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Search for Dark Matter

Lecture 2: Thermal Particle Candidates

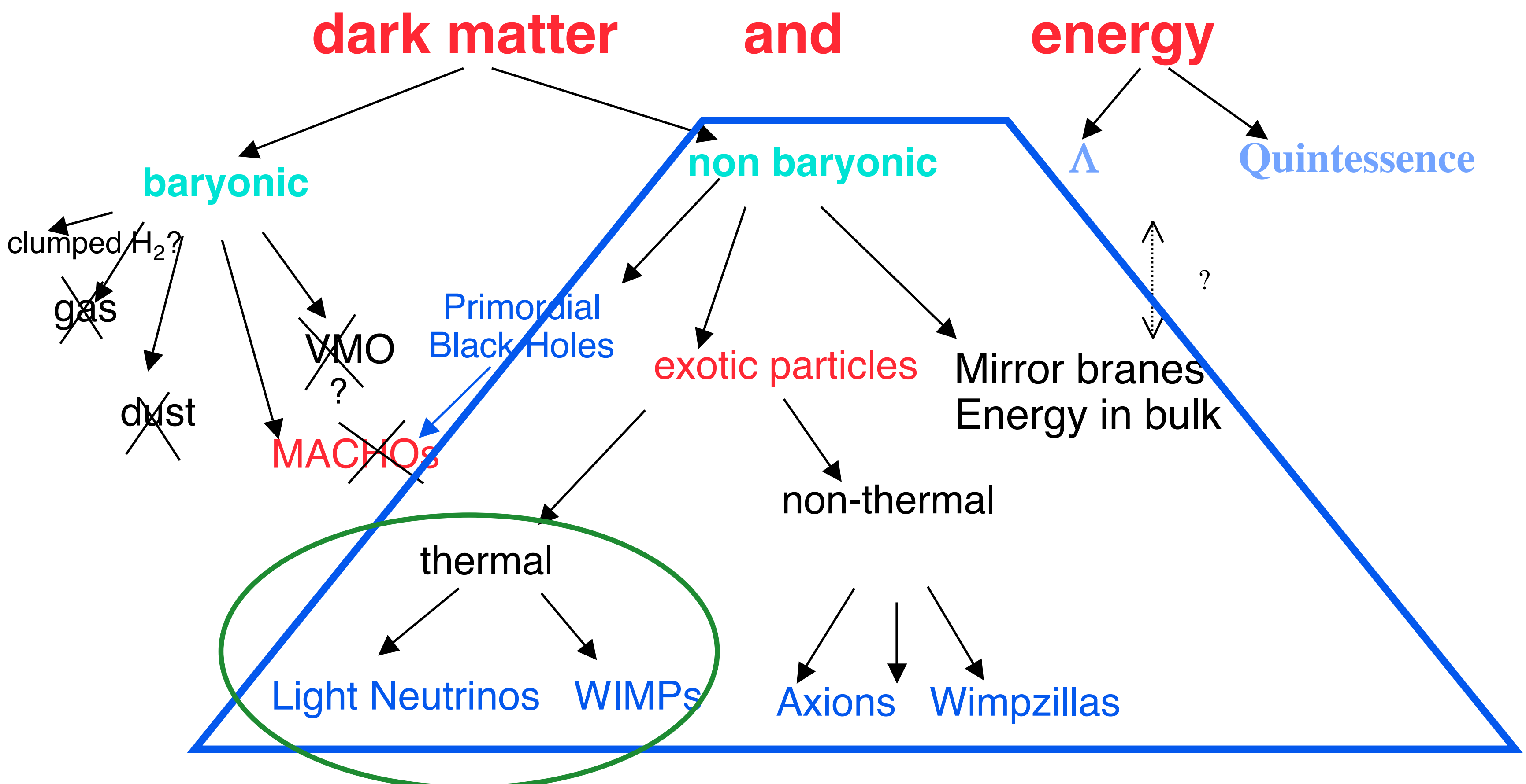
Light neutrinos:

- Cosmological limits on the mass

Weakly Interactive Massive Particles:

- Generic properties
- Supersymmetry

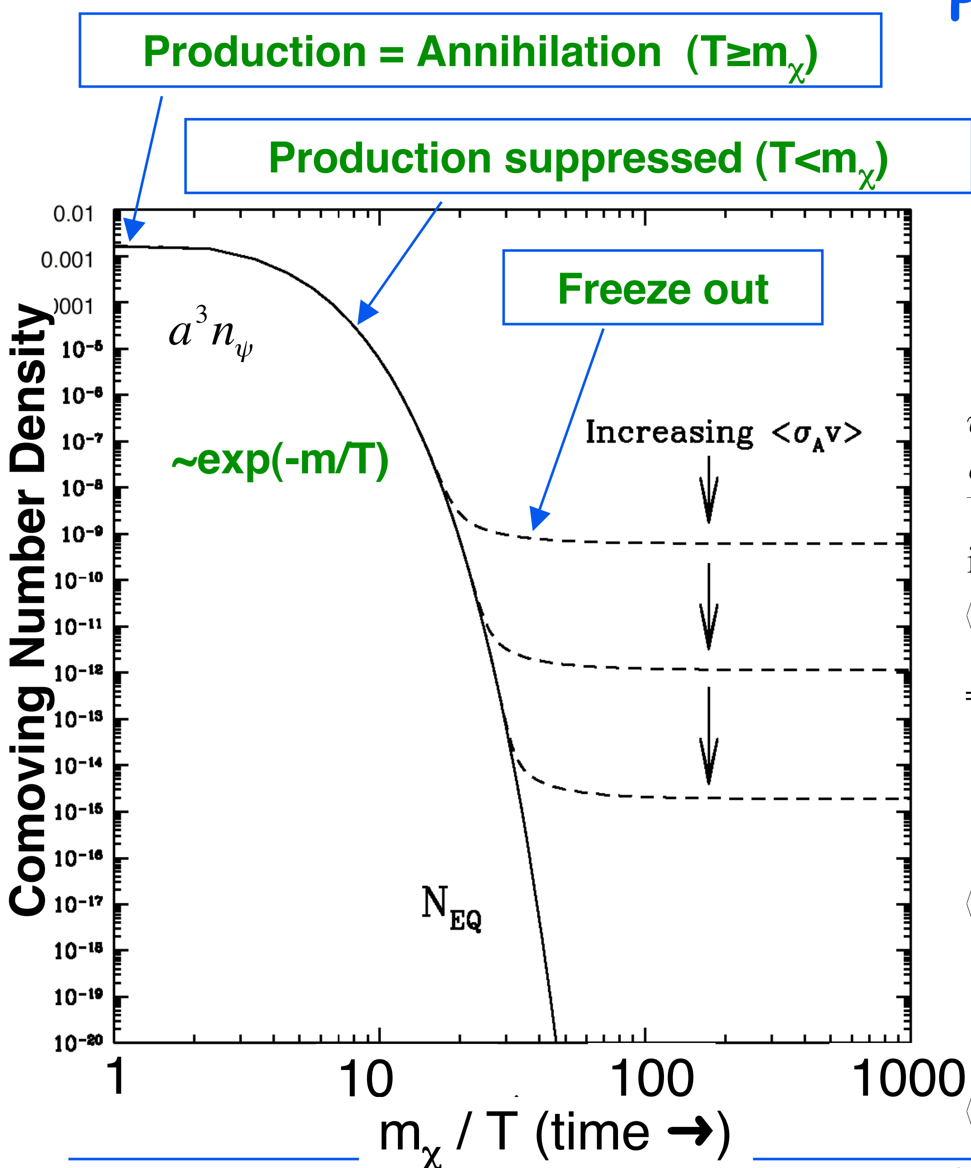
Deciphering the Nature of Dark Matter



The silent revolution: Dark Matter is non baryonic

How to search for it? An example: Thermal candidates

Thermal Relics



Particles in thermal equilibrium in early universe

e.g. $\psi\bar{\psi} \leftrightarrow X\bar{X}$

How the density evolve (e.g. Kolb,Turner)

Let us consider a 2 body annihilation channel (can be generalized)

$\psi\bar{\psi} \leftrightarrow X\bar{X}$ where we assume the X to stay in equilibrium

$$\frac{dn_\psi}{dt} + 3\frac{\dot{a}}{a}n_\psi = -\langle\sigma_{\psi\bar{\psi}\to X\bar{X}}|v|\rangle n_\psi^2 + \langle\sigma_{X\bar{X}\to\psi\bar{\psi}}|v|\rangle n_{XEQ}^2$$

in equilibrium

$$\langle\sigma_{X\bar{X}\to\psi\bar{\psi}}|v|\rangle n_{XEQ}^2 = \langle\sigma_{\psi\bar{\psi}\to X\bar{X}}|v|\rangle n_{\psi EQ}^2$$

$$\Rightarrow \frac{dn_\psi}{dt} + 3\frac{\dot{a}}{a}n_\psi = -\langle\sigma_{\psi\bar{\psi}\to X\bar{X}}|v|\rangle\left(n_\psi^2 - n_{\psi EQ}^2\right)$$

Relativistic (Bosons: 1, Fermions: 3/4)

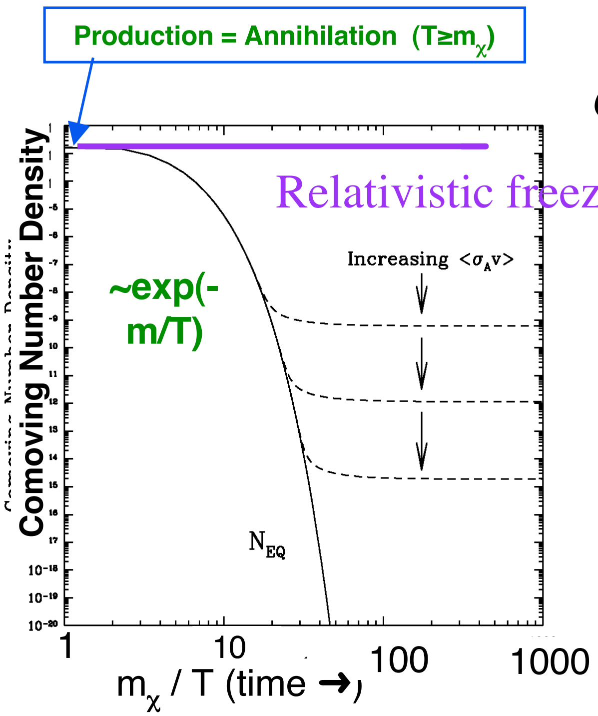
$$\langle\sigma_{\psi\bar{\psi}\to X\bar{X}}|v|\rangle \text{ large enough } n_\psi = n_{\psi EQ} \propto \begin{cases} \left[\begin{pmatrix}1\\3/4\end{pmatrix} g\frac{\zeta(3)}{\pi^2\hbar^3c^3}(kT)^3\right] \\ \exp\left(-\frac{\varepsilon}{k_BT}\right) \end{cases}$$

Non relativistic

$$\langle\sigma_{\psi\bar{\psi}\to X\bar{X}}|v|\rangle \text{ too small } \frac{dn_\psi}{dt} + 3\frac{\dot{a}}{a}n_\psi = 0 \quad \Rightarrow n_\psi \propto a^{-3}$$

Light Massive Neutrinos

Thermal equilibrium in early universe
+ *Decoupling when relativistic*



Case of the light week interactions neutrinos

number ≈ number of photons
density <-> mass

$$\Omega_x h^2 = \frac{\sum_i m_{\nu_i}}{94 \text{ eV}}$$

40 eV/c^2 => $\Omega \approx 1$

Astrophysics + laboratory =>
Strong evidence for massive neutrinos

Mostly limits on direct mass measurement (Laboratory, Cosmology)

Neutrinos Oscillations

Formalism

cf. Gonzales-Garcia, Nir hep-ph/020258

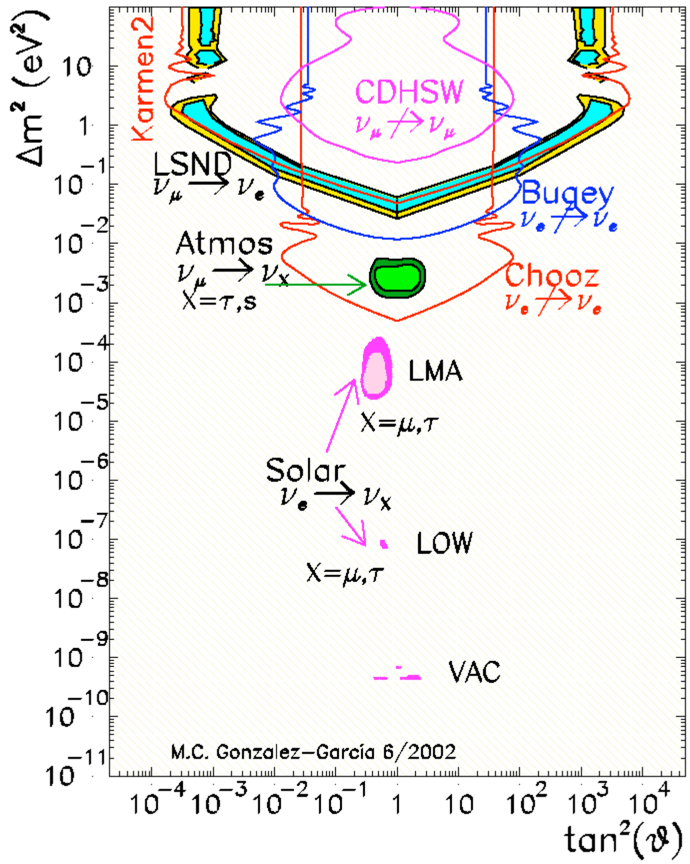
$$\underbrace{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \dots\end{pmatrix}}_{\text{Weak Interactions}} \neq \underbrace{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \dots\end{pmatrix}}_{\text{Mass}} \neq \underbrace{\begin{pmatrix}\nu_\alpha\\ \nu_\beta\\ \nu_\gamma\\ \dots\end{pmatrix}}_{\text{Energy in matter}} \Rightarrow \text{Mixing}$$

e.g. for 2 flavors in vacuum :
in weak basis ν_e, ν_μ
such as $e^- \leftrightarrow \nu_e + W^-$ $\mu^- \leftrightarrow \nu_\mu + W^-$

$$M = \begin{pmatrix} m_{\nu e} & m_{\nu e\mu} \\ m_{\nu e\mu} & m_{\nu\mu} \end{pmatrix}$$

Eigenvectors are ν_1, ν_2 : $\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$
with mass m_1, m_2 $\quad \nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$
Evolution $|\nu_1\rangle = e^{E_1 t}|\nu_1\rangle_o \quad |\nu_2\rangle = e^{E_2 t}|\nu_2\rangle_o$
$\Rightarrow$ Oscillations between ν_e and ν_μ. In relativistic limit

$$P(\nu_e \to \nu_\mu) = |\langle \nu_e | \nu_\mu \rangle|^2 = \frac{1}{2}\sin^2 2\theta \left(1 - \cos\left[\underbrace{m_2^2 - m_1^2}_{\Delta m^2} \frac{c^2}{2\hbar}\frac{L}{E}\right]\right)$$



Situation June 2002
Matter oscillation not symmetrical $\theta \to \pi/2 - \theta$

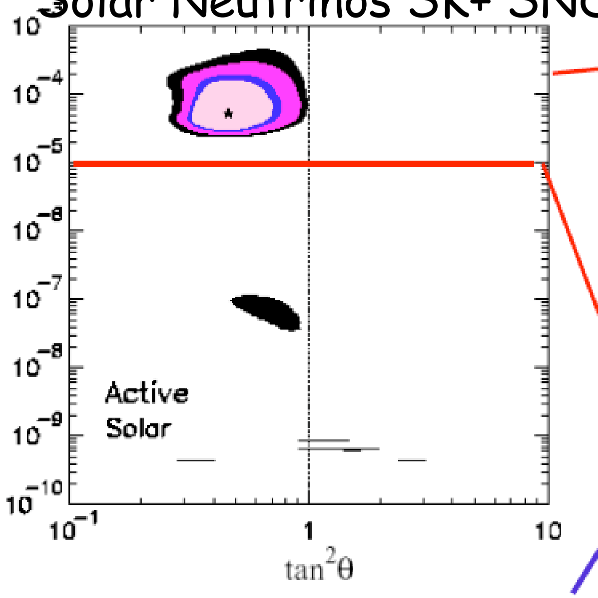
Neutrino Oscillations 2

Neutrino 2004

Great improvement on Δm^2_{12}

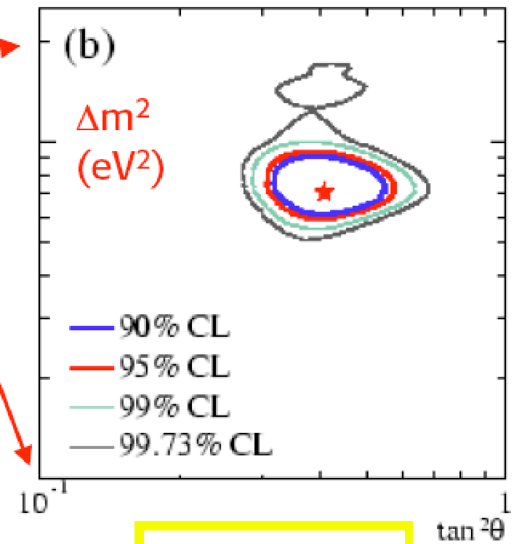
Before KamLAND

Solar Neutrinos SK+ SNO



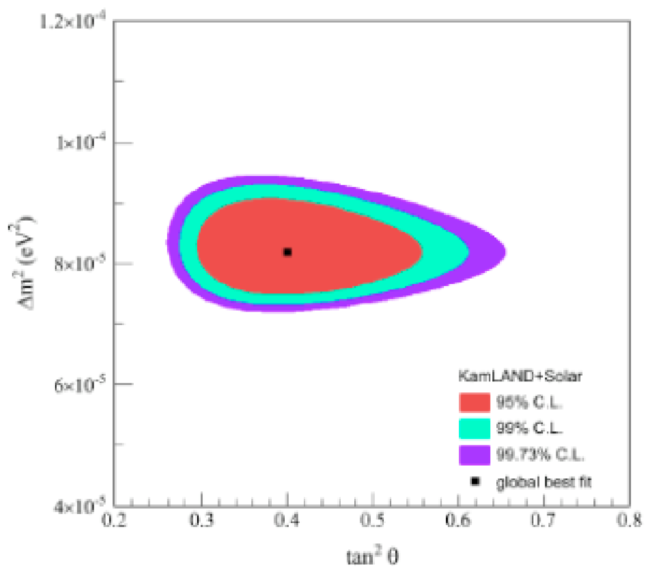
G. Altarelli

After KamLAND I & SNO(salt)



Note the change of scale

Nu'04: KamLAND II



$$\Delta m_{12}^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5} eV^2$$

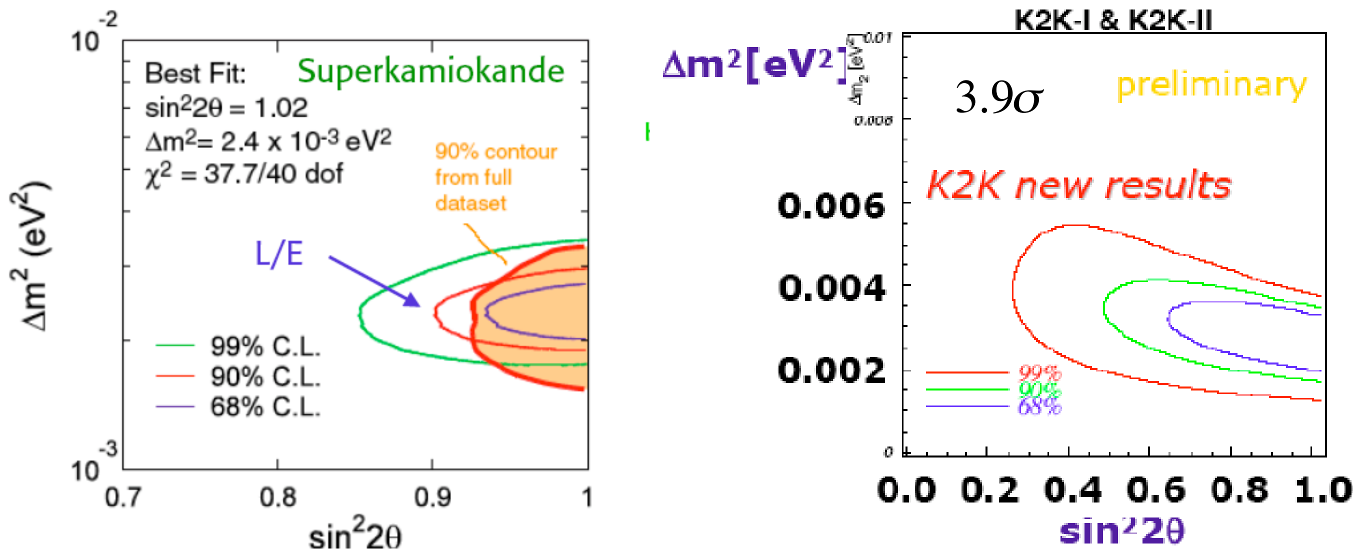
$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$

Neutrino Oscillations 2

Neutrino 2004

Atmospheric neutrinos

Δm^2_{23} goes down? Mixing θ_{23} still maximal



Big question remains θ_{13}

All data (Maltoni 04) $\sin^2\theta_{13} < 0.061$

Reactor experiments->long baseline JFK/NuMI/neutrino factories

LSND?

MiniBoon in a few years

Neutrino Direct Mass Measurements

Oscillations gives only Δm^2

$$m_{\max} \geq \Delta m^2$$

Neutrinos can be degenerate

In any case, density of cosmological neutrinos at minimum $\Omega \approx 10^{-3} \approx$ density of stars

Direct measurement:

Extremely important to fix mass hierarchy and amount in universe

Electron neutrino

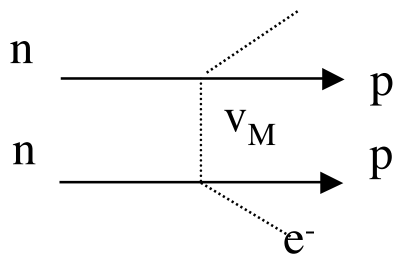
Tritium decay: $m_{\nu e} < 2.2$eV (Mainz, Troisk) Future Katrin sub eV

Other neutrinos

$M_{\nu\mu} < 170$ keV

$m_{\nu\tau} < 18.2$ MeV

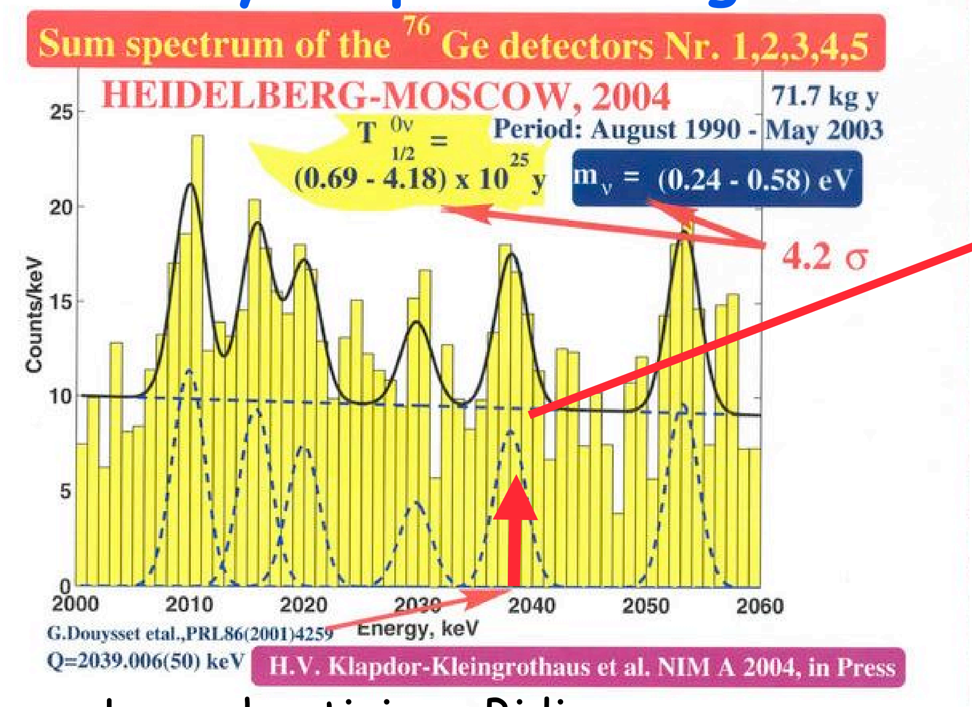
Neutrinoless Double Beta Decay

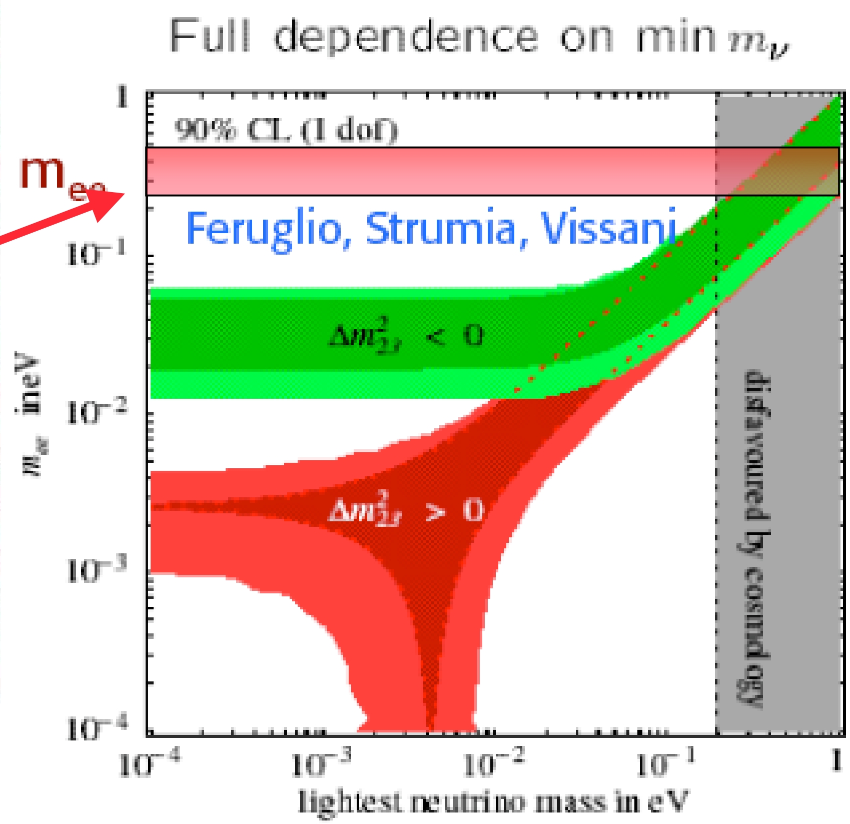


$$\langle m_{\nu_M} \rangle = \sum_i U_{ei} U_{ei}^* m_i$$

Note : $U_{ei} U_{ei}^*$ is not necessarily >0

Claim by Klapdor-Kleingrothaus





Less skepticism: Bi lines
Single site cut decreases Bi >> "signal"
But level of background ??

Neutrinoless Double Beta

Important to check!

Running experiments

CUORECINO (^{130}Te)

-> CUORE

NEMO 3 -> Super NEMO

XMASS (Xe)

In project

^{76}Ge

Heidelberg-Moscow+IGEX material

in "naked" Genius like detector

Majorana (US)

^{136}Xe

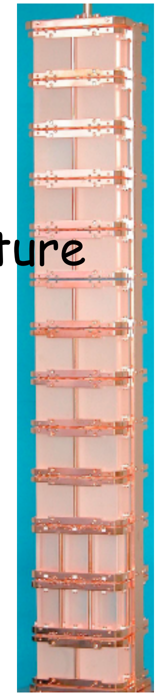
EXO (USA)

enriched+ Ba detection with single laser spectroscopy

^{100}Mo

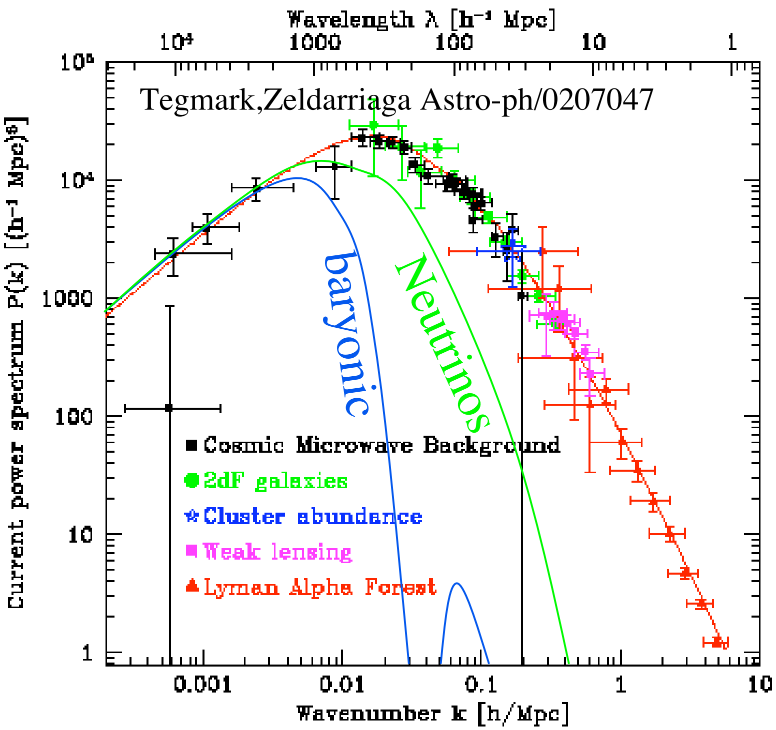
MOON (Japan)

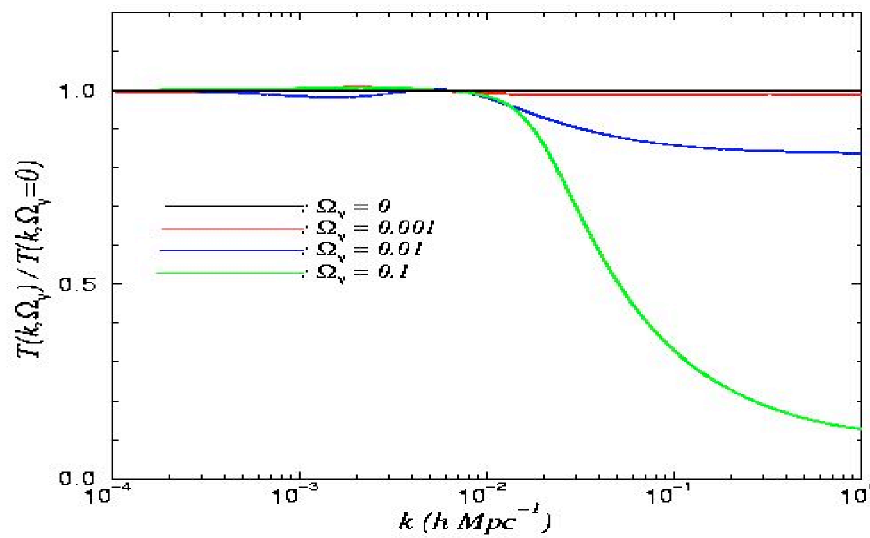
Low Temperature Detector



Neutrino Mass Limit from Cosmology

Neutrinos erase structure at small scale



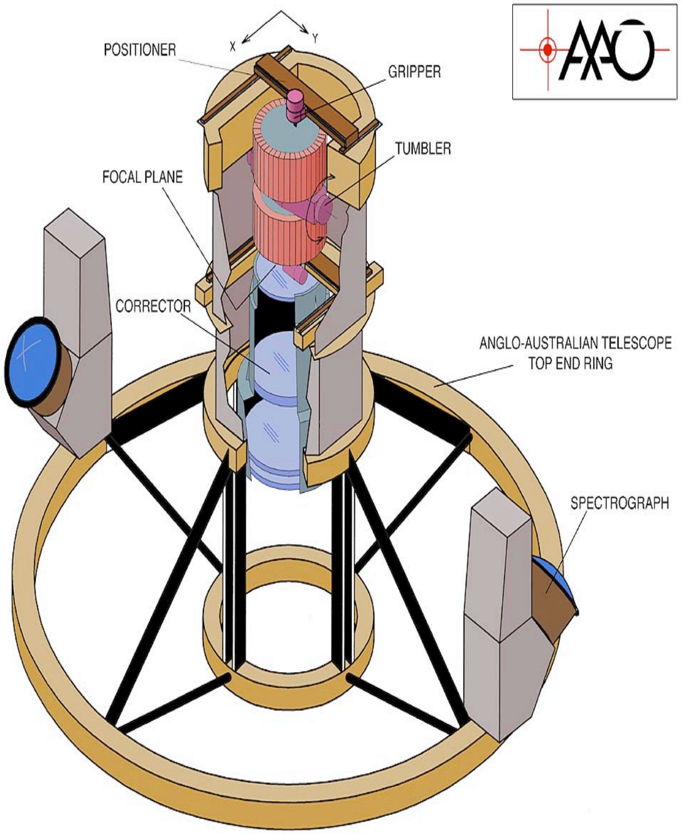


Neutrino Free Streaming

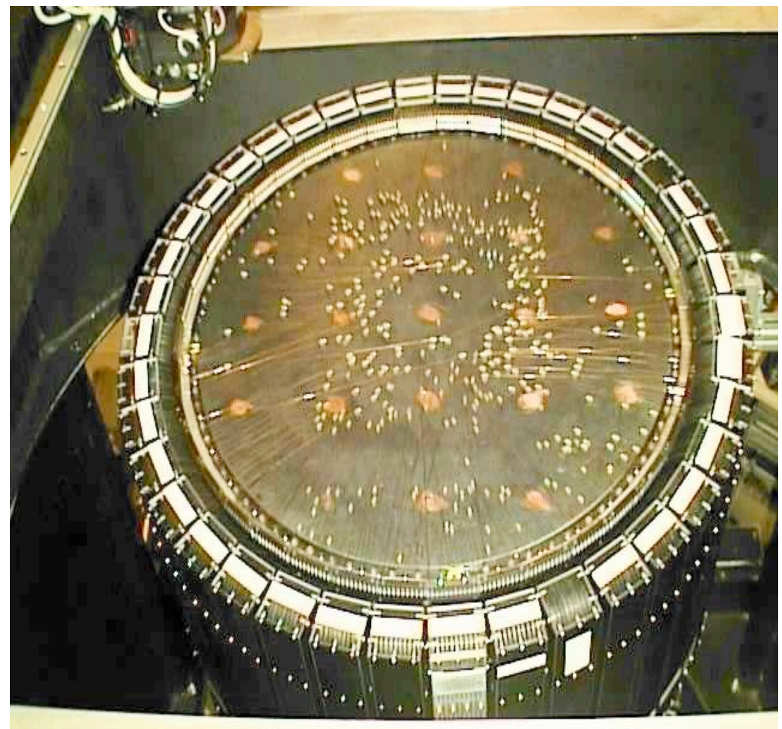
$\Delta P(k)/P(k) = -8\ \Omega_\nu / \Omega_m$

(Hu et al. 1998)

The 2dF Redshift Machine

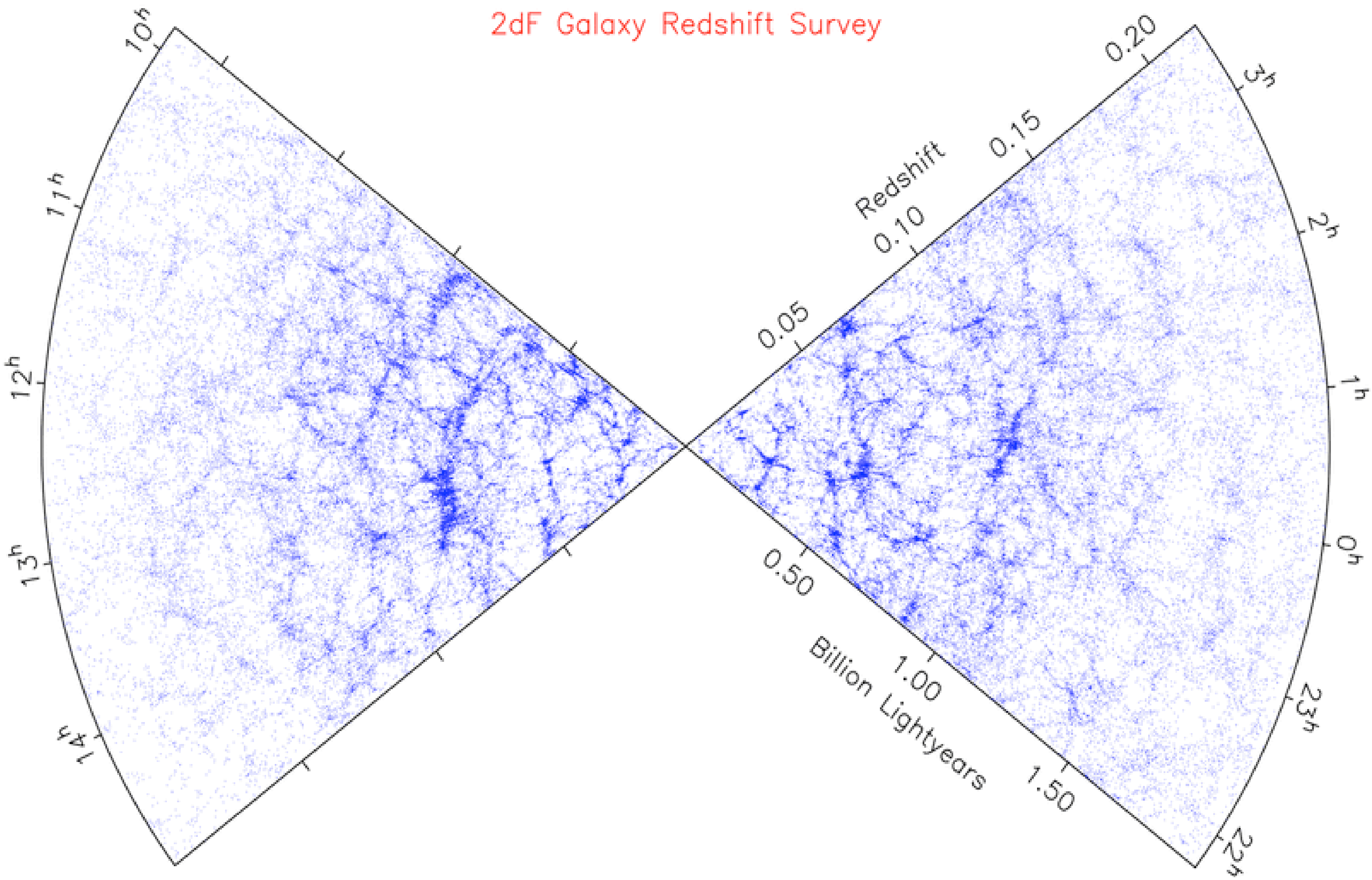


400 fibres in 2 deg Field

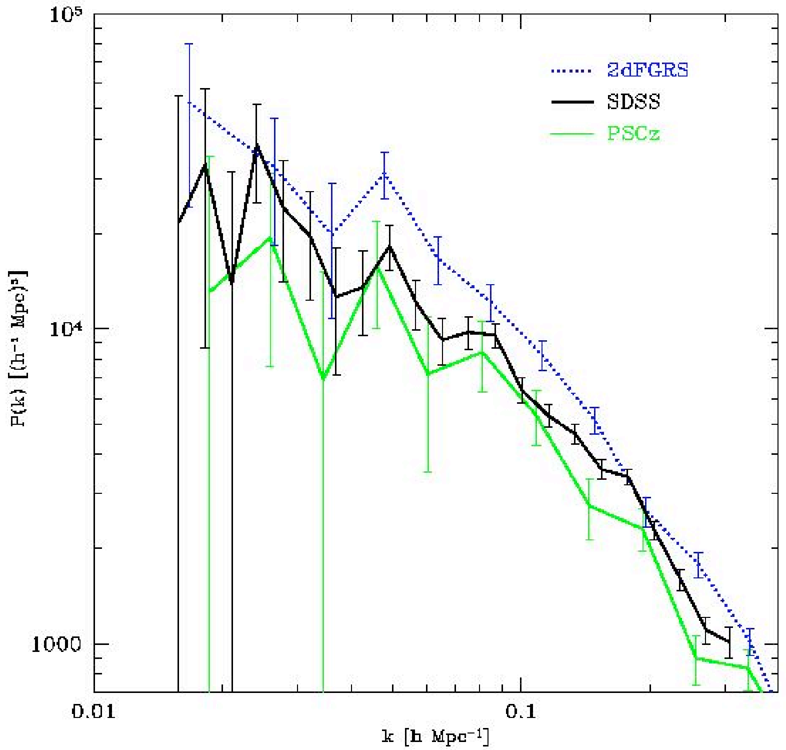


Similarly Sloan Digital Sky Survey

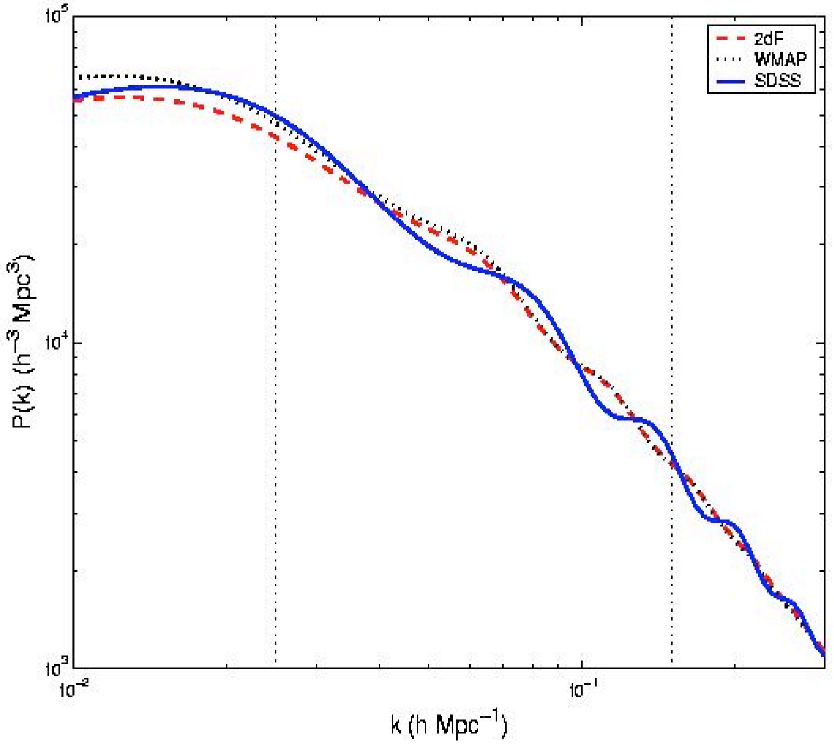
2 Degree Field



2dF vs SDSS



Tegmark et al. 2003



Pope et al. 2004

Limits on Neutrino Mass

2dF + SDSS alone

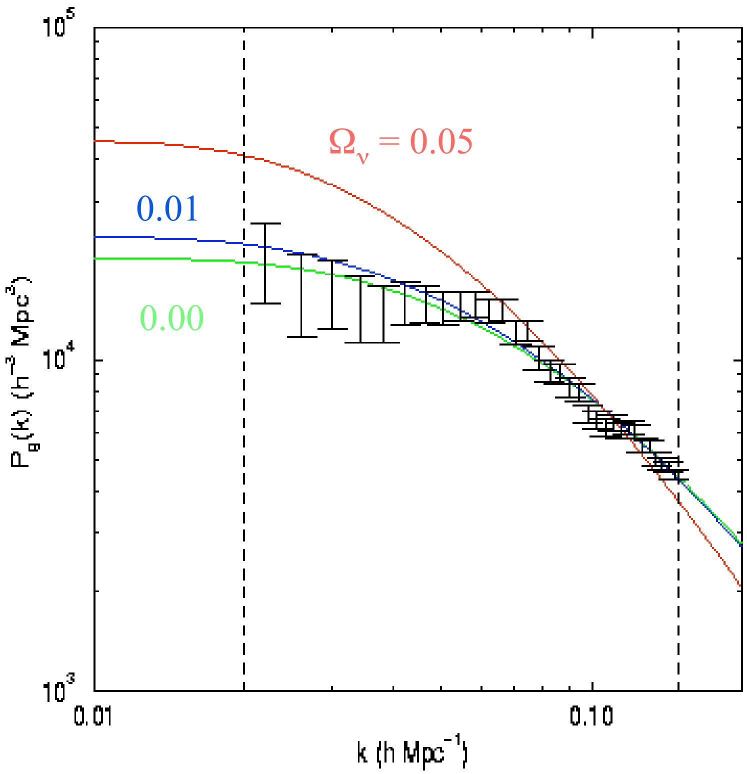
Measure Ω_ν/Ω_m

e.g. Elgaroy et al

$\Omega_\nu/\Omega_m < 0.13$ => $\Sigma m_\nu < 1.8 eV$

Assume Λ CDM

Mild dependence on spectrum index and bias



Elgaroy , Lahav & 2dFGRS team, astro-ph/0204152 , PRL

Add CMBR

Measure Ω_m!

e.g. Spergel et al.

$\Sigma m_\nu < 0.7 eV$

Lyman$_\alpha$

More priors!

Applies to sterile neutrino if mixes enough with other neutrinos

Neutrino mass from Cosmology

Ofer Lahav Neutrino 2004

Data	Authors	$M_\nu = \Sigma m_i$
2dFGRS	Elgaroy et al. 02	< 1.8 eV
WMAP+2dF+…	Spergel et al. 03	< 0.7 eV
WMAP+2dF	Hannestad 03	< 1.0 eV
SDSS+WMAP	Tegmark et al. 04	< 1.7 eV
WMAP+2dF+ SDSS	Crotty et al. 04	< 1.0 eV
Clusters +WMAP	Allen et al. 04	$0.56^{+0.30}_{-0.26}$ eV

All upper limits 95% CL, but different assumed priors !

Conclusion (Altarelli Neutrino 2004)

A very natural and appealing explanation:

ν's are nearly massless because they are Majorana particles and get masses through L non conserving interactions suppressed by a large scale $M \sim M_{GUT}$

$$m_\nu \sim \frac{m^2}{M}$$

$m \sim m_t \sim v \sim 200$ GeV
M: scale of L non cons.

Note:

$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.05$ eV
$m \sim v \sim 200$ GeV

$M \sim 10^{15}$ GeV

Neutrino masses are a probe of physics at M_{GUT} !

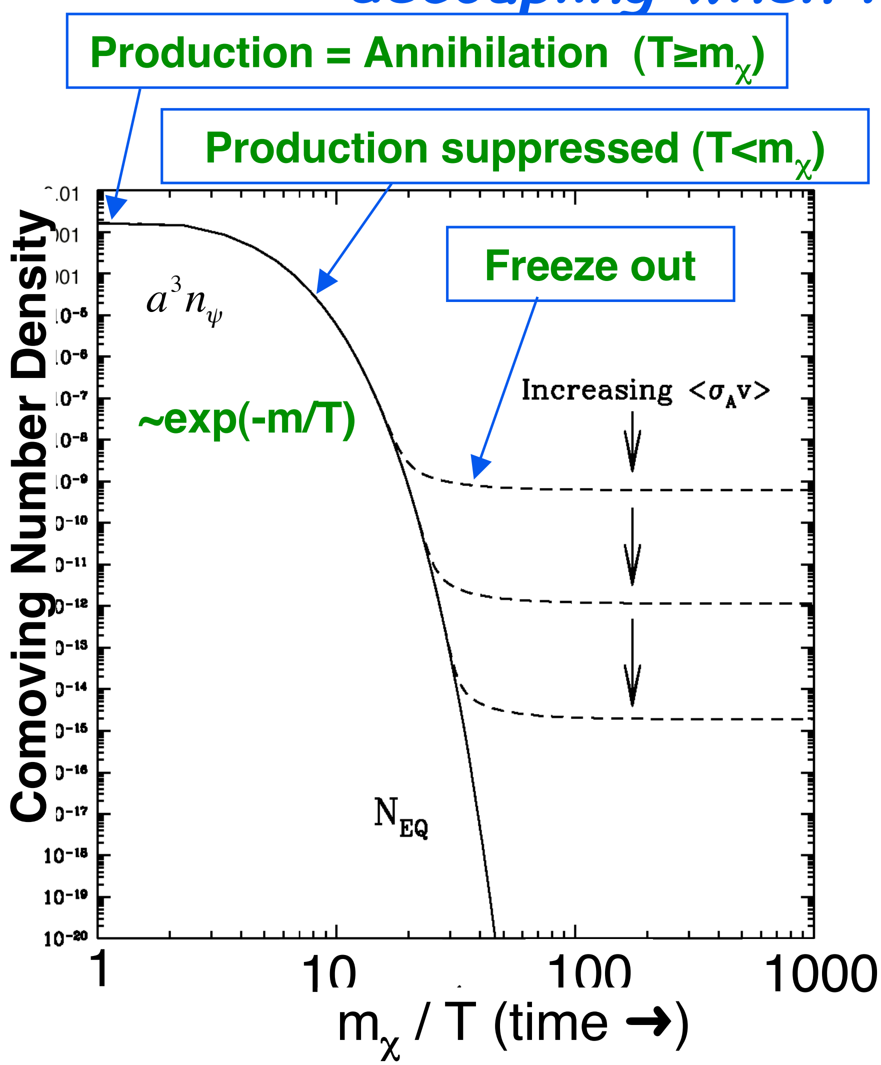
G. Altarelli

Most natural: Supersymmetry

Weakly Interactive Massive Particles

Particles in thermal equilibrium

+ decoupling when nonrelativistic



Density ~ 1/(interaction rate)
$\Omega \approx 1 \Rightarrow \sigma v \approx 10^{-26}\ cm^3/s$
Generic Class

Intuitive argument

If cross section is too large: will annihilate before decoupling

Not the dark matter today

If cross section is too small: will be diluted away by the expansion

Would over-close the universe

Delicate balance

Note involves both the Hubble constant and cross section.

The "fine tuning" can be in the Hubble constant

Weakly Interactive Massive Particles

Calculation

cf. Supersymmetric Dark Matter G. Jungman, M. Kamionkowski, K. Griest Phys.Rept. 267 (1996) 195-373. See also Kolb and Turner 119-130

Assuming $\sigma_A v = a + bv^2$
the solution of the Boltzmann equation is approximatively given by

$$\Omega_x h^2 \propto \frac{x_f}{\sqrt{g^*_{T_{freeze}}}\left\{a + 3\frac{(b - 1/4a)}{x_f}\right\}}$$

with $x_f = \frac{k_b T_{freeze}}{m_\chi}$ given by the solution of $x_f \approx \ln \frac{0.1\ m_{Planck} m_\chi (a + 6b/x_f)}{(\hbar c)^2 \left(g^*_{T_{freeze}} x_f\right)}$

Typically $x_f \approx 0.05$ with a logarithmic dependence on m_χ

and $\Omega_x h^2 = \frac{3 \cdot 10^{-27} cm^3/s}{\langle \sigma_A v \rangle}$ This implies a $\langle \sigma_A v \rangle$ of the order of the Weak Scale

Cosmology points to W&Z scale

Inversely standard particle model requires new physics at this scale

(e.g. supersymmetry) => significant amount of dark matter

We have to investigate this convergence!

Weakly Interactive Massive Particles

Ways to turn argument:

- Initial asymmetry $\chi \neq \bar{\chi}$

Suppose that

Cross section may be very large (e.g. heavy Dirac neutrino)

we are left with only small excess

Attractive to explain why same order of magnitude as protons

- Dilution by entropy production after freeze out

e.g. QCD or electroweak (if low enough) in case they are strongly first order

Unlikely

Note:

Formula in previous slide not valid near pole, threshold or coannihilation

$$\chi\bar{\chi} \underbrace{\leftrightarrow}_{\text{strong interactions}} \chi'\bar{\chi}' \text{ with } \chi' \text{ slightly heavier :}$$

governed by the largest annihilation cross section

Weakly Interactive Massive Particles

Generic model

Independent of supersymmetry!

Although supersymmetry is best motivation!

Annihilation rate provides a normalization

The higher the cross section the lower the density!

- Directly fixes annihilation rate in halo

  However we are sensitive only to specific channels

  e.g. $\chi\bar{\chi} \to \gamma\gamma$ while $\sigma_A v = \sum_{\text{all final states}} \chi\bar{\chi} \to \cdots$

  Rate depends on square of density n_χ!

- Elastic scattering : Direct detection

  $\chi q \to \chi q$ = crossed channel of $\chi\bar{\chi} \to q\bar{q}$

Usually crossing operation gives factor of the order of unity

Still dependent on ratio of the annihilation cross section into quarks to total (usually few %)