The Neutrino Puzzle: Anomalies, Interactions, and Cosmological Tensions

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Disclaimer

- This talk might solicit a strong response from members of the audience. Viewer discretion is advised.
- Spherical cows will be used in this talk. However, they will not be harmed.

Precision Cosmology Era

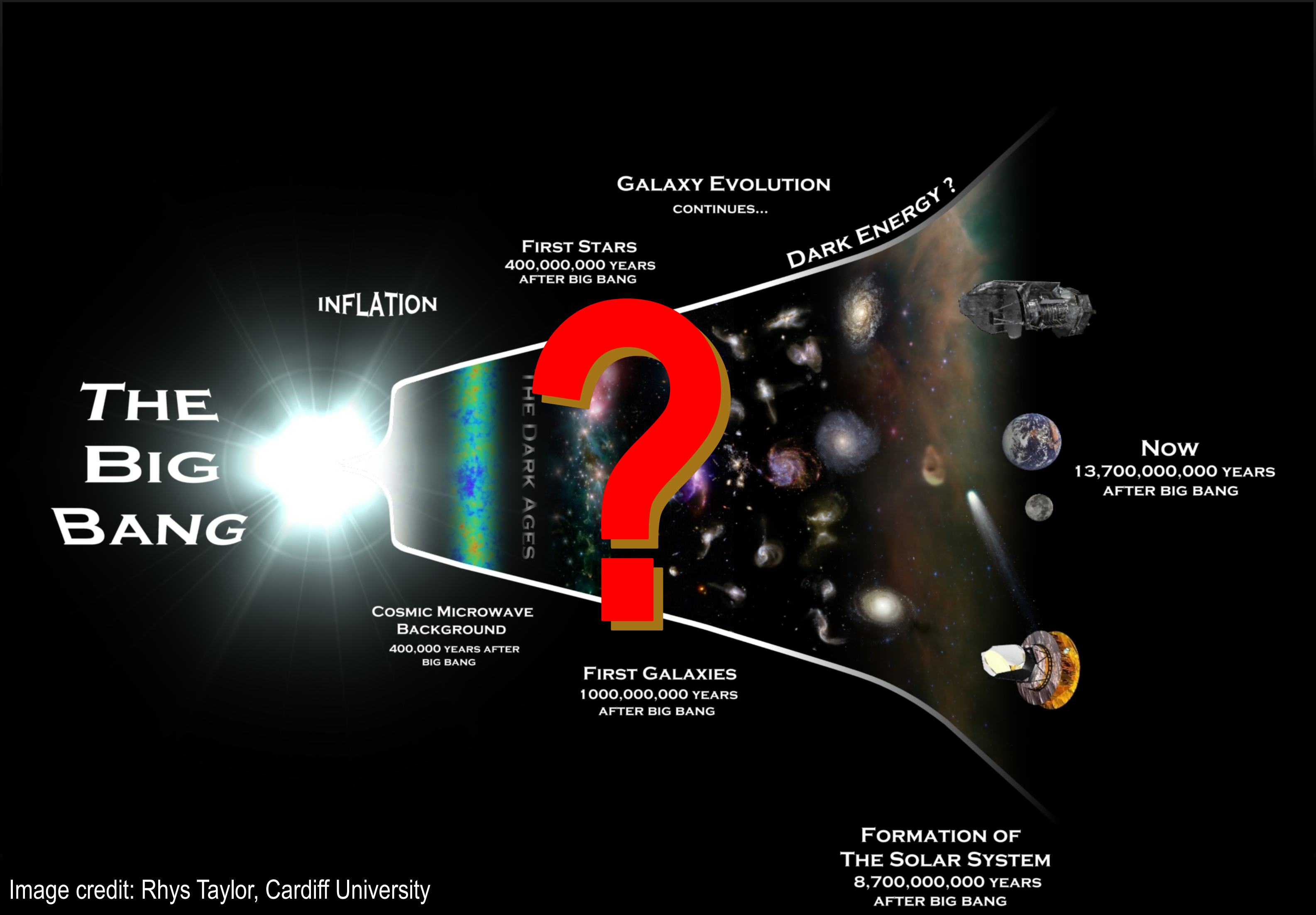
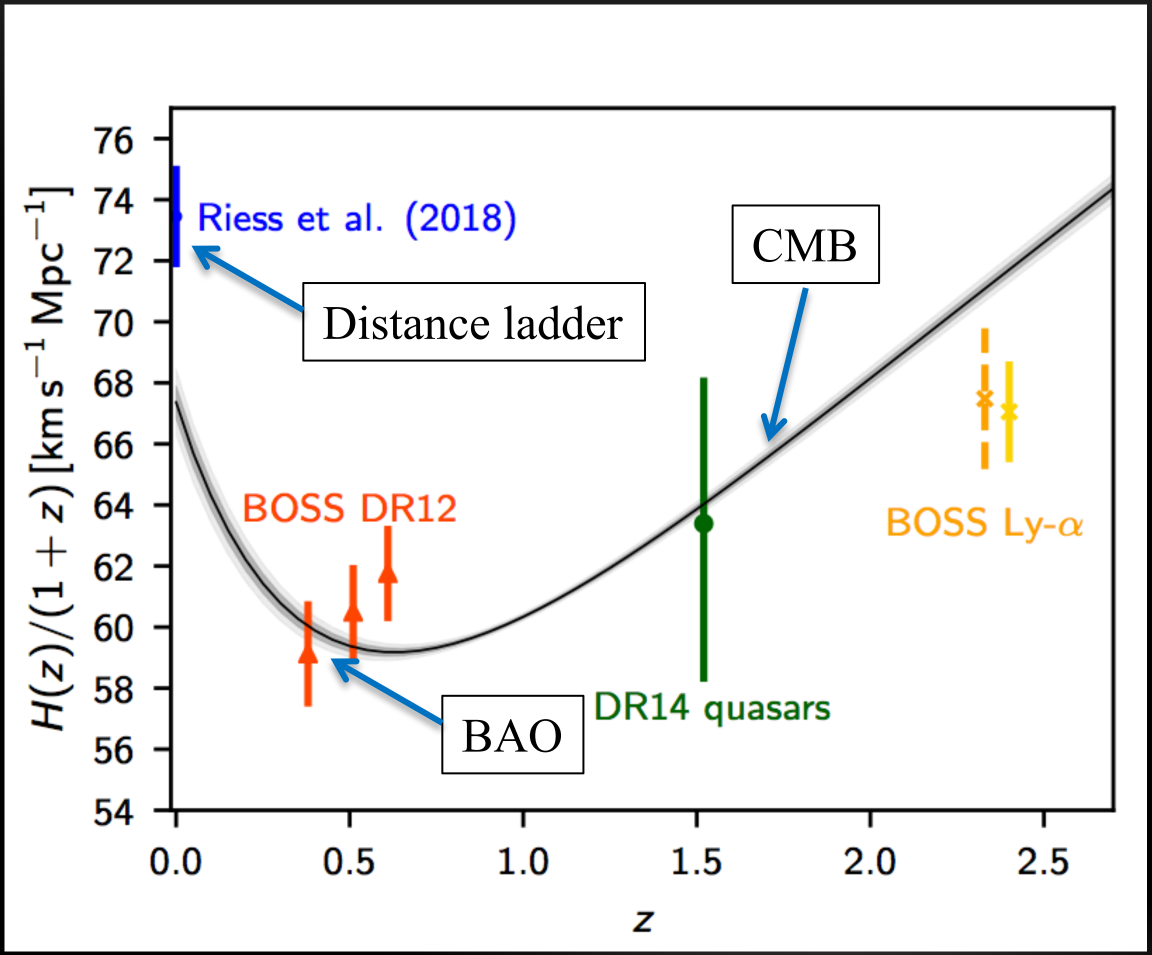


Image credit: Rhys Taylor, Cardiff University

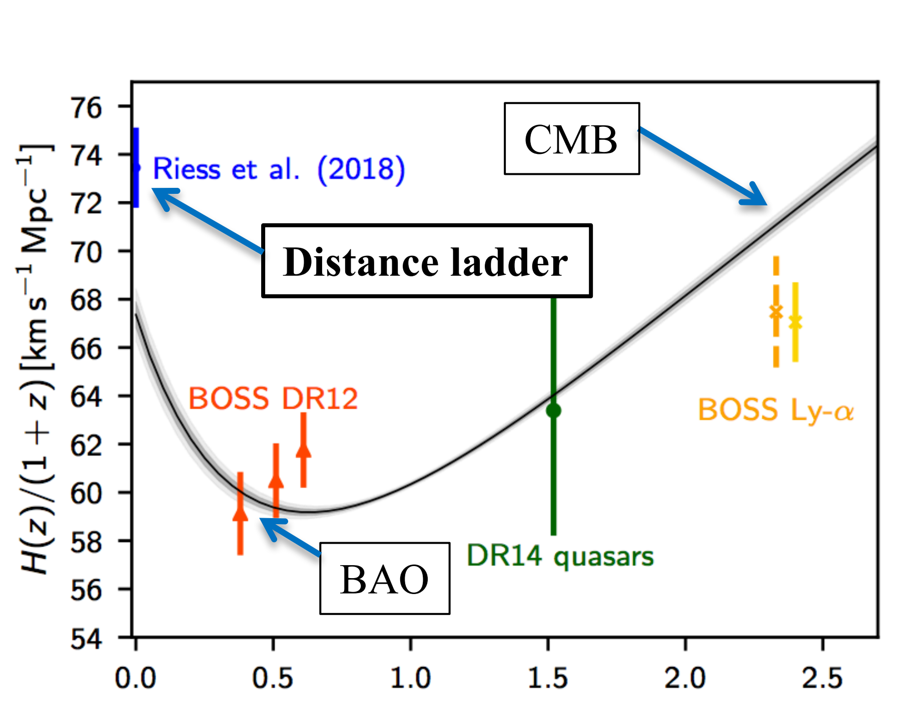
Precision Cosmology Era?



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)

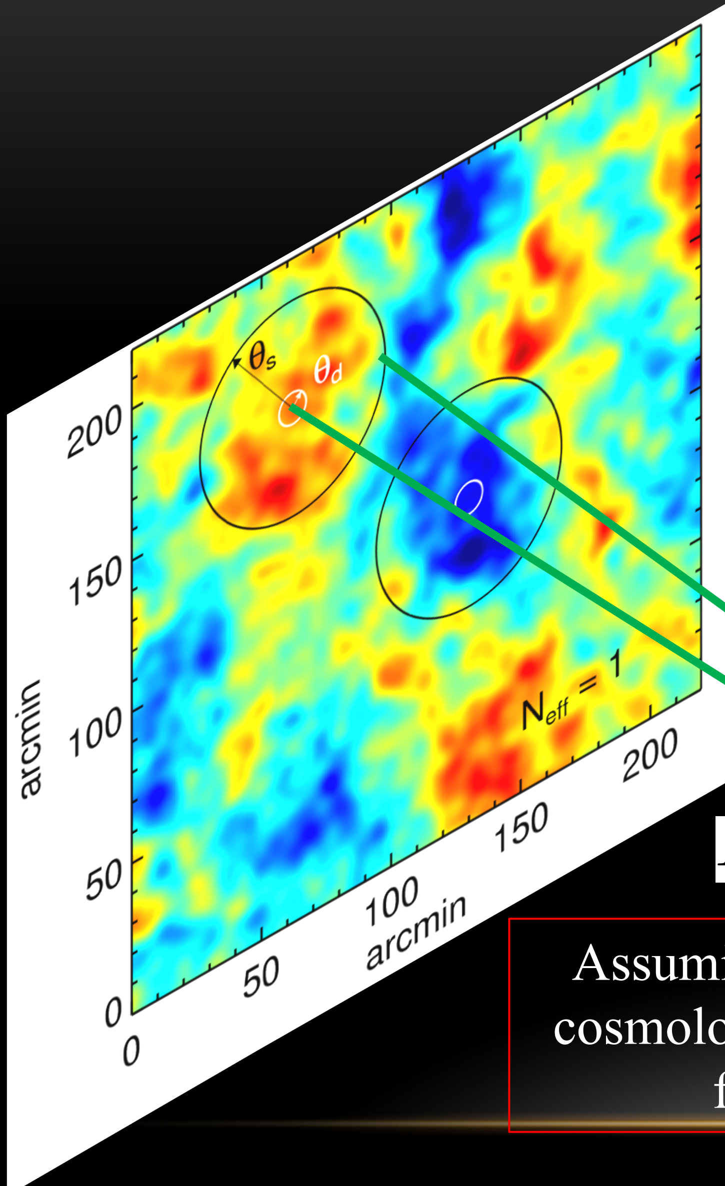
On this plot, only Riess et al. (2018) provides a *direct* measurement of the current Hubble rate.

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

Time of baryon decoupling

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

Cosmic Microwave Background



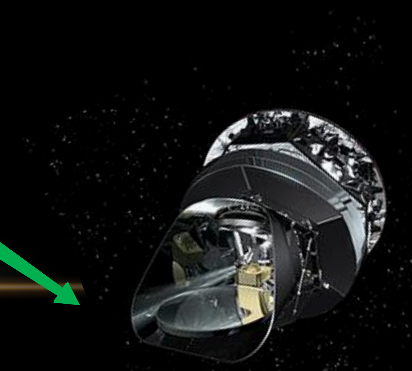
The CMB primarily measures angles on the sky.

$$\theta_{\rm s} = r_{\rm s}/D_A(z_{\rm d})$$

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

$D_A(z_{\rm d})$

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

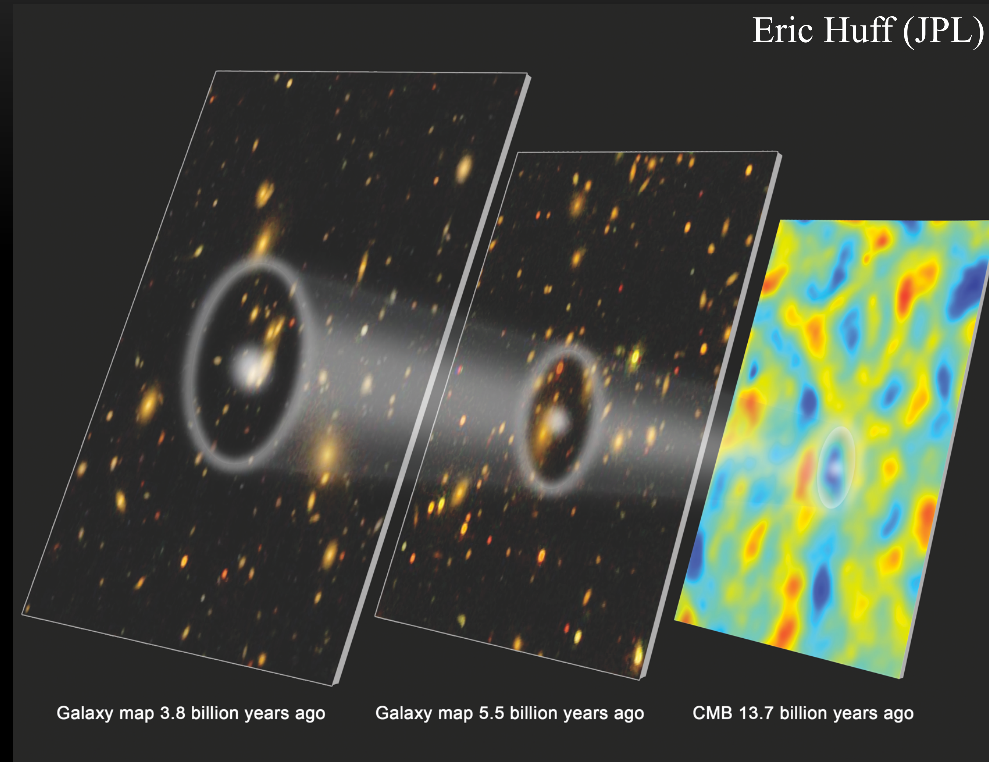


Baryon Acoustic Oscillations (BAO)

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

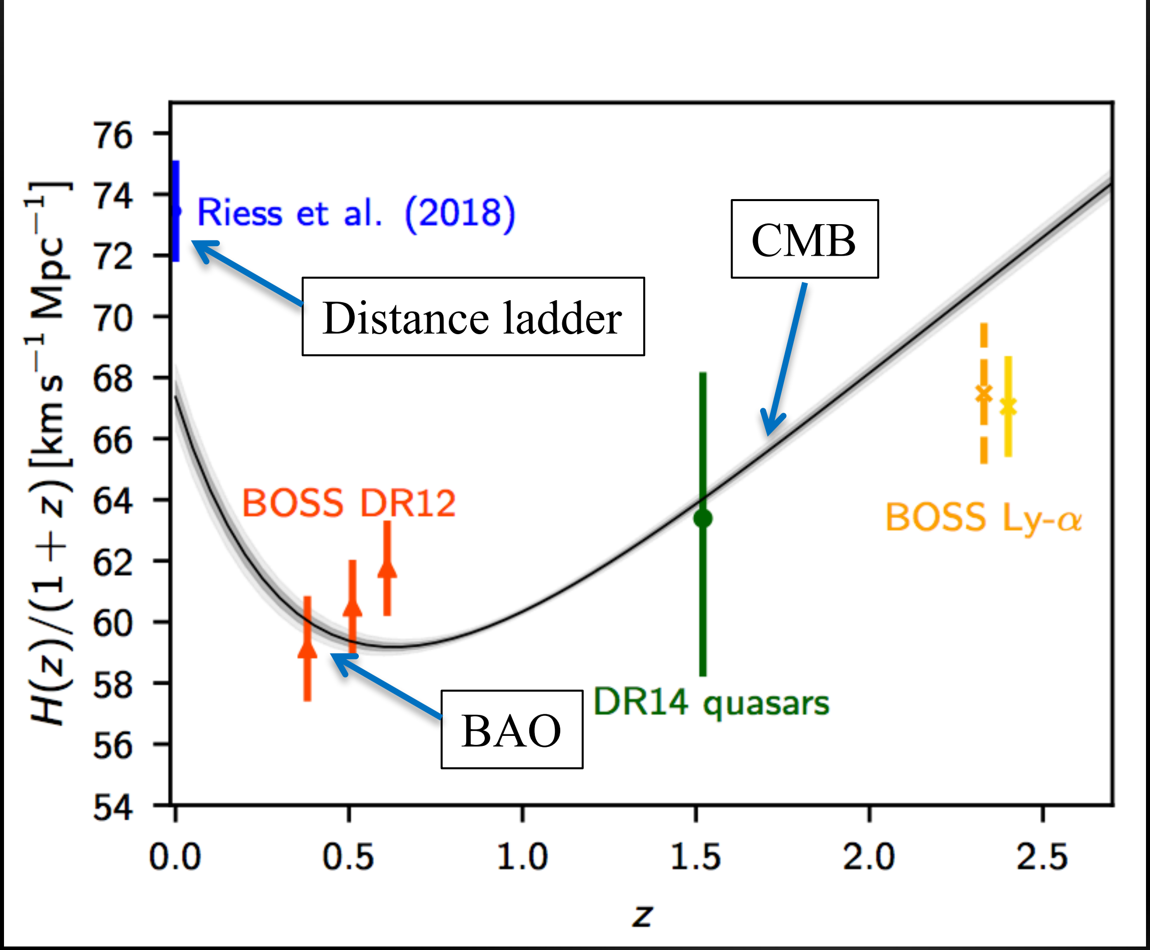
Line of sight: $H(z)r_{\mathrm{s}}$

Transverse: $r_{\mathrm{s}}/D_A(z)$



- 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.

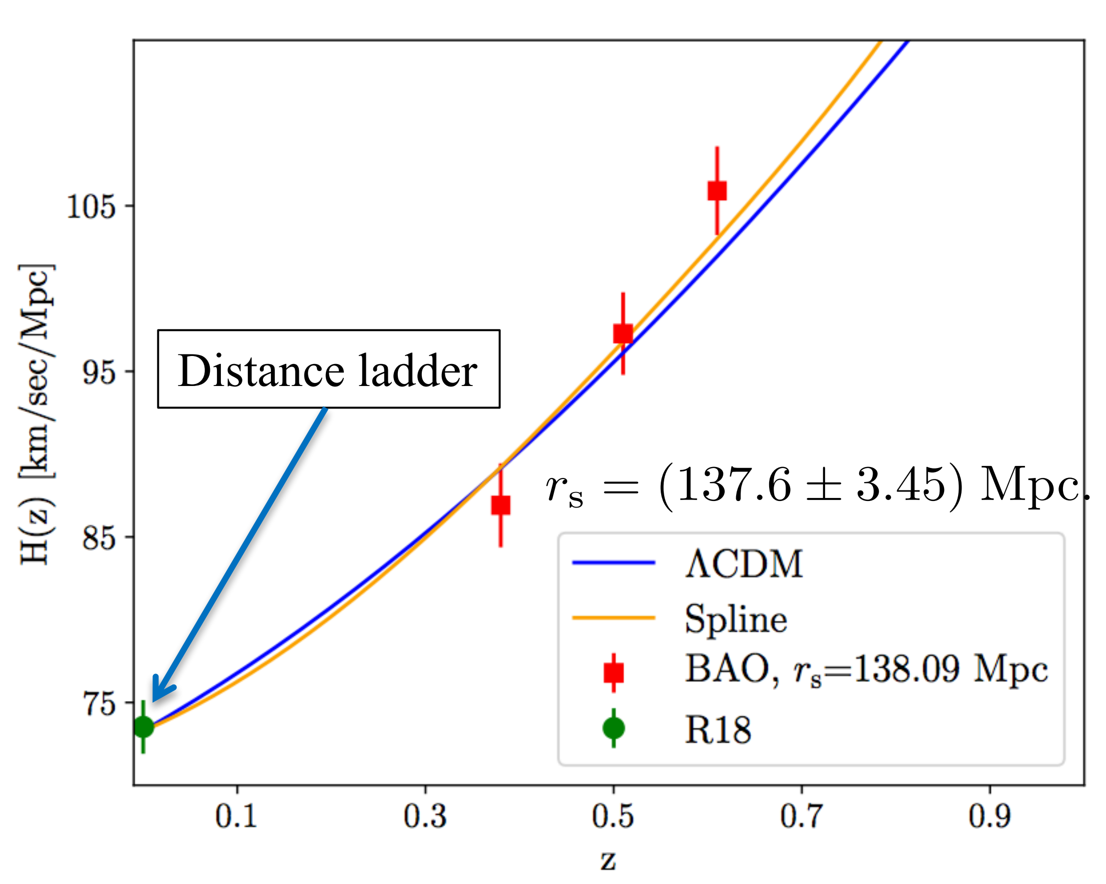
A little misleading?



Planck collaboration (2018)

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

Calibrate BAO with local distance ladder



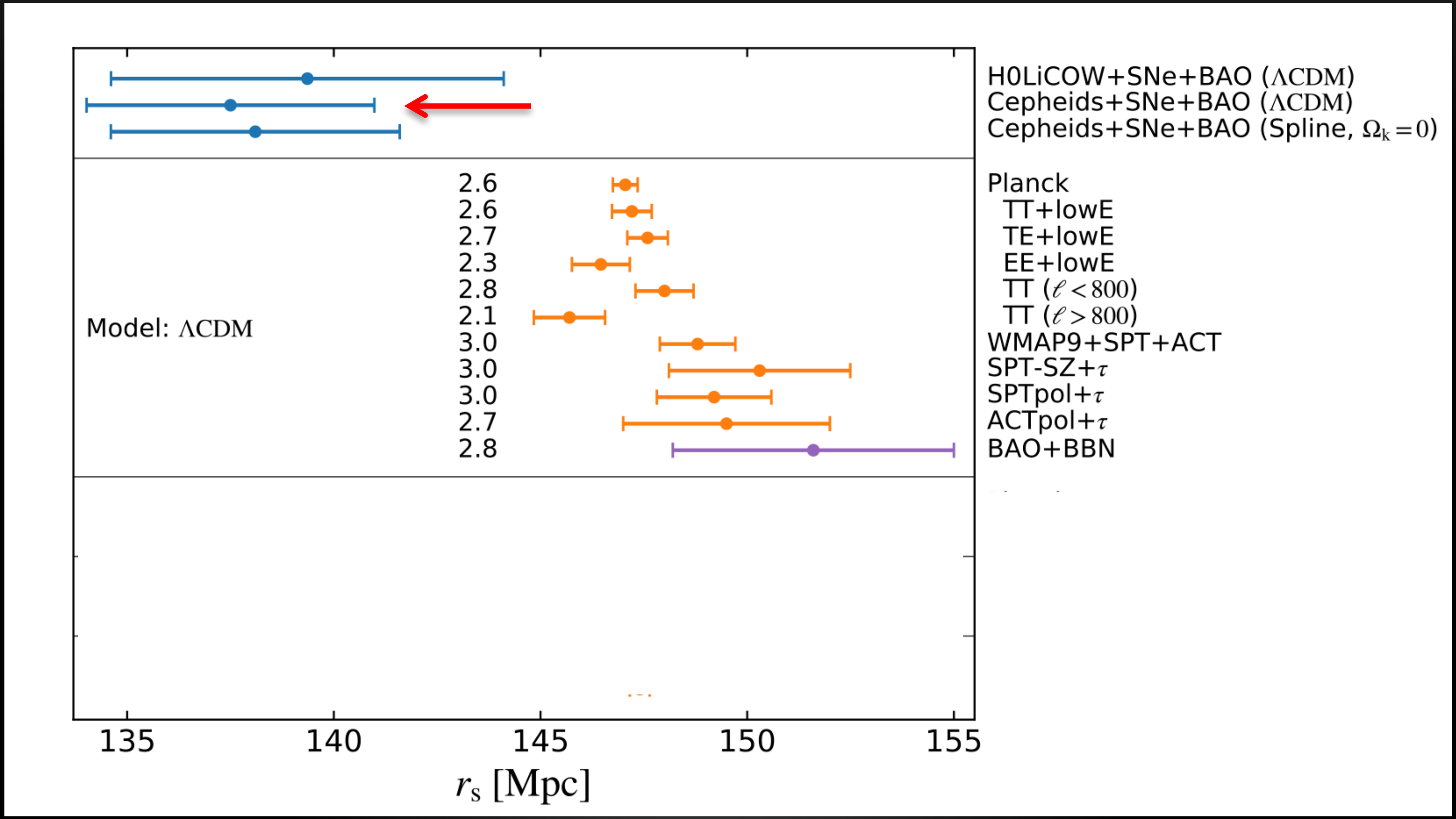
Aylor et al, (2018)

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

For comparison, Planck's CMB value is:

$r_s = 147.05 \pm 0.30\,\mathrm{Mpc}$

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.

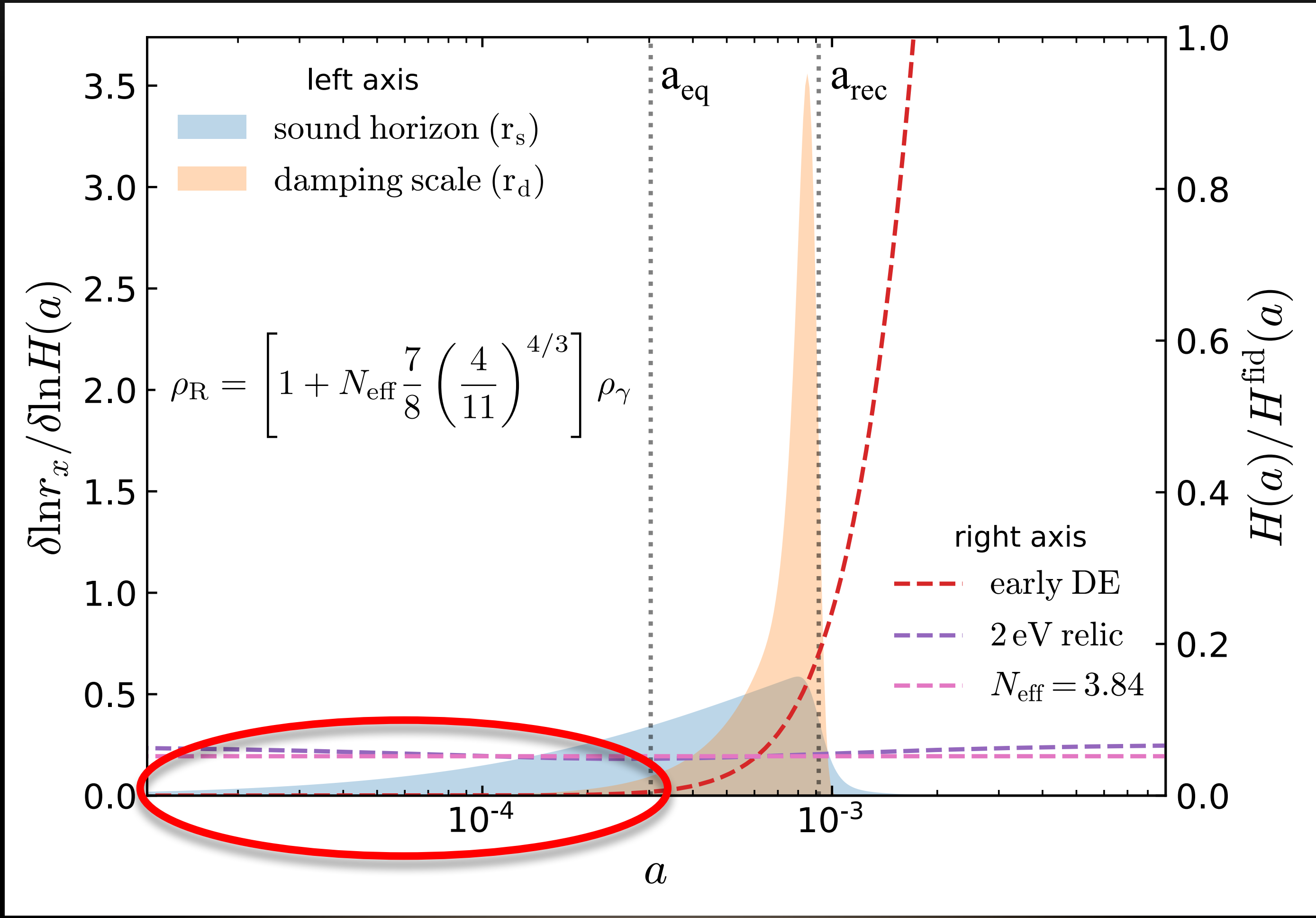
$$\cancel{c_{\rm s} = \frac{1}{\sqrt{3\left(1+\frac{3\rho_{\rm b}}{4\rho_\gamma}\right)}}}$$

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

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

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

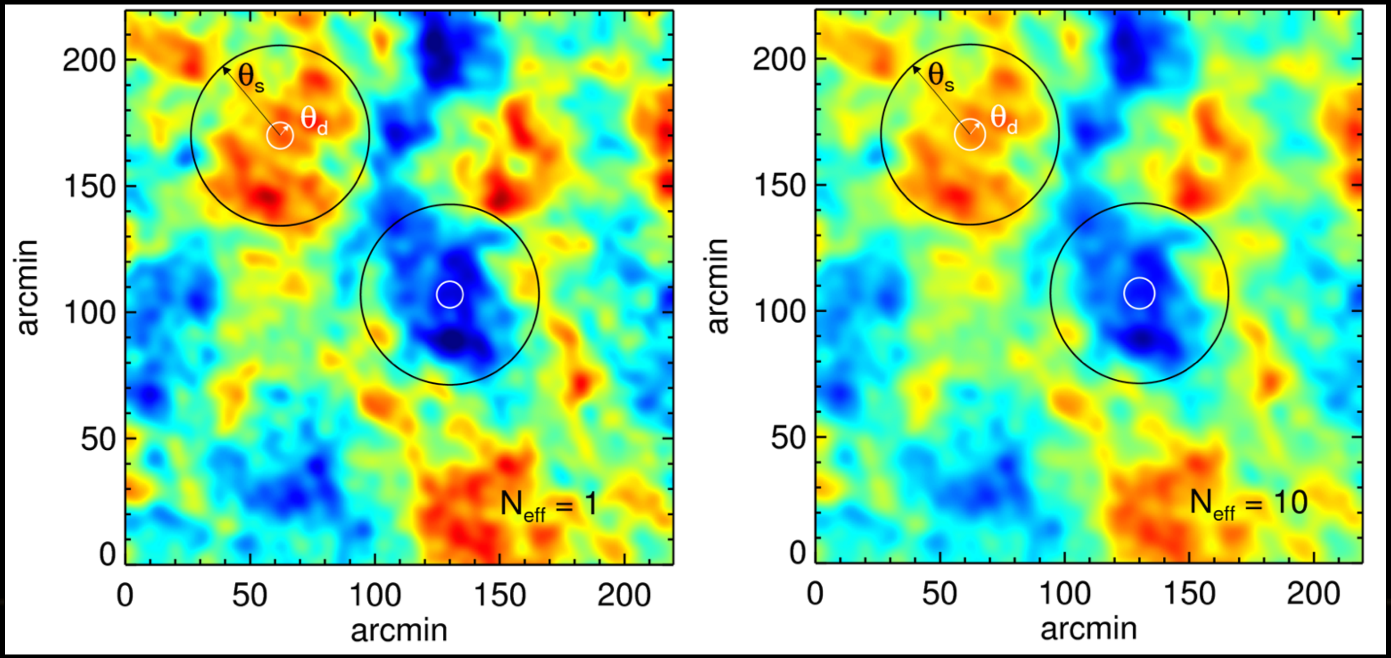
Issue: Sound horizon vs Damping scale



Credits: Lloyd Knox

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!



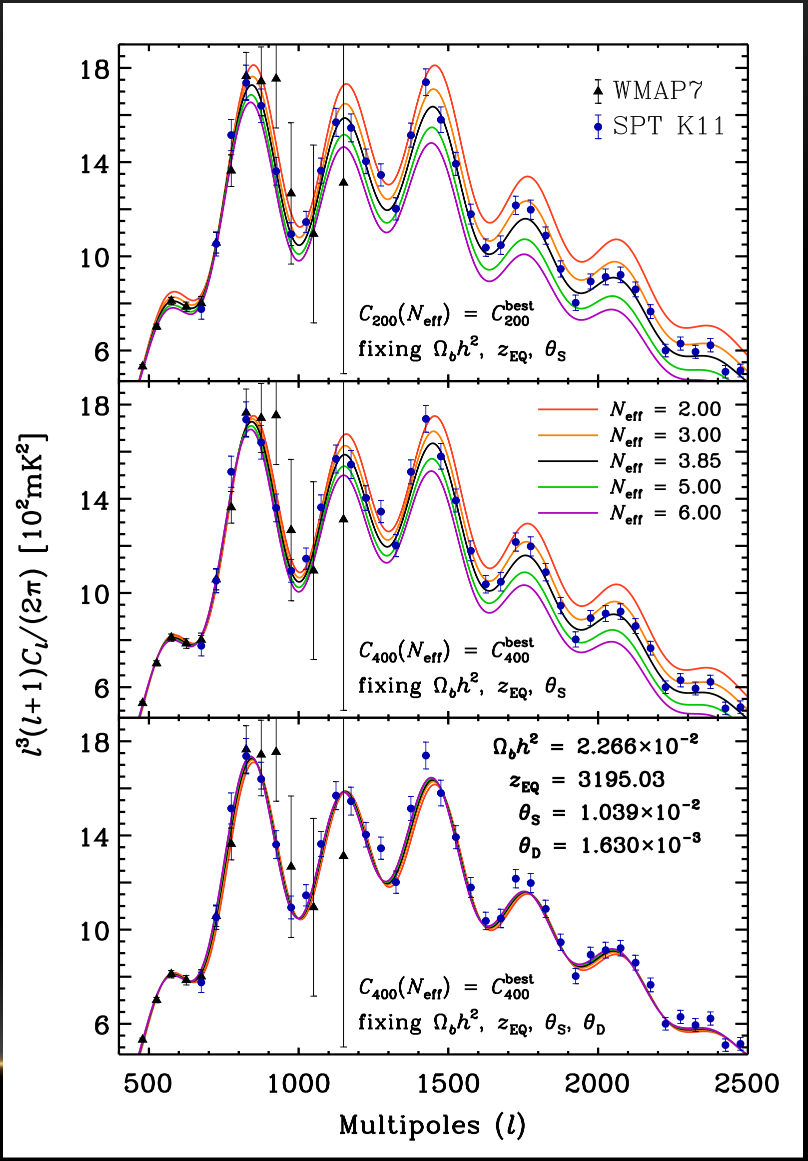
The problem with N_{eff}

Hou et al. (2012)

- 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.

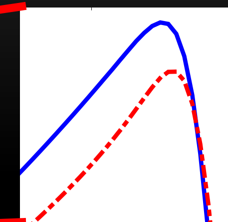
  Bashinsky & Seljak (2004)
  Baumann et al. (2016)

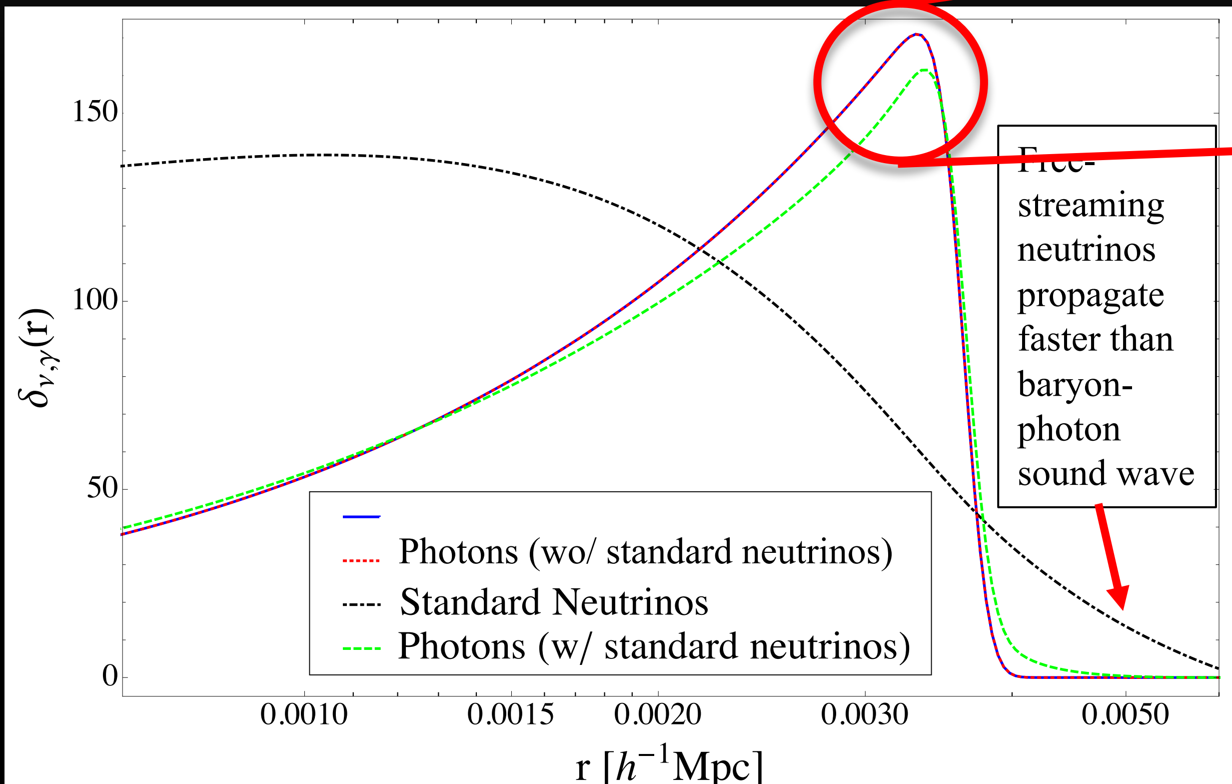
- Need to examine the behavior of fluctuations.



Free-streaming Radiation and the CMB

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





Cyr-Racine & Sigurdson (2014)

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

where

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

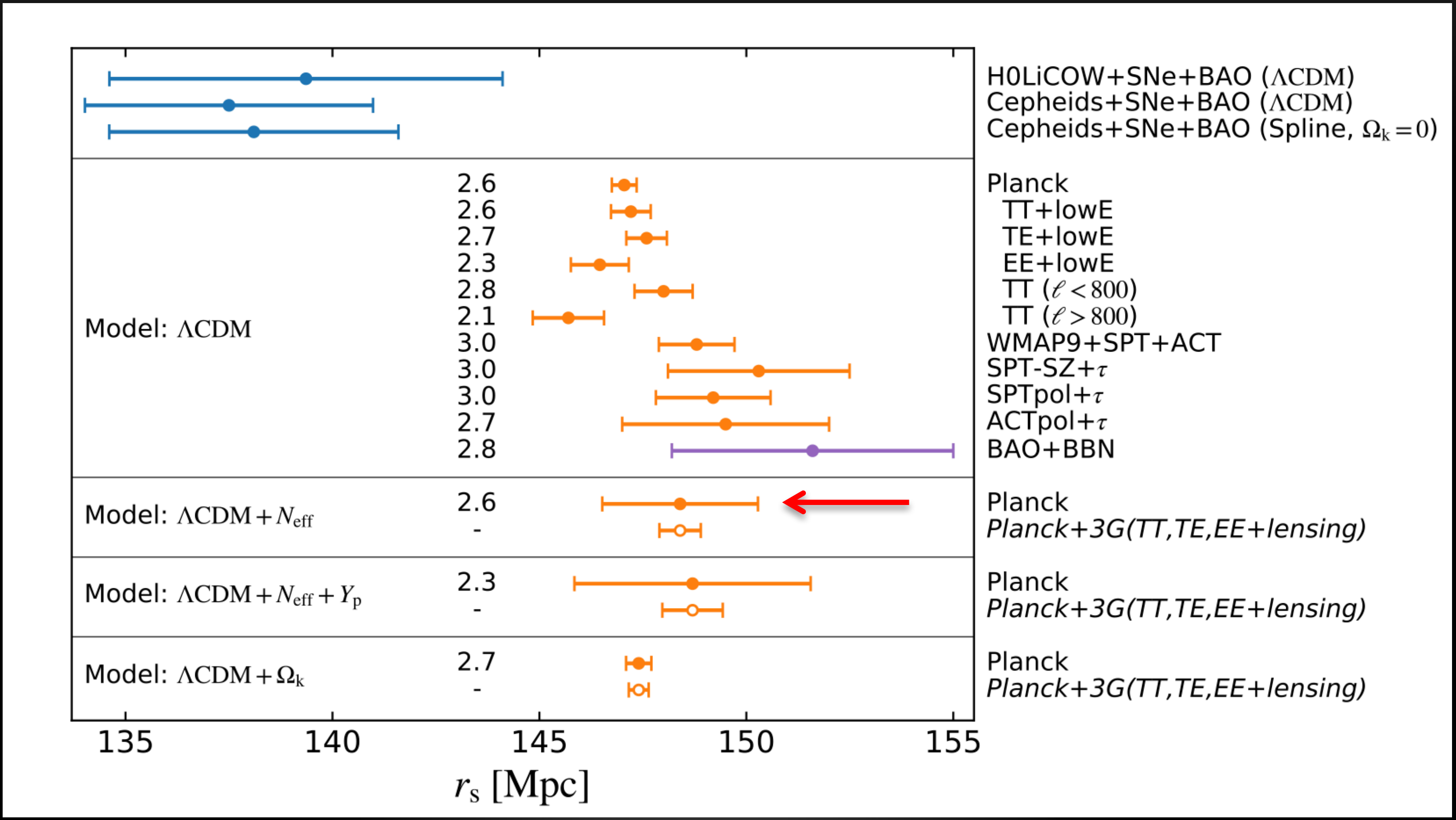
$$\delta\varphi \simeq 0.1912\,\pi R_\nu + O(R_\nu^2).$$

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

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

Bashinsky & Seljak (2004)

The problem with N_{eff}



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

Sound horizon discrepancy and relativistic species

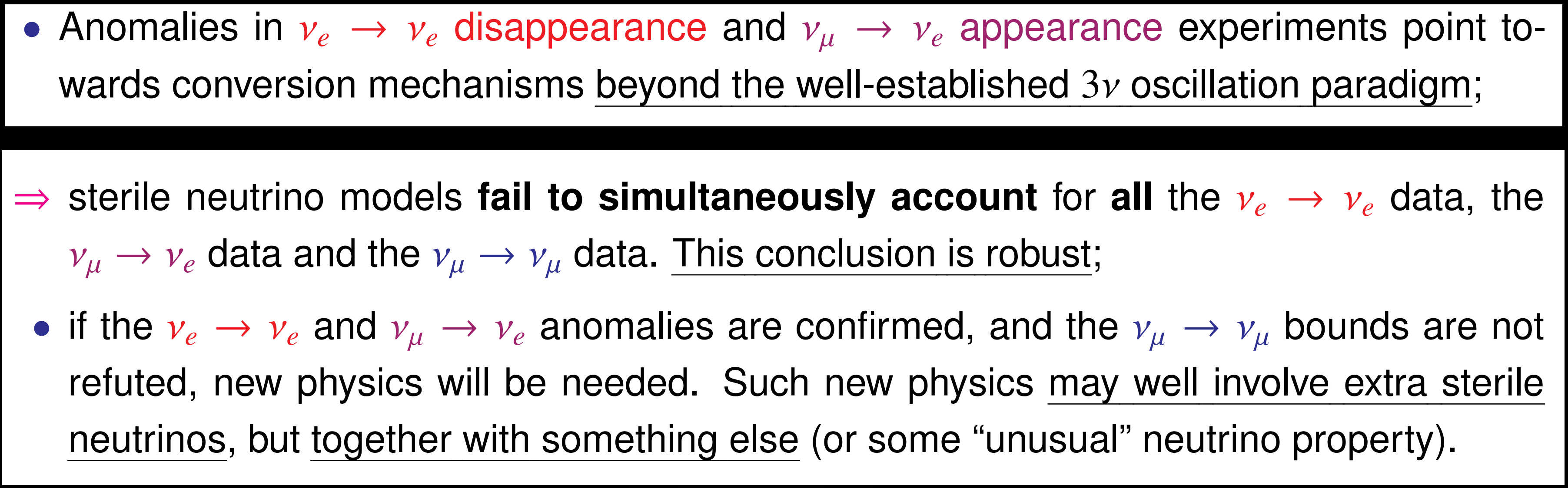
- One way to interpret the current tension among cosmological datasets is that the baryon-photon sound horizon estimates from early time and late time probes is discrepant.
- This could be fixed by changing the Hubble expansion rate in the two decades in scale factor before recombination.
- Adding relativistic 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

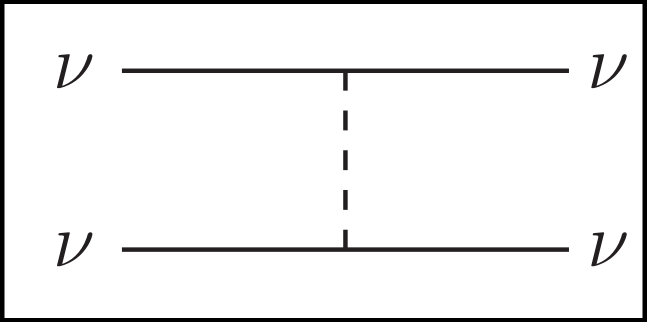
From Michele Maltoni's talk at the Neutrino 2018 conference:



_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

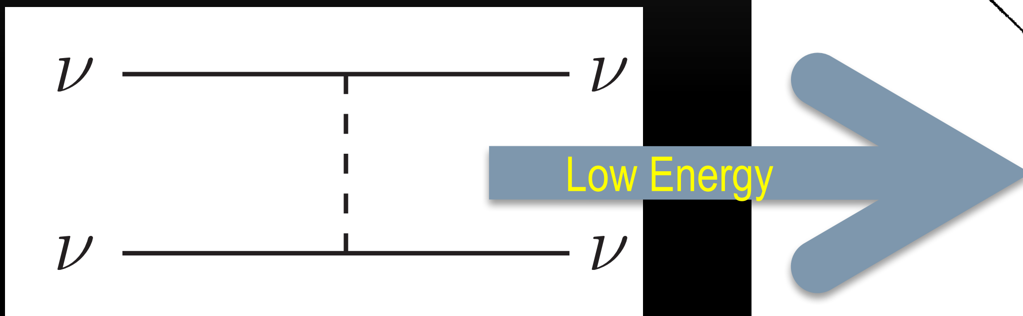
Beyond Free-streaming Neutrinos

- 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…**

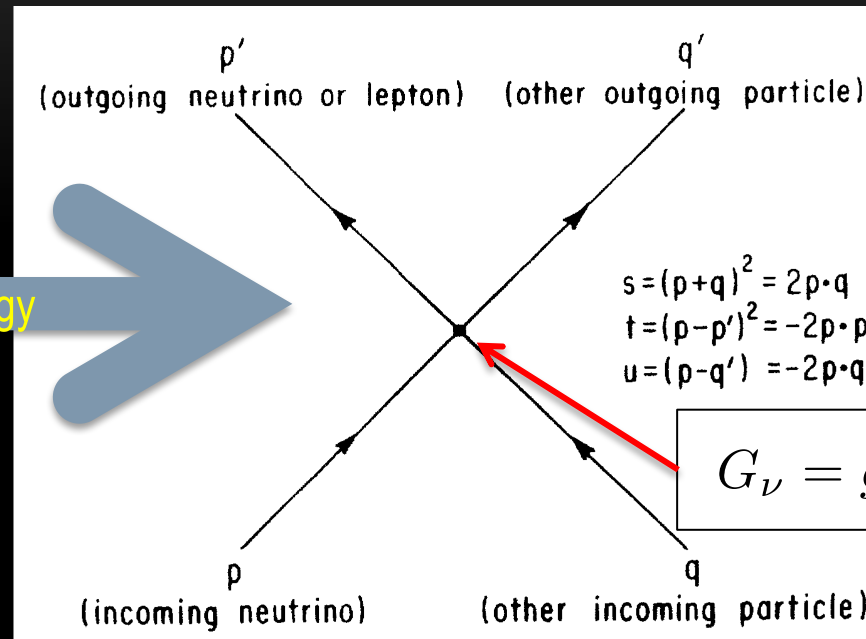
Beyond Free-streaming Neutrinos

See e.g. Cherry, Friedland & Shoemaker (2014), Ng & Beacom (2014)



New Unknown Interaction

$$\mathcal{L}_{\rm int} = g_{ij}\phi\bar{\nu}_i\nu_j$$



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

4-Fermion Interaction

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

$$G_\nu \lesssim 144\ {\rm MeV}^{-2}$$

Kolb and Turner (1987)

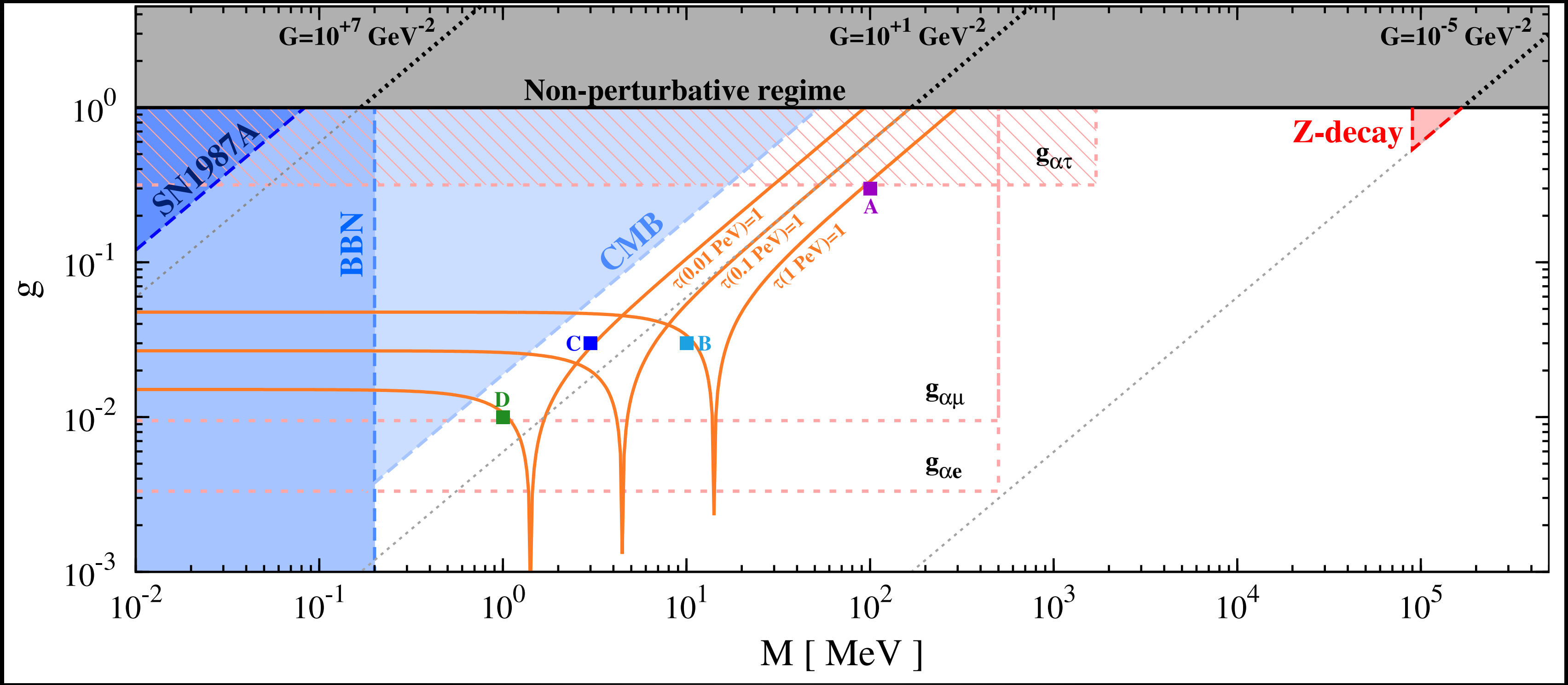
TABLE III. Comparison between the strongest bounds (including the scalar χ) obtained here and the previous bounds from the same processes. All bounds are at 90% C.L. and the previous bounds are from [14–16].

Previous Bounds	Revised Bounds
$\sum_\alpha \lvert g_{e\alpha}\rvert^2 < 3 \times 10^{-5}$	$\sum_\alpha \lvert g_{e\alpha}\rvert^2 < 5.5 \times 10^{-6}$
$\sum_\alpha \lvert g_{\mu\alpha}\rvert^2 < 2.4 \times 10^{-4}$	$\sum_\alpha \lvert g_{\mu\alpha}\rvert^2 < 4.5 \times 10^{-5}$
none	$\sum_\alpha \lvert g_{\tau\alpha}\rvert^2 < 5.5 \times 10^{-2}$

Lessa and Peres (2007)

Beyond Free-streaming Neutrinos

- Summary of current bounds



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

Delayed Neutrino Decoupling

Neutrino Opacity:

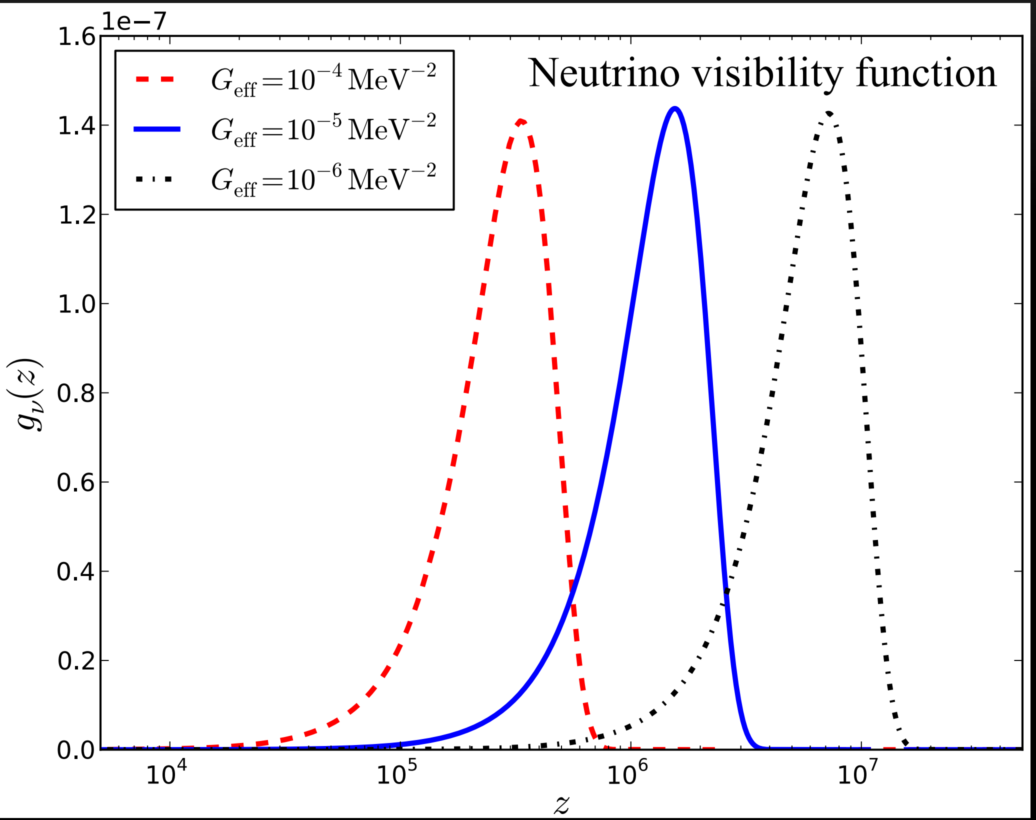
$$\dot{\tau}_\nu \propto -aG_{\rm eff}^2 T_\nu^5$$

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

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

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

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):

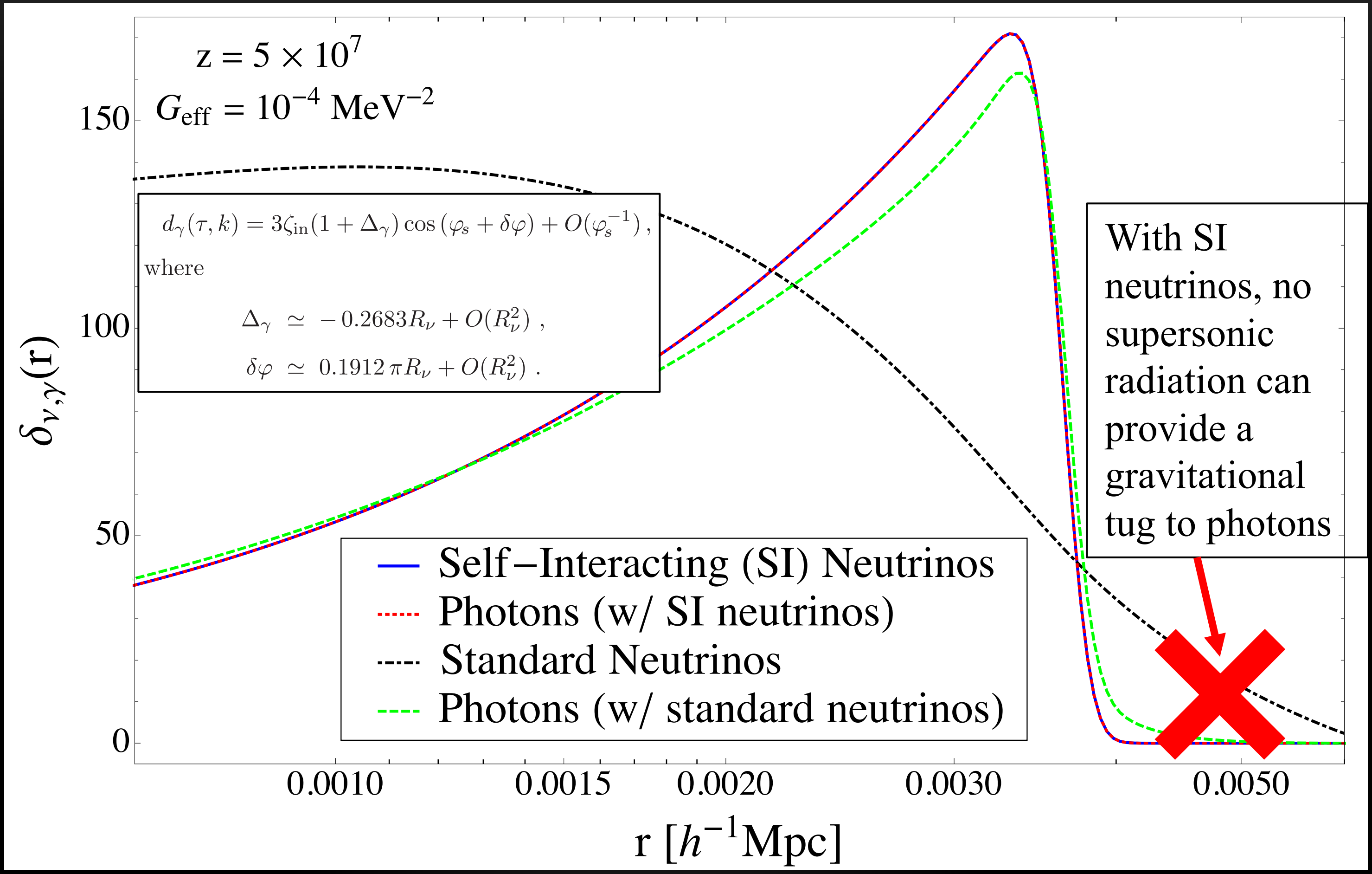
$$\frac{\partial \nu_l}{\partial \tau} + k\frac{q}{\epsilon}\left(\frac{l+1}{2l+1}\nu_{l+1} - \frac{l}{2l+1}\nu_{l-1}\right) - 4\left[\frac{\partial \phi}{\partial \tau}\delta_{l0} + \frac{k}{3}\frac{\epsilon}{q}\psi\delta_{l1}\right] = -a\frac{G_{\rm eff}^2 T_\nu^5 \nu_l}{f_\nu^{(0)}(q)}\left(\frac{T_{\nu,0}}{q}\right)\left(A\left(\frac{q}{T_{\nu,0}}\right)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

Relaxation-time approximation

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

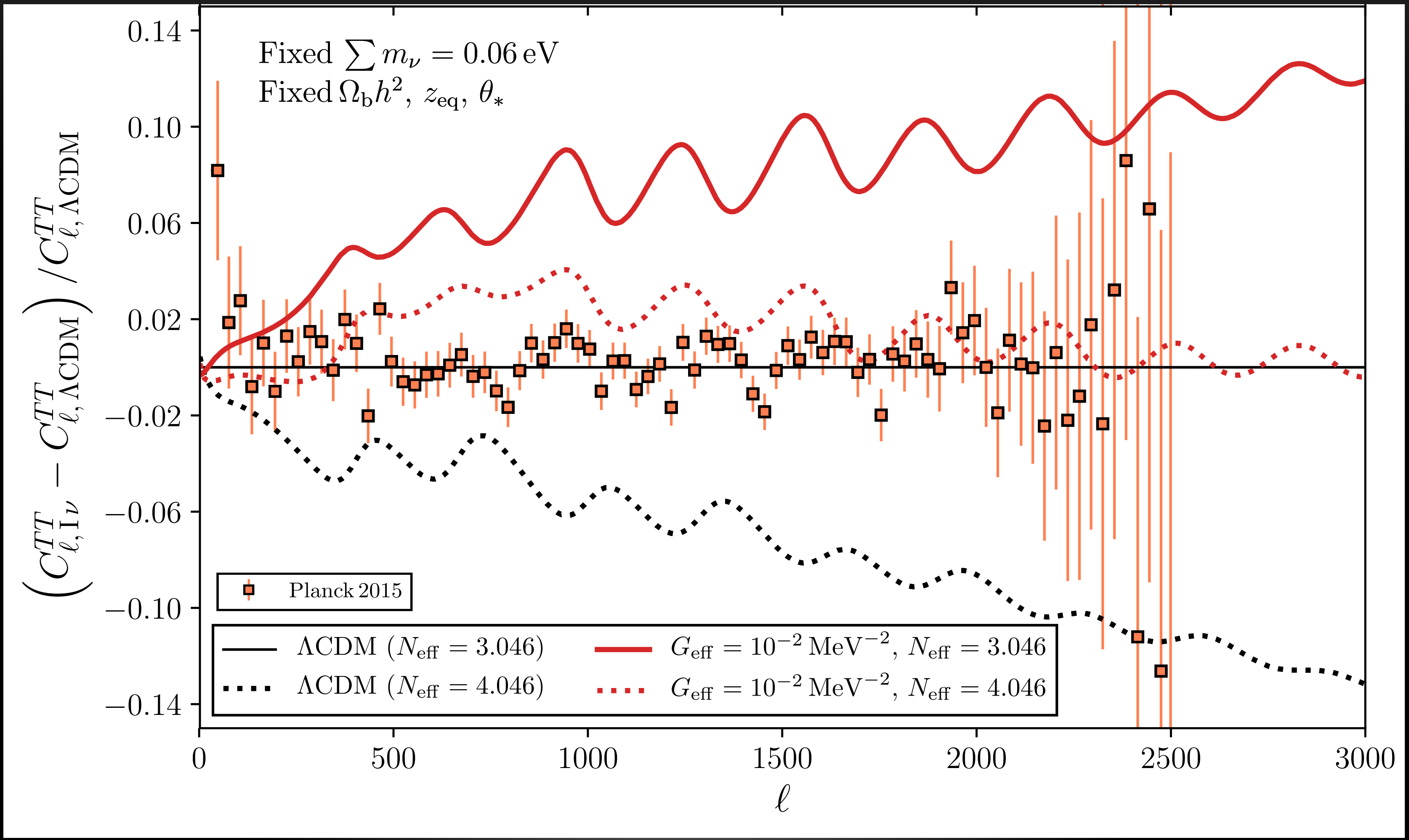
Cyr-Racine & Sigurdson (2014)
Oldengott, Rampf & Wong (2015)
Kreisch, Cyr-Racine+ (2019)

Impact of self-interacting Neutrinos on CMB



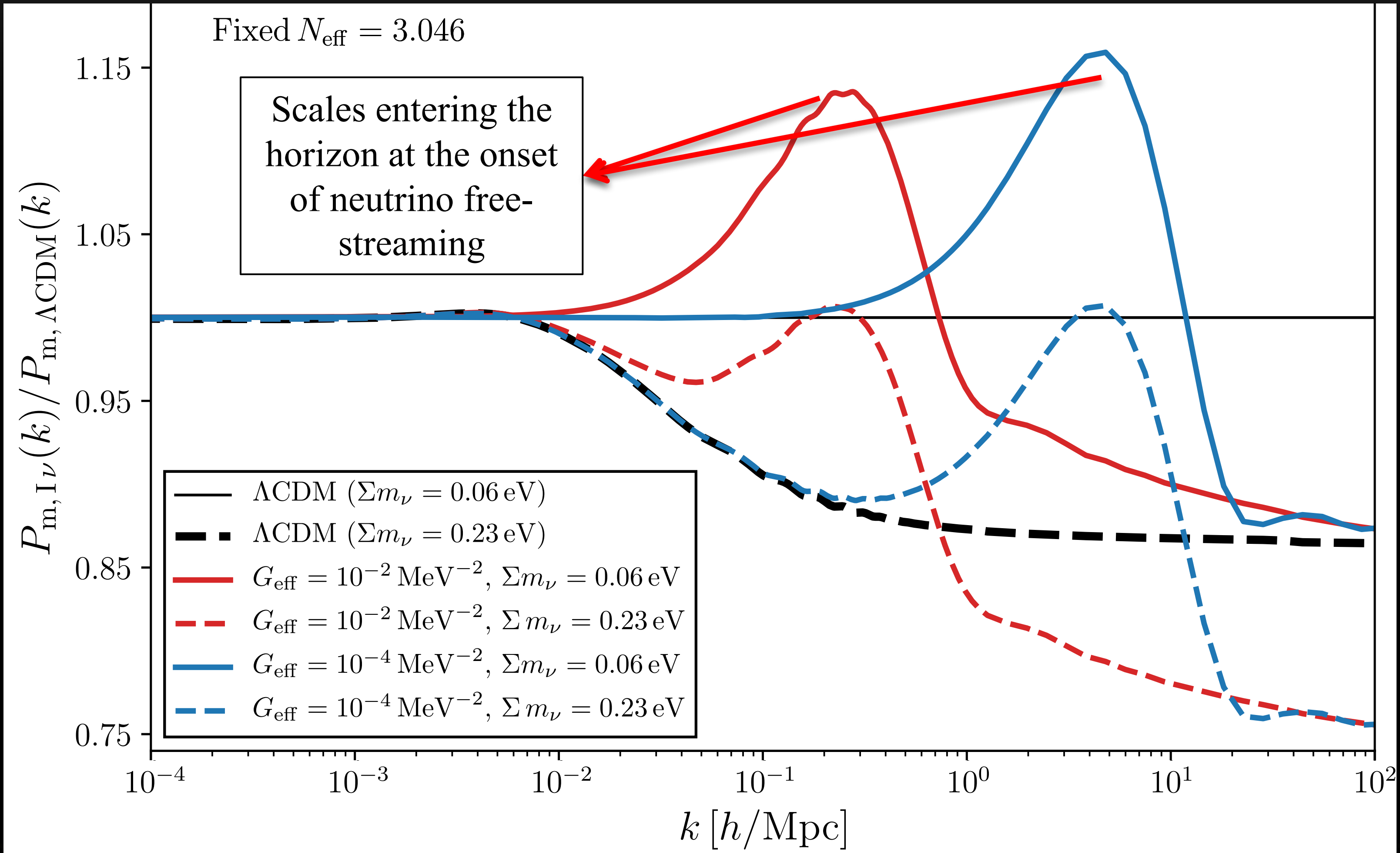
Cyr-Racine & Sigurdson (2014)

Impact of self-interacting Neutrinos on CMB



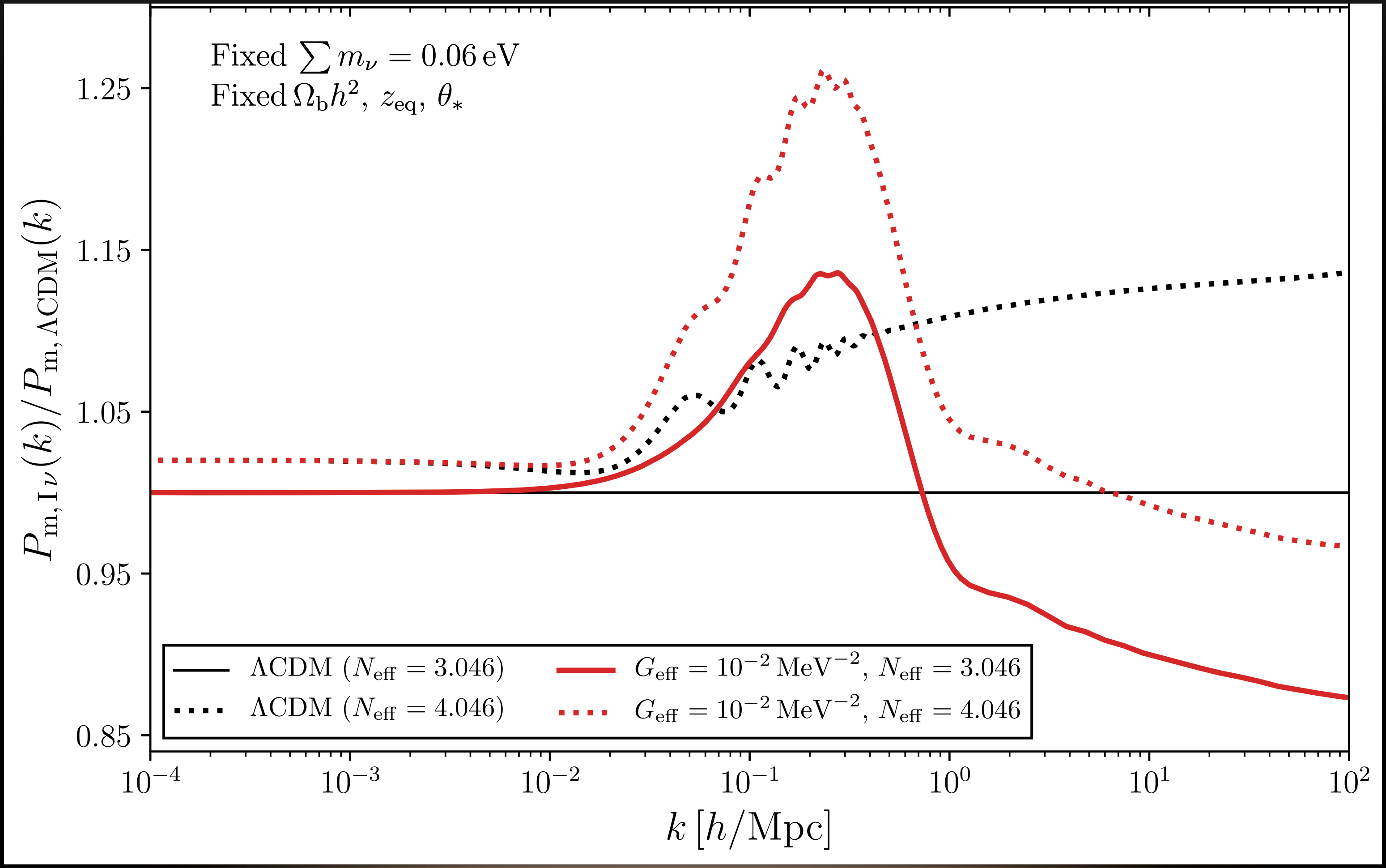
Kreisch, Cyr-Racine + (2019)

Impact of self-interacting Neutrinos on matter clustering



Kreisch, Cyr-Racine + (2019)

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



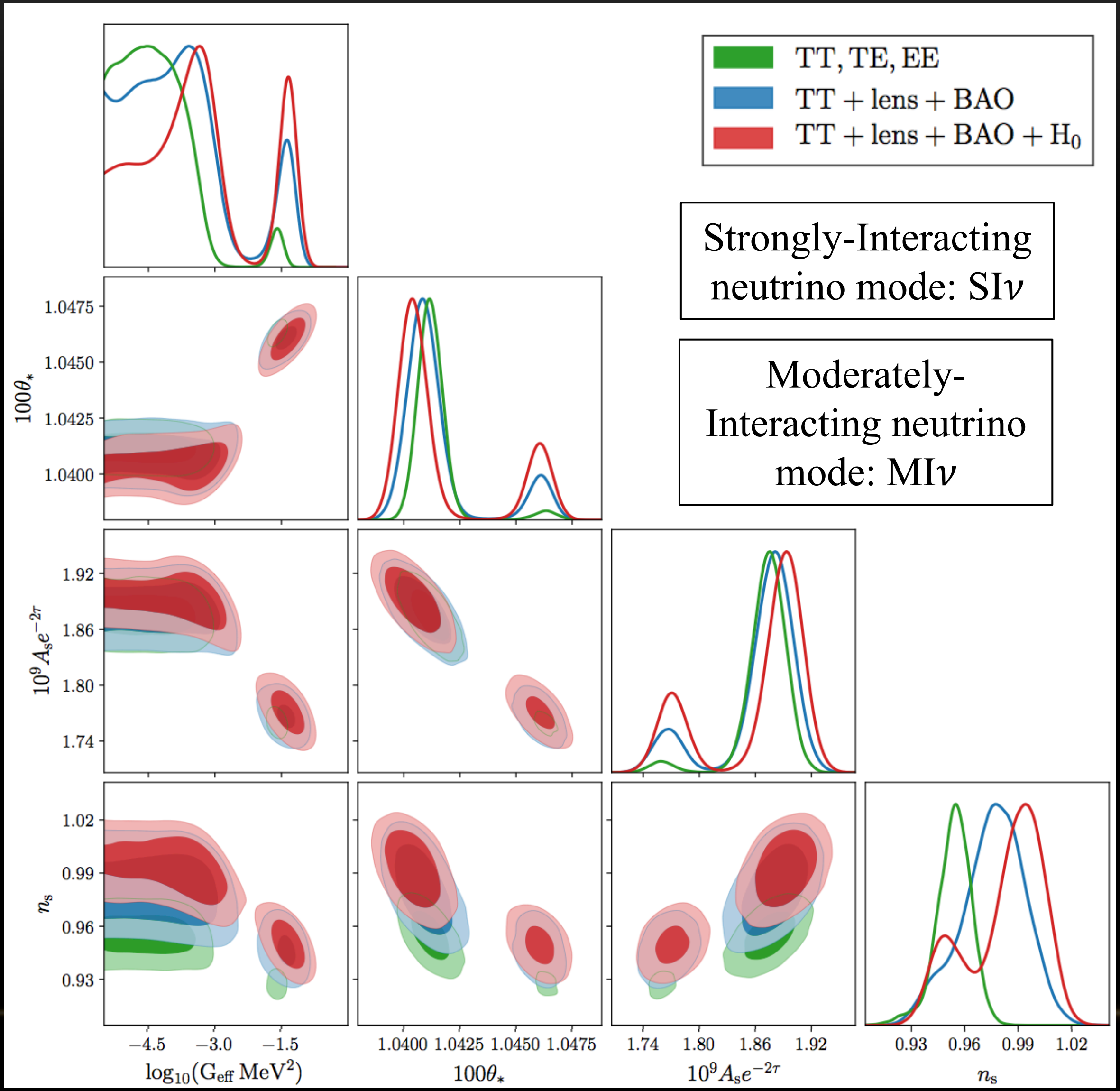
Kreisch, Cyr-Racine + (2019)

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

Let's ask Christina

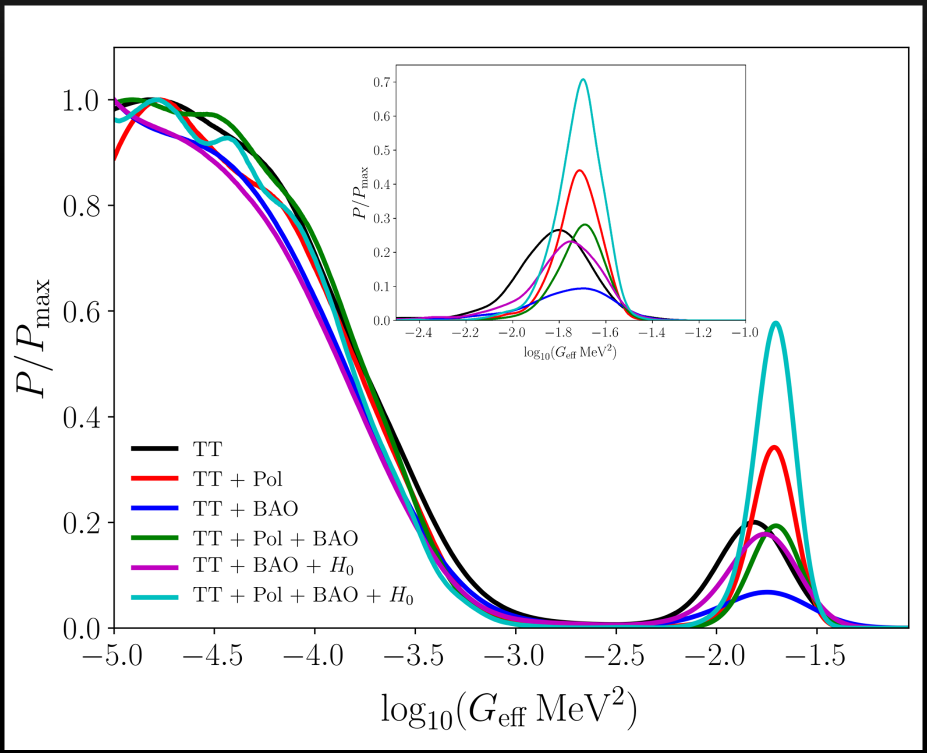
Christina Kreisch

A Tale of two statistical modes



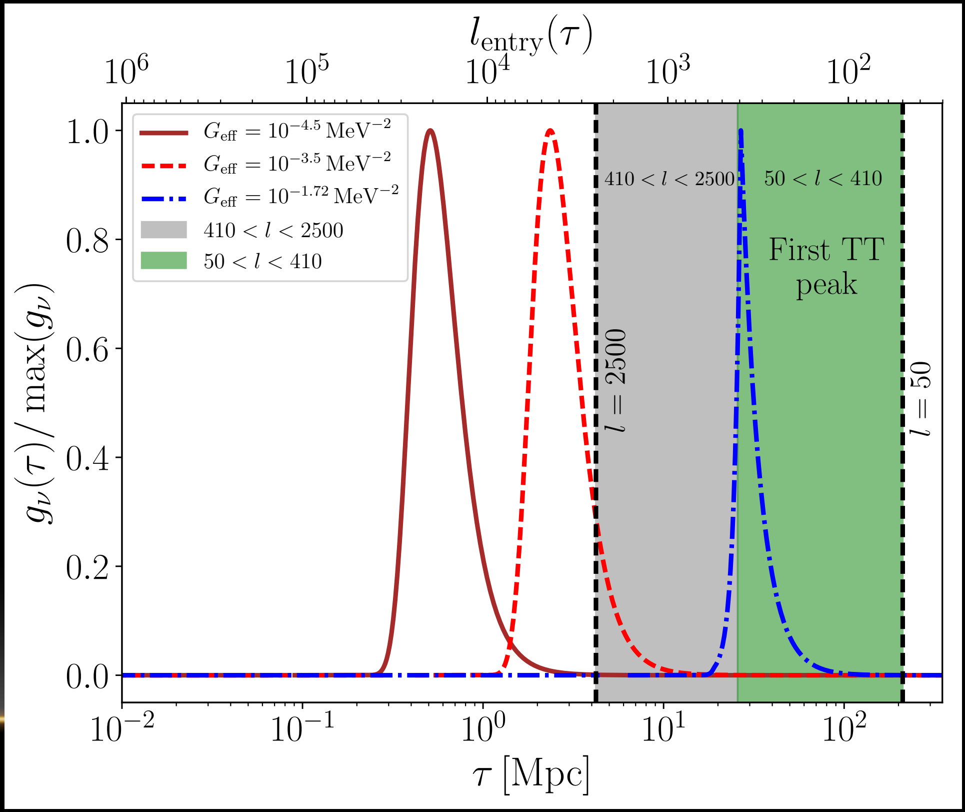
Kreisch, Cyr-Racine + (2019)

What is this SIν mode?



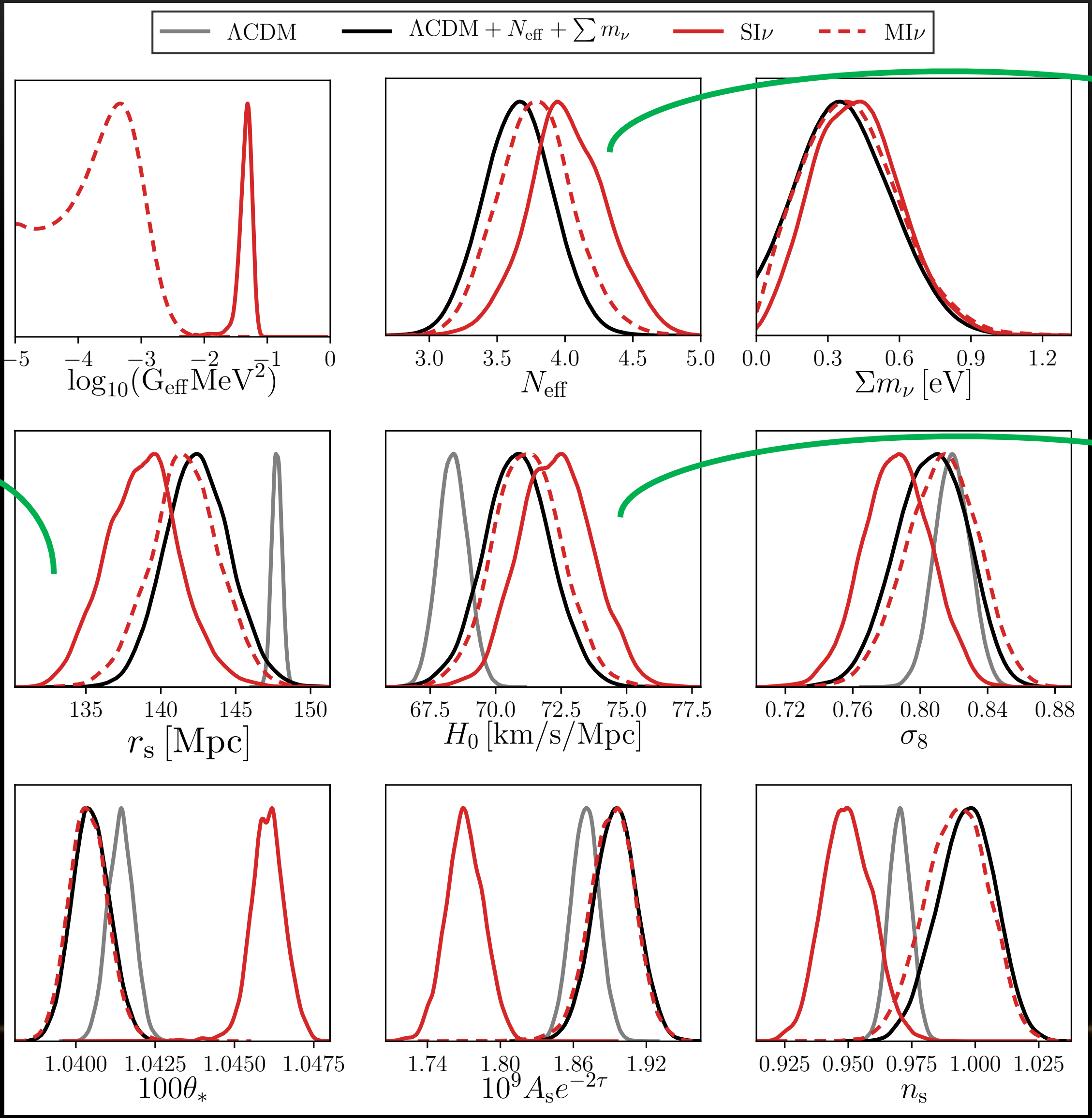
$$\dot{\tau}_\nu = -aG_{\rm eff}^2 T_\nu^5.$$

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



Cyr-Racine & Sigurdson (2014)
Lancaster, Cyr-Racine, Knox, Pan (2017)
Oldengott, Tram, Rampf & Wong (2017)

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



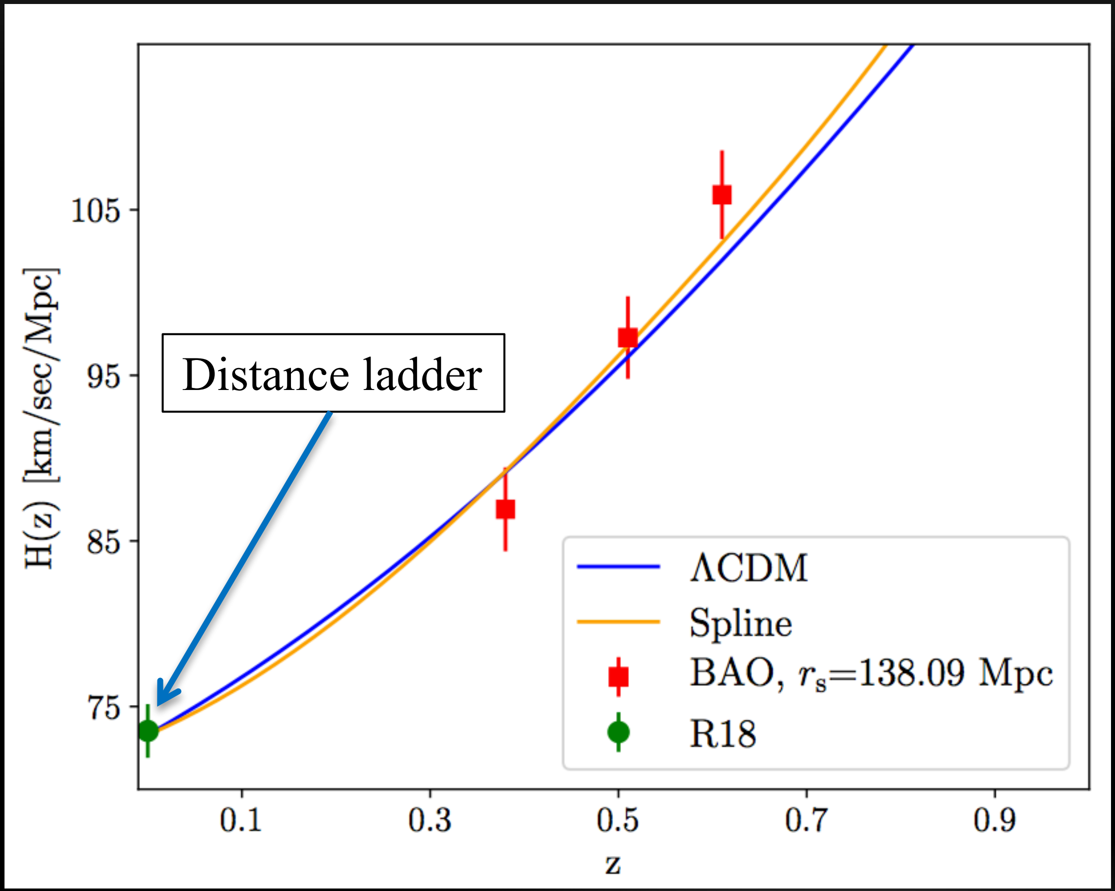
$N_{\rm eff} \sim 4$: extra energy density at early times

Sound horizon is smaller than in LCDM

Hubble constant is compatible with local measurement

Kreisch, Cyr-Racine + (2019)

Concordant direct and inverse distance ladders



Aylor et al, (2018)

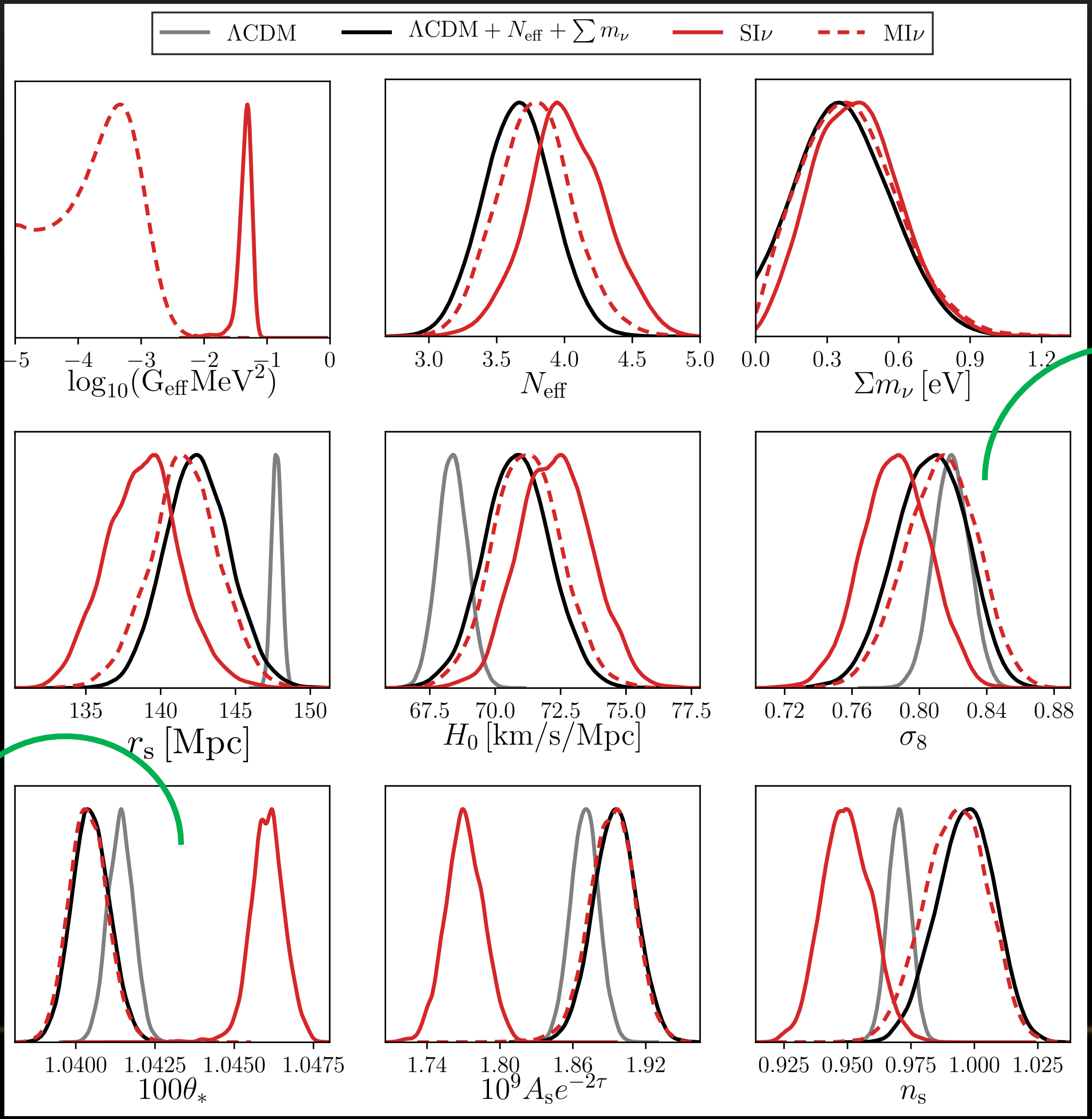
The SIν sound horizon:

$$r_\mathrm{s} = 138.8 \pm 2.5\,\mathrm{Mpc}$$

The local distance ladder sound horizon:

$$r_\mathrm{s} = (137.6 \pm 3.45)\ \mathrm{Mpc}.$$

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



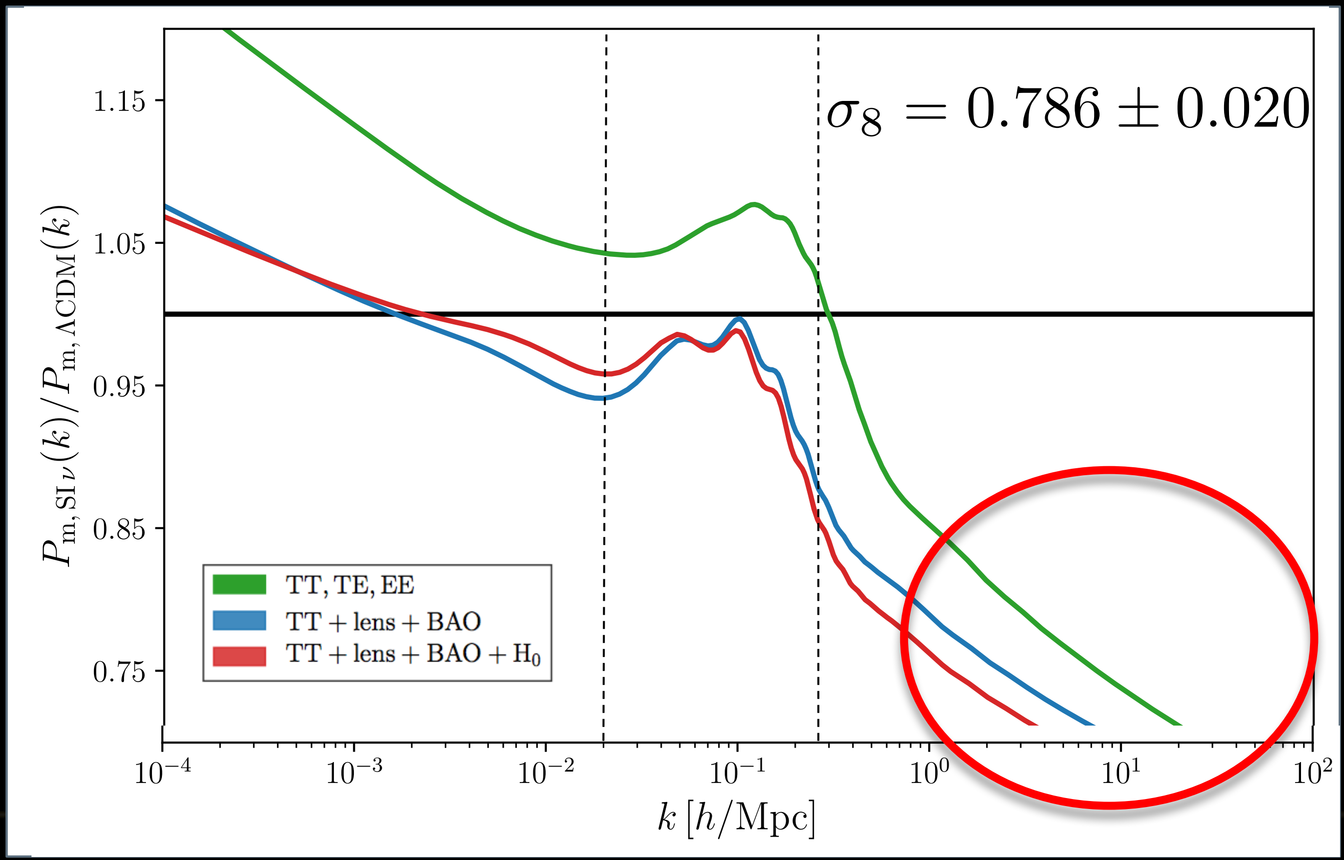
Value of σ_8 is slightly smaller than LCDM

Clearly see effect of suppressing neutrino phase shift

Kreisch, Cyr-Racine + (2019)

SIν Cosmology and matter clustering

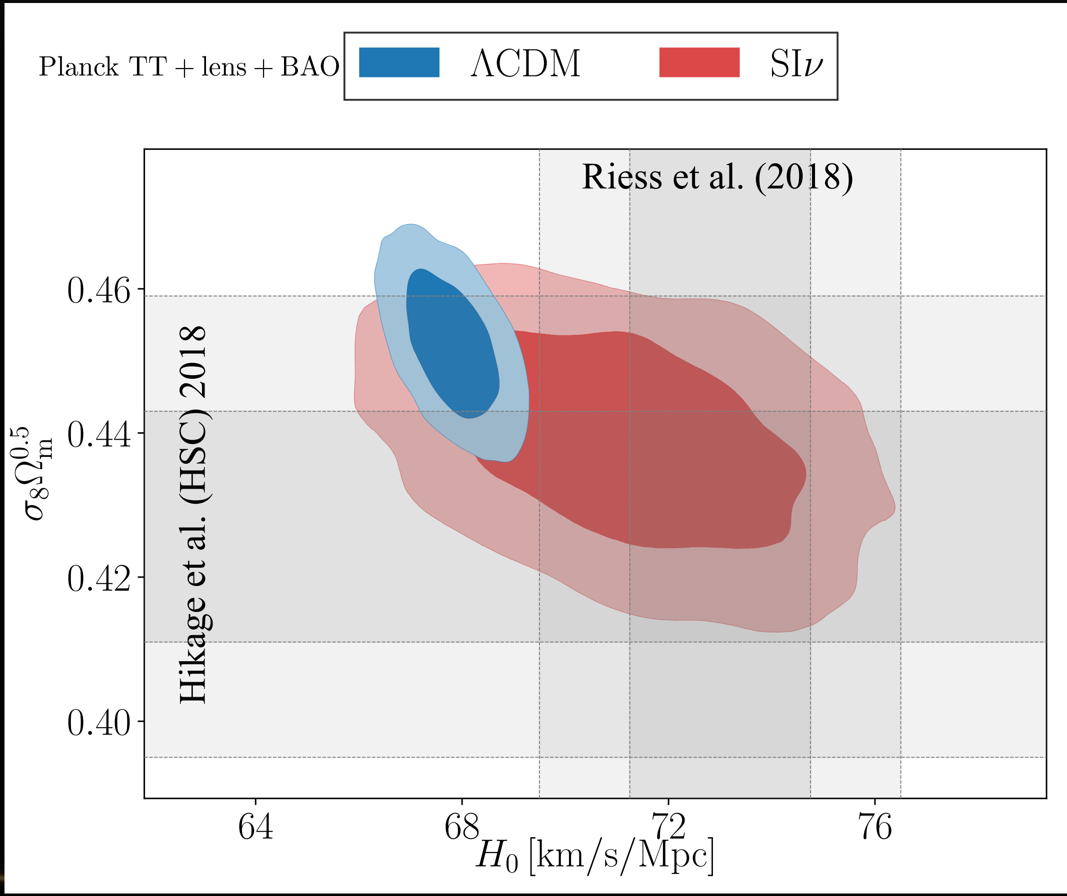
- The combined effect of N_{eff}, neutrino masses, self-interaction, A_s, and n_s leave large-scale structure largely unchanged on scales where it best measured.



Kreisch, Cyr-Racine + (2019)

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.

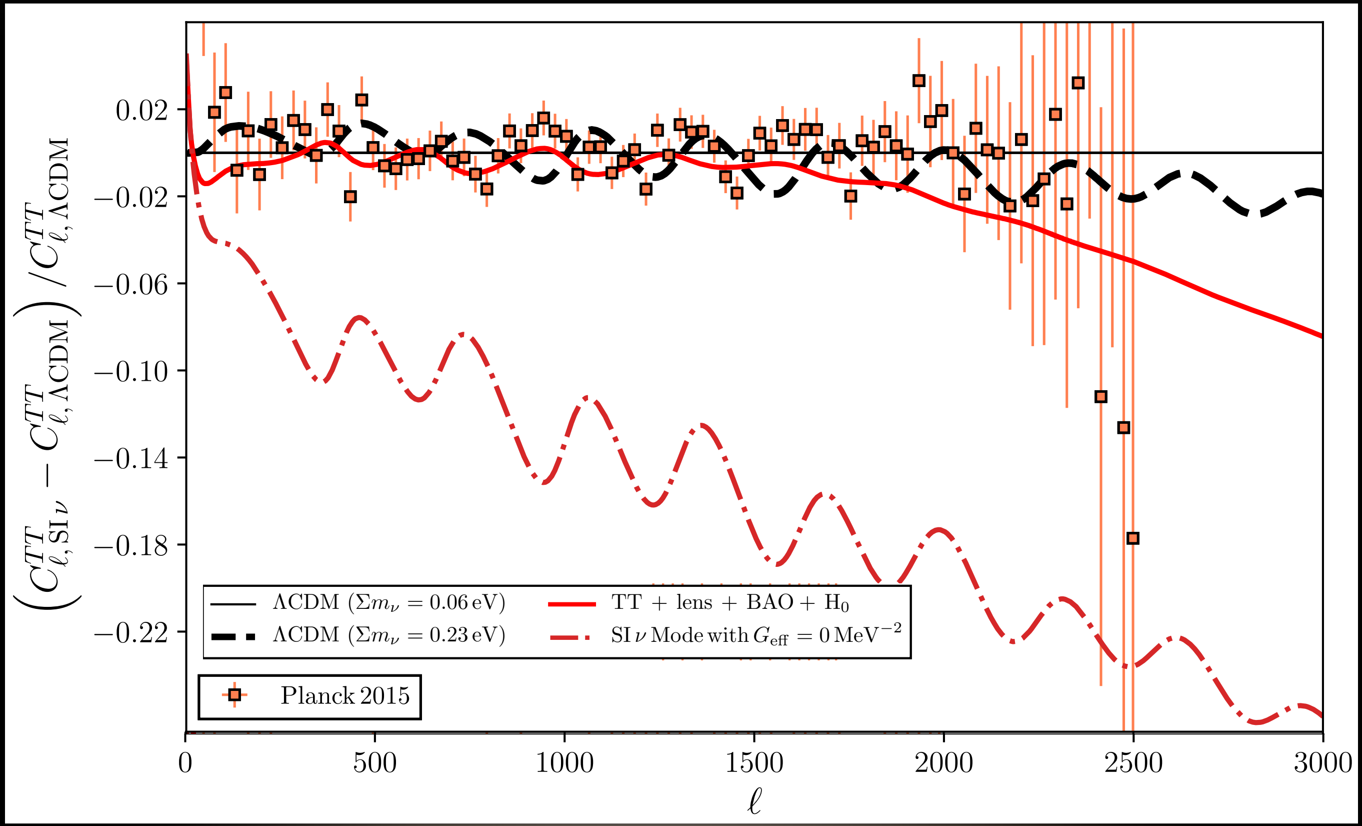
Parameter	Strongly Interacting Neutrino Mode
$\Delta\chi^2_{\mathrm{low}\,\ell}$	0.66
$\Delta\chi^2_{\mathrm{high}\,\ell}$	-1.15
$\Delta\chi^2_{\mathrm{lens}}$	0.06
$\Delta\chi^2_{H_0}$	-6.68
$\Delta\chi^2_{\mathrm{BAO}}$	-0.81
$\Delta\chi^2_{\mathrm{Total}}$	-7.91
ΔAIC	-1.91 → Correcting for extra parameters

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

Kreisch, Cyr-Racine + (2019)

How important are the neutrino self-interaction?

- Answer: very much so!



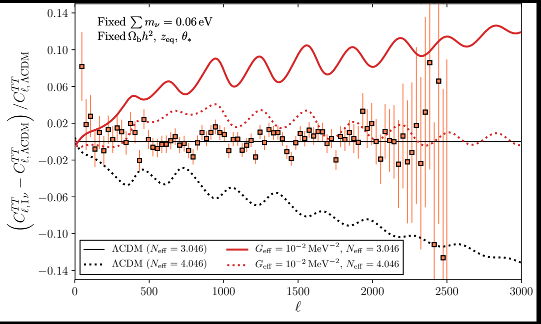
Kreisch, Cyr-Racine + (2019)

Why does the SIν work?

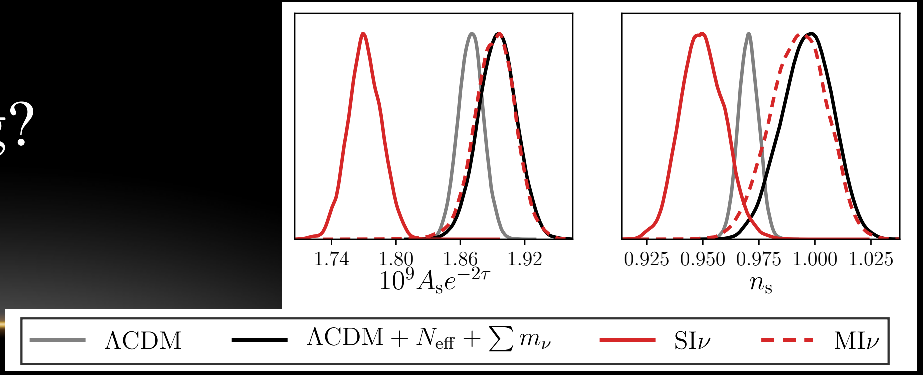
- $N_{\rm eff}$ increases Hubble at early times, hence reducing the sound horizon.

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

- 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.
- What about matter clustering?

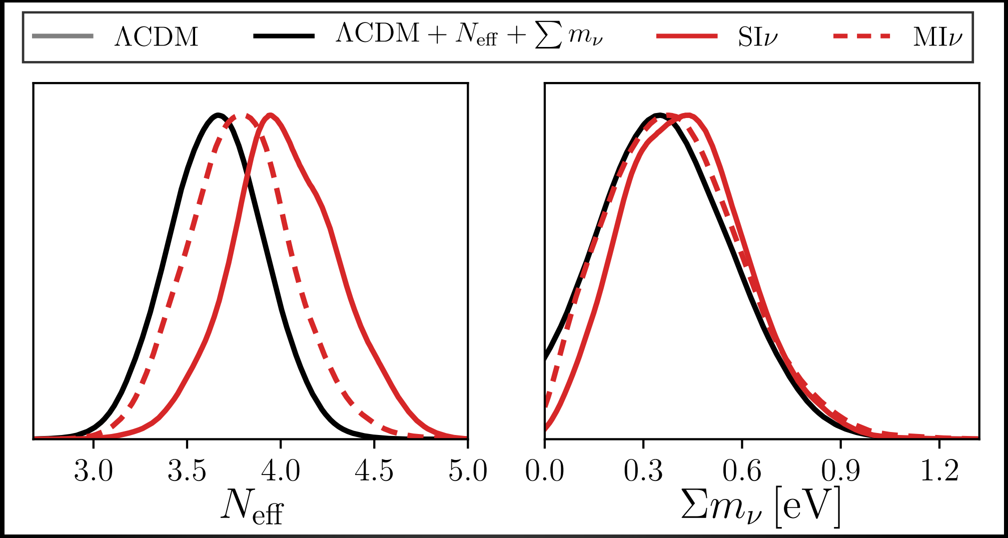


SIν Cosmology and neutrino physics

- The model allows for a whole new neutrinos species and favors a non-vanishing neutrino mass at 2-σ

$$N_{\text{eff}} = 4.02 \pm 0.29$$

$$\sum m_\nu = 0.42^{+0.17}_{-0.20}\,\text{eV}$$

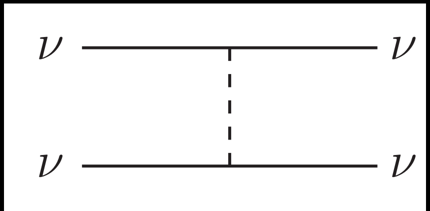


Kreisch, Cyr-Racine + (2019)

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.

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.

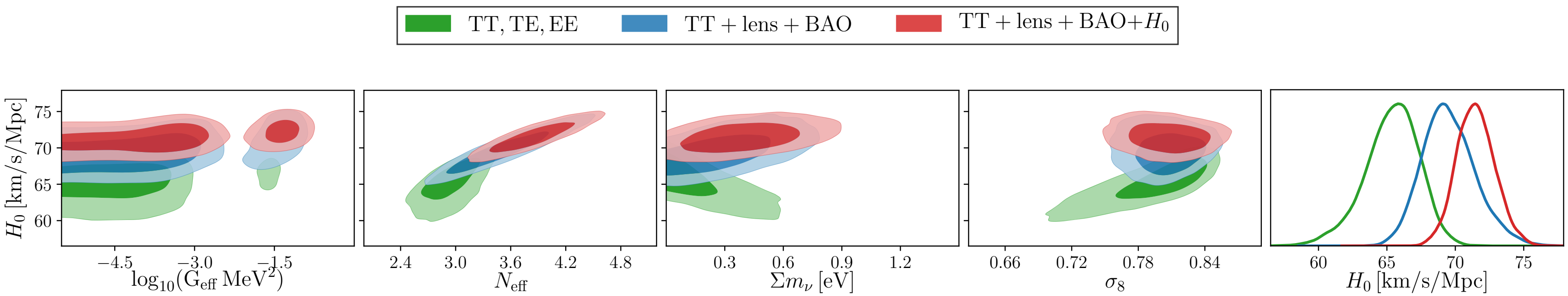
Backup: Compare to standard extension

- The model does improve the fit compares to ΛCDM + $N_{\rm eff}$ + m_ν, even after accounting for the extra parameter.

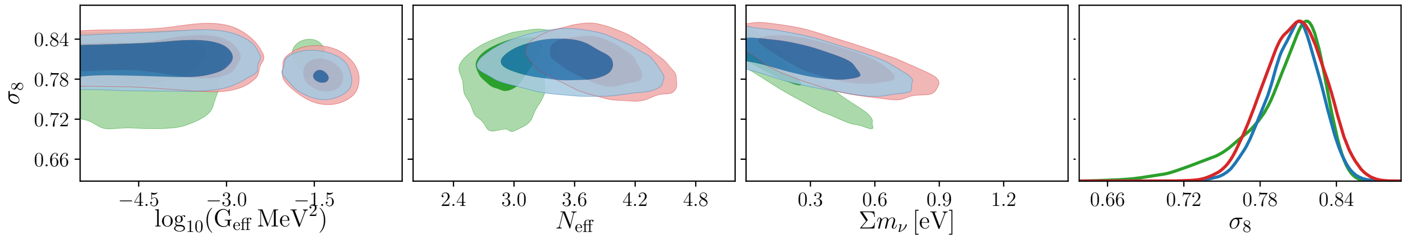
Parameter	Strongly Interacting Neutrino Mode
$\Delta\chi^2_{\text{low}\,\ell}$	2.40
$\Delta\chi^2_{\text{high}\,\ell}$	-3.40
$\Delta\chi^2_{\text{lens}}$	-0.20
$\Delta\chi^2_{H_0}$	-1.32
$\Delta\chi^2_{\text{BAO}}$	-0.81
$\Delta\chi^2_{\text{Total}}$	-3.33
ΔAIC	-1.33

Kreisch, Cyr-Racine + (2019)

Backup: Mediating Controversy



(a) H_0 correlations.



(b) σ_8 correlations.

Kreisch, Cyr-Racine + (2019)

Backup: Impact of self-interacting Neutrinos on matter clustering

- Dark matter perturbation equation can be written as:

$$\ddot{d}_{\mathrm{c}} + \frac{\dot{a}}{a}\dot{d}_{\mathrm{c}} = -k^2\psi,$$

$$d_{\mathrm{c}} \equiv \delta_{\mathrm{c}} - 3\phi,$$

where $ds^2 = a^2(\tau)[-(1+2\psi)d\tau^2 + (1-2\phi)d\vec{x}^2],$

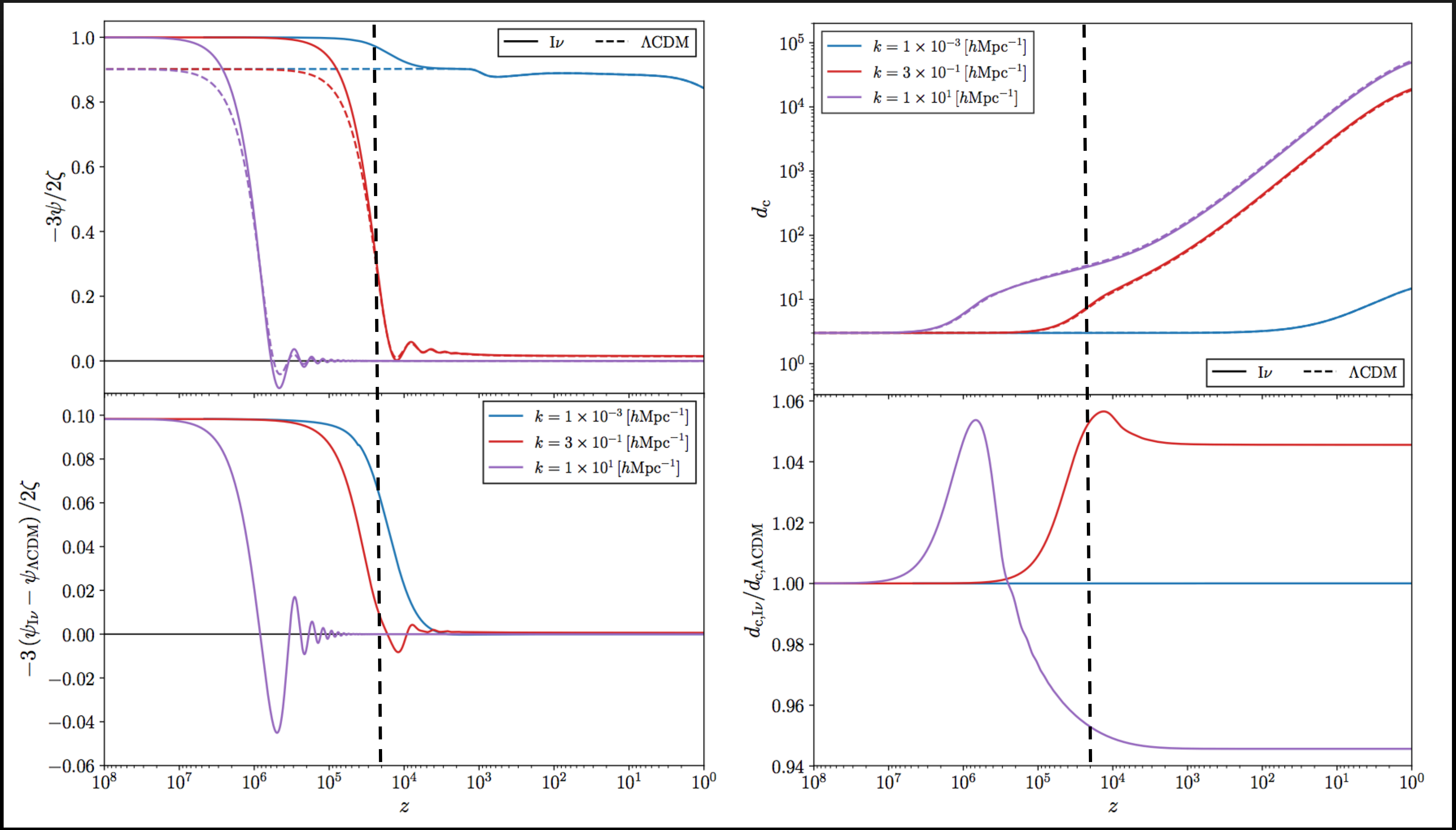
- The general solution (in radiation domination):

$$d_{\mathrm{c}}(k,\tau) = -\frac{9}{2}\phi_{\mathrm{p}} + k^2\int_0^\tau d\tau'\tau'\psi(k,\tau')\ln(\tau'/\tau),$$

- Without free-streaming neutrinos, we have:

$\boxed{\phi - \psi = 0}$ instead of $\boxed{\phi = (1 + 2R_\nu/5)\psi}$

Backup: Impact of self-interacting Neutrinos on matter clustering



Kreisch, Cyr-Racine + (2019)