Large Extra Dimensions and Hot Dark Matter

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Neutrino mass-mixing scheme for all oscillation data
LSND/KARMEN favored regions for hot dark matter
Neutrino scheme saves supernova nucleosynthesis
Solar neutrinos and extra large dimensions
Neutrino Mass Schemes

Hints of neutrino mass 8 years ago

Solar $\nu_e$ deficit
Atmospheric $\nu_\mu/\nu_e$ discrepancy
Cold+hot dark matter

Compatible neutrino schemes 1/93 Moriond; D.C., R. Mohapatra '93

(A) $m_{\nu_e} \approx m_{\nu_\mu} \approx m_{\nu_\tau}$, sharing dark matter (sol. $\nu_e \rightarrow \nu_\mu$, atm. $\nu_\mu \rightarrow \nu_\tau$)
(B) solar $\nu_e \rightarrow \nu_s$; atm. $\nu_\mu \rightarrow \nu_\tau$; HDM: $m_{\nu_\mu} \approx m_{\nu_\tau}$ J. Peltoniemi, J. Valle '93

Newer inputs

LSND ($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$) rules out (A) and requires (B)

Supernova nucleosynthesis

If $\Omega_m \ll 1$, HDM is apparently unimportant
Evidence for $\nu_s$: Heavy-Element Nucleosynthesis

Rapid neutron capture (supernova r process)

- Occurs far outside the neutron star at late time ($\sim 10^5$)
- Needs very neutron-rich region ($\nu_e n \rightarrow p e^- \text{ vs. } \nu_e p \rightarrow n e^+$)

Problem if LSND MSW region is inside r region

- Thermal $\nu_e$ have $\langle E \rangle \approx 11$ MeV, but $\nu_\mu$ have $\langle E \rangle \approx 25$ MeV
- If $\nu_\mu \rightarrow \nu_e$, high-energy converted $\nu_e$ have larger $\sigma \sim E^2$
- $\nu_e n \rightarrow p e^-$ depletes neutrons, stopping the r process

Sure problem: models give too few neutrons in r region

- Too few neutrons per seed nucleus (e.g., Fe)
- Need $\sim 10^2 n/\text{"Fe}^-$ to make the heaviest elements

Fatal problem: $\alpha$ effect kills the r process

- All protons form $\alpha$'s, removing neutrons
- More neutrons removed by $\nu_e n \rightarrow e^- p$, so $p \rightarrow \alpha$, etc.
Solving the Problems

What is needed

Large $\nu_e$ flux to eject baryons near the neutron star
Near removal of $\nu_e$ flux farther out where $\alpha$'s form

Neutrino features to accomplish this

Existence of at least one light sterile neutrino
Near-maximally-mixed $\nu_\mu-\nu_\tau$
Small but $>10^{-4}$ $\nu_\mu-\nu_e$ mixing
Two neutrino doublets well separated ($\geq 2\text{eV}^2$)

Exactly model needed for solar, atmospheric, LSND, HDM
Problem-Solving Mechanism

First level crossing: $\nu_\mu, \tau \rightarrow \nu_5$

Gets rid of dangerous high-energy $\nu_\mu, \tau$

Near radius where $V(\nu_\mu, \tau) \propto (n_{\nu_e} - n_n/2) \rightarrow 0$

Second level crossing: $\nu_e \rightarrow \nu_\mu, \tau$

LSND MSW region now not $\nu_\mu, \tau \rightarrow \nu_e$, since few $\nu_\mu, \tau$

Outside neutron star but inside weak freezeout radius

Needed density puts a requirement on $\Delta m^2_{\nu_e, \nu_\mu, \tau} \geq 2eV^2$

Two resonances are close, so coherence + maximal mixing gives

$\text{Prob.}(\nu_\mu \rightarrow \nu_\mu) = 1/4$, $\text{Prob.}(\nu_\mu \rightarrow \nu_\tau) = 1/4$, $\text{Prob.}(\nu_\mu \rightarrow \nu_5) = 1/2$

$\text{Prob.}(\nu_\tau \rightarrow \nu_\tau) = 1/4$, $\text{Prob.}(\nu_\tau \rightarrow \nu_\mu) = 1/4$, $\text{Prob.}(\nu_\tau \rightarrow \nu_5) = 1/2$

$\text{Prob.}(\nu_5 \rightarrow \nu_e) = 0$, $\text{Prob.}(\nu_\tau \rightarrow \nu_e) = 0$, $\text{Prob.}(\nu_e \rightarrow \nu_e) = 0$

$r$-process problems are solved!
Atmospheric $\delta m^2_{\mu-\tau} \sim 10^{-2}\text{eV}^2$

$\nu_\mu$ \hspace{1cm} $\nu_\tau$

LSND $\delta m^2_{\text{doublets}}$

MSW $\nu_s \hspace{1cm} \nu_e$

$\delta m^2_{\text{se}} \leq 10^{-5}\text{eV}^2$

Solar $\delta m^2_{e-s} \sim 10^{-10}\text{eV}^2$

$\nu_s \hspace{1cm} \nu_e \hspace{1cm} \text{V.O.}$
Relevance of the Solar Neutrino Deficit

Measurements to test MSW or vacuum oscillations (V.O.)

Rates: GALLEX+SAGE (>0.23 MeV), Cl (>0.81), SuperK (>6.5)

Energy spectrum in SuperK (looks like V.O.)

Day-Night (MSW only, but measured effect is small)

Seasonal: indication, favoring V.O.

Nothing fits well for $\nu_e \rightarrow \nu_x$ or $\nu_e \rightarrow \nu_s$

$\nu_s$ seems required, so how can $\nu_e \rightarrow \nu_s$ work?

MSW (small-angle only) gives a poor fit

V.O. fits energy spectrum, seasonal variation well

V.O. does not fit rates of all 3 types of experiments

Increase Cl by 1.3 (3.4$\sigma$) and V.O. works ($\nu_e \rightarrow \nu_s$ or $\nu_e \rightarrow \nu_x$)

Berezinsky, Fiorentini, and Lissia
Super-Kamiokande fit to V.O.

Other V.O. fit

Above V.O. fit

Small-$\Delta$ MSW

Large-$\Delta$ MSW
Possible Effect of Extra Dimensions

Not usual $\nu_s$ for extra dimensions of size $R$

$\nu_s$ is a bulk state with other $\nu$'s on a brane

$\nu_s$ has Kaluza-Klein (K-K) higher mass states ($m_n \approx \frac{n}{R}$)

Dienes, Dudas, Gherghetta; Arkani-Hamed, Dimopoulos, March-Russell

Dvali, Smirnov; Das, Kong; Mohapatra, Nandi, Pérez-Lorenzana

For ground-state $\nu_s$ having $m_{\nu_s} \approx m_{\nu_e}$, get V.O.

But limit on $R$ puts K-K states in the MSW region

Can choose $R$ to suppress CI relative to Ga, Super-K

It is possible to fit all the solar neutrino data

R.N. Mohapatra, S.J. Yellin
Conclusions

4-ν scheme required by all ν oscillations and r process
Since ν{s} is needed, have to fit solar ν{e} data
There is a good fit to all ν data if ν{s} is a bulk neutrino
A strong hint for large extra dimensions
Indicates appreciable hot dark matter