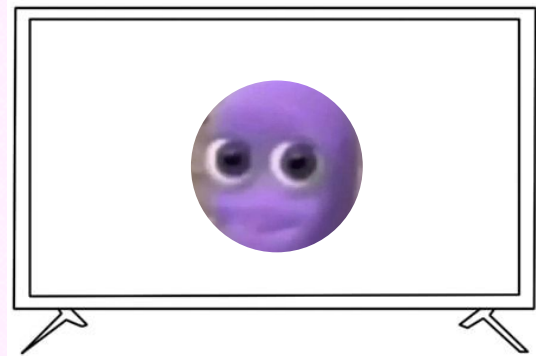
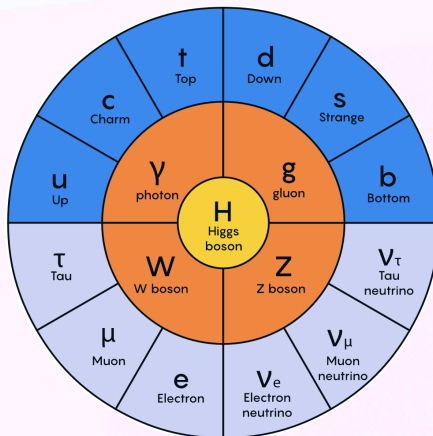


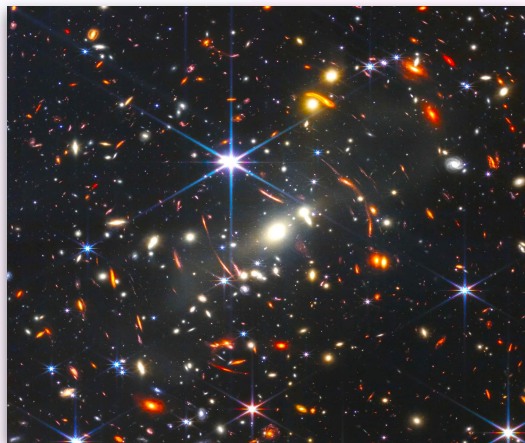
# Scalar-tensor theories

## from a particle's perspective



# Scalar interactions

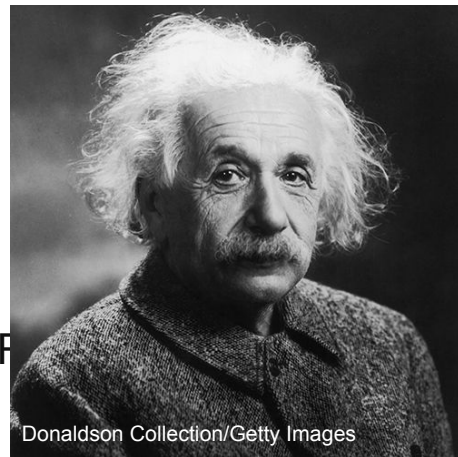
## from a cosmologist's perspective



# Why would we need to extend our models?

There are many problems to choose from with GR and the Standard Model

- The cosmological constant.
- What is dark matter.
- The early universe (Inflation, phase transitions)
- The coincidence problem, Hubble tension, DESI!!!, Strong CP



**Pick your favourite!**

# Why would we need to extend our models?

Some of these problems require an extension of the Standard Model:

**Standard Model**  $\longrightarrow$  **Beyond the Standard Model theories (BSM)**

Axion, inflation, quintessence...

But in this talk we will focus on theories that instead modify the gravitational action

**Standard Einstein-Hilbert action**  $\longrightarrow$  **New Modified gravity (?)**

$$S = \int d^4x \sqrt{-g} \left[ -\frac{M_{\text{pl}}^2}{2} R + \mathcal{L}_{\text{m}}\{\psi_i, \phi_i, g_{\mu\nu}, \dots\} \right]$$



# Why would we need to extend our models?

In most minimal cases, we find

**Beyond the Standard Model = Modified gravity**

$$S = \int d^4x \sqrt{-g} \left[ -\frac{M_{\text{pl}}^2}{2} R + \mathcal{L}_{\text{m}}\{\psi_i, \phi_i, g_{\mu\nu}, \dots\} \right]$$

We can use particle physics to constrain scalar-tensor theories

# Modified gravity = BSM

As an example, let's study the simplest modified theory of gravity

## Brans-Dicke Action:

$$S = \int d^4x \sqrt{-g} \left[ -\frac{F(\varphi)}{2} R + \frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi - U(\varphi) + \mathcal{L}_m \{ \psi_i, \phi_i, g_{\mu\nu}, \dots \} \right]$$

Matter action  
↙

$$F(v_\varphi) \equiv M_{\text{pl}}^2$$

# Modified gravity = BSM

The common way of solving this called [Transforming to the Einstein frame](#)

Make a conformal transformation such that gravity becomes canonical

$$g_{\mu\nu} \rightarrow \frac{\tilde{M}_{\text{Pl}}^2}{F(\varphi)} \tilde{g}_{\mu\nu}, \quad g^{\mu\nu} \rightarrow \frac{F(\varphi)}{\tilde{M}_{\text{Pl}}^2} \tilde{g}^{\mu\nu},$$

$$S_{\text{EF}} = \int d^4x \sqrt{-\tilde{g}} \left[ -\frac{\tilde{M}_{\text{Pl}}^2}{2} \tilde{R} + \frac{\tilde{M}_{\text{Pl}}^2}{2} \left[ \frac{1}{F(\varphi)} + \frac{3F'(\varphi)^2}{2F(\varphi)^2} \right] \tilde{g}^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi \right. \\ \left. - \frac{\tilde{M}_{\text{Pl}}^4}{F(\varphi)^2} U(\varphi) + \mathcal{L}_m\{\psi_i, \phi_i, \varphi, \tilde{g}_{\mu\nu}, \dots\} \right]$$

Standard gravity

Beyond the Standard Model matter sector

# Matter sector:

As an example, let's see how this affects a QED+Higgs singlet model:

$$\begin{aligned}
 S_m[g_{\mu\nu}] = \int d^4x \sqrt{-g} & \left[ \overbrace{-\frac{1}{4} g^{\alpha\mu} g^{\beta\nu} F_{\alpha\beta} F_{\mu\nu}}^{\text{Photon}} + \overbrace{\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi}^{\text{Higgs}} \right. \\
 & \left. + i\bar{\psi} e_a^\mu \gamma^a \partial_\mu \psi + \frac{1}{2} \bar{\psi} e_a^\mu \gamma^a \Omega_\mu \psi - q \bar{\psi} e_a^\mu \gamma^a A_\mu \psi \right. \\
 & \left. - \overbrace{y \bar{\psi} \phi \psi}^{\text{Fermion}} + \overbrace{\frac{1}{2} \mu^2 \phi^2 - \frac{\lambda}{4!} \phi^4 - \frac{3\mu^4}{2\lambda}}^{\text{Higgs}} \right],
 \end{aligned}$$

# Matter sector:

$$\tilde{\chi} = \int d\hat{\chi} \sqrt{1 + \tilde{\phi}^2 \left( \frac{A'(\hat{\chi})}{A(\hat{\chi})} \right)^2}$$

Making further redefinitions to canonically normalize the kinetic terms:

$$\phi \rightarrow A^{-1}(\chi) \tilde{\phi},$$

$$\psi \rightarrow A^{-3/2}(\chi) \tilde{\psi}$$

$$S_m[\tilde{g}_{\mu\nu}] = \int d^4x \sqrt{-\tilde{g}} \left[ -\frac{\tilde{M}_{\text{Pl}}^2}{2} \tilde{R} + \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\chi} \partial_\nu \tilde{\chi} - \tilde{V}(\tilde{\chi}) \right]$$

$A^2(\chi) = \tilde{M}_{\text{Pl}}^2 / F(\varphi(\chi))$   
Higgs

Photon

$$-\frac{1}{4} \tilde{g}^{\alpha\mu} \tilde{g}^{\beta\nu} F_{\alpha\beta} F_{\mu\nu} + \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\phi} \partial_\nu \tilde{\phi} - \frac{\tilde{A}'(\tilde{\chi})}{\tilde{A}(\tilde{\chi})} \tilde{\phi} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\chi} \partial_\nu \tilde{\phi}$$

Fermion

$$+ i \tilde{\psi} \tilde{e}_a^\mu \gamma^a \partial_\mu \tilde{\psi} + \frac{1}{2} \tilde{\psi} \tilde{e}_a^\mu \gamma^a \tilde{\Omega}_\mu \tilde{\psi} - q \tilde{\psi} \tilde{e}_a^\mu \gamma^a A_\mu \tilde{\psi}$$

$$- y \tilde{\psi} \tilde{\phi} \psi + \left( \frac{1}{2} \mu^2 \tilde{A}^2(\tilde{\chi}) \tilde{\phi}^2 - \frac{\lambda}{4!} \tilde{\phi}^4 - \tilde{A}^4(\tilde{\chi}) \frac{3\mu^4}{2\lambda} \right) \Big], \quad \text{Higgs}$$

# Matter sector:

$$S_m[\tilde{g}_{\mu\nu}] = \int d^4x \sqrt{-\tilde{g}} \left[ -\frac{\tilde{M}_{\text{Pl}}^2}{2} \tilde{R} + \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\chi} \partial_\nu \tilde{\chi} - \tilde{V}(\tilde{\chi}) \right. \quad \text{Higgs}$$

Photon

$$\left. -\frac{1}{4} \tilde{g}^{\alpha\mu} \tilde{g}^{\beta\nu} F_{\alpha\beta} F_{\mu\nu} + \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\phi} \partial_\nu \tilde{\phi} - \frac{\tilde{A}'(\tilde{\chi})}{\tilde{A}(\tilde{\chi})} \tilde{\phi} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\chi} \partial_\nu \tilde{\phi} \right.$$

Fermion

$$\left. + i \bar{\psi} \tilde{e}_a^\mu \gamma^a \partial_\mu \tilde{\psi} + \frac{1}{2} \bar{\psi} \tilde{e}_a^\mu \gamma^a \tilde{\Omega}_\mu \tilde{\psi} - q \bar{\psi} \tilde{e}_a^\mu \gamma^a A_\mu \tilde{\psi} - y \bar{\psi} \tilde{\phi} \psi + \left( \frac{1}{2} \mu^2 \tilde{A}^2(\tilde{\chi}) \tilde{\phi}^2 - \frac{\lambda}{4!} \tilde{\phi}^4 - \tilde{A}^4(\tilde{\chi}) \frac{3\mu^4}{2\lambda} \right) \right], \quad \text{Higgs}$$

The extra scalar only couples to the scale dependent quantities!

Brans-Dicke type theories are equivalent to Higgs-portal terms

# Constraints:

$$\left( \frac{1}{2} \mu^2 \tilde{A}^2(\tilde{\chi}) \tilde{\phi}^2 - \frac{\lambda}{4!} \tilde{\phi}^4 - \tilde{A}^4(\tilde{\chi}) \frac{3\mu^4}{2\lambda} \right), \quad \text{Higgs}$$

These couplings introduce new dynamics into the matter sector (**fifth forces**)

The tightest constraints come from large scales (linear couplings):

-Solar system scales (Cassini spacecraft)

Bertotti et al. 2003

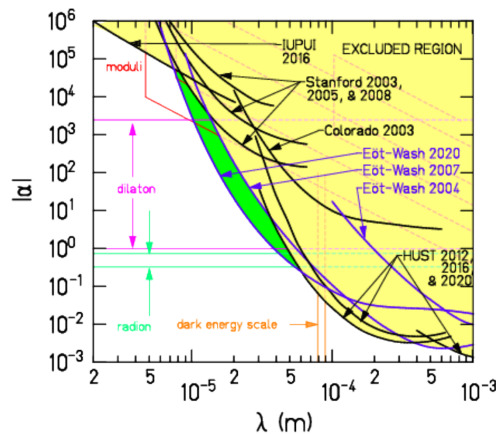
-See Annes talk for a great review

Burrage and Sakstein ( 1709.09071)



# Constraints:

$$\left( \frac{1}{2} \mu^2 \tilde{A}^2(\tilde{\chi}) \tilde{\phi}^2 - \frac{\lambda}{4!} \tilde{\phi}^4 - \tilde{A}^4(\tilde{\chi}) \frac{3\mu^4}{2\lambda} \right), \quad \text{Higgs}$$



$$V(r) = \frac{Gm_1m_2}{r} \left( 1 + \alpha e^{-r/\lambda} \right)$$

J. G. Lee, E. G. Adelberger, T. S. Cook,  
S. M. Fleischer, and B. R. Heckel (2020)



# Screening mechanisms:

Screening mechanisms help evading most of these bounds. Let's see how:

$$-y\bar{\psi}\tilde{\phi}\psi + \left( \frac{1}{2}\mu^2 \tilde{A}^2(\tilde{\chi}) \tilde{\phi}^2 - \frac{\lambda}{4!} \tilde{\phi}^4 - \tilde{A}^4(\tilde{\chi}) \frac{3\mu^4}{2\lambda} \right)$$

Don't assume that  $\tilde{A}(v_{\tilde{\chi}}) \approx 1$ , and find the effect on the Higgs vev ( $v_{\tilde{\phi}}$ ):

$$\frac{\lambda}{6} v_{\tilde{\phi}}^4 - \mu^2 v_{\tilde{\phi}}^2 \tilde{A}^2(v_{\tilde{\chi}}) + \rho_{\psi} = 0, \quad \rho_{\psi} = y v_{\tilde{\phi}} \bar{\psi} \psi$$

$$\tilde{A}'(v_{\tilde{\chi}}) \tilde{A}^3(v_{\tilde{\chi}}) \frac{6\mu^4}{\lambda} - \mu^2 v_{\tilde{\phi}}^2 \tilde{A}'(v_{\tilde{\chi}}) \tilde{A}(v_{\tilde{\chi}}) + \tilde{V}'(v_{\tilde{\chi}}) = 0,$$

# Screening mechanisms:

While  $\rho_\psi$  does not affect the Higgs' vev,  
it does affect  $\tilde{\chi}$

$$-y\bar{\psi}\tilde{\phi}\psi + \left( \frac{1}{2}\mu^2 \tilde{A}^2(\tilde{\chi})\tilde{\phi}^2 - \frac{\lambda}{4!}\tilde{\phi}^4 - \tilde{A}^4(\tilde{\chi})\frac{3\mu^4}{2\lambda} \right)$$

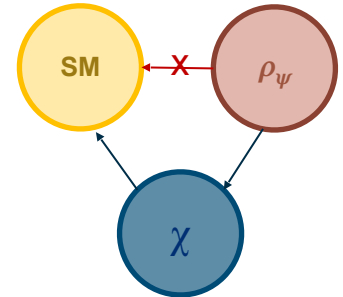
$$v_{\tilde{\phi}}^2 = \frac{v^2}{2} \tilde{A}^2(v_{\tilde{\chi}}) \left( 1 + \sqrt{1 - \frac{4\rho_\psi}{v^2\mu^2\tilde{A}^4(v_{\tilde{\chi}})}} \right)$$

$$\tilde{V}'(v_{\tilde{\chi}}) = -\frac{\tilde{A}'(v_{\tilde{\chi}})}{\tilde{A}(v_{\tilde{\chi}})}\rho_\psi,$$

$$v^2 = 6\mu^2/\lambda.$$

We therefore recover the usual screening equation for  $\chi$ .

The Higgs does not modify the screening, only enables it!



# Screening mechanisms:

From this, we can already see an important implication of screening mechanisms

Assuming

$$\rho_\psi \ll v^2 \mu^2 \tilde{A}^4(v_{\tilde{\chi}})$$

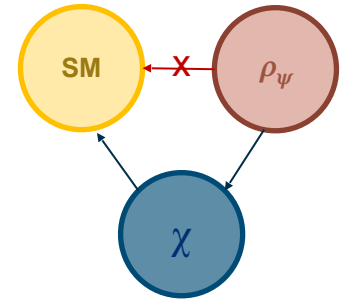
This means that the fermion's masses now rescale by:

$$m_\psi = y v_{\tilde{\phi}} \approx y \sqrt{\frac{6\mu^2}{\lambda}} \tilde{A}(v_{\tilde{\chi}})$$

Which from the vev equations we can see that it is density dependent!

$$\tilde{V}'(v_{\tilde{\chi}}) = -\frac{\tilde{A}'(v_{\tilde{\chi}})}{\tilde{A}(v_{\tilde{\chi}})} \rho_\psi$$

$$\tilde{V}'(v_{\tilde{\chi}}) = -\tilde{A}'(v_{\tilde{\chi}}) \rho$$



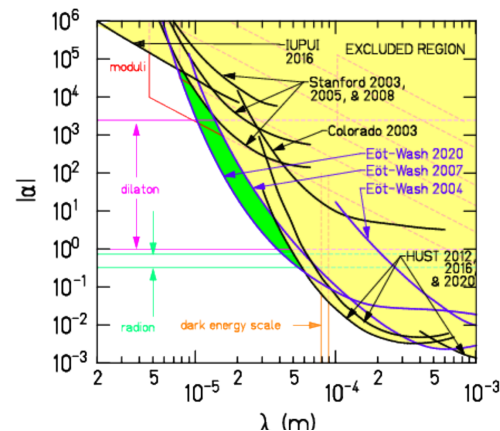
$$\rho = y v \tilde{\psi} \tilde{\psi}$$

# Screening mechanisms:

For every observable, we may always be able to hide the effects due to screening mechanisms

Nice paradox: It may be that the very own experiments we build to test for fifth forces are screening them away

Can we use screening in our advantage?



# Can we use screening in our advantage?

Yes!



Temporal evolution

Spatial variation

# Temporal evolution of masses

## Growing neutrinos and cosmological selection

C. Wetterich  
*Institut für Theoretische Physik  
Universität Heidelberg  
Philosophenweg 16, D-69120 Heidelberg*

## Cosmology of Mass-Varying Neutrinos Driven by Quintessence: Theory and Observations

A. W. Brookfield,<sup>1</sup> C. van de Bruck,<sup>2</sup> D. F. Mota,<sup>3</sup> and D. Tocchini-Valentini<sup>4</sup>

## Early dark energy from massive neutrinos — a natural resolution of the Hubble tension

Jeremy Sakstein\* and Mark Trodden<sup>†</sup>  
*Center for Particle Cosmology, Department of Physics and Astronomy,  
University of Pennsylvania 209 S. 33rd St., Philadelphia, PA 19104, USA*

## Coupled Quintessence

Luca Amendola  
*Osservatorio Astronomico di Roma,  
Viale Parco Mellini 84,  
00136 Roma, Italy  
amendola@oarhp1.rm.astro.it*

Many more with DESI!

# Temporal evolution of masses

## Misalignment from kicks: the impact of particle interactions on ultra-light dark matter

Clare Burrage<sup>1, \*</sup> and Sergio Seivillano Muñoz<sup>2, 3, †</sup>

<sup>1</sup>*School of Physics and Astronomy, University of Nottingham, University Park, Nottingham, NG7 2RD, UK*

<sup>2</sup>*Institute for Particle Physics Phenomenology, Durham University, South Road, DH1 3LE, Durham, UK*

<sup>3</sup>*Center for Particle Cosmology, Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*

Oscillating ultra-light scalar fields are a natural explanation for the dark matter in our universe, as long as a mechanism, often called a misalignment mechanism, exists to explain the amplitude of the scalar oscillations. If the dark matter scalar couples to the Standard Model, then the dynamics of ordinary matter can influence the behaviour of dark matter in the early universe. In this work we show how this changes the expected value of the scalar field, and the resulting amplitude of late time scalar oscillations, and therefore the abundance of dark matter at late times. For dark matter scalars that interact quadratically with Standard Model fields we derive estimates of the size of this effect as a function of the strength of the coupling, and for axion-like fields we show that interactions

Many more with DESI!

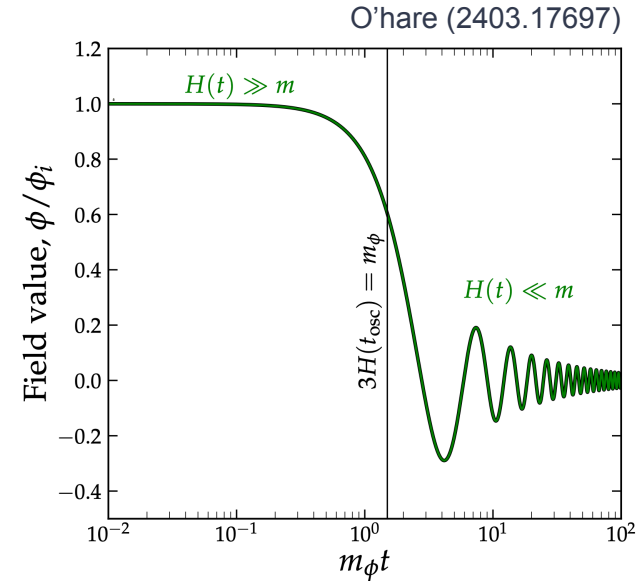
# Temporal evolution of masses

Recently we applied it to ultra-light scalar dark matter

$$\phi'' + \left(3 + \frac{H'}{H}\right) \phi' + \frac{m^2}{H^2} \phi = 0$$

The oscillations behave as dark matter

$$\langle \rho_\phi \rangle = \frac{1}{2} m^2 \langle \phi^2 \rangle$$



Abundance depends on initial conditions!



# Temporal evolution of masses

Can we change initial conditions with a kick?

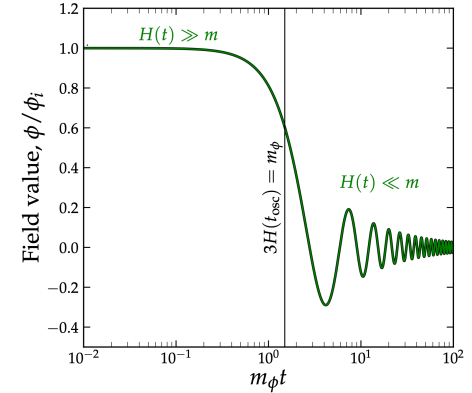
Couple to matter species:

$$\mathcal{L} \supset \frac{1}{2}(\nabla\phi)^2 - V(\phi) + i\bar{\psi}_i \not{\nabla} \psi_i - m_i(1 + A(\phi))\bar{\psi}_i\psi_i,$$

The equations of motion on-shell  $V(\phi) = \frac{\mu^2}{2}\phi^2$ ,  $A(\phi) = \frac{\beta}{2M_{\text{Pl}}^2}\phi^2$

$$\phi'' + \phi' \approx -\frac{\mu^2\phi}{H^2} - 3\beta\phi\Sigma(T_i)$$

Where  $\Sigma_i = (\rho_i - 3P_i)/\rho_R$   $\Sigma_i(T) = \frac{15}{\pi^4} \frac{g_i}{g_*(T)} \left( \frac{m_i^2}{T^2} \right) \int_{m_i/T}^{\infty} \frac{\sqrt{u^2 - (m_i/T)^2}}{e^u \pm 1} du$



# Temporal evolution of masses

Can we change initial conditions with a kick?

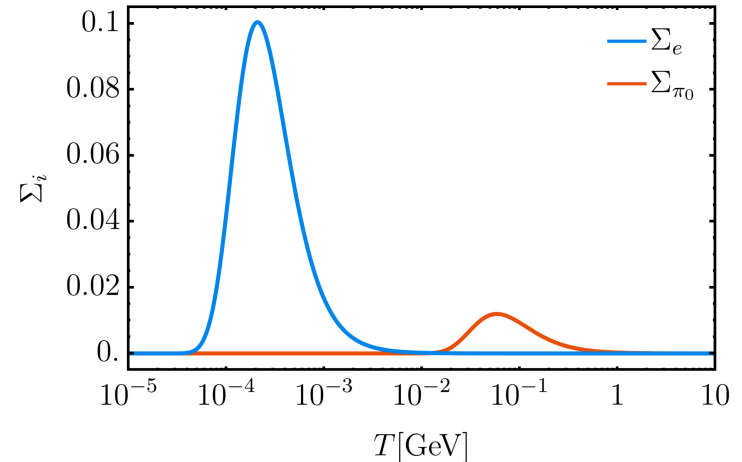
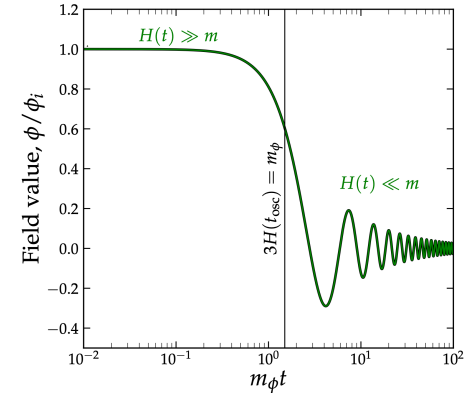
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The equations of motion on-shell

$$\phi'' + \phi' \approx -\frac{\mu^2 \phi}{H^2} - 3\beta\phi\Sigma(T_i)$$

Where  $\Sigma_i = (\rho_i - 3P_i)/\rho_R$



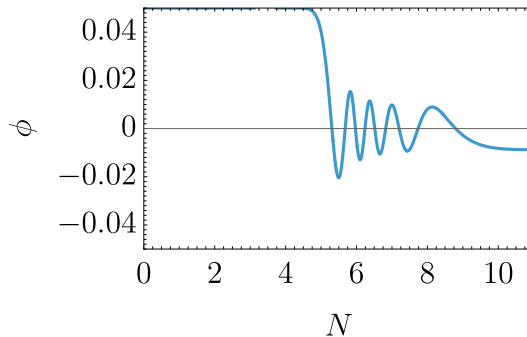
# Temporal evolution of masses

Can we change initial conditions with a kick?

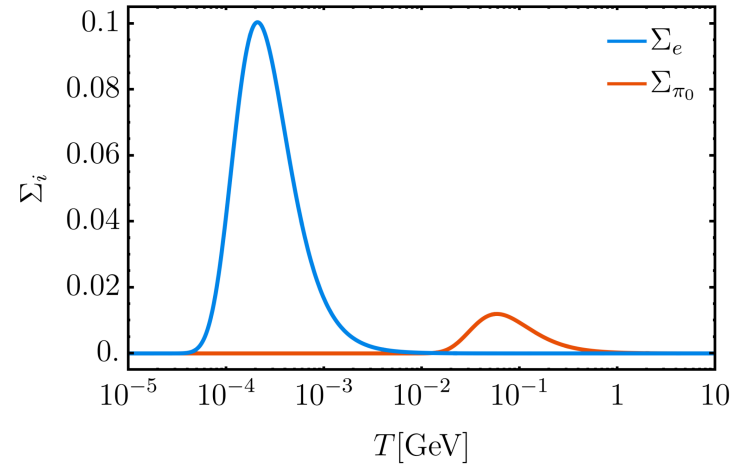
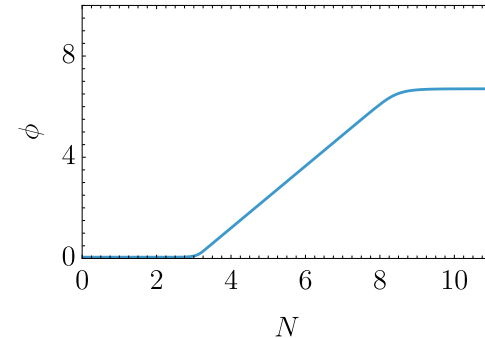
$$\phi'' + \phi' \approx -\frac{\mu^2 \phi}{H^2} - 3\beta \phi \Sigma(T_i)$$

If the kick occurs while it is frozen:

$$\beta > 0$$

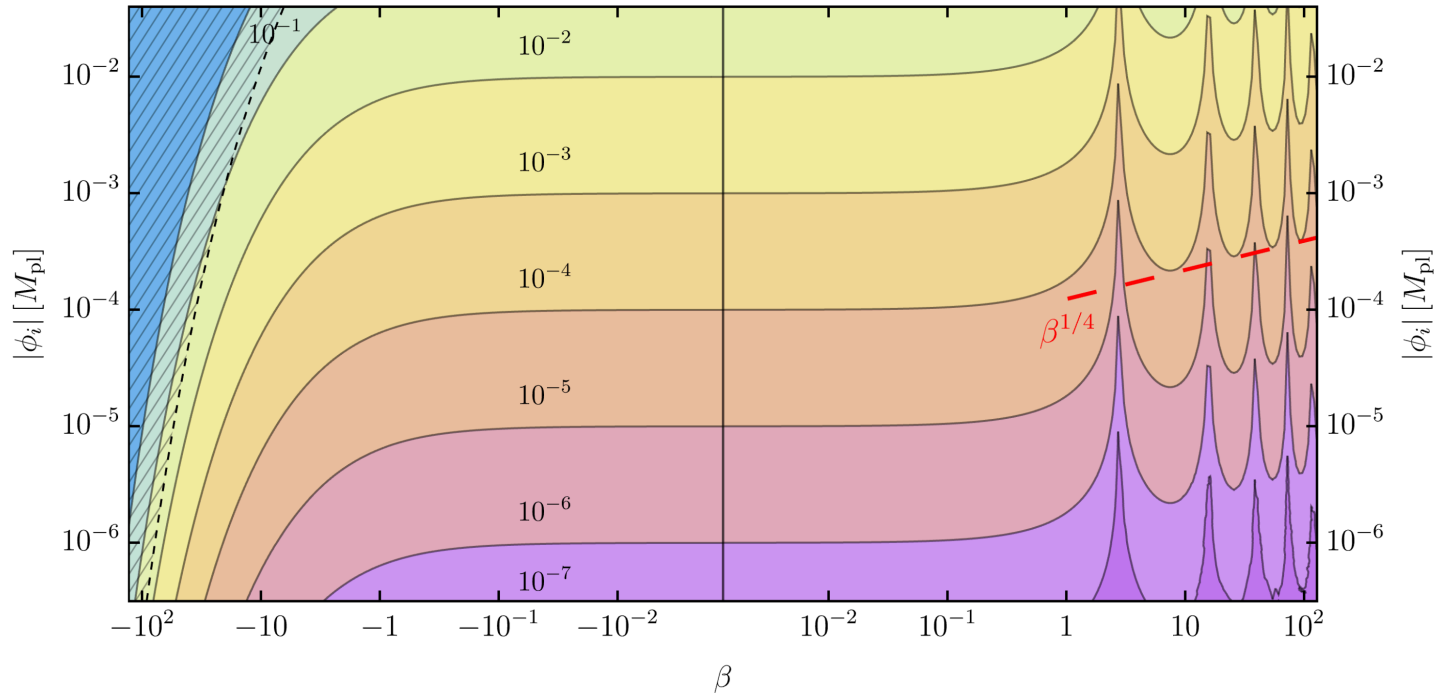


$$\beta < 0$$



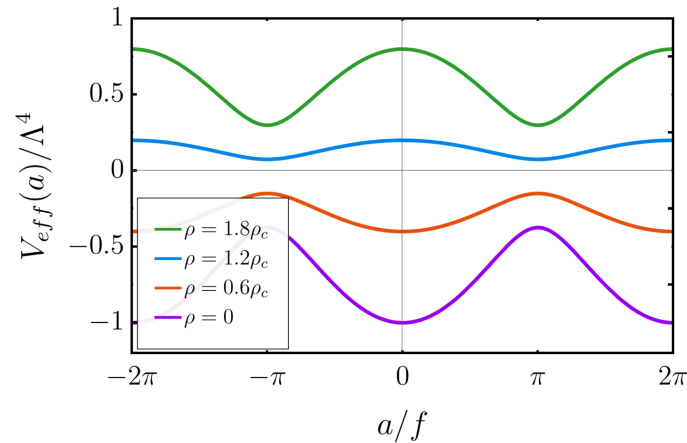
# Temporal evolution of masses

Can we change initial conditions with a kick?



# Temporal evolution of masses

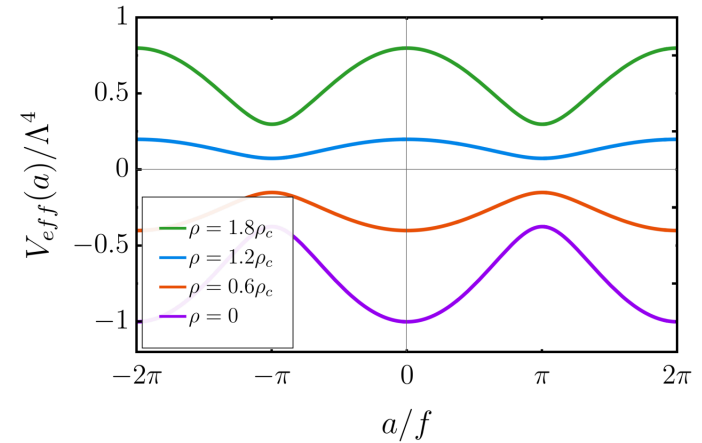
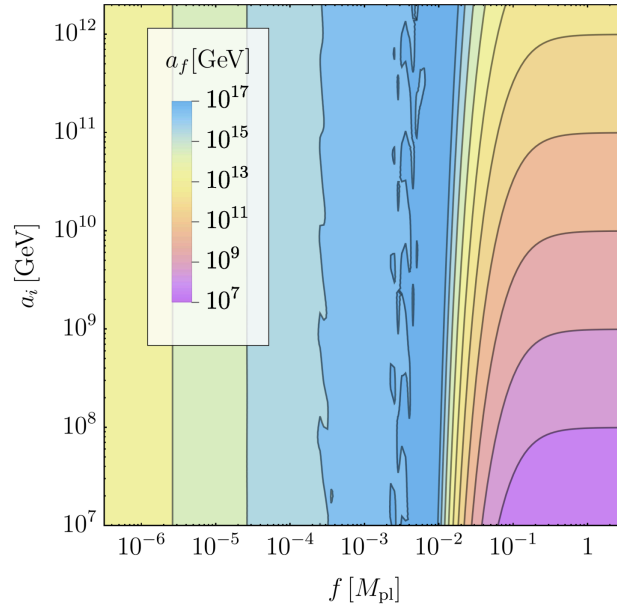
This is actually even cooler if we have a maximum in the potential, such as dark-QCD axion:



The kick is flips the effective potential for a while

# Temporal evolution of masses

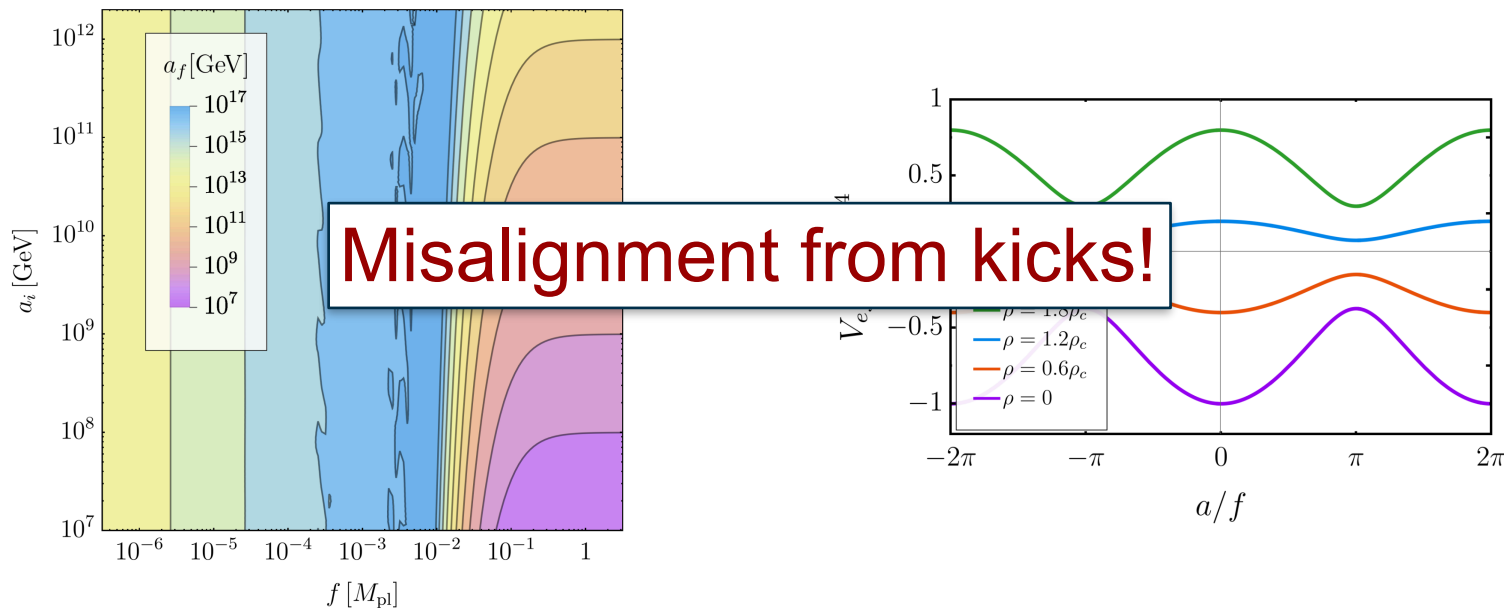
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# Temporal evolution of masses

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The kick is flips the effective potential for a while

# Spatial variation of masses



# Spatial variation of masses

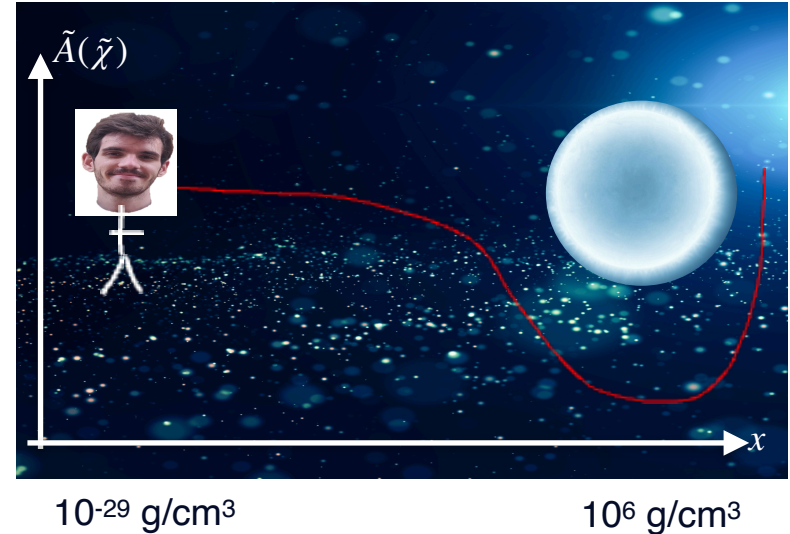
$$m_\psi = y v_{\tilde{\phi}} \approx y \sqrt{\frac{6\mu^2}{\lambda}} \tilde{A}(v_{\tilde{\chi}})$$

Only massive fields feel this interaction:

$$u^\alpha \nabla_\alpha p^\mu = -\partial^\mu m(\varphi)$$

$$p^\mu = m(\varphi) dx^\mu / d\tau$$

(assuming Einstein frame metric)



# Spatial variation of masses

$$m_\psi = y v_{\tilde{\phi}} \approx y \sqrt{\frac{6\mu^2}{\lambda}} \tilde{A}(v_{\tilde{\chi}})$$

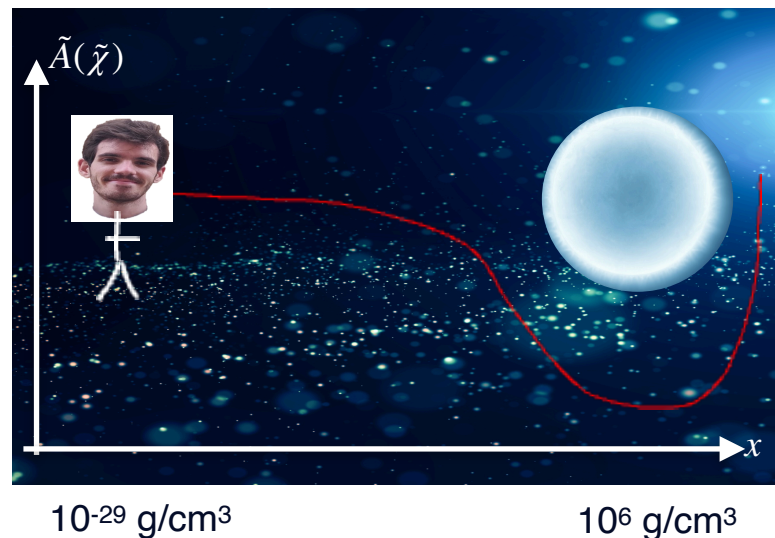
Only massive fields feel this interaction:

$$u^\alpha \nabla_\alpha p^\mu = -\partial^\mu m_\psi(\tilde{\chi})$$

$$p^\mu = m_\psi(\tilde{\chi}) \frac{dx^\mu}{d\tau}$$

(assuming Einstein frame metric)

If we can measure the time a particle takes to travel some distance, we can place bounds on their mass



**Best candidate?**

**Photons?**  
**Electrons?**

# Spatial variation:

IPPP/25/90

Only massive fields feature

## Neutrino Constraints on Scalar-Tensor Gravity

Arturo de Giorgi <sup>1,\*</sup> Ivan Martinez Soler <sup>1,†</sup> and Sergio Sevillano Muñoz <sup>1,2,‡</sup>  
<sup>1</sup>*Institute for Particle Physics Phenomenology, Durham University, South Road, DH1 3LE, Durham, UK*  
<sup>2</sup>*Center for Particle Cosmology, Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*

In this work, we derive novel constraints on scalar-tensor theories from neutrino physics. Spatial variations of the background scalar field effectively generate density and position-dependent Standard Model masses, including neutrinos. Neutrinos are a unicum in the SM due to their ability both to propagate over galactic distances and to traverse dense media such as Earth. This makes them an ideal probe of the background scalar field, which can in turn alter flavour oscillations and supernova time delays. As we enter the era of precision neutrino physics, we are compelled to explore such a scenario. We derive expressions for the relevant observables and obtain new bounds on a broad class of scalar-tensor models. We finally map the bounds to popular screening mechanisms models, such as the Symmetron and Chameleon.

If v  
dis

Use neutrinos!

# Neutrino observables

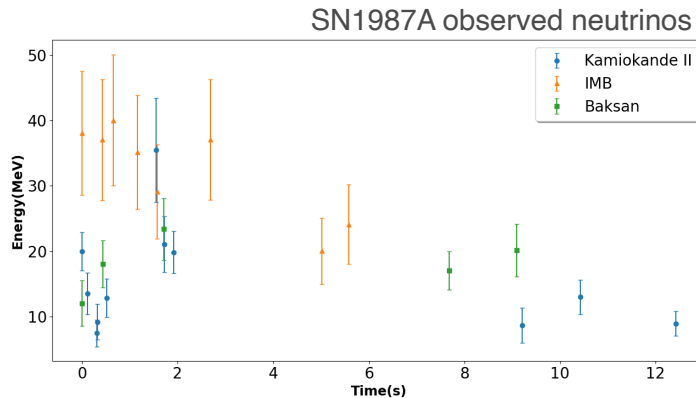
Neutrinos are generated in supernovae collapse ( $\sim 10^{51}$  per event)

$$e^- + p \rightarrow \nu_e + n$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$e^- + e^+ \rightarrow \bar{\nu}_\alpha + \nu_\alpha$$

Emitted at the same time, and calibrated using light!



# Neutrino observables

SSM (2407.08779)  
de Giorgi, Martinez Soler, SSM (2512.13798)

If masses shift there is a different arrival times for different energies

$$\Delta t_{21} \approx \frac{m_\nu^2}{2} \left( \frac{1}{E_2^2} - \frac{1}{E_1^2} \right) \int_{r_A}^{r_B} dr A(r)^2$$

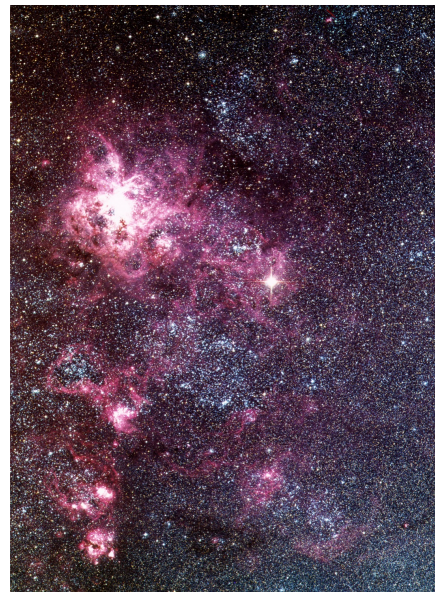
SN1987A observed neutrinos

We already have a bound on neutrino masses from this!

Loredo and Lamb (astro-ph/0107260)

$$M_{\text{lim}} \approx 5.8 \text{ eV}$$

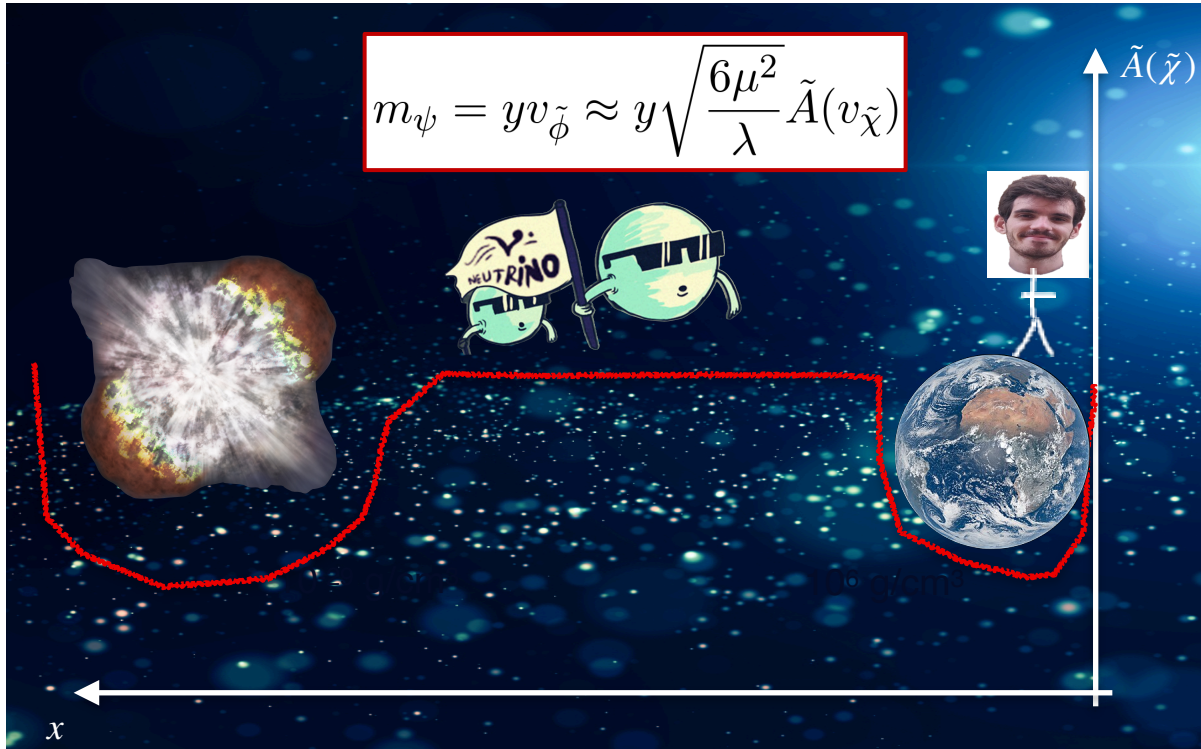
Using another independent local test of neutrino masses we can compare with any rescaling in “vacuum”



SN1987A

# Neutrino observables

We must improve this picture:





# Neutrino observables

We need to model the matter background

Dark matter halos

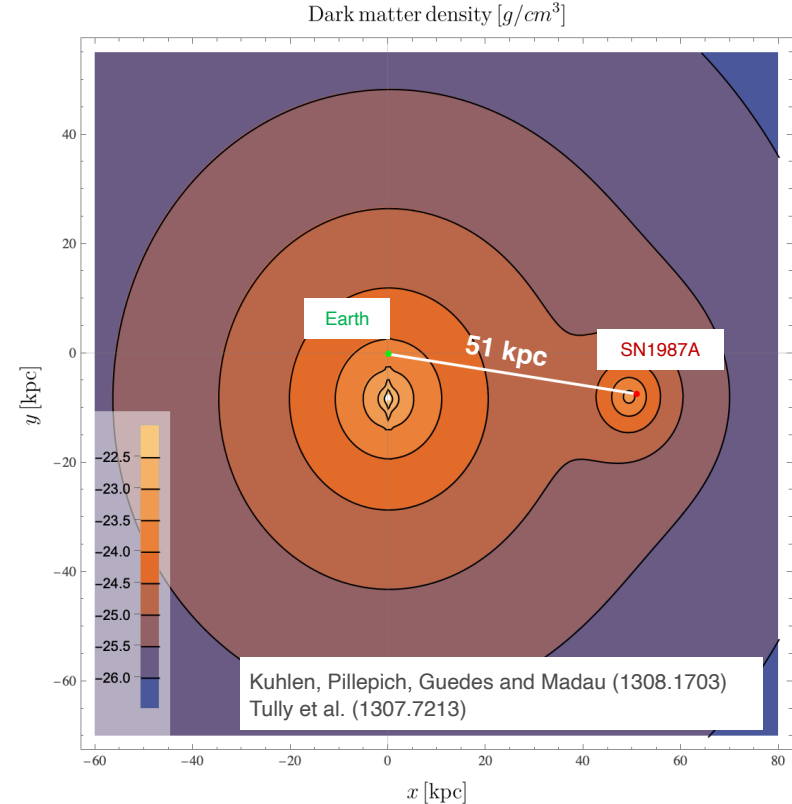
$$\rho_{\text{MW}}(x, y) = \frac{1.3 \times 10^{-24}}{\left(\frac{r}{20}\right) \left(1 + \frac{r}{20}\right)^2} \quad [\text{cm}^3/\text{g}]$$

$$\rho_{\text{LMC}}(x, y) = \frac{5 \times 10^{-24}}{\left(1 + \frac{r}{3}\right) \left(1 + \left(\frac{r}{3}\right)^2\right)} \quad [\text{cm}^3/\text{g}]$$

Baryonic matter

$$\rho_{\text{disk}}(x, y, z) = \frac{\Sigma_{\text{disk}}}{2 z_{\text{disk}}} \exp\left(-\frac{\sqrt{x^2 + y^2} \text{ kpc}}{R_{\text{disk}}}\right) \exp\left(-\frac{|z| \text{ kpc}}{z_{\text{disk}}}\right) \quad [\text{cm}^3/\text{g}]$$

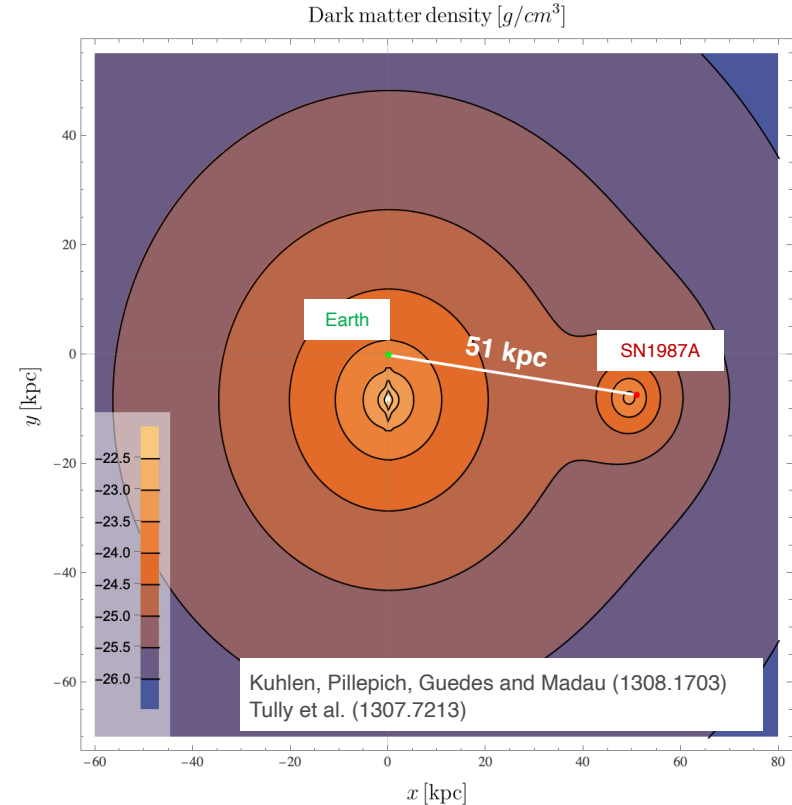
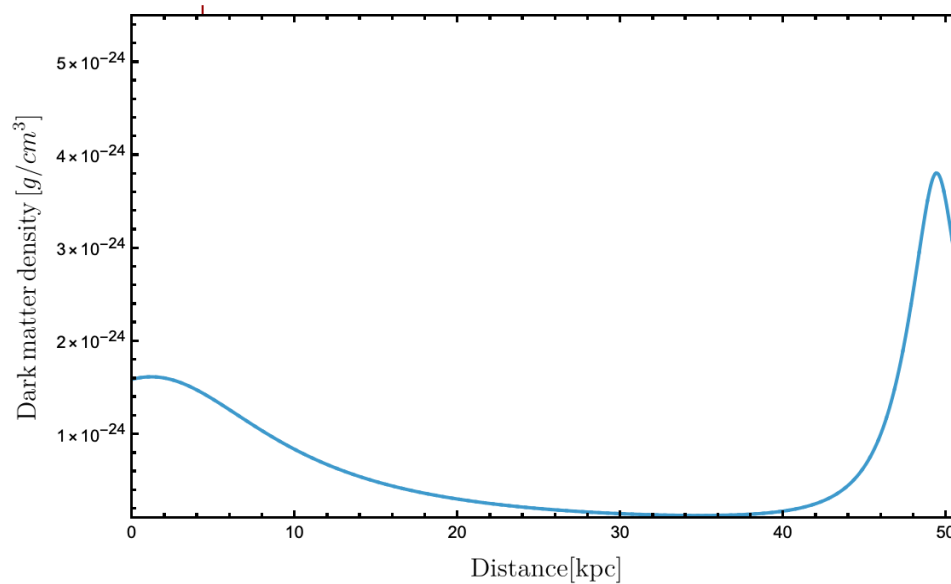
Tilted over 35deg over the plane



# Neutrino observables

SSM (2407.08779)  
de Giorgi, Martinez Soler, SSM (2512.13798)

First we need to model the matter background

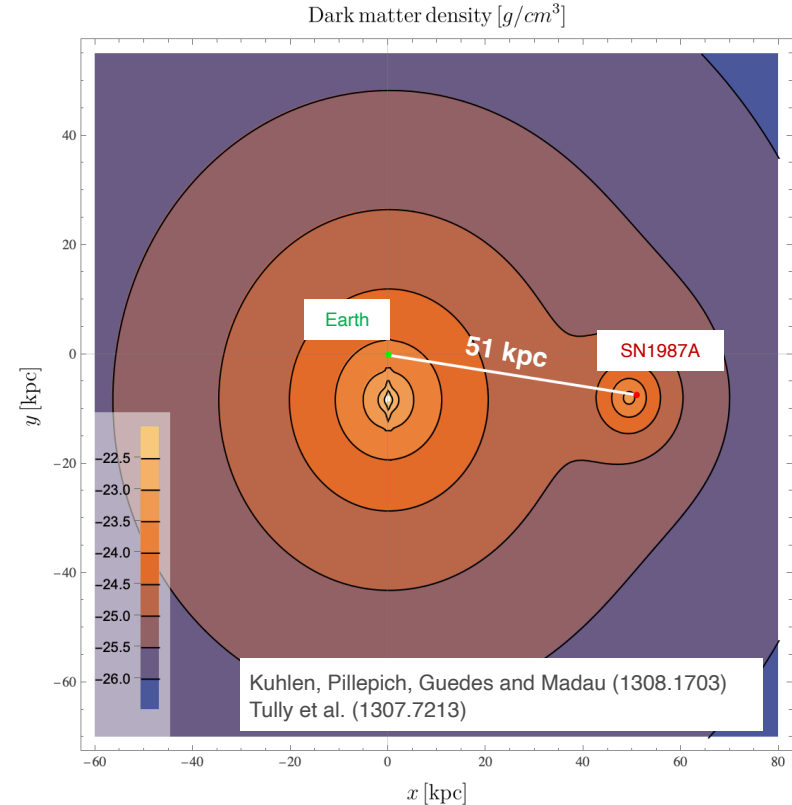
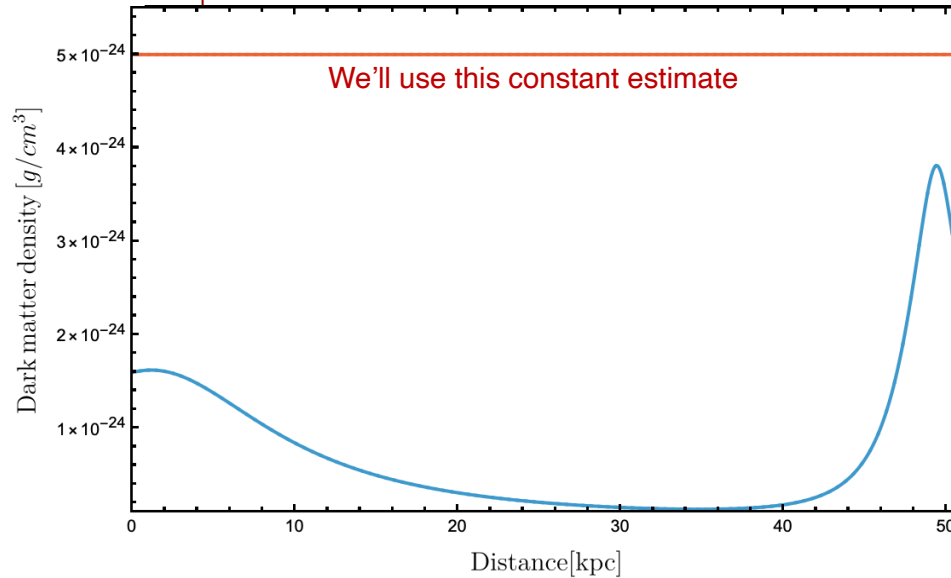




# Neutrino observables

SSM (2407.08779)  
de Giorgi, Martinez Soler, SSM (2512.13798)

First we need to model the matter background



# Neutrino observables

Time delay bounds can be obtained by solving

$$|A_\infty^2 m_0^2 - A_0^2 m_0^2| > M_{\text{lim}}^2$$

Mass in vacuum

Observed mass  
KATRIN (2406.13516)  
 $m_0 < 0.45 \text{ eV}$

Constraint  
(upper bound)

$$\Delta t_{21} \approx \frac{m_\nu^2}{2} \left( \frac{1}{E_2^2} - \frac{1}{E_1^2} \right)$$

Today:

$$M_{\text{lim}} \approx 5.8 \text{ eV}$$

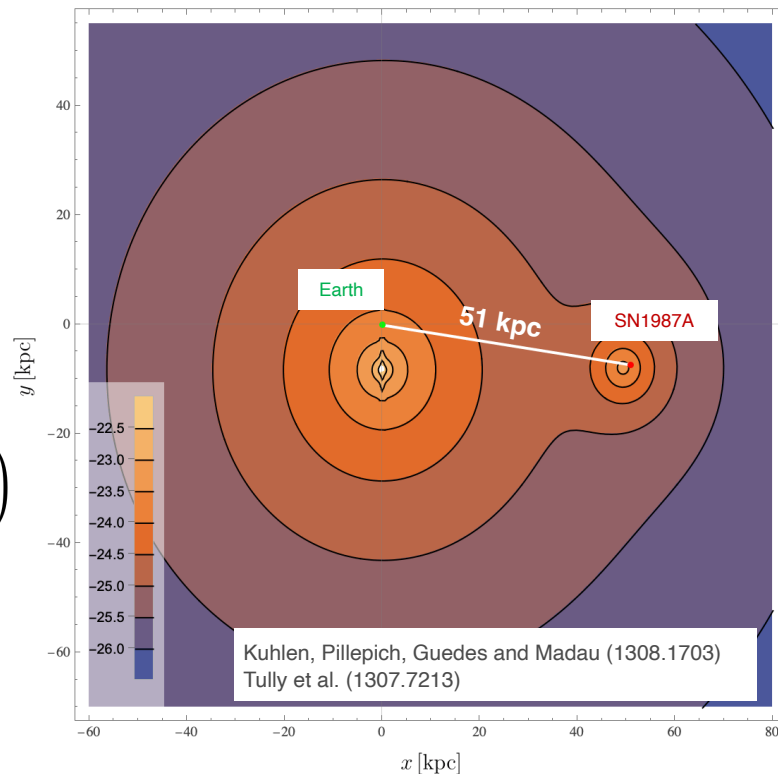
Future prospects:

$$M_{\text{lim}} \approx 0.06 \text{ eV}$$

Parker, Wurm (2311.10682)

SSM (2407.08779)  
de Giorgi, Martinez Soler, SSM (2512.13798)

Dark matter density [ $\text{g}/\text{cm}^3$ ]



March, Burrage and Naik (2409.10623)

# Neutrino observables

Neutrinos are special for more than just being weakly interacting

## Flavor distortion

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\psi(s)\rangle = U \exp(i\tilde{S}(s)) U^\dagger |\psi(0)\rangle$$

$$\tilde{S}(s) \equiv \int_0^s g_{\mu\nu} p^\mu dx^\nu$$

In vacuum:

$$\tilde{S}(s) \approx \frac{m^2}{2E} \int_0^s dr A(r)^2$$

In matter:

$$(i\gamma^\mu \partial_\mu + \gamma^\mu A_\mu + M)\psi = 0,$$

$$A^\mu = \text{diag}\left(-\sqrt{2}G_F N_e^\mu, 0, 0\right)$$

$$S(s) \approx \int_0^s dr A(r)^2 \left(\frac{M^2}{2E} + V_{\text{CC}}\right)$$

# Neutrino observables

What is “matter”?

$$(i\gamma^\mu \partial_\mu + \gamma^\mu A_\mu + M)\psi = 0,$$

$$A^\mu = \text{diag}\left(-\sqrt{2}G_F N_e^\mu, 0, 0\right)$$

$$S(s) \approx \int_0^s dr A(r)^2 \left( \frac{M^2}{2E} + V_{CC} \right)$$

-Number of electrons given by:  $n_e = n_p = \frac{\rho_{Earth}}{m_p}$

-Earth density obtained from seismic events.

-As particle physics is assumed to be SM-like

$$\rho_{\text{eff.}}(x) = \rho_E(x) A(x)^{-4} = \rho_J(x)$$

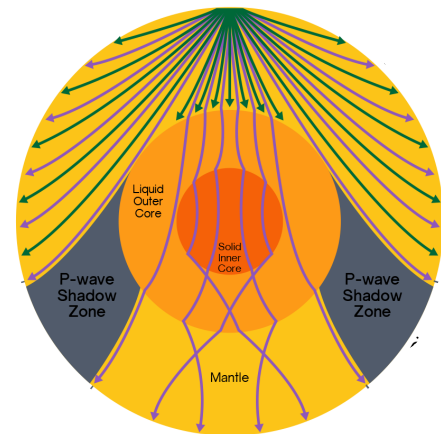
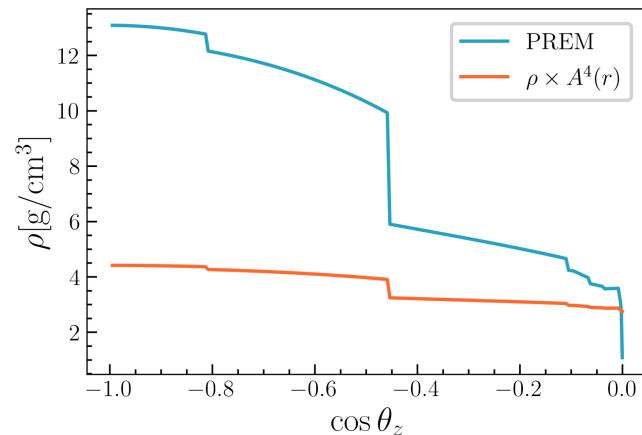


Image by Rachel D'Erminio for HarvardX



# Neutrino observables

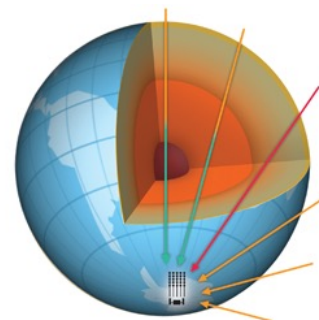
## Flavour distortion

When neutrinos travel through Earth they interact with electrons, which changes their flavour distribution once detected

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\psi_\alpha(s)\rangle = \exp\left(\frac{i}{2} \int_0^s A(r)^2 H_{\alpha\beta}(r) dr\right) |\psi_\beta\rangle$$

$$H = \underbrace{U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U^\dagger}_{\text{Free propagation}} + \underbrace{\begin{pmatrix} V_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}}_{\text{Interaction}}$$



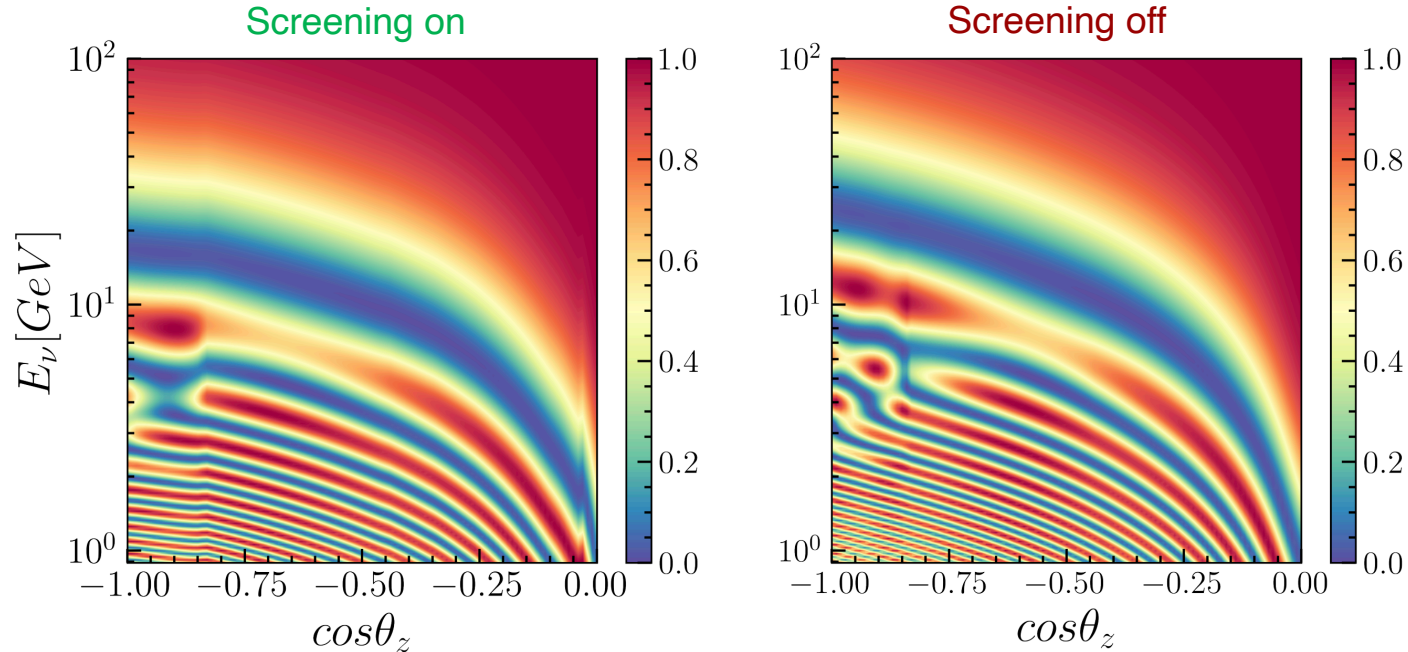
- The number of electrons in Earth will depend on the mass of particles
- Oscillation wavelength depends on neutrino masses

# Neutrino observables

## Flavour distortion

Survival probability of muon neutrino through Earth

$$|\psi_\alpha(s)\rangle = \exp\left(\frac{i}{2} \int_0^s A(r)^2 H_{\alpha\beta}(r) dr\right) |\psi_\beta\rangle$$

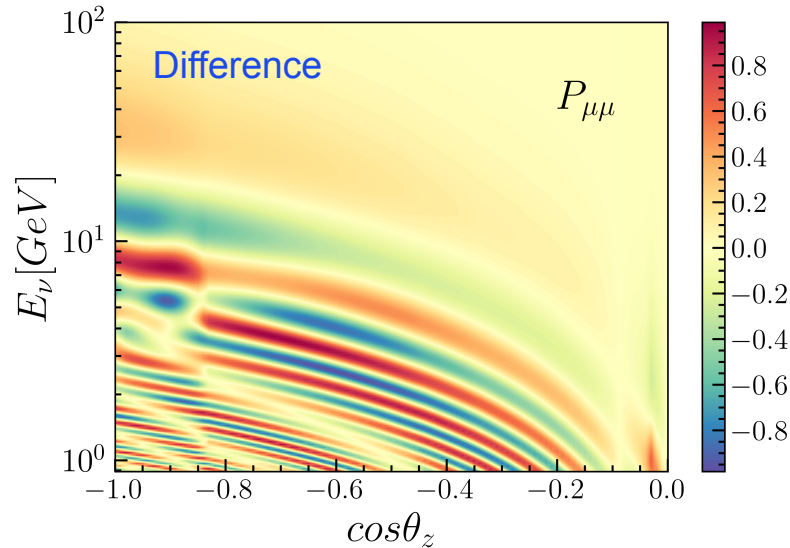


# Neutrino observables

## Flavour distortion

Survival probability of muon neutrino through Earth

$$|\psi_\alpha(s)\rangle = \exp\left(\frac{i}{2} \int_0^s A(r)^2 H_{\alpha\beta}(r) dr\right) |\psi_\beta\rangle$$

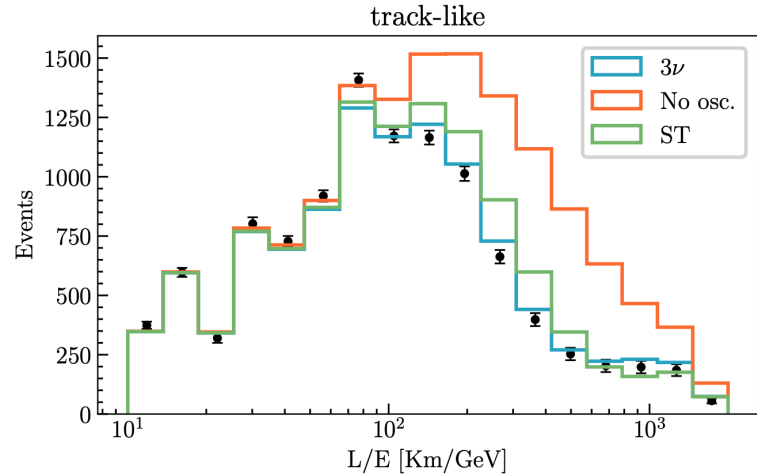
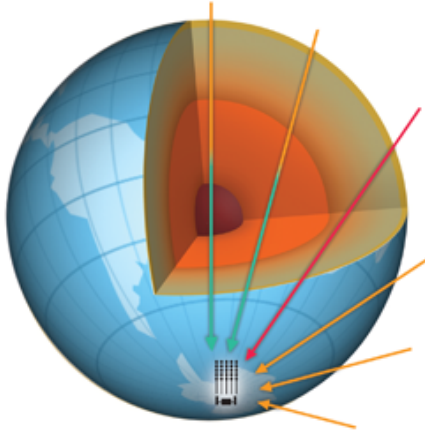


We (Ivan) placed constraints against 9.3 years of data from Icecube

# Neutrino observables

## Flavour distortion

To place bounds, we first modeled the Earth and then simulated the oscillations



We (Ivan) placed constraints against 9.3 years of data from IceCube

We just need to find  $A(r)$ , model dependent

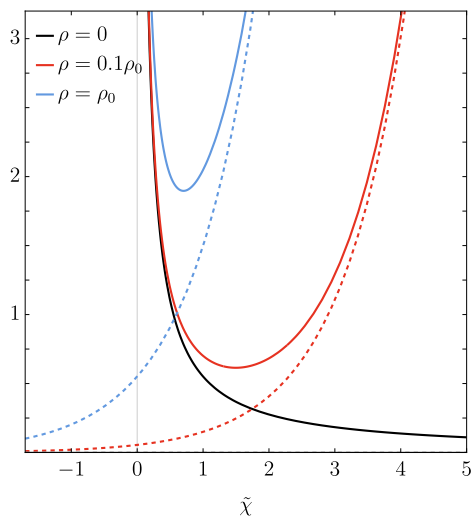


# Models:

$$V_{\text{eff}}(\tilde{\chi}) = \tilde{V}(\tilde{\chi}) + \tilde{A}(\tilde{\chi})\rho$$

**Chameleon:** Khoury, Weltman (0309411)

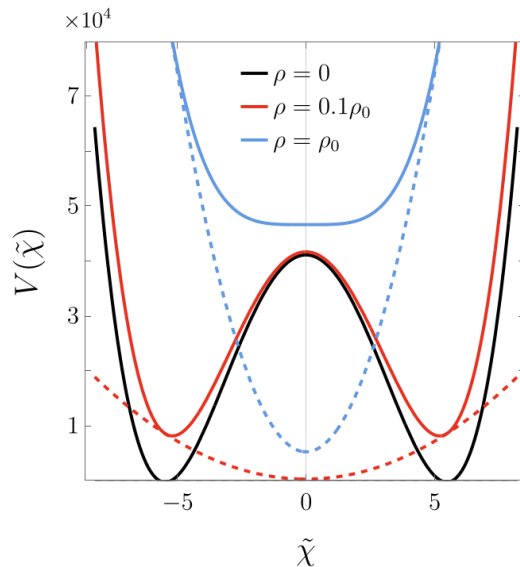
$$\tilde{A}(\tilde{\chi}) = e^{\frac{\tilde{\chi}}{M}}, \quad \tilde{V}(\tilde{\chi}) = \frac{\Lambda^{4+n}}{\tilde{\chi}^n}$$



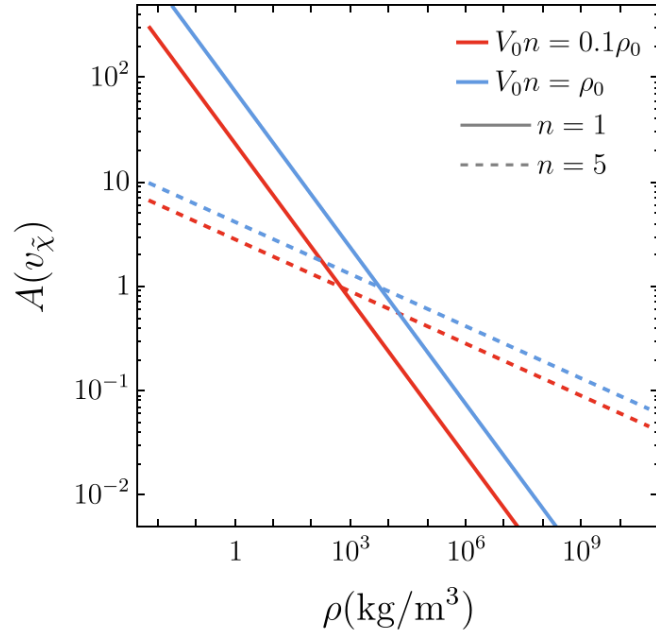
$$\rho_0 = 5.51 \times 10^3 \text{ kg/m}^3$$

**Symmetron:** Hitchbinder, Khoury, Levy and Matas (1107.2112)

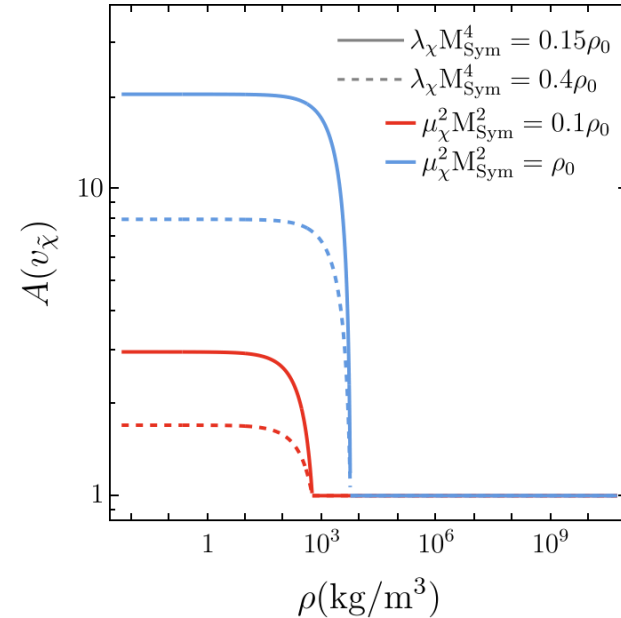
$$\tilde{V}(\tilde{\chi}) = -\frac{1}{2}\mu_\chi^2\tilde{\chi}^2 + \frac{\lambda_\chi}{4!}\tilde{\chi}^4 \quad \tilde{A}(\tilde{\chi}) = 1 + \frac{\tilde{\chi}^2}{2M_{\text{sym}}^2}$$



## Chameleon



## Symmetron



$$m_{\psi} = y v_{\tilde{\phi}} \approx y \sqrt{\frac{6\mu^2}{\lambda}} \tilde{A}(v_{\tilde{\chi}})$$

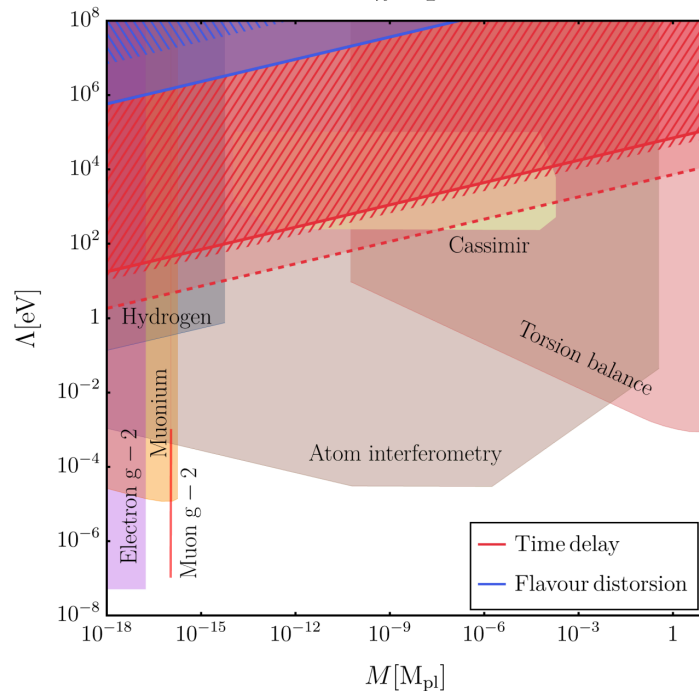
# Final constraints

SSM (2407.08779)  
de Giorgi, Martinez Soler, SSM (2512.13798)

$$A_{c,n}(\varphi) \approx 1 + \left( \frac{n\Lambda^{4+n}}{M_c^n \rho} \right)^{1/(n+1)}$$

## Chameleon

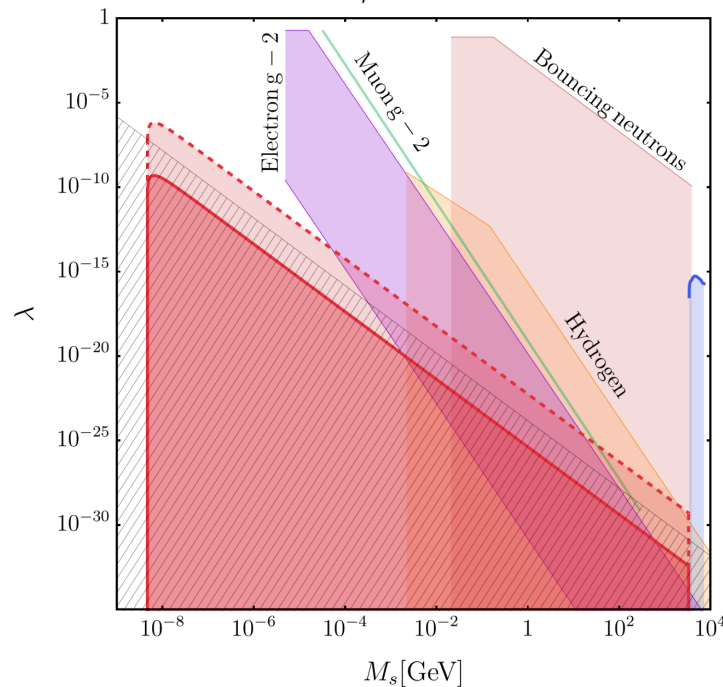
$n = 1$



$$A_s(\varphi) \approx 1 + \mu^2 \begin{cases} \frac{1-\rho/\rho_{\text{crit}}}{2\lambda M_s^2}, & \rho \leq \rho_{\text{crit}} \\ 0, & \rho > \rho_{\text{crit}} \end{cases}$$

## Symmetron

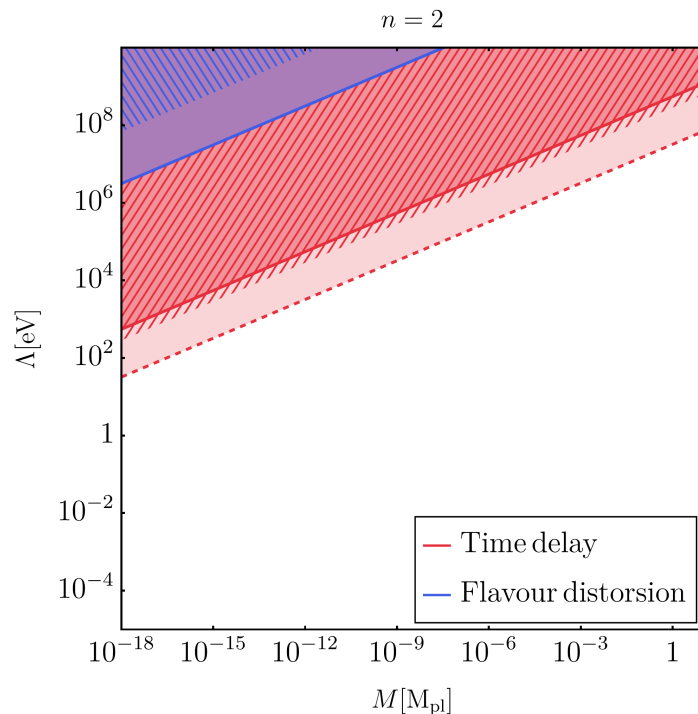
$\mu = \text{meV}$



# Final constraints

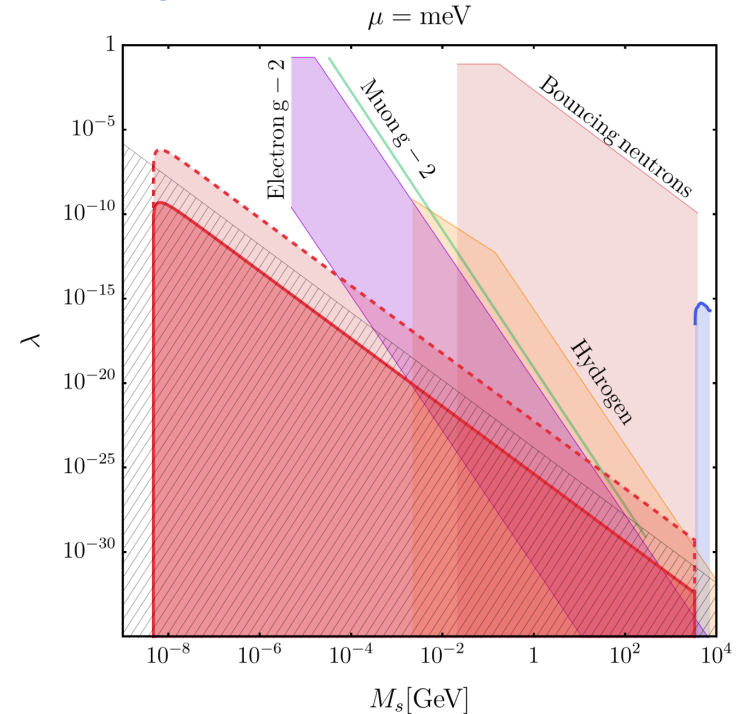
$$A_{c,n}(\varphi) \approx 1 + \left( \frac{n\Lambda^{4+n}}{M_c^n \rho} \right)^{1/(n+1)}$$

## Chameleon

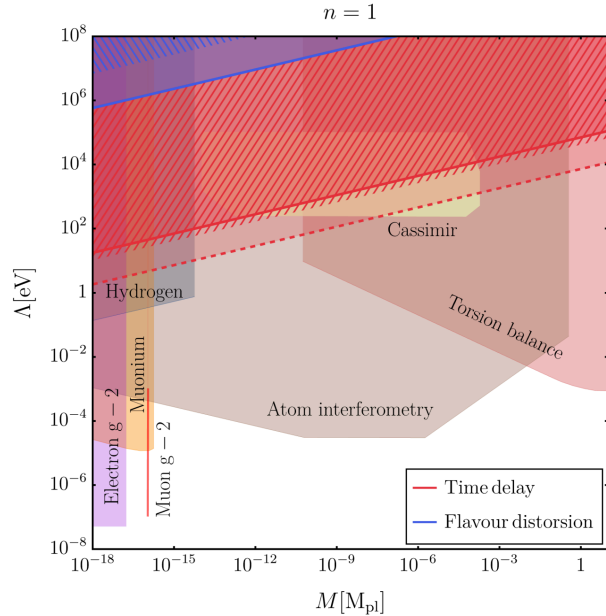


$$A_s(\varphi) \approx 1 + \mu^2 \begin{cases} \frac{1-\rho/\rho_{\text{crit}}}{2\lambda M_s^2}, & \rho \leq \rho_{\text{crit}} \\ 0, & \rho > \rho_{\text{crit}} \end{cases}$$

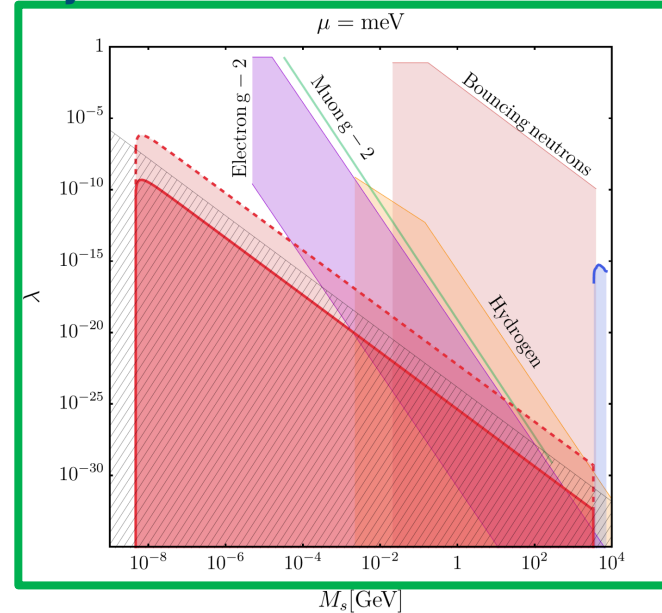
## Symmetron



## Chameleon



## Symmetron



Neutrinos are a better probe of Symmetron-like screenings

- In chameleon screening one can always do experiments within the Compton wavelength
- Neutrinos integrate over all its trajectory, so they are sensitive to any potential shape

## One last thing :)

# Unified dark sector approaches to cosmological tensions

**Sergio Sevillano Muñoz, Mark Trodden**

Center for Particle Cosmology, Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

E-mail: [sergiosm@sas.upenn.edu](mailto:sergiosm@sas.upenn.edu), [trodden@upenn.edu](mailto:trodden@upenn.edu)

29 Jul 2026

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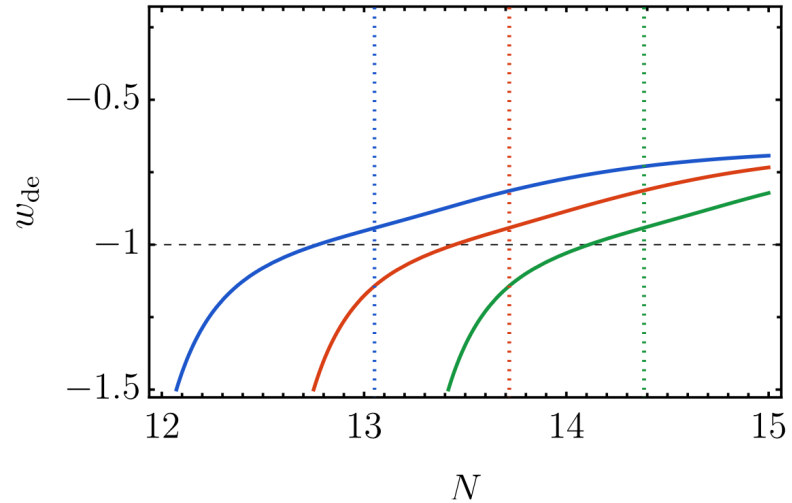
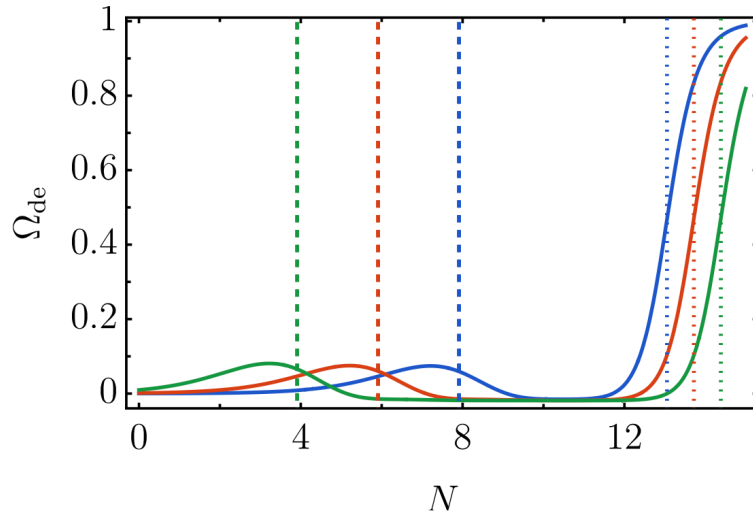
$N$

$N$

## One last thing :)

These types of couplings can help with cosmological tensions and coincidence issues

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi}(\phi) - \frac{d \ln m(\phi)}{d\phi} \rho_{\text{dm}}(\phi).$$



# Final remarks

Arturo de Giorgi, Ivan Martinez-Soler, SSM (2512.13798)  
Clare Burrage and SSM (2603.28881)  
SSM and Mark Trodden (2607.27515)

- We can use particle physics to constrain scalar-tensor theories and motivate new models
- This can help with the misalignment mechanism
- Neutrinos are great candidates to measure modified gravitational geodesics due to their weakly interacting nature
- We built models that relax coincidences in some cosmological tension resolutions

## Thank you for your time!

Sergiosm@sas.upenn.edu



# Multi-fermion case

Let's take a Lagrangian with multiple mass formation mechanisms

In the Jordan frame:

$$\begin{aligned}
 S_m[g_{\mu\nu}] = \int d^4x \sqrt{-g} & \left[ \frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi + \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi \right. \\
 & + \left( \sum_{\alpha}^N i \bar{\psi}_\alpha \gamma^\mu \nabla_\mu \psi_\alpha - y_\alpha \bar{\psi}_\alpha \phi \psi_\alpha \right) \\
 & + \left( \sum_{\beta}^M i \bar{\tau}_\beta \gamma^\mu \nabla_\mu \tau_\beta - m_{\beta,0} \bar{\tau}_\beta \tau_\beta \right) \\
 & \left. - U(\varphi) + \frac{1}{2} \mu^2 \phi^2 - \frac{\lambda}{4!} \phi^4 - \frac{3\mu^4}{2\lambda} \right],
 \end{aligned}$$

# Multi-fermion case

Let's take a Lagrangian with multiple mass formation mechanisms

In the Einstein frame

$$\begin{aligned}
 S_{\text{m}}[\tilde{g}_{\mu\nu}] = & \int d^4x \sqrt{-\tilde{g}} \left[ \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \chi \partial_\nu \chi + A^2(\chi) \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \phi \partial_\nu \phi \right. \\
 & + \left( \sum_{\alpha}^N i A^3(\chi) \bar{\psi}_\alpha \tilde{e}_a^\mu \gamma^a \tilde{\nabla}_\mu \psi_\alpha - y_\alpha A^4(\chi) \bar{\psi}_\alpha \phi \psi_\alpha \right) \\
 & + \left( \sum_{\beta}^M i A^3(\chi) \bar{\tau}_\beta \tilde{e}_a^\mu \gamma^a \tilde{\nabla}_\mu \tau_\beta - m_{\beta,0} A^4(\chi) \bar{\tau}_\beta \tau_\beta \right) \\
 & \left. - V(\chi) + A^4(\chi) \left( \frac{1}{2} \mu^2 \phi^2 - \frac{\lambda}{4!} \phi^4 - \frac{3\mu^4}{2\lambda} \right) \right],
 \end{aligned}$$

# Multi-fermion case

Rescaling the fields as before:

$$\begin{aligned}
 \phi &\rightarrow A^{-1}(\chi)\tilde{\phi}, & \psi_i &\rightarrow A^{-3/2}(\chi)\tilde{\psi}_i, & \tau_i &\rightarrow A^{-3/2}(\chi)\tilde{\tau}_i, \\
 S_m[\tilde{g}_{\mu\nu}] &= \int d^4x \sqrt{-\tilde{g}} \left[ \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\chi} \partial_\nu \tilde{\chi} + \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\phi} \partial_\nu \tilde{\phi} - \frac{\tilde{A}'(\tilde{\chi})}{\tilde{A}(\tilde{\chi})} \tilde{\phi} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\chi} \partial_\nu \tilde{\phi} \right. \\
 &\quad + \left( \sum_{\alpha}^N i \tilde{\bar{\psi}}_{\alpha} \tilde{e}_a^{\mu} \gamma^a \tilde{\nabla}_{\mu} \tilde{\psi}_{\alpha} - y_{\alpha} \tilde{\bar{\psi}}_{\alpha} \phi \tilde{\psi}_{\alpha} \right) \\
 &\quad + \left( \sum_{\beta}^M i \tilde{\bar{\tau}}_{\beta} \tilde{e}_a^{\mu} \gamma^a \tilde{\nabla}_{\mu} \tilde{\tau}_{\beta} - m_{\beta,0} \tilde{A}(\tilde{\chi}) \tilde{\bar{\tau}}_{\beta} \tilde{\tau}_{\beta} \right) \\
 &\quad \left. - \tilde{V}(\tilde{\chi}) + \left( \frac{1}{2} \mu^2 \tilde{A}(\tilde{\chi})^2 \tilde{\phi}^2 - \frac{\lambda}{4!} \tilde{\phi}^4 - \frac{3\mu^4}{2\lambda} \tilde{A}(\tilde{\chi})^4 \right) \right],
 \end{aligned}$$

# Multi-fermion case

As earlier, we just need to calculate the vev of the fields, including the background's density by

$$\rho_\psi = \sum_{\alpha}^N y_{\alpha} v_{\tilde{\phi}} \bar{\tilde{\psi}}_{\alpha} \tilde{\psi}_{\alpha} \qquad \rho_{\tau} = \sum_{\beta}^M m_{\beta,0} \bar{\tilde{\tau}}_{\beta} \tilde{\tau}_{\beta}$$

$$\frac{\lambda}{6} v_{\tilde{\phi}}^4 - \mu^2 v_{\tilde{\phi}}^2 A^2(v_{\tilde{\chi}}) + \rho_{\psi} = 0,$$

$$\tilde{A}'(v_{\tilde{\chi}}) \tilde{A}^3(v_{\tilde{\chi}}) \frac{6\mu^4}{\lambda} - \mu^2 v_{\tilde{\phi}}^2 \tilde{A}'(v_{\tilde{\chi}}) \tilde{A}(v_{\tilde{\chi}}) + \tilde{V}'(v_{\tilde{\chi}}) + \frac{\tilde{A}'(v_{\tilde{\chi}})}{\tilde{A}(v_{\tilde{\chi}})} \rho_{\tau} = 0.$$

# Multi-fermion case

As earlier, we just need to calculate the vev of the fields, including the background's density by

$$\rho_\psi = \sum_\alpha^N y_\alpha v_{\tilde{\phi}} \bar{\tilde{\psi}}_\alpha \tilde{\psi}_\alpha \qquad \rho_\tau = \sum_\beta^M m_{\beta,0} \bar{\tilde{\tau}}_\beta \tilde{\tau}_\beta$$

$$\frac{\lambda}{6} v_{\tilde{\phi}}^4 - \mu^2 v_{\tilde{\phi}}^2 A^2(v_{\tilde{\chi}}) + \rho_\psi = 0,$$

$$\tilde{A}'(v_{\tilde{\chi}}) \tilde{A}^3(v_{\tilde{\chi}}) \frac{6\mu^4}{\lambda} - \mu^2 v_{\tilde{\phi}}^2 \tilde{A}'(v_{\tilde{\chi}}) \tilde{A}(v_{\tilde{\chi}}) + \tilde{V}'(v_{\tilde{\chi}}) \left( + \frac{\tilde{A}'(v_{\tilde{\chi}})}{\tilde{A}(v_{\tilde{\chi}})} \rho_\tau \right) = 0.$$

# Multi-fermion case

As earlier, we just need to calculate the vev of the fields, including the background's density by

$$v_{\tilde{\phi}}^2 = \frac{v^2}{2} \tilde{A}^2(v_{\tilde{\chi}}) \left( 1 + \sqrt{1 - \frac{4\rho_{\psi}}{v^2 \mu^2 \tilde{A}^4(v_{\tilde{\chi}})}} \right)$$

$$\tilde{V}'(v_{\tilde{\chi}}) = - \frac{\tilde{A}'(v_{\tilde{\chi}})}{\tilde{A}(v_{\tilde{\chi}})} (\rho_{\psi} + \rho_{\tau}),$$

All sources of scale breaking contribute equally

# Multi-fermion case

Moreover, recalling the Lagrangian

$$\begin{aligned}
 & + \left( \sum_{\alpha}^N i \bar{\tilde{\psi}}_{\alpha} \tilde{e}_a^{\mu} \gamma^a \tilde{\nabla}_{\mu} \tilde{\psi}_{\alpha} - y_{\alpha} \bar{\tilde{\psi}}_{\alpha} \phi \tilde{\psi}_{\alpha} \right) \\
 & + \left( \sum_{\beta}^M i \bar{\tilde{\tau}}_{\beta} \tilde{e}_a^{\mu} \gamma^a \tilde{\nabla}_{\mu} \tilde{\tau}_{\beta} - m_{\beta,0} \tilde{A}(\tilde{\chi}) \bar{\tilde{\tau}}_{\beta} \tilde{\tau}_{\beta} \right)
 \end{aligned}$$

We find the effective masses to be

$$\begin{aligned}
 m_{\alpha} &= y_{\alpha} v_{\tilde{\phi}} = y_{\alpha} v \tilde{A}(v_{\tilde{\chi}}) \\
 m_{\beta} &= m_{\beta,0} \tilde{A}(v_{\tilde{\chi}}),
 \end{aligned}$$

All sources of scale breaking get also rescaled equally

# Einstein frame:

The common way of solving this called [Transforming to the Einstein frame](#)

Make a conformal transformation such that gravity becomes canonical

$$g_{\mu\nu} \rightarrow \frac{\tilde{M}_{\text{Pl}}^2}{F(\varphi)} \tilde{g}_{\mu\nu}, \quad g^{\mu\nu} \rightarrow \frac{F(\varphi)}{\tilde{M}_{\text{Pl}}^2} \tilde{g}^{\mu\nu},$$

$$S_{\text{EF}} = \int d^4x \sqrt{-\tilde{g}} \left[ -\frac{\tilde{M}_{\text{Pl}}^2}{2} \tilde{R} + \frac{\tilde{M}_{\text{Pl}}^2}{2} \left[ \frac{1}{F(\varphi)} + \frac{3F'(\varphi)^2}{2F(\varphi)^2} \right] \tilde{g}^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi \right. \\ \left. - \frac{\tilde{M}_{\text{Pl}}^4}{F(\varphi)^2} U(\varphi) + \mathcal{L}_{\text{m}}\{\psi_i, \phi_i, \varphi, \tilde{g}_{\mu\nu}, \dots\} \right]$$

Standard gravity

Beyond the Standard Model matter sector