Solar: LMA (SNO, KamLAND)**
- $\Delta m^2_\odot \sim 8\times10^{-5}$ **eV^2, nonmaximal**
- **Atmospheric:** $|\Delta m^2_{\rm Atm}| \sim 2\times10^{-3}$ **eV^2, near-maximal mixing**
- **Reactor:** U_{e3} **small**



http://hitoshi.berkeley.edu/neutrino

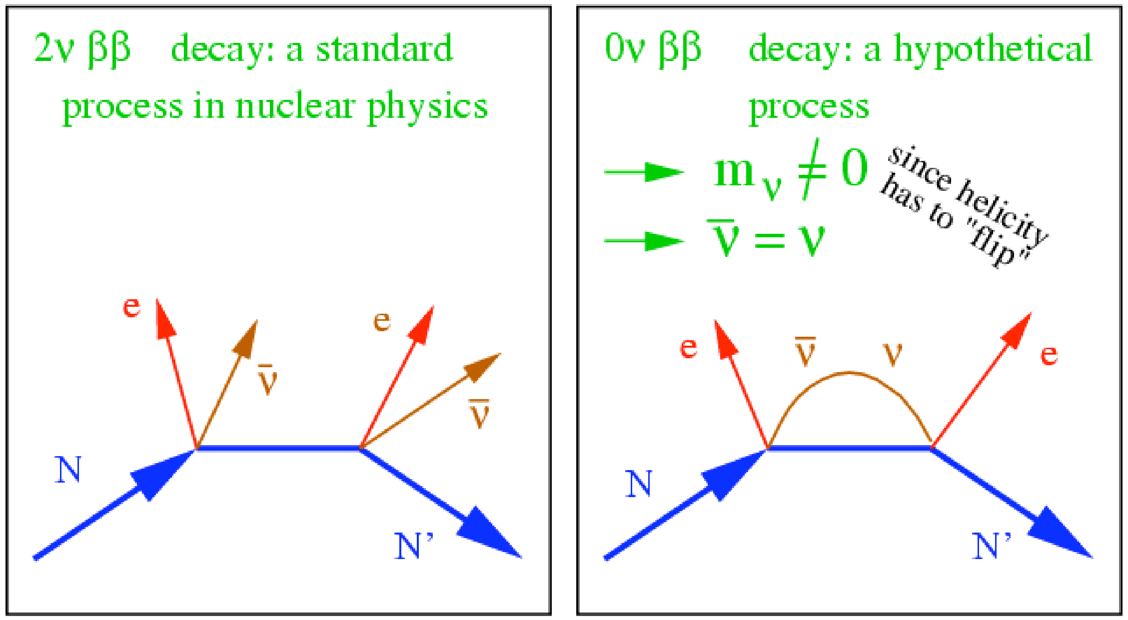
Neutrino Implications/questions

- 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)

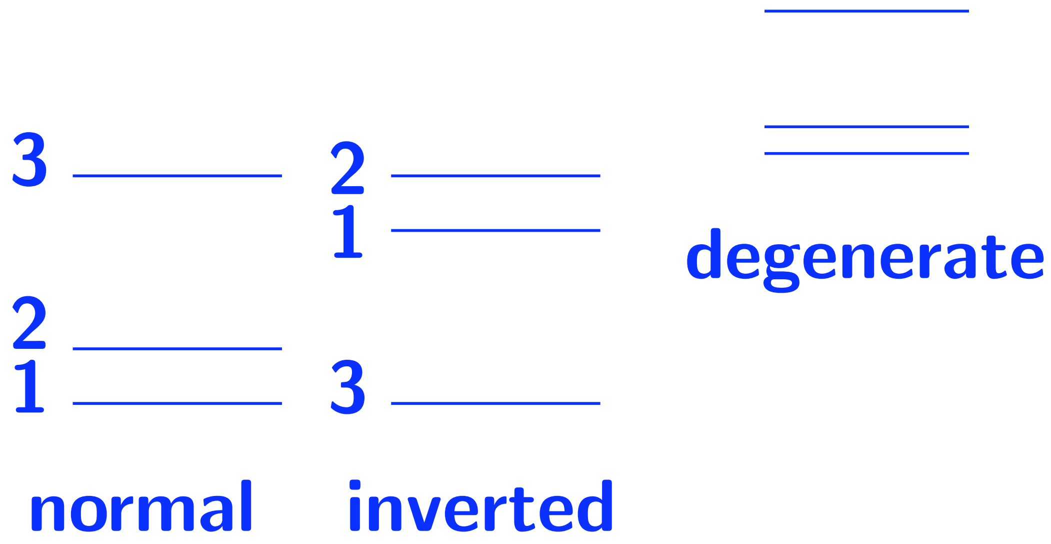


Dirac Majorana

- 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 Minimal Seesaw Model?

- Very simple from bottom up: $m_\nu \sim m_D^2/M_N$

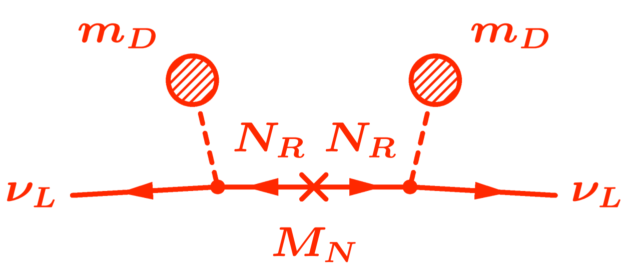
- Recent study of Z_3 heterotic orbifold (Giedt, Kane, PL, Nelson)

- Systematically studied large class of vacua

  – Is minimal seesaw common?

  – If rare, guidance to model building?

  – Clues to textures, etc.



- *None* had simultaneous Dirac and Majorana masses needed for minimal seesaw

- **Property of class of vacua?**

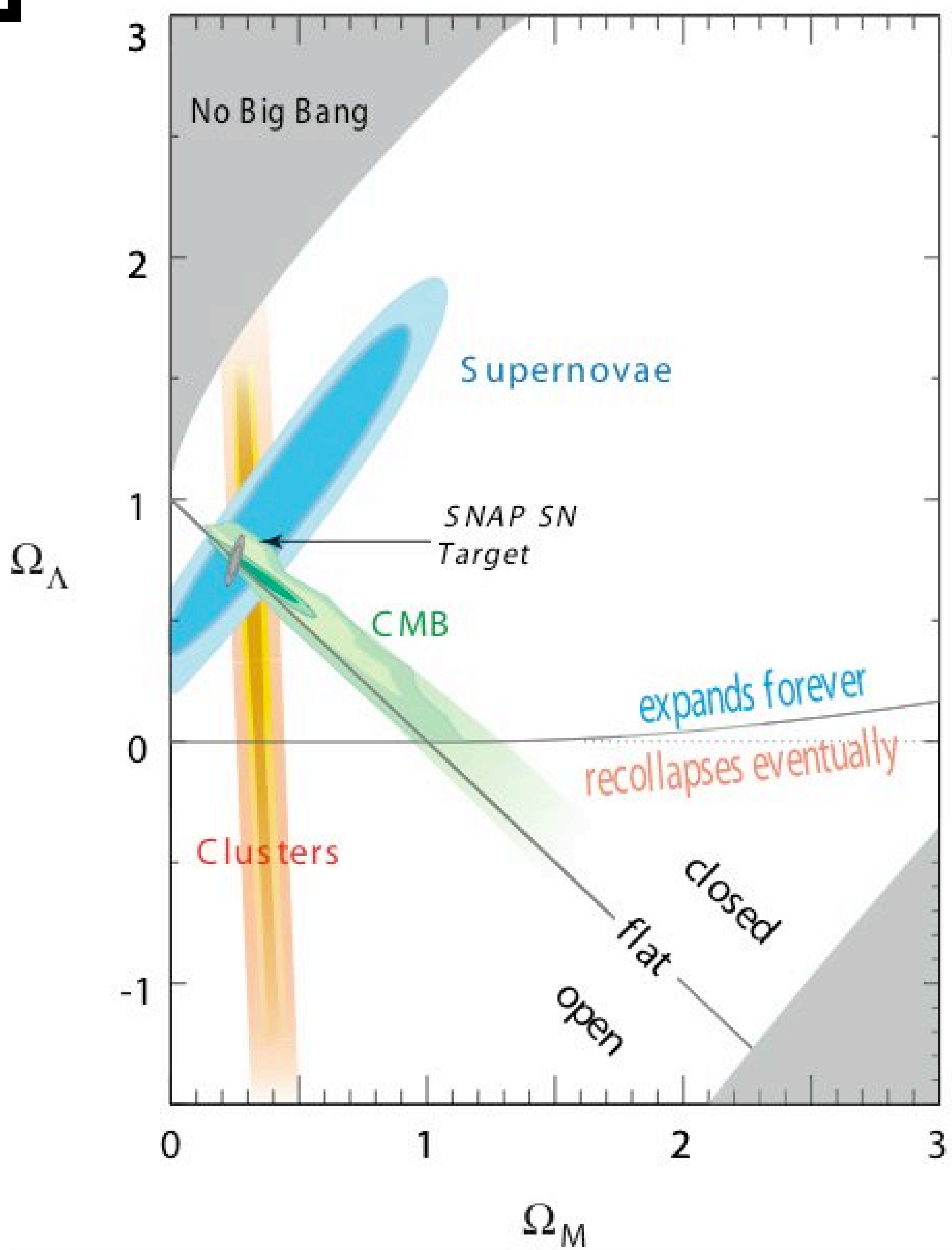
- **Insist on** $rare$ **seesaw-type vacua?**

- **Anthropic motivations for small neutrino masses?** **(nucleosynthesis, galaxy formation, type II supernovae)**

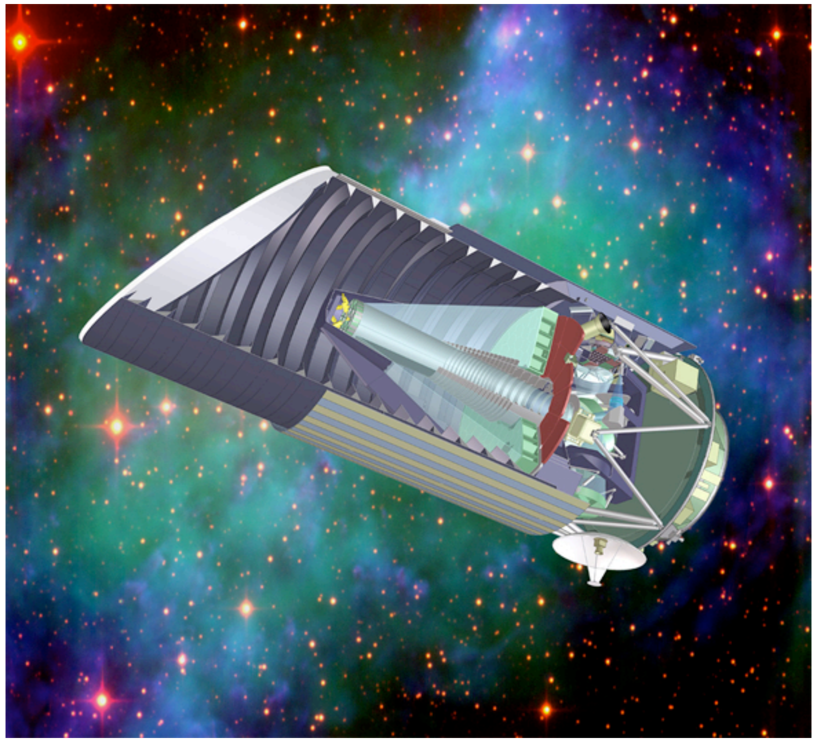
- **Alternatives?** **(Small Dirac by high-dimensional operators? Extended seesaw? Higgs triplet in higher level embedding** $\longrightarrow$**inverted hierarchy (B. Nelson, PL)?)**

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))

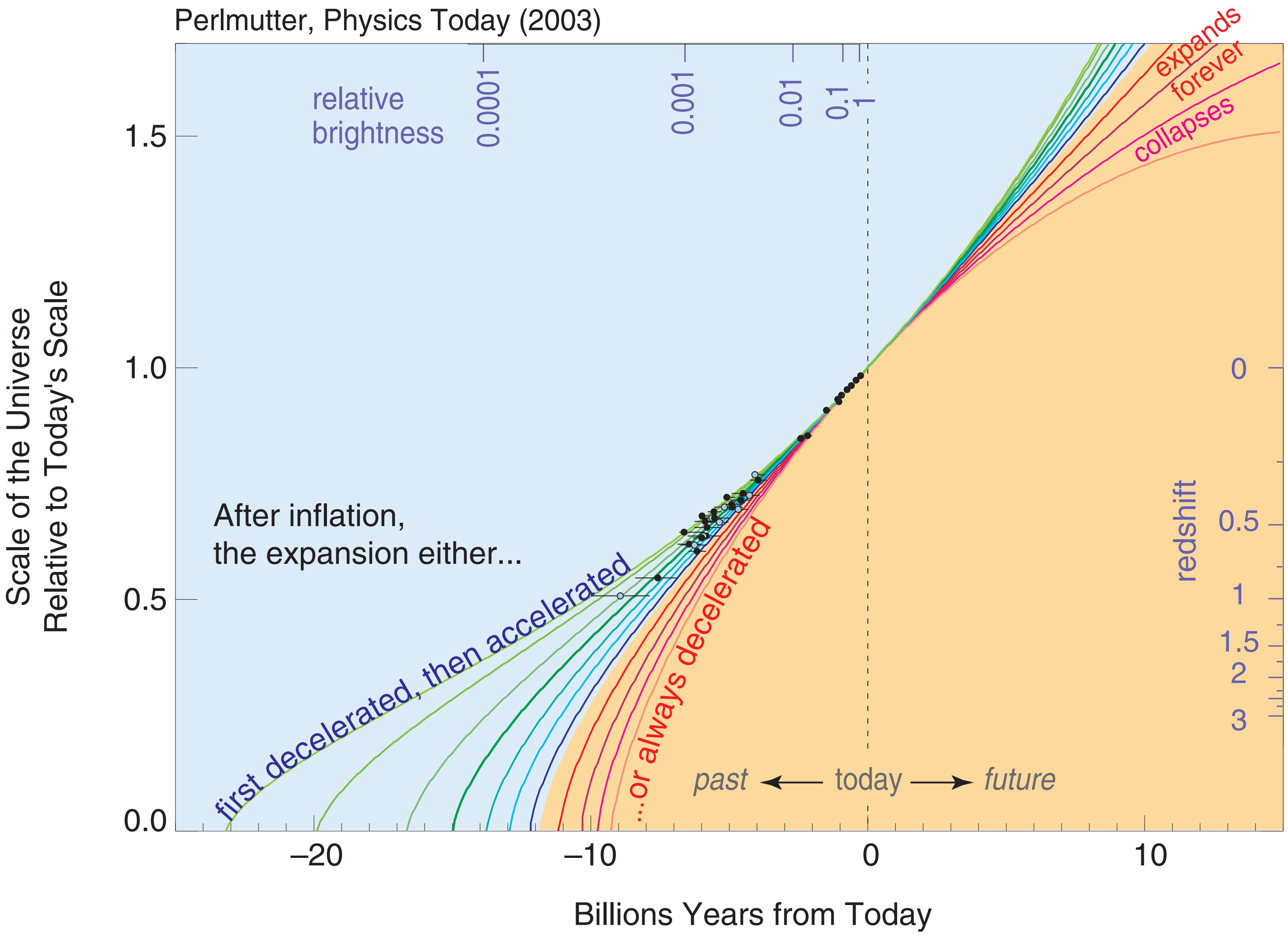


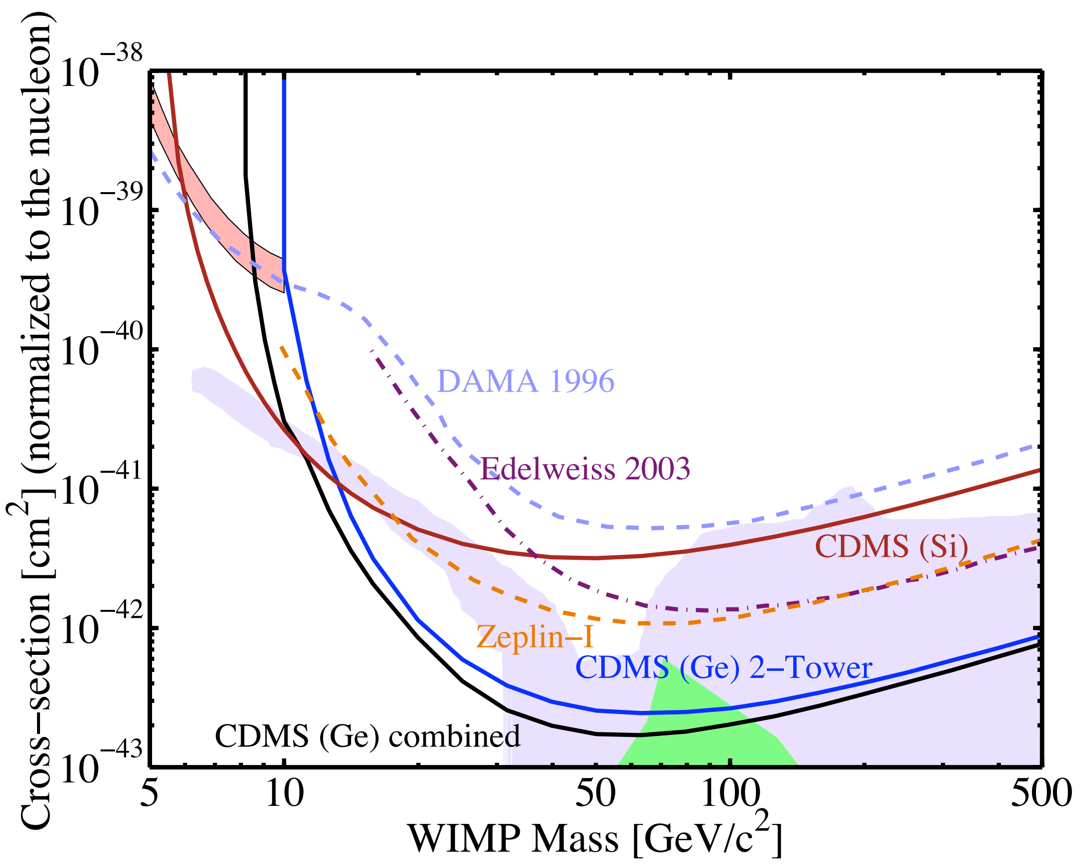
- **What is the dark energy?**
  - **Vacuum energy (cosmological constant); time varying field (quintessence)?**
  - **High precision supernova survey (SNAP); CMB (Planck)**

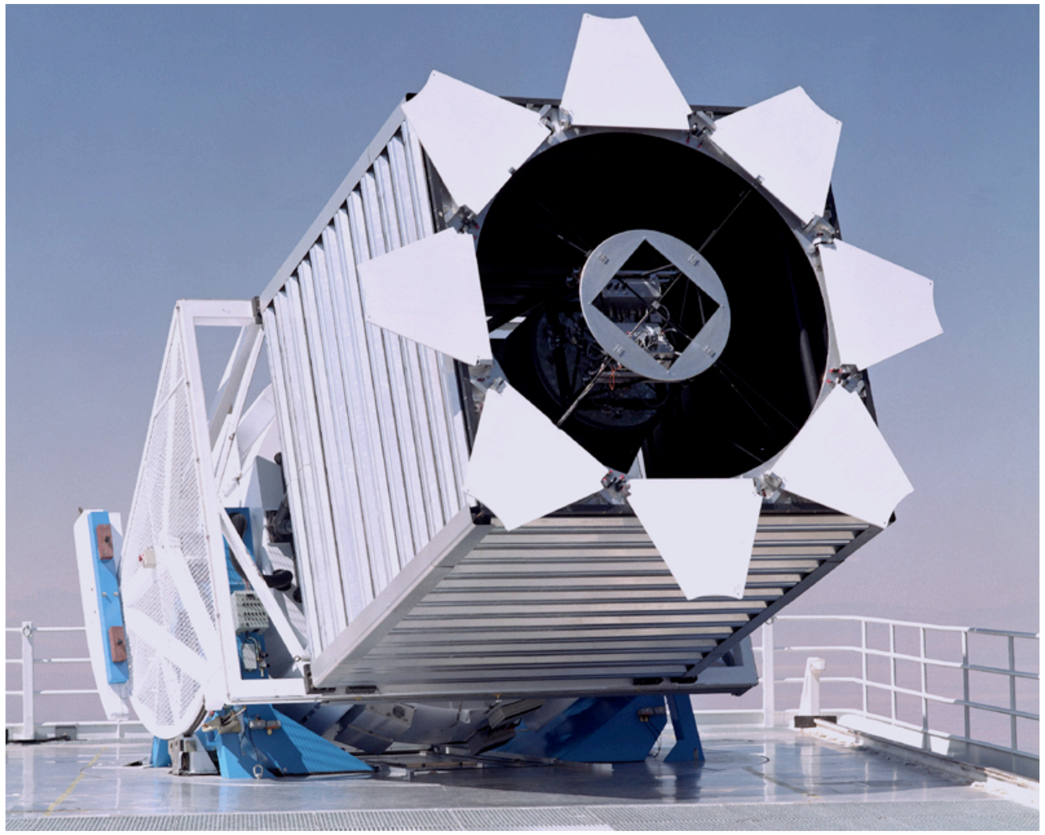


Expansion History of the Universe

Perlmutter, Physics Today (2003)

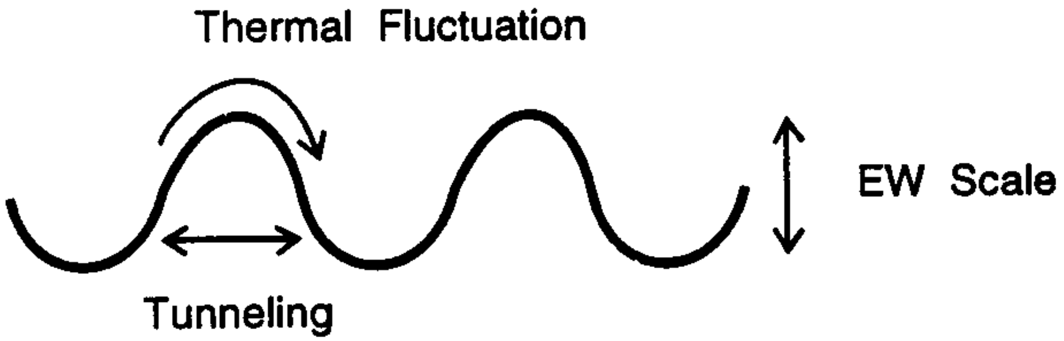


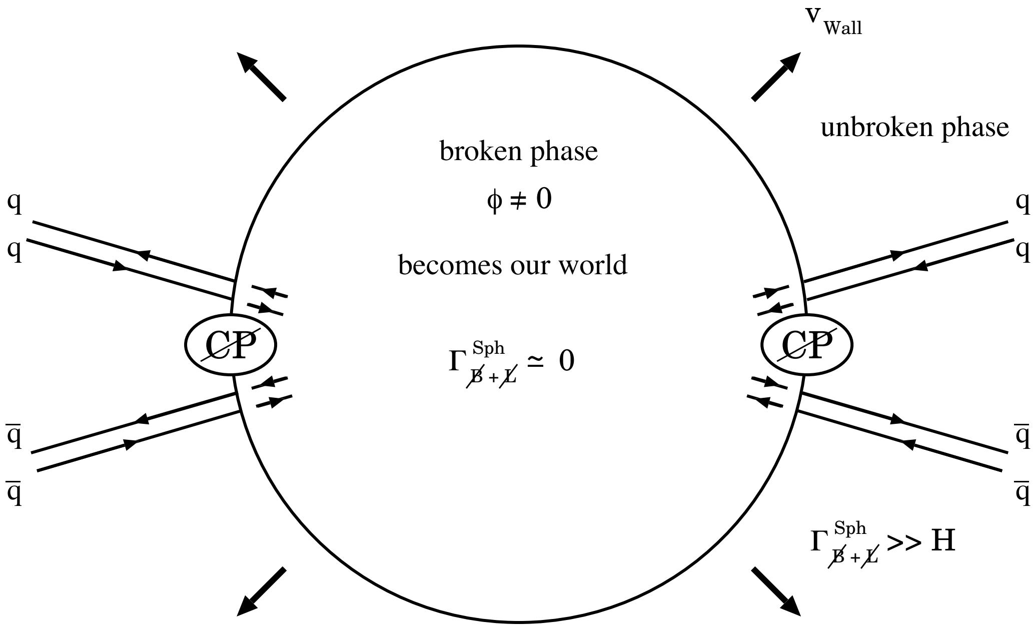




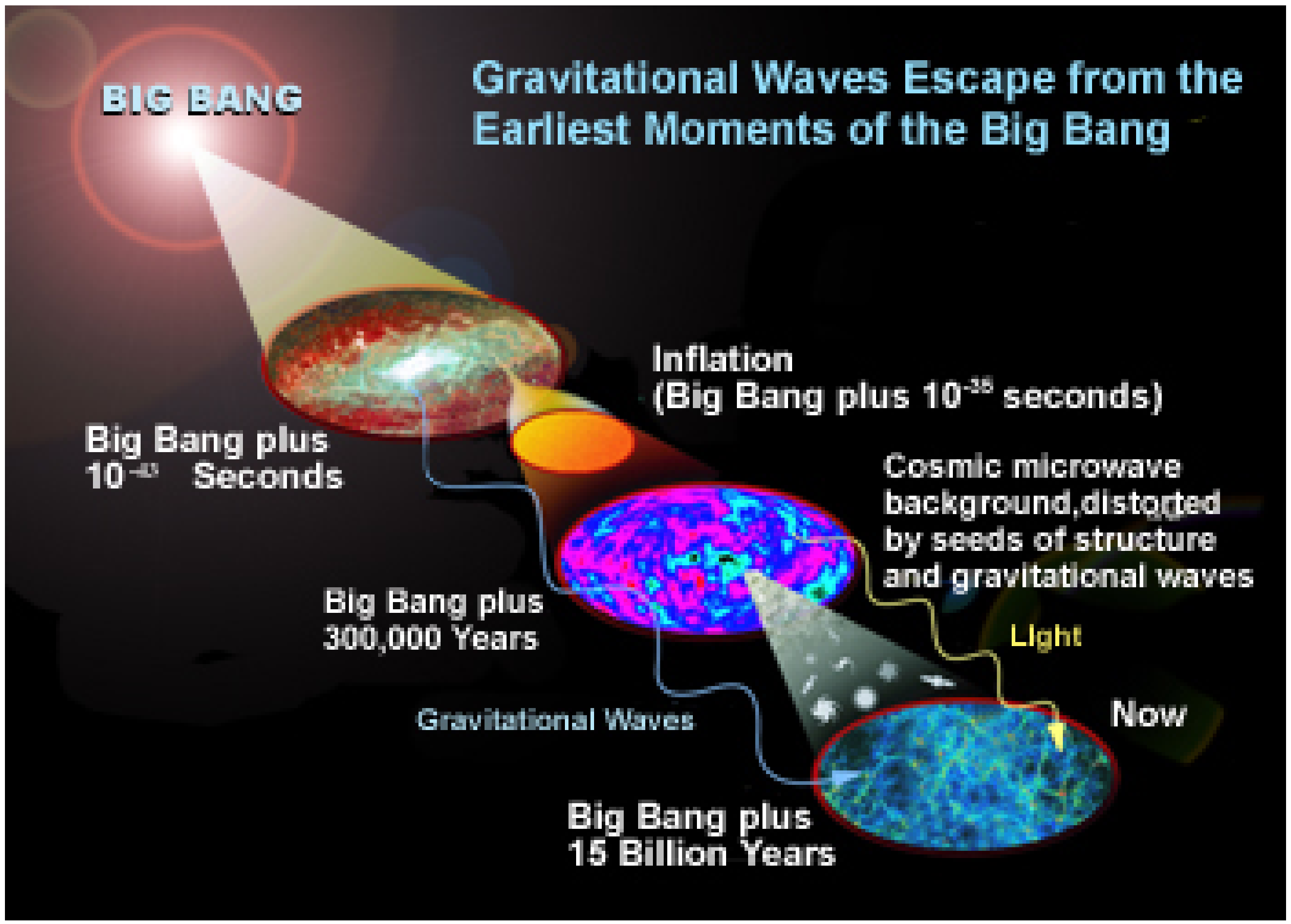
- **What is the dark matter?**
  - **Lightest neutralino in supersymmetry (if R parity conserved)? Axion?**
  - **Direct searches: LHC, ILC; cold dark matter searches; high energy annihilation ν's**
  - **Axion searches (resonant cavities)**
  - **Galaxy surveys (SDSS)**
  - **Gravitation lensing (SNAP),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

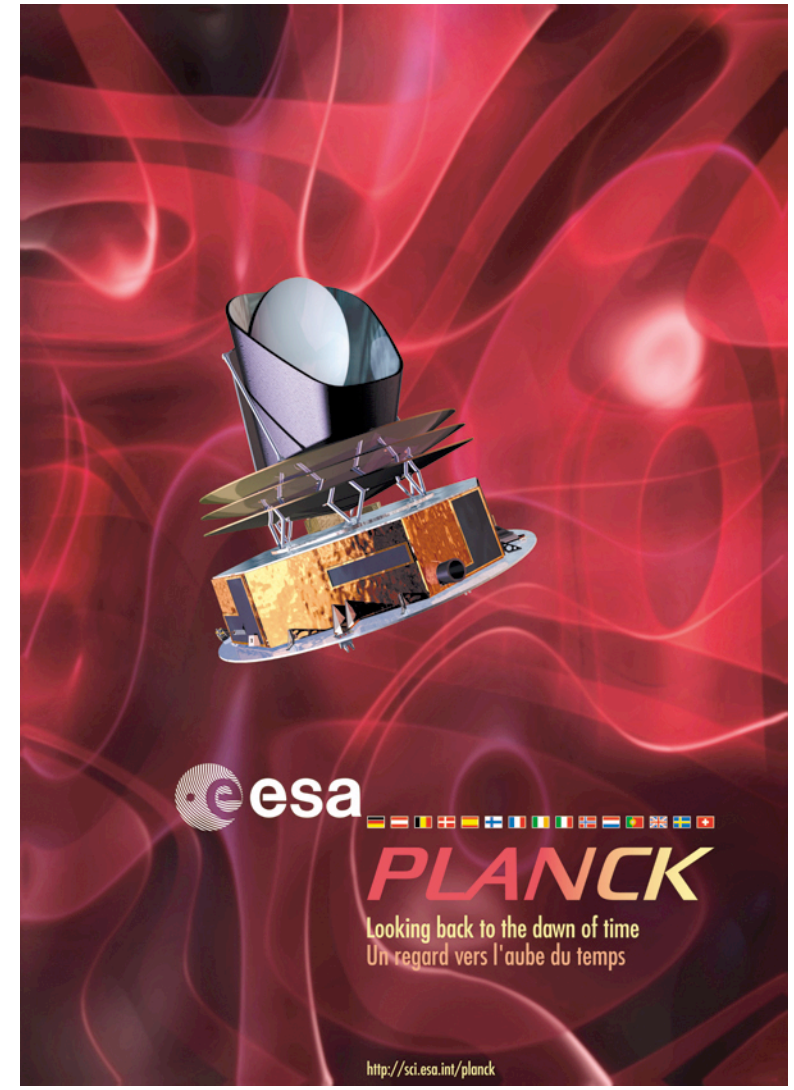
- **Why is there matter and not antimatter?**
  - $n_B/n_\gamma \sim 10^{-10}$, $n_{\bar{B}} \sim 0$
  - **Electroweak baryogenesis** (extensions of MSSM)? **Leptogenesis? Decay of heavy fields?** CPT **violation?**

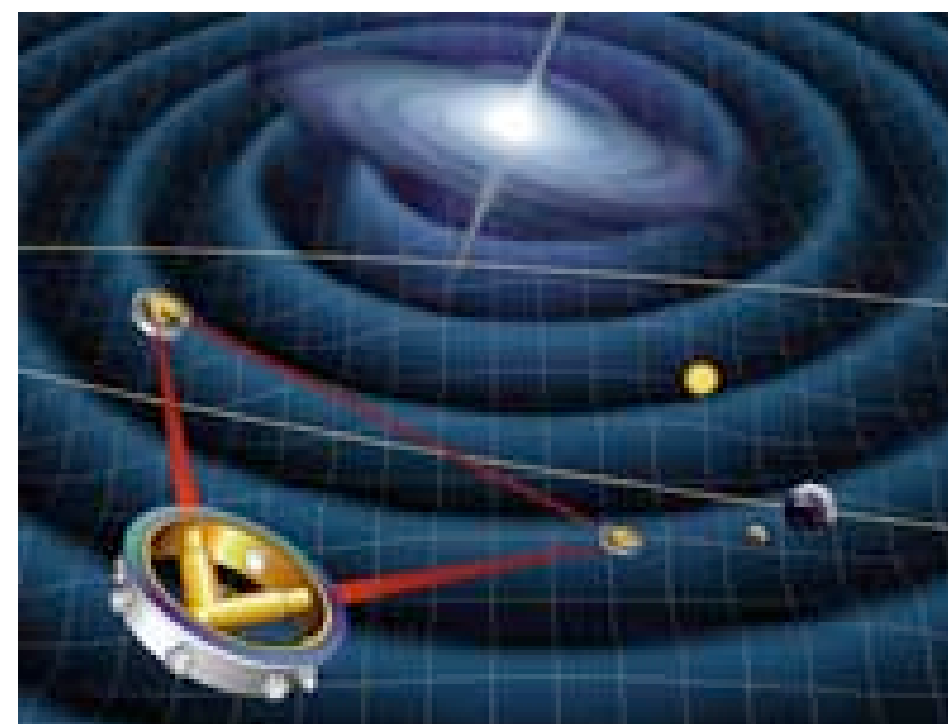




- The very beginning (inflation)
  - Relation to particle physics, strings, Λ?
  - CMB (Planck); gravity waves (LISA)





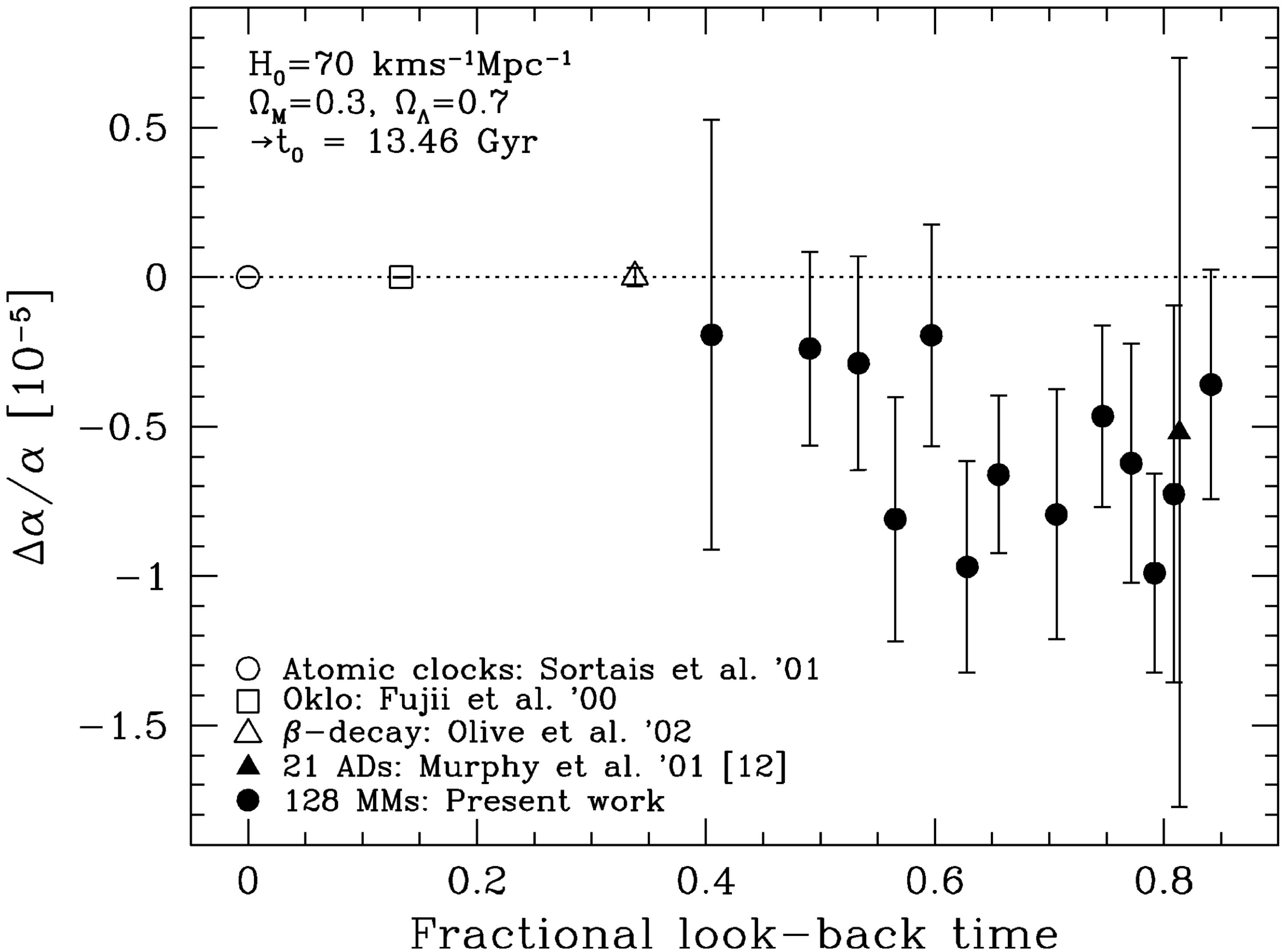


Far-Out Stuff

- **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 $\sim \frac{1}{1\ \text{TeV}}$
- 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
- Semi-realistic string constructions suggest extended gauge, Higgs, neutralino, fermion sectors