The Hot Dark Matter Conundrum

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One- and three-neutrino hot dark matter

Two-neutrino dark matter with 4 neutrinos

The astrophysical paradox: universe structure

Important new input from LSND and KARMEN

Corroberation from supernova nucleosynthesis

Bad News for Neutrino Dark Matter?

One-neutrino dark matter $\sum m_{\nu_i} = 93\,\Omega_\nu h^2$

ν_τ is the most likely candidate (solar: $\nu_e \to \nu_\mu$)

CHORUS and NOMAD do not see $\nu_\mu \to \nu_\tau$

Atmospheric ν_μ/ν_e likely due to $\nu_\mu \to \nu_\tau$ with $\Delta m^2 \sim 10^{-3}\,\mathrm{eV}^2$

Not $\nu_\mu \to \nu_e$: CHOOZ $\nu_e \to \nu_i$; Super-K ∠ distributions

$\nu_\mu \to \nu_s$ (sterile) unlikely: nucleosynthesis limit

$\nu_\mu \to \nu_\tau$ fits Super-K data best **(would kill 1-ν_τ DM)**

Three-ν dark matter (D.O.C.+R.Mohapatra, Phy. Rev. '93; rediscoveries)

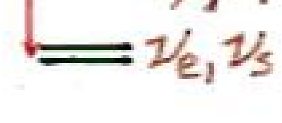
$\nu_\mu \to \nu_\tau$ (atm.), $\nu_\mu \to \nu_e$ (solar); $m_{\nu_e} \approx m_{\nu_\mu} \approx m_{\nu_\tau} \sim 1.5$ eV

$\beta\beta_{0\nu}$ presents difficulties for Majorana ν **(LSND kills it)**

Two-ν dark matter (also D.O.C.+R. Mohapatra '93; J. Peltoniemi +J. Valle)

$\nu_\mu \to \nu_\tau$ (atm.), $\nu_e \to \nu_s$ (solar); m_{ν_e}, m_{ν_s} light; $m_{\nu_\mu} \approx m_{\nu_\tau} \sim 2.3$ eV

Since '93, $\bar{\nu}_\mu \to \bar{\nu}_e$ (LSND)



Universe Structure and Neutrino Dark Matter

Fit to all published CMB, galaxy survey data

E. Gawiser and J. Silk used 10 models [Science 280, 1405, '98]

Covers 3 orders of magnitude in spatial scale

Only one model fits: $\Omega_m = 1$, $\Omega_\nu = 0.2$, $\Omega_{bar} = 0.1$

Most more direct measurements give $0.2 \leq \Omega_m \leq 0.5$

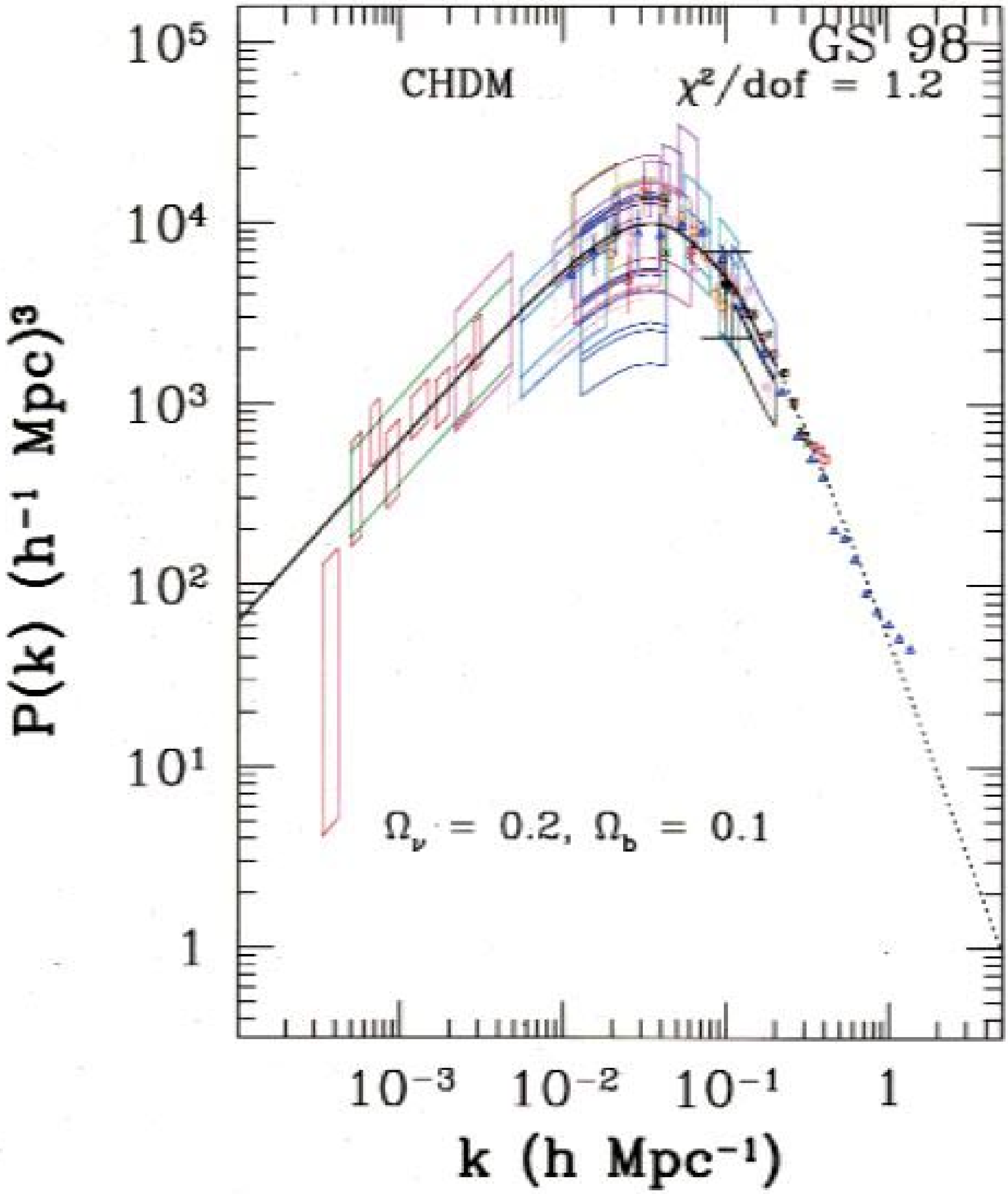
Will conflict remain with more precise data coming soon?

Conclusion now: low Ω_m and $\Omega_m + \Lambda$ models don't work

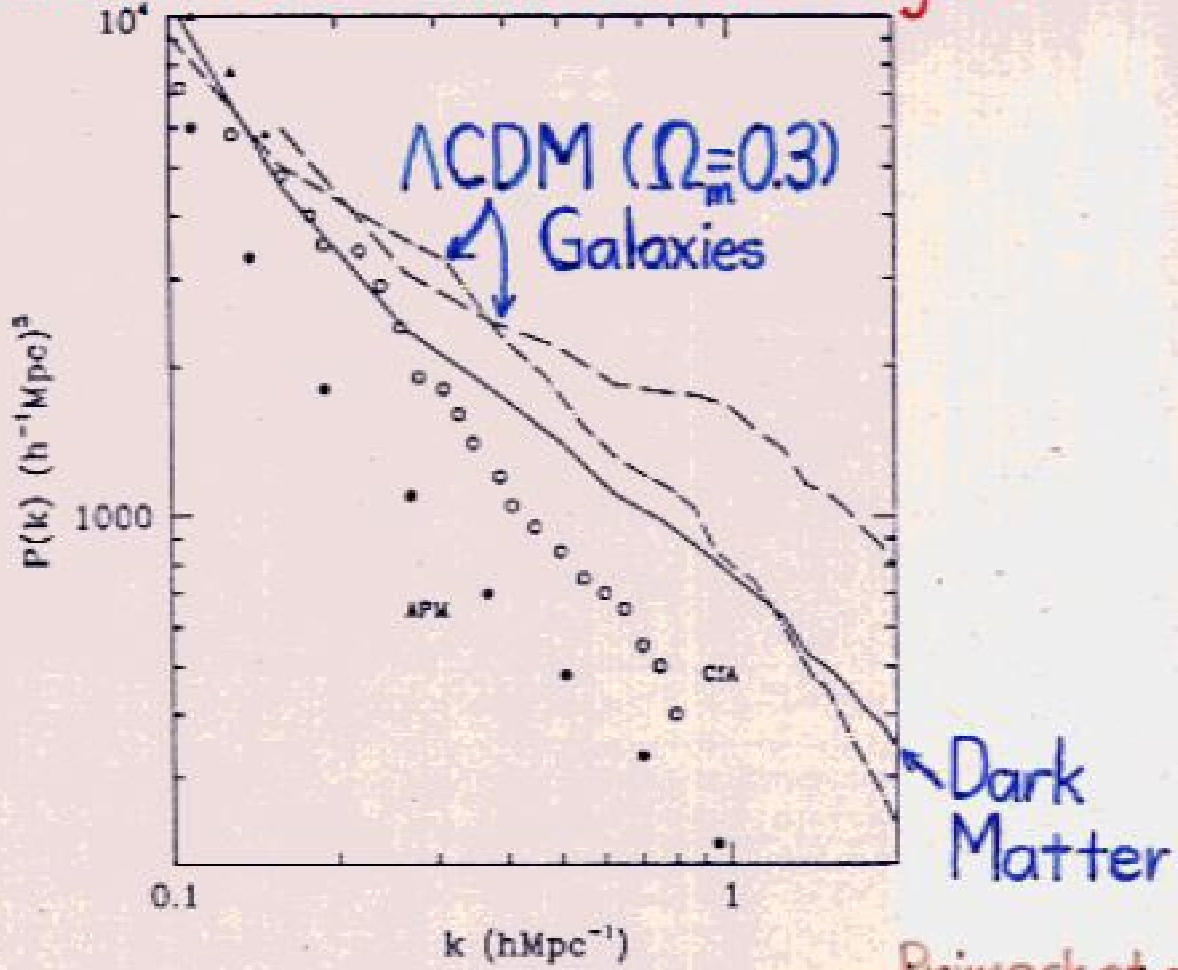
Neutrinos help, but not enough (Primack and Gross)

	All		No APM Clusters	
Model	$\chi^2/70$	Probability	$\chi^2/62$	Probability
Standard CDM	3.8	$<10^{-7}$	3.7	$<10^{-7}$
Tilted CDM	2.1	1.8×10^{-7}	2.0	1.1×10^{-5}
Hot + CDM	1.2	0.09	1.06	0.34
Ω=0.5 CDM	1.8	2.9×10^{-5}	1.67	6.7×10^{-4}
Λ+CDM	1.9	1.1×10^{-5}	1.71	4.3×10^{-4}
Late ϕ+CDM	2.2	$<10^{-7}$	2.0	3.8×10^{-6}
Λ=0.88+BCDM	7.3	$<10^{-7}$	7.7	$<10^{-7}$
Isocurv. CDM	2.5	$<10^{-7}$	2.5	$<10^{-7}$
PBH BDM	2.0	8.3×10^{-7}	1.9	1.4×10^{-5}
Strings+Λ	2.6	$<10^{-7}$	2.6	$<10^{-7}$

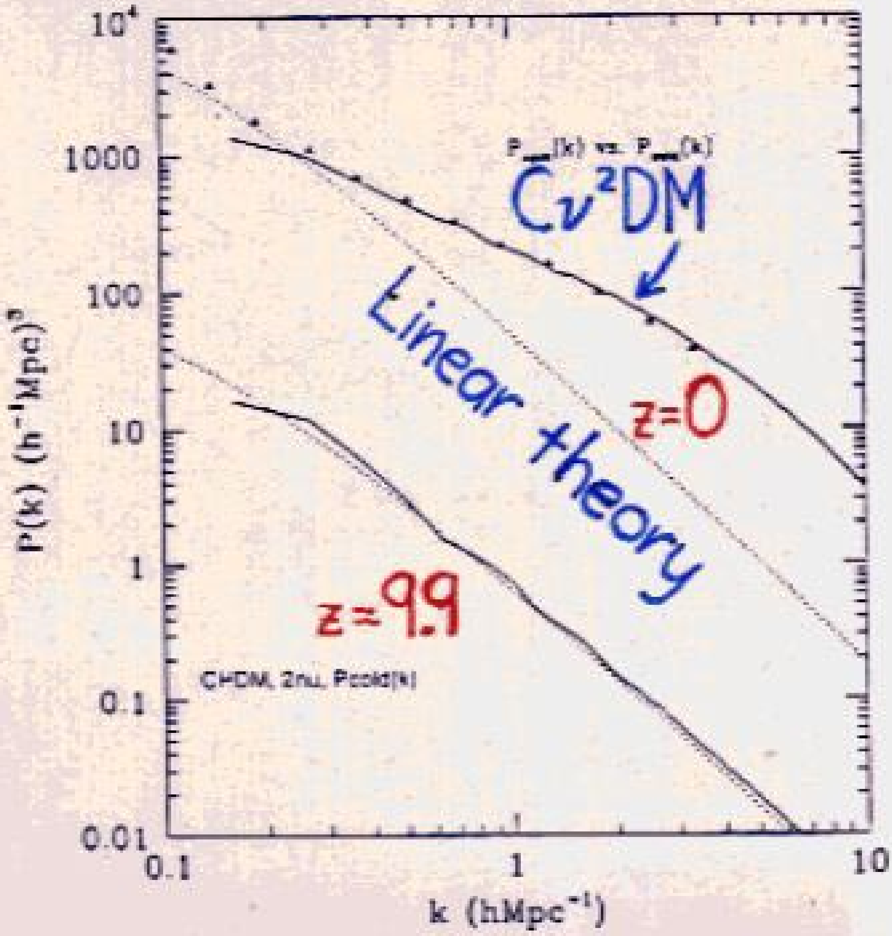
Uses H_0=65±15 km/s Mpc; cf. Nevalainen, Roos 68±5; Tammann 57±7


GS 98
CHDM
$\chi^2/\mathrm{dof} = 1.2$
$\Omega_\nu = 0.2,\ \Omega_b = 0.1$
10^5
10^4
10^3
10^2
10^1
1
10^{-3}
10^{-2}
10^{-1}
1
$P(k)\ (h^{-1}\ \mathrm{Mpc})^3$
$k\ (h\ \mathrm{Mpc}^{-1})$

Simulations for the Nonlinear Region



Primack et al.

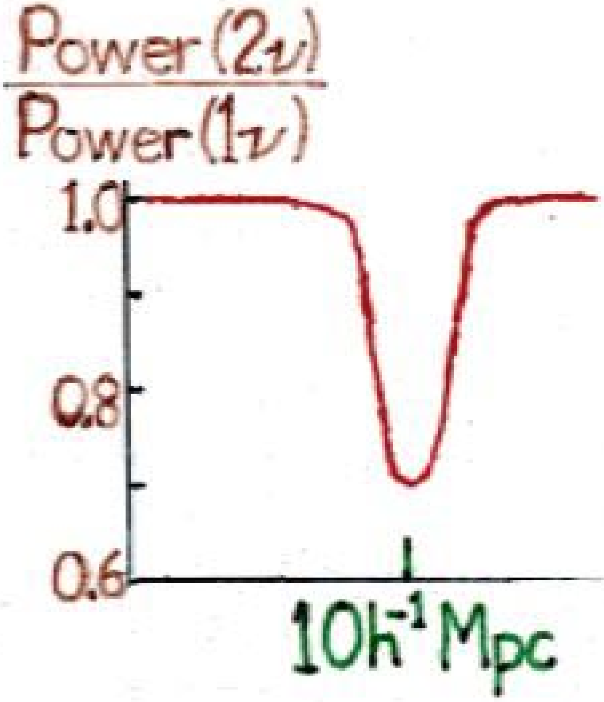


2ν Better than 1ν Dark Matter

Problems of 1ν dark matter at $\sim 10h^{-1}$ Mpc

- Galaxy clusters overproduced
- Galaxy pairwise velocities too low
- Void regions incorrect

2ν increased streaming length solves these



Primack, Holtzman, Klypin, D.O.C. '95

Can $\Delta m^2_{e,\mu}$ be Big Enough for Hot Dark Matter?

Past comparisons of LSND with other experiments

LSND's "likelihood" vs. others' confidence levels

Typical values: 90% likelihood (-2.3 LLU) → 90% C.L. (-3.3 LLU)

KARMEN (ν98): no events "excluded" LSND (Feldman-Cousins)

Now have ~8 events, about the expected background

Joint LSND/KARMEN analysis (Eitel, Yellin)

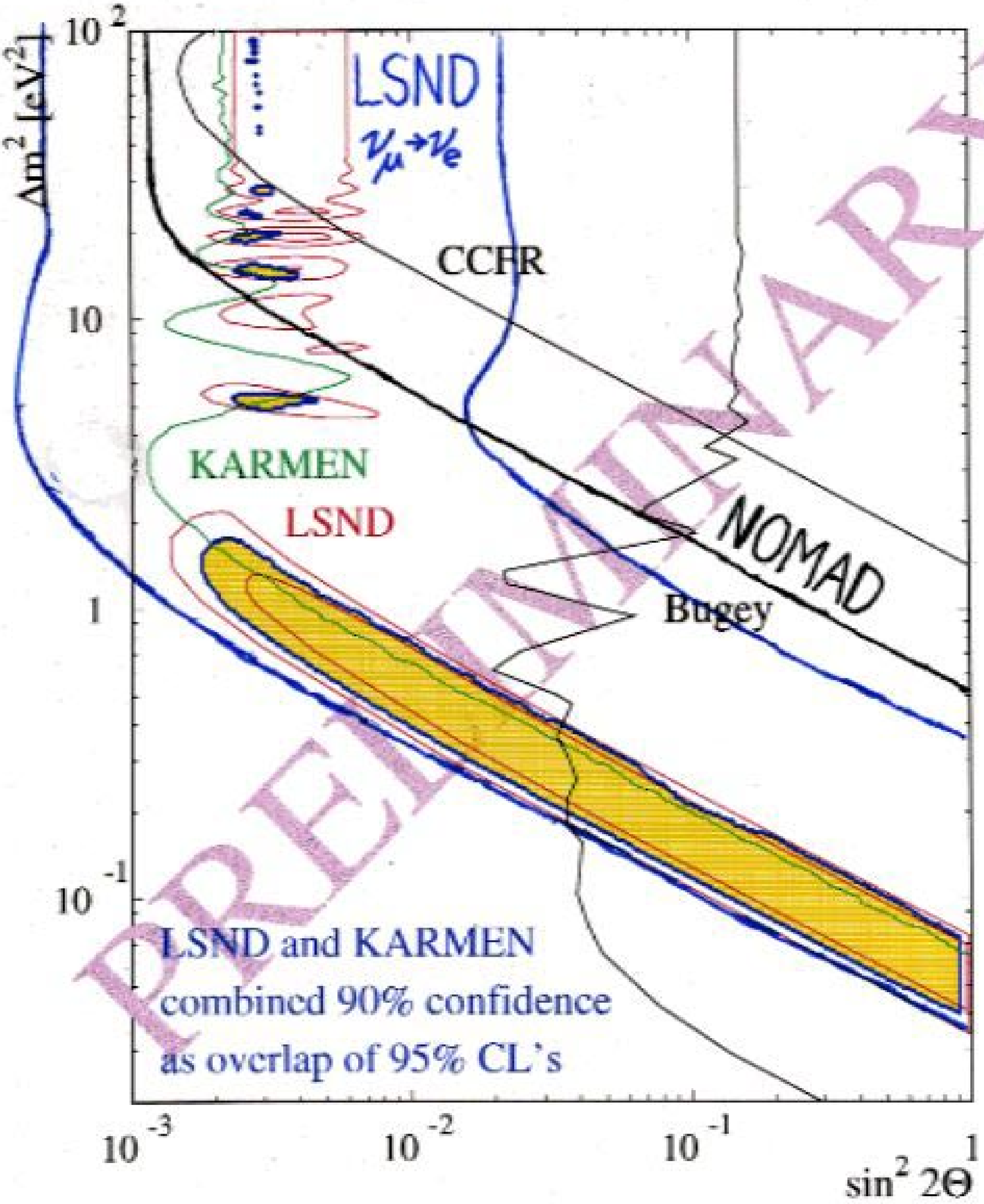
Overlap of 95% C.L.'s to give joint 90% (at IS/OS II)

Better method (adding likelihoods) emphasizes ~6 eV^2

LSND's $\nu_\mu \to \nu_e$ favors this region

Coming: more KARMEN data, better LSND analysis

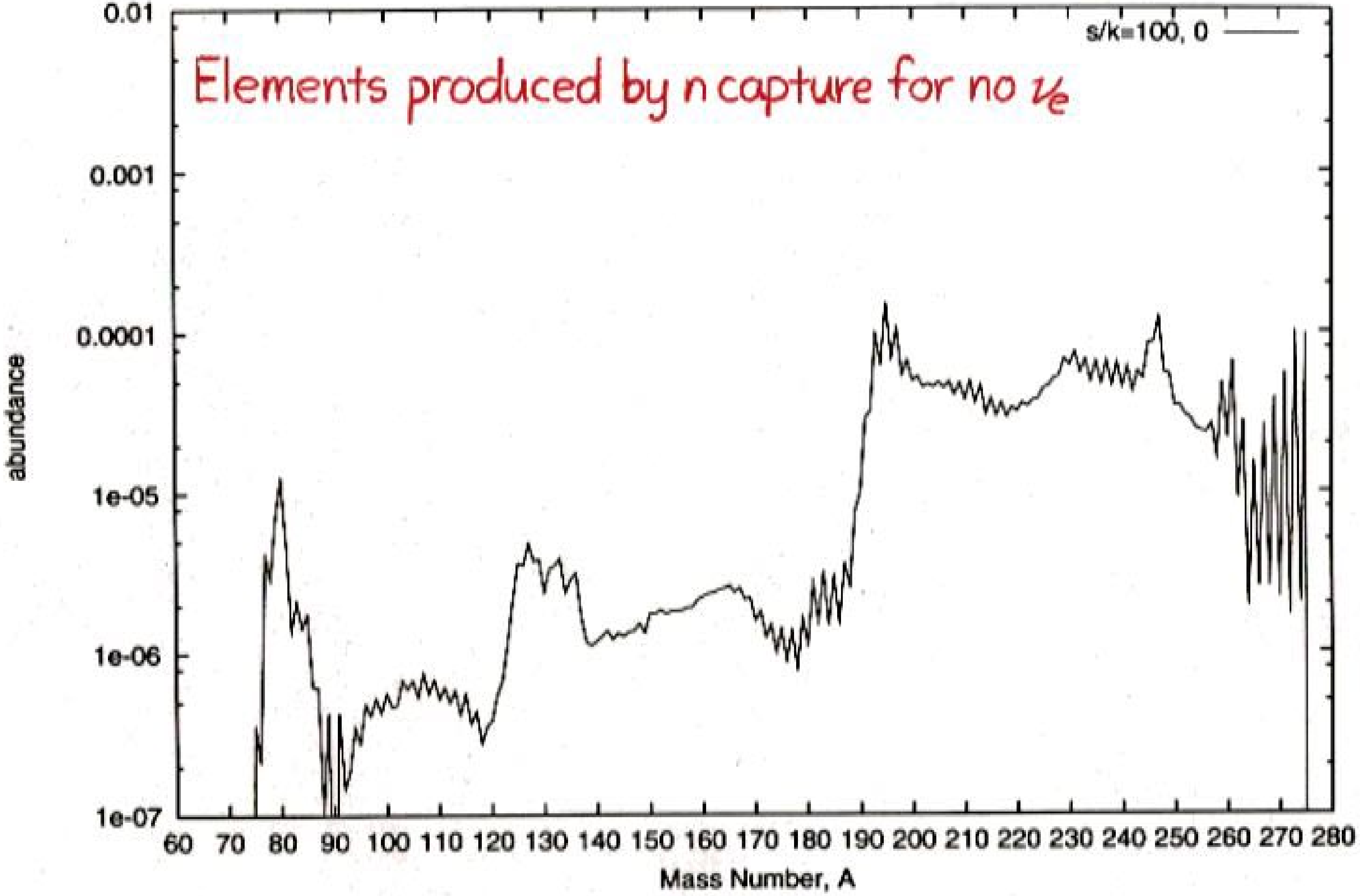
Later: MiniBooNE, I216 (?)



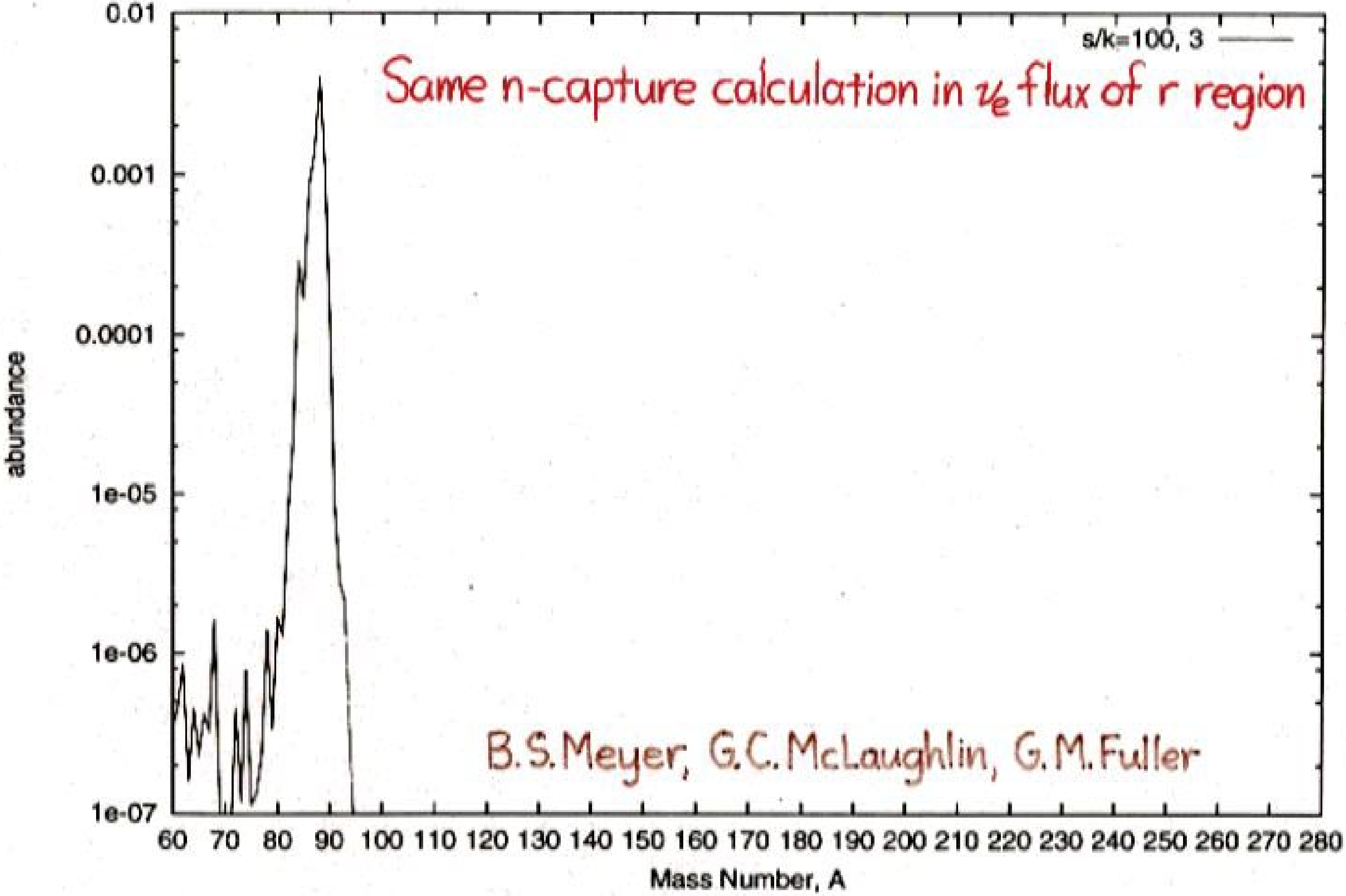
Δm^2 [eV^2]
10^2
10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\Theta$
LSND
$\nu_\mu \to \nu_e$
CCFR
KARMEN
LSND
NOMAD
Bugey
LSND and KARMEN
combined 90% confidence
as overlap of 95% CL's
PRELIMINARY

Evidence for ν_s: Heavy-Element Nucleosynthesis

- Rapid neutron capture (supernova r process)
  - Occurs far outside the neutron star at late time (~10s pb)
  - Needs very neutron-rich region ($\nu_e n \to p e^-$ vs. $\bar{\nu}_e p \to n e^+$)
- Problem if LSND MSW region is inside r region
  - Thermal ν_e have $\langle E \rangle \approx 11$ MeV, but ν_μ have $\langle E \rangle \approx 25$ MeV
  - If $\nu_\mu \to \nu_e$, high-energy converted ν_e have larger $\sigma \sim E^2$
  - $\nu_e n \to p e^-$ 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/"Fe" to make the heaviest elements
- Fatal problem: α effect kills the r process
  - All protons form α's, removing neutrons
  - More neutrons removed by $\nu_e n \to e^- p$, so $p \to \alpha$, etc.



Elements produced by n capture for no ν_e



Same n-capture calculation in ν_e flux of r region

B.S.Meyer, G.C.McLaughlin, G.M.Fuller

Solving the Problems

What is needed

Large ν_e flux to eject baryons near the neutron star

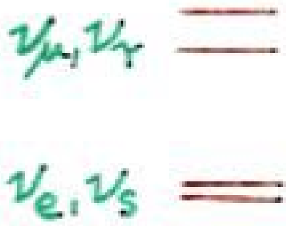
Near removal of ν_e flux farther out where α's form

Neutrino features to accomplish this

Existence of at least one light sterile neutrino

Near-maximally-mixed ν_μ-ν_τ

Small ν_μ-ν_e mixing



Two neutrino doublets well separated ($\gtrsim 2 eV^2$)

Exactly model needed for solar, atmospheric, LSND, HDM!

Problem-Solving Mechanism

First level crossing: $\nu_{\mu,\tau} \rightarrow \nu_s$ D.O.C, G.M.Fuller, Y.-Z.Qian

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 $\Delta m^2_{e,(\mu,\tau)}$

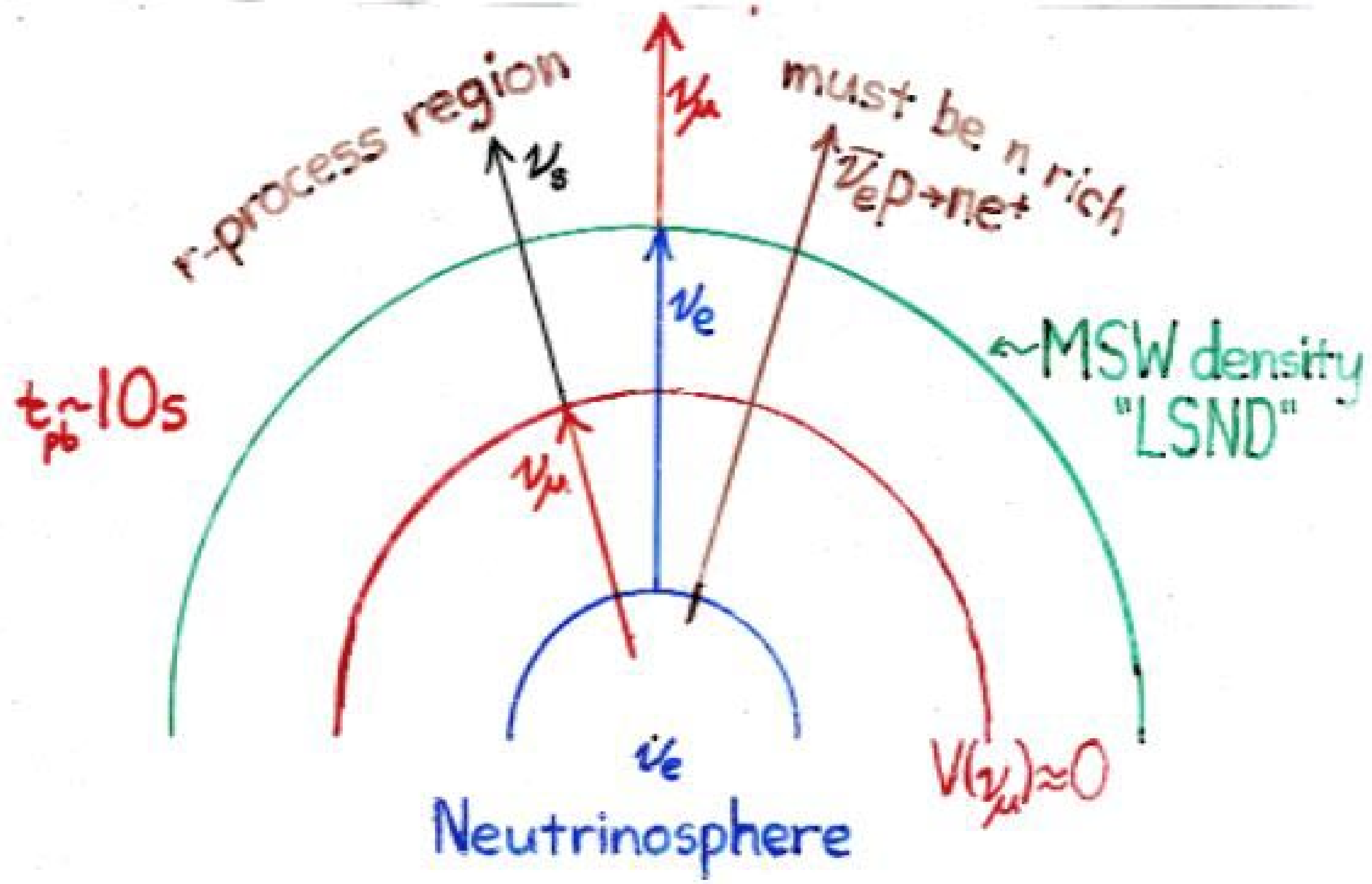
Two resonances are close, so coherence + maximal mixing gives

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

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

$\mathrm{Prob.}(\nu_\mu \rightarrow \nu_e) = 0$, $\mathrm{Prob.}(\nu_\tau \rightarrow \nu_e) = 0$, $\mathrm{Prob.}(\nu_e \rightarrow \nu_e) = 0$

r-process problems are solved!


r-process region
ν_μ
ν_s
must be n rich
$\bar{\nu}_e p \to n e^+$
ν_e
~MSW density
"LSND"
$t_{pb} \sim 10s$
ν_μ
ν_e
$V(\nu_\mu) \approx 0$
Neutrinosphere

Astrophysical Need for Large $\Delta m^2_{\mu e}$

5.5 eV^2 region gives desired 15-20% hot dark matter

$\Sigma m_{\nu_i} = 2 \times 2.35 = 4.7\,eV$ and $\Omega_\nu = \frac{4.7}{93h^2}$

If $\Omega_m = 1$, $h = 0.55$, then $\Omega_\nu = 0.17$

If $h = 0.65$, then $\Omega_\nu = 0.12$, or 20% of $\Omega_m = 0.6$

Supernova nucleosynthesis needs resonances ordered

$\nu_\mu \rightarrow \nu_s$ inside of $\nu_\mu \rightleftarrows \nu_e$ and both inside of WFO radius

Density variation with radius sets $\Delta m^2_{\mu e}$

$\sim 6\,eV^2$ is ideal

New Astrophysical Inputs

Doubts about the distance scale

Geometric measurement to galaxy NGC4258 (H_2O maser)

Disagrees with Cepheid ladder by 15-20%

Shorter universe age would agree with Ω_m=1, not 0.3

Doubts about Supernova Ia determination of Ω_m, Λ

Possibilities of dust or evolution

Close SN take $\gtrsim$2 d. longer for peak brightness than far SN

May not be a true standard candle

Measurements in next few years should settle issues

Distance from Space Interferometry Mission (2005)

MAP, Planck, Sloan Digital Sky Survey → # ν's, m_ν

Conclusions

- Hot dark matter is most likely 2ν $(\nu_\mu + \nu_\tau)$
  - 1ν dark matter ruled out if atmospheric $\nu_\mu \to \nu_\tau$
  - If correct, LSND rules out 3ν dark matter
  - r-process nucleosynthesis works with this 4ν scheme
- $\Omega_m = 1$, $\Omega_\nu \approx 0.2$ fits universe structure
  - 2ν dark matter works better than 1ν $(\nu_\mu + \nu_\tau \sim 5\,\mathrm{eV})$
  - If $\Omega_m \lesssim 0.5$, just CDM or CDM+Λ does not work
  - Conflict with low-Ω_m results needs new $\left\langle \begin{matrix}\text{measurements}\\ \text{physics}\end{matrix} \right.$?