Neutrinos: Theory Summary

- Neutrinos as probes
- Mass, mixing, intrinsic properties
- Astrophysics/cosmology

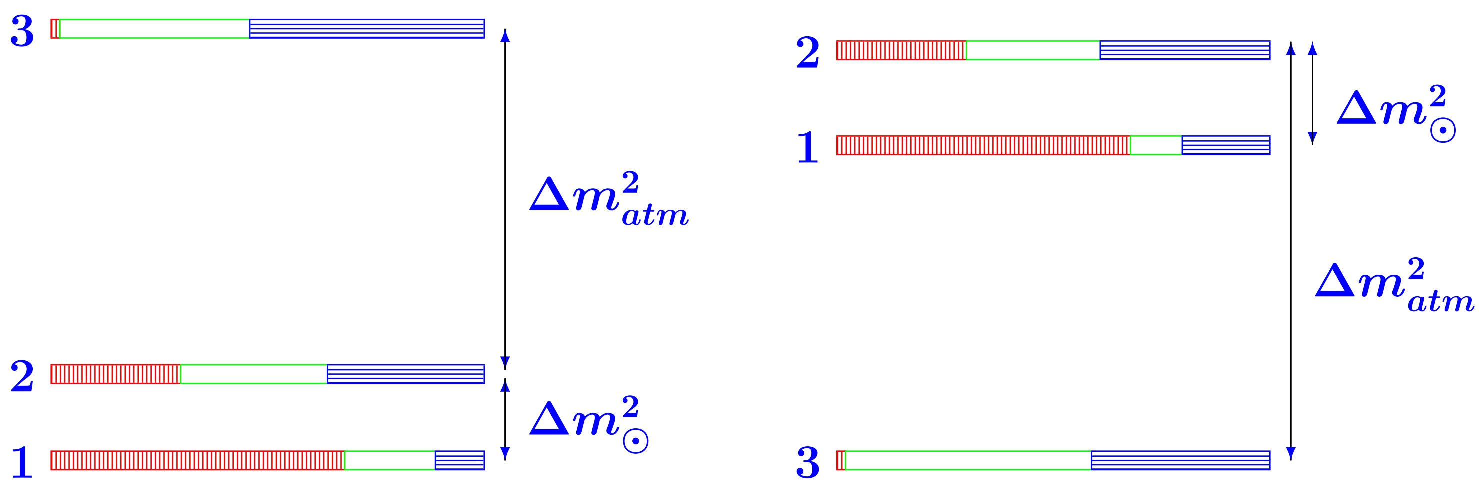
Neutrinos as a Unique Probe: $10^{-33} - 10^{+28}$ cm

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

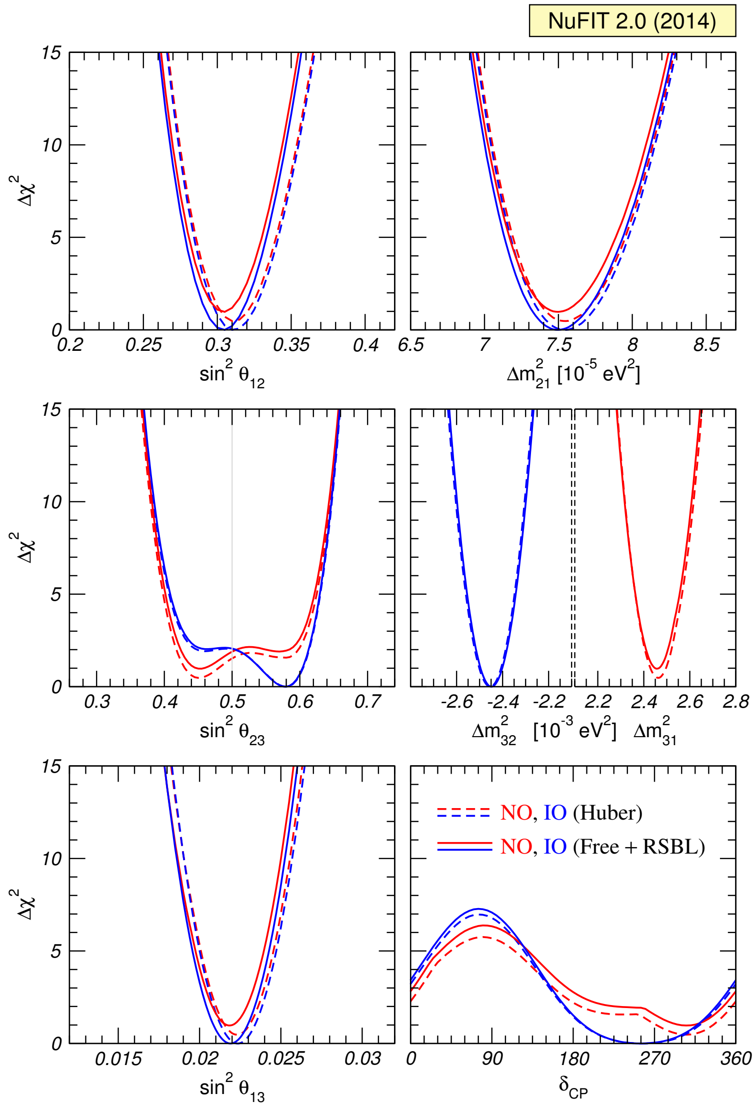
- **Astrophysics/Cosmology**
  - Core of Sun
  - Supernova dynamics
  - Atmospheric neutrinos (cosmic rays)
  - Violent events (AGNs, GRBs, cosmic rays)
  - Large scale structure/CMB (dark matter, dark radiation)
  - Nucleosynthesis (big bang - small A; stars $\rightarrow$ iron; supernova - large N)
  - Baryogenesis (?)
  - Simultaneous probes of ν and astrophysics
- **Interior of Earth**

Mass, mixing, intrinsic properties

- **Talks by L. Everett, R. Mohapatra, S. Petcov, s. Pascoli**
- **Spectrum (assuming 3 active ν's)**



Left: normal hierarchy (NH); Right: inverted hierarchy (IH). Red, green, blue are the central values of $|V_{ei}|^2$, $|V_{\mu i}|^2$, and $|V_{\tau i}|^2$.



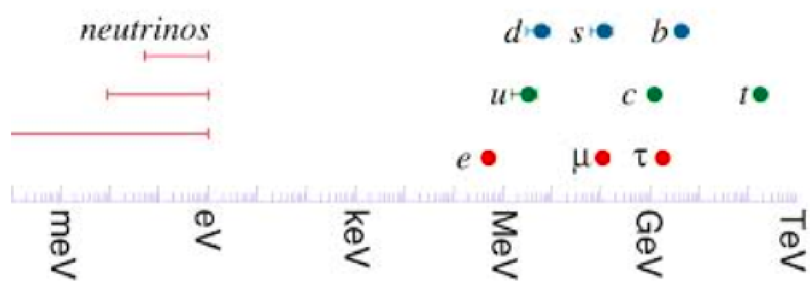
Gonzalez-Garcia et al, 2014 (1409-5439)

- θ_{23} **large: hint of non-maximal; either octant**
- θ_{12} **large but non-maximal**
- θ_{13} **small but non-zero (CP, hierarchy)**
- **Hint of** $\delta \sim 3\pi/2$

(Broad) Theoretical Implications

Shifts in the paradigm for SM flavor puzzle:

Suppression of neutrino mass scale



Seemingly milder hierarchies for neutrinos

Quark, Lepton Mixing Angles strikingly different

implications for quark-lepton unification?

(Lisa Everett talk)

- **Majorana or Dirac**
- **Overall neutrino mass scale**
  (power law (HDO) vs exponential suppression)
- **Mass hierarchies** (NH, IH, degenerate, comparison with quark and $\ell^{\pm}$)
- **Lightest mass** (cosmology)
- **Mixing angles** (anarchy or symmetry?)
- **CP violation**

Majorana or Dirac

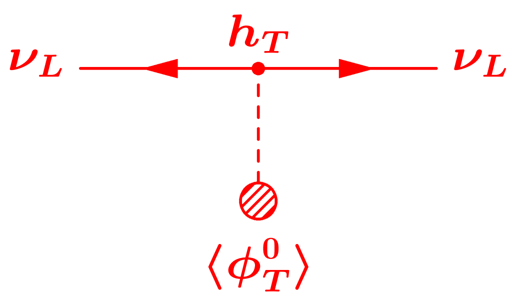
- **No distinction except mass** (or new interactions)
- **Start with Weyl 2-component**
  - ν_L active (doublet) neutrino, ν_R^c = active antineutrino
    ($\nu_L \xrightarrow[CP]{} \nu_R^c$)
  - Possible sterile: $\nu_R \xrightarrow[CP]{} \nu_L^c$

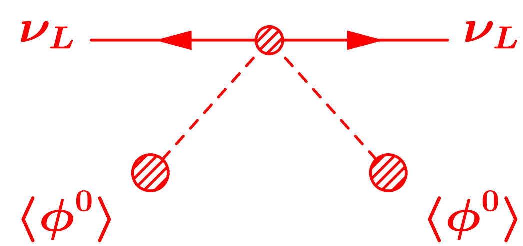
Majorana mass

$$-\mathcal{L}_T = \frac{m_T}{2}\left(\bar{\nu}_L \nu_R^c + \bar{\nu}_R^c \nu_L\right) = \frac{m_T}{2}\left(\bar{\nu}_L \mathcal{C} \bar{\nu}_L^T + \nu_L^T \mathcal{C} \nu_L\right) = \frac{m_T}{2} \bar{\nu}_M \nu_M$$

with ν_L active (doublet) neutrino, ν_R^c = active antineutrino ($\nu_L \xrightarrow[CP]{} \nu_R^c$), $\nu_M \equiv \nu_L + \nu_R^c$

- $|\Delta L| = 2$; $|\Delta t_L^3| = 1$ **(Higgs triplet or higher dimensional (Weinberg) operator)**





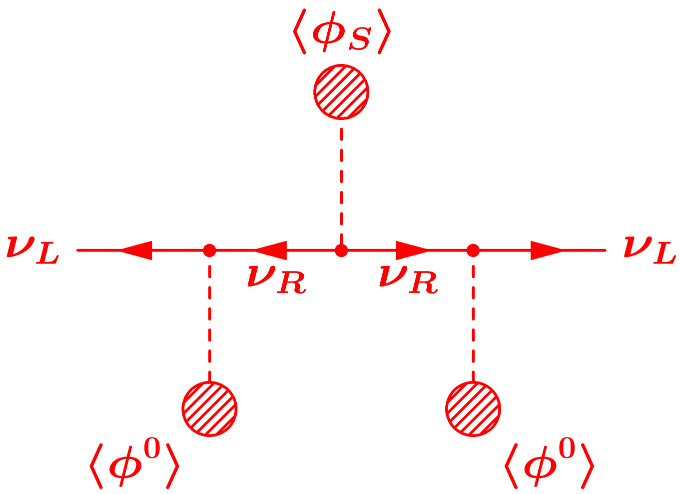
- **Not forbidden by any unbroken gauge symmetry**
  - (Probably) L **must be violated,** but
    [non-gravity: large 126 of $SO(10)$ or HDO added by hand]
    [gravity: $m_\nu \lesssim \nu_{EW}^2/\overline{M}_P \sim 10^{-5}$ eV (unless LED); often much smaller]
  - **New TeV or string scale physics/symmetries/constraints may invalidate assumptions**
    [No 126 in string-derived $SO(10)$]

- **Connection with leptogenesis** (P. Di Bari talk)

- **Naturally small by HDO** (Weinberg op) **if $\mathcal{M}$ large** ($\nu = \langle \phi^0 \rangle$):

$$\mathcal{L} \sim \frac{h^2}{\mathcal{M}} L H_u L H_u \to m_T \sim h^2 \nu^2 / \mathcal{M}$$

- **Minimal Type I seesaw:** $m_T \sim m_D^2/\mathcal{M} \ll m_D$, $m_D \sim h\nu$



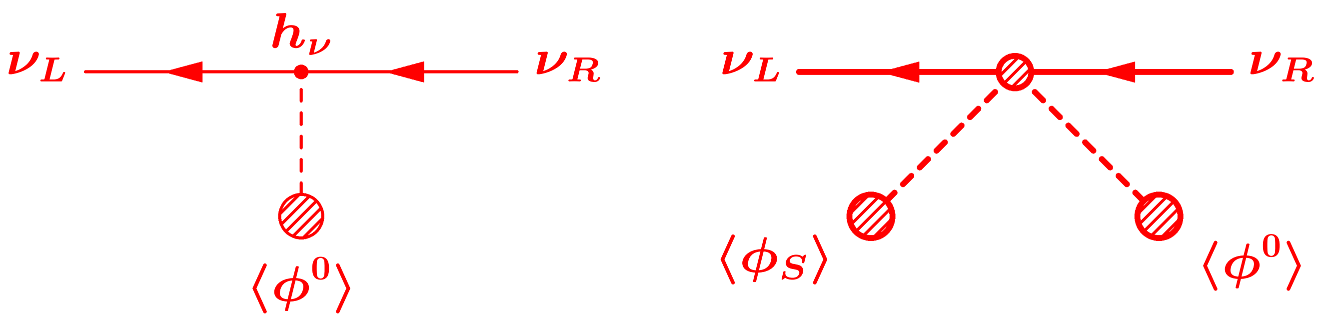
- **Bottom-up alternatives: Higgs (or fermion) triplets, extended (TeV) seesaws, loops, R_p violation**

Dirac mass

$$-\mathcal{L}_D = m_D\,(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L) = m_D \bar{\nu}_D \nu_D$$

$\nu_L \xrightarrow[CP]{} \nu_R^c$ is active; $\nu_R \xrightarrow[CP]{} \nu_L^c$ is sterile; $\nu_D = \nu_L + \nu_R$

- $\Delta L = 0$; $|\Delta t_L^3| = \frac{1}{2}$ (Higgs doublet, $m_D \sim h_\nu \nu$)

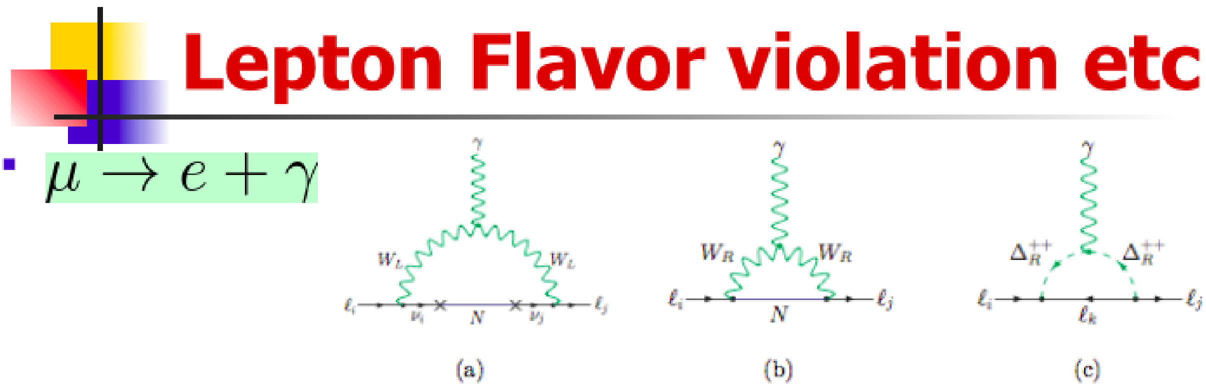


- Can be small if suppressed by symmetry ($m_D \sim h_\nu \nu \langle \phi_S \rangle / \mathcal{M}$)

Overall neutrino mass scale

- **Simplest possibility: (Majorana) seesaw with $m_D \sim m_t$ and $\mathcal{M} \sim 10^{14}$ GeV** (near GUT scale)

- **However, can have smaller m_D and $\mathcal{M}$, e.g., $m_D \sim m_e$ and $\mathcal{M} = \mathcal{O}(\text{TeV})$, allowing for LHC physics**
  - **e.g., LFV or lepton number violation**
  - **e.g., SUSY or left-right model** (Mohapatra talk)



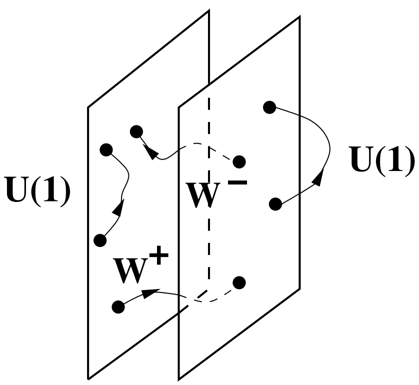
- **String-motivated alternatives**
  - **Higher-dimensional operators (HDO)**
    (cf, Froggatt-Nielsen, but for scale)
    [non-minimal seesaw (not GUT-like), direct Majorana (Weinberg op); small Dirac (e.g., $U(1)'$ or non-holomorphic soft); mixed (LSND, MiniBooNE)]
  - **String instantons (exponential suppressions)**
    [non-minimal seesaw, direct Majorana, small Dirac]
  - **Geometric suppressions (large/warped dimensions)** **[small Dirac]**
- **Alternatives often associated with new TeV physics, electroweak baryogenesis, etc.**

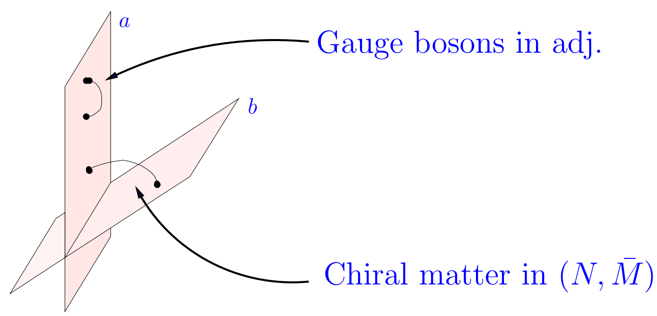
Mass hierarchies

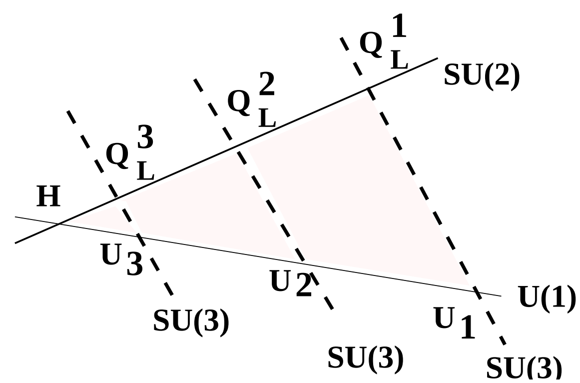
- **Smaller for neutrinos than quarks and ℓ**

- **Order n of HDO $(\langle \phi_S \rangle / \mathcal{M})^n$ (Froggatt-Nielson)**
  (field theory symmetry or stringy operators)

- **Geometric: e^{-A} where A is area of intersecting branes triangle in extra dimensions**

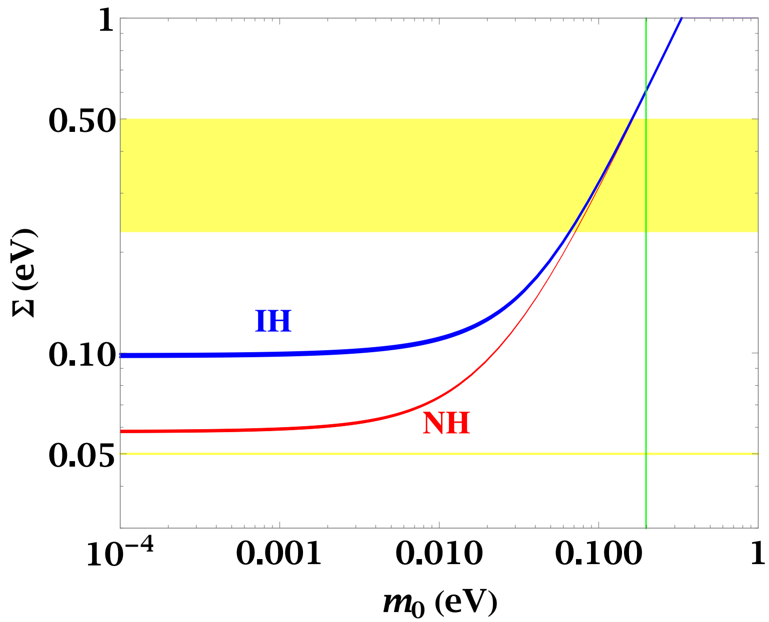






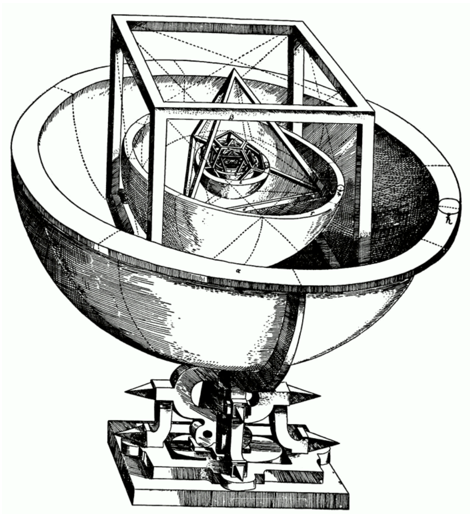
Lightest mass

- **Constrained by and critical for cosmology** (Raffelt talk)
- **Direct measurements** (S. Mertens talk)



Mixing angles and CP violation

- Family symmetries
  - Discrete non-abelian, e.g., leading to tri-bimaximal mixing
    (motivation weakened by $\theta_{13} \neq 0$ and possible non-maximal θ_{23})
  - Parameter correlations (sum rules)
  - Continuous global/gauge, e.g., Froggatt-Nielsen
  - Possible special string vacua



- **Anarchy**
  - **Consistent with observed angles**
  - **General string landscape** (e.g., windings of branes in extra dimensions)
- CP **violation: possible/probable in all/most models**
  (typical of QM for complicated systems)
- **Complication: Cabibbo haze**

Possible sterile neutrinos

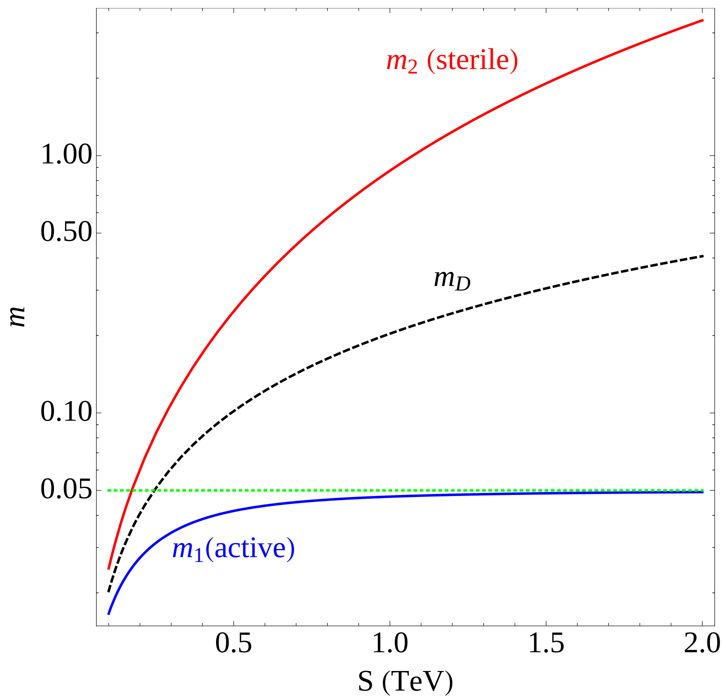
- Talks by B. Louis, S-B. Kim, K. Heeger
- Active mixing with eV-sterile suggested by LSND, MiniBooNE, gallium anomaly, reactor anomaly (however, reactor recalibration of energy spectrum has large uncertainties, from forbidden transitions and from "bump"; A. Hayes talk)
- Tension with ν_μ disappearance
- $3+N$ schemes, especially $N>1$ for CP violation
  ($N+3$, $1+3+1$, etc, more problematic cosmologically)
- Decaying keV steriles with tiny mixing may be warm dark matter/pulsar kick candidates (3.5 keV line; M. Lowenstein talk)
- Sterile neutrinos expected in most models

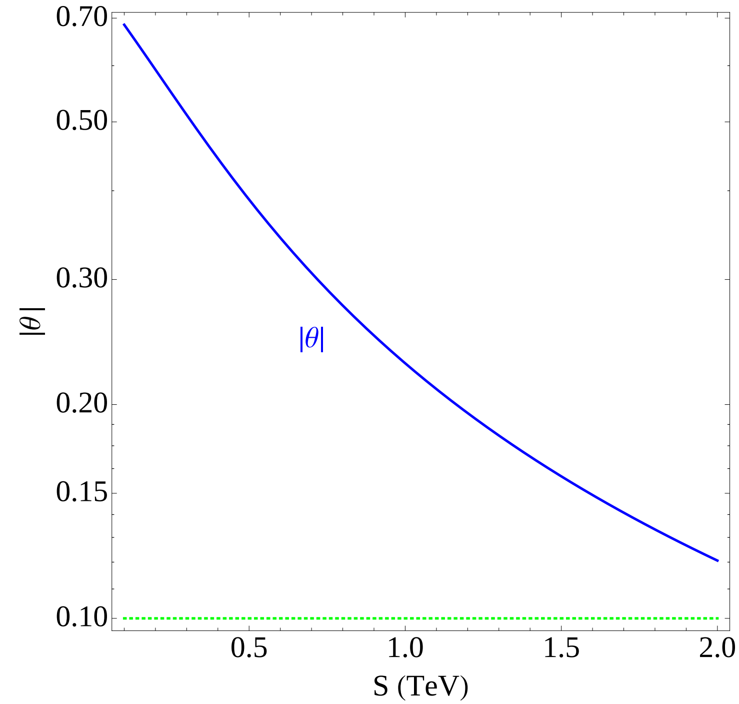
- However, mixing of active and sterile neutrinos of same helicity is difficult
  - Pure Majorana masses: no active-sterile coupling
  - Pure Dirac masses: conserved L; no $\nu_L - \nu_L^c$ mixing
  - Normal seesaw with large $\mathcal{M}$: mass too large, mixing too small
- Need tiny Majorana mass for sterile *and* tiny Dirac mass *and* non-thermalized cosmology (G. Raffelt talk) $\Rightarrow$ major paradigm shift
- Likely implication: both Dirac and Majorana couplings vanish to lowest order by new symmetry, and arise from HDO

$$\mathcal{L} \sim \frac{S^p}{\mathcal{M}^p} L H_u \nu_L^c, \qquad \frac{S^{q+1}}{\mathcal{M}^q} \nu_L^c \nu_L^c, \qquad \frac{S^{r-1}}{\mathcal{M}^r} L H_u L H_u$$

For $p = q = r = 1$ can obtain approximate suggested scales for $\langle S \rangle \sim$ TeV and $\mathcal{M} \sim 10^{14}$ GeV (i.e., new physics at TeV scale and high scale)

- **Special case: no LH_uLH_u term (many authors): mini-seesaw**





$$M = \begin{pmatrix} 0 & \Gamma_D \frac{\nu S}{\mathcal{M}} \\ \Gamma_D \frac{\nu S}{\mathcal{M}} & \Gamma_S \frac{S^2}{\mathcal{M}} \end{pmatrix}$$

$$\Gamma_D = \Gamma_S = 1$$

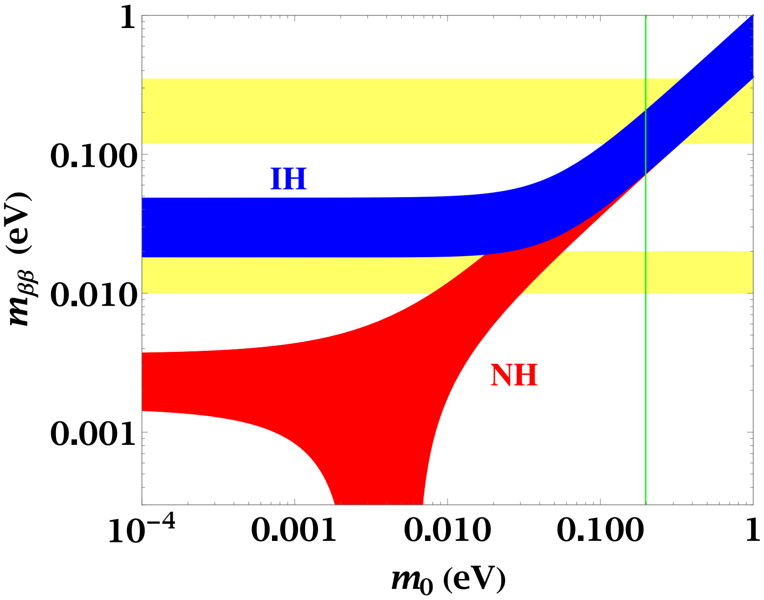
$$\mathcal{M} = 1.2 \times 10^{15} \text{ GeV}$$

$$\nu = 246 \text{ GeV}$$

Neutrinoless double beta decay

- **Talks by S. Petcov, S. Elliott, T. Banks**

- **Three active neutrinos**

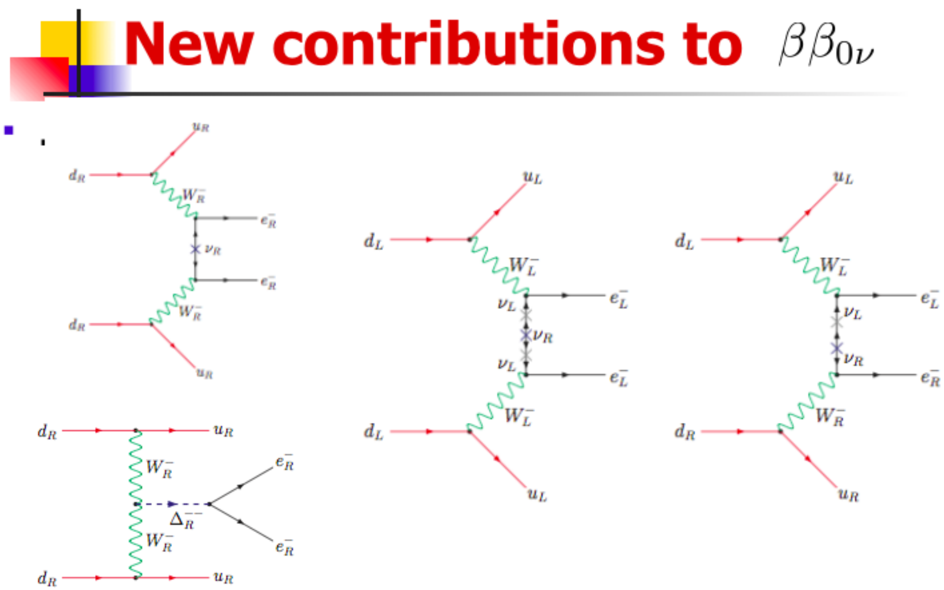


- **Planned experiments may ultimately cover full IH range, confirming Majorana** (or excluding if IH known)

- **Significant NME uncertainties** (needed to extract $m_{\beta\beta}$ and to discriminate light Majorana from other mechanisms)

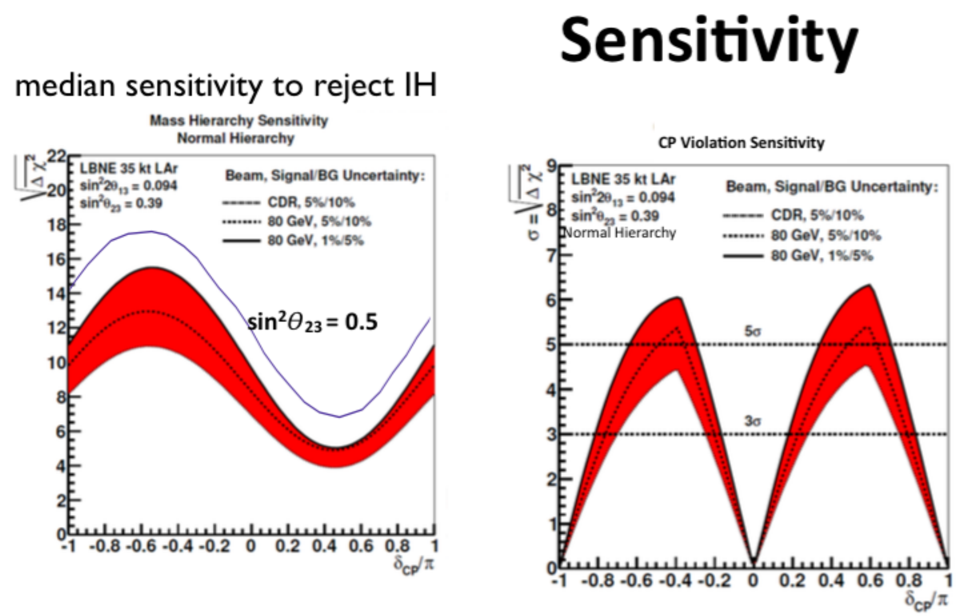
- **eV-scale sterile ν allow entire $m_{\beta\beta}$ range** (e.g., zero in mini-seesaw)

- **Other mechanisms** (e.g., left-right model, Mohapatra talk)



Long baseline/atmospheric

- Talks by J. Learned, T. DeYoung, R. Gandhi, E. Noah, S. Pascoli, M. Diwan
- Determine hierarchy and CP violation
- L; 1^{st}, 2^{nd} max; ND
- Precision measurements
- Test 3ν scheme
- Non standard interactions (NSI), supernova, proton decay, cross sections, $\sin^2\theta_W$



(M. Diwan talk)

Exotica (subdominant)

- Non-standard interactions
- ν decays
- Large elm moments (G. Raffelt)
  - Expect $\mathcal{O}(10^{-20}\mu_B)$
  - Stellar cooling $\lesssim 4.5 \times 10^{-12}\mu_B$
  - Theory arguments (for Dirac) $\lesssim 10^{-15}\mu_B$ (or fine-tuning)
  - Spin-flavor precession $\Rightarrow$ Solar ν_R^c
- Mass variation
- Lorentz, CPT, or equivalence principal violation
- Extra-dimensional effects

Astrophysics/cosmology

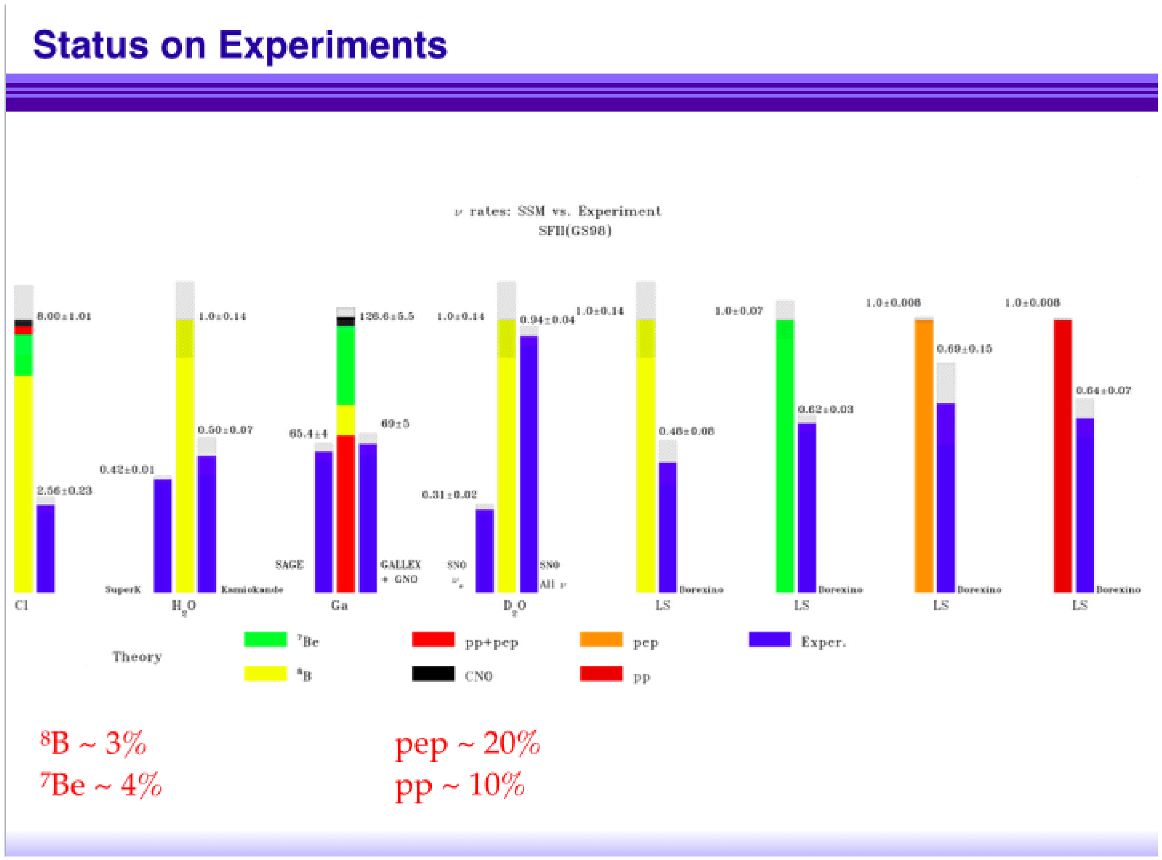
- Relic neutrinos
- Solar neutrinos
- BBN/CMB
- Leptogenesis
- Core collapse supernovae
- Cosmic neutrinos

Relic neutrinos

- P. Vogel talk
- Left over from ν decoupling at few MeV (~ 1 s)
- Indirect tests in BBN, CMB, but no direct observation
- Expect $\sim 3 \times 112/\text{cm}^3$ with $T_\nu \sim 1.94\text{K} = 1.67 \times 10^{-4}$ eV (possible local enhancement)
- Extremely hard to detect, but $\nu_e T \to e^- \, {}^3He$ conceivable ($2m_\nu$ above endpoint)
- Test non-standard cosmology (e.g., T_ν/T_γ), Dirac vs Majorana

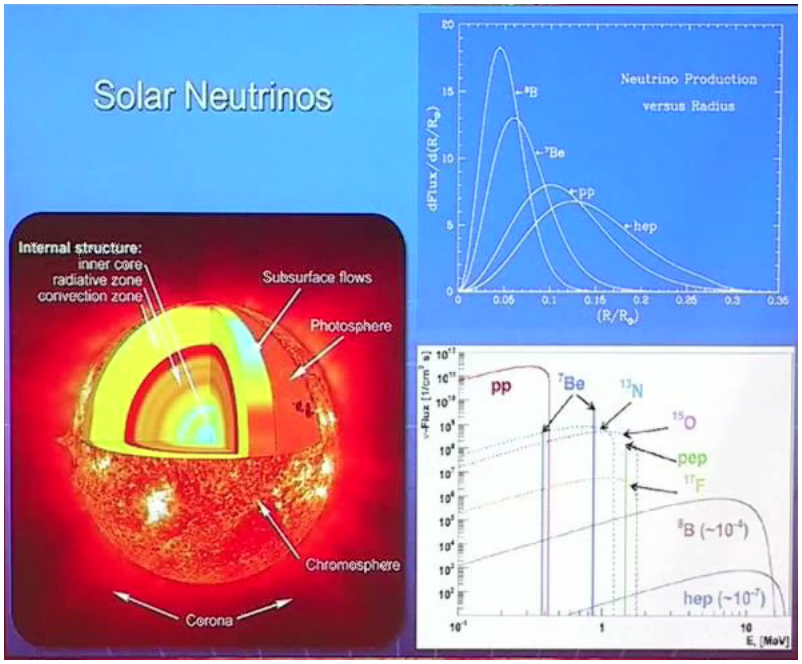
Solar neutrinos

- **Talks by B. Vogelaar, A. Serenelli**



(Serenelli talk)

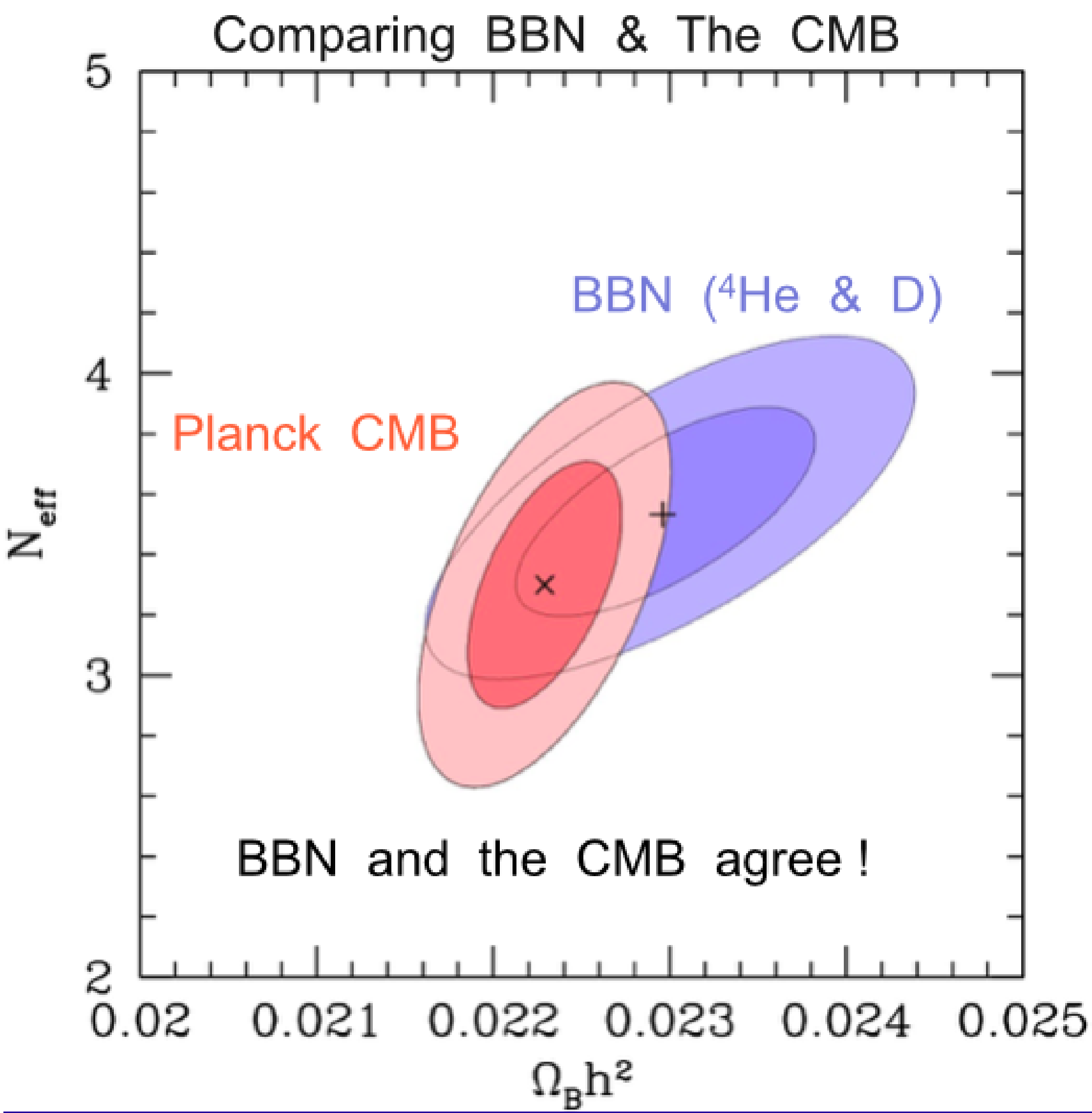
- Beautiful confirmation of Solar and neutrino physics
- Most components measured
- However, recent 3d modeling of Solar atmosphere yields lower metallicity than helioseismology
  (CN neutrinos could resolve)
- Position of MSW rise
  (e.g., steriles, mass-variation, NSI)
- Time variability, etc.



(Vogelaar talk)

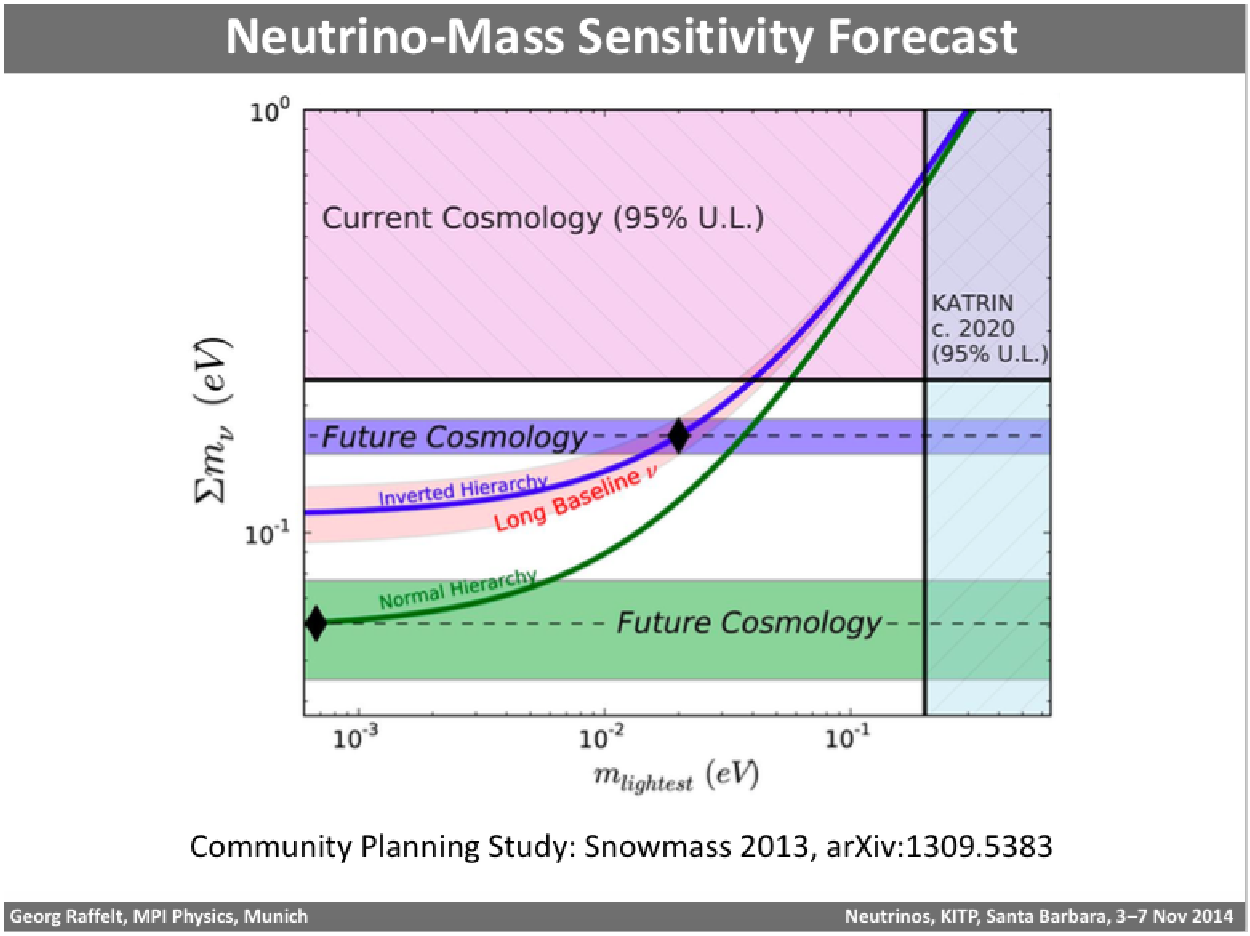
BBN/CMB

- Talks by G. Steigman, G. Raffelt
- Extra radiation density can be parametrized by number $\Delta N_\nu = N_{eff} - 3.046$ of fully-populated equivalent neutrinos. Modifies expansion rate for BBN, CMB
- Neutrinos free stream, damping small scale structure
- CMB and BBN data consistent with $\Delta N_\nu = 0$ or 1



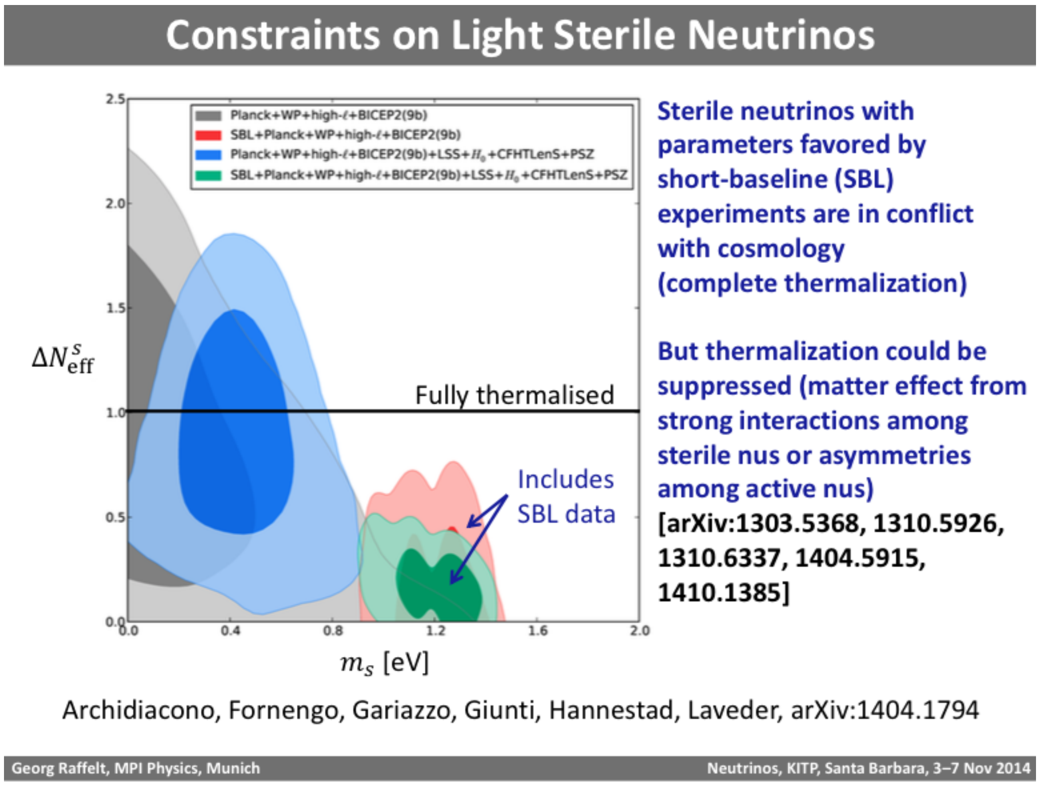
(Steigman talk)

- **Present/future constraints on $\Sigma = \sum_i m_{\nu_i}$, including thermal sterile** **(CMB + BAO: $\Sigma < 0.23$ eV (95% cl), but caveats)**



- **$3+1$ not consistent with full thermal density** (expected for SBL mixings); **worse for other schemes**

- **Can reduce N_{eff} by new interactions, ν asymmetries, etc.**



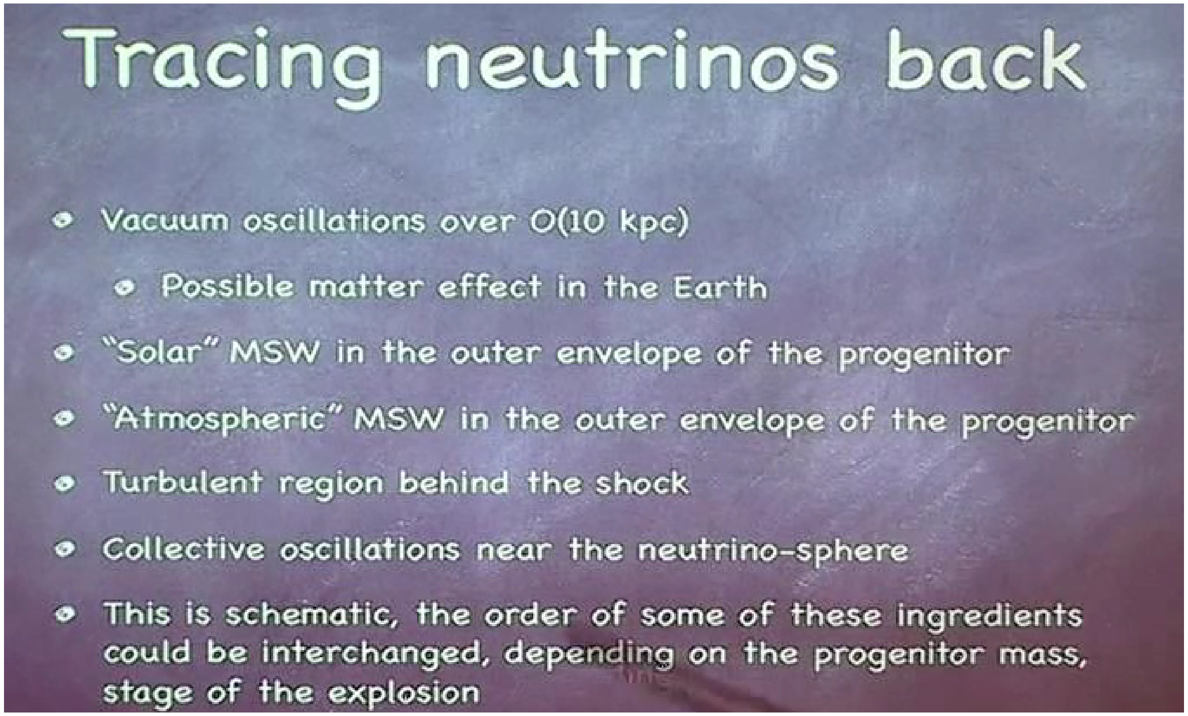
Leptogenesis

- P. Di Bari, S. Pascoli, R. Mohapatra talks
- Elegant idea
- High scale seesaw
  - In general, too many parameters to determine from low energy
  - Specific flavor schemes can lead to constraints/predictions for low scale neutrino physics
    (e.g., NH with $|\sin\theta_{13}\sin\delta| > 0.11$ (Pascoli et al))
- Alternatives: low-scale seesaw; electroweak baryogenesis (new TeV-scale physics), Affleck-Dine (color-charge breaking in early universe), . . .

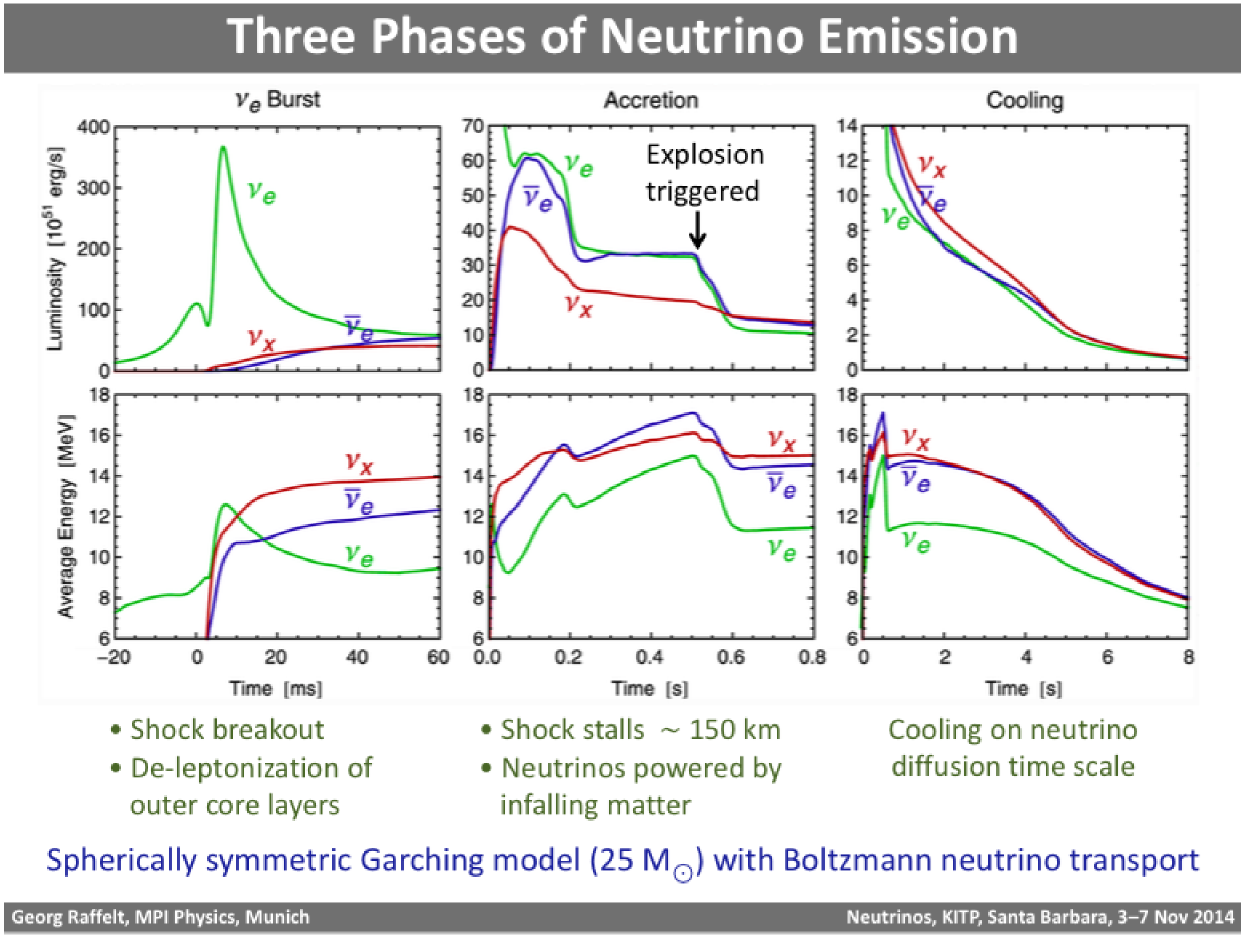
Core collapse supernovae

- **Talks by C. Fryer, A. Friedland, K. Scholberg, G. Raffelt**

- **Tremendous amount of ν physics, supernova dynamics, and other physics (cf 1987A)**



(Friedland talk)

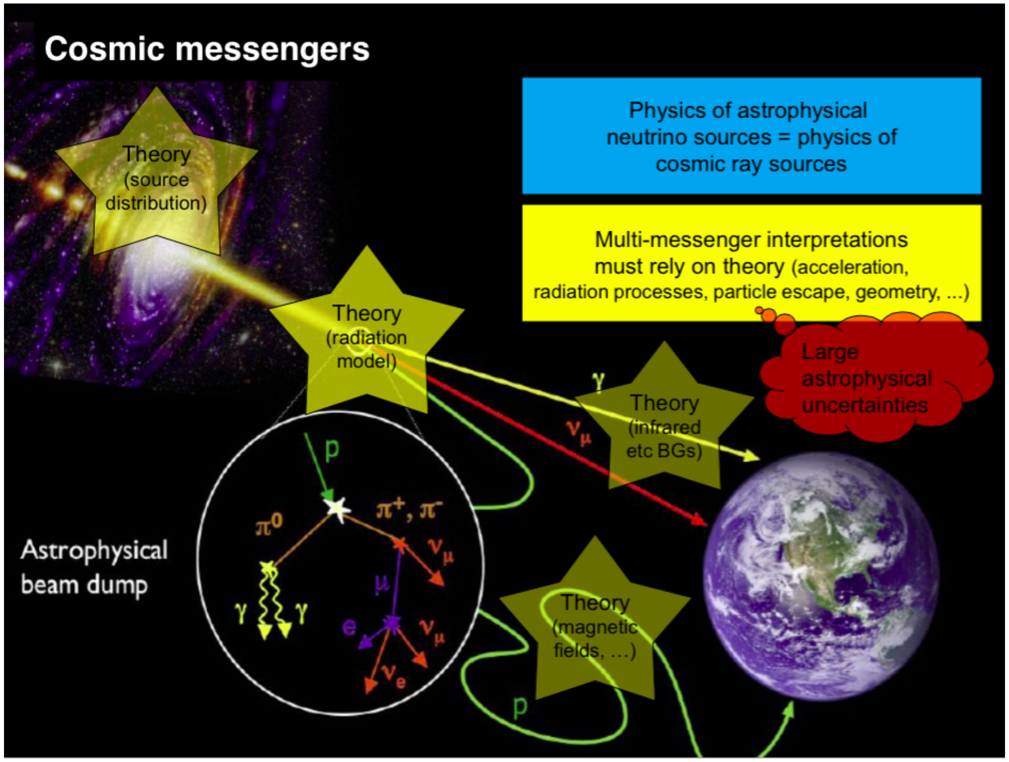


- **However, incompetent scheduling committee**

- **Need detectors to run for many years; supernova watch**

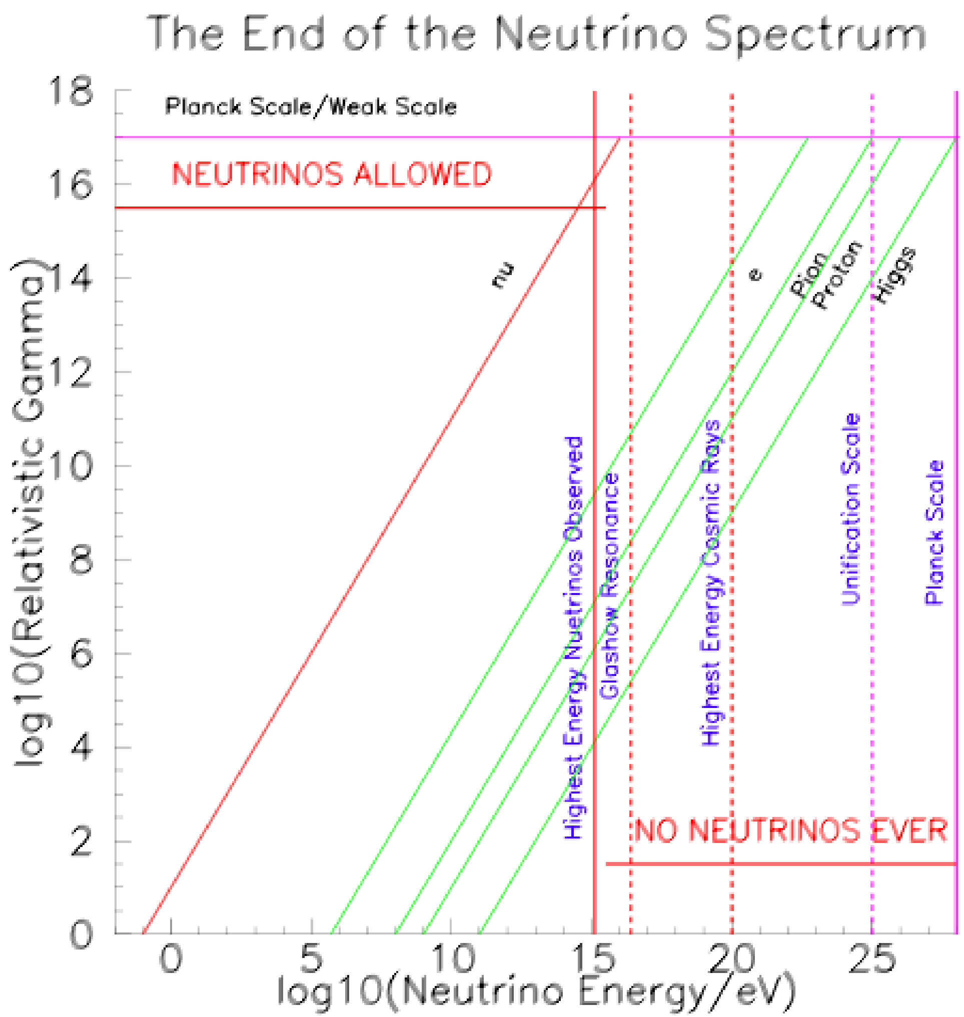
Cosmic neutrinos

- **Talks by F. Halzen, C. Kopper, W. Winter, T. Weiler**



(Winter talk)

- **IceCube: $36(+1)$ events with $50 \lesssim E_\nu \lesssim 2000$ TeV** (2 PeV)
- **Not GZK** ($p + \gamma_{CMB} \to \Delta^+ \to \pi^+ n$)**, GRB, atm, μ**
- **Sources unknown** (AGN?, starburst galaxies?)
- **Need directions, spectral shapes, flavors, anisotropies; consistent study with p and γ** (Winter)
- **Why no events above 2 PeV? Why no Glashow resonance** ($\bar{\nu}_e e^- \to W^-$ at 6.3 PeV)**?** (Weiler)
  - **Fluctuation?**
  - **Stabilization of π and n above 10^{15} eV** (LIV)



(Learned and Weiler, 1407.0739)

Conclusions

- Neutrinos are interesting and important on scales from 10^{-33} to 10^{+28} cm

- Thanks to Graciela, Danny, Sandip, the KITP, and the KITP staff