Probing models of neutrino mass and neutrino interactions with cosmology and colliders

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A. Friedland, KZ, S. Bashinsky **arXiv:0704.3271**

Cosmology and Colliders

Low energy

High energy

Cosmology and Colliders

Low energy

High energy

Dark matter

Cosmology and Colliders

Low energy

High energy

Dark matter

Completely stable

TeV mass

Cosmology and Colliders

Low energy   High energy

Higher dimension operator

Cosmology and Colliders

Low energy   High energy

Higher dimension operator

Sensitive to very low rates (small couplings)

Produce directly

Models of Neutrino Mass

- Generate higher dimension operator with see-saw mechanism

$$L_{mass} = \frac{y^2 LHLH}{M}$$

$$(m_\nu \sim \frac{(100\ \text{GeV})^2}{M})$$

$$L_{mass} = yHLe_R + yHL\nu_R + M\nu_R\nu_R$$

$$\begin{matrix} & \nu_L & \nu_R \end{matrix}$$

$$m = \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \quad m_{light} \sim \frac{m_D^2}{M} \quad \Longleftrightarrow \quad L_{mass} = \frac{y^2 LHLH}{M}$$

Models of Neutrino Mass

- Right handed neutrino mass generated by additional scalar

$$L_{mass} = yHLe_R + yHL\nu_R + M\nu_R\nu_R \qquad L_{mass} = \frac{y^2 LHLH}{M}$$

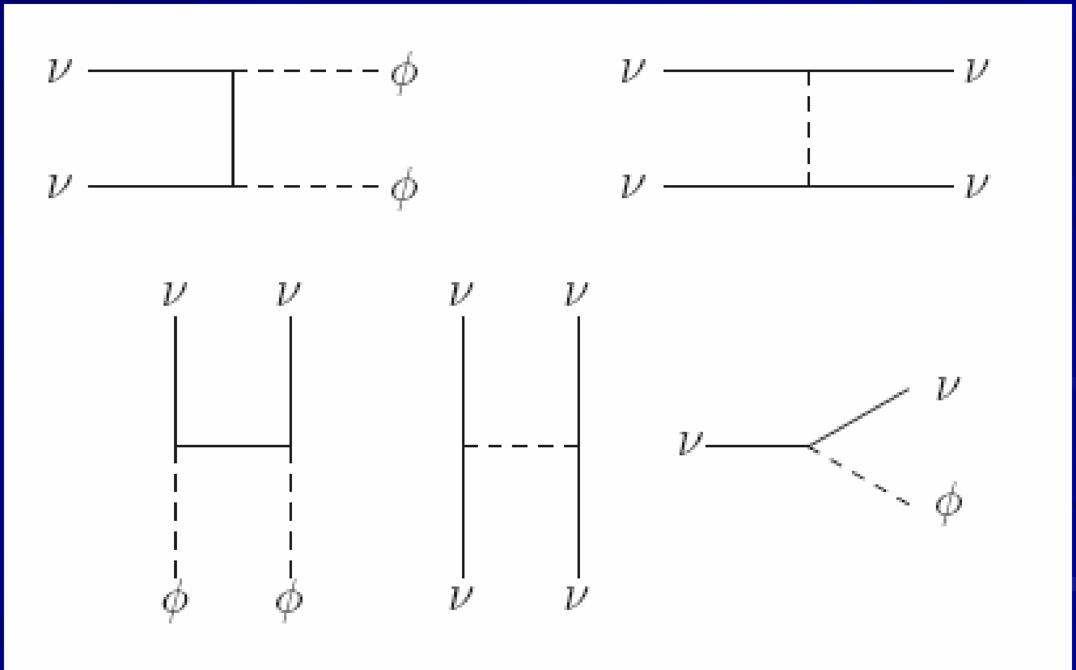
$$L_{mass} = yHLe_R + yHL\nu_R + \lambda\Phi\nu_R\nu_R \qquad L_{mass} = \frac{y^2 LHLH}{M}\frac{\lambda\Phi}{M}$$

- Effective interaction

$$L_{maj} = g\Phi\nu\nu \qquad g = \lambda\frac{m_D^2}{M^2}$$

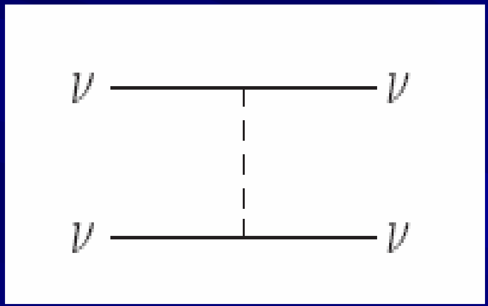
Coupled neutrinos

- Behaves like a fluid when $\Gamma_{scatt} > H$
- Turns off free-streaming and effects CMB spectrum

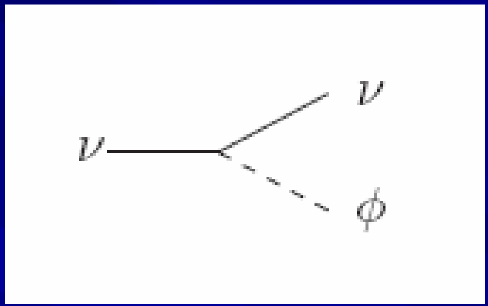


Implications for models

- CMB very sensitive to g through neutrino non-free-streaming $L_{maj} = g\Phi\nu\nu$



$\Gamma \sim g^4 T$



$\Gamma \sim g^2 T$

- Compare H at T ~ 1 eV
  – If neutrinos free-streaming → $g < 10^{-7} - 10^{-13}$

Sensitive to TeV scale neutrino mass generation

- Effective operator $$L_{mass} = \frac{y^2 LHLH}{M}\frac{\lambda\Phi}{M}$$

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Sensitive to TeV scale neutrino mass generation

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- Neutrino mass $$m_\nu = \lambda \frac{y^2 \langle H \rangle^2}{M} \sim 10^{-1}\ \text{eV}$$
  - Fix to experimental value

Sensitive to TeV scale neutrino mass generation

- Effective operator

$$L_{mass} = \frac{y^2 LHLH}{M}\frac{\lambda\Phi}{M}$$

- Neutrino couplings

$$L_{maj} = g\Phi\nu\nu \quad g = \lambda\frac{y^2\langle H^2\rangle}{M^2}$$

- Neutrino mass
  - Fix to experimental value

$$m_\nu = \lambda\frac{y^2\langle H\rangle^2}{M} \sim 10^{-1}\ \mathrm{eV}$$

- CMB sensitive to
  $g \sim 10^{-13}$ OR $M \sim 1\text{TeV}$

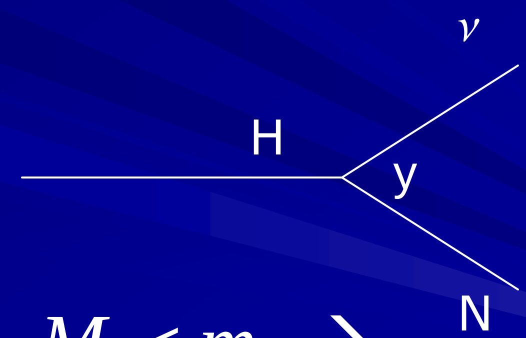
$$g \sim \frac{m_\nu}{M}$$

For collider physics

- TeV or lighter sterile neutrinos
- Higgs decays to heavier steriles?
- Too small Yukawas?

$$\begin{matrix} & \nu_L & N \end{matrix}$$

$$m = \begin{pmatrix} 0 & y\langle v \rangle \\ y\langle v \rangle & M \end{pmatrix}$$



– Satisfy $m_\nu \sim \frac{y^2 \langle v \rangle^2}{M} \sim 0.1\,\text{eV}$ $\quad M < m_h \rightarrow$

$$y < 10^{-5}$$

For collider physics

- Too naïve (de Gouvea 0706.1732)

$$m_\nu = \frac{y^2 \langle \mathrm{v} \rangle^2}{M \cos\zeta^* \sin\zeta^*}$$

- ζ (parameter in matrix diagonalizing ν masses) imaginary → exponential suppression of neutrino mass
- Can maintain large mixing

A toy example

From A. Nelson

See also Kersten and Smirnov, arXiv:0705.3221

$$\begin{matrix} \nu & N_1 & N_2 \end{matrix}$$

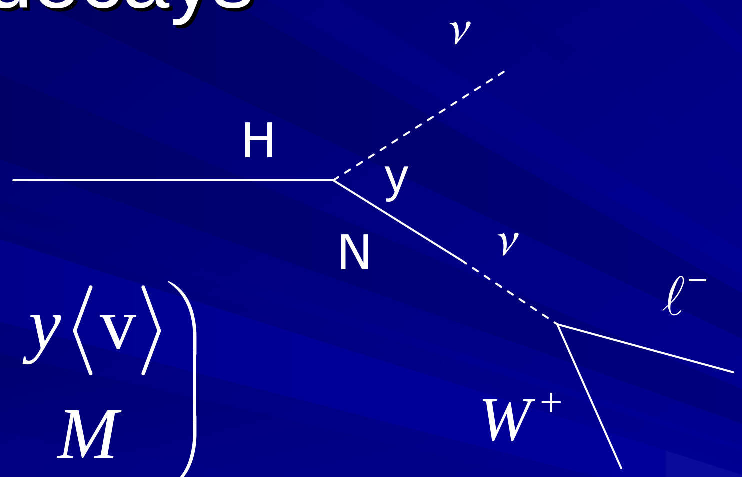
$$M = \begin{pmatrix} \varepsilon & m_D & 0 \\ m_D & M_1 & M_2 \\ 0 & M_2 & 0 \end{pmatrix}$$

$$\varepsilon \rightarrow 0,\ \det(M) \rightarrow 0 \ \Rightarrow \ \mathrm{m}_1 \rightarrow 0$$

Neutrino mass goes to zero as $\epsilon \rightarrow 0$, but mixing still large!

For collider physics

- Enhanced *y* → large branching fraction for exotic Higgs decays



$$m = \begin{pmatrix} 0 & y\langle \mathrm{v} \rangle \\ y\langle \mathrm{v} \rangle & M \end{pmatrix}$$

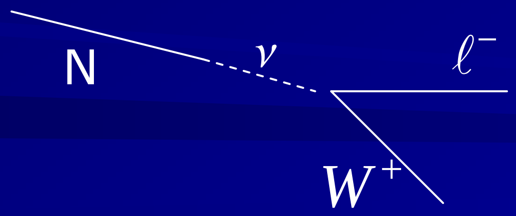
- H → missing energy + W^{+} + l^{-}

For collider physics

- Significant Higgs branching to neutrino singlets (Graesser 0704.0438, 0705.2190)

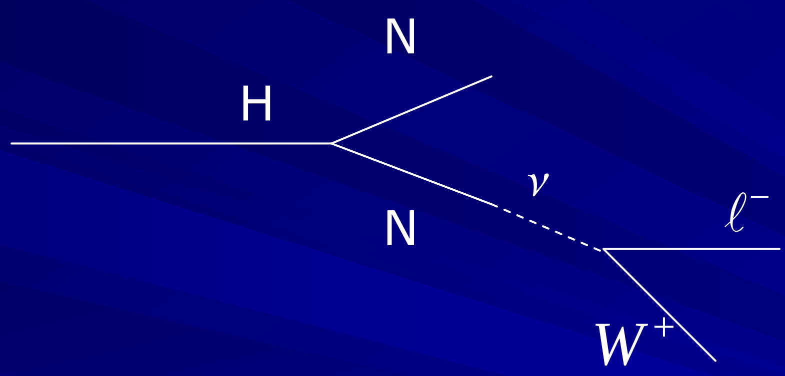
$$\frac{\lambda H^{\dagger} H N N}{\Lambda}$$

- Neutrinos decay through see-saw operators



Displaced vertices and hidden sectors

- Significant branching, but long lifetimes



- Decay length

$$\ell_N = 0.9\ \mathrm{m}\left(\frac{30\ \mathrm{GeV}}{\mathrm{M}}\right)^3\left(\frac{120\ \mathrm{kev}}{\mathrm{m_D}}\right)^2$$

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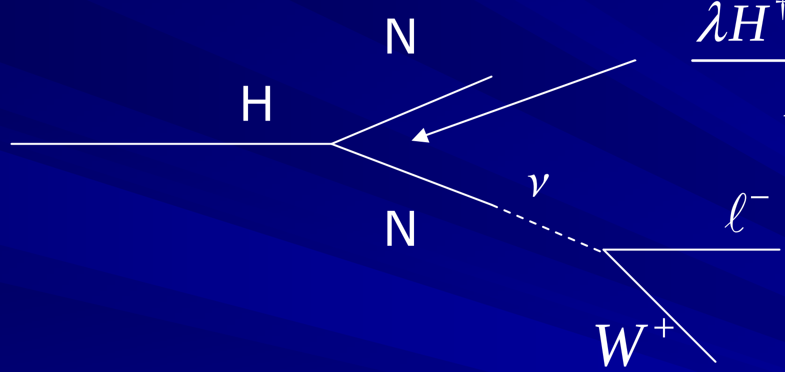

$$\frac{\lambda H^\dagger H N N}{\Lambda}$$ big

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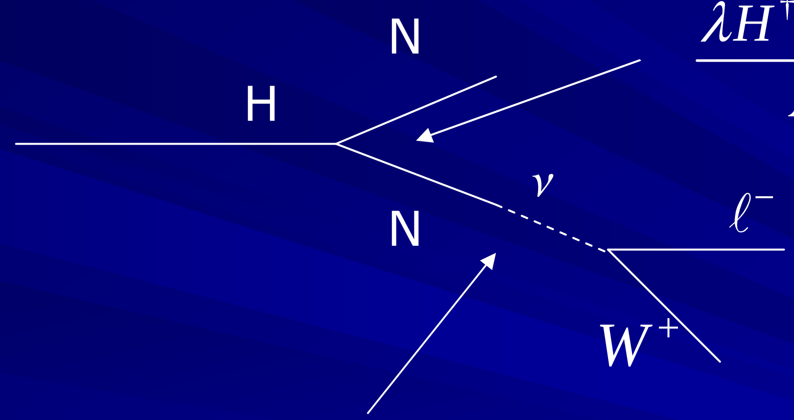


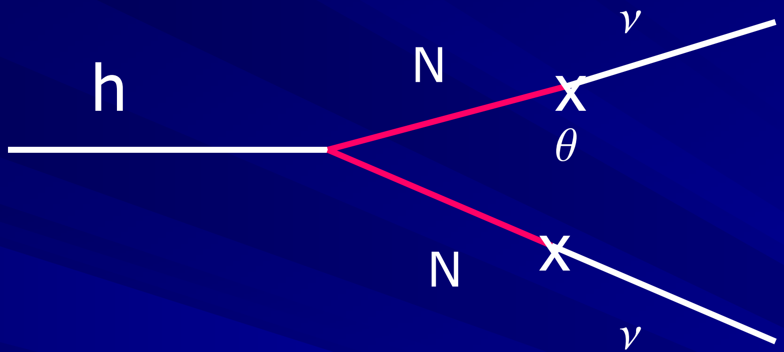
$$\theta \sim m_D / M \ll 1$$ small

- Decay length

$$\ell_N = 0.9 \text{ m} \left(\frac{30 \text{ GeV}}{\text{M}} \right)^3 \left(\frac{120 \text{ kev}}{\text{m}_\text{D}} \right)^2$$

Extend beyond neutrino singlets

- Hidden sector Higgs decays



- *a* is hidden sector pseudoscalar in NMSSM
- a→-a symmetry nearly exact
  - Mixing θ with Higgs small
  - Lifetimes long
  - Appearance of displaced vertices
  - Strassler and KZ, hep-ph/0605193

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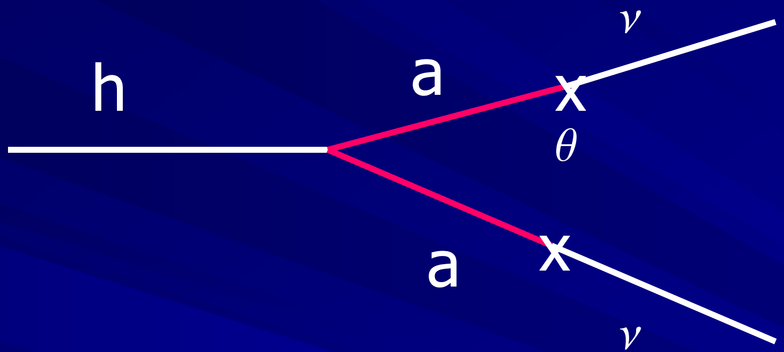

Dermisek and Gunion

PRL95:041801,2005

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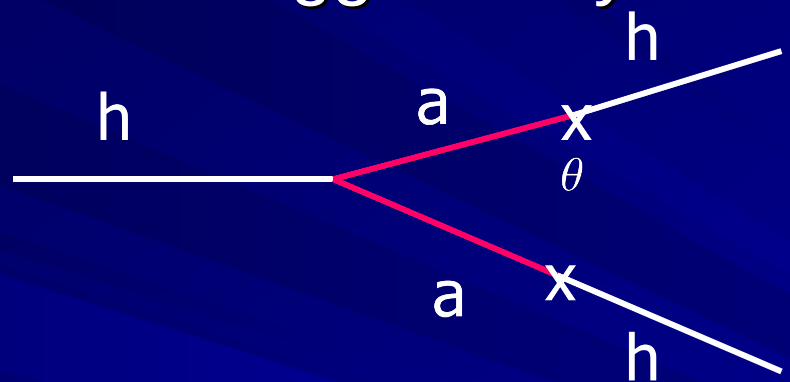

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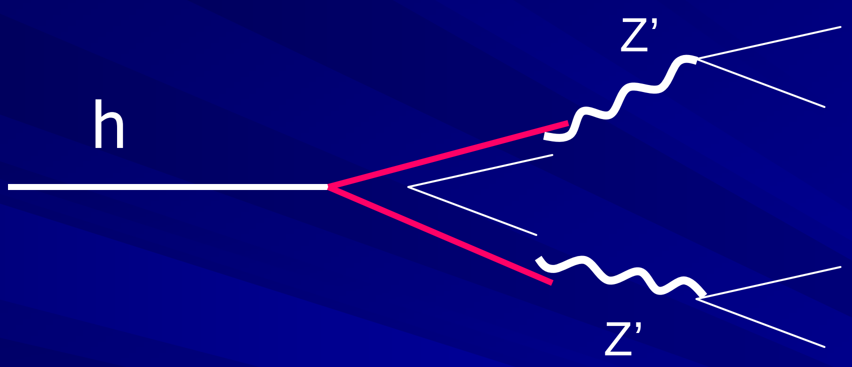


Strassler and Zurek

hep-ph/0604261

- Create light hidden sector bound states
- Long lived: decay through heavy Z'

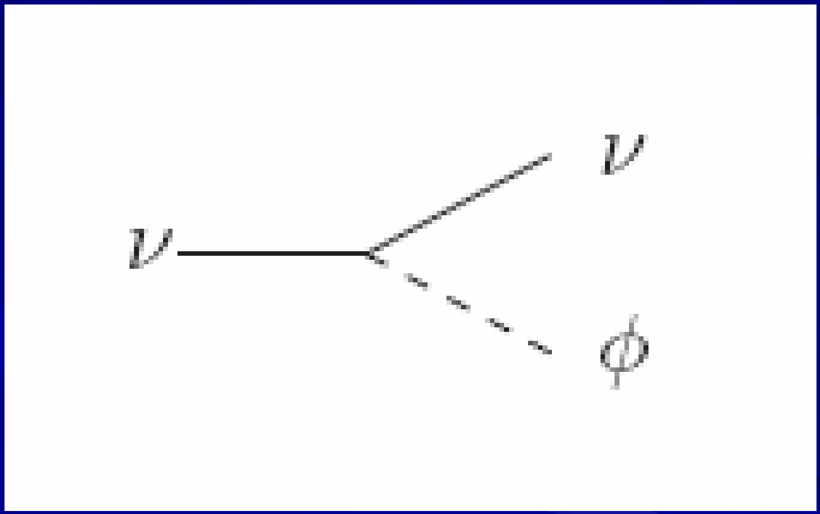
Collider physics and cosmology

- Higher dimension operators
  - Exotic Higgs decays
    - Significant branching to singlet states h → NN or h→νN
    - Singlets long lived
      - Decay through higher dimension operators
      - Displaced vertices
- CMB (can be) very sensitive to higher dimension operators of this type
  - Provided the operator invokes light states (neutrinos)

Return to CMB

$$L_{mass} = \frac{y^2 LHLH}{M}\frac{\lambda\Phi}{M} \rightarrow g\phi\nu\nu$$

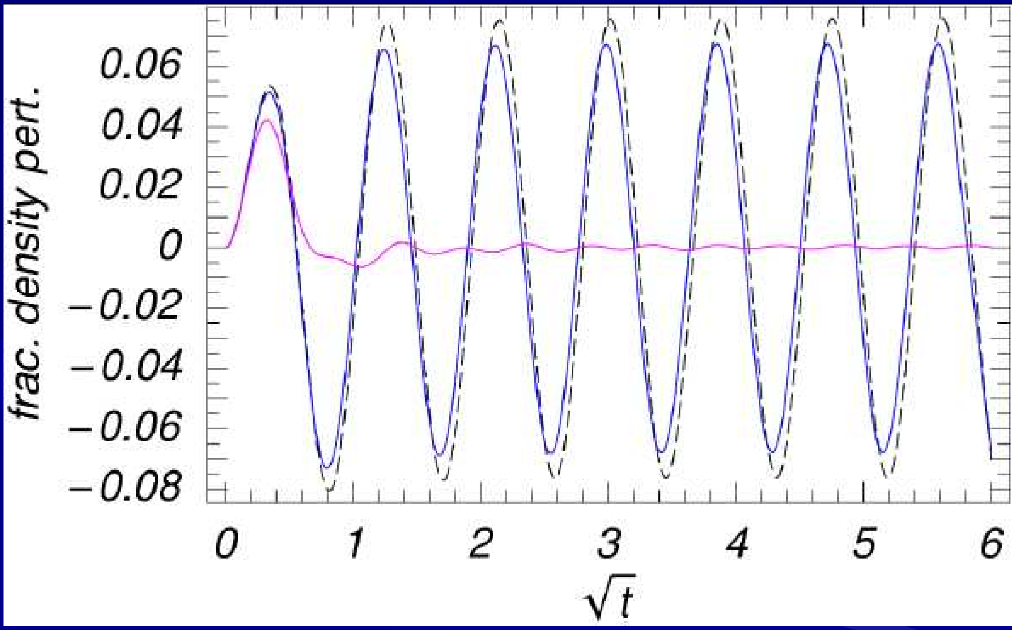
$$g \sim \frac{m_\nu}{M}$$



- Coupling turns off neutrino free-streaming if g > 10^{-13}

Effects of neutrinos on the CMB

- Gravitational coupling of neutrinos to photons has two effects
  - Oscillation amplitude suppressed (~10%)
  - Oscillation phase shifted



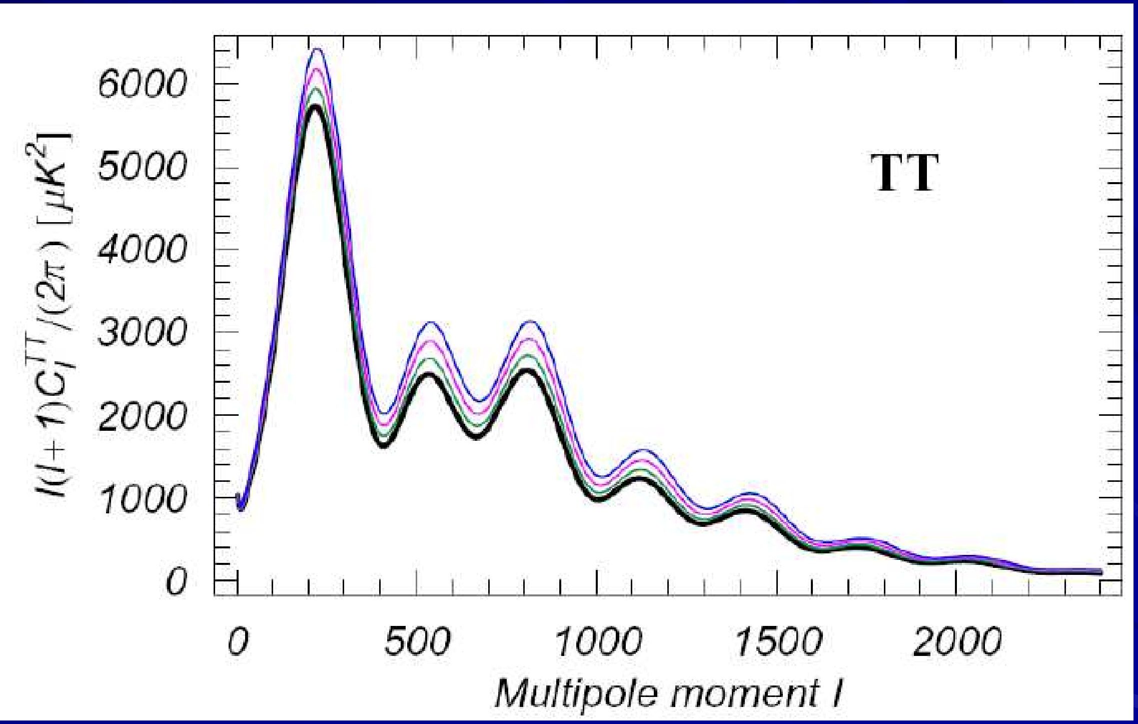
Peebles 1973

Turn off free-streaming with CMBFast

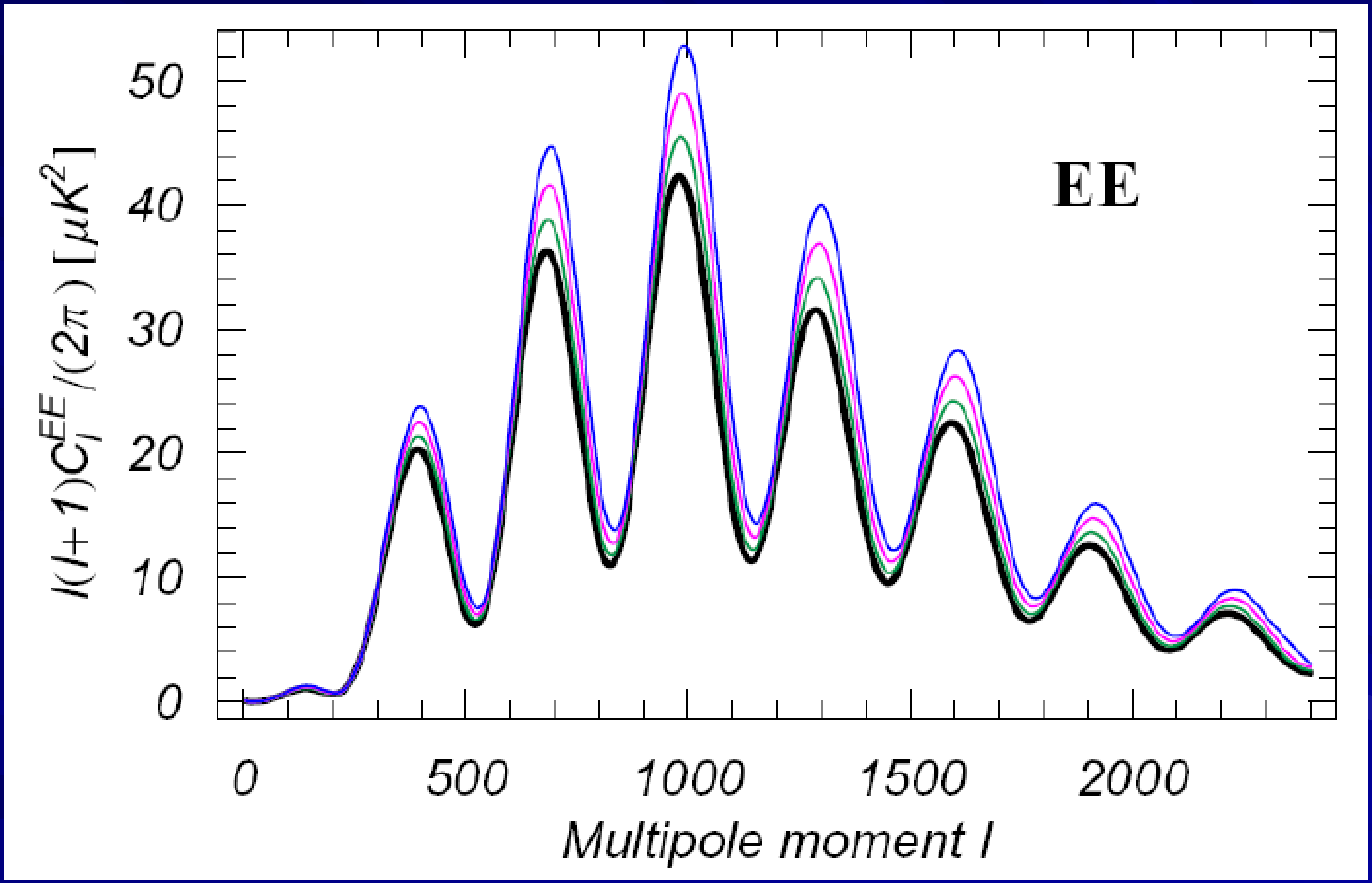
$$\dot{\delta}_\nu = -\frac{4}{3}\theta_n - \frac{2}{3}\dot{h}_\nu$$

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_n - \sigma_\nu\right)$$

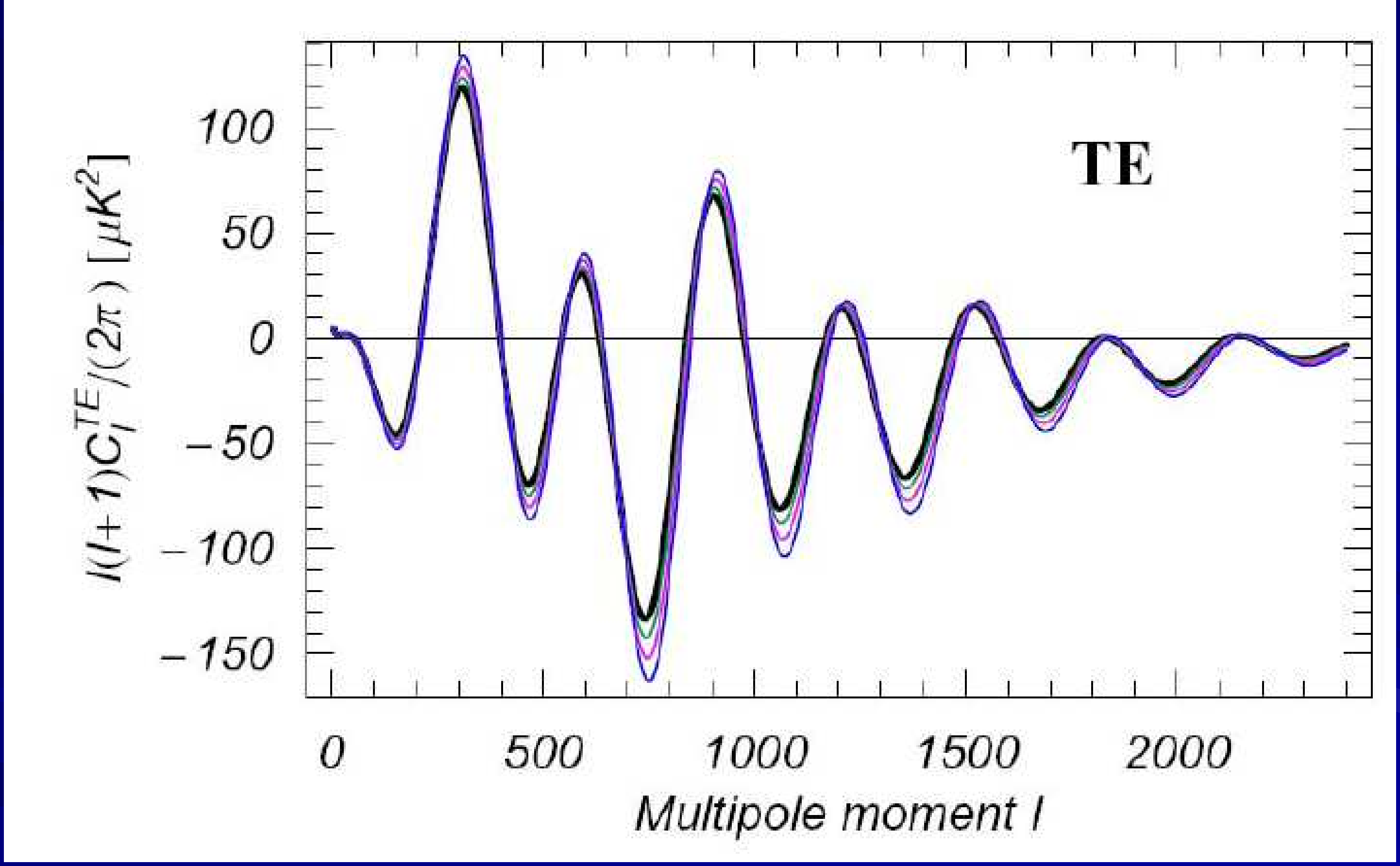
$$\dot{F}_{\nu l} = \frac{k}{2l+1}\left[lF_{\nu(l-1)} - (l+1)F_{\nu(l+1)}\right]$$



Turn off free-streaming with CMBFast



Turn off free-streaming with CMBFast



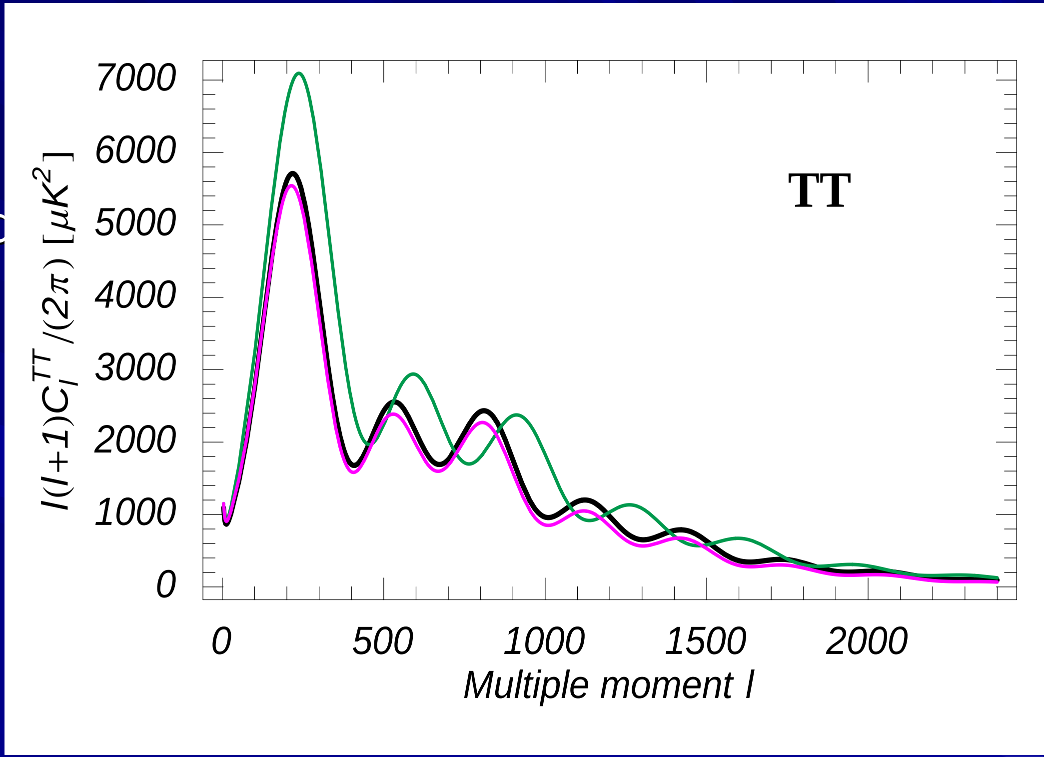
Coupled Neutrinos

- Effect appears to be large
- Current constraints on 3 coupled neutrinos
  - Trotta and Melchiorri, 2.4σ with all data
  - Bell, Pierapaoli, Sigurdson, 2σ with all data
- Single coupled neutrino unconstrained
- They are quite weak—why?
- Parameter degeneracies

$$\left(\rho_m, \rho_b, \omega_{\nu \text{ massive,}} N_\nu, N_\nu^{fs}, \rho_{de}, w_{de}, \tau_{reion}, P, n_s, n_s', Y\right)$$

Illustrated with extra neutrinos

- 3 neutrinos (black) → 7 neutrinos (green)
- Surprising results
  - The plot shows a boost and not a suppression in the amplitude
  - Effect is very big → might imply high exclusion of additional neutrinos
  - Current constraints: $N_{FS}=5^{+2}_{-2}$

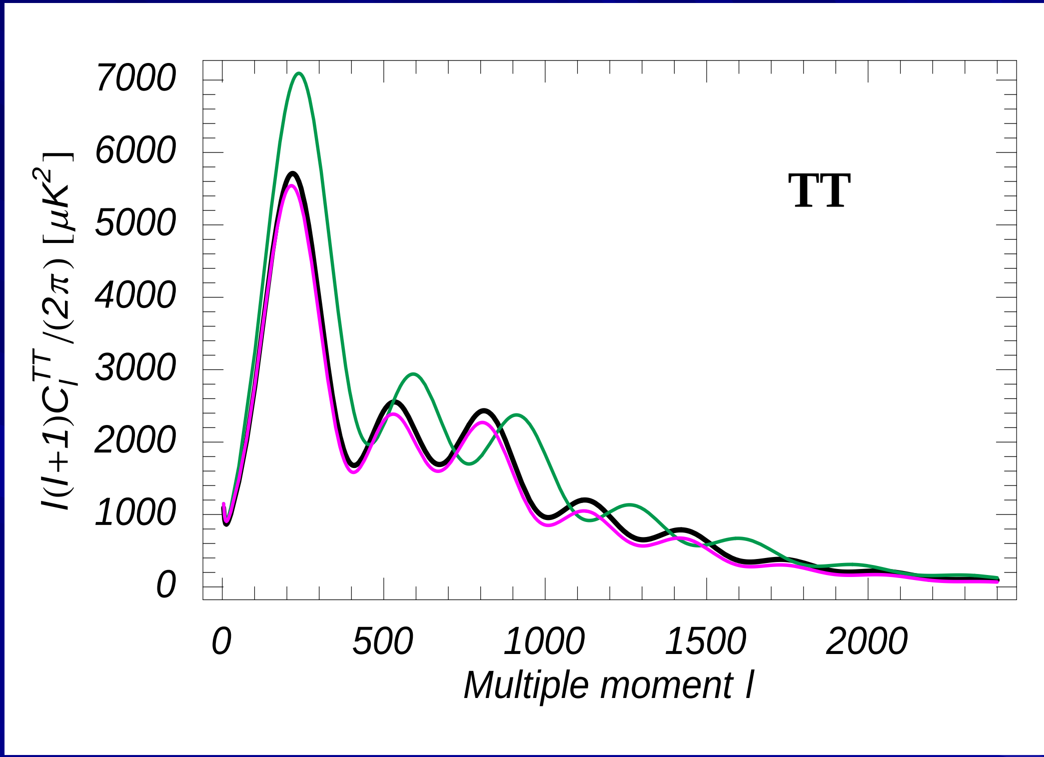


Background effects

- Boost due to delay in zeq
- Rescale h to re-fix zeq (magenta)

$$1 + z_{eq} = 4.05\times10^4 \frac{\Omega_m h^2}{1+0.6905 N_\nu / 3.04}$$

- Small suppression of Peebles' solution now evident
- Due to neutrino anisotropy



Residual Effects

- Real challenge is to establish the residual differences between two models (within experimental precision) after "nuisance parameters" have been adjusted for
- The residual differences are much smaller
- Cannot be estimated analytically
  - Fisher matrix method can be used
  - Best to do a scan in the parameter space using Monte Carlo

WMAP alone

- WMAP cannot rule out coupled neutrinos, tells you little about $N_{coupled}$, N_{FS}
- Parameter degeneracies
  - – N_{FS} Preseve zeq by raising $\Omega_m h^2$, compensate other residuals by bias and n_s
  - – $N_{coupled}$ Compensate primarily by bias and n_s

$(N_{FS}, N_{coupled})$	$\delta\chi^2$	C.L.
$(3,0)$	–	–
$(2,1)$	0.2	0.1σ
$(1,2)$	0.4	0.2σ
$(0,3)$	1.4	0.7σ
$(1,0)$	0.6	0.3σ
$(5,0)$	0.6	0.3σ

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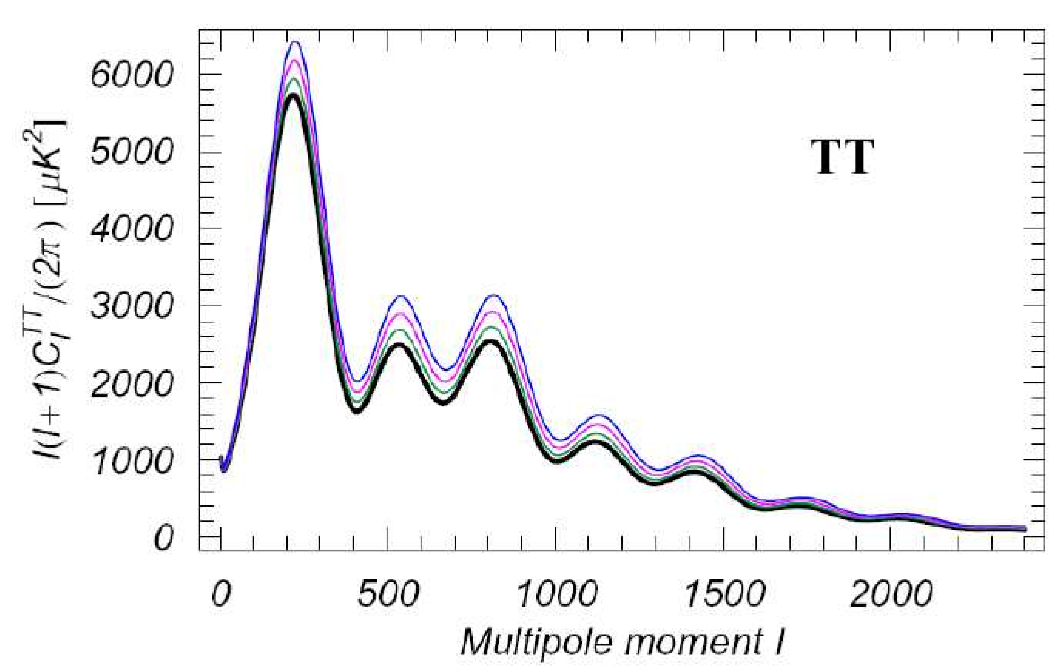

$N_{coupled}$	n_s	$\log(10_{10} A_s)$
0	.95	3.0
1	.93	2.9
3	.90	2.8

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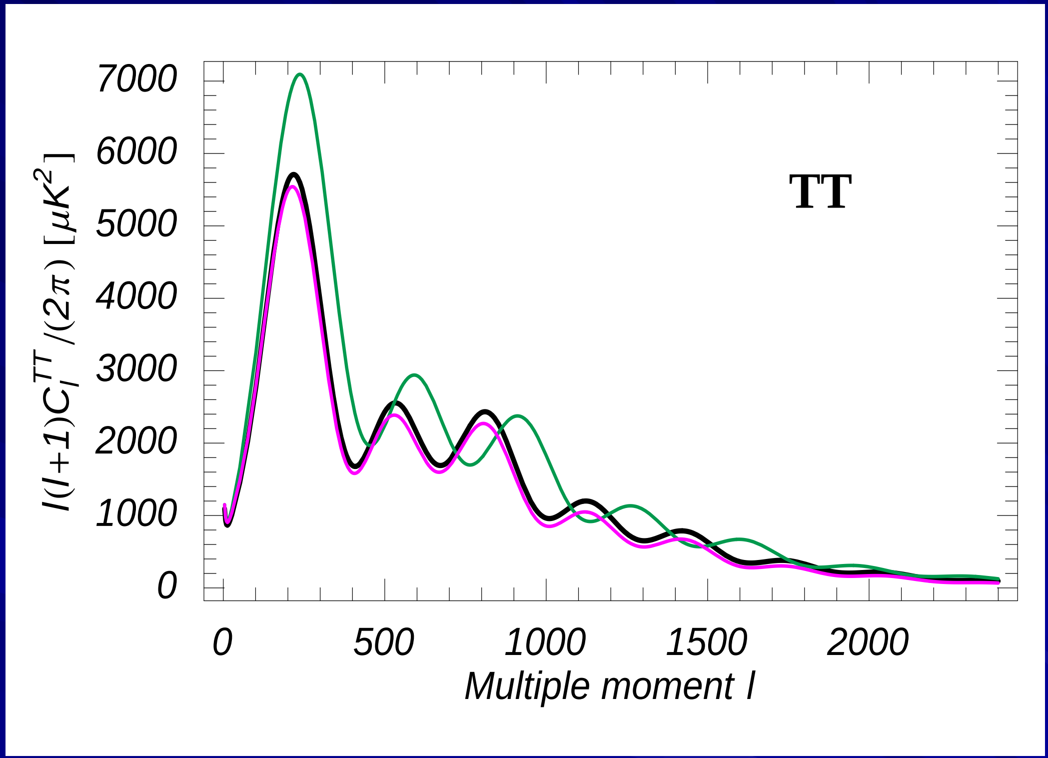


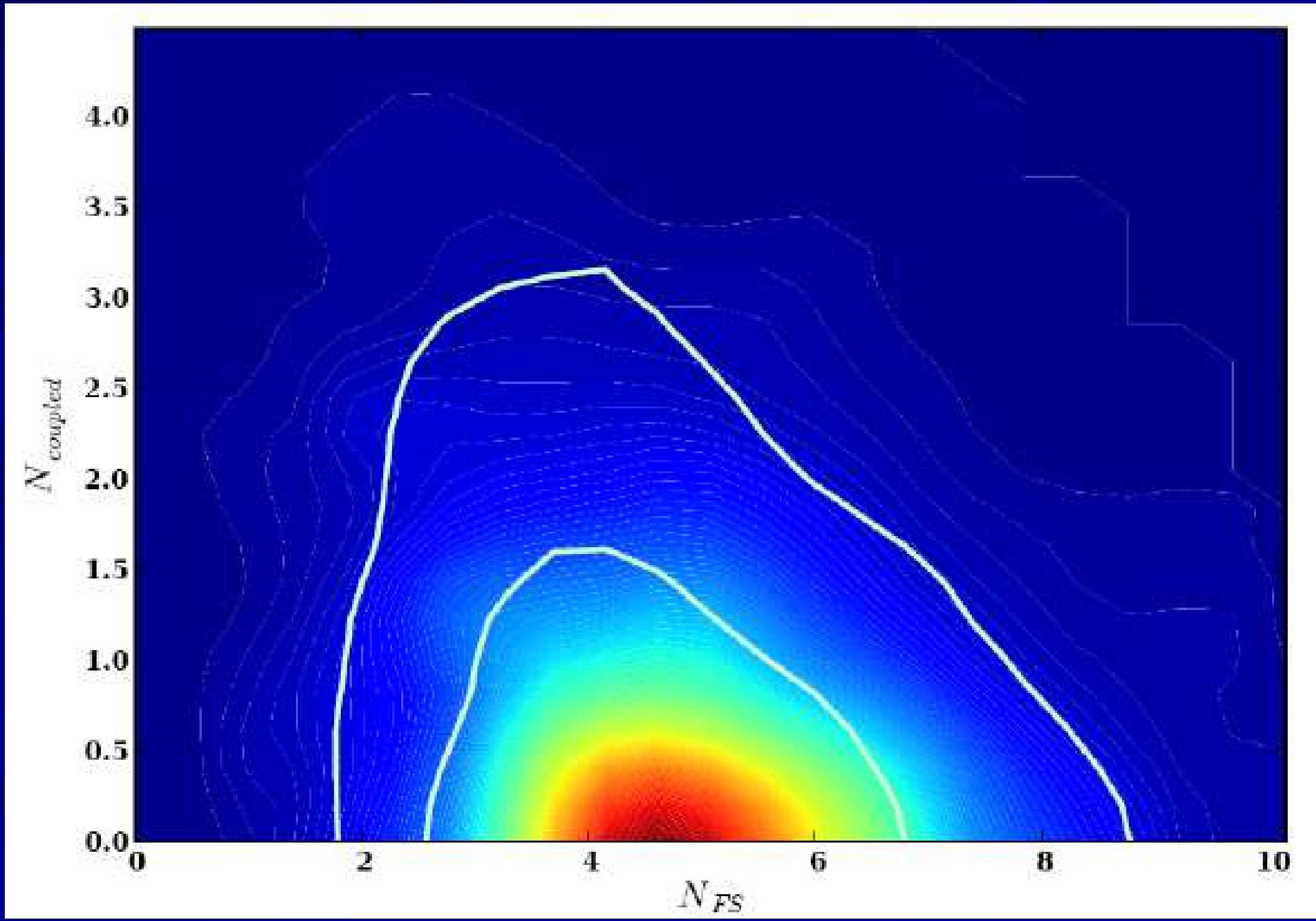
N_{FS}	$\Omega_m h^2$	n_s	$\log(10_{10} A_s)$
3	.11	.95	3.0
5	.07	.91	2.9
1	.14	.97	3.1

WMAP+LSS+HST+SNIa

- The LSS data do help break degeneracies
- …But it depends strongly on which data are used
- SDSS main and LRG data samples are not equivalent

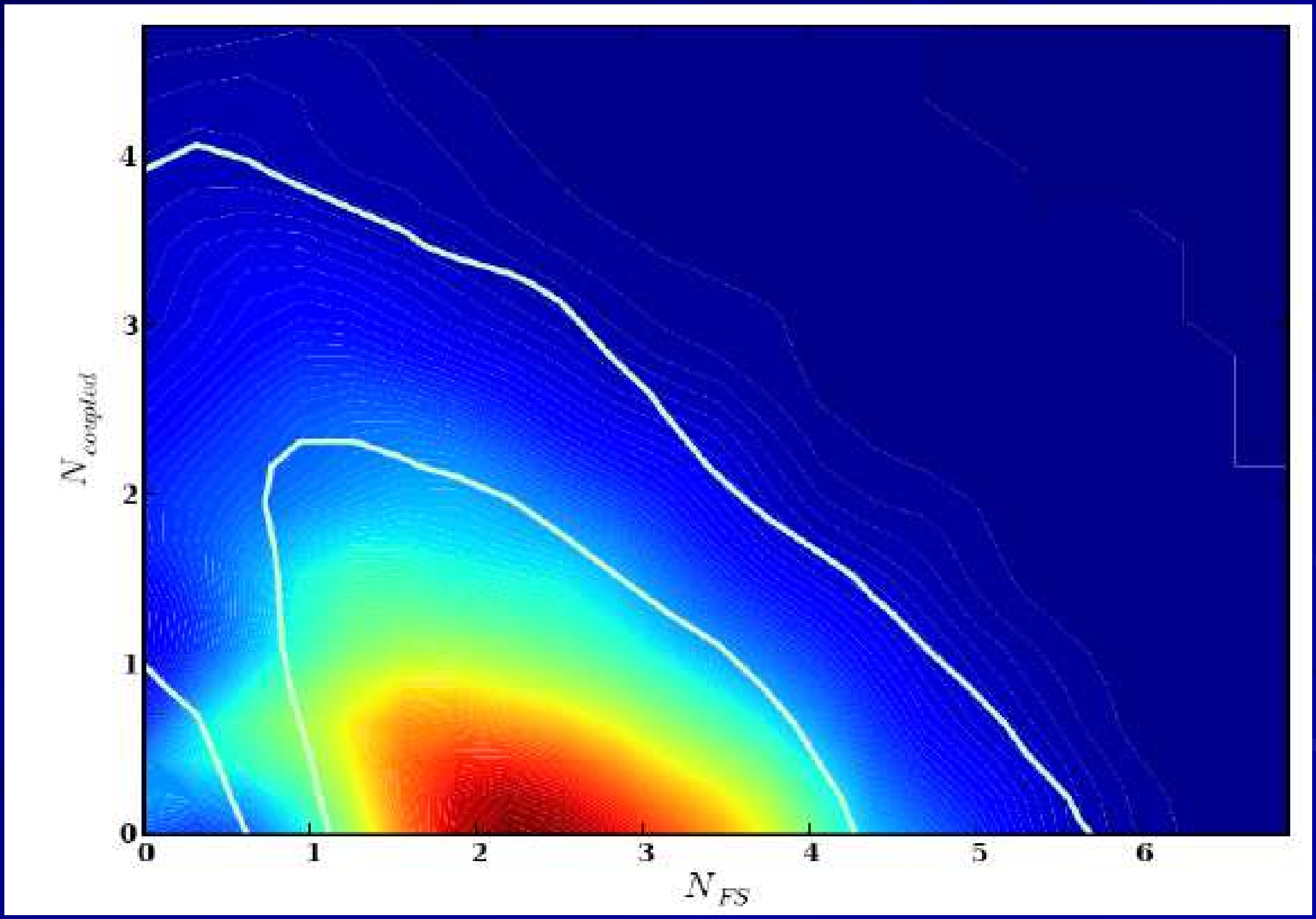
WMAP+2dF+SDSS main+HST+SNIa

- Best fit N_{FS}=5
- Excludes $N_{coupled}$ =3 at > 3σ



WMAP+2dF+SDSS LRG+HST+SNIa

- Best fit N_{FS}=3
- $N_{coupled}$ =3 disfavored at < 2σ



Consistent with the trends in N_{FS} observed in other works

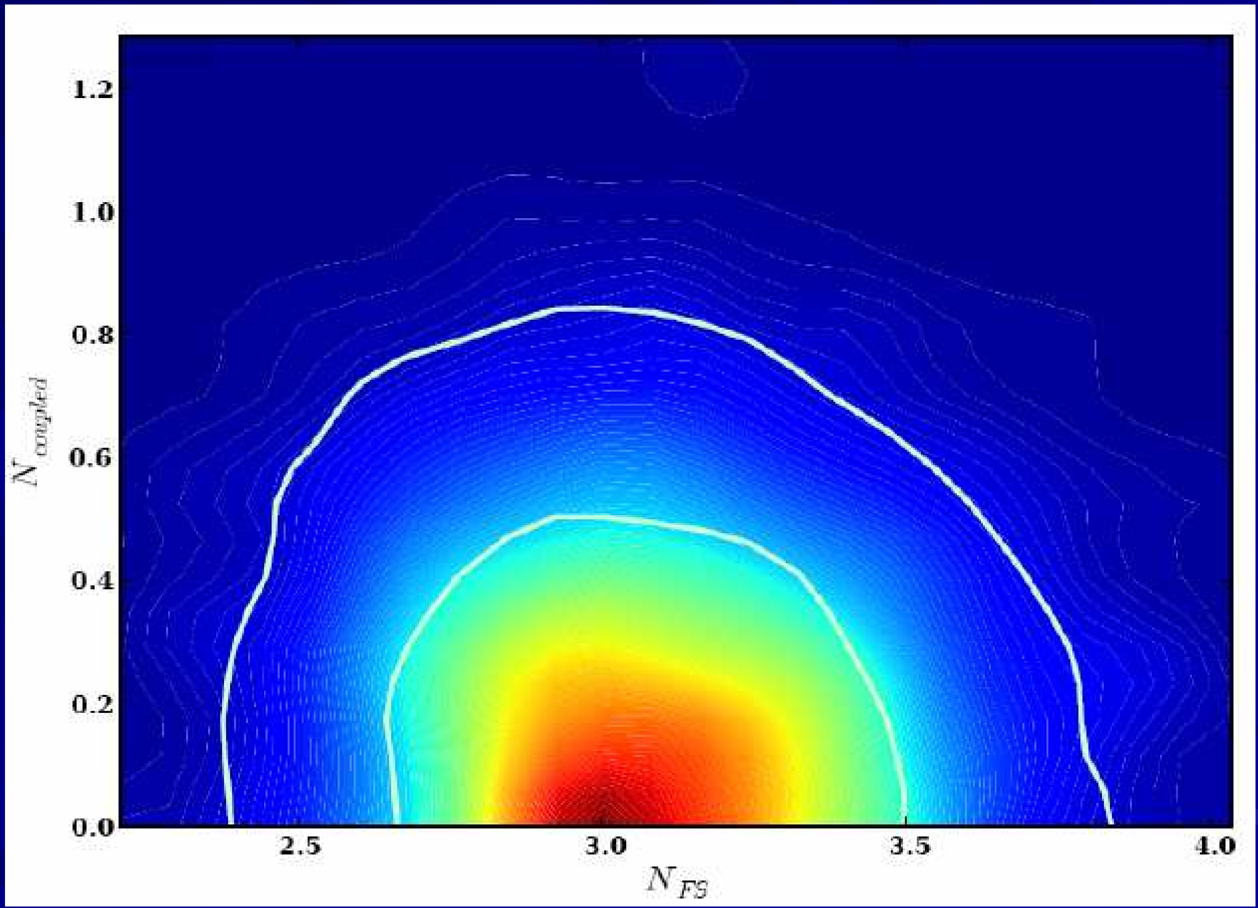
- LRG pulls the fit to smaller N_{FS}
  - Ichikawa, Kawasaki, and Takahashi $N_{FS}=3.1^{+5.1}_{-2.2}$
  - Hamann, Hannestad, Raffelt, Wong $N_{FS}=2.7^{+6.2}_{-1.2}$
- Lyα tends to pull it up
  - Hamann, Hannestad, Raffelt, Wong $N_{FS}=6.6^{+10}_{-3.3}$
  - Seljak, Slosar, McDonald All: $N_{FS}=5.3^{+2.9}_{-1.7}$
    All – Lyα $N_{FS}=3.9^{+2.9}_{-1.7}$
- Also shown to be sensitive to type of statistical inference utilized
  - Hamann, Hannestad, Raffelt, Wong

At the end of the day….

- Data consistent with 3 SM neutrinos
  - Seljak, Slosar, McDonald $N_{FS}=5.3^{+2.9}_{-1.7}$
  - Large errors (+/- several neutrinos)
- Data constent with having those neutrinos coupled at CMB temperatures
  - Friedland, KZ, Bashinsky
- Strongly dependent on the data set
- Constraints are not conclusive!

Planck trumps all

- Only Planck
- $\Delta N_{FS} = {}^{+0.5}_{-0.3}$
- $\Delta N_{coupled} = {}^{+0.4}$
- Other data doesn't change exclusion on ΔN_{FS}



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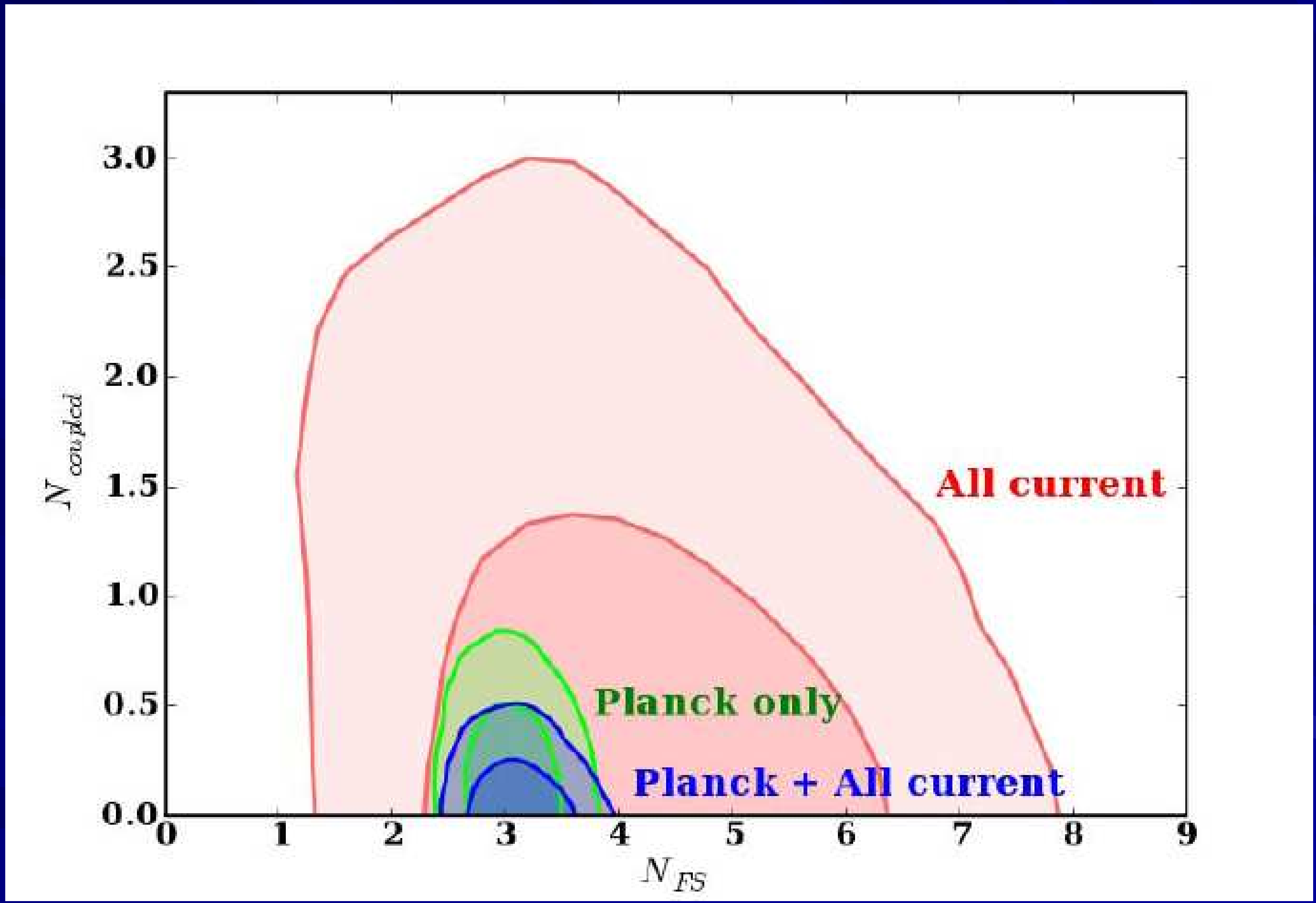
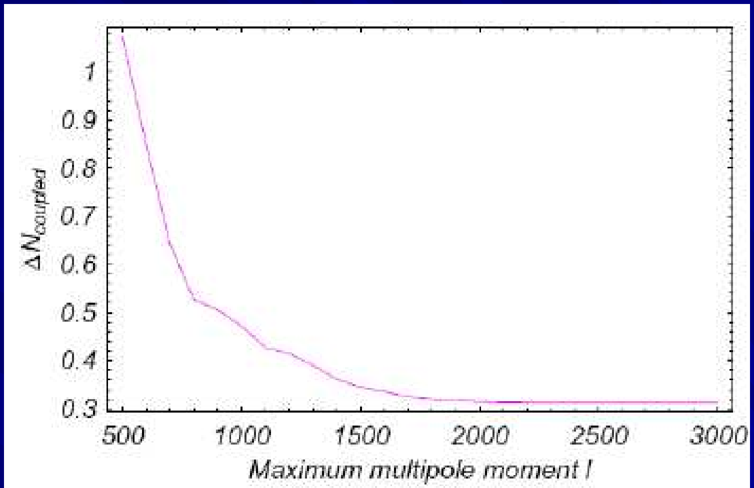
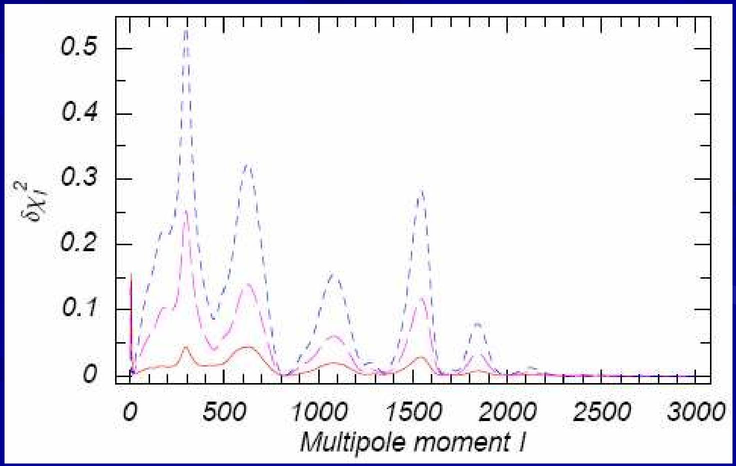


Why does Planck do so well?

- High multipole or good polarization info?





Conclusions

- Many interesting models generate non-standard neutrino interactions
  - Neutrino see-saws
  - Majoron models
- These models may generate signals in CMB through removing neutrino free-streaming / populating extra states
- Some of the same models generate exotic Higgs physics
- While WMAP + all other data constrains rather little neutrino free-streaming and additional thermalized neutrinos, Planck will rule out (or detect at 2 – 3 σ level) single coupled neutrino or additional neutrinos.