Neutrinos and Cosmos

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Texas Conference at Stanford

Outline

- A Little Historical Perspective
- Interpretation of Data & Seven Questions
- Matter Anti-Matter Asymmetry
- Conclusions

A Little Historical Perspective

Rare Effects from High-Energies

$$L = L_{SM} + \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \cdots$$

- Effects of physics beyond the SM as effective operators

$$L_5 = (LH)(LH) \to \frac{1}{\Lambda} (L\langle H \rangle)(L\langle H \rangle) = m_\nu \nu \nu$$

- Can be classified systematically (Weinberg)

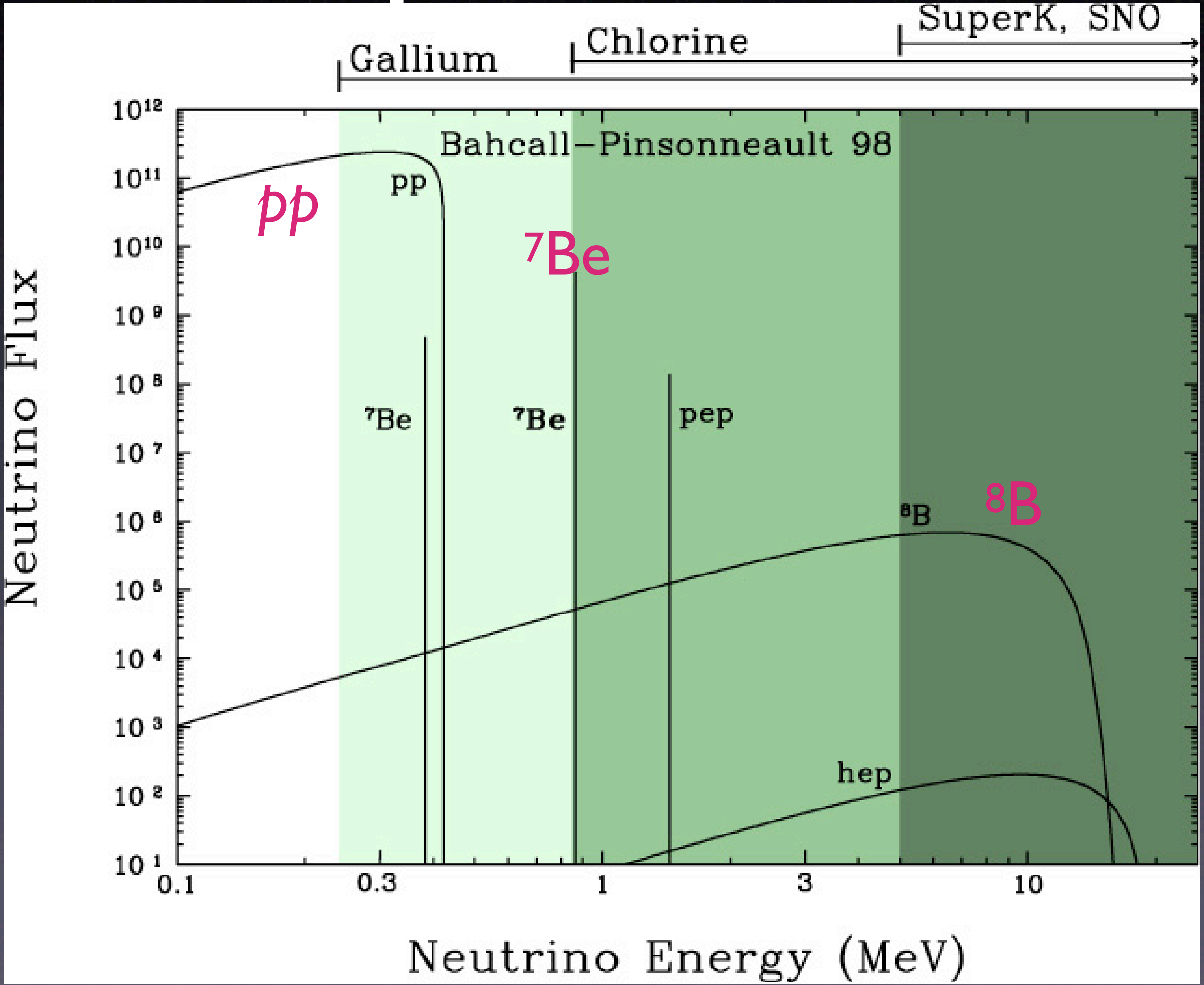
$$L_6 = QQQL, \bar{L}\sigma^{\mu\nu} W_{\mu\nu} H e,$$
$$W^\mu_\nu W^\nu_\lambda B^\lambda_\mu, (H^\dagger D_\mu H)(H^\dagger D^\mu H), \cdots$$

Unique Role of Neutrino Mass

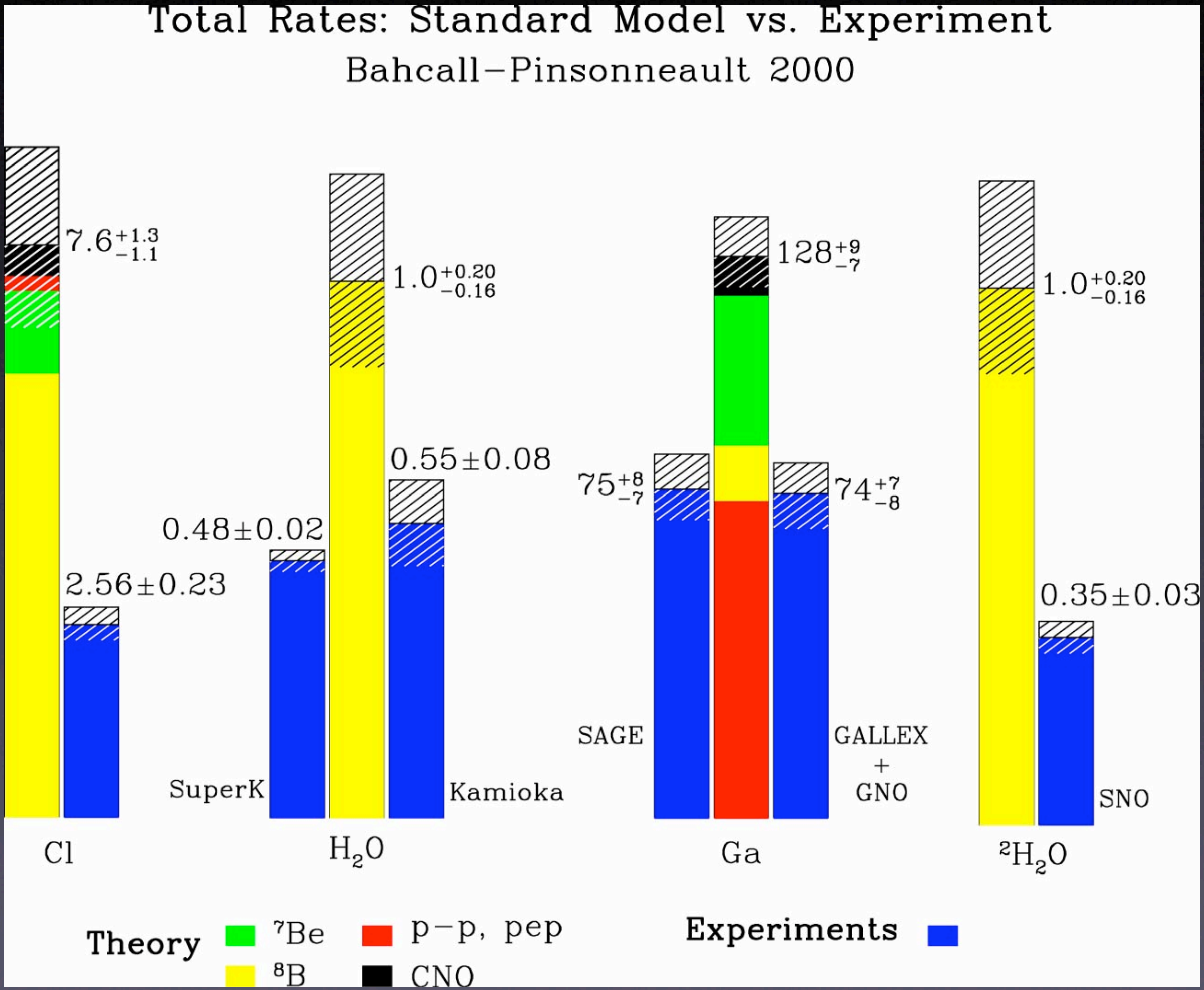
- Lowest order effect of physics at short distances
- Tiny effect $(m_\nu/E_\nu)^2 \sim (\mathrm{eV/GeV})^2 = 10^{-18}$!
- Interferometry (i.e., Michaelson-Morley)!
  - Need coherent source
  - Need interference (i.e., large mixing angles)
  - Need long baseline

  Nature was kind to provide all of them!
- "neutrino interferometry" (a.k.a. neutrino oscillation) a unique tool to study physics at very high scales

Solar Neutrino Spectrum



We don't get enough



Can we get three numbers correctly with only two parameters?

$(\Delta m^2, \theta)$

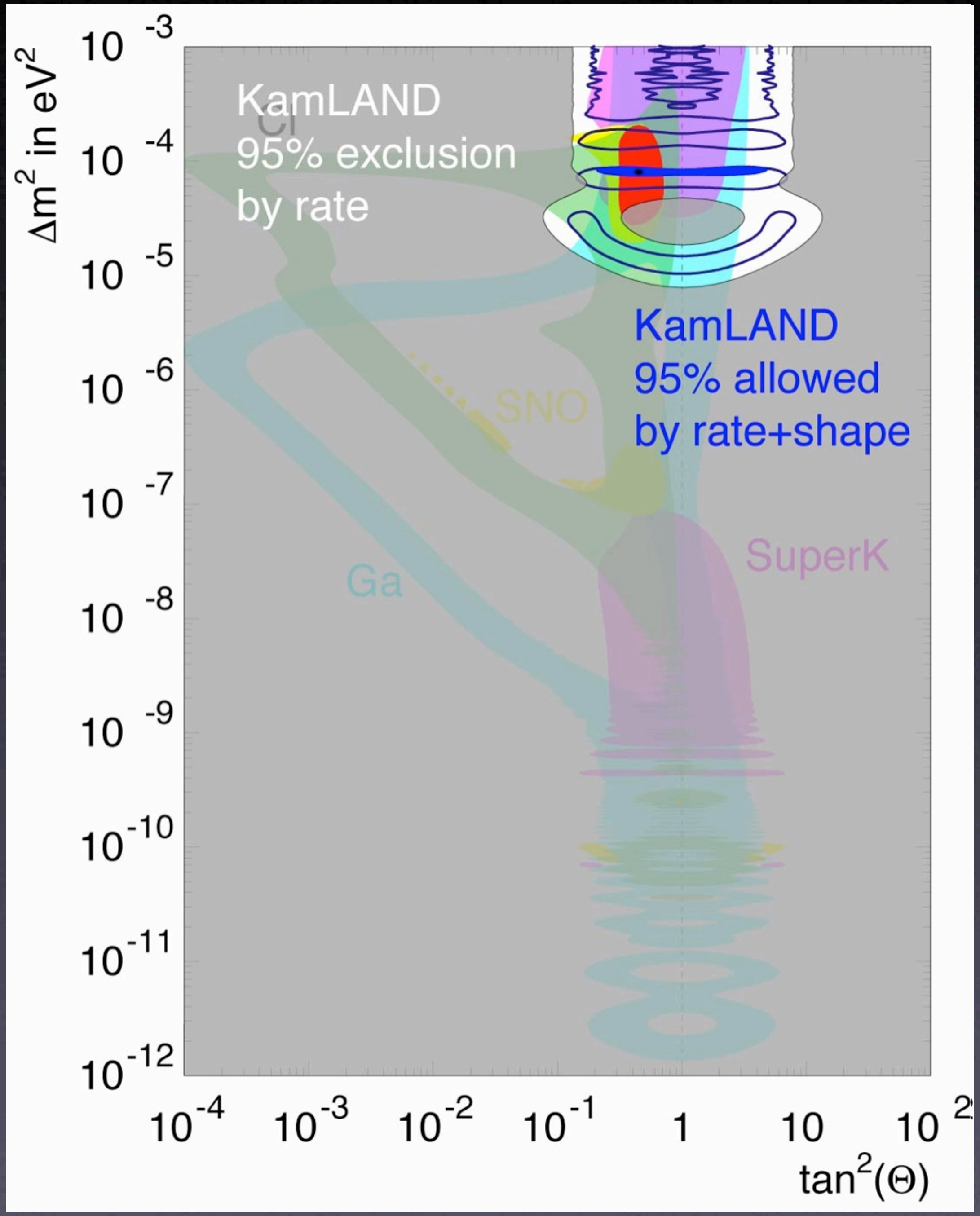
Year of Neutrino: 2002

March 2002

April 2002
with SNO

Dec 2002
with KamLAND

June 2004
with KamLAND



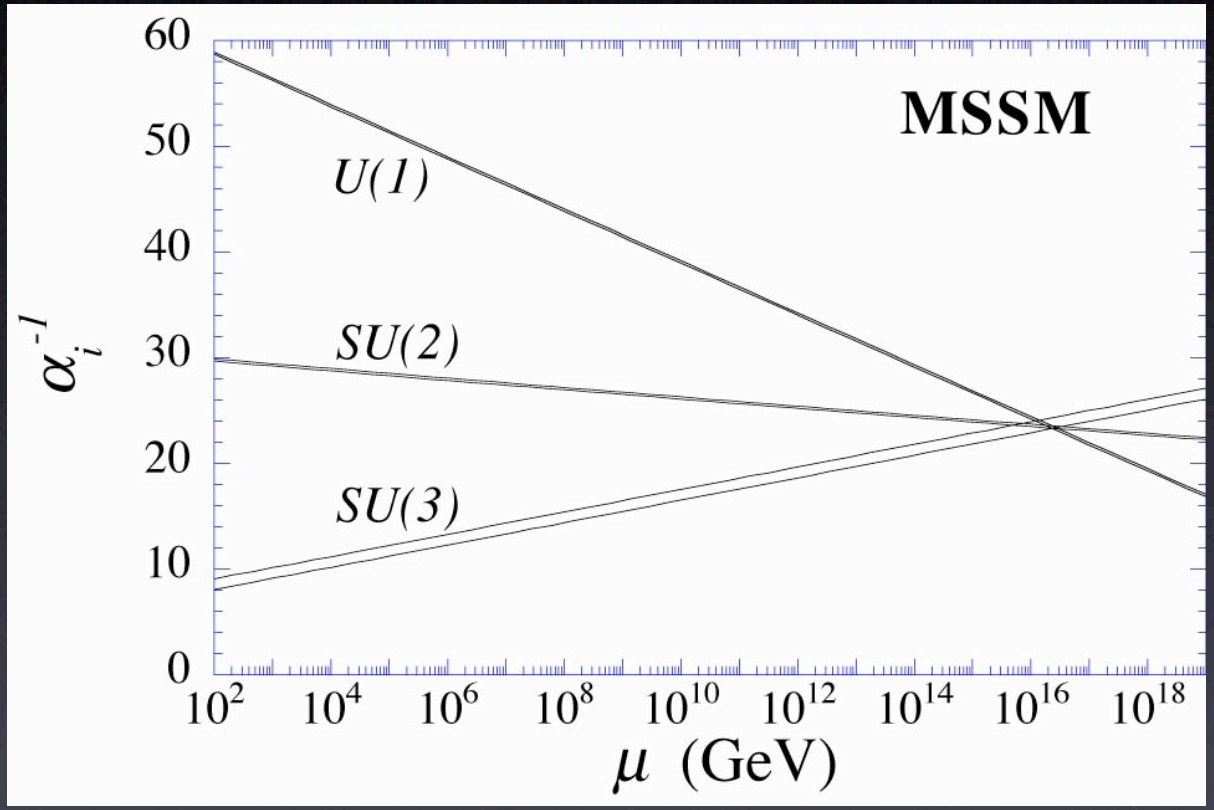
Solar Neutrino Problem Finally Solved After 35 Years!

What we learned

- Atmospheric ν_μs are lost. P=4.2 10^{-26} (SK)
- converted most likely to ν_τ (>99%CL)
- Solar ν_e is converted to either ν_μ or ν_τ (>5σ) (SNO)
- Reactor anti-ν_e disappear and reappear (99.6%CL) (KamLAND)
- Only LMA solution left for solar neutrinos
- Tiny neutrino mass: *the first evidence for incompleteness of Minimal Standard Model*

Grand Unification

- electromagnetic, weak, and strong forces have very different strengths
- But their strengths become the same at 10^{16} GeV if supersymmetry
- A natural candidate energy scale Λ~10^{16}GeV
  $\Rightarrow m_\nu$~0.003eV



m_ν~$(\Delta m^2_{atm})^{1/2}$~0.05eV

m_ν~$(\Delta m^2_{sol})^{1/2}$~0.009eV

Neutrino mass may be probing unification!

$$L_5 = (LH)(LH) \rightarrow \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

Typical Theorists' View ca. 1990

- Solar neutrino solution *must be* small angle MSW solution because it's cute *Wrong!*
- Natural scale for $\Delta m^2_{23} \sim 10\text{–}100\ eV^2$ because it is cosmologically interesting *Wrong!*
- Angle θ_{23} must be $\sim V_{cb} = 0.04$ *Wrong!*
- Atmospheric neutrino anomaly must go away because it needs a large angle *Wrong!*

Surprises

Prejudice from quarks, charged leptons:

- Mixing angles are small
- Masses are hierarchical

All mixing except U_{e3} large

- $(e \mu \tau) \begin{pmatrix} \text{big} & \text{big} & \text{small?} \\ \text{big} & \text{big} & \text{big} \\ \text{big} & \text{big} & \text{big} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$ $\qquad \dfrac{\Delta m^2_{solar}}{\Delta m^2_{atm}} \sim 0.18^2$
- Two mass splittings not very different
- Atmospheric mixing near maximal
- Any new symmetry or structure behind it? ⇒ many models

Interpretation of Data & Seven Questions

Three-generation Framework

- Standard parameterization of MNS matrix for 3 generations: 3 angles, one phase
- $M_{MNS} = \begin{pmatrix} U_{e1} U_{e2} U_{e3} \\ U_{\mu 1} U_{\mu 2} U_{\mu 3} \\ U_{\tau 1} U_{\tau 2} U_{\tau 3} \end{pmatrix}$
-
- ??? atmospheric
- solar $\begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix}$
-
- Three mass eigenvalues m_1, m_2, m_3

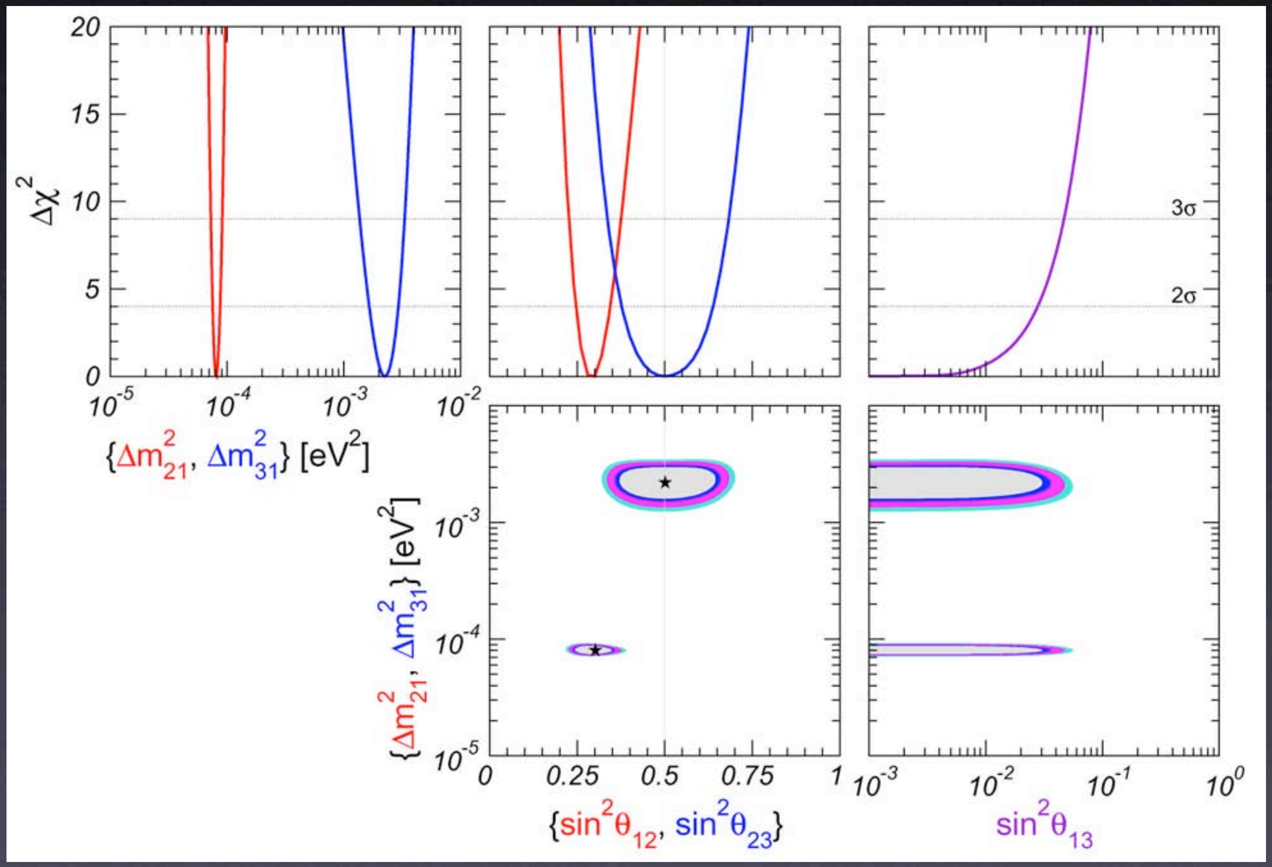
Two mass-squared differences $\Delta m^2_{12}, \Delta m^2_{23}$

Three-generation

- Solar, reactor, atmospheric and K2K data easily accommodated within three generations
- $\sin^2 2\theta_{23}$ near maximal

  $\Delta m^2_{atm} \sim 2.5\times10^{-3} eV^2$
- $\sin^2 2\theta_{12}$ large

  $\Delta m^2_{solar} \sim 8\times10^{-5} eV^2$
- $\sin^2 2\theta_{13} = |U_{e3}|^2 < 0.05$ from CHOOZ, Palo Verde
- Because of small $\sin^2 2\theta_{13}$, solar (reactor) & atmospheric ν oscillations almost decouple

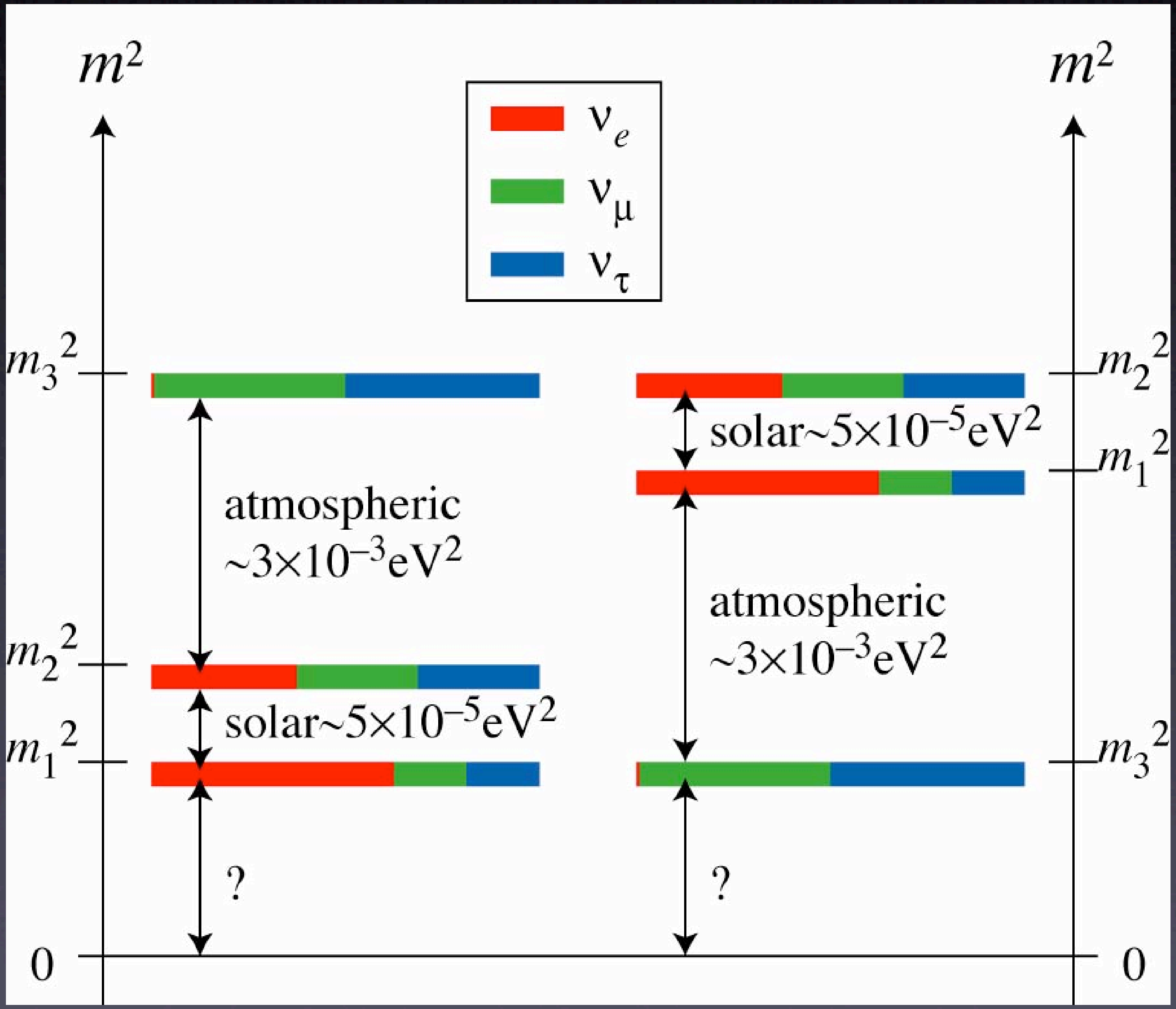


Maltoni et al, hep-ph/0405172

Unknowns: θ_{13}, δ

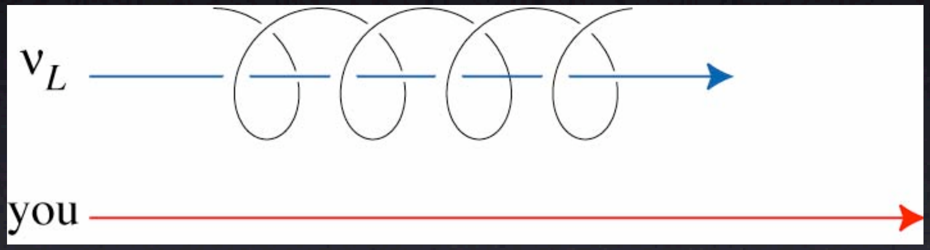
~~Seven~~ Six Questions

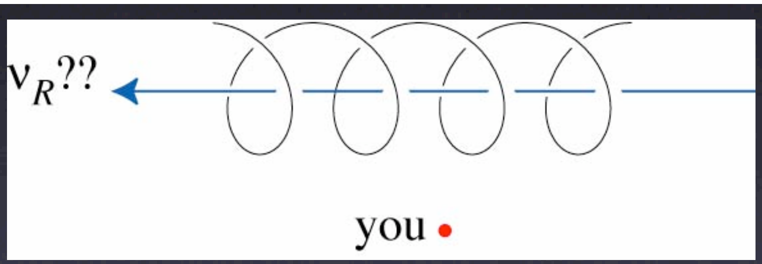
- Dirac or Majorana?
- Absolute mass scale?
- How small is θ_{13}?
- CP Violation?
- Mass hierarchy?
- ~~Verify Oscillation?~~
- LSND? Sterile neutrino(s)? CPT violation?



Neutrinos have mass

- They have mass. Can't go at speed of light.
-
-
-
-





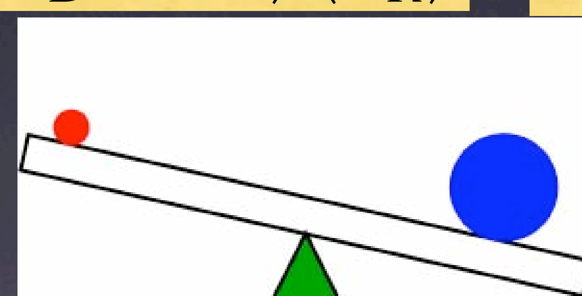
What is this right-handed particle?

- New particle: right-handed neutrino (Dirac)
- Old anti-particle: right-handed anti-neutrino (Majorana)

Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass, but ν_R SM neutral

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad m_\nu = \frac{m_D^2}{M} << m_D$$



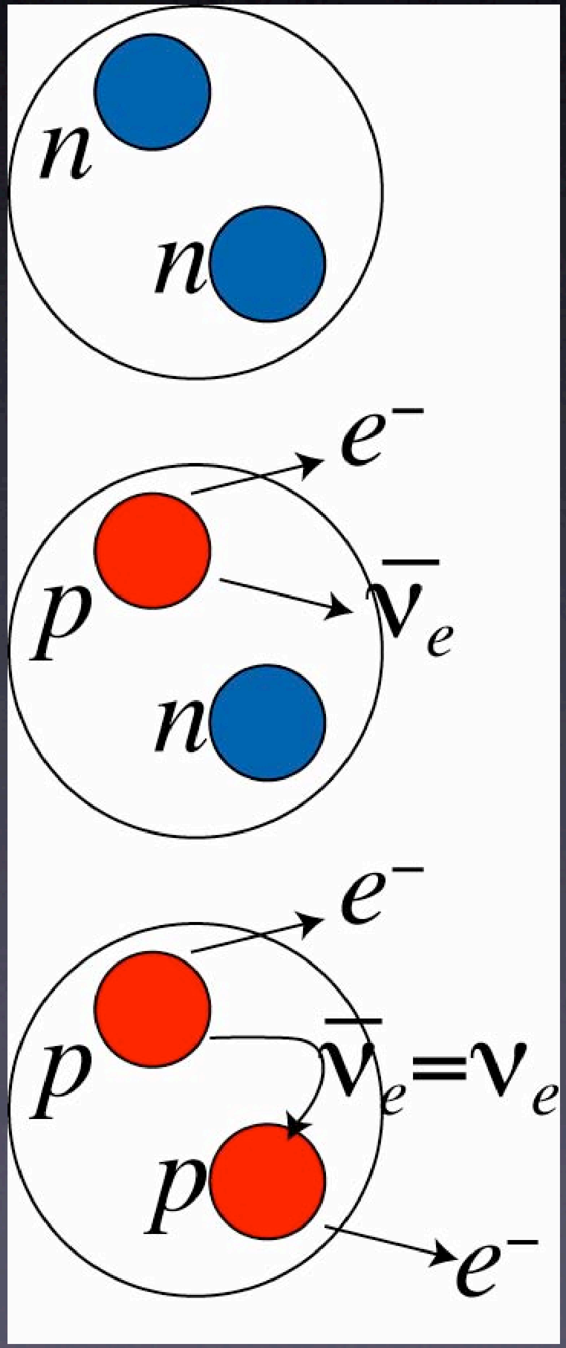
To obtain $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$,

$M_3 \sim 10^{15}$GeV (GUT!)

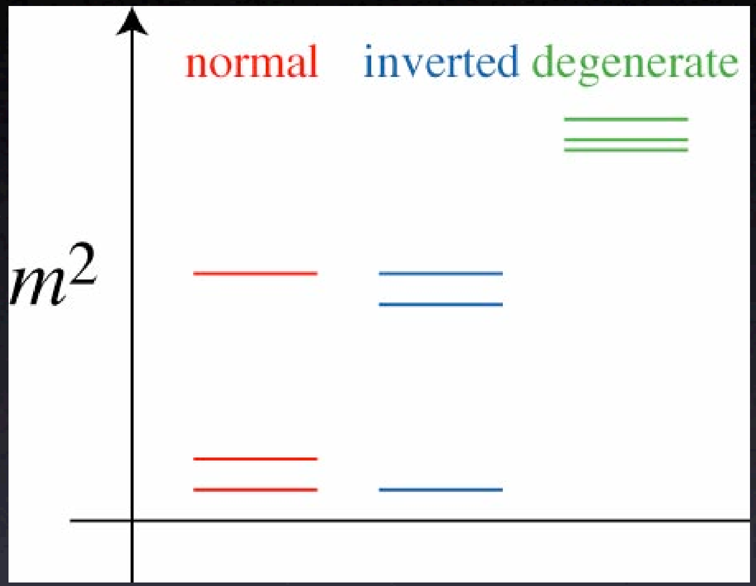
Neutrinos are Majorana

Neutrinoless Double-beta Decay

- The only known practical approach to discriminate Majorana vs Dirac neutrinos
- 0νββ: $nn \rightarrow ppe^{-}e^{-}$ with no neutrinos
- Matrix element $\propto \langle m_{\nu_e} \rangle = \sum_i m_\nu |U_{ei}|^2$
- Current limit $|\langle m_{\nu_e} \rangle| \leq$ about 1eV



Three Types of Mass Spectra



Degenerate

- All three around >0.1eV with small splittings
- Laboratory limit: m<2.3eV
- May be confirmed by KATRIN, cosmology
- $|\langle m_{\nu e}\rangle| > 0.07m$

Inverted

- $m_3{\sim}0, m_1{\sim}m_2{\sim}(\Delta m^2_{23})^{1/2}{\approx}0.05$eV
- May be confirmed by long-baseline experiment with matter effect
- $|\langle m_{\nu e}\rangle|>0.013$eV (HM, Peña-Garay)

Normal

- $m_1{\sim}m_2{\sim}{\sim}0, m_3{\sim}(\Delta m^2_{23})^{1/2}{\approx}0.05$eV
- $|\langle m_{\nu e}\rangle|$ may be zero even if Majorana

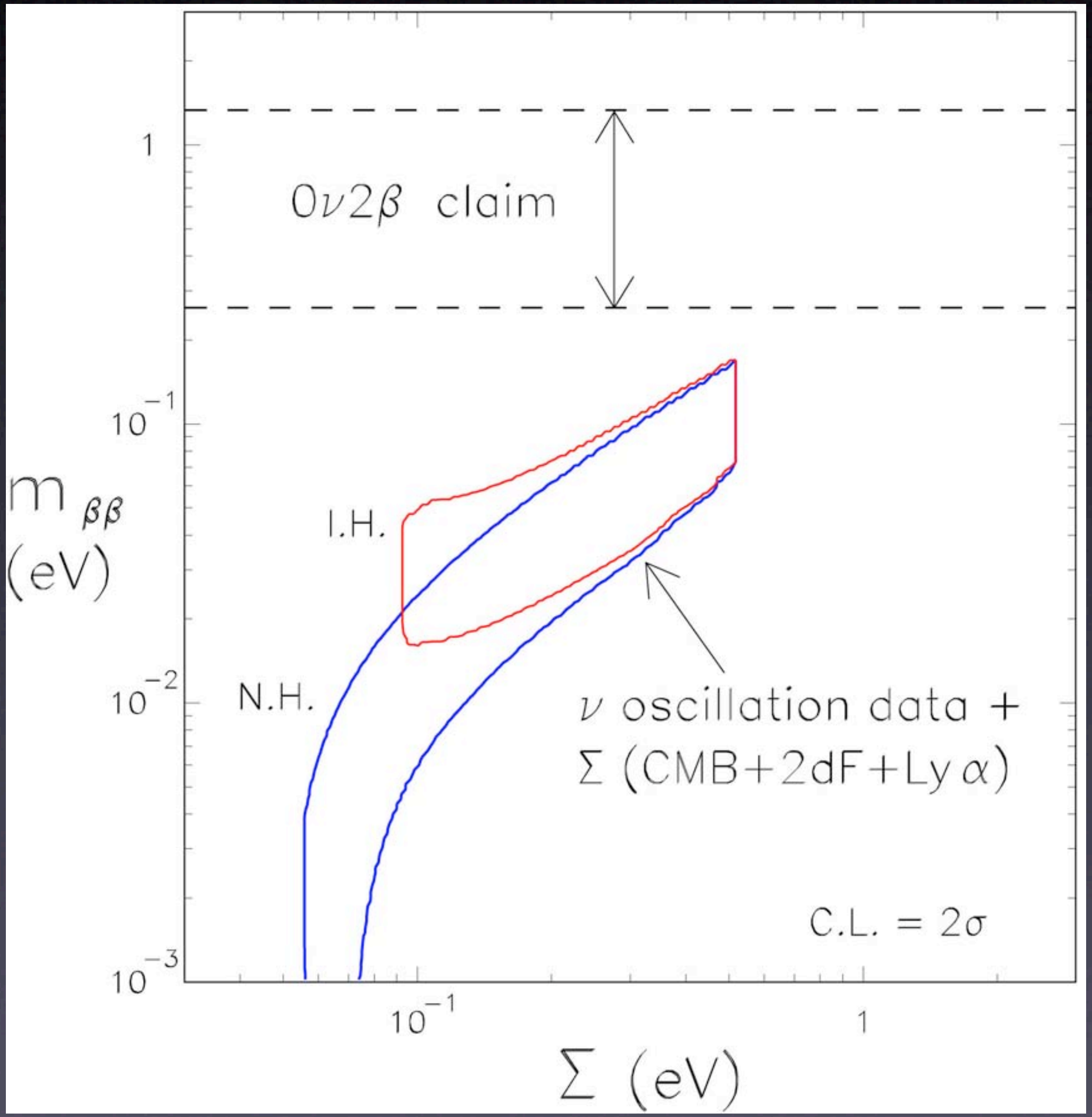
Cosmological Limit

- CMB+LSS+Lyman α (Seljak et al, astro-ph/0407372) :
  $\Sigma_i\ m_{\nu i}<0.42$ eV, $m_{\nu 1}<0.13$ eV (95% CL)
- Puts upper limit on the effective neutrino mass in the neutrinoless double beta decay $|\langle m_{\nu e}\rangle|<0.13$eV (Pierce, HM)
- Heidelberg-Moscow: $|\langle m_{\nu e}\rangle|=0.11–0.56$ eV

Conflict?

Cosmology vs Laboratory

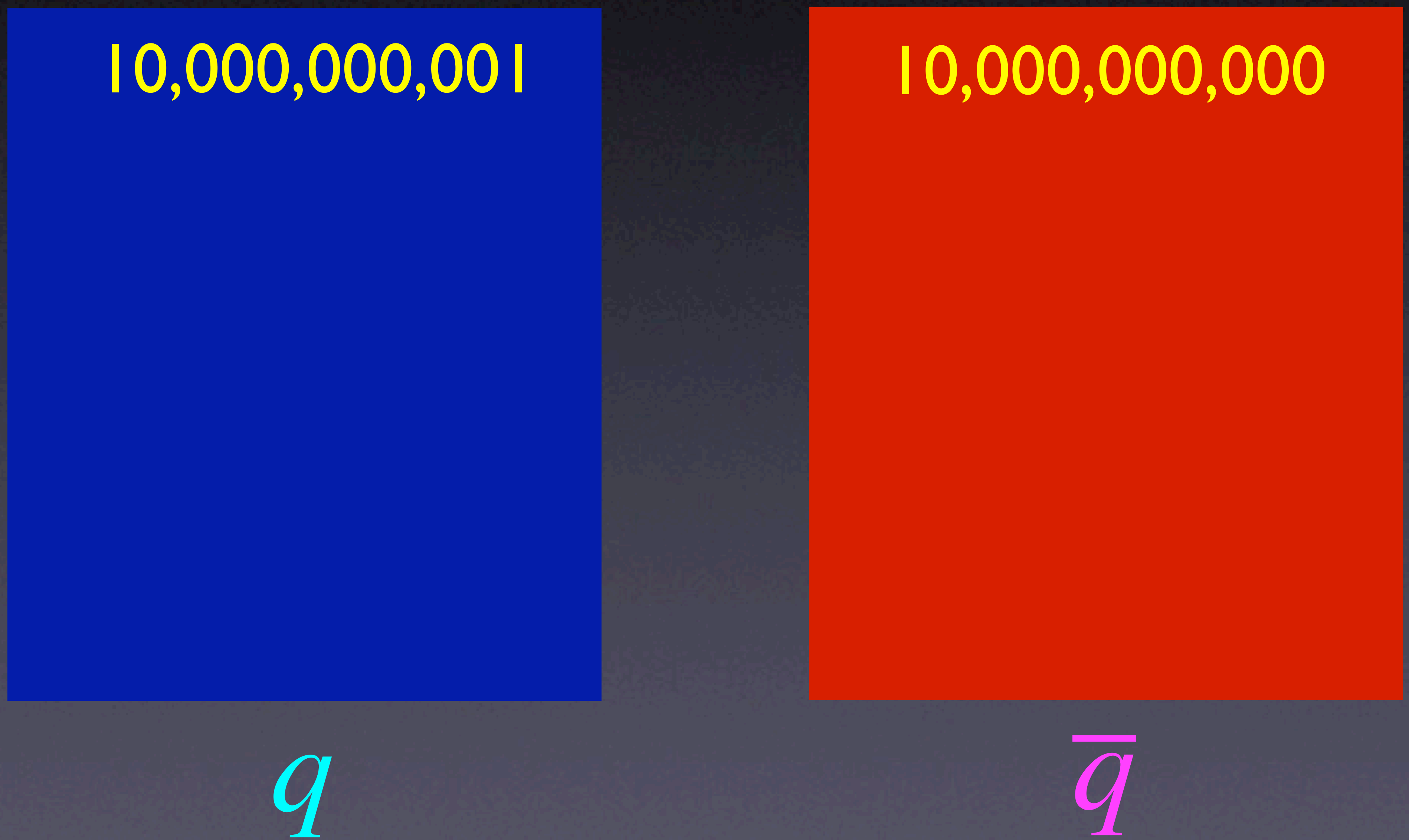
- Global fit to the "World Data"
- indeed, tension between the Heidelberg-Moscow claim and cosmology
- Still subject to the uncertainties in nuclear matrix element (Bahcall, HM, Peña-Garay)
- Better data and theory needed!



Lisi et al, hep-ph/0408045

Matter Anti-matter Asymmetry

Matter and Anti-Matter
Early Universe



Matter and Anti-Matter
Current Universe

1

us

q $\bar{q}$

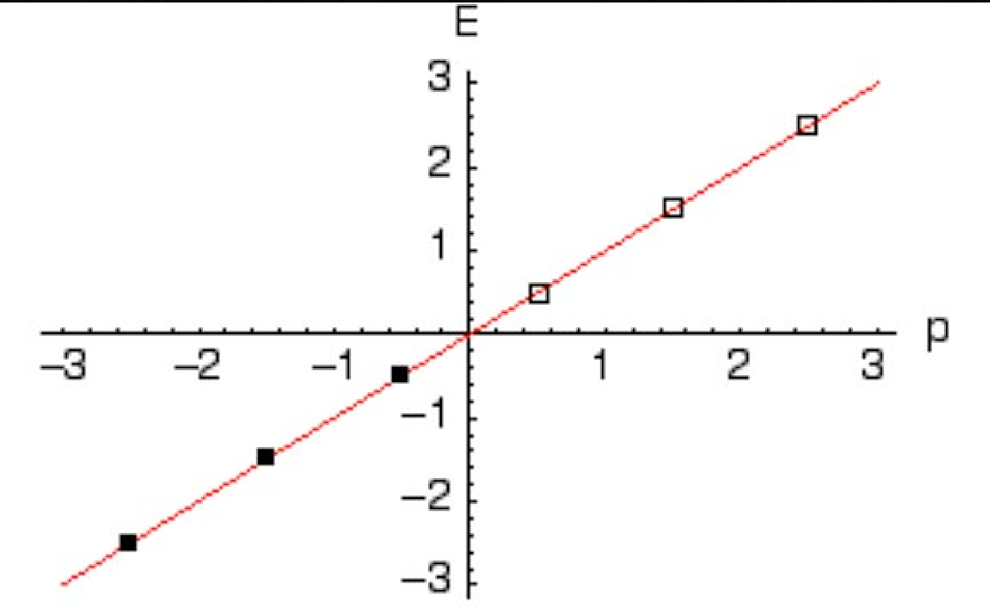
The Great Annihilation

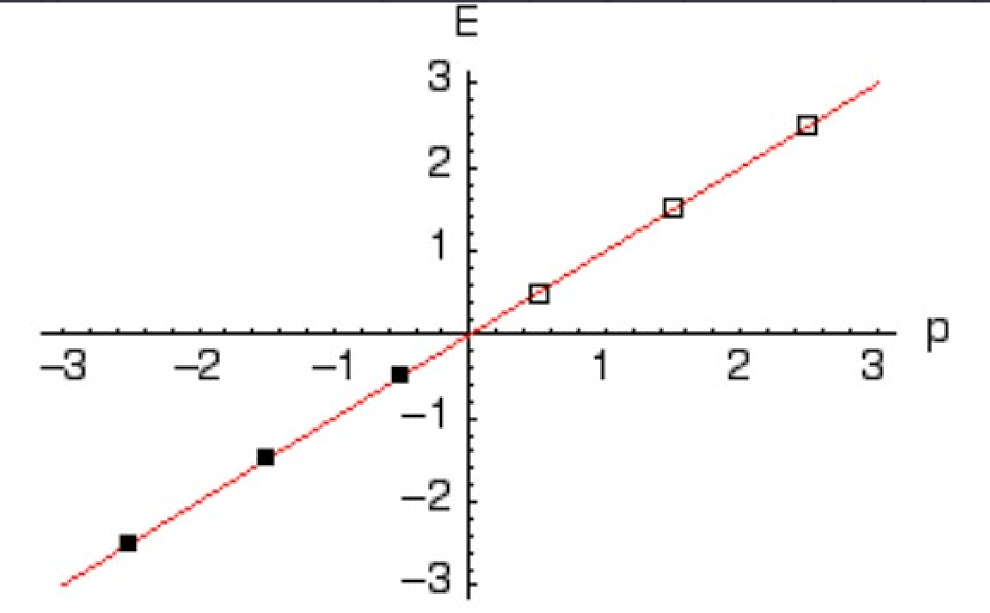
Baryogenesis

- Gaussian scale-invariant fluctuation ⇒ inflation
  Initial condition wiped out
- What created this tiny excess matter?
- Necessary conditions for baryogenesis (Sakharov):
  1. Baryon number non-conservation
  2. CP violation (subtle difference between matter and anti-matter)
  3. Non-equilibrium
     $\Rightarrow \Gamma(\Delta B>0) > \Gamma(\Delta B<0)$
- It looks like neutrinos have no role in this…

Electroweak Anomaly

- Actually, SM converts L (ν) to B (quarks).
- In Early Universe (T > 200GeV), W is massless and fluctuate in W plasma
- Energy levels for left-handed quarks/leptons fluctuate correspon-dingly



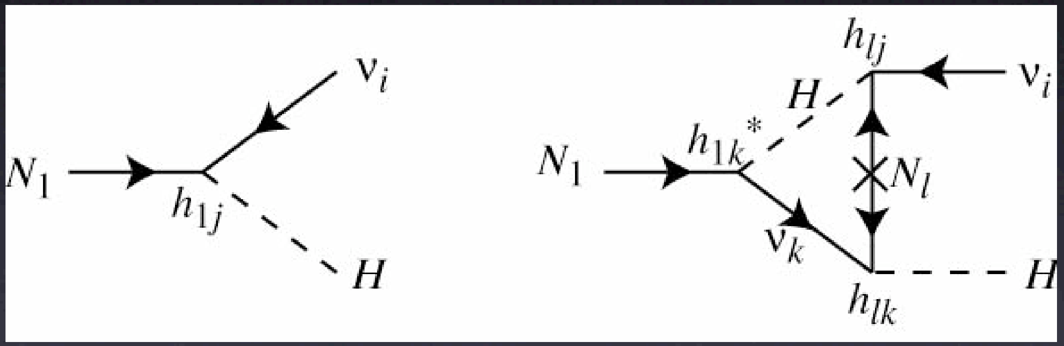


$\Delta L = \Delta Q = \Delta Q = \Delta Q = \Delta B = 1 \Rightarrow \Delta (B - L) = 0$

Leptogenesis

- You generate Lepton Asymmetry first. (Fukugita, Yanagida)
- Generate L from the direct CP violation in right-handed neutrino decay

$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H) \propto \mathrm{Im}(h_{1j} h_{1k} h^*_{lk} h^*_{lj})$$

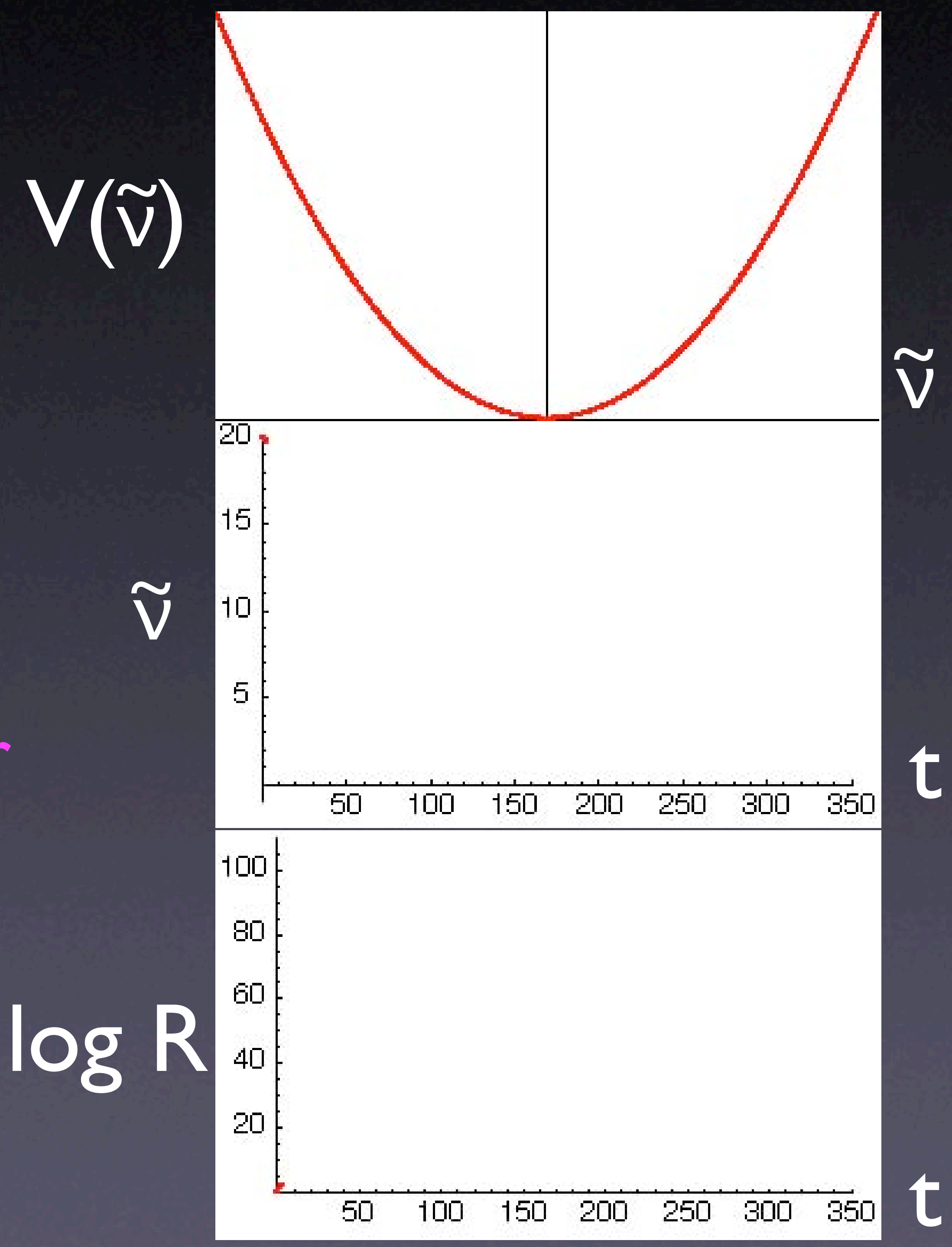


- L gets converted to B via EW anomaly
  - ⇒ More matter than anti-matter
  - ⇒ *We have survived "The Great Annihilation"*
- Despite detailed information on neutrino masses, it still works! (e.g., Bari, Buchmüller, Plümacher)

Neutrino as inflaton

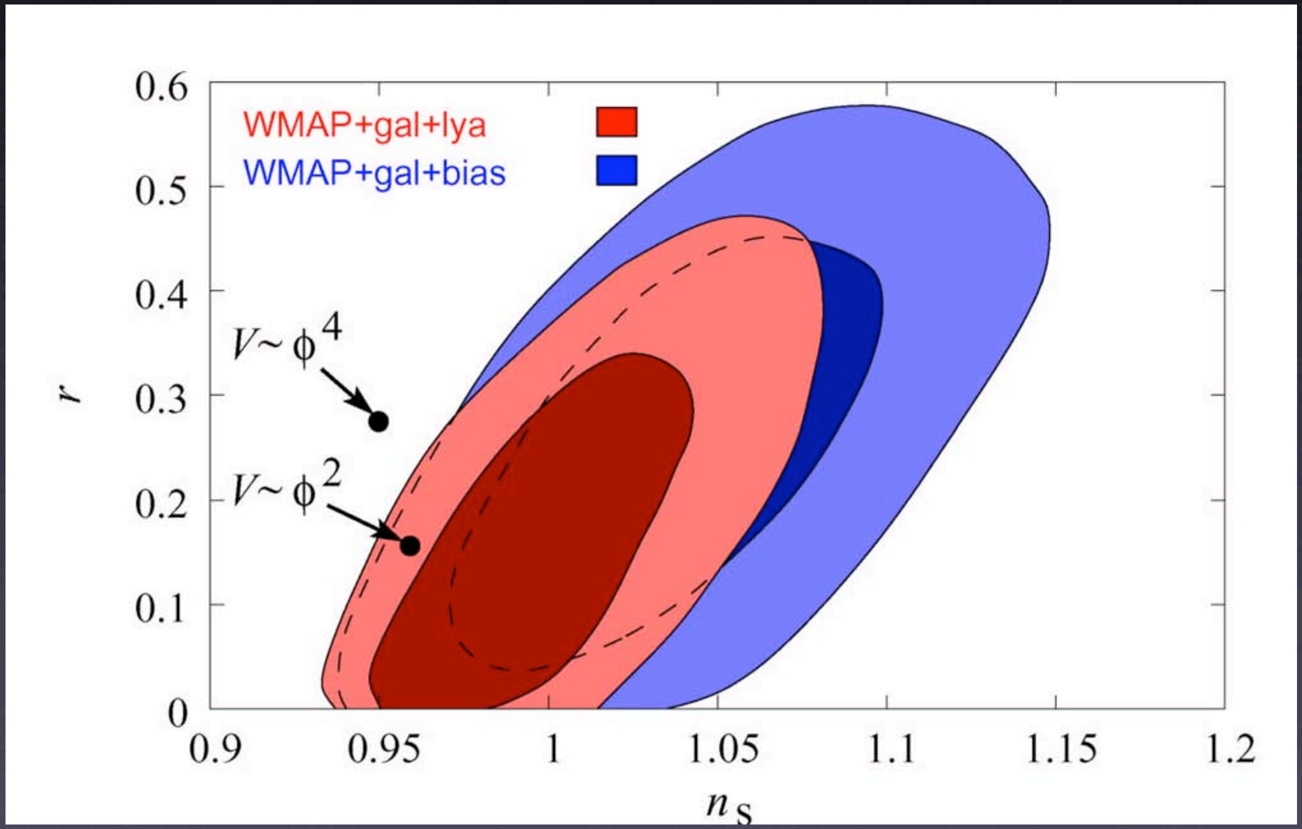
- Superpartner of a right-handed neutrino
- $V = m^2 \tilde{\nu}^2$
- displaced from the minimum at the beginning
- rolls down slowly: inflation
- decays into both matter and anti-matter, but with a slight preference to matter
- decay products contain supersymmetry and hence Dark Matter

H. Murayama et al, PRL 70, 1912



Origin of the Universe

- Right-handed scalar neutrino: $V = m^2 \varphi^2$
- $n_s = 0.96$
- $r = 0.16$
- Verification/exclusion possible in the near future
- even if not inflaton, it may show up as a small isocurvature component



Conclusions

- Revolution in neutrino physics
  - The solar neutrino problem solved!
- Small but finite neutrino mass:
  - Interesting interplay between neutrinos and cosmos
- Neutrino mass may be responsible for our existence
- Neutrinos may even be the origin of the universe
- A lot more to learn in the next few years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