Title: The Neutrino Puzzle: Anomalies, Interactions, and Cosmological Tensions

Speakers: Francis-Yan Cyr-Racine

Series: Particle Physics

Date: June 11, 2019 - 1:00 PM

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Abstract: New physics in the neutrino sector might be necessary to address anomalies between different neutrino oscillation experiments. Intriguingly, it also offers a possible solution to the discrepant cosmological measurements of H_0.
We show here that delaying the onset of neutrino free-streaming until close to the epoch of matter-radiation equality can naturally accommodate a larger value for the Hubble constant, while not degrading the fit to the cosmic microwave background (CMB) damping tail. We achieve this by introducing neutrino self-interactions in the presence of a non-vanishing sum of neutrino masses. This "strongly interacting" neutrino cosmology prefers a 3+1 neutrino scenario, which has interesting implications for particle model-building and neutrino oscillation anomalies. Due to their impact on the evolution of the gravitational potential at early times, self-interacting neutrinos and their subsequent decoupling leave a tell-tale structure on the matter power spectrum.
Our analysis shows that it is possible to find radically different cosmological models that nonetheless provide excellent fits to the data, hence providing an impetus to thoroughly explore alternate cosmological scenarios.

Precision Cosmology Era

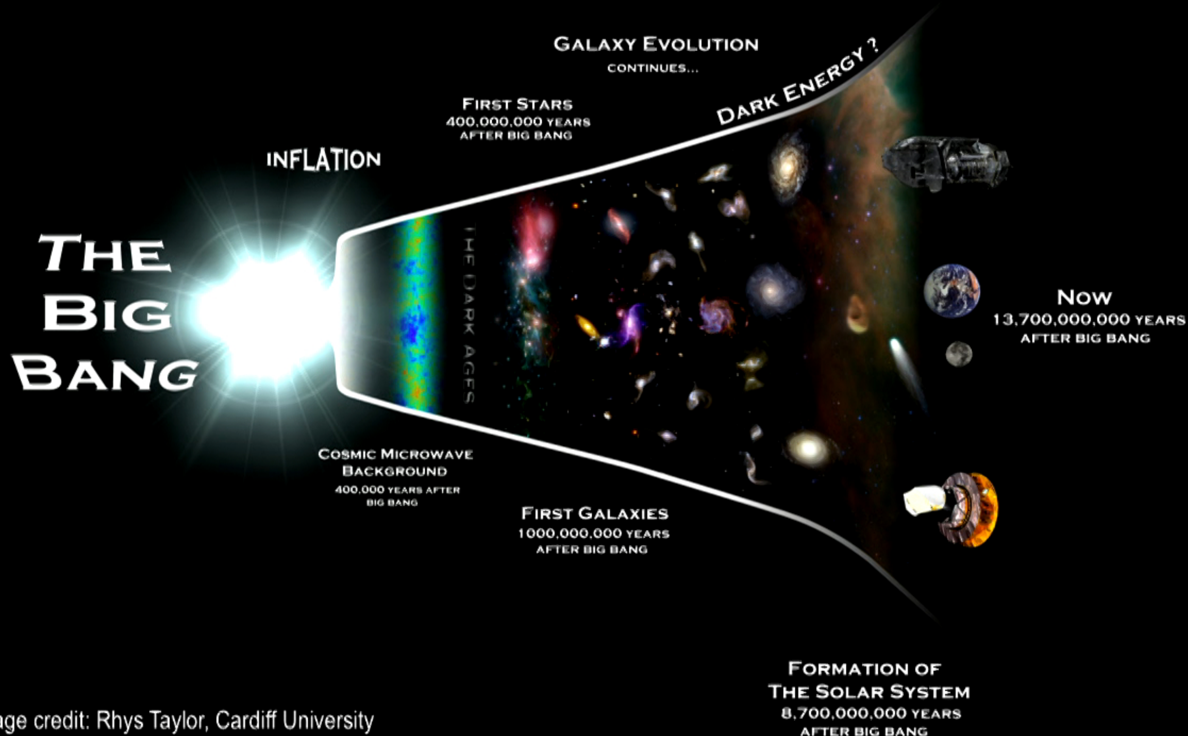


Image credit: Rhys Taylor, Cardiff University

Precision Cosmology Era

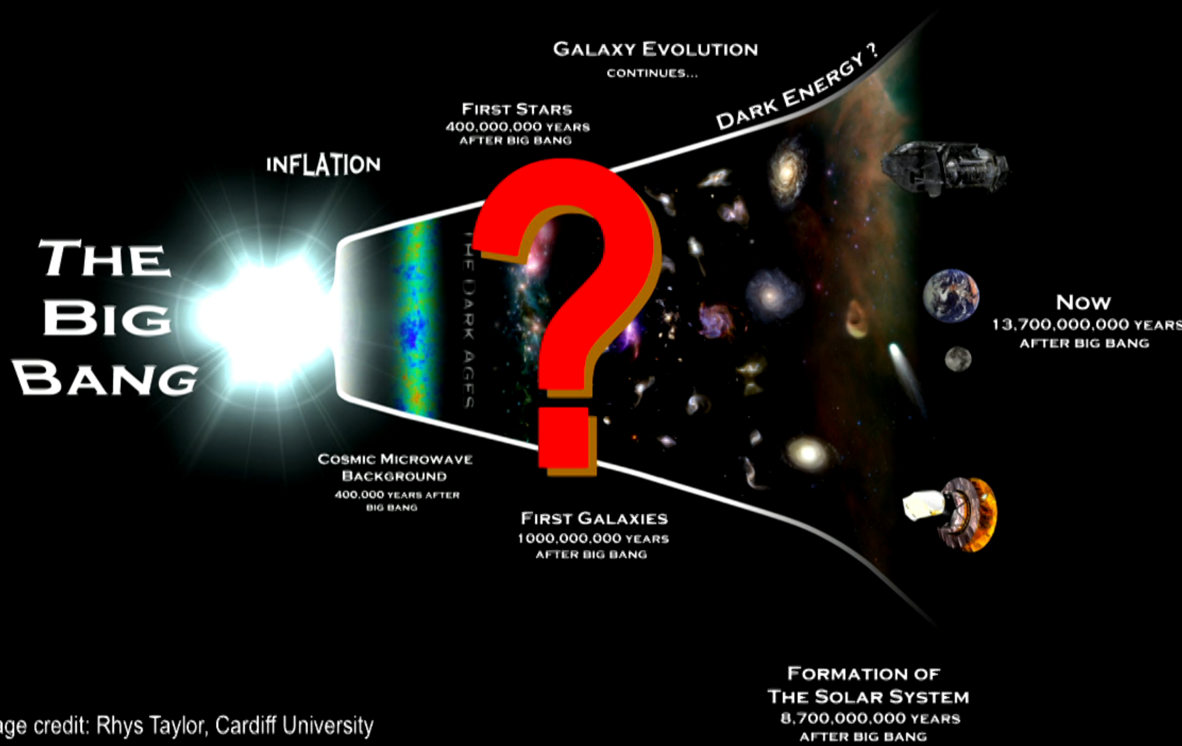
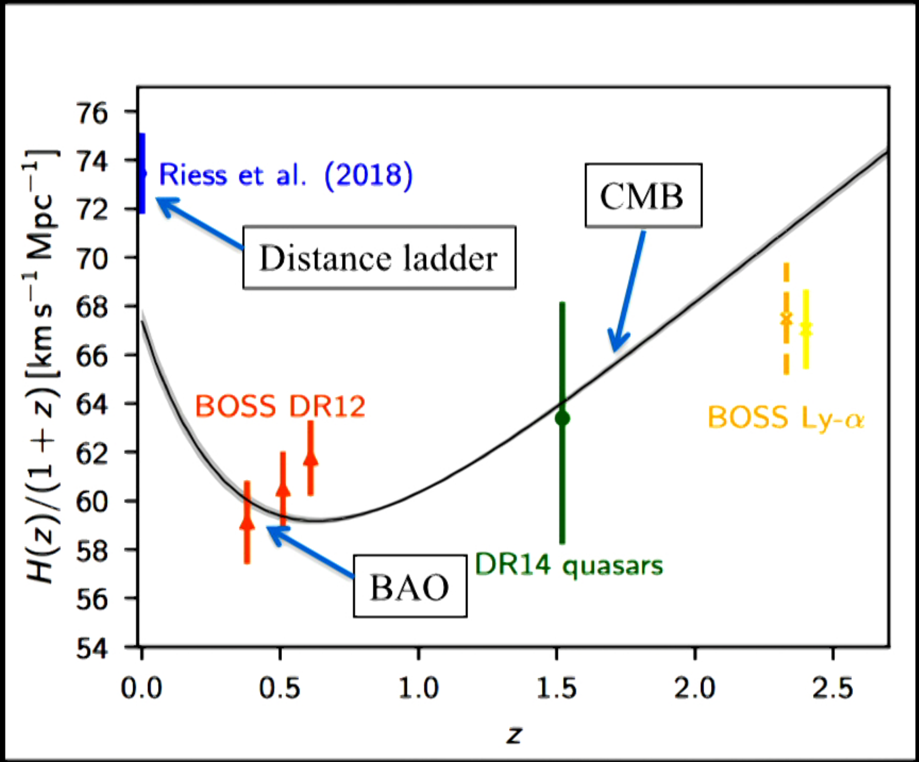


Image credit: Rhys Taylor, Cardiff University

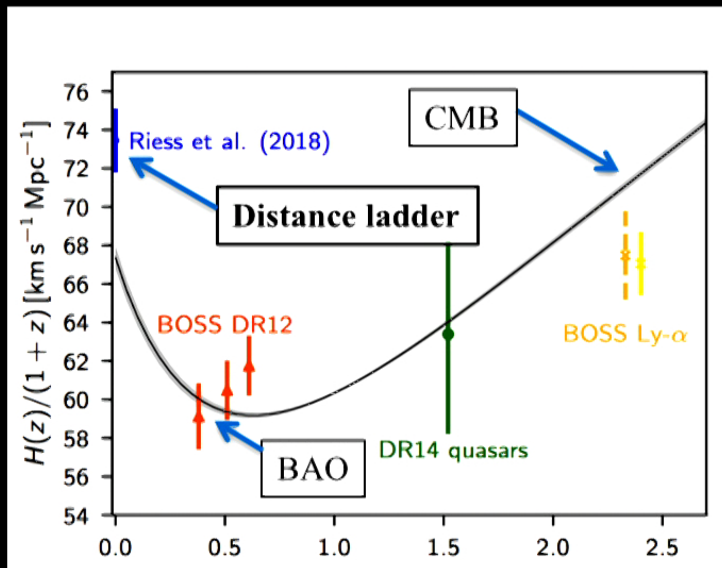
Precision Cosmology Era?



Planck collaboration (2018)

How much do we really know the expansion history of our Universe?

Not all probes of *H(z)* are born equal…



Planck collaboration (2018)

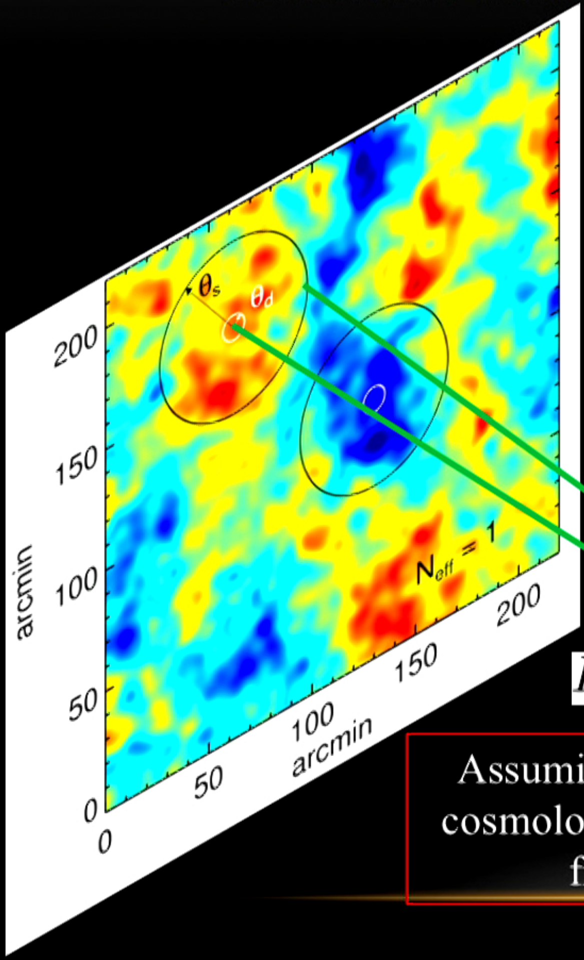
On this plot, only Riess et al. (2018) provides a *direct* measurement of the current Hubble rate.

Other measurements requires the knowledge of the baryon-photon sound horizon, r_s.

Time of baryon decoupling

$$r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Cosmic Microwave Background



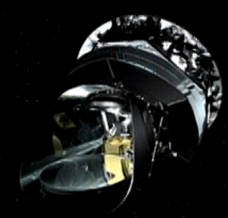
The CMB primarily measures angles on the sky.

$$\theta_s = r_s / D_A(z_d)$$

$$D_A(z) = \int_0^z dz'/H(z')$$

$D_A(z_d)$

Assuming a late-time cosmology, can infer r_s from θ_s.

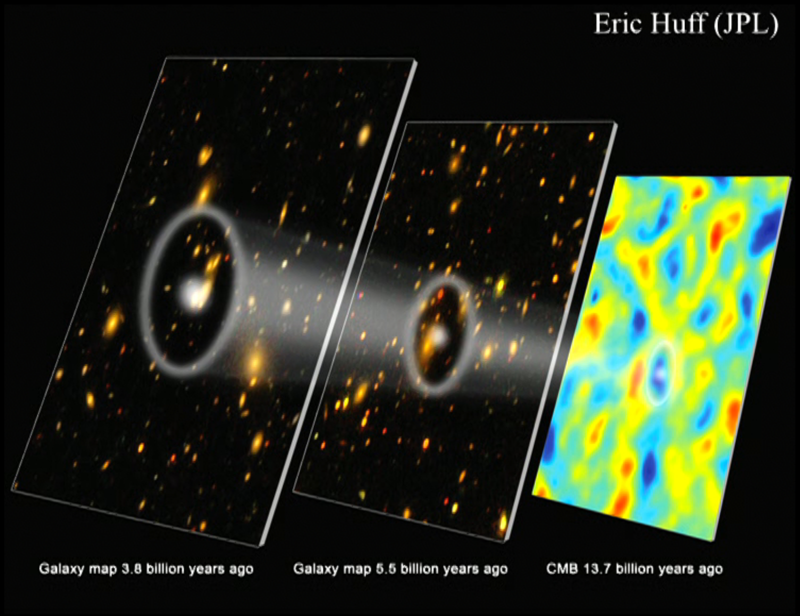


Baryon Acoustic Oscillations (BAO)

BAO primarily measures 2 "processed" versions of the baryon-photon sound horizon.

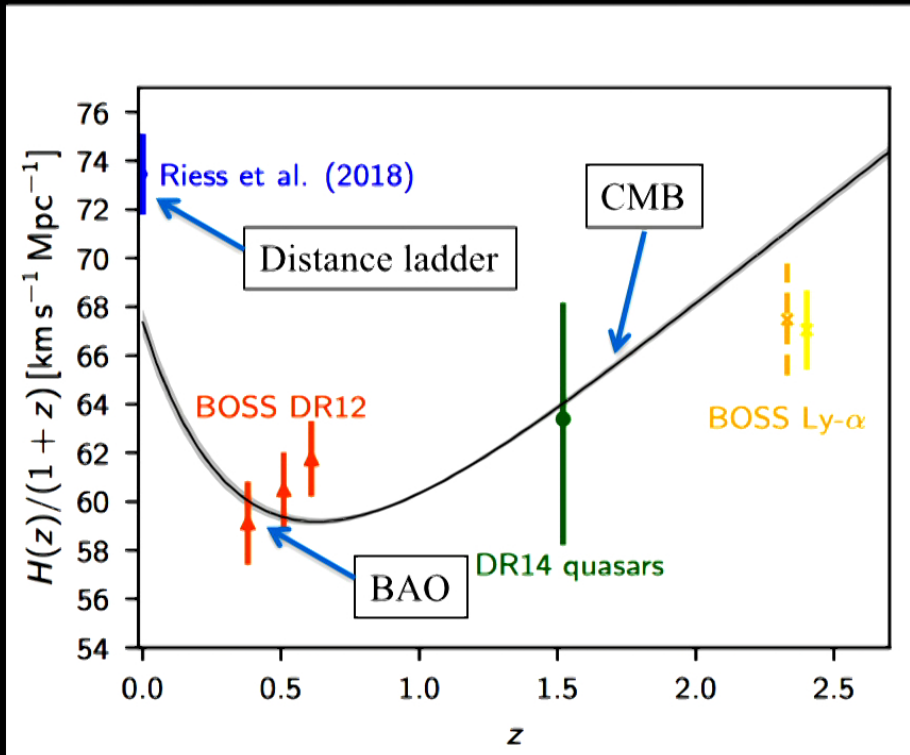
Line of sight: $H(z)r_s$

Transverse: $r_s/D_A(z)$



- If sound horizon if known (from CMB, say), then can use BAO to infer Hubble rate.
- Conversely, if Hubble rate is known, can use BAO to infer sound horizon.

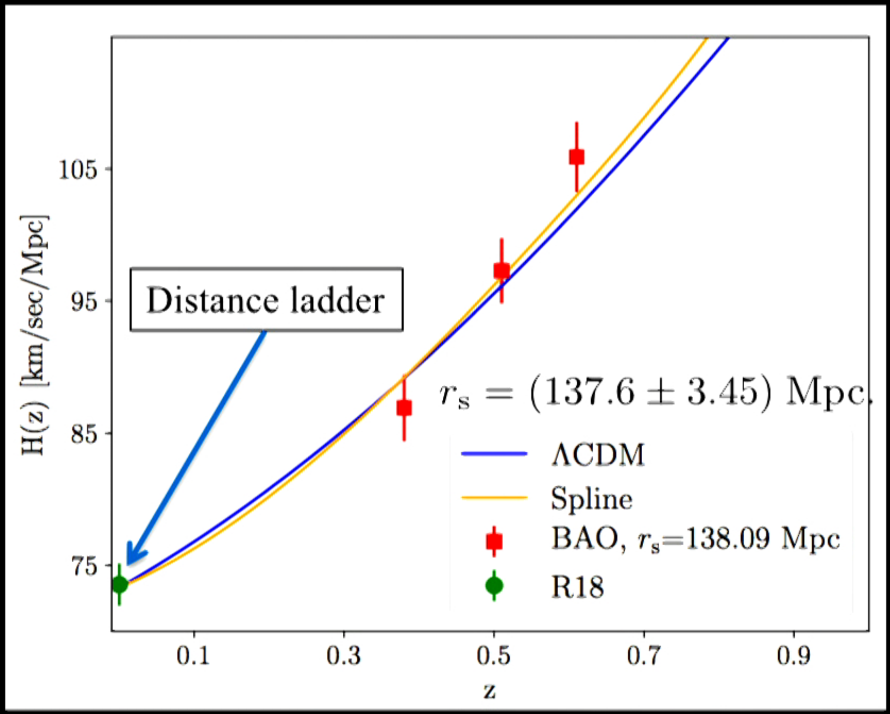
A little misleading?



BOSS data points on this plot use CMB-measured value of the sound horizon as calibration!

Planck collaboration (2018)

Calibrate BAO with local distance ladder



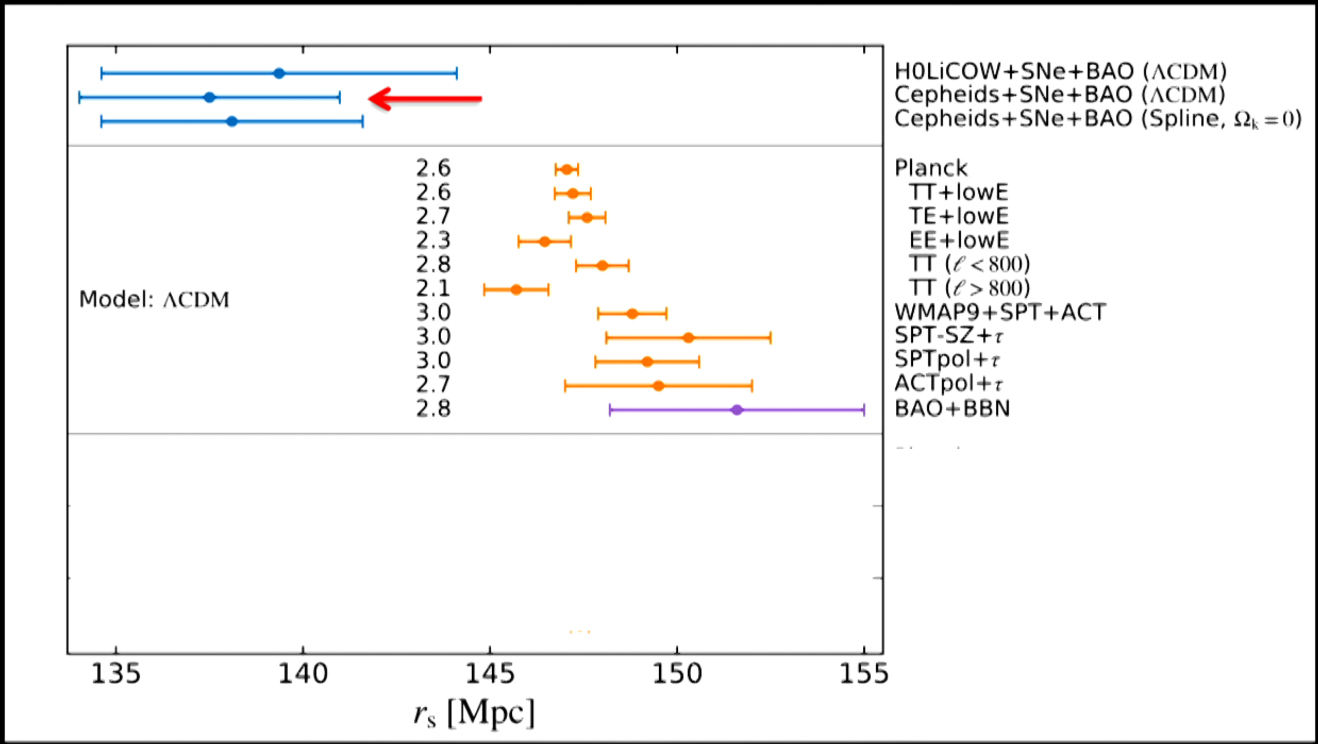
Aylor et al, (2018)

Can make BAO compatible with local H_0 measurement with a smaller baryon-photon sound horizon.

For comparison, Planck's CMB value is:

$r_s = 147.05 \pm 0.30$ Mpc

Discrepancy in the baryon sound horizon



Aylor et al. (2018)
See also Bernal et al. (2016)

How to modify the Baryon-Photon Sound Horizon

- Can either change the sound speed, or the Hubble rate at early times.

$$c_\mathrm{s} = \frac{1}{\sqrt{3(1+\frac{3\rho_\mathrm{b}}{4\rho_\gamma})}}$$

$$r_\mathrm{s} = \int_0^{a_\mathrm{d}} da \, \frac{c_\mathrm{s}(a)}{a^2 H(a)}$$

$$H^2(a) = \frac{8\pi G}{3}\sum_i \rho_i(a)$$

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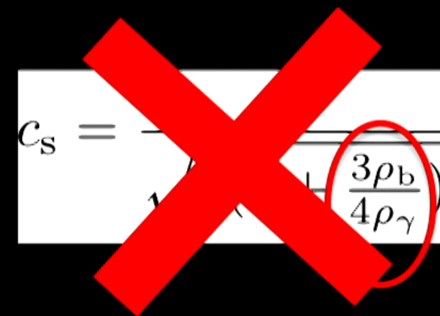
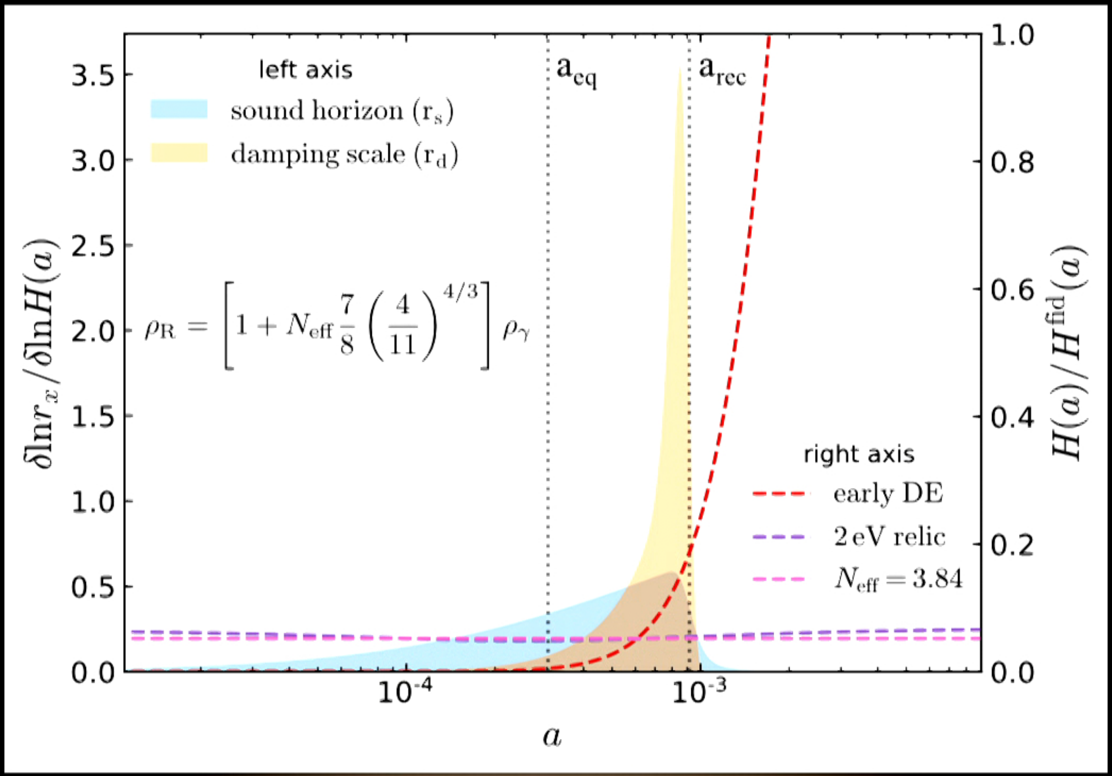


$$r_s = \int_0^{a_d} da \frac{c_s(a)}{a^2 H(a)}$$

Can we change the Hubble rate before recombination without ruining everything else?

$$H^2(a) = \frac{8\pi G}{3} \sum_i \rho_i(a)$$

Issue: Sound horizon vs Damping scale



Credits: Lloyd Knox

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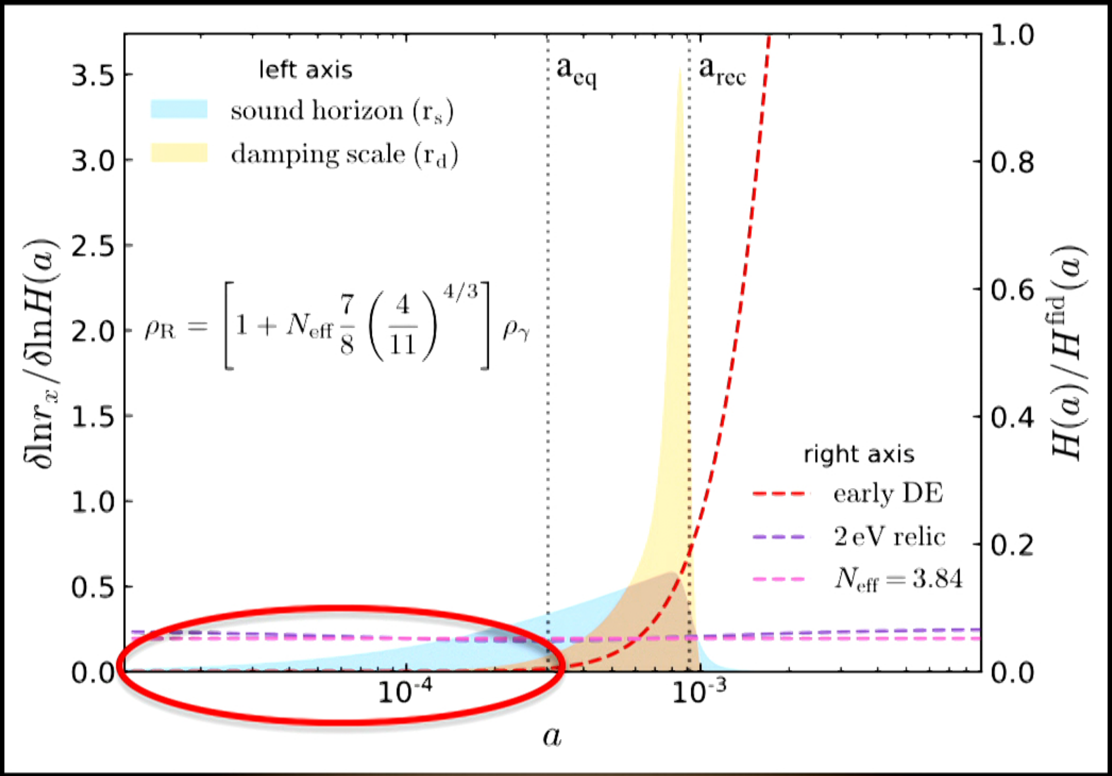
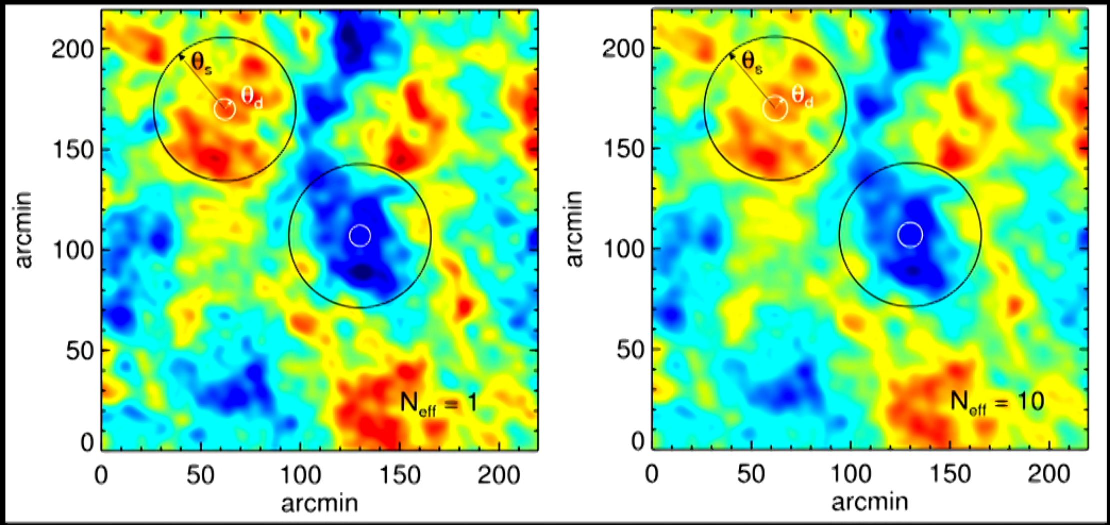


Credits: Lloyd Knox

The problem with N_{eff}

- The presence of extra relativistic species is a hallmark of many extensions of the Standard Model (*N*-Naturalness, Twin Higgs, etc.)
- However, it leads to too much damping in the temperature spectrum of the CMB!

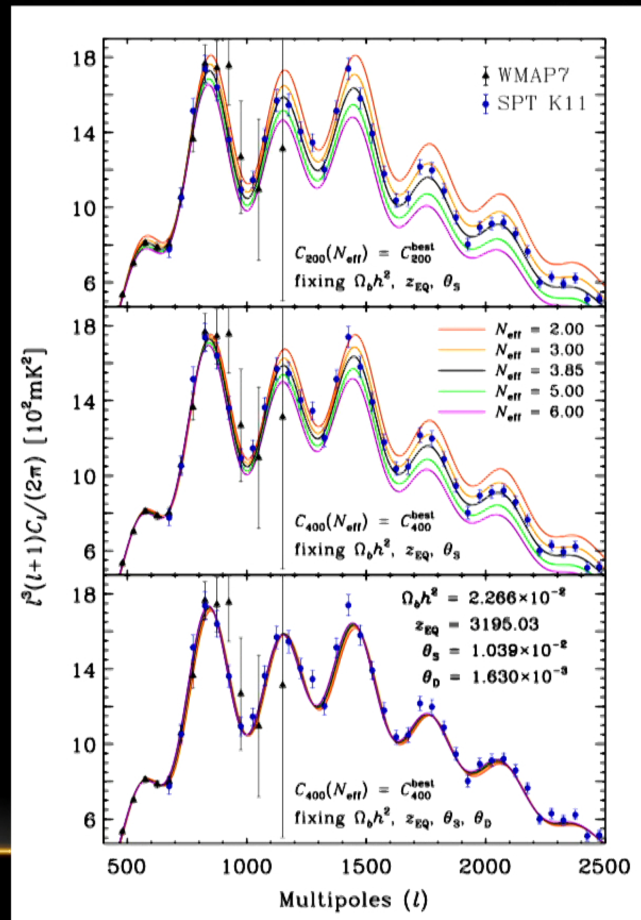


The problem with $N_{\rm eff}$

- But, wait, can't the damage to the damping tail can be undone by changing the helium abundance? Sure…
- However, a phase shift of the CMB peaks towards lower l remains.

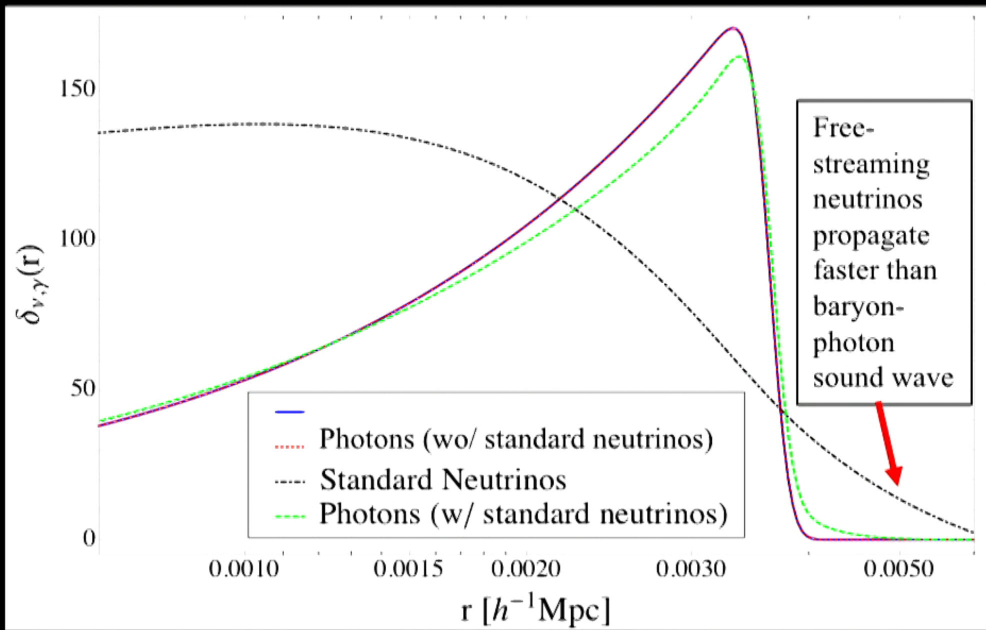
  Bashinsky & Seljak (2004)
  Baumann et al. (2016)
- Need to examine the behavior of fluctuations.

Hou et al. (2012)



Free-streaming Radiation and the CMB

Baryon-photon perturbations interact with all relativistic species through their gravitational coupling



Cyr-Racine & Sigurdson (2014)

$$d_\gamma(\tau, k) = 3\zeta_{\rm in}(1+\Delta_\gamma)\cos(\varphi_s + \delta\varphi) + O(\varphi_s^{-1}),$$

where

$$\Delta_\gamma \simeq -0.2683 R_\nu + O(R_\nu^2),$$

$$\delta\varphi \simeq 0.1912\,\pi R_\nu + O(R_\nu^2).$$

$$R_\nu = \frac{\rho_\nu}{\rho_\gamma + \rho_\nu} \simeq 0.403$$

for $N_{\rm eff} \simeq 3.046$

Bashinsky & Seljak (2004)

Free-streaming Radiation and the CMB

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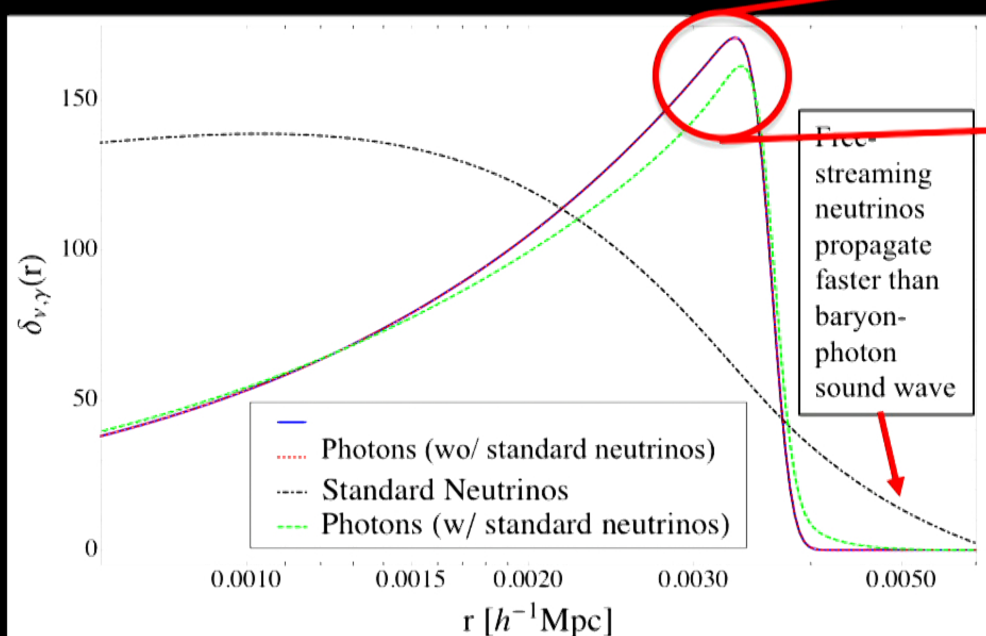

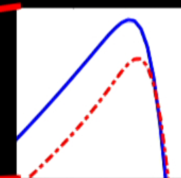

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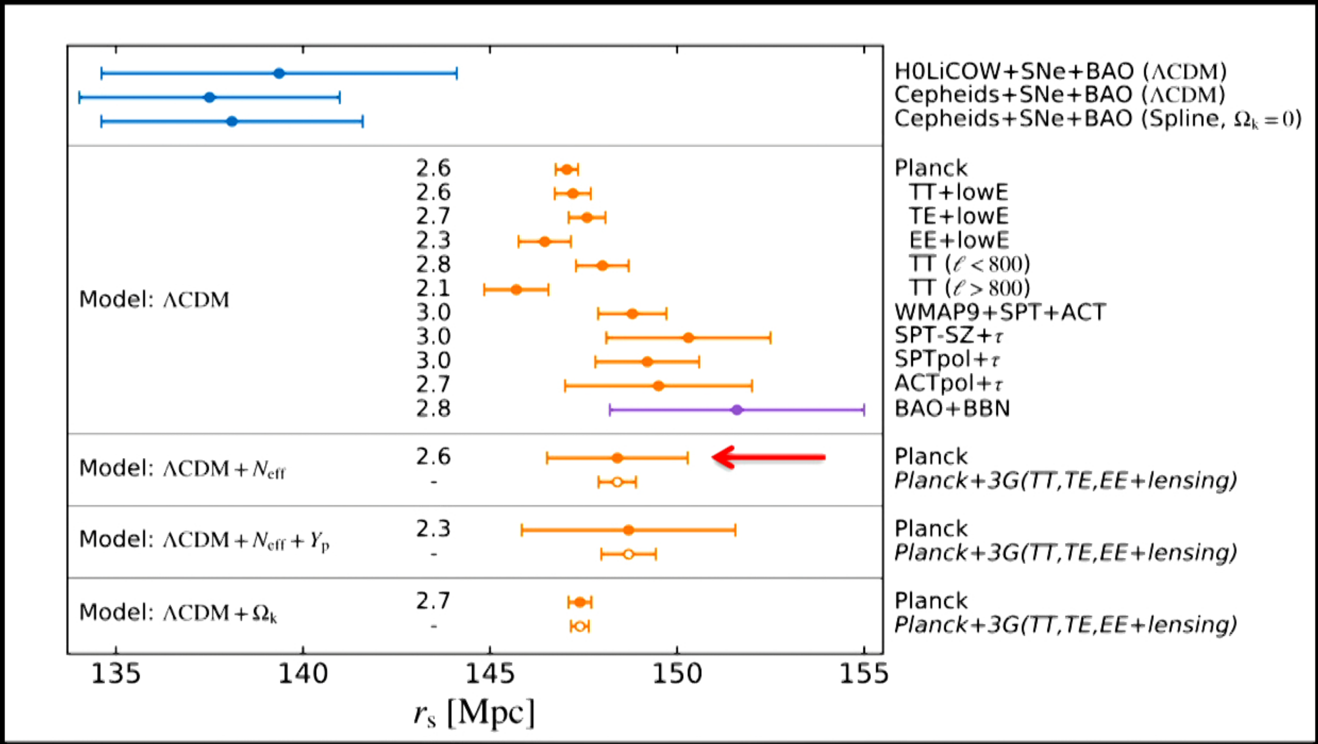
The problem with N_{eff}



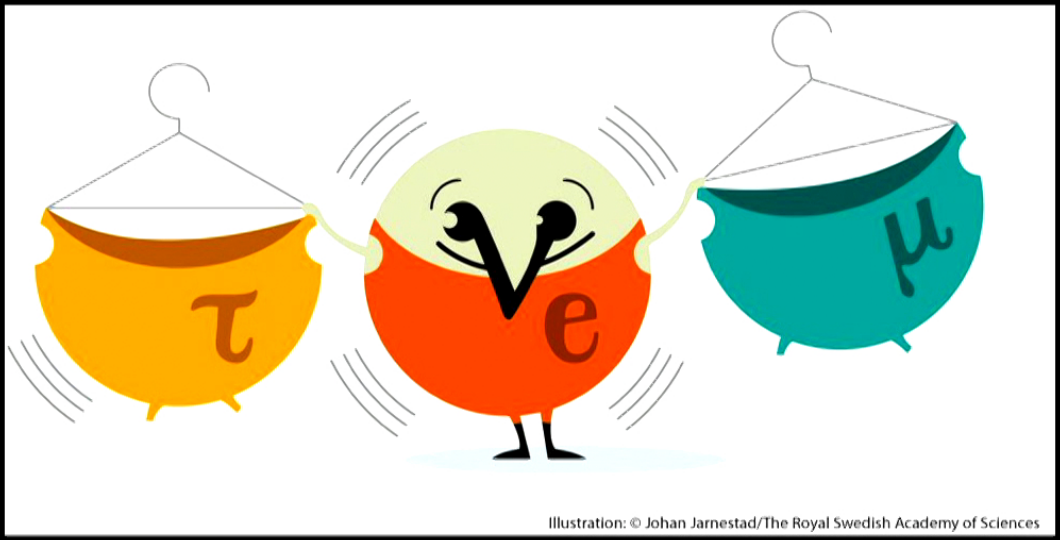
Aylor et al. (2018)
See also Bernal et al. (2016)

Sound horizon discrepancy and relativistic species

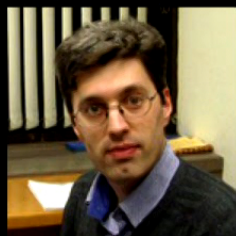
- One way to interpret the current tension among cosmological datasets is that the baryon-photon sound horizon estimates from early time and late time probes is discrepant.
- This could be fixed by changing the Hubble expansion rate in the two decades in scale factor before recombination.
- Adding relativistic species is a natural way to achieve this, but it introduces more problems than it solves (damping tail, phase shift, matter fluctuation amplitude, etc.)

Any way to rescue N_{eff} ?

- Since most (if not all) of the non-photon radiation at early times is made of neutrinos, let's have a look at the status of neutrino physics.



The current status of neutrino physics



From Michele Maltoni's talk at the Neutrino 2018 conference:

- Anomalies in $\nu_e \to \nu_e$ disappearance and $\nu_\mu \to \nu_e$ appearance experiments point towards conversion mechanisms beyond the well-established 3ν oscillation paradigm;

$\Rightarrow$ sterile neutrino models **fail to simultaneously account** for **all** the $\nu_e \to \nu_e$ data, the $\nu_\mu \to \nu_e$ data and the $\nu_\mu \to \nu_\mu$ data. This conclusion is robust;

- if the $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_e$ anomalies are confirmed, and the $\nu_\mu \to \nu_\mu$ bounds are not refuted, new physics will be needed. Such new physics may well involve extra sterile neutrinos, but together with something else (or some "unusual" neutrino property).

_XXVIII International Conference on Neutrino Physics and Astrophysics (Neutrino 2018), Heidelberg, Germany, 4-9 June 2018 (Session Sterile Neutrinos and Interpretations , Part 2)

New Physics in the Neutrino sector

- Introduce new neutrino self-interaction that suppresses neutrino free-streaming at early times.

Kreisch, Cyr-Racine & Doré, 1902.00534

Beyond Free-streaming Neutrinos

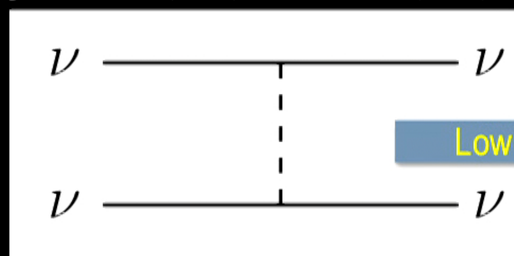
- A significant recent interest in non free-streaming (fluid-like) radiation:
  - Affect background cosmology similarly to standard N_{eff} .
  - However, cosmological perturbation evolution is very different.

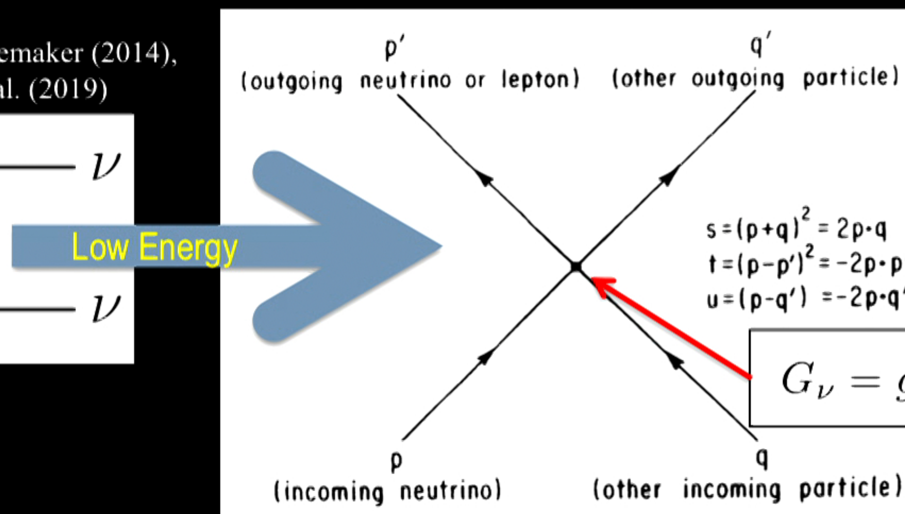
- Hannestad (2005)
- Trotta & Melchiorri (2005)
- Melchiorri & Serra (2006)
- Bell, Pierpaoli & Sigurdson (2006)
- De Bernardis et al. (2008)
- Basboll, Bjaelde, Hannestad &Raffelt (2009)
- Smith, Das & Zahn (2012)
- Cyr-Racine & Sigurdson (2014)
- Archidiacono & Hannestad (2014)
- Forastieri, Lattanzi & Natoli (2015)
- Baumann, Green, Meyers & Wallisch (2016)
- Brust, Cui & Sigurdson (2017)
- Lancaster, Cyr-Racine, Knox, Pan (2017)
- Choi, Chiang & Loverde (2018)
- Song, Gonzalez-Garcia & Salvado (2018)
- **And many more…**

Beyond Free-streaming Neutrinos

New Unknown Interaction: $\mathcal{L}_{\rm phen} \supset -\frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}(g_\phi^{\alpha\beta}\nu_\alpha\nu_\beta\phi + {\rm h.c.})$

See e.g. Cherry, Friedland & Shoemaker (2014), Ng & Beacom (2014), Blinov et al. (2019)





$G_\nu = g_\nu^2/M_\phi^2$

4-Fermion Interaction stronger than Fermi constant

$$G_\nu > G_{\rm F}$$

Delayed Neutrino Decoupling

Neutrino Opacity:

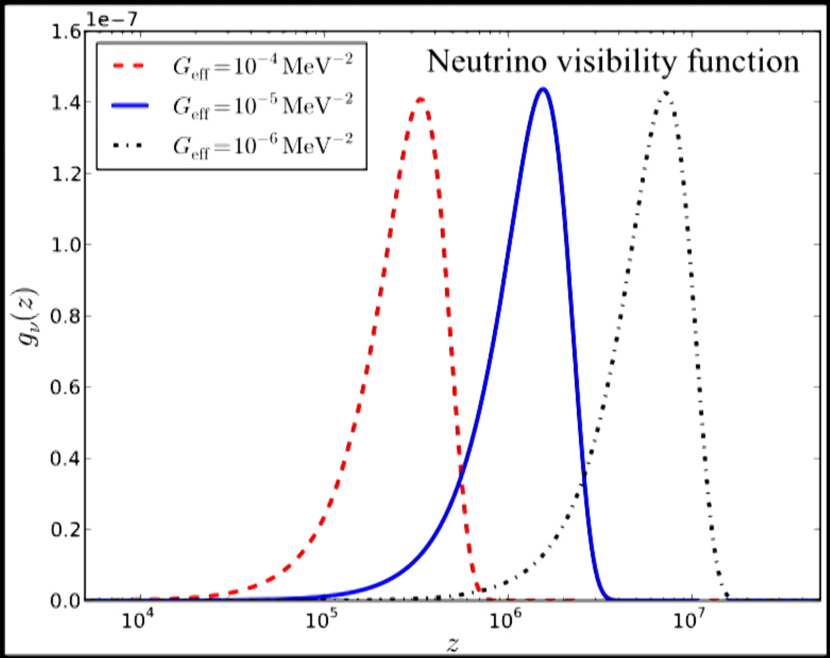
$$\dot{\tau}_\nu \propto -aG_{\rm eff}^2 T_\nu^5$$

$$G_{\rm eff} \propto G_\nu$$

$$G_\nu = g_\nu^2/M_\phi^2$$

$$g_\nu(\tau) \equiv -\dot{\tau}_\nu e^{-\tau_\nu}$$

Extra Neutrino Interactions →
Delayed Neutrino free streaming!



Cyr-Racine & Sigurdson (2014)
Oldengott, Rampf & Wong (2015)

Massive Neutrino Boltzmann Hierarchy

Simplified Boltzmann Hierarchy (assume decoupling in relativistic regime):

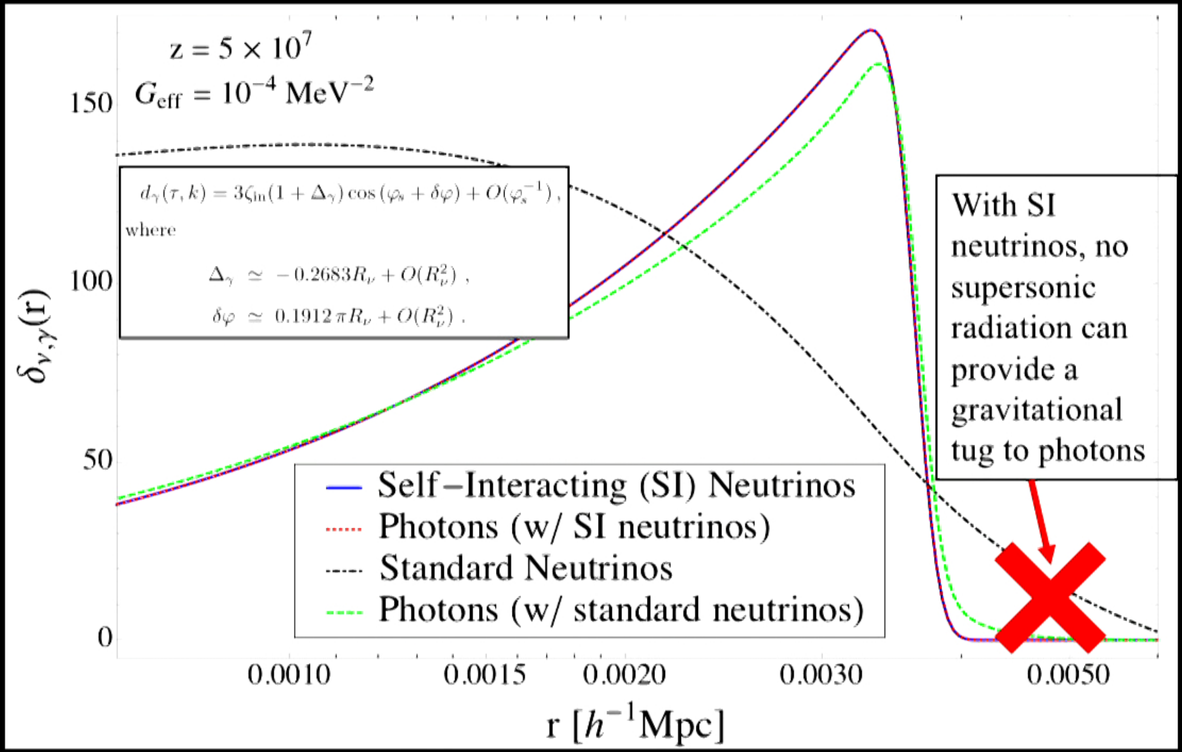
$$\frac{\partial \nu_l}{\partial \tau} + k\frac{q}{\epsilon}\left(\frac{l+1}{2l+1}\nu_{l+1} - \frac{l}{2l+1}\nu_{l-1}\right) - 4\left[\frac{\partial \phi}{\partial \tau}\delta_{l0} + \frac{k}{3}\frac{\epsilon}{q}\psi\delta_{l1}\right] = -a\frac{G_{\rm eff}^2 T_\nu^5 \nu_l}{f_\nu^{(0)}(q)}\left(\frac{T_{\nu,0}}{q}\right)\left(A\left(\frac{q}{T_{\nu,0}}\right) + B_l\left(\frac{q}{T_{\nu,0}}\right) - 2D_l\left(\frac{q}{T_{\nu,0}}\right)\right)$$

Relaxation-time approximation

$$\epsilon = \sqrt{q^2 + a^2 m_\nu^2},$$

Cyr-Racine & Sigurdson (2014)
Oldengott, Rampf & Wong (2015)
Kreisch, Cyr-Racine+ (2019)

Impact of self-interacting Neutrinos on CMB



Cyr-Racine & Sigurdson (2014)

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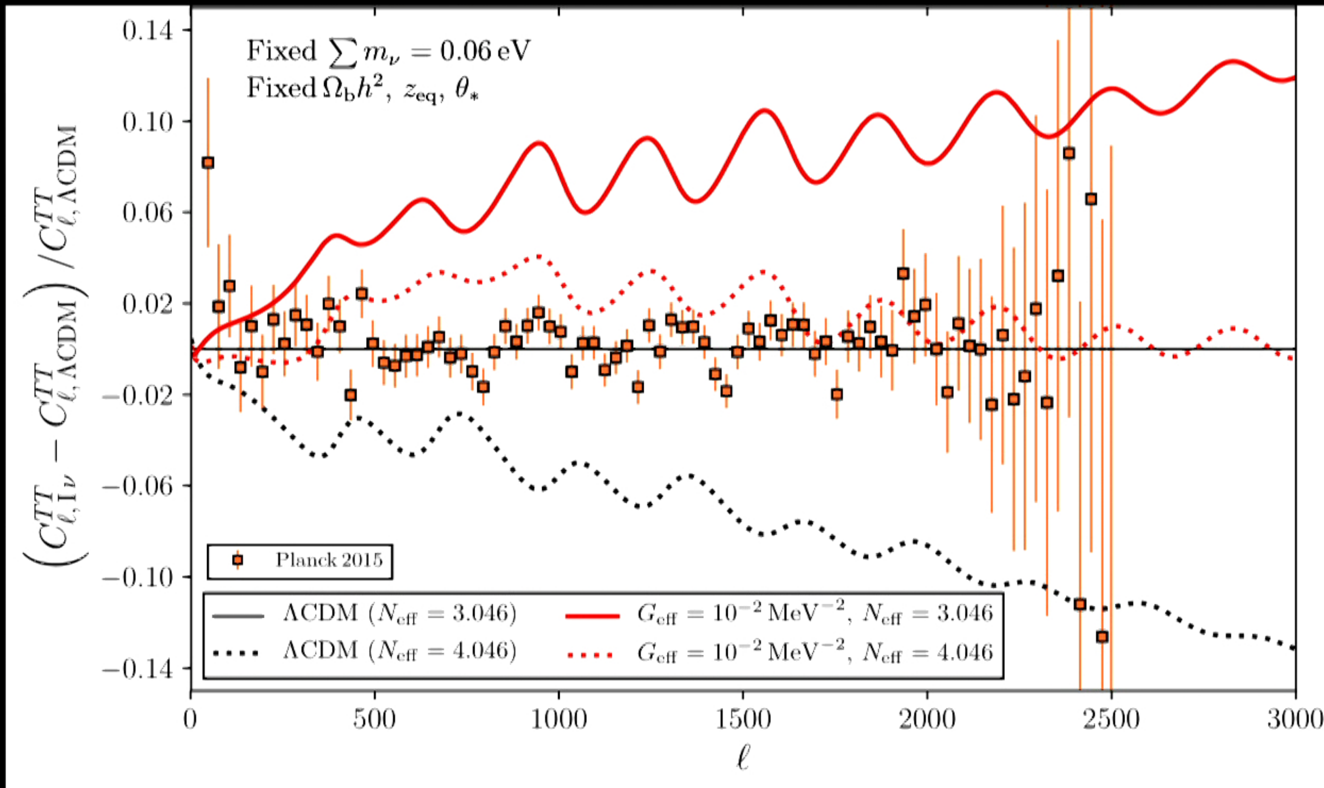
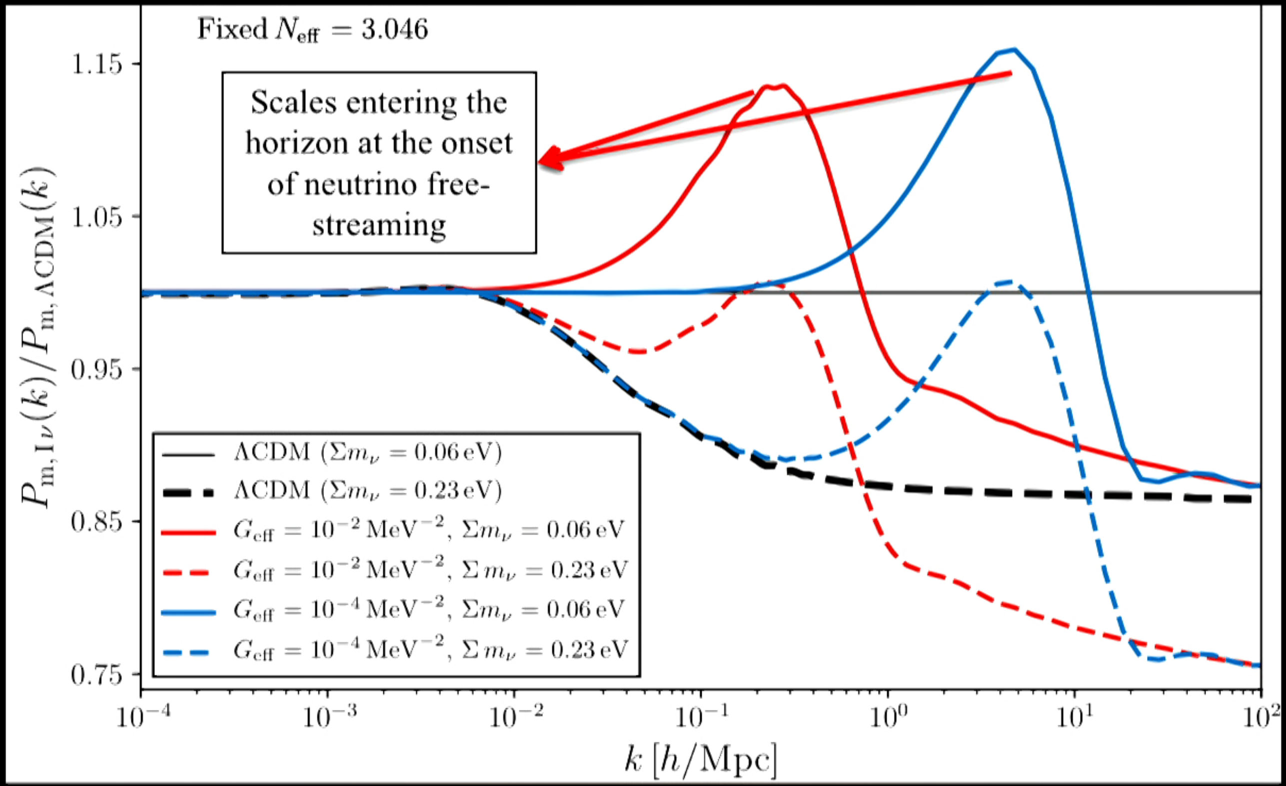


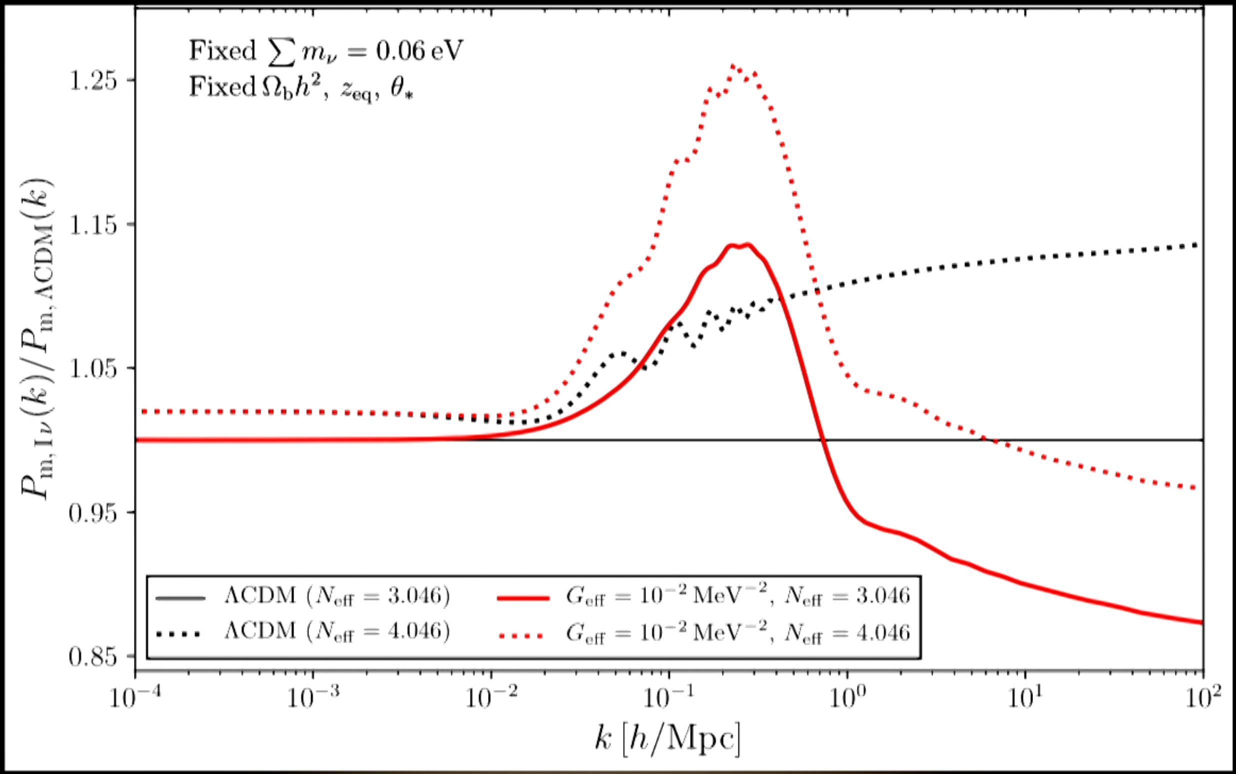
Kreisch, Cyr-Racine + (2019)

Impact of self-interacting Neutrinos on matter clustering



Kreisch, Cyr-Racine + (2019)

Impact of self-interacting Neutrinos on matter clustering: $N_{\rm eff}$



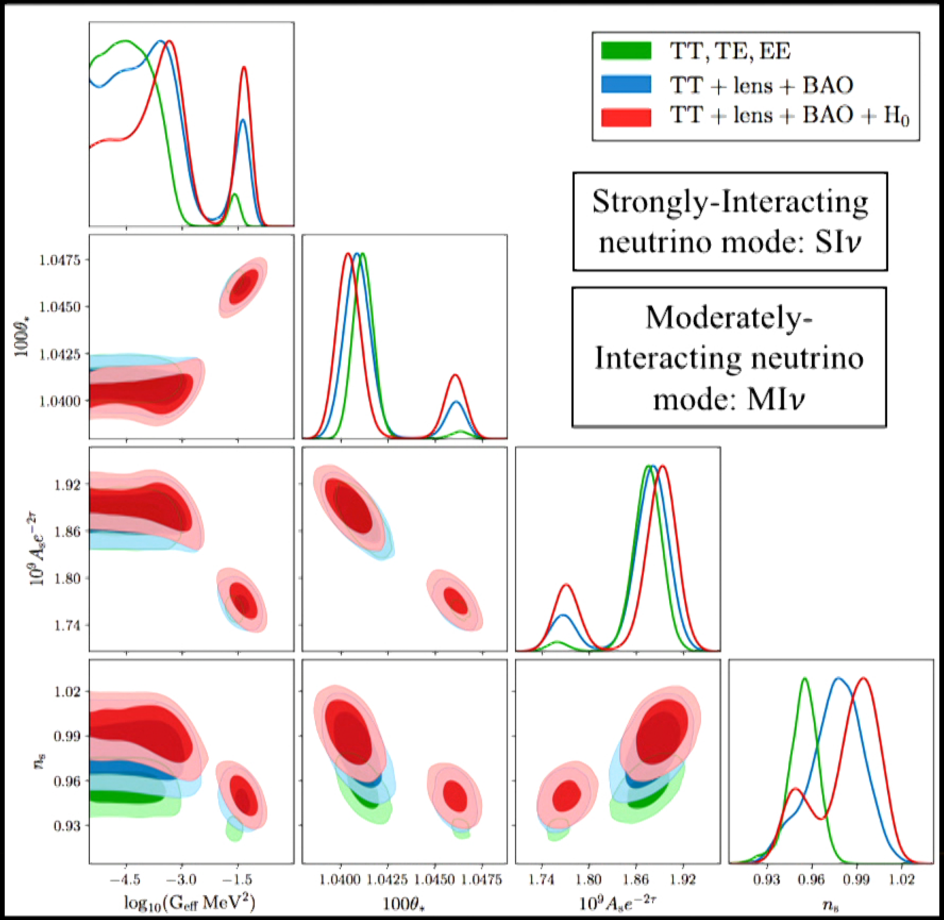
Kreisch, Cyr-Racine + (2019)

Now that we understand the physics, what does the data say?

Let's ask Christina

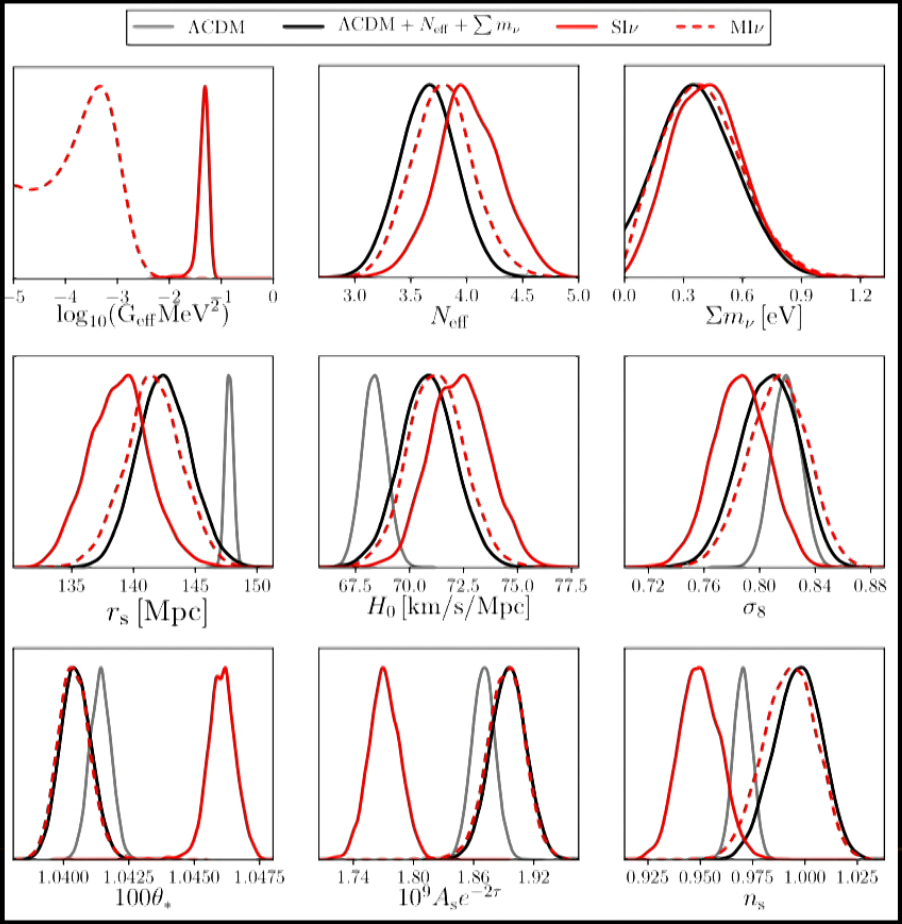
Christina Kreisch

A Tale of two statistical modes



Kreisch, Cyr-Racine + (2019)

Let's compare the two modes side-by-side



Kreisch, Cyr-Racine + (2019)

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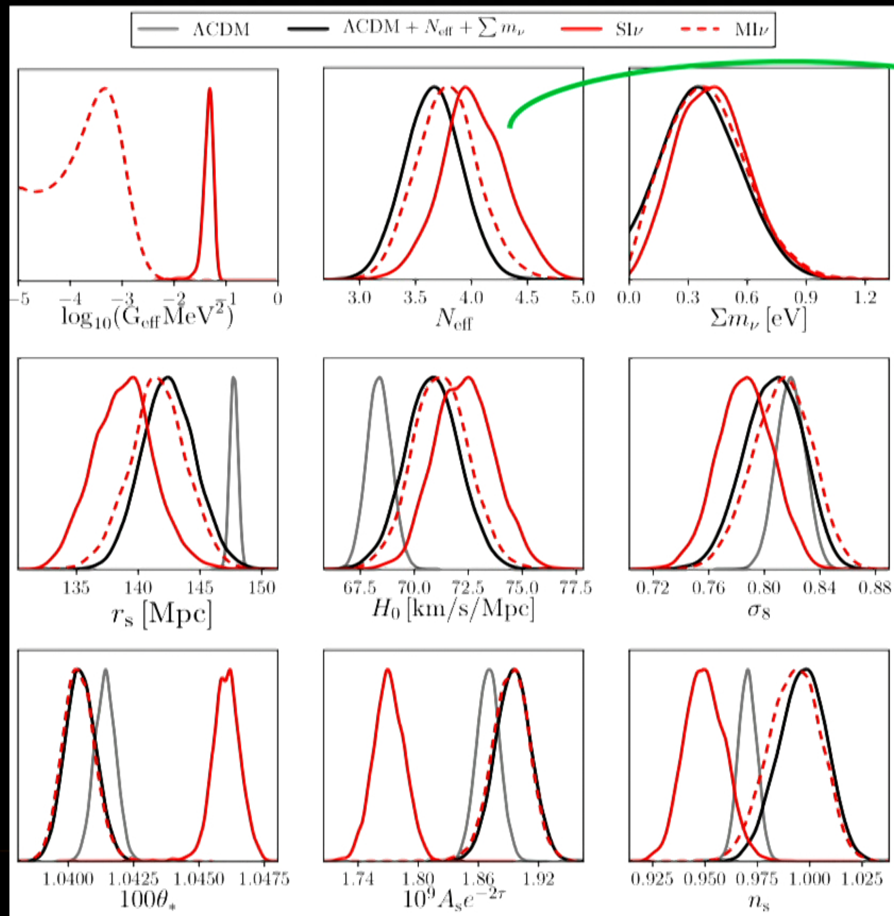

$N_{\rm eff} \sim 4$: extra energy density at early times

Kreisch, Cyr-Racine + (2019)

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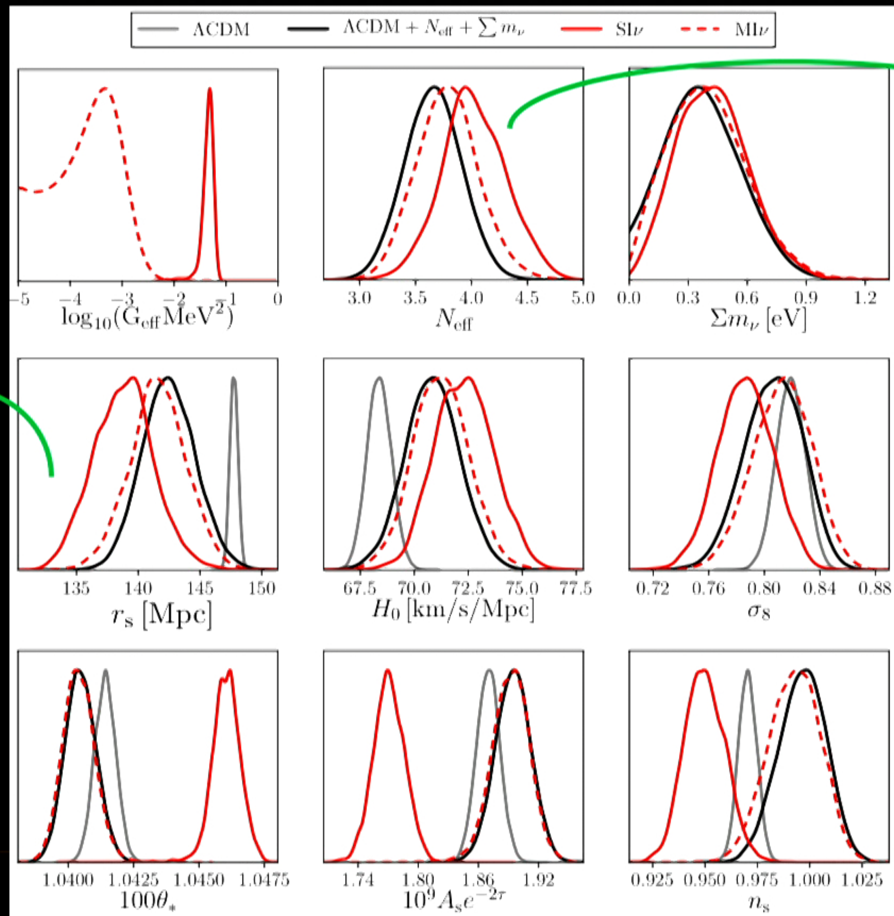
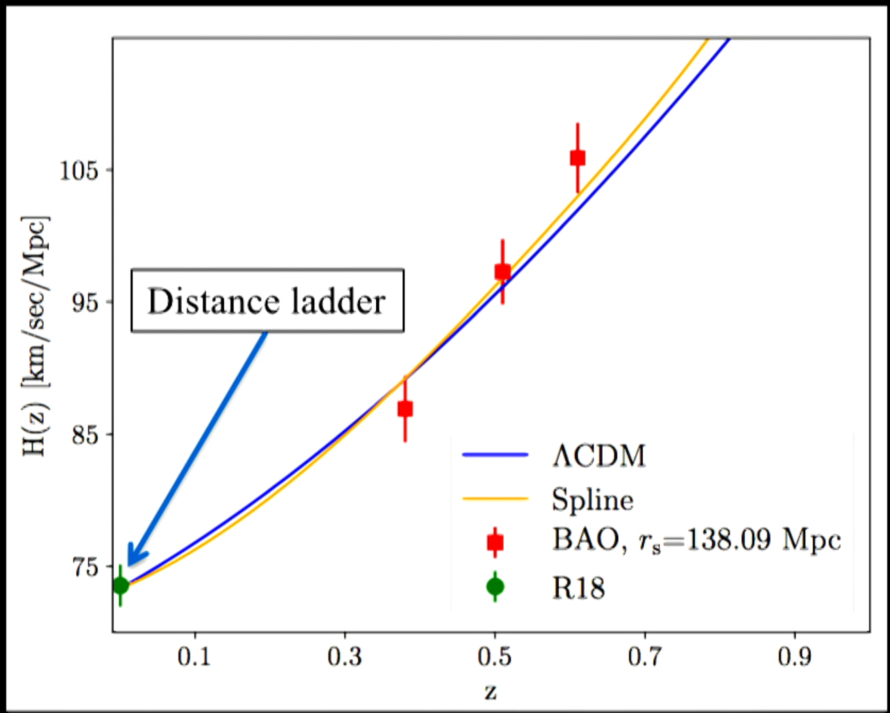


$N_{\rm eff}$ ~ 4: extra energy density at early times

Sound horizon is smaller than in LCDM

Kreisch, Cyr-Racine + (2019)

Concordant direct and inverse distance ladders



Aylor et al, (2018)

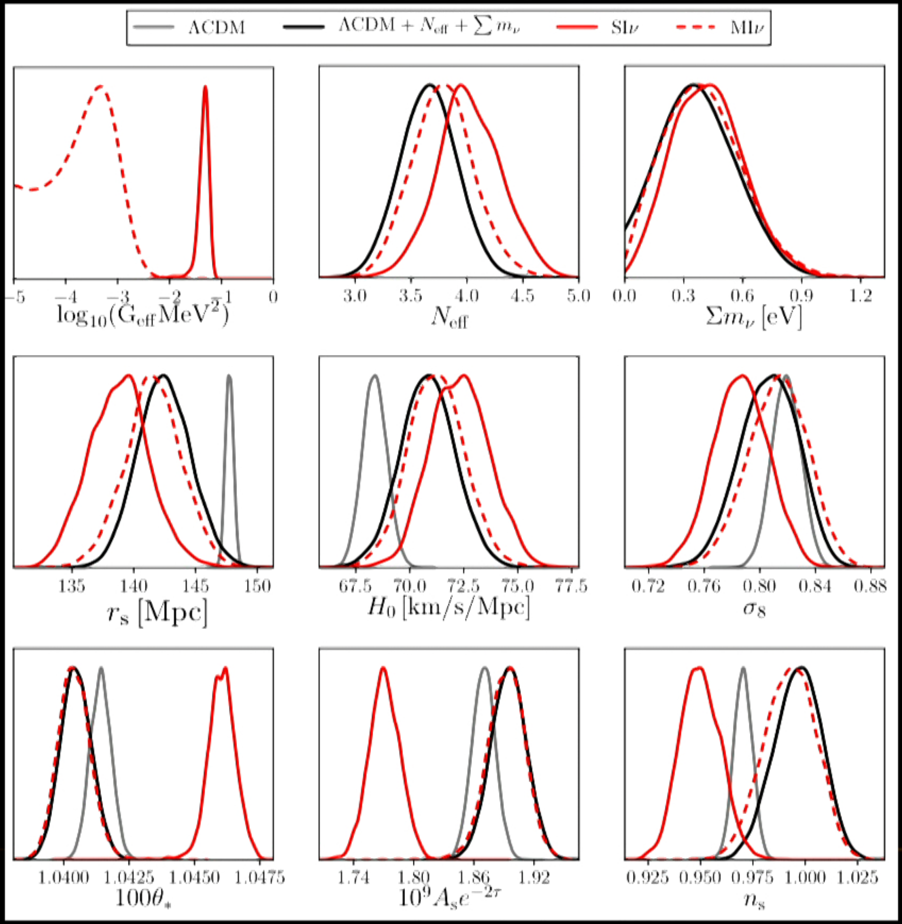
The SIν sound horizon:

$r_s = 138.8 \pm 2.5$ Mpc

The local distance ladder sound horizon:

$r_s = (137.6 \pm 3.45)$ Mpc.

Let's compare the two modes side-by-side



Kreisch, Cyr-Racine + (2019)

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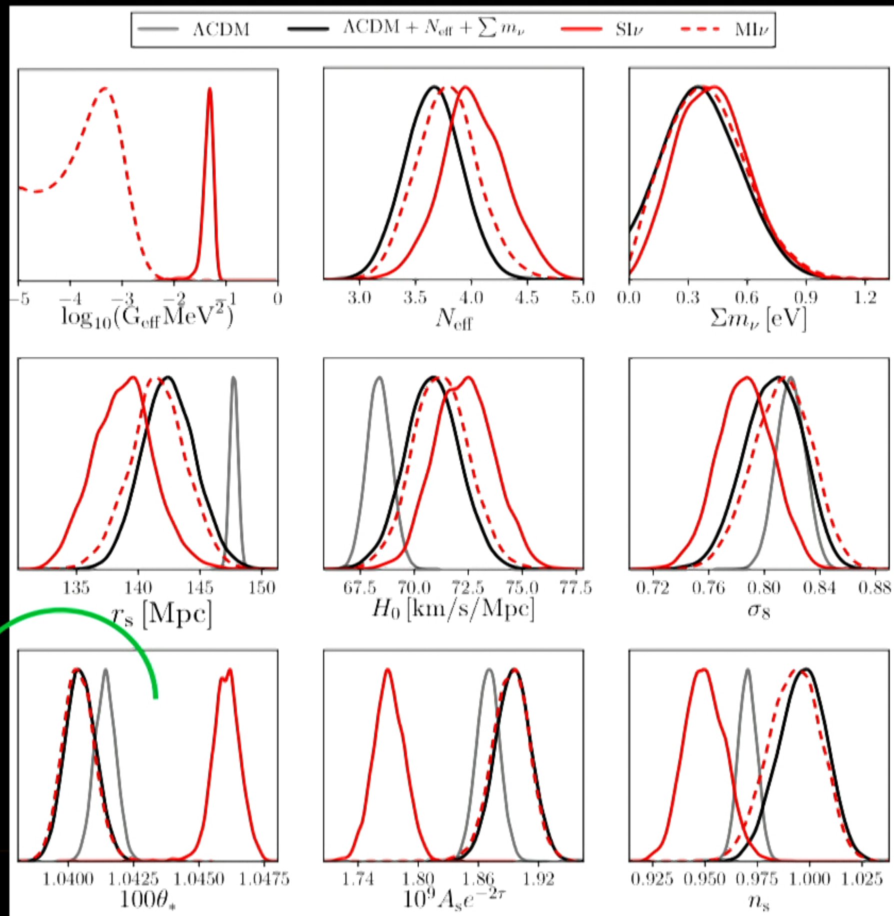
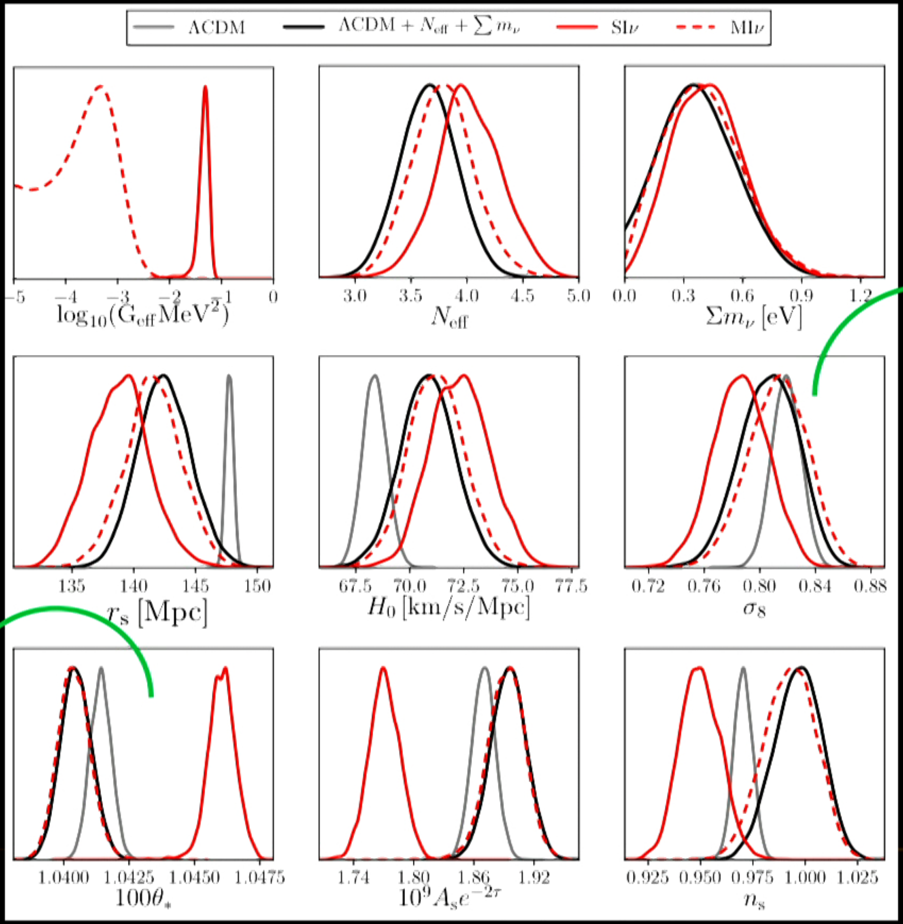


Clearly see effect of suppressing neutrino phase shift

Kreisch, Cyr-Racine + (2019)

Let's compare the two modes side-by-side



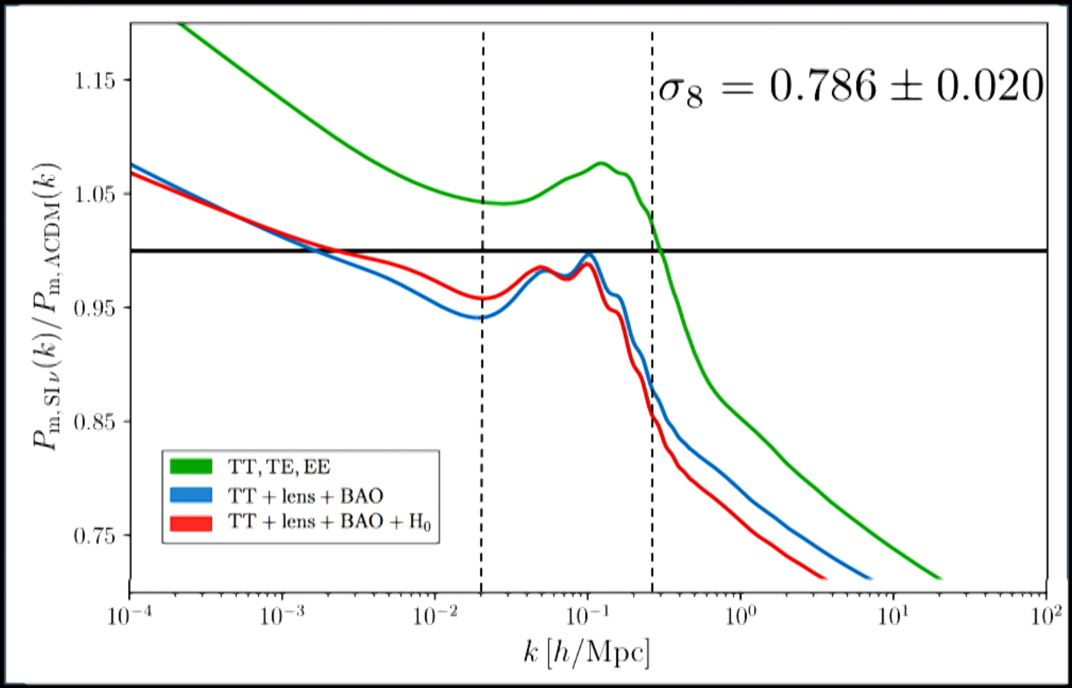
Value of σ_8 is slightly smaller than LCDM

Clearly see effect of suppressing neutrino phase shift

Kreisch, Cyr-Racine + (2019)

SIν Cosmology and matter clustering

- The combined effect of N_{eff}, neutrino masses, self-interaction, A_s, and n_s leave large-scale structure largely unchanged on scales where it best measured.



Kreisch, Cyr-Racine + (2019)

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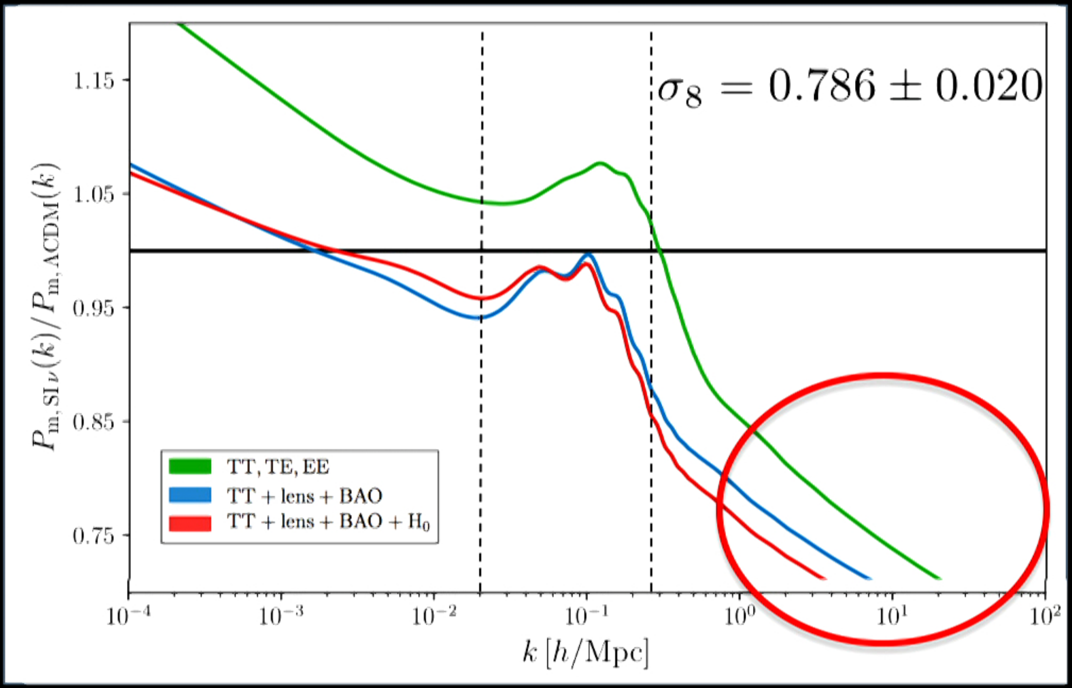
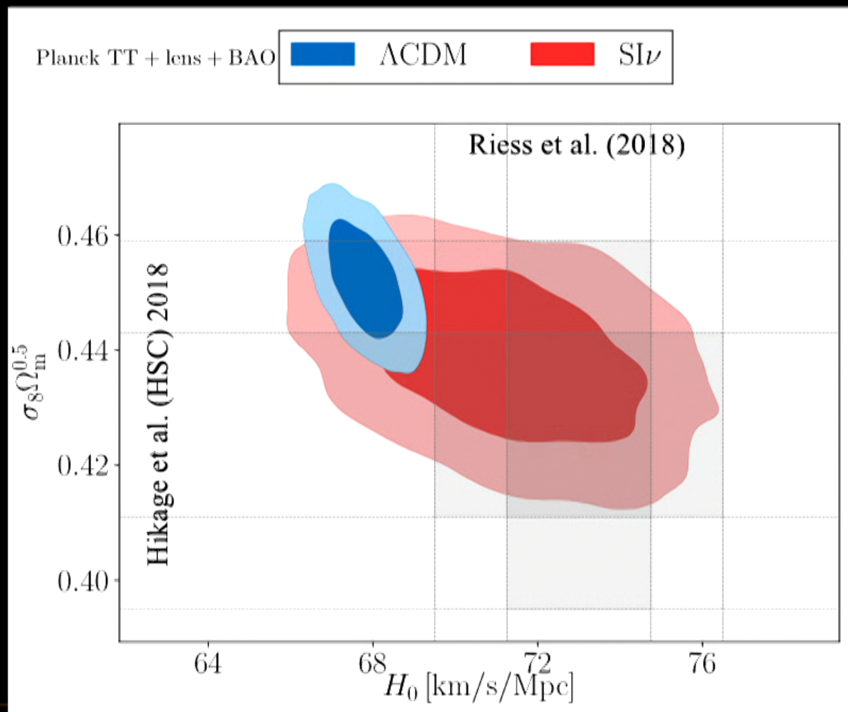


Kreisch, Cyr-Racine + (2019)

SIν Cosmology and cosmological tensions

- Even without using these data in our analysis, the SIν model can naturally accommodate a lower σ_8 value and larger H_0



Kreisch, Cyr-Racine + (2019)

Sure, the sound horizon is good, but the fit must be terrible, right?

- The model does improve the fit compares to ΛCDM, even after accounting for the extra parameters.

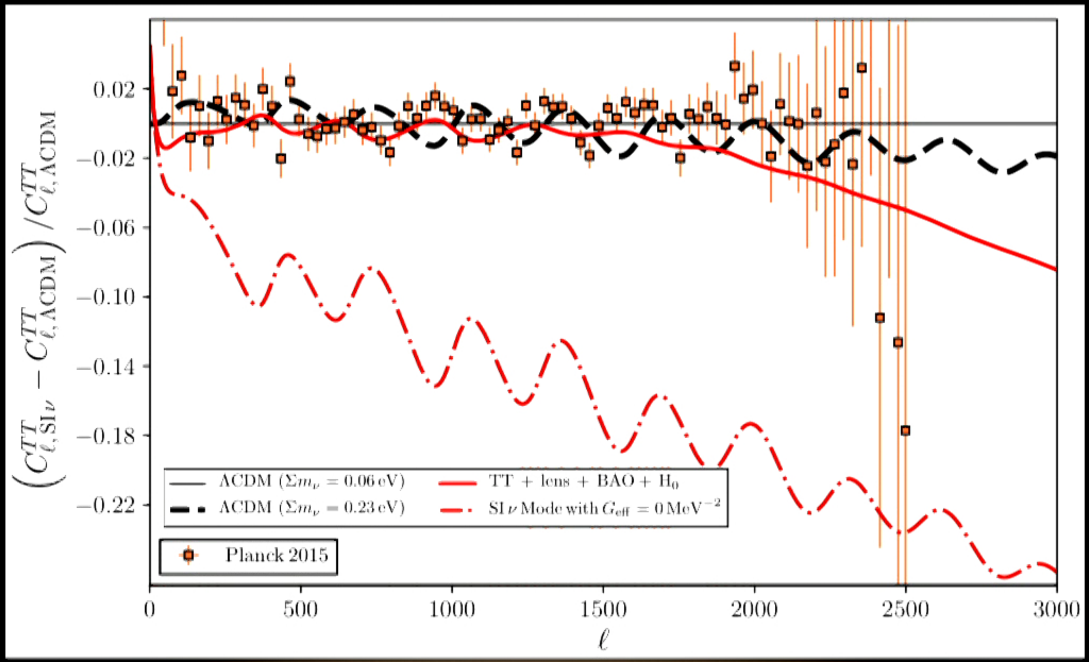
Parameter	Strongly Interacting Neutrino Mode
$\Delta\chi^2_{\mathrm{low}\,\ell}$	0.66
$\Delta\chi^2_{\mathrm{high}\,\ell}$	-1.15
$\Delta\chi^2_{\mathrm{lens}}$	0.06
$\Delta\chi^2_{H_0}$	-6.68
$\Delta\chi^2_{\mathrm{BAO}}$	-0.81
$\Delta\chi^2_{\mathrm{Total}}$	-7.91
ΔAIC	-1.91 ⟶ Correcting for extra parameters

$$\Delta\mathrm{AIC} = \mathrm{AIC}_{\mathrm{I}\nu} - \mathrm{AIC}_{\Lambda\mathrm{CDM}} = \Delta\chi^2 + 2\Delta k,$$

Kreisch, Cyr-Racine + (2019)

How important are the neutrino self-interaction?

- Answer: very much so!



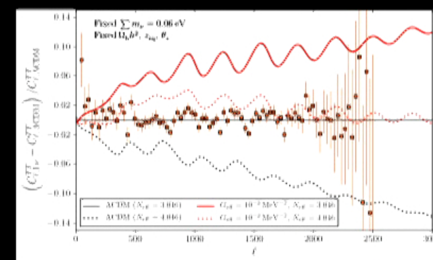
Kreisch, Cyr-Racine + (2019)

Why does the SIν work?

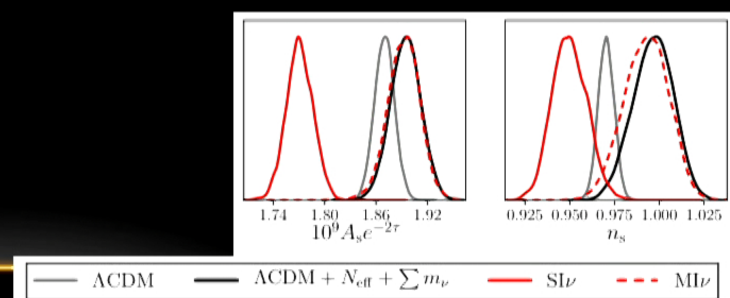
- $N_{\rm eff}$ increases Hubble at early times, hence reducing the sound horizon.

$$r_{\rm s} = \int_0^{a_{\rm d}} da \frac{c_{\rm s}(a)}{a^2 H(a)}$$

- The tightly-coupled neutrinos do not over damp or phase shift the photon-baryon fluctuations.



- Changes in the primordial spectrum of fluctuations (n_s, A_s) absorbs the remainder of the changes.



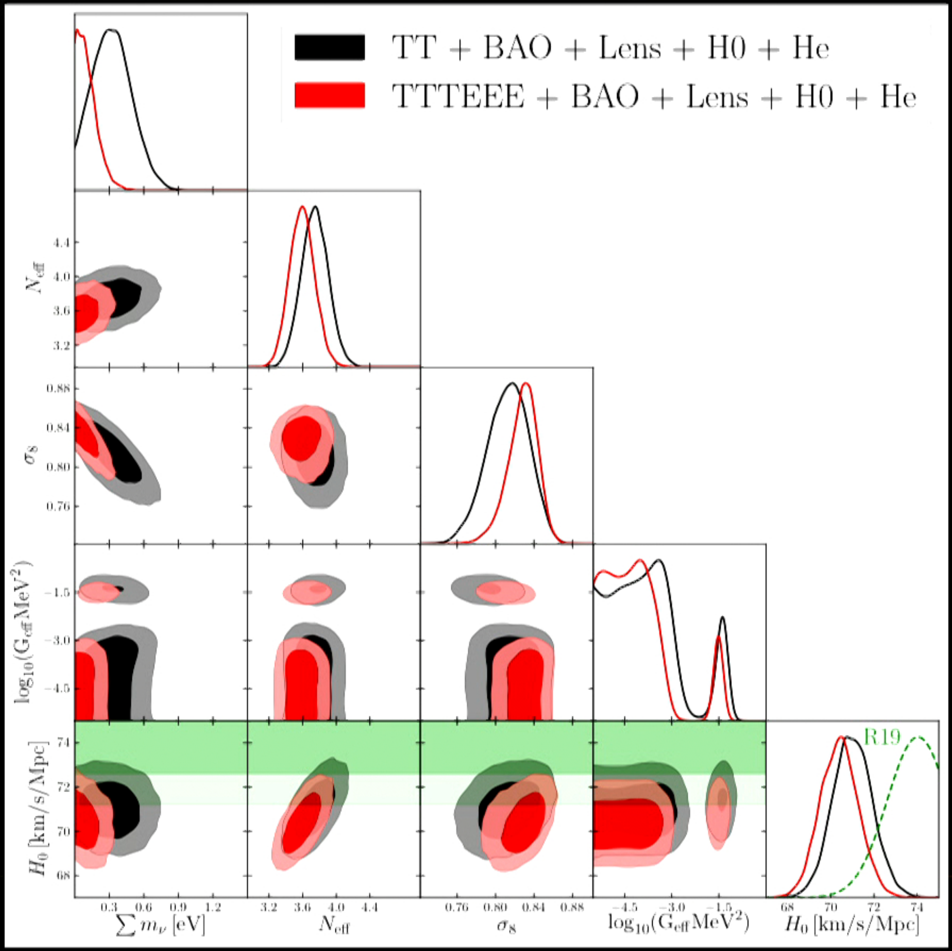
SIν Cosmology: The dark side

- The required strength of the neutrino self-interaction might be very difficult to model build.

$$G_{\rm eff} \sim 10^{10} G_{\rm F}$$

- It is still unclear whether CMB polarization data can fully accommodate the SIν cosmology.
- The shape of the matter power spectrum might become problematic.

CMB Polarization data



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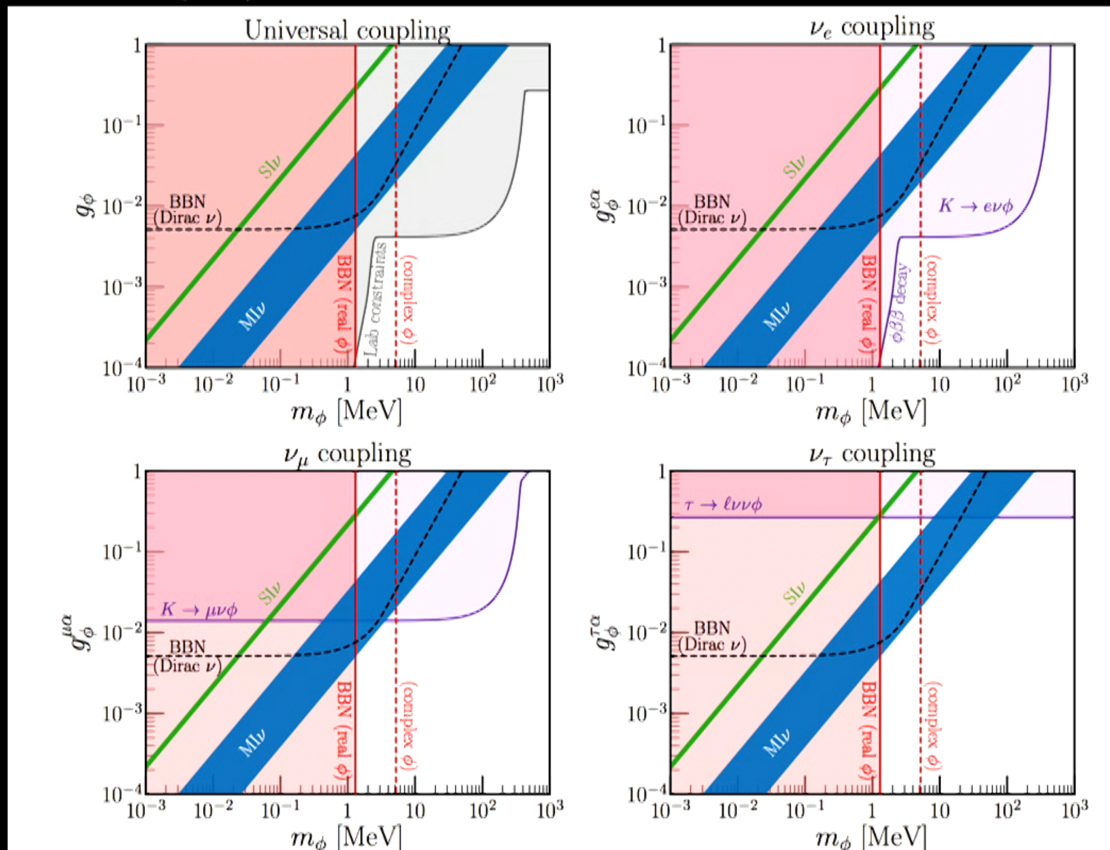
Particle model constraints

Blinov et al. (2019)

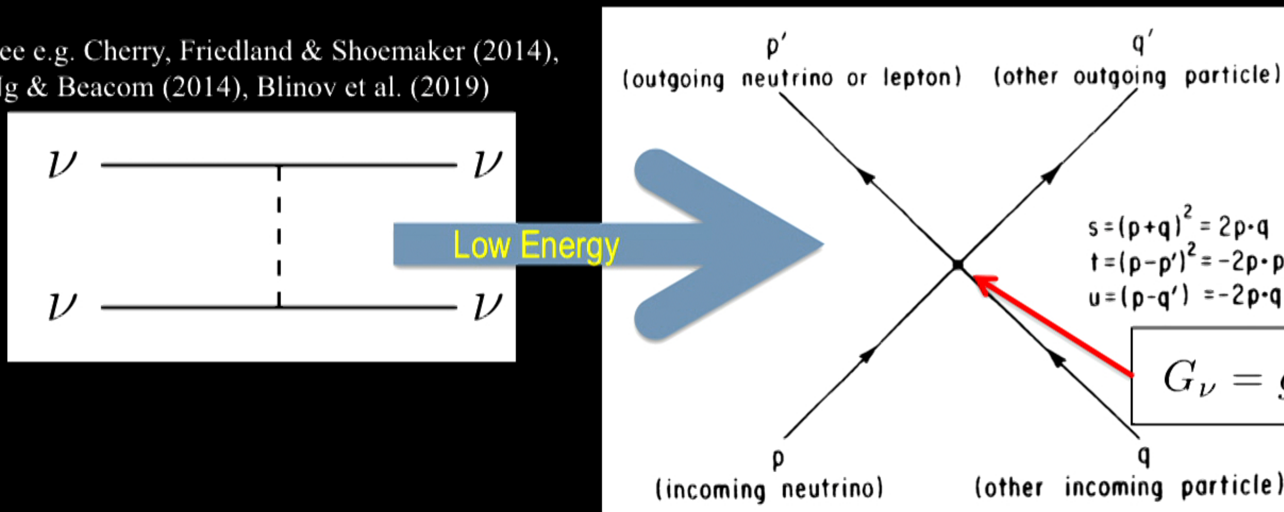


See also Ng & Beacom (2014) and Arcadi et al. (2018)

Beyond Free-streaming Neutrinos

New Unknown Interaction: $\mathcal{L}_{\rm phen} \supset -\frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}(g_\phi^{\alpha\beta}\nu_\alpha\nu_\beta\phi + {\rm h.c.})$

See e.g. Cherry, Friedland & Shoemaker (2014), Ng & Beacom (2014), Blinov et al. (2019)



$$G_\nu = g_\nu^2/M_\phi^2$$

4-Fermion Interaction stronger than Fermi constant

$$G_\nu > G_{\rm F}$$

Important Take Home Messages

- As precision increases, cracks might be appearing in the standard cosmological model.
- Inspired by status of neutrino physics, we have explored a self-interacting neutrino scenario that might help reconcile datasets.

- Main message: It is possible to find radically different cosmological model that nonetheless can provide excellent fit to the data.