Sterile Neutrino Dark Matter after QCD PT

L. Lello, D. Boyanovsky, arXiv:1411.260

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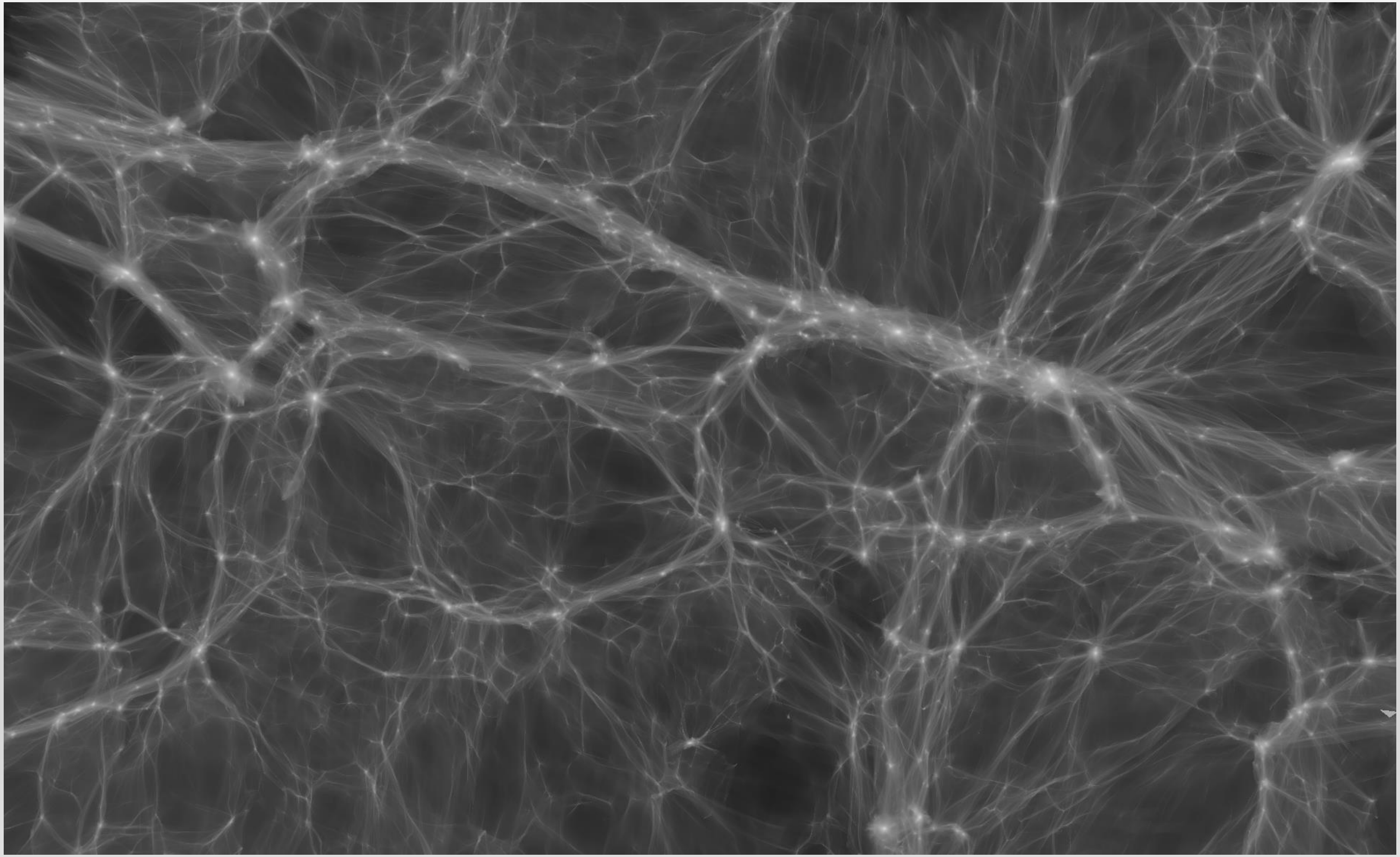
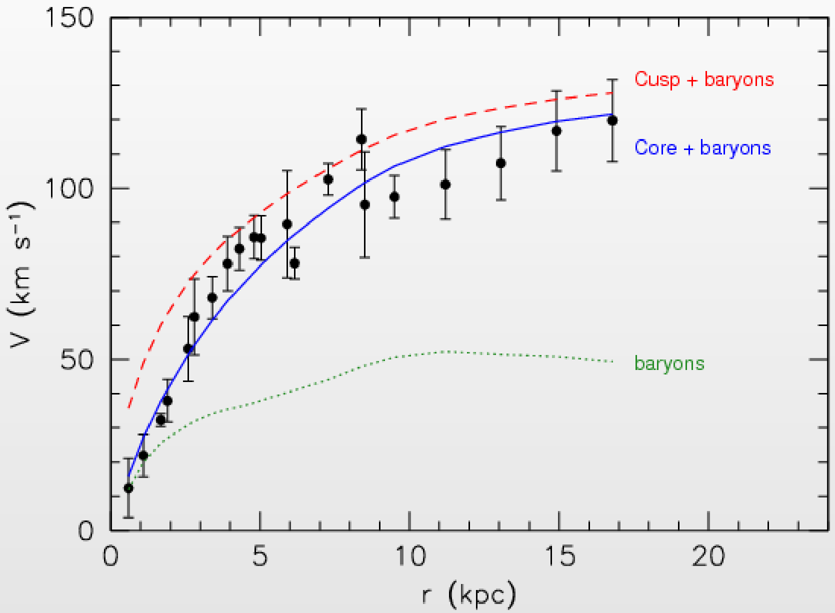


Issues with CDM N-Body Simulations

Cuspy halo problem – N-body CDM simulations predict DM halos fit NFW cusp profile.

$$\rho_{\rm NFW}(r) = \frac{\rho_i}{(r/R_s)(1+r/R_s)^2}$$

Observations of galaxies suggest a core dark matter profile fits better.

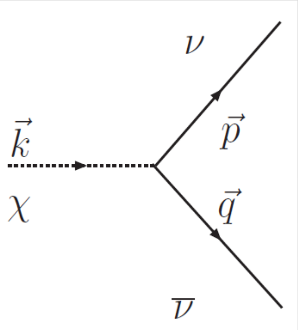


F-568-3: David H. Weinberg, James S. Bullock, Fabio Governato, Rachel Kuzio de Naray, Annika H. G. Peter, arXiv:1306.0913

Missing satellites problem – N-body predict many more dwarf satellites around galaxies.

$$N_{obs} = 11 \quad ; \quad N_{CDM} \sim 500$$

Possible resolution to small scale problem - WDM

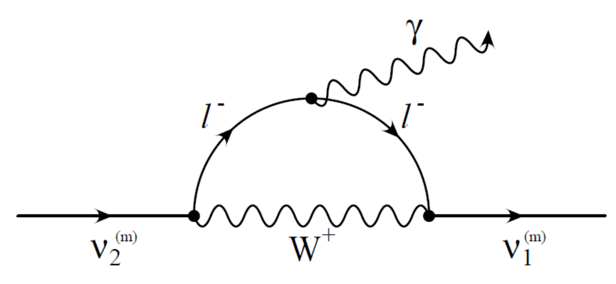


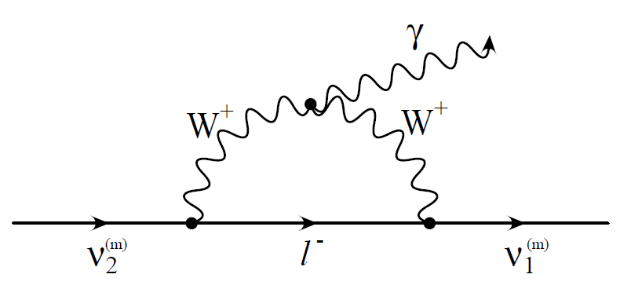
Sterile Neutrinos out of equilibrium: Dodelson-Widrow, Shi-Fuller, Scalar decays

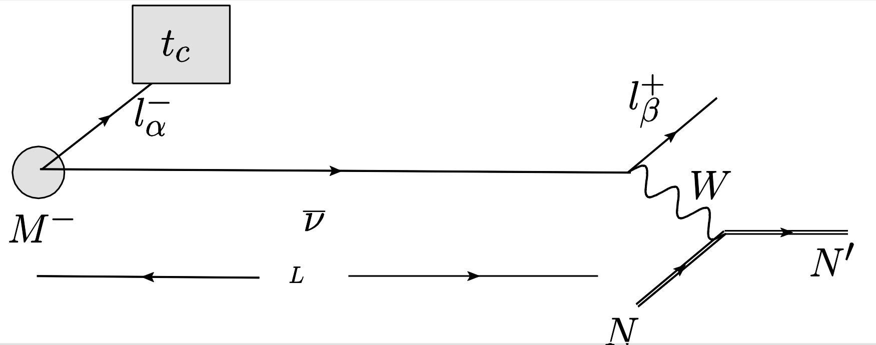
$$|\nu_1^{(m)}\rangle = \cos\theta_m\,|\nu_e\rangle - \sin\theta_m\,|N_1\rangle$$
$$|\nu_2^{(m)}\rangle = \sin\theta_m\,|\nu_e\rangle + \cos\theta_m\,|N_1\rangle$$

Signals of Sterile Neutrinos?

Recent observations of X-ray spectra (3.5 keV) potential evidence for sterile.







Oscillation experiments suggests ~eV sterile. Produced through pion decays.

GOAL: Explore sterile neutrino production in the early universe resulting from pion decay. Inspired by terrestrial experiments.

PLAN:

- Obtain distribution function – steriles not in LTE.
- Need finite temperature corrections for the calculation, no pions not until QCD PT (T~150MeV).
- Use distribution to calculate contributions to observations in cosmo.
- Free streaming, dark matter density, dark radiation, phase space density.
- Place limits from observations in cosmo.

How to address: quantum kinetics– Boltzmann EQ

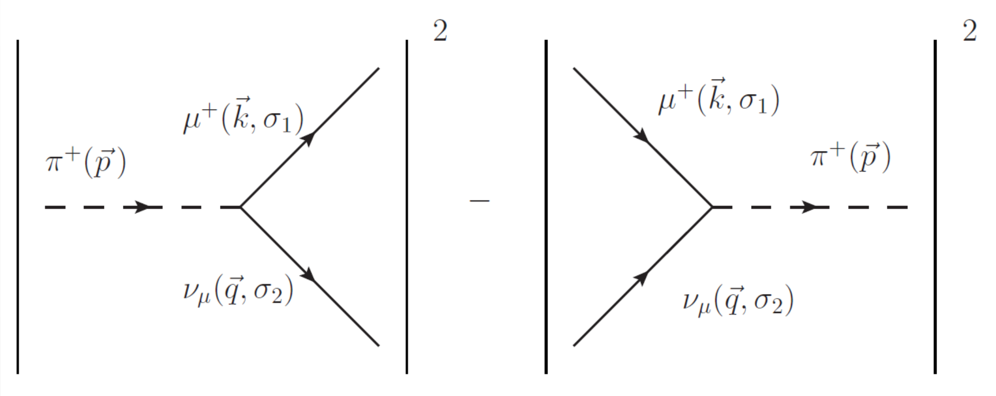
Obtain sterile neutrino distribution as function of momentum.

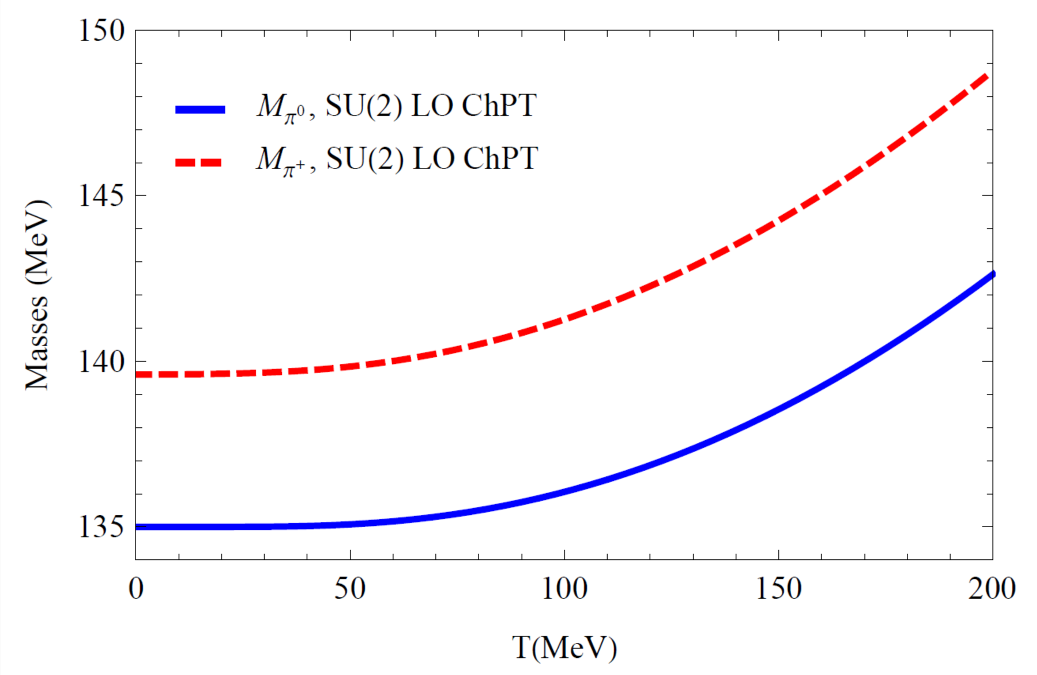
$$\frac{dn}{dt}(q,t) = \delta n_{Gain} - \delta n_{Loss}$$

Ingredients of Calculation - Finite T corrections to pion decay constant and pion mass.

$$f_\pi^2(t) = f_\pi^2(0)\left(1 - \frac{T(t)^2}{6 f_\pi(0)^2}\right)$$

Mass corrections are relatively small, approx. constant.





R. Torres Andrews, A. Gomez Nicola, arXiv:1303.6328

Full quantum kinetic equation depends on distributions of all particles.

$$\frac{dn}{dt} = \frac{|U_{ls}|^2|V_{ud}|^2G_F^2f_\pi^2}{8\pi}\frac{m_\pi^2(m_l^2+m_\nu^2)-(m_l^2-m_\nu^2)^2}{qE_\nu(q)}$$
$$* \int_{p_-}^{p_+}\frac{dp\,p}{\sqrt{p^2+m_\pi^2}}\left[N_\pi(p)(1-n_{\bar{l}}(\vec{p}-\vec{q}))(1-n_\nu(q))-(1+N_\pi(p))n_{\bar{l}}(\vec{p}-\vec{q})n_\nu(q)\right]$$

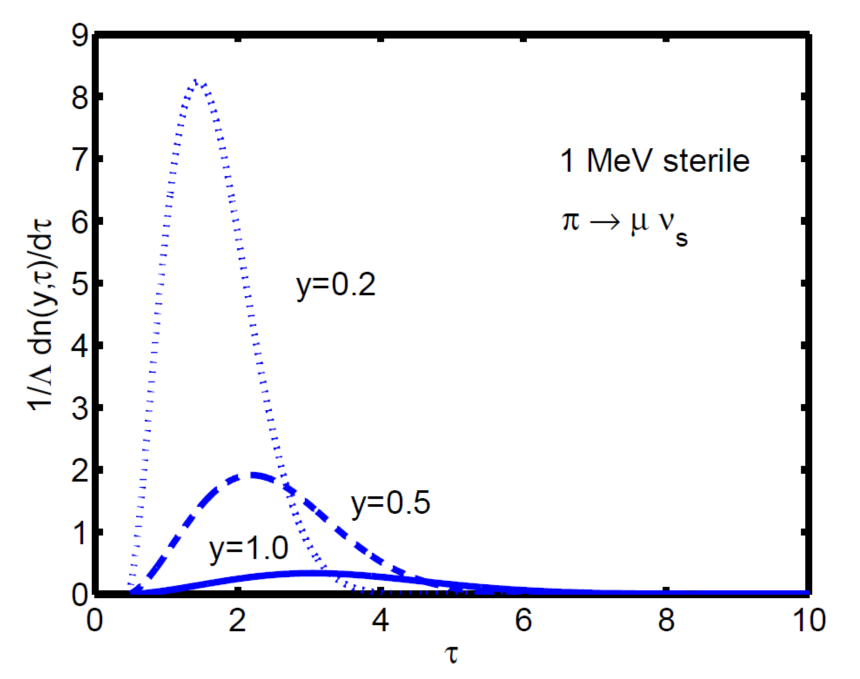
Considering build up of steriles (zero initial population). Population remains perturbatively small and neglect sterile population entirely.

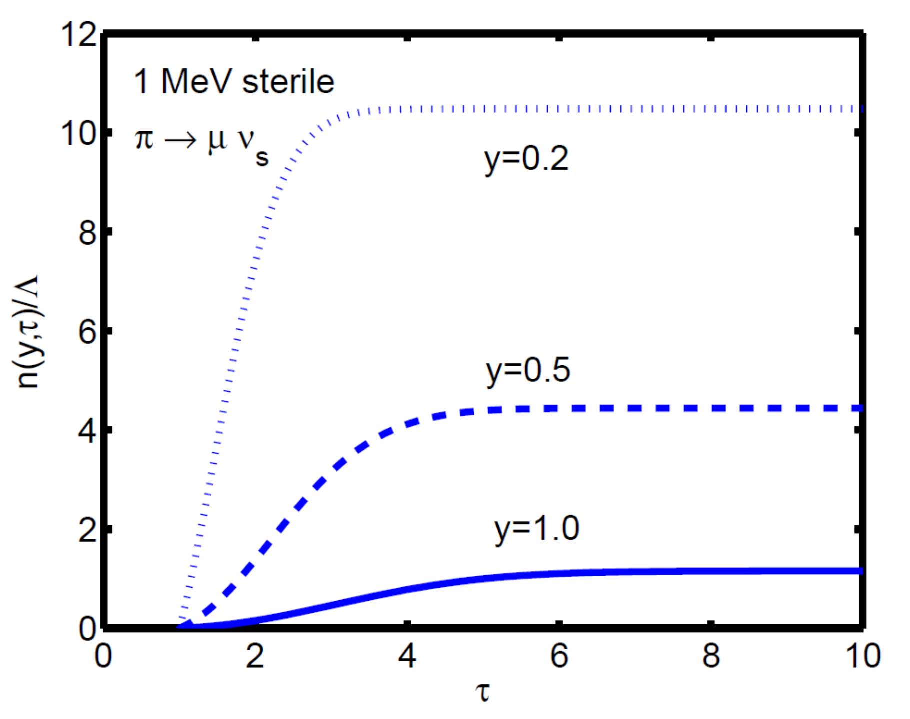
Pion thermal suppression drops rate as universe expands. Leads to large suppression when m/T >> 1 (T ~10MeV).

$$T(t) = \frac{T_0}{a(t)} \qquad n_\pi = \frac{1}{e^{E_\pi/T(t)}-1} \qquad T \ll m_\pi \to n_\pi \sim 0$$

Rate peaks early, falls off before 10 MeV as expected. Proxies for momentum and temp – y and τ.

Enhancement for small momentum.

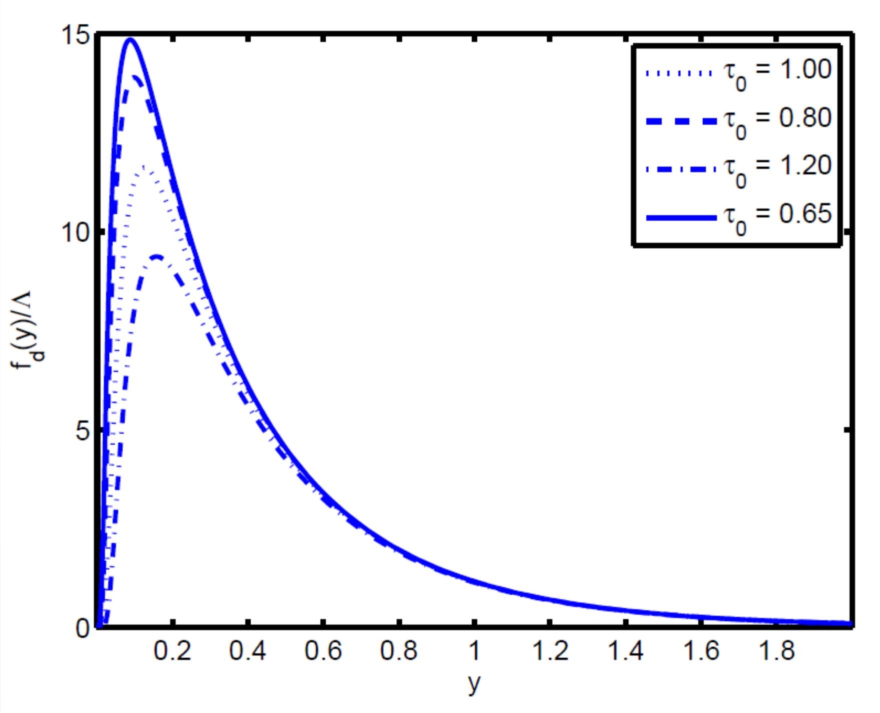




Exact distribution can be obtained numerically.

Freezeout occurs at temperatures hotter than 10 MeV for all momentum.

Region of temperatures where steriles are produced is small. What is the distribution?



Distribution shown as function of momentum.

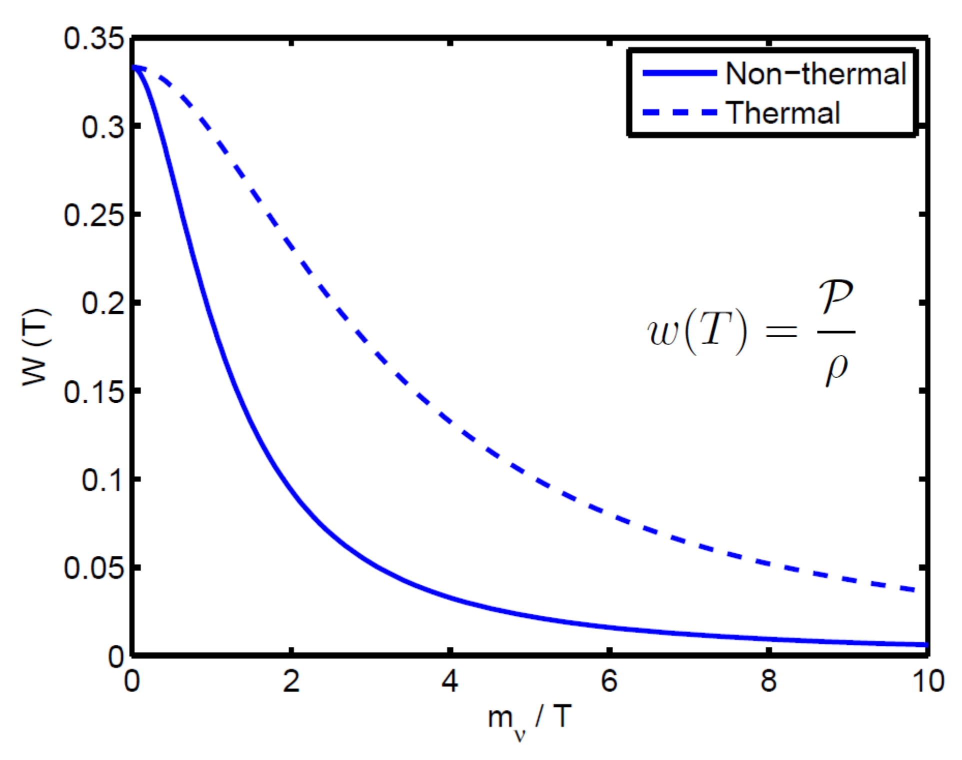
Frozen distribution has sharp peak at low momentum. Produces a colder dark matter.

Similar enhancement to Shi-Fuller but non lepton asymmetry.

Highly non-thermal character seen by equation of state.

Becomes nonrelativistic much sooner than thermal.

For a thermally distributed particle of the same mass, this distribution produces a COLDER species.



$$k_{fs}^2 = \frac{4\pi G\rho}{\overline{\vec{V}^2}}$$

$$\lambda_{fs}^e(0) = 16.7\text{kpc}\left(\frac{\text{keV}}{m_\nu}\right)$$

$$\lambda_{fs}^\mu(0) = 7.6\text{kpc}\left(\frac{\text{keV}}{m_\nu}\right)$$

Free streaming can be calculated with distribution function.

Depends on mass of sterile and production channel.

Consistent with observations of DSph and interpretation of core profile (~few kpc).

Contributions to relativistic degrees of freedom only valid for steriles lighter than ~1 eV (must be relativistic at MRE).

Different for different channels. Places bounds on mixing matrix using Planck result.

$$|U_{\mu s}|^2 < 3.8 * 10^{-4}$$

$$\rho_{rel} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right)$$

$$\Delta N_{eff}\Big|_{\pi\to\mu\nu} = 0.0040 * \frac{|U_{\mu s}|^2}{10^{-5}}$$

$$\Delta N_{eff}\Big|_{\pi\to e\nu} = 9.7 * 10^{-7}\frac{|U_{es}|^2}{10^{-5}}$$

$$m_\nu \left(\frac{|U_{\mu s}|^2}{10^{-5}} \right)^{1/4} \geq 0.38\text{keV}$$

$$m_\nu \left(\frac{|U_{es}|^2}{10^{-5}} \right)^{1/4} \geq 6.77\text{keV}$$

Lower bounds on combinations of mass and mixing from dark matter abundance.

Values taken from Planck – lower bound if all DM is this type of sterile.

Upper bounds on combinations of mass and mixing from dwarf spheroidals. Phase space is nearly constant during collapse.

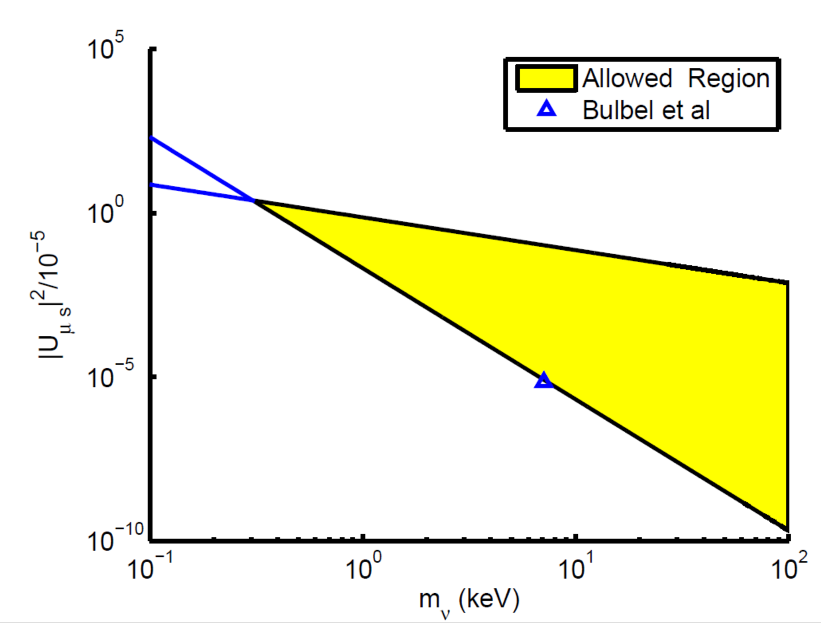
Values taken from older data set. Bounds are "soft" – depend on which galaxy you use.

Combined bounds set allowed region. Top set by Planck, bottom by DSph.

Muon decay channel consistent with 3.5 keV line (electron is not).

$$\mathcal{D}_p \geq \frac{1}{3^{3/2} m_{\nu_s}^4} \left.\frac{\rho}{\sigma^3}\right|_{today}$$

$$m_{\nu_s} \frac{|U_{\mu s}|^2}{10^{-5}} \leq 0.739keV \qquad m_{\nu_s} \frac{|U_{es}|^2}{10^{-5}} \leq 7242keV$$



Summary

Finite temperature corrections used to get non-thermal distribution of sterile neutrinos from pion decay.

Observations of CMB DM abundance and DSph's lead to bounds on masses and mixing.

Contributions to Neff leads to bound on muon/sterile mixing (for light 1eV sterile).

$$\lambda^{e}_{fs}(0) = 16.7\mathrm{kpc}\left(\frac{\mathrm{keV}}{m_\nu}\right)$$

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Thanks for listening!!