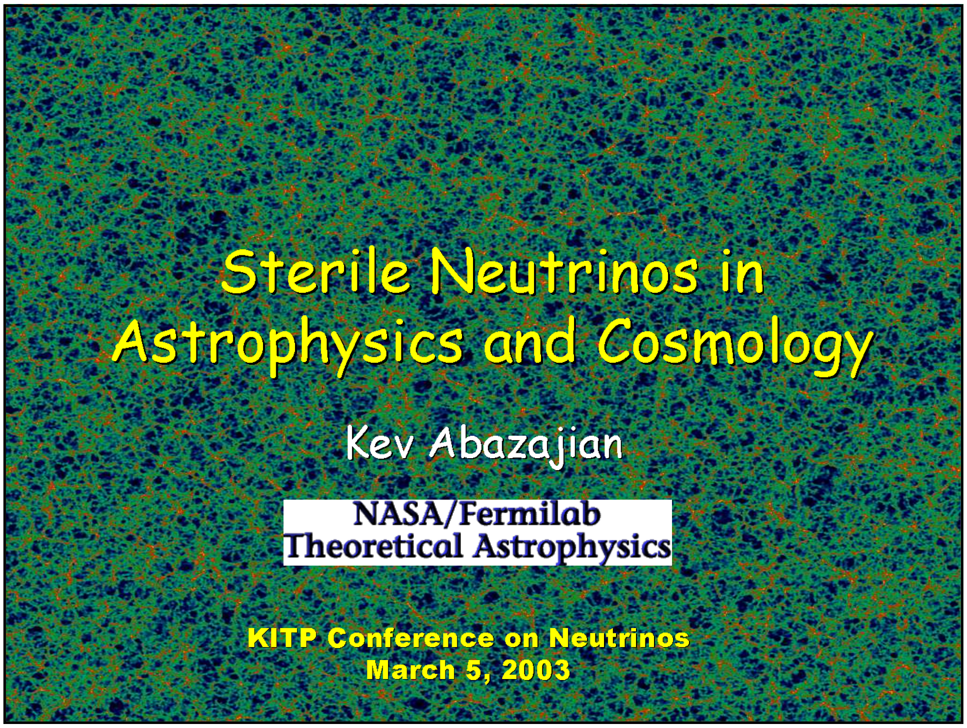
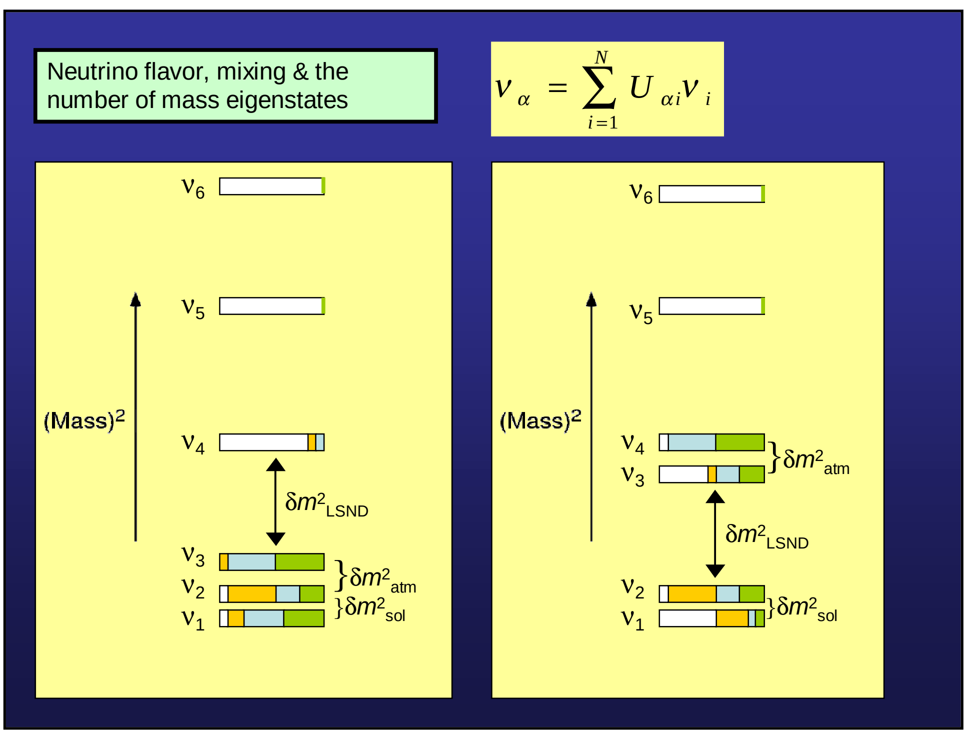
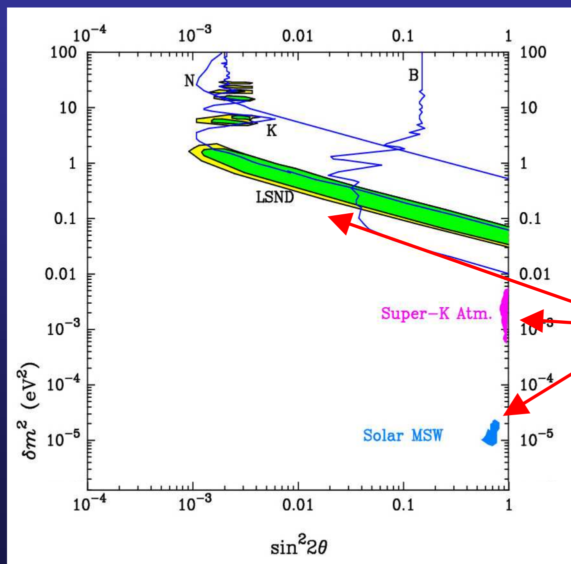

Sterile Neutrinos in
Astrophysics and Cosmology
Kev Abazajian
NASA/Fermilab
Theoretical Astrophysics
KITP Conference on Neutrinos
March 5, 2003


Neutrino flavor, mixing & the number of mass eigenstates
$\nu_\alpha = \sum_{i=1}^{N} U_{\alpha i} \nu_i$
(Mass)^2
ν_6
ν_5
ν_4
δm^2_{LSND}
ν_3
ν_2
ν_1
δm^2_{atm}
δm^2_{sol}
(Mass)^2
ν_6
ν_5
ν_4
ν_3
δm^2_{atm}
δm^2_{LSND}
ν_2
ν_1
δm^2_{sol}

New Physics

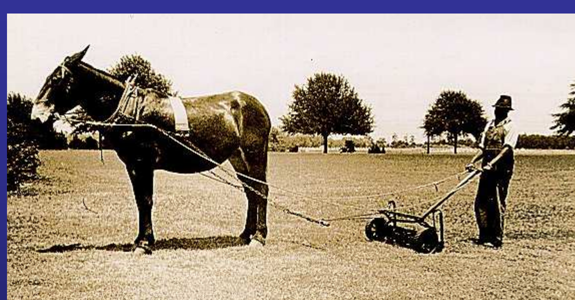


Three different δm² separated by orders of magnitude

➔a new mass eigenstate?

➔Z^0 width requires "sterility"

Sterile Neutrinos?



active/sterile mass term:

$$-L = \frac{1}{2}(\,\nu_L \;\; N_L^c\,)\begin{pmatrix} m_T & m_D \\ m_D^T & m_M \end{pmatrix}\begin{pmatrix} \nu_R^c \\ N_R \end{pmatrix} + h.c.,$$

active neutrino   sterile neutrino

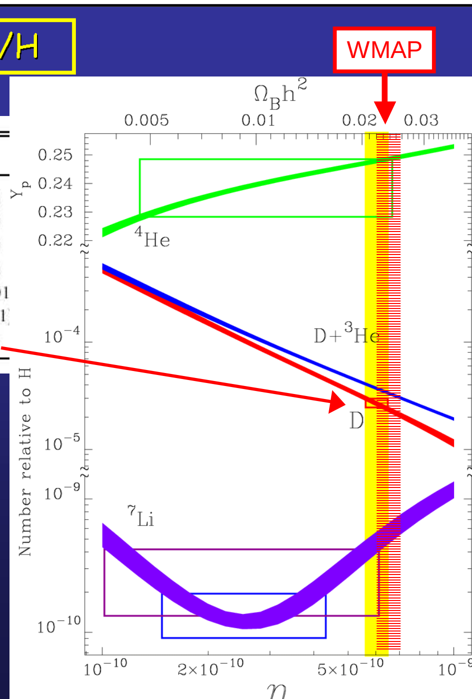
for appreciable mixing, $m_T \sim m_M \sim m_D$

Arise in several GUT extensions to the Standard Model [e.g. SO(10), E_6]

Sterile Neutrinos in the Early Universe & Big Bang Nucleosynthesis

Big Bang Nucleosynthesis & D/H

Quasar	[D]/[H]	Reference
Q0130-403	$< 6.8 \times 10^{-5}$	O'Meara et al. (2001)
Q1009+299	$4.0 \pm 0.65 \times 10^{-5}$	O'Meara et al. (2001)
PKS 1937-1009	$3.25 \pm 0.3 \times 10^{-5}$	O'Meara et al. (2001)
HS0105+1619	$2.5 \pm 0.25 \times 10^{-5}$	O'Meara et al. (2001)
Q2206-199	$1.65 \pm 0.35 \times 10^{-5}$	Pettini & Bowen (2001
Q0347-383	$2.24 \pm 0.67 \times 10^{-5}$	D'Odorico et al. (2001
Q1243+3047	$2.42^{+0.35}_{-0.25} \times 10^{-5}$	Kirkman et al. (2003)



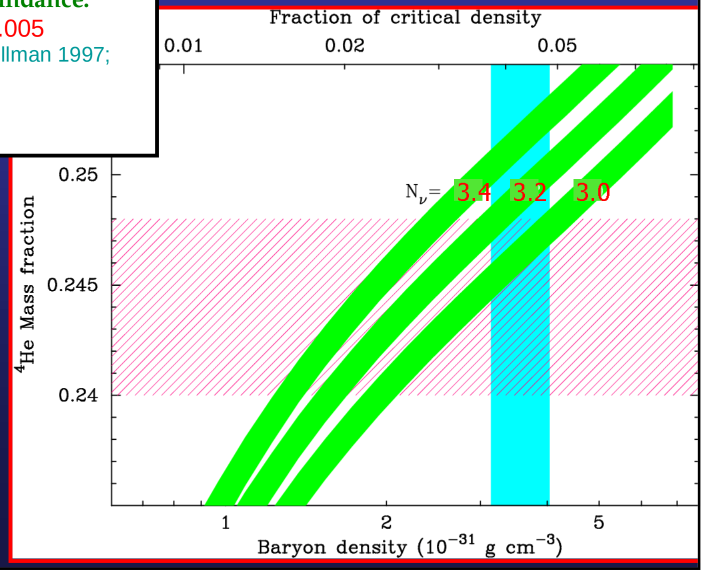
Two Baryometers:
- ▶ D/H and SBBN
- ▶ Acoustic Peaks of the CMB

BBN: From a baryometer to a calorimeter

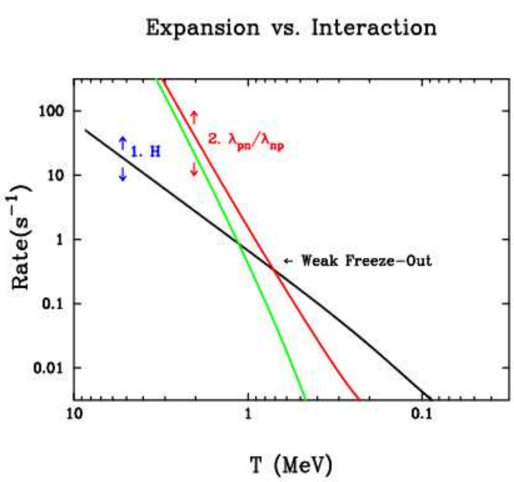
The primordial He abundance:

$Y_p = 0.238 \pm 0.002 \pm 0.005$
(Olive, Steigman & Skillman 1997; Fields & Olive 1998)

$Y_p = 0.244 \pm 0.002$
(Izotov & Thuan 1998)



Primordial nucleosynthesis in two easy steps:



1. **Hubble Expansion:**

$$H \propto \rho^{1/2}$$
$$H \propto (\rho_\gamma + \rho_{e^\pm} + \rho_{\nu_\alpha} + \rho_{\nu_s} + \ldots)^{1/2}$$

2. **Weak Interaction Rates:**

$$\lambda_{n\to p} \begin{cases} n + e^+ \to p + \bar{\nu}_e \\ n + \nu_e \to p + e^- \\ n \to p + e^- + \bar{\nu}_e \end{cases}$$

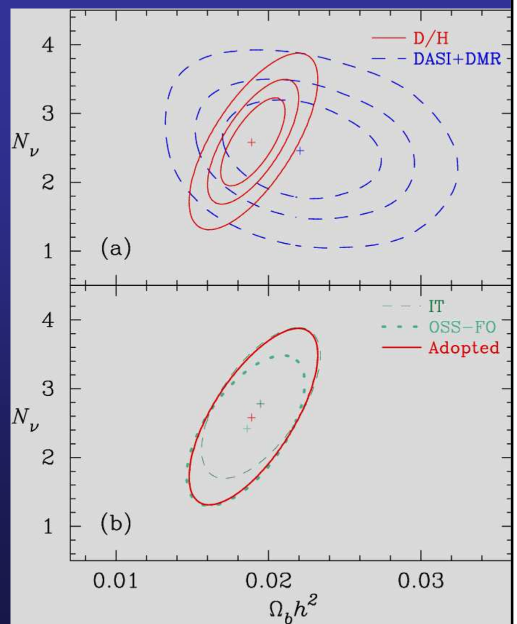
$$\lambda_{p\to n} \begin{cases} p + \bar{\nu}_e \to n + e^+ \\ p + e^- \to n + \nu_e \\ p + e^- + \bar{\nu}_e \to n \end{cases}$$

Assuming Standard Big Bang Nucleosynthesis

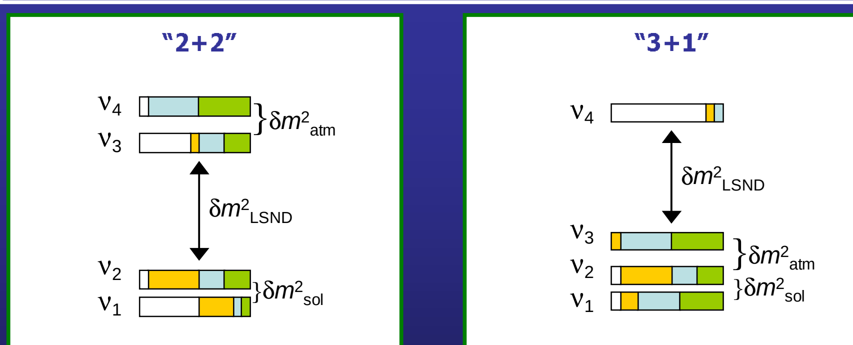
Something more specific than "optimistic" and "pessimistic" limits

And using only:

1. The cosmological baryon density from the deuterium abundance:
   D/H = (3.0 ± 0.4) x 10^{-5}
   $\Omega_b h^2 = 0.020 \pm 0.002$ (95% CL)
   (Burles, Nollet & Turner 2000; Burles & Tytler 1998)
2. The CMB-determined baryon density:
   $\Omega_b h^2 = 0.022(+0.004)(-0.003)$
   (DASI+DMR)
3. The primordial helium abundance:
   Yp = 0.238 ± 0.002 ± 0.005
   (Olive, Steigman & Skillman 1997; Fields & Olive 1998)
   Yp = 0.244 ± 0.002
   (Izotov & Thuan 1998)



4-Neutrino Mass-modelling



$$\nu_\alpha = \sum_i^4 U_{\alpha i}\nu_i \,, \quad \Rightarrow$$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\,\sin^2\left(\delta m^2_{ij}\frac{L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\,\sin\left(\delta m^2_{ij}\frac{L}{2E}\right),$$

Maltoni, Schwetz, & Valle 2001, 2002; Päs, Song & Weiler 2002

Constraining Sterile Neutrino Mixing

- Collisions decohere neutrino gas and populate sterile neutrinos
- Requiring that ν_s are not equilibrated (N_ν<4) – for most conservative case with no resonances $\delta m^2 > 0$

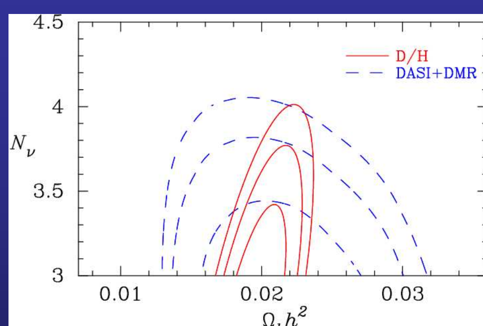
$$\delta m^2_{\alpha s} \sin^4 2\theta_{\rm BBN} \lesssim \begin{cases} 5\times 10^{-6}, & \text{for } \alpha = e \\ 3\times 10^{-6}, & \text{for } \alpha = \mu, \tau \end{cases}$$

The relevant amplitude is simply:

$$A_{\alpha;s} = 4|U_{\alpha 4}|^2 |U_{s4}|^2 \simeq \sin^2 2\theta_{\rm BBN}\,.$$

K. Abazajian, Astropart. Phys. (2003) [astro-ph/0205238]

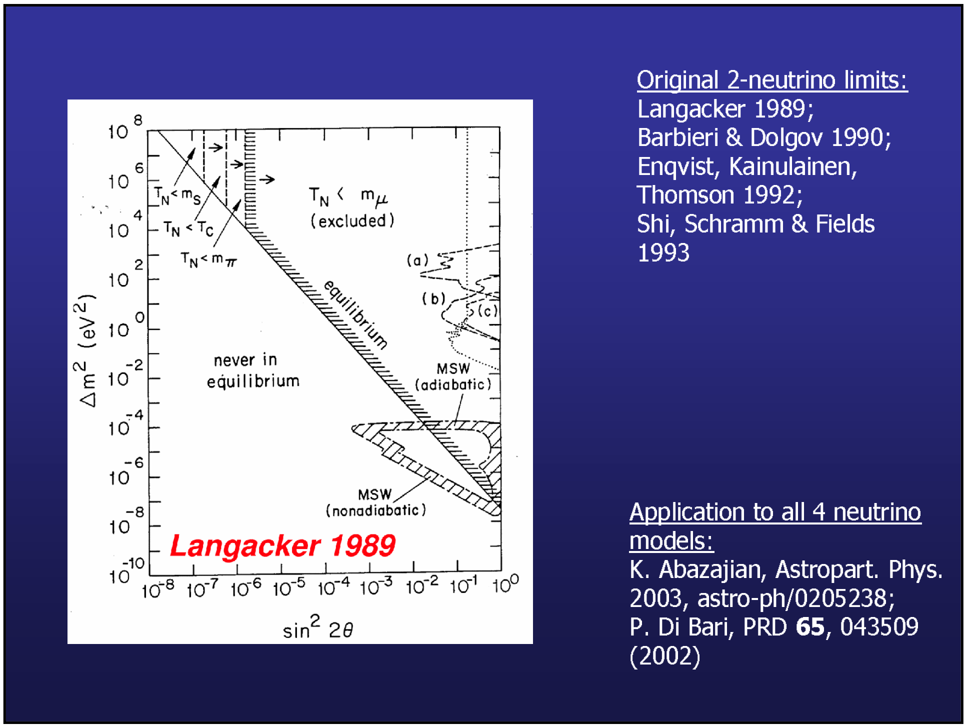
Active Neutrino Thermalization Prior: $N_\nu > 3$

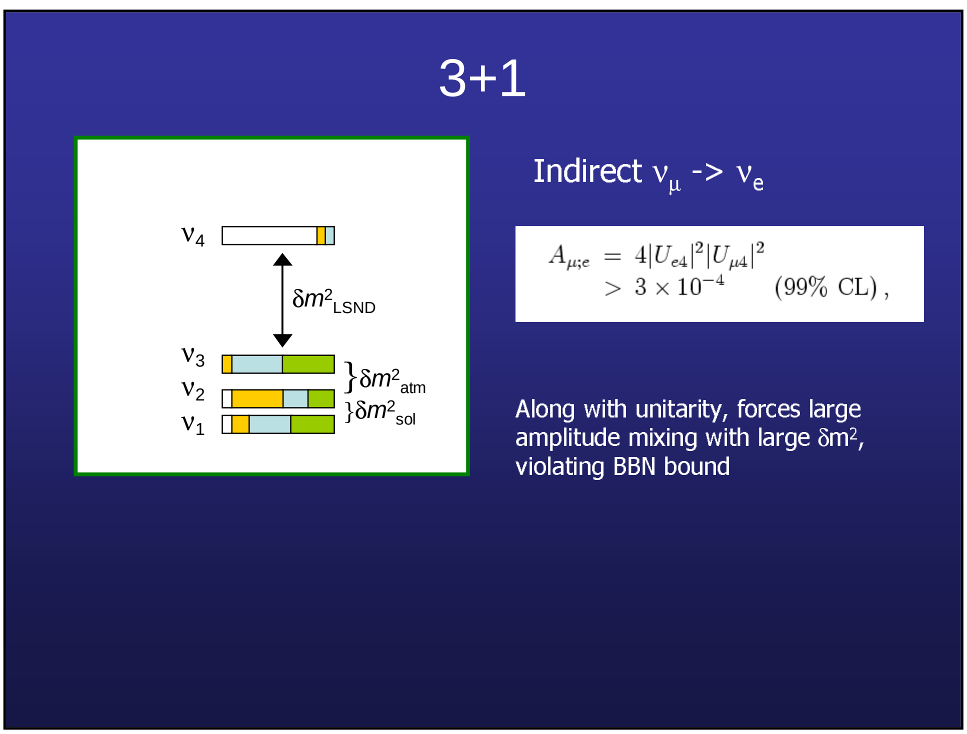


K. Abazajian, Astropart. Phys. (2003) [astro-ph/0205238]

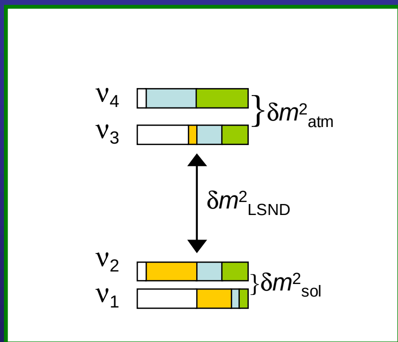
With a precise determination of $\Omega_b h^2$ from MAP satellite:

$$\mathrm{CL}(N_\nu) = \int_3^{N_\nu} p(N'_\nu | Y_p)\, dN'_\nu .$$


Langacker 1989
Δm^2 (eV^2)
$\sin^2 2\theta$
$T_N < m_s$
$T_N < T_c$
$T_N < m_\pi$
$T_N < m_\mu$ (excluded)
equilibrium
never in equilibrium
MSW (adiabatic)
MSW (nonadiabatic)
Original 2-neutrino limits:
Langacker 1989;
Barbieri & Dolgov 1990;
Enqvist, Kainulainen, Thomson 1992;
Shi, Schramm & Fields 1993
Application to all 4 neutrino models:
K. Abazajian, Astropart. Phys. 2003, astro-ph/0205238;
P. Di Bari, PRD 65, 043509 (2002)


3+1
ν_4
δm^2_{LSND}
ν_3
ν_2
ν_1
$\}\delta m^2_{atm}$
$\}\delta m^2_{sol}$
Indirect ν_μ -> ν_e
$A_{\mu;e} = 4|U_{e4}|^2|U_{\mu4}|^2 > 3 \times 10^{-4} \quad (99\% \text{ CL})\,,$
Along with unitarity, forces large amplitude mixing with large δm^2, violating BBN bound

2+2



Both solar (SNO) – neutral current signal of D breakup and capture

and atmospheric (Super-K) – enhanced neutral current component and matter effects

experiments are now effectively appearance experiments, and disfavor large sterile components

Sterile must be split between upper and lower doublet

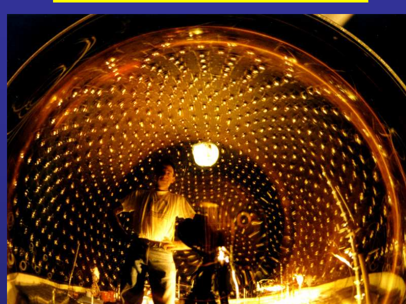
$U_{s1} = U_{s3} = 0$, but by unitarity $|U_{s2}|^2 + |U_{s4}|^2 = 1$,

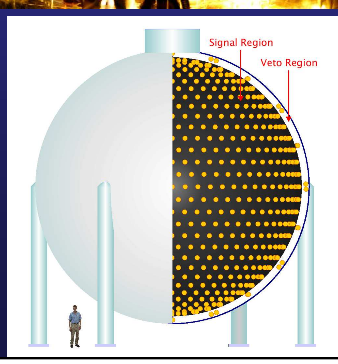
$$|U_{s2}|^2 = |U_{s4}|^2 = 1/2.$$

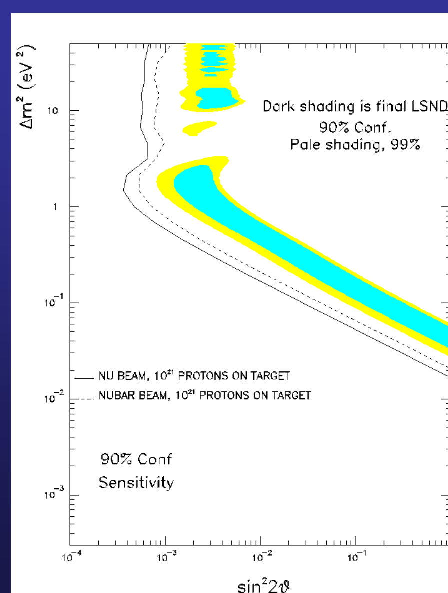
$$A_{\mu;s} = 4|U_{\mu 2}|^2|U_{s2}|^2 \text{ and } A_{e;s} = 4|U_{e4}|^2|U_{s4}|^2$$

$$|U_{e4}|^2 = |U_{e1}|^2 \tan^2\theta_{\rm LMA}$$

The MiniBooNE Experiment

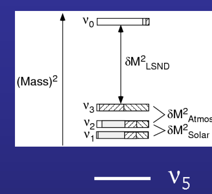






Constraint Evasion & New Physics

1. Pre-existing lepton number ($L \sim 10^7$ B)
2. A fifth mass eigenstate, mostly sterile

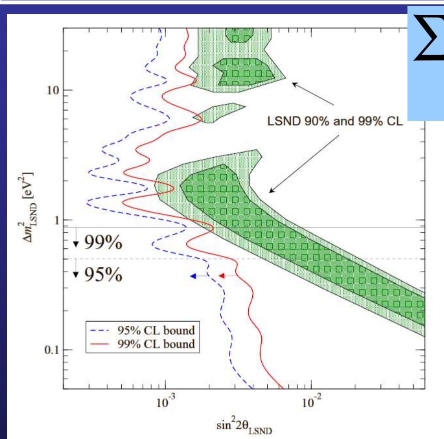


may dynamically generate lepton number (Foot, Thomson & Volkas, 1996) sufficiently early

3. Generation of majoron fields (Berezinsky & Bento 2001)
4. Low reheating temperature (3 active neutrinos are not thermalized)
5. Baryon-Antibaryon inhomogeneities: $N_\nu < 7$ (Giovannini, Kurki-Suonio & Sihvola 2002)
6. Extended quintessence (“dark radiation”) (Chen, Scherrer & Steigman 2001)
7. CPT violating Neutrinos (Murayama & Yanagida 2001; Barenboim, Borrisov, Lykken & Smirnov 2001)

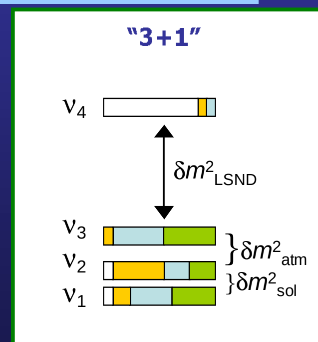
The CMB, Large Scale Structure, limits on Neutrino Mass & Sterile Neutrinos

WMAP+2dFGRS+Ly-α, Neutrino Mass, and 4-Neutrino Models



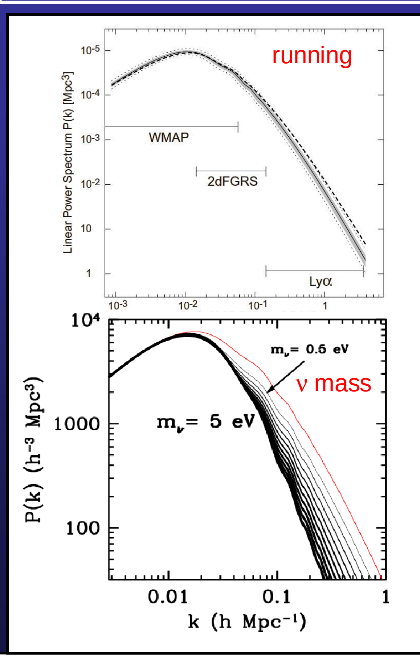
$$\sum m_\nu < 0.69\,\mathrm{eV}\ (95\%\ \mathrm{CL})$$

[Spergel et al WMAP]

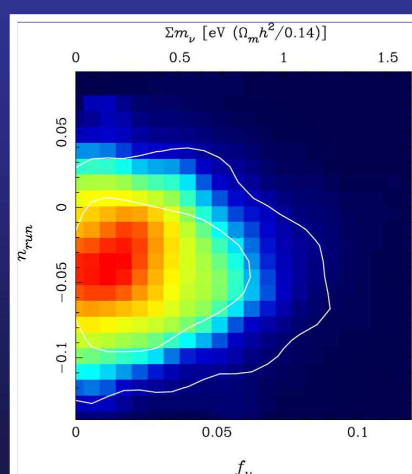


Pierce & Murayama [hep-ph/0302131]; C. Giunti [hep-ph/0302173];
But, see Seljak, McDonald & Makarov [astro-ph/0302571];
Hannestad [astro-ph/0303076]; Abazajian, Dodelson, Gates (in prep)

The perils of conceding primordial scale-invariance



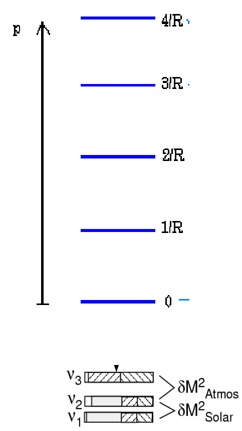
$$\sum m_\nu \leq 1.2\,\mathrm{eV}\ (\mathrm{prelim.})$$



Abazajian, Dodelson, Gates (2003)

Neutrinos from Large Extra Dimensions

Large Extra Dimensions: Neutrino mass & Sterile Neutrinos



Reduced Fundamental scale: (ADD model)

$$M_{\rm Pl}^2 = M_F^{n+2} V_n$$

$$M_F \sim 10 \text{ TeV}$$

No longer a large scale to suppress neutrino masses. Introduce a bulk fermion ν_b that couples to active neutrinos giving Dirac masses:

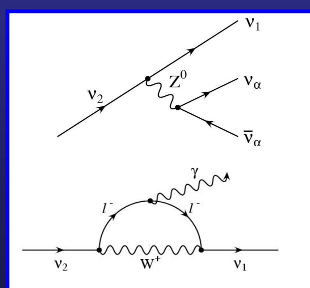
$$m_{\alpha\beta}^D = h_{\alpha\beta}(v M_F/\overline{M}_{\rm Pl}),$$

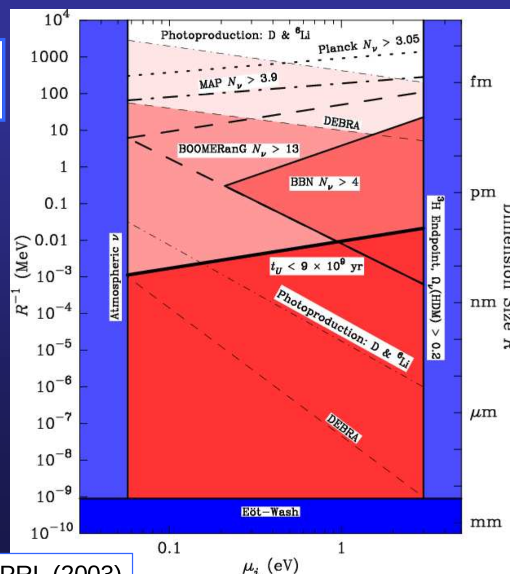
$$M_i = \begin{pmatrix} m_i^D & 0 & 0 & \dots \\ \sqrt{2} m_i^D & 1/R & 0 & \dots \\ \sqrt{2} m_i^D & 0 & 2/R & \dots \\ \dots & \dots & \dots & \dots \end{pmatrix}$$

K.R. Dienes, E. Dudas and T. Gherghetta, Nucl. Phys. **B557**, 25 (1999); N. Arkani-Hamed, S. Dimopoulos, G. Dvali and J. March-Russell, hep-ph/9811448.
R. N. Mohapatra and A. Perez-Lorenzana, Nucl. Phys. **B593**, 451 (2001); H. Davoudiasl, P. Langacker and S. Perelstein, Phys. Rev. **D 65**, 105015 (2002).

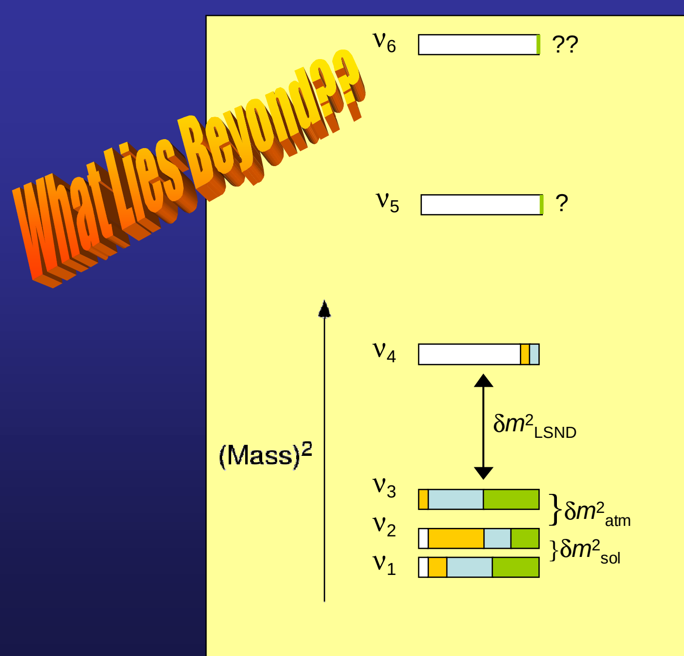
If one sterile is bad is an infinite number infinitely worse?

$$\frac{d}{dt} f_k = \Gamma_{\alpha k} f_\alpha - \frac{m_k}{E}\frac{1}{\tau_k} f_k + \sum_{l>k} \mathrm{C}_{k,l}[f_l],$$



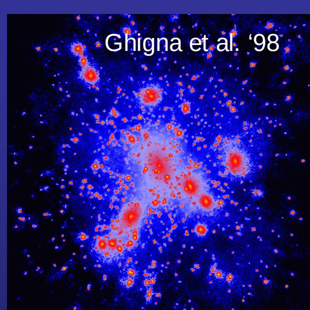


K. Abazajian, G. Fuller & M. Patel, PRL (2003)

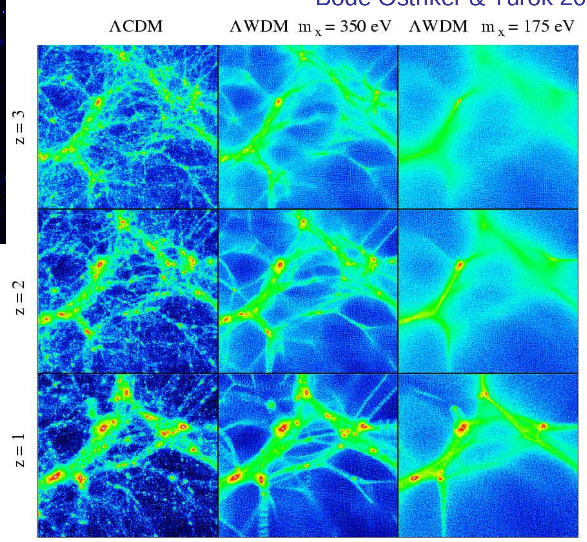


The Dark Matter

Sterile ν Dark Matter?



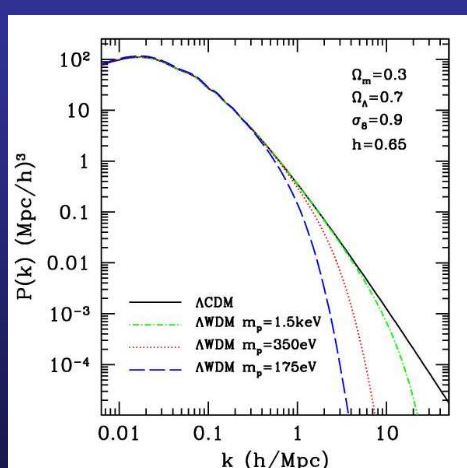
Bode Ostriker & Turok 2001



Is there a dwarf halo problem?

- Suppression of gas infall into dwarf halos after reionization, and tidal disruption of halos (Bullock, Kravtsov & Weinberg 2001)
- Disruption of gas infall due to winds from star formation and supernovae in small potential wells (Binney et al 2001)
- Breaking the power spectrum produced by inflation at the proper scale (Kamionkowski & Liddle 2001)
- Warm dark matter: thermal suppression of small scale power

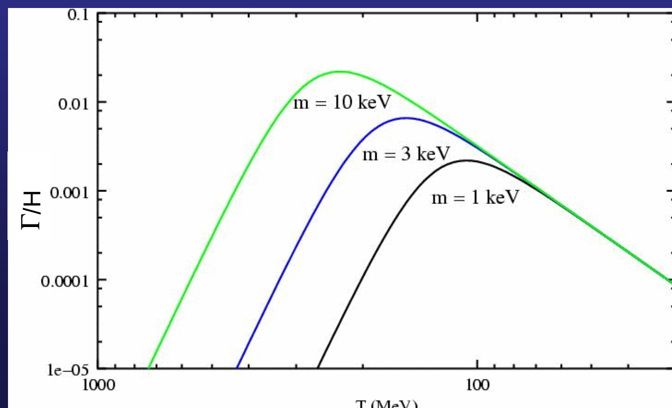
Power Spectrum Suppression with Warm Dark Matter



Sterile Neutrino Dark Matter Production

Boltzmann equation for production:

$$\frac{\partial}{\partial t} f_s(p,t) - H\,p\,\frac{\partial}{\partial p} f_s(p,t) \approx \Gamma(\nu_\alpha \to \nu_s; p, t)\,[f_\alpha(p,t) - f_s(p,t)]\,.$$



QCD Thermodynamics

3.4 Entropy **65**

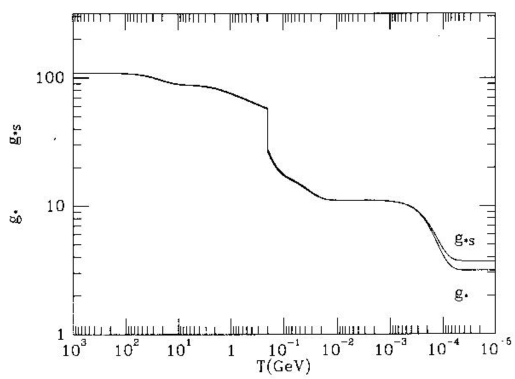
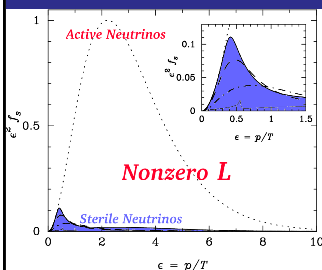


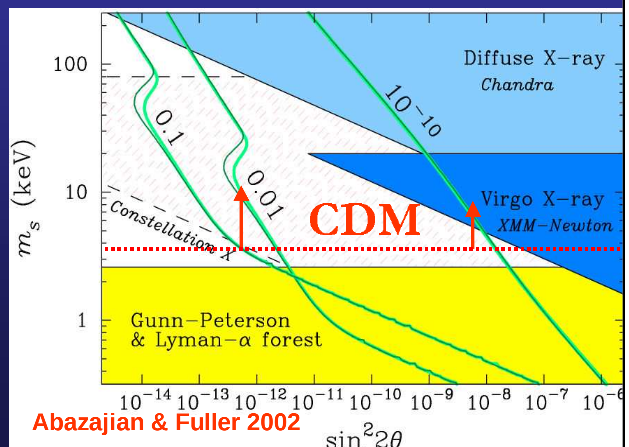
Fig. 3.5: The evolution of $g_*(T)$ as a function of temperature in the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ theory.

Kolb & Turner 1990

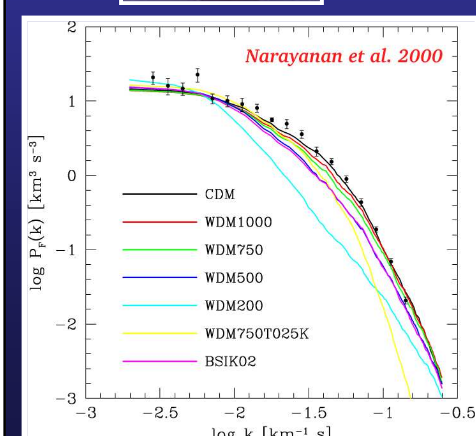
Sterile Neutrino Dark Matter: Production & Prediction



Dodelson & Widrow (1993),
Shi & Fuller (1998),
Abazajian, Fuller & Patel (2001),
Dolgov & Hansen (2001)



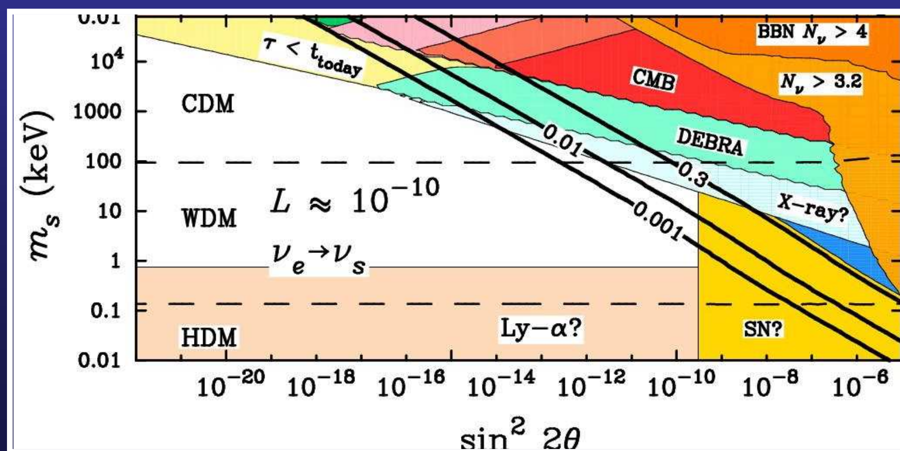
Lower bounds on mass: when is warm too hot?



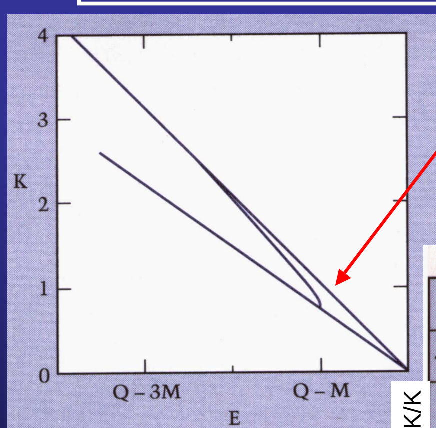
- Suppression of the observed Lyman-α *flux* power spectrum (Narayanan et al 2000)
- Reionization [Barkana, Haiman & Ostriker 2001; Spergel et al (WMAP) 2003]
- m > 0.75 keV for gravitino WDM
- m > 2.6 keV for warmer sterile neutrino WDM
- for m > 1 (3) keV, no difference in the nonlinear power spectrum from CDM

All Constraints:
CMB, Diffuse Photon Background, BBN, Type II Supernovae, Small Scale Structure, X-Ray…

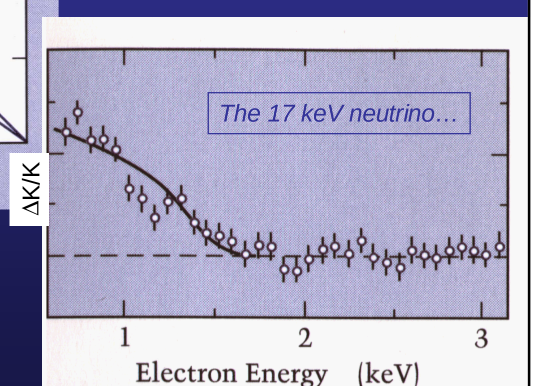
Abazajian, Fuller & Patel 2001

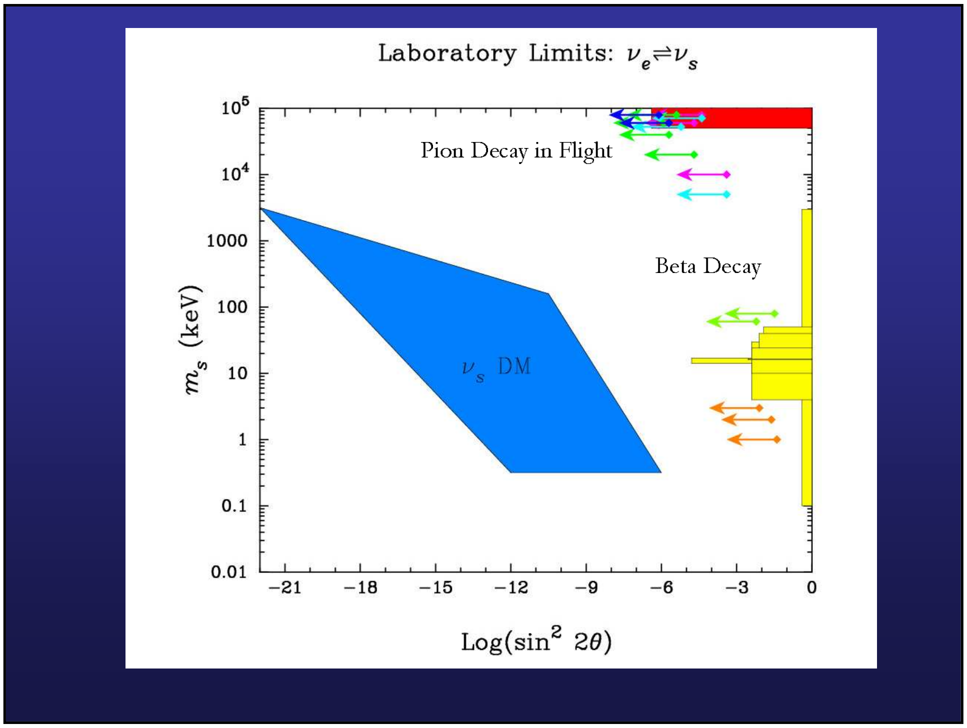


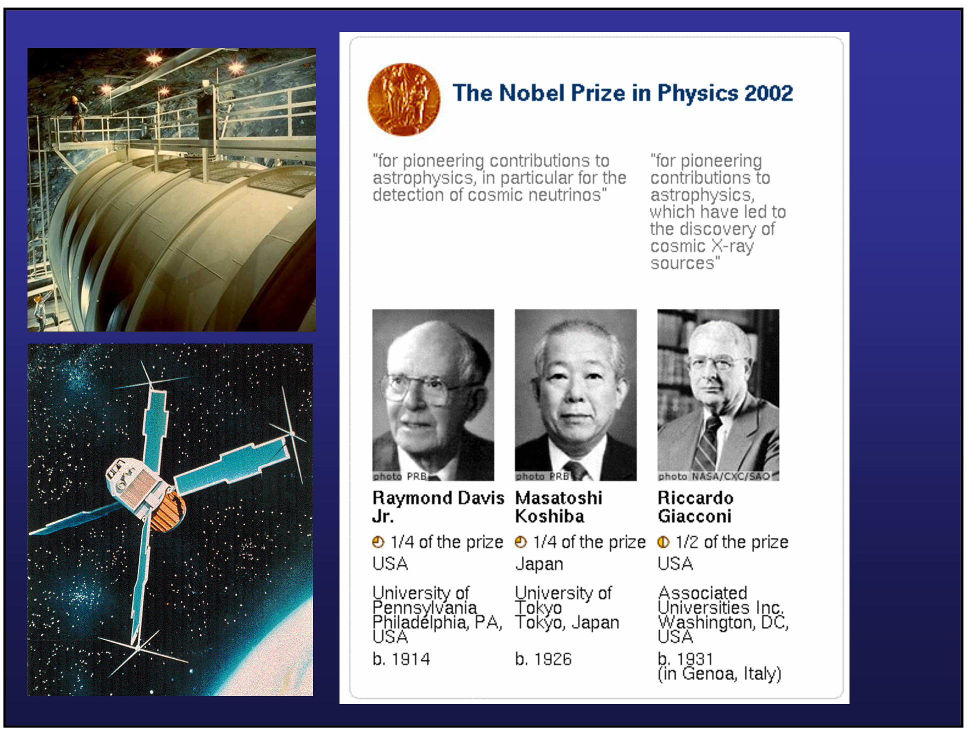
Laboratory Methods for detection of massive sterile neutrinos



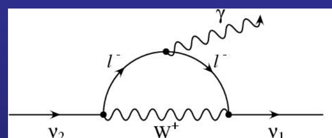
kink-searches in nuclear beta-decay




Laboratory Limits: $\nu_e \rightleftharpoons \nu_s$
Pion Decay in Flight
Beta Decay
ν_s DM
m_s (keV)
10^5
10^4
1000
100
10
1
0.1
0.01
−21
−18
−15
−12
−9
−6
−3
0
Log($\sin^2 2\theta$)


The Nobel Prize in Physics 2002
"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"
"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"
photo PRB
photo PRB
photo NASA/CXC/SAO
Raymond Davis Jr.
1/4 of the prize
USA
University of Pennsylvania Philadelphia, PA, USA
b. 1914
Masatoshi Koshiba
1/4 of the prize
Japan
University of Tokyo Tokyo, Japan
b. 1926
Riccardo Giacconi
1/2 of the prize
USA
Associated Universities Inc. Washington, DC, USA
b. 1931 (in Genoa, Italy)

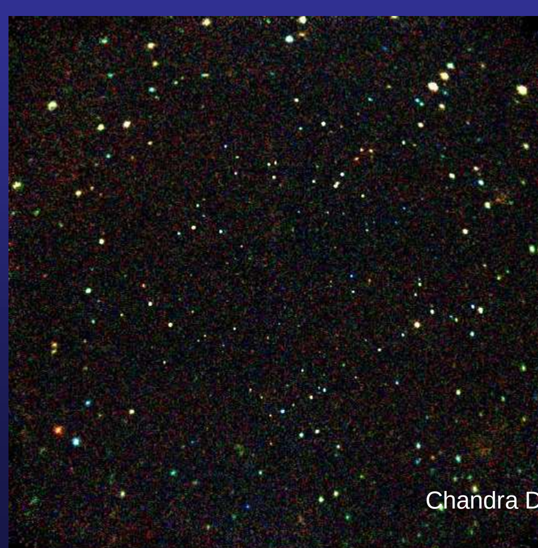
Radiative decay



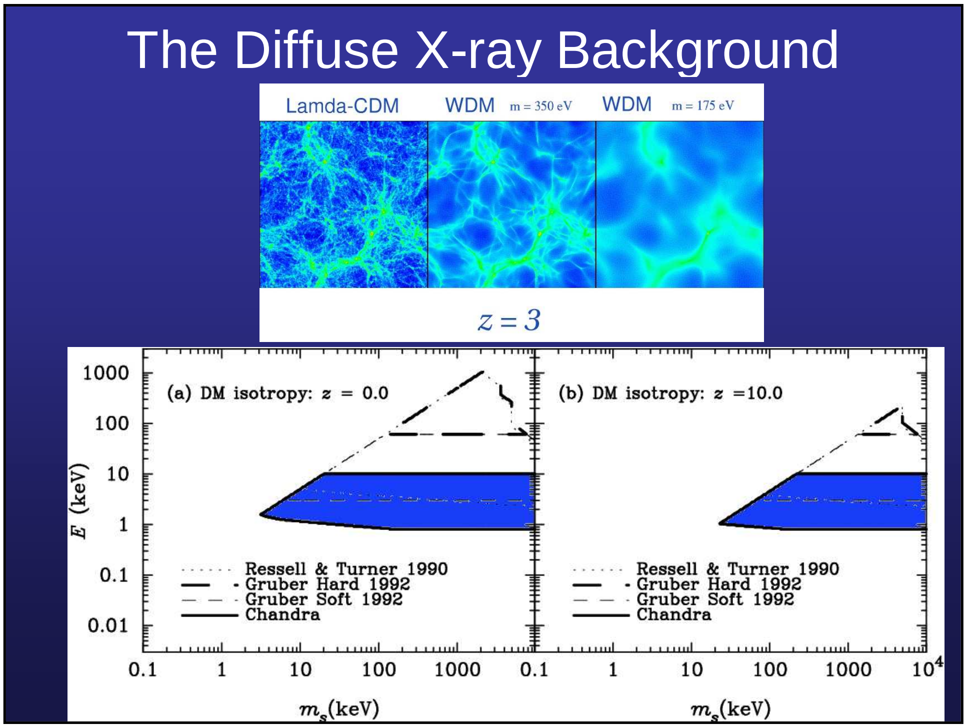
$$\nu_s \rightarrow \nu_\alpha + \gamma$$

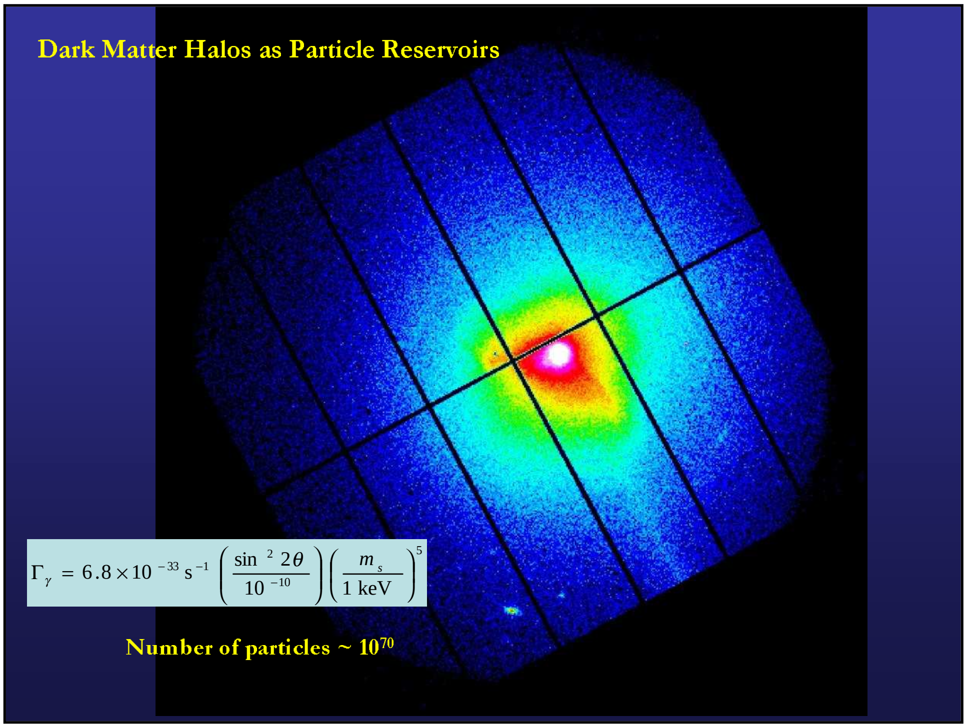
$$\Gamma_\gamma = 6.8 \times 10^{-33}\,\mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

Resolving the Diffuse X-ray Background…



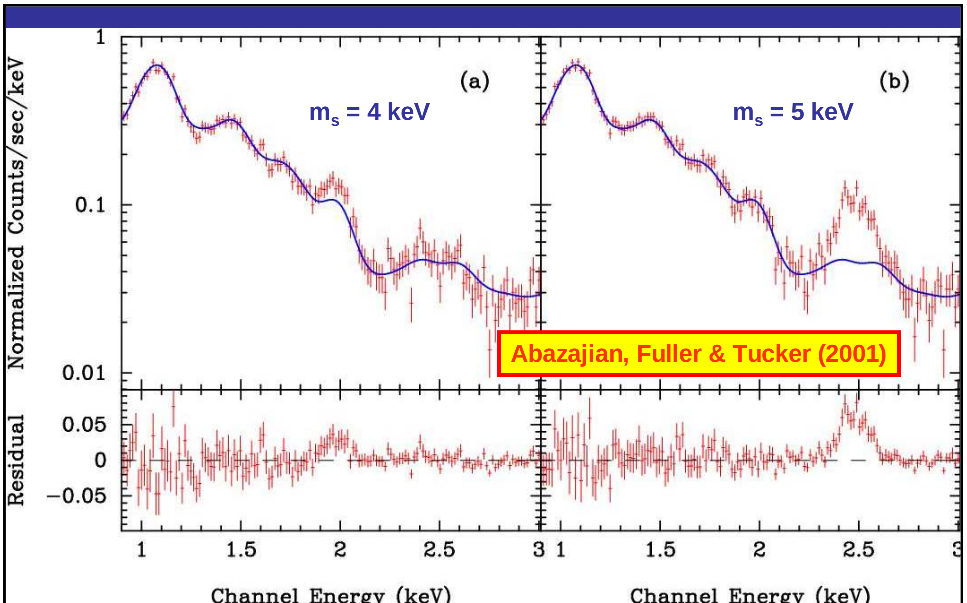
Chandra Deep Field South


The Diffuse X-ray Background
Lamda-CDM
WDM m = 350 eV
WDM m = 175 eV
z = 3
(a) DM isotropy: z = 0.0
(b) DM isotropy: z = 10.0
E (keV)
m_s(keV)
Ressell & Turner 1990
Gruber Hard 1992
Gruber Soft 1992
Chandra

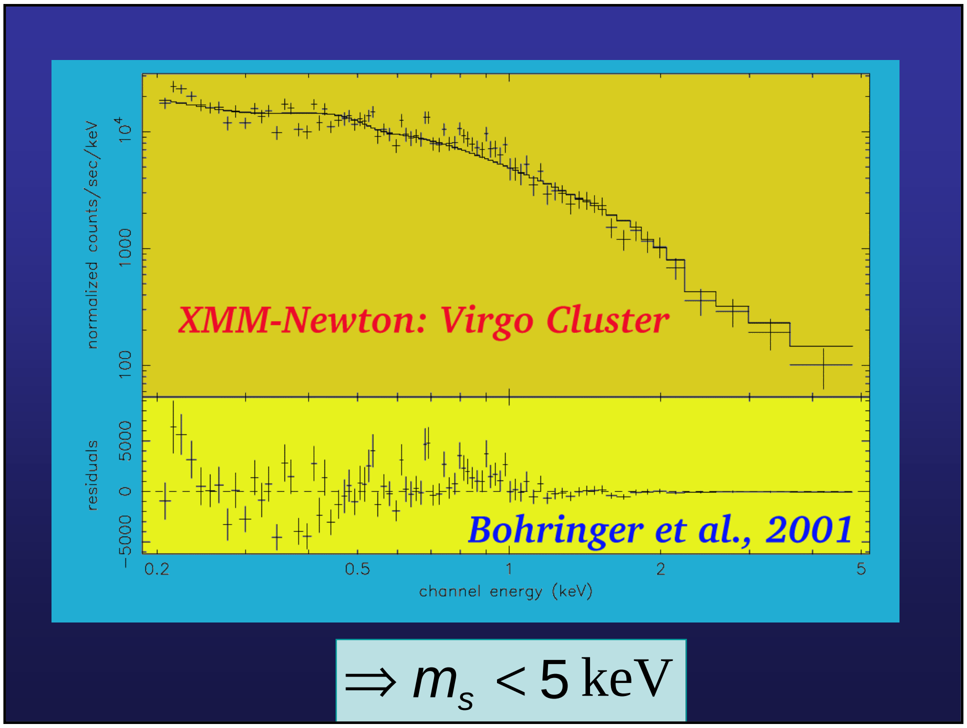

Dark Matter Halos as Particle Reservoirs
$\Gamma_\gamma = 6.8\times10^{-33}\,\mathrm{s}^{-1}\left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$
Number of particles ~ 10^{70}

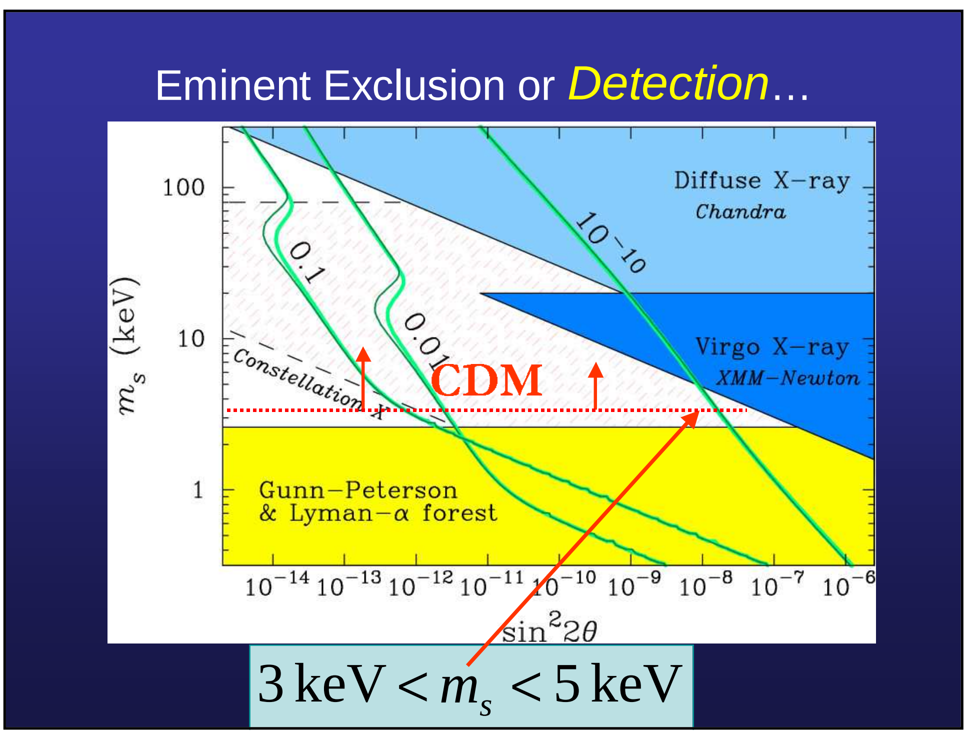
X-ray Telescopes as dark matter particle detectors…

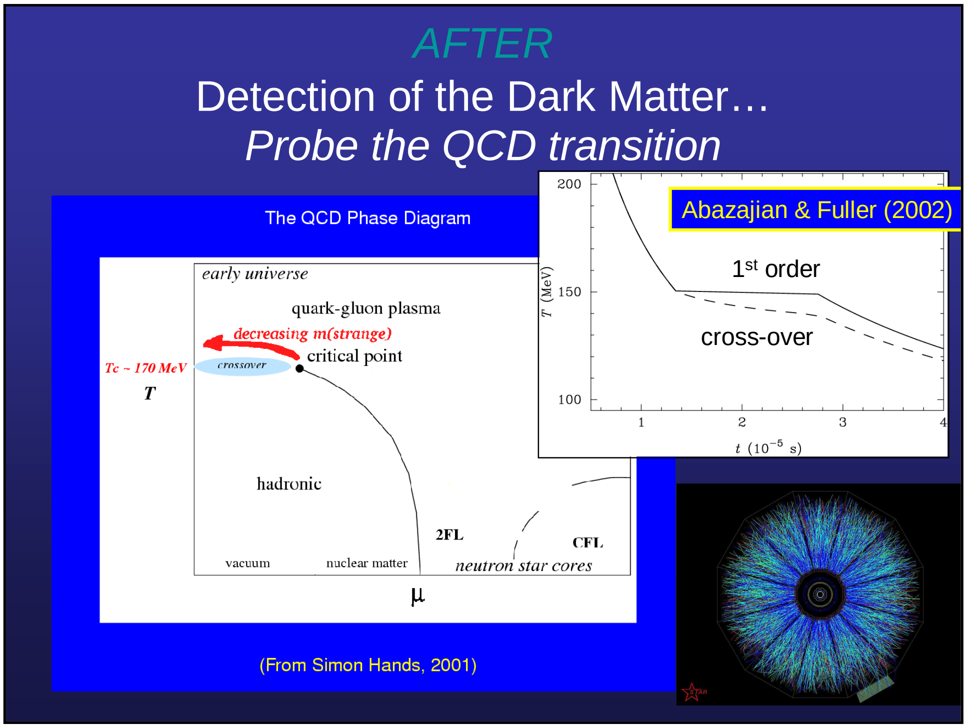
XMM-Newton

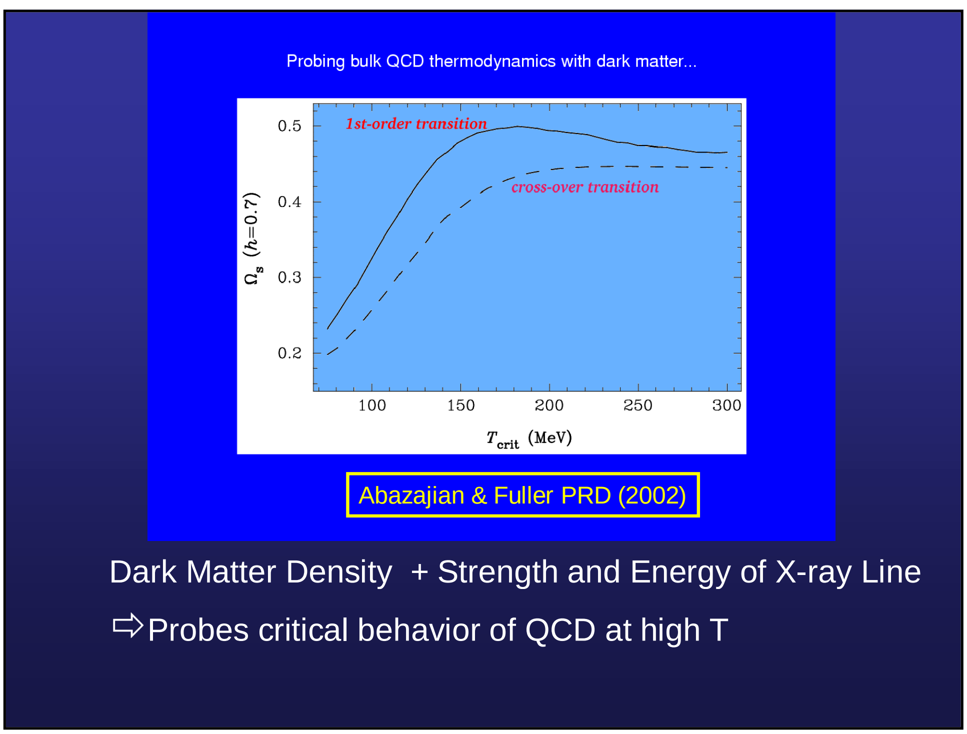


$$\Gamma_\gamma = 6.8\times 10^{-33}\ \mathrm{s}^{-1}\left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

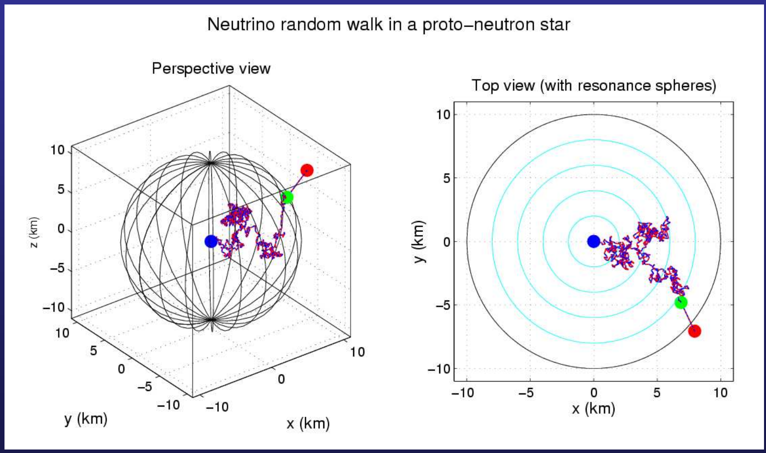

normalized counts/sec/keV
residuals
channel energy (keV)
XMM-Newton: Virgo Cluster
Bohringer et al., 2001
⇒ $m_s < 5\,\mathrm{keV}$


Eminent Exclusion or Detection…
Diffuse X-ray
Chandra
Virgo X-ray
XMM-Newton
CDM
Constellation-X
Gunn-Peterson
& Lyman-α forest
m_s (keV)
$\sin^2 2\theta$
$3\,\mathrm{keV} < m_s < 5\,\mathrm{keV}$


AFTER
Detection of the Dark Matter…
Probe the QCD transition
The QCD Phase Diagram
early universe
quark-gluon plasma
decreasing m(strange)
critical point
crossover
Tc ~ 170 MeV
T
hadronic
2FL
CFL
vacuum
nuclear matter
neutron star cores
μ
(From Simon Hands, 2001)
Abazajian & Fuller (2002)
1st order
cross-over
200
150
100
T (MeV)
1
2
3
4
t (10^-5 s)

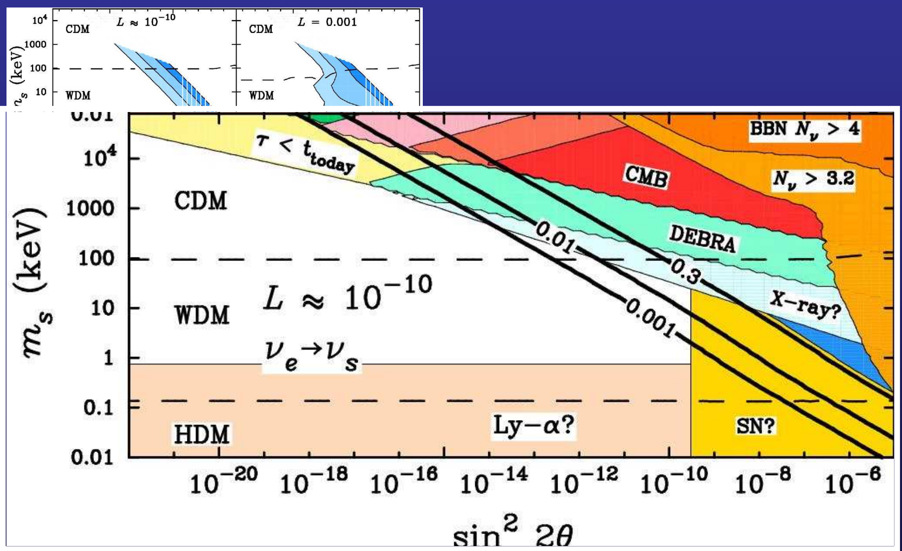

Probing bulk QCD thermodynamics with dark matter...
1st-order transition
cross-over transition
0.5
0.4
0.3
0.2
Ωs (h=0.7)
100
150
200
250
300
Tcrit (MeV)
Abazajian & Fuller PRD (2002)
Dark Matter Density + Strength and Energy of X-ray Line
⇨Probes critical behavior of QCD at high T

Sterile Neutrino Cooling in Stellar Core-Collapse SNe



Raffelt & Sigl (1991); Abazajian, Fuller & Patel (2001)

SNe Constraints on ν_s Dark Matter



Summary…

- Sterile neutrinos arise in several extensions to the SM
- Minimal models of the big bang and nucleosynthesis are in conflict 4 neutrino models accommodating LSND+Solar+Atm results
  - If LSND is verified, it will require new physics in the early universe and in particle physics
- Neutrino cosmology places some of the strongest limits on large extra dimensions containing bulk neutrinos
- CMB+LSS+Ly-α constraints on neutrino mass must be carefully interpreted
- More massive sterile neutrinos are a viable, detectable dark matter candidate
  - Such detections may probe the physics of the early universe beyond the epoch of nucleosynthesis to the QCD transition