Probing self-interacting neutrinos with cosmological data

Based on arXiv:2403.05496 and arXiv:2309.03941

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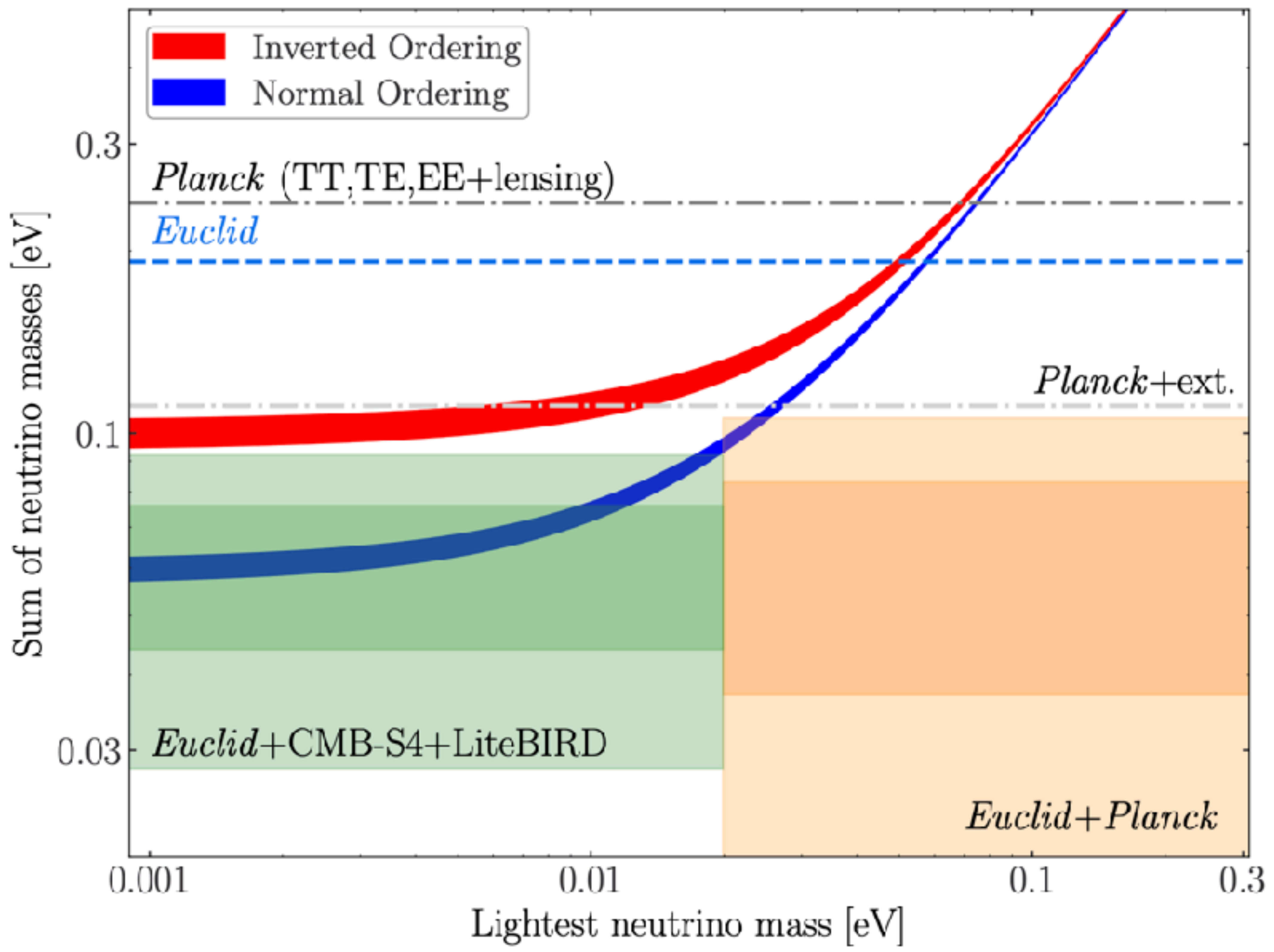
Neutrino cosmology

- Neutrinos represent 41% of the energy budget in the early Universe.
- Their gravitational interactions leave distinct imprints in various cosmological observables.
- Cosmological observations enable tight constraints on pivotal parameters describing neutrino properties, e.g., $\sum m_\nu$.

See Maria Archidiacono's Talk

- Upcoming surveys will contribute to unveiling the nature of neutrinos!

Euclid Collaboration M. Archidiacono et al., arXiv:2405.06047



A fundamental SM prediction

- According to the SM, neutrinos commence to free-streaming at $\sim$ 1 MeV (1s after BB).

$$\Gamma \sim G_F^2 T^5 \text{ and } H \sim T^2/m_{\rm Pl}$$

$$\left(\frac{\Gamma}{H}\right) \sim \left(\frac{T_{\rm FS}}{1\ \rm MeV}\right)^3$$

- SM implies that before recombination, ν are the only source free-streaming radiation.
- Evolution of cosmological perturbations are sensitive to the free-streaming nature of neutrinos.
- Cosmological data can be used to test physics BSM capable of modifying the free-streaming nature of neutrinos!

CMB data and neutrino self-interactions

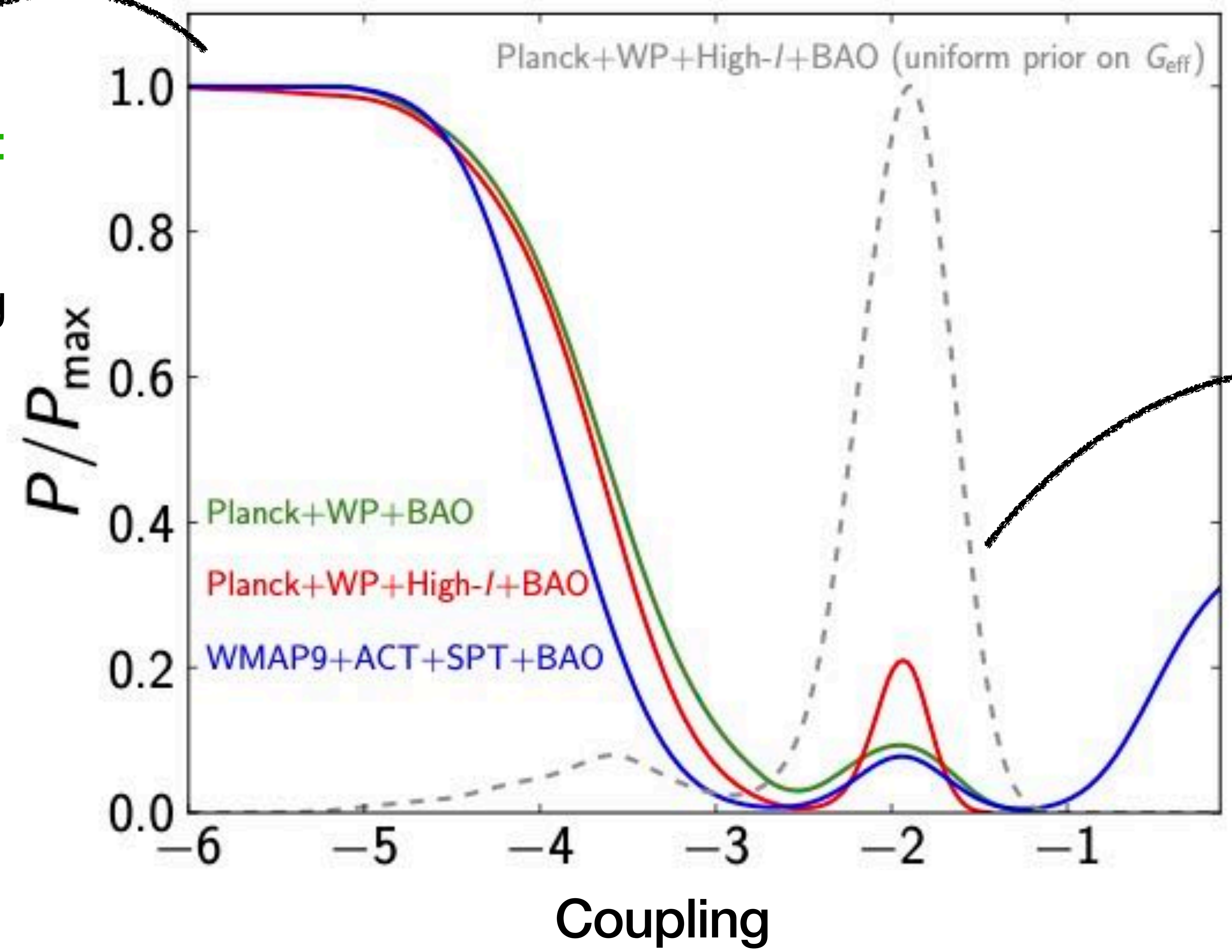
Some CMB data allow a cosmological scenario in which ν strongly interact, delaying their free-streaming until close to matter-radiation equality!

F.-Y. Cyr-Racine, K. Sigurdson arXiv:1306.1536

Mild interacting regime:

MI_ν

Neutrino free streaming ~ 1 MeV



Strong interacting regime:

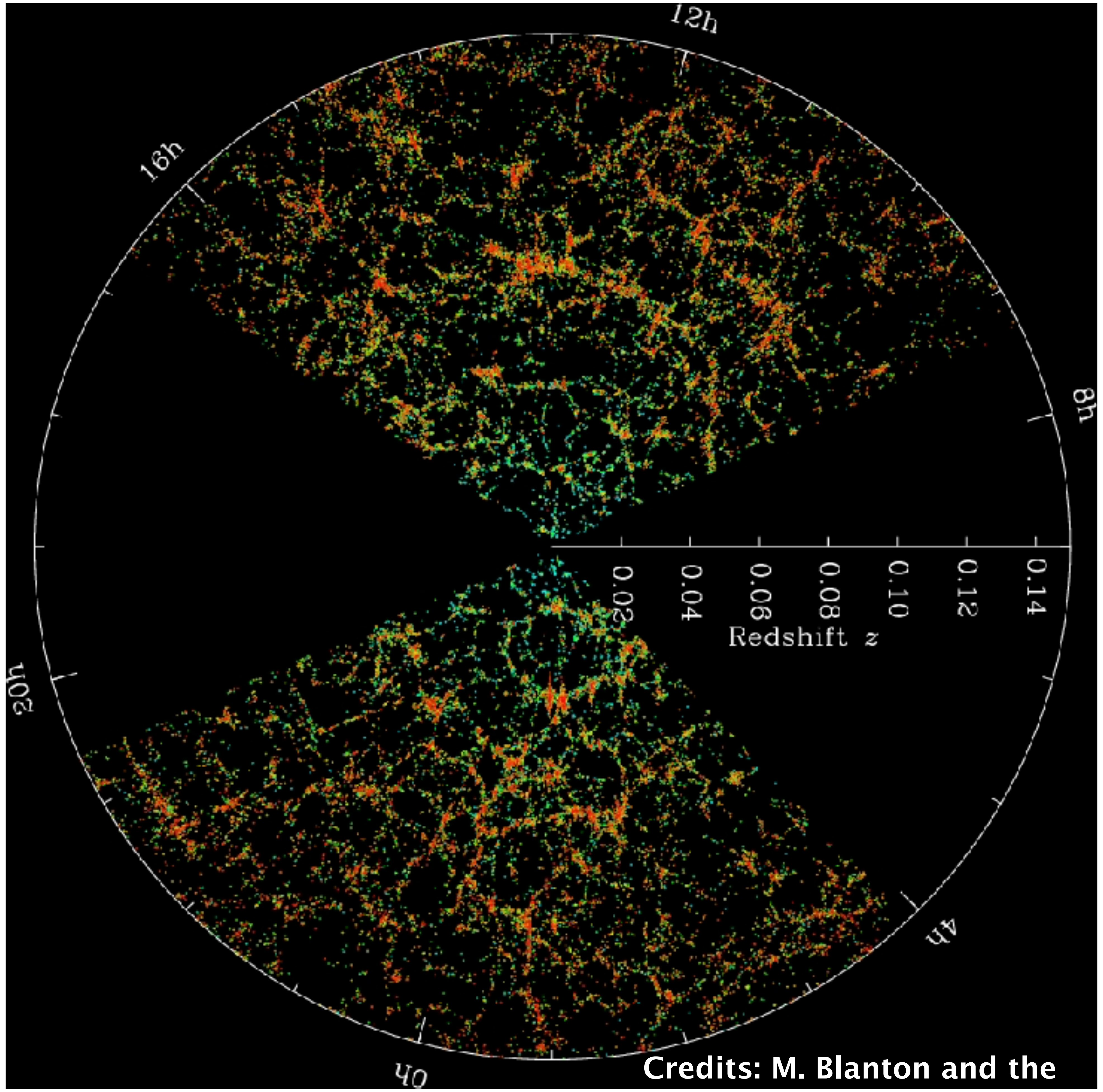
SI_ν

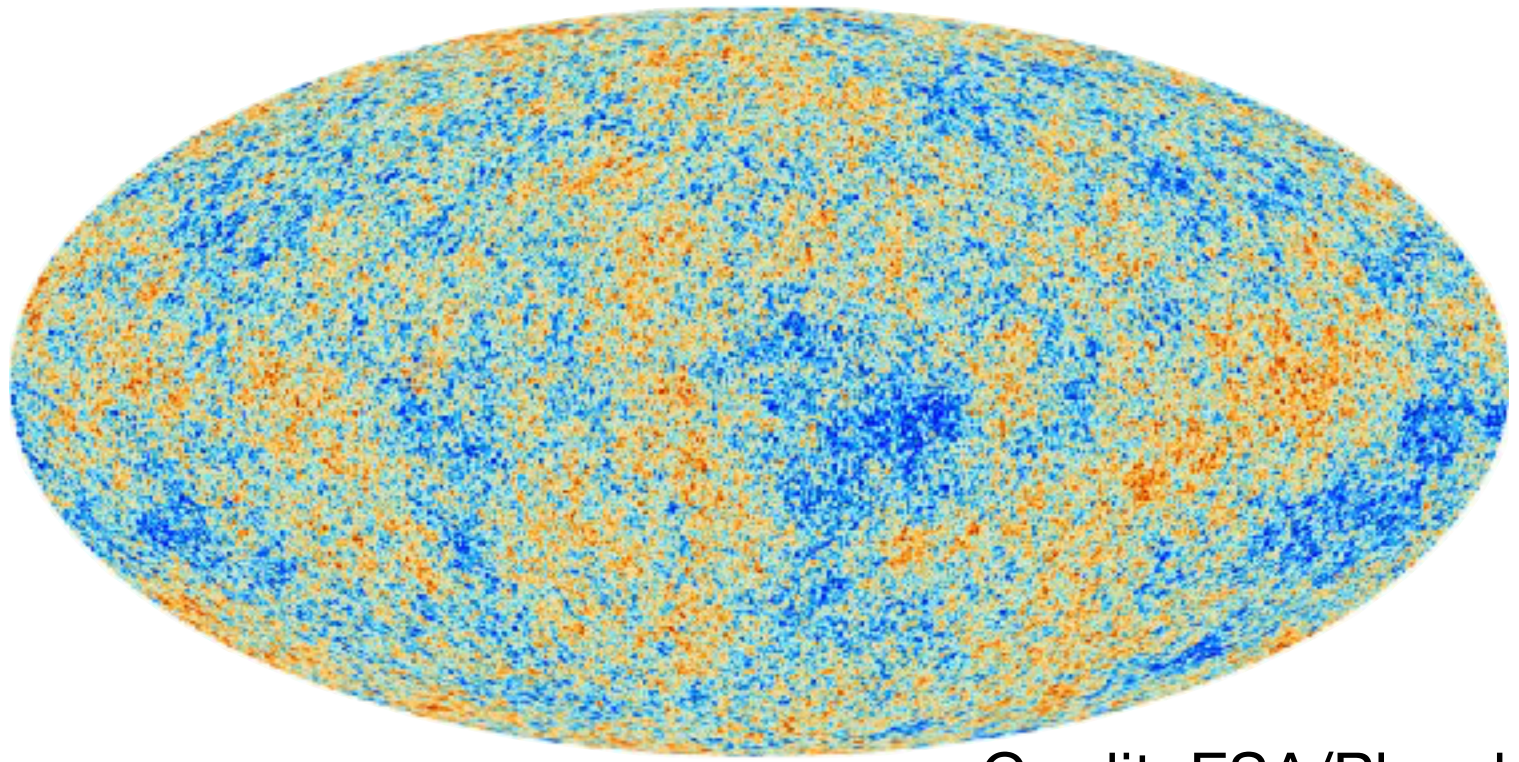
Neutrino free streaming ~ 1.5 eV

Archidiacono & Hannestad 2013, Lancaster et al. 2017, Oldengott et al. 2017, Kreisch et al. 2019, Brinckmann et al. 2020, Das & Ghosh 2021 + others

Broadening the cosmological landscape

The evolution of perturbations as presented by the CMB data suggest that our Universe could feature novel interactions in the neutrino sector, yet…





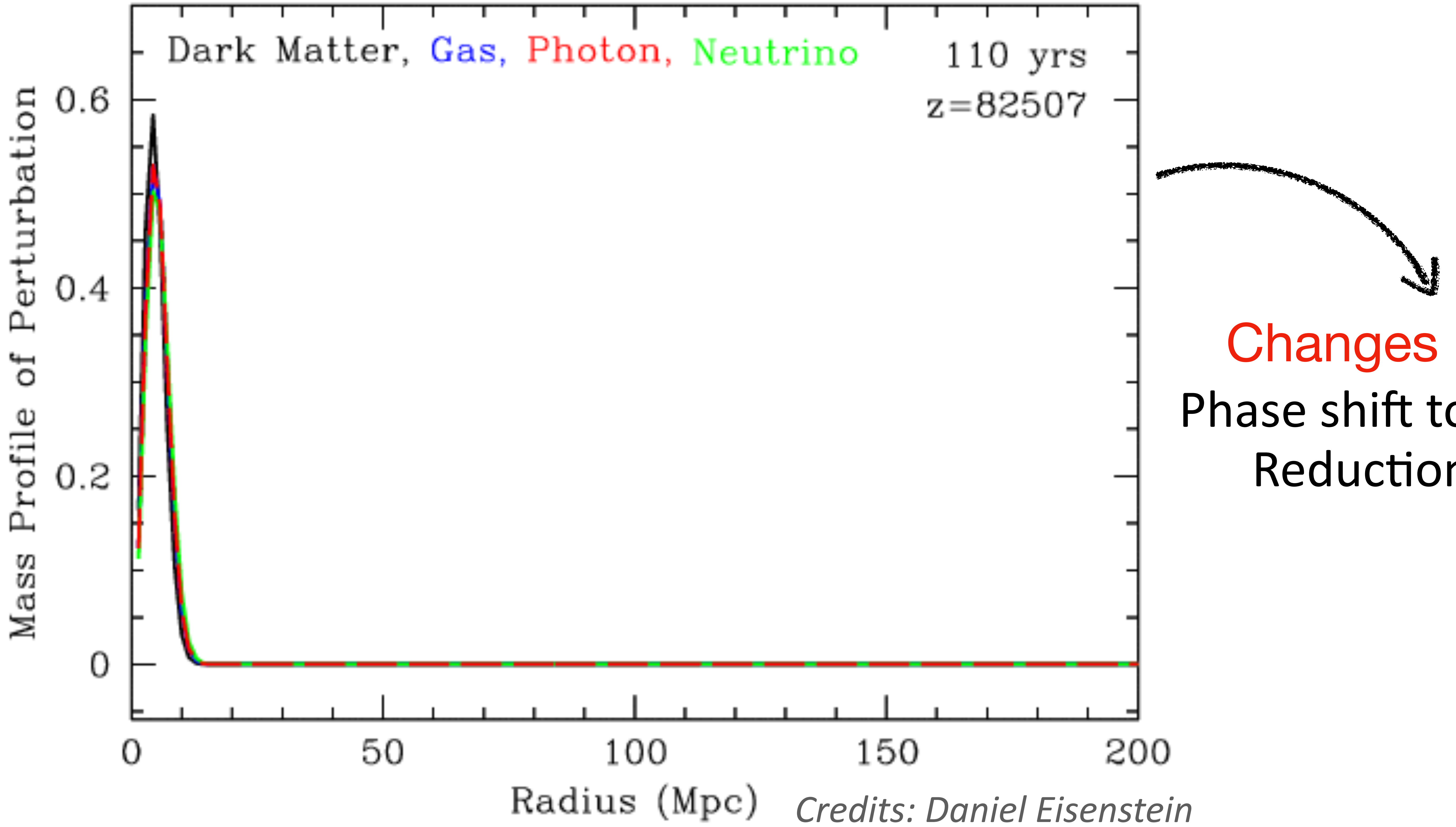
Credit: ESA/Planck

Free-streaming neutrinos

Neutrinos start to free streaming at ~ 1 MeV

$$\frac{\Gamma_{\text{weak}}}{H} \sim \left(\frac{T}{1\ \text{MeV}}\right)^3$$

Neutrinos travel supersonically, gravitationally pulling the baryon-photon wave front slightly ahead!



Credits: Daniel Eisenstein

Changes in the CMB?

Phase shift towards larger scales

Reduction of the amplitude

Neutrino free streaming and its impact on the CMB

Neutrino FS leads to a phase shift and amplitude suppression of the photon perturbations

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

$$\Delta_\gamma \simeq -0.2683R_\nu + \mathcal{O}(R_\nu^2)$$

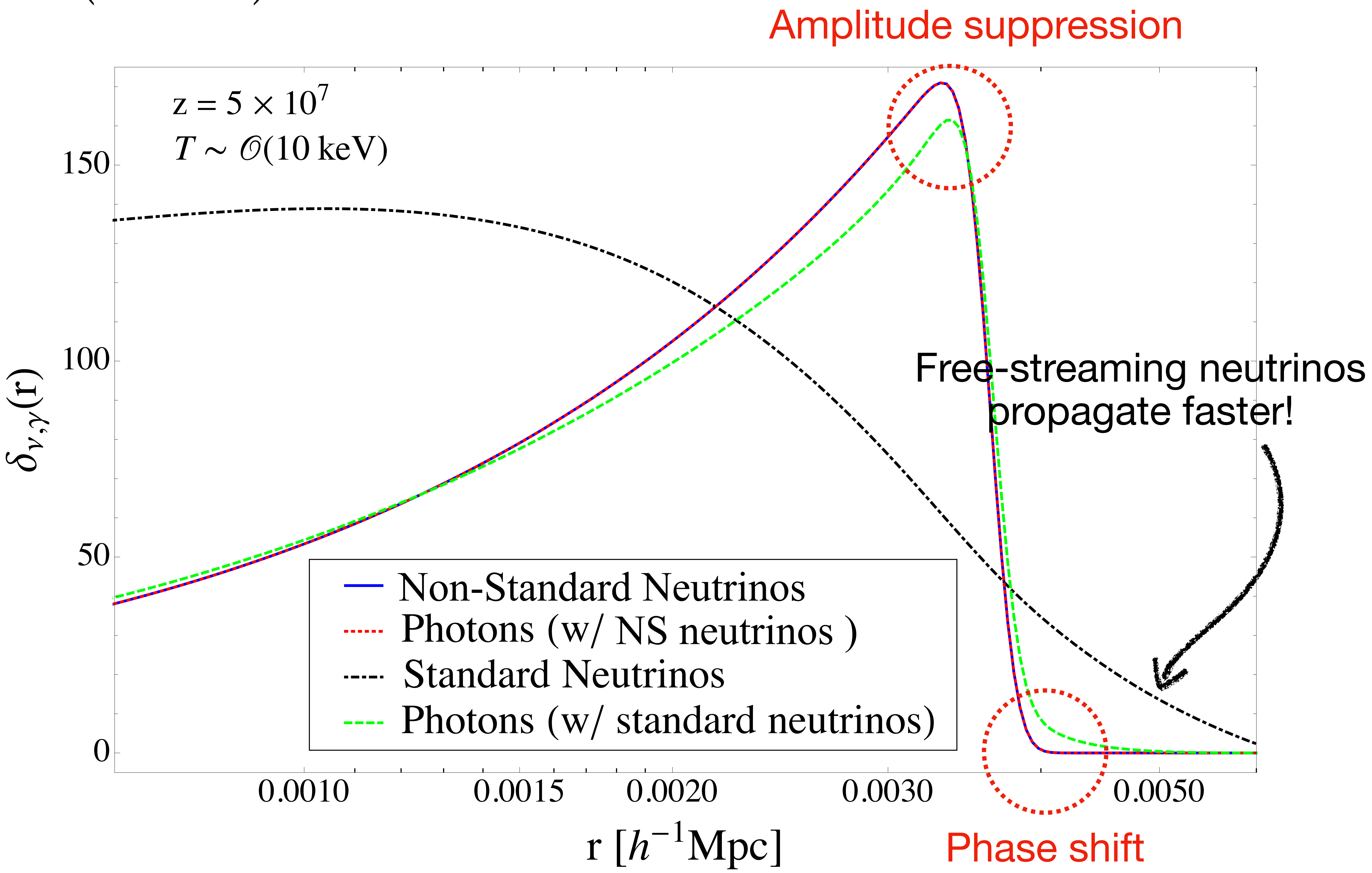
$$\delta\varphi = 0.1912\pi R_\nu + \mathcal{O}(R_\nu^2)$$

Characterized by the radiation free-streaming fraction

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

In the standard paradigm

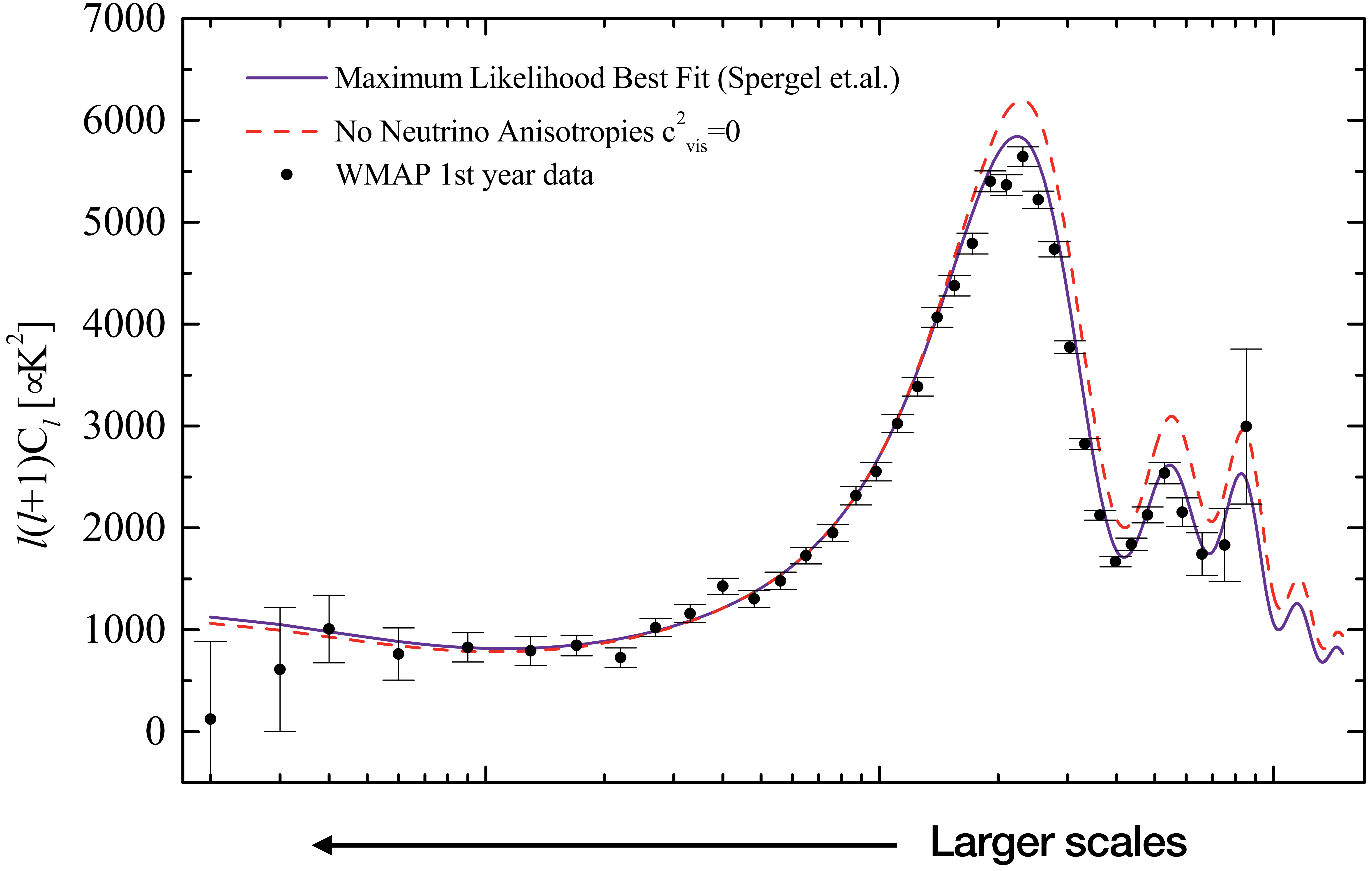
Bashinsky & Seljak, astro-ph/0310198
Baumann et al., arXiv:1508.06342



Neutrino free streaming and its impact on the CMB

Neutrino FS leads to a phase shift and amplitude suppression of the photon perturbations

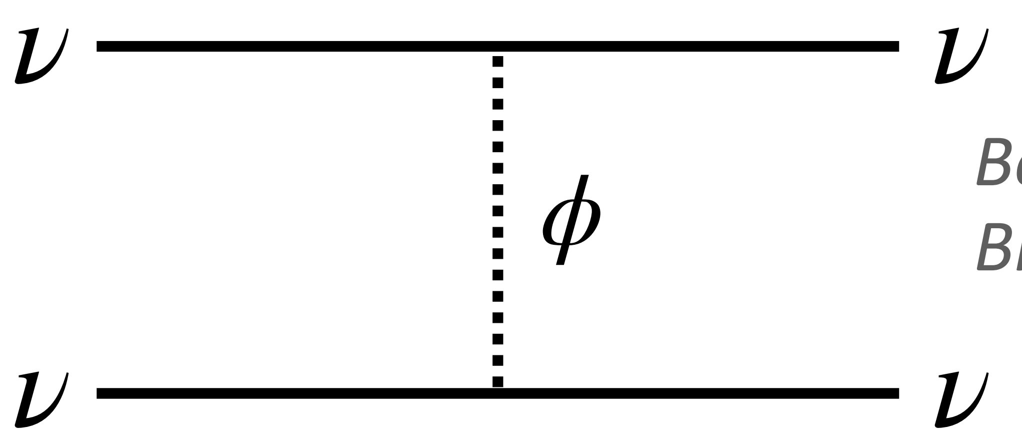
R. Trotta, A. Melchiorri, astro-ph/0412066



Delayed neutrino free streaming: self-interacting neutrinos

Neutrino free streaming can be delayed by the self-interactions among neutrinos:

$$\mathscr{L} \supset -\frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}\left(g_\phi^{\alpha\beta}\nu_\alpha\nu_\beta\phi + \mathrm{h.c.}\right)$$



Berryman et al., arXiv:2203.01955
Blinov et al., arXiv:1905.02727

Phenomenology dictated by the energy scale to be probe and mass of the mediator

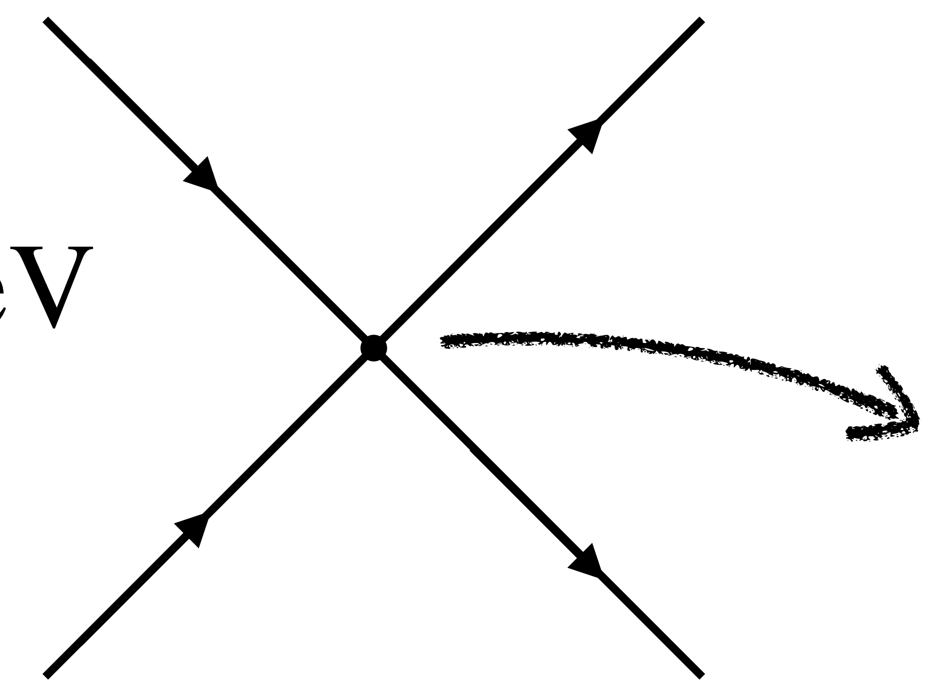
The highest observed multipole of the CMB cross the horizon when $T_\nu < 100\ \mathrm{eV}$

SM Fermi constant

$G_{\rm eff} \sim \mathcal{O}(10^{-11})\ \mathrm{MeV}^{-2}$

For a massive scalar particles $m_\phi \gtrsim 1\ \mathrm{keV}$

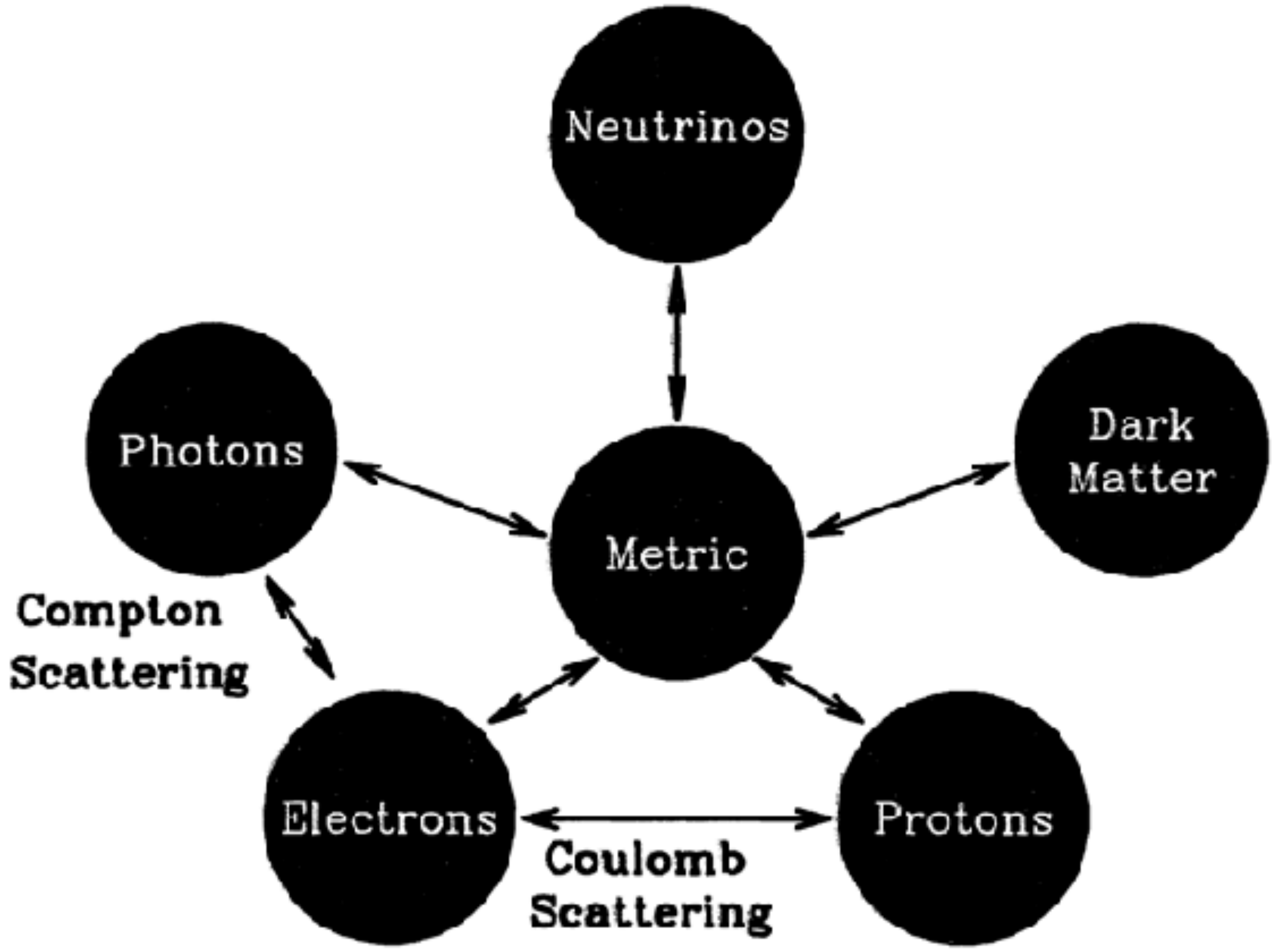
4-Fermion interaction



$G_{\rm eff} = g_\nu^2/m_\phi^2$

Simplest cosmological representation: $g_\phi^{\alpha\beta} = g_\nu\delta^{\alpha\beta}$ (universal coupling)

Cosmological perturbations in light of neutrino self-interactions



Credits: Scott Dodelson

Neutrino inhomogeneities and anisotropies are determined via Boltzmann eqs:

$$\frac{\partial \nu_\ell}{\partial \tau} = -\frac{kq}{\epsilon}\left(\frac{\ell+1}{2\ell+1}\nu_{\ell+1} - \frac{\ell}{2\ell+1}\nu_{\ell-1}\right) + 4\left[\frac{\partial \Phi}{\partial \tau}\delta_{\ell 0} + \frac{k}{3}\frac{\epsilon}{q}\Psi\delta_{\ell 1}\right]$$

$$-\frac{aG_{\rm eff}^2 T_{\nu,0}^5}{f_\nu^{(0)}}\left(\frac{T_{\nu,0}}{q}\right)\left[A\left(\frac{q}{T_{\nu,0}}\right) + B_\ell\left(\frac{q}{T_{\nu,0}}\right) - 2D_\ell\left(\frac{q}{T_{\nu,0}}\right)\right]\nu_\ell$$

Collision term (Relaxation-time approximation)

Cyr-Racine, Sigurdson arXiv:1306.1536
Oldengott et al., arXiv:1706.02123

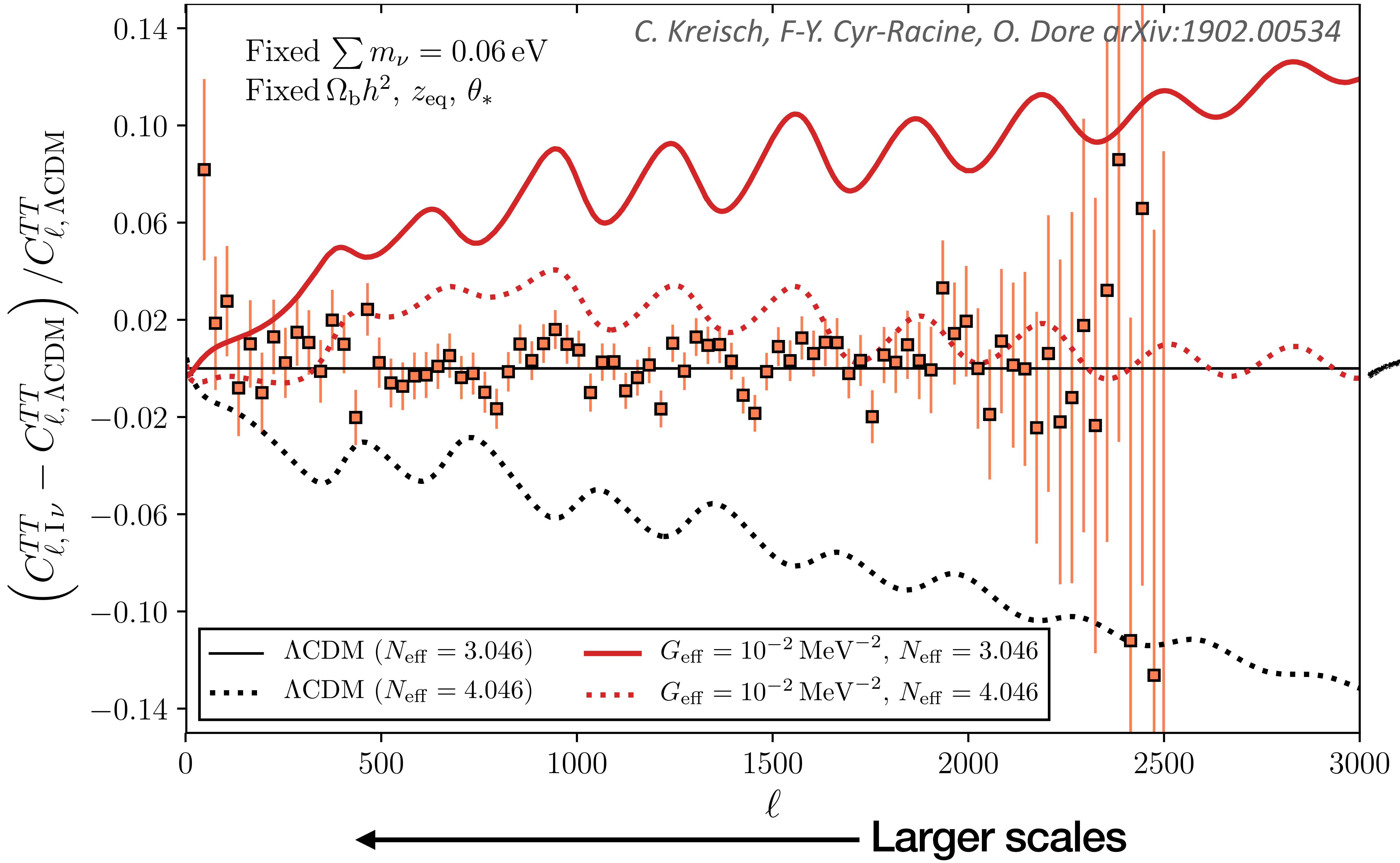
In the presence of self-interactions, neutrinos contribute to the anisotropic stress!

$$k^2(\Phi - \Psi) = 12\pi G a^2(\bar{\rho} + \bar{P})\sigma$$ → Anisotropic stress

See Yvonne Y.Y. Wong's Talk

Neutrino self-interactions and their impact on the CMB

Cosmological scenarios in the SI_ν regime suppress the free streaming of neutrinos eliminating the typical amplitude increase and a phase shift produced by the SM neutrinos

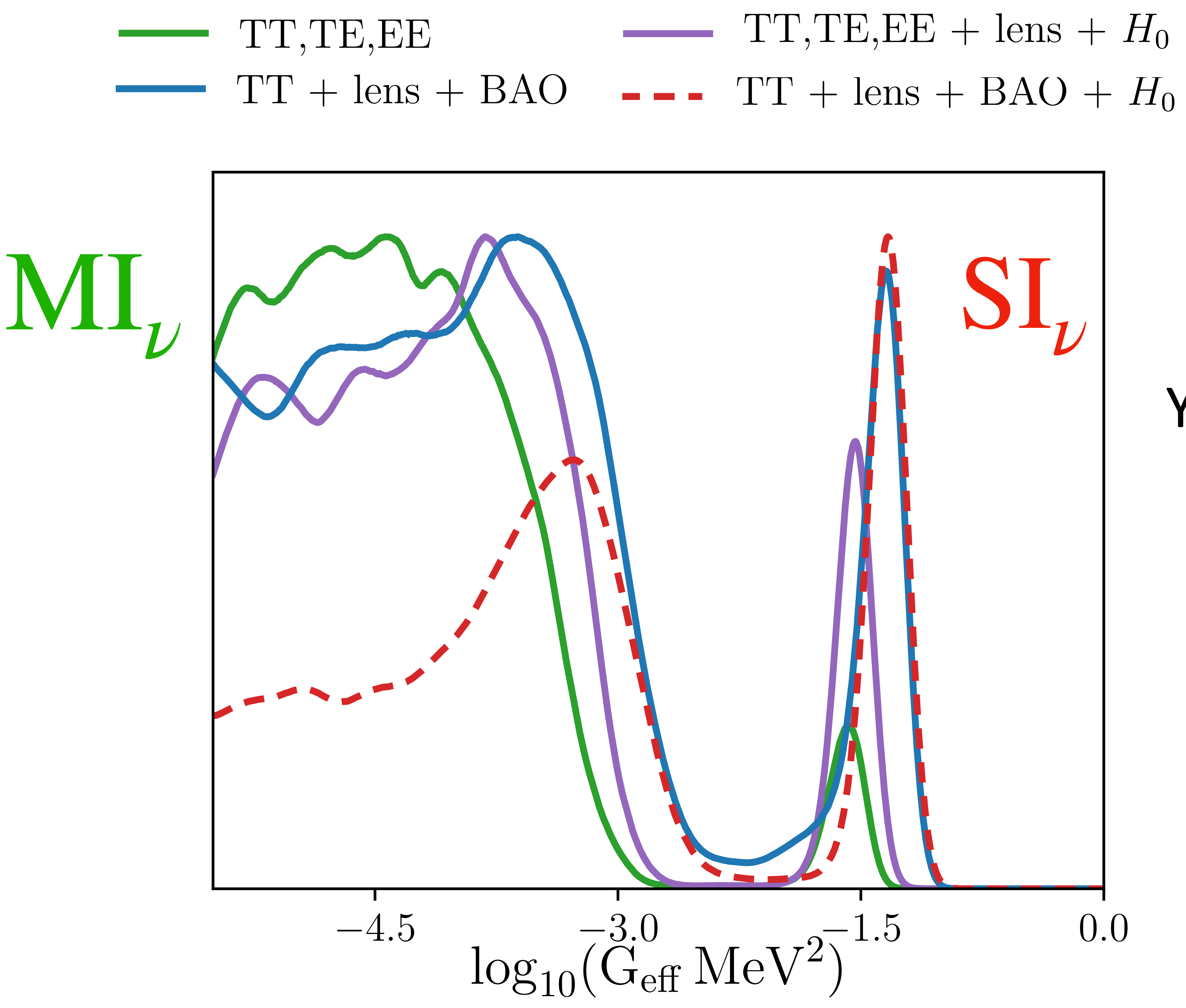


$$\Gamma \propto G_{\rm eff}^2 T^5$$

$$T_{\rm FS} \sim \left(\frac{G_F}{G_{\rm eff}}\right)^{2/3} \mathrm{MeV}$$

$N_{\rm eff}$ can compensate the effects produced by $G_{\rm eff}$

Persistent results in the CMB data



C. Kreisch, F-Y. Cyr-Racine, O. Dore arXiv:1902.00534

Some CMB data show a persistent preference for neutrino in the SI_ν regime.

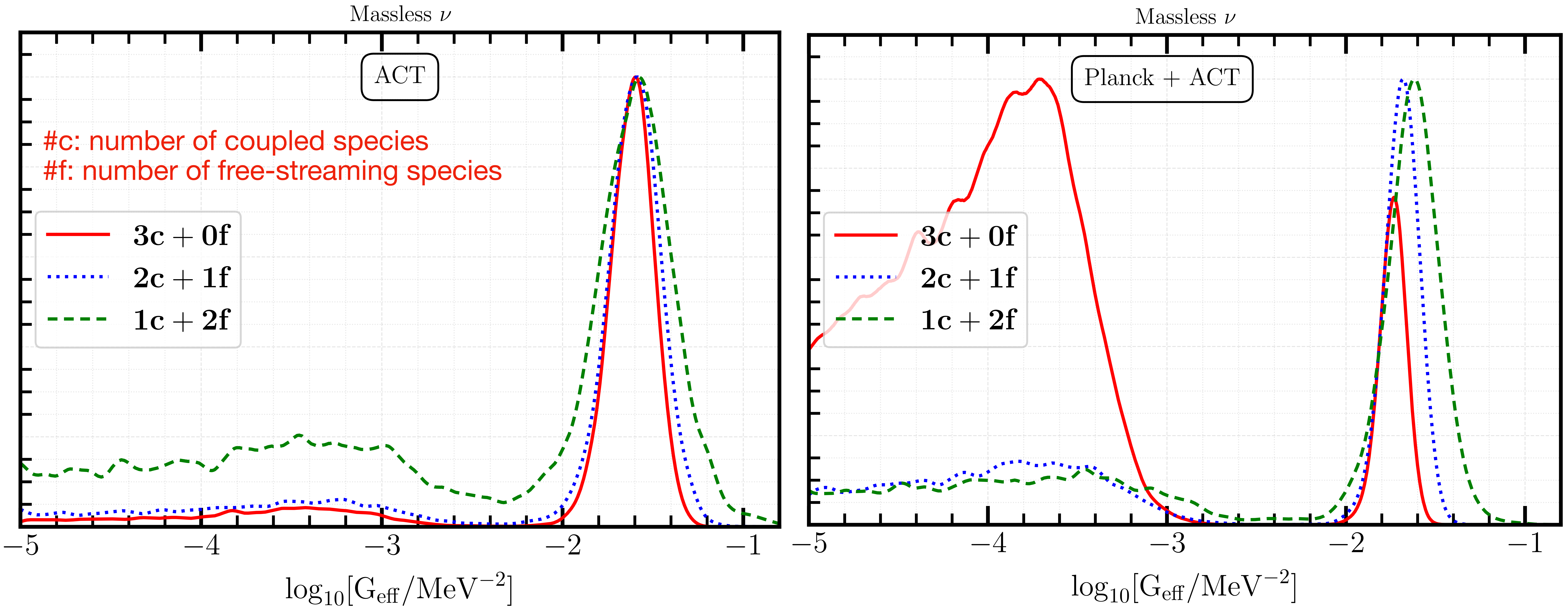
Yet, CMB polarization significant disfavor the simplest cosmological representation of this mode.

Archidiacono & Hannestad, arXiv:1311.3873
Lancaster et al., arXiv:1704.06657
Oldengott et al., arXiv:1706.02123
Kreisch, Cyr-Racine, Dore arXiv:1902.00534
+ others

Persistent and perplexing results in the CMB data

The Atacama Cosmology Telescope (ACT) CMB data display
an outrageous preference for SI_ν neutrinos!

Kreisch et al., arXiv:2207.03164
Das & Ghosh, arXiv:2303.08843



Parameter correlations

Strong self-interacting neutrinos can provide a good fit to some CMB data by means of correlations with other cosmological parameters.

C. Kreisch, F-Y. Cyr-Racine, O. Dore arXiv:1902.00534

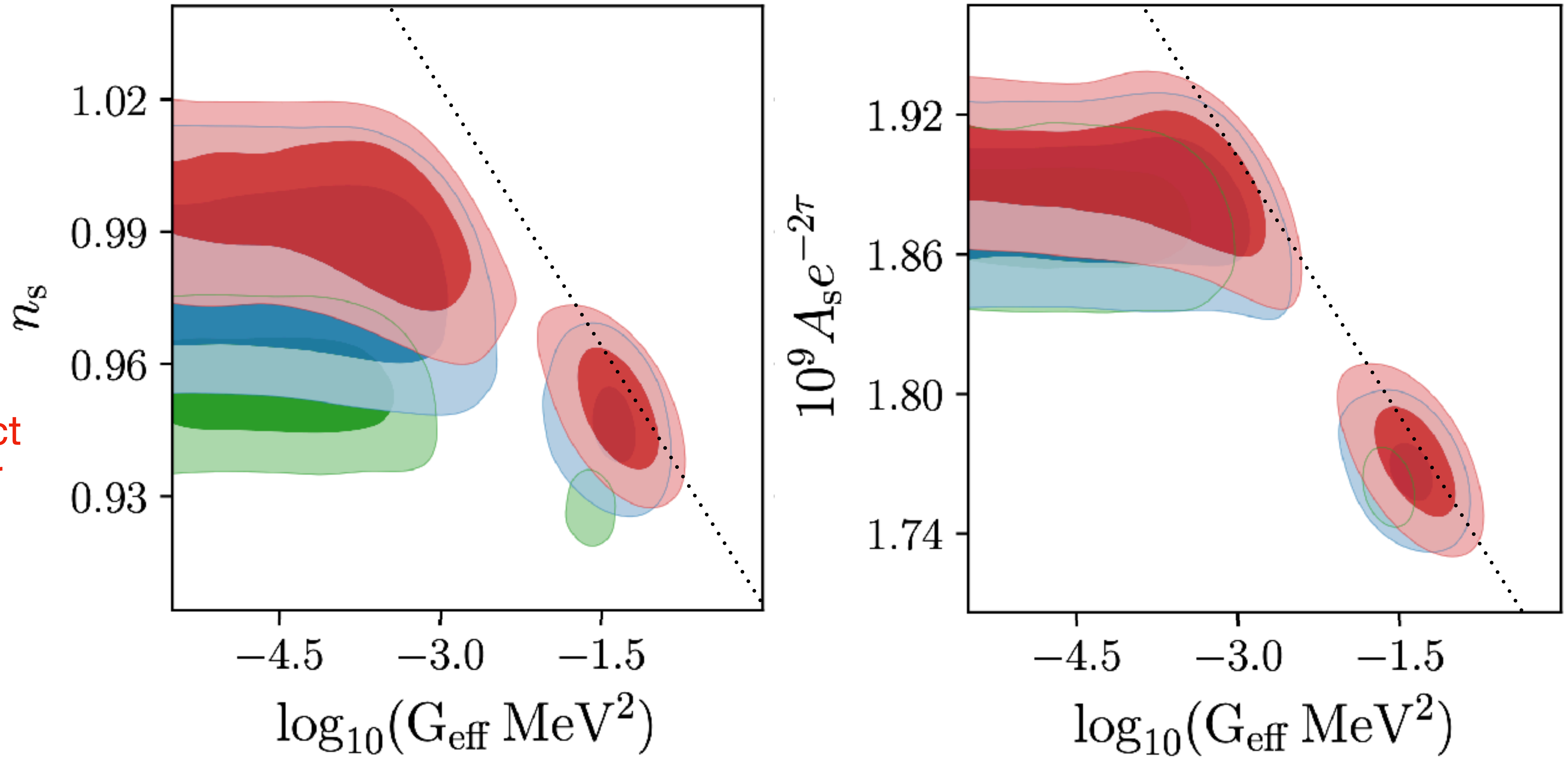
Primordial power spectrum:

$$\Delta_s^2(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

The simplest models of inflation predict almost a nearly scale-invariant power spectrum

$$n_s \approx 1$$

Barenboim et al., arXiv:1903.02036
Choudhury et al., arXiv:2207.07142
+ others



What we have learned so far from CMB data

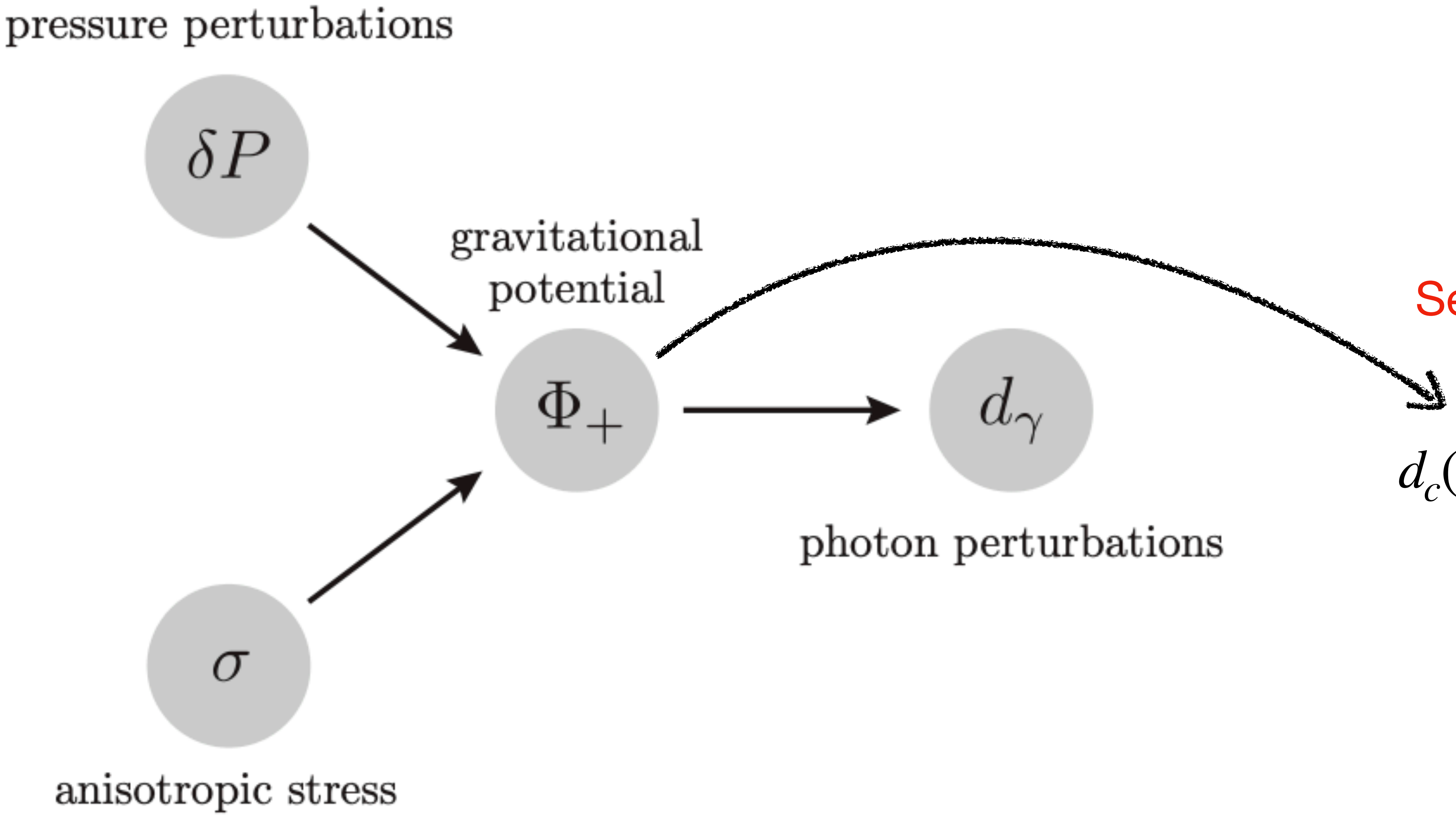
- SI_ν neutrinos provides a good fit to some CMB data by means of correlations with others cosmological parameters — in particular those related with the primordial power spectrum.
- A cosmological scenario in which the neutrino free streaming is delayed is favored by the Planck temperature, ACT, and BAO data.
- The simplest representation of this scenario is greatly disfavored by CMB polarization data.

What about large-scale structure (LSS) data?

Is the large-scale distribution of galaxy consistent with this picture?

Dark Matter perturbations in light of neutrino self-interactions

Self-interactions among neutrinos impact the evolution of cosmological perturbations:



Baumann et al., arXiv:1508.06342

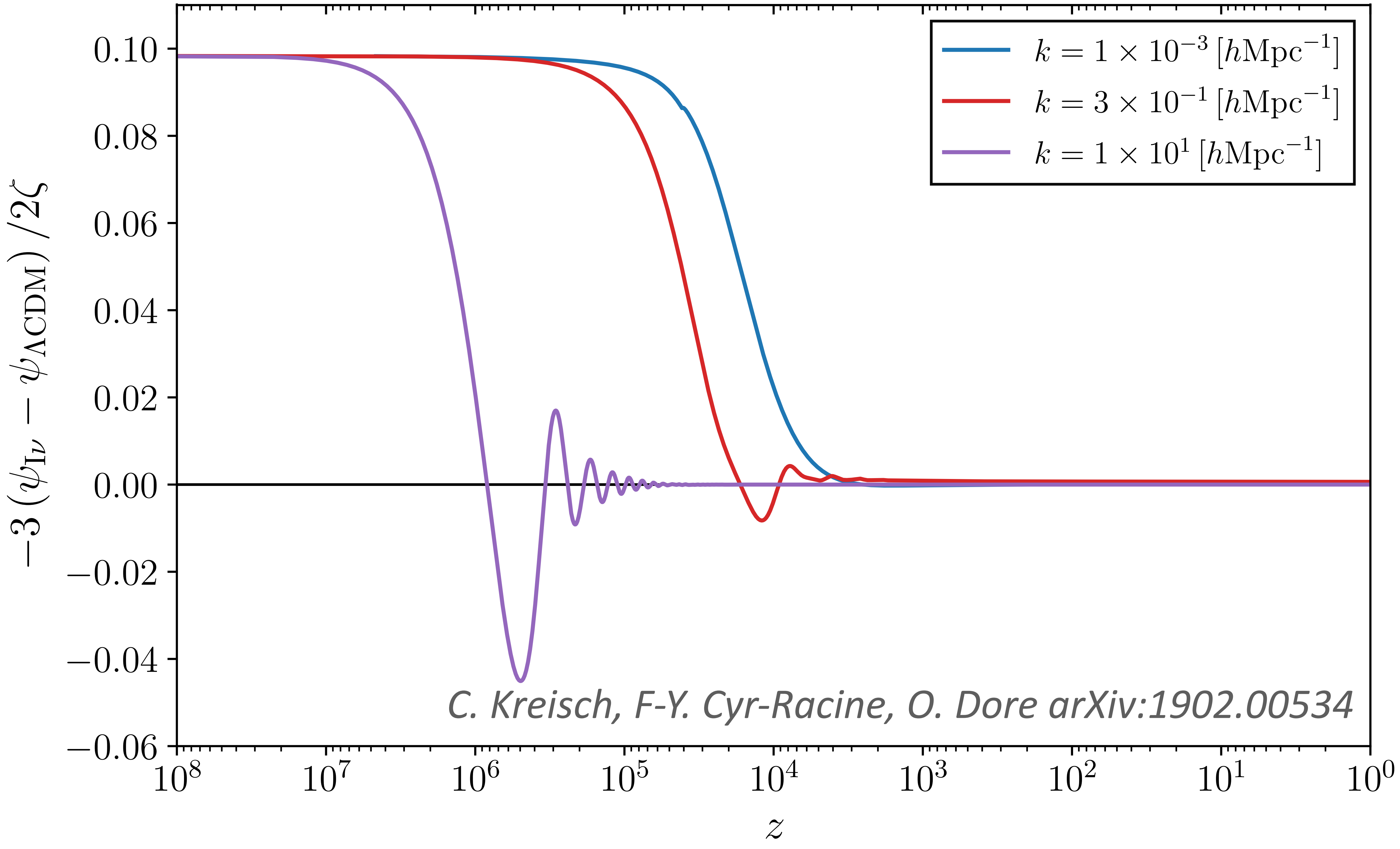
Self-interactions also modify the evolution of dark matter perturbations

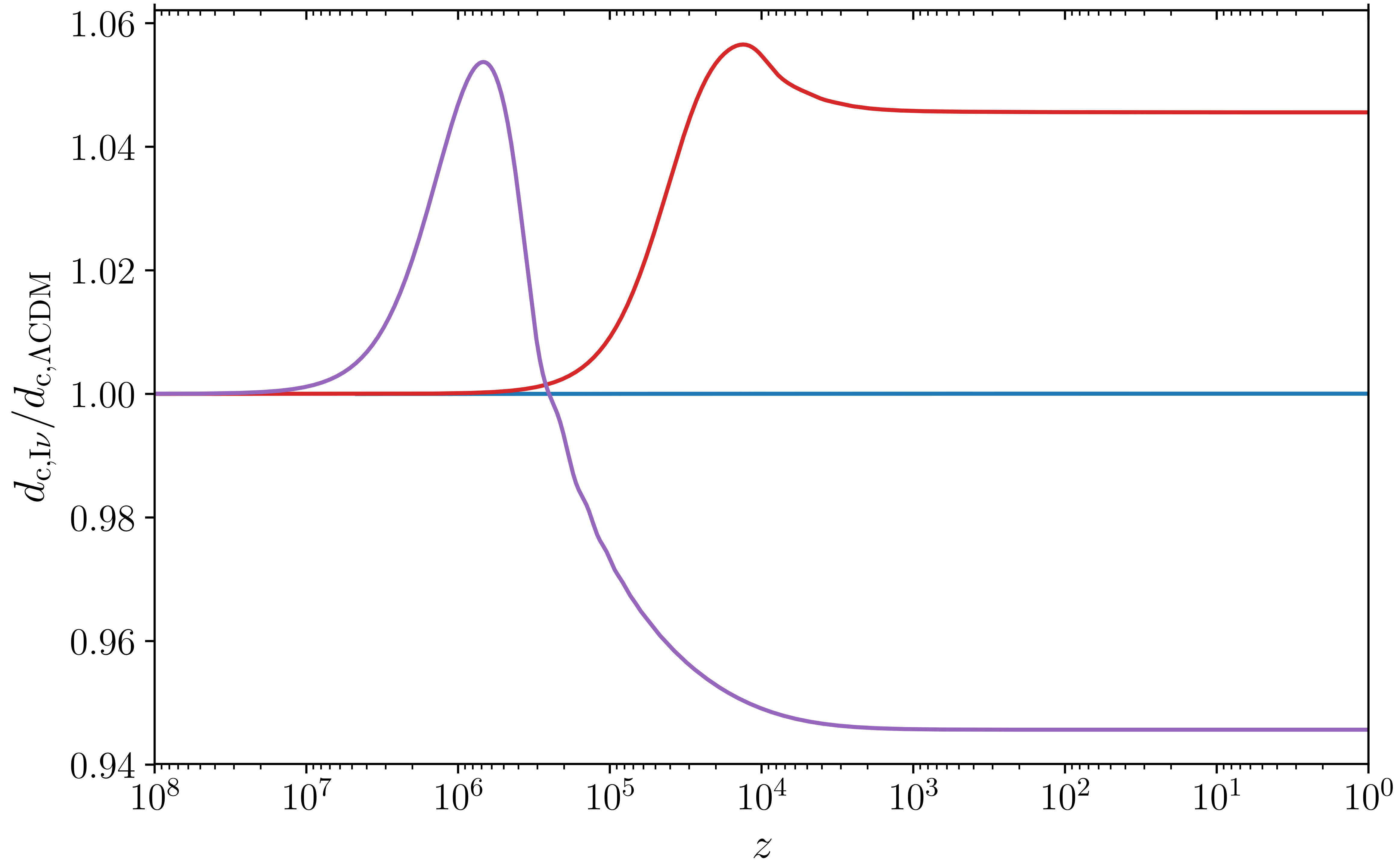
$$d_c(k,\tau) = -\frac{9}{2}\Phi_p + k^2 \int_0^{\tau} d\tau' \tau' \, \Psi(k,\tau') \, ln(\tau'/\tau)$$

Bashinsky & Seljak, astro-ph/0310198

Self-interacting neutrinos and their imprint on DM perturbations

Self-interacting neutrinos imprint scale-dependent features on the evolution of dark matter perturbations





$$d_c(k,\tau) = -\frac{9}{2}\Phi_p + k^2 \int_0^{\tau} d\tau'\tau'\,\Psi(k,\tau')\,ln(\tau'/\tau)$$

Modes entering the horizon:

Tightly coupled regime

$$\Gamma_\nu/aH \gg 1 \rightarrow k_h^{\mathrm{tc}}$$

Beginning of free streaming

$$\Gamma_\nu/aH \approx 1 \rightarrow k_h^{\mathrm{fs}}$$

Well after self-decoupling

$$\Gamma_\nu/aH \ll 1 \rightarrow k_h$$

Neutrino self-interactions in the linear power spectrum

Substantial (scale-dependent) changes in the power spectrum are produced by the presence of self-interactions in the neutrino sector

Modes entering the horizon

Tight coupled regime

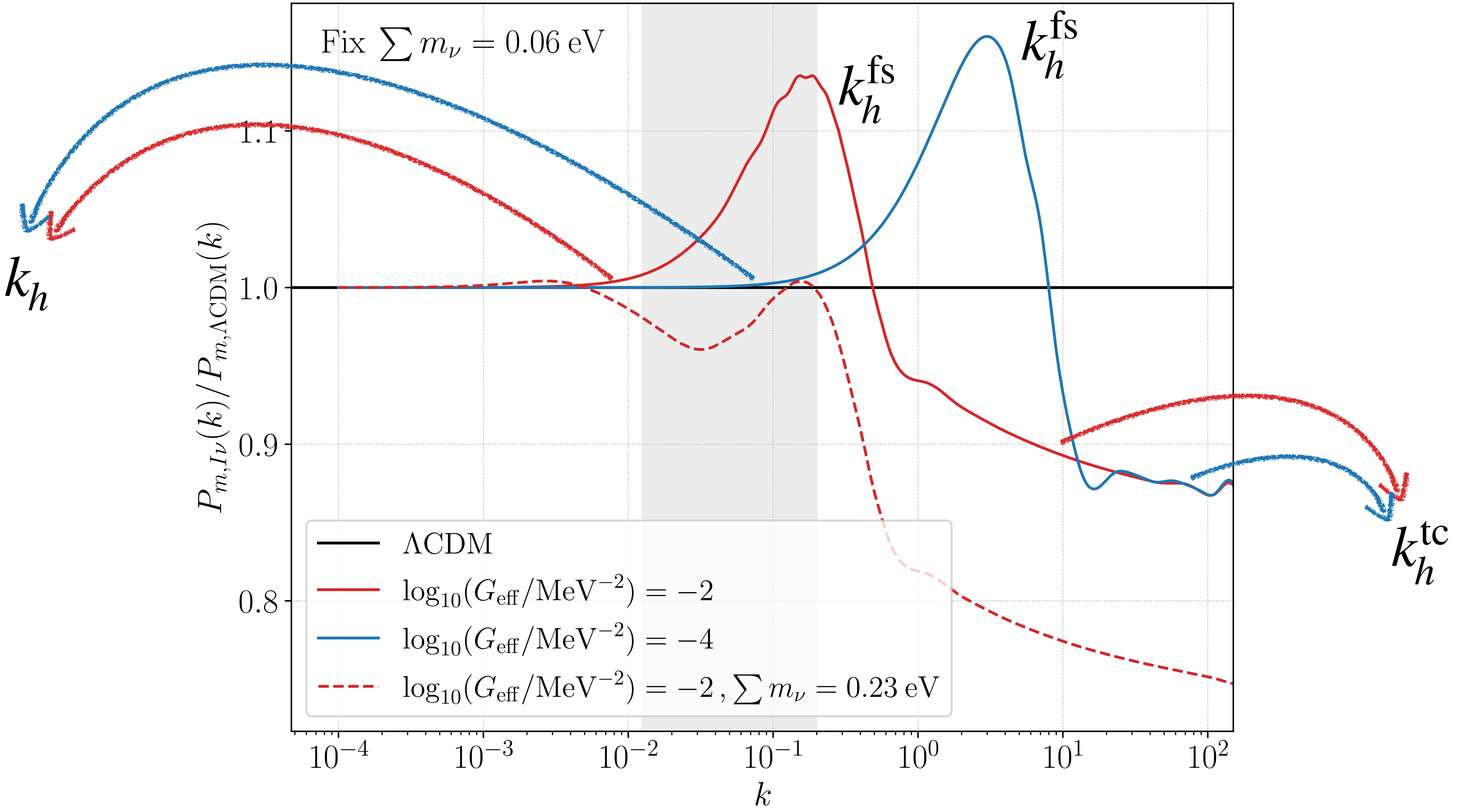
$\Gamma_\nu/aH \gg 1\,,\, k_h^{\rm tc}$

Begin of free streaming

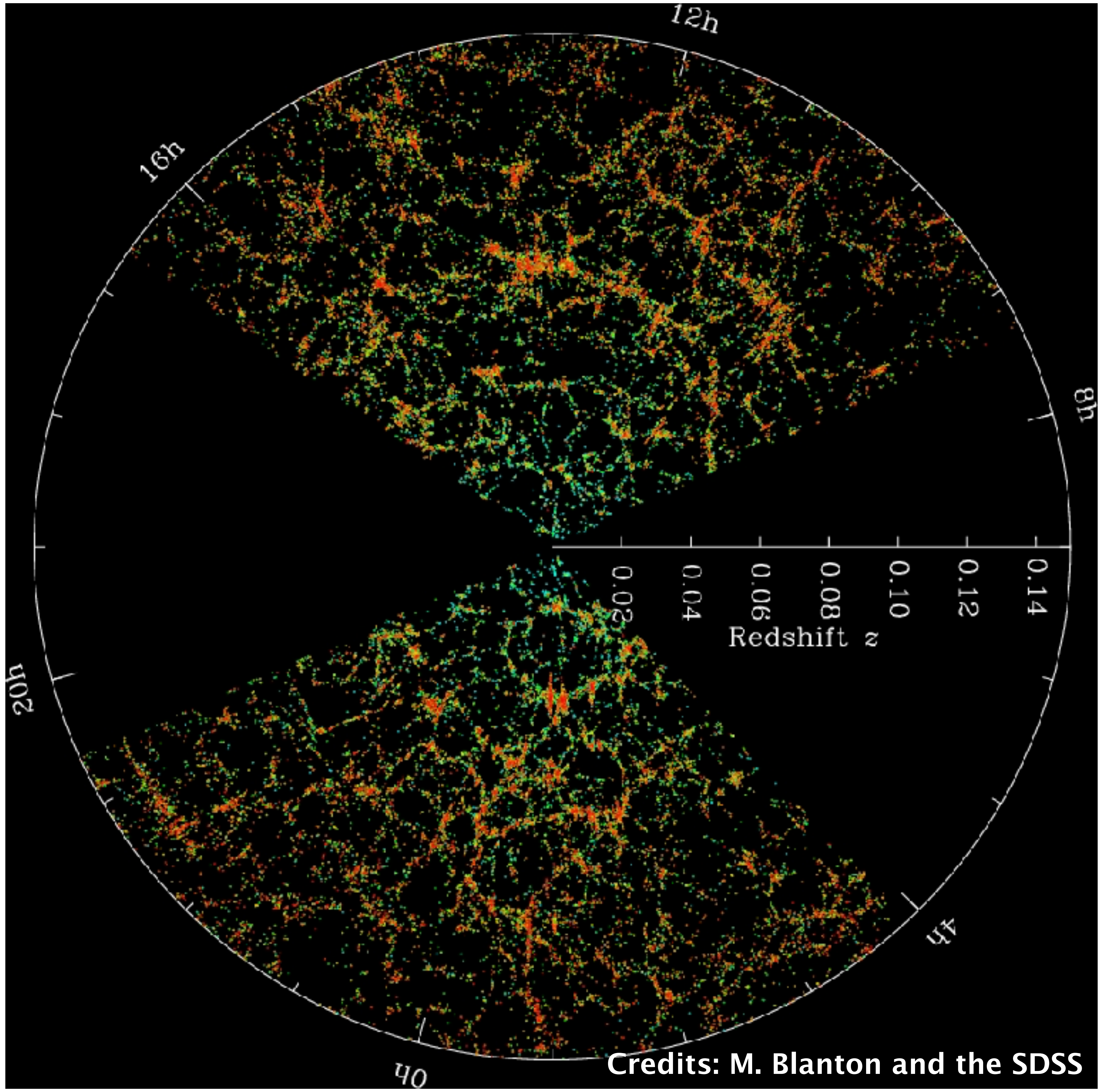
$\Gamma_\nu/aH \approx 1\,,\, k_h^{\rm fs}$

Well after self-decoupling

$\Gamma_\nu/aH \ll 1\,,\, k_h$

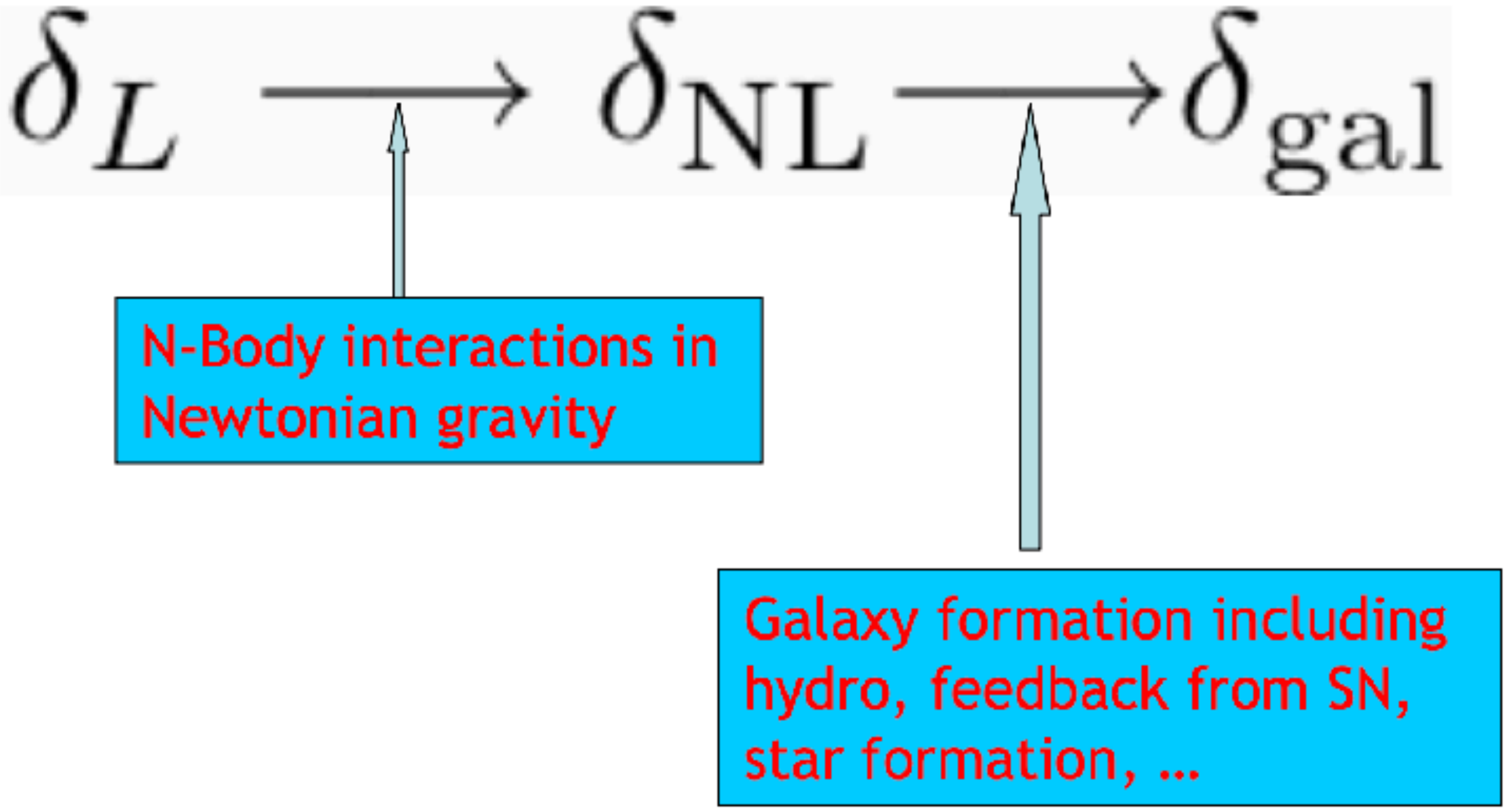


Neutrino self-interactions in the (mildly) non-linear regime



There is a nontrivial connection between our prediction (DM perturbations at linear-scales) and our observables (the distribution of galaxies across the Universe)

Credits: S. Dodelson

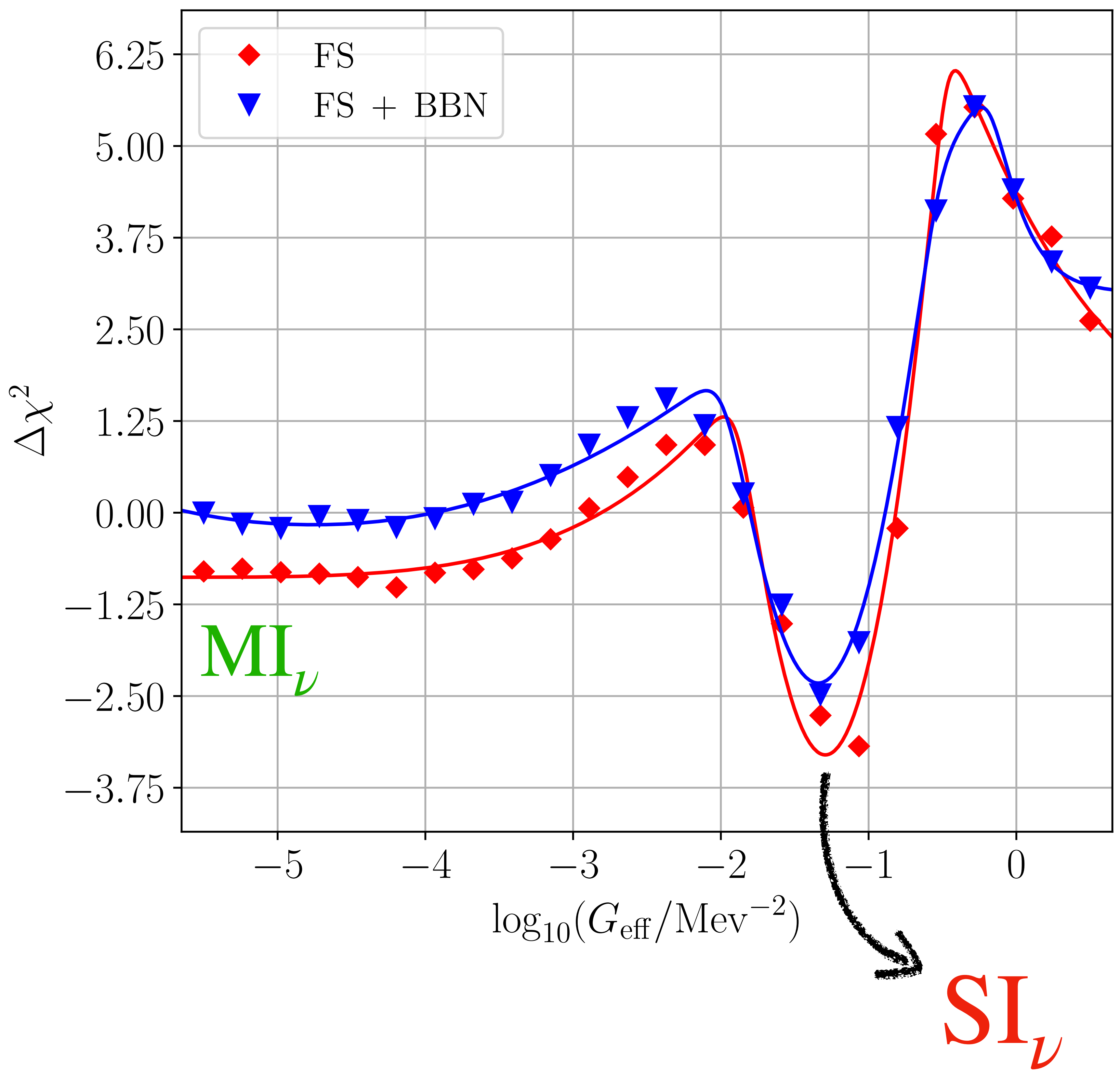


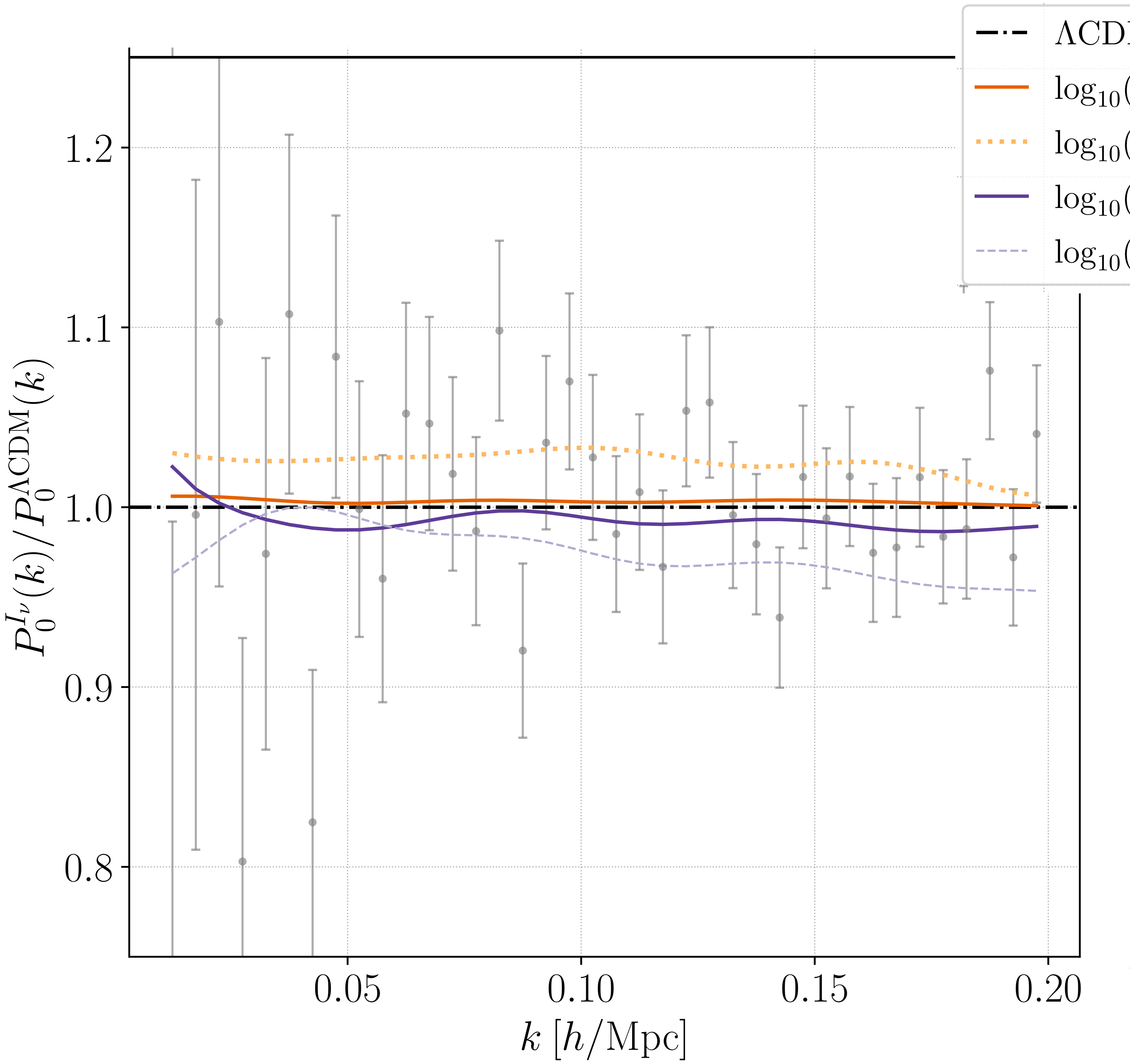
We compute the galaxy power spectrum using the EFTofLSS (CLASS-PT)

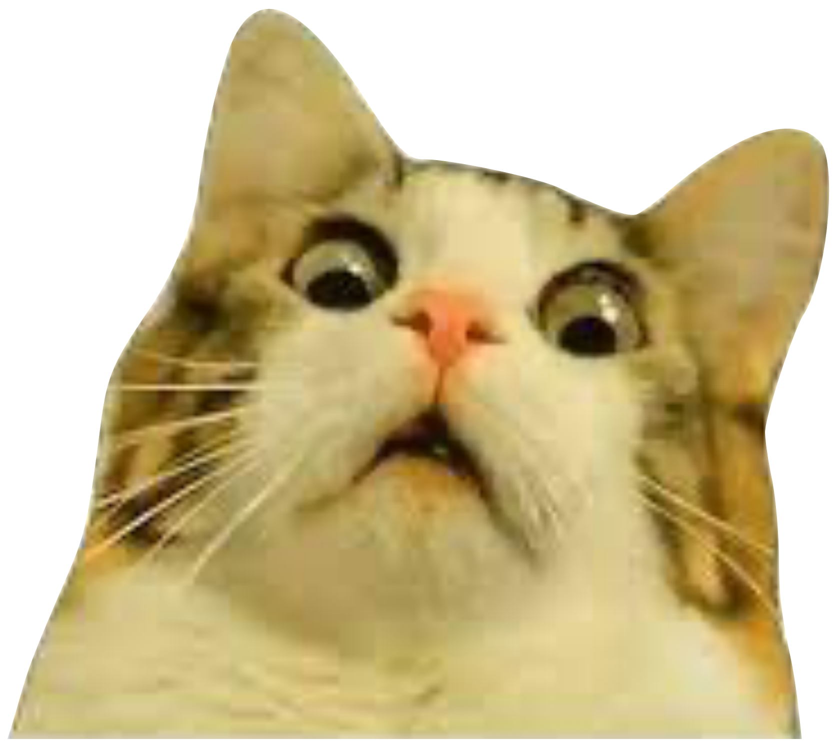
Galaxy power spectrum: profile likelihood

The galaxy power spectrum displays a mild preference for strongly self-interacting neutrinos!

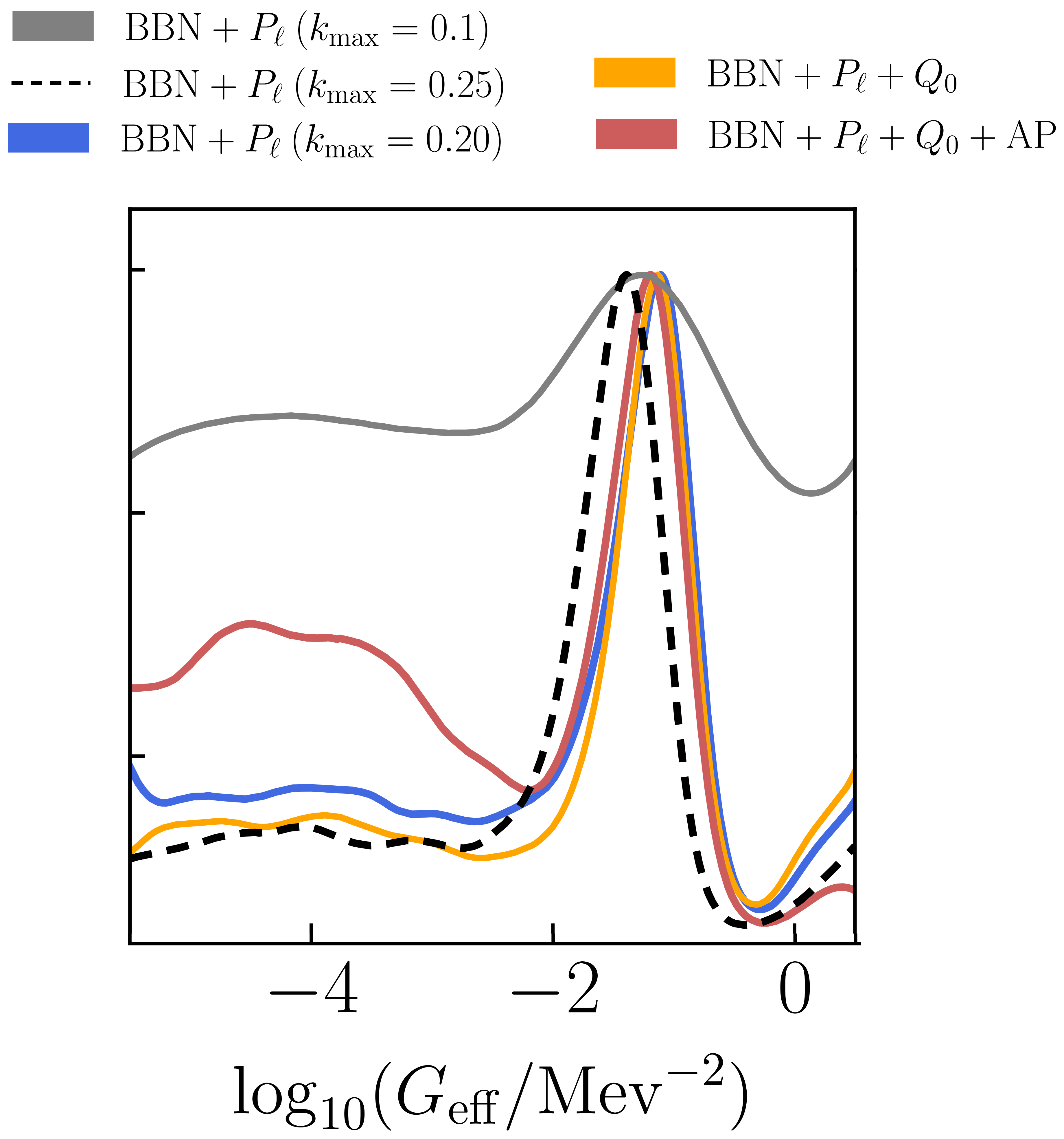
D.C, Cyr-Racine, Houghteling arXiv:2309.03941





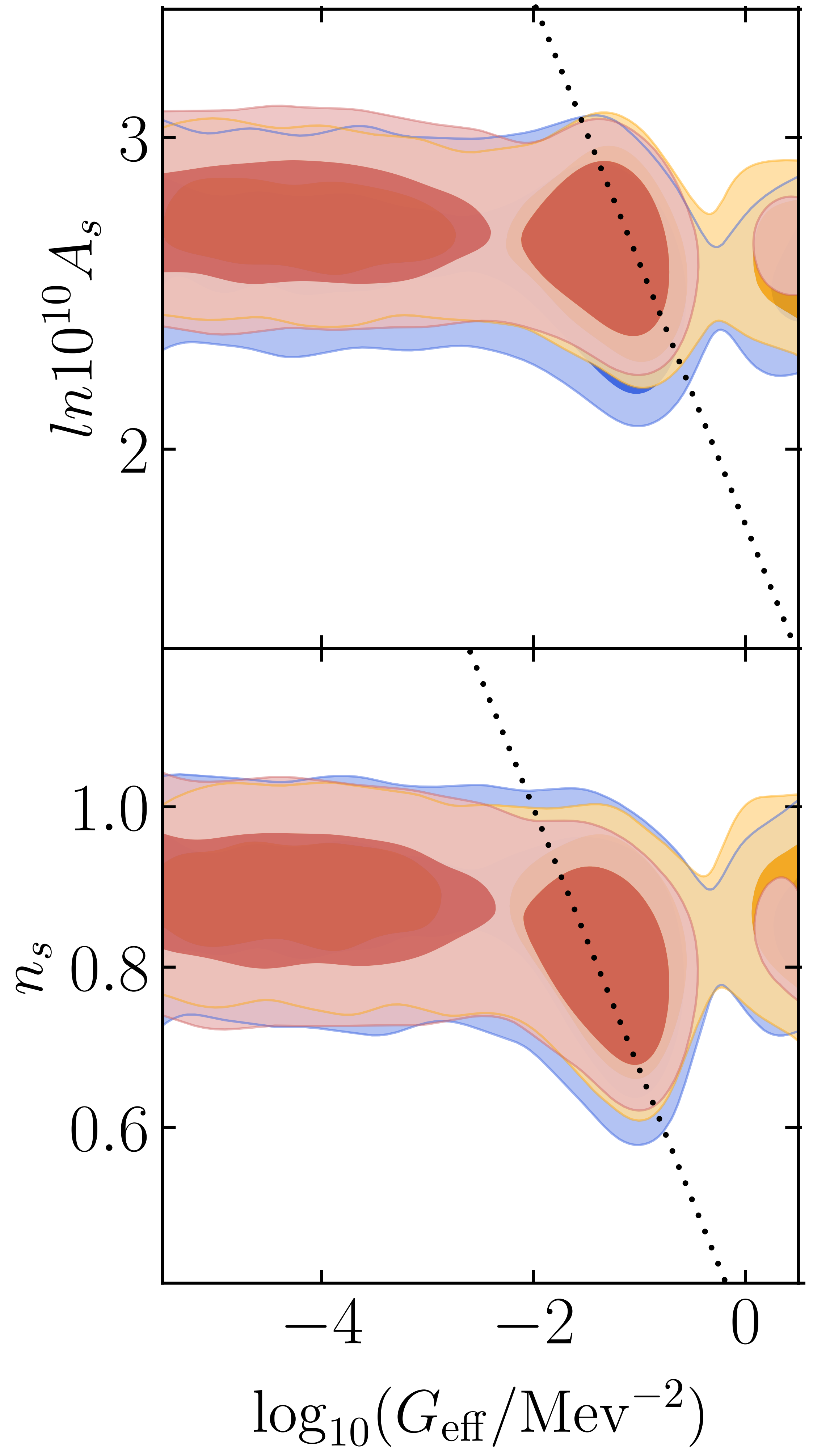


Galaxy power spectrum: Bayesian analysis



D.C, Cyr-Racine, Houghteling arXiv:2309.03941

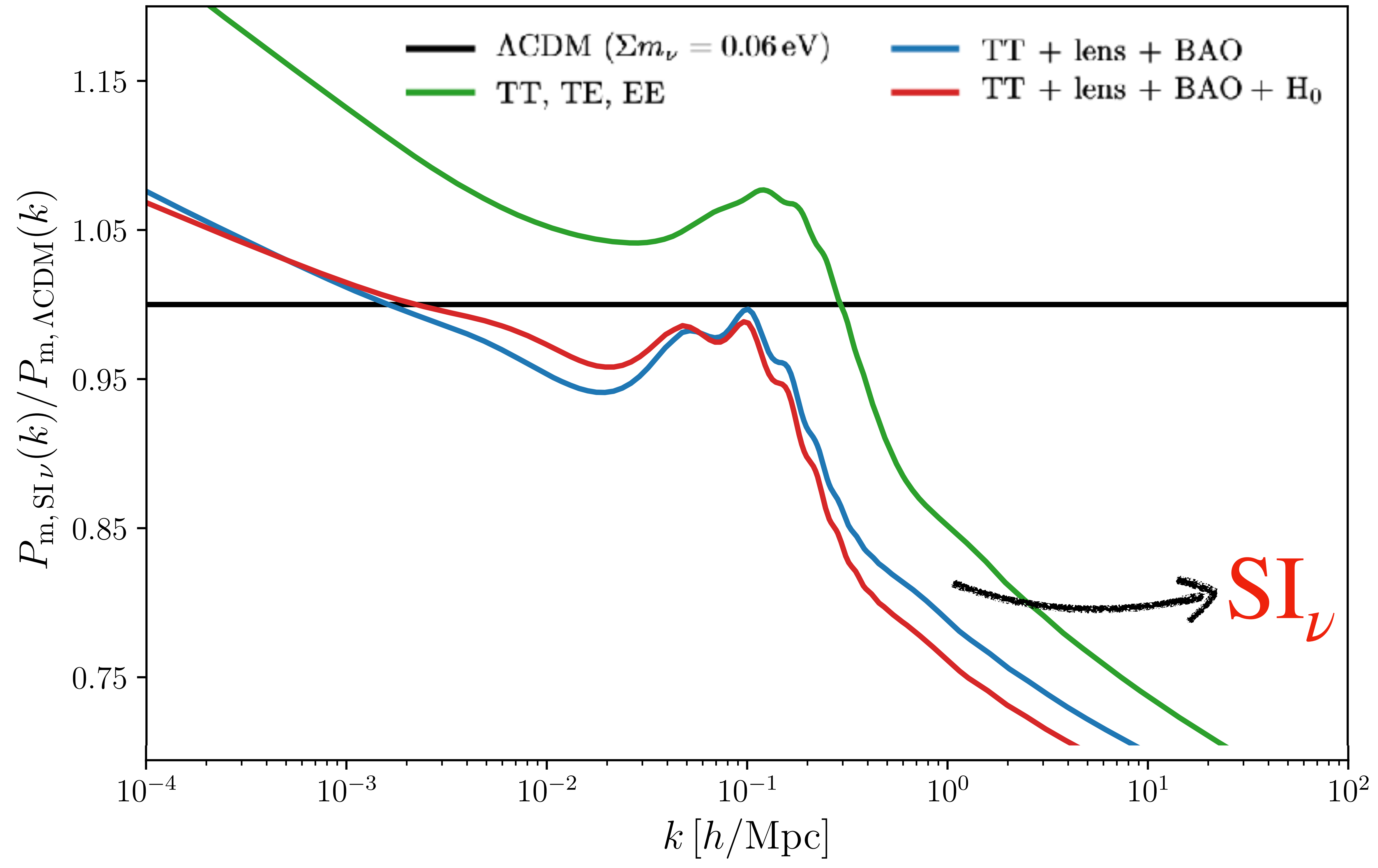
SI_ν cosmologies attain a good fit to the data by decreasing the values of n_s & A_s



Clustering suppression at sub-galactic scales

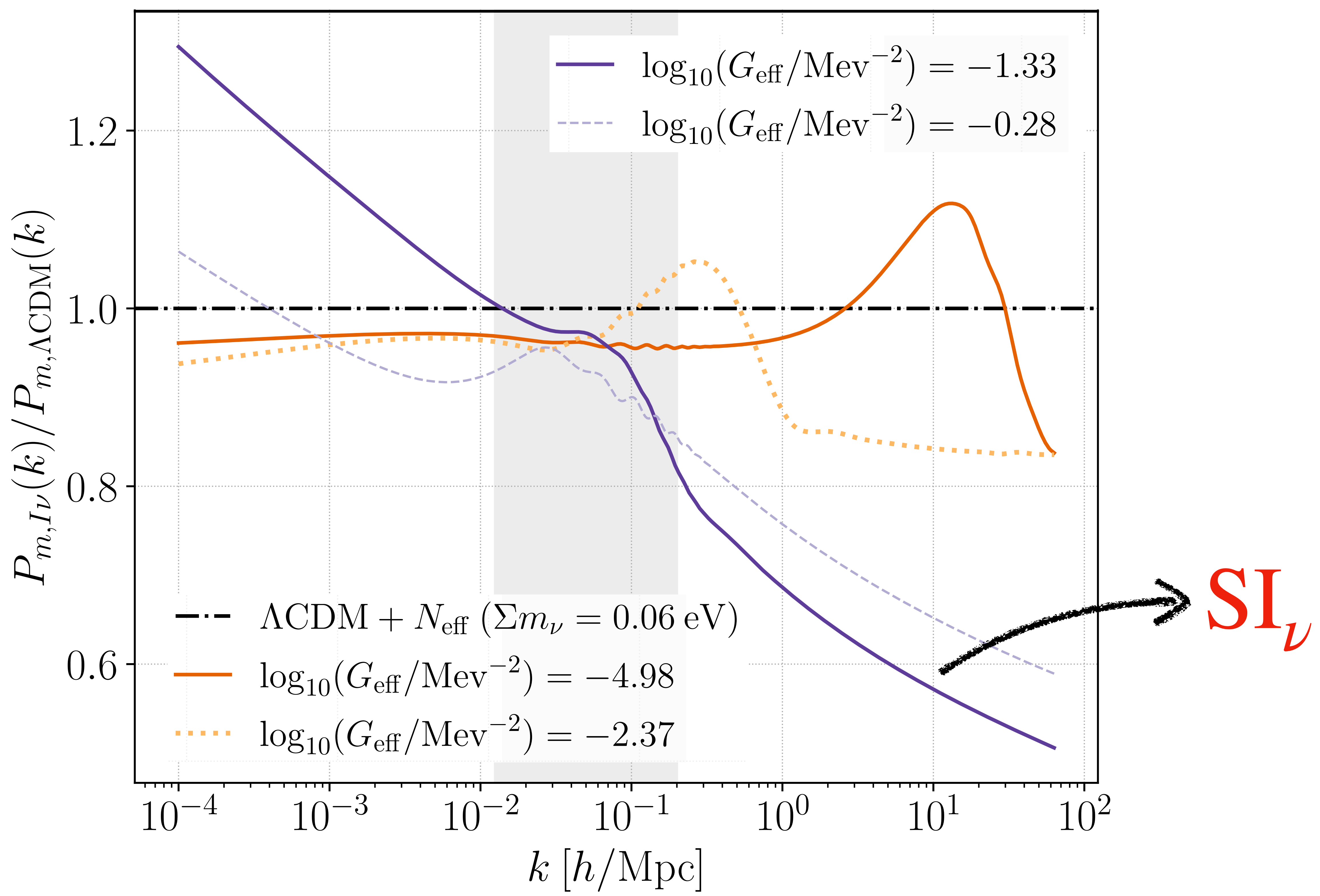
Owing to correlations with the primordial power spectrum parameters,
self-interacting neutrinos predict an important clustering suppression at sub-galactic scales!

CMB + BAO



C. Kreisch, F-Y. Cyr-Racine, O. Dore arXiv:1902.00534

LSS

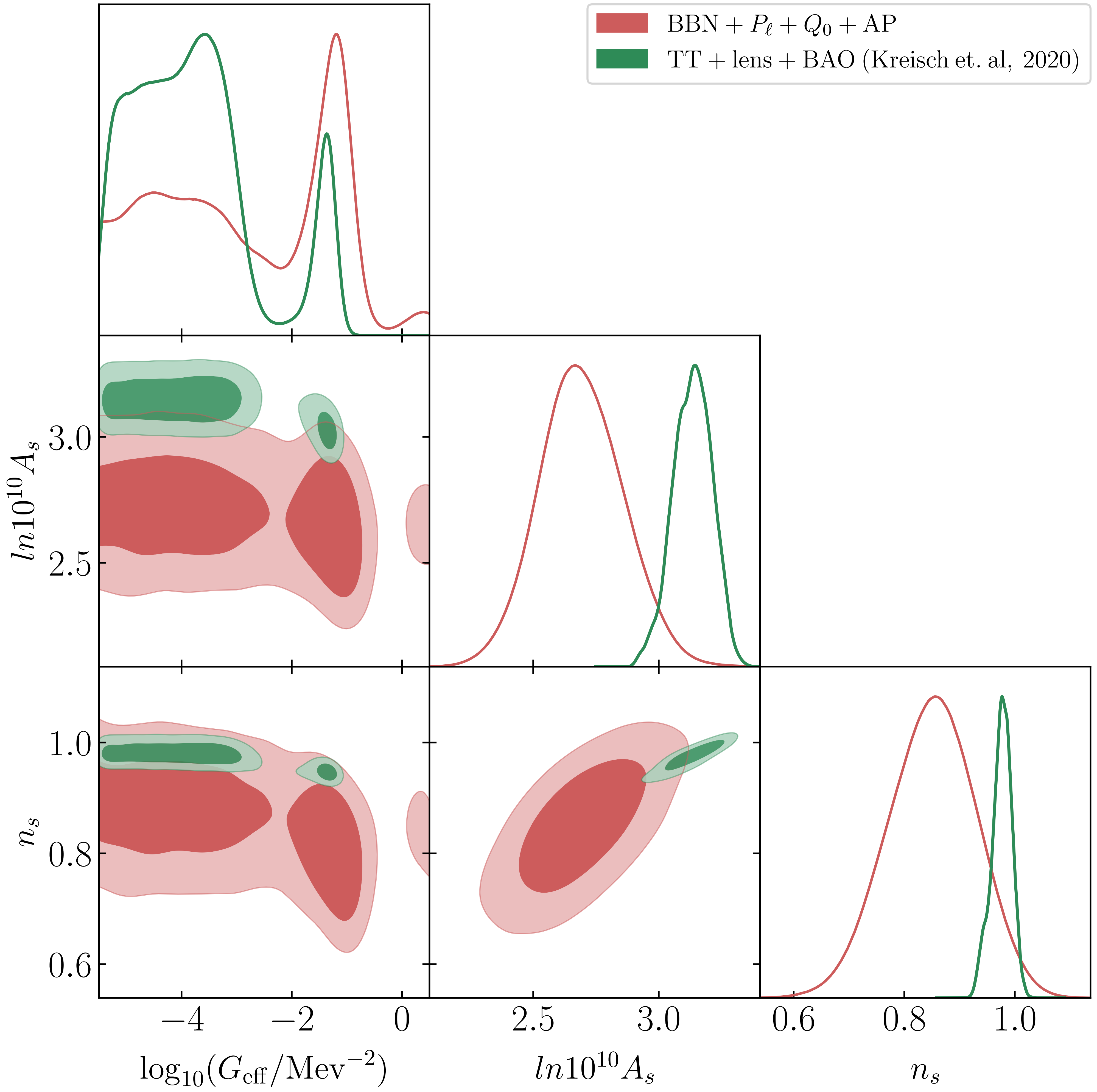


D.C, Cyr-Racine, Houghteling arXiv:2309.03941

What we have learned so far from LSS data

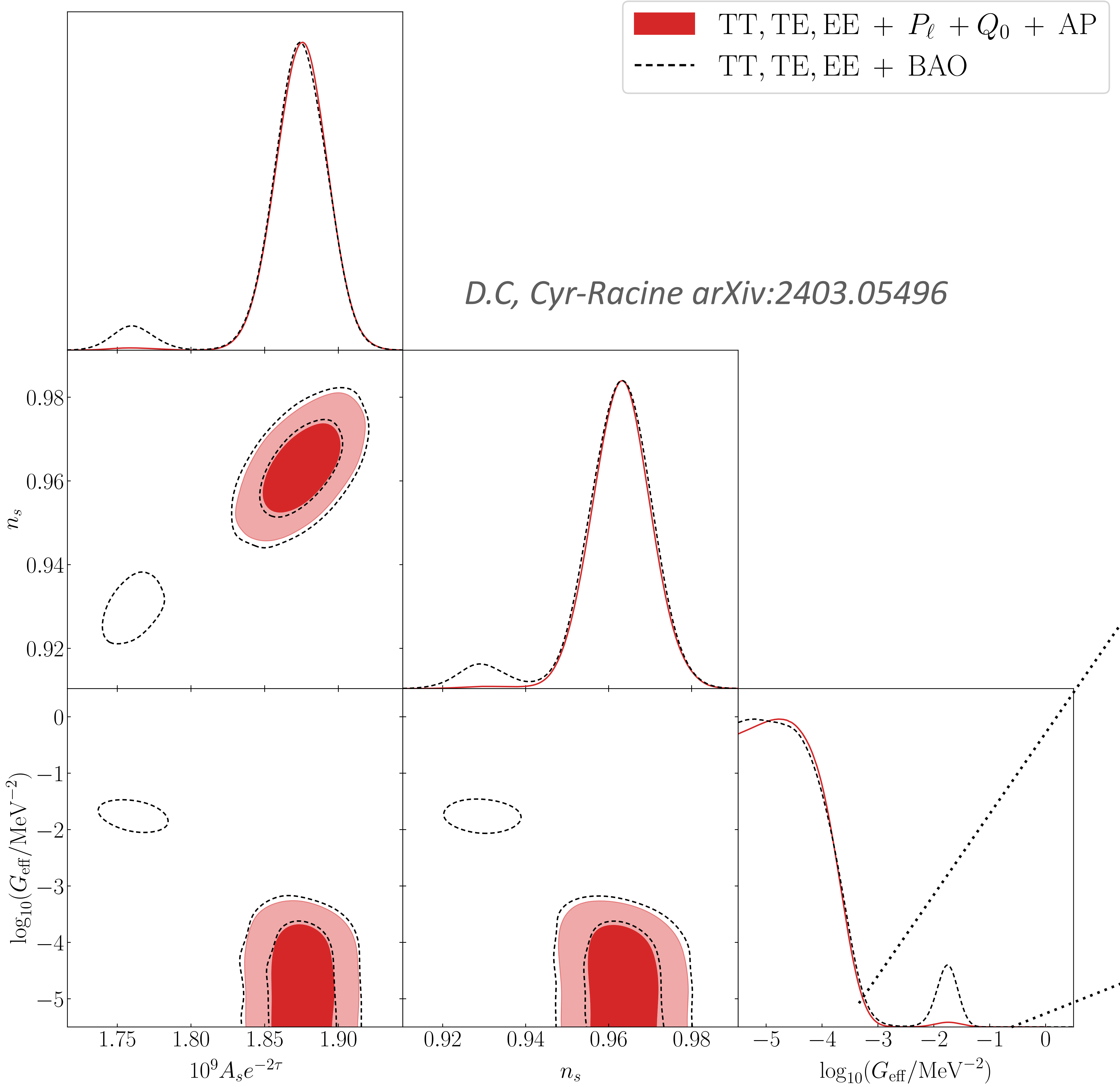
D.C, Cyr-Racine, Houghteling arXiv:2309.03941

- Galaxy data display a mild preference for SI_ν.
- We ruled out the possibility of an accidental feature in the CMB sky.
- Similar to the CMB analysis, the strong mode is possible thanks a multi-parameter correlation.
- SI_ν neutrinos predict a significant clustering suppression on small scales.



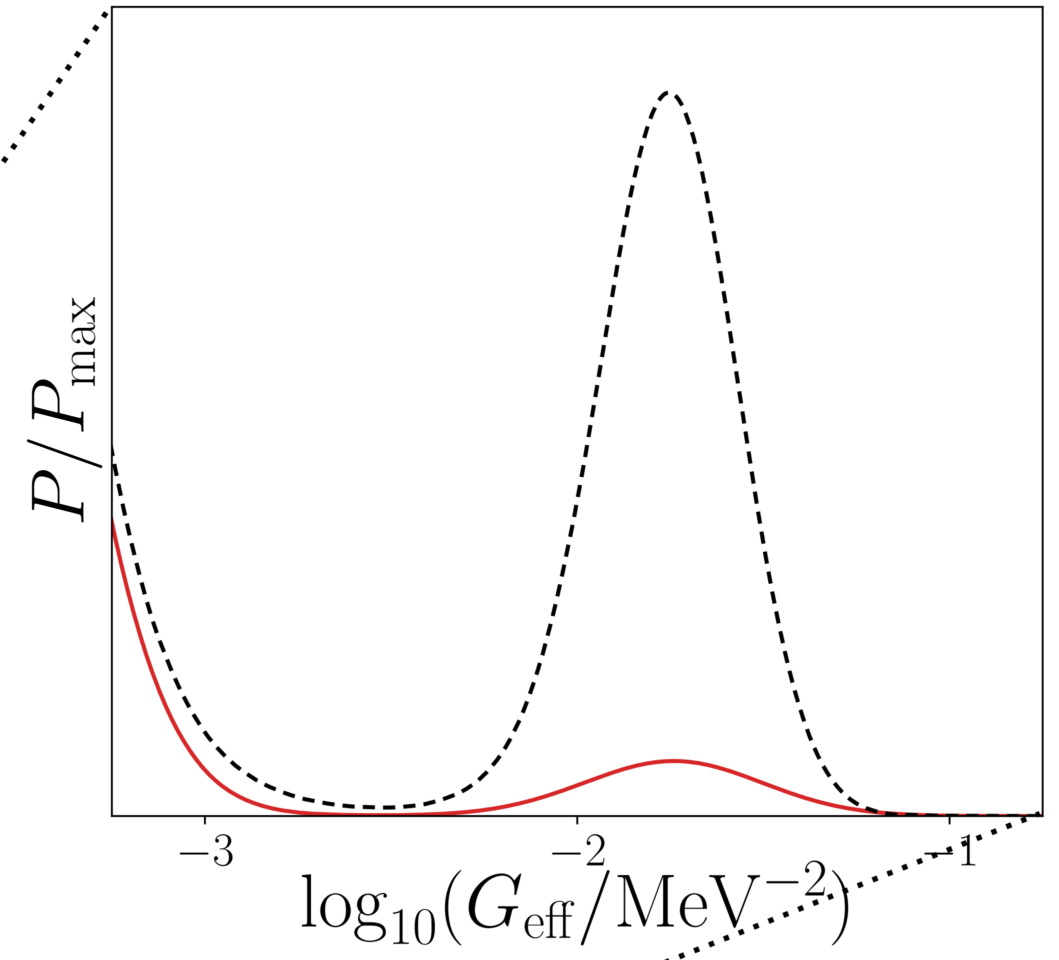
Are these results consistent with both LSS and the CMB data?

Joint analysis of the CMB and LSS data



D.C, Cyr-Racine arXiv:2403.05496

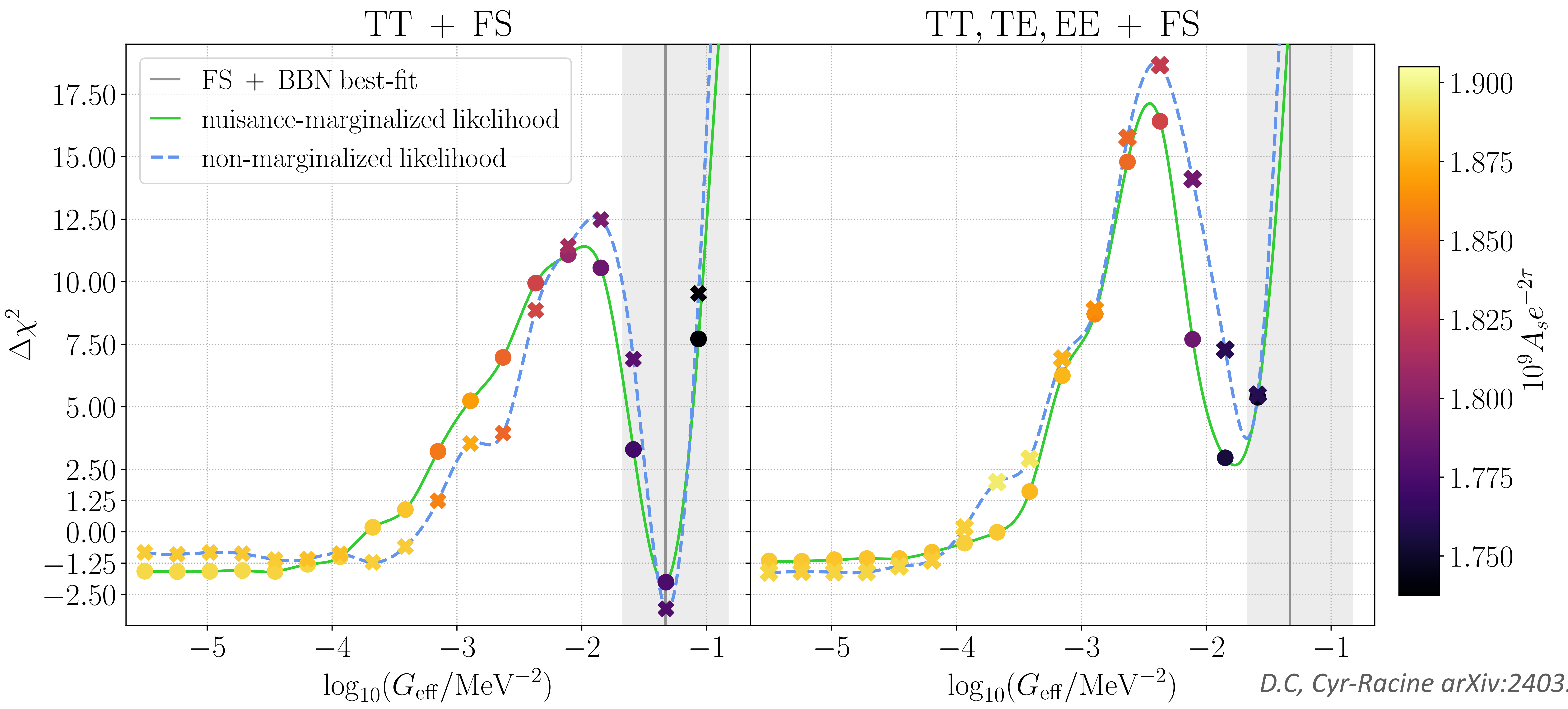
Data	ΛCDM	ΛCDM + $N_{\rm eff}$ + $\sum m_\nu$	MI_ν
$\Delta\chi^2_{\rm total}$	2.46	3.84	3.65
$\Delta\mathrm{AIC}_{i0}$	8.46	5.84	3.65
B_{i0}	0.0007 ± 0.0005	0.023 ± 0.015	0.0066 ± 0.0045



Our analysis disfavor the simplest representation of the SI_ν mode!

Joint analysis of the CMB and LSS data

The difficulty of simultaneously fitting the CMB and galaxy power spectra employing the simplest neutrino self-interaction scenario relates A_s and polarization data!



D.C, Cyr-Racine arXiv:2403.05496

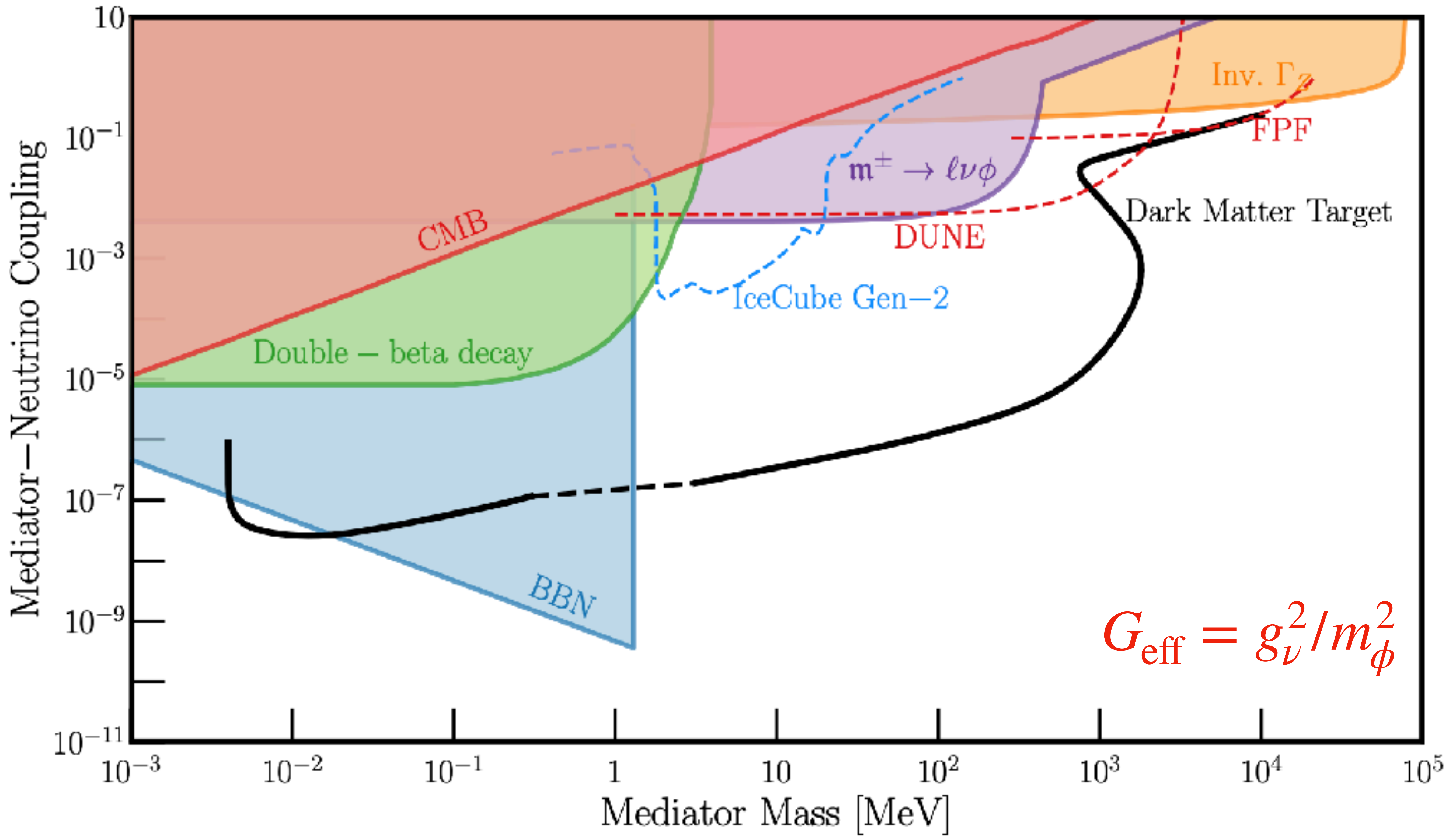
Self-interacting neutrinos: theoretical challenges

Cosmological observables offer a complementary way of studying new physics in the neutrino sector.

Our data allow for a cosmological scenario with a delayed neutrino free streaming.

Being clear that the simplest approximation to this phenomenology can not fully explain our observations more complex phenomenologies are needed!

Berryman et al., arXiv:2203.01955



$SI_\nu \rightarrow$ **Delay in the onset of neutrino free-streaming**

Great opportunity to explore BSM physics!

Self-interacting neutrinos: theoretical challenges

Although LSS data offers a unique way to test new physics, predicting the observables is beyond a trivial task!

Me : This new BSM model is so cool ! How about some LSS constraints ?

Also me :

1) Denial : I'm never going to redo all the calculation I did for the standard model. There has to be a way out !

2) Anger : What's wrong with these people !

3) Bargaining : Can I get away with only 1/2 of the calculations and wave my hands for the rest?

4) Depression : I'm never going to do it. It's ΛCDM all the way.

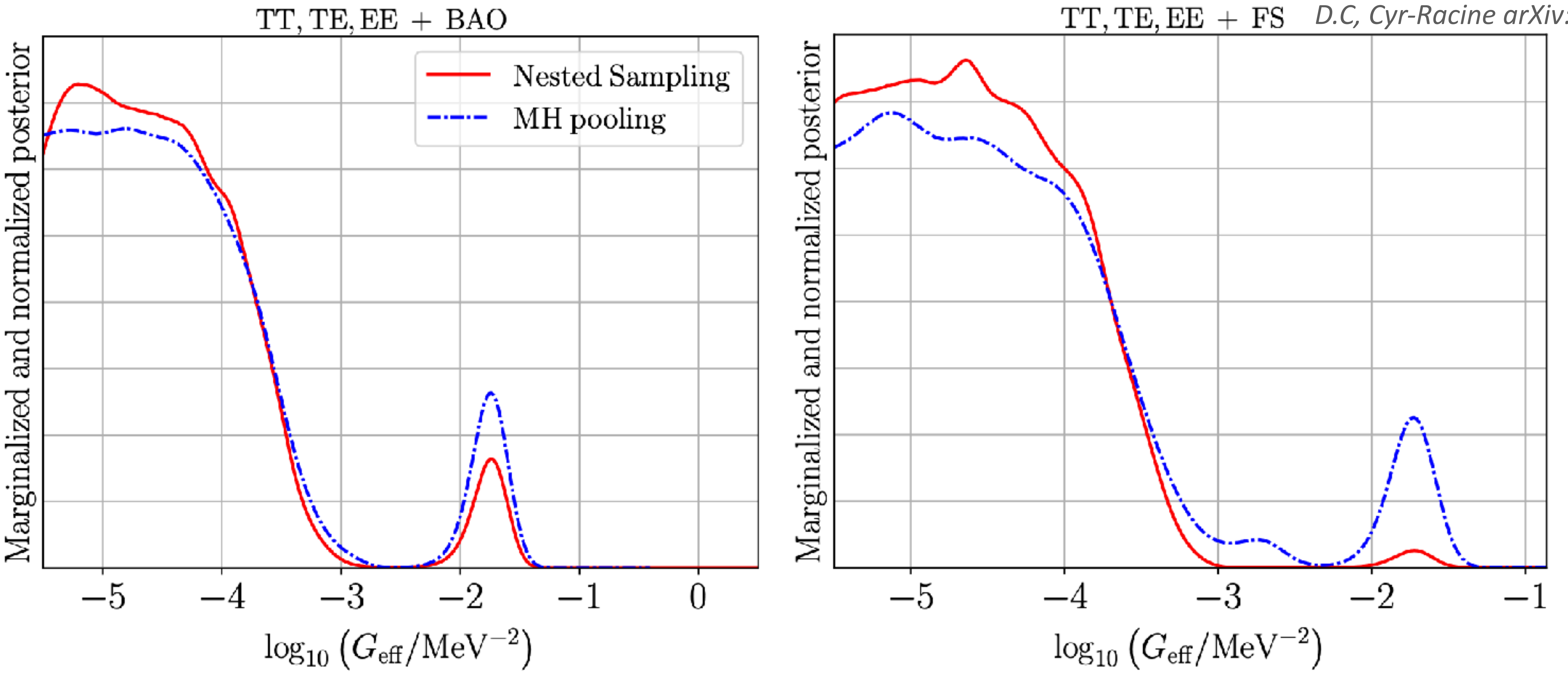
5) Acceptance : Alright, I'll do it.

Credits: Emanuele Castorina

Self-interacting neutrinos: data analysis

Even in its most simplest form, numerical artifacts affect the analysis of cosmological data

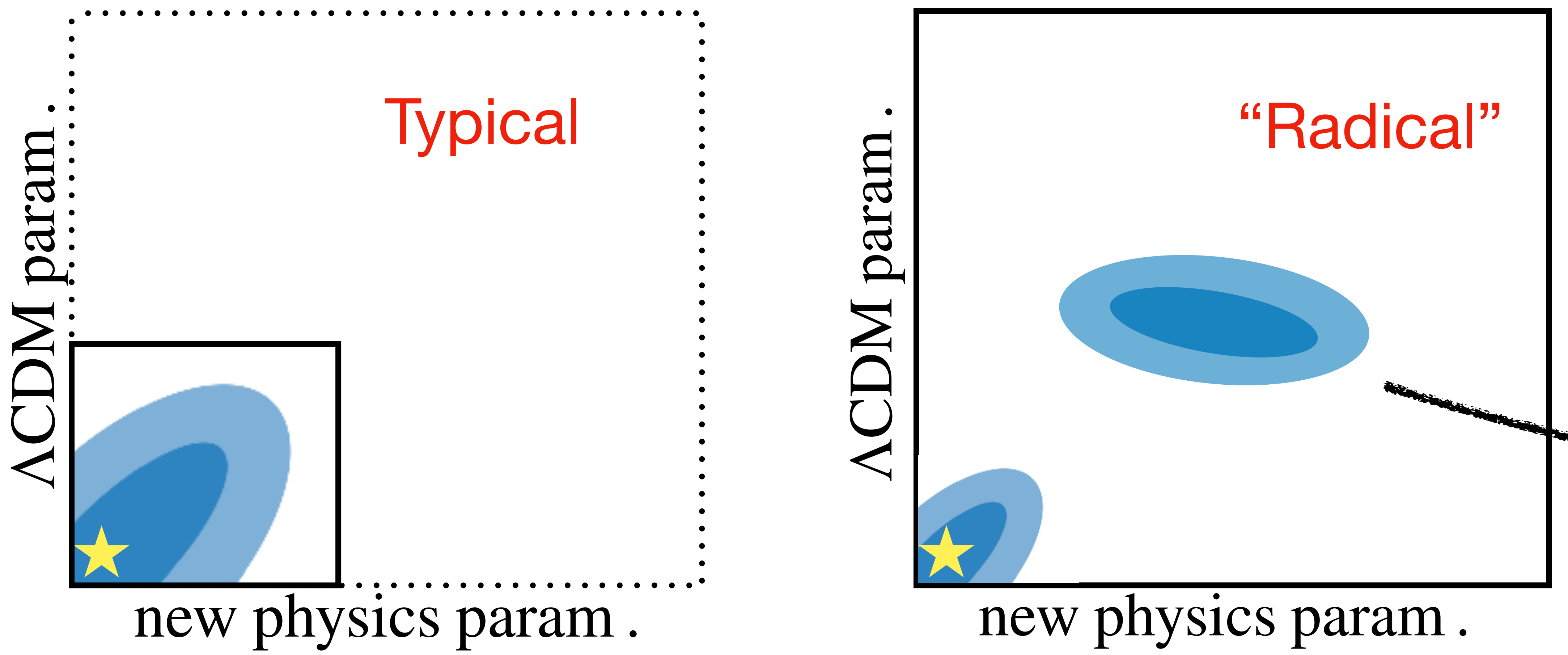
D.C, Cyr-Racine arXiv:2403.05496



The search for new physics in the neutrino sector can be troublesome!

Takeaways

- Galaxy power spectrum also allows the SI_ν mode (it is not an incidental feature in the CMB).
- Join analysis of galaxy and CMB data largely disfavor the simples representation (S8 tension).
- The SI_ν mode could hint at a yet-to-be-discovered feature in the Early Universe.
- Our results motivates the exploration of more complex models.

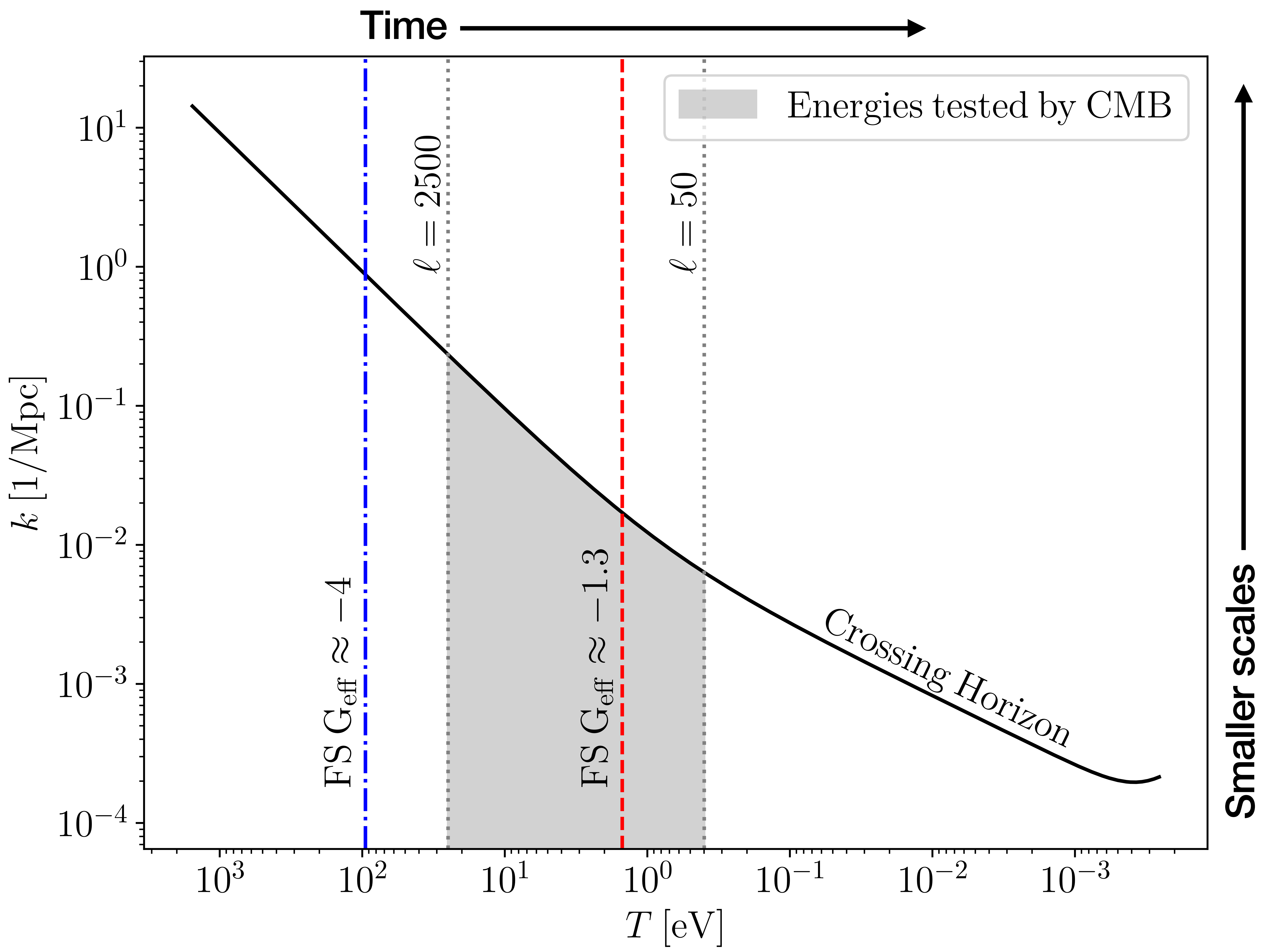


It is crucial to bear in mind that “radically” different scenarios could provide a good fit to the cosmological observables!

Thank you!

Credits: Symmetry Magazine

Energy scales and phenomenology at crossing horizon



Models with $\log_{10}\left(G_{\rm eff}/{\rm MeV}^{-2}\right) \lesssim -4$ will result indistinguishable from the Standard paradigm

Cosmological data probes the free-streaming nature of neutrinos at energies $\lesssim$100 eV.

Self-interacting neutrinos: data analysis

The addition of more LSS data restore the preference for the strong mode in its simplest form