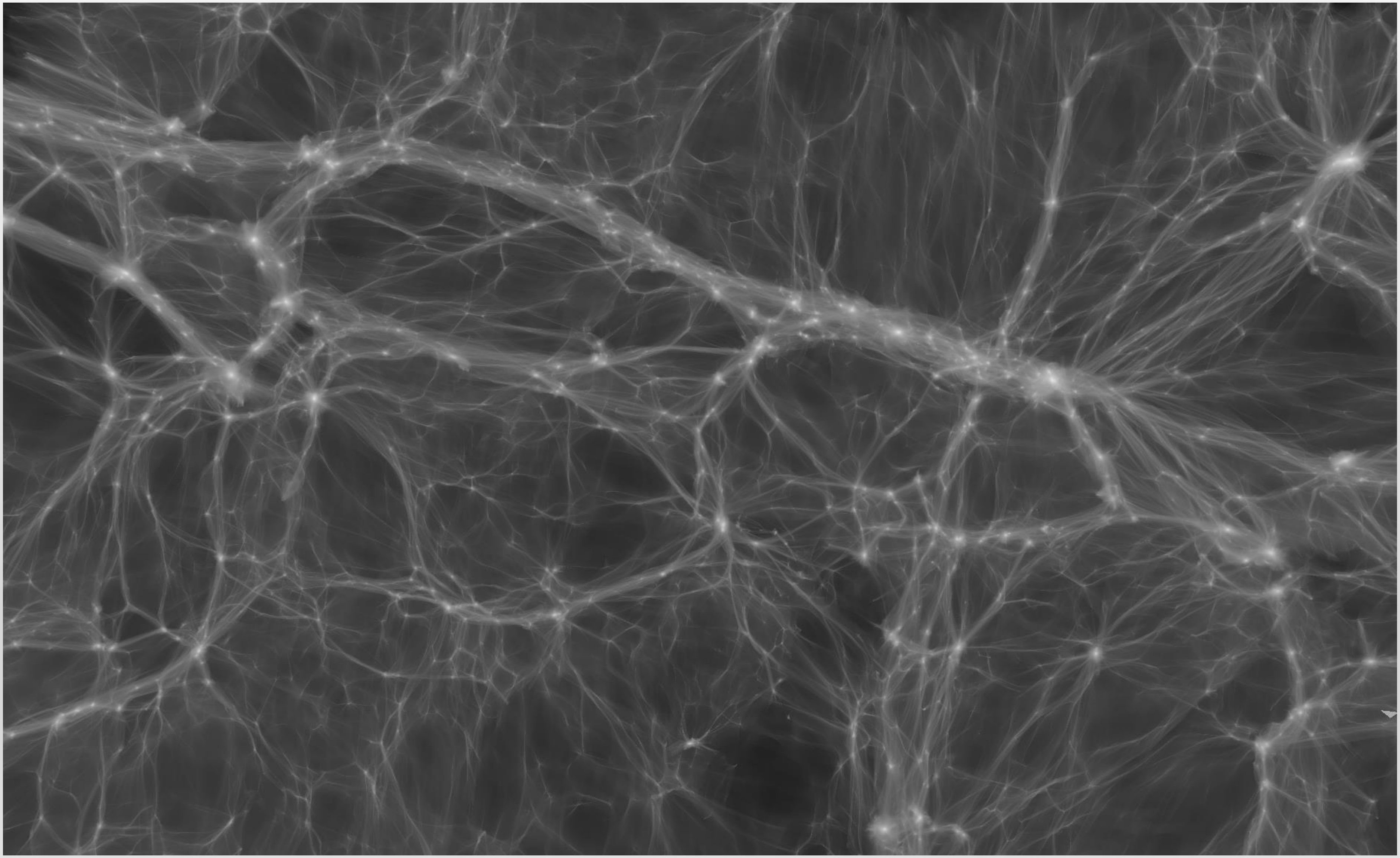
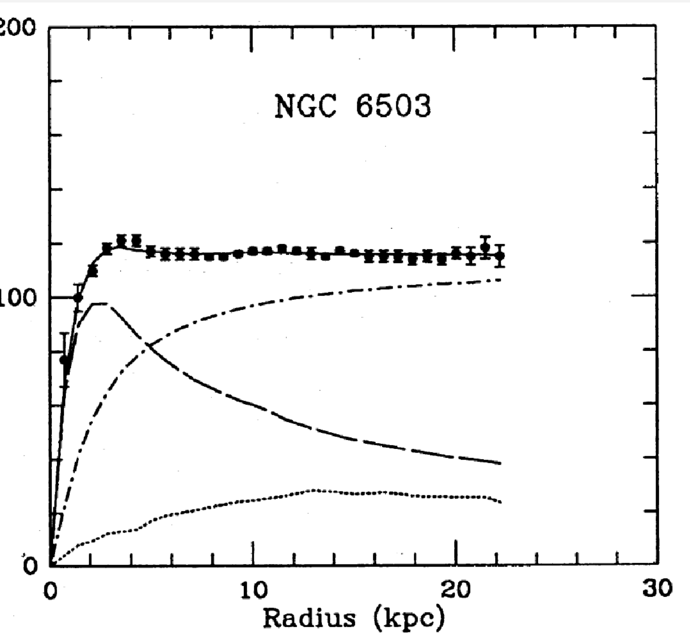
It has been a privilege and an honor to have known Hector for over twenty years, as a mentor, a collaborator and a friend.
During our collaboration I have learned much from him, I remember him very fondly by celebrating his life and numerous scientific achievements in this Workshop.
I will miss him.

Sterile Neutrino Dark Matter after QCD PT
L. Lello, D. Boyanovsky, arXiv:1411.260
PRD 91 (2015)



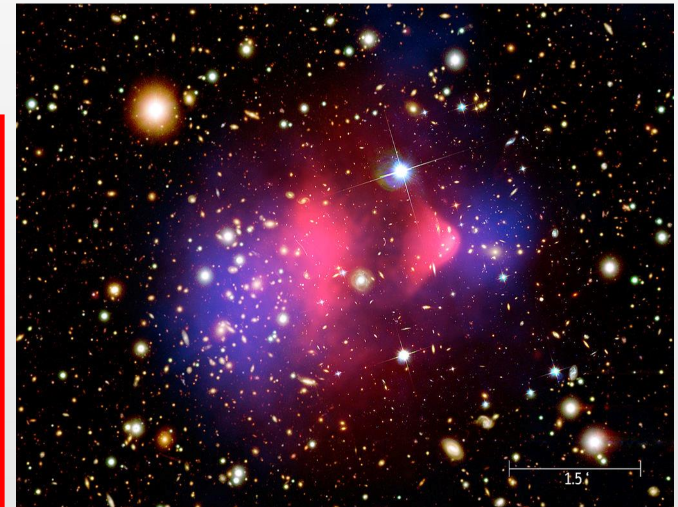
Evidence for Dark Matter



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

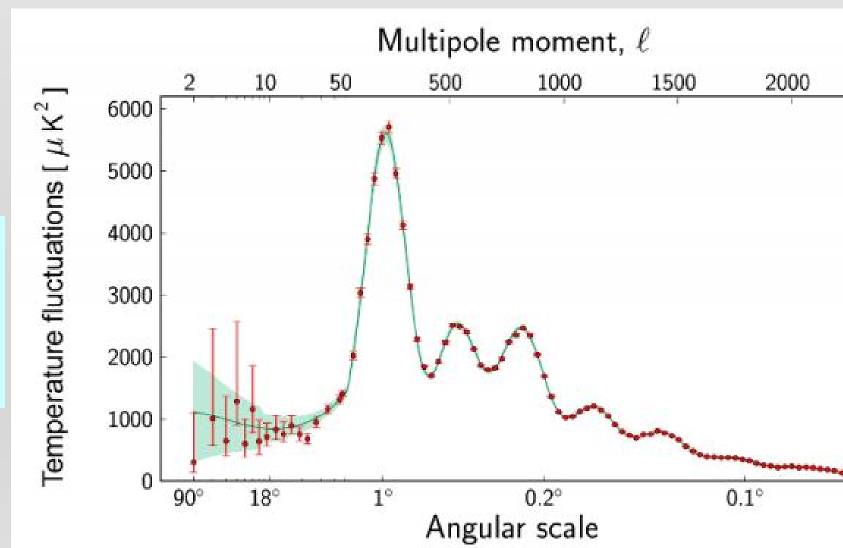
Rotation Curves – First evidence. Should fall off, remain flat.

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.; Lensin NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et

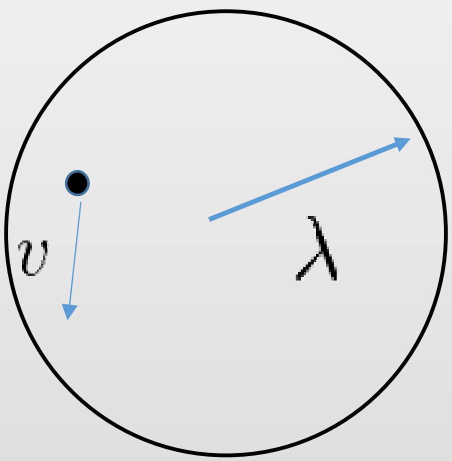
CMB – Acoustic oscillations in primordial power spectrum. 1st peak sensitive to curvature, 2nd and 3rd peaks sensitive to baryon and DM abundance.



Planck collaboration: arXiv:1502.01589

Growth of Structure

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



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

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

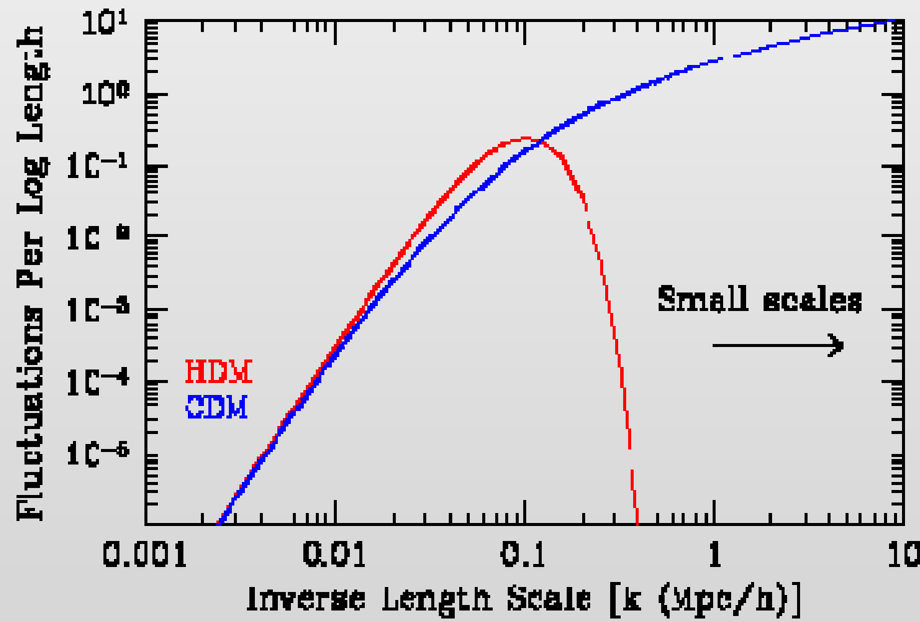
$$\lambda_J = \frac{\langle v \rangle}{\sqrt{G\rho}}$$

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.



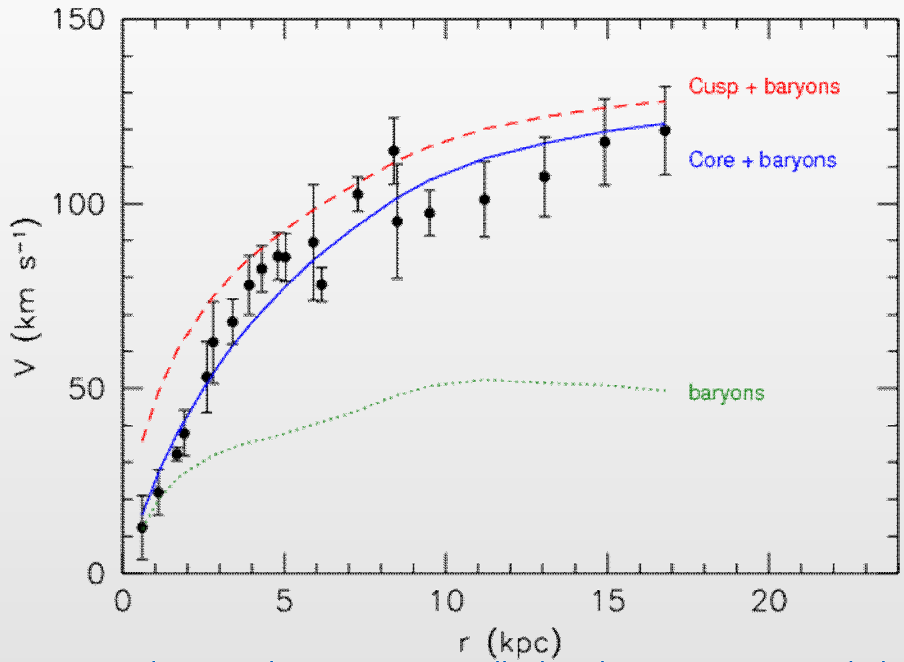
Hot DM would not produce observed small structures, CDM is favored. Need free streaming smaller than size of a baby galaxy (~few kpc).

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.

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

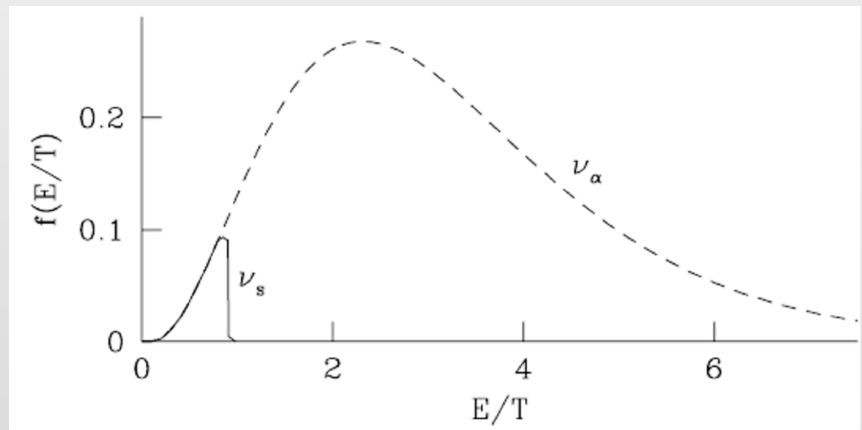
Maybe we can't see them because they never lit up. N-body simulations show that there should've been big enough clumps to "light up" – "too big to fail"

Possible resolution to small scale problem – WDM: sterile neutrinos-SU(2) singlets

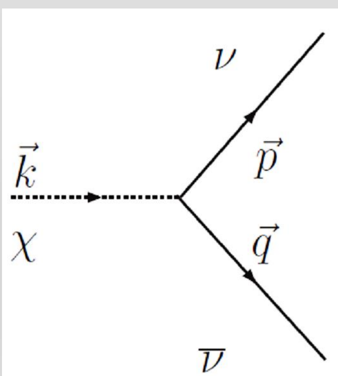
$$|\nu_1^{(\mathrm{m})}\rangle = \cos\theta_m\,|\nu_e\rangle - \sin\theta_m\,|N_1\rangle$$
$$|\nu_2^{(\mathrm{m})}\rangle = \sin\theta_m\,|\nu_e\rangle + \cos\theta_m\,|N_1\rangle$$

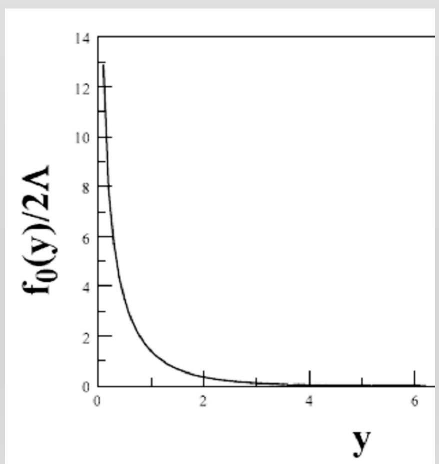
Dodelson-Widrow
Extended SM. Sterile neutrino produced via oscillations from actives. ***Basically thermal distribution.***

Shi-Fuller: Produced via oscillations in presence of lepton asymmetry.



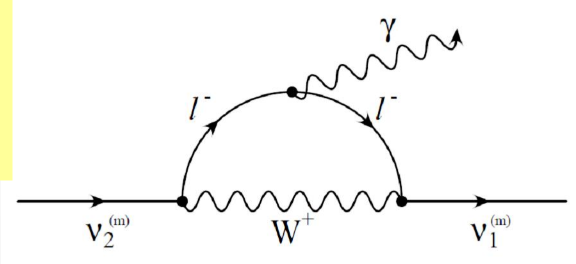
X. Shi, G. Fuller, PRL 82, 1999

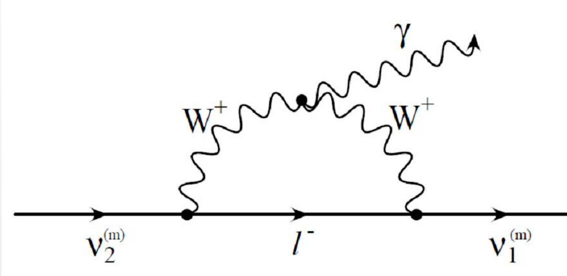


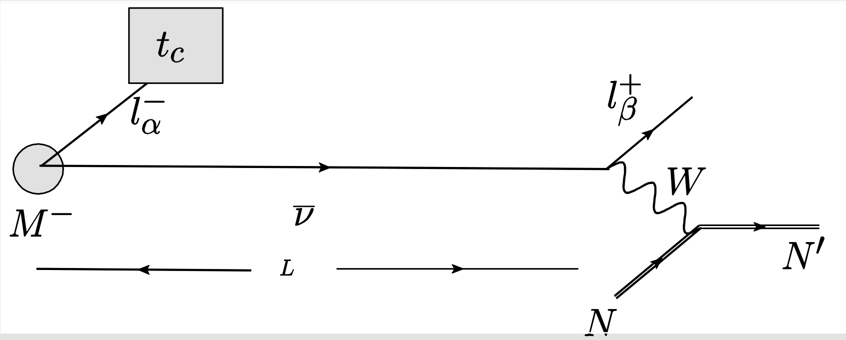


Scalar decay (ie Higgs) to sterile pairs. Low momentum enhancement. Cold species

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





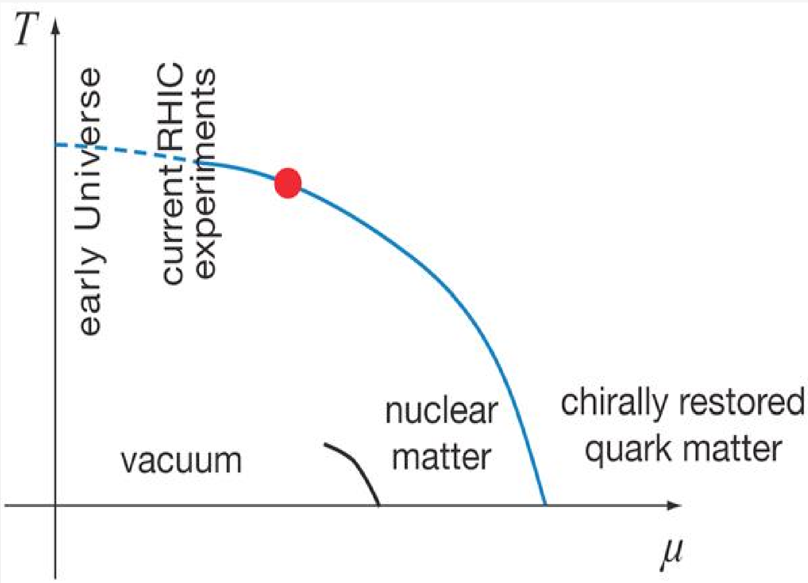


Oscillation experiments suggests ~eV sterile. Produced through pion decays.

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

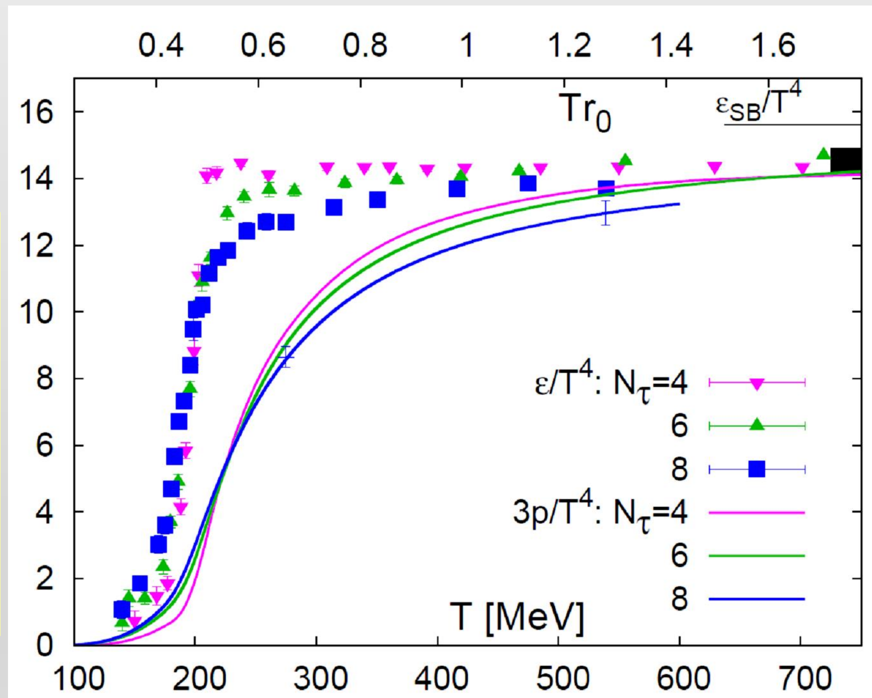
PLAN:
-Obtain distribution function – steriles not in LTE.
-Need finite temperature corrections for the calculation, no pions not until QCD PT (T~150MeV).
-Use distribution to calculate contributions to observations in cosmo.
-Free streaming, dark matter density, dark radiation, phase space density (Tremaine-Gunn).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

QCD Phase Transition: 10 $\mu - secs$ after BB



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

Most exact way to study this regime – lattice QCD.



T. Bhattacharya et. al. arXiv:0903.4379

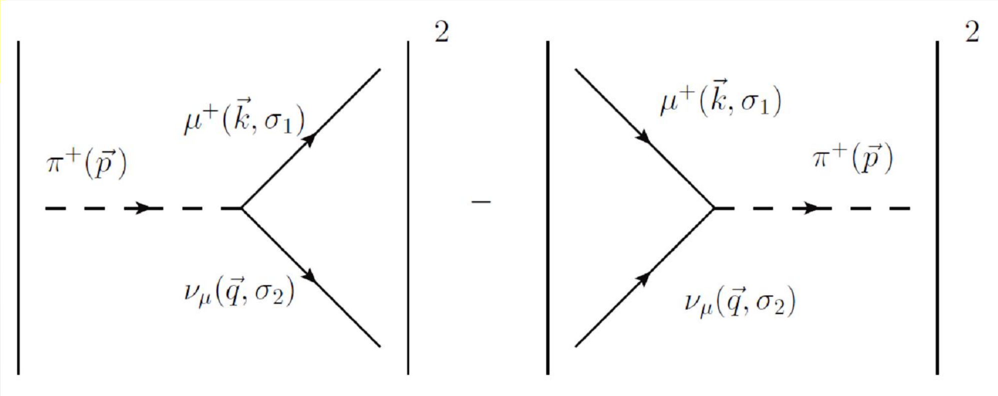
Lattice data suggests phase transition is continuous.

PT happens very slowly compared to strong interaction time scales.

Pions will be in LTE after phase transition.

How to address: quantum kinetics– Boltzmann EQ:
Obtain sterile neutrino distribution as function of momentum.

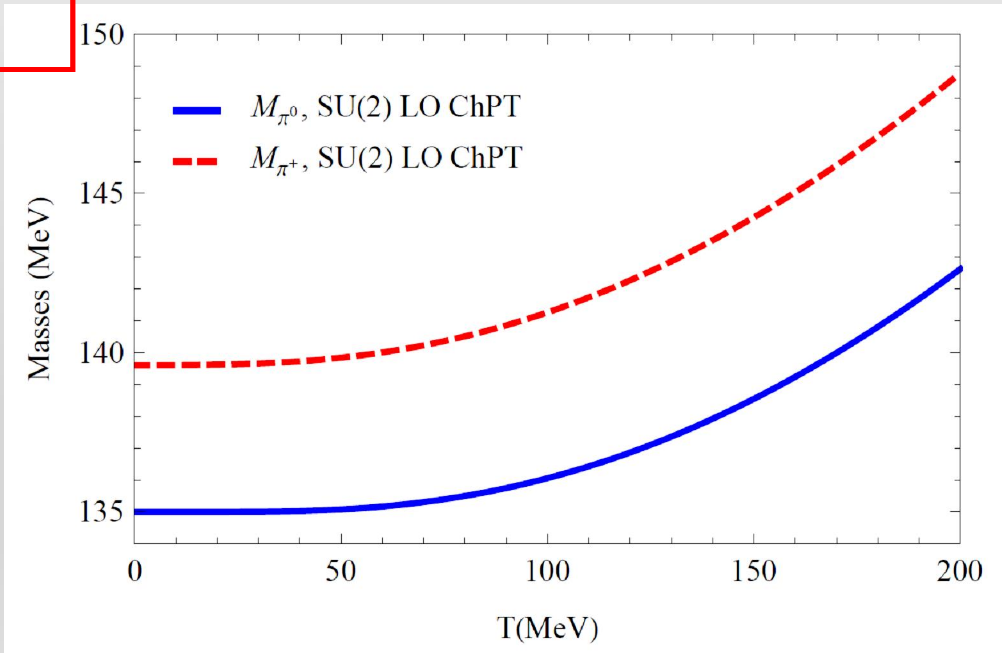
$$\frac{dn}{dt}(q,t) = \delta n_{Gain} - \delta n_{Loss}$$



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.

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

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

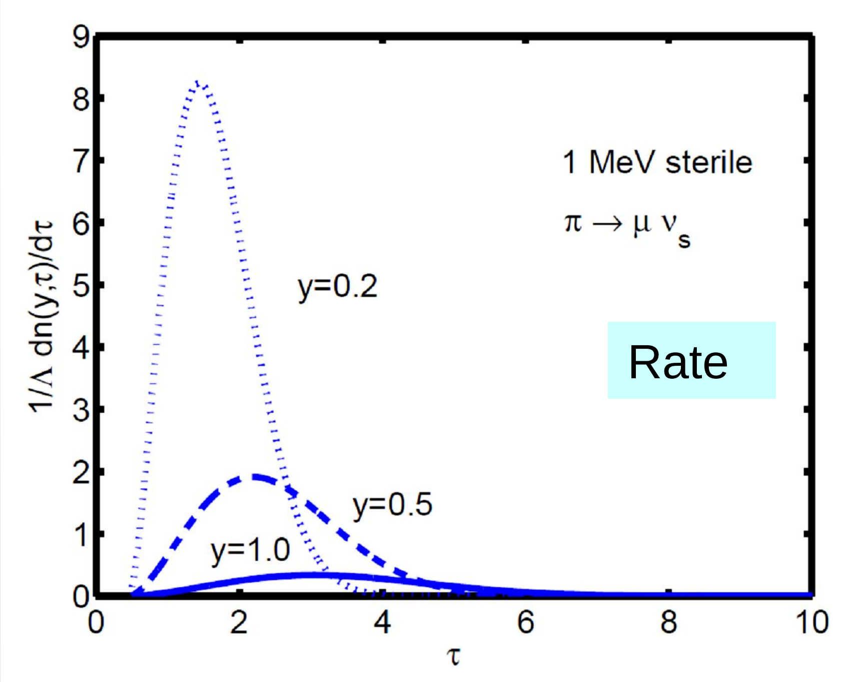
Pion thermal suppression drops rate as universe expands. Leads to large suppression when m/T >> 1 (T ~10MeV).

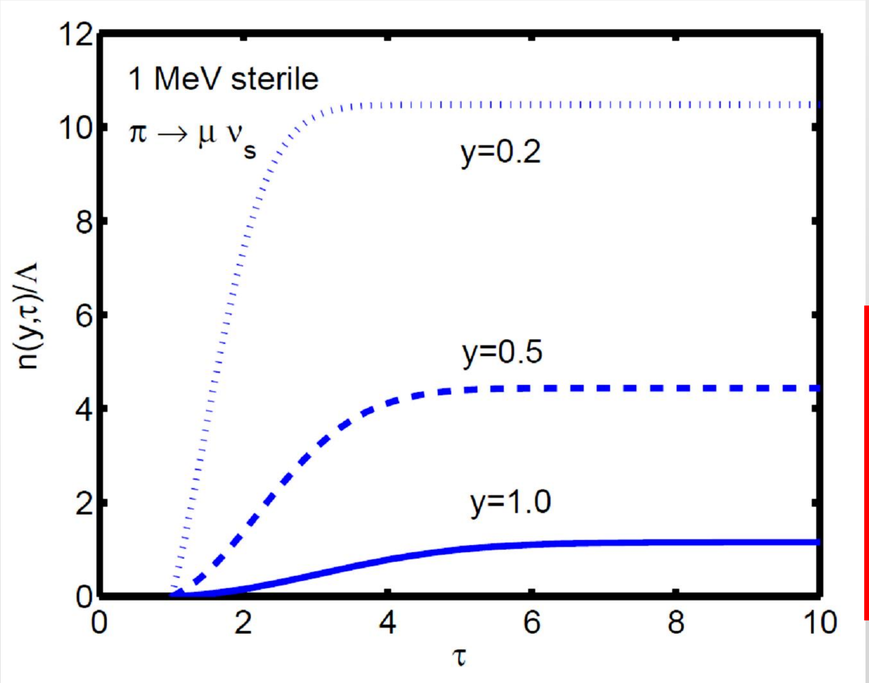
$$n_\pi = \frac{1}{e^{E_\pi/T(t)}-1} \qquad T \ll m_\pi \rightarrow n_\pi \sim 0$$

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

Freeze-out at $T \simeq 10\mathrm{MeV}$

Distribution enhanced at low momentum

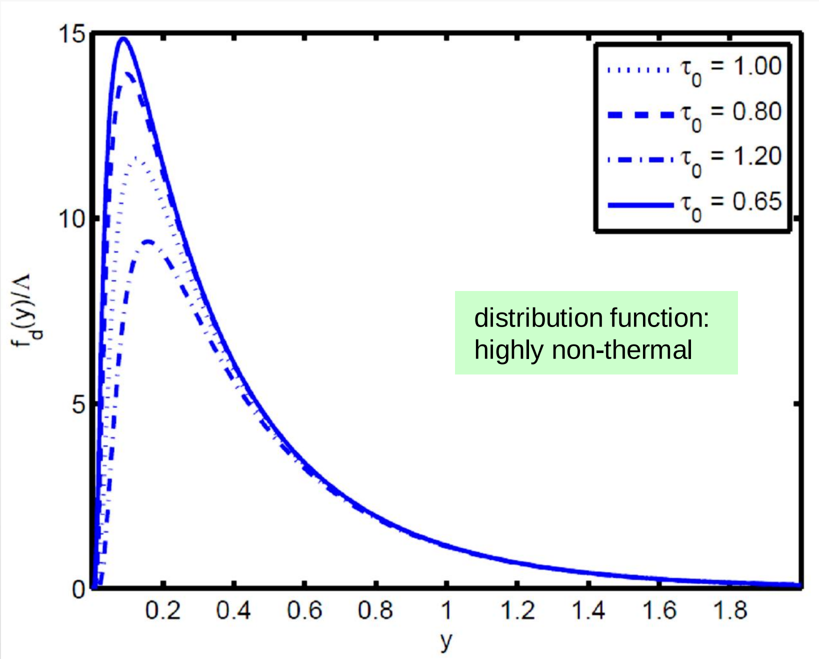




Exact distribution can be obtained numerically.

Freezeout occurs at temperatures about 10 MeV for all momentum.

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



Distribution shown as function of momentum.

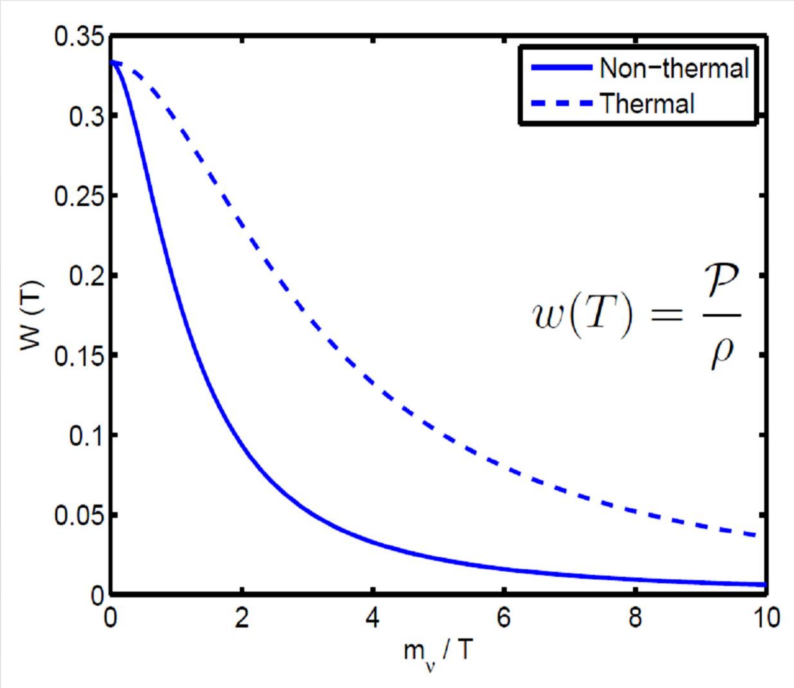
Frozen distribution has sharp peak at low momentum. Produces a colder dark matter.

Similar enhancement to Shi-Fuller but no 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 length is calculated with distribution function. (cutoff in power spectrum)

Depends on mass of sterile and production channel.

Consistent with observations of DSph and interpretation of core profile (~few kpc) for m a few keV.

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

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

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

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

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

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

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

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

Ω_{DM} : ***Lower bounds on combinations of mass and mixing from da matter abundance if steriles dominant.***

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

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

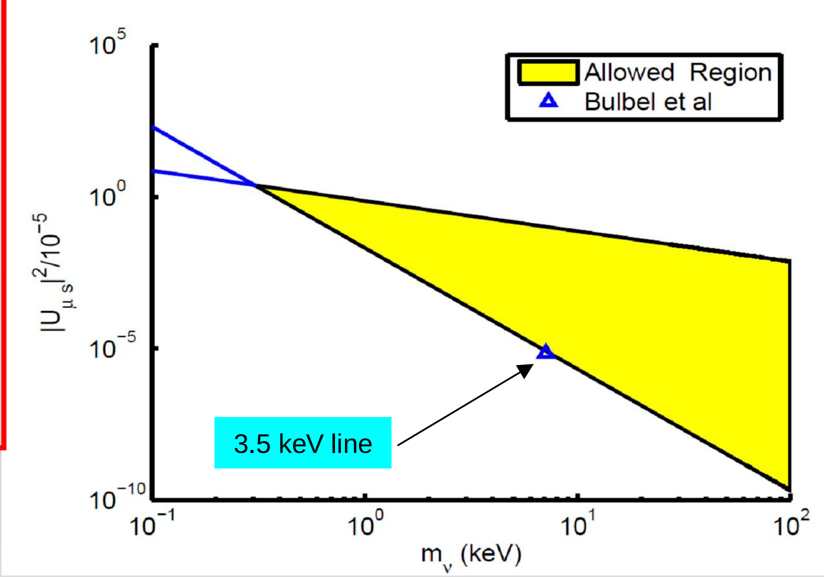
$$m_{\nu_s} \frac{|U_{\mu s}|^2}{10^{-5}} \leq 0.739keV \qquad m_{\nu_s} \frac{|U_{es}|^2}{10^{-5}} \leq 7242keV$$

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

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

Combined bounds set allowed region. Top set by Planck Ω_{DM} ***bottom by DSph (T-G bound).***

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



Summary

Sterile neutrinos are produced by pion decay after QCD PT—Ubiquitous production mechanism in accelerator expts!! decouple and freeze out at $T \simeq 10 MeV$ with non-thermal distribution, enhanced at low momentum Ω_{DM} + Tremaine Gunn (phase space) of dwarf spheroidal galaxies → constraints on mass/mixing, narrow window for 3.5 keV line. KeV consistent with cores in dsPhs. Species is COLDER than thermal for same mass → smaller free streaming length and cutoff scale in power spectrum.

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 upper and lower 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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$$m_{\nu_s}\frac{|U_{\mu s}|^2}{10^{-5}} \leq 0.739 keV$$

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