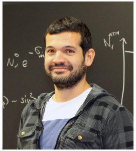
Long Range Interactions in Cosmology: Implications for Neutrinos

Beyond Standard Model: From Theory to Experiment — 2021

Ivan Esteban

Center for Cosmology and Astroparticle Physics (CCAPP), Ohio State University



Based on arXiv:2101.05804

In collaboration with J. Salvado (ICCUB)

31st March 2021

CCAPP

ccapp.osu.edu

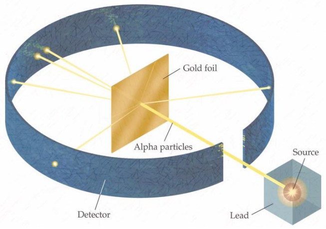
The Ohio State University

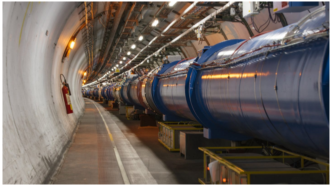
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

Ivan Esteban, Ohio State University
arXiv:2101.05804

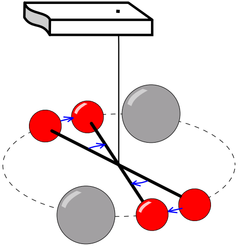
Looking for new interactions

Short distances
(heavy mediators)



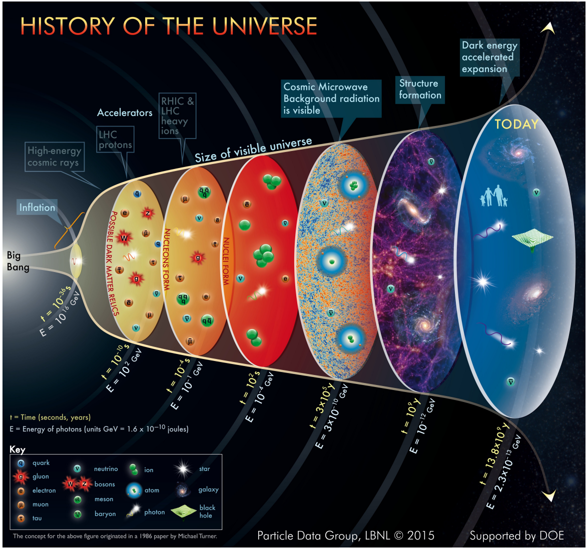


Long distances
(light mediators, small couplings)



Ivan Esteban, Ohio State University
arXiv:2101.05804

Looking for new interactions: cosmology



In the past, densities were *high*:

- Big Bang Nucleosynthesis: $\sim 10^{29}\,\mathrm{cm}^{-3}$
- Cosmic Microwave Background: $\sim 10^{14}\,\mathrm{cm}^{-3}$

New long-range interactions could have *observational* consequences.

Ivan Esteban, Ohio State University
arXiv:2101.05804

Looking for new interactions: cosmology

- What are the cosmological consequences of light mediators $\Longleftrightarrow$ long-range interactions?
  How does a long-range interaction affect ρ, p, $w \ldots$, commonly assumed to follow an ideal gas?
  E.g., Van der Waals gas.

- What are the observational consequences and possible bounds?
  - Cosmic Microwave Background anisotropies
  - Large Scale Structure observations (Baryon Acoustic Oscillations)

  for simplicity, for this we will focus on *neutrinos*.

  There are many recent works on cosmological consequences of neutrino self-interactions (neutrino mass models, H_0 tension, short baseline anomalies. . .) (Archidiacono et. al. (2013-2016); Hannestad et. al. (2013); Dasgupta et. al. (2013); Forastieri et. al. (2019); Kreisch et. al. (2019); Escudero et. al. (2019); Park et. al. (2019); Blinov et. al. (2019); Beacom et. al. (2004).
  But these have *heavy* mediators (they just induce ν-ν scattering), and we are interested in *long-range* effects.

Ivan Esteban, Ohio State University
arXiv:2101.05804

Yukawa interaction

$$\mathcal{S} = \int \sqrt{-g}\mathrm{d}^4x \left(-\frac{1}{2}D_\mu\phi D^\mu\phi - \frac{1}{2}M_\phi^2\phi^2 + i\bar{\psi}\not{D}\psi - m_0\bar{\psi}\psi - g\phi\bar{\psi}\psi\right)$$

- Being a scalar interaction,
  - both fermions and antifermions equally contribute,
  - both spins equally contribute,
  - is suppressed for relativistic fermions ($\bar{\psi}\psi = \overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L$).
- Fermions will source scalar field ϕ, with
  - strength $\sim g$,
  - range $\sim 1/M_\phi$.
- The field will *backreact on the fermions*.
- This will be important for **fermion energies** $\lesssim m_0$ and **number densities** $\gtrsim M_\phi^3$.

N.B.: we will ignore scatterings, a good approximation for $g \lesssim 10^{-7}$.

Ivan Esteban, Ohio State University

arXiv:2101.05804

Equations of motion

$$i\not{D}\psi - (m_0 + g\phi)\psi = 0 \implies$$

Effective fermion mass $\tilde{m}(\phi) \equiv m_0 + g\phi$.

Time-dependent as ϕ evolves.

$$\underbrace{-D_\mu D^\mu \phi}_{\supset 3H\dot{\phi}} + M_\phi^2 \phi = -g\bar{\psi}\psi$$

Ivan Esteban, Ohio State University
arXiv:2101.05804

Equations of motion

$i\not{D}\psi - (m_0 + g\phi)\psi = 0$ $\Longrightarrow$ Effective fermion mass $\tilde{m}(\phi) \equiv m_0 + g\phi$. Time-dependent as ϕ evolves.

$\underbrace{-D_\mu D^\mu \phi}_{\supset 3H\dot{\phi}} + M_\phi^2 \phi = -g\bar{\psi}\psi$ $\Longrightarrow$ Klein-Gordon equation with *Hubble friction* and **source term**. For $M_\phi \gg H$ and average rhs over fermion (+antifermion) distribution $f(p)$,

$$M_\phi^2 \phi = -g \int \mathrm{d}^3 p \frac{\tilde{m}(\phi)}{\sqrt{p^2 + \tilde{m}(\phi)^2}} f(p)$$

N.B.: $M_\phi \gg H$ means $M_\phi \gtrsim 10^{-25}\,\mathrm{eV}$. I.e., we are exploring interaction ranges $\ll \mathrm{Mpc}$. Otherwise, we recover quintessence.

Equations of motion

$$i\not{D}\psi - (m_0 + g\phi)\psi = 0 \quad \Longrightarrow$$

Effective fermion mass $\boxed{\tilde{m}(\phi) \equiv m_0 + g\phi}$.

Time-dependent as ϕ evolves.

$$\underbrace{-D_\mu D^\mu \phi}_{\supset 3H\dot{\phi}} + M_\phi^2 \phi = -g\bar{\psi}\psi \quad \Longrightarrow$$

Klein-Gordon equation with *Hubble friction* and **source term**. For $M_\phi \gg H$ and average rhs over fermion (+antifermion) distribution $f(p)$,

$$\boxed{M_\phi^2 \phi = -g \int \mathrm{d}^3 p \frac{\tilde{m}(\phi)}{\sqrt{p^2 + \tilde{m}(\phi)^2}} f(p)}$$

N.B.: $M_\phi \gg H$ means $M_\phi \gtrsim 10^{-25}\,\mathrm{eV}$. I.e., we are exploring interaction ranges $\ll \mathrm{Mpc}$. Otherwise, we recover quintessence.

Ivan Esteban, Ohio State University
arXiv:2101.05804

Equations of motion

$$i\not{D}\psi - (m_0 + g\phi)\psi = 0 \quad \Longrightarrow$$

Effective fermion mass $\boxed{\tilde{m}(\phi) \equiv m_0 + g\phi}$.

Time-dependent as ϕ evolves.

$$\underbrace{-D_\mu D^\mu \phi}_{\supset 3H\dot{\phi}} + M_\phi^2 \phi = -g\bar{\psi}\psi \quad \Longrightarrow$$

Klein-Gordon equation with *Hubble friction* and **source term**. For $M_\phi \gg H$ and average rhs over fermion (+antifermion) distribution $f(p)$,

$$f(p) = \frac{\mathfrak{g}}{(2\pi)^3} \frac{1}{e^{p/T} + 1}$$

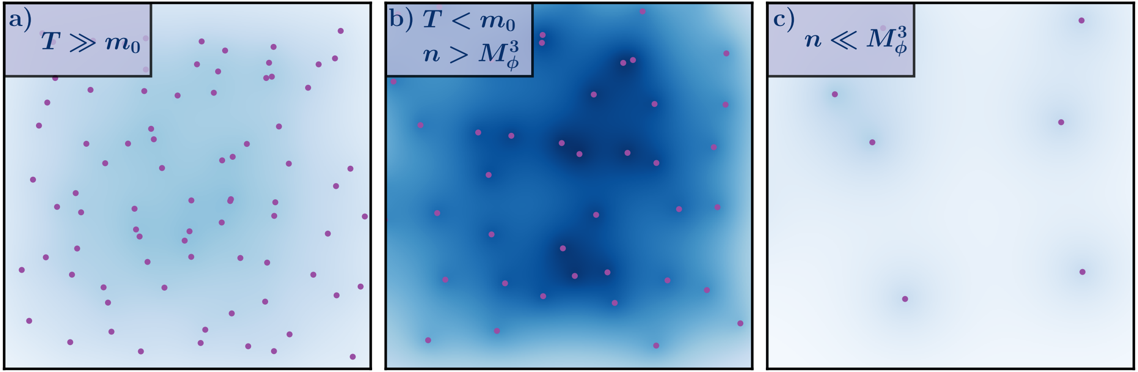
$$\boxed{M_\phi^2 \phi = -g \int \mathrm{d}^3 p \frac{\tilde{m}(\phi)}{\sqrt{p^2 + \tilde{m}(\phi)^2}} f(p)}$$

N.B.: $M_\phi \gg H$ means $M_\phi \gtrsim 10^{-25}\,\mathrm{eV}$. I.e., we are exploring interaction ranges $\ll \mathrm{Mpc}$. Otherwise, we recover quintessence.

Homogeneous background

Ivan Esteban, Ohio State University
arXiv:2101.05804

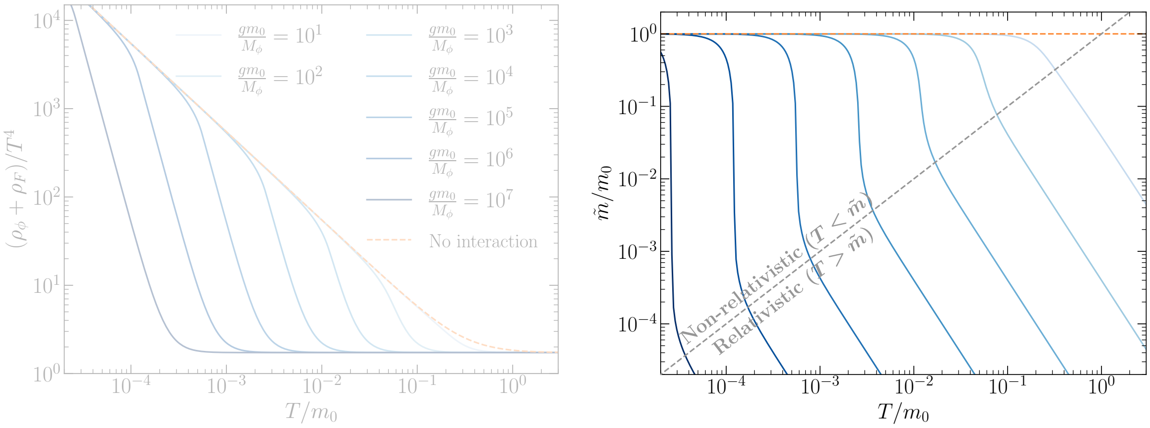
Pictorial overview



Homogeneous background

Ivan Esteban, Ohio State University
arXiv:2101.05804

Numerical results

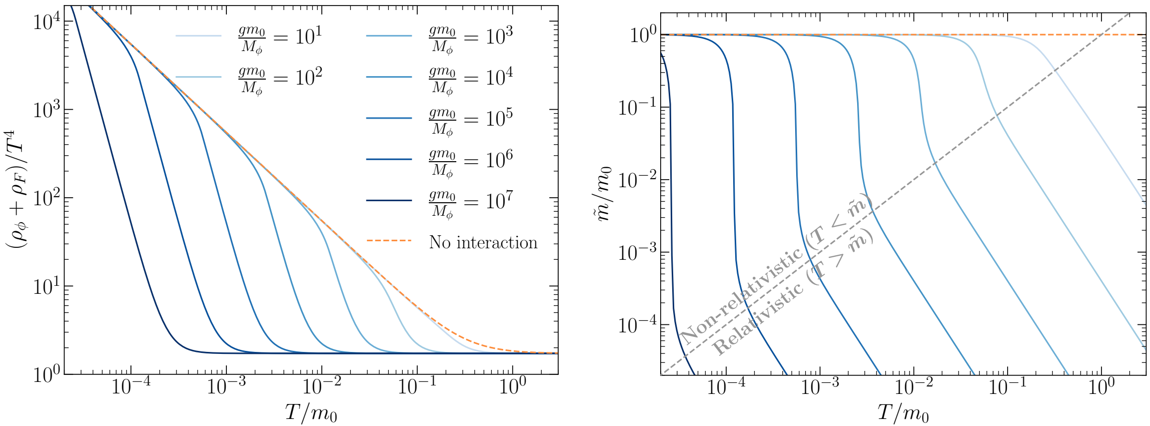


The fermion will stay *relativistic* as long as there are many fermions within the interaction range.

Homogeneous background

Ivan Esteban, Ohio State University
arXiv:2101.05804

Numerical results

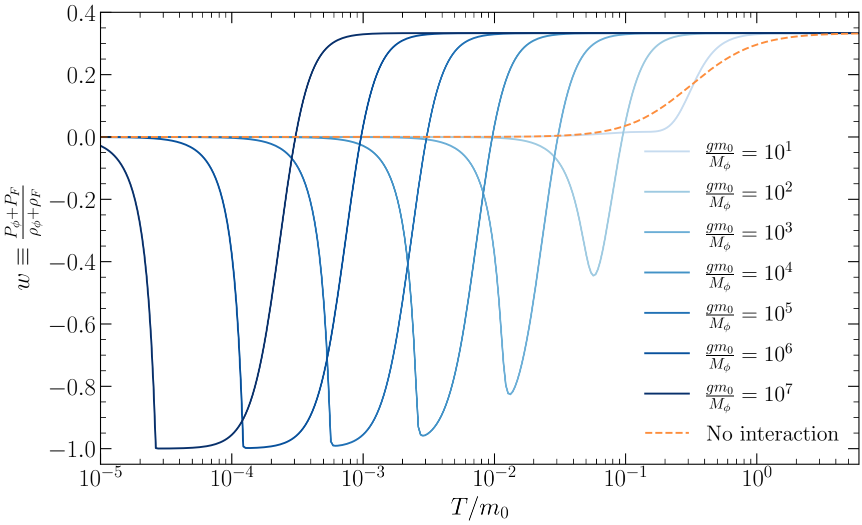


$$\rho_\phi = \frac{1}{2} M_\phi^2 \phi^2 \; ; \; \rho_F = \int \mathrm{d}^3 p \sqrt{p^2 + \tilde{m}^2}\, f(p)\,.$$

Notice that $\rho \leq \rho_{\text{Nointeraction}}$: Yukawas are *attractive*.

Ivan Esteban, Ohio State University
arXiv:2101.05804

Numerical results (cont.)



The equation of state $w \equiv \frac{P}{\rho}$ is relevant as

$$\frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}t} = -3H(1+w)$$

(i.e., how fastly ρ changes)

$$P_\phi = -\frac{1}{2}M_\phi^2\phi^2$$

$$P_F = \int \mathrm{d}^3p \frac{p^2}{3\sqrt{p^2+\tilde{m}^2}} f(p)$$

Observational consequences

Ivan Esteban, Ohio State University
arXiv:2101.05804

Let's look for this!

As a *benchmark*, we will focus on neutrino self-interactions:

- We know they abundantly exist.
- Self-interactions are poorly constrained.
- They become non-relativistic relatively late.
- Cosmology can provide a measurement of neutrino mass, **the energy scale of our first laboratory evidence of BSM physics**. Current bounds well beyond KATRIN laboratory sensitivity.

We will assume three degenerate neutrinos of vacuum mass m_ν, with a scalar universally coupling to all mass eigenstates.

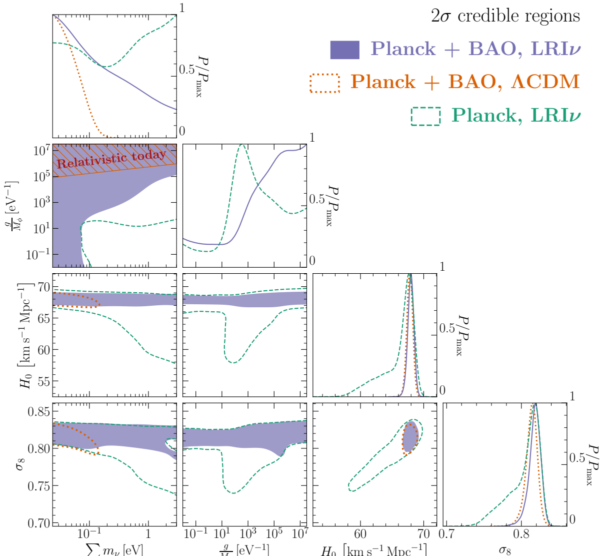
We will study consequences in

- CMB anisotropies (Planck).
- Large Scale Structure (BAOs + Euclid).

CLASS + MontePython: github.com/jsalvado/class_public_lrs

Cosmological constraints

Ivan Esteban, Ohio State University
arXiv:2101.05804



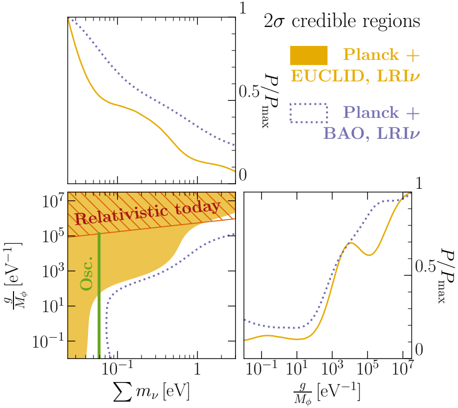
- Both BAO and Planck data are quite sensitive to the neutrino equation of state.
- Neutrino mass bound *fully avoided*. **KATRIN could see something!**

Euclid

T. Sprenger *et al.*, "Cosmology in the era of Euclid and the Square Kilometre Array," arXiv:1801.08331.

Euclid should have $\sim$ 2–3σ sensitivity to $\sum m_\nu = 0.06\,\mathrm{eV}$, the smallest value allowed by oscillations.

Scenario 1: Euclid compatible with $\sum m_\nu = 0$



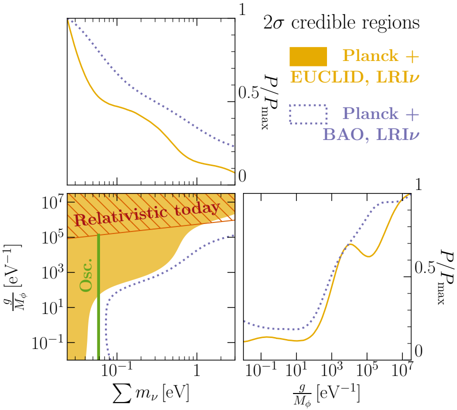
Future: Large Scale Structure

Ivan Esteban, Ohio State University
arXiv:2101.05804

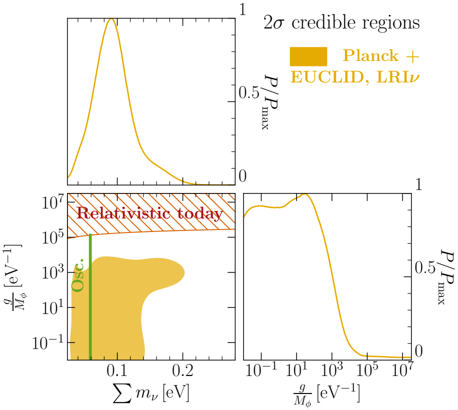
Euclid

Interesting complementarity with KATRIN!

Scenario 1: Euclid compatible with $\sum m_\nu = 0$



Scenario 2: Euclid measures $\sum m_\nu = 0.08\,\mathrm{eV}$



Conclusions

Ivan Esteban, Ohio State University
arXiv:2101.05804

- We have consistently addressed the cosmological effects of a scalar long range interaction among fermions.
  From a particle physics perspective, we are exploring fermions + light mediators in a *simple*, **minimal** interaction model.
- Up to now, studies mostly focused on either
  - Interactions with cosmological ranges: *modified gravity*.
  - Scattering effects (*heavy mediators*).

  in between, there are $\sim$ *15 orders of magnitude* with a very rich phenomenology!
- The effects turn on at $T \sim m_0$, and can be summarized as
  $$\text{Radiation (even for } T \ll m_0) \Longrightarrow \text{Dark energy} \Longrightarrow \text{Dust}$$
  relevant for $\boldsymbol{\frac{g m_0}{M_\phi} > 1}$.
- As a benchmark, we have studied cosmological bounds on *neutrino self-interactions*:
  - Neutrino mass bound is **completely avoided**. KATRIN could see something!
  - Planck + BAO constraint $\frac{g m_\nu}{M_\phi} \gtrsim 10^2 (10^4)$ for $\sum m_\nu = 0.1(1)\,\mathrm{eV}$.
- LSS could be very powerful, and has an interesting complementarity with Katrin & oscillations.
- The formalism could also be applied to other scenarios. github.com/jsalvado/class_public_lrs

Thanks!

Homogeneous background: approximate solutions

We will assume a fermion thermal *relic*

$$f(p) = \frac{\mathfrak{g}}{(2\pi)^3} \frac{1}{e^{p/T} + 1} \,,$$

for which the scalar field equation can be approximately solved in 2 limits

$\boldsymbol{T \gg \tilde{m}}$

$$\phi = -\frac{\frac{\mathfrak{g}}{24} g T^3 \frac{m_0}{T}}{M_\phi^2 + \frac{\mathfrak{g}}{24} g^2 T^2}$$

coupling $\times$ fermion number density $\times \frac{m_0}{T}$

$\div$ *effective* scalar mass

$$\tilde{m} = m_0 \frac{1}{1 + \frac{\mathfrak{g}}{24} \frac{g^2 T^2}{M_\phi^2}}$$

relativistic as long as $\boldsymbol{T \gg \frac{M_\phi}{g}\sqrt{\frac{m_0}{T}}}$

$\boldsymbol{T \ll \tilde{m}}$

$$\phi = -\frac{3\zeta(3)\mathfrak{g}}{4\pi^2} g \frac{T^3}{M_\phi^2}$$

$$\tilde{m} = m_0 \left(1 - \frac{3\zeta(3)\mathfrak{g}}{4\pi^2} \frac{g^2 T^2}{M_\phi^2} \frac{T}{m_0}\right)$$

Ivan Esteban, Ohio State University
arXiv:2101.05804

Perturbation equations & instability

In the Newtonian gauge,

$$f = f_0(q)[1 + \Psi(\vec{q}, \tau, \vec{x})]$$

$$\Psi_0' = -\frac{qk}{\varepsilon}\Psi_1 - \phi' \frac{\mathrm{d}\log f_0}{\mathrm{d}\log q} \,,$$

$$\Psi_1' = \frac{qk}{3\varepsilon}(\Psi_0 - 2\Psi_2) - \left[\varepsilon\psi + \boldsymbol{g\delta\phi\frac{\tilde{m}}{\varepsilon}a^2}\right]\frac{k}{3q}\frac{\mathrm{d}\log f_0}{\mathrm{d}\log q} \,,$$

$$\Psi_\ell' = \frac{qk}{(2\ell+1)\varepsilon}[\ell\Psi_{\ell-1} - (\ell+1)\Psi_{\ell+1}] \quad \forall \ell \geq 2 \,.$$

$$\phi = \phi_0(\tau) + \delta\phi(\vec{x}, \tau)$$

For $M_\phi \gg H$,

$$\delta\phi \simeq \frac{-g\frac{4\pi}{a^2}\int \mathrm{d}q\, q^2 \frac{\tilde{m}}{\varepsilon} f_0(q)\Psi_0(\vec{q}, \tau, \vec{k})}{(k/a)^2 + M_\phi^2 + M_T^2}$$

$$M_T^2 \equiv g^2 \int \mathrm{d}^3p \frac{p^2}{[p^2 + \tilde{m}^2]^{3/2}} f_0(p) \,.$$

Ivan Esteban, Ohio State University
arXiv:2101.05804

Perturbation equations & instability

In the Newtonian gauge,

$$f = f_0(q)[1 + \Psi(\vec{q}, \tau, \vec{x})]$$

$$\Psi_0' = -\frac{qk}{\varepsilon}\Psi_1 - \phi' \frac{\mathrm{d}\log f_0}{\mathrm{d}\log q}\,,$$

$$\Psi_1' = \frac{qk}{3\varepsilon}(\Psi_0 - 2\Psi_2) - \left[\varepsilon\psi + \boldsymbol{g\delta\phi\frac{\tilde{m}}{\varepsilon}a^2}\right]\frac{k}{3q}\frac{\mathrm{d}\log f_0}{\mathrm{d}\log q}\,,$$

$$\Psi_\ell' = \frac{qk}{(2\ell+1)\varepsilon}[\ell\Psi_{\ell-1} - (\ell+1)\Psi_{\ell+1}] \quad \forall \ell \geq 2\,.$$

$$\phi = \phi_0(\tau) + \delta\phi(\vec{x}, \tau)$$

For $M_\phi \gg H$,

$$\delta\phi \simeq \frac{-g\frac{4\pi}{a^2}\int \mathrm{d}q\, q^2 \frac{\tilde{m}}{\varepsilon} f_0(q)\Psi_0(\vec{q}, \tau, \vec{k})}{(k/a)^2 + M_\phi^2 + M_T^2}$$

$$M_T^2 \equiv g^2 \int \mathrm{d}^3 p \frac{p^2}{[p^2 + \tilde{m}^2]^{3/2}} f_0(p)\,.$$

N. Afshordi, M. Zaldarriaga and K. Kohri, "On the stability of dark energy with mass-varying neutrinos," Phys. Rev. D **72**, 065024 (2005) arXiv:astro-ph/0506663.

See also Bjaelde et al, arXiv:0705.2018; Bean et al, arXiv:0709.1124; Beca and Avelino, arXiv:astro-ph/0507075; Kaplinghat and Rajaraman, arXiv:astro-ph/0601517 ...

There is a new attractive force, stronger than gravity: perturbations at scales $a/k \gtrsim 1/M$ are **unstable**.

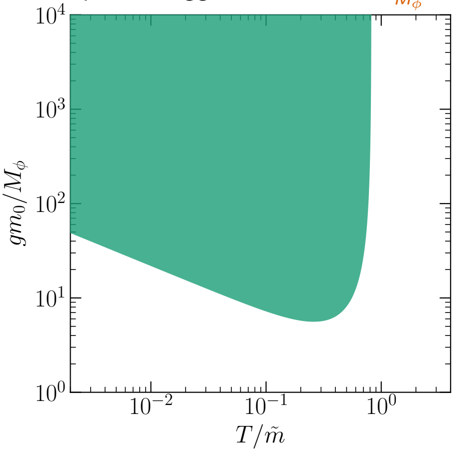
Ivan Esteban, Ohio State University
arXiv:2101.05804

Instability

N. Afshordi, M. Zaldarriaga and K. Kohri, "On the stability of dark energy with mass-varying neutrinos," Phys. Rev. D **72**, 065024 (2005) arXiv:astro-ph/0506663.

When they become non-relativistic, in a time $\ll \frac{1}{M_\phi}$, fermions will collapse in *nuggets* with size $\ll \frac{1}{M_\phi}$.
These will behave as dust, as no scalar field is left out.

- We have numerically verified this for a large fraction of parameter space (shaded).



Ivan Esteban, Ohio State University
arXiv:2101.05804

Instability

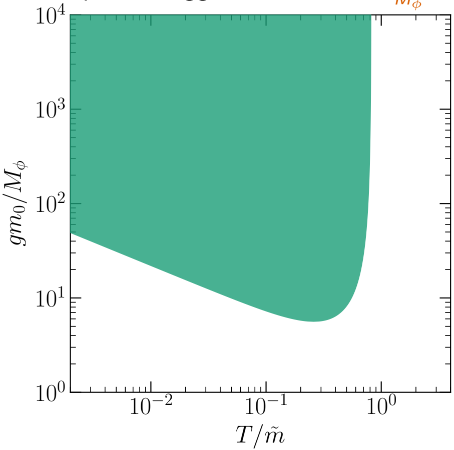
N. Afshordi, M. Zaldarriaga and K. Kohri, "On the stability of dark energy with mass-varying neutrinos," Phys. Rev. D **72**, 065024 (2005) arXiv:astro-ph/0506663.

When they become non-relativistic, in a time $\ll \frac{1}{M_\phi}$, fermions will collapse in *nuggets* with size $\ll \frac{1}{M_\phi}$. These will behave as dust, as no scalar field is left out.

- We have numerically verified this for a large fraction of parameter space (shaded).
- Nevertheless, as $M_\phi \gg H$, the involved scales are much smaller than cosmological scales!

  As $M_\phi \lesssim H$, we recover modified gravity

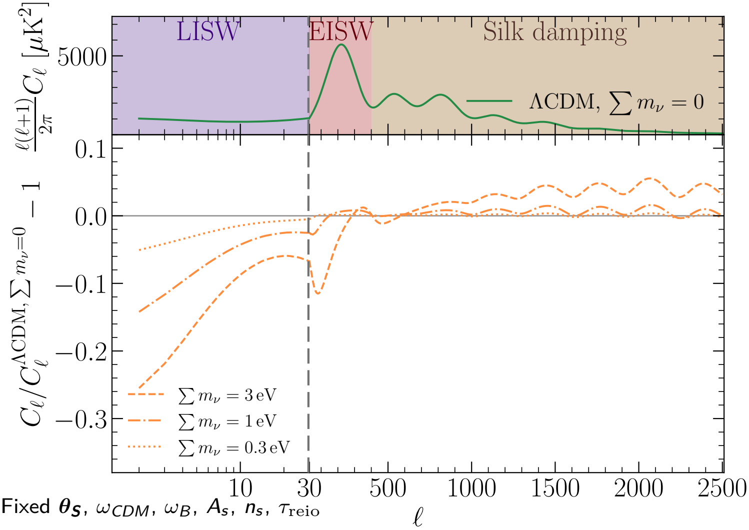
  For $m_0 \sim \mathrm{eV}$, $1/M_\phi \sim \mathrm{km} - \mathrm{pc} \sim 10^{-6}\,\mathrm{s} - \mathrm{year}$
- For the purpose of cosmological observables, we can assume an *instantaneous* transition to dust-like behaviour.



Backup: effects on CMB

Ivan Esteban, Ohio State University
arXiv:2101.05804

Neutrino masses



Fixed $\boldsymbol{\theta_s}$, ω_{CDM}, ω_B, A_s, n_s, τ_{reio}

J. Lesgourgues, G. Mangano, G. Miele, S. Pastor, Neutrino Cosmology (2013)

For fixed $\theta_s = \dfrac{\int_{z_{\text{rec}}}^{\infty} c_s \frac{dz'}{H(z')}}{\int_0^{z_{\text{rec}}} \frac{dz'}{H(z')}}$,

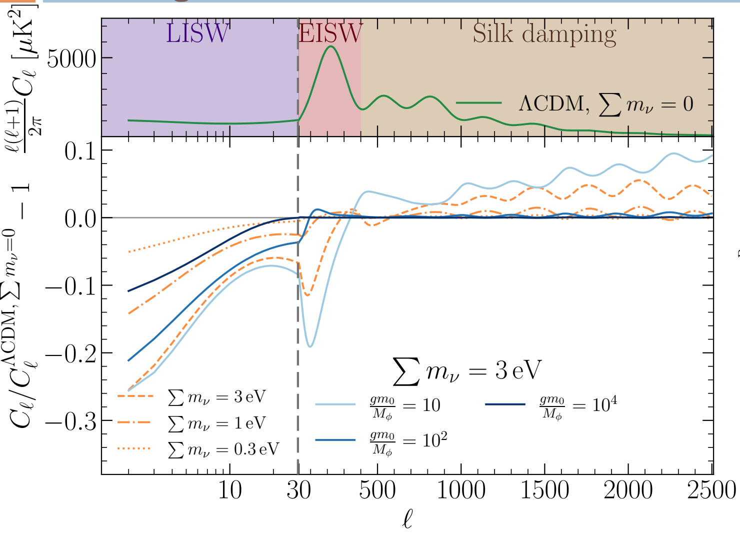
$\sum m_\nu \neq 0$ has 3 main effects:

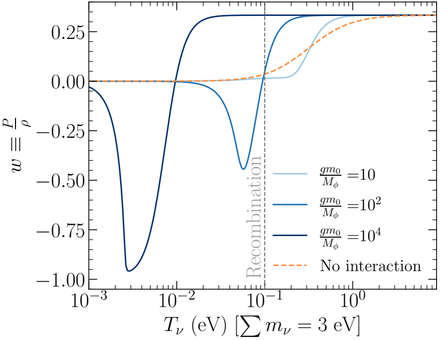
1. EISW, which directly tests the *equation of state*.
2. To keep θ_s fixed, H_0 decreases $\Rightarrow \Omega_\Lambda$ decreases $\Rightarrow$ less LISW.
3. $\theta_D \sim \dfrac{\sqrt{\int_{z_{\text{rec}}}^{\infty} \frac{1}{a n_e \sigma_T} \frac{dz'}{H(z')}}}{\int_0^{z_{\text{rec}}} \frac{dz'}{H(z')}}$

Backup: effects on CMB

Ivan Esteban, Ohio State University
arXiv:2101.05804

Adding the interaction

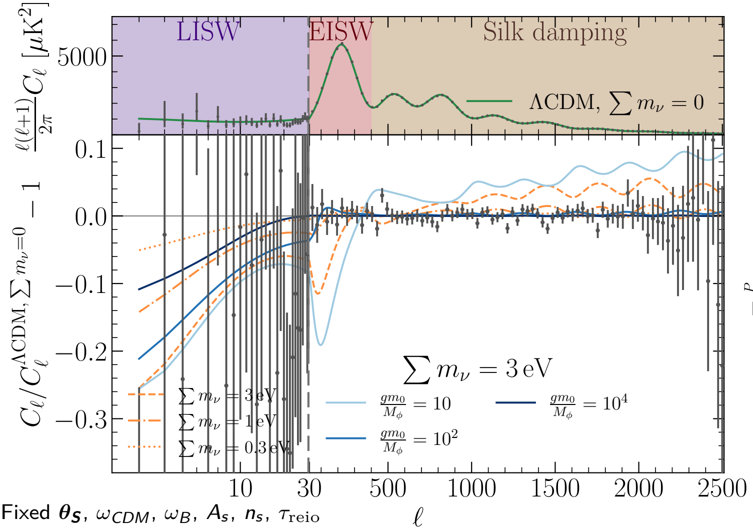




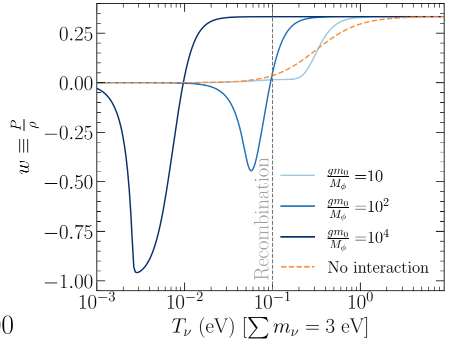
Fixed θ_s, ω_{CDM}, ω_B, A_s, n_s, τ_{reio}

Ivan Esteban, Ohio State University
arXiv:2101.05804

Data



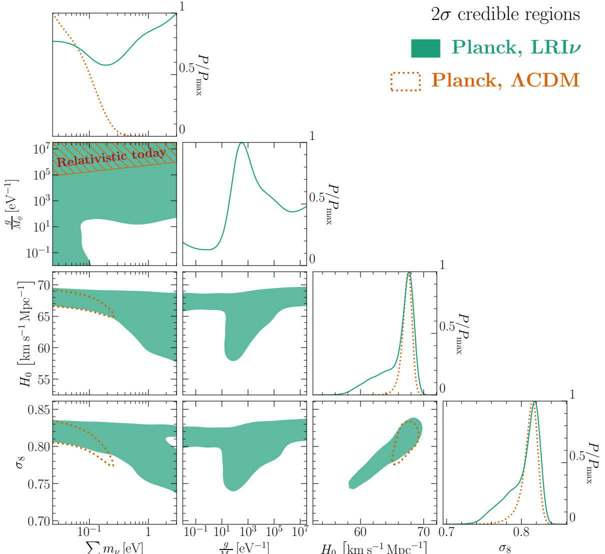
The Planck constraint will be essentially *behave like radiation for* $T > T_{\mathrm{rec}}$.



Fixed $\boldsymbol{\theta_s}$, ω_{CDM}, ω_B, A_s, n_s, τ_{reio}

Backup: results from Planck

Ivan Esteban, Ohio State University
arXiv:2101.05804



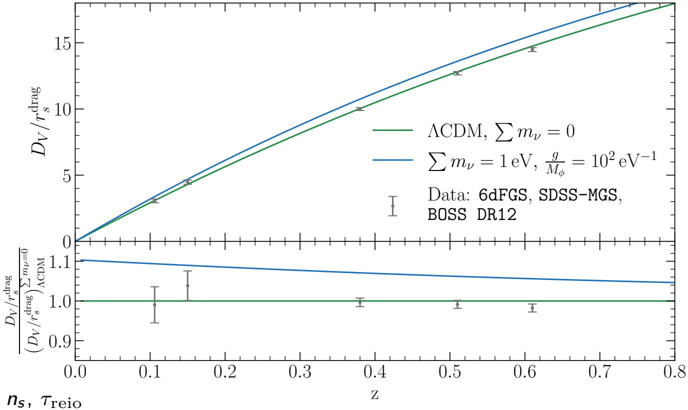
All the allowed region has essentially the same behavior before recombination: neutrinos with $w = 1/3$.

Backup: BAO constraints

Ivan Esteban, Ohio State University
arXiv:2101.05804

Data

BAO approximately measure $\frac{\int_{z_{\rm drag}}^{\infty} c_s \frac{\mathrm{d}z'}{H(z')}}{\left[\frac{z}{H(z)}\left(\int_0^z \frac{\mathrm{d}z'}{H(z')}\right)^2\right]^{1/3}}$, sensitive to late-time evolution of H, i.e., to ρ.



Fixed $\boldsymbol{\theta_s}$, ω_{CDM}, ω_B, A_s, n_s, $\tau_{\rm reio}$

Future: Large Scale Structure

- As we have seen, late-time probes can efficiently explore neutrino long-range interactions.

- This decade, we expect precise LSS probes of the matter power spectrum!

L. Amendola *et al.* [Euclid Theory WG], "Cosmology and fundamental physics with the Euclid satellite," arXiv:1606.00180.

R. Maartens *et al.* [SKA Cosmology SWG], "Overview of Cosmology with the SKA," arXiv:1501.04076.

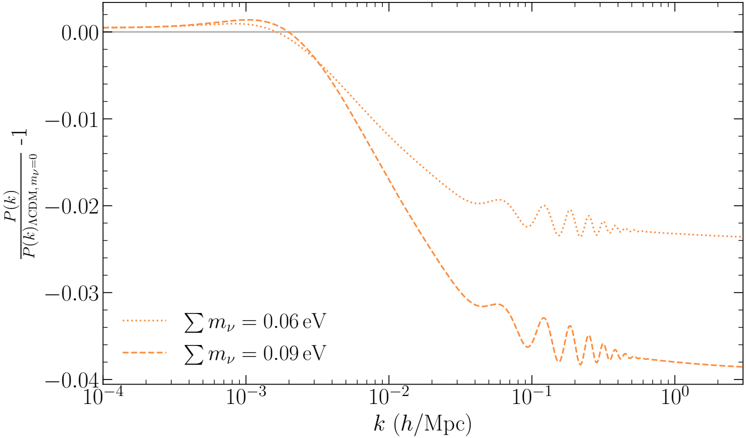
J. Pritchard *et al.* [Cosmology-SWG and EoR/CD-SWG], "Cosmology from EoR/Cosmic Dawn with the SKA," arXiv:1501.04291.

P. A. Abell *et al.* [LSST Science and LSST Project], "LSST Science Book, Version 2.0," arXiv:0912.0201.

T. Sprenger *et al.*, "Cosmology in the era of Euclid and the Square Kilometre Array," arXiv:1801.08331.

Ivan Esteban, Ohio State University
arXiv:2101.05804

Impact on matter power spectrum



$\sum m_\nu \neq 0$ has two main effects:

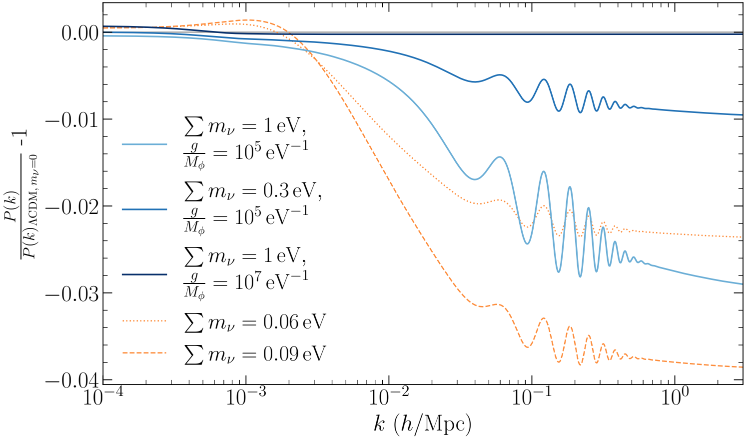
1. Small enhancement at $k \sim 10^{-3}\ h/\mathrm{Mpc}$, due to clustering.
2. Suppression at large k, as for $w < 1/3$ neutrinos redshift slower and contribute more to Hubble friction.

Sensitive to energy density in neutrinos and **equation of state**!

Fixed Ω_M, ω_{CDM}, ω_B, A_s, n_s, τ_{reio}. $z = 0$.

Ivan Esteban, Ohio State University
arXiv:2101.05804

Impact on matter power spectrum



Fixed Ω_M, ω_{CDM}, ω_B, A_s, n_s, τ_{reio}. $z = 0$.

$\sum m_\nu \neq 0$ has two main effects:

1. Small enhancement at $k \sim 10^{-3}\, h/\text{Mpc}$, due to clustering.
2. Suppression at large k, as for $w < 1/3$ neutrinos redshift slower and contribute more to Hubble friction.

Sensitive to energy density in neutrinos and **equation of state**!