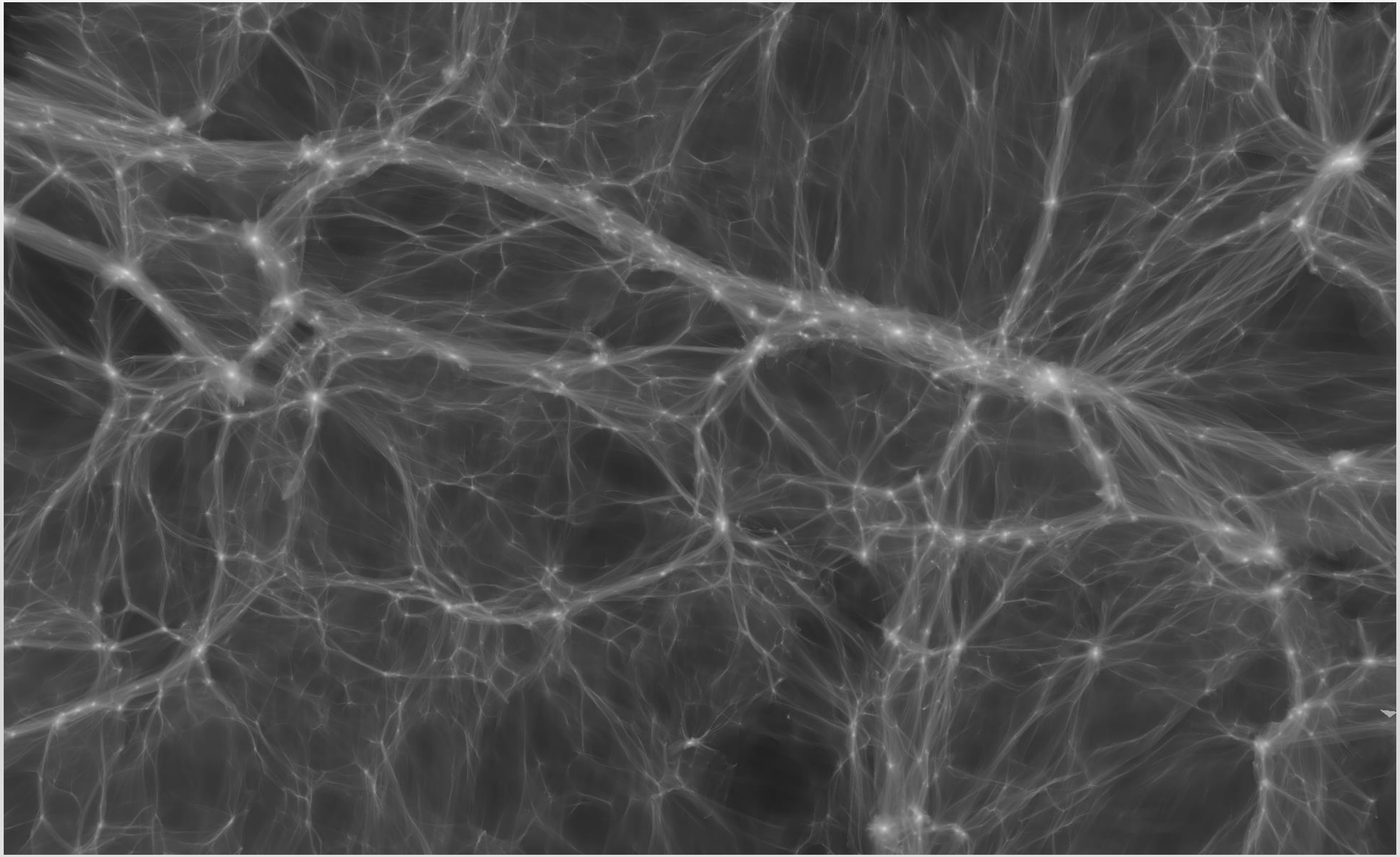
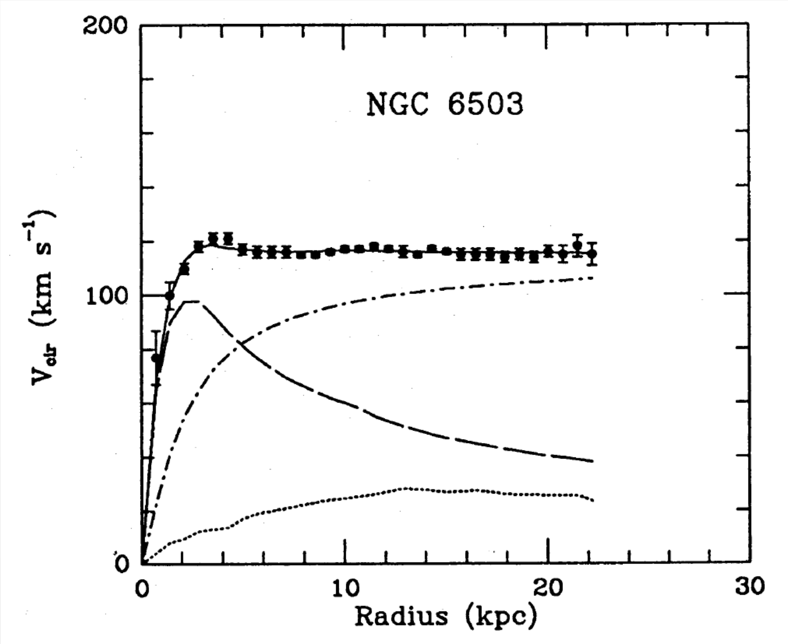
Sterile Neutrino Dark Matter after QCD PT

L. Lello, D. Boyanovsky, arXiv:1411.260,1508.04077

PRD 91 (2015)



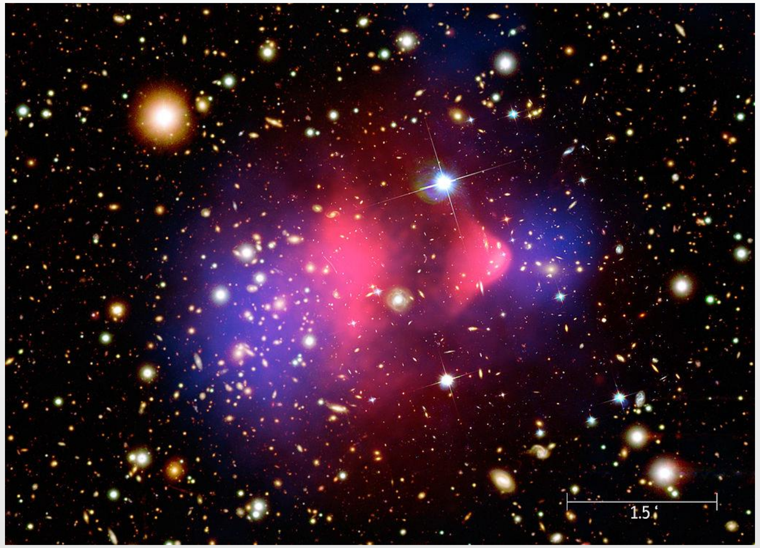
Evidence for Dark Matter



Begeman, K. G., Broeils, A. H., & Sanders, R. H., MNRAS

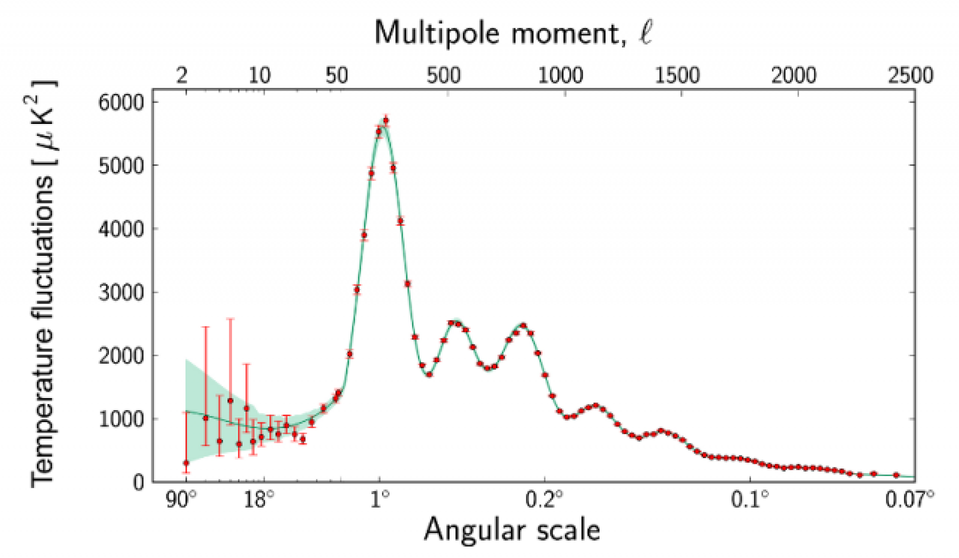
Rotation Curves – First evidence. Should fall off, remain flat.

Bullet Cluster – Gravitational lensing, can look at mass dist. Baryonic center



X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

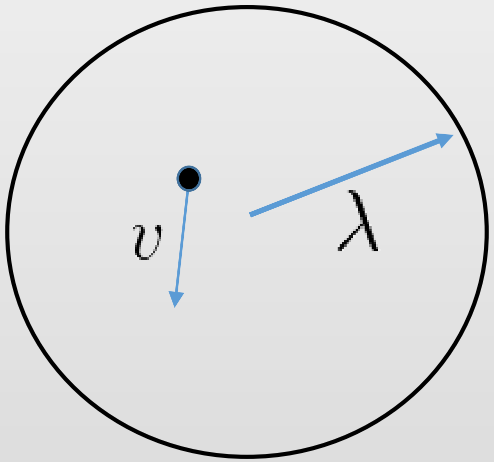
CMB – Acoustic oscillations in primordial power spectrum. 1st peak sensitive to curvature, 2nd and 3rd peaks sensitive to baryon and DM abundance.



Planck collaboration: arXiv:1502.01589

Growth of Structure

Structure formation determined by free streaming length – average velocity. Sets scale in density perturbations.



$$t_\lambda = \frac{\lambda}{\langle v \rangle}$$

$$t_{ff} = \frac{1}{\sqrt{G\rho}}$$

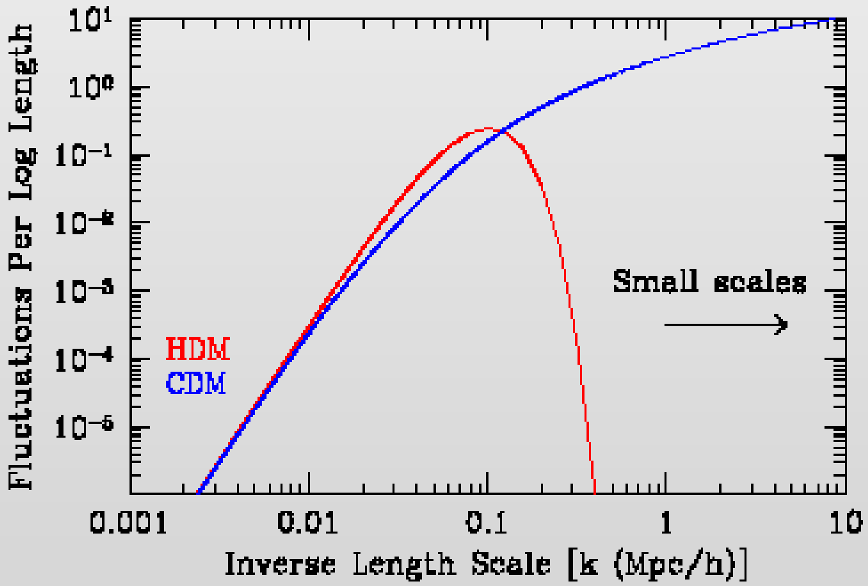
$$\lambda_J = \frac{\langle v \rangle}{\sqrt{G\rho}}$$

Jean’s instability – collapse above particular length scale. Jean’s length = maximum free-streaming.

Dark matter candidates – Cold vs Hot – free streaming very small vs very large.

Proper treatment requires linearizing density perturbations. Gives the Jean’s length.

Power spectrum of density perturbations obtained from large scale observations.



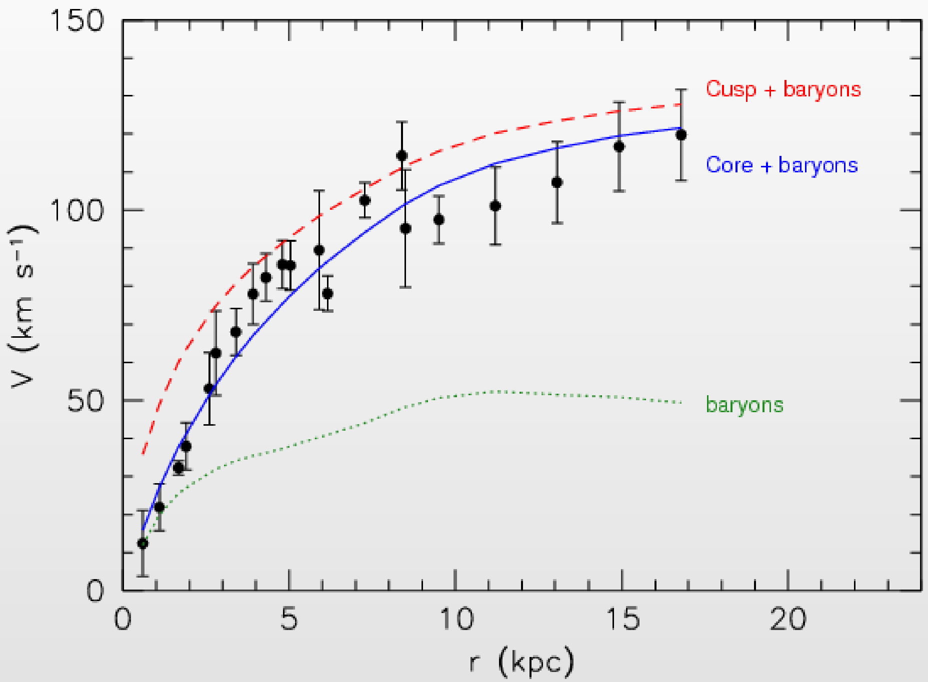
Hot DM would not produce observed small structures, CDM is favored. Need free streaming smaller than size of a baby galaxy (~few kpc).

Issues with CDM

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

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

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.

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

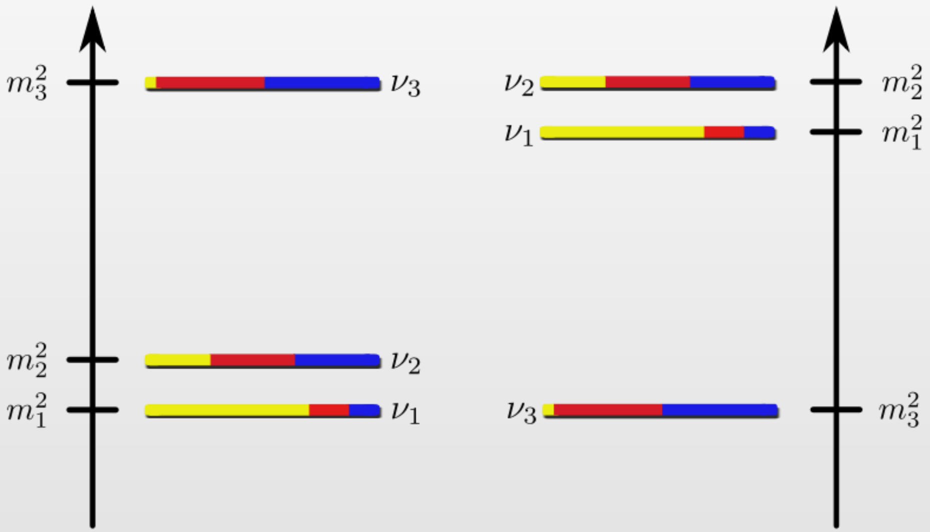
Maybe we can't see them because they never lit up. N-body simulations show that there should've been big enough clumps to "light up" – "too big to fail"

Dark Matter – Hints of Sterile Neutrinos

Neutrino masses – BSM physics. Flavor eigenstates vs mass eigenstates

Experimental program measuring properties of 3 flavor mixing

Many parameters measured – more remains to be done



$$\Psi_{\nu_\alpha} = \sum_j U_{\alpha j} \Psi_{\nu_j}$$

$$N_{eff} = 4.34 + 0.86 - 0.88$$

*WMAP

Additional neutrino species?? Motivated by theory and experiment.

SBL oscillation experiments suggest additional ~eV species (LSND, MiniBooNE). WMAP and Planck suggest additional neutrinos.

See-saw mechanisms explain light mass actives. SO(10) GUT. These are HEAVY (M ~ GUT scale).

And keV mass is viable dark matter – solves small scale problems.

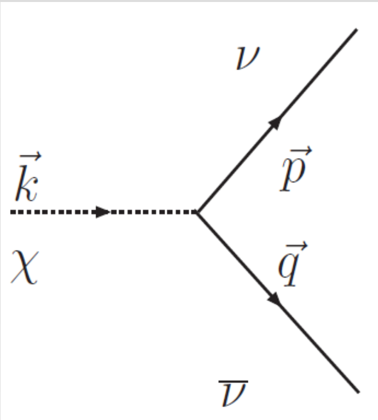
Possible resolution to small scale problem – Sterile WDM

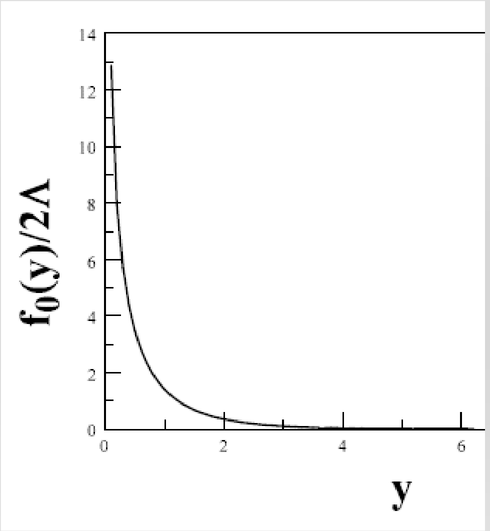
$$|\nu_1^{(\mathrm{m})}\rangle = \cos\theta_m\,|\nu_e\rangle - \sin\theta_m\,|N_1\rangle$$
$$|\nu_2^{(\mathrm{m})}\rangle = \sin\theta_m\,|\nu_e\rangle + \cos\theta_m\,|N_1\rangle$$

Dodelson-Widrow
Extended SM. Sterile neutrino produced via oscillations from actives. Basically thermal distribution.

Shi-Fuller
Produced via oscillations in presence of lepton asymmetry – “resonant mixing”

$$\sin(2\theta_m) = \frac{\sin 2\theta}{\left[\sin^2 2\theta + (\cos 2\theta + V^{th}/\Delta)^2\right]^{1/2}}$$



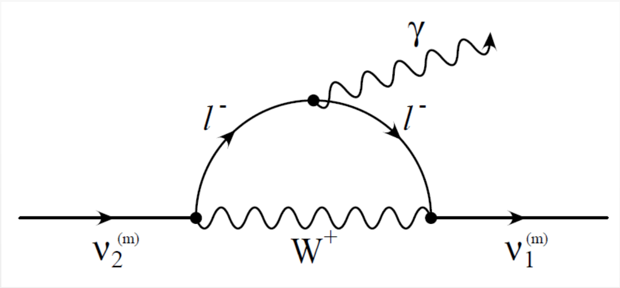


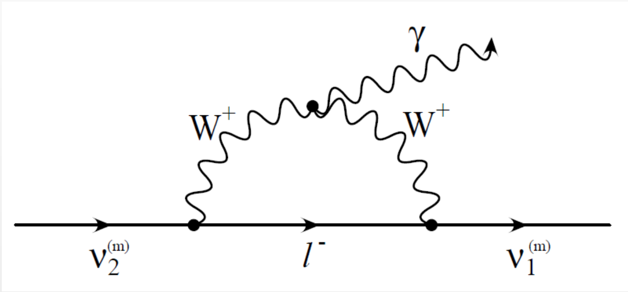
Scalar Decay
Scalar decay (ie Higgs, inflaton) to sterile pairs. Low momentum enhancement. Cold species.

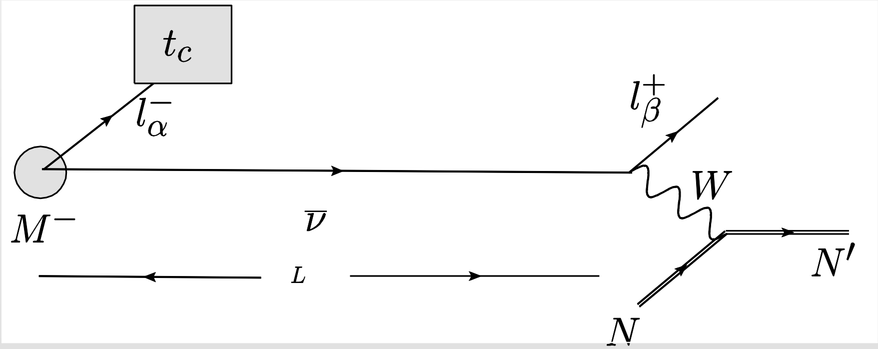
Most strongly produced with ~keV masses near temperatures of ~150 MeV

Signals of Sterile Neutrinos?

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







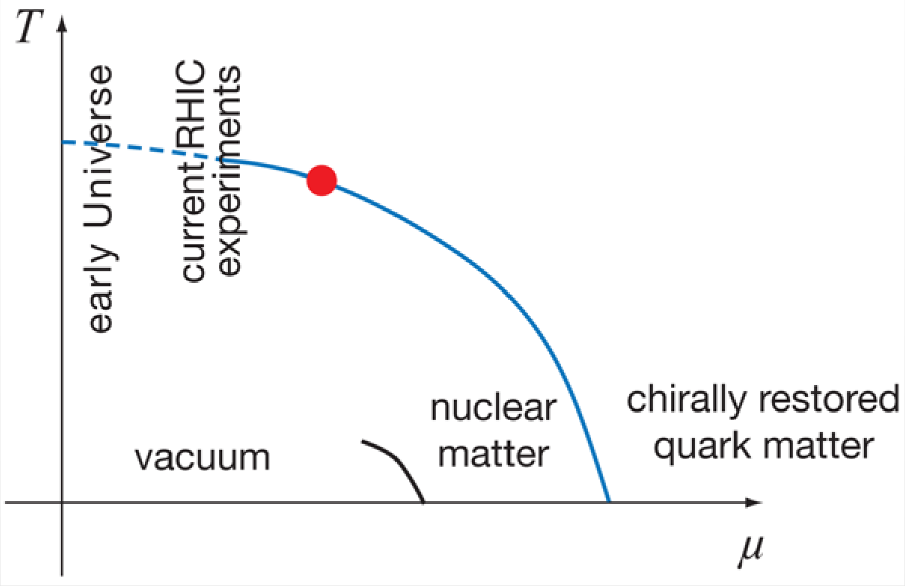
Oscillation experiments suggests sterile. Produced through pion decays. Some say ~eV, some say ~MeV.

GOAL: Explore sterile neutrino production in the early universe resulting from <u>pion decay</u>. 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.

QCD Phase Transition: ~10 μs after BB



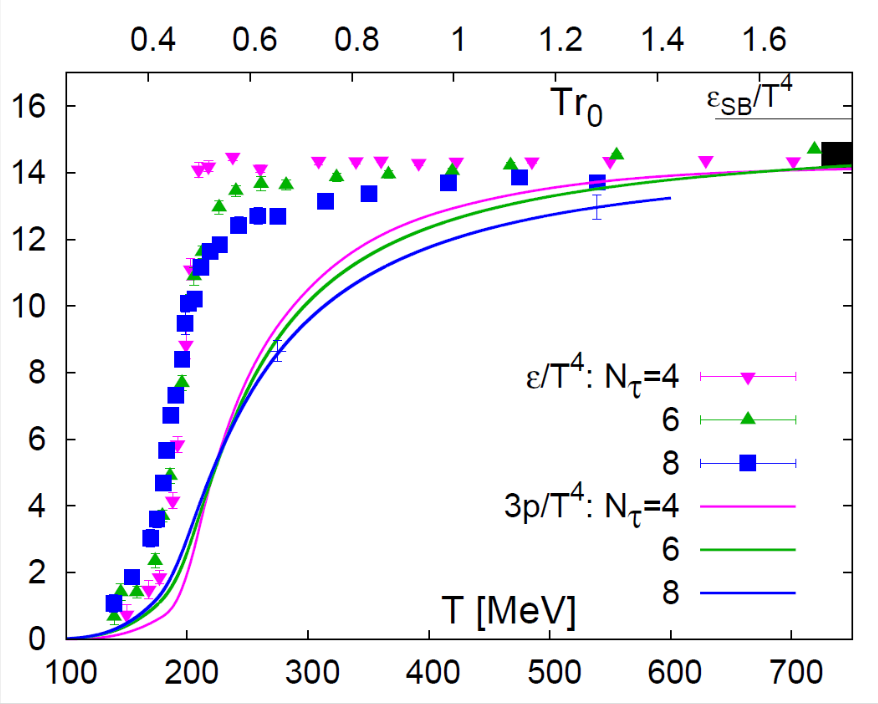
QCD PT – pions form after phase transition. Free quarks/gluons at higher temperature.

Most exact way to study this regime – lattice QCD.

Lattice data suggests phase transition is continuous.

PT happens very slowly compared to strong interaction time scales.

Pions will be in LTE after phase transition.



T. Bhattacharya et. al. arXiv:0903.4379

How to address: quantum kinetics– Boltzmann EQ

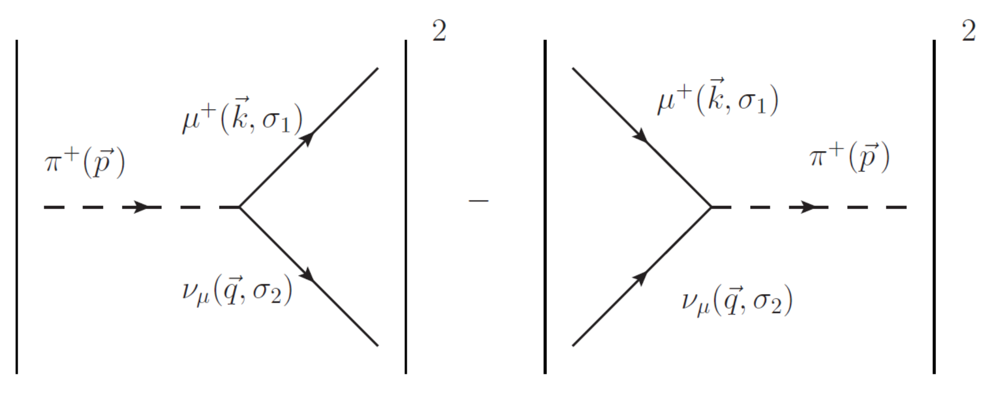
Obtain sterile neutrino distribution as function of momentum.

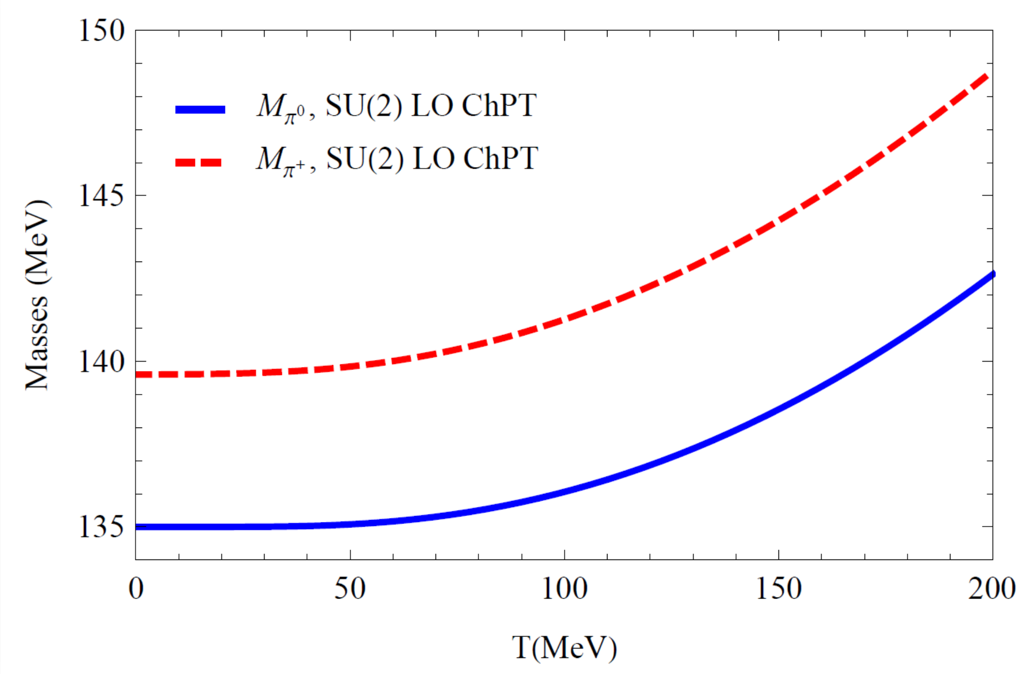
$$\frac{dn}{dt}(q,t) = \delta n_{Gain} - \delta n_{Loss}$$

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

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

Mass corrections are relatively small, approx. constant.





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

Quantum Kinetic Equation

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.

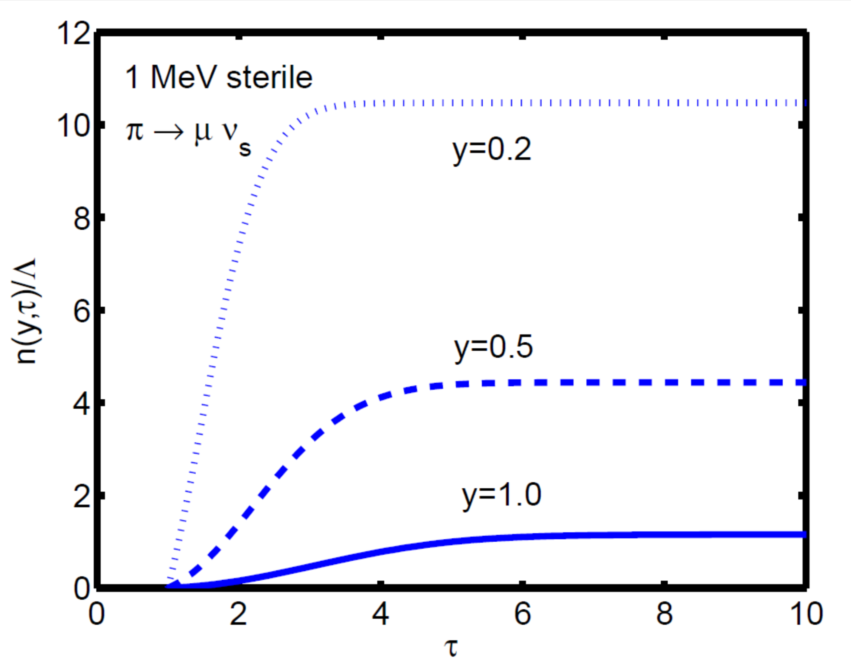
Pion thermal suppression drops rate as universe expands. Leads to large suppression when m/T >> 1 (T ~10MeV).

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

Production and Freezeout

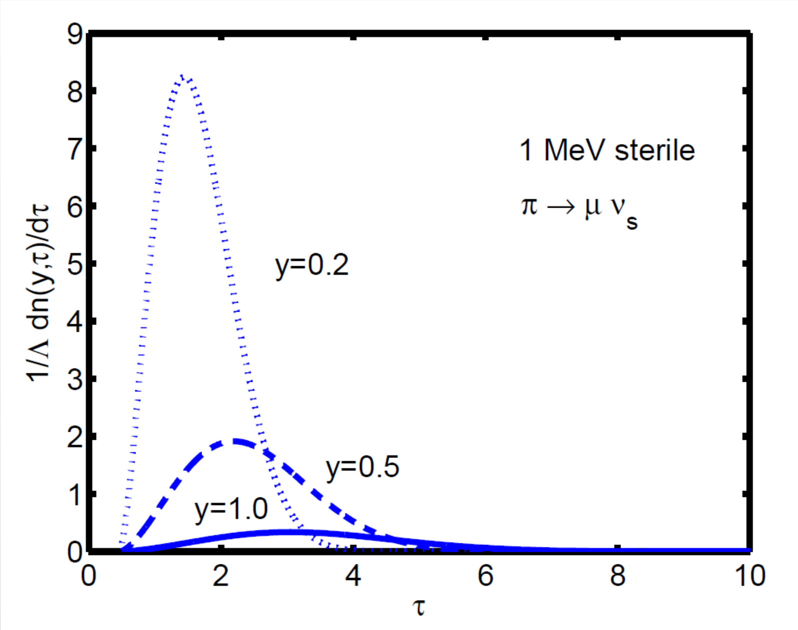
Rate peaks early, falls off before 10 MeV as expected.
Proxies for momentum and temp – y and τ.

Enhancement for small momentum.



$$\tau = \frac{M_\pi}{T(t)} = \frac{M_\pi}{T_0} a(t)$$

$$y = \frac{p_f(t)}{T(t)} = \frac{p_c}{T_0}$$

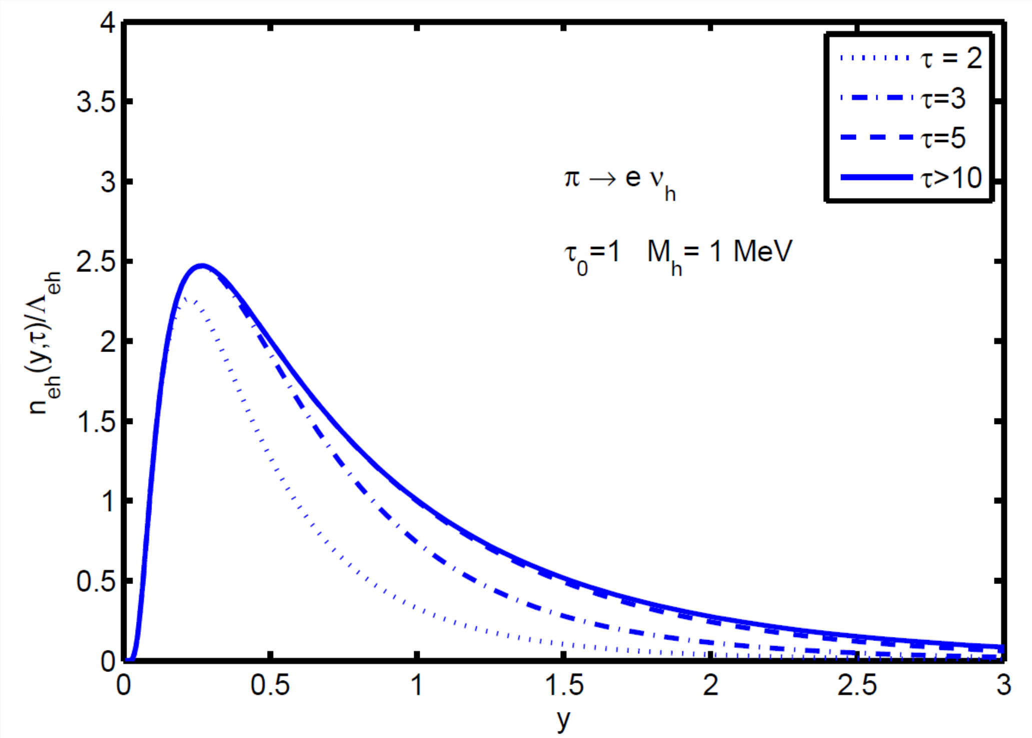


Exact distribution can be obtained numerically.

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 Functions: Light species



Distribution shown as function of momentum.

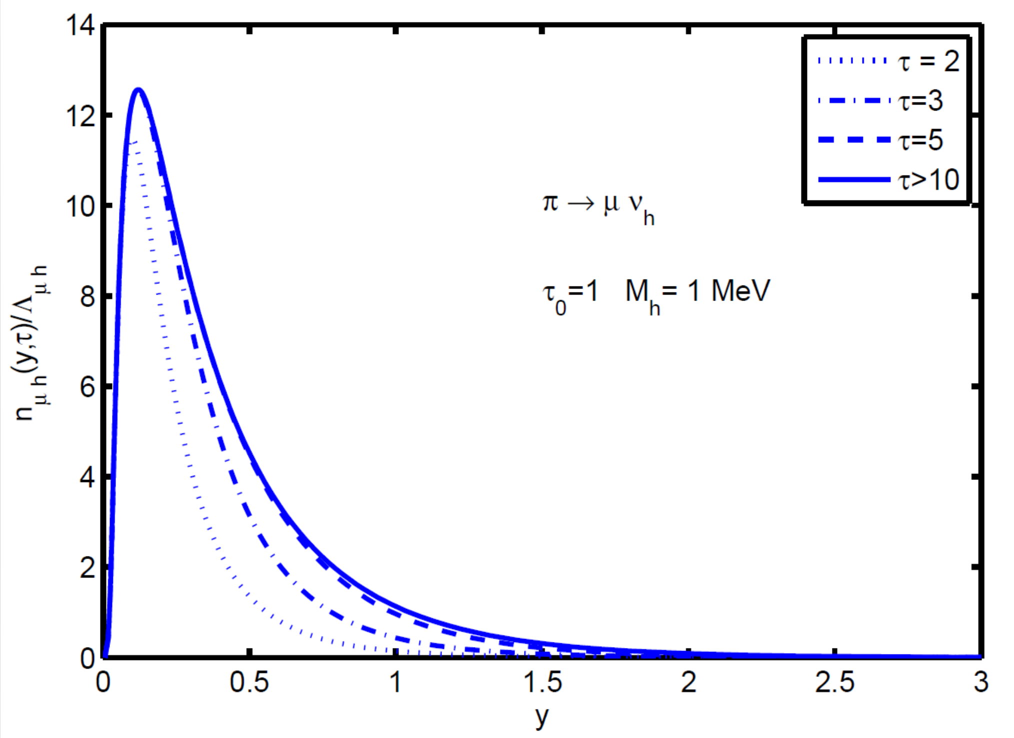
Frozen distribution for light masses has sharp peak at low momentum. Produces a colder dark matter.

Similar enhancement to Shi-Fuller but non lepton asymmetry.

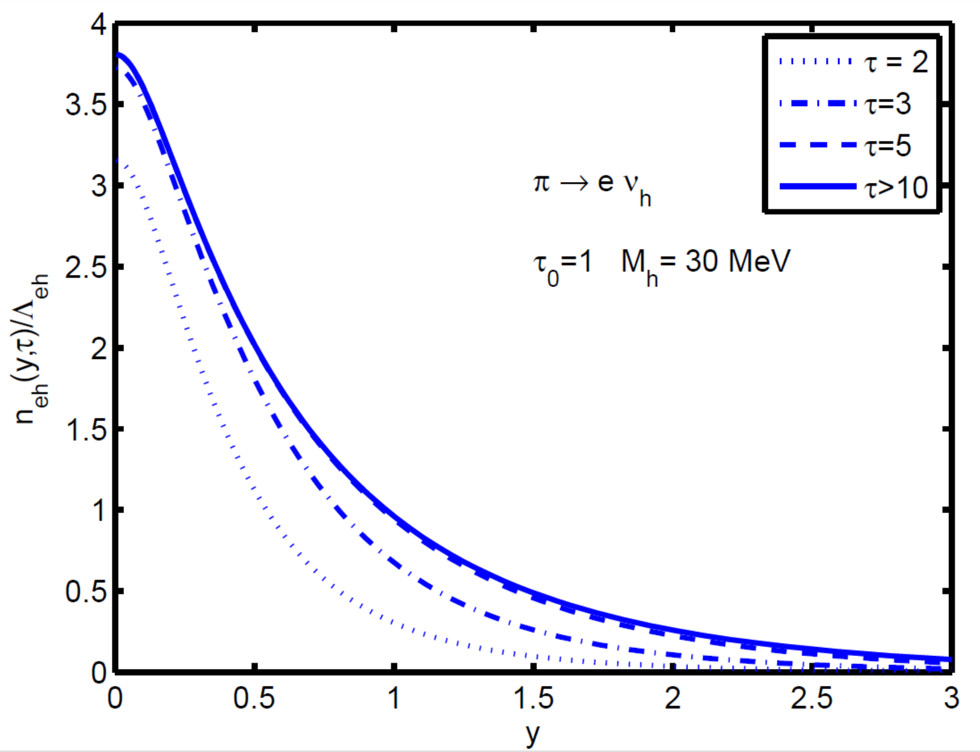
Distributions depend on other daughter particle – distribution has memory

Muon channel produces more low momentum than electron channel – COLDER channel

Channels are essentially the same for <1 MeV



Distribution Functions: Heavy species



Heavier sterile species has plateau at zero momentum

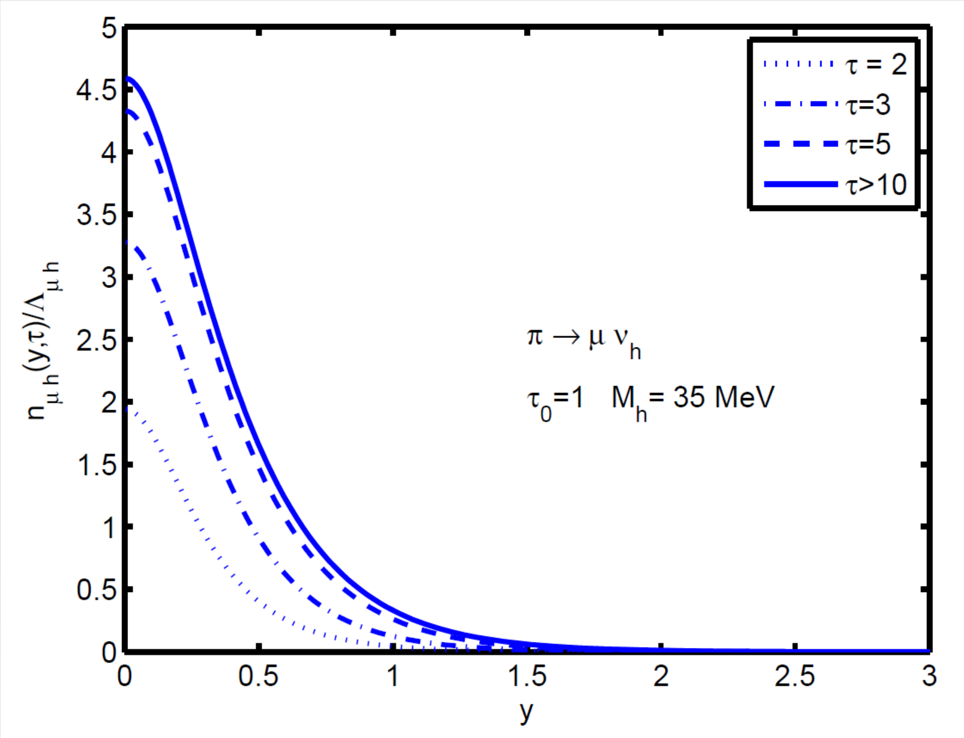
Colder distribution than light steriles

Again, muon channel has more support at low momentum

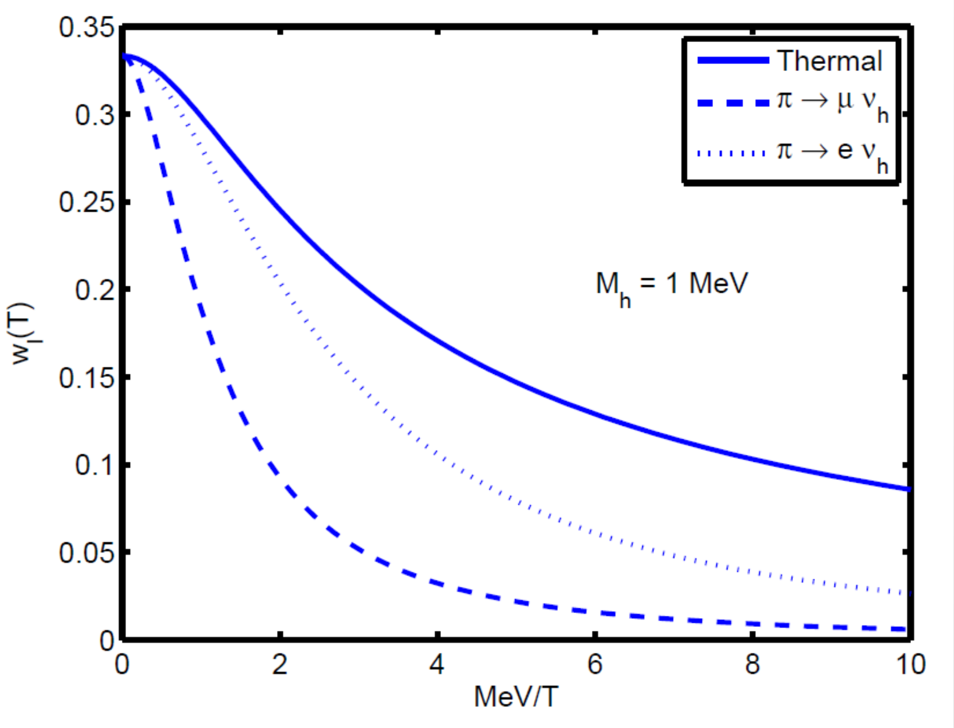
Light mass steriles are all produced ultra-relativistically

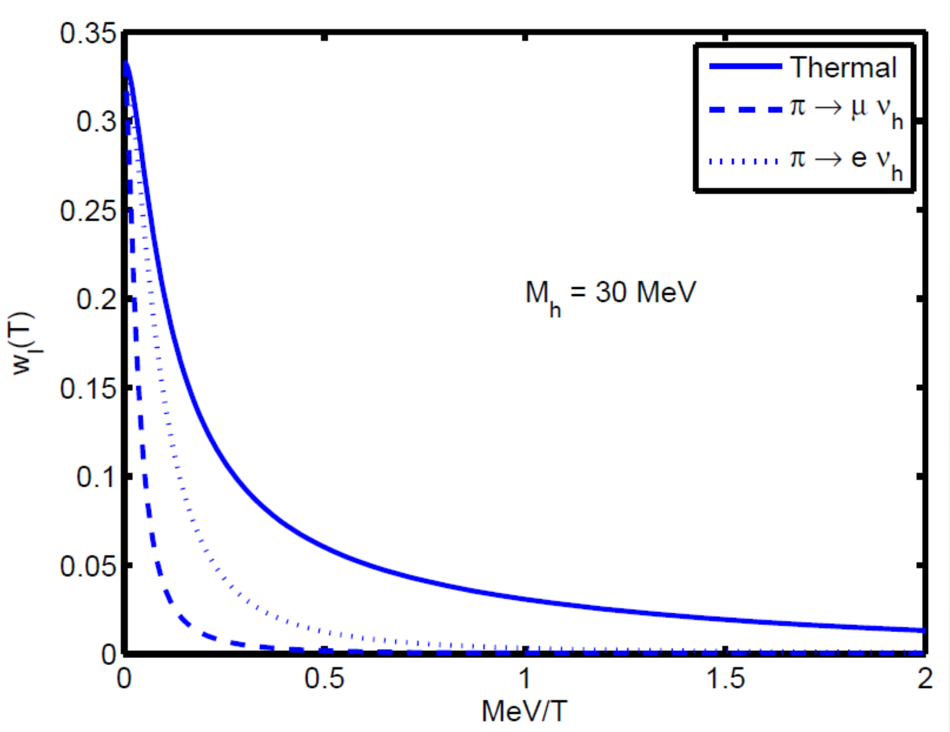
Heavier steriles are non-relativistic at low momentum, ultra relativistic at higher momentum

Even just one sterile leads to multiple distributions – ie different channels.



Equation of state: components



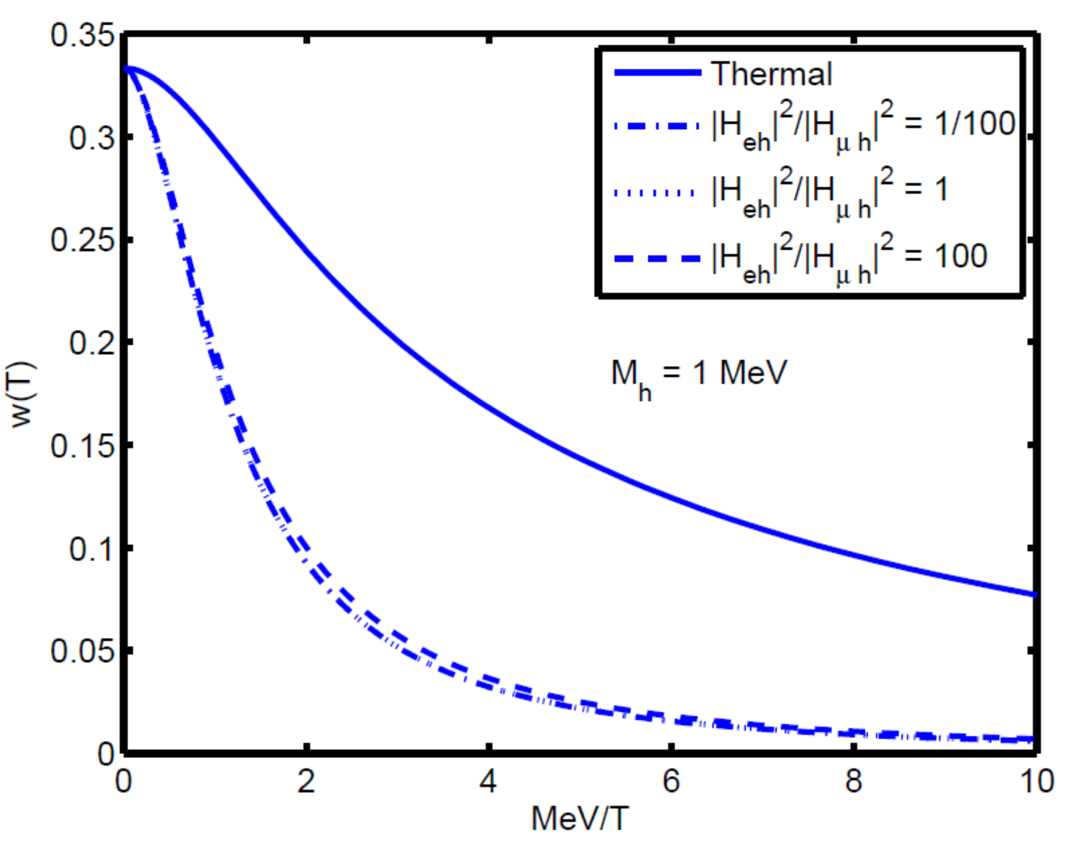


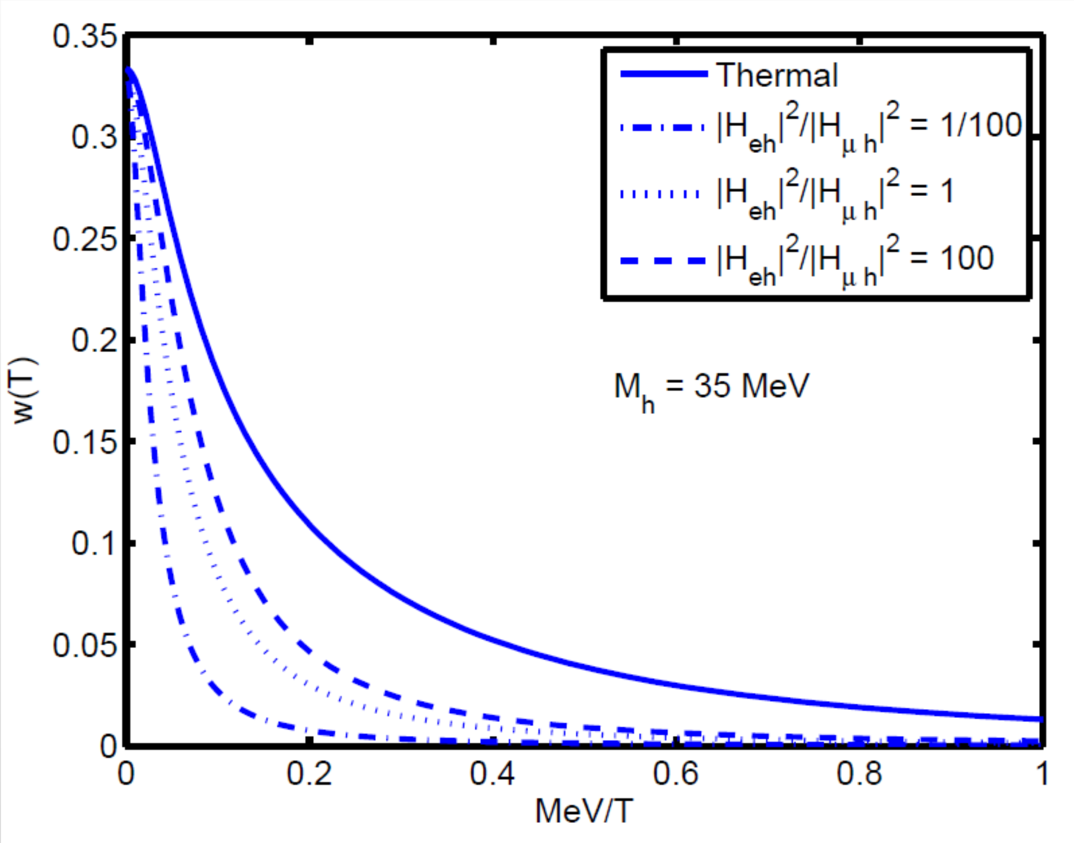
Highly non-thermal character seen by equation of state. Individual components shown.

Becomes nonrelativistic much sooner than thermal.

This distribution produces a COLDER species today than thermal relic.

Equation of state: mixture of channels





Full equation of state depends on mixing parameters.

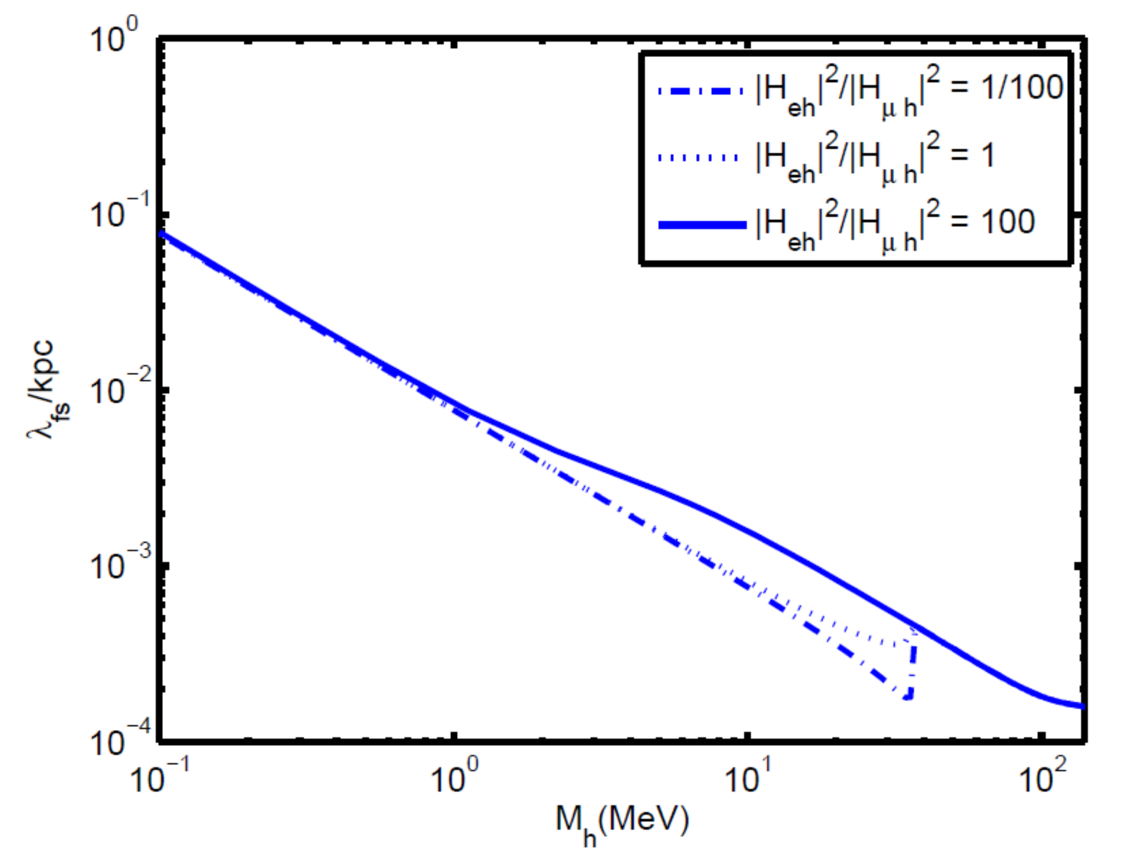
Can tune to be warmer or colder today (electron or muon like) depending on mixing.

Free Streaming

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

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

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



Warm or cold characterized by free streaming length.

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).

Light mass – straightforward free streaming

Heavier mass – depends on mixing

Constraints from Observations

Bounds from observations set allowed region of parameters.

Dark matter abundance from Planck satellite.

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

Stability – lifetime long enough to be present today

Phase space can only decrease during gravitational collapse – Tremain-Gunn bound.

TG uses observations of DSph. Values taken from older data set. Bounds are “soft” – depend on which galaxy you use.

$$\Omega_\nu h^2 \leq \Omega_{DM} h^2 = 0.1199$$

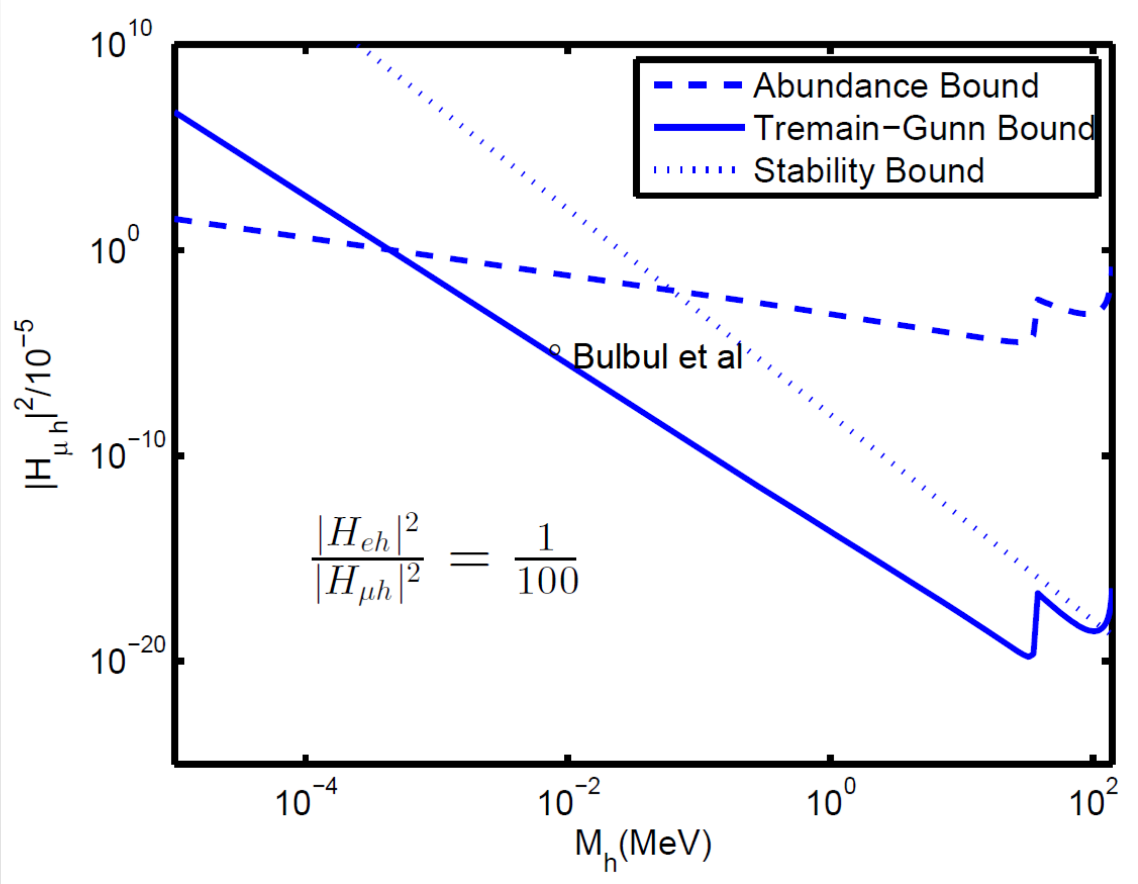
$$\nu_h \to \nu_{a_1}\nu_{a_2}\nu_{a_3} \qquad \nu_h \to \nu_a \gamma$$

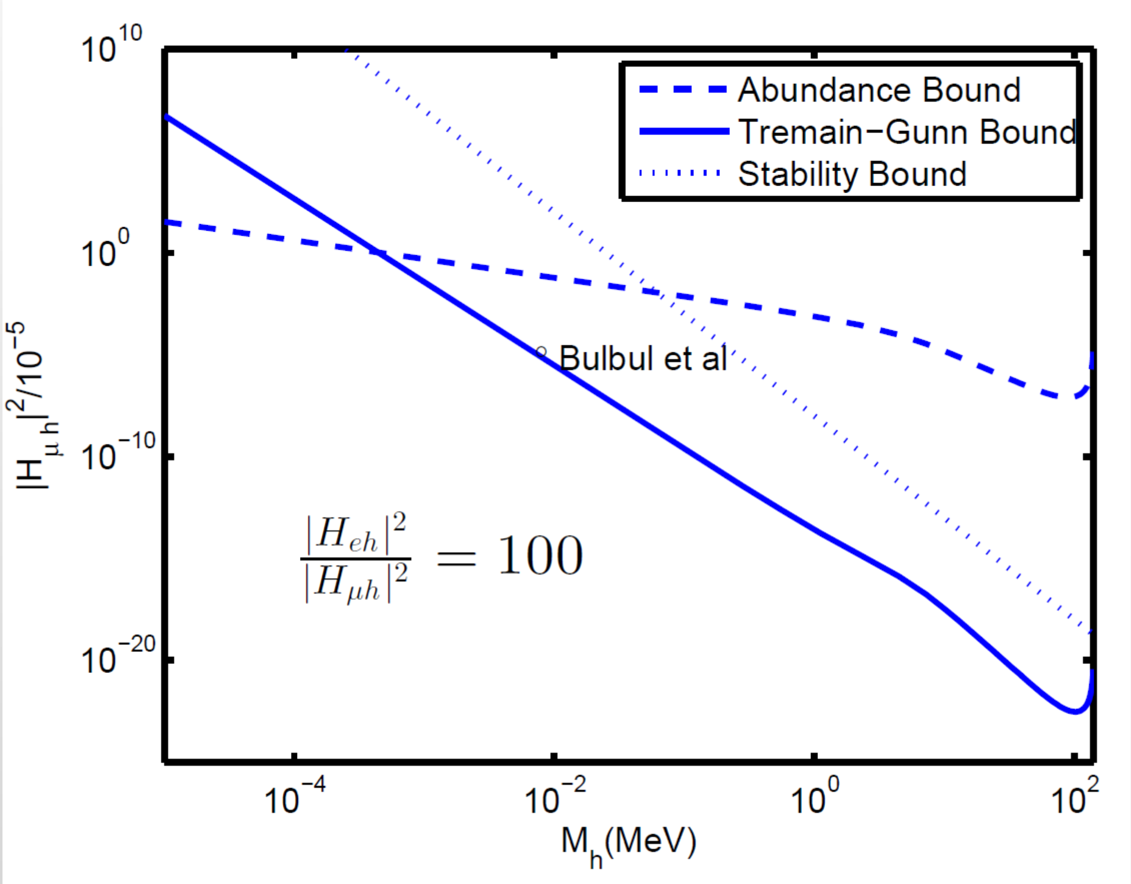
$$\nu_h \to e^+ e^- \nu_a$$

$$\tau \gtrsim \frac{1}{H_0} \qquad |U_{\alpha h}|^2 \left(\frac{m_\nu}{MeV}\right)^5 \lesssim 10^{-13}$$

$$\mathcal{D}_p \geq \frac{1}{3^{3/2} m_\nu^4} \frac{\rho}{\sigma^3}\bigg|_{today}$$

Constraints and Parameter Space





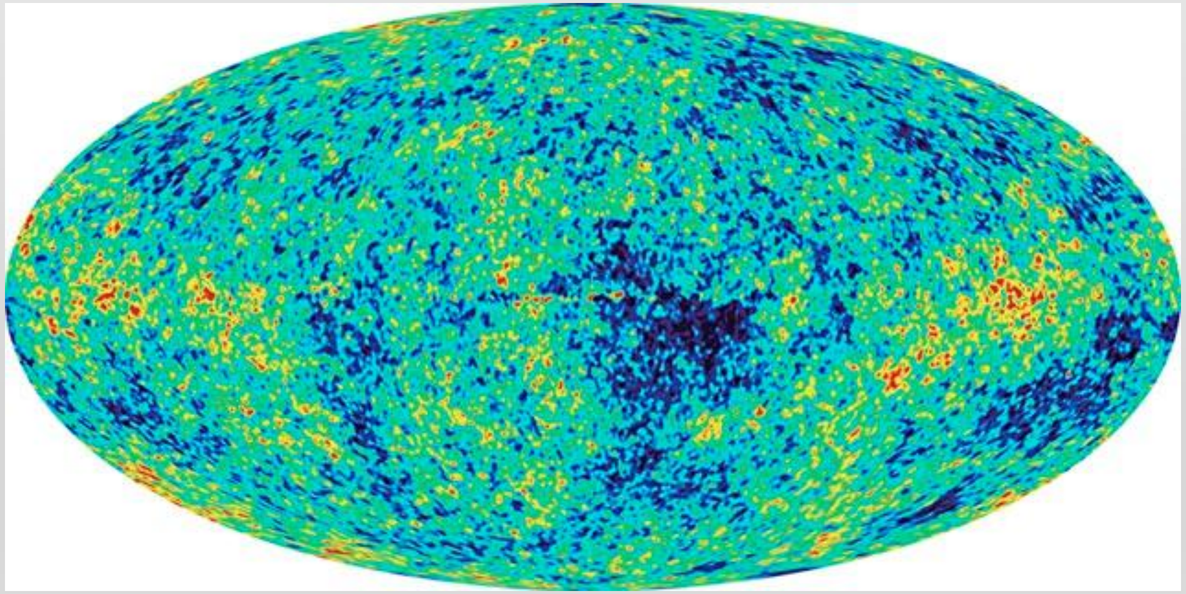
Constrained region depends on mixing parameters, not relevant for heavier regime.

X-ray signal compatible with bounds.

Contributions to Dark Radiation

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.



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

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

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

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

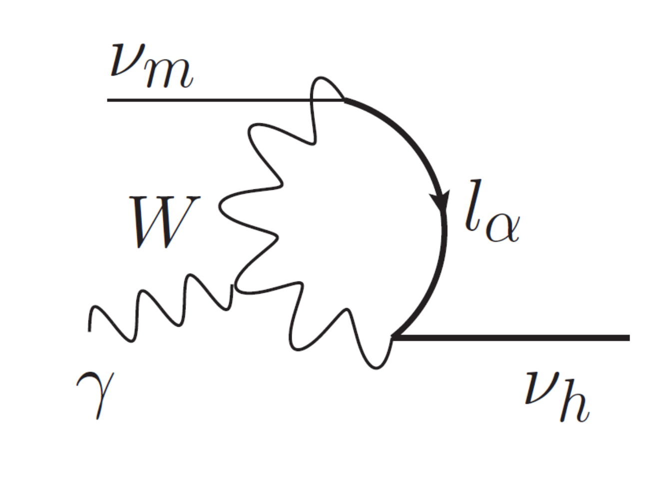
Additional Channels and Regimes

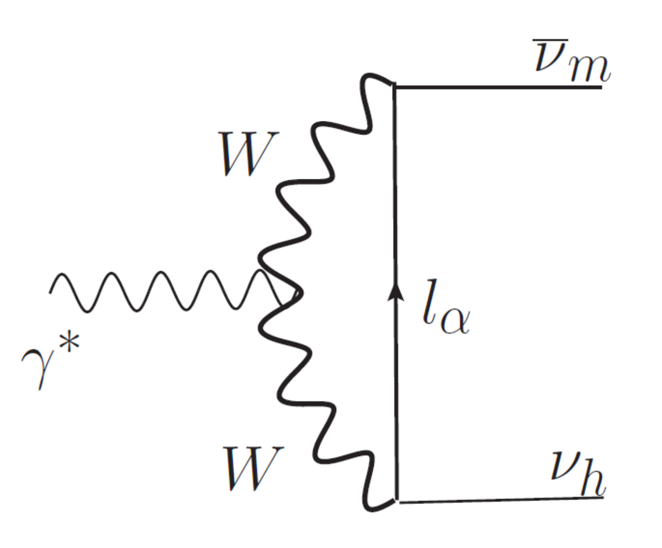
Other sources to consider – finite temperature photon masses open up processes.

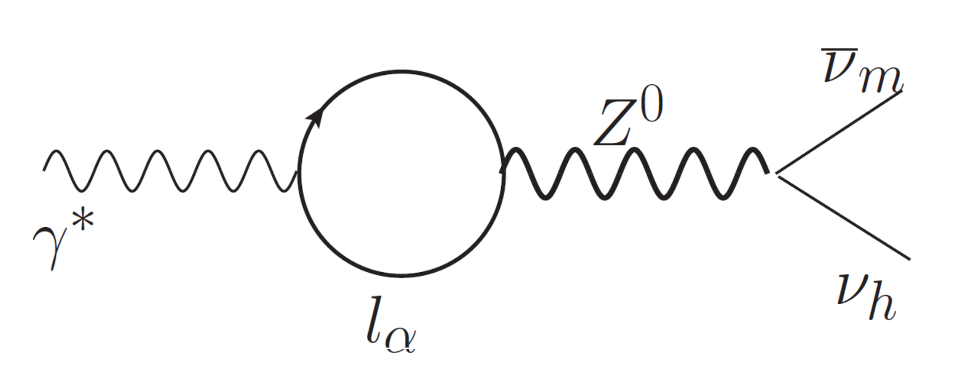
Heavier masses studied near the electroweak scale, also requiring finite temperature corrections. W,Z in the plasma.

Obviously this treatment could be further refined. Corrections to lepton masses, sterile mixing, etc.

QGP EFT useful?? Ask Rob.







Summary

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

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

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

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

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

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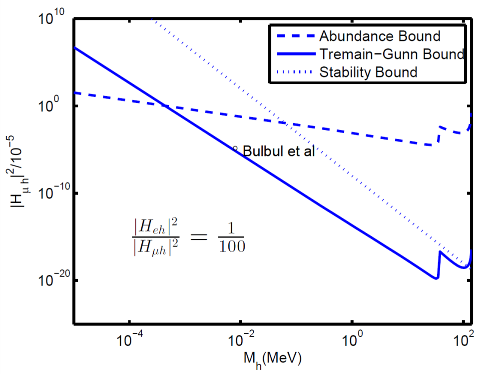

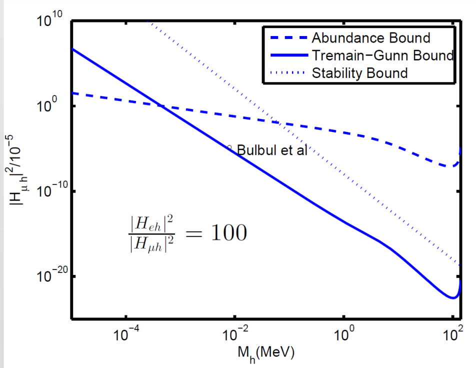

Future Plans

Use finite temperature corrections near the EW scale.

Include lepton asymmetry to study MSW resonances at finite T. Also requires finite density corrections.