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>
<thead>
<tr>
<th>Strong</th>
<th>Electromagnetic</th>
<th>Weak</th>
<th>Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>$\pi^0$</td>
<td>$e^-$</td>
<td>$g$</td>
</tr>
<tr>
<td>$p$</td>
<td>$\pi^0$</td>
<td>$\gamma$</td>
<td>graviton (spin 2)</td>
</tr>
<tr>
<td>$d$</td>
<td>$\pi^0$</td>
<td>$e^-$</td>
<td></td>
</tr>
<tr>
<td>$d$</td>
<td>$\pi^0$</td>
<td>$\gamma$</td>
<td></td>
</tr>
<tr>
<td>$G$</td>
<td>$\pi^0$</td>
<td>$\gamma$</td>
<td></td>
</tr>
<tr>
<td>$u$</td>
<td>$\pi^0$</td>
<td>$\gamma$</td>
<td></td>
</tr>
<tr>
<td>$u$</td>
<td>$\pi^0$</td>
<td>$\gamma$</td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>$\pi^0$</td>
<td>$\gamma$</td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>$\pi^0$</td>
<td>$\gamma$</td>
<td></td>
</tr>
</tbody>
</table>

- **Strong**: $V = g_\pi^2 \frac{e^{-m_\pi r}}{r}$
- **Electromagnetic**: $e^2 / r$
- **Weak**: $g_\pi^2 \frac{e^{-M_W r}}{r}$
- **Gravity**: $G_N \frac{m_1 m_2}{r}$

**Strength**: $\frac{g_\pi^2}{4\pi} \sim 14$

- $\alpha = \frac{e^2}{4\pi} \sim \frac{1}{137}$
- $\frac{g_\pi^2}{M_W^2} \sim 10^{-11}$
  
  (for $E = 1$ MeV)  

- $G_N m_1 m_2 \sim 10^{-38}$  
  ($m_1 = m_2 = 1$ GeV)

**Range**: $\frac{\hbar}{m_\pi c} \sim 10^{-13}$ cm $\equiv$ 1 fm

- $\frac{\hbar}{M_W c} \sim 10^{-16}$ cm
- $\infty$
### Unification of Forces

<table>
<thead>
<tr>
<th>Strong</th>
<th>Electromagnetic</th>
<th>Weak</th>
<th>Gravity</th>
</tr>
</thead>
</table>
| hadrons: \( p, n; \)  
  pions: \( \pi^\pm, \pi^0; \)  
  (QCD: quarks, gluons) | charged particles: \( e^-, \mu^-, \tau^-; \) \( p; \pi^\pm \) | \( p, n, \pi; \)  
  \( e, \mu, \tau; \)  
  neutrinos: \( \nu_e, \nu_\mu, \nu_\tau \) | all particles (always attractive) |
| nuclear binding; energy in stars | atoms, crystals, molecules; light; chemical energy | decays: \( n \rightarrow p e^- \bar{\nu}_e; \) element synthesis | weight; binding of solar system, stars, galaxies |
| \( \leftarrow E + B \rightarrow \) (Maxwell) | \( \leftarrow \text{Electroweak } (SU(2) \times U(1)) \rightarrow \) | \( \leftarrow \text{Grand Unification (GUT)? } \rightarrow \) | \( \leftarrow \text{Theory of Everything (superstring)? } \rightarrow \) |

---

Collective forces

- Strong: \( p, n; \pi^\pm, \pi^0 \)  
- Electromagnetic: \( e^-, \mu^-, \tau^-; p, \pi^\pm \)  
- Weak: \( p, n, \pi; e, \mu, \tau; \nu_e, \nu_\mu, \nu_\tau \)  
- Gravity: all particles (always attractive)
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 $g_s, g, g'$

\[
\begin{pmatrix}
  u \\
  d
\end{pmatrix}_L 
\begin{pmatrix}
  u \\
  d
\end{pmatrix}_L 
\begin{pmatrix}
  u \\
  d
\end{pmatrix}_L 
\begin{pmatrix}
  \nu_e \\
  e^-
\end{pmatrix}_L
\]

\[
\begin{array}{cccc}
  u_R & u_R & u_R & \nu_{eR}(?) \\
  d_R & d_R & d_R & e^-_R
\end{array}
\]

($L = \text{left-handed}, \quad R = \text{right-handed}$)

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

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

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

- Heavy families ($c, s, \nu_\mu, \mu^-$), ($t, b, \nu_\tau, \tau^-$)

Penn State, November 2007  
Paul Langacker (IAS)
Quantum Chromodynamics (QCD)

Modern theory of the strong interactions

\[ \alpha_s(M_Z) \]

\[ \alpha_s(\mu) \]

Penn State, November 2007

Paul Langacker (IAS)
# Quantum Electrodynamics

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value of $\alpha^{-1}$</th>
<th>Difference from $\alpha^{-1}(a_e)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deviation from gyromagnetic ratio, $a_e = (g - 2)/2$ for $e^-$</td>
<td>137.035 999 58 (52)</td>
<td>$[3.8 \times 10^{-9}]$</td>
</tr>
<tr>
<td>ac Josephson effect</td>
<td>137.035 988 0 (51)</td>
<td>$[3.7 \times 10^{-8}]$</td>
</tr>
<tr>
<td>$h/m_n$ (where $m_n$ is the neutron mass)</td>
<td>137.036 011 9 (51)</td>
<td>$[3.7 \times 10^{-8}]$</td>
</tr>
<tr>
<td>from $n$ beam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyperfine structure in muonium, $\mu^+e^-$</td>
<td>137.035 993 2 (83)</td>
<td>$[6.0 \times 10^{-8}]$</td>
</tr>
<tr>
<td>Cesium $D_1$ line</td>
<td>137.035 992 4 (41)</td>
<td>$[3.0 \times 10^{-8}]$</td>
</tr>
</tbody>
</table>
The Electroweak Theory

- QED and weak charged current unified
- Weak neutral current \((Z)\) predicted \((\nu N \rightarrow \nu X, \text{atomic parity violation})\)
- Stringent tests of wnc, \(Z\)-pole and beyond
- Fermion gauge and gauge self interactions

Penn State, November 2007  
Paul Langacker (IAS)
### SM correct and unique to zeroth approx. (gauge principle, group, representations)

- SM correct at loop level (renorm gauge theory; $m_t, \alpha_s, M_H$)
- TeV physics severely constrained (unification vs compositeness)
- Consistent with light elementary Higgs
- Precise gauge couplings (gauge unification)

| Measurement                  | Fit       | $|O_{\text{meas}} - O_{\text{fit}}|/\sigma_{\text{meas}}$ |
|-----------------------------|-----------|--------------------------------------------------------|
| $\Delta c_{\text{had}}^{(5)}(m_Z)$ | 0.02758 ± 0.00035 | 0.02768                                                  |
| $m_Z$ [GeV]                 | 91.1875 ± 0.0021 | 91.1875                                                  |
| $\Gamma_Z$ [GeV]           | 2.4952 ± 0.0023 | 2.4957                                                  |
| $\sigma_{\text{had}}$ [nb] | 41.540 ± 0.037  | 41.477                                                  |
| $R_l$                       | 20.767 ± 0.025  | 20.744                                                  |
| $A_{l}^{0,1}$               | 0.1714 ± 0.00095| 0.1645                                                  |
| $A_{l}(P_{\tau})$          | 0.1465 ± 0.0032 | 0.1481                                                  |
| $R_b$                       | 0.21629 ± 0.00066| 0.21586                                                 |
| $R_c$                       | 0.1721 ± 0.0030 | 0.1722                                                  |
| $A_{l,b}^{0}$               | 0.0992 ± 0.0016 | 0.1038                                                  |
| $A_{l,c}^{0}$               | 0.0707 ± 0.0035 | 0.0742                                                  |
| $A_{l,b}$                   | 0.923 ± 0.020  | 0.935                                                   |
| $A_{b}$                     | 0.670 ± 0.027  | 0.668                                                   |
| $A_{l}(\text{SLD})$        | 0.1513 ± 0.0021| 0.1481                                                  |
| $\sin^2\theta_{\text{lep}}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314                                                  |
| $m_W$ [GeV]                 | 80.398 ± 0.025 | 80.374                                                  |
| $\Gamma_W$ [GeV]           | 2.140 ± 0.060  | 2.091                                                   |
| $m_t$ [GeV]                 | 170.9 ± 1.8  | 171.3                                                   |
The Higgs Mechanism

- Gauge symmetry forbids elementary masses for $W$, $Z$, fermions

- Introduce Higgs field $H$, with classical value $\nu$ and potential energy
  \[ V(\nu) = \frac{1}{2} \mu^2 \nu^2 + \frac{1}{4} \lambda \nu^4 \]

- $W$, $Z$, fermions acquire effective masses by coupling to $H$ (transparent to photon)
- Higgs mass $M_H = \sqrt{-2\mu^2} = \sqrt{2\lambda\nu}$ ($\nu \sim 246$ GeV, $\lambda$ unknown)

- LEP search $e^+e^- \rightarrow Z^* \rightarrow ZH$: $M_H > 114.4$ GeV

- Indirect (electroweak radiative corrections)): $M_H < 144$ GeV (95%)

- Tevatron searches not yet sensitive enough, but may be by 2009

- LHC will cover full range for standard model Higgs
Consequences
– additional charged and neutral Higgs particles
– $M_{H^0} < \cos^2 2\beta M_{Z^0} + \text{H.O.T.}$

CDF/D0 searches for heavier states

Simplest version: supersymmetric contribution to Higgs mass must be of $O(100)$ GeV but $10^{19}$

$\mu$ problem

Penn State, November 2007 Paul Langacker (IAS)
Problems with the Standard Model

Lagrangian after symmetry breaking:

\[ \mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_i \bar{\psi}_i \left( i \slashed{\partial} - m_i - \frac{m_i H}{\nu} \right) \psi_i \]

\[ -\frac{g}{2\sqrt{2}} \left( J_{\mu}^W W^{-}_\mu + J_{\mu}^{\dagger} W^{+}_\mu \right) - eJ_{\mu}^Q A_\mu - \frac{g}{2 \cos \theta_W} J_{\mu}^Z Z_\mu \]

Standard model: \( SU(2) \times U(1) \) (extended to include 3 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 $\nu$) 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 \( \frac{\theta}{32\pi^2}g_s^2F\tilde{F} \) to QCD (breaks, P, T, CP)
- \( d_N \Rightarrow \theta < 10^{-9}, \text{ but } \delta\theta|_{\text{weak}} \sim 10^{-3} \)
- 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: \( \Lambda_{SSB} = 8\pi G_N \langle V \rangle > 10^{50} \Lambda_{\text{obs}} \)
    \( (10^{124} \text{ for GUTs, strings}) \)

Possible solutions:

– supergravity and Kaluza Klein unify
– strings yield finite gravity.
– \( \Lambda \)? 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 \( \to \) nucleus \( + e^- \to p + n \to \) quark
- Other new TeV layer: Little Higgs
- At most one more layer accessible (Tevatron, LHC, ILC)
- Rare decays (e.g., \( K \to \mu e \))
- Typically, few % effects at LEP/SLC, WNC (challenge for models)
- anomalous \( VVVV \), new particles, future \( WW \to WW \), 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 $\delta$ 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 ↔ boson symmetry

• Motivations
  – stabilize weak scale ⇒ $M_{SUSY} < O(1 \, \text{TeV})$
    (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
  - \( M_{H^0}^2 < \cos^2 2\beta M_Z^2 + \text{H.O.T.} \) (\( O(m_t^4) \)) < (135 GeV)², consistent with LEP (standard model: \( M_{H^0} < 1000 \) GeV)
  - CDF/D0 searches for heavier states

- Simplest version: supersymmetric contribution to Higgs mass must be of \( O(100) \) GeV (not \( 10^{19} \)) (\( \mu \) 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** $m_{\nu}$ (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 $\rightarrow$ particles
  - Consistent in 10 space-time dimensions $\rightarrow$ 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 → 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!
Consequences
– additional charged and neutral Higgs particles
– $M^2_{H^0} < \cos^2 2\beta M^2_Z + \text{H.O.T.}$
\[ tO(m^4) u < t_{135} \text{GeV} \]
consistent with LEP standard model:
– $M_{H^0} < 1000 \text{GeV} \text{GeV}$
– CDF/D0 search for heavier states

• Simplest version: supersymmetric contribution to Higgs mass must be of $O(100) \text{GeV}$
tnot $10^{19}$
tµ problem

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 $\gamma$, $e$, gravity waves ($\nu'$s))
• 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), $|\theta_{Z-Z'}| < \text{few } \times 10^{-3}$ (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 $\mu$ 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
Consequences
– additional charged and neutral Higgs particles
– $M_{H_0}^2 < \cos^2 2\beta M_Z^2 + \text{H.O.T.}$

consistent with LEP standard model:
$M_{H_0} < 1000 \text{GeV}$

– CDF/D0 search for heavier states

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

$\mu$ problem

Penn State, November 2007
Paul Langacker (IAS)
Quasi-Chiral Exotics

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

- Exotic fermions (anomaly-cancellation)

- Examples in 27-plet of $E_6$
  
  \[ D_L + D_R \ (SU(2) \text{ singlets, chiral wrt } U(1)') \]
  
  \[ \left( \begin{array}{c} E^0 \\ E^- \end{array} \right)_L + \left( \begin{array}{c} E^0 \\ E^- \end{array} \right)_R \ (SU(2) \text{ doublets, chiral wrt } U(1)') \]

- 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, ...)
  - 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
The Universe

- The concordance
  - 5% matter (including dark baryons): CMB, BBN, Lyman $\alpha$
  - 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](image)

**Penn State, November 2007**

*Paul Langacker (IAS)*
• **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 $\nu$’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?

---

**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?

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**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, \( \Lambda \)?
  – CMB (Planck); gravity waves (LISA)
- **LIV, VEP** (e.g., maximum speeds, decays, (oscillations) of HE $\gamma$, $e$, gravity waves ($\nu$’s))

- **LED, TeV black holes**

- **Time varying couplings**

---

**Graph**

- $H_0 = 70 \text{ km s}^{-1}\text{Mpc}^{-1}$
- $\Omega_\Lambda = 0.3$, $\Omega_m = 0.7$
- $t_0 = 13.46 \text{ Gy}$

**Legend**

- Atomic clocks: Sortais et al. ’01
- Oklo: Fujii et al. ’00
- $\beta$-decay: Olive et al. ’02
- 21 ADs: Murphy et al. ’01 [12]
- 128 MMs: Present work

(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 $\rightarrow$ 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