SOLAR NEUTRINOS

Source of Energy of the SUN : Nuclear Fusion

$$4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu_e$$

Energy Released per each Cycle

$$Q = 4m_p + 2m_e - m_{He} = 26.73 \ \mathrm{MeV}$$

$$\Phi_{\nu_e} \simeq \frac{1}{4\pi\, d_\odot^2} \frac{2\, L_\odot}{(Q - \langle E_\nu \rangle)}$$

$$\phi_{\nu_\odot} \sim 6 \times 10^{10} \ (\mathrm{cm}^2 \ \mathrm{s})^{-1}$$

Neutrino Flux

STANDARD SOLAR MODEL

Spherical symmetry

$\rho(r)$ density

$T(r)$ Temperature

$P(r)$ Pressure

$\{X_Z(r)\}$ composition

$L(r)$ [erg s^{-1}] Energy Flux

$\epsilon(r)$ [erg g^{-1} s^{-1}]. Energy Released in nuclear reactions

- Equation of State $f(\rho, P, T)$
- Opacity $k(T, \rho, \{X_Z\})$
- Nuclear Cross Sections $\sigma_{ab\to cd}(E)$

1. Hydrostatic Equilibrium
2. Energy Conservation
3. Radiative Transport

$L_\odot = 3.86 \times 10^{33}$ erg

$M_\odot = 1.99 \times 10^{33}$ g

$R_\odot = 6.96 \times 10^{10}$ cm

$T_{eff} = 5.78 \times 10^3 \circ K$

$t_\odot = 4.55 \times 10^9$ years

Initial composition = Composition at surface

$$\frac{dP}{dr} = -\frac{G\,M(r)\,\rho(r)}{r^2}$$

Hydrostatic Equilibrium

$$\sigma[(T+dT)^4 - T^4] \simeq 4\,\sigma\,T^3 dT$$

$$L(r) = -4\pi\,r^2\,\frac{16\sigma}{3\kappa\rho}\,T^3\,\frac{dT}{dr}$$

Radiative Transport

$$(4\pi r^2 dr)\;\rho(r)\;\left[\epsilon(r) - \frac{dQ(r)}{dt}\right] = [L(r+dr) - L(r)]$$

$$\frac{dL(r)}{dr} = 4\pi r^2\,\rho(r)\left[\epsilon(r) - T(r)\,\frac{dS(r)}{dt}\right]$$

Energy Conservation

NUCLEAR REACTIONS

$$p + p \rightarrow d + e^+ + \nu_e$$

$$^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$$

$$r = N_a\, N_b \int d^3 v_a \phi_a(v_a) \int d^3 v_b\, \phi_b(v_b)\, v\, \sigma(v)$$

Rate of interactions
($cm^{-3}\, s^{-1}$)

$$\sigma(E) = \frac{S(E)}{E} \exp\left[-\frac{2\pi Z_a\, Z_b}{\hbar\, v}\right]$$

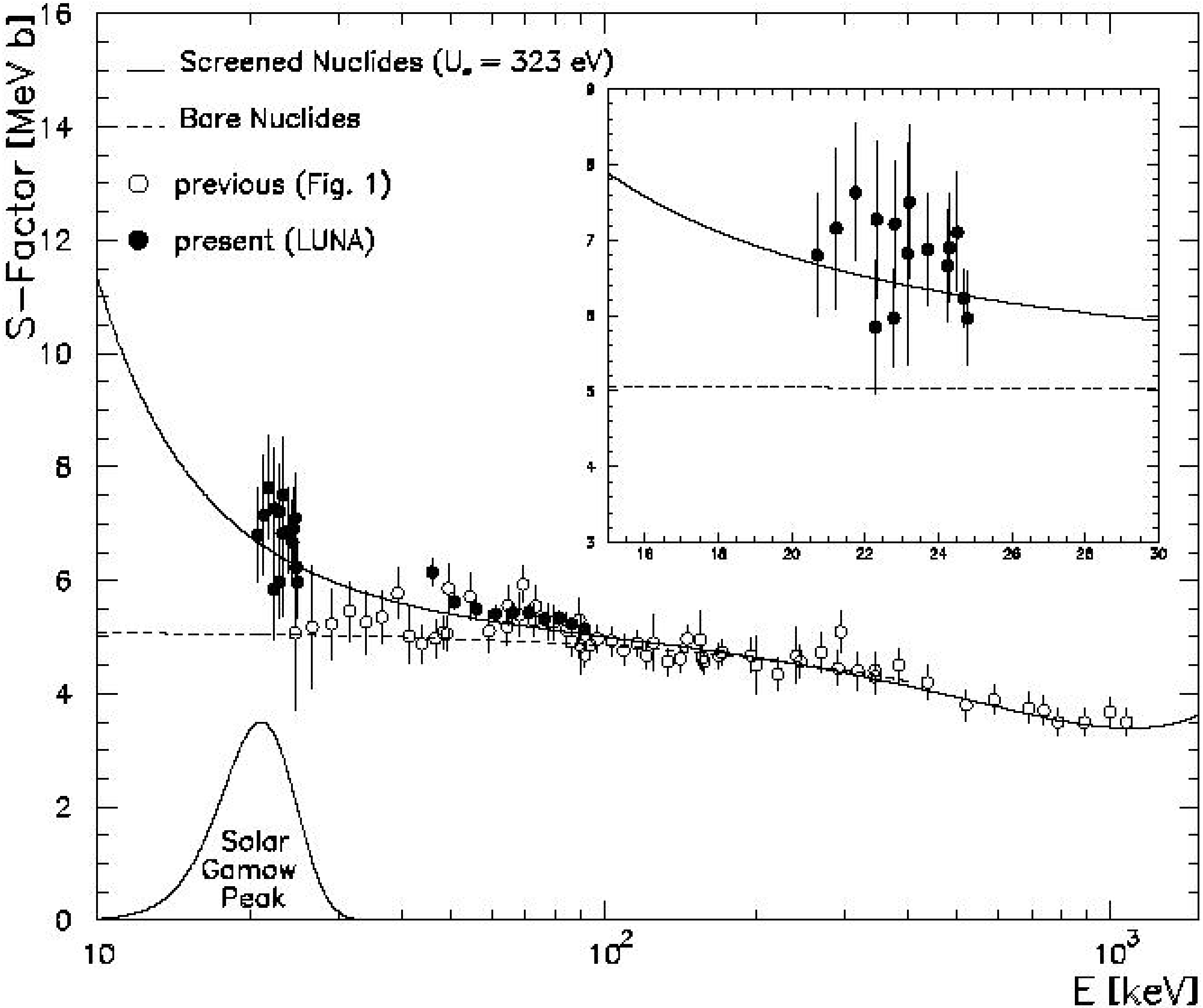
Cross section

$$\epsilon = \sum_j Q_j\, r_j$$

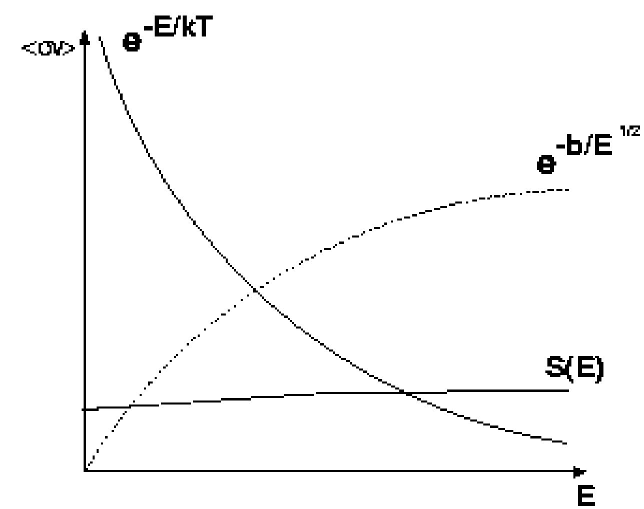
Energy production
erg/(cm^3 s)

$$^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$$

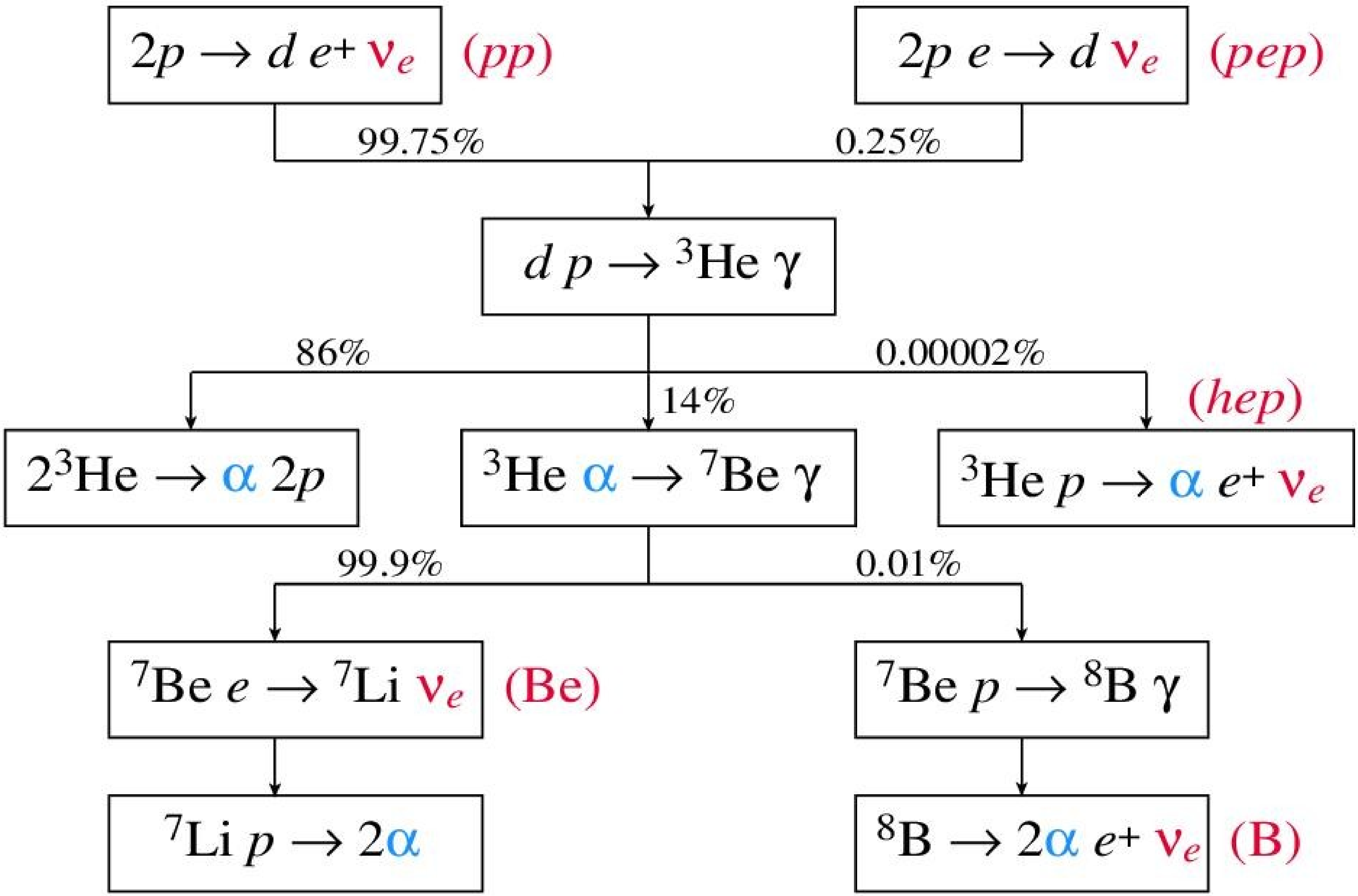
$$\sigma(E) = \frac{S(E)}{E}\ \exp\left[-\frac{2\pi Z_a Z_b}{\hbar v}\right]$$



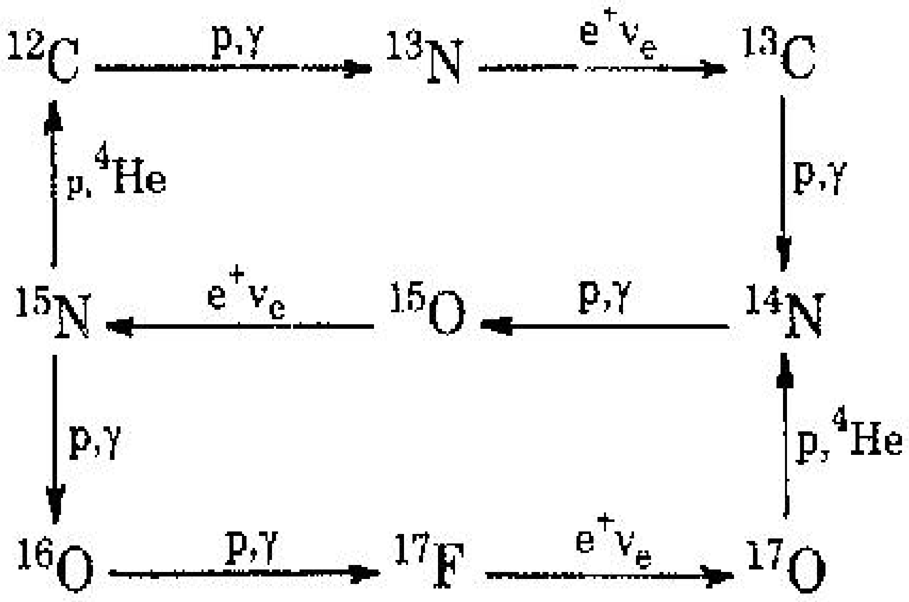
LUNA experiment (Gran Sasso)



PP cycles

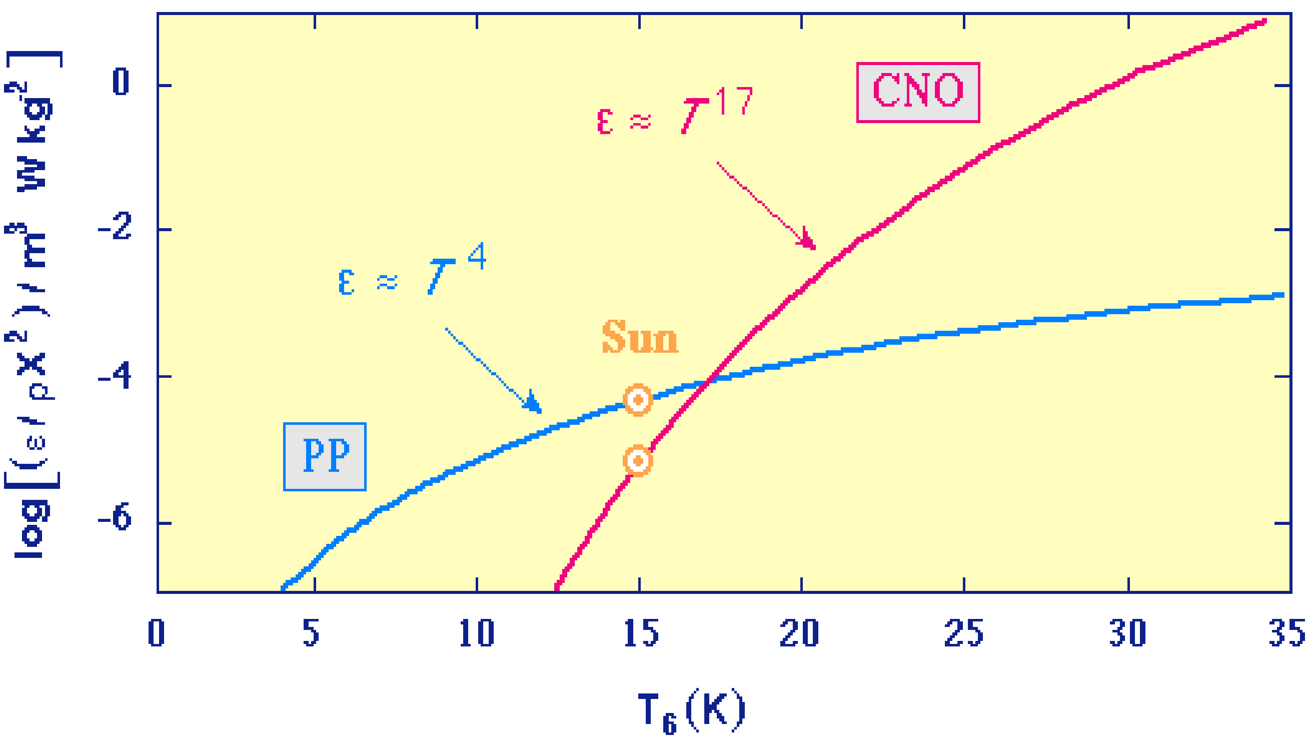


$2p \to d\, e^+ \nu_e$
(pp)
$2p\, e \to d\, \nu_e$
(pep)
99.75%
0.25%
$d\, p \to {}^3\mathrm{He}\, \gamma$
86%
14%
0.00002%
(hep)
$2\,{}^3\mathrm{He} \to \alpha\, 2p$
${}^3\mathrm{He}\, \alpha \to {}^7\mathrm{Be}\, \gamma$
${}^3\mathrm{He}\, p \to \alpha\, e^+ \nu_e$
99.9%
0.01%
${}^7\mathrm{Be}\, e \to {}^7\mathrm{Li}\, \nu_e$
(Be)
${}^7\mathrm{Be}\, p \to {}^8\mathrm{B}\, \gamma$
${}^7\mathrm{Li}\, p \to 2\alpha$
${}^8\mathrm{B} \to 2\alpha\, e^+ \nu_e$
(B)

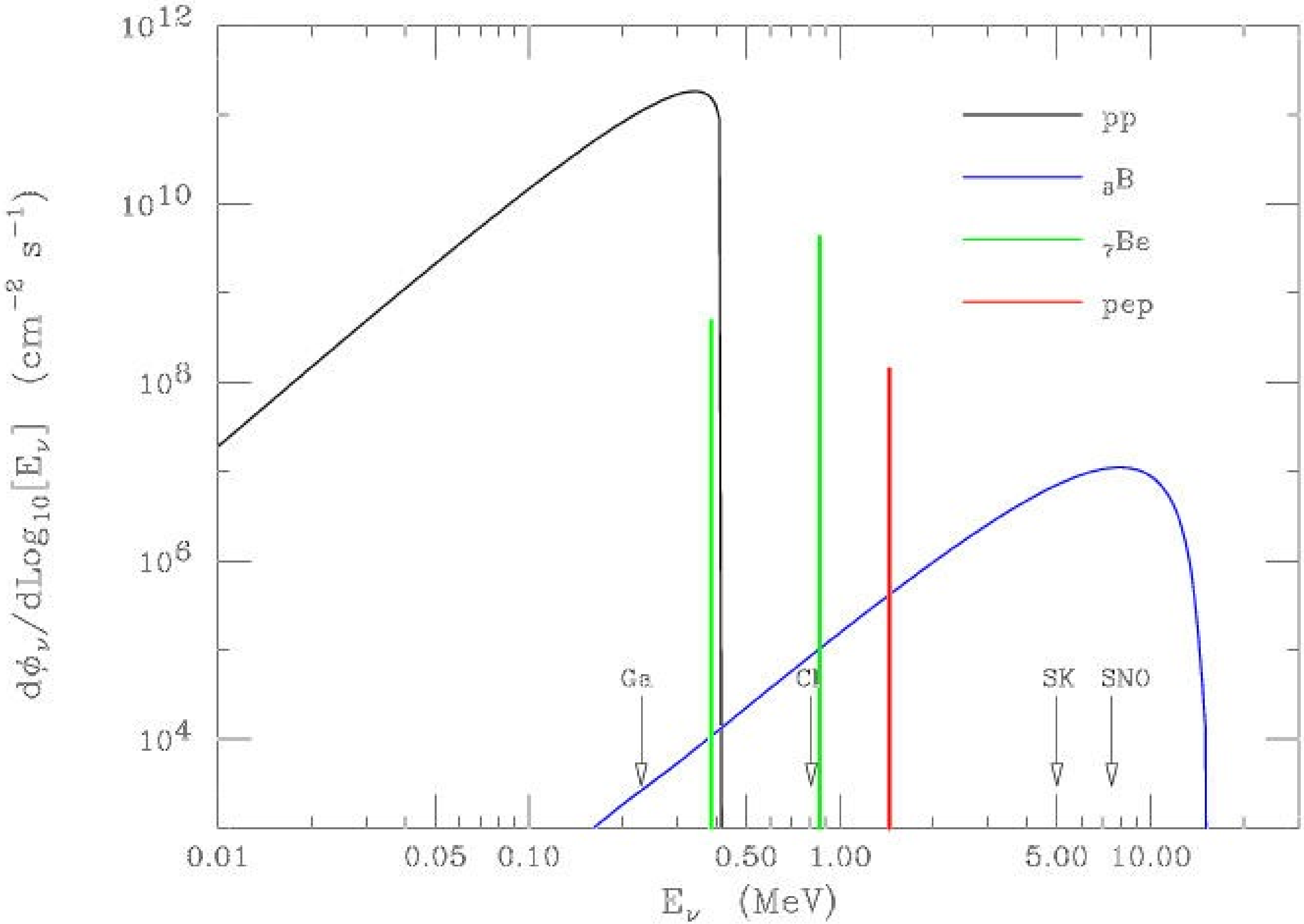


CNO bi-cycle

Dominant for
stars more massive than the sun



Main 3 Components of Solar Neutrino Flux



Detection of Solar Neutrinos:

Chlorine Experiment
(Ray Davis)

$$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$$

Gallium Experiments
[Gallex, Sage]

$$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$$

(Super)-Kamiokande
Electron Scattering

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

Heavy Water [SNO]

$$\nu_e + d \rightarrow e^- + p + p$$

$$\nu_x + d \rightarrow \nu_x + p + n$$

Radio-Chemical Experiments

$$\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$$

$$C_j = \int dE\, \phi_{\nu_\odot}(E)\, \sigma_j(E)$$

Capture Rate

$$1\ \mathrm{SNU} \equiv 1\ \mathrm{Solar\ Neutrino\ Unit} = 10^{-36}\ \mathrm{sec}^{-1}$$

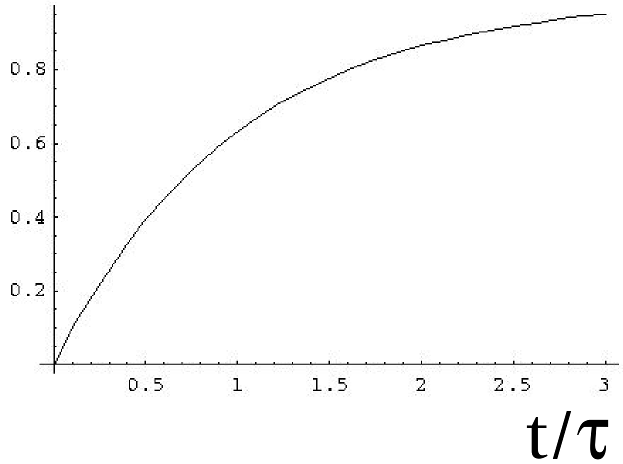
$$ {}^{37}\mathrm{Ar} + e^- \to {}^{37}\mathrm{Ar} + \nu_e $$

DECAY

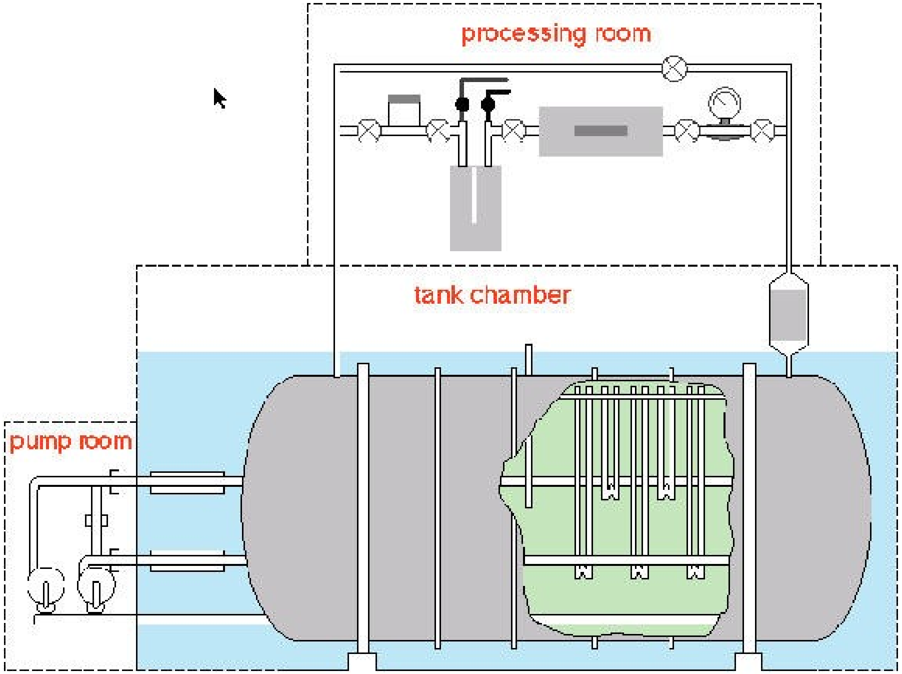
$T_{1/2} = 35$ days

$$\frac{dN_{\mathrm{Ar}}}{dt} = N_{\mathrm{Cl}}\, C_{(\mathrm{Cl}\to\mathrm{Ar})} - \frac{N_{\mathrm{Ar}}}{\tau_{\mathrm{Ar}}}$$

$$N_{\mathrm{Ar}}(t) = N_{\mathrm{Cl}}\, C\, \tau_{\mathrm{Ar}}\, [1 - \exp(-t/\tau_{\mathrm{Ar}})]$$



1. A Small quantity of stable and isotopically pure Argon ^{36}Ar or ^{37}Ar (the *carrier*) is introduced in the detector.
2. The Chlorine is exposed to solar neutrinos.
3. The detector is fluxed with Helium to remove all Argon.
4. The Argon (stable and unstable isotopes) is chemically isolated and introduced into a small counter ($\sim$ 0.4 cc).
5. The extraction efficiency is estimated with tha fraction of the *carrier* that is recovered.
6. The Argon–37 is revealed via the emission of an Auger electron of 2.82 KeV.

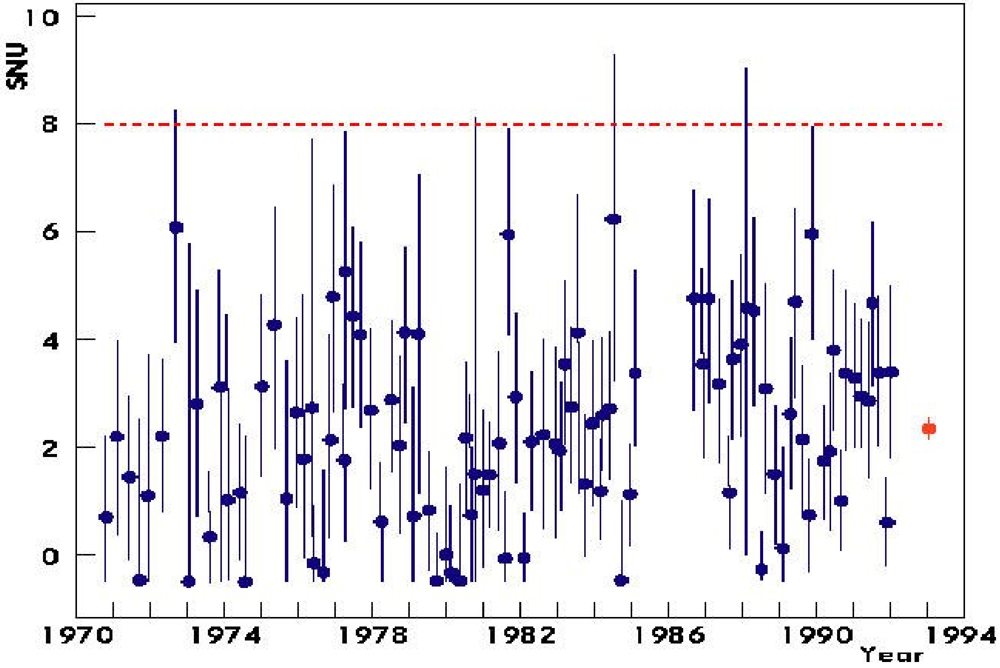


Davis experiment

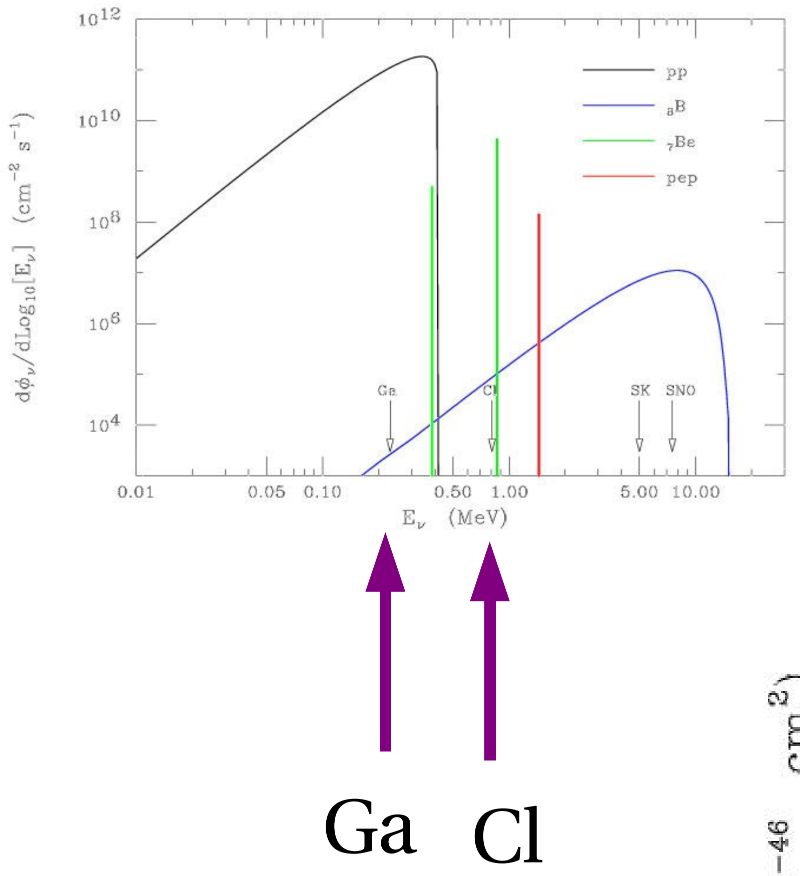
Chlorine

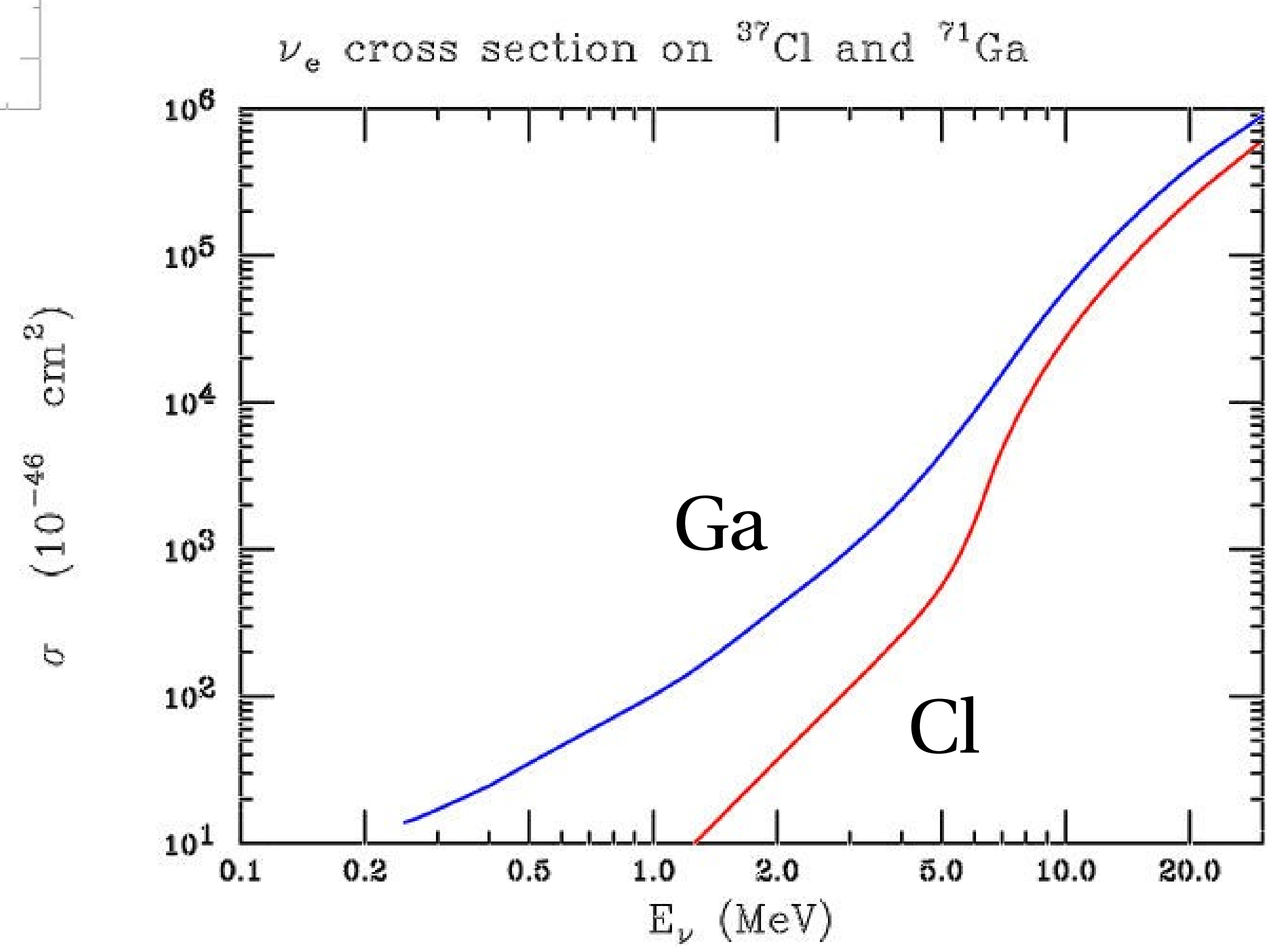
$$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$$

615 tons $C_2 Cl_4$

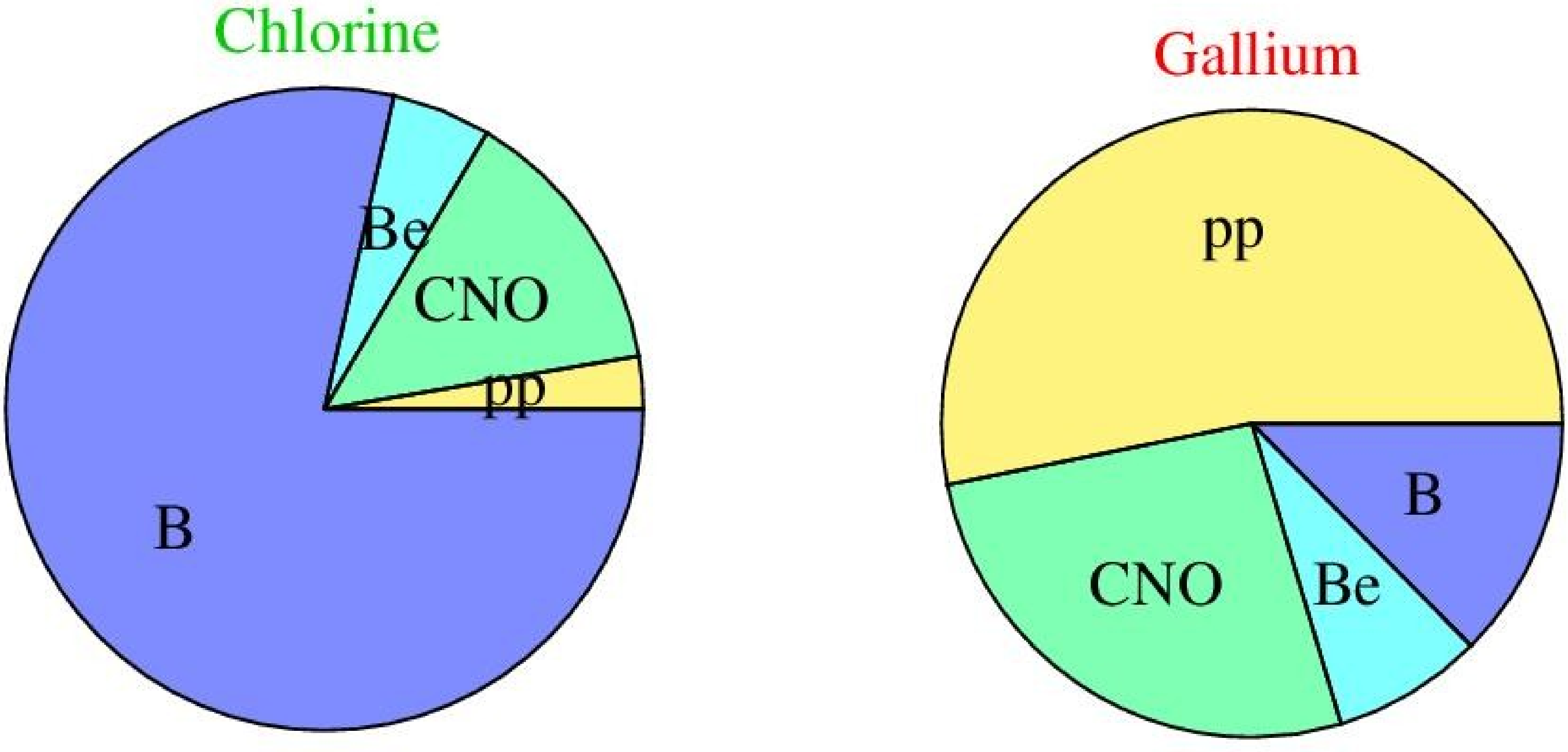


Capture Cross Section

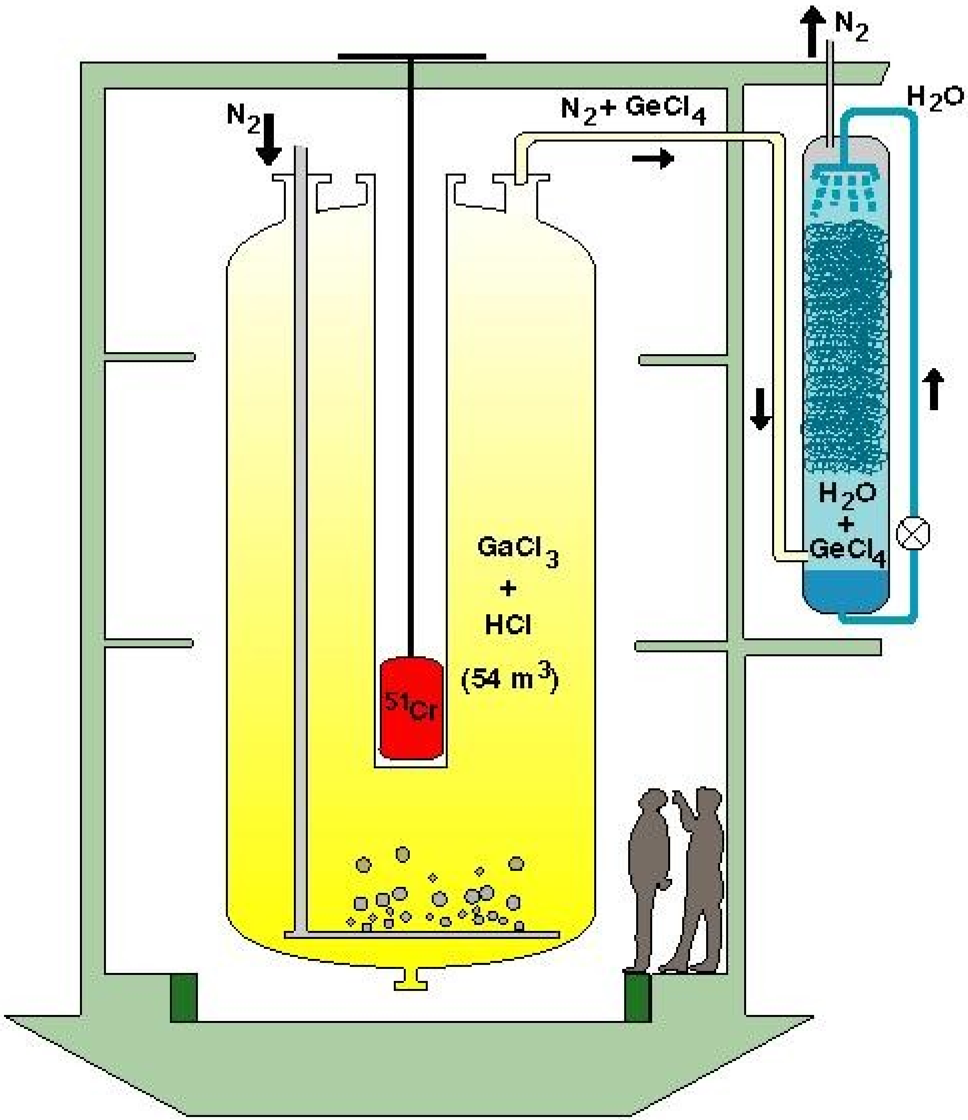




Fraction of the Solar Neutrino Capture Rate due to different components of the flux

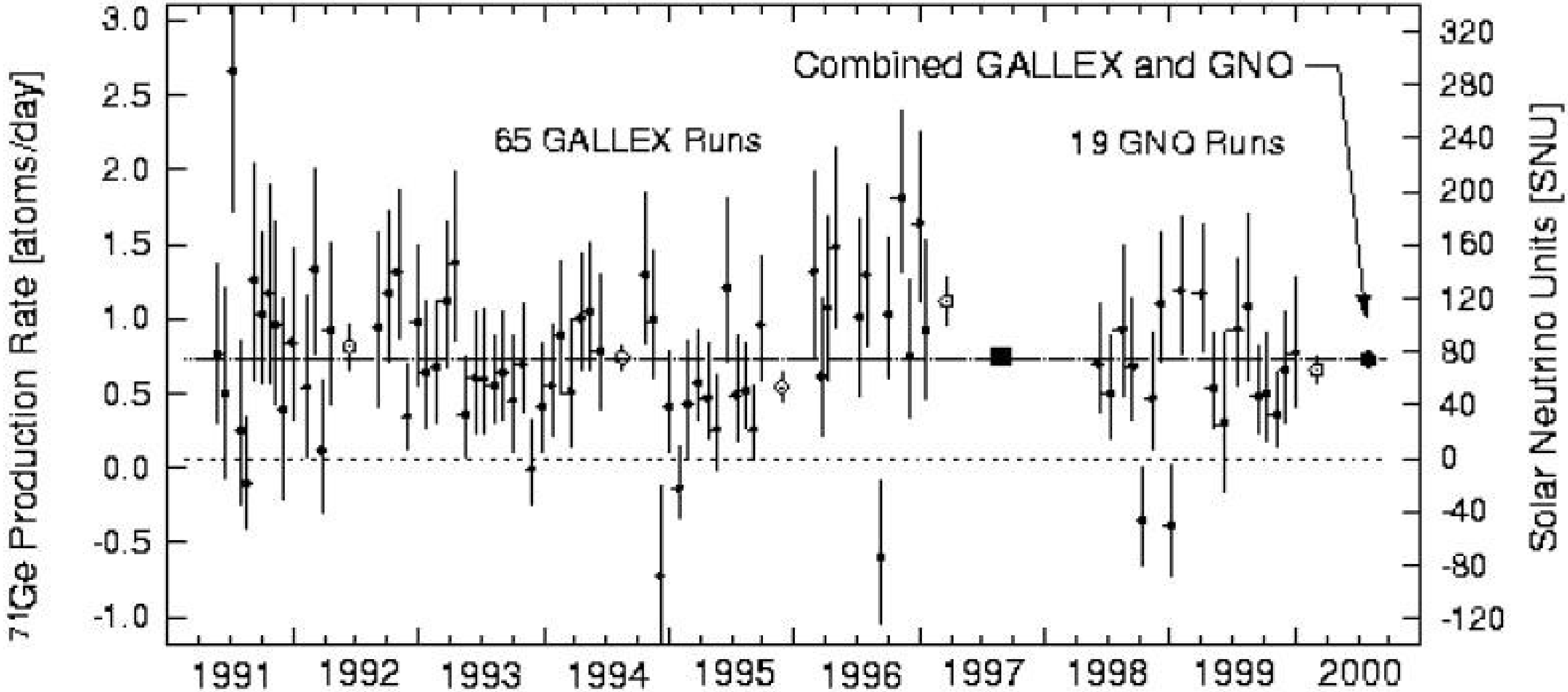


Gallex (Gran Sasso)

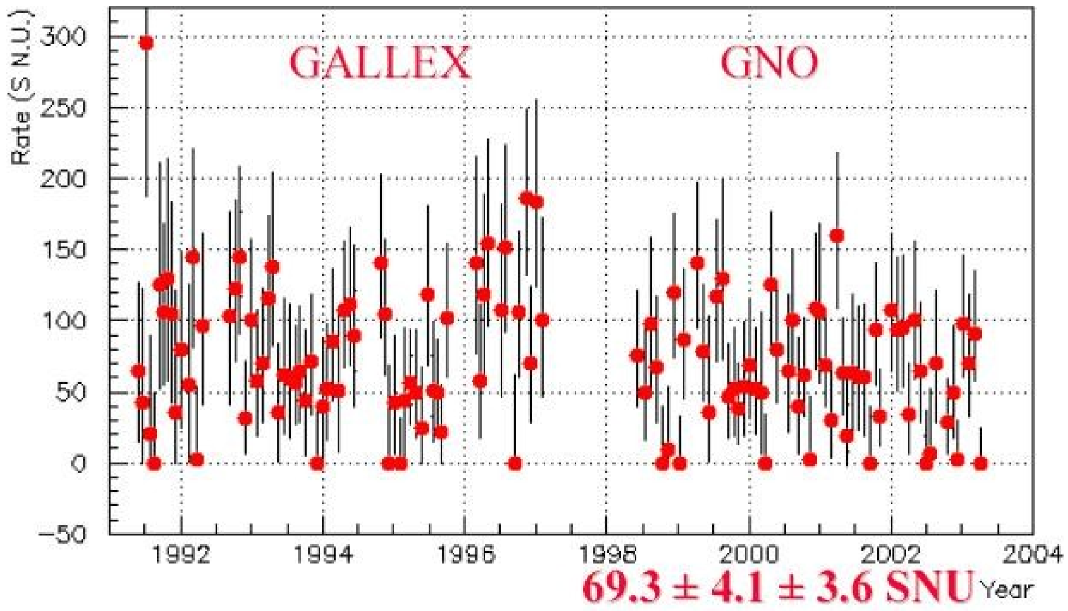


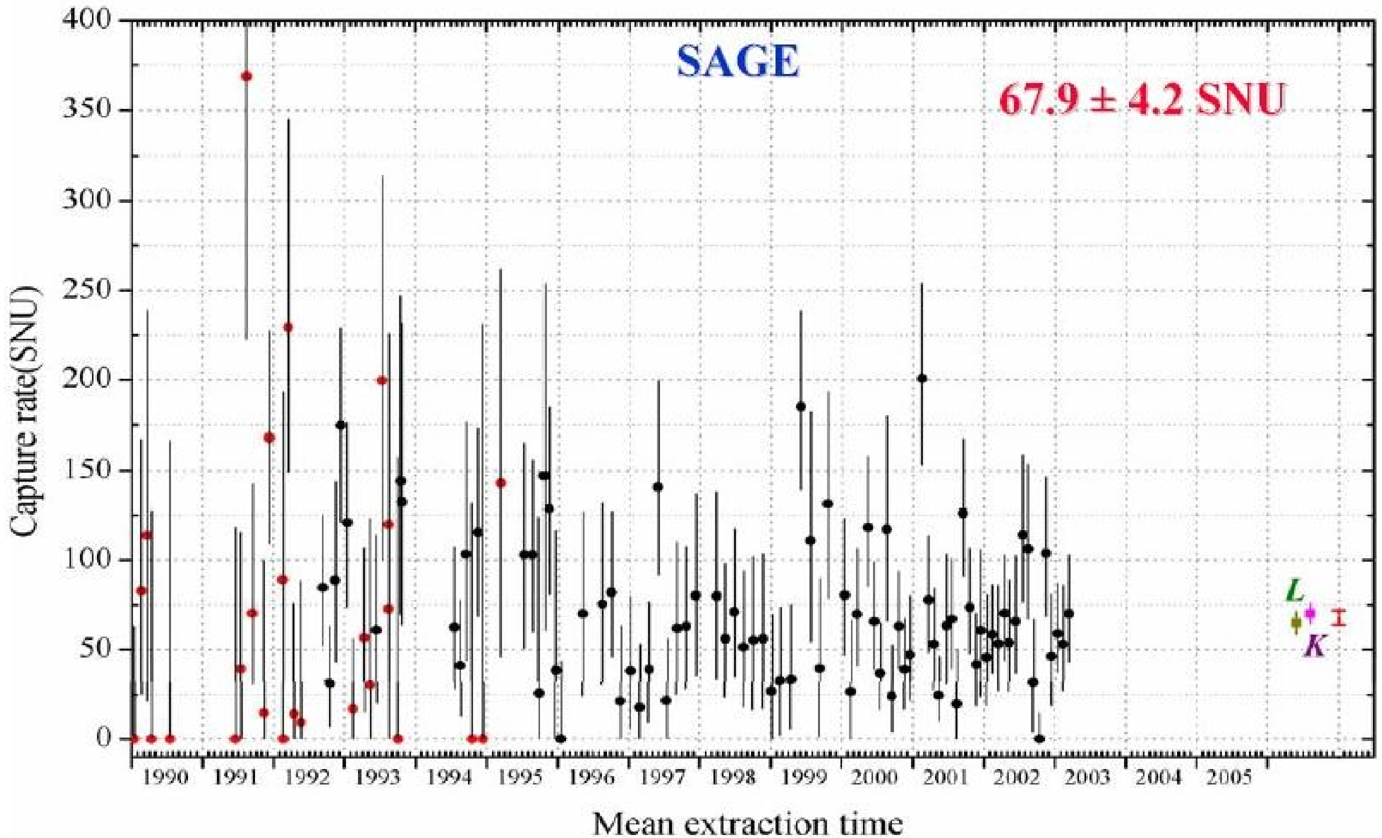
$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

30.3 tons of Gallium



Experiment	(SNU) Prediction	Data	Data/Prediction
Chlorine	$7.6^{+1.3}_{-1.1}$	2.56 ± 0.23	0.34 ± 0.06
GALLEX + GNO	128^{+9}_{-7}	$74.1^{+6.7}_{-7.8}$	0.58 ± 0.07
SAGE	128^{+9}_{-7}	$75.4^{+7.8}_{-7.4}$	0.59 ± 0.07


GALLEX
GNO
Rate (S.N.U.)
300
250
200
150
100
50
0
−50
1992
1994
1996
1998
2000
2002
2004
Year
69.3 ± 4.1 ± 3.6 SNU


SAGE
67.9 ± 4.2 SNU
Capture rate(SNU)
400
350
300
250
200
150
100
50
0
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
L
K
Mean extraction time

Electron Scattering

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

$$\frac{d\sigma_{\nu_x e}}{dT} = \frac{2G_F^2 m_e^2}{\pi}\left[g_L^2 + g_R^2\,\left(1 - \frac{T}{E_\nu}\right)^2 - g_L\, g_R\,\frac{m_e c^2 T}{E_\nu^2}\right]$$

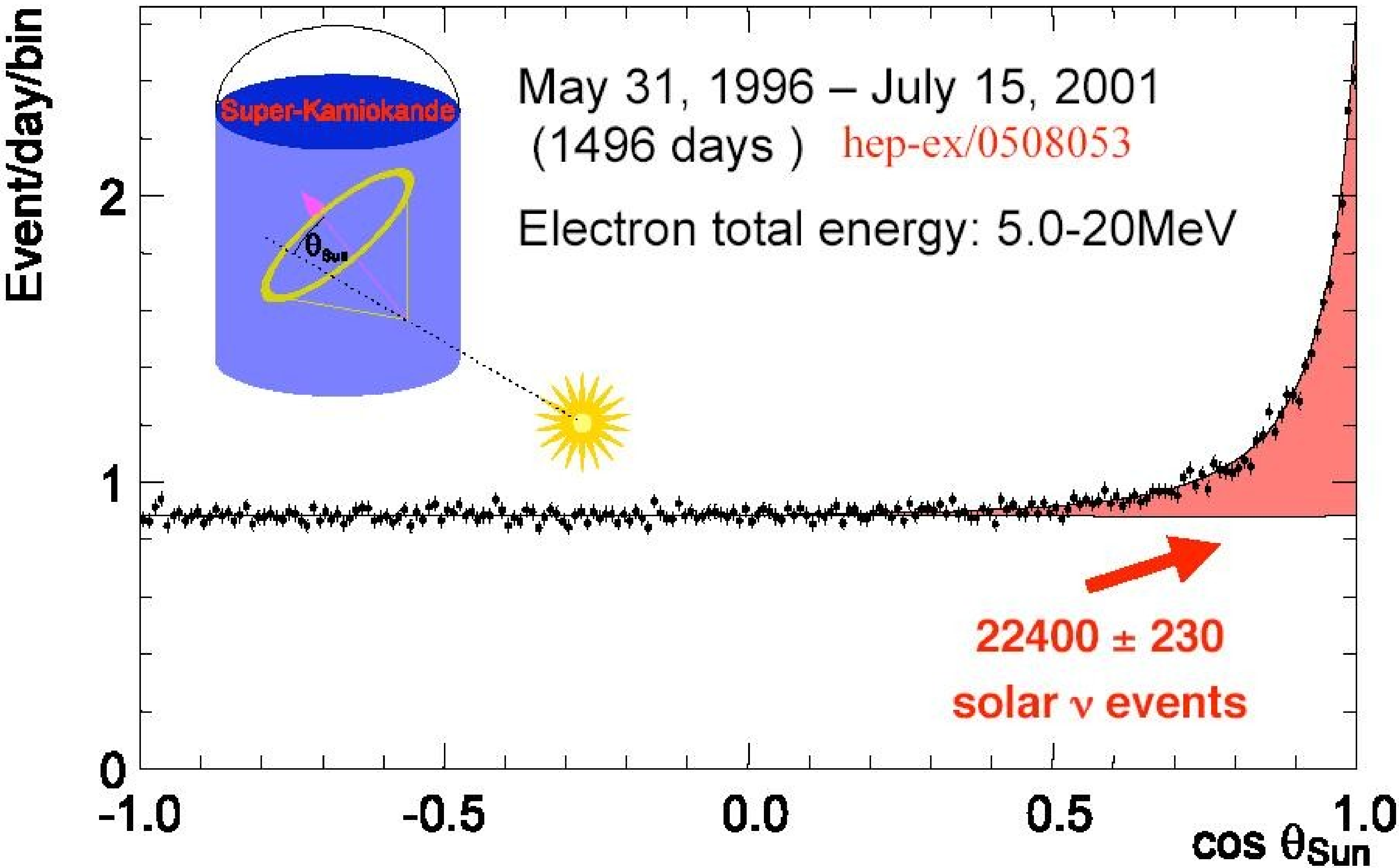
T = Kinetic Energy of
the final state electron

$$g_L^2 = \begin{cases} \left(\frac{1}{2} + \sin^2\theta_W\right)^2 & \simeq & 0.536 & , & \nu_e \\ \sin^4\theta_W & \simeq & 0.0538 & , & \bar{\nu}_e \\ \left(-\frac{1}{2} + \sin^2\theta_W\right)^2 & \simeq & 0.0719 & , & \nu_i \\ \sin^4\theta_W & \simeq & 0.0538 & , & \bar{\nu}_i \end{cases}$$

Cross section strongly
peaked for electron emission
in the neutrino direction

$$g_R^2 = \begin{cases} \sin^4\theta_W & \simeq & 0.0538 & , & \nu_e \\ \left(\frac{1}{2} + \sin^2\theta_W\right)^2 & \simeq & 0.536 & , & \bar{\nu}_e \\ \sin^4\theta_W & \simeq & 0.0538 & , & \nu_i \\ \left(-\frac{1}{2} + \sin^2\theta_W\right)^2 & \simeq & 0.0719 & , & \bar{\nu}_i \end{cases}$$

SK-I: ^{8}B Solar Neutrino Flux



$$\phi_{ES} = 2.35 \pm 0.02 \pm 0.08 \ \ [\times 10^{6}/cm^{2}/s]$$

- 22,385 solar neutrino events

^{8}B flux : $2.35 \pm 0.02 \pm 0.08$ [x 10^{6} /cm^{2}/sec]

48,200 solar neutrinos (from SSM)

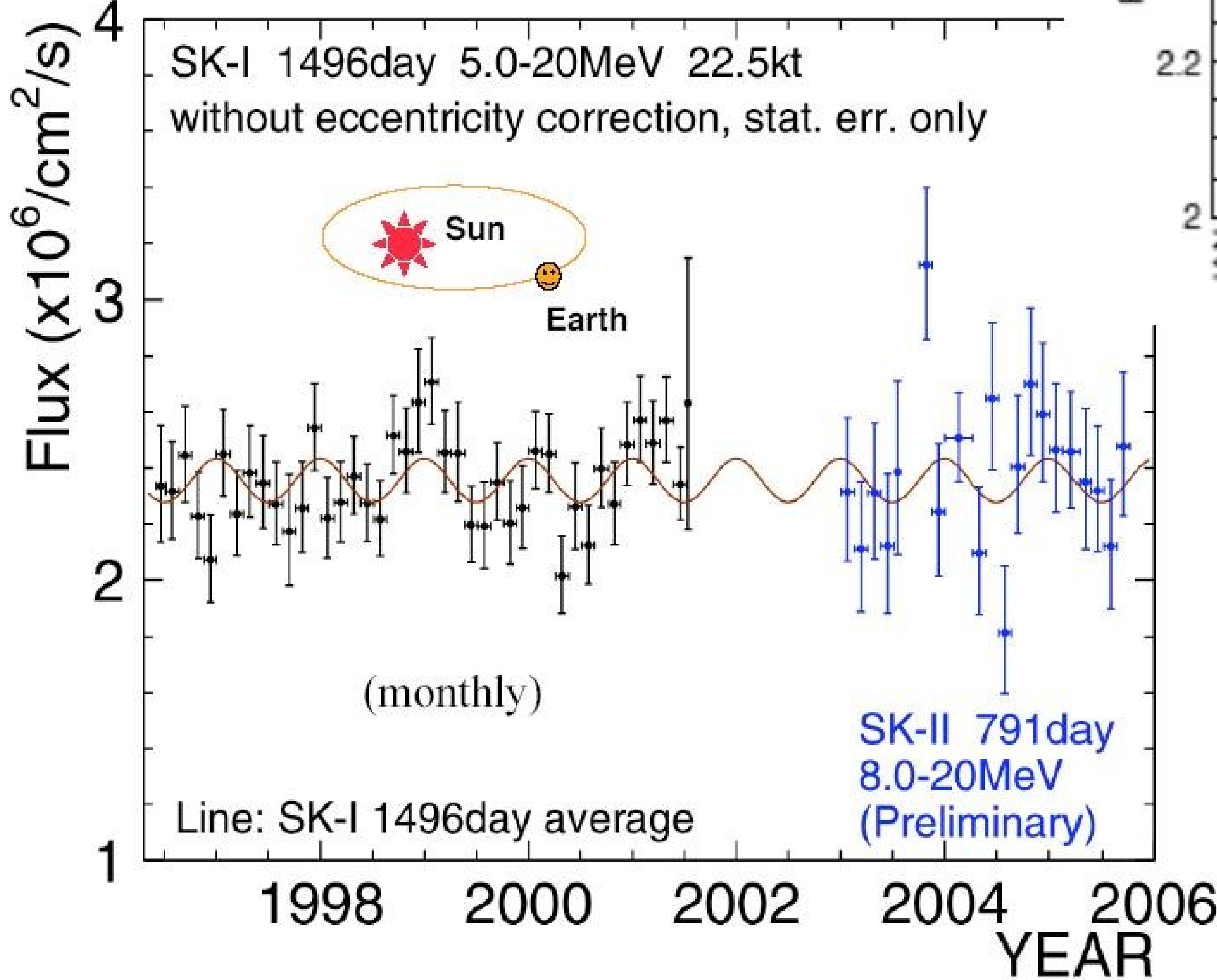
$$\frac{\text{Data}}{\text{SSM(BP2000)}} = 0.465 \pm 0.005 {}^{+0.016}_{-0.015}$$

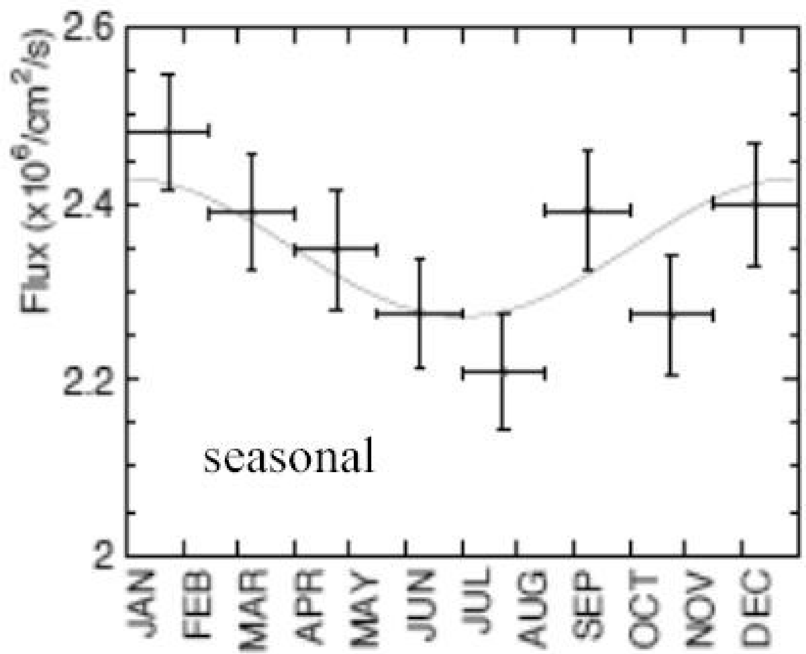
3 Dogs that did not bark :

Day- Night Effect
[Zenith angle dependence (Matter effects)]

Distortion of Energy Spectrum

Seasonal Effects
(Sun-Earth distance dependence)



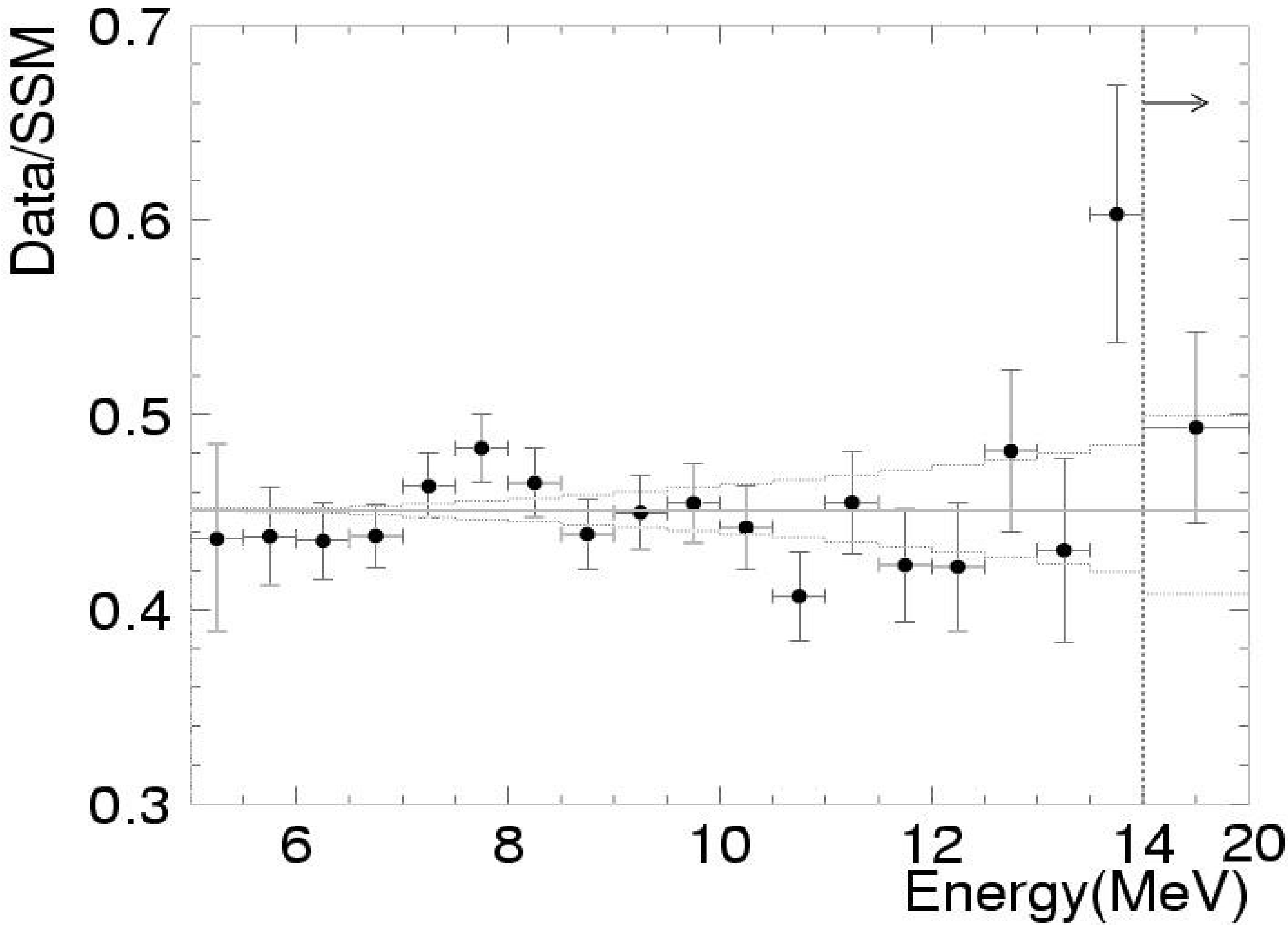


SK-I

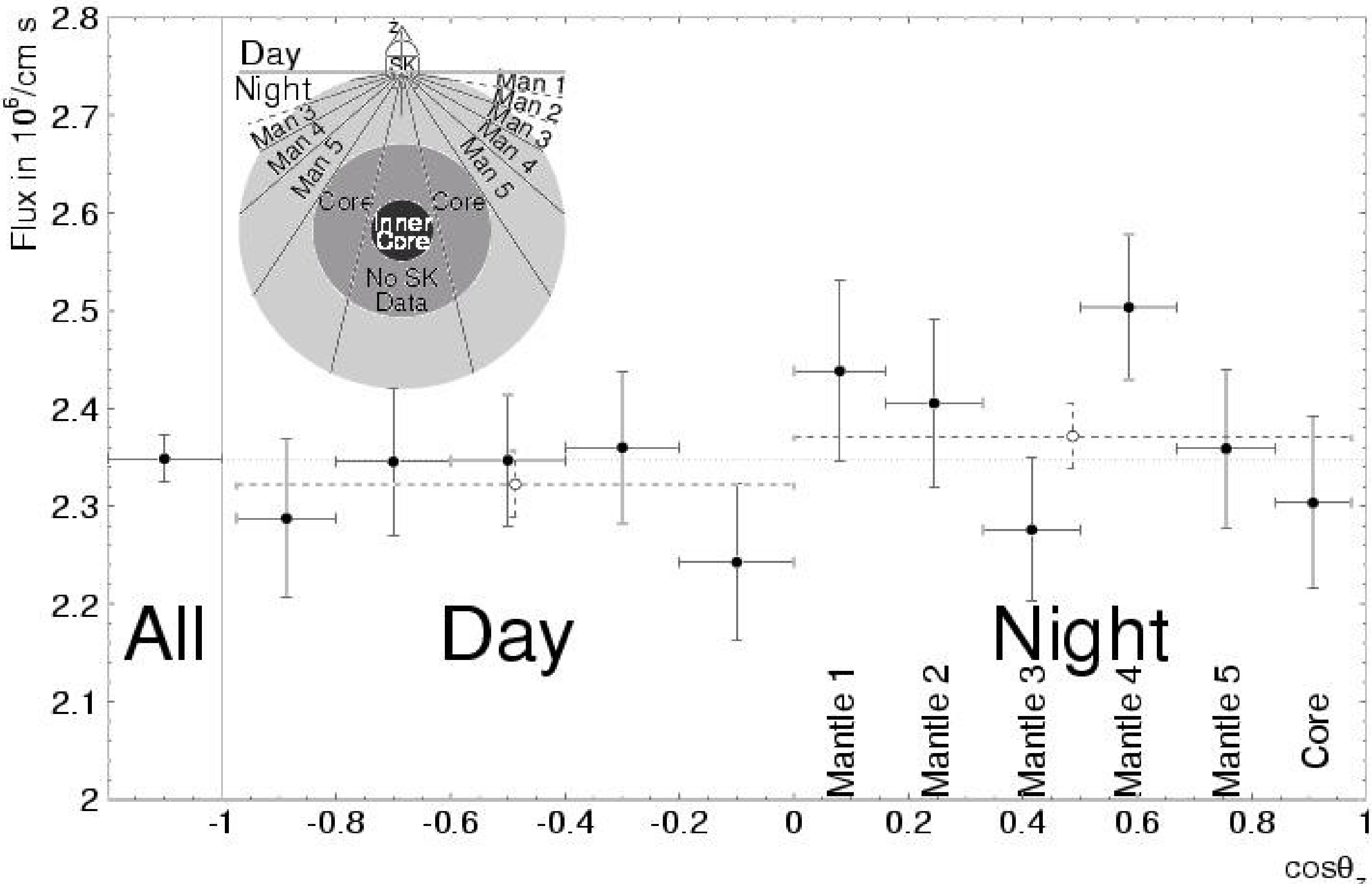
↓

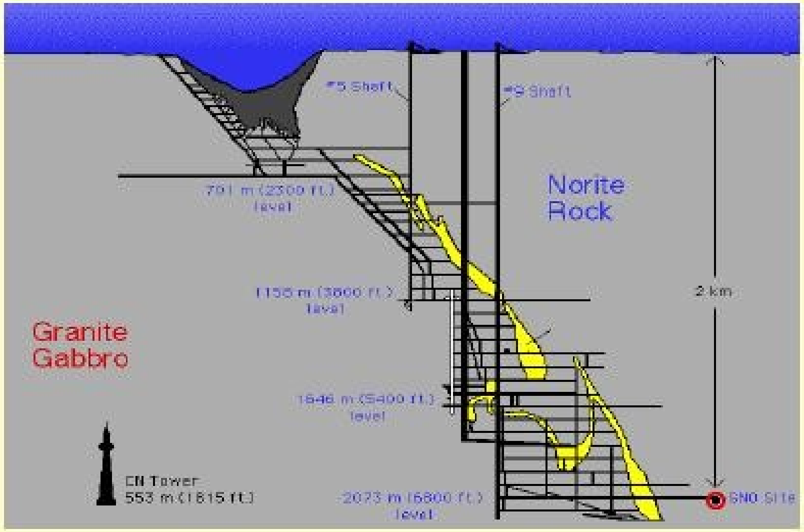
Eccentricity = (2.1 ± 0.3) %

SK Energy Spectrum



SK Zenith angle effect





Sudbury Neutrino Observatory

1000 tonnes D_2O

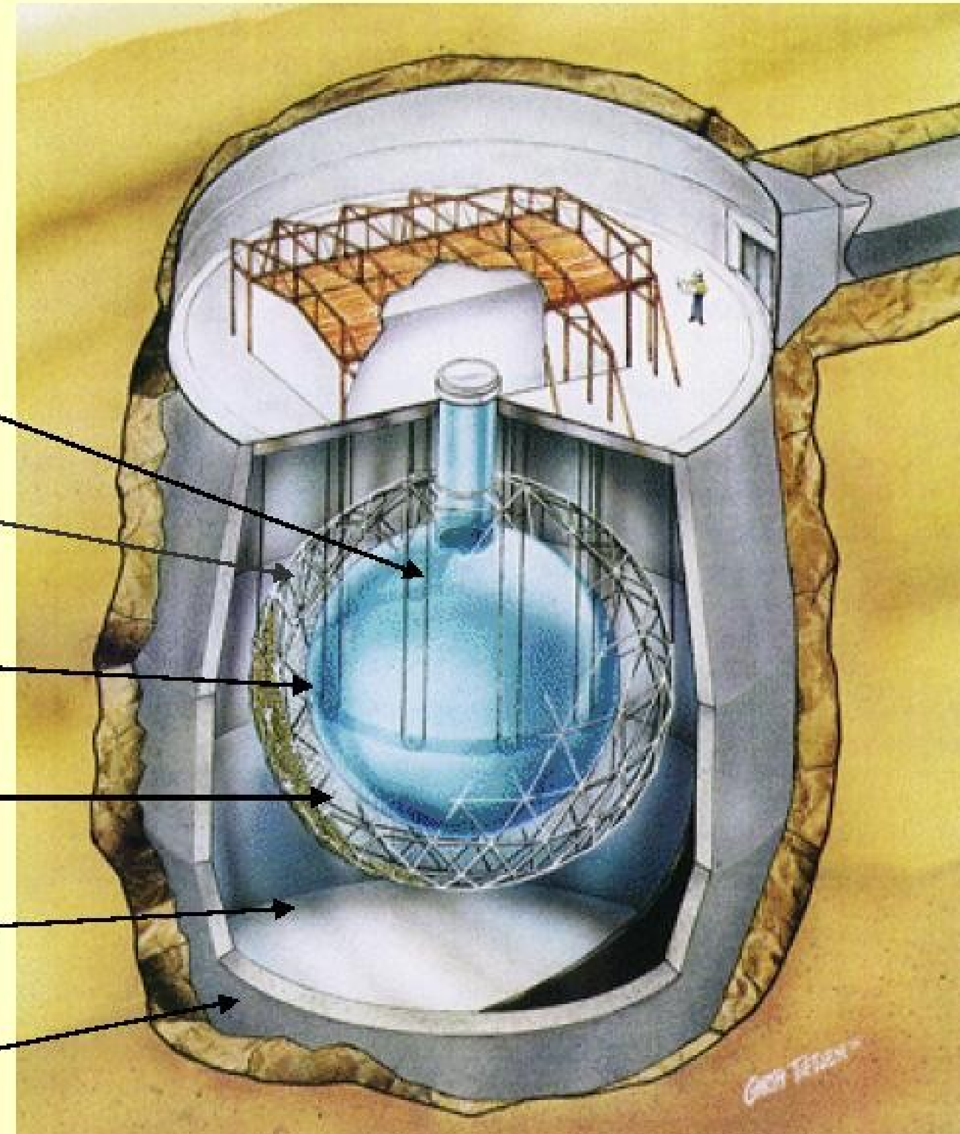
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

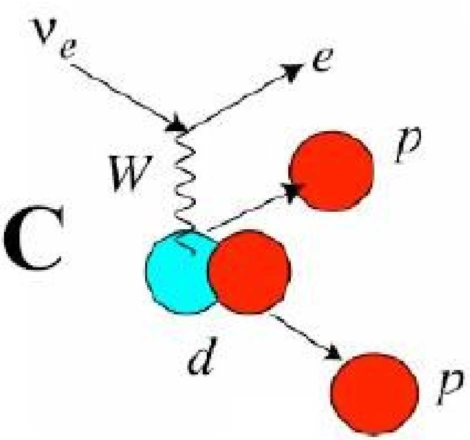
1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

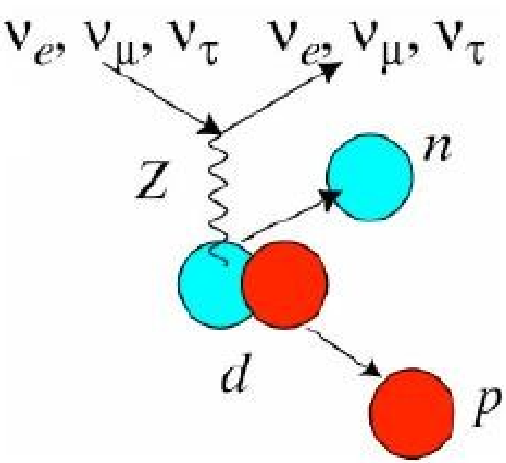
Urylon Liner and Radon Seal



CC



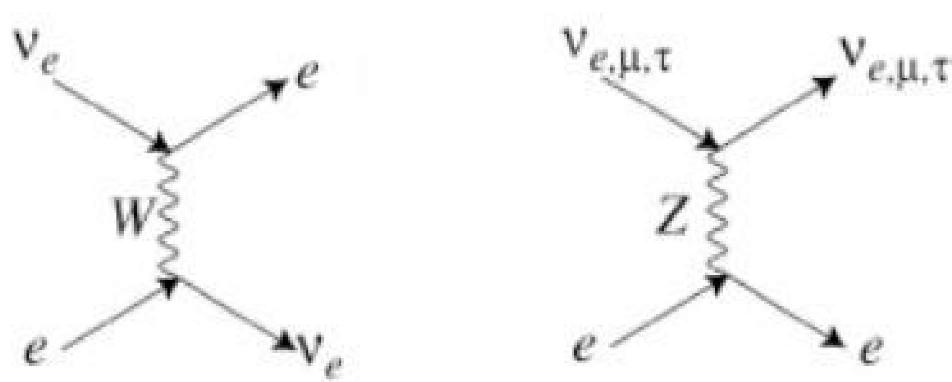
Charged Current Interactions



NC

Neutral Current Interactions

ES



Electron Scattering

CC

$$\nu_e + d \Rightarrow p + p + e^-$$

- Gives ν_e energy spectrum well
- Weak direction sensitivity $\propto 1 - 1/3\cos(\theta)$
- ν_e only.

NC

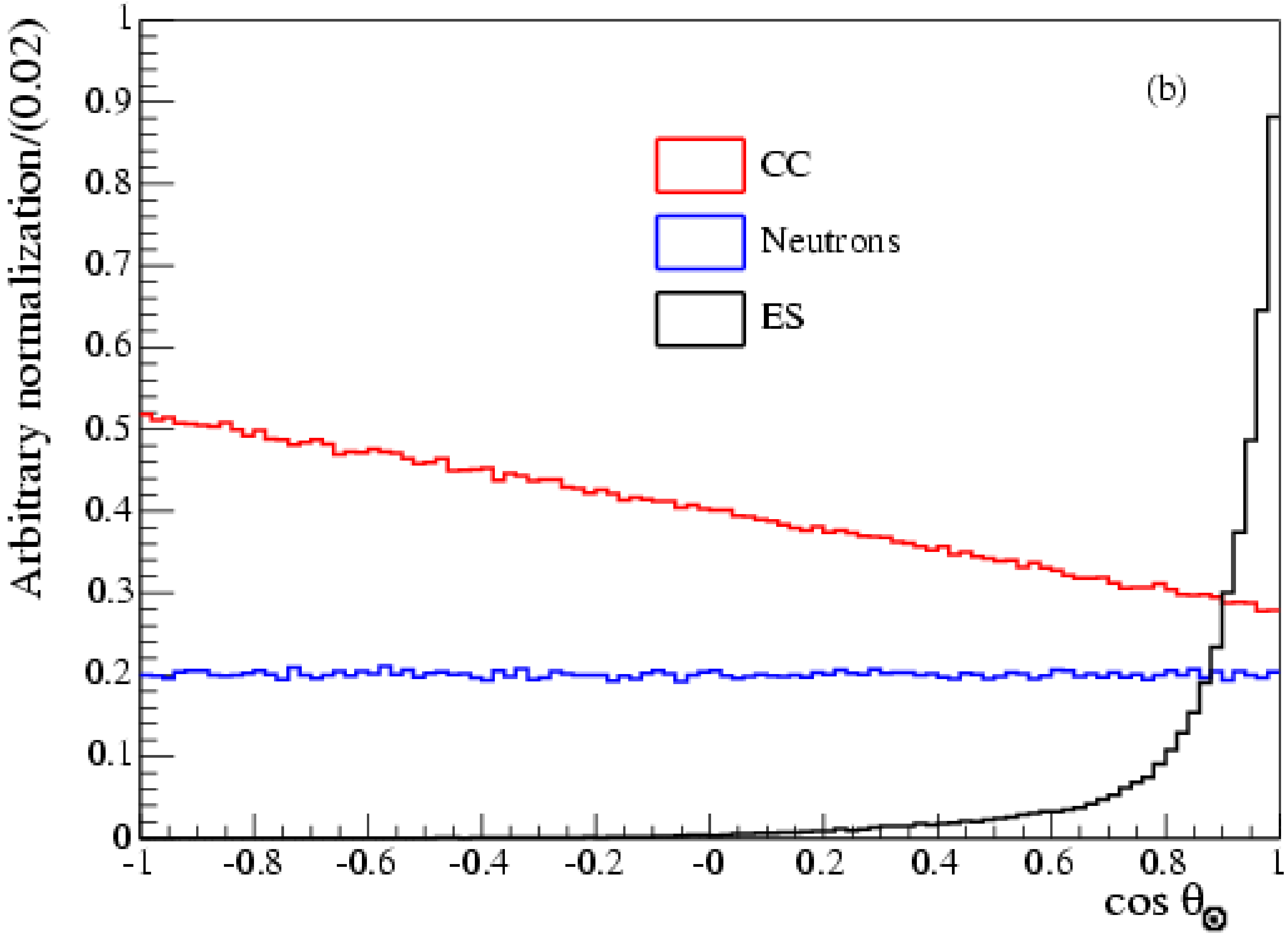
$$\nu_x + d \Rightarrow p + n + \nu_x$$

- Measure total ^8B ν flux from the sun.
- Equal cross section for all ν types

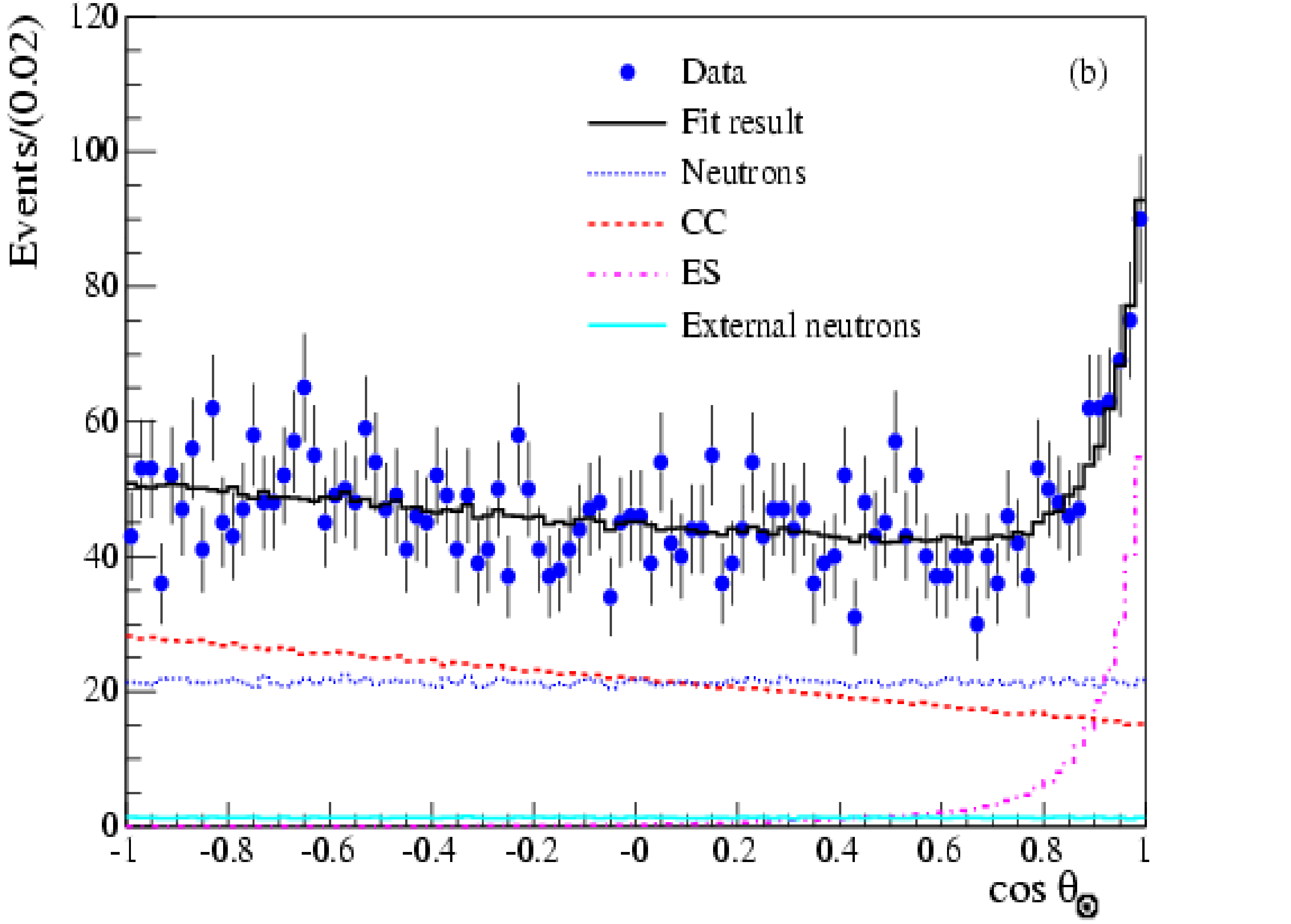
ES

$$\nu_x + e^- \Rightarrow \nu_x + e^-$$

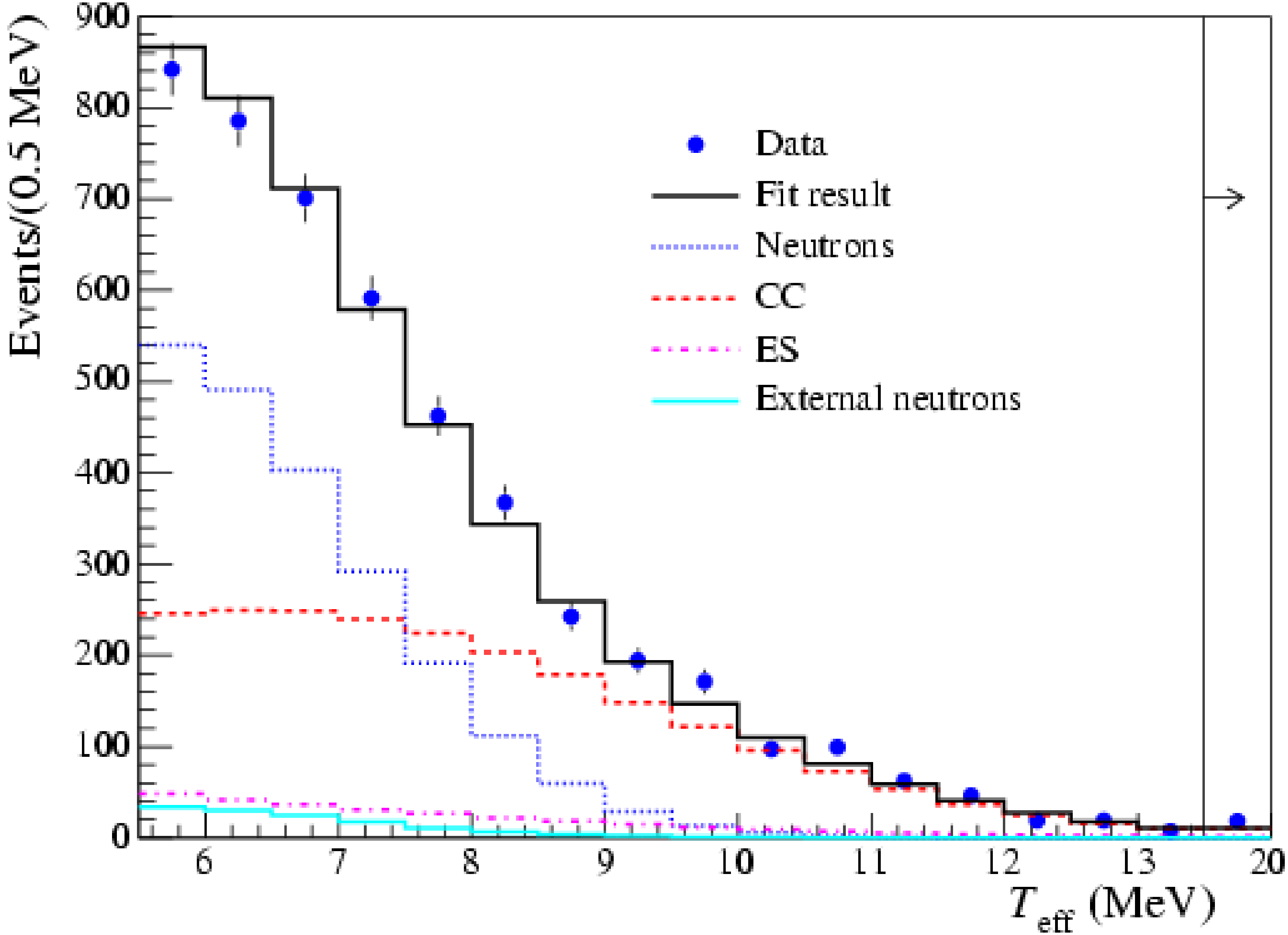
ANGLE with RESPECT To the SUN



ANGLE with RESPECT To the SUN



Visible Energy Spectrum



Fluxes ($\times 10^6$ cm^{-2} sec^{-1})

$$\phi_{CC} = 1.76^{+0.06}_{-0.05}\,(\text{stat.}) \pm 0.09\,(\text{sys.})$$

$$\phi_{ES} = 2.39^{+0.24}_{-0.23}\,(\text{stat.}) \pm 0.12\,(\text{sys.})$$

$$\phi_{NC} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{sys.})$$

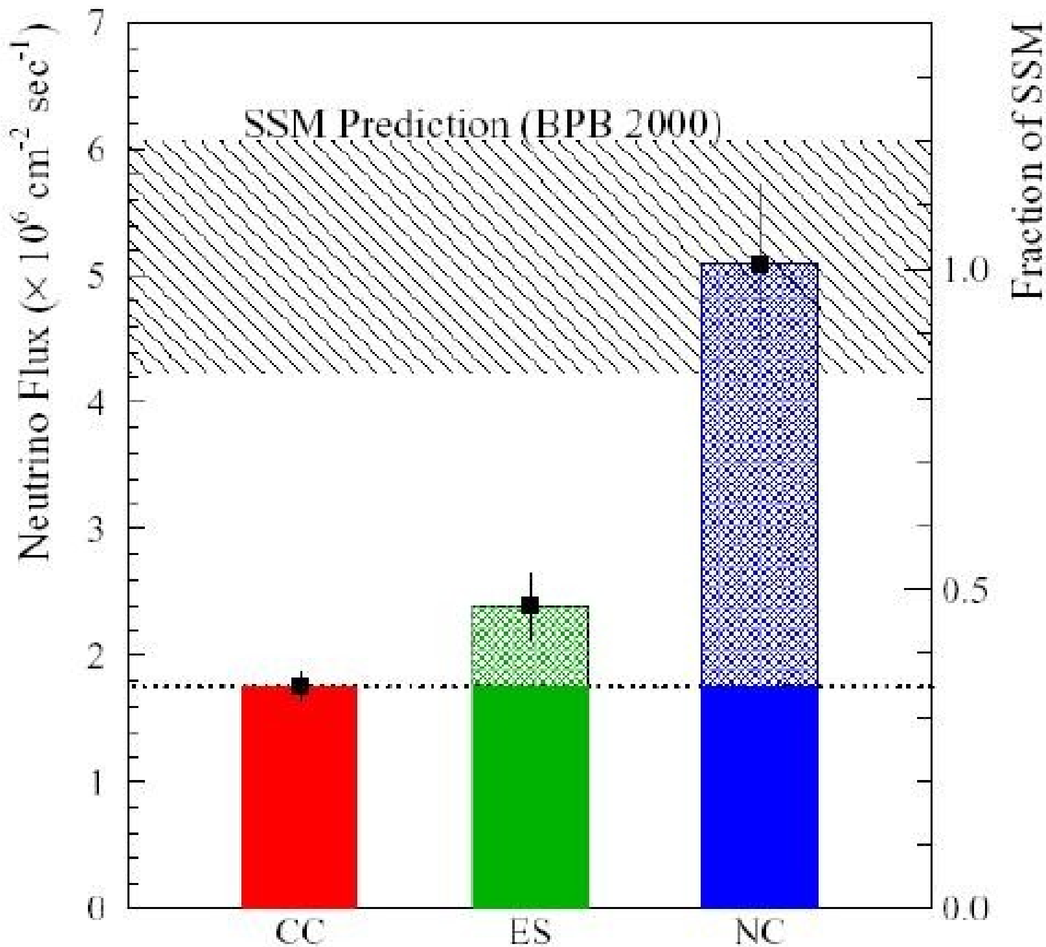
#EVENTS

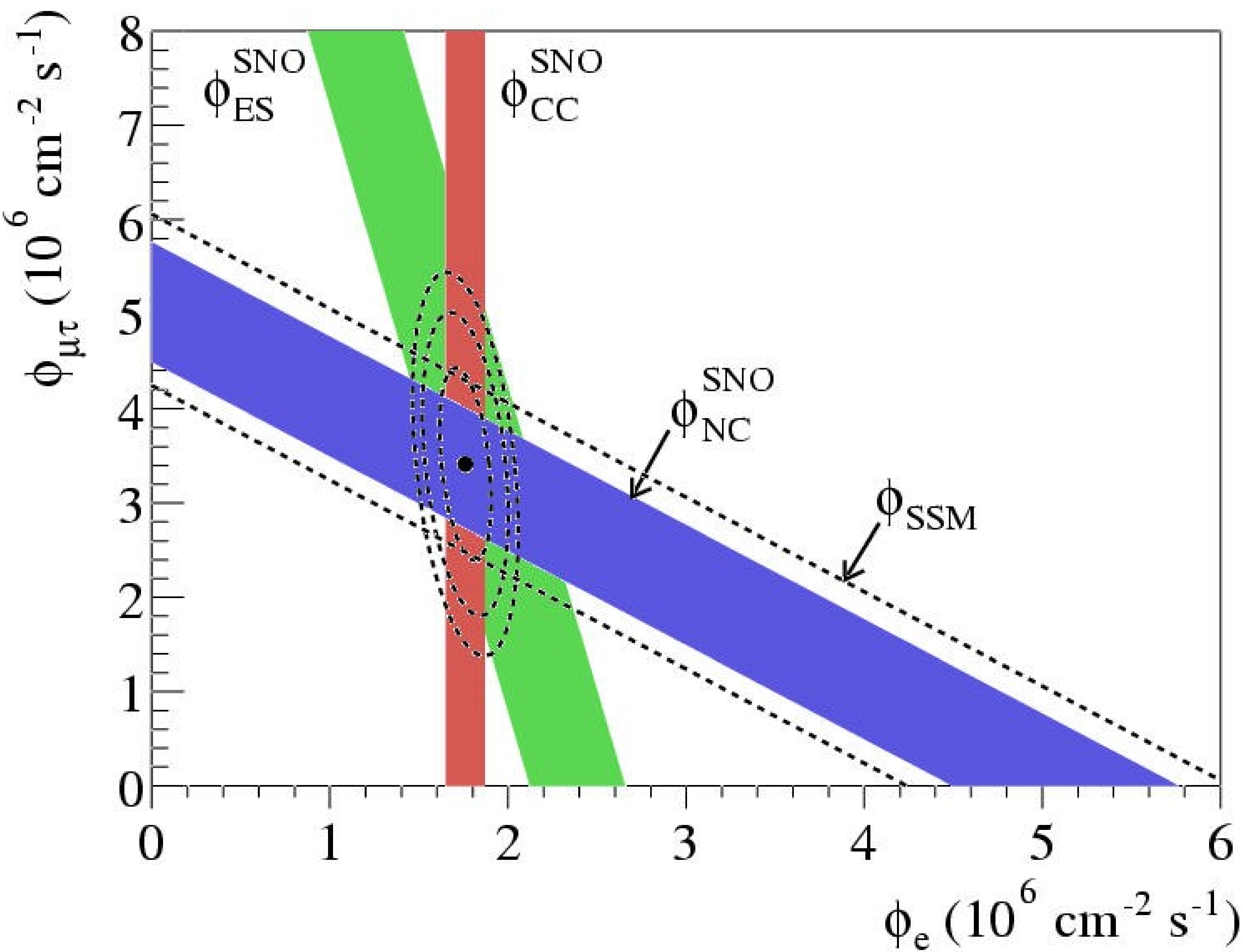
CC	1967.7	$^{+61.9}_{+60.9}$
ES	263.6	$^{+26.4}_{+25.6}$
NC	576.5	$^{+49.5}_{+48.9}$

$$\phi_{\nu_e}$$

$$\phi_{\nu_e} + \phi_{\nu_\mu}\,\frac{\sigma_{\nu_\mu}}{\sigma_{\nu_e}}$$

$$\phi_{\nu_e} + \phi_{\nu_\mu}$$





$\phi_{\mu\tau}$ (10^6 cm^{-2} s^{-1})
ϕ_e (10^6 cm^{-2} s^{-1})
ϕ_{ES}^{SNO}
ϕ_{CC}^{SNO}
ϕ_{NC}^{SNO}
ϕ_{SSM}
0
1
2
3
4
5
6
7
8

SNO - 3 neutron detection methods

Phase I (D_2O)

Nov. 99 - May 01

n captures on
$^{2}H(n, \gamma)^{3}H$
σ = 0.0005 b
Observe 6.25 MeV γ
PMT array readout
Good CC

Phase II (salt)

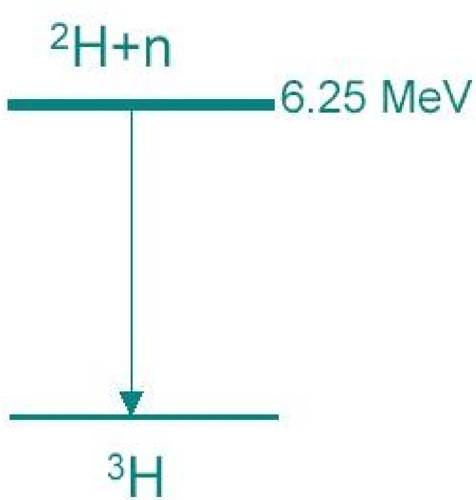
July 01 - Sep. 03

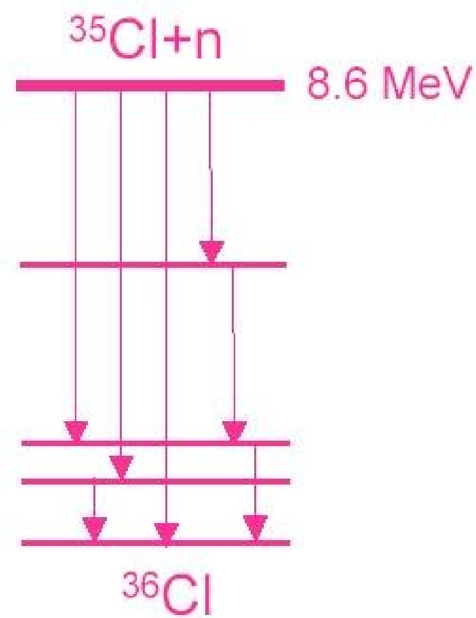
2 t NaCl. n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
σ = 44 b
Observe multiple γ's
PMT array readout
Enhanced NC

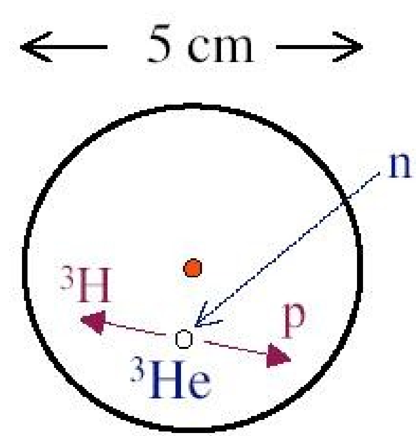
Phase III (^{3}He)

Summer 04 - Dec. 06

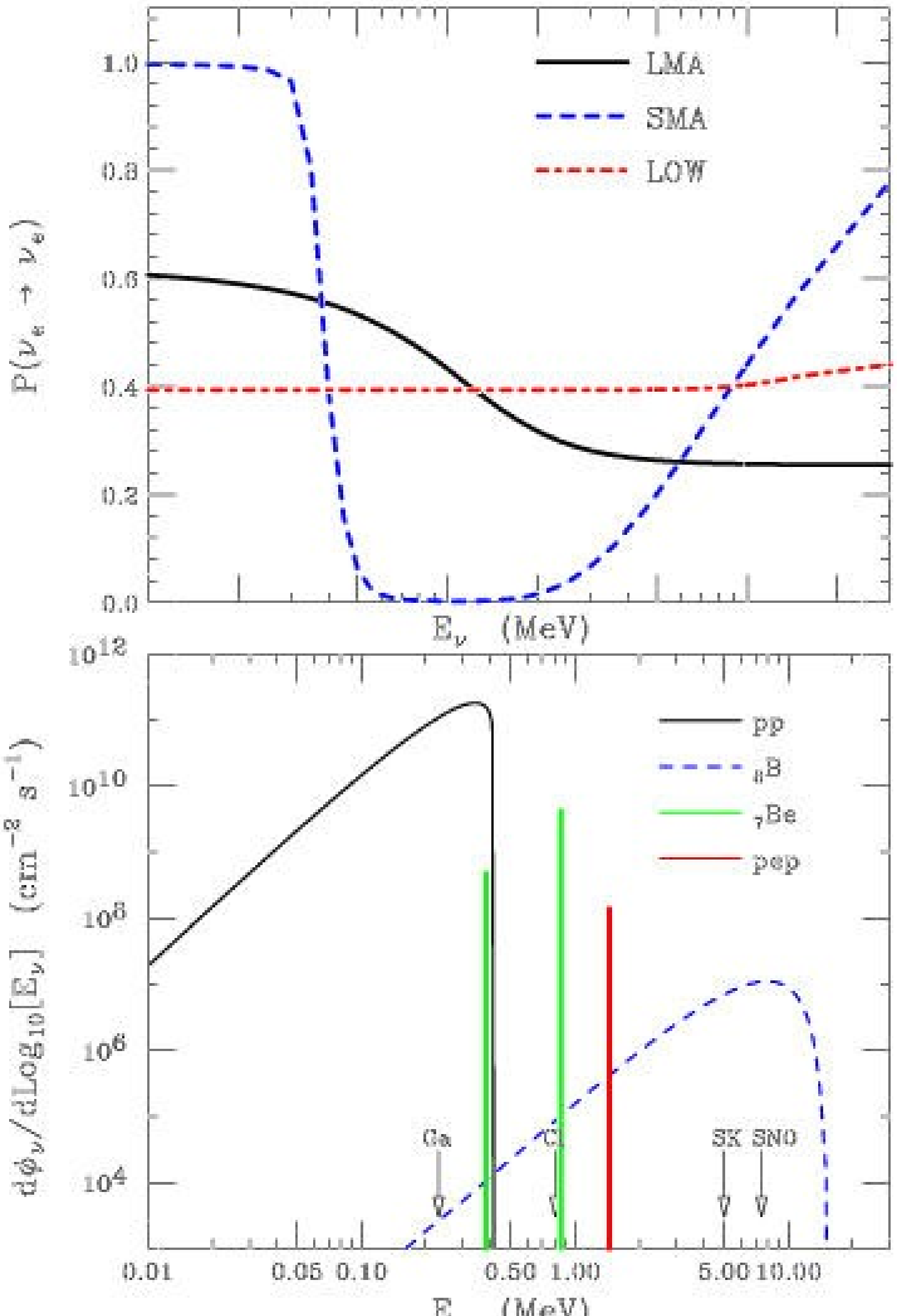
40 proportional counters
$^{3}He(n, p)^{3}H$
σ = 5330 b
Observe p and ^{3}H
PC independent readout
Event by Event Det.



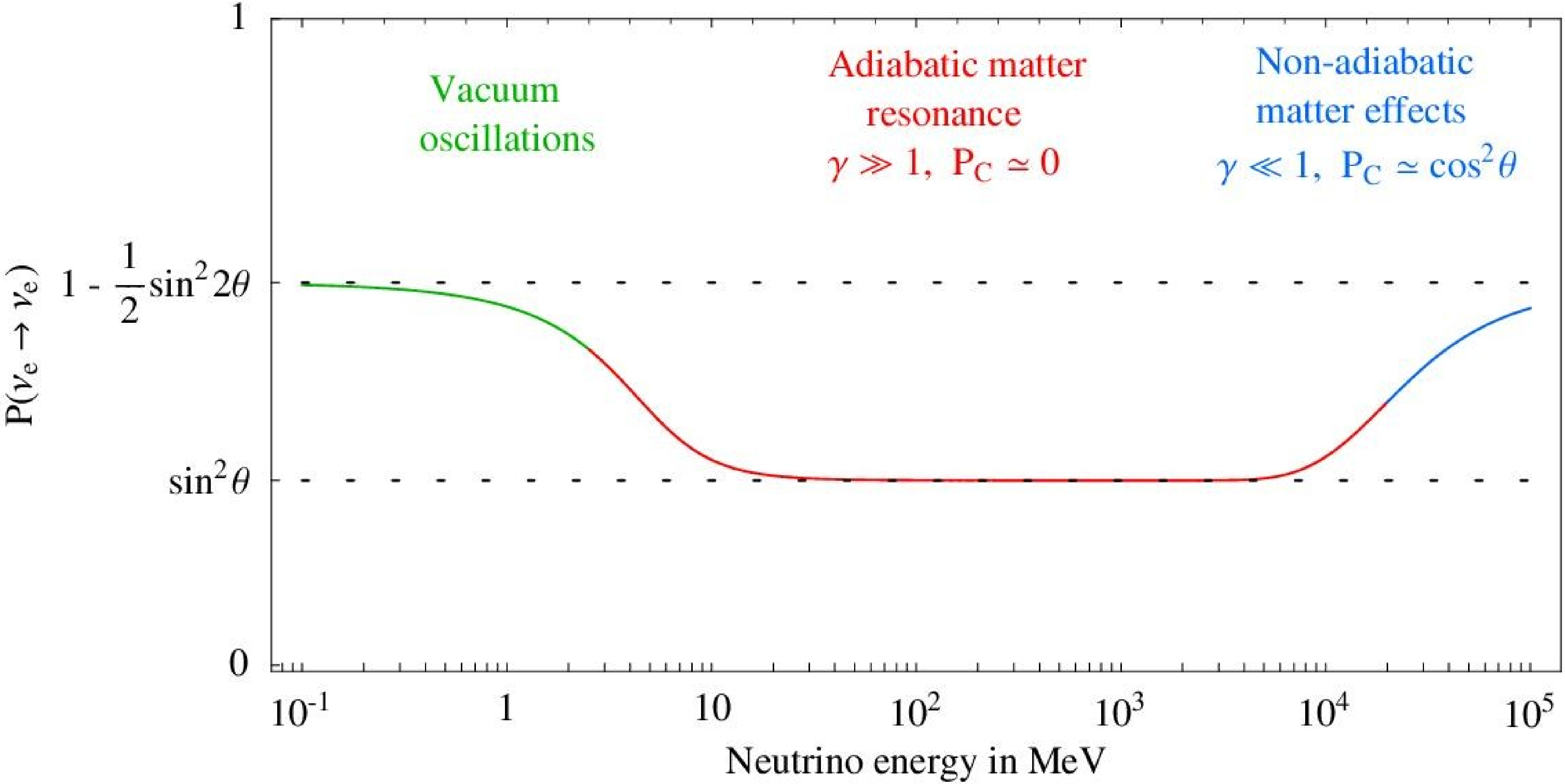




$n + {}^{3}He \rightarrow p + {}^{3}H$



LMA
SMA
LOW
$P(\nu_e \to \nu_e)$
1.0
0.8
0.6
0.4
0.2
0.0
E_ν (MeV)
pp
$_8B$
$_7Be$
pep
$d\phi_\nu/dLog_{10}[E_\nu]$ $(cm^{-2}\ s^{-1})$
10^{12}
10^{10}
10^8
10^6
10^4
Ga
Cl
SK
SNO
0.01
0.05
0.10
0.50
1.00
5.00
10.00
E_ν (MeV)



Vacuum oscillations
Adiabatic matter resonance
$\gamma \gg 1,\ P_C \simeq 0$
Non-adiabatic matter effects
$\gamma \ll 1,\ P_C \simeq \cos^2\theta$
$P(\nu_e \to \nu_e)$
1
$1 - \frac{1}{2}\sin^2 2\theta$
$\sin^2\theta$
0
10^{-1}
1
10
10^2
10^3
10^4
10^5
Neutrino energy in MeV

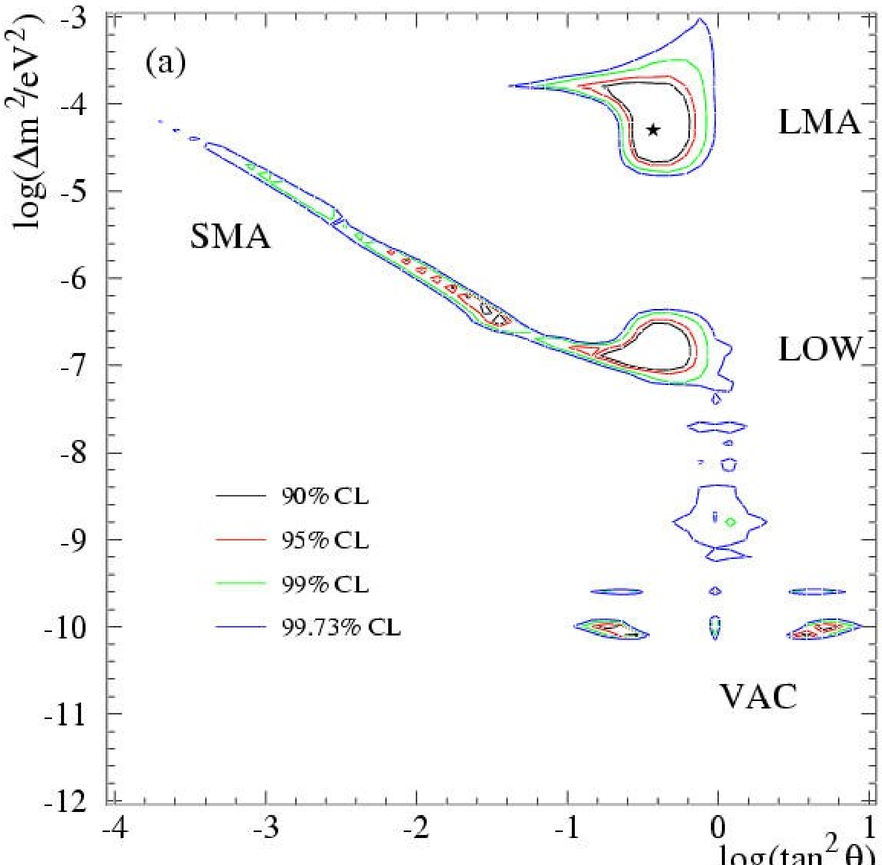
INTERPRETATION
of the
SOLAR NEUTRINO DATA :

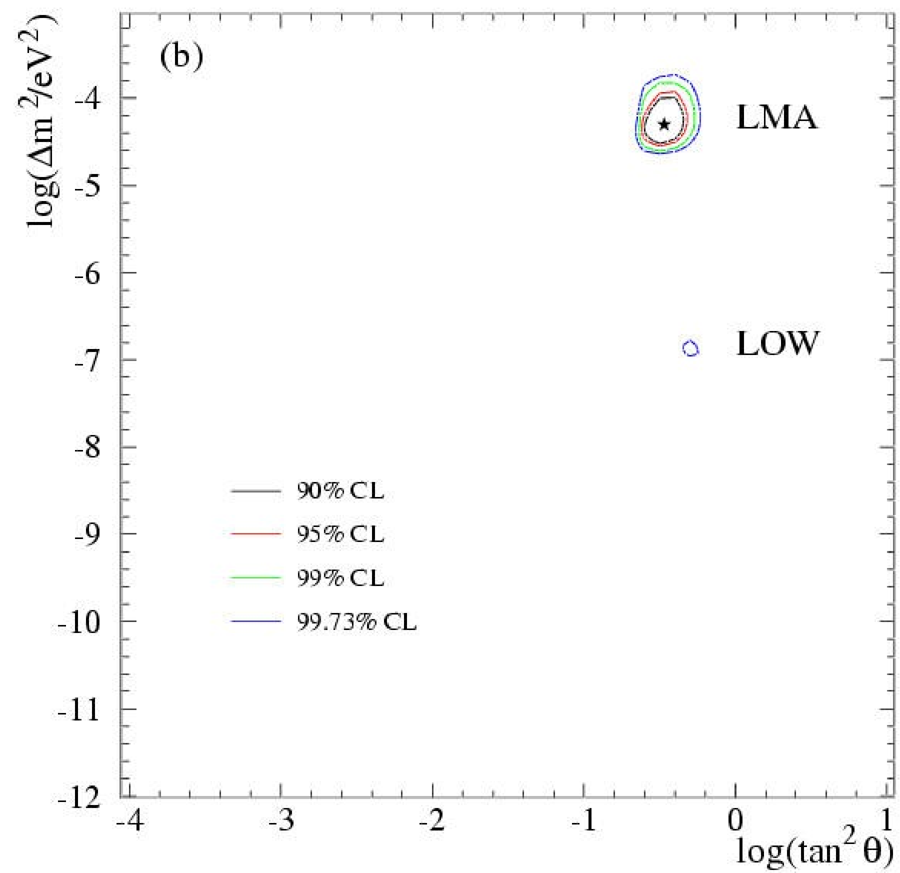
MATTER EFFECTS
in NEUTRINO OSCILLATIONS

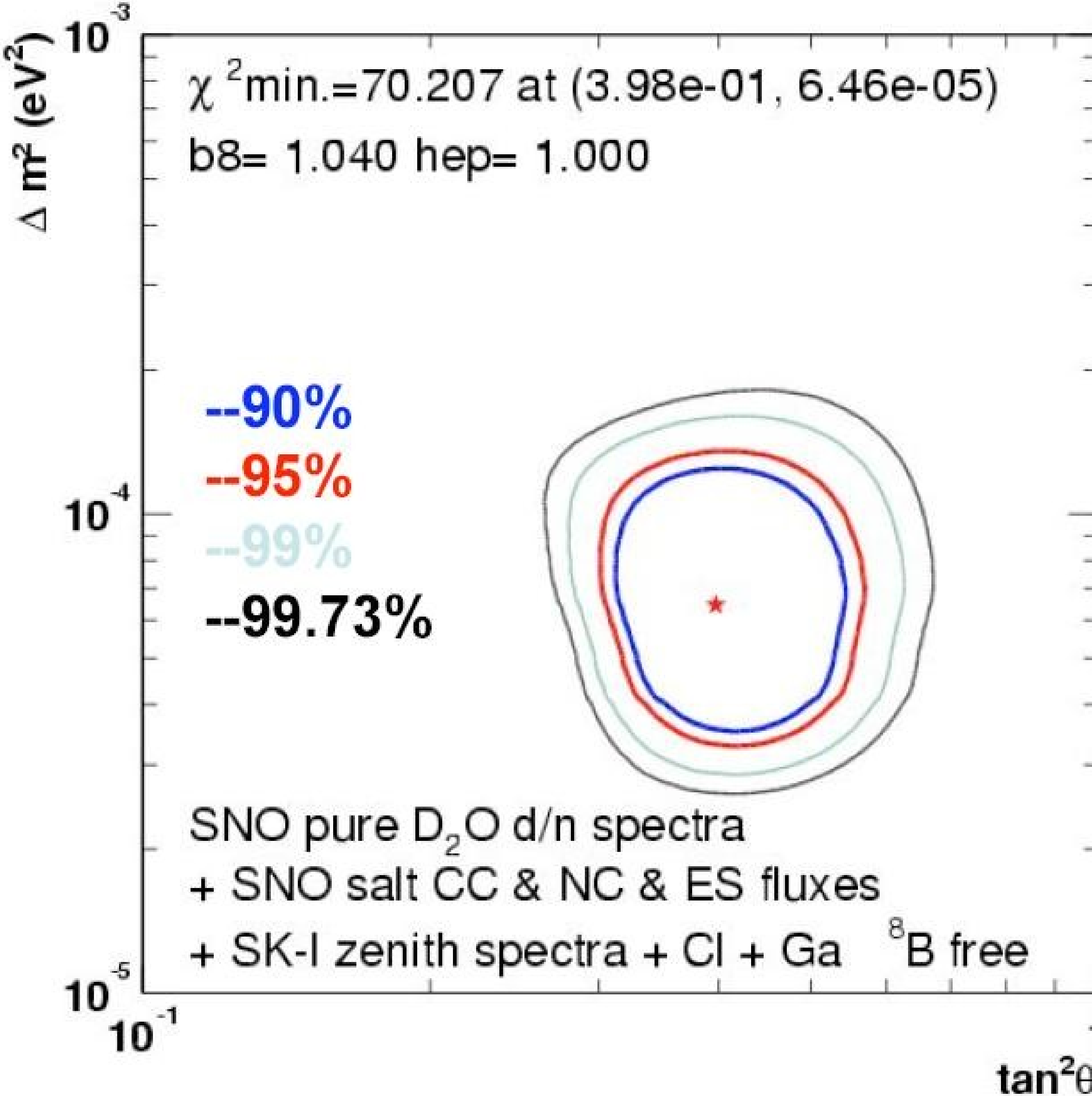
SOLAR NEUTRINOS

Chlorine
Kamiokande
SuperKamiokande
Gallex
Sage

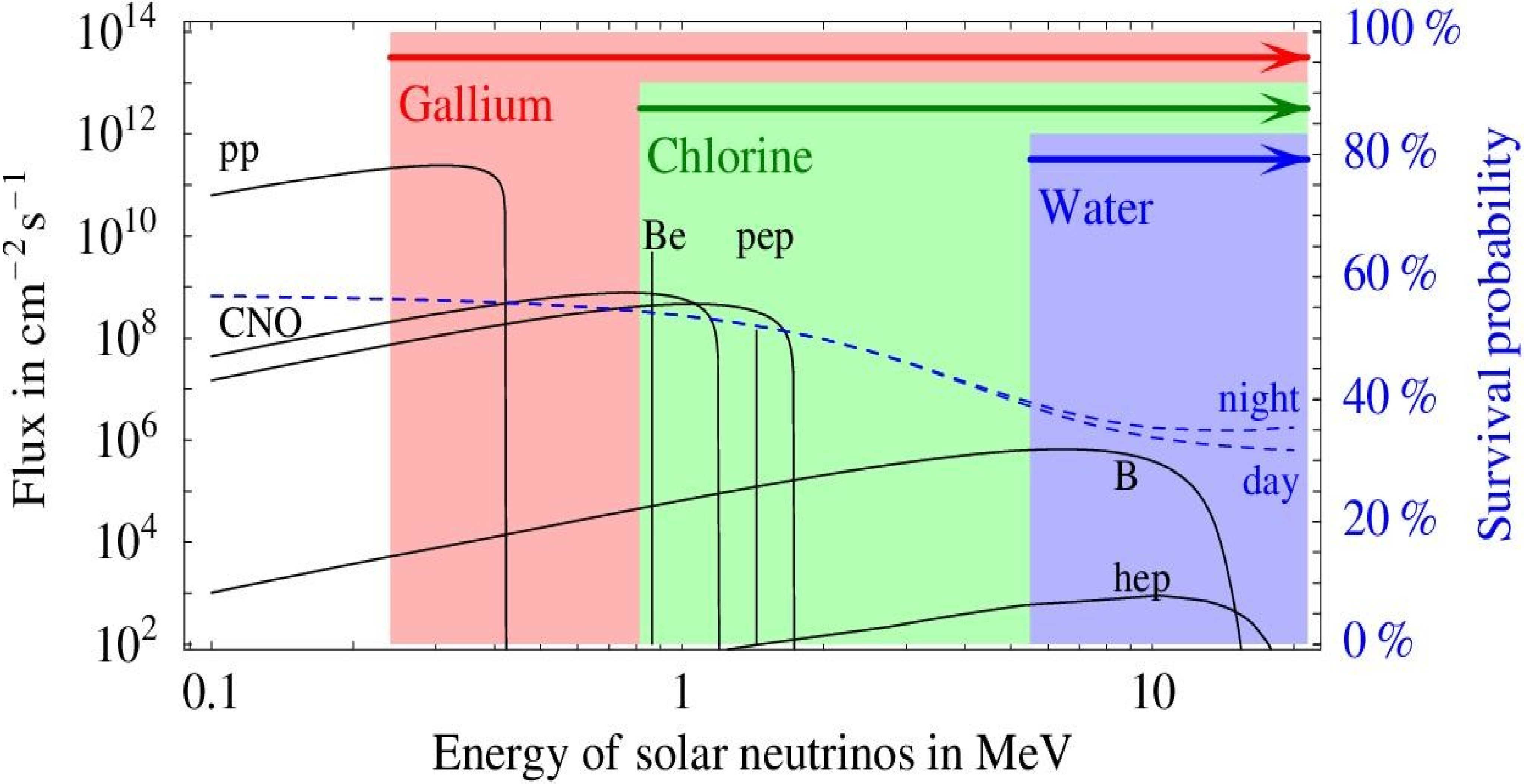
+ SNO





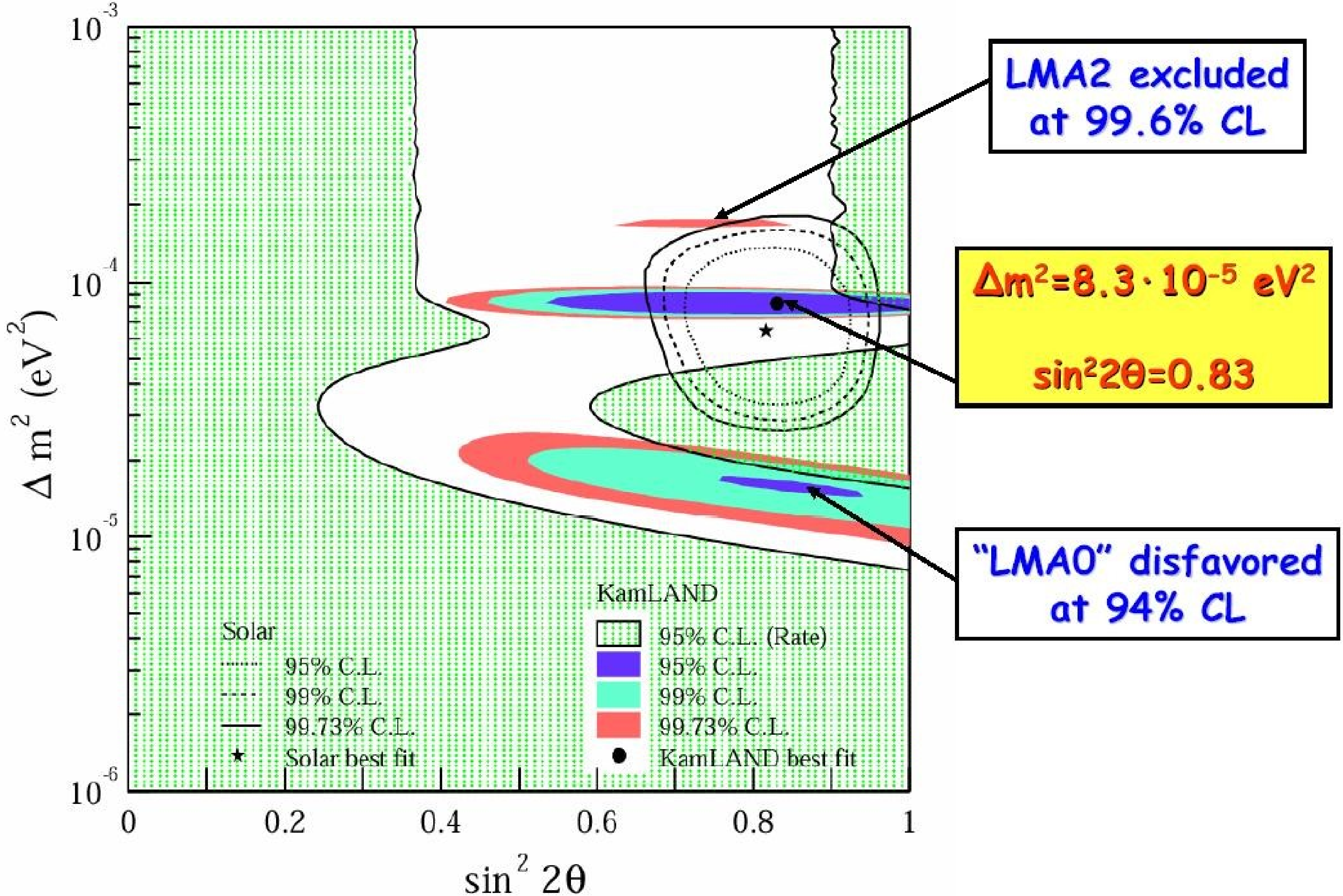


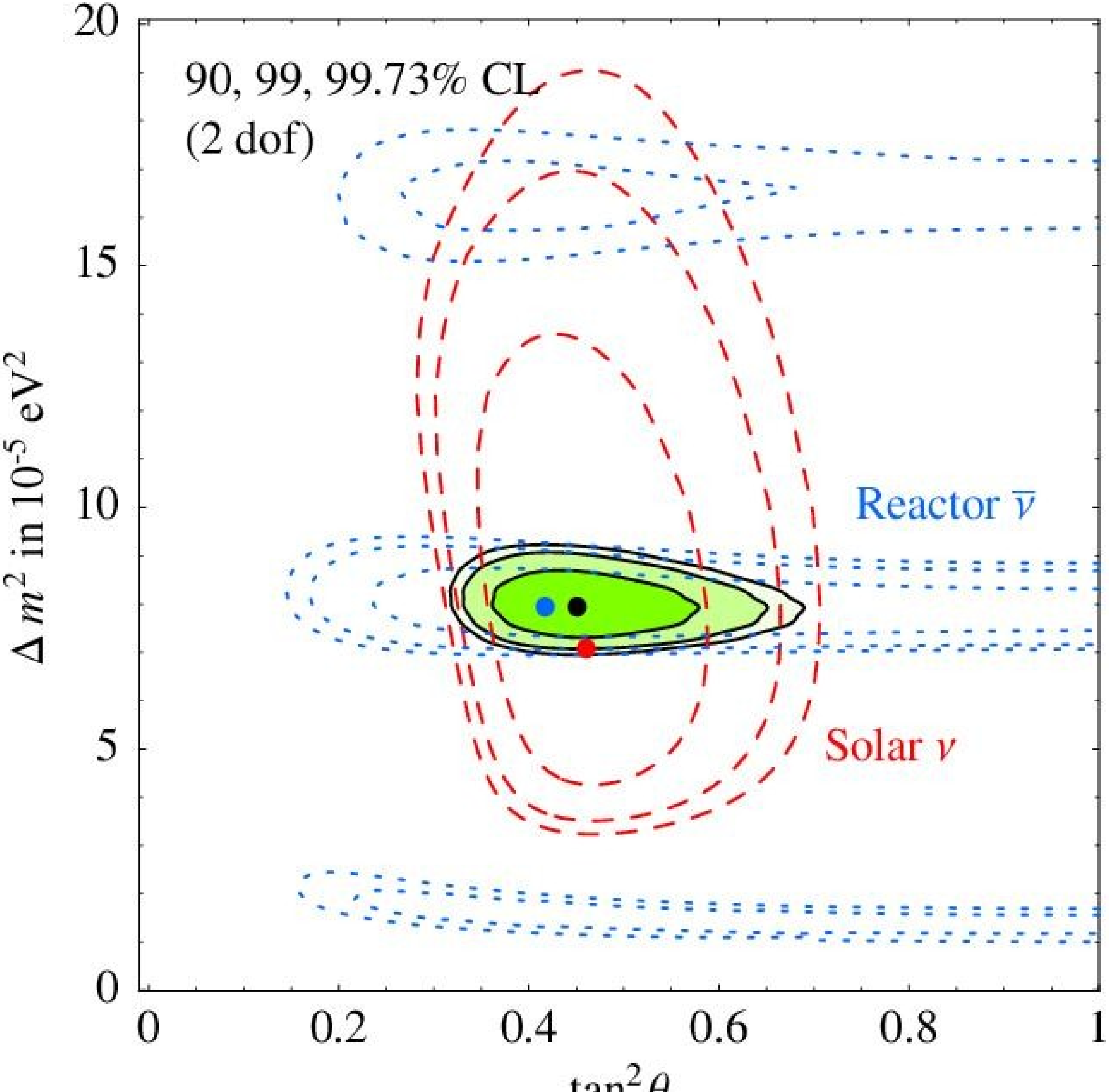
χ^2min.=70.207 at (3.98e-01, 6.46e-05)
b8= 1.040 hep= 1.000
--90%
--95%
--99%
--99.73%
SNO pure D_2O d/n spectra
+ SNO salt CC & NC & ES fluxes
+ SK-I zenith spectra + Cl + Ga ^8B free
Δm^2 (eV^2)
10^{-3}
10^{-4}
10^{-5}
10^{-1}
1
$tan^2\theta$



10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
Flux in $cm^{-2}s^{-1}$
Gallium
Chlorine
Water
pp
Be
pep
CNO
B
hep
night
day
100 %
80 %
60 %
40 %
20 %
0 %
Survival probability
0.1
1
10
Energy of solar neutrinos in MeV

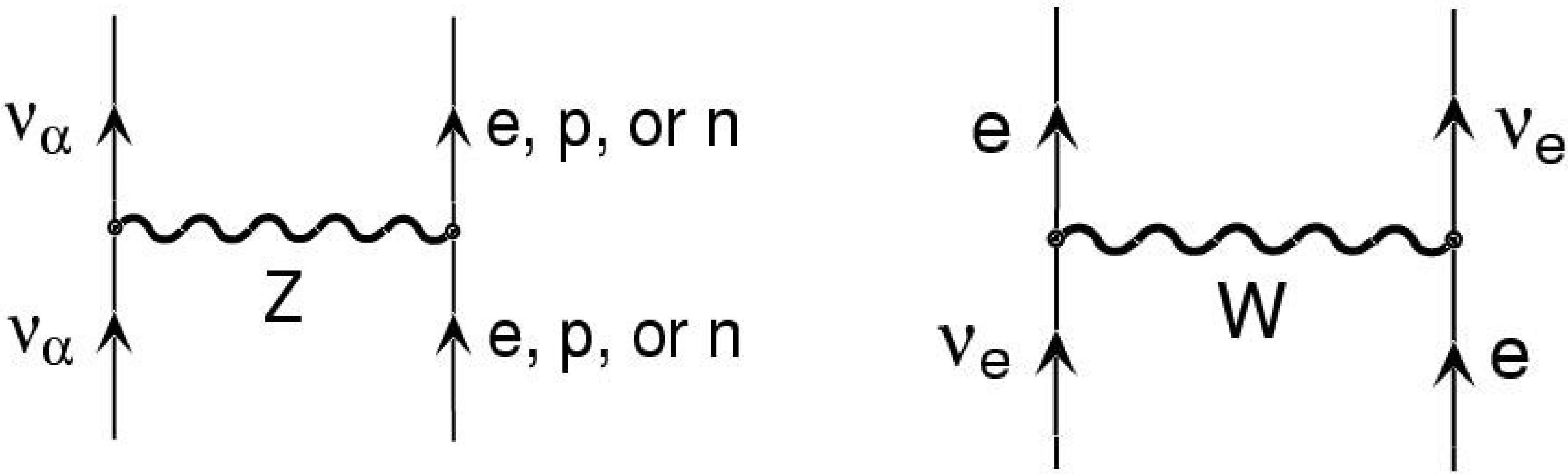
Un-binned likelihood fit to 2-flavor oscillations





90, 99, 99.73% CL
(2 dof)
Reactor $\bar{\nu}$
Solar ν
Δm^2 in 10^{-5} eV^2
$\tan^2\theta$
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1

MATTTER EFFECTS



Neutrino Propagation:

Amplitude =
Amplitude (No-Scattering) + Amplitude (forward Scattering)

EFFECTIVE POTENTIAL

$$V_{\nu_\mu e} = V_{\nu_\tau e} = \quad V^{Z}_{\nu_e e} = \quad -\frac{\sqrt{2}}{2} G_F N_e$$

$$V_{\nu_\mu p} = V_{\nu_\tau p} = \quad V_{\nu_e p} = \quad +\frac{\sqrt{2}}{2} G_F N_p$$

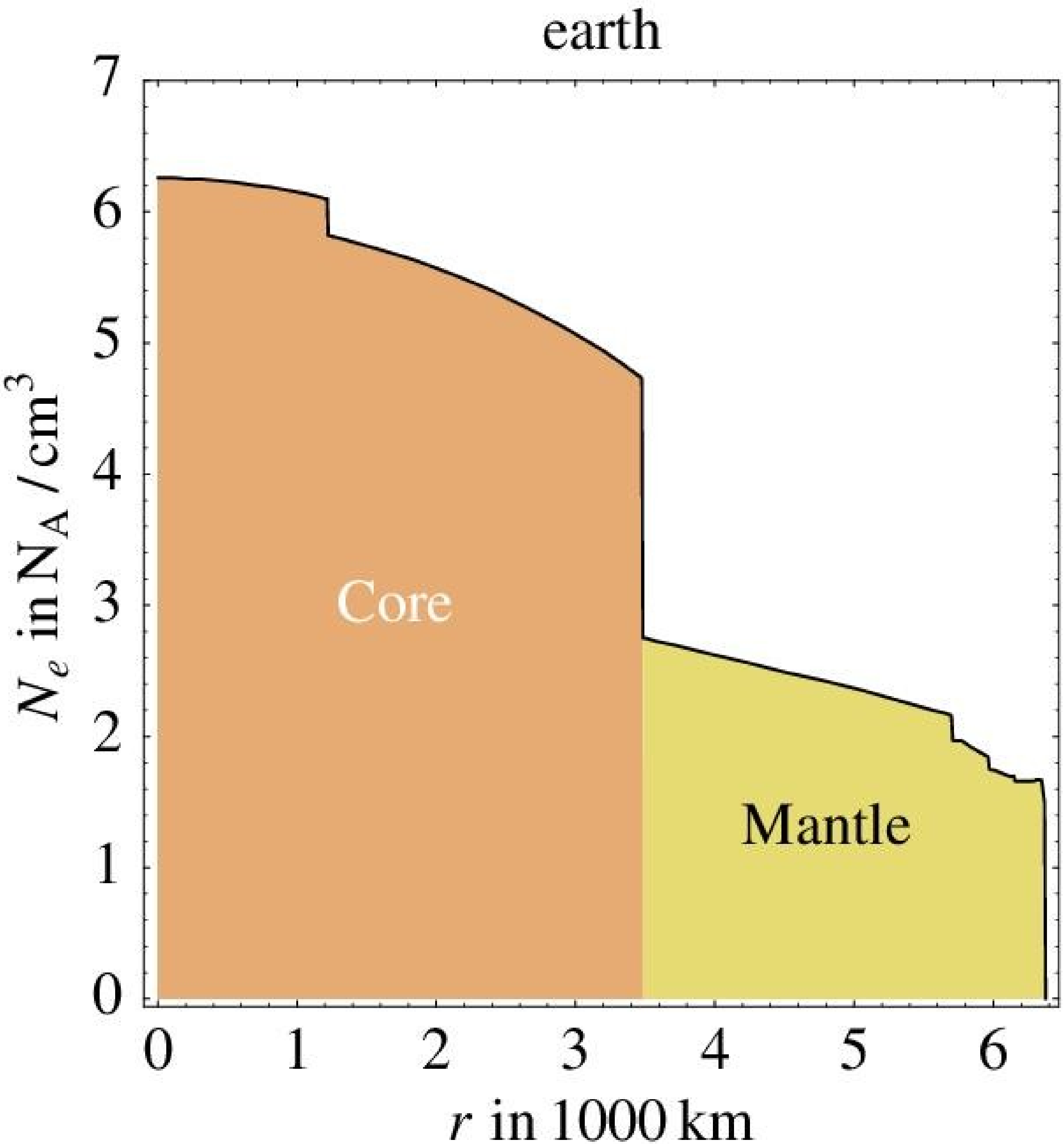
$$V_{\nu_\mu n} = V_{\nu_\tau n} = \quad V_{\nu_e n} = \quad -\frac{\sqrt{2}}{2} G_F N_n$$

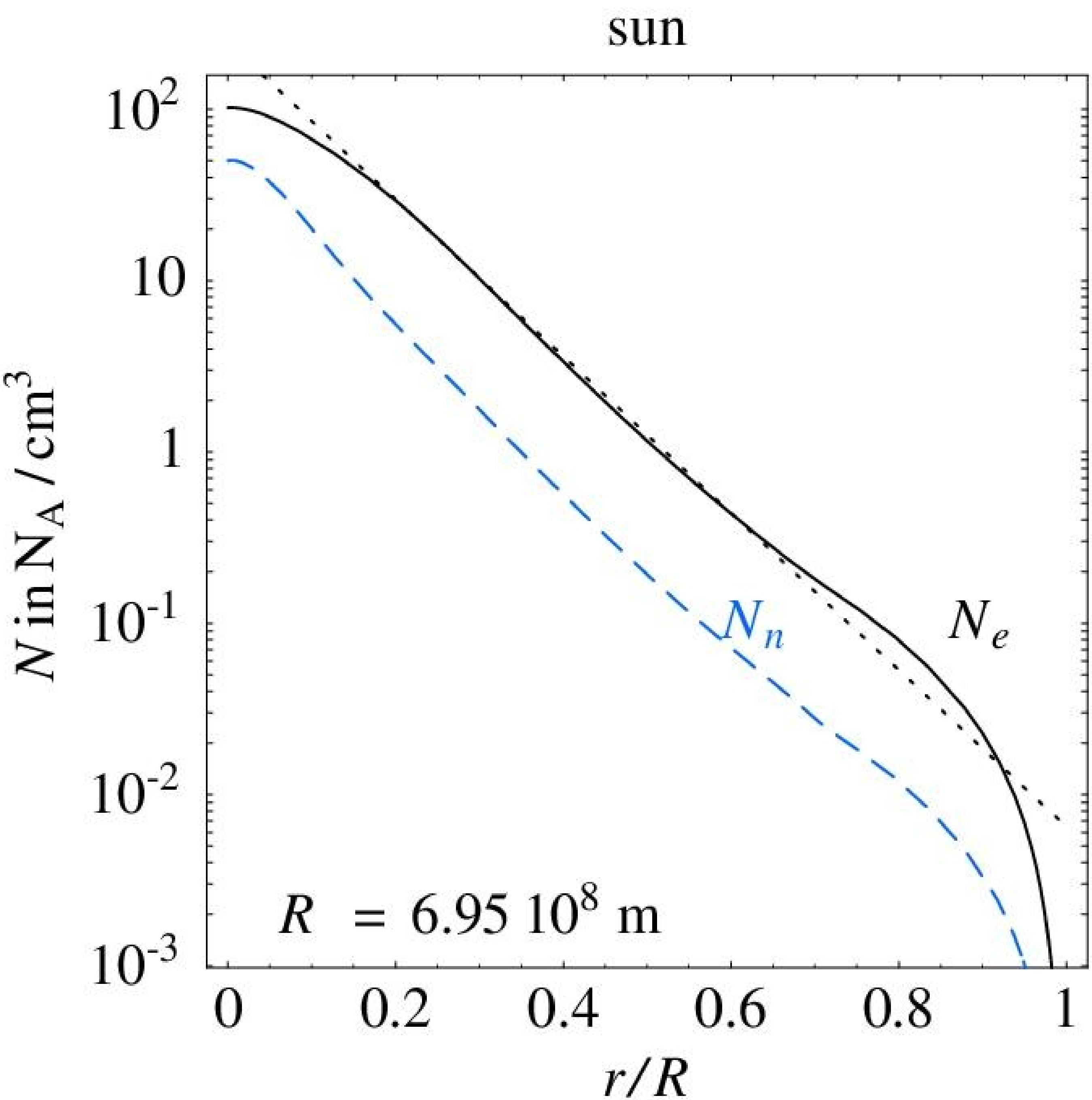
$$V_{\overline{\nu}_\alpha} = -V_{\nu_\alpha}$$

$$V_{\nu_e e} = V^{Z}_{\nu_e e} + V^{W}_{\nu_e e} = -\frac{\sqrt{2}}{2} G_F N_e + \sqrt{2} G_F N_e$$

$$V \equiv V_{\nu_e} - V_{\nu_\mu} = V_{\nu_e} - V_{\nu_\tau} = +\sqrt{2} G_F N_e$$

$$3.8 \times 10^{-14} \left(\frac{\rho}{\mathrm{g\ cm^{-3}}} \right) \left(\frac{Y_e}{0.5} \right) \mathrm{eV}$$


earth
Core
Mantle
N_e in N_A /cm^3
r in 1000 km
0
1
2
3
4
5
6
7



sun
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
N in N_A /cm^3
N_n
N_e
R = 6.95 10^8 m
0
0.2
0.4
0.6
0.8
1
r/R

$$E - V = \sqrt{p^2 + m^2} \simeq p + \frac{m^2}{2p}$$

$$m^2 \rightarrow m^2 + 2EV$$

$$i\frac{\mathrm{d}}{\mathrm{d}x}\nu_\alpha = \mathcal{H}\,\nu_\alpha$$

$$\mathcal{H}(\nu) = U \begin{bmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{bmatrix} U^\dagger + \begin{bmatrix} V_e & 0 & 0 \\ 0 & V_\mu & 0 \\ 0 & 0 & V_\tau \end{bmatrix}$$

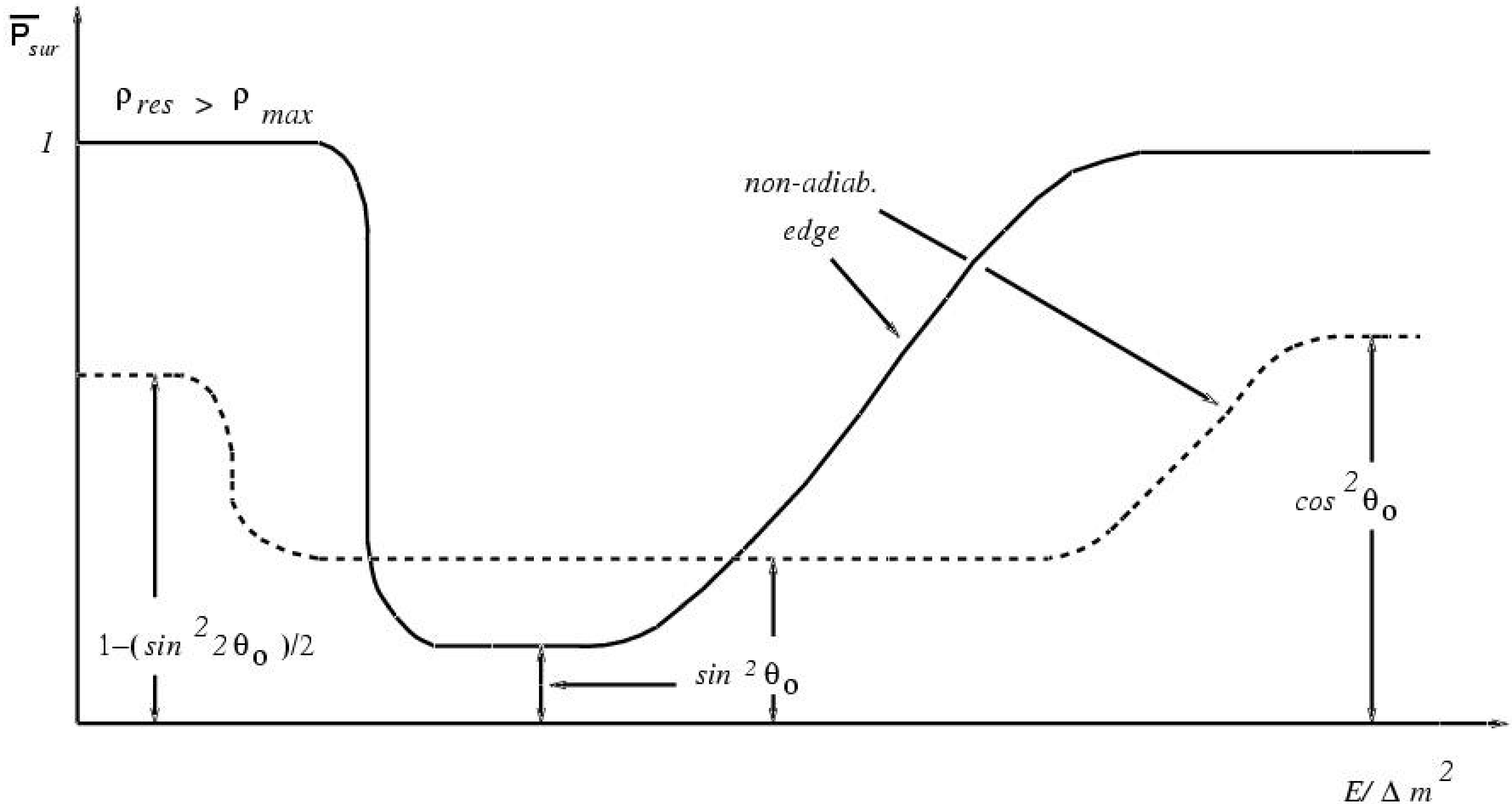
$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = [\mathcal{H}_0+\mathcal{H}_{\rm mat}(x)]\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$= \left\{\frac{1}{2E}\,U\begin{bmatrix}m_1^2 & 0\\ 0 & m_2^2\end{bmatrix}U^\dagger+\begin{bmatrix}V(x) & 0\\ 0 & 0\end{bmatrix}\right\}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$V(x) = V_e(x) - V_\mu(x) = \sqrt{2}\,G_F\,N_e(x)$$

$$\phi_{\nu_{e,\odot}}(E) = \phi_{\nu_\odot}^{\rm SSM}(E)\times P_{\nu_e\to\nu_e}(E)$$

$$\phi_{\nu_\odot}^{\rm SSM}(E)\to\phi_{\nu_\odot}^{\rm SSM}(E)\times\left\{P_{\nu_e\to\nu_e}(E)+[1-P_{\nu_e\to\nu_e}(E)]\times\frac{\sigma_{\nu_{\mu,\tau}}(E)}{\sigma_{\nu_e}(E)}\right\}$$



$$P_{\nu_e \to \nu_e}(E) \simeq \begin{cases} 1 - \frac{\sin^2 2\theta}{2} & \text{for } E < E_A \\ \sin^2\theta & \text{for } E_A < E < E_B \\ \sin^2\theta \le P \le \cos^2\theta & \text{for } E > E_B \\ \cos^2\theta & \text{for } E \gg E_B \end{cases}$$

Oscillation Probability

ν_e from the center of the sun

Survival Probability in the Adiabatic Limit

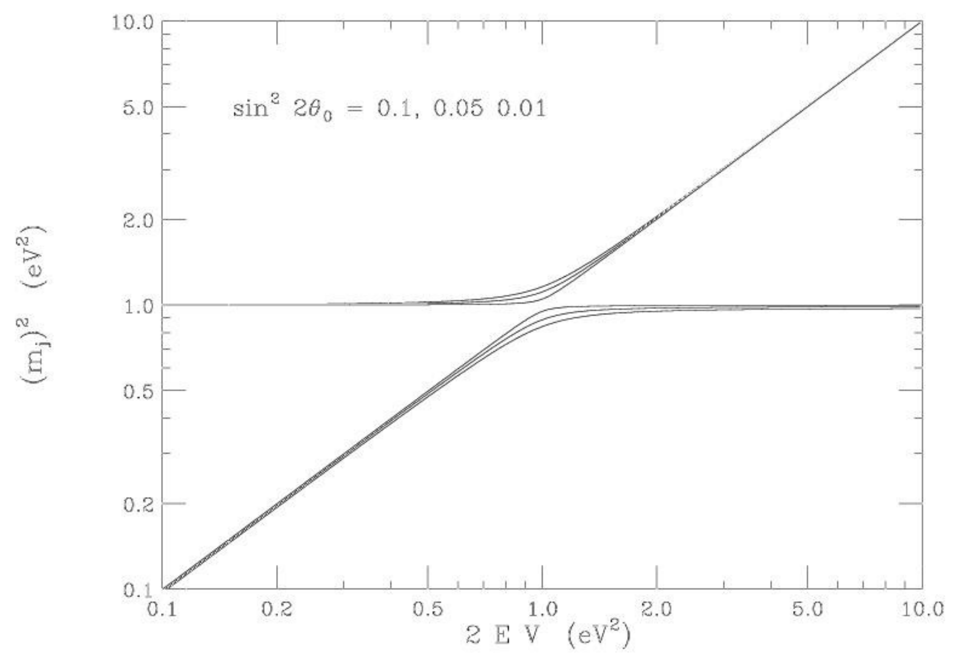
$$|\nu_{\rm ini}\rangle \equiv |\nu_e\rangle = \cos\theta_{\rm m}|\nu_{1,\rm m}\rangle + \sin\theta_{\rm m}|\nu_{2,\rm m}\rangle$$

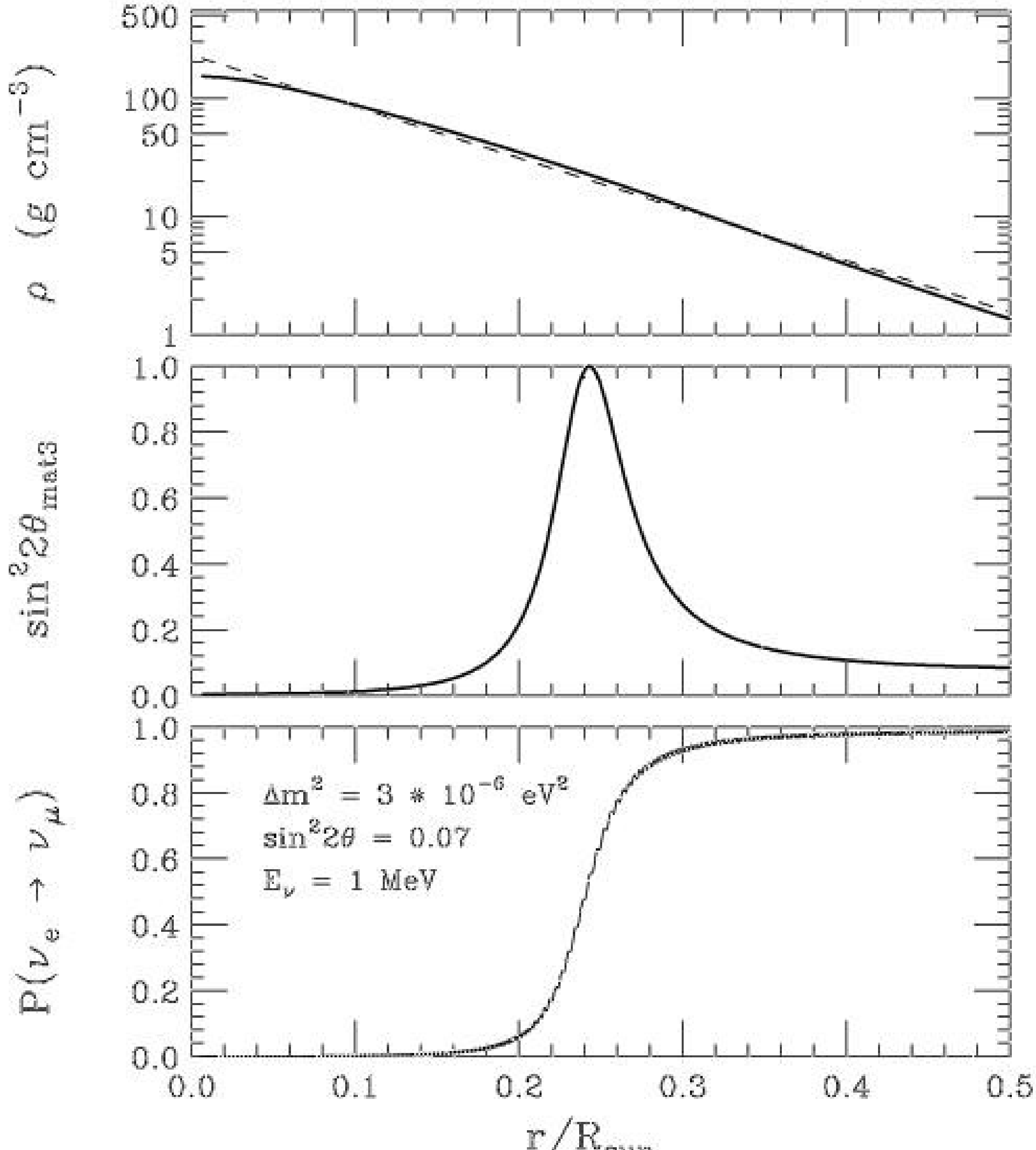
$$|\nu_{\rm fin}\rangle = \cos\theta_{\rm m}\,|\nu_1\rangle + \sin\theta_{\rm m}\,|\nu_2\rangle$$

$$P_{\nu_e\to\nu_e} = |\langle\nu_e|\nu_{\rm fin}\rangle|^2 = (\cos\theta\cos\theta_{\rm m} + \sin\theta\sin\theta_{\rm m})^2$$

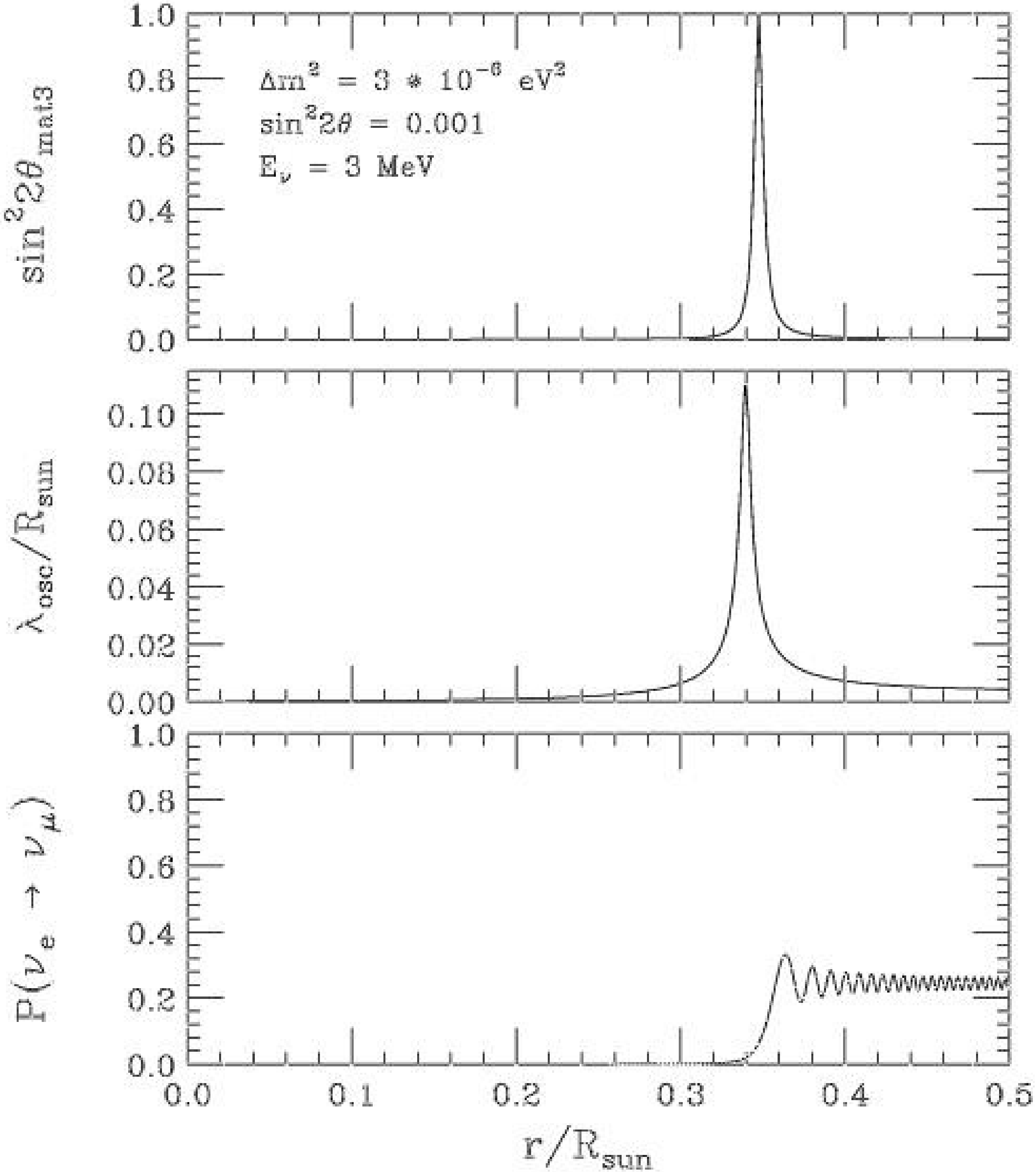
$$|\nu_{2,\rm m}\rangle \to |\nu_e\rangle$$

$$P_{\nu_e\to\nu_e} \to \sin^2\theta$$

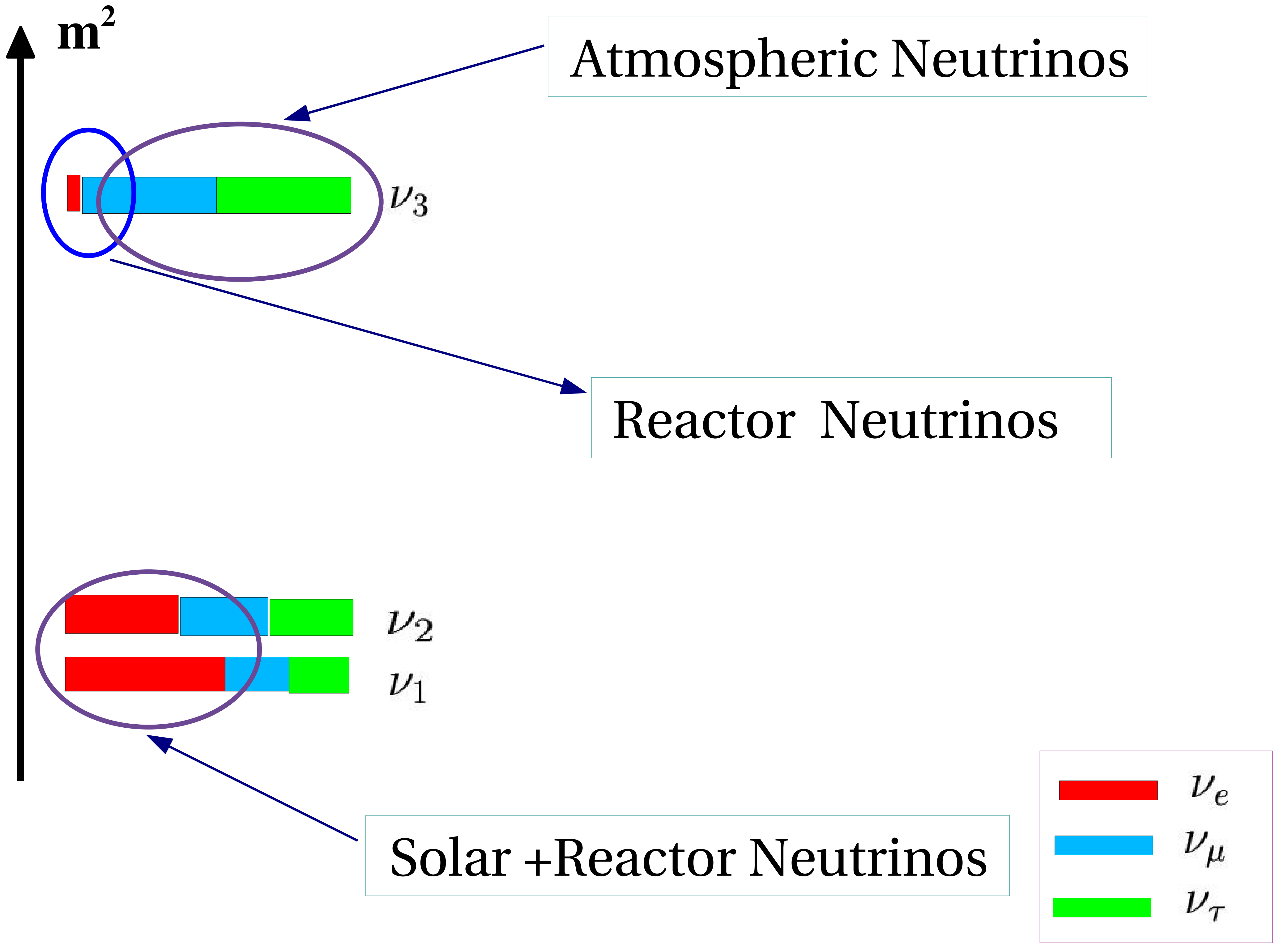




ρ (g cm^-3)
500
100
50
10
5
1
sin^2 2θ_mat3
1.0
0.8
0.6
0.4
0.2
0.0
P(ν_e → ν_μ)
Δm^2 = 3 * 10^-6 eV^2
sin^2 2θ = 0.07
E_ν = 1 MeV
0.0
0.1
0.2
0.3
0.4
0.5
r/R_sun

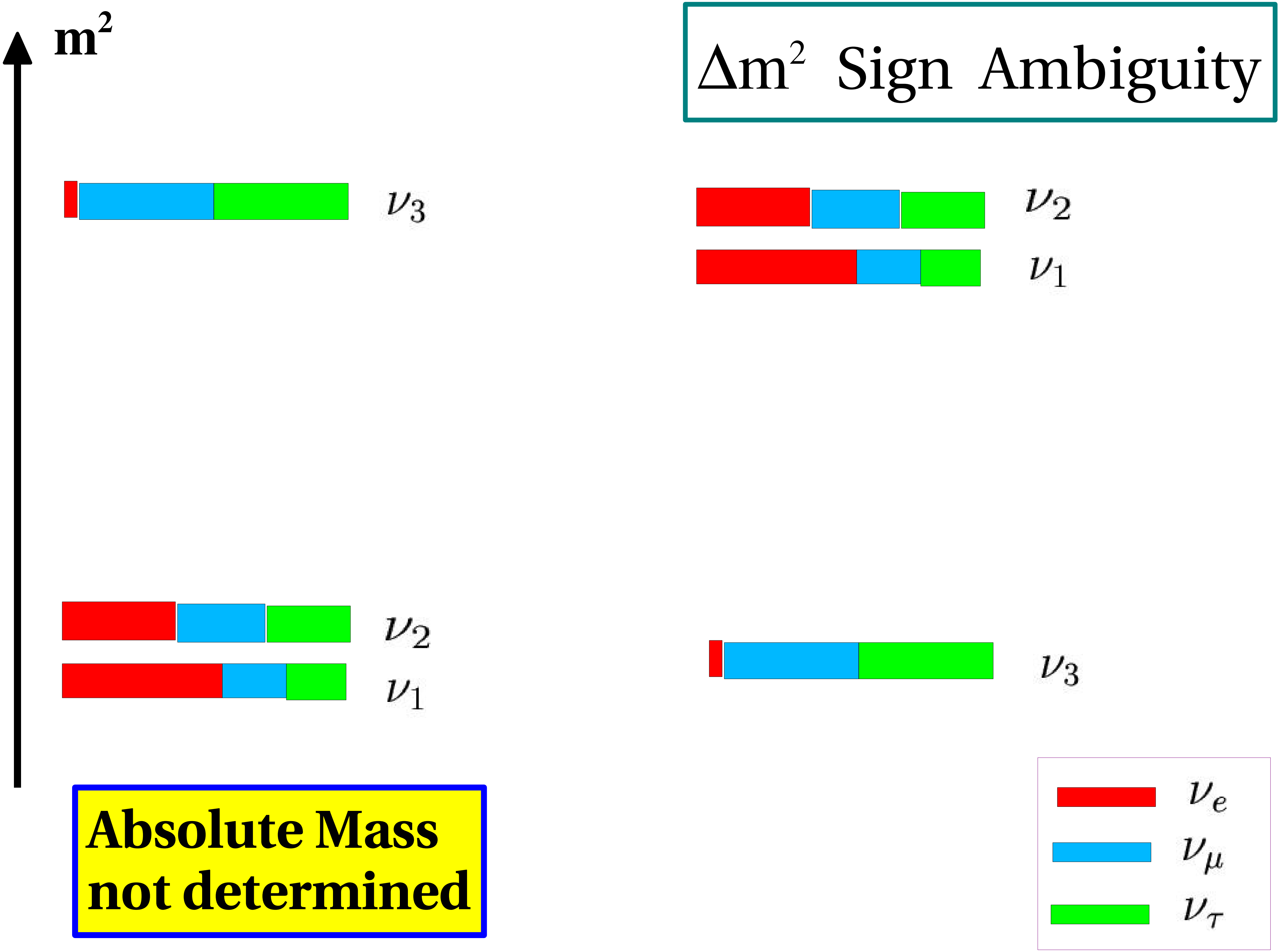


$\Delta m^2 = 3 * 10^{-6}\ eV^2$
$\sin^2 2\theta = 0.001$
$E_\nu = 3$ MeV
$\sin^2 2\theta_{mat3}$
λ_{osc}/R_{sun}
$P(\nu_e \rightarrow \nu_\mu)$
r/R_{sun}



m^2
Atmospheric Neutrinos
ν_3
Reactor Neutrinos
ν_2
ν_1
Solar +Reactor Neutrinos
ν_e
ν_μ
ν_τ

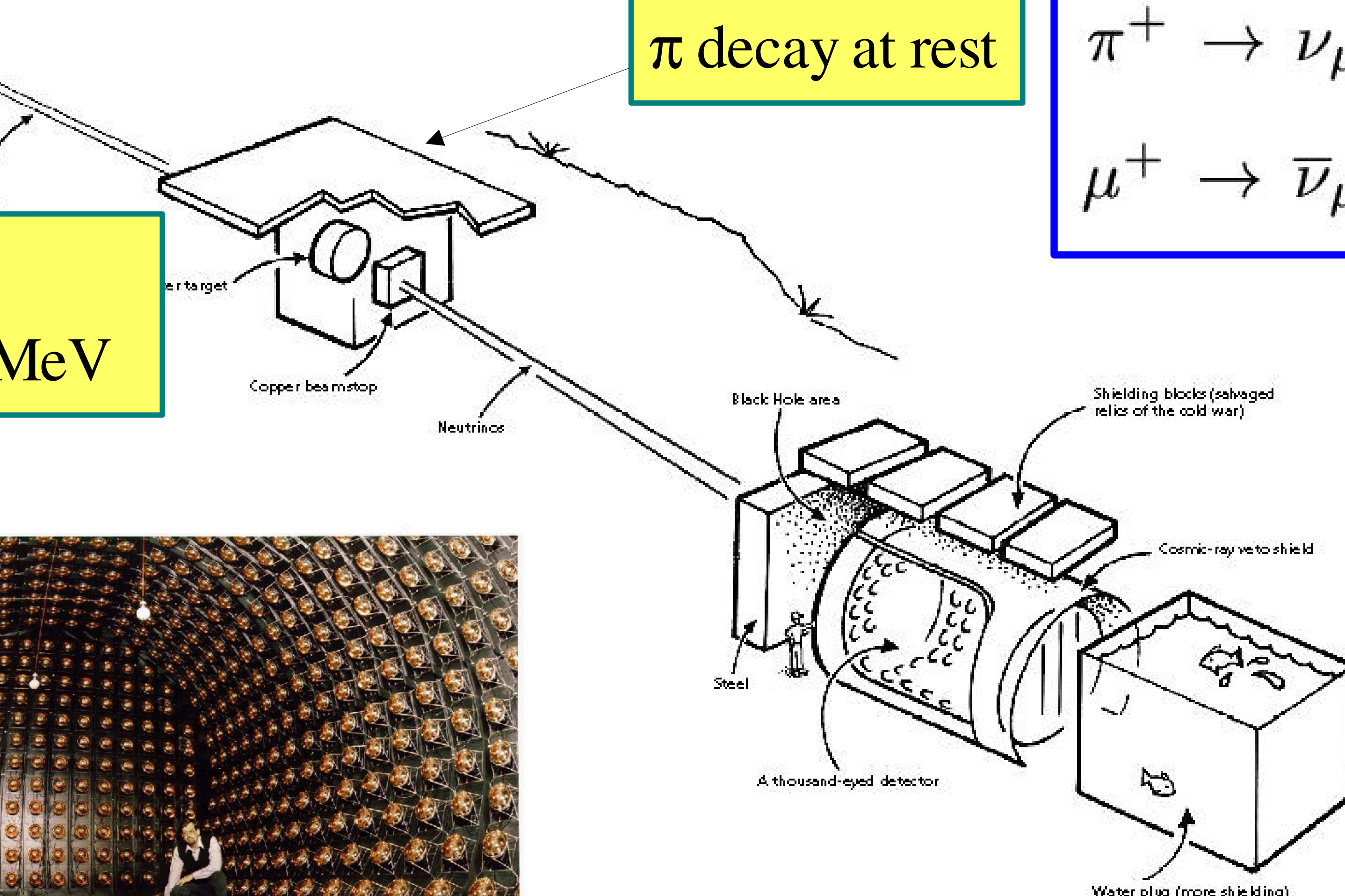
Δm^2 Sign Ambiguity



The LSND

PROBLEM

The LSND experiment



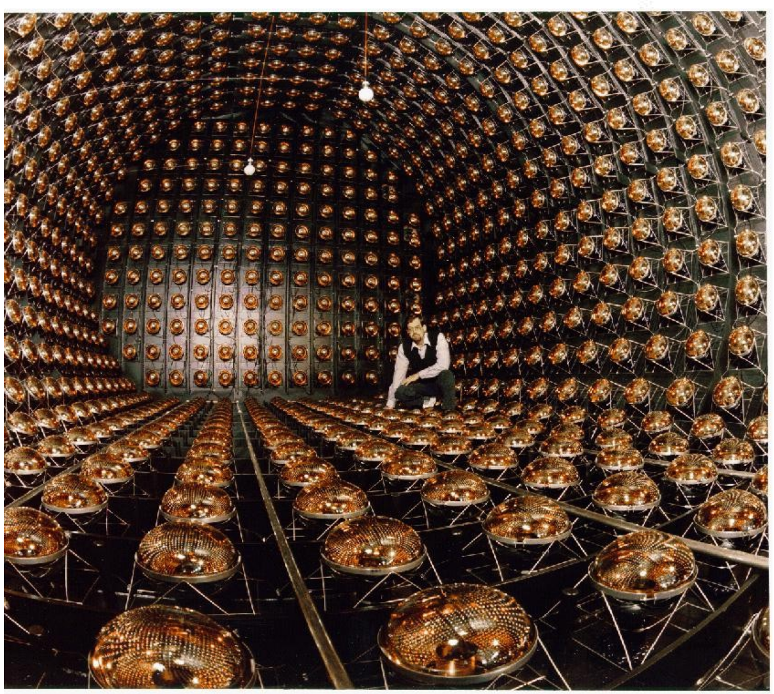
π decay at rest

$$\pi^+ \rightarrow \nu_\mu + \mu^+$$

$$\mu^+ \rightarrow \overline{\nu}_\mu + \nu_e + e^-$$

Protons

p = 800 MeV



$\overline{\nu}_e$

Appearance

$\overline{\nu}_e + p \to e^+ + n$

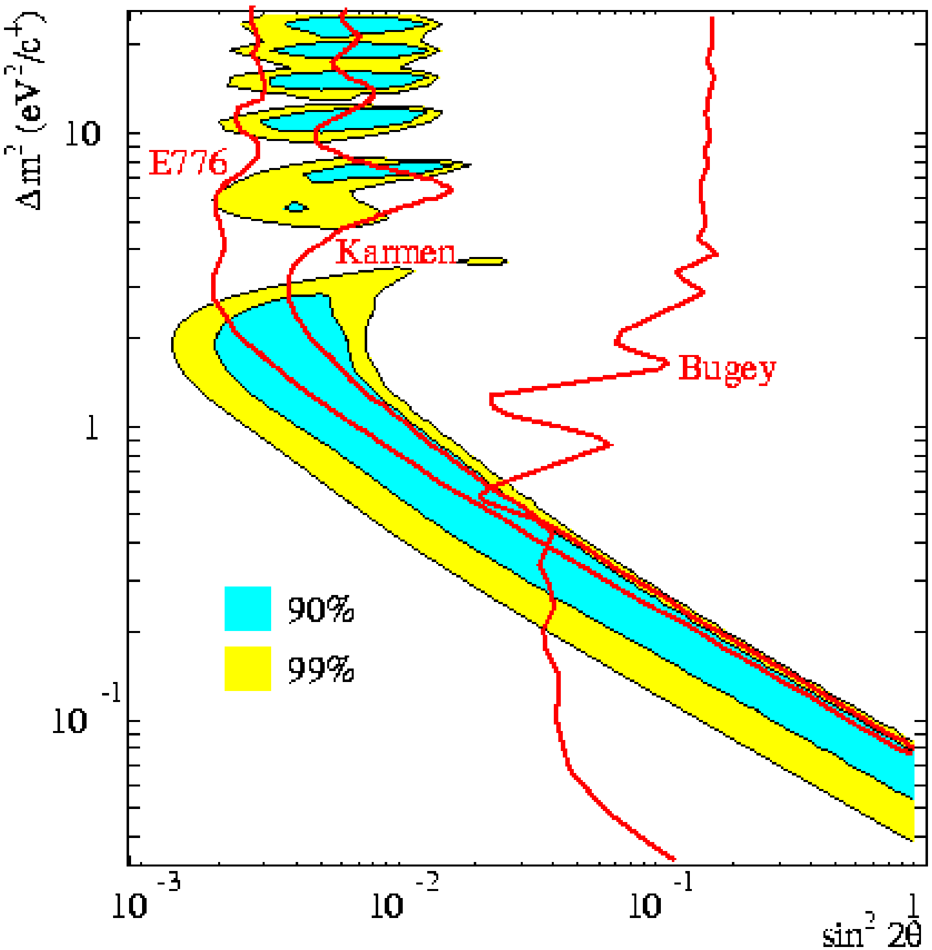
$n + p \to d + \gamma(2.2\ \mathrm{MeV})$

$87.9 \pm 22.4 \pm 6.0$ events

$\langle P_{\overline{\nu}_\mu \to \overline{\nu}_e} \rangle = (2.64 \pm 0.67 \pm 0.45) \times 10^{-3}$

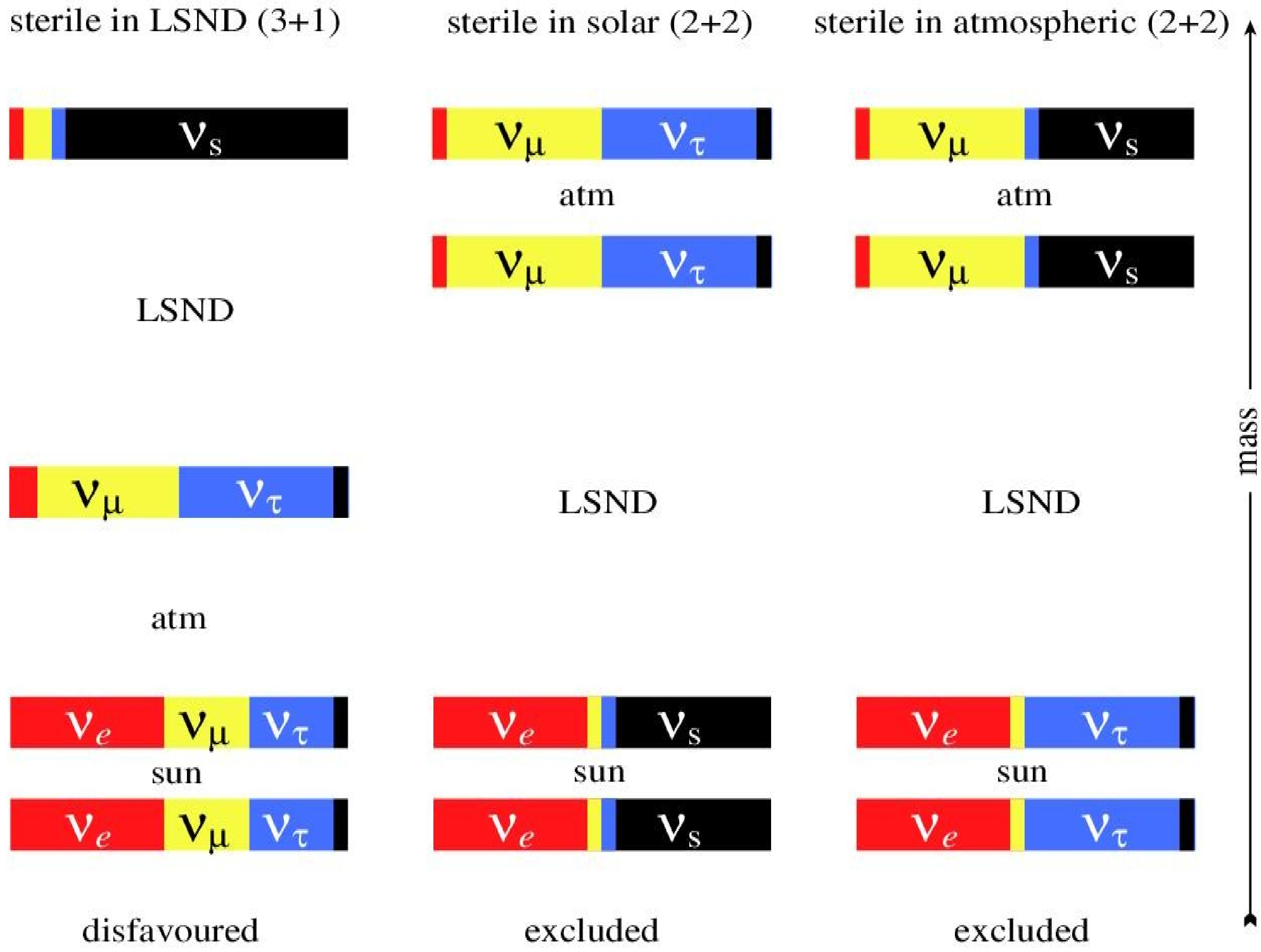
E ≈ 20 MeV

L ≈ 30 m



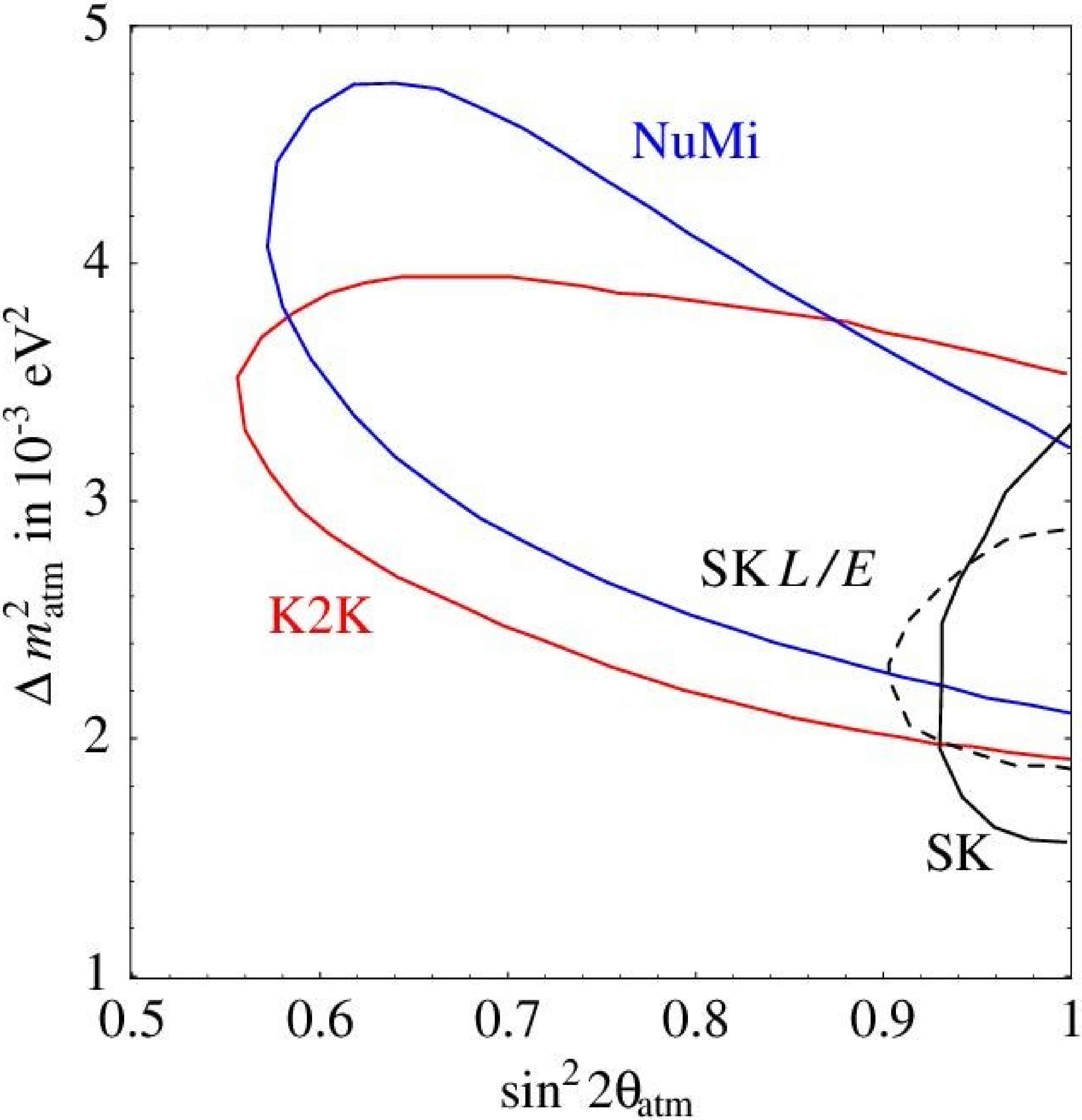
$$\Delta m^2_{\odot} \lesssim 10^{-4}\ \mathrm{eV}^2$$
$$\Delta m^2_{\mathrm{atm}} \simeq 3 \times 10^{-3}\ \mathrm{eV}^2$$
$$\Delta m^2_{\mathrm{LSND}} \gtrsim 0.2\ \mathrm{eV}^2$$

Sterile Neutrinos ?



sterile in LSND (3+1)
sterile in solar (2+2)
sterile in atmospheric (2+2)
ν_s
ν_μ
ν_τ
atm
ν_μ
ν_τ
ν_μ
ν_s
atm
ν_μ
ν_s
LSND
ν_μ
ν_τ
LSND
LSND
mass
atm
ν_e
ν_μ
ν_τ
sun
ν_e
ν_μ
ν_τ
ν_e
ν_s
sun
ν_e
ν_s
ν_e
ν_τ
sun
ν_e
ν_τ
disfavoured
excluded
excluded

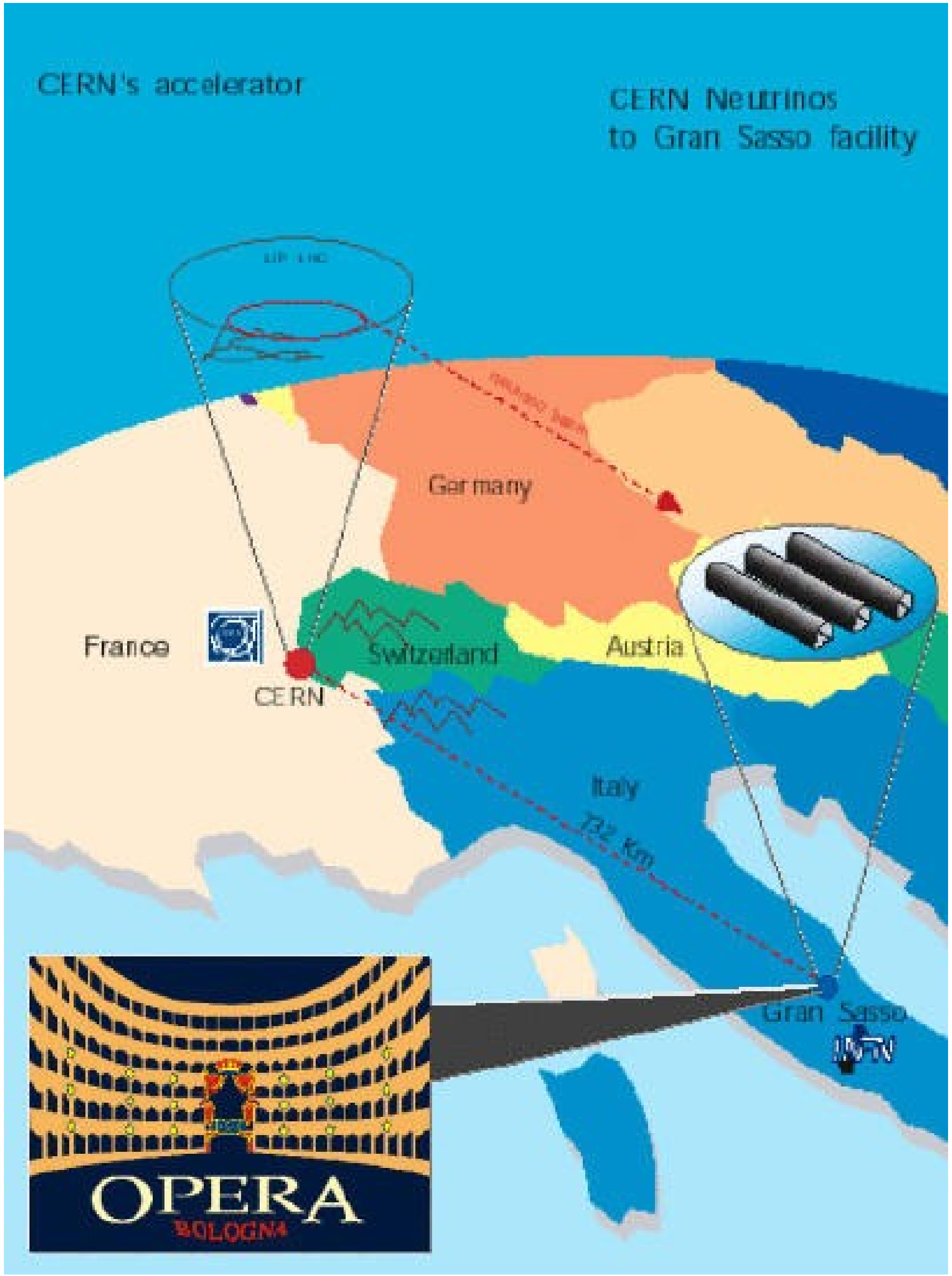
FUTURE STUDIES of OSCILLATIONS



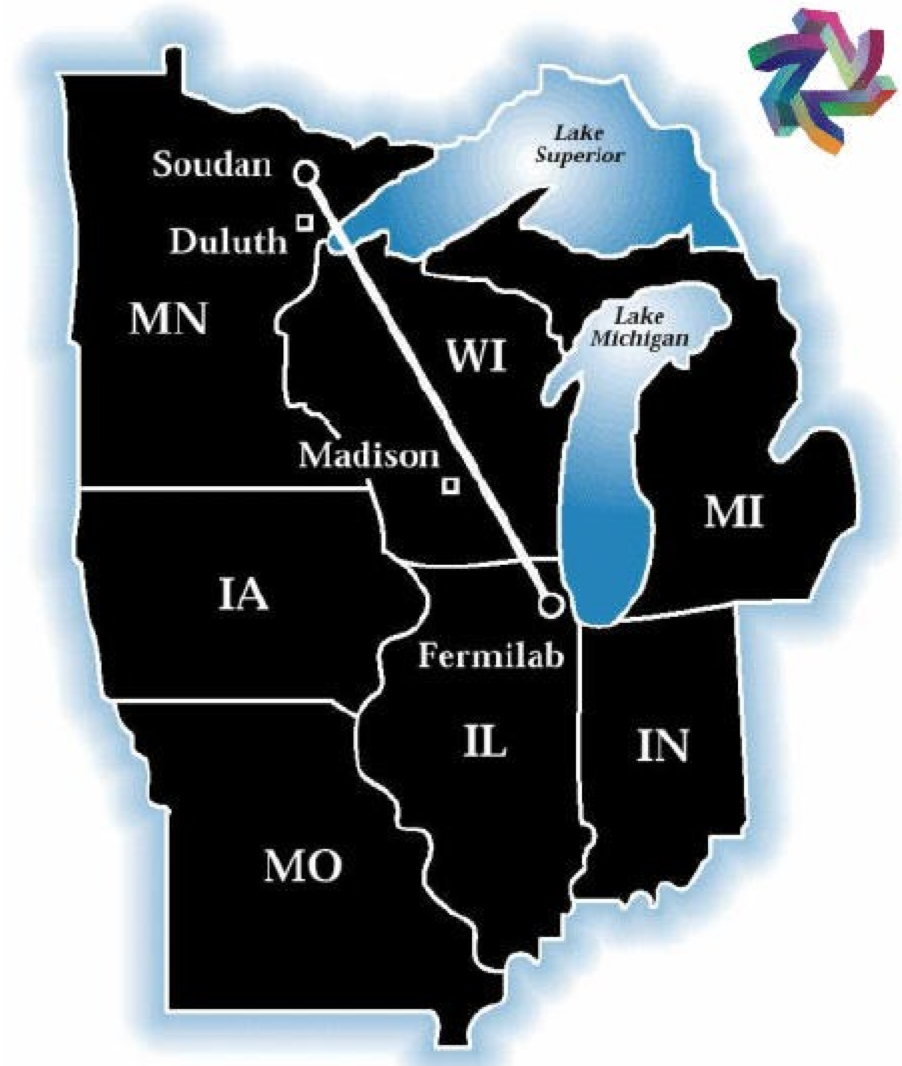
5
4
3
2
1
0.5
0.6
0.7
0.8
0.9
1
Δm^2_{atm} in 10^{-3} eV^2
$\sin^2 2\theta_{atm}$
NuMi
K2K
SK L/E
SK

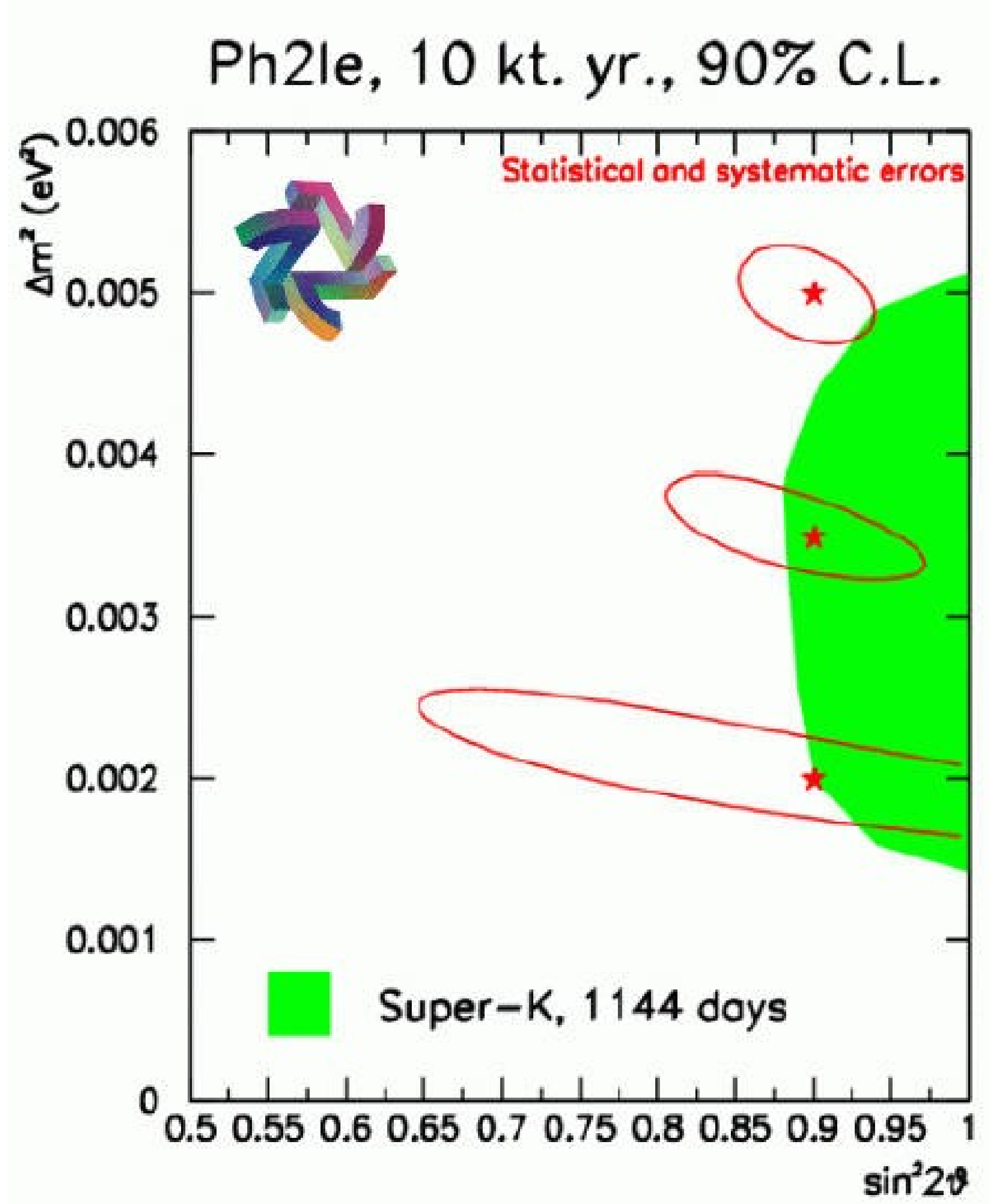
Fermilab to Minos

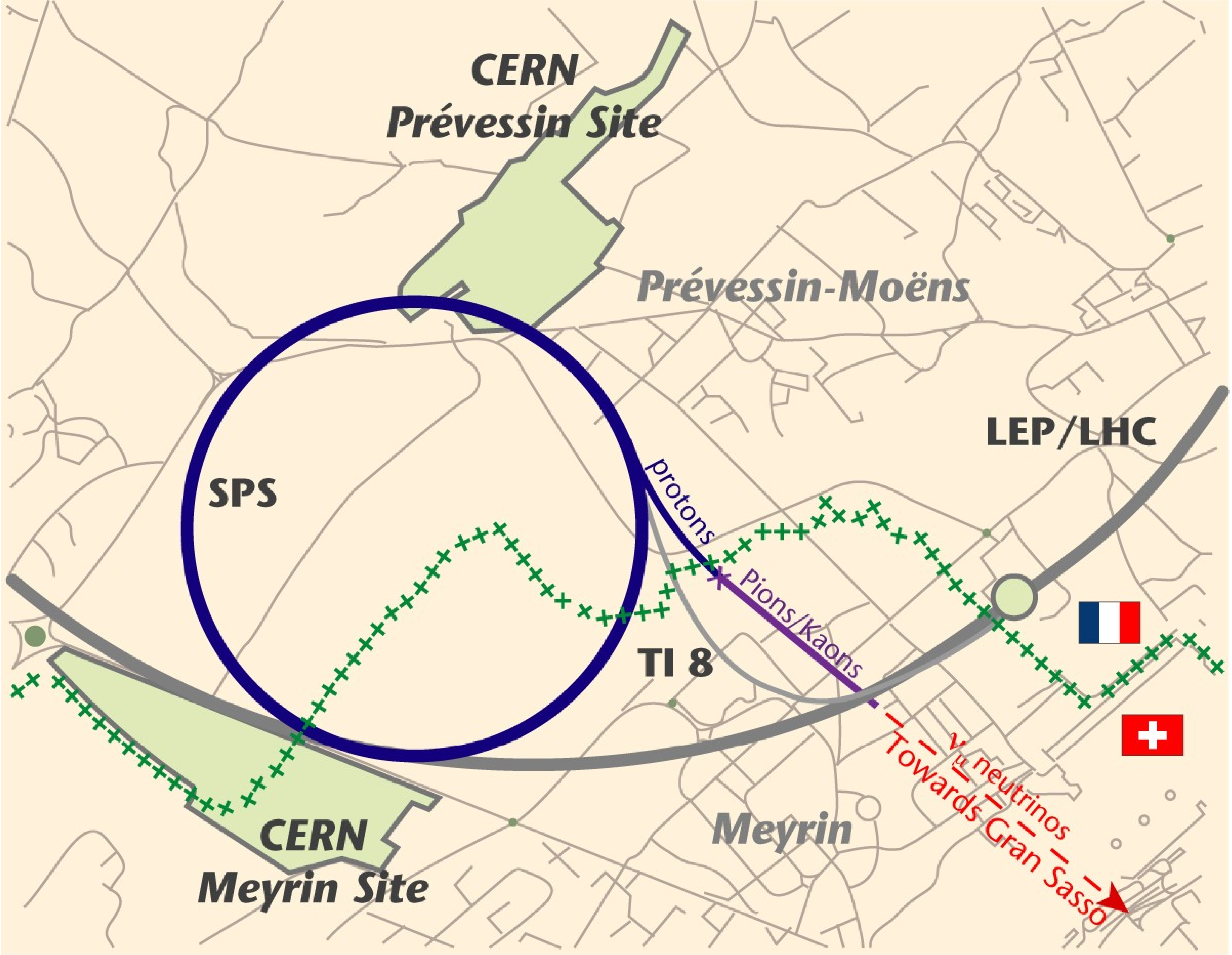
CERN to Gran Sasso



Fermilab to MINOS







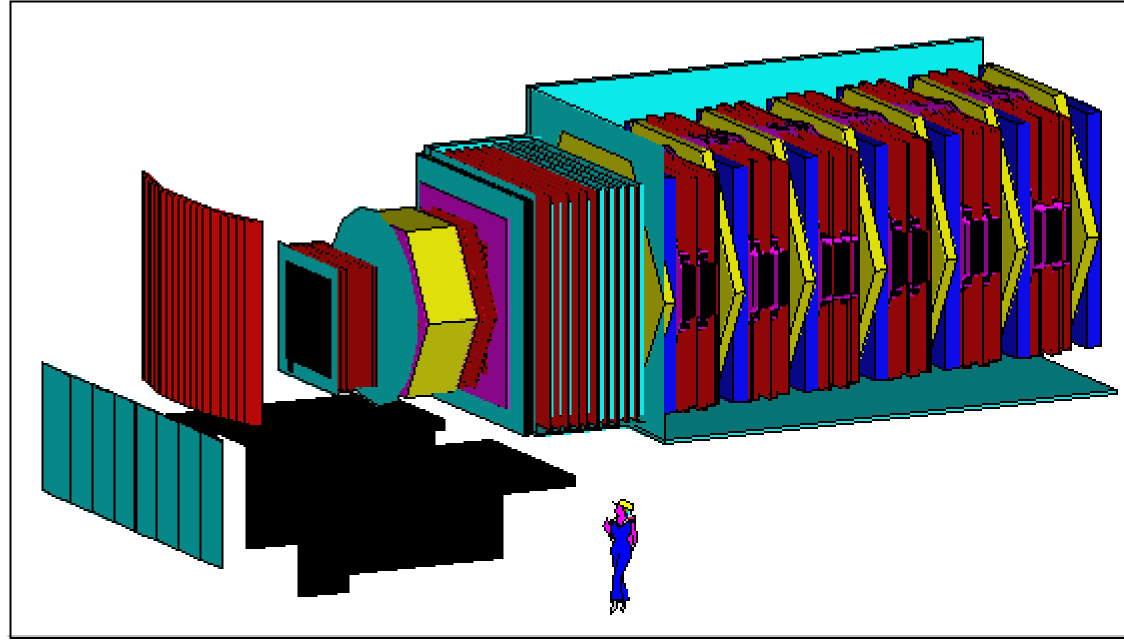
CERN
Prévessin Site
Prévessin-Moëns
LEP/LHC
SPS
protons
Pions/Kaons
TI 8
ν_μ neutrinos
Towards Gran Sasso
CERN
Meyrin Site
Meyrin

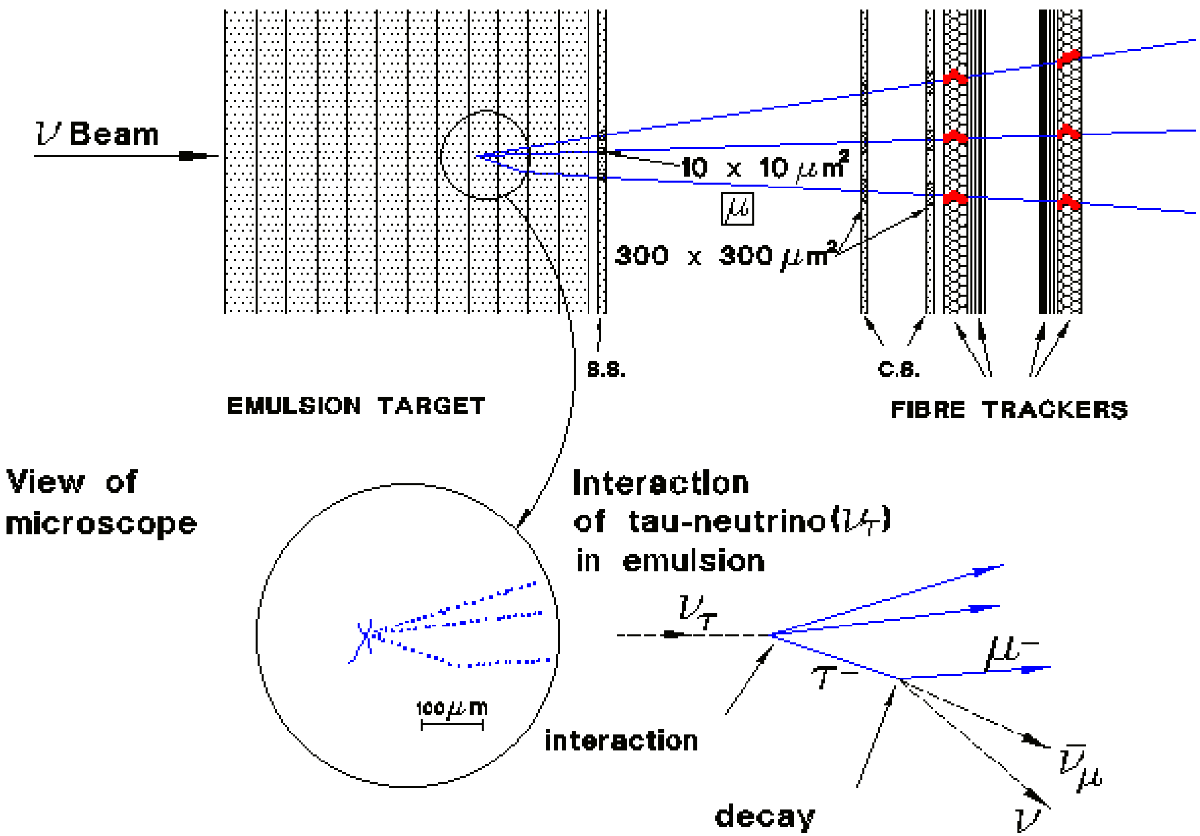

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
CNGS Works
55m
SPS tunnel
TJ8
Access shaft
PGCN
SPS/ECA4
protons
TT41
Access galleries
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
140m
Decay tunnel
pions
kaons
Hadron stop
and first muon detector
Connection gallery
to TI8/LHC
muons
neutrinos
Second muon detector
neutrinos
to Gran Sasso
CNGS-OuvragesSouterrains-2001/06 CERN AC/DI/MM

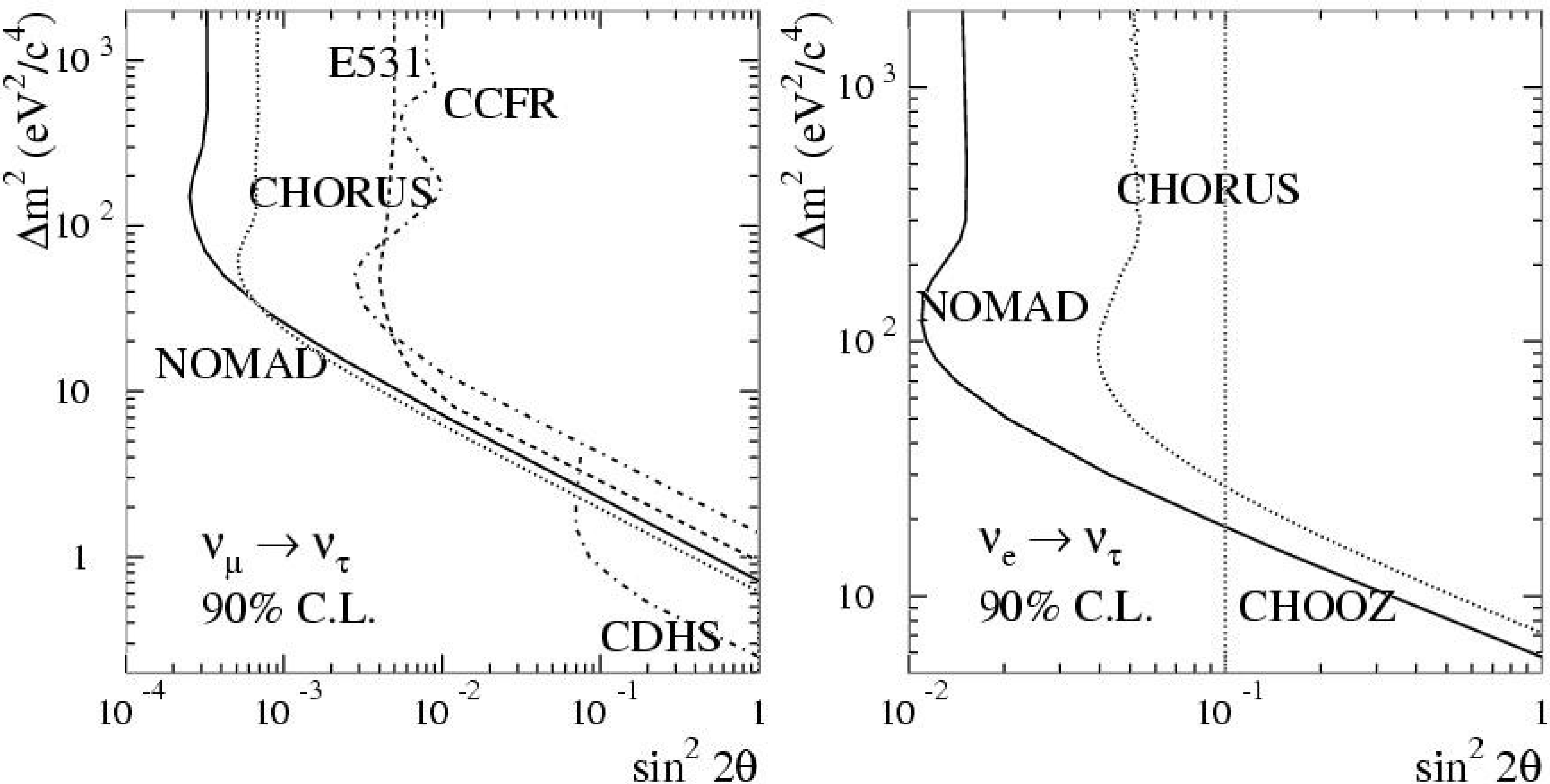
Short Baseline ν_τ Appearance Experiments

Chorus

Nomad



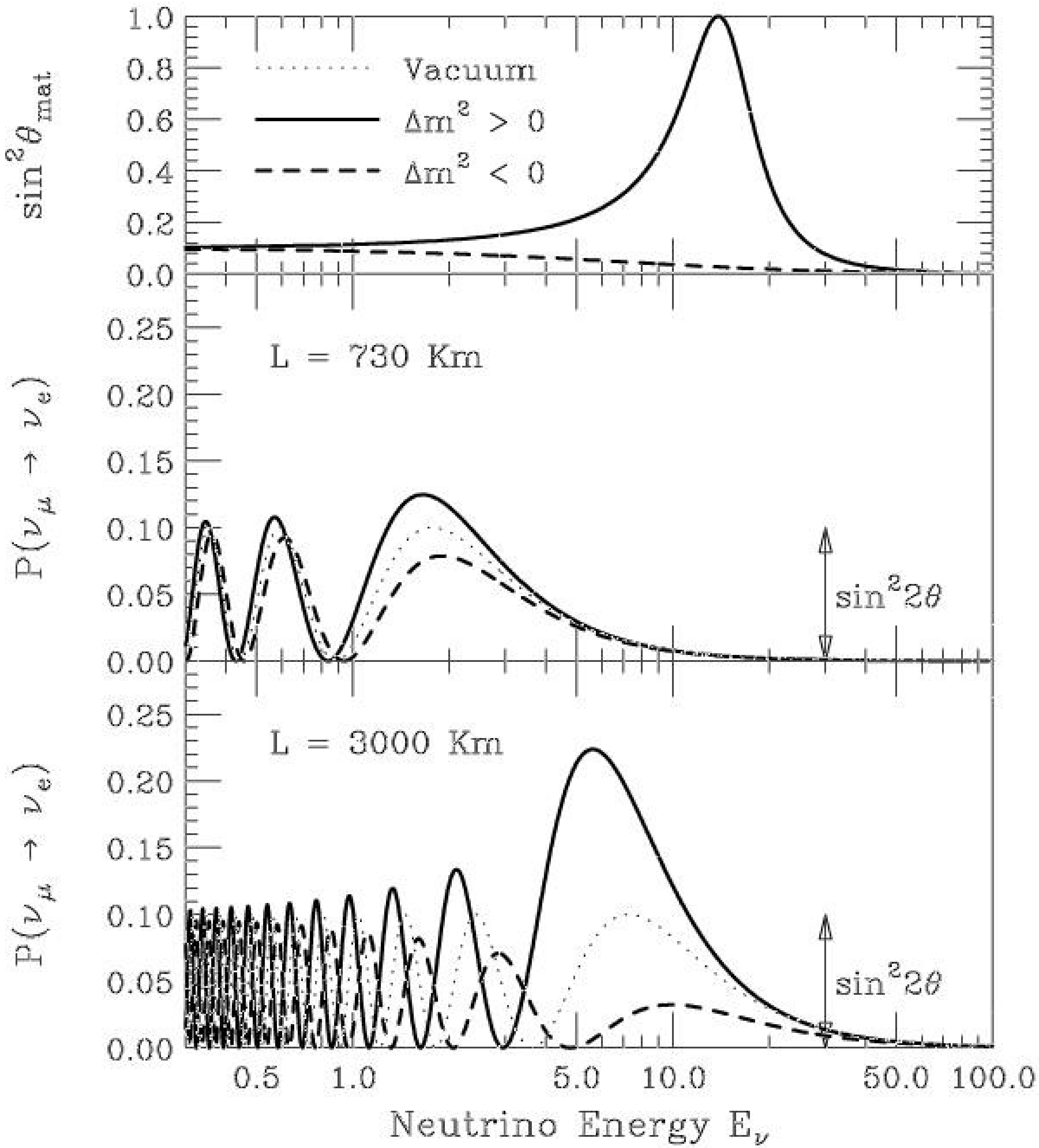




Δm^2 (eV^2/c^4)
10^3
10^2
10
1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$
E531
CCFR
CHORUS
NOMAD
CDHS
$\nu_\mu \rightarrow \nu_\tau$
90% C.L.
Δm^2 (eV^2/c^4)
10^3
10^2
10
10^{-2}
10^{-1}
1
$\sin^2 2\theta$
CHORUS
NOMAD
CHOOZ
$\nu_e \rightarrow \nu_\tau$
90% C.L.

Search for U_{e3}

Solve the ambiguity in the mass hyerarchy

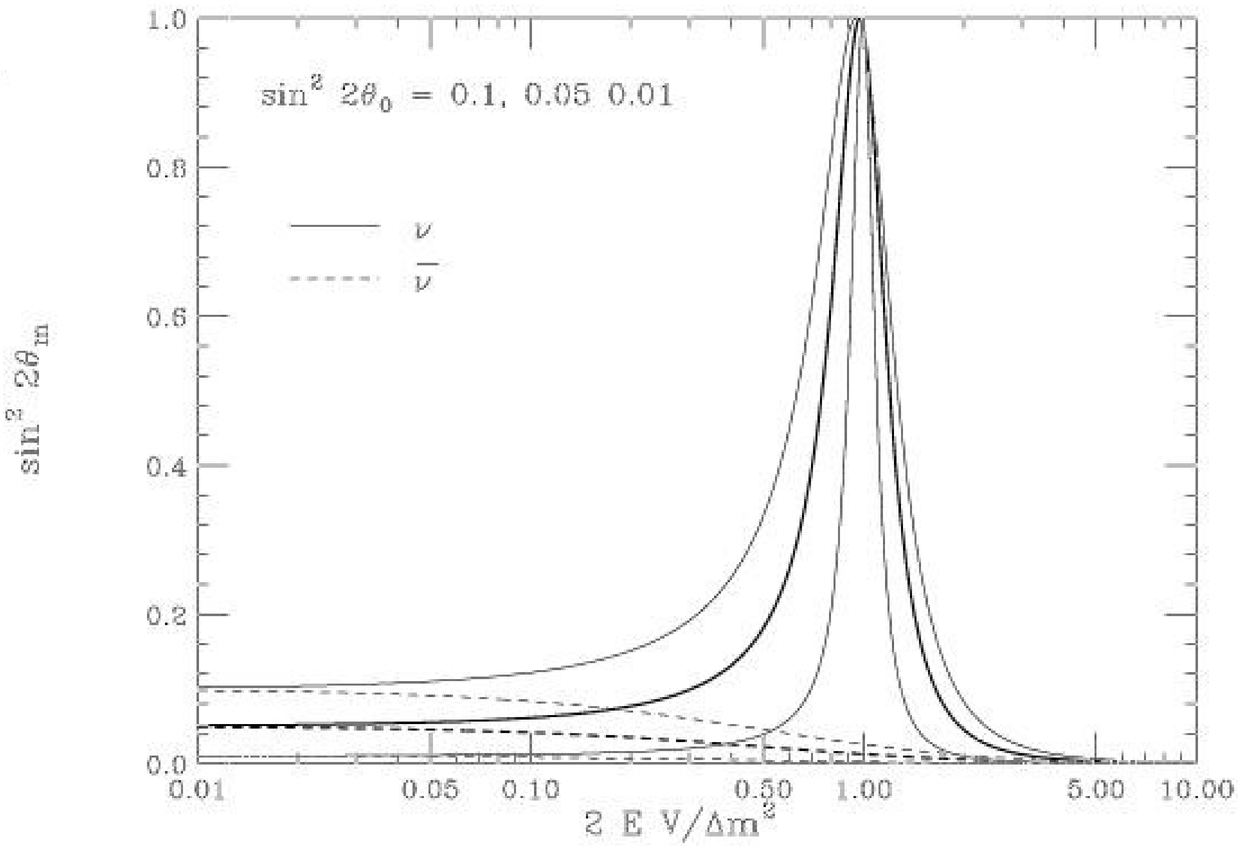


Matter Effects

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - \xi)^2}$$

$$(\Delta m^2)_{\text{eff}} = \Delta m^2 \times \sqrt{\sin^2 2\theta + (\cos 2\theta - \xi)^2}$$

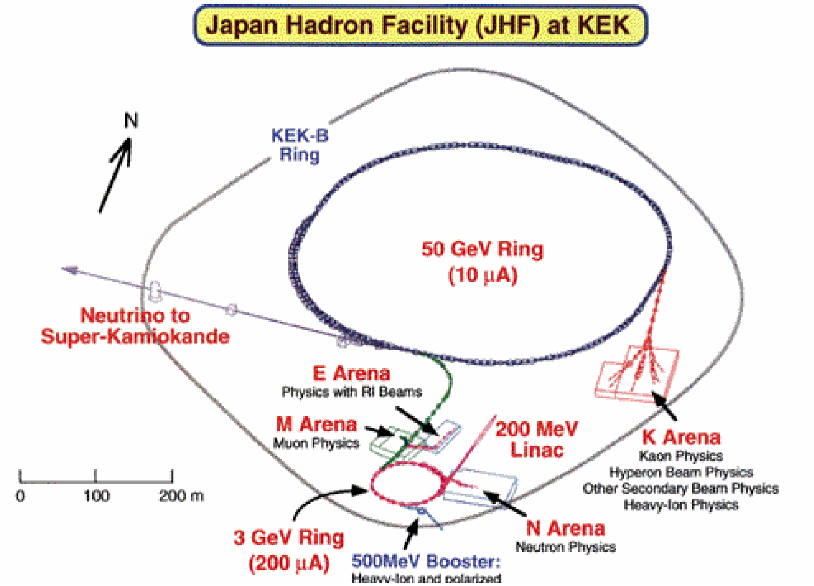
$$\xi = \frac{2VE}{\Delta m^2} = \frac{2\sqrt{2} G_F N_e}{\Delta m^2}$$

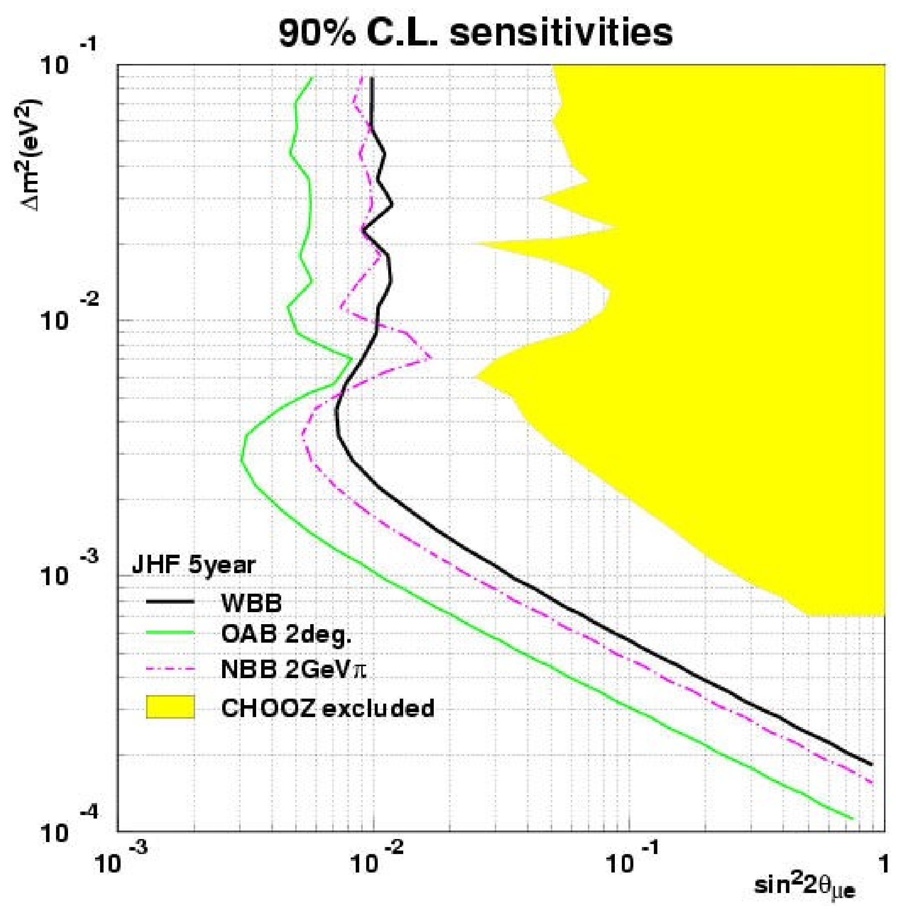


JHF project

$$\nu_\mu \rightarrow \nu_e$$

$$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$$





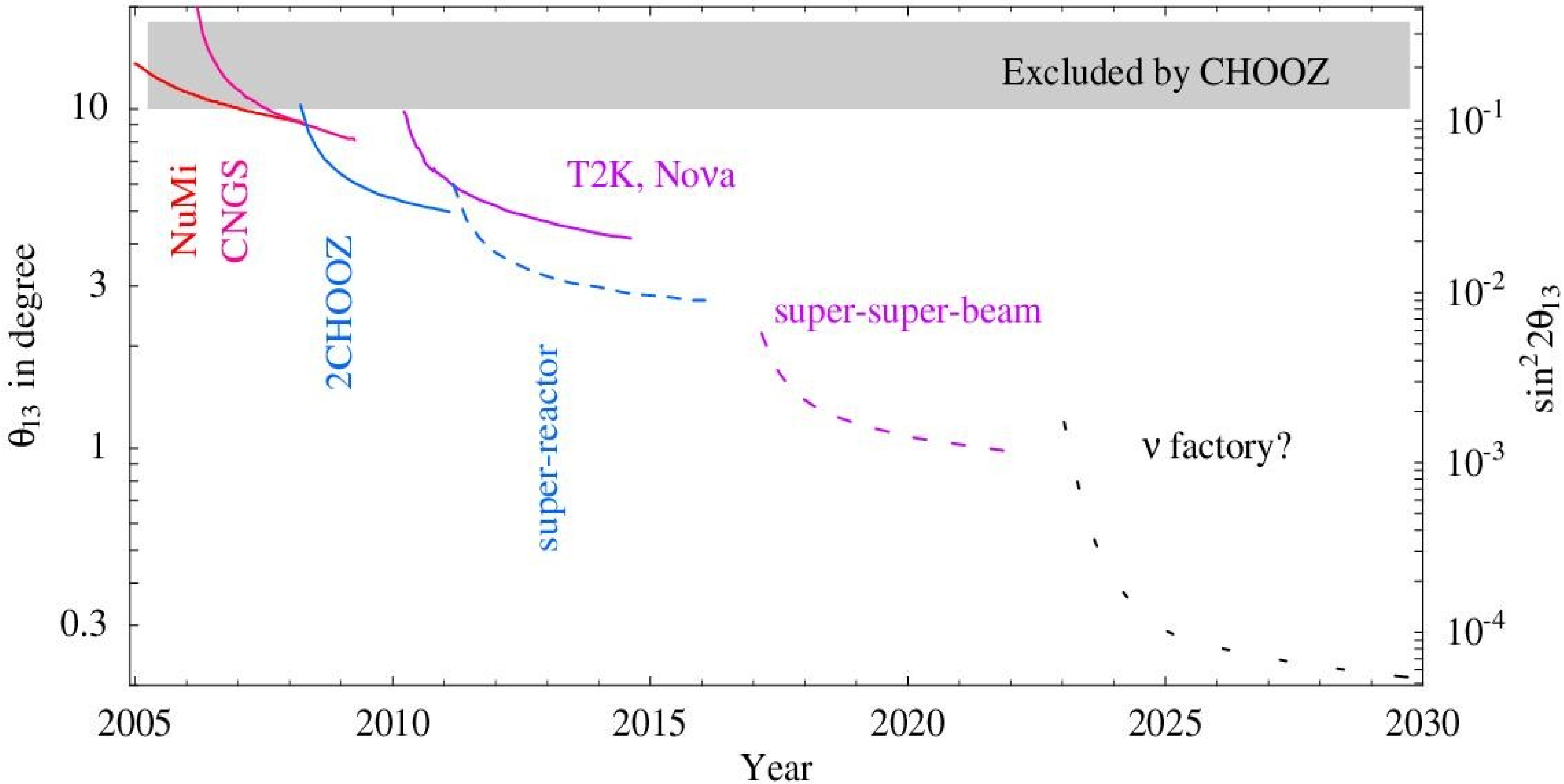
CP Violation Effects in Neutrino Oscillations

$$P_{\nu_\alpha \to \nu_\beta} = P_{\overline{\nu}_\beta \to \overline{\nu}_\alpha} \qquad \text{CPT symmetry}$$
$$P_{\nu_\alpha \to \nu_\beta} = P_{\overline{\nu}_\alpha \to \overline{\nu}_\beta} \qquad \text{CP symmetry}$$
$$P_{\nu_\alpha \to \nu_\beta} = P_{\nu_\beta \to \nu_\alpha} \qquad \text{T symmetry}$$

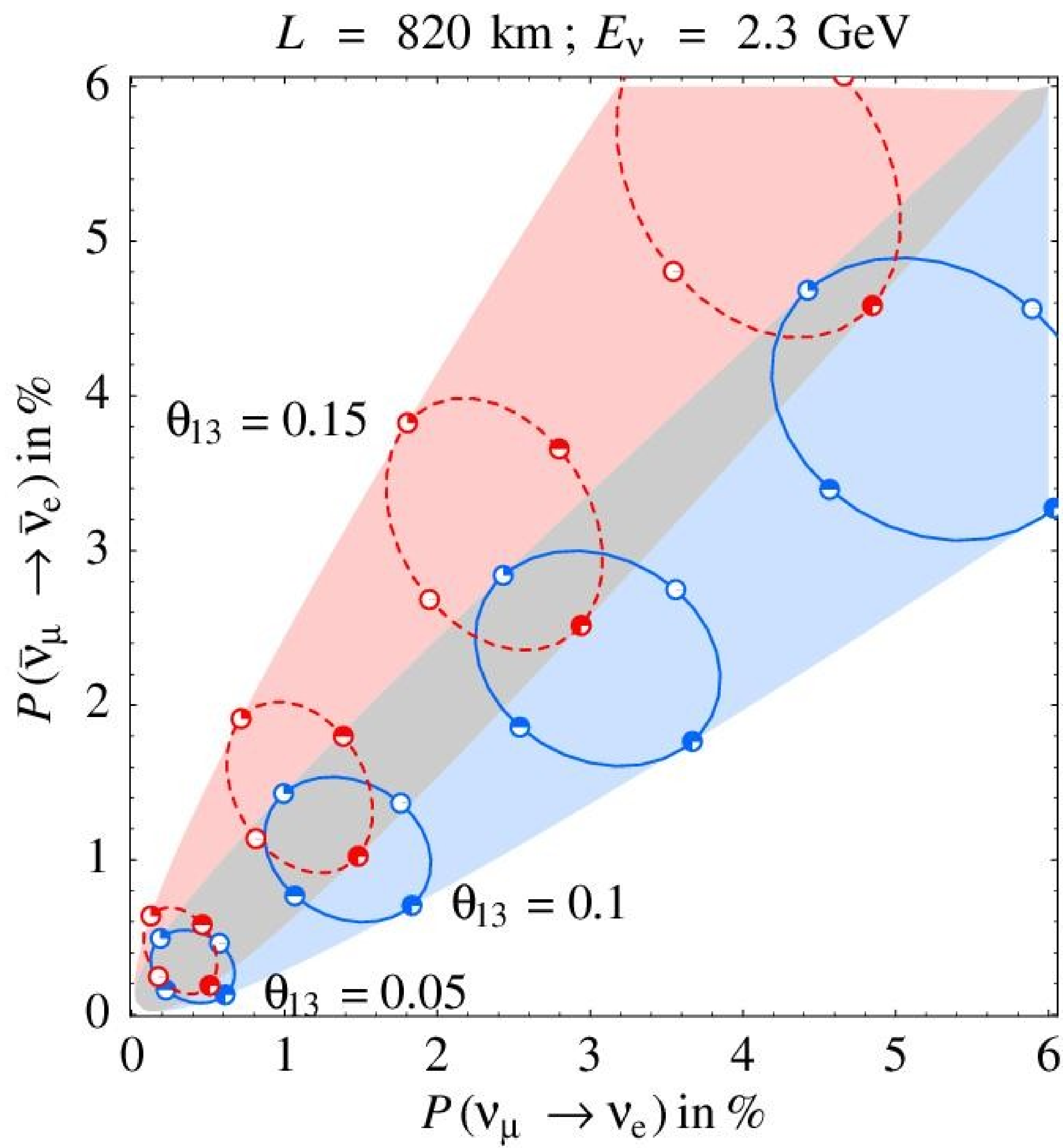
In Vacuum

$$\begin{aligned} \Delta P_{\alpha\beta} &= P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) = P(\nu_\alpha \to \nu_\beta) - P(\nu_\beta \to \nu_\alpha) \\ &= 16\, J\, \sin\left(\frac{\Delta m^2_{12}\, L}{2E_\nu}\right) \sin\left(\frac{\Delta m^2_{13}\, L}{2E_\nu}\right) \sin\left(\frac{\Delta m^2_{23}\, L}{2E_\nu}\right) \end{aligned}$$

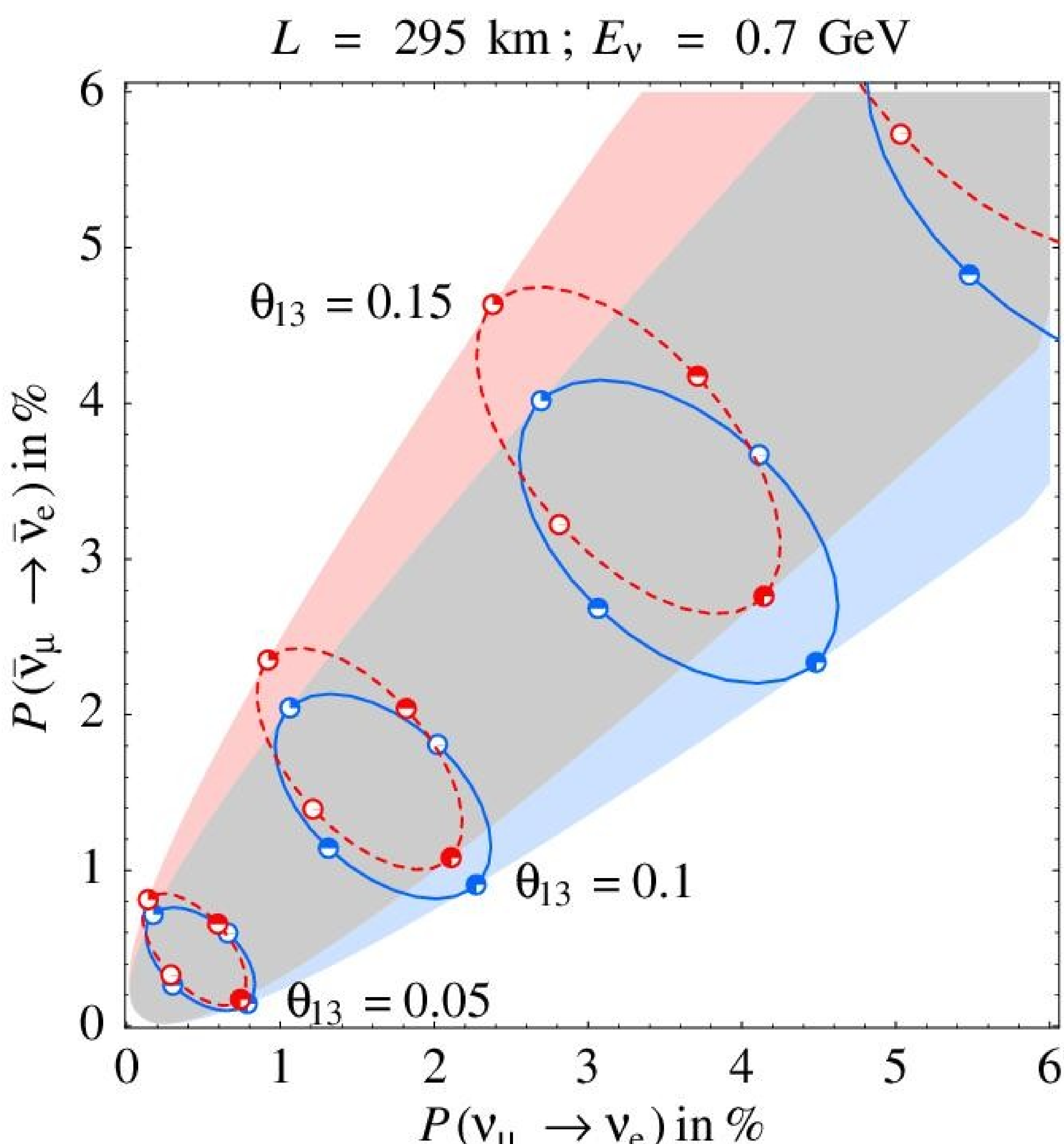
$$\begin{aligned} J &= J^{e\mu}_{12} = -\mathrm{Im}[U_{e1}\, U^*_{\mu 1}\, U^*_{e2}\, U_{\mu 2}] \\ &= c^2_{13}\, s_{13}\, s_{12}\, c_{12}\, s_{23}\, c_{23}\, \sin\delta \end{aligned}$$



Excluded by CHOOZ
NuMi
CNGS
2CHOOZ
T2K, Nova
super-reactor
super-super-beam
ν factory?
10
3
1
0.3
10^{-1}
10^{-2}
10^{-3}
10^{-4}
θ_{13} in degree
$\sin^2 2\theta_{13}$
2005
2010
2015
2020
2025
2030
Year

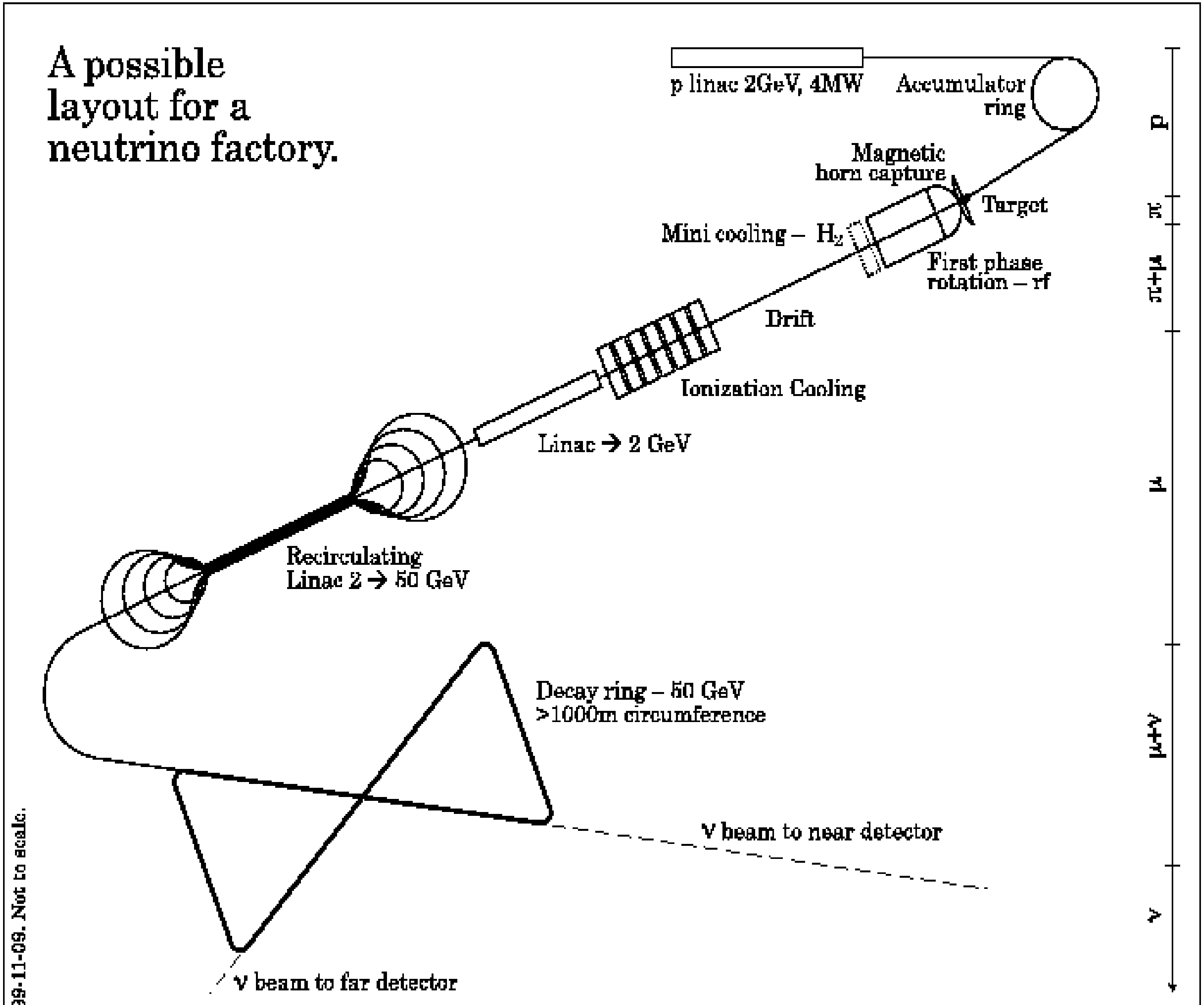


$L = 820$ km ; $E_\nu = 2.3$ GeV
$\theta_{13} = 0.15$
$\theta_{13} = 0.1$
$\theta_{13} = 0.05$
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ in %
$P(\nu_\mu \rightarrow \nu_e)$ in %
0
1
2
3
4
5
6



$L = 295$ km ; $E_\nu = 0.7$ GeV
$\theta_{13} = 0.15$
$\theta_{13} = 0.1$
$\theta_{13} = 0.05$
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ in %
$P(\nu_\mu \to \nu_e)$ in %
0
1
2
3
4
5
6

Neutrino Factory



Absolute Neutrino Mass

DIRAC versus MAJORANA

$$m_{\text{cosmological}} = \sum m_j$$

Cosmology

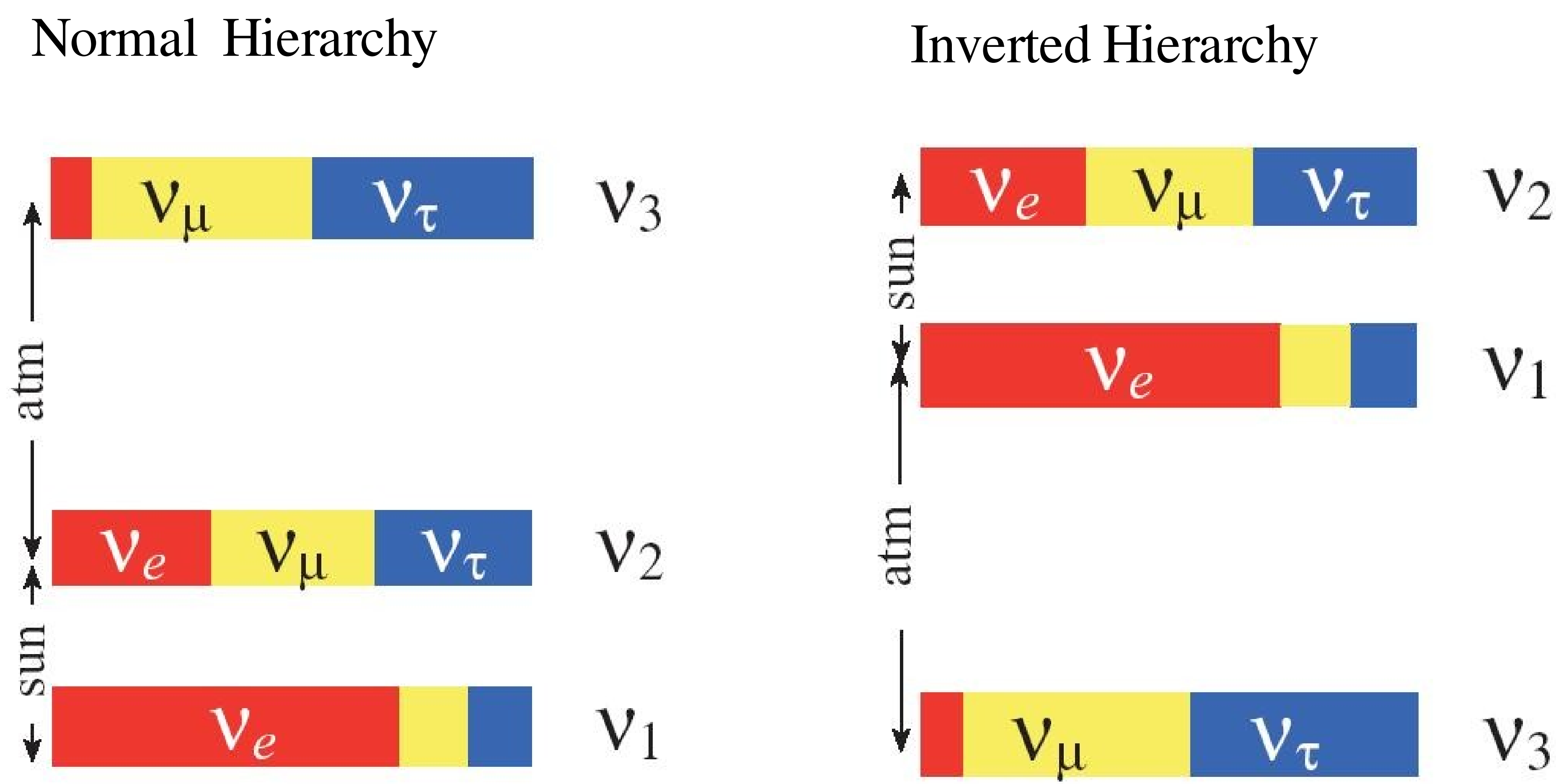
$$m_\beta \equiv m_{\text{kinematic}} = \left[\sum_j |U_{ej}|^2 m_j^2 \right]^{\frac{1}{2}}$$

Beta Decay

$$m_{\beta\beta} = \left| \sum_j U_{ej}^2 \, e^{i\varphi_j} \, m_j^2 \right|$$

Neutrino-less
Double Beta Decay

Neutrino MASS Hierarchy



Mass of the lightest Neutrino m_0

$$\sqrt{\Delta m^2_\odot} \simeq 9 \text{ meV}$$

$$\sqrt{|\Delta m^2_{\rm atm}|} \simeq 49 \text{ meV}$$

Normal Hierarchy

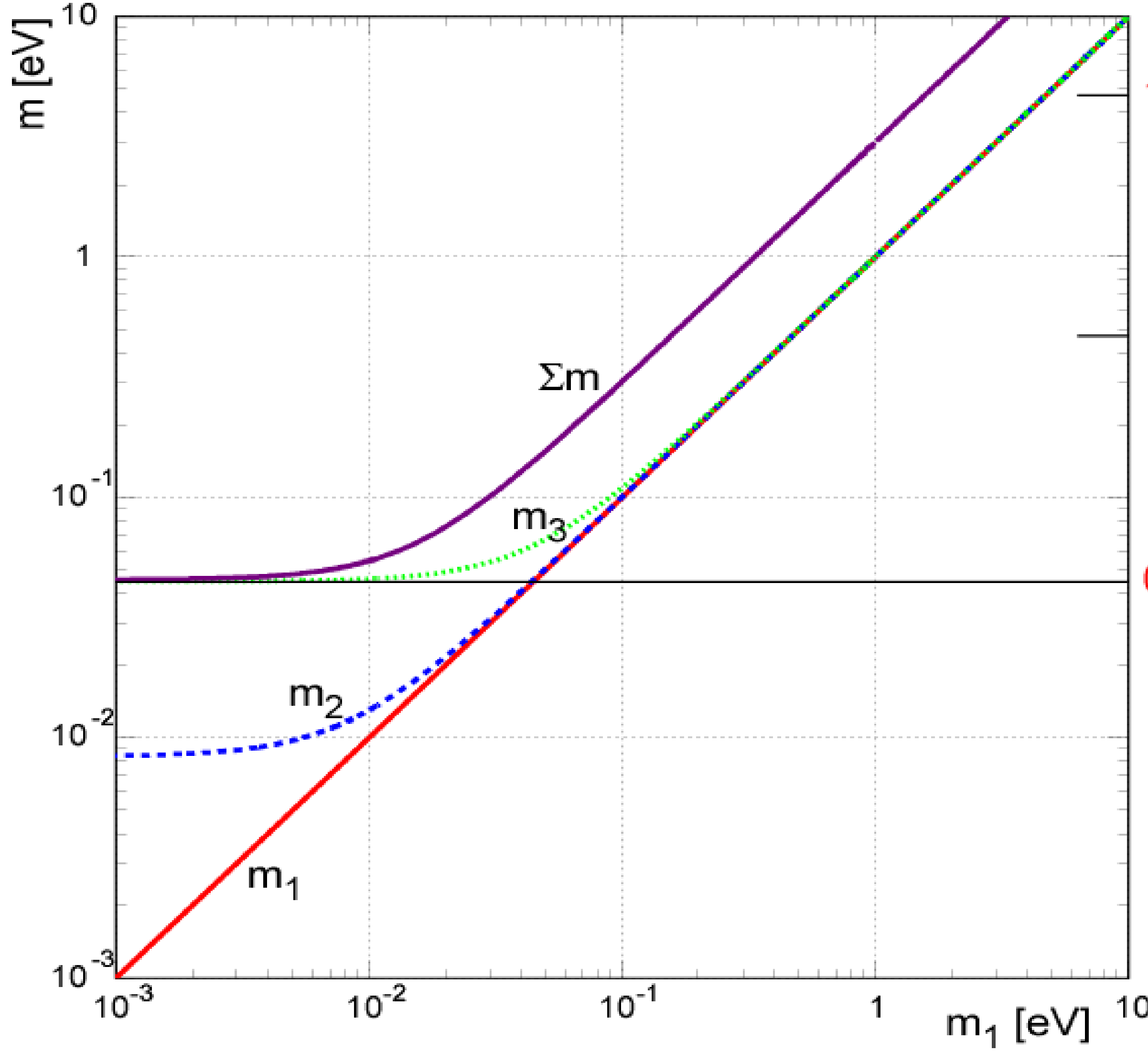
$$\begin{aligned} m_1 &= m_0 \\ m_2 &= \sqrt{m_0^2 + \Delta m^2_\odot} \\ m_3 &= \sqrt{m_0^2 + \Delta m^2_\odot + \Delta m^2_{\rm atm}} \end{aligned}$$

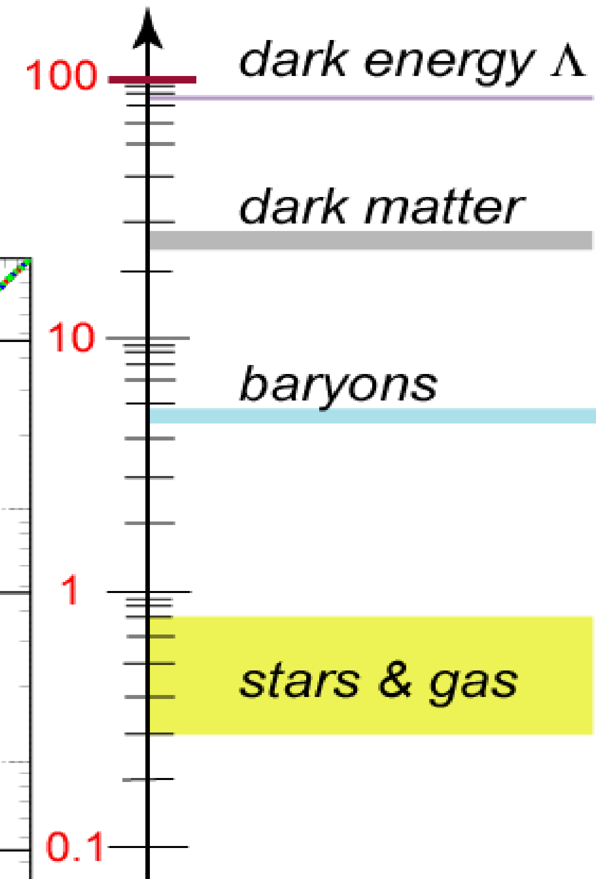
Inverted Hierarchy

$$\begin{aligned} m_3 &= m_0 \\ m_1 &= \sqrt{m_0^2 + \Delta m^2_{\rm atm}} \\ m_2 &= \sqrt{m_0^2 + \Delta m^2_{\rm atm} + \Delta m^2_\odot} \end{aligned}$$

Degenerate masses

$$m_0 \gg \sqrt{\Delta m^2_{\rm atm}} \qquad m_1 \simeq m_2 \simeq m_3$$



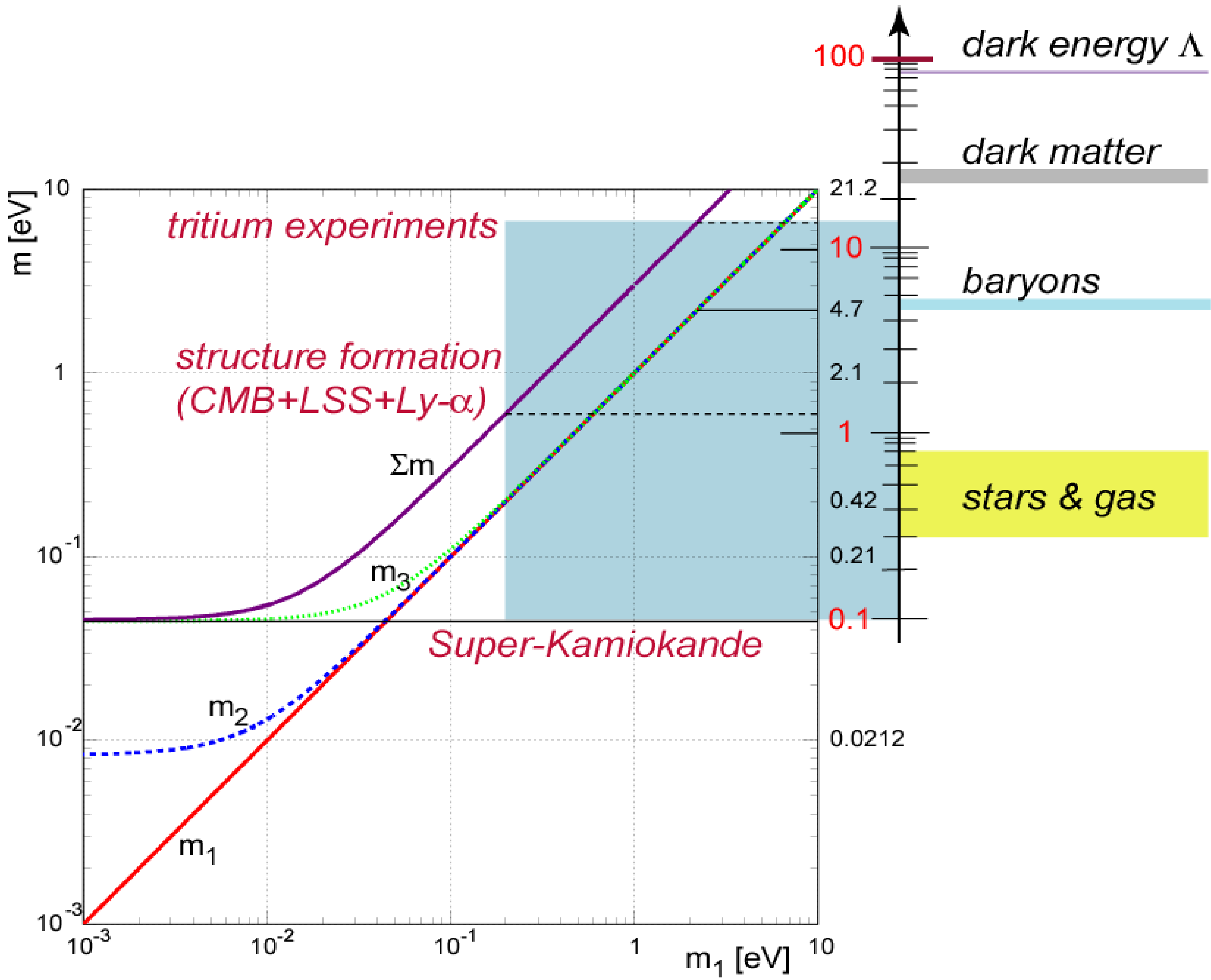


Normal Hierarchy

$$m_1 = m_0$$

$$m_2 = \sqrt{m_0^2 + \Delta m_\odot^2}$$

$$m_3 = \sqrt{m_0^2 + \Delta m_\odot^2 + \Delta m_{\rm atm}^2}$$



dark energy Λ
100
dark matter
21.2
10
baryons
4.7
2.1
1
stars & gas
0.42
0.21
0.1
0.0212
tritium experiments
structure formation
(CMB+LSS+Ly-α)
Σm
m3
Super-Kamiokande
m2
m1
m [eV]
m1 [eV]
10
1
10^-1
10^-2
10^-3

Limit of small "lightest mass" :

$$m_0 \to 0$$

$$m_0 \ll \sqrt{\Delta m^2_\odot}$$

Normal Hierarchy

$$m_1 \simeq 0$$

$$m_2 \simeq \sqrt{\Delta m^2_\odot} \simeq 9 \text{ meV}$$

$$m_3 \simeq \sqrt{\Delta m^2_{\rm atm}} \simeq 49 \text{ meV}$$

Inverted Hierarchy

$$m_3 \simeq 0$$

$$m_1 \simeq \sqrt{\Delta m^2_{\rm atm}} \simeq 49 \text{ meV}$$

$$m_2 \simeq \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_\odot} \simeq 49.8 \text{ meV}$$

$$m_{\text{cosmological}} = \sum_j m_j$$

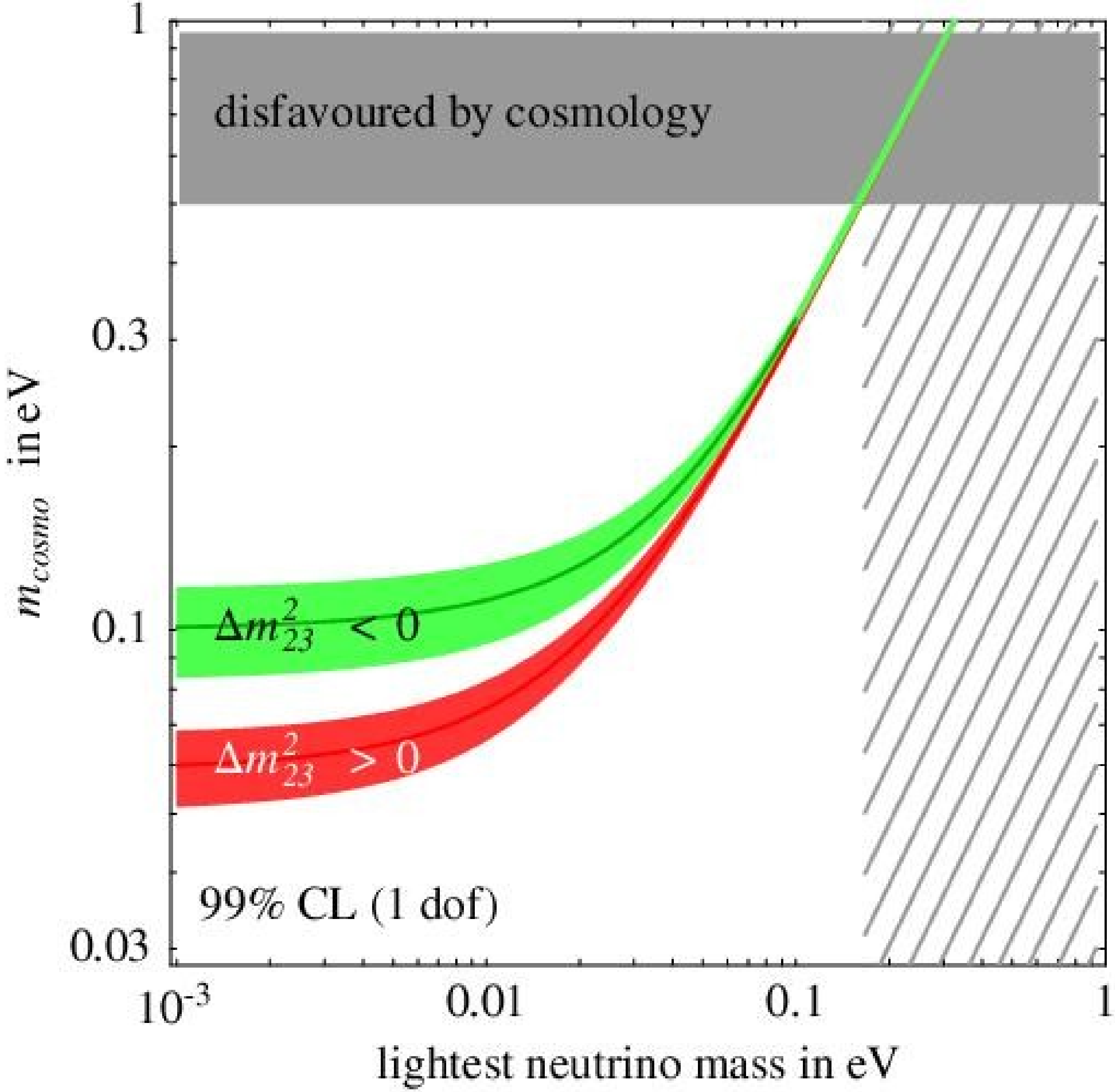
Flavor Oscillation Studies:

Lower Limit on neutrino mass

Degenerate Spectrum $= 3\,m_0$

Normal Hierarchy $\simeq \sqrt{\Delta m^2_{\text{atm}}} \simeq 0.05\text{eV}$

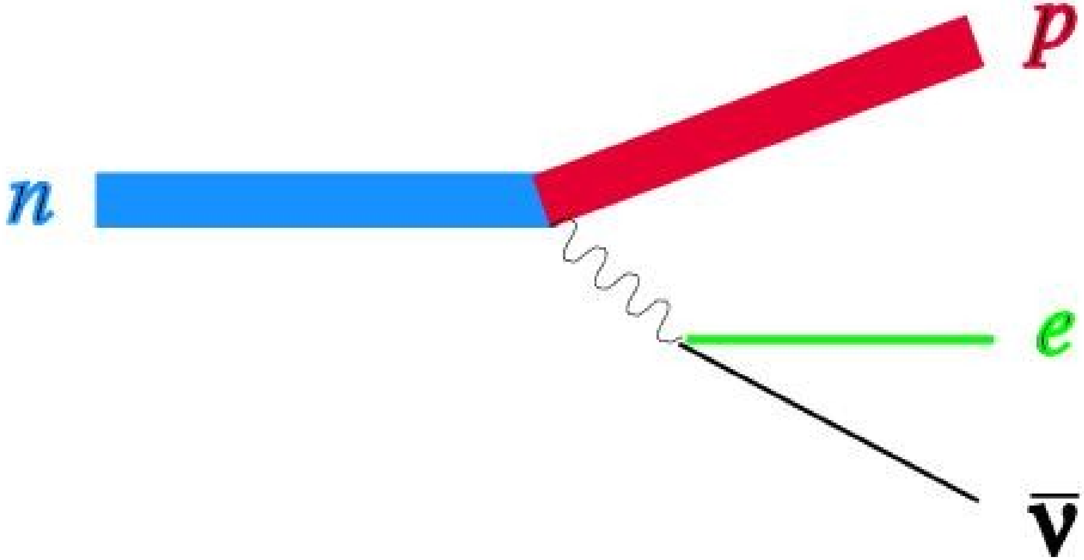
Inverse Hierarchy $\simeq 2\sqrt{\Delta m^2_{\text{atm}}} \simeq 0.1\text{eV}$



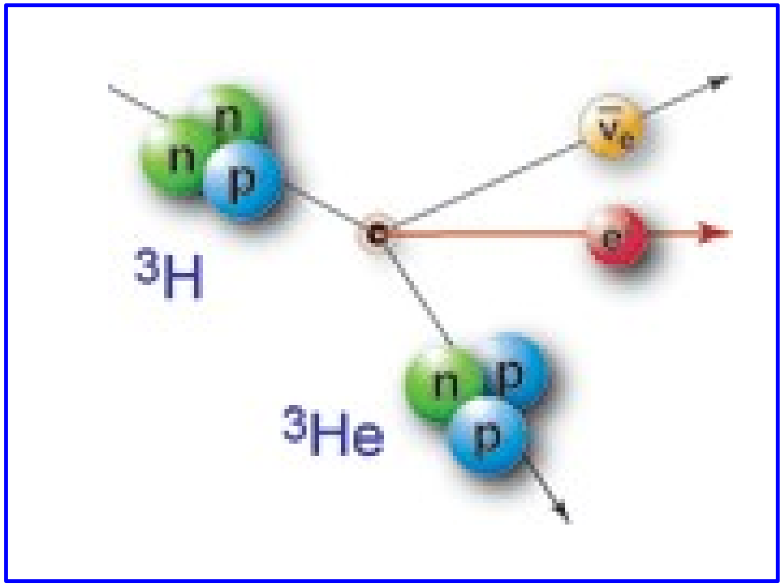
$$
\begin{aligned}
m_{\text{cosmological}} &= \sum_j m_j \\
&= 3\,m_0 \\
&\simeq \sqrt{\Delta m^2_{\text{atm}}} \simeq 0.05\text{eV} \\
&\simeq 2\sqrt{\Delta m^2_{\text{atm}}} \simeq 0.1\text{eV}
\end{aligned}
$$

BETA decay

Kinematical measurement of the Neutrino Mass



$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He}\, e\, \bar{\nu}_e$$

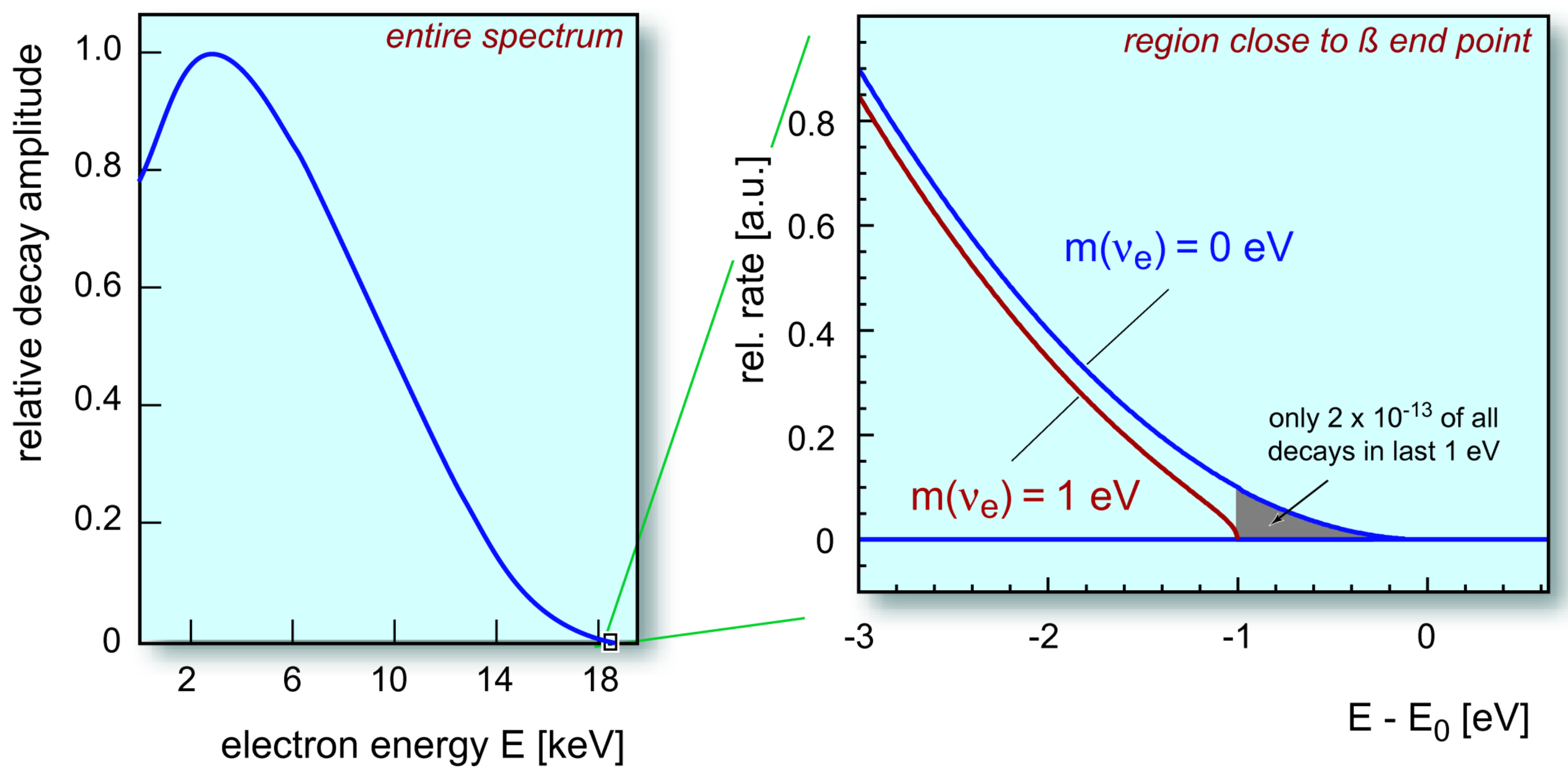


$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$$

superallowed

half life : $t_{1/2}$ = 12.32 a

ß end point energy : E_0 = 18.57 keV



FROM G. DREXLIN

Beta Decay Spectrum near End Point

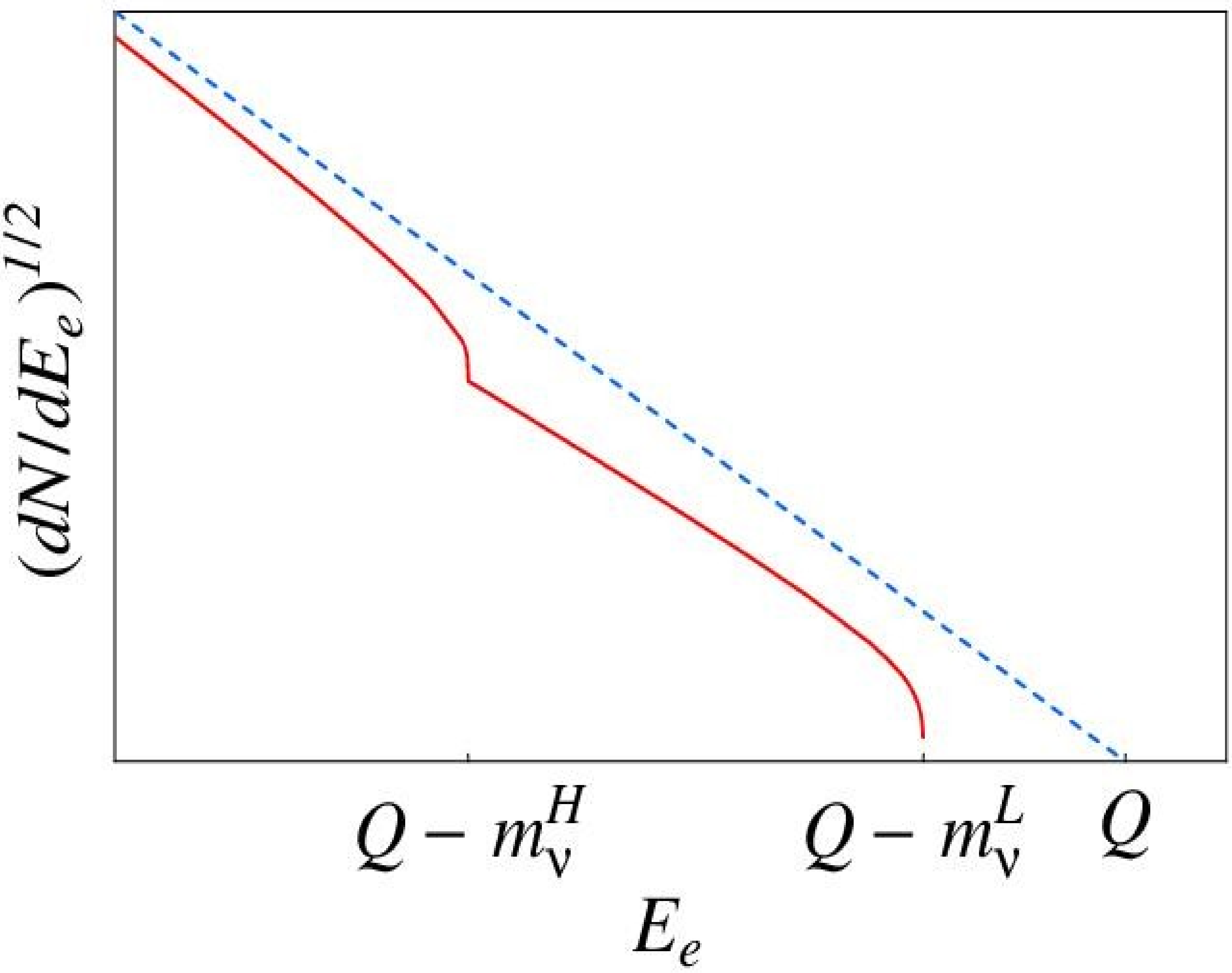
$$\frac{dN}{dE_e} \propto E_\nu p_\nu$$

$$(Q - E_e)\sqrt{(Q - E_e)^2 - m_\nu^2}$$

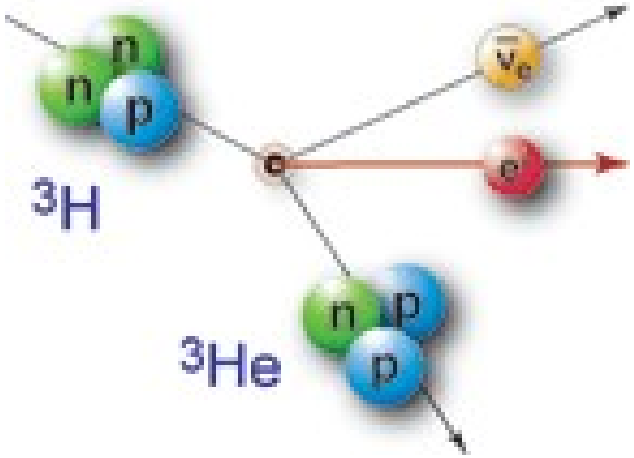
$$(Q - E_e)\sum_j |U_{ej}|^2 \sqrt{(Q - E_e)^2 - m_j^2}$$

$$m_\beta \equiv m_{\text{kinematic}} = \left[\sum_j |U_{ej}|^2 m_j^2\right]^{\frac{1}{2}}$$

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$



$(dN/dE_e)^{1/2}$
$Q - m_\nu^H$
$Q - m_\nu^L$
Q
E_e



Results of Measurements of Tritium:

$$m_\beta^2 = -1.2 \pm 3.0 \text{ eV}^2 \text{ (Mainz)}$$
$$m_\beta^2 = -2.3 \pm 3.2 \text{ eV}^2 \text{ (Troitsk)}$$

$$m_\beta < 2.2 \text{ eV (Mainz)}$$
$$m_\beta < 2.1 \text{ eV (Troitsk)}$$

Beta Decay Mass

$$m_\beta = \left[\sum_j |U_{ej}|^2\, m_j^2\right]^{\frac{1}{2}}$$

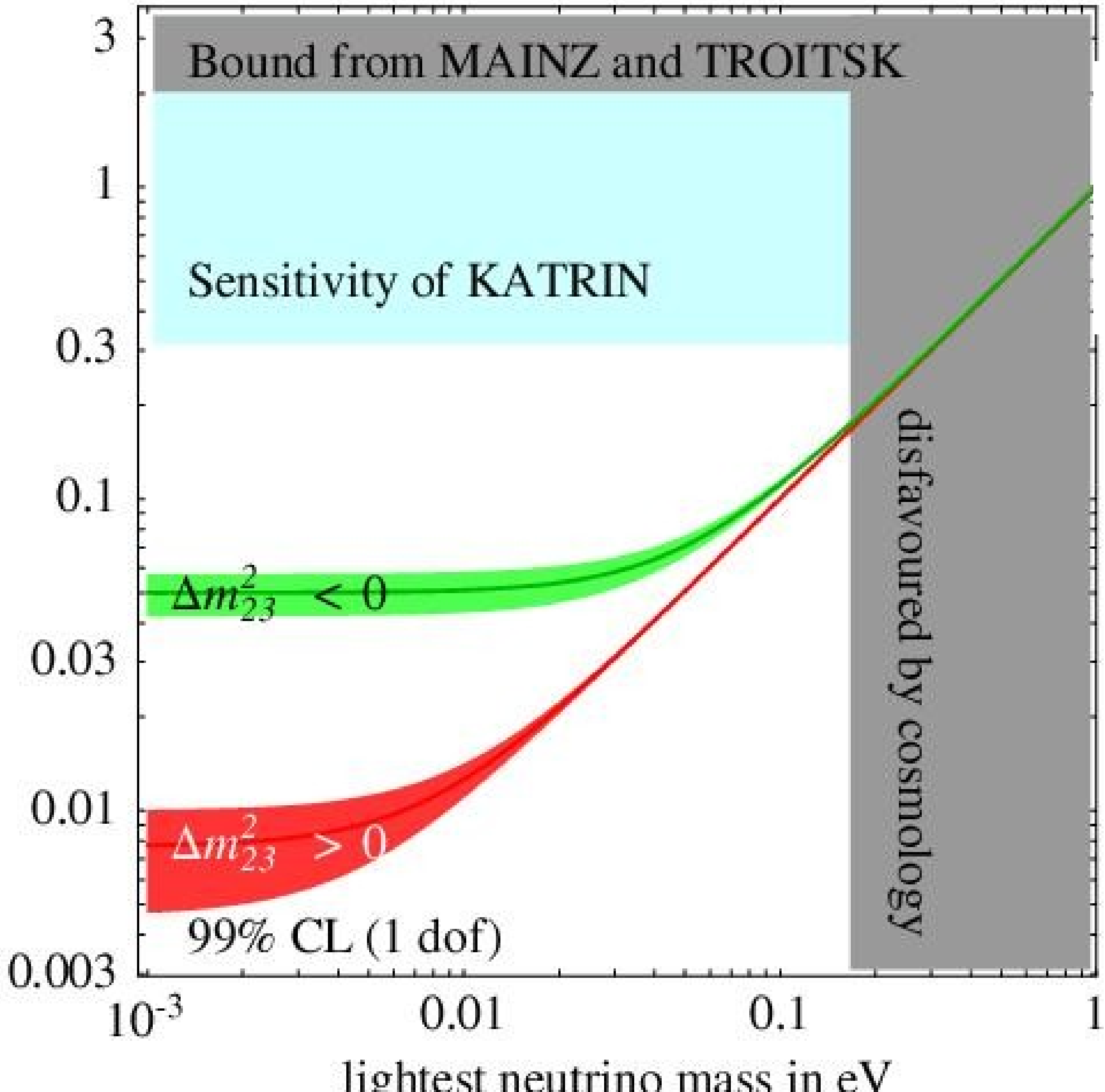
$$= \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

$$\simeq \left[c_{12}^2 m_1^2 + s_{12}^2 m_2^2\right]^{\frac{1}{2}} \qquad \theta_{13} \to 0 \qquad (c_{13} \to 1, \quad s_{13} \to 0)$$

$$\simeq m_0$$ Degenerate Spectrum

$$\simeq s_{12}\sqrt{\Delta m_\odot^2} \simeq 5 \text{ meV}$$ Normal Hierarchy

$$\simeq \sqrt{\Delta m_{\rm atm}^2} \simeq 49 \text{ meV}$$ Inverse Hierarchy



$$m_\beta = \left[\sum_j |U_{ej}|^2 m_j^2\right]^{\frac{1}{2}}$$

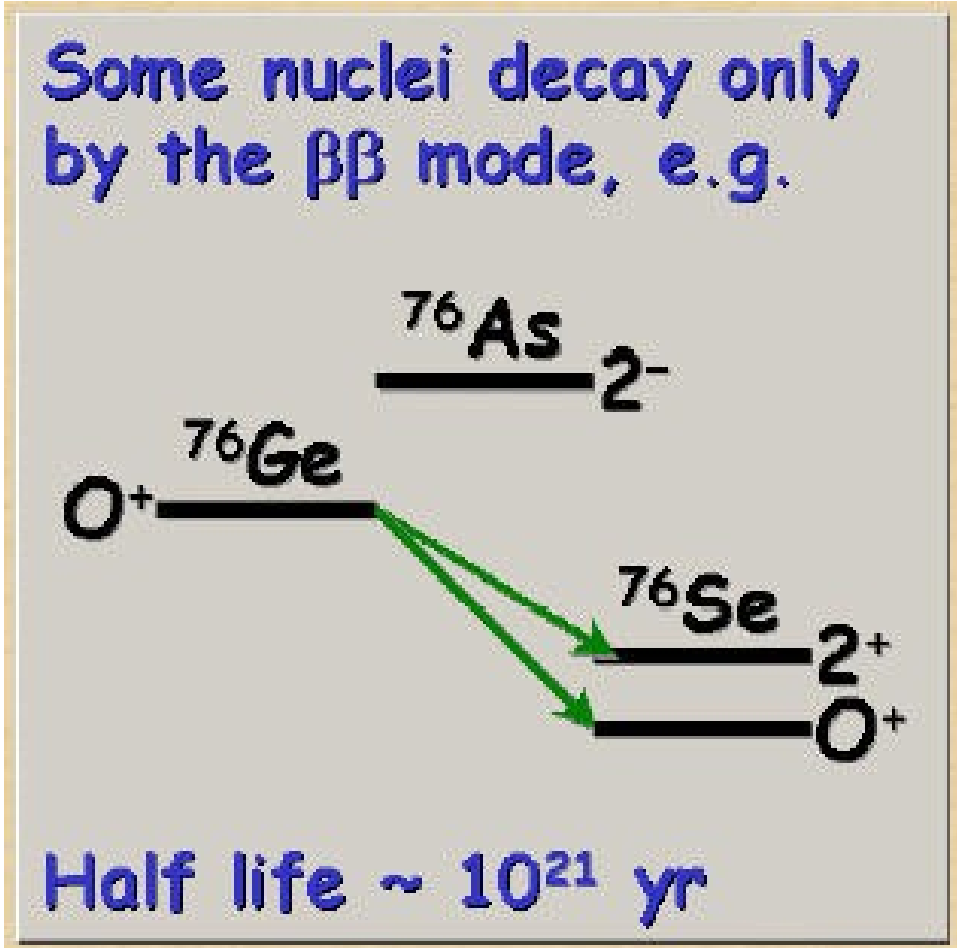
$$= \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

$$\simeq \left[c_{12}^2 m_1^2 + s_{12}^2 m_2^2\right]$$

$$\simeq m_0$$

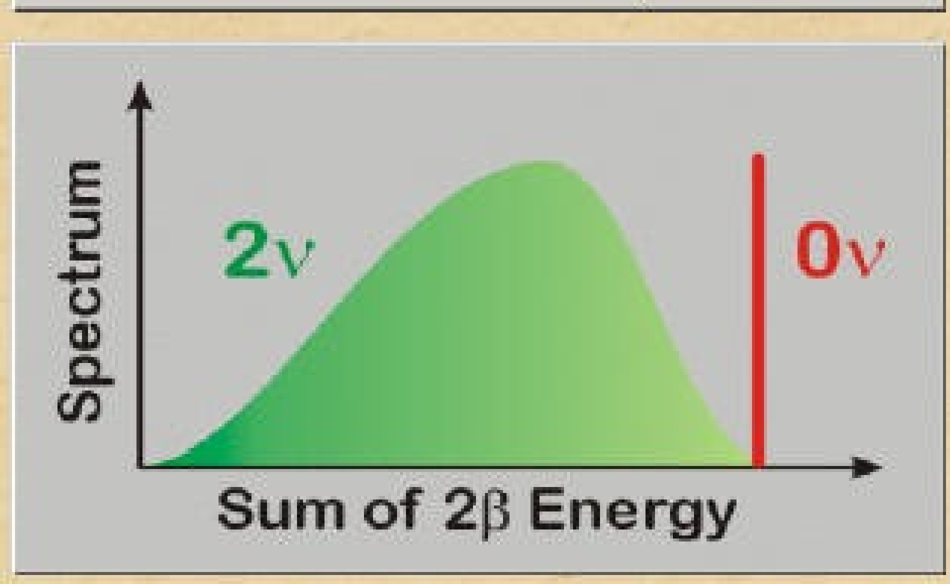
$$\simeq s_{12}\sqrt{\Delta m^2_\odot} \simeq 5 \text{ meV}$$

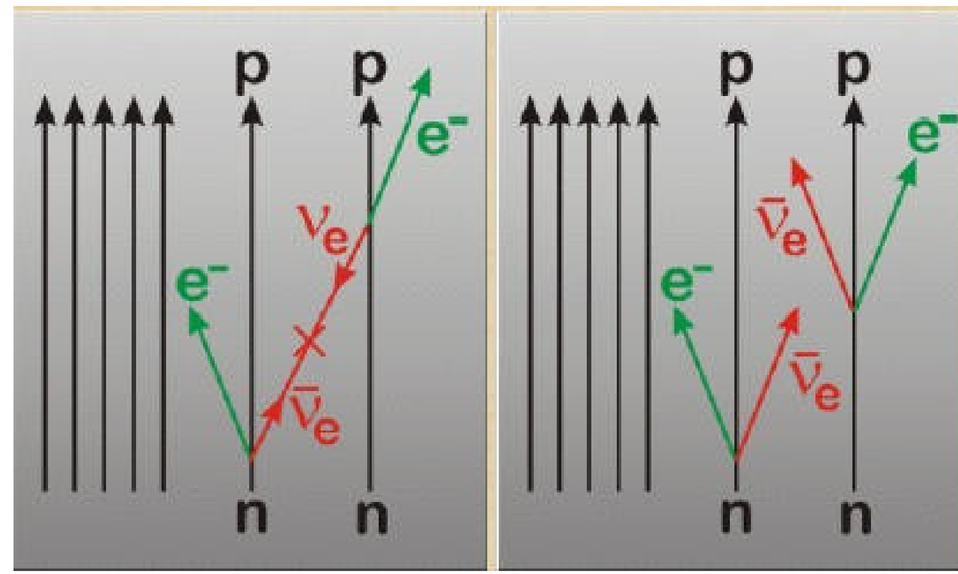
$$\simeq \sqrt{\Delta m^2_{\text{atm}}} \simeq 49 \text{ meV}$$



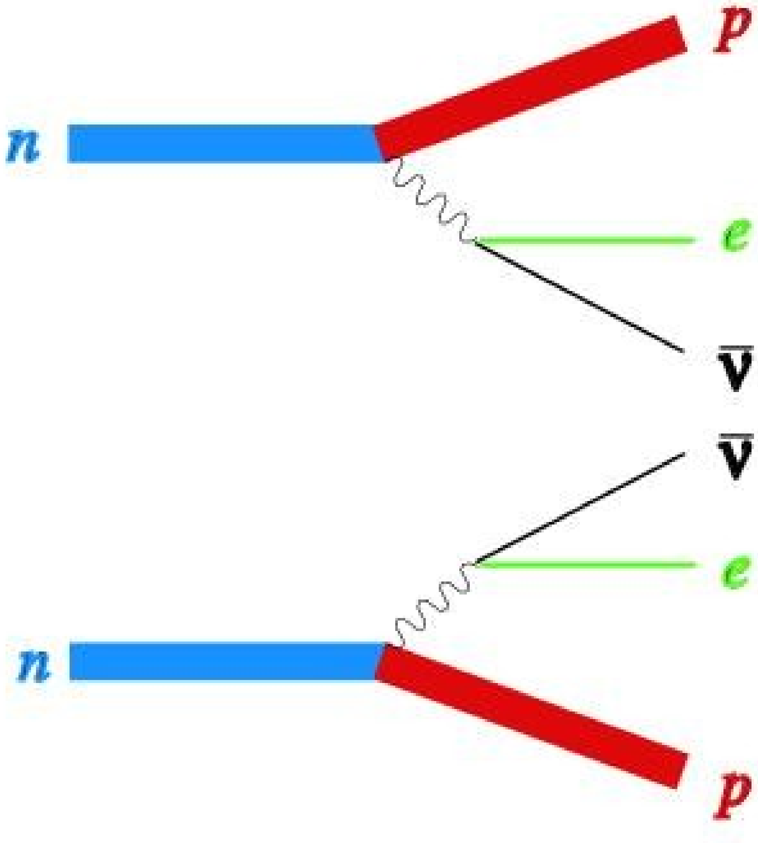
$$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e \quad (2\nu\beta\beta \text{ decay})$$

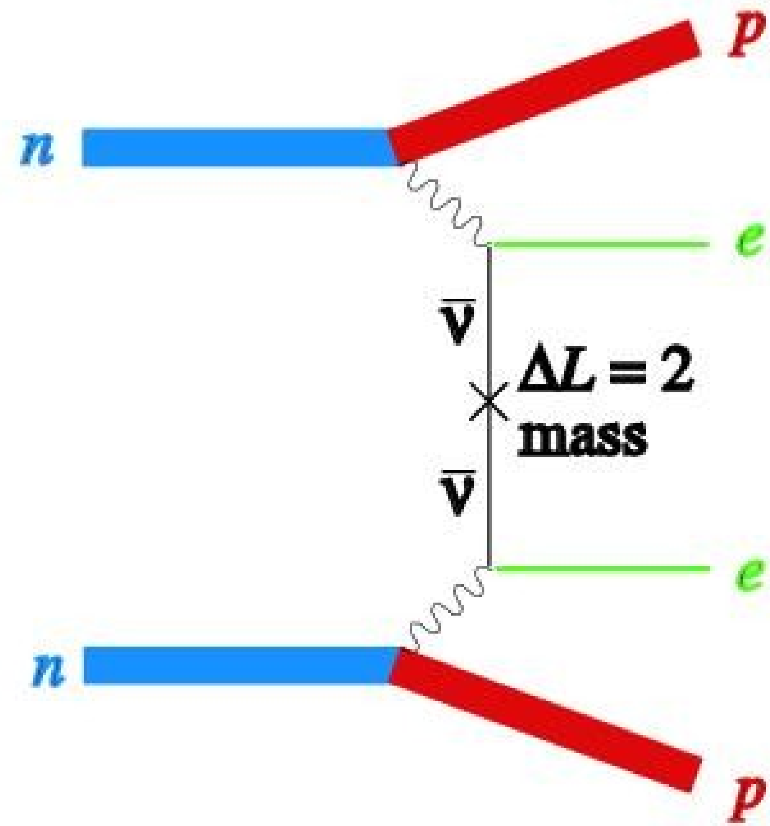
$$(Z, A) \rightarrow (Z+2, A) + 2e^- \quad (0\nu\beta\beta \text{ decay})$$



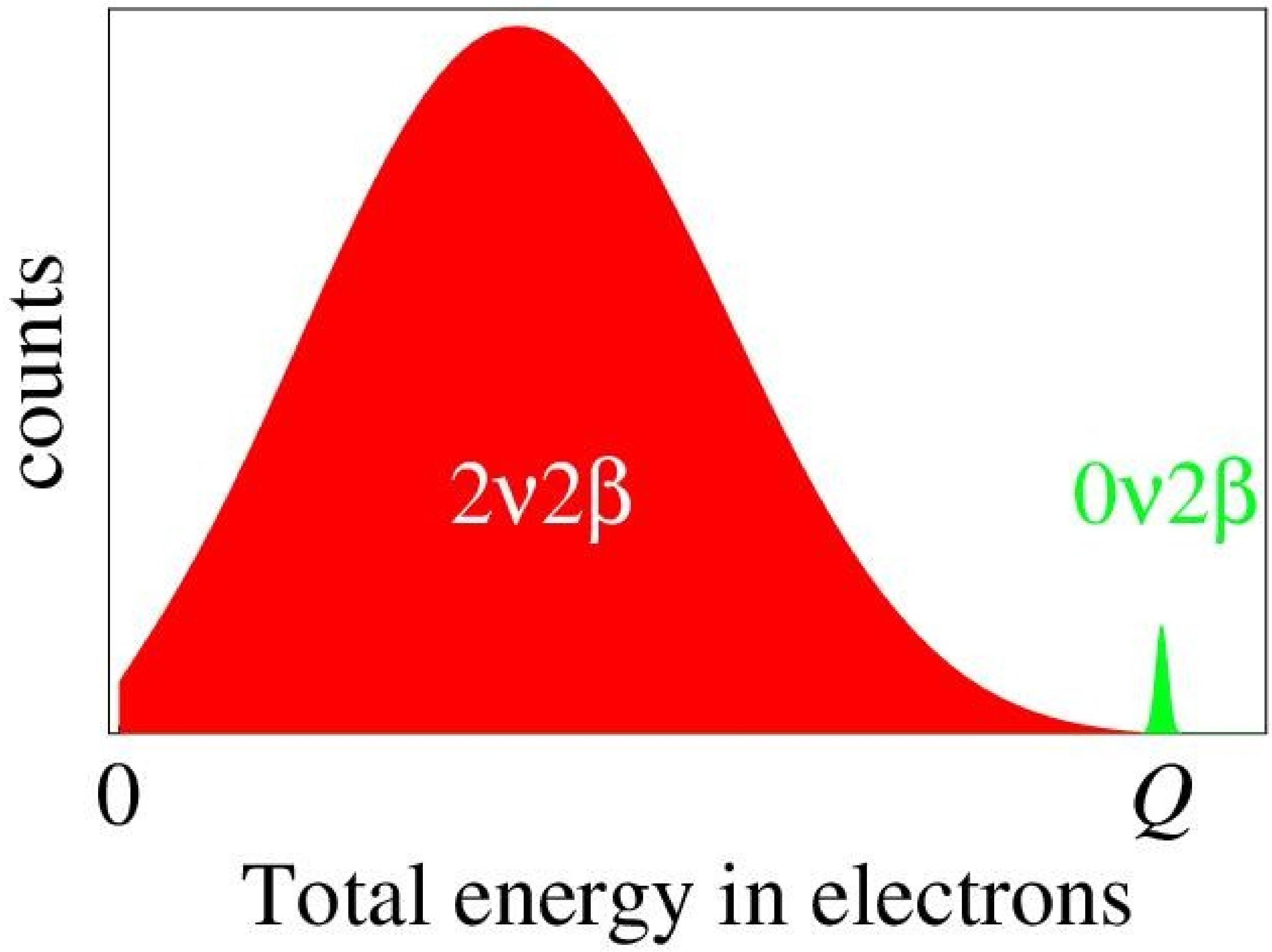


DOUBLE BETA DECAY





$Q\ (^{76}Ge \rightarrow {}^{76}Se) = 2.038$ Mev



DIRAC

or

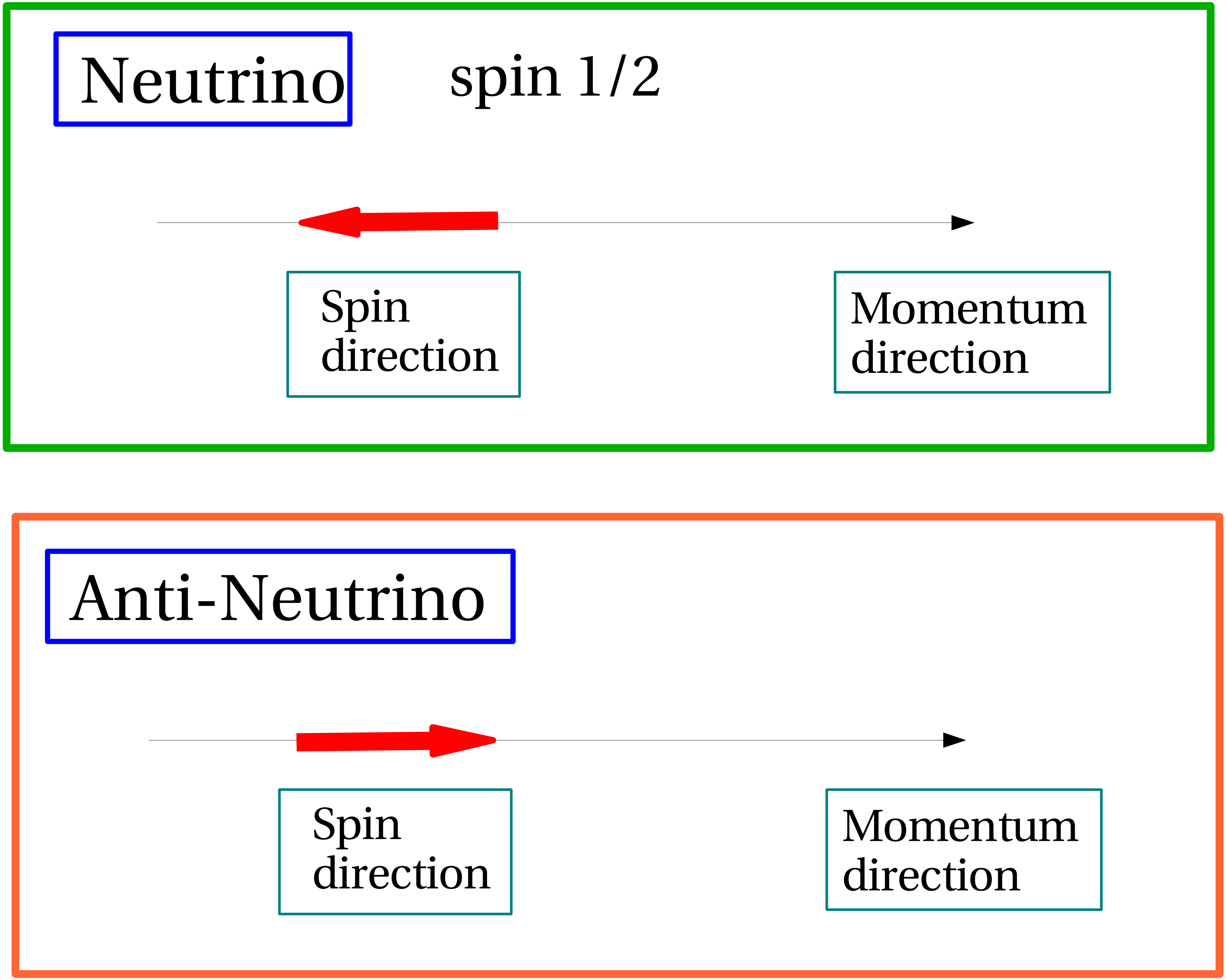
MAJORANA ??

Dirac Particle | **Majorana Particle**

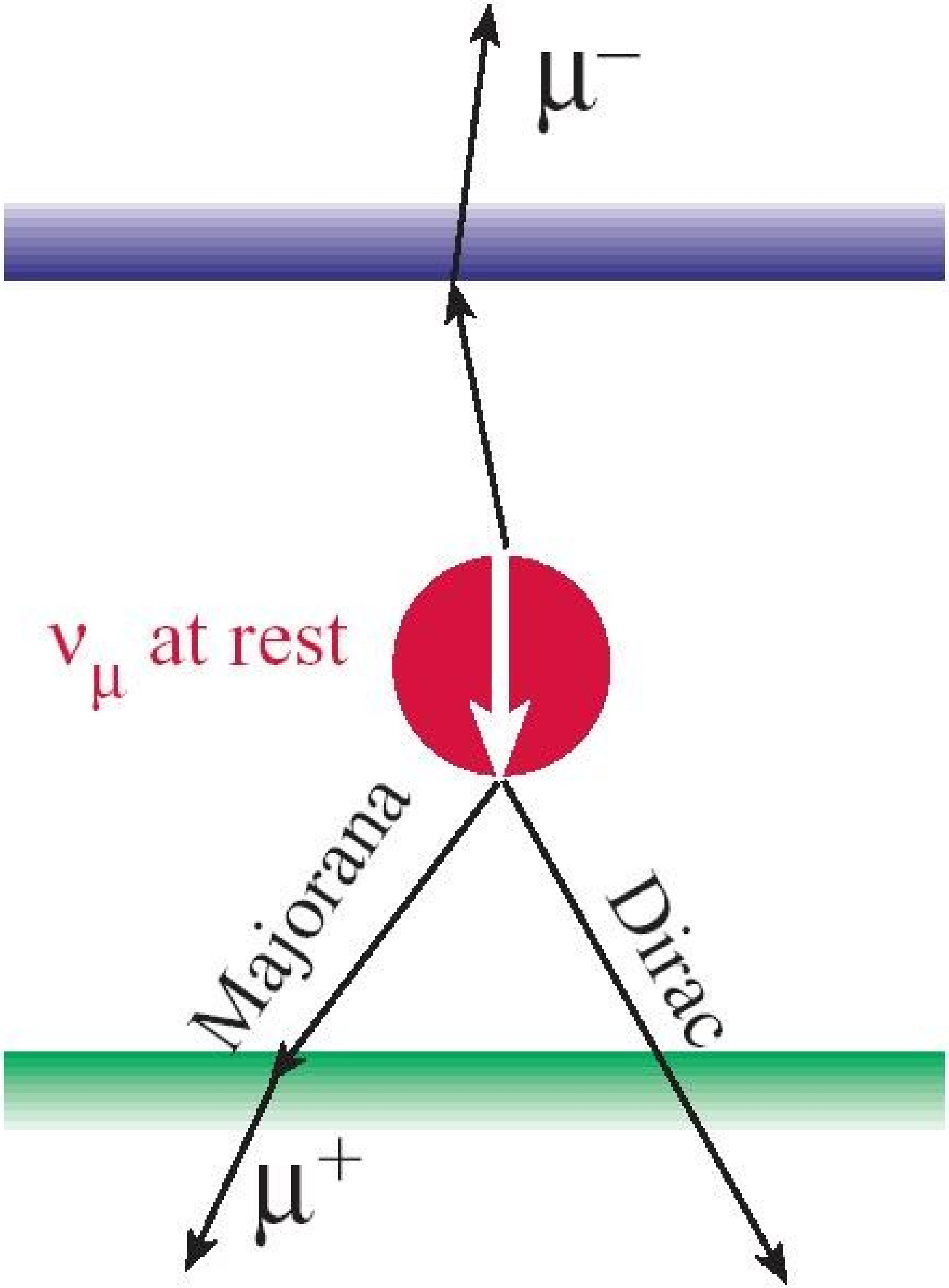
e^-_{L}	e^-_{R}
e^+_{L}	e^+_{R}

ν_{L}	ν_{R}
$\overline{\nu}_{\mathrm{L}}$	$\overline{\nu}_{\mathrm{R}}$

ν_{L}	
	$\overline{\nu}_{\mathrm{R}}$



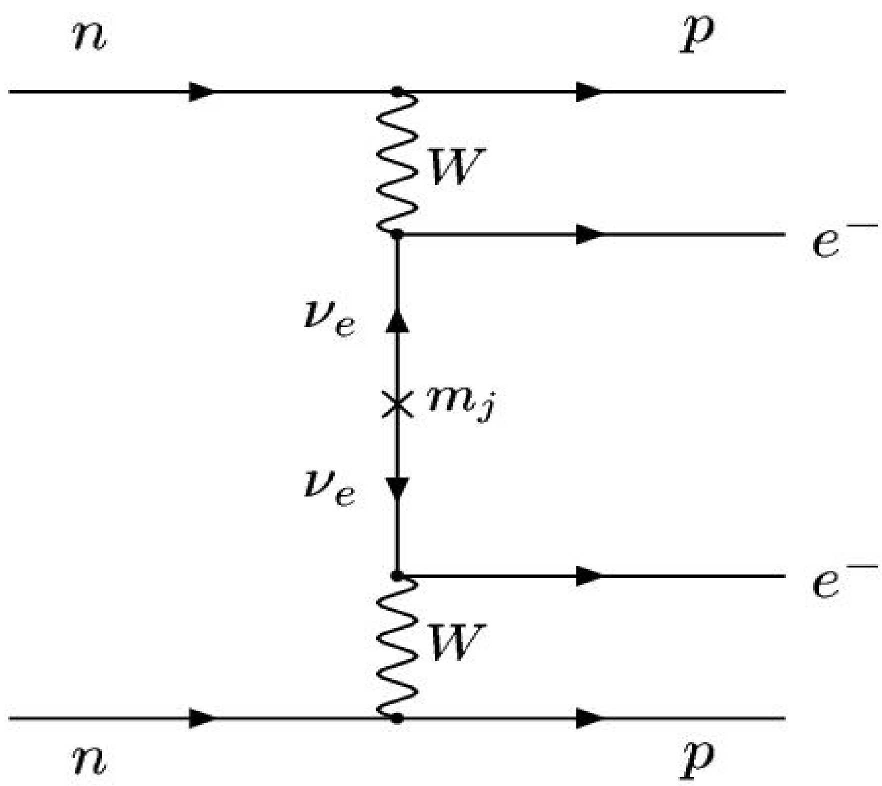
Neutrino
spin 1/2
Spin direction
Momentum direction
Anti-Neutrino
Spin direction
Momentum direction



Gedanken Experiment

Neutrino at Rest with spin pointing downward.

Strumia, Vissani



Majorana Particle

$$A(2\beta 0\nu) \propto \sum_i U_{ei}^2\, m_i \equiv \langle m_{\nu_e}\rangle_{\text{eff}}$$

$$m_{\beta\beta} = \left|\sum_j U_{ej}^2 m_j\right| \equiv \left|\sum_j |U_{ej}|^2 e^{-\varphi_j}\, m_j\right|$$

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

Neutrinoless
Double Beta Decay

$$m_{\beta\beta} = \left| \sum_j U_{ej}^2 \, e^{i\,\varphi_j} \, m_j^2 \right|$$

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

$$\left| c_{12}^2 m_1 + s_{12}^2 m_2 e^{i\varphi_2} \right| \qquad \theta_{13} \to 0 \qquad (c_{13} \to 1, \quad s_{13} \to 0)$$

Degenerate Spectrum

$$\begin{aligned} m_{\beta\beta} &= \\ &\simeq m_0 \left| c_{12}^2 + s_{12}^2 e^{i\varphi_2} \right| \\ &\simeq m_0 \left| 0.71 + 0.29\, e^{i\varphi_2} \right| \\ &\simeq m_0 \,(0.4 - 1.0) \end{aligned}$$

Inverse Hierarchy

$$\begin{aligned} m_{\beta\beta} &= \\ &\simeq \sqrt{\Delta m_{\text{atm}}^2} \left| c_{12}^2 + s_{12}^2 e^{i\varphi_2} \right| \\ &\simeq 49 \text{ meV} \left| 0.71 + 0.29\, e^{i\varphi_2} \right| \\ &\simeq (25 - 50) \text{ meV} \end{aligned}$$

Normal Hierarchy

$$m_{\beta\beta} \simeq \left| c_{12}^2\, m_1 + s_{12}^2 \sqrt{m_1^2 + \Delta m_\odot^2}\, e^{i\varphi_2} \right|$$

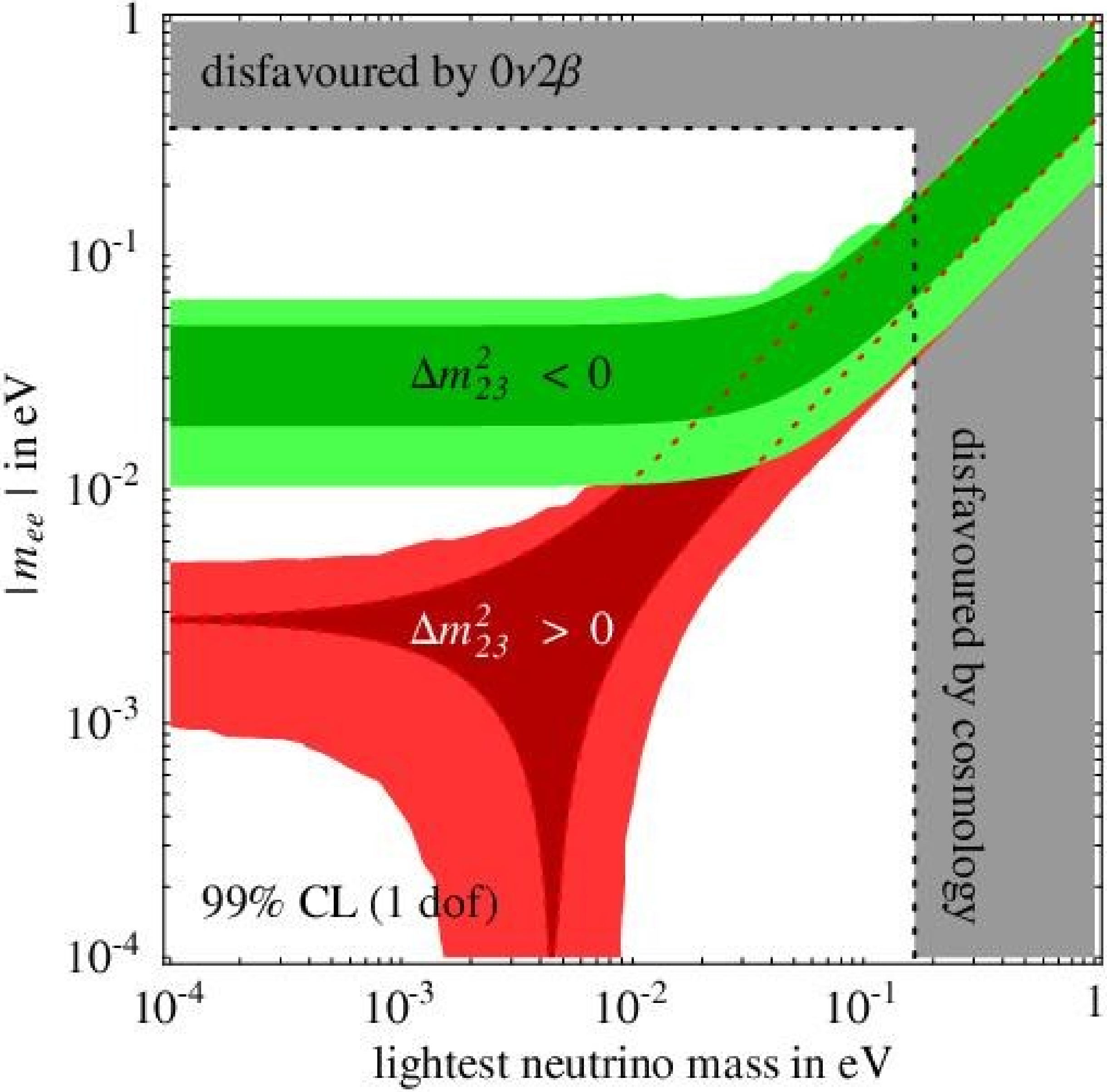
Possibility of exact cancellation

$$m_{\beta\beta} \simeq 0 \qquad \varphi_2 \simeq \pi$$

$$m_1 \simeq \frac{s_{12}^2}{c_{12}^4 - s_{12}^4} \sqrt{\Delta m_\odot^2} \simeq 0.45 \sqrt{\Delta m_\odot^2} \simeq 4 \text{ meV}$$

$$m_0 \to 0$$

$$m_{\beta\beta} \simeq s_{12}^2 \sqrt{\Delta m_\odot^2} \simeq 2.6 \text{ meV}$$



$$\begin{aligned} m_{\beta\beta} &= \\ &\simeq m_0 \left|c_{12}^2 + s_{12}^2 e^{i\varphi_2}\right| \\ &\simeq m_0 \left|0.71 + 0.29\, e^{i\varphi_2}\right| \\ &\simeq m_0\ (0.4 - 1.0) \end{aligned}$$

$$\begin{aligned} m_{\beta\beta} &= \\ &\simeq \sqrt{\Delta m_{\rm atm}^2}\ \left|c_{12}^2 + s_{12}^2 e^{i\varphi_2}\right| \\ &\simeq 49\ \text{meV}\ \left|0.71 + 0.29\, e^{i\varphi_2}\right| \\ &\simeq (25 - 50)\ \text{meV} \end{aligned}$$

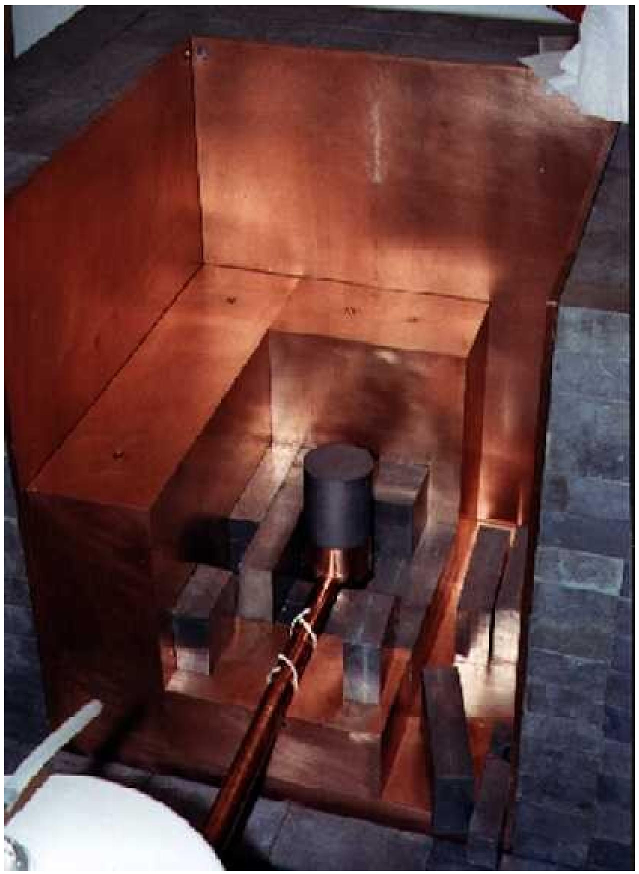
$$m_{\beta\beta} \simeq s_{12}^2 \sqrt{\Delta m_\odot^2} \simeq 2.6\ \text{meV}$$

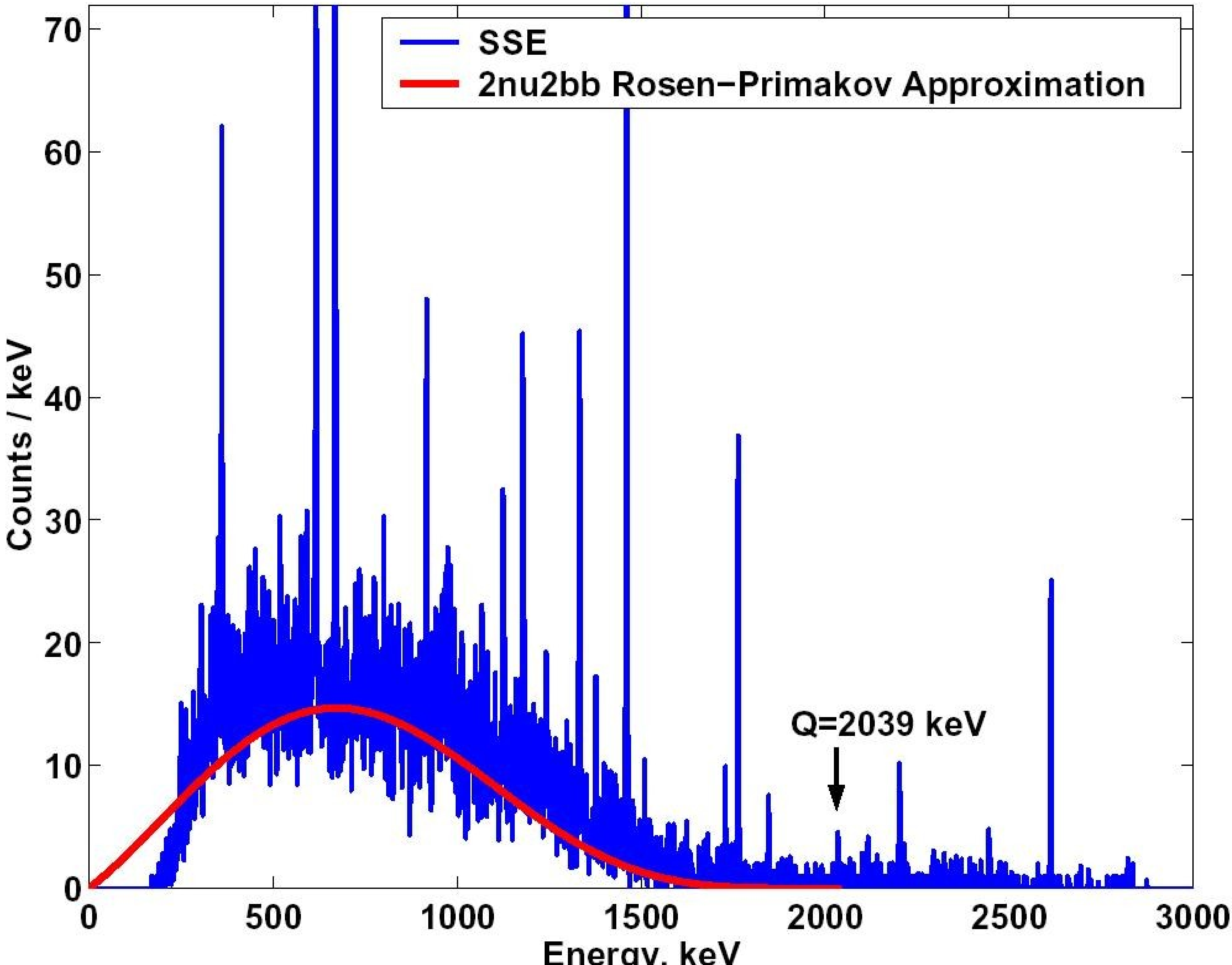
THE HEIDELBERG – MOSCOW EXPERIMENT

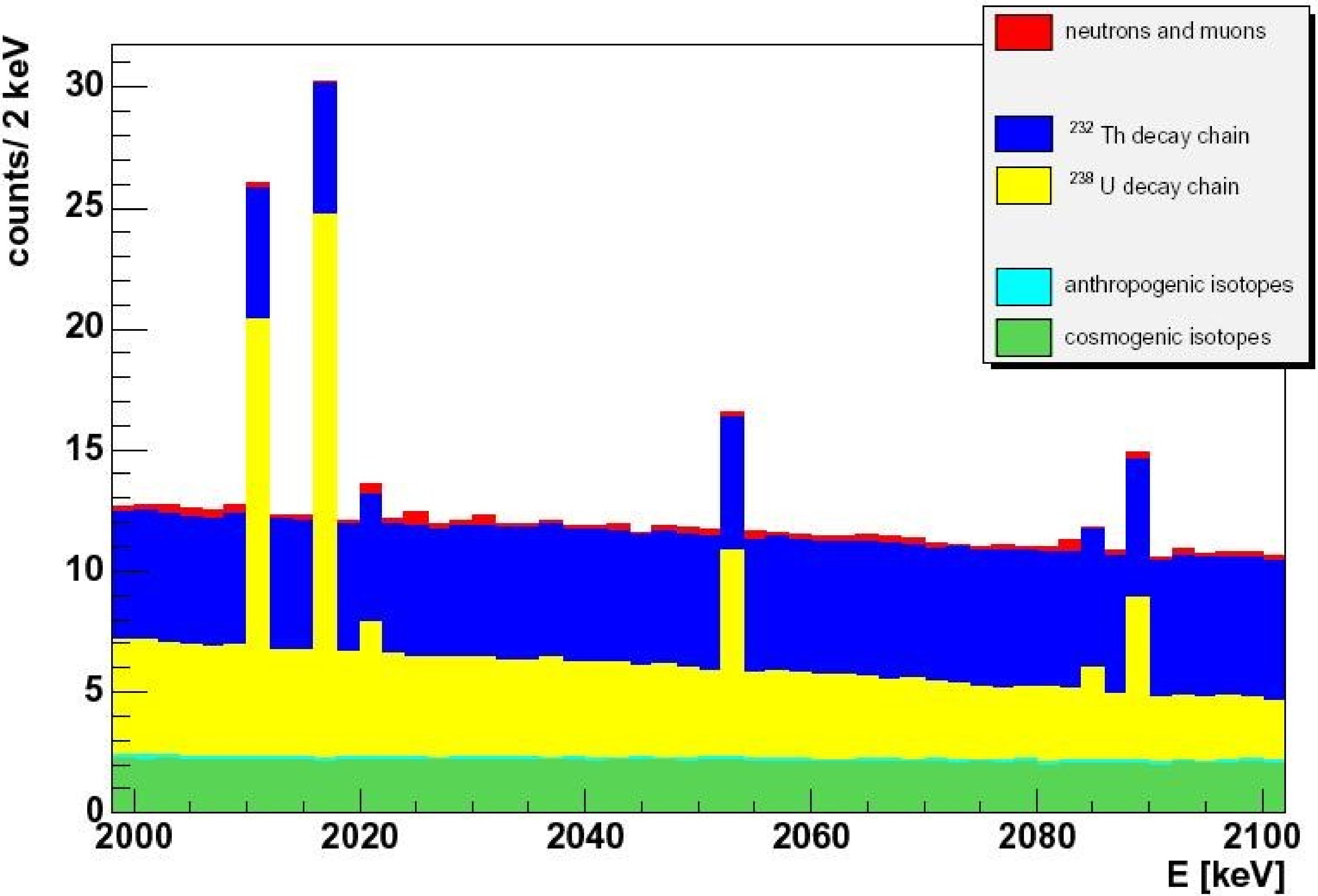
Controversal Claim:

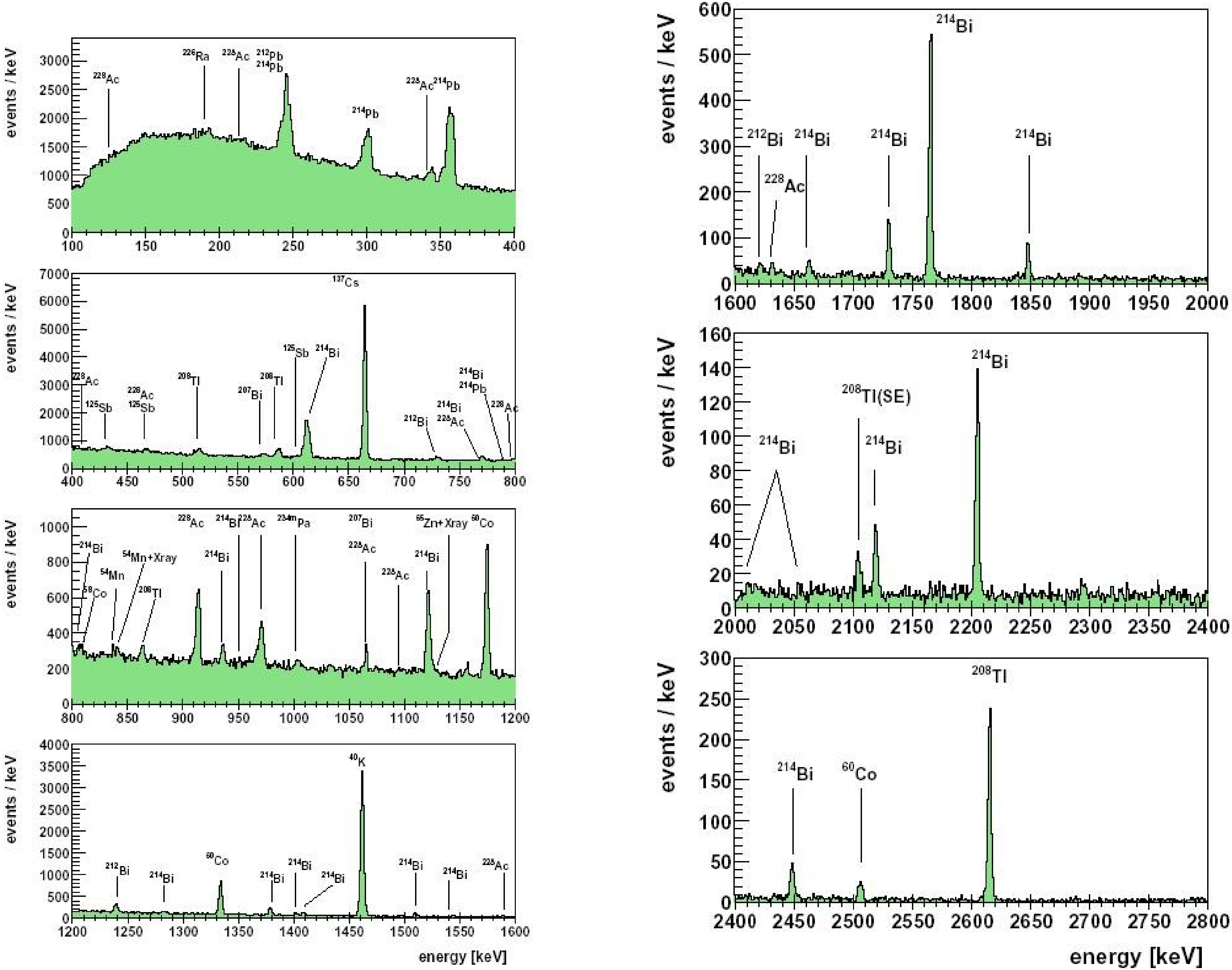
$$T^{0\nu}_{1/2} = (1.19^{+0.37}_{-0.23}) \times 10^{25}\ years$$

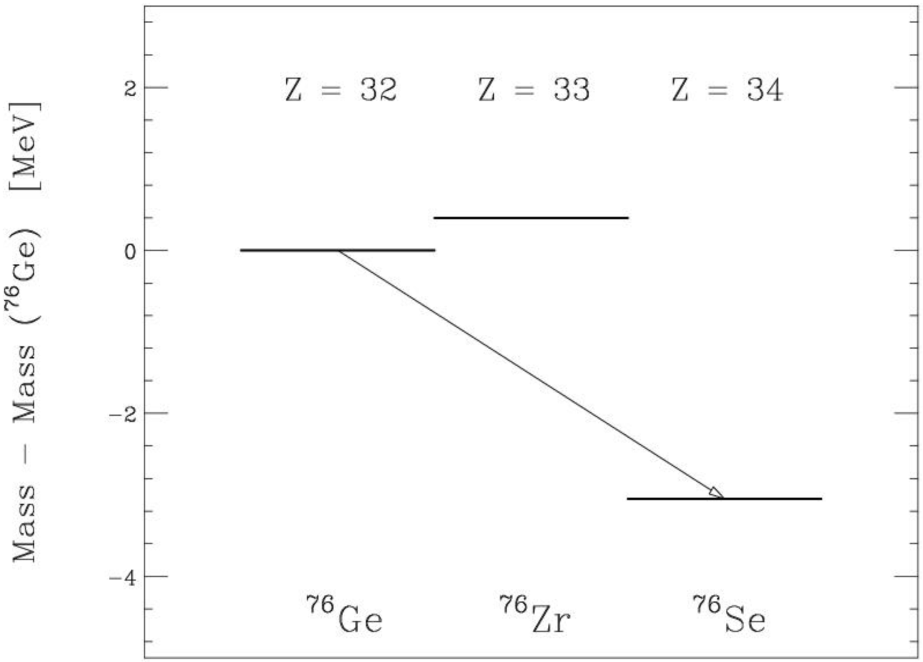
$$m_{\beta\beta} = (0.2 - 0.6)\,\mathrm{eV}\ \ (99.73\%\ \mathrm{c.l.})$$




SSE
2nu2bb Rosen−Primakov Approximation
Q=2039 keV
Counts / keV
Energy, keV
0
10
20
30
40
50
60
70
0
500
1000
1500
2000
2500
3000


neutrons and muons
232 Th decay chain
238 U decay chain
anthropogenic isotopes
cosmogenic isotopes
counts/ 2 keV
0
5
10
15
20
25
30
2000
2020
2040
2060
2080
2100
E [keV]


events / keV
energy [keV]
228Ac
226Ra
228Ac
212Pb
214Pb
214Pb
228Ac 214Pb
137Cs
125Sb
214Bi
208Tl
207Bi
208Tl
212Bi
214Bi
214Pb
228Ac
54Mn+Xray
54Mn
58Co
208Tl
234mPa
207Bi
65Zn+Xray
60Co
40K
212Bi
214Bi
228Ac
208Tl(SE)
208Tl

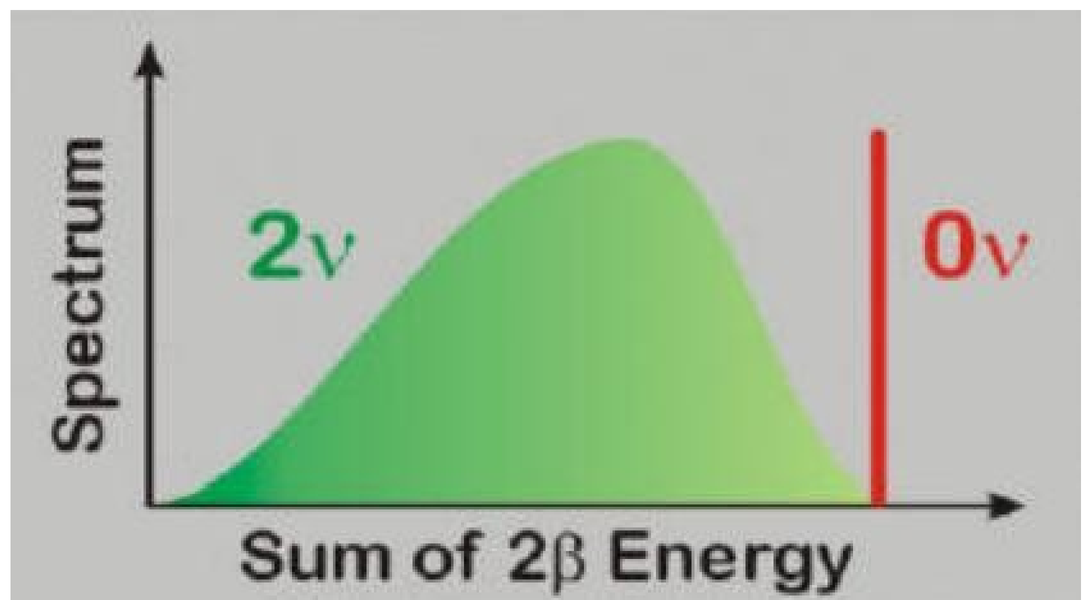


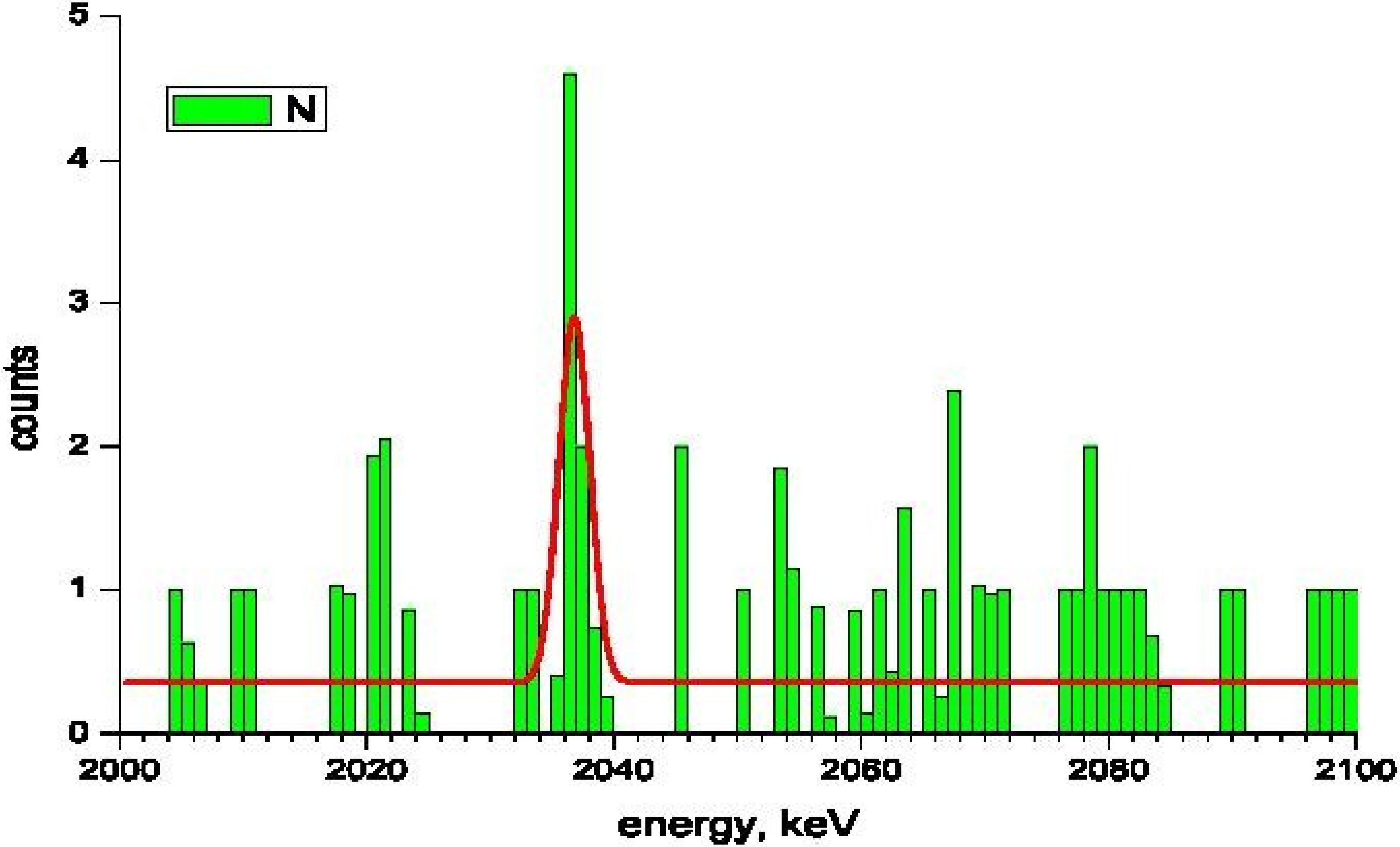
Energy levels for the $A = 76$ nuclei.

$$T^{2\nu}_{1/2} = [1.55 \pm 0.01(\mathrm{stat})\ ^{+0.19}_{-0.15}\ (\mathrm{syst})\ ] \times 10^{21}\ \mathrm{years}$$

$$\mathrm{T}^{0\nu}_{1/2} \geq 1.9 \times 10^{25}\ \mathrm{years} \quad 90\%\ \mathrm{C.L.}$$

$$\mathrm{Q} = \quad (2038.56 \pm 0.32\ \mathrm{KeV})$$



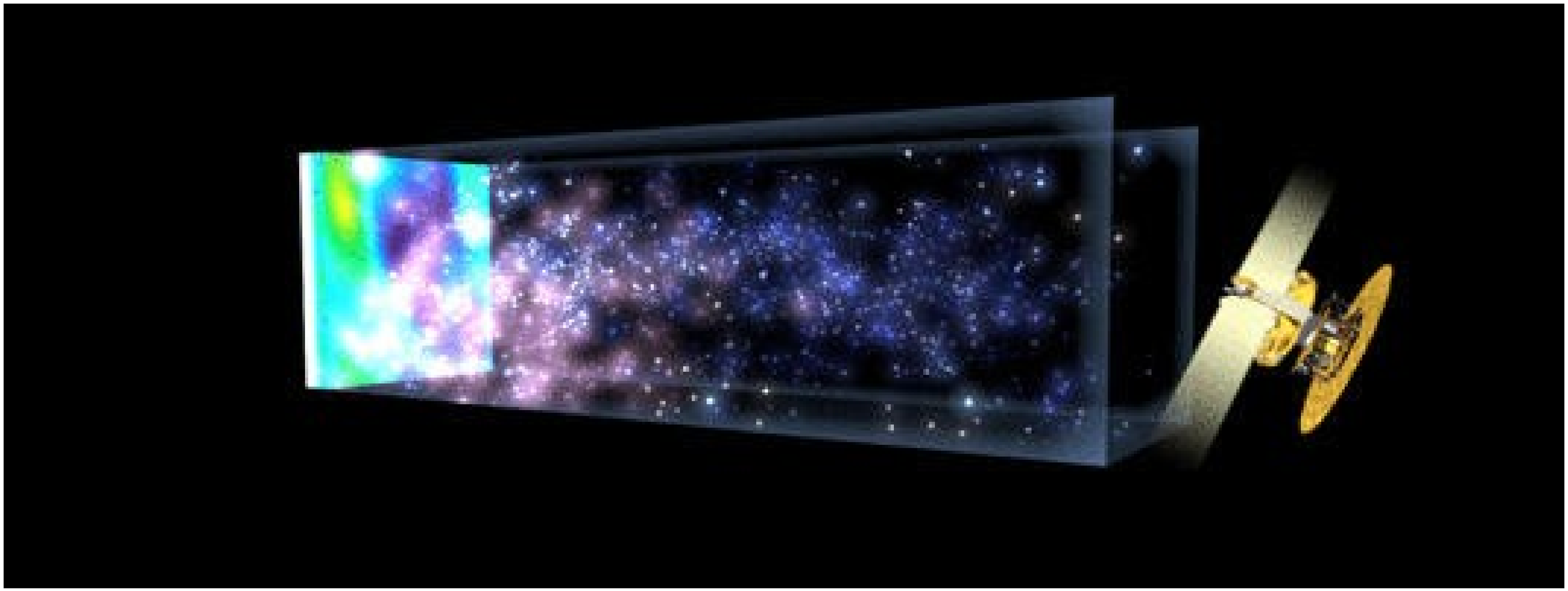


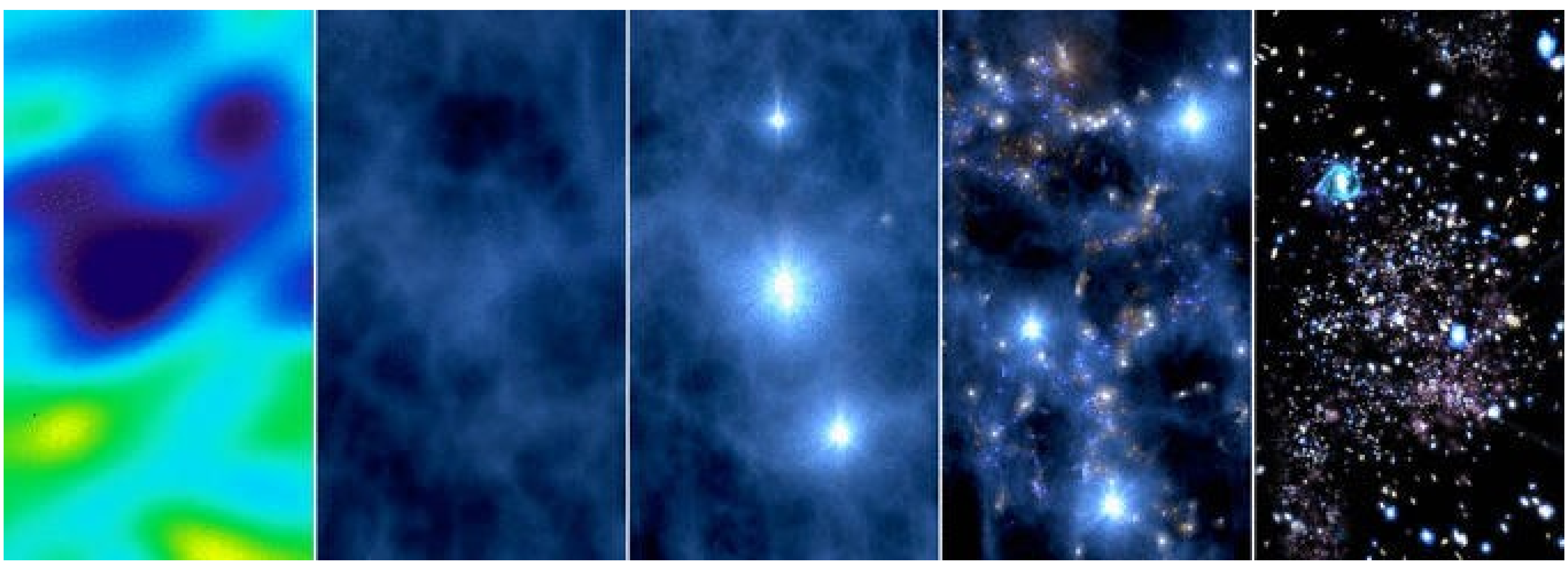
N
counts
0
1
2
3
4
5
2000
2020
2040
2060
2080
2100
energy, keV

$$\simeq m_0 \left|c_{12}^2 + s_{12}^2 e^{i\varphi_2}\right|$$
$$\simeq m_0 \left|0.71 + 0.29\, e^{i\varphi_2}\right|$$
$$\simeq m_0 \, (0.4 - 1.0)$$

$$\simeq \sqrt{\Delta m^2_{\rm atm}} \left|c_{12}^2 + s_{12}^2 e^{i\varphi_2}\right|$$
$$\simeq 49 \text{ meV} \left|0.71 + 0.29\, e^{i\varphi_2}\right|$$
$$\simeq (25 - 50) \text{ meV}$$

COSMOLOGY





COSMOLOGICAL NEUTRINOS

$$T_\gamma^{\mathrm{now}} = 2.728\,\mathrm{Kelvin}$$

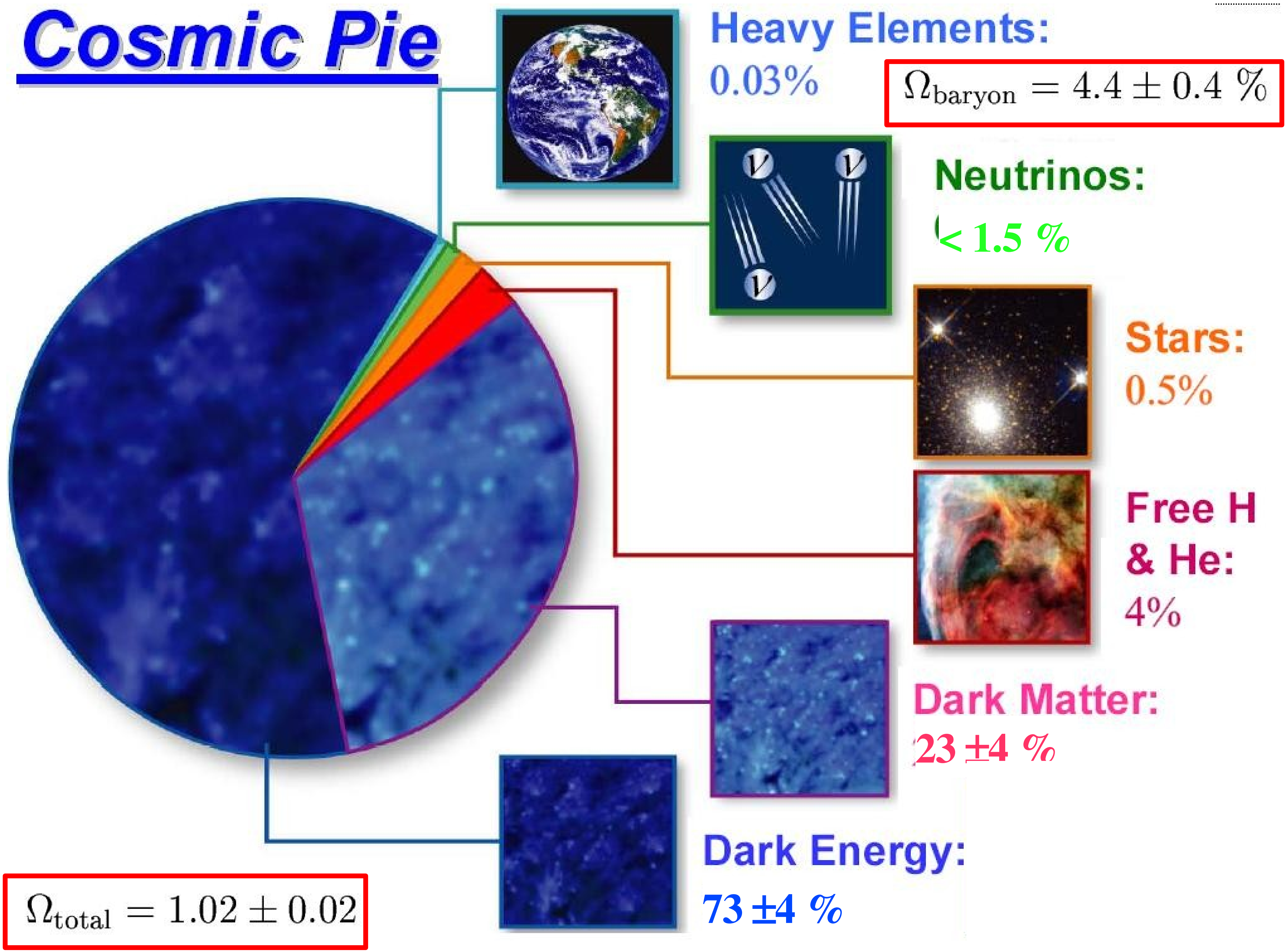
$$T_\gamma^3 \times 2 = T_\nu^3 \times \left[2 + 4 \times \frac{7}{8}\right]$$

$$T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma \quad = 1.98\ \mathrm{Kelvin}$$

$$n_\gamma = \frac{2}{(2\pi\hbar)^3} \int d^3 p_\gamma \, \frac{1}{e^{E/T} - 1} \simeq 412 \text{ cm}^{-3}$$

$$n_\nu = \frac{1}{(2\pi\hbar)^3} \int d^3 p \, \frac{1}{e^{E/T} + 1} \simeq 56 \text{ cm}^{-3}$$

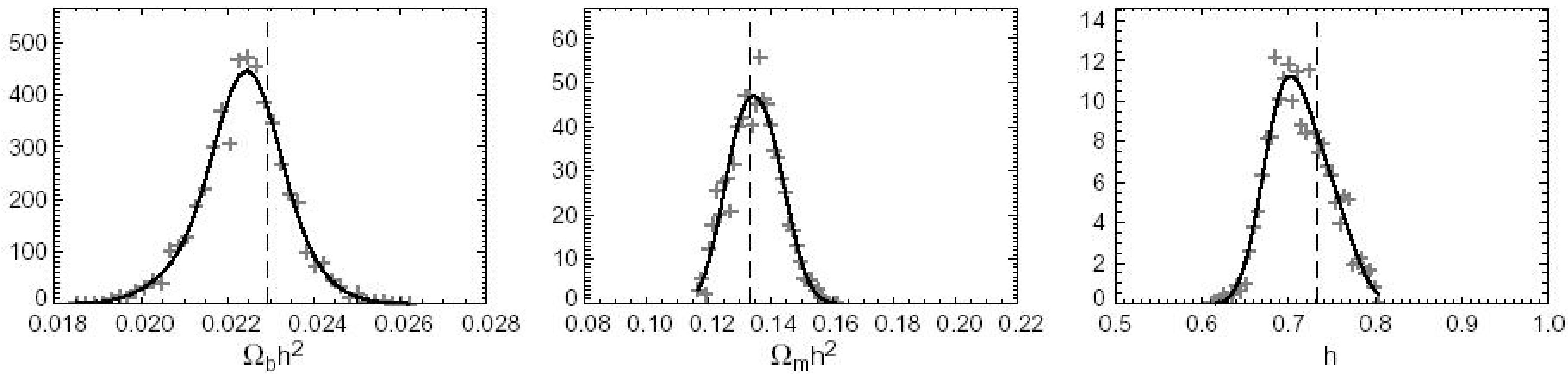
$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{1}{h^2} \frac{\sum_j m_j}{93 \text{ eV}}$$

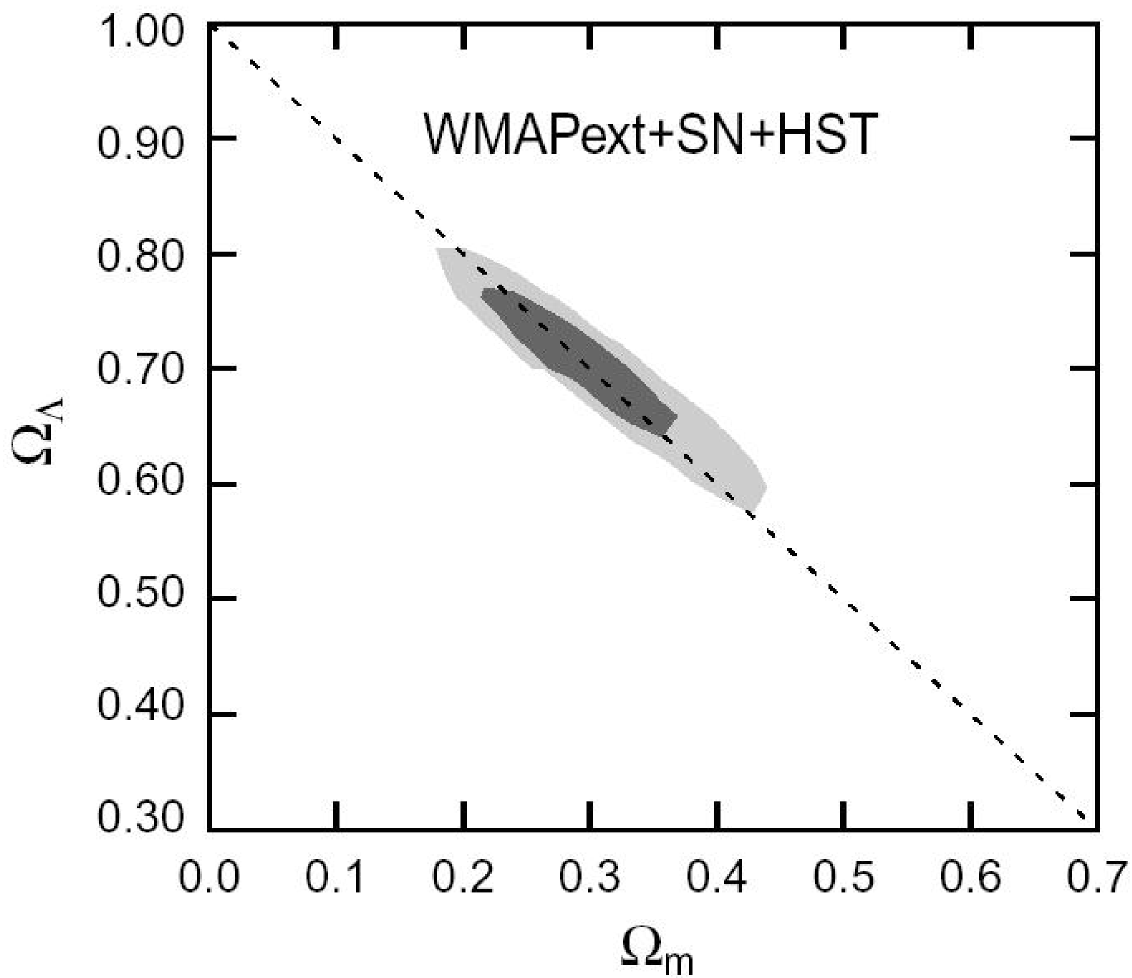

Cosmic Pie
Heavy Elements:
0.03%
$\Omega_{baryon} = 4.4 \pm 0.4\ \%$
Neutrinos:
< 1.5 %
Stars:
0.5%
Free H
& He:
4%
Dark Matter:
23 ±4 %
Dark Energy:
73 ±4 %
$\Omega_{total} = 1.02 \pm 0.02$

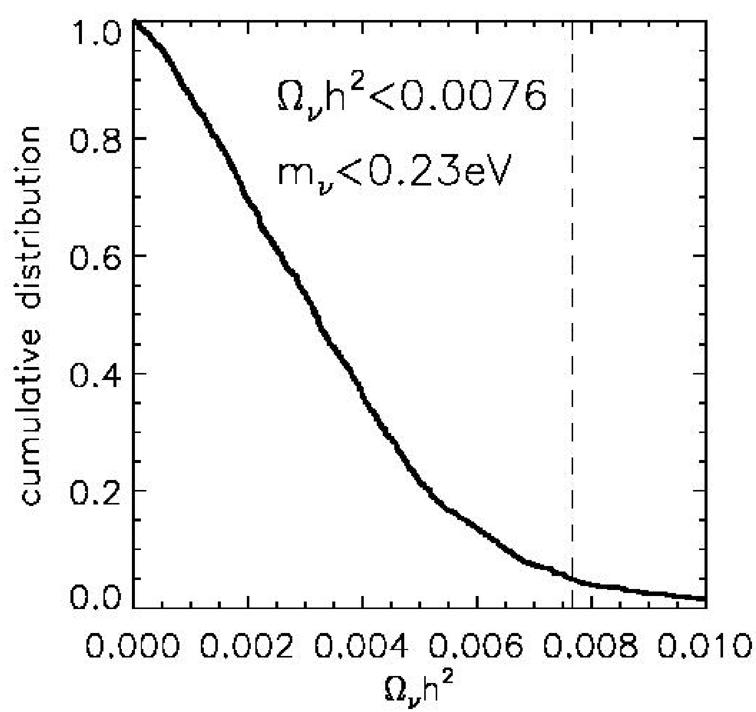
Cosmology in the "Precision Era"

Description	Symbol	Value	+ uncertainty	− uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—
CMB temperature (K)[a]	T_{cmb}	2.725	0.002	0.002
CMB photon density (cm^{-3})[b]	n_γ	410.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_b \Omega_m^{-1}$	0.17	0.01	0.01
Fluctuation amplitude in $8h^{-1}$ Mpc spheres	σ_8	0.84	0.04	0.04
Low-z cluster abundance scaling	$\sigma_8 \Omega_m^{0.5}$	0.44	0.04	0.05
Power spectrum normalization (at $k_0 = 0.05$ Mpc^{-1})[c]	A	0.833	0.086	0.083
Scalar spectral index (at $k_0 = 0.05$ Mpc^{-1})[c]	n_s	0.93	0.03	0.03
Running index slope (at $k_0 = 0.05$ Mpc^{-1})[c]	$dn_s/d\ln k$	−0.031	0.016	0.018
Tensor-to-scalar ratio (at $k_0 = 0.002$ Mpc^{-1})	r	< 0.71	95% CL	—
Redshift of decoupling	z_{dec}	1089	1	1
Thickness of decoupling (FWHM)	Δz_{dec}	195	2	2
Hubble constant	h	0.71	0.04	0.03
Age of universe (Gyr)	t_0	13.7	0.2	0.2

From Spergel et al. 2003

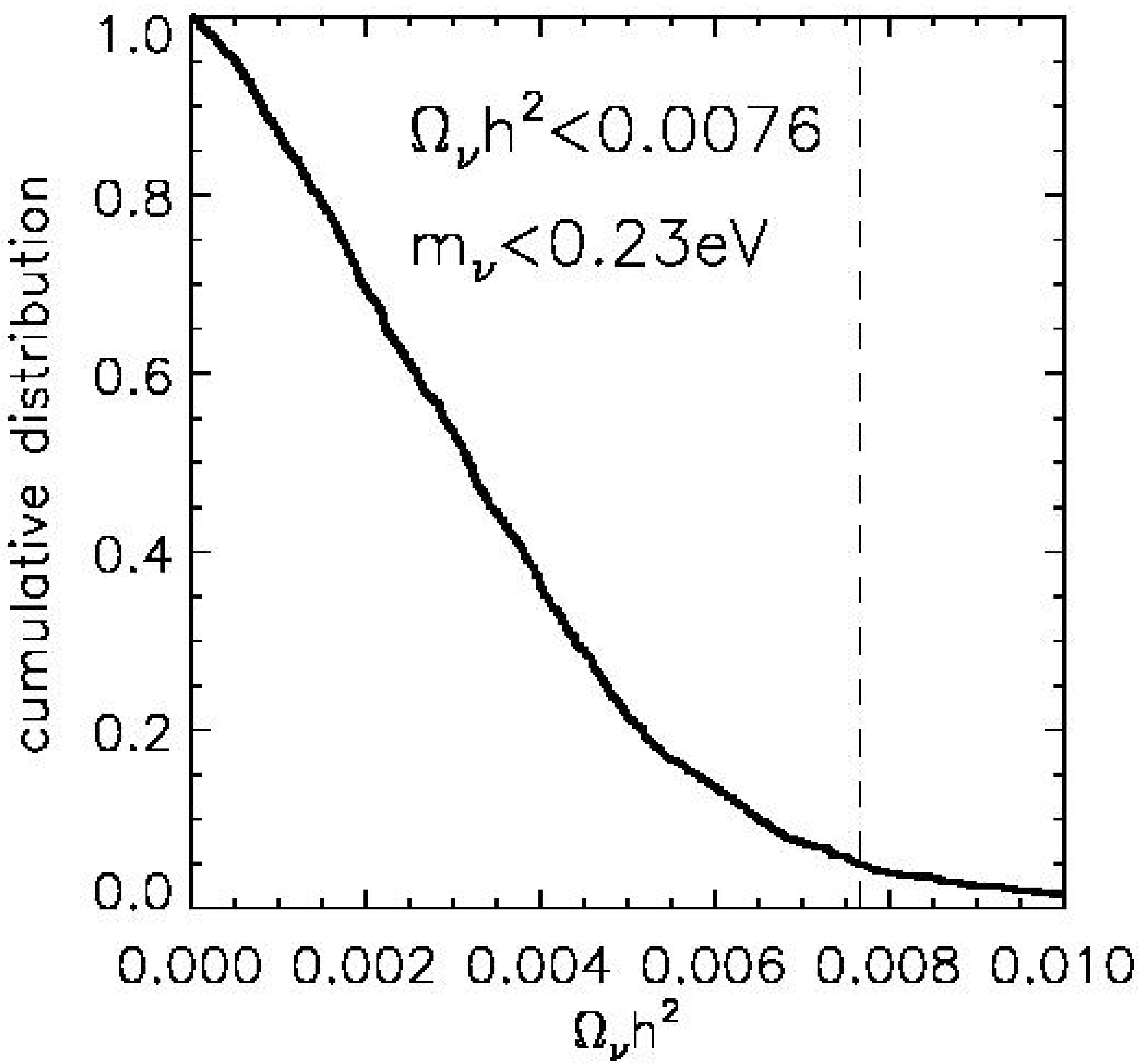




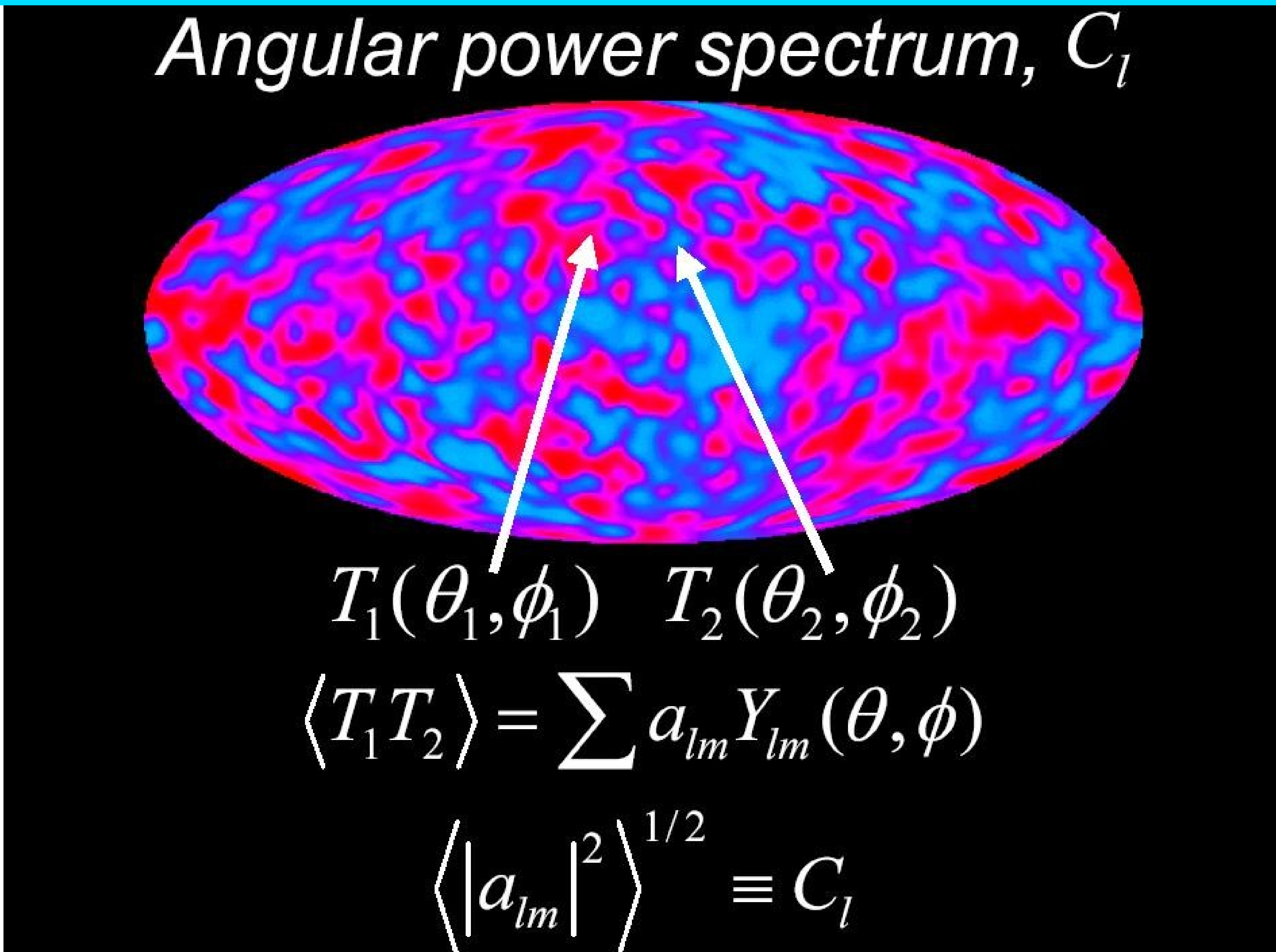


$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{1}{h^2} \frac{\sum_j m_j}{93 \text{ eV}}$$

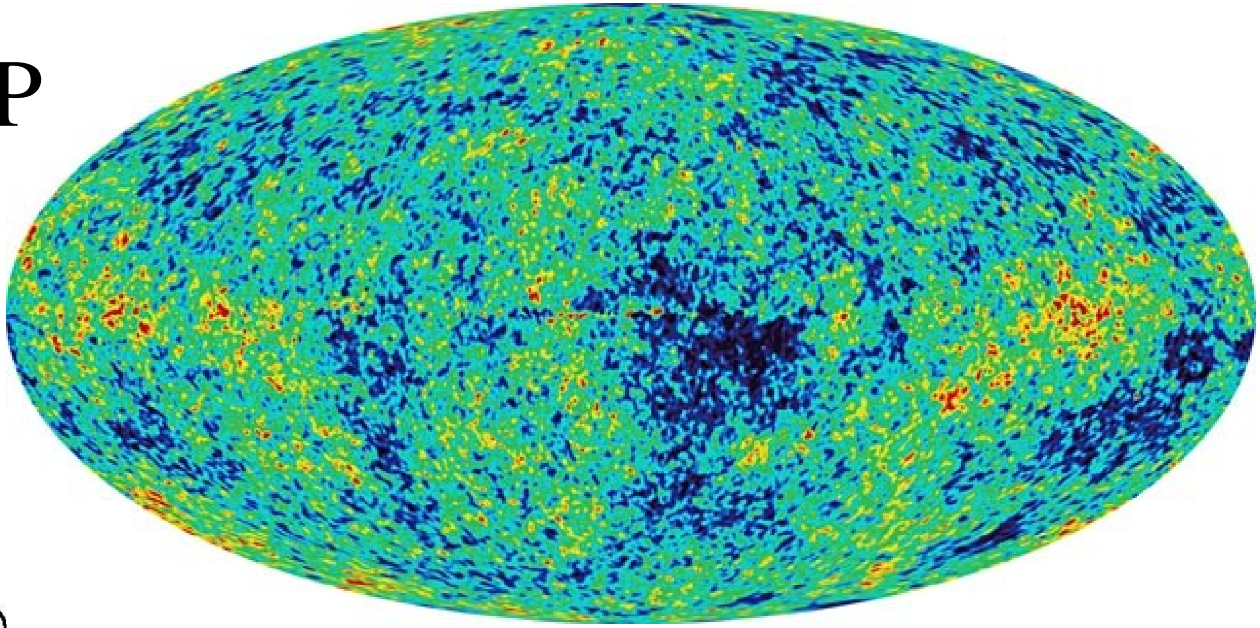
$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{1}{h^2}\,\frac{\sum_j m_j}{93\ \mathrm{eV}}$$

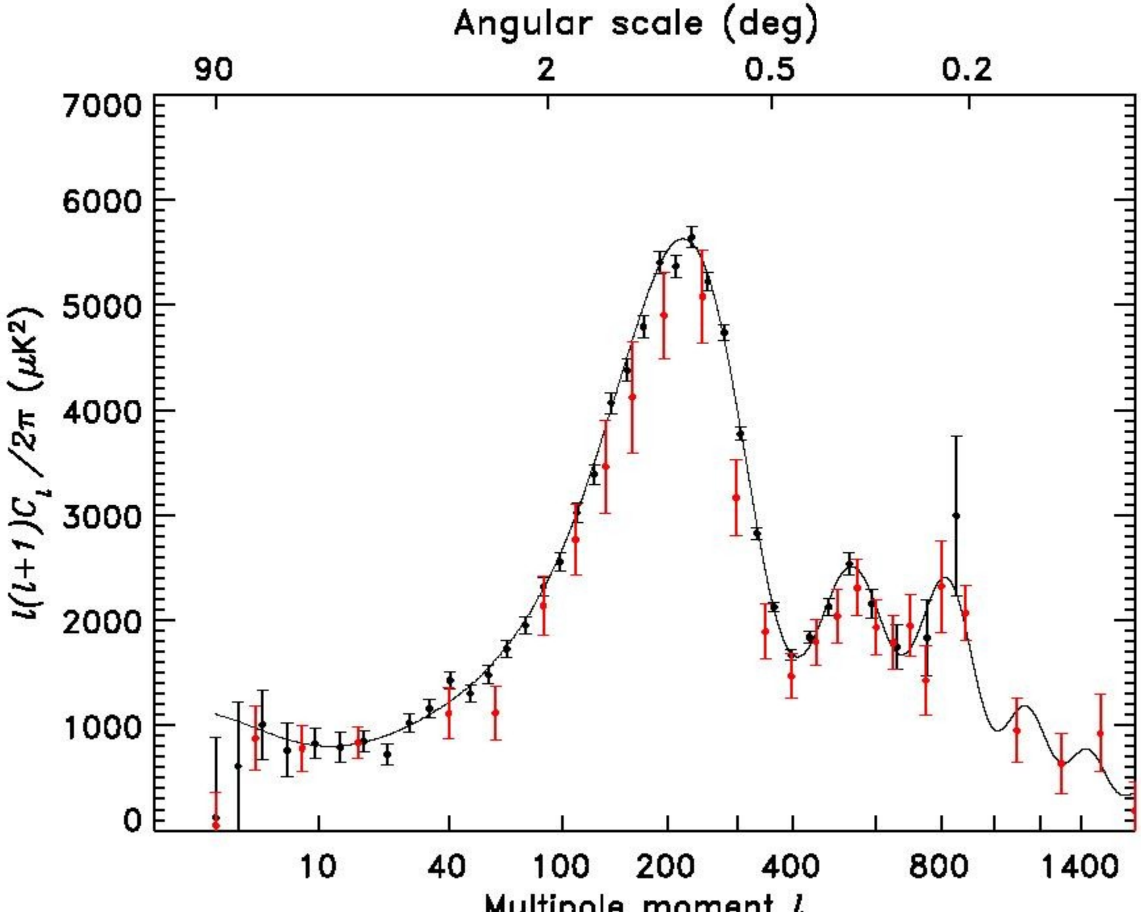


ckground Radiation (2.7 K) anisotropies

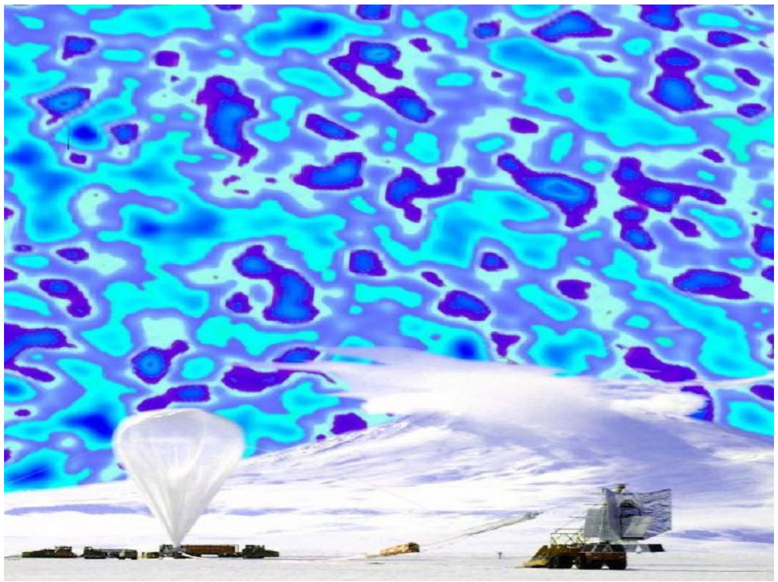


WMAP

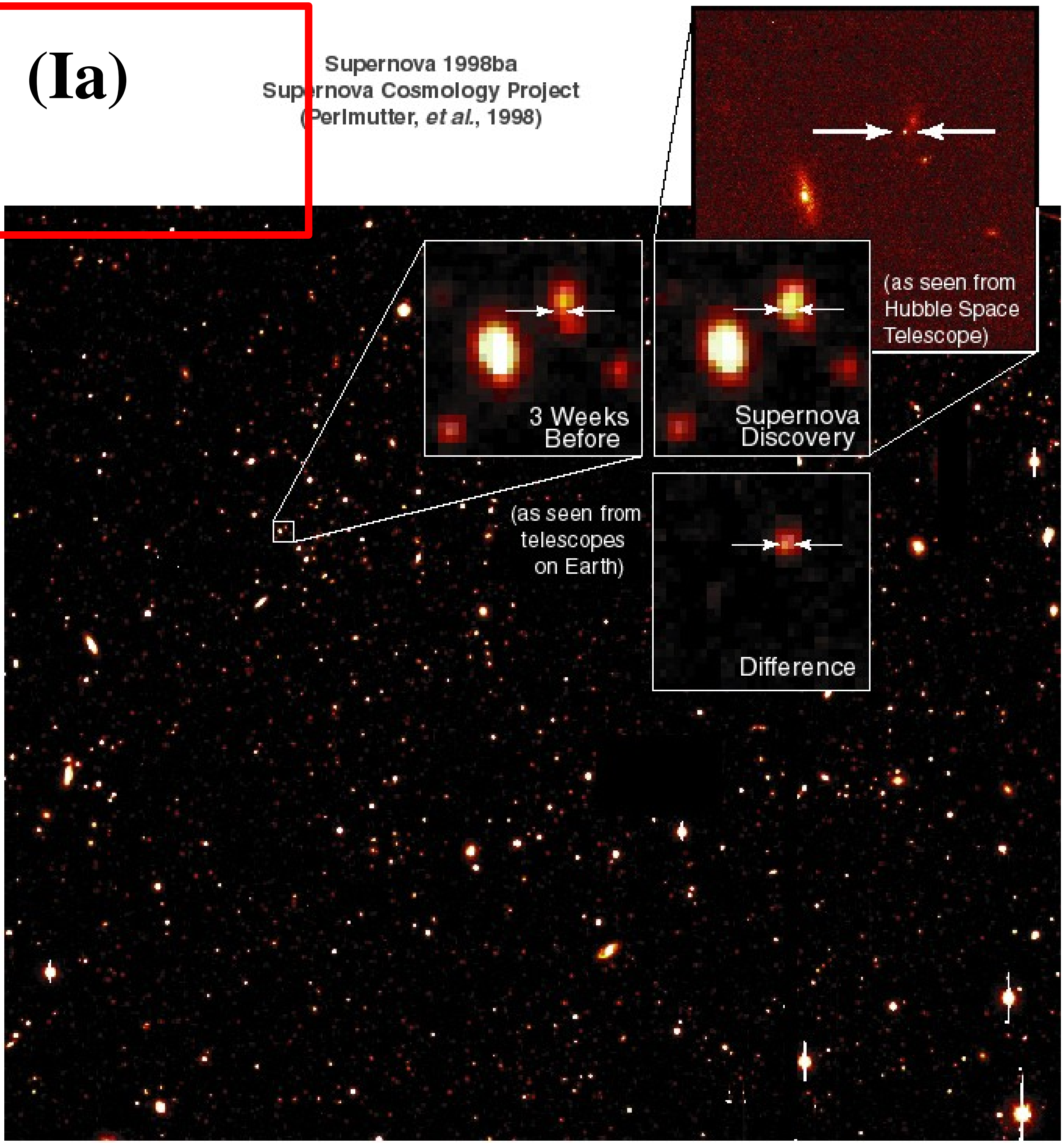




Boomerang



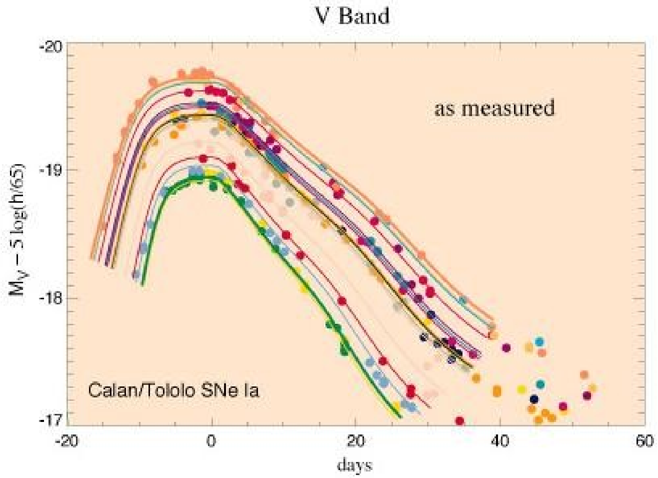
SUPERNOVAE (Ia) STUDIES

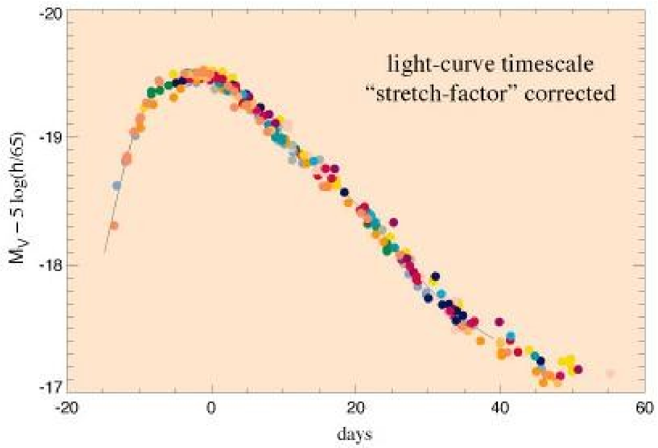


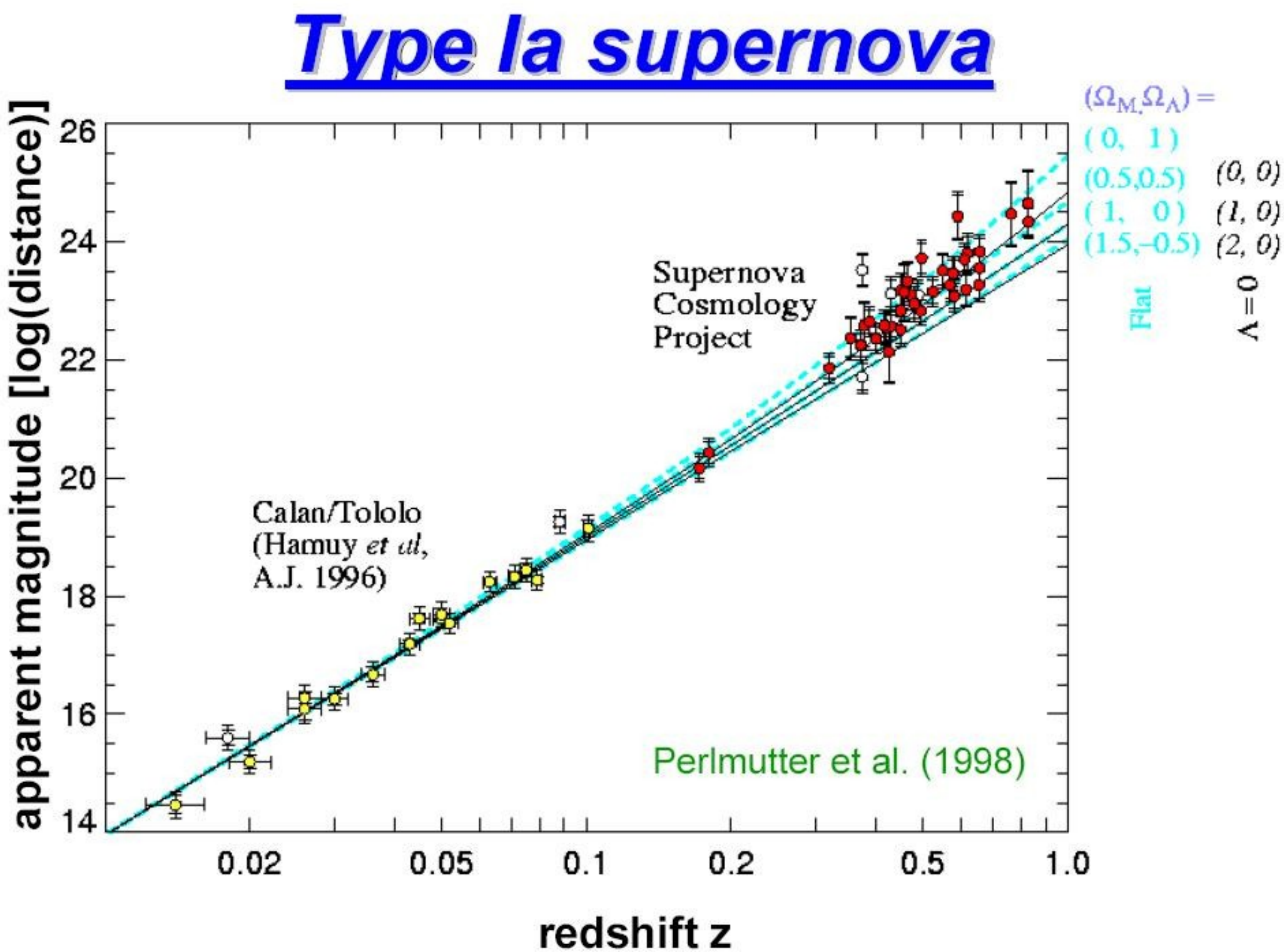
SN of type Ia : STANDARD CANDLES

Apparent Luminosity ↔ Distance

Distance - Redshift Relation

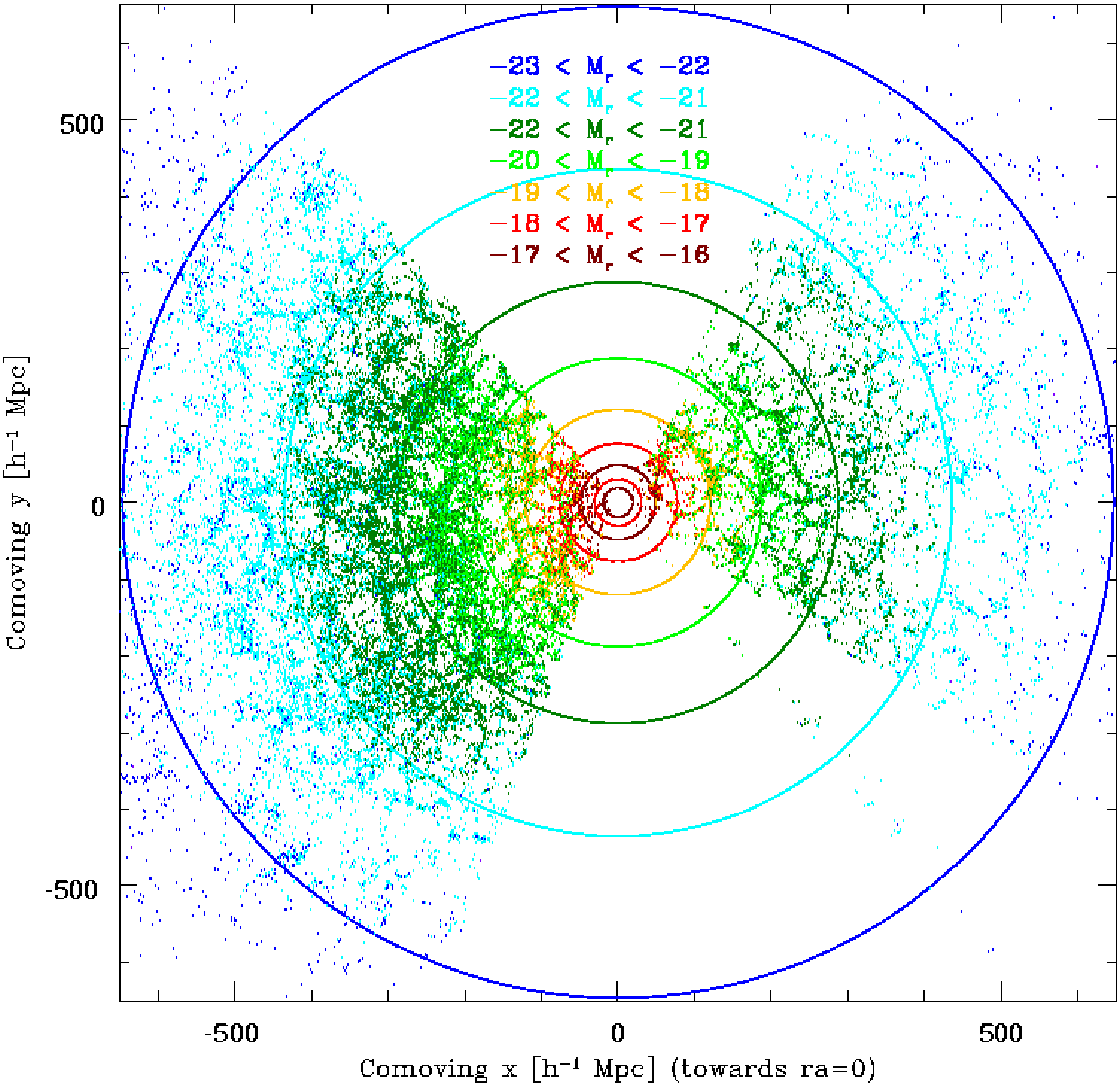




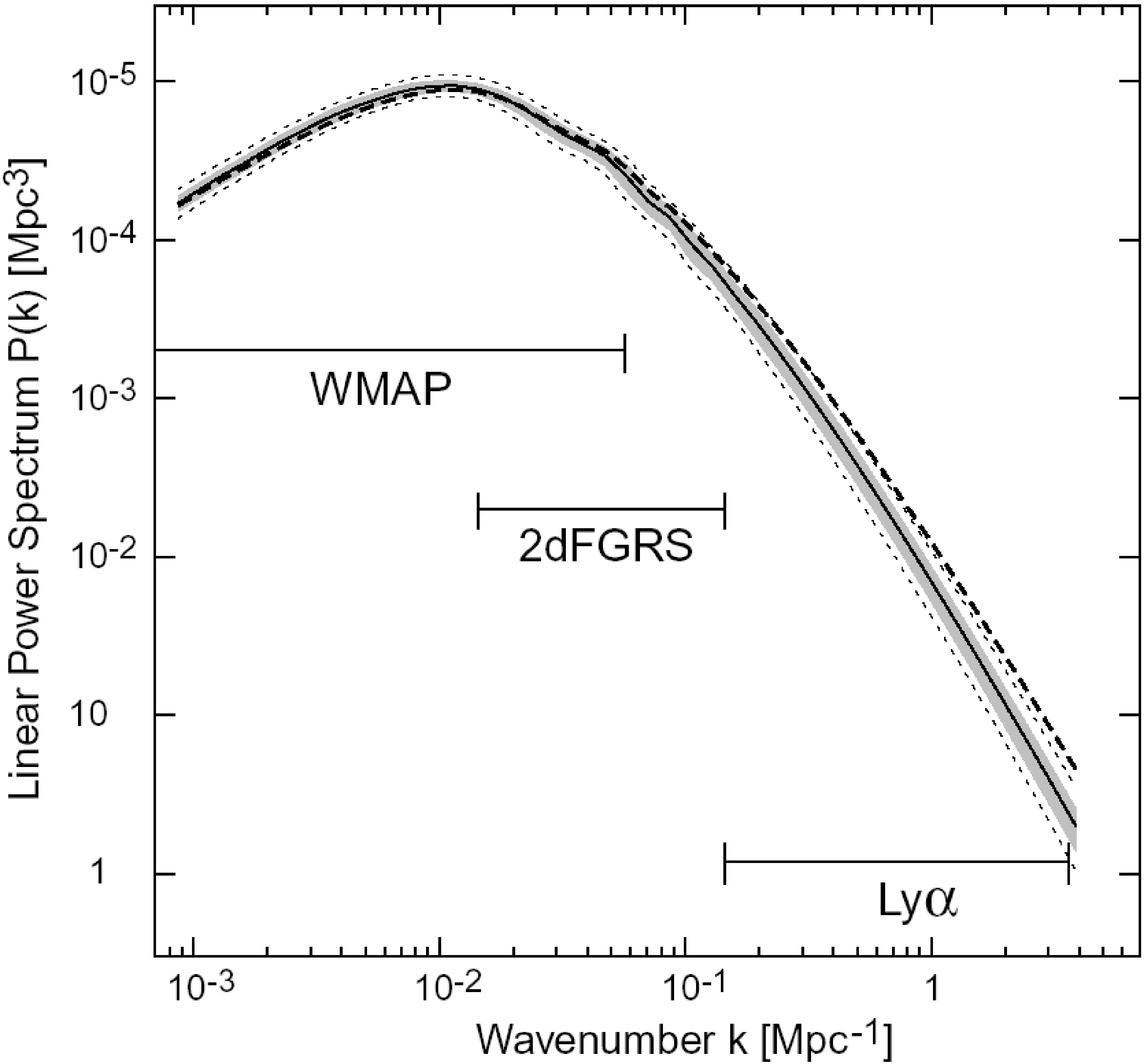


Cosmic Expansion is Accelerating


SDSS SURVEY



−23 < M_r < −22
−22 < M_r < −21
−22 < M_r < −21
−20 < M_r < −19
−19 < M_r < −18
−18 < M_r < −17
−17 < M_r < −16
500
0
-500
-500
0
500
Comoving y [h⁻¹ Mpc]
Comoving x [h⁻¹ Mpc] (towards ra=0)

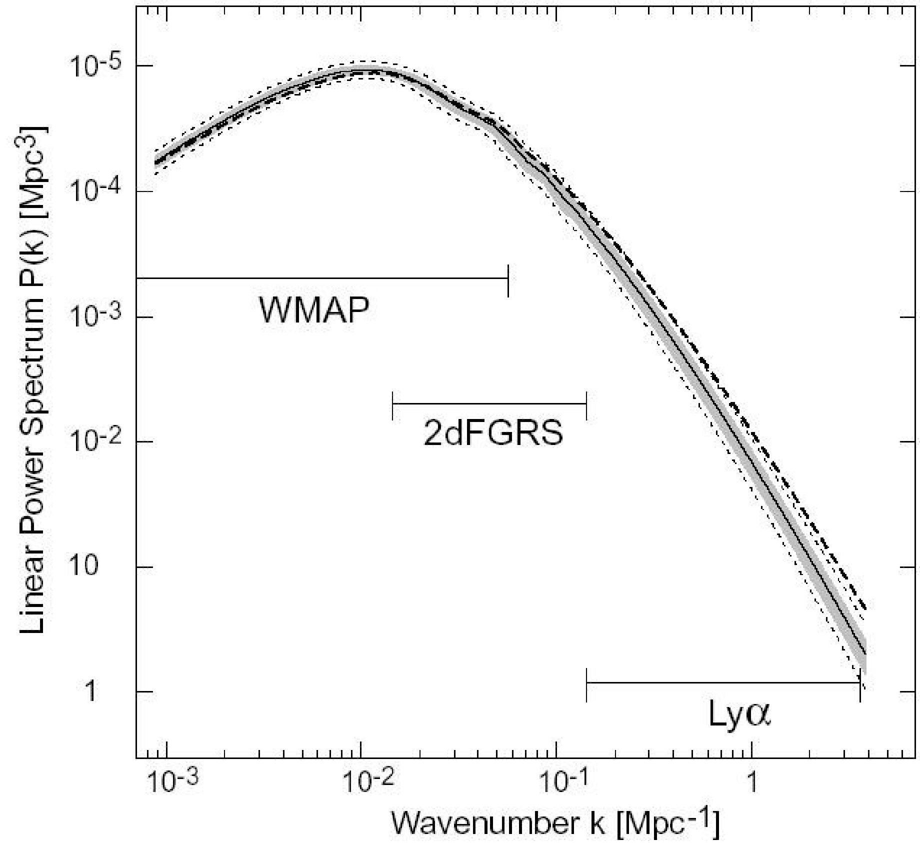


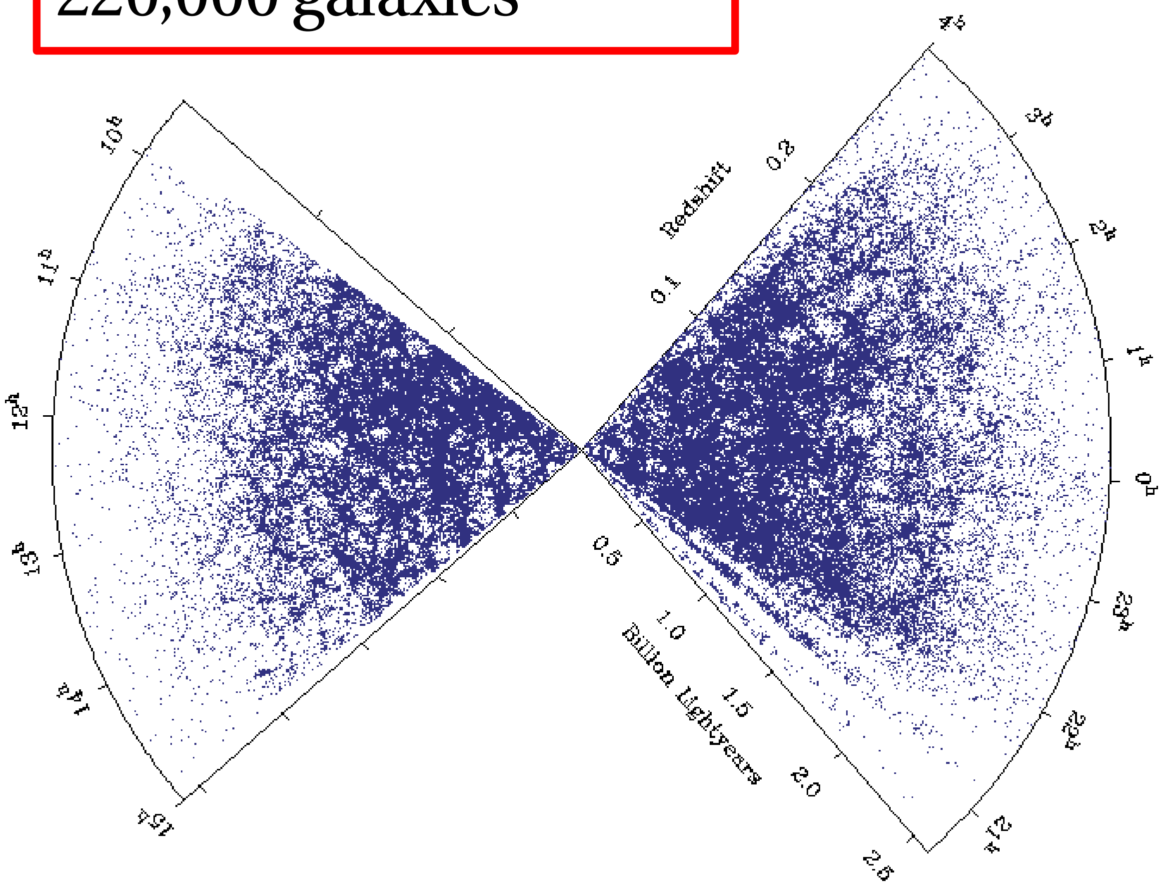
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10
1
Linear Power Spectrum P(k) [Mpc^3]
WMAP
2dFGRS
Lyα
10^{-3}
10^{-2}
10^{-1}
1
Wavenumber k [Mpc^{-1}]

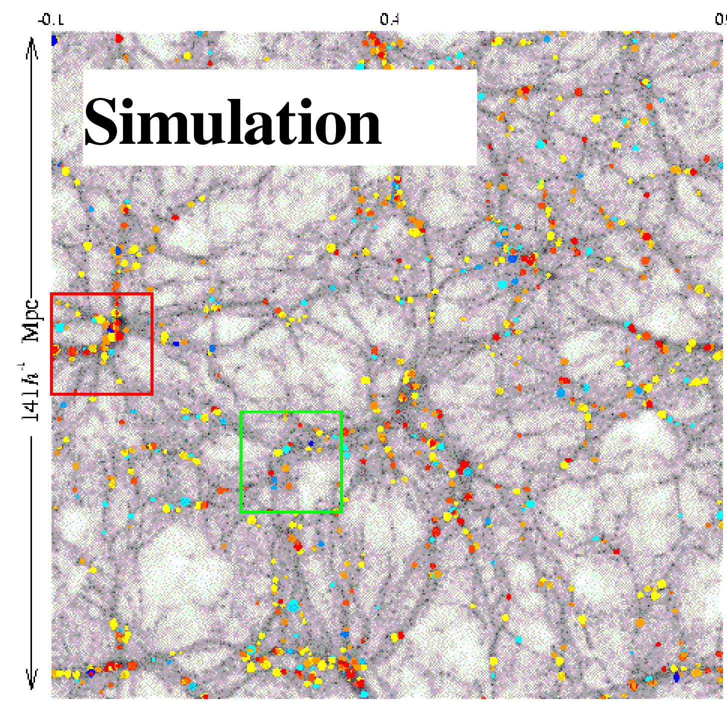
Large Scale Galaxy Survey

2 Degree Field
Galaxy Redshift Survey

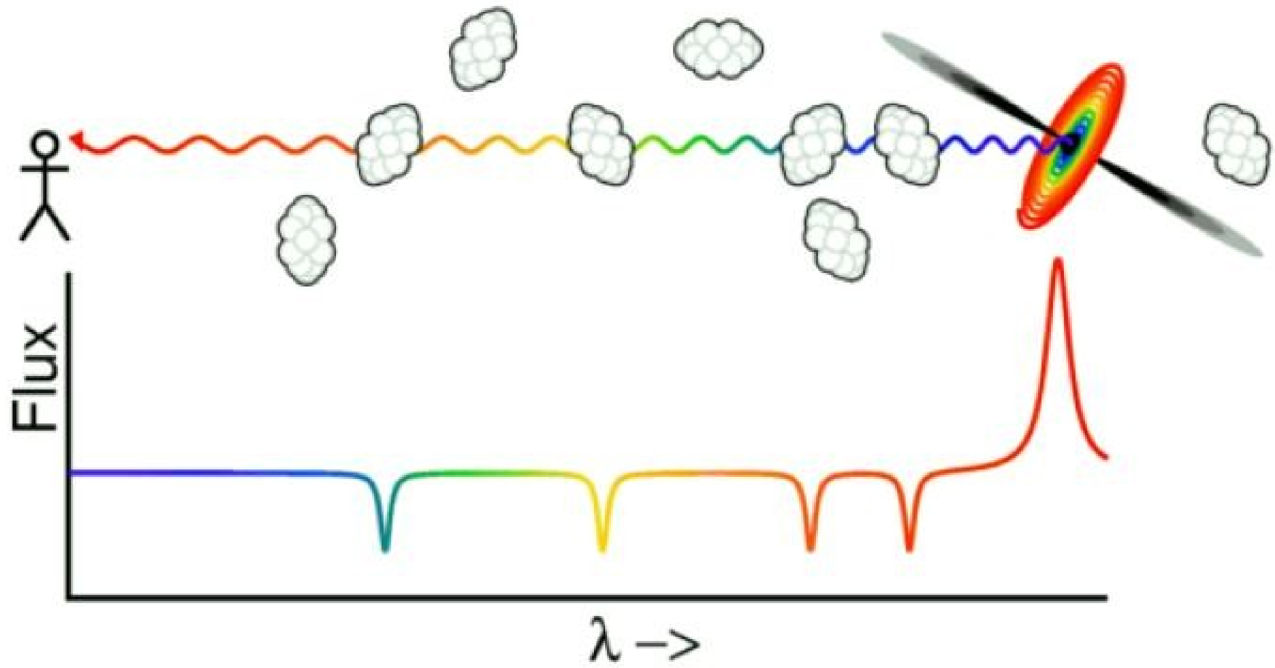
220,000 galaxies



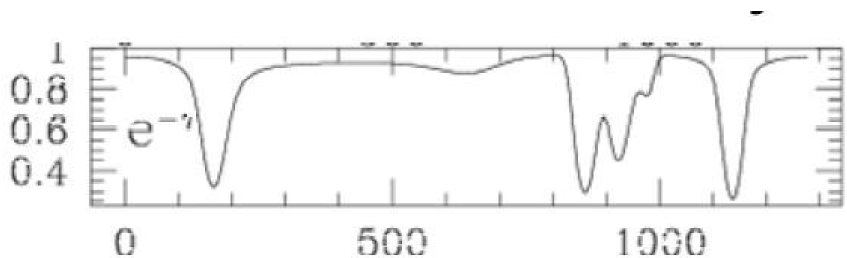




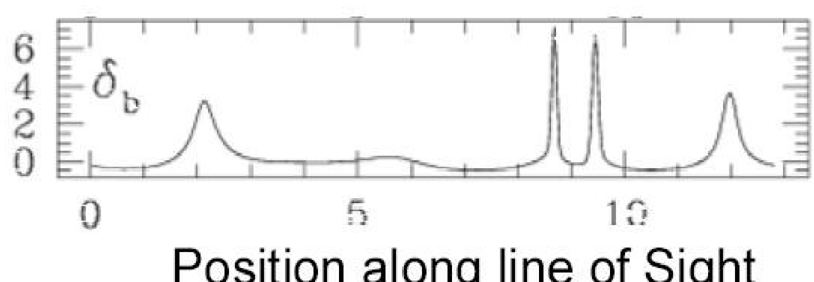
Lyman Alpha studies



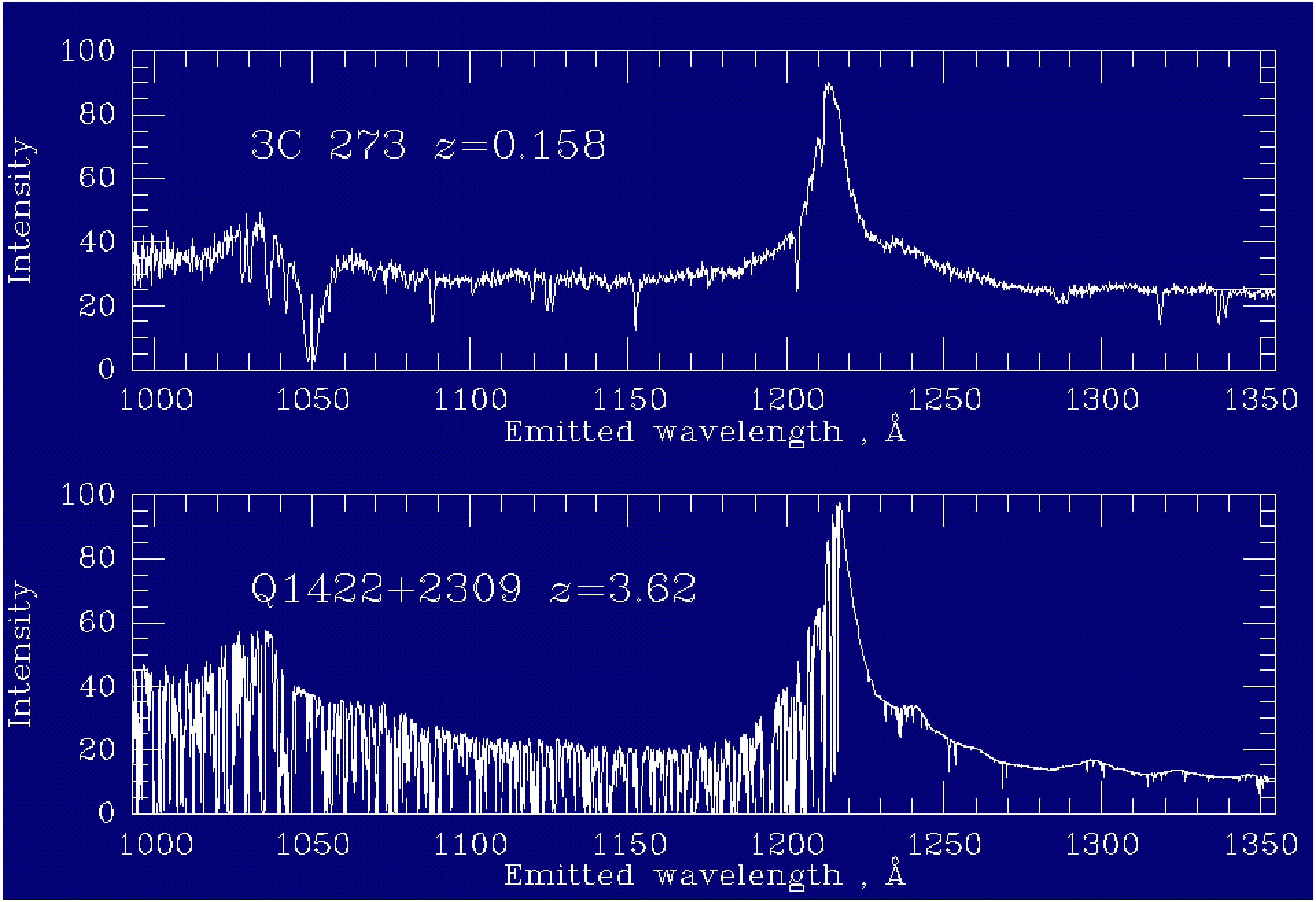
Flux



Baryon Density

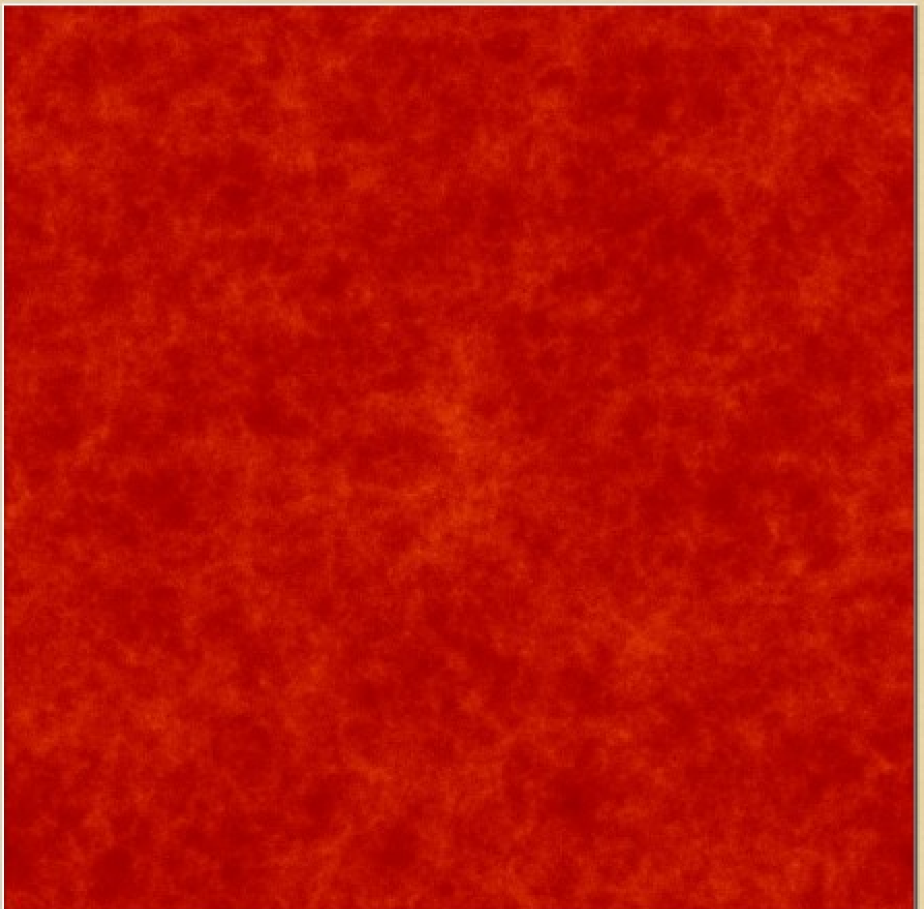


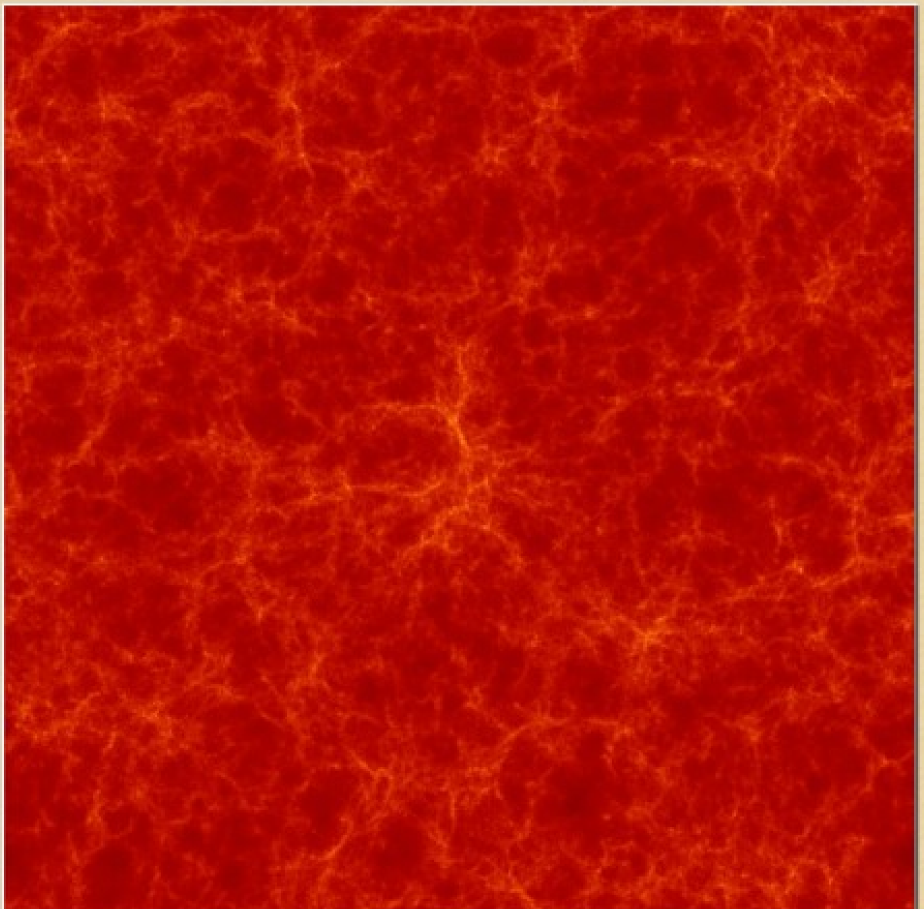
Lyman Alpha Forest



Formation of Structure

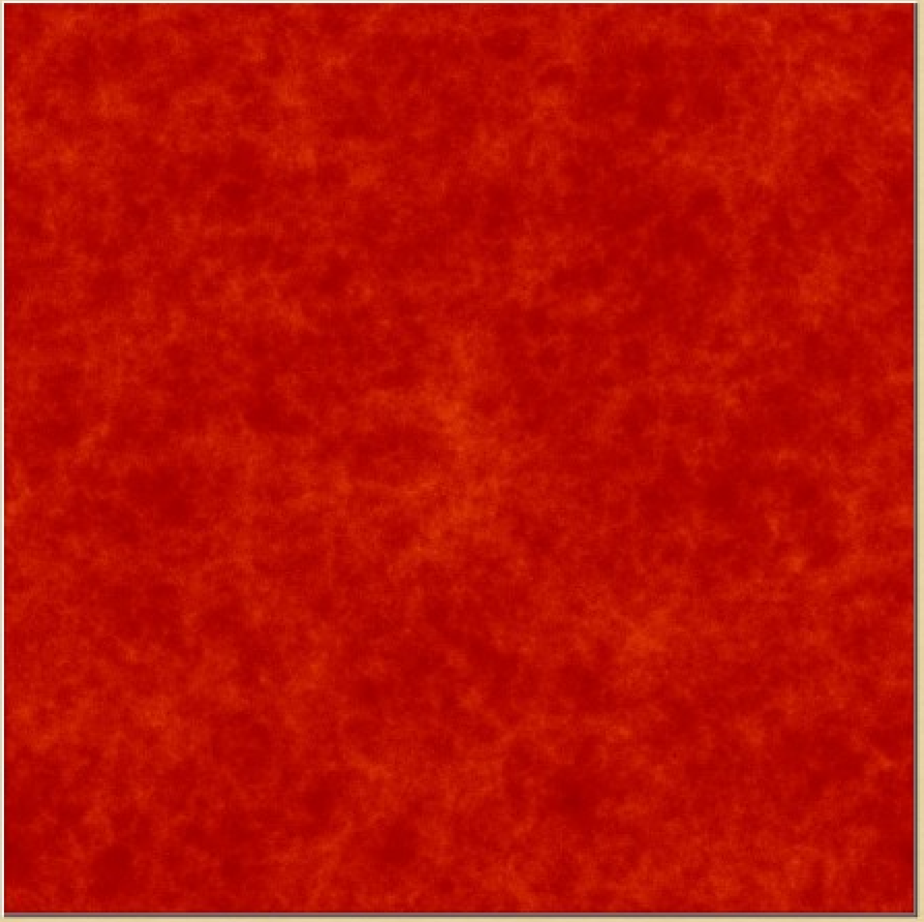
Smooth → Structured

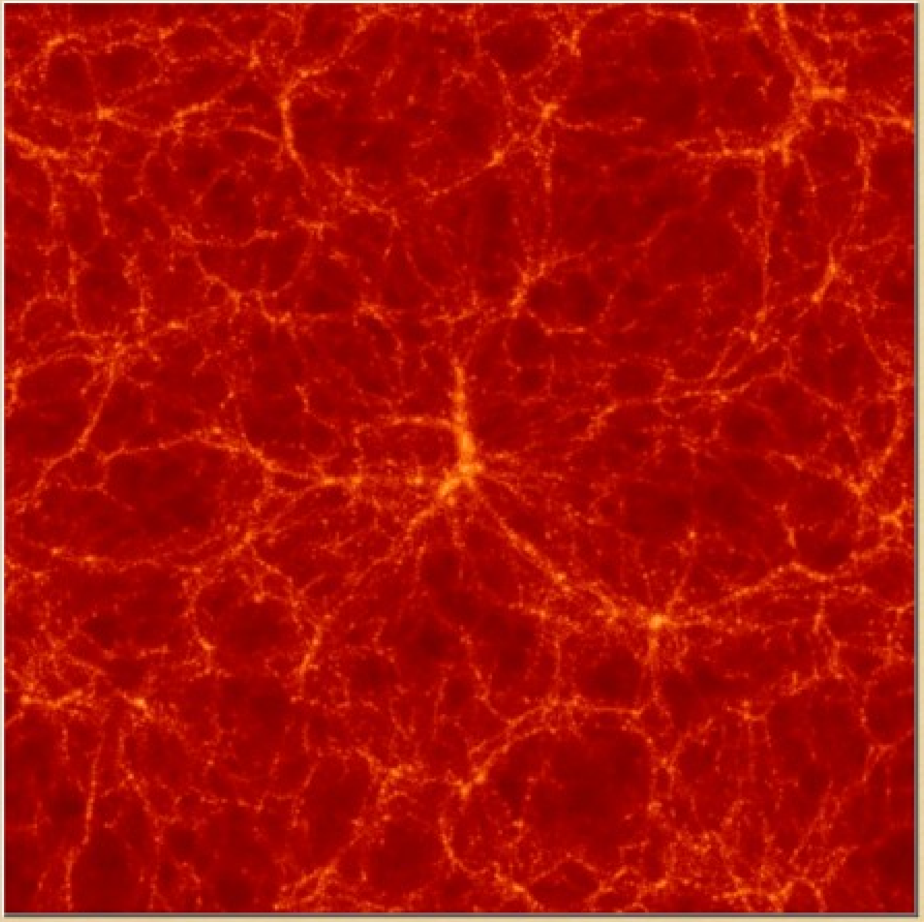




Formation of Structure

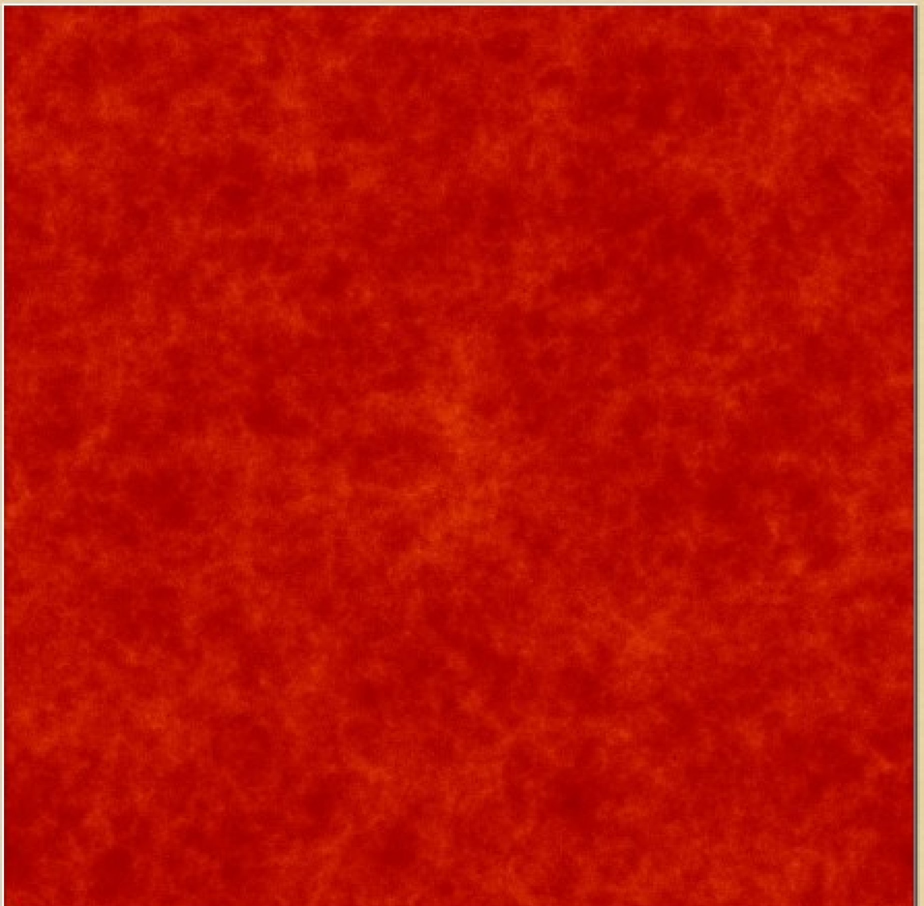
Smooth	Structured

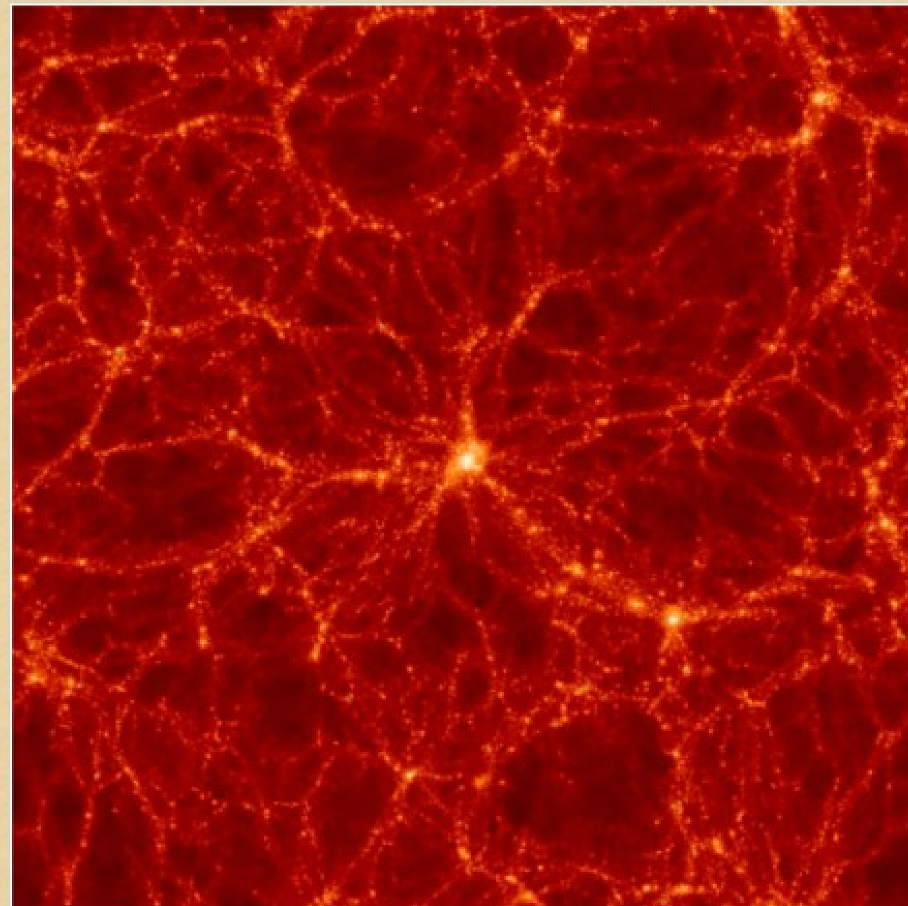




Formation of Structure

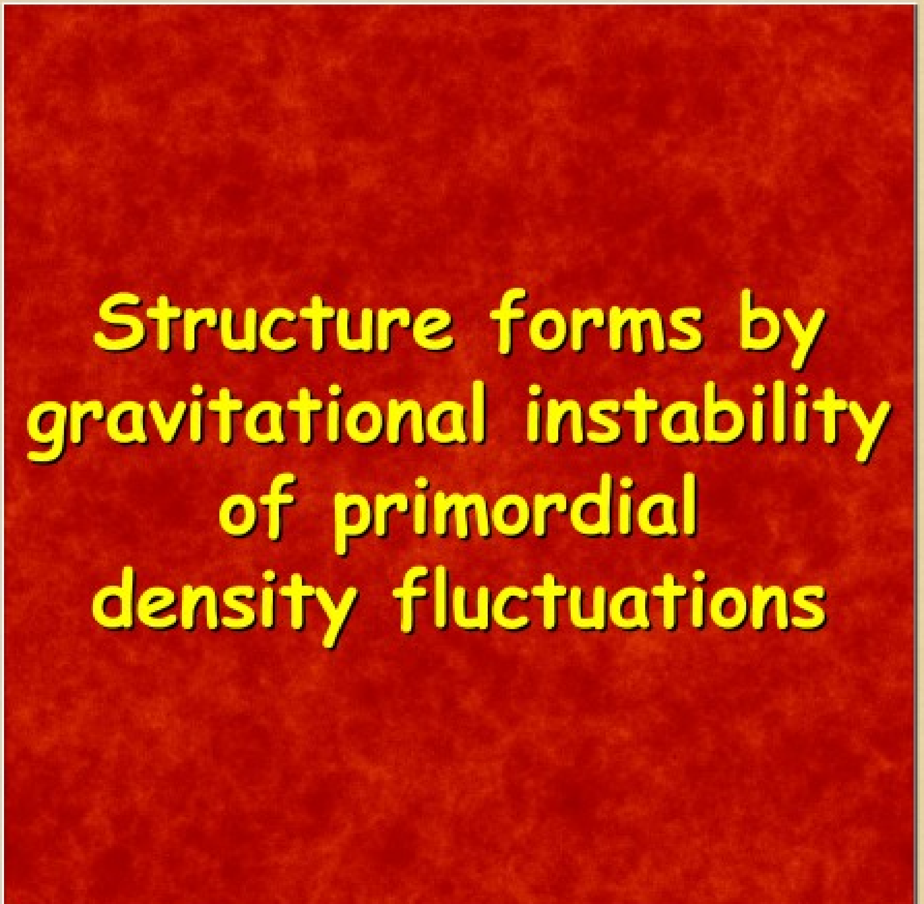
Smooth → Structured

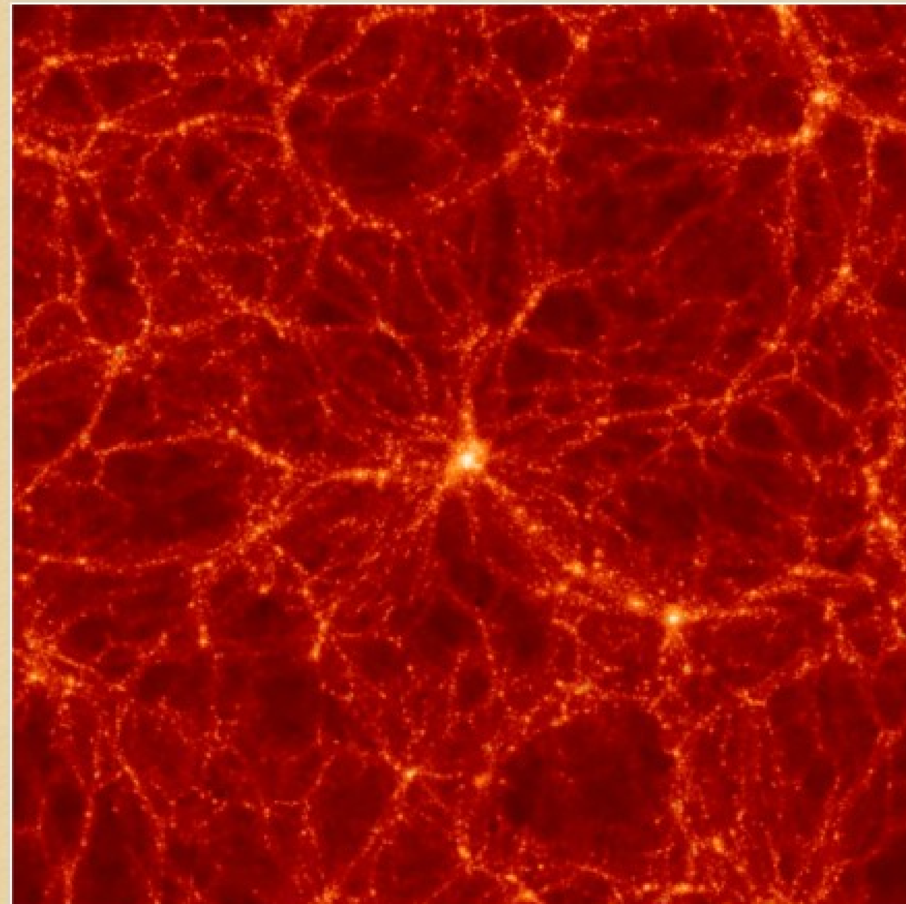




Formation of Structure

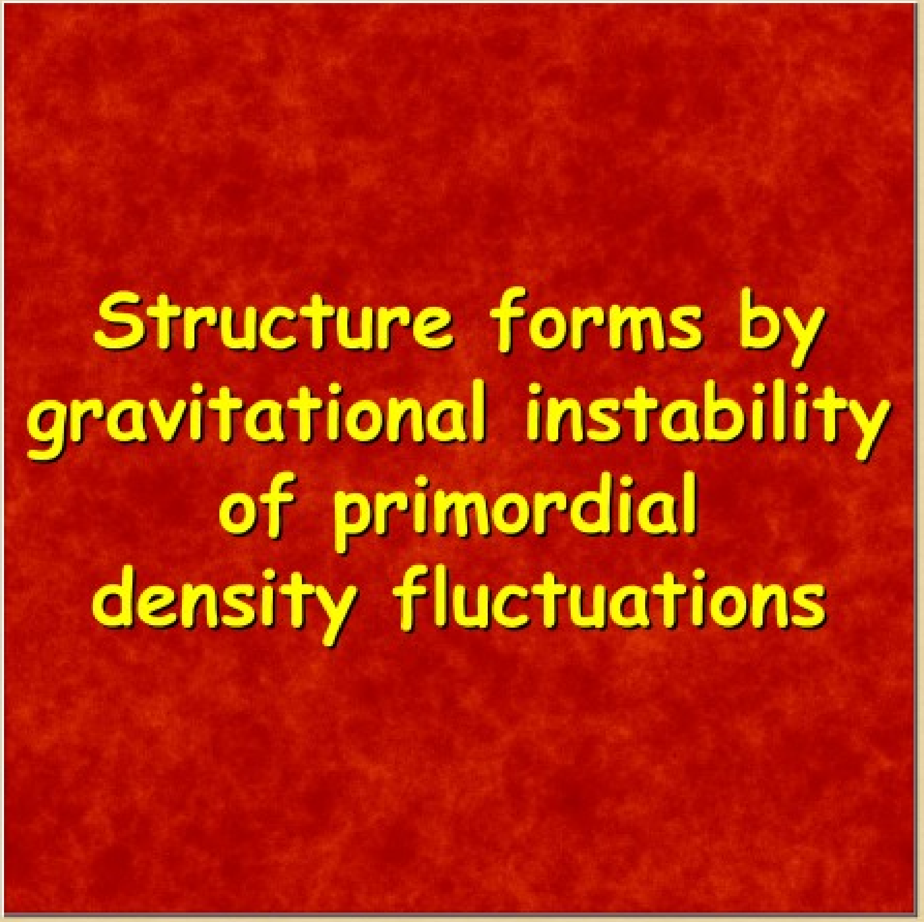
Smooth	Structured

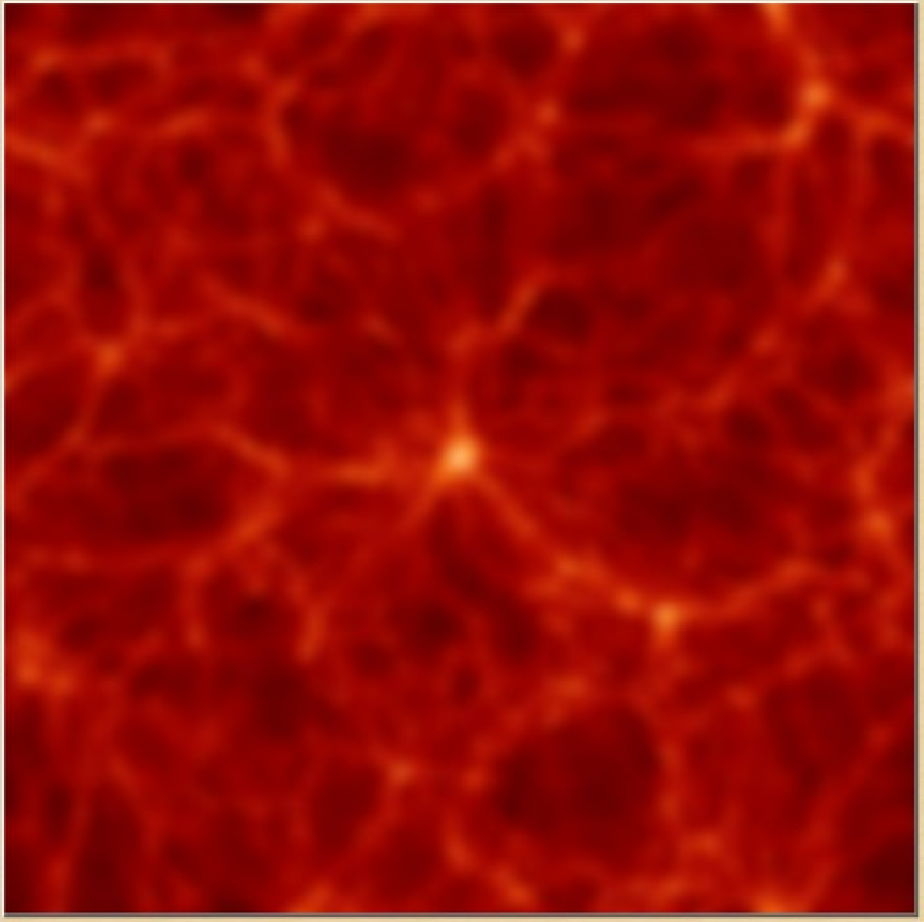




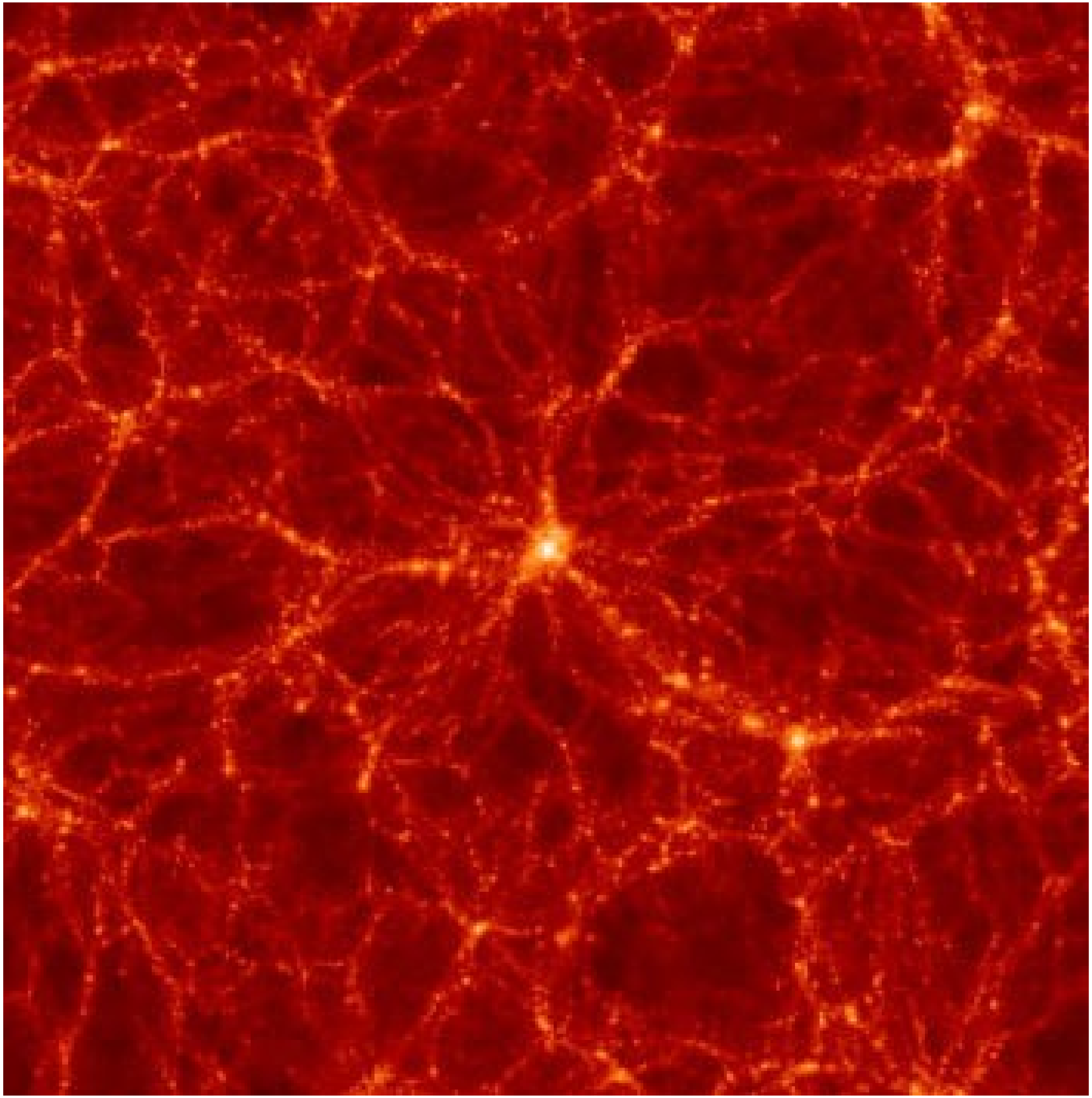
Formation of Structure

Smooth → **Structured**

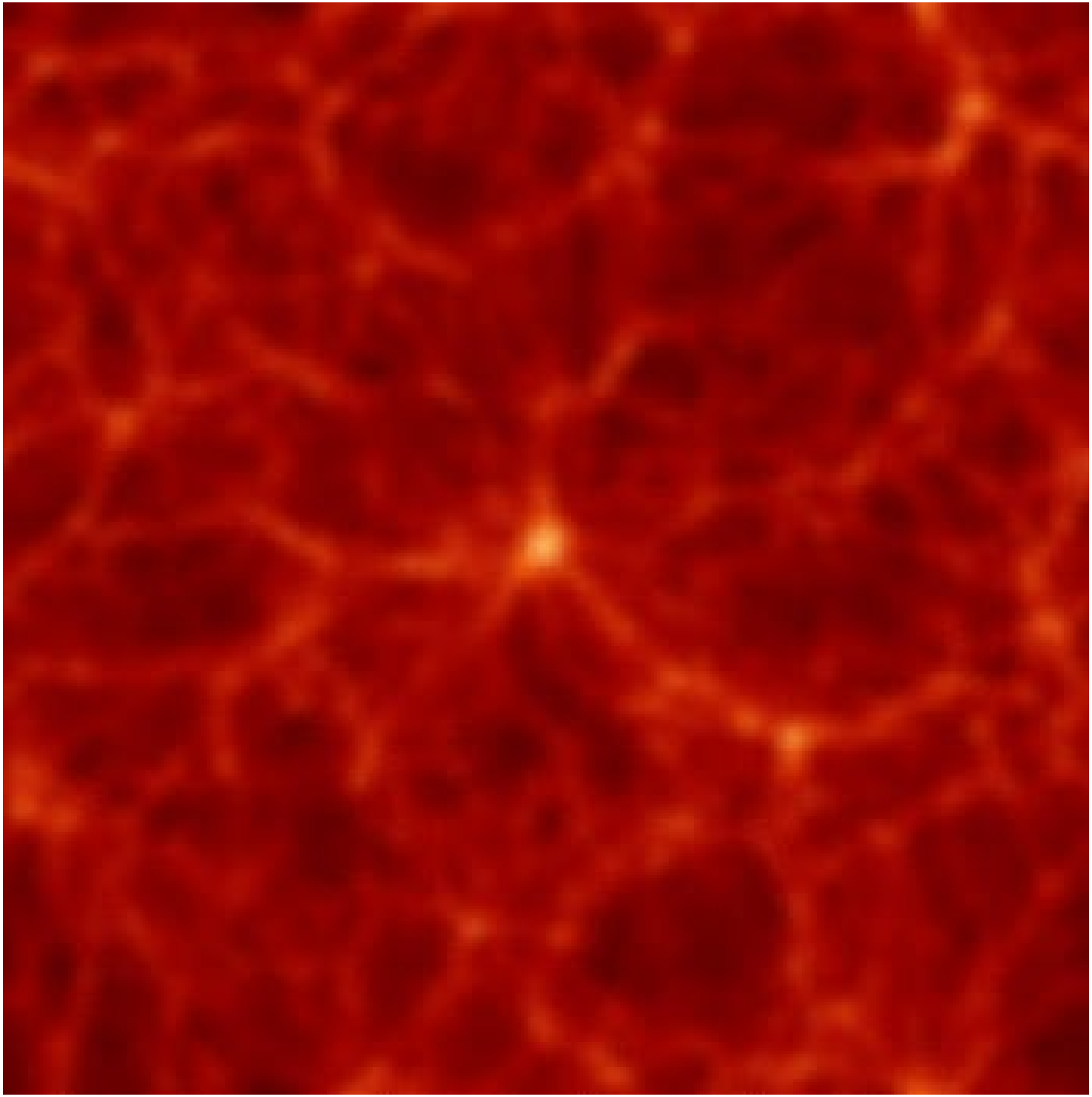




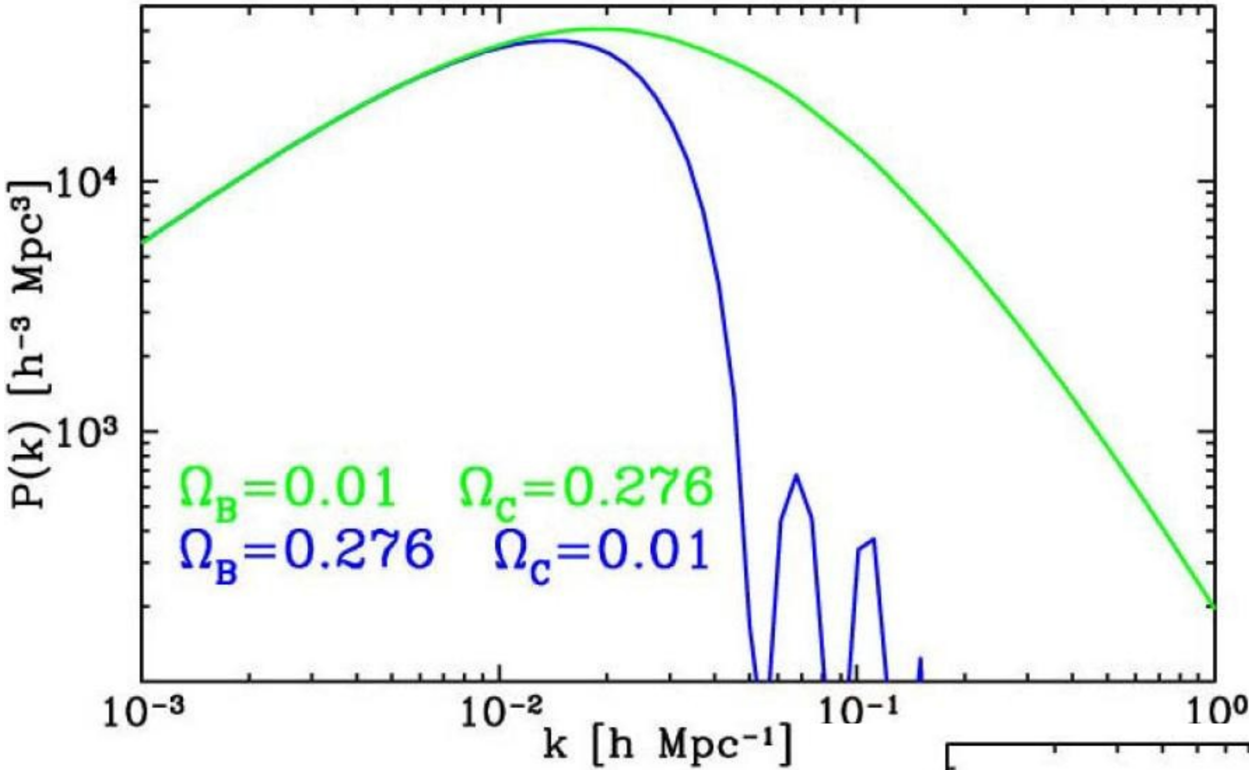
A fraction of hot dark matter suppresses small-scale structure



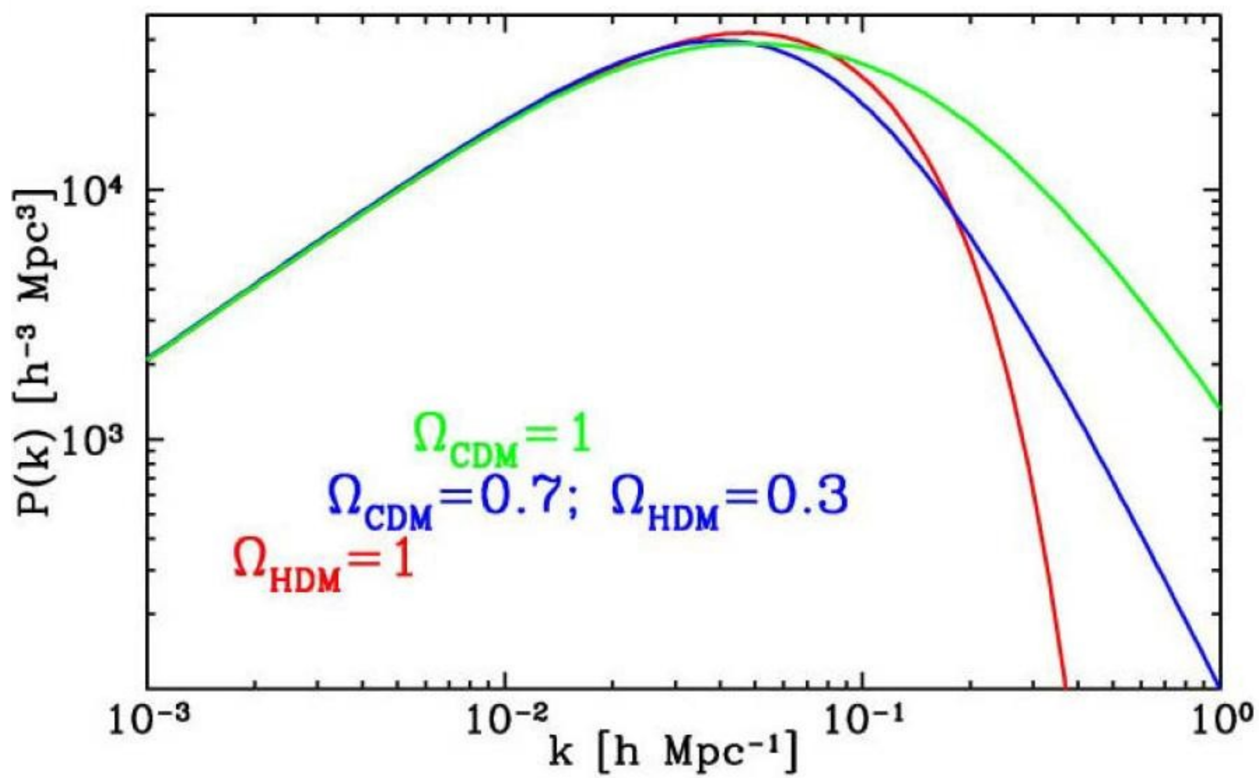
Structured Universe



Added
Hot Dark Matter

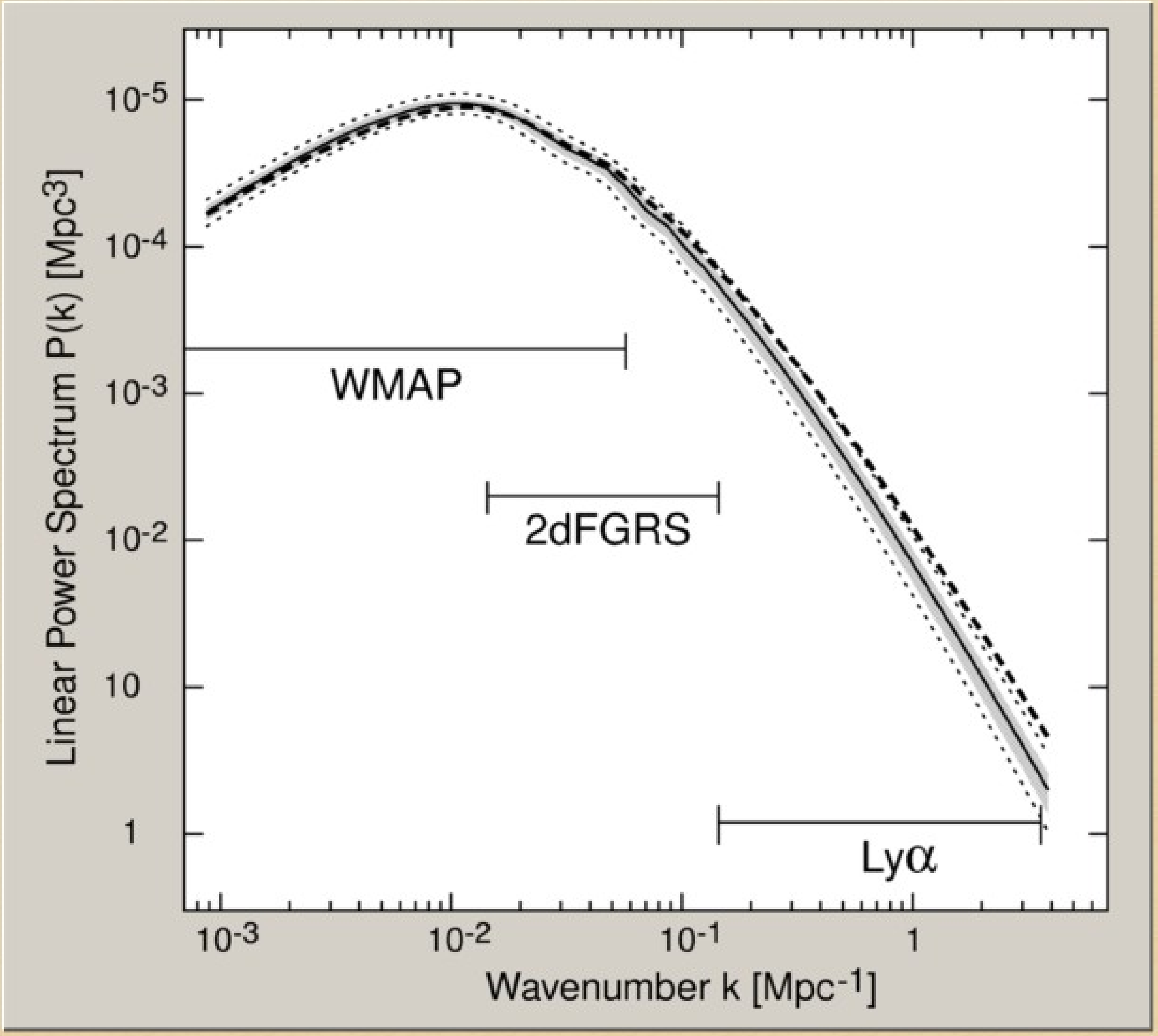


P(k) [h⁻³ Mpc³]
10⁴
10³
$\Omega_B=0.01$ $\Omega_C=0.276$
$\Omega_B=0.276$ $\Omega_C=0.01$
10⁻³
10⁻²
10⁻¹
10⁰
k [h Mpc⁻¹]



P(k) [h⁻³ Mpc³]
10⁴
10³
$\Omega_{CDM}=1$
$\Omega_{CDM}=0.7$; $\Omega_{HDM}=0.3$
$\Omega_{HDM}=1$
10⁻³
10⁻²
10⁻¹
10⁰
k [h Mpc⁻¹]

Probes of Cosmic Structure

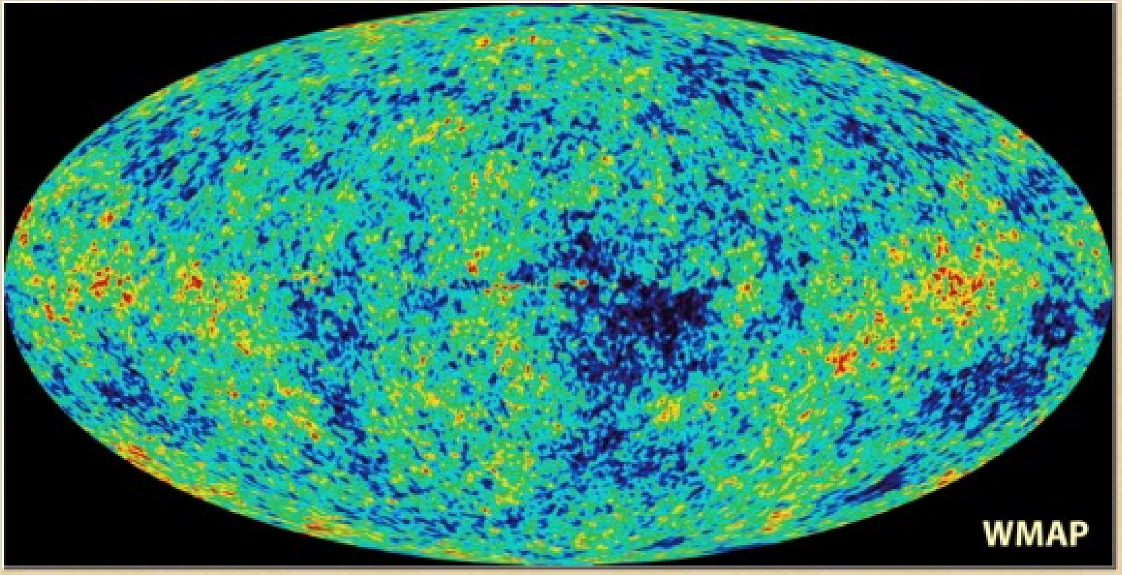


WMAP Collaboration:
First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations:
Determination of Cosmological Parameters [astro-ph/0302209]

Power Spectrum of CMBR Temperature Fluctuations

Sky map of CMBR temperature fluctuations

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

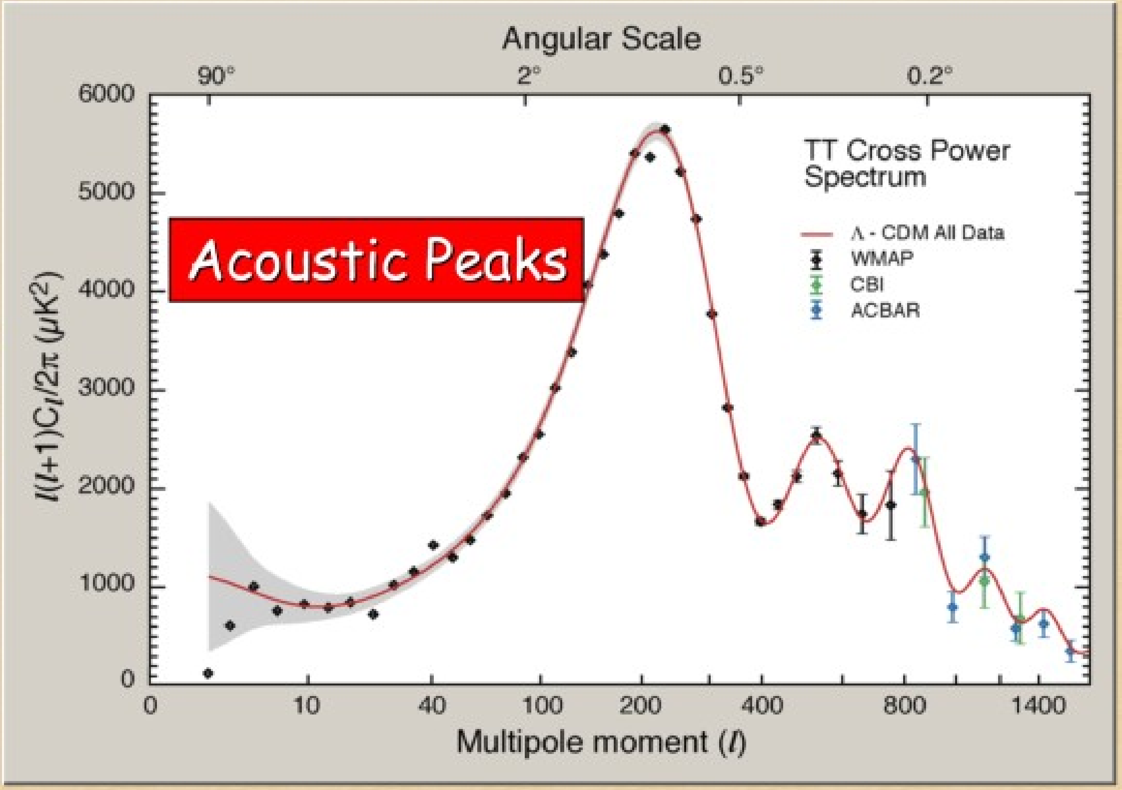


Multipole expansion

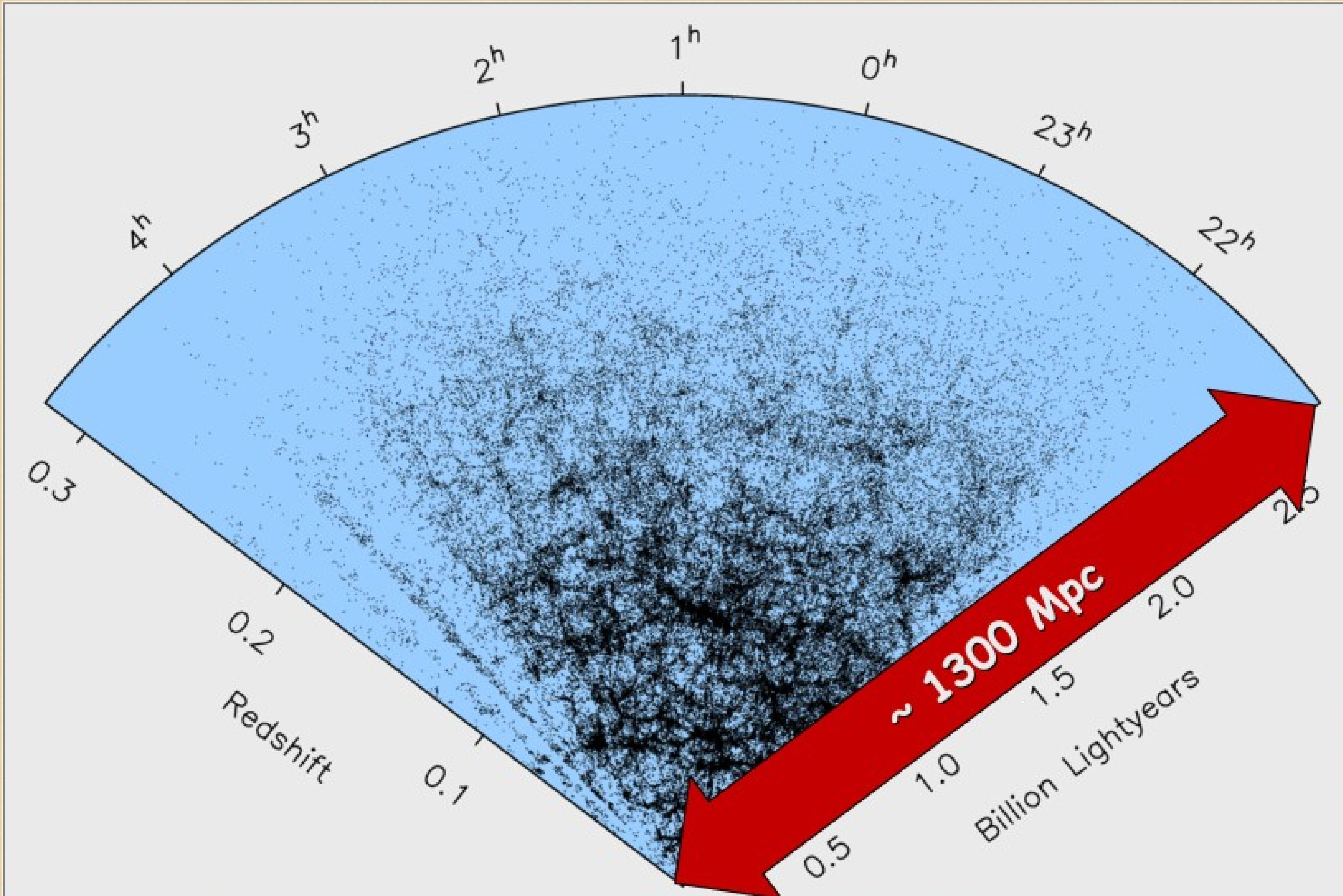
$$\Delta(\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$

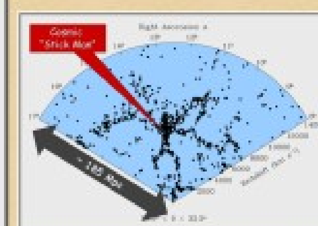
Angular power spectrum

$$C_\ell = \langle a_{\ell m}^* a_{\ell m} \rangle = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell m}^* a_{\ell m}$$



Galaxy Redshift Surveys





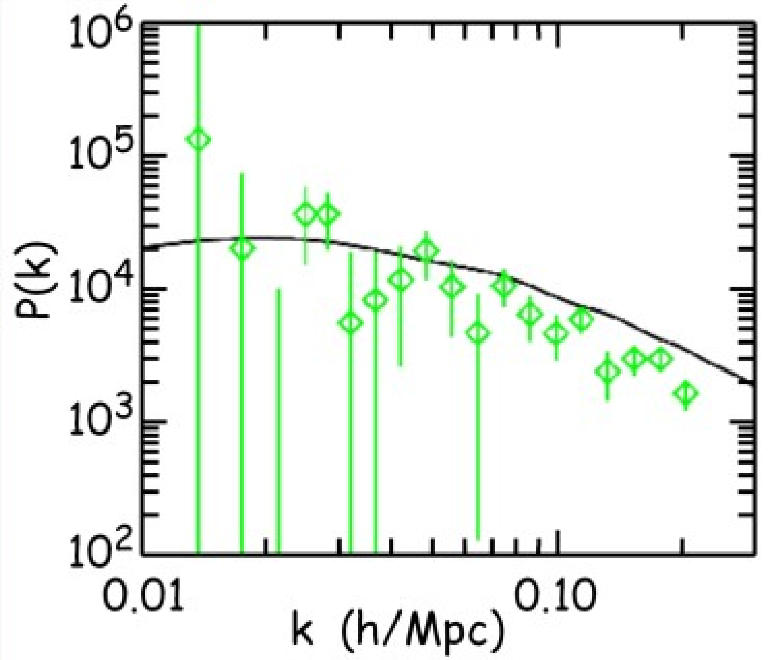
Galaxy distribution from the CfA redshift survey [ApJ 302 (1986) L1]

2dF Galaxy Redshift Survey (May 2002), Northern Slice
http://www.mso.anu.edu.au/2dFGRS/

Cosmic Structure Modified by Hot Dark Matter

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



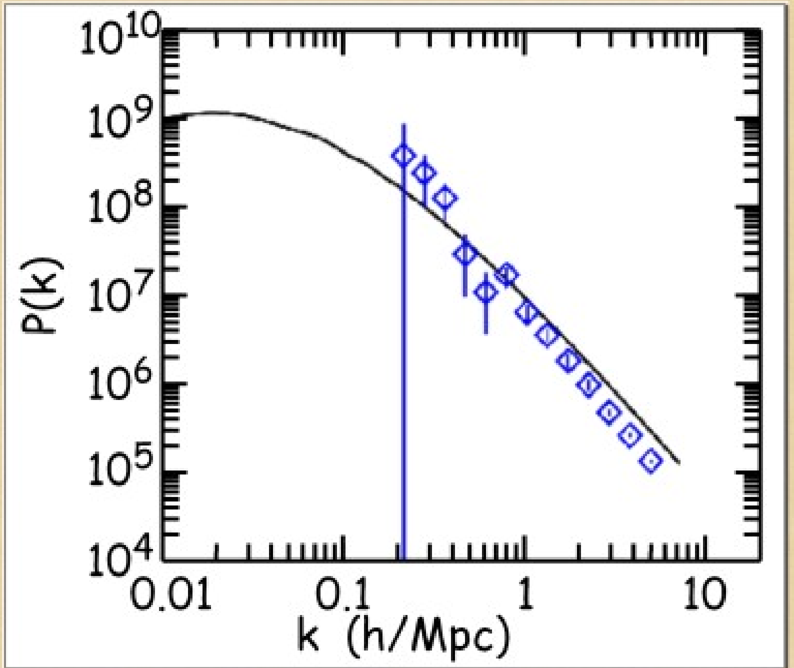
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

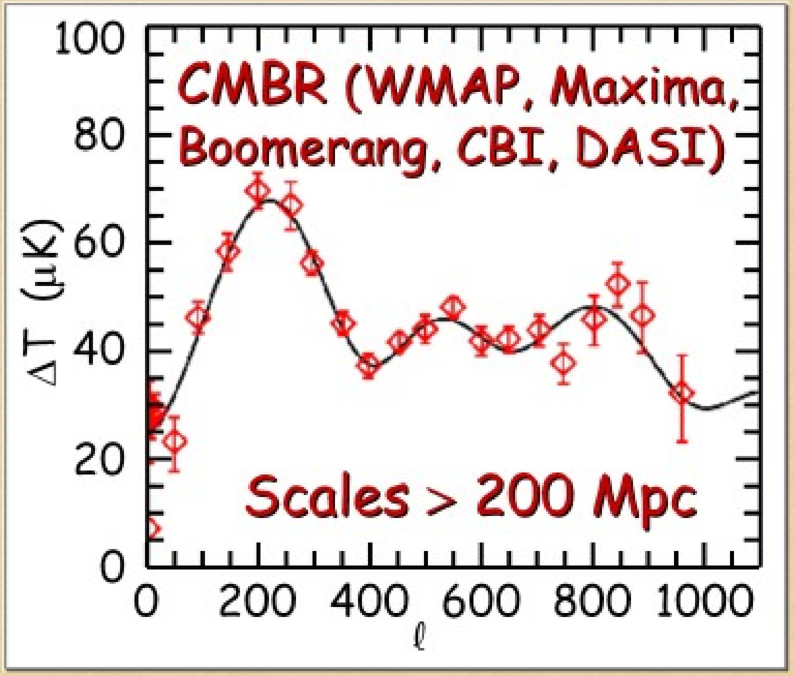
$\Omega_\nu = 0.00$

Adapted from S.Hannestad

Lyman-α forest at large redshift $\langle z \rangle = 2.72$

Scales 0.1–10 Mpc

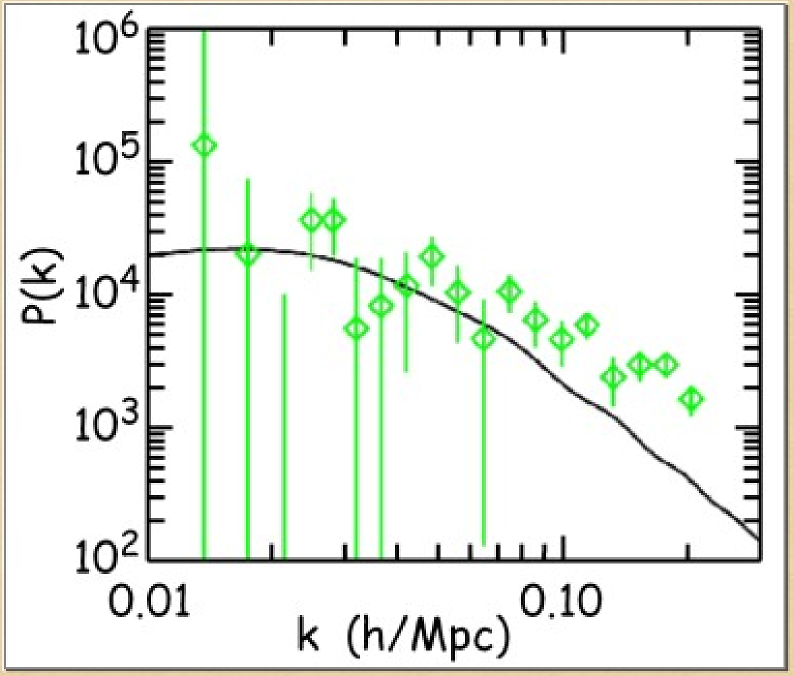




Cosmic Structure Modified by Hot Dark Matter

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



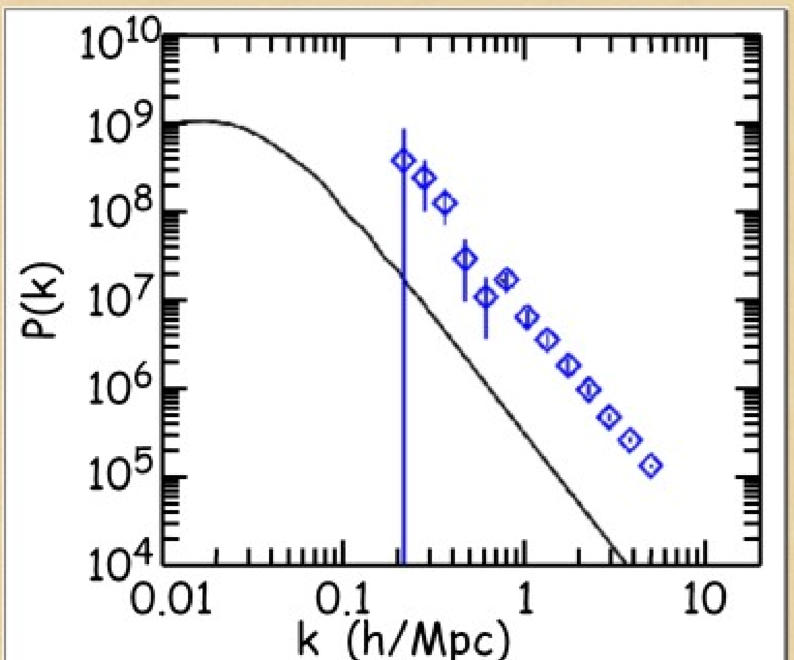
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

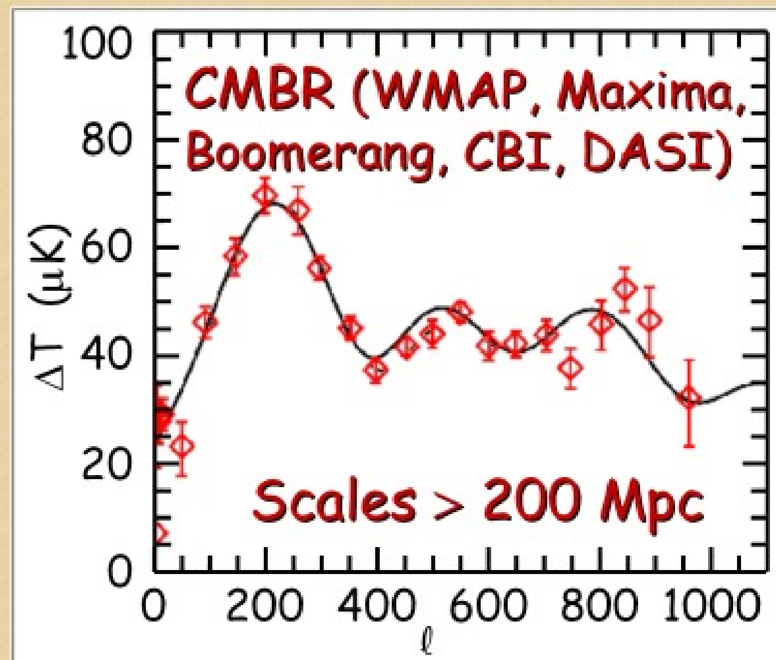
$\Omega_\nu = 0.10$

Adapted from S.Hannestad

Lyman-α forest at large redshift $\langle z \rangle = 2.72$

Scales 0.1–10 Mpc

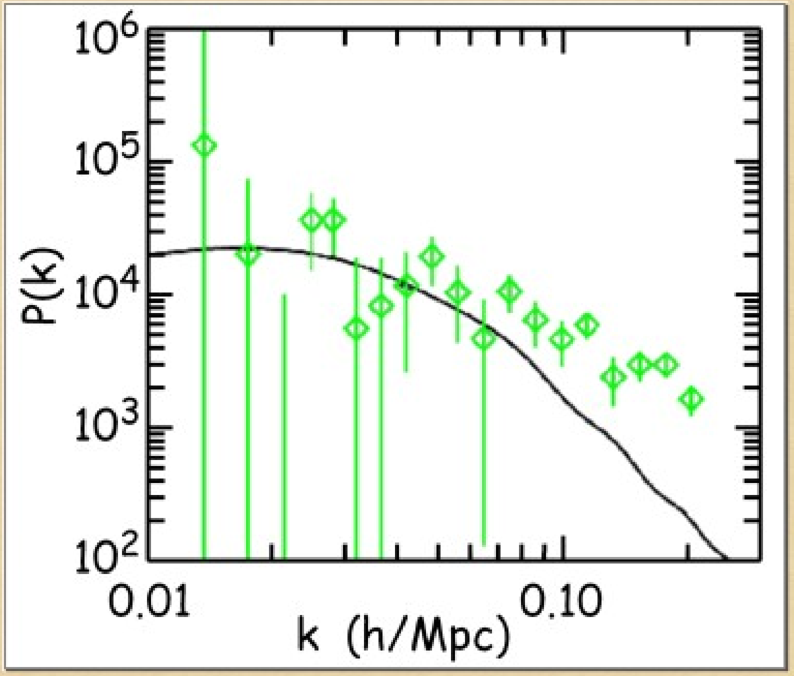




Cosmic Structure Modified by Hot Dark Matter

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



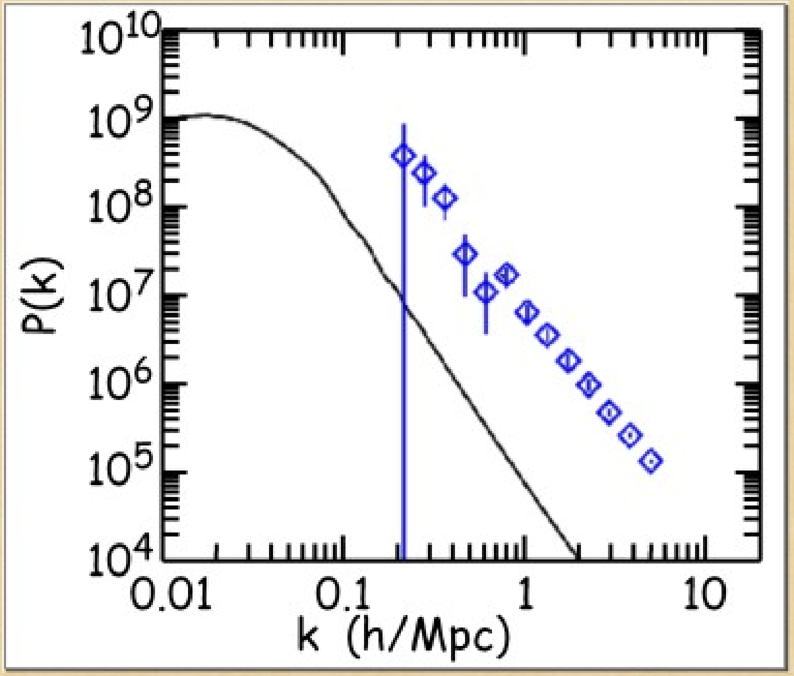
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

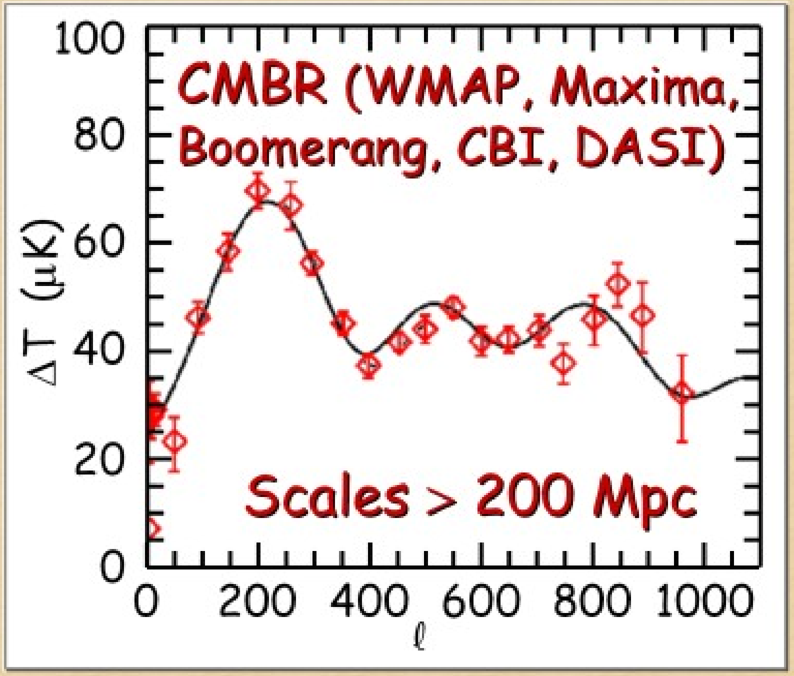
$\Omega_\nu = 0.15$

Adapted from S.Hannestad

Lyman-α forest at large redshift $\langle z \rangle = 2.72$

Scales 0.1–10 Mpc

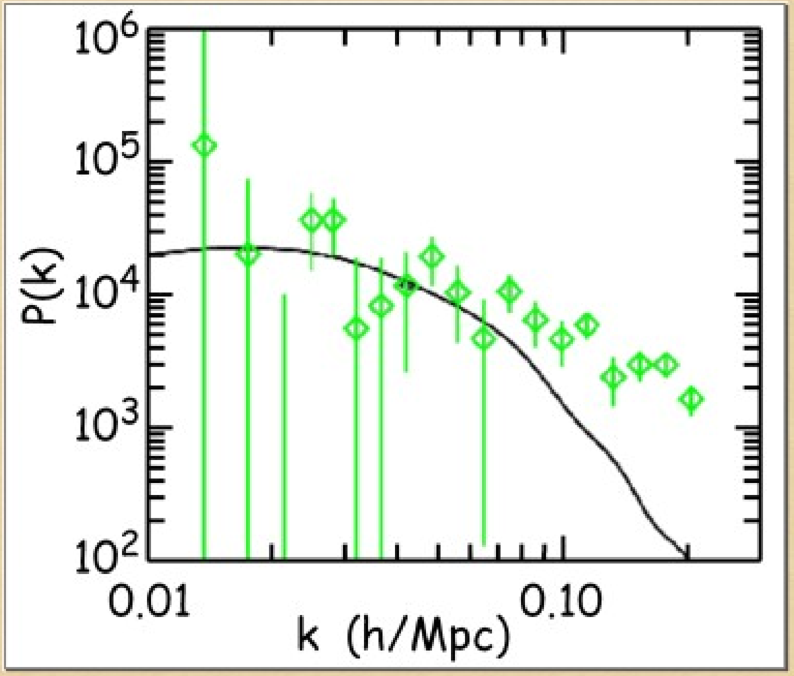




Cosmic Structure Modified by Hot Dark Matter

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



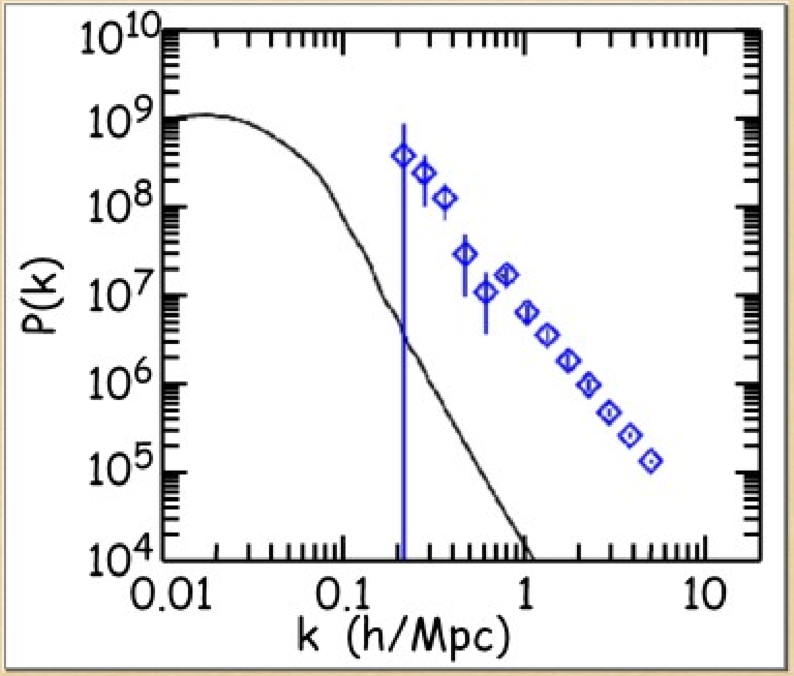
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

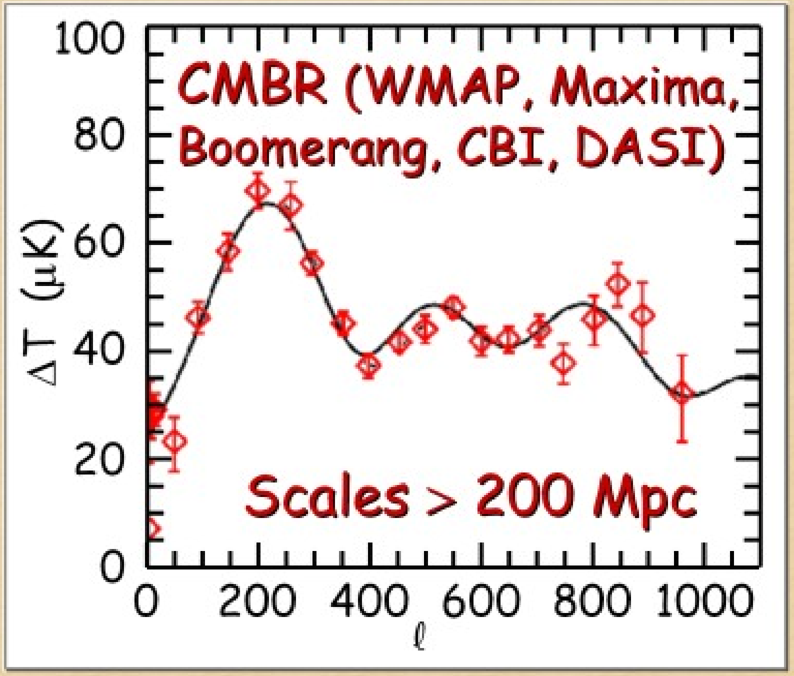
$\Omega_\nu = 0.20$

Adapted from S.Hannestad

Lyman-α forest at large redshift $\langle z \rangle = 2.72$

Scales 0.1–10 Mpc

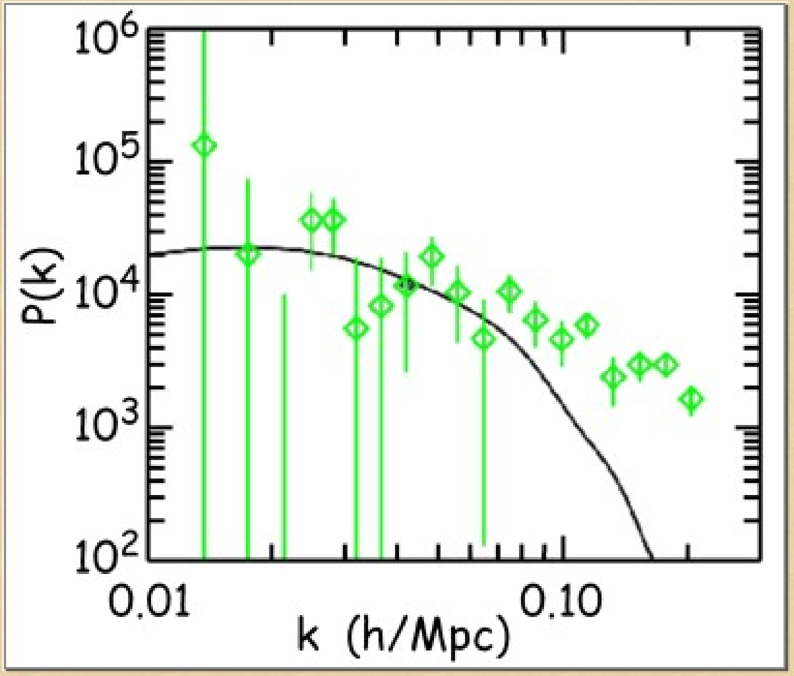




Cosmic Structure Modified by Hot Dark Matter

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



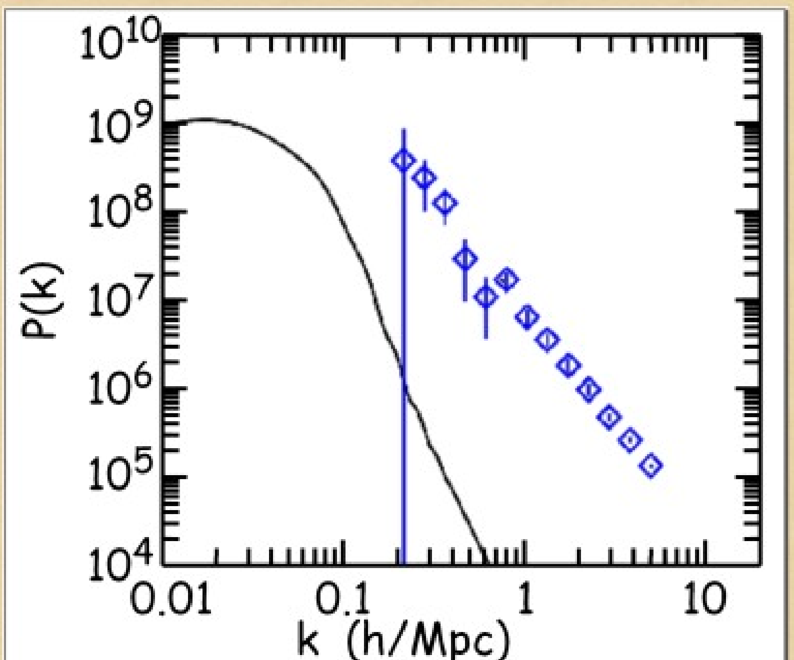
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

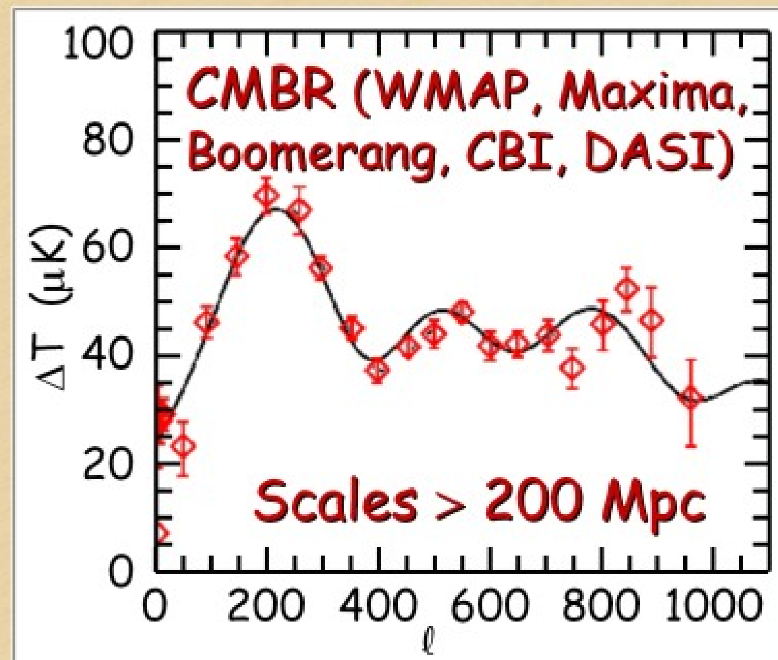
$\Omega_\nu = 0.25$

Adapted from S.Hannestad

Lyman-α forest at large redshift $\langle z \rangle = 2.72$

Scales 0.1–10 Mpc

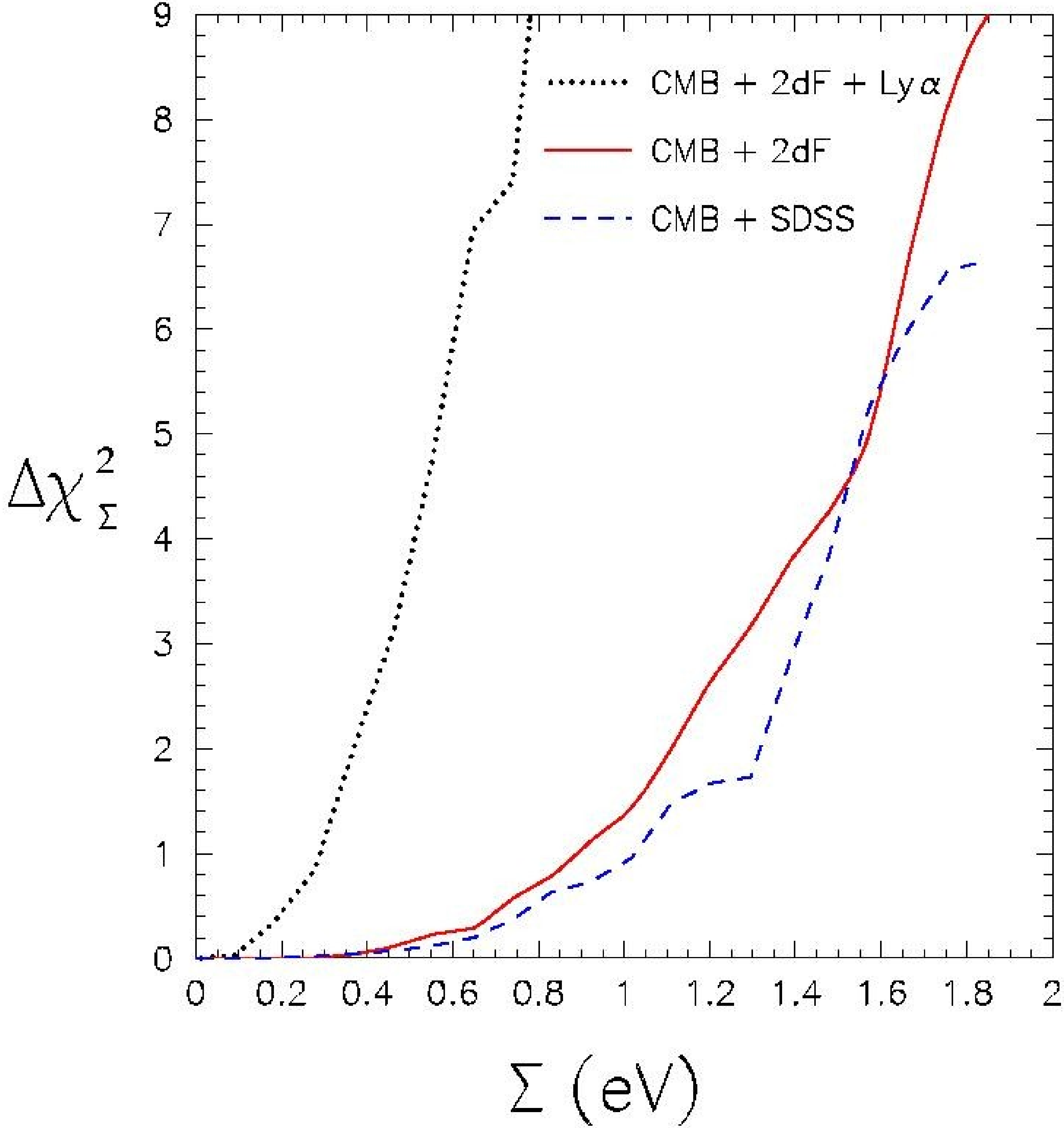




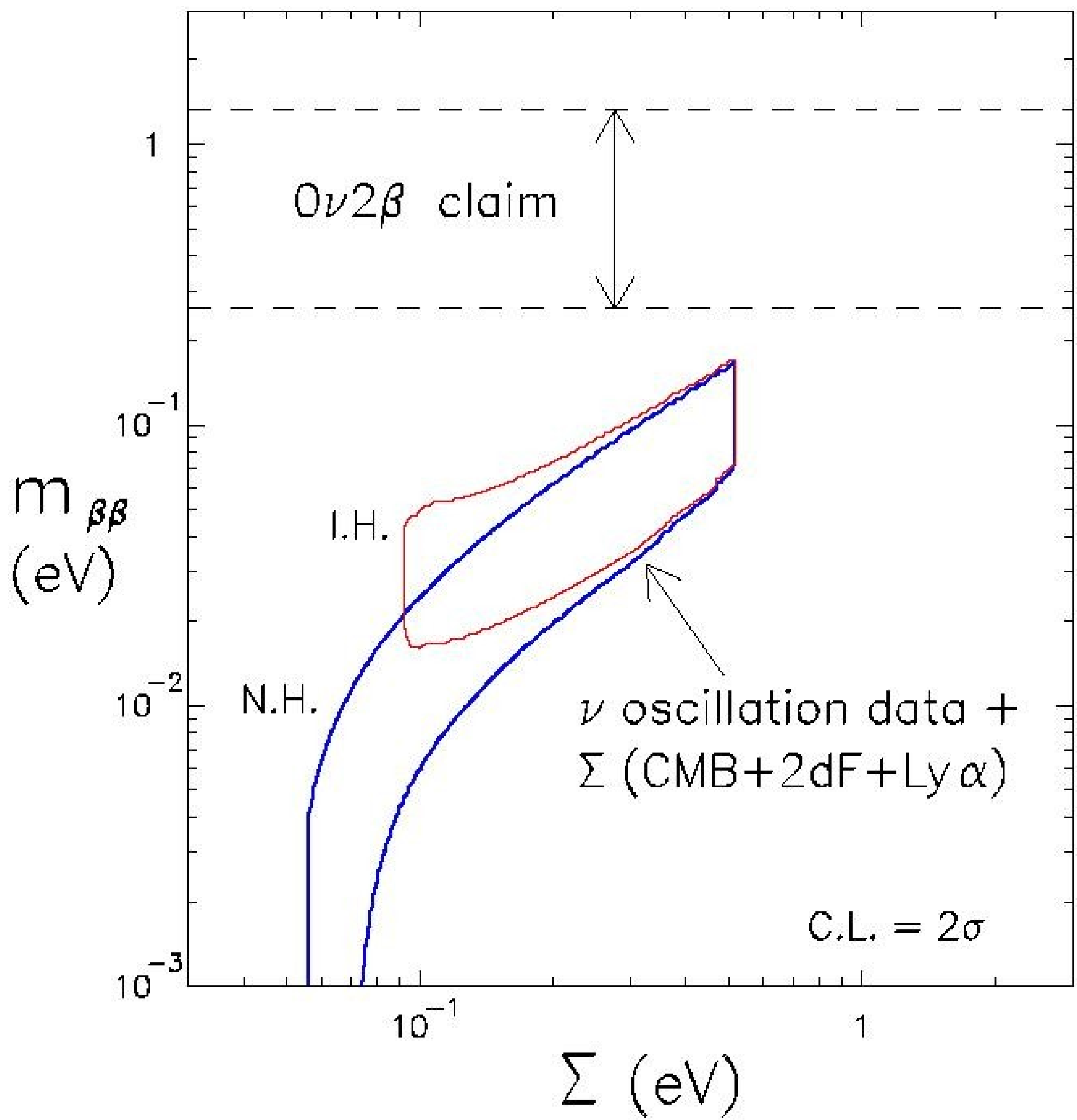
Neutrino Mass Limits from Large-Scale Structure

Statistical 95% C.L. limits depend on used data and on priors for other parameters. For detailed analyses see
- Hannestad, astro-ph/0303076
- Elgaroy & Lahav, astro-ph/0303089

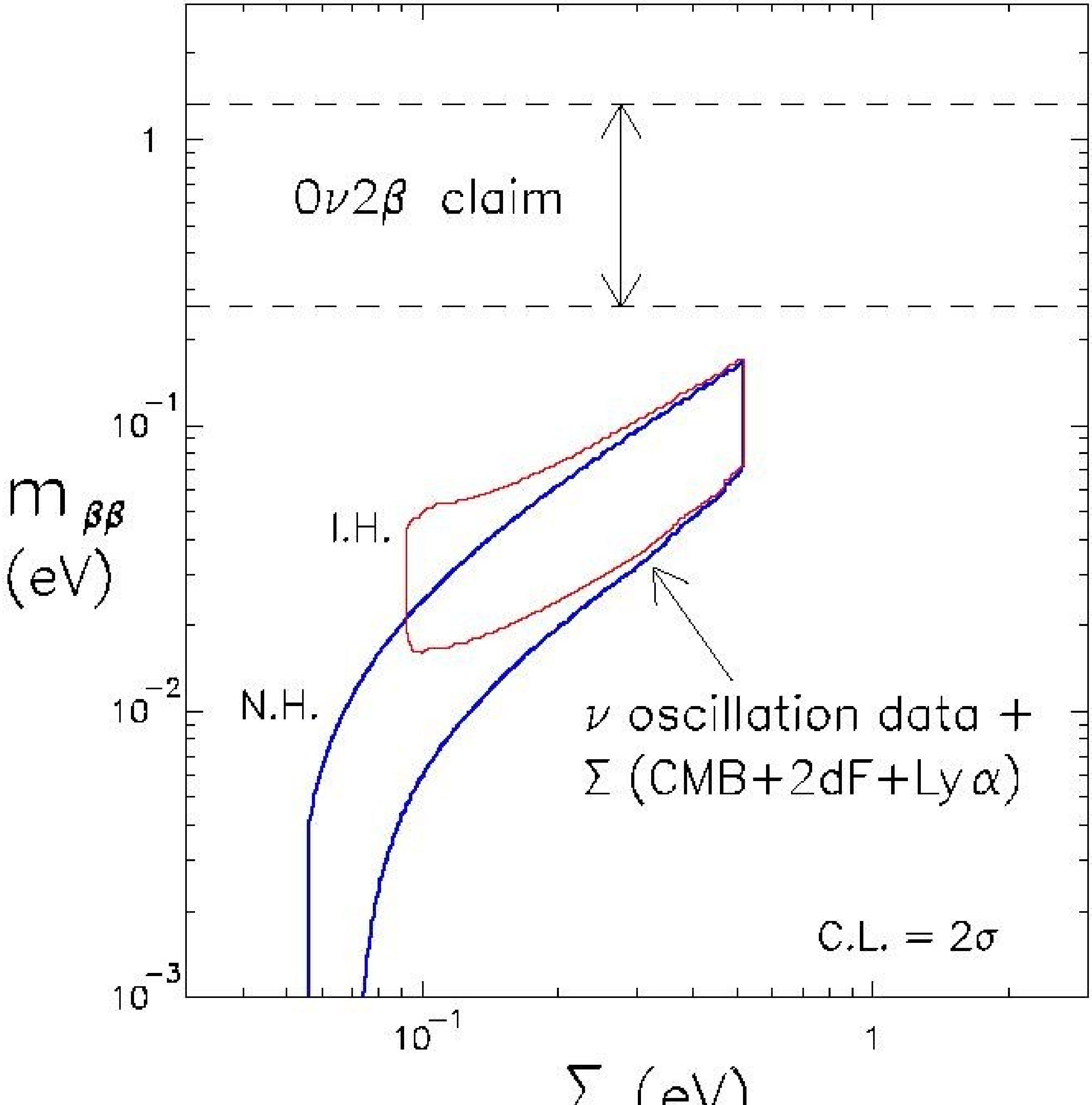
$\Sigma m_\nu < 2.1$ eV	WMAP (Cosmic microwaves) 2dF (Galaxy-galaxy correlation)
$\Sigma m_\nu < 1.2$ eV	+ Small-scale CMBR (breaks degeneracy with bias)
$\Sigma m_\nu < 1.0$ eV	+ Priors (1σ) $h = 0.72 \pm 0.08$ $\Omega_M = 0.28 \pm 0.14$
$\Sigma m_\nu < 0.7$ eV	+ Lyman-α forest data



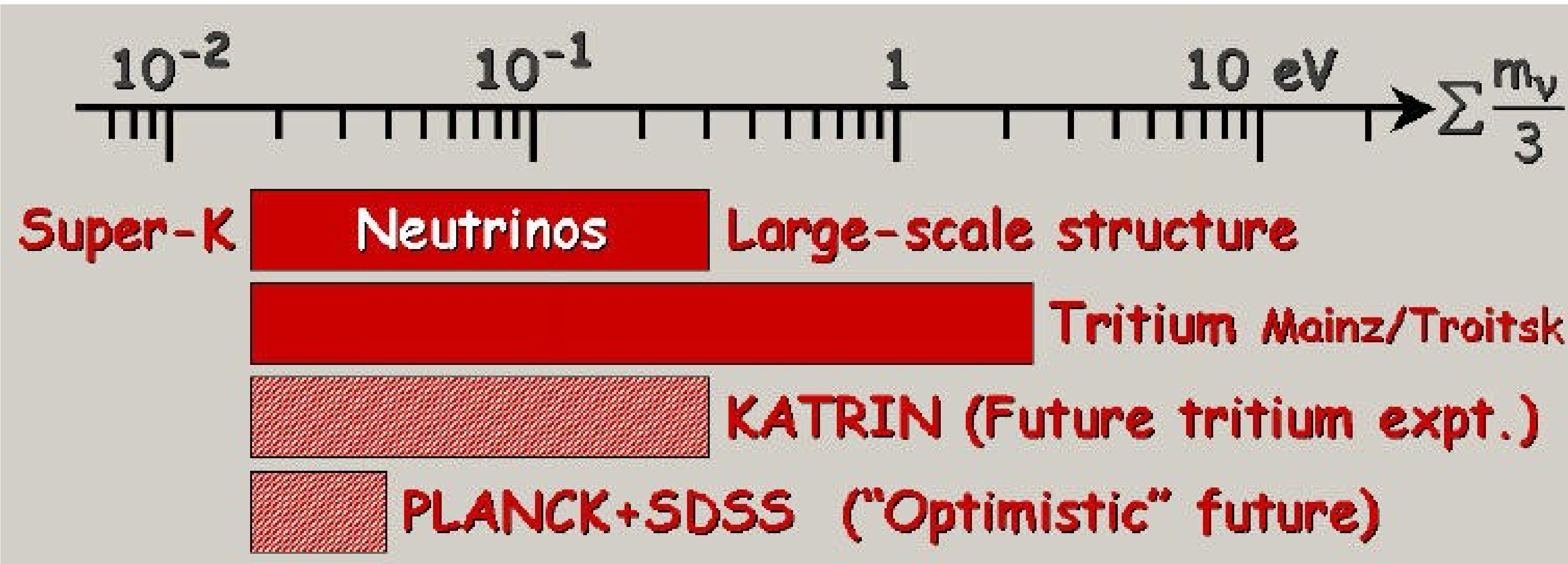
CMB + 2dF + Ly α
CMB + 2dF
CMB + SDSS
$\Delta\chi^2_\Sigma$
Σ (eV)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
1
2
3
4
5
6
7
8
9



0ν2β claim
1
10^{-1}
10^{-2}
10^{-3}
$m_{\beta\beta}$ (eV)
I.H.
N.H.
ν oscillation data +
Σ (CMB+2dF+Ly α)
C.L. = 2σ
10^{-1}
1
Σ (eV)



0ν2β claim
m ββ (eV)
Σ (eV)
I.H.
N.H.
ν oscillation data +
Σ (CMB+2dF+Lyα)
C.L. = 2σ
1
10−1
10−2
10−3
10−1
1



10^{-2}
10^{-1}
1
10 eV
$\sum \frac{m_\nu}{3}$
Super-K
Neutrinos
Large-scale structure
Tritium Mainz/Troitsk
KATRIN (Future tritium expt.)
PLANCK+SDSS ("Optimistic" future)

HOW MANY NEUTRINOS in the UNIVERSE

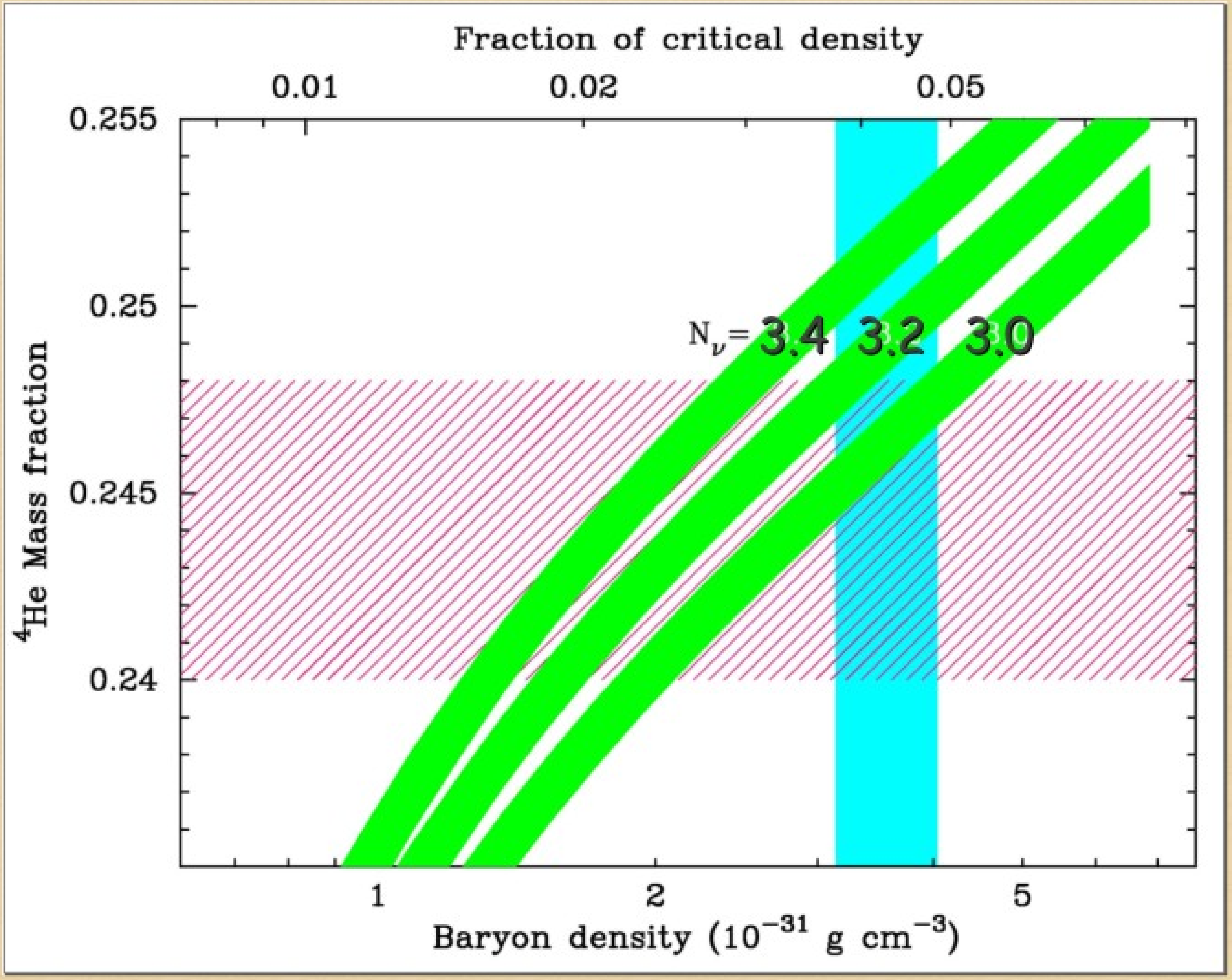
How Many Relic Neutrinos?

Standard thermal population in one flavor $n_{\nu\bar{\nu}} = \frac{3}{11} n_\gamma \approx 112\,\mathrm{cm}^{-3}$

Additional active neutrinos beyond standard population of ν_e, ν_μ, ν_τ	Additional families	Excluded by Z^0 width ($N_\nu = 3$)
	Chemical potentials for ν_e, ν_μ, ν_τ	Possible

Sterile (right-handed) states Populated by $\nu_L \rightarrow \nu_R$ transitions	Dirac mass	Not effective in sub-eV range
	Right-handed currents	Excluded by energy loss of SN 1987A
	Electromagnetic dipole moments	Excluded by energy loss of globular cluster stars
	Oscillations/collisions	Hot/warm/cold DM possible

BBN Limits on Neutrino Flavors



- At BBN one flavor contributes about 16% to cosmic mass-energy density
- Extra flavors modify expansion parameter accordingly

Conservative limit

$|\Delta N_{eff}| < 1$

Burles, Nollett & Turner, astro-ph/9903300

BBN and Neutrino Chemical Potentials

Expansion Rate Effect (all flavors)	Energy density in one neutrino flavor with degeneracy parameter $\xi = \eta/T$ $$\rho_{\nu\overline{\nu}} = \frac{7\pi^2}{120} T_\nu^4 \left[1 + \underbrace{\frac{30}{7}\left(\frac{\xi}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi}{\pi}\right)^4}_{\Delta N_{eff}} \right]$$
Beta equilibrium effect for electron flavor $n + \nu_e \leftrightarrow p + e^-$	Helium abundance essentially fixed by n/p ratio at beta freeze-out $$\frac{n}{p} = e^{-(m_n - m_p)/T - \xi_{\nu_e}}$$ Effect on helium equivalent to $\Delta N_{eff} \sim -18\ \xi_{\nu_e}$

$|\Delta N_{eff}| < 1$ → $|\xi_{\nu_e}| < 0.06$

- ν_e beta effect can compensate expansion-rate effect of $\nu_{\mu,\tau}$
- No significant BBN limit on neutrino number density

Chemical Potentials and Flavor Oscillations

Flavor mixing (neutrino oscillations)

Flavor lepton numbers not conserved

Only one common nu chemical potential

Stringent ξ_{ν_e} limit applies to all flavors $|\xi_{\nu_{e,\mu,\tau}}| < 0.07$

Extra neutrino density $\Delta N_{eff} < 0.0064$

Cosmic neutrino density close to standard value

Flavor equilibrium before n/p freeze out?

yes	Solar LMA solution
maybe	LOW (depends on Θ_{13})
no	SMA or VAC

- Our knowledge of the cosmic nu density depends on the solution of the solar neutrino problem
- KamLAND most relevant experiment

- Lunardini & Smirnov, hep-ph/0012056
- Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287
- Abazajian, Beacom & Bell, astro-ph/0203442
- Wong, hep-ph/0203180

Baryogenesis in the Early Universe

Andrei Sakharov
1921 - 1989

Sakharov conditions for creating the Baryon Asymmetry of the Universe (BAU)

- C and CP violation
- Baryon number violation
- Deviation from thermal equilibrium

Particle-physics standard model

- Violates C and CP
- Violates B and L by EW instanton effects (B – L conserved)

- However, electroweak baryogenesis not quantitatively possible within particle-physics standard model
- Works in SUSY models for small range of parameters

A.Riotto & M.Trodden: Recent progress in baryogenesis
Ann. Rev. Nucl. Part. Sci. 49 (1999) 35

Neutrino Physics

Where do we stand ?

Where are we going ?

Neutrino Oscillations are established

Mixing angles are large !?

If LSND is confirmed more exotic new physics required

Precision Measurements of parameters needed

θ_{13} Ordering of mass eigenstates

Open Problems : Absolute Mass & Dirac versus Majorana

Tritium (Katrin) beta decay. COSMOLOGY

Neutrinos as a Messenger from the Universe

SN neutrinos. Km^3 Telescopes, Dark Matter annihilation