

Massive neutrinos in Astrophysics and Cosmology

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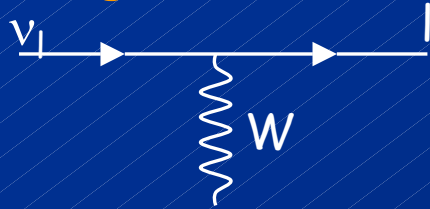
Outline

- Neutrino masses and mixing
- Neutrinos and the Sun
- Neutrinos in the Cosmos:
BBN, CMB and LSS

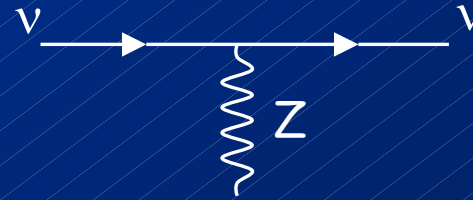
In the standard model:

- Neutrinos are **neutral**, **massless** fermions. They interact with quarks and leptons via weak interactions:

Charged currents (CC)



Neutral currents (NC)



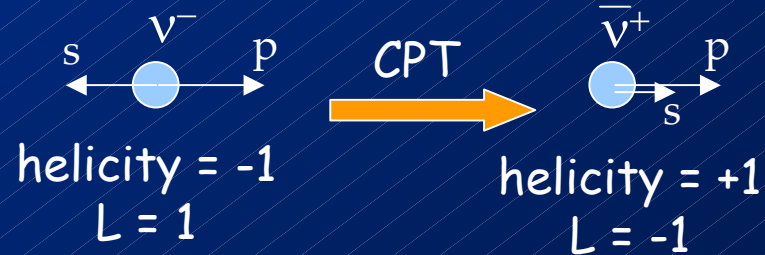
$$\mathcal{L}_I^{\text{CC}} = -\frac{g}{2\sqrt{2}} j_\rho^{\text{CC}} W^\rho + \text{h.c.}$$

$$\mathcal{L}_I^{\text{NC}} = -\frac{g}{2 \cos \theta_W} j_\rho^{\text{NC}} Z^\rho.$$

$$j_\rho^{\text{CC}} = 2 \sum_{l=e,\mu,\tau} \bar{\nu}_{lL} \gamma_\rho l_L + \dots$$

$$j_\rho^{\text{NC}} = \sum_{l=e,\mu,\tau} \bar{\nu}_{lL} \gamma_\rho \nu_{lL} + \dots$$

Weak currents are left handed:



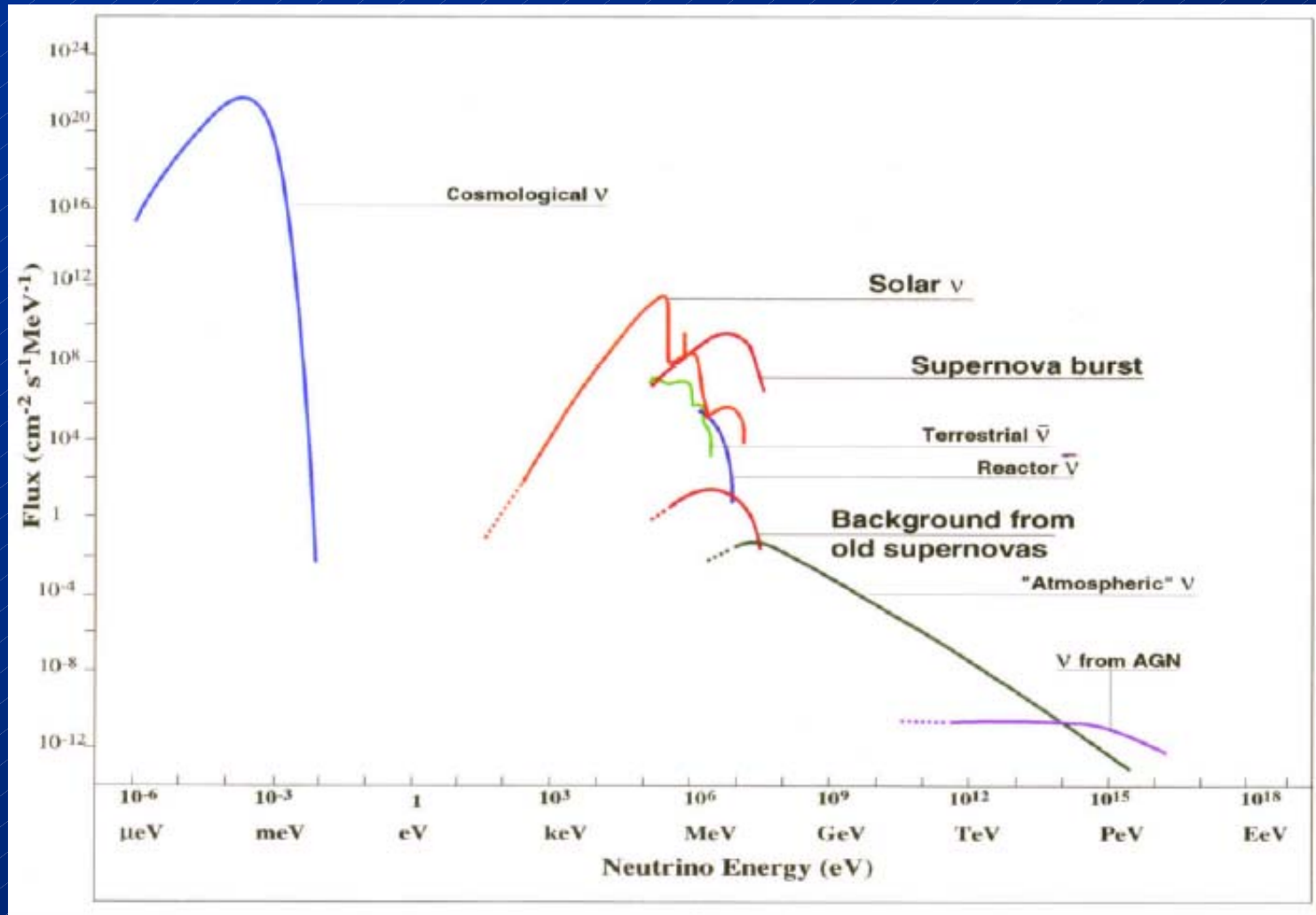
- Lepton Number (L) is conserved.
- Family lepton numbers (L_α) are conserved.

The number of **active** neutrinos can be determined with high accuracy from the decay width of the Z bosons:

$$N_\nu = 2.994 \pm 0.012$$

Neutrinos in nature

Neutrinos are produced in several different contexts:



Basic questions about (massive) neutrinos

- How small are neutrino masses?

β decay endpoint,
Cosmic neutrinos (CMB, LSS, etc.)
 0ν double-beta decay,

- Can ν transform into anti- ν ?

0ν double-beta decay, ...

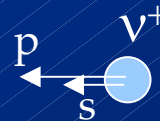
If neutrinos are massive:

$$v < c$$



helicity = -1

Lorenz Boost
→



helicity = +1

$$\nu^+ = \bar{\nu}^+$$

Majorana

L = not conserved

$$\nu^+ \neq \bar{\nu}^+$$

Dirac

L = conserved

For a simple introduction - Kaiser, Comm. Nuc.Part. Phys. 198

- Can ν_α transform (oscillate) into ν_β ?

Solar and reactor ν s

Atmospheric and accelerator ν s, ...

Flavor eigenstates (ν_α) may not coincide with mass eigenstates (ν_i):



Neutrino oscillations

Neutrino propagation is described in the flavor basis by:

$$i \frac{\partial}{\partial t} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = H \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$H = H_{\text{free}} + V \longrightarrow \text{Neutrino matter potentials: } V \approx G_F N_{\text{target}}$$

ν are ultra-relativistic:
 $H_{\text{free}} = (P^2 + m^2)^{1/2} \approx P + m^2/2E$

ν -oscillations are consequence of ν -mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \dots \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \dots \end{pmatrix}$$

U = unitary matrix

N_ν larger than 3 \leftrightarrow ν_{sterile}

$$H = P + U \frac{M^2}{2E} U^\dagger + V \quad \text{Not diagonal in flavor basis}$$

$$M^2 = \text{diag}(m_1^2, m_2^2, m_3^2, \dots)$$

2 ν mixing:

$$U = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \longrightarrow$$

$$c_\theta = \cos(\theta); \quad s_\theta = \sin(\theta)$$

- In vacuum: $P_{\alpha\beta} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$ $\Delta m^2 = m_1^2 - m_2^2$
 L = oscillation baseline

- More complicated phenomenology in matter

Neutrino mixing

3ν mixing - no CP violation → U is real → 3 angles ($\theta_{12}, \theta_{13}, \theta_{23}$)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{12} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

Atmo ν, LBL accelerator ν
SBL reactor ν
Solar ν, LBL reactor ν

$\cancel{\phi}$, mass-mixing originating from Dirac mass term (1 $\cancel{\phi}$ phase - δ)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta}s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Superbeams, ν factories (???)

Majorana mass term (2 additional phases - φ_2, φ_3)

$$U \rightarrow U \cdot V \quad V = \begin{pmatrix} 1 \\ e^{\frac{i}{2}\varphi_2} \\ e^{\frac{i}{2}(\varphi_3+2\delta)} \end{pmatrix}$$

φ_2 and φ_3 not observable in oscillations. Important for $0\nu\beta\beta$ decay.

Basic questions about neutrinos ...

Majorana or Dirac ?

Masses - m_1, m_2, m_3

Mixing angles - $\theta_{12}, \theta_{13}, \theta_{23}$

CP phases - δ (φ_2, φ_3 if Majorana)

And, moreover,

Sterile neutrinos? Number of neutrino Flavors

Basic answers from neutrinos

- Neutrinos have a unique role in astrophysics and cosmology because of their peculiar properties:

Light and weakly interacting

allow to see deeper and earlier than photons

Unique probe for:

- stellar interiors (solar, stellar and SN neutrinos)
- earth interior (geo-neutrinos)
- star formation rates (SN relic neutrinos)
- early universe (cosmic neutrinos)
-

Very effective cooling/energy transfer mechanism

- SN explosions?
-

Non vanishing masses

Different cosmological behaviour with respect to

Relevant contribution to Dark Matter

Influence structure formation in the Universe

.....

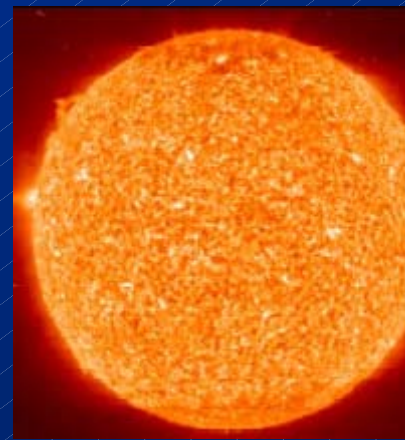
L violation, CP violation

Baryogenesis

.....

Solar Neutrinos

The Sun is powered by nuclear reactions transforming H into ${}^4\text{He}$:



$Q = 26,7 \text{ MeV}$ (globally)

Heat the plasma \rightarrow provide the pressure to balance gravitation

Emitted at the surface (photosphere) - Black body spectrum ($T \approx 6000 \text{ K}$)

heat diffusion time = $10^5\text{-}6$ years

Free stream - 8 minutes to reach the earth

Direct information on the energy producing region ($R \approx 0.1 R_\odot$)

Solar luminosity constraint

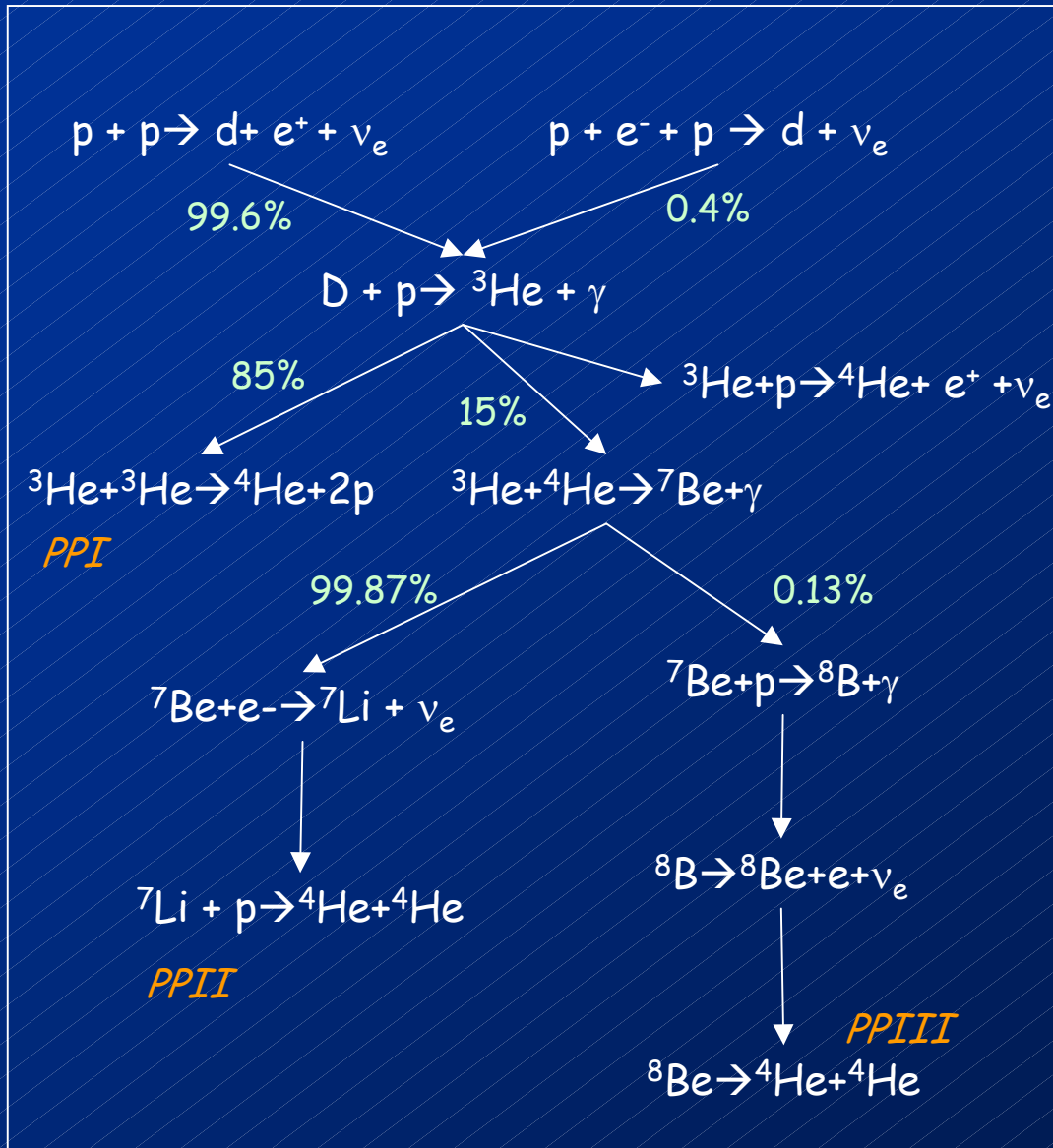
The total solar neutrino flux is directly related to the energy radiated by the sun:

$$\Phi_\nu \approx 2 K_\odot / Q = 6.4 \cdot 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$$

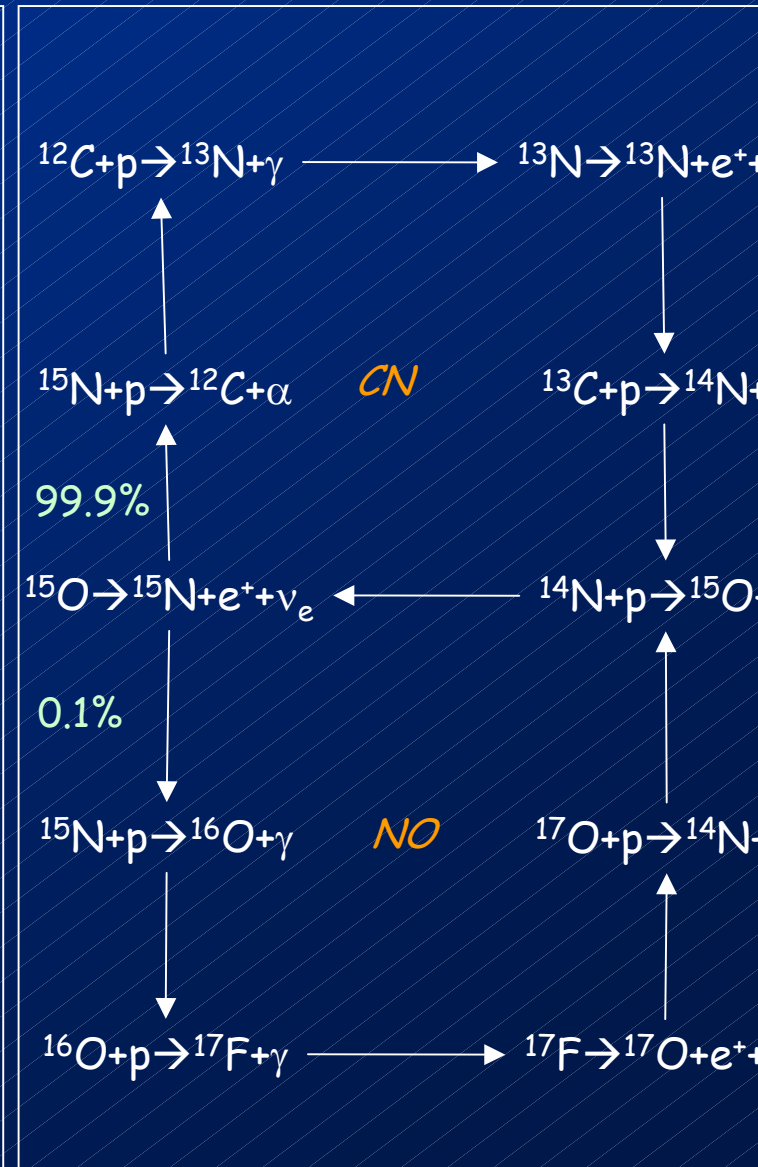
K_\odot = solar constant

Hydrogen Burning: PP chains and CNO cycle

PP chains - 98%

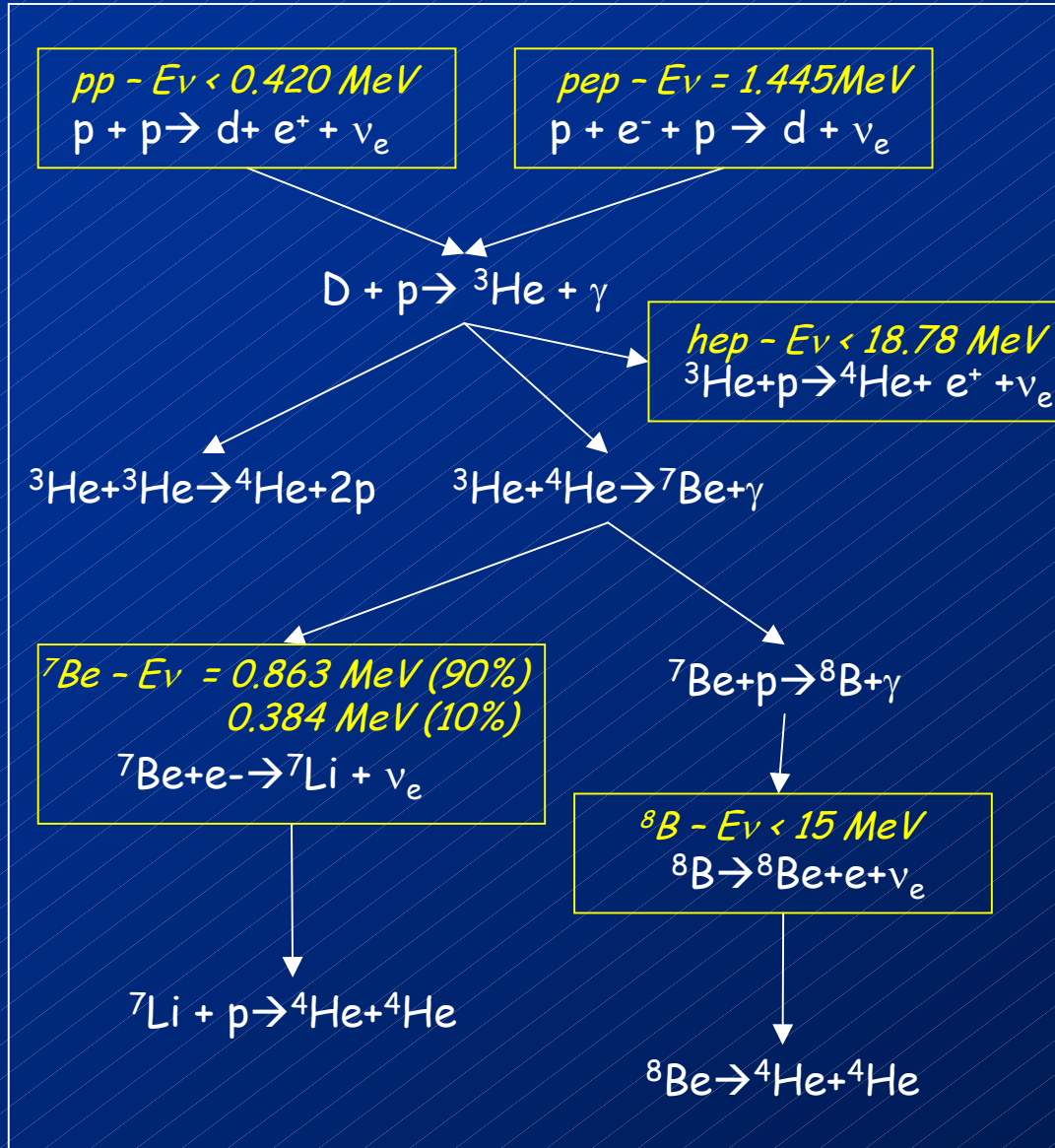


CN-NO bi-cycle - 2%

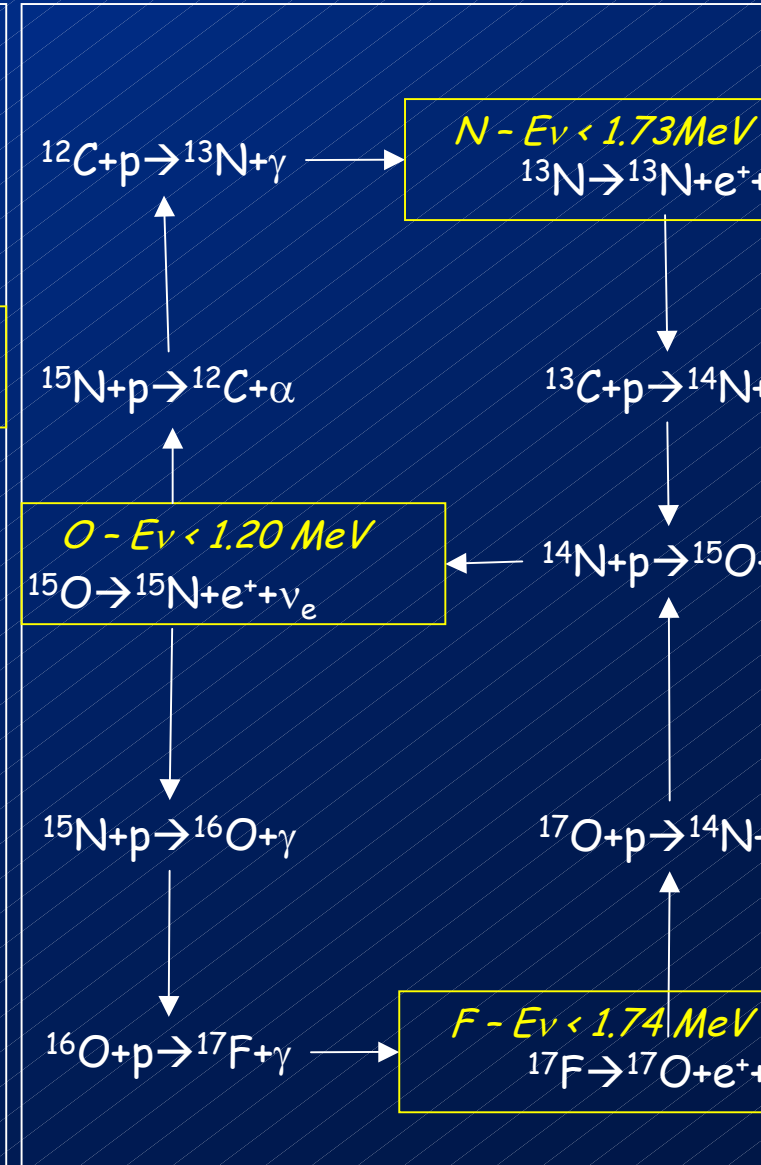


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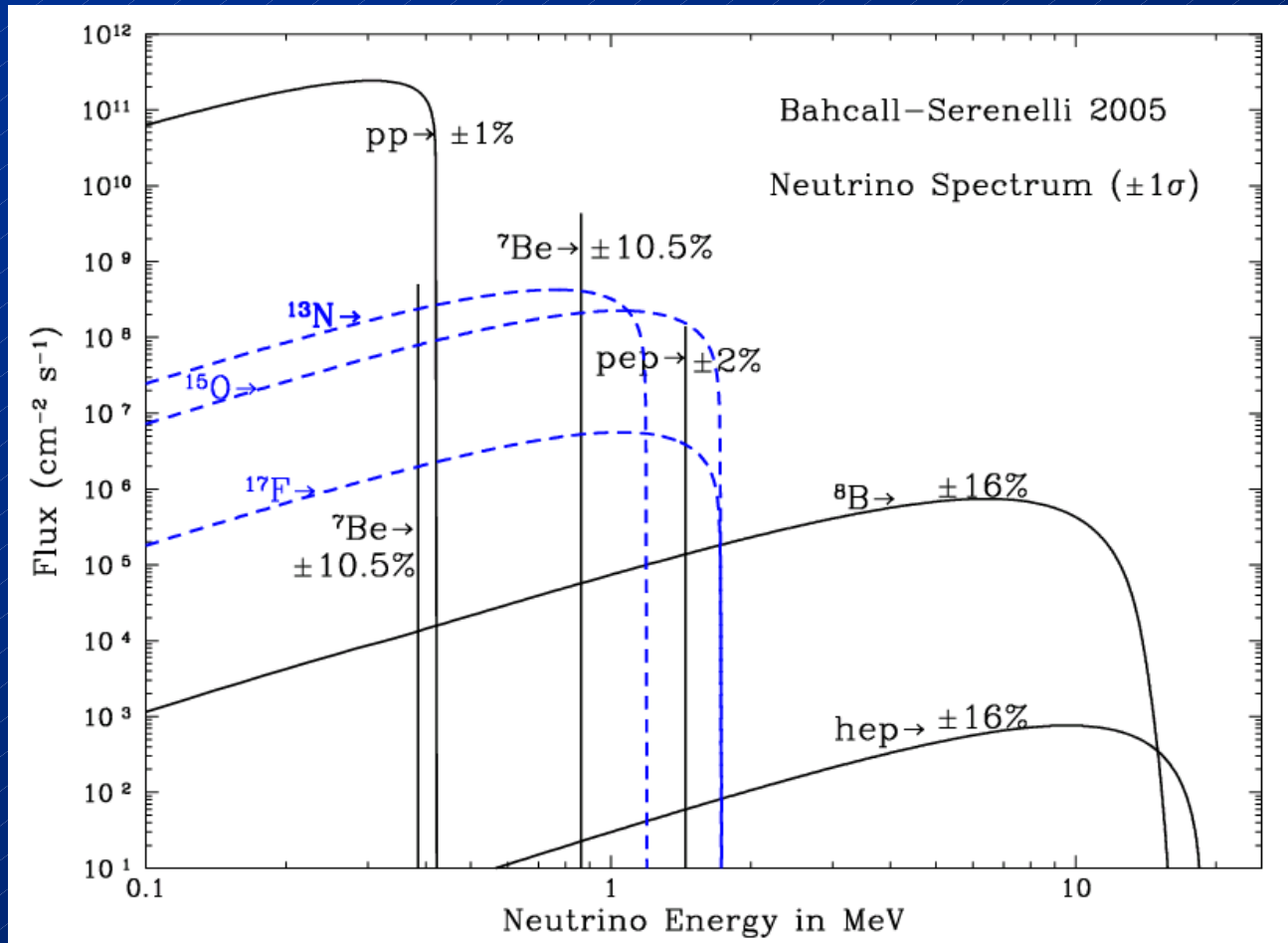
The solar neutrino spectrum

SNO

SK

Ga

Homestake

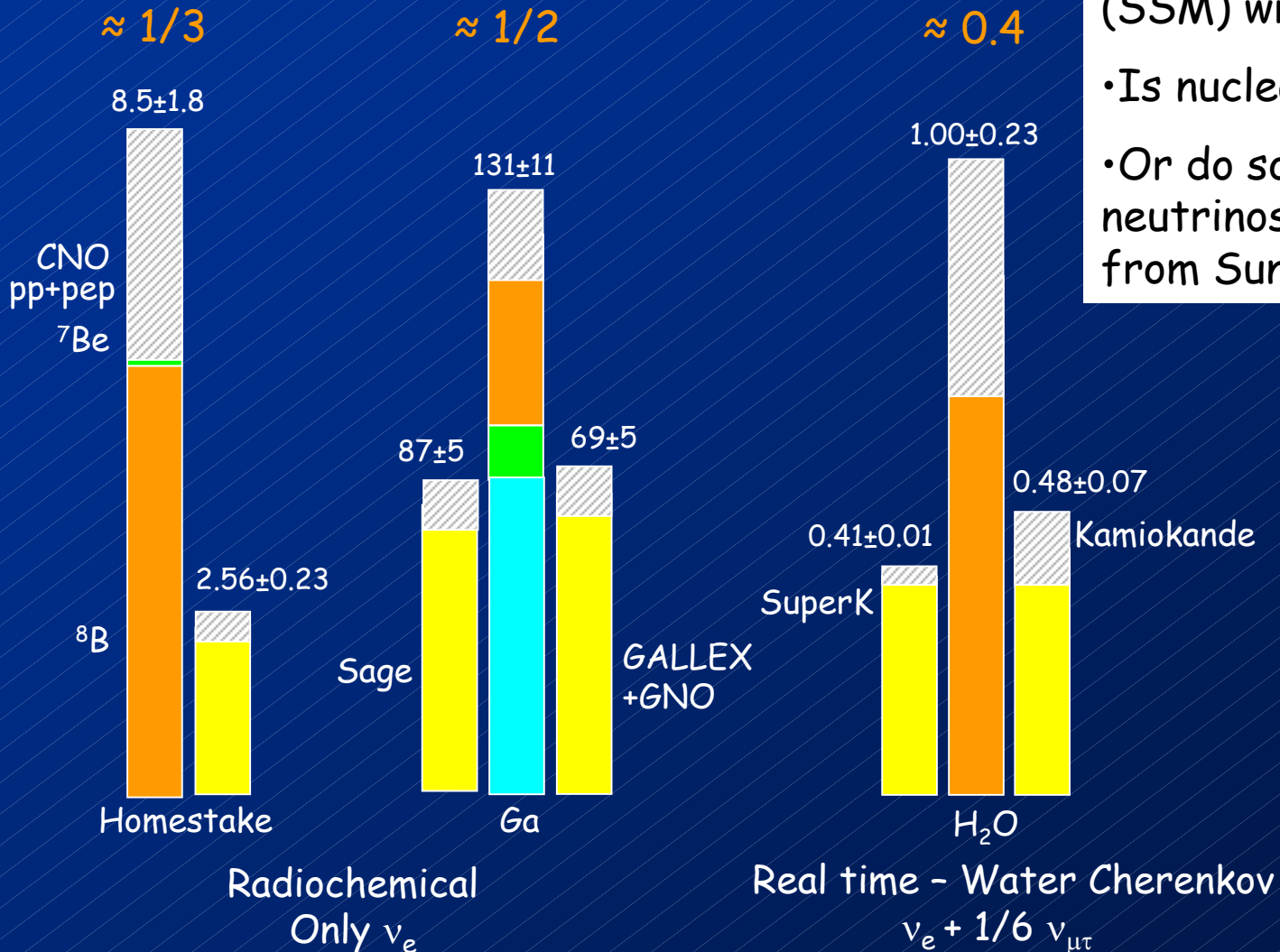


KamLand, Borexino, SNO+

Ianni, Montanino, FLV, Physics/0506171

Solar neutrino experiments - before 2002

Observed/Predicted



- Are all experiments wrong?
- Is the Standard Solar Mod (SSM) wrong?
- Is nuclear physics wrong?
- Or do something happen to neutrinos during their trip from Sun to Earth?

Solar neutrino experiments - after 2002

Villante et al., hep-ph/9807360

3 equations and 2 unknowns

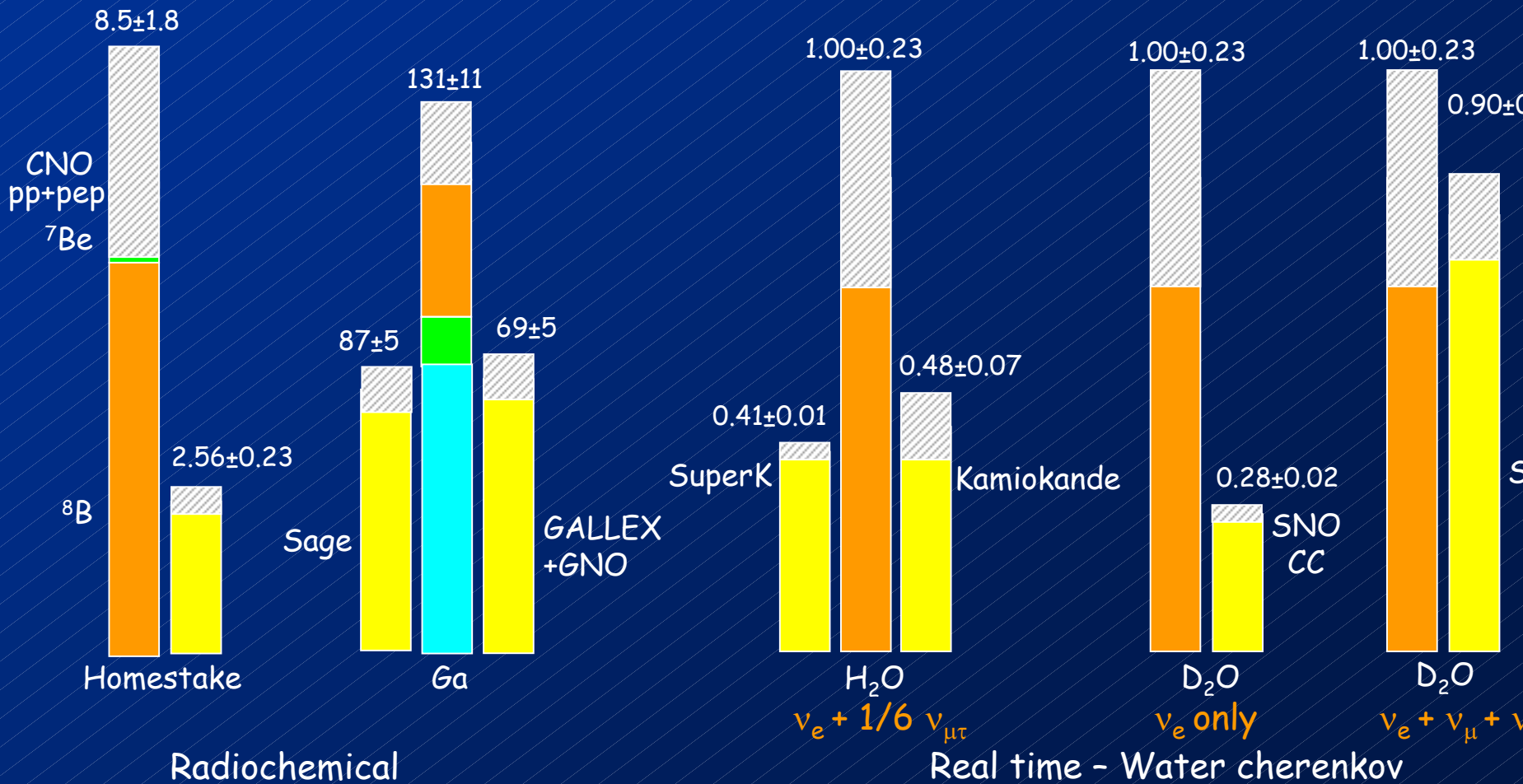
Φ_B = Total Boron neutrino flux

$\langle P_{ee} \rangle$ = Energy averaged ν_e survival probab.

$$\Phi_{ES}^{SK} = \Phi_B[\langle P_{ee} \rangle + r(1 - \langle P_{ee} \rangle)],$$

$$\Phi_{CC}^{SNO} = \Phi_B \langle P_{ee} \rangle,$$

$$\Phi_{NC}^{SNO} = \Phi_B,$$



So what?

• Is the SSM wrong?

NO. The total ${}^8\text{B}$ neutrino flux is in good agreement with predictions:

$$\Phi = 5.5 (1 \pm 0.7) 10^6 \text{ cm}^2 \text{ s}^{-1} \quad (1\sigma)$$

$$\Phi_{SSM} = 5.69 (1 \pm 0.16) 10^6 \text{ cm}^2 \text{ s}^{-1}$$

Bahcall and Serenelli, 2005

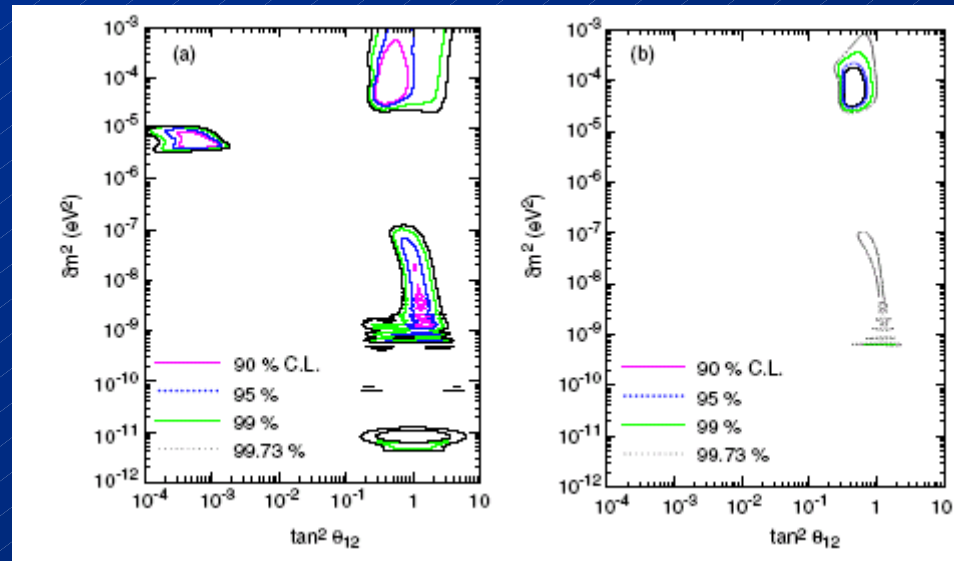
• Or do something happen to neutrinos during their trip from Sun to Earth?

YES. About 2/3 of ν_e transform into $\nu_{\mu\tau}$

$$\langle P_{ee} \rangle = 0.31 \pm 0.10 \quad (3\sigma)$$

Cl+ Ga+ SK

Cl+ Ga+ SK+ (SNO-I)



Fogli et al., 20

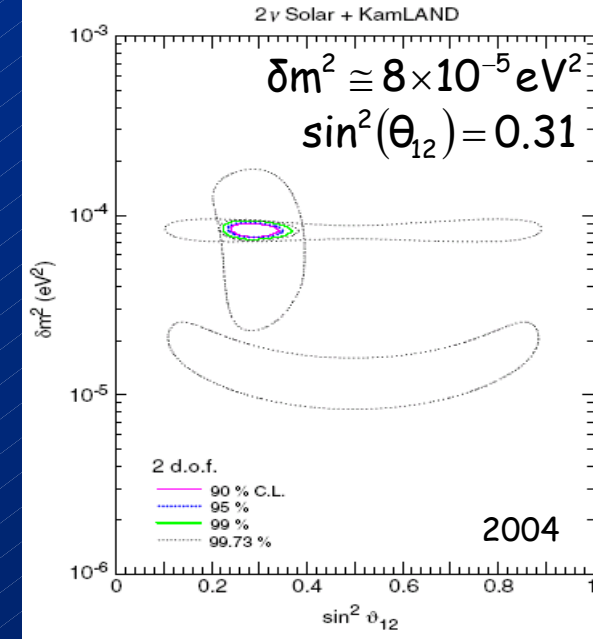
The KamLAND confirmation

- $\bar{\nu}_e$ from distant (≈ 100 km) nuclear reactors are detected in 1Kton liquid scintillator:



- Obs./Expected = 54/ (86 \pm 5.5)
KamLAND, 2002

- Oscillation of reactor $\bar{\nu}_e$ proven
- SNO is confirmed with man made (anti)neutrinos



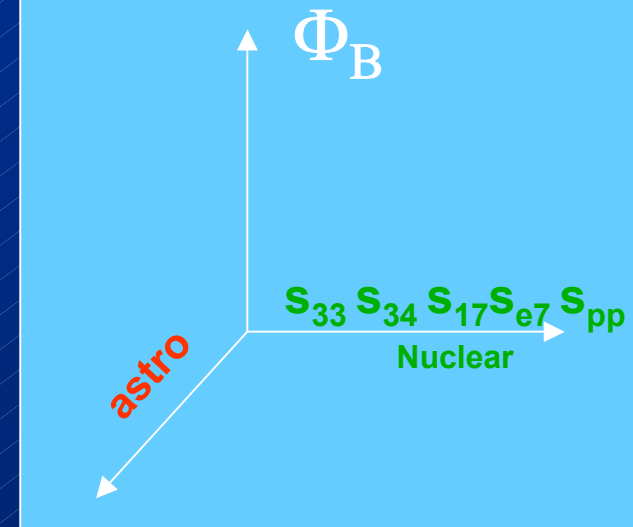
Fogli et al., 2004

- Oscillation channel $\nu_e \rightarrow \nu_{\mu\tau}$ (not sterile - full flux at SNO)
- Matter effects crucial
- Mixing angle large but not maximal
- Good fit to all data

The Boron neutrino flux

Φ_B depends on:

- nuclear physics inputs
- astrophysics inputs - *composition, opacity, diffusion coefficients, luminosity.*



Φ_B is a now **measured quantity** ($\Delta\Phi_B/\Phi_B=7\%$).
Can learn astrophysics if nuclear physics is known well enough

The effect of the astrophysical inputs variations can (**largely**) be reabsorbed into a variation of the "central" solar temperature:

$$\Phi_B = \Phi_B(\text{SSM}) [T / T(\text{SSM})]^{20}$$

Boron neutrinos



Solar thermometer

Assuming $\Delta\Phi_B/\Phi_B=7\%$
and $\Delta S_{\text{NUC}}/S_{\text{NUC}}=10\%$:

$$\Delta T/T \approx 0.6\%$$

Helioseismology

- From the measured oscillation frequencies of the solar surface one reconstructs **sound speed** in the solar interior.
- Excellent agreement with Standard Solar Model (till 2004)
- Complementary to neutrinos

2004

New determination of solar abund.

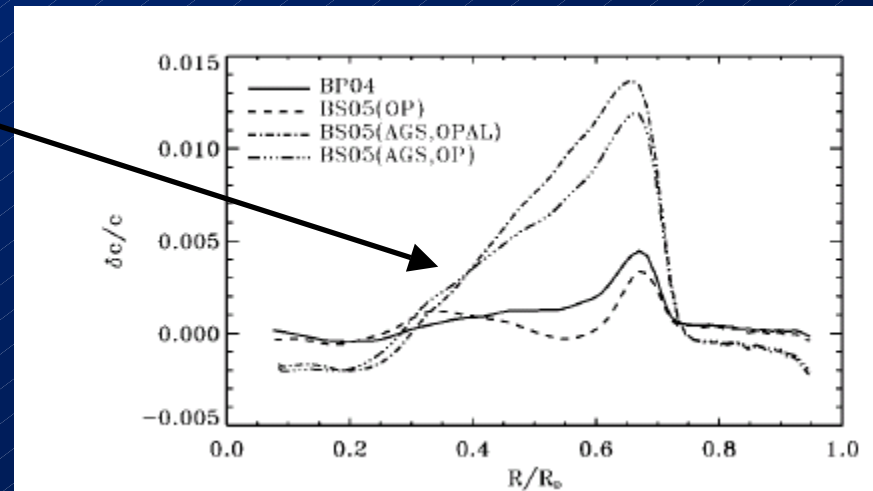
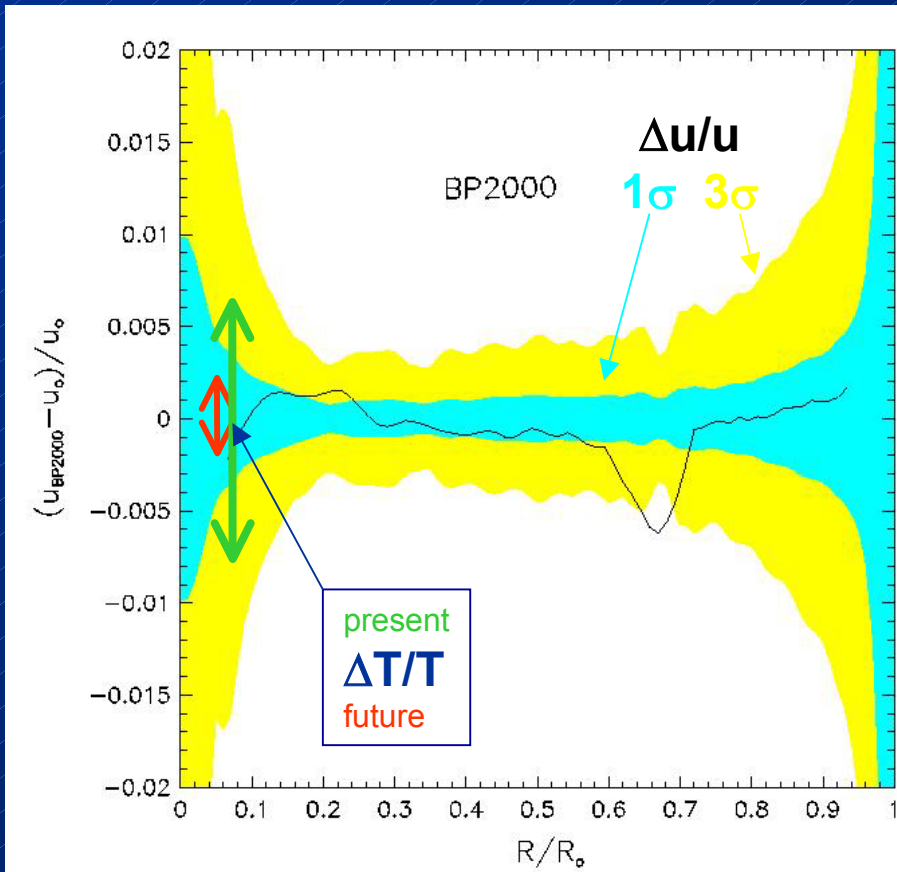
Problems with the SSM?

$\Phi_{SSM} = 4.51 (1 \pm 0.16) 10^6 \text{ cm}^2 \text{ s}^{-1}$
(still consistent with SNO+SK)

Bahcall et al., APJ 2005

Possibly related to neon abund.

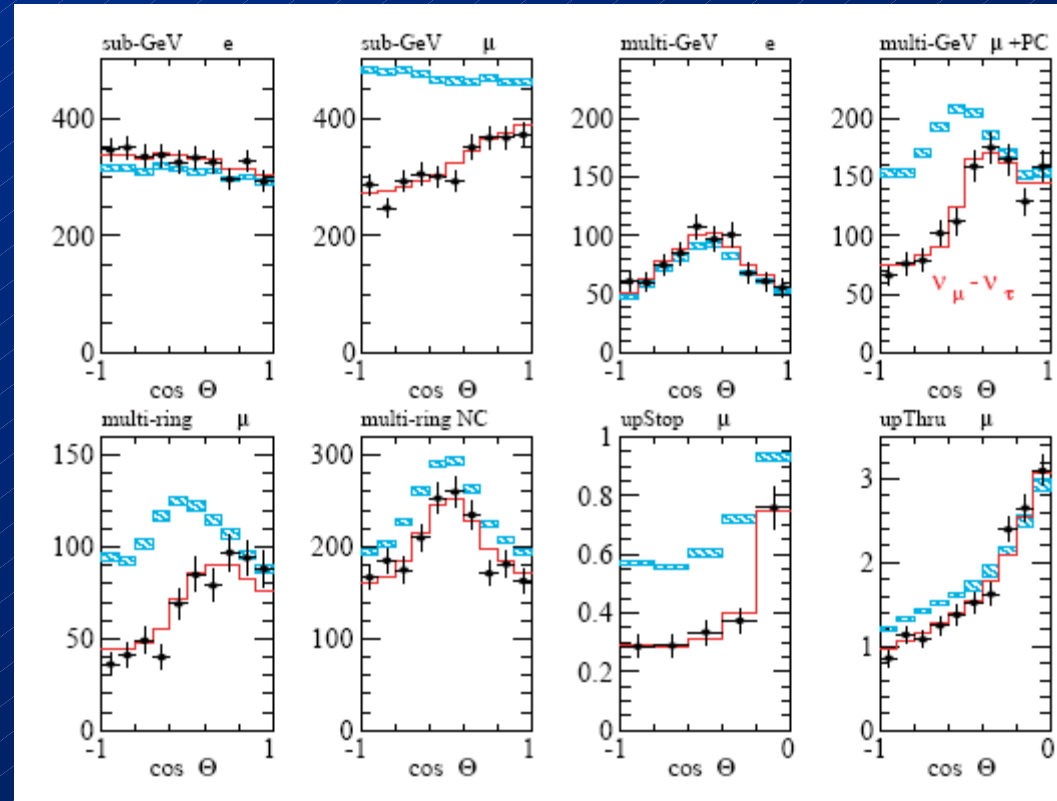
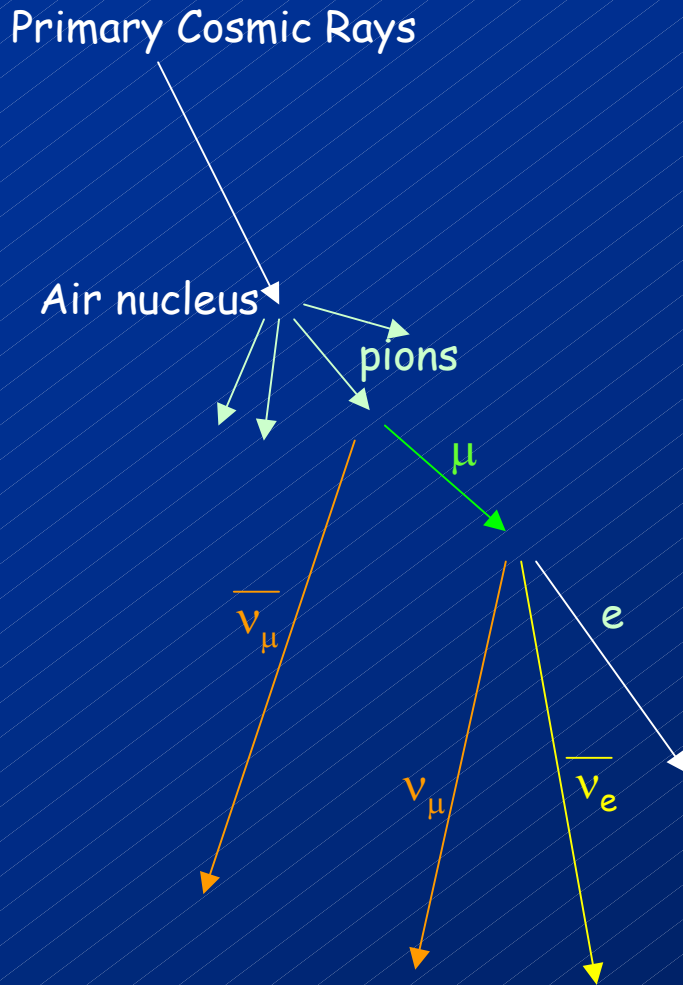
Bahcall et al., astro-ph/0502563



Atmospheric neutrinos

In the absence of oscillations:

- $N(\nu_\mu + \bar{\nu}_\mu) / N(\nu_e + \bar{\nu}_e) \approx 2$
- Up-down symmetry



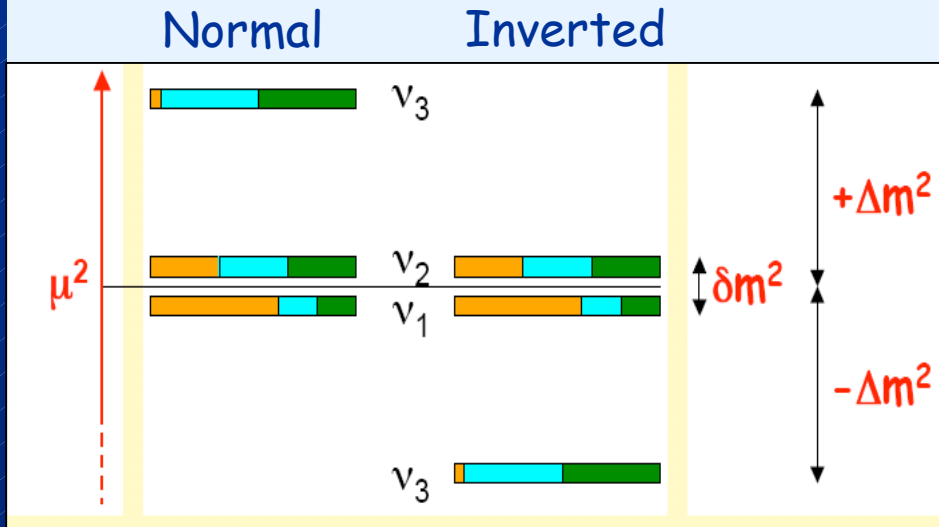
Muon neutrino from below are missing $\rightarrow \nu_\mu - \nu_\tau$ oscillations

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{\frac{i}{2}\varphi_2} & 0 \\ 0 & 0 & e^{\frac{i}{2}(\varphi_3+2\delta)} \end{pmatrix}$$

$$\sin^2(\theta_{23}) = 0.44(1_{-0.22}^{+0.41}) \quad \sin^2(\theta_{13}) \leq 0.03 \quad \sin^2(\theta_{12}) = 0.314(1_{-0.15}^{+0.18})$$

$$\delta m^2 = m_2^2 - m_1^2 = 7.92(1 \pm 0.09) \times 10^{-5} \text{ eV}^2 \quad \Delta m^2 = \left| m_3^2 - \frac{m_2^2 + m_1^2}{2} \right| = 2.4(1_{-0.26}^{+0.21}) \times 10^{-3} \text{ eV}^2$$

$\delta, \varphi_2, \varphi_3$ unknown



Open problems

- Dirac or Majorana?
- Mass ordering?
- θ_{13} ?
- CP violation?
- Absolute neutrino masses?
- **LSND** - requires $\delta m^2 = O(\text{eV}^2)$.
If confirmed (Miniboone) \rightarrow major revision of current ideas.

Absolute neutrino masses

Tritium β decay (${}^3\text{H} \rightarrow {}^3\text{He} + e^- + \nu_e$)

Non vanishing neutrino masses \rightarrow endpoint of positron spectrum decreased

ν_e is not a mass eigenstate \rightarrow

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2 \right]^{1/2} \leq 2.2 \text{ eV}$$

Mainz and Troitzk experiments - 95% C.L.

$0\nu\beta\beta$ decay - $N(Z,A) \rightarrow N(Z+2,A) + 2e^-$

Lepton number violation \rightarrow Only possible for Majorana neutrinos

$$m_{\beta\beta} = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\varphi_2} + s_{13}^2 m_3 e^{i\varphi_3} \right|$$

$$m_{\beta\beta} \leq O(\text{eV})$$

$$m_{\beta\beta} = (0.10-0.51) \text{ eV} \quad (90\% \text{ CL})$$

Klapdor-KleinGrothaus et al., 2001

Cosmology (see next)

Sensitive to:

$$m_{\text{tot}} = m_1 + m_2 + m_3$$

Cosmic neutrinos

Standard cosmology predicts that:

- The universe is filled by a (nearly) isotropic and homogeneous neutrino background
- Neutrinos decoupled from the e^\pm, p, n, γ plasma at $T \approx 1 \text{ MeV}$
- After decoupling, neutrinos free-streamed, maintaining the distribution function of relativistic species:
- The present temperature of neutrino background is $T_\nu = (4/11)^{1/3} T_\gamma = 1.9 \text{ K}$:

$$f_\nu(\mathbf{p}, T) = \frac{1}{e^{p/T} + 1} \longrightarrow n_\nu = \int \frac{d^3p}{(2\pi)^3} f_\nu(\mathbf{p}, T_\nu) = \frac{6\zeta(3)}{11\pi^2} T_\gamma^3$$

In the present Universe
 $112 (\nu + \bar{\nu}) \text{ cm}^{-3}$ per flavor

The cosmic neutrino background has not been directly detected.
Several indirect proof of its existence.

Neutrinos and the cosmos

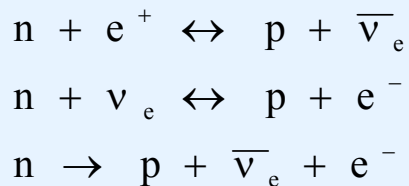
Neutrinos affect the universe evolution via several mechanisms:

- They contribute to the **energy density** of the universe:

$$\rho_{\nu_i} = \begin{cases} \frac{7\pi^2}{120} T^4 & T \gg m_{\nu_i} \\ m_{\nu_i} n_{\nu} & T \ll m_{\nu_i} \end{cases}$$

$$\Omega_{\nu} \equiv \frac{\rho_{\nu}}{\rho_{\text{critical}}} = \frac{\sum_i m_i}{93.2 \text{ h}^2 \text{ eV}}$$

- They affect **weak interactions** in the early universe



Deviation from Fermi-Dirac distribution or neutrino-antineutrino asymmetry affects n/p equilibrium.

- They influence **structure formation** (see next...)

Neutrinos and BBN

Big Bang Nucleosynthesis (BBN)

Light elements (D, ^3He , ^4He , ^7Li) have been efficiently produced during the first 3 minutes of the Universe.

BBN depends on:

How many baryons are available to build light nuclei:

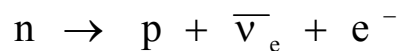
→ Baryon to photon ratio - $\eta \approx 5 \cdot 10^{-10}$

How many neutrons survive till the onset of nucleosynthesis:

→ Γ_w / H ($T \approx 1 \text{ MeV}$)

$\Gamma_w =$ Weak interaction rate $\approx G_F^2 T^5$

$H =$ Universe expansion rate



$$H \approx g_*^{1/2} G_N^{1/2} T^2$$

$$g_* = 10.75 + \frac{7}{4} (N_\nu - 3)$$

How much time is available to build light nuclei:

→ Universe expansion rate H during light element production ($T \approx 0.01\text{-}0.1 \text{ MeV}$)

Neutrinos and BBN

BBN bounds summary:

$$\Omega_B h^2 = 0.0214 \pm 0.0020$$

Kirkmann et al, 2003 \rightarrow consistent with CMB

Extra ν -flavors:

$$\Delta N_\nu < 1.0 \text{ (pessimistic)}$$

$$\Delta N_\nu < 0.2 \text{ (optimistic)}$$

See e.g. Villante and Dolgov, 2005

Neutrino chemical potentials: (related ν anti- ν asymmetries)

$$|\xi| \leq 0.05 \text{ for any neutrino flavor}$$

See e.g. Dolgov et al. 2002

Active-Sterile neutrino oscillations

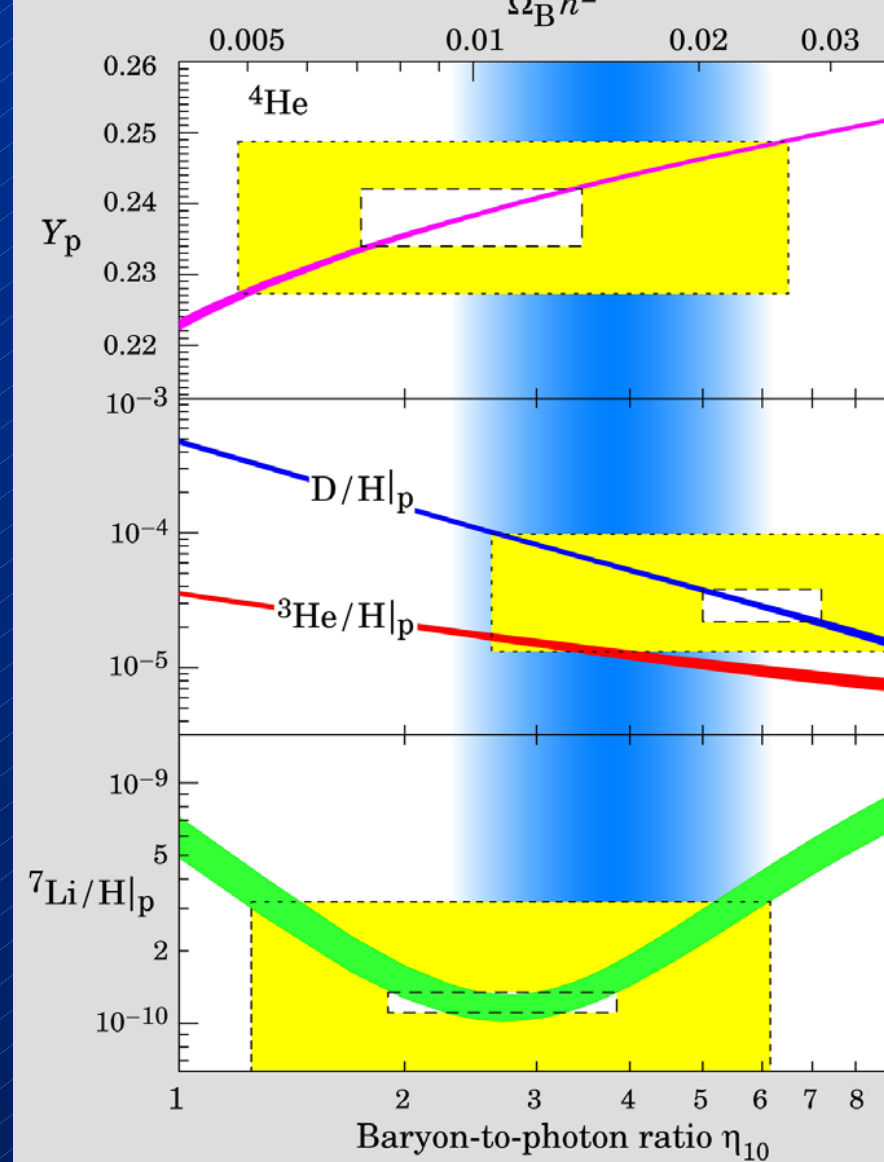
$$(\delta m^2 / eV^2) \sin^4(2\theta) < 1.7 * 10^{-5} (\Delta N_\nu)^2$$

$$(\delta m^2 / eV^2) \sin^4(2\theta) < 3.2 * 10^{-5} (\Delta N_\nu)^2$$

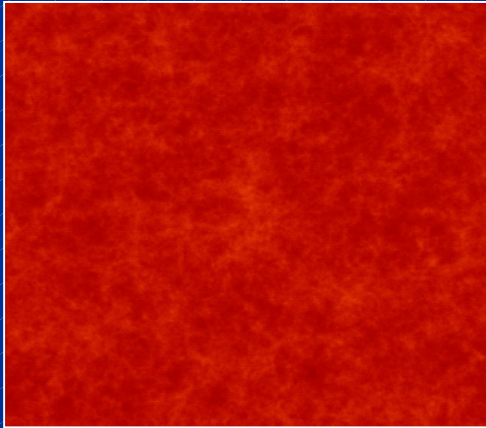
$\nu_\mu - \nu_s$ mixing

$\nu_e - \nu_s$ mixing

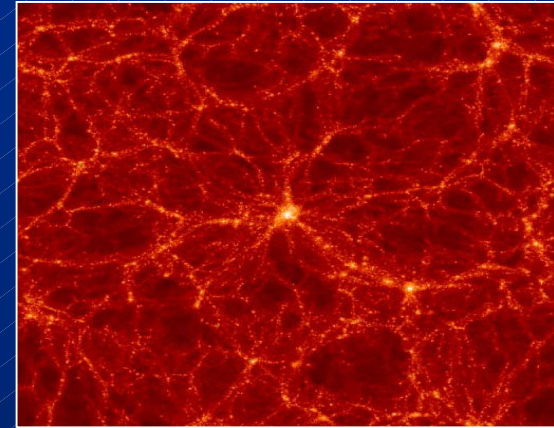
Dolgov and Villante, 2003



Structure Formation: the standard paradigm



Structures form by gravitational instability of primordial density fluctuations



Density fluctuations

$$\delta_i(\mathbf{x}) = \frac{\rho_i(\mathbf{x}) - \bar{\rho}_i}{\bar{\rho}_i}$$



In linear regime ($\delta \ll 1$):

$$\delta_{i,k} = \int d^3x \delta_i(\mathbf{x}) e^{-i\mathbf{k} \cdot \mathbf{x}}$$

• Perturbation evolution in the expanding universe

• Multi - component fluid. Perturbation in the various component are coupled by gravity and by other interactions.

• Initial conditions:

$$P_k = |\delta_k|^2 \propto k^n \quad n \approx 1$$

$$\delta_{\text{CDM}} = \delta_b = \frac{3}{4} \delta_\gamma = \frac{3}{4} \delta_\nu$$

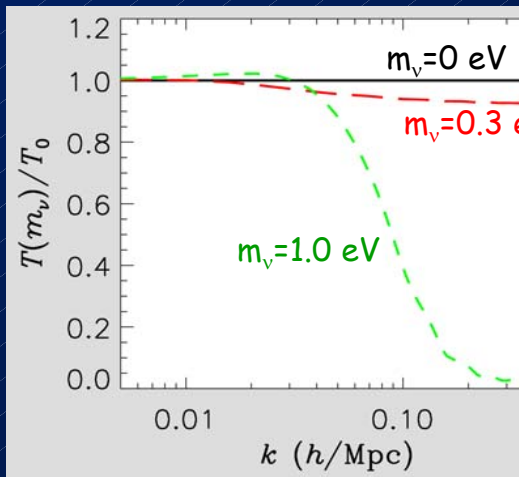
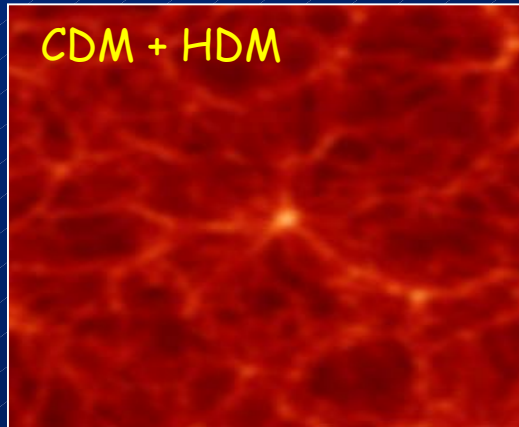
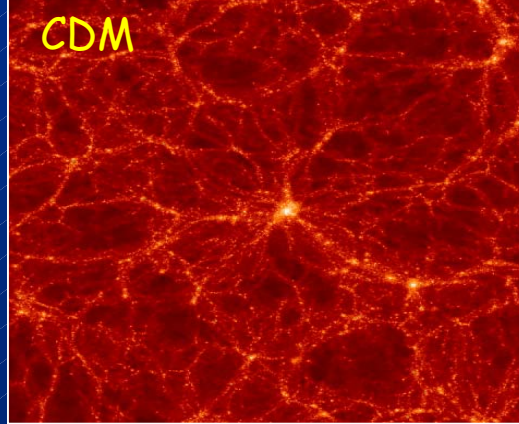
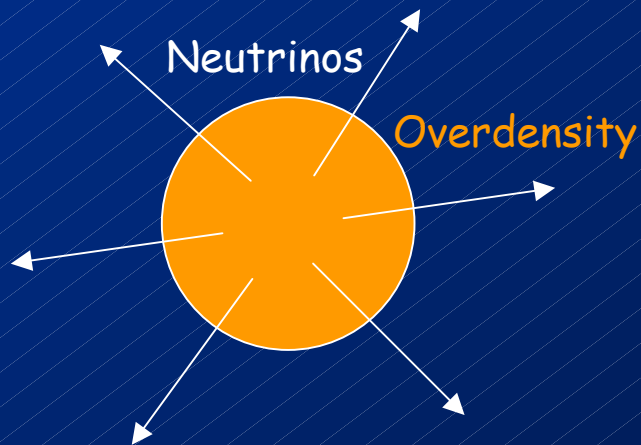
δ_γ } Due to photon pressure, perturbation in baryon grow after decoupling ($z \approx 1100$)
 δ_{Baryon} }

δ_{CDM} → Structure start to form after Matter-radiation equality

δ_ν → ($T < 1 \text{ MeV}$) - Free stream till they become non relativistic

Neutrinos and Structure Formation

- At $T < 1$ MeV neutrino scattering is ineffective
- Neutrinos free stream until they are non-relativistic (hot dark matter)
- Wash out density contrast on scales smaller than the free streaming length



Structure Formation: the data

Three main probes:

Cosmic Microwave Background

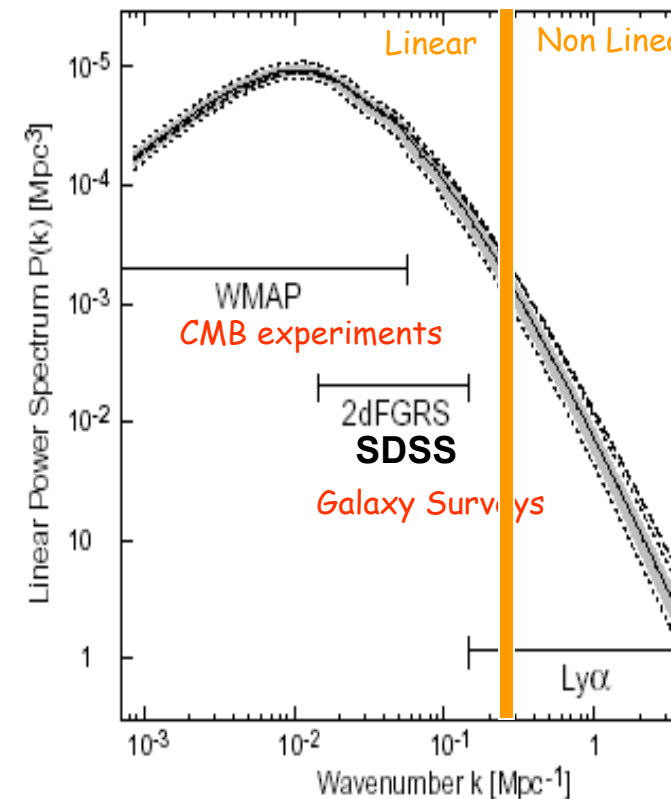
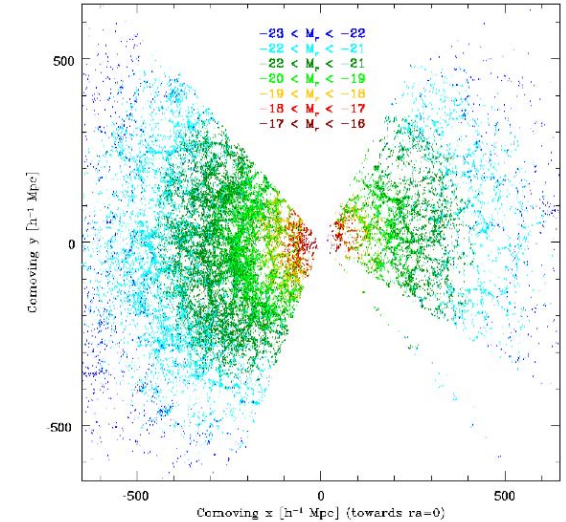
Snapshot of the universe at decoupling ($z = 1100$).
Sensitive to large scales ($k < 10^{-2} \text{ Mpc}^{-1}$).

Galaxy Redshift Survey

Spatial distribution of galaxies.
Sensitive to intermediate scales

Lyman alpha forest

Distribution of matter (baryons) close to quasars
at redshifts $z \approx \text{few}$.
Sensitive to small scales.
(Mildly non linear at redshift $z \approx \text{few}$.
Non linear in the present universe).



CMB, LSS and neutrinos

Sky map of CMB temperature fluctuations:

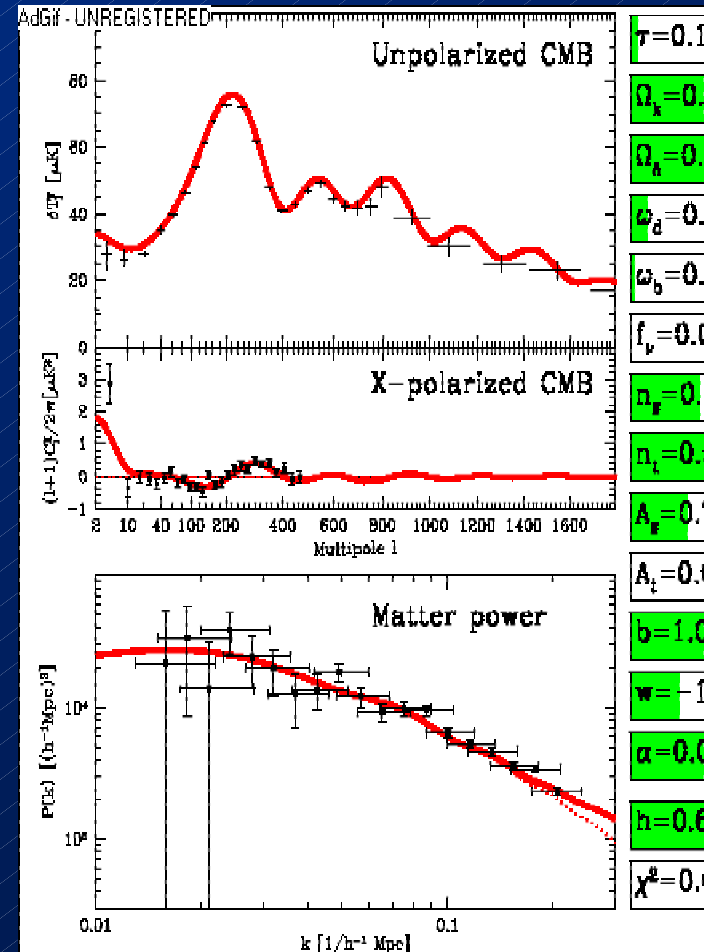
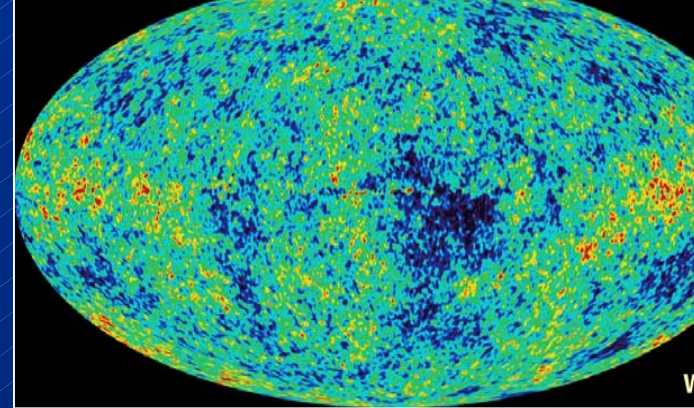
$$\Delta(\theta, \varphi) = \frac{T(\theta, \varphi) - \langle T \rangle}{\langle T \rangle}$$

Multipole expansion:

$$\Delta(\theta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^l a_{lm} Y_{lm}(\theta, \varphi)$$

Angular power spectrum:

$$C_l = \langle a_{lm}^* a_{lm} \rangle = \frac{1}{2l+1} \sum_{m=-l}^l a_{lm}^* a_{lm}$$



LSS power spectrum is the Fourier transform of the two point correlation function ($x=x_2-x_1$):

$$\xi(x) = \langle \delta(x_2) \delta(x_1) \rangle = \int \frac{d^3k}{(2\pi)^3} e^{ik \cdot x} P(k)$$

From **CMB** and **galaxy clustering** data

$$\sum_i m_i \leq 1.0 \text{ eV} \quad 95\% \text{ C.L.}$$

Adding **Ly- α** data

$$\sum_i m_i \leq 0.5 \text{ eV} \quad 95\% \text{ C.L.}$$

Bound on $\sum m_\nu$ (eV, 95% CL)	Data (in addition to WMAP)
2.0	–
1.7	SDSS
1.0	other CMB, 2dF, HST, SN
1.0 [0.6]	other CMB, 2dF, SDSS [HST, SN]
0.75	other CMB, 2dF, SDSS, HST
0.7	other CMB, 2dF, σ_8 , HST
0.47	other CMB, 2dF, SDSS (Ly- α), HST, S
0.42	SDSS (bias, galaxy clustering, Ly- α)

Sensitivity at a level comparable (or better) than terrestrial searches (β decay, $0\nu\beta\beta$ decay). But ...

- Possible degeneracies - e.g. m_ν and N_ν

See, Crotty et al. 2004

- "Standard" scenario assumed (Inflation + Standard Cosmology + neutrino masses)

Several possible modifications:

- non thermal neutrino spectra
- violation of Fermi-Dirac statistics
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Conclusions

A lot has been understood:

- evidence for ν oscillations
- evidence for matter effects
- θ_{12}, θ_{23} mixing angles measured
- Upper limits $O(\text{eV})$ on absolute ν masses

A lot has still to be understood:

- Dirac or Majorana?
- Mass ordering?
- θ_{13} ?
- CP violation?
- Absolute neutrino masses?
- LSND?

The better we know neutrinos, the better we can use them to understand astrophysics and cosmology.