Cosmological Signatures of Neutrino Interactions

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Outline

- Neutrino mass from cosmology
- Models with non-standard interactions

& suppressed neutrino dark matter density.

- CMB signatures of neutrinos
- Free-streaming vs interacting neutrinos and the CMB.

Neutrino Mass from Cosmology

Measuring neutrino mass

Neutrino mass in the lab - Tritium endpoint experiments:

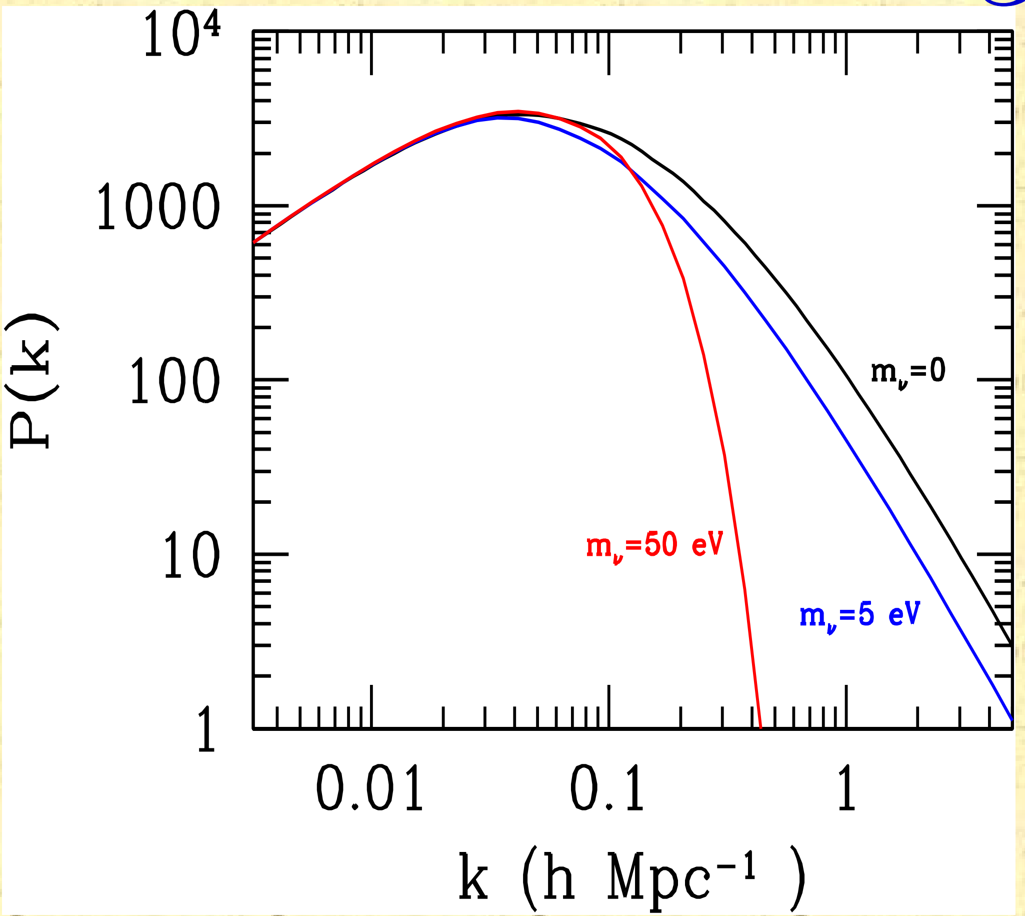
$$m_\nu < 2.2 \text{ eV} \quad \Rightarrow \quad \sum m_\nu < 6.6 \text{ eV}$$

"Weighing" neutrinos with cosmology - Large scale structure:

$$\sum m_\nu < \sim 0.5 \text{ - } 2 \, \text{eV}$$

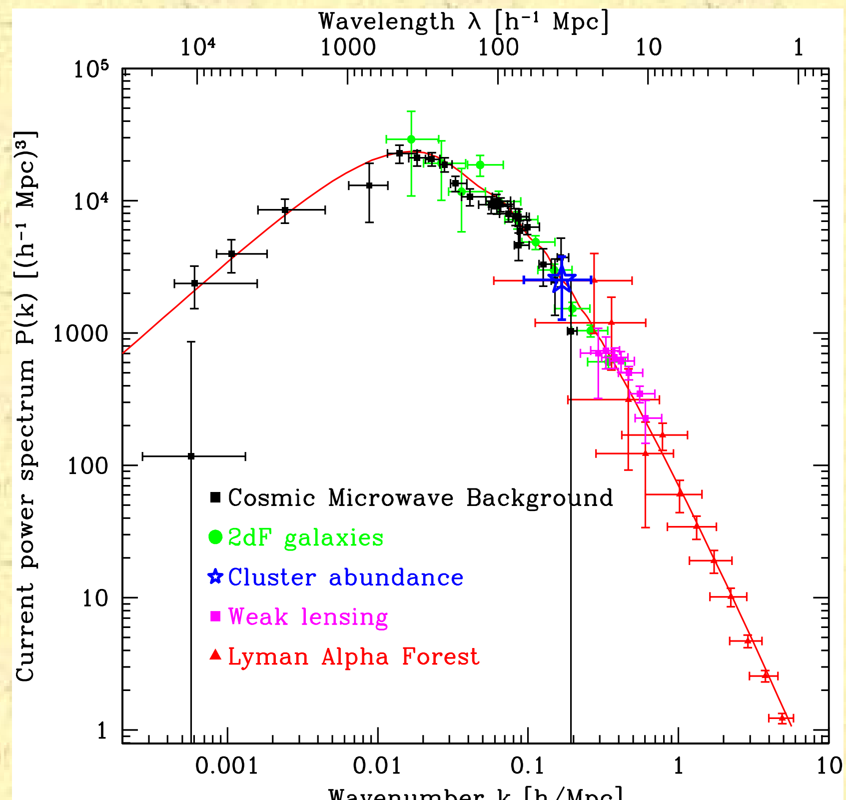
See talk by Kev Abazajian

Neutrino Mass & Large scale structure



Dodelson

Tegmark and Zaldarriaga



Neutrino mass and Cosmology

Neutrinos are only a small component of the dark matter
… but the effects of the neutrino component can be large.

$$\frac{\Delta P}{P} \approx -8 \frac{\Omega_\nu}{\Omega_m}$$

Hu, Eisenstein and Tegmark

•Free-stream from density perturbations when relativistic
•Behave more like cold dark matter when non-relativistic

→Suppression of the growth of structure on all scales below the size of the horizon at the time the neutrinos became non-relativistic

Neutrino contribution to the matter density:

$$\rho_\nu = \sum m_\nu n_\nu \rightarrow \frac{\sum m_\nu}{93.5 h^2 \mathrm{eV}} \rho_{\mathrm{critical}}$$

This assumes the standard cosmological neutrino abundance.
i.e. We can weigh neutrinos with cosmology ***provided we know N_ν =3.***

If the relic neutrinos had large chemical potentials, N_ν would be significantly enhanced…but this is no longer permitted (BBN+LMA).

Could the relic neutrino abundance be lower than we think?

Neutrinoless Universe ?

Vanishing relic neutrino density ?

If the neutrinos remained in thermal equilibrium until non-relativistic, their abundance would be suppressed by a Boltzmann factor:

$$n_\nu \propto e^{-m/T}$$

This would require non-standard neutrino couplings to a light boson.

Couplings in the allowed range can lead to a *vanishing cosmic neutrino density today* and *evade the cosmological neutrino mass limits*

Interaction model

$$\mathcal{L} = g_{ij}\overline{\nu}_i \nu_j \phi + g'_{ij}\overline{\nu}_i \gamma_5 \nu_j \phi + \text{h.c.}$$

Where ϕ is a massless (or light compared to m_ν) boson.

Couplings constraints

$g < 10^{-2}$ neutrino decay and meson decay limits

$g_{ee} < 10^{-4}$ neutrinoless double beta decay

Supernova constraints exclude a narrow range of couplings around $g \sim 10^{-5}$

Neutrino mass from late-time (low scale) phase transitions?

Chacko, Hall, Okui and Oliver, 2003;
Chacko, Hall, Oliver and Perelstein 2004.

- ❖Neutrino mass is protected at the TeV scale by a global symmetry.
- ❖Neutrino mass operators involve a scalar field ϕ which carries a charge under the global symmetry

$$\mathcal{L}_\nu = \sqrt{2} g_i \left(\nu_i n_i \phi,\ \frac{1}{2} \nu_i \nu_i \phi \right) + \text{h.c.} - (-\mu^2 \phi^\dagger \phi + \frac{\lambda}{2} (\phi^\dagger \phi)^2)$$

- ❖Neutrino mass arise through spontaneous symmetry breaking at a low energy scale.
- ❖Neutrinos couple to light or massless (pseudo)-goldstone boson.

See talk by Maxim Perelstein.

The ϕ boson can be brought into thermal equilibrium through:

$$\nu + \phi \leftrightarrow \nu + \phi$$

$$\nu_i \leftrightarrow \nu_j + \phi$$

$$\nu + \nu \leftrightarrow \phi + \phi$$

The process $\nu + \nu \to \phi + \phi$ will deplete the neutrino number density once the temperature drops below the neutrino mass.

If $g>10^{-5}$, all neutrinos annihilate into bosons when T ~ 1eV,
→ A "Neutrinoless Universe" today.

Energy Density

The neutrino/boson fluid is heated as the neutrinos annihilate.

In the standard scenario: $\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{1/3}$

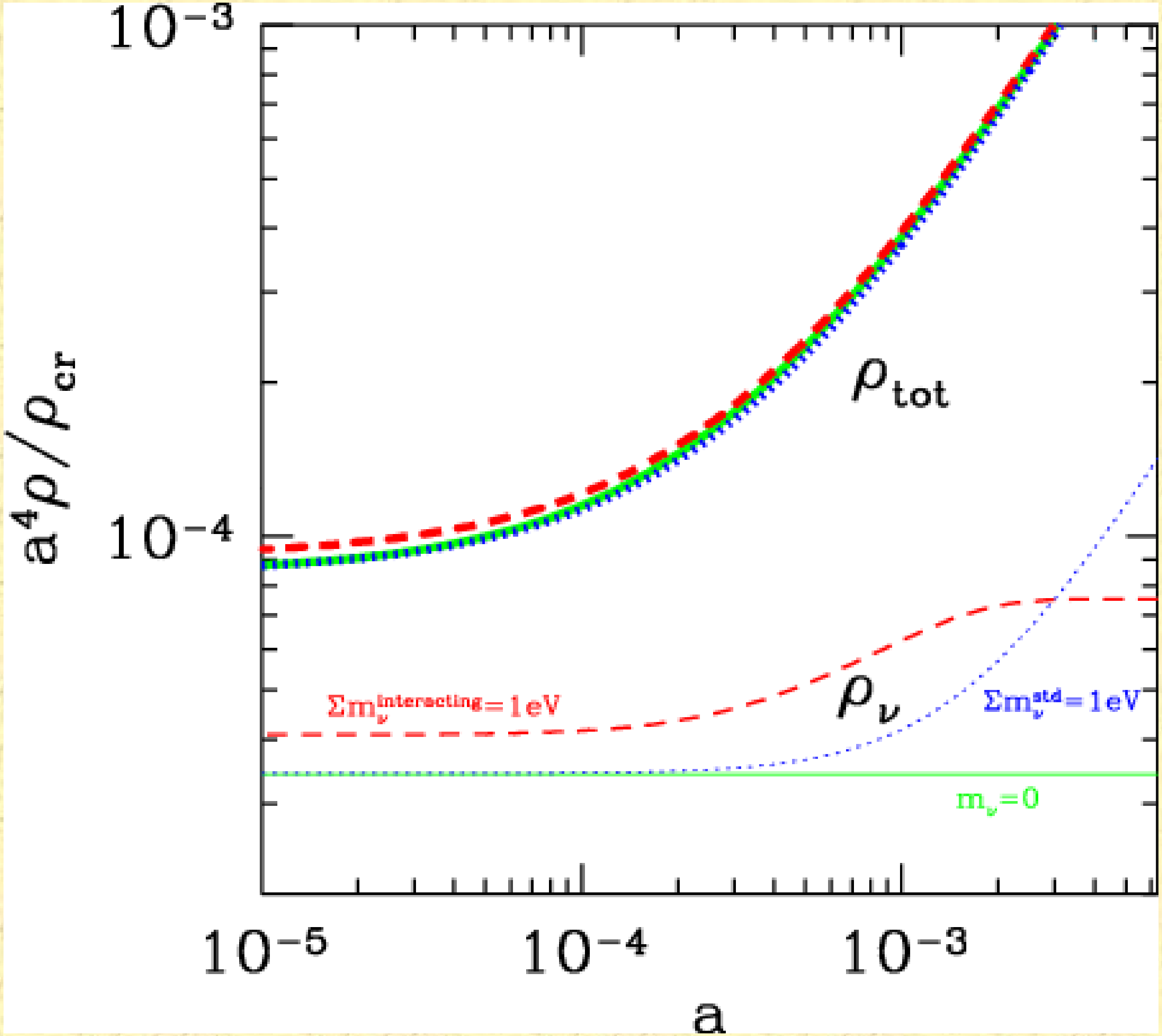
As the neutrinos annihilate, the neutrino temperature falls less sharply than usual.

$$\frac{T_{\nu\phi}}{T_\gamma} = \left(\frac{25}{11}\right)^{1/3}$$

This implies an increase in the energy density corresponding to an effective number of neutrinos: $N_\nu^{\text{eff}} = 6.6$

This delays the epoch of matter domination
→ Small suppression of the power spectrum.

Evolution of the Energy Density



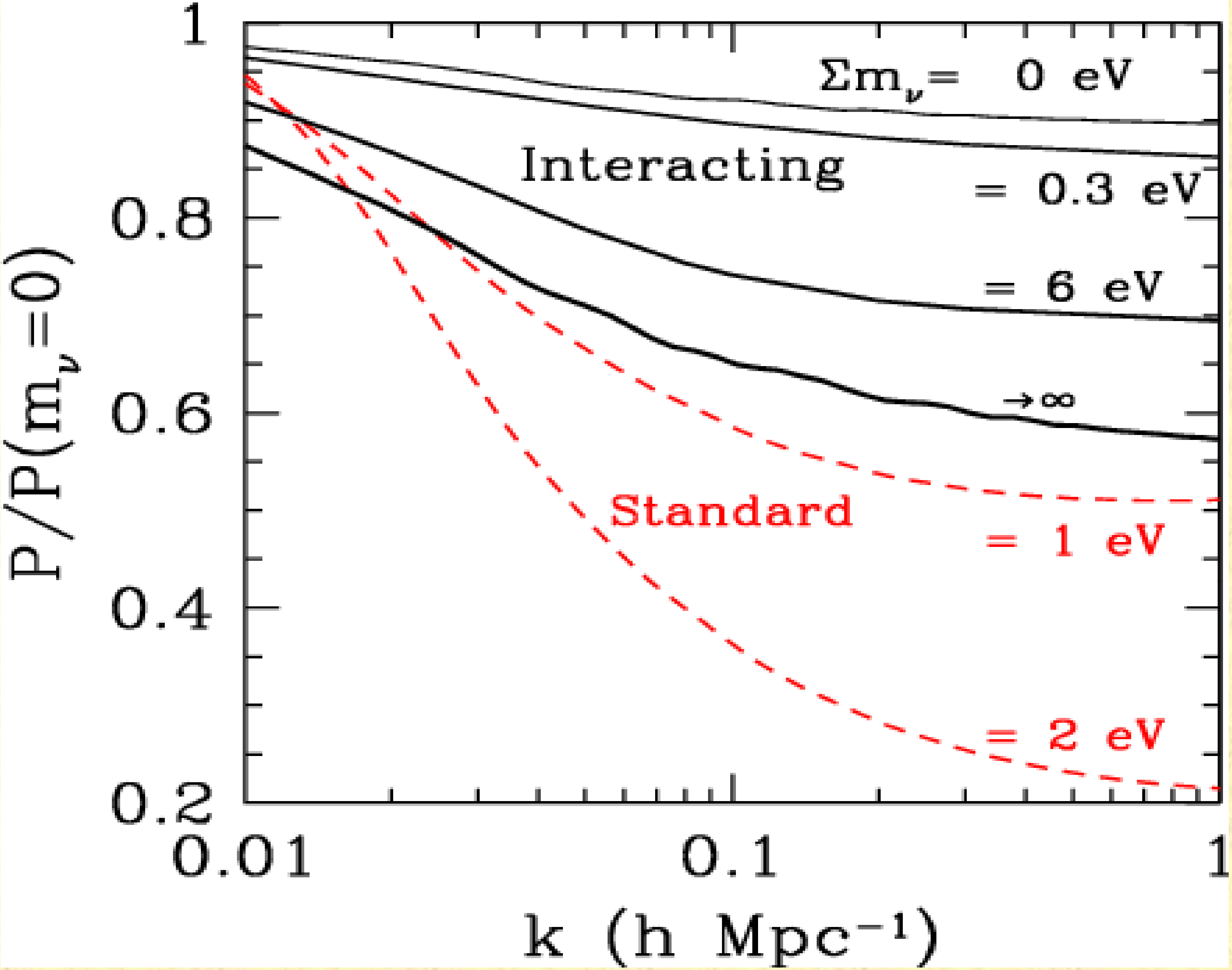
In the interacting scenario:

- Neutrinos don't free-stream like usual (though density perturbations in the neutrino/scalar fluid still cannot grow, due to pressure).

- The usual power spectrum suppression due to neutrino mass is absent, because the neutrinos all annihilated away and so make no contribution to the matter density today.

Effect on the power spectrum
→ entirely due to the slightly modified expansion history

Power Spectrum suppression:



Neutrinos and the
Cosmic Microwave Background

Neutrino signatures in the CMB

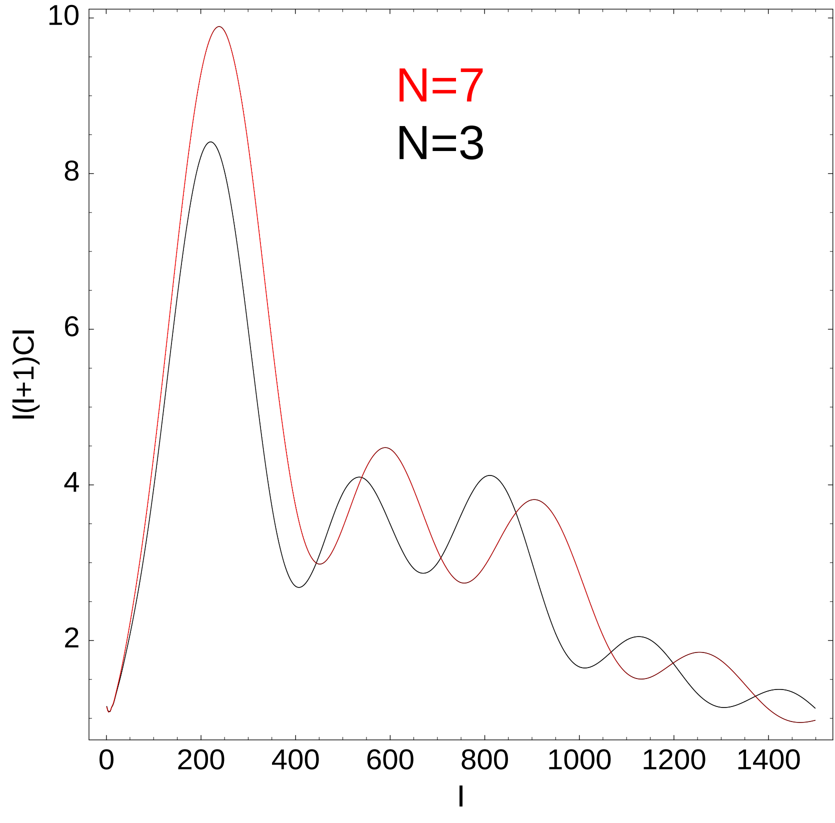
TOTAL RELATIVISTIC ENERGY DENSITY

Extra radiation (neutrinos or anything else) would mean the Universe was less matter dominated at CMB last scattering.

→ ISW effect enhances the first peak.
→ Phase shifts of the other peaks.

Present limit $N_\nu^{\rm eff}({\rm CMB}) < 7.1$

Compare $N_\nu^{\rm eff}({\rm BBN}) < 3.3 - 4$



See talk by Sergei Bashinsky.

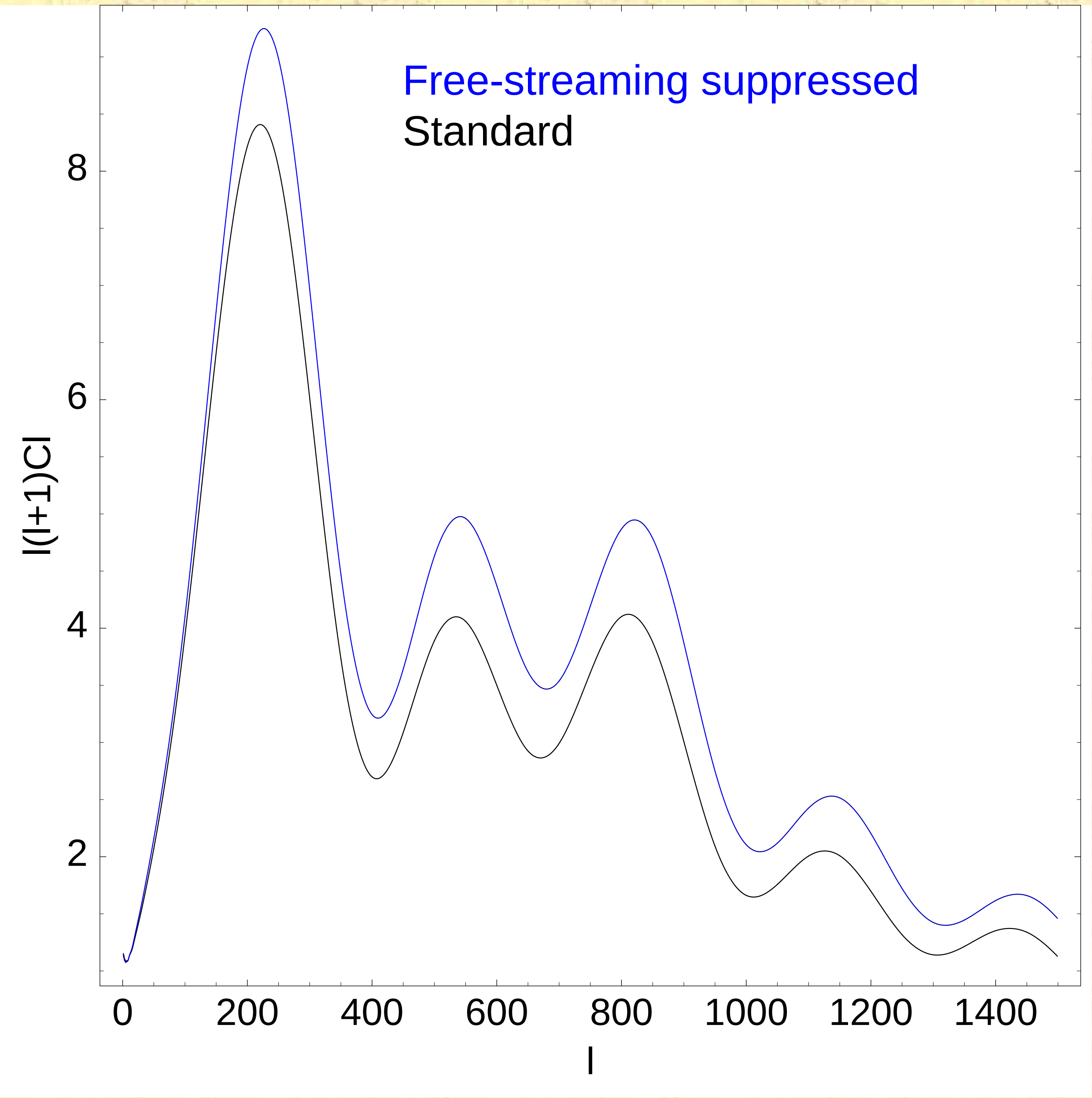
Neutrino *Interactions* & CMB

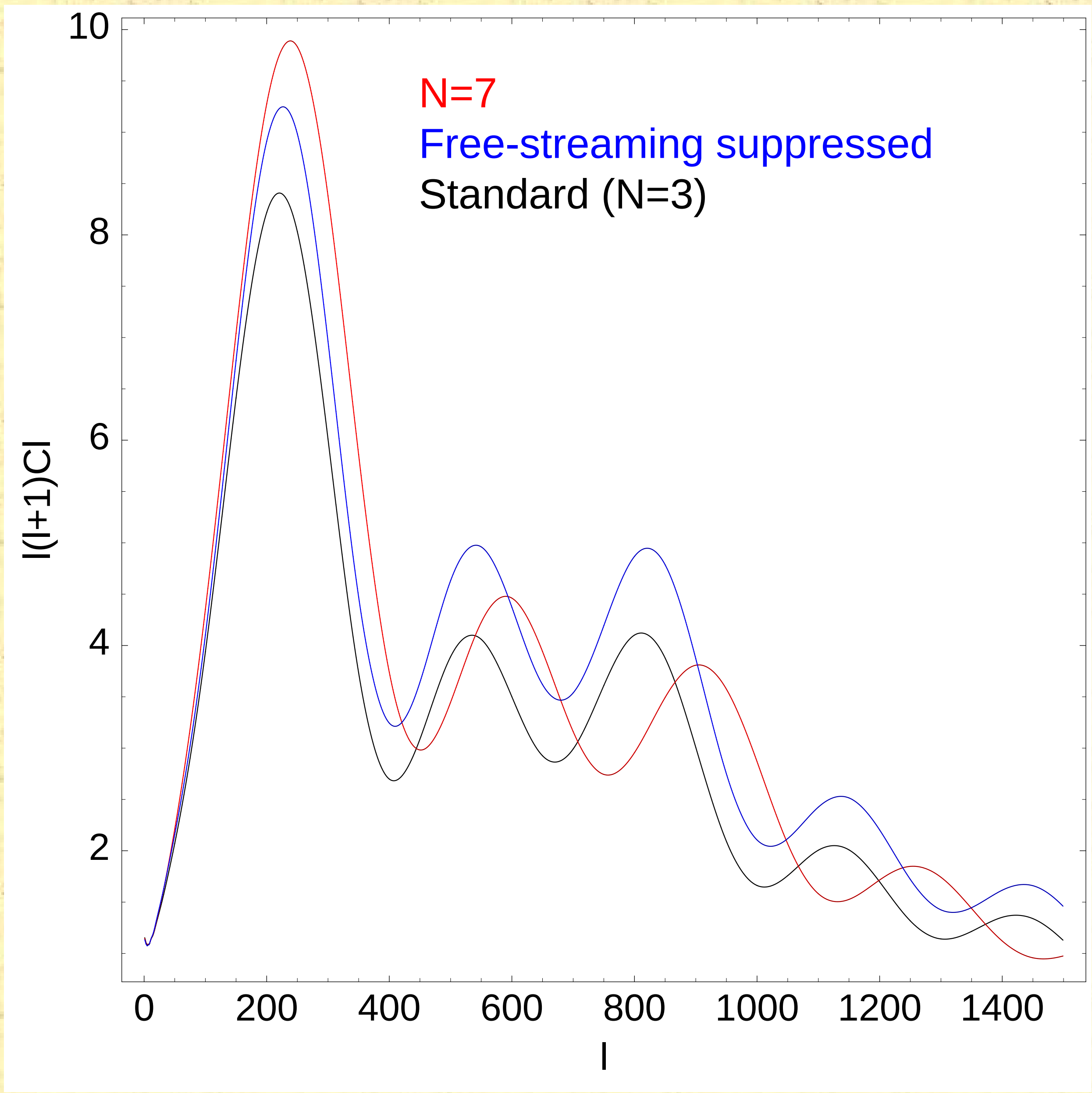
❖CMB sensitive to the presence of neutrino free-streaming.

❖Free-streaming affects the evolution of the neutrino perturbations → feedback to the CMB spectrum via gravity.

→**i.e. CMB is sensitive not only to the total relativistic energy density** ***but also to the microscopic interactions of the particles that contribute to the energy density***

Tightly coupled neutrino fluid:
→ Boltzmann eqns. truncated at the quadrupole.
→ Only have density and pressure perturbations.
→"Sheer" term is absent.


Free-streaming suppressed
Standard
8
6
4
2
l(l+1)Cl
0
200
400
600
800
1000
1200
1400
l



N=7
Free-streaming suppressed
Standard (N=3)
l(l+1)Cl
10
8
6
4
2
0
200
400
600
800
1000
1200
1400
l

Extra Neutrino Interactions & CMB

In general the effects will be a combination of:

1. Elimination of free-streaming
2. Extra relativistic degrees of freedom
3. Non-standard equation of state

→ 3. arises because the sound speed temporarily decreases during the epoch of neutrino annihilation.

Note also, that since the neutrino mass is close to the CMB decoupling temperature (T ~ 0.3 eV), the number of relativistic degrees of freedom (N_ν^{eff}) is not constant, but evolves during the CMB last scattering era.

Simplest Model

Fix the number of relativistic degrees of freedom to be constant.

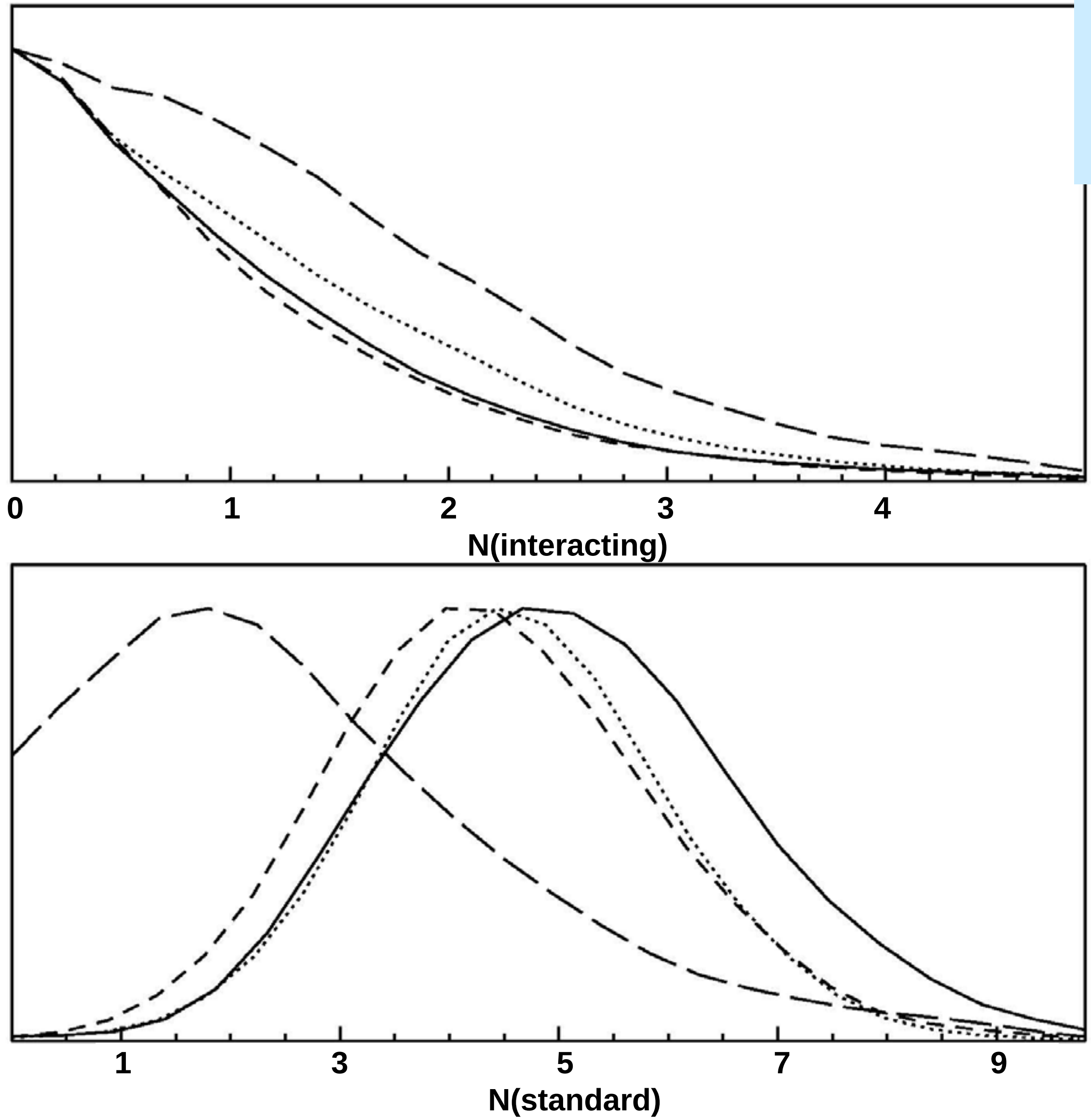
(A good approximation for models in which any annihilation or decay occurs well before or well after CMB last scattering)

Free parameters to be constrained:

→ N_ν^{standard} (standard free-streaming neutrinos)

$N_\nu^{\text{interacting}}$ (interacting neutrinos)

Marginalized likelihood distributions

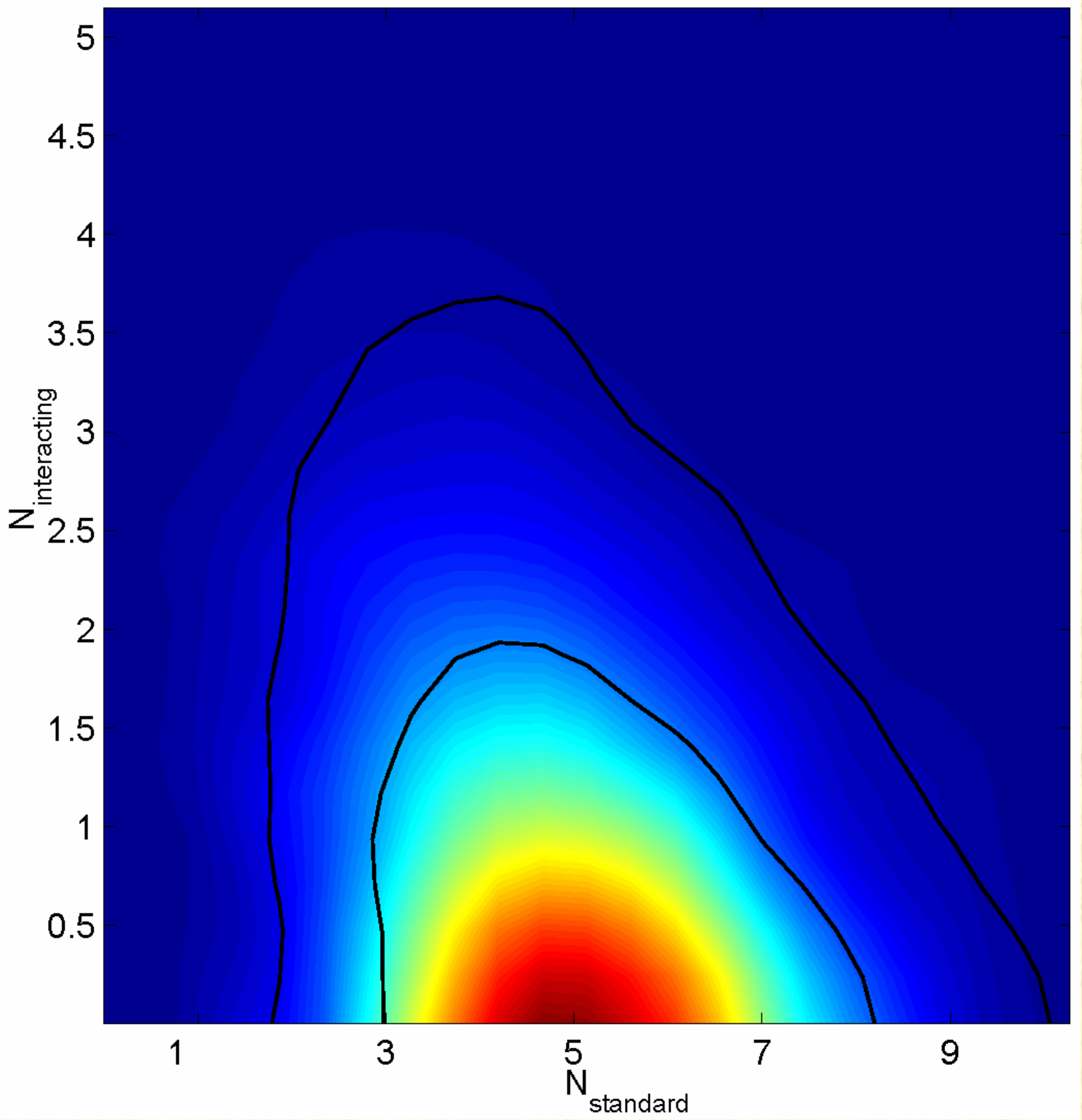


Long dashed → CMB only

Solid → CMB + SDSS/2dF

Dotted → CMB + SDSS/2dF + Lyman alpha

Bell, Pierpaoli and Sigurdson, in preparation.



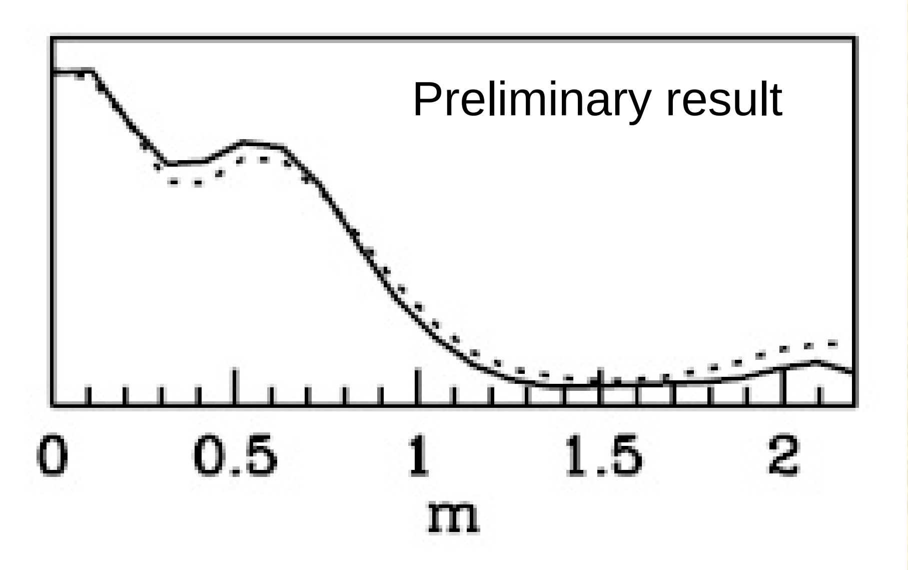
Bell, Pierpaoli and Sigurdson, in preparation.

Neutrinoless Universe Model

Neutrino annihilation → increase in number of relativistic degrees freedom during the during CMB decoupling era.

However, we find that these models are still a very good fit to all the data.

Marginalized likelihood



Bell, Pierpaoli and Sigurdson, in preparation.

Summary...

Extra interactions might keep the relic neutrinos in equilibrium until late times → leaving a *Neutrinoless Universe* today.

This can evade cosmological neutrino mass limits.

Beacom, Bell and Dodelson, Phys. Rev. Lett. 93, 121302 (2004)

The cosmic microwave background is sensitive to:

❖The total number of neutrinos

and

❖Any extra neutrino interactions which prevent free-streaming

Z. Chacko, L. Hall, T. Okui & S. Oliver; Bashinsky & Seljak; Hannestad; Trotta and Melchiorri; Bell, Pierpaoli and Sigurdson

...Summary

Other consequences of these interactions:

❖Drastic effects on supernova explosion mechanism

Fuller, Mayle and Wilson, ApJ 332, 826 (1988)

❖Neutrinos would decay over astronomical distances

→ Signals in neutrino telescopes

Beacom, Bell, Hooper, Pakvasa & Weiler, Phys. Rev. Lett. 90, 181301 (2003)

→Despite impressive cosmological neutrinos mass limits, laboratory methods (i.e. tritium beta decay and neutrinoless double beta decay) remain the most robust probe of the absolute neutrino mass scale.