Abstract

A new, strong, neutrino-neutrino interaction will significantly affect our understanding of the early universe. By analyzing the data from Planck, we found that a stronger interaction is allowed than would be expected from thermalization requirements. This new interaction has many interesting features. It opens up the inflation parameter space allowing models previously ruled out such as Natural Inflation or Coleman-Weinberg inflation to be allowed again. It also may alleviate the H_0 light sterile neutrino tensions with early universe data. Finally, it is, in principle, testable at IceCube.

Neutrino Self Interactions in the Early Universe

(Inflation and NSI)

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Inflation Meets Neutrinos

1903.02036

with G. Barenboim and I. Oldengott

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Bambi Meets Godzilla (1969) [1:30]

youtu.be/8s3UogfAGg0

Broad range of topics

The following are all connected through new ν interactions:

- CMB
- BBN
- Precision decay measurements
- H_0 tension
- Inflation models
- IceCube

Conventional Wisdom

1. 1 eV^2 sterile neutrinos suggested by LSND, MiniBooNE, Source anomalies, RAA, new SBL reactors...
2. Incompatible with N_{eff} from CMB and BBN and $\sum m_\nu$ from CMB+
3. New neutrino interactions
4. ????
5. Victory!

Does this actually work?
What does the data actually say?

Non-Standard neutrino Self Interactions

NSSI

$$\mathcal{L} \supset g_{\alpha\beta}\bar{\nu}_\alpha \nu_\beta \phi$$

Sometimes called secret interactions

Beyond new interactions/propagation effects:

- Neutrino decay: $m_\phi < m_\nu$

  A. Acker, S. Pakvasa, J. Pantaleone PRD 45 (1992)

- Neutrino mass generation: $\langle\phi\rangle \neq 0$

  Y. Chikashige, R. Mohapatra, R. Peccei PLB 98 (1981)

Constraints from:

- CMB
- BBN
- SN
- Z-boson
- IceCube?

NSSI $\leftrightarrow$ NSI

"Regular" NSI:

$$\epsilon^f_{\alpha\beta} \propto \frac{g^\nu_{\alpha\beta} g^f_{\alpha\beta}}{m^2}$$

$f = e, u, d$

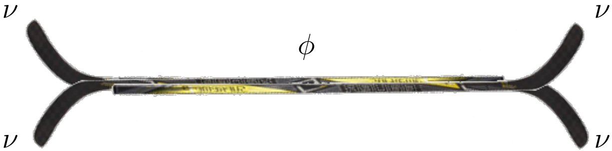
Usually V or A, but can also be S, P, T

D. Sierra, V. Romeri, N. Rojasa 1806.07424

S. Ge, S. Parke 1812.08376

NSSI:

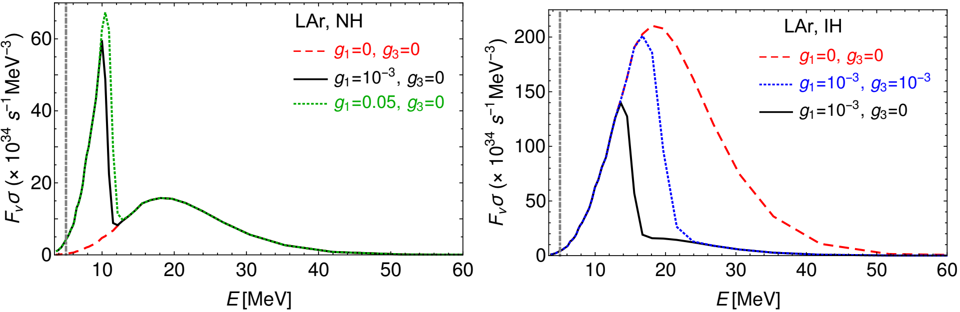
$$\epsilon_{\alpha\beta} \propto \frac{(g^\nu_{\alpha\beta})^2}{m^2}$$



Any NSI guarantees NSSI

Core-Collapse Supernova NSSI

NSSI leads to non-linear collective flavor oscillations



This is from a two flavor approximation,
Three flavors may induce a second flavor conversion.

NSSI can make MO identification harder

A. Das, A. Dighe, M. Sen 1705.00468

Constraints

$$G_{\text{eff}} = \frac{1}{\sqrt{4\pi}} \frac{g^2}{m_\phi^2}$$

- **Perturbativity**: $g < 1$
- **SN1987A**: neutrinos aren't absorbed by CνB: $G_{\text{eff}} < 10^{-8}$ GeV^{-2}

  E. Kolb, M. Turner PRD 36, 2895 (1987)
- **Z-decay**: $G_{\text{eff}} \lesssim 10^{-5}$ GeV^{-2} for $m_\phi \gtrsim 80$ GeV

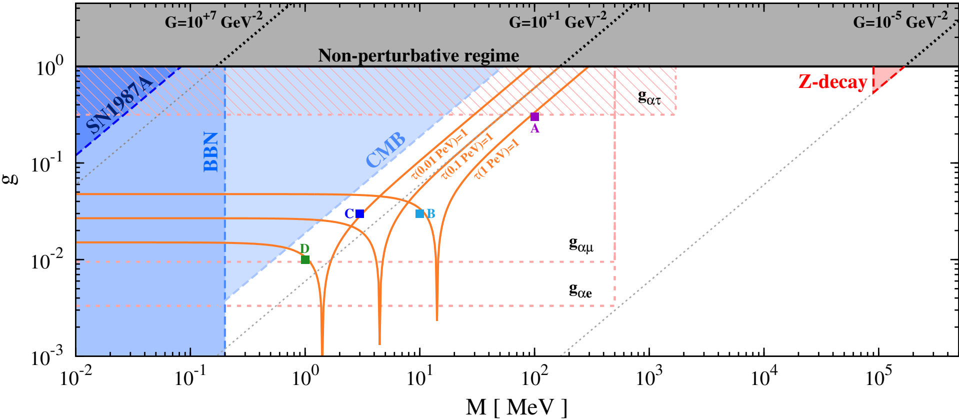
  M. Bilenky, A. Santamaria `hep-ph/9908272`
- **Mediator brem**: Kaon/tau decays: $g < \{0.003, 0.01, 0.3\}$ for $m_\phi < \{0.5, 0.5, 2\}$ GeV

  A. Lessa, O. Peres `hep-ph/0701068`
- **BBN/CMB**: Thermal mediator $\to \Delta N_{\text{eff}}$: $m_\phi > 0.2$ MeV

  B. Ahlgren, T. Ohlsson, S. Zhou `1309.0991`
- **CMB**: Neutrinos should be free-streaming until $z \sim 2 \times 10^5$: $G_{\text{eff}} < 100$ GeV^{-2}

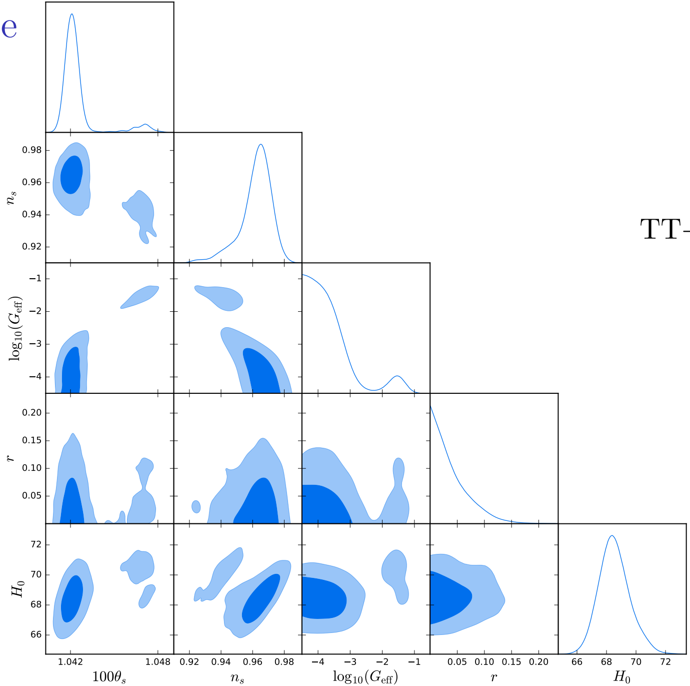
  F. Cyr-Racine, K. Sigurdson `1306.1536`
- **IceCube?**: Absorption

Constraints



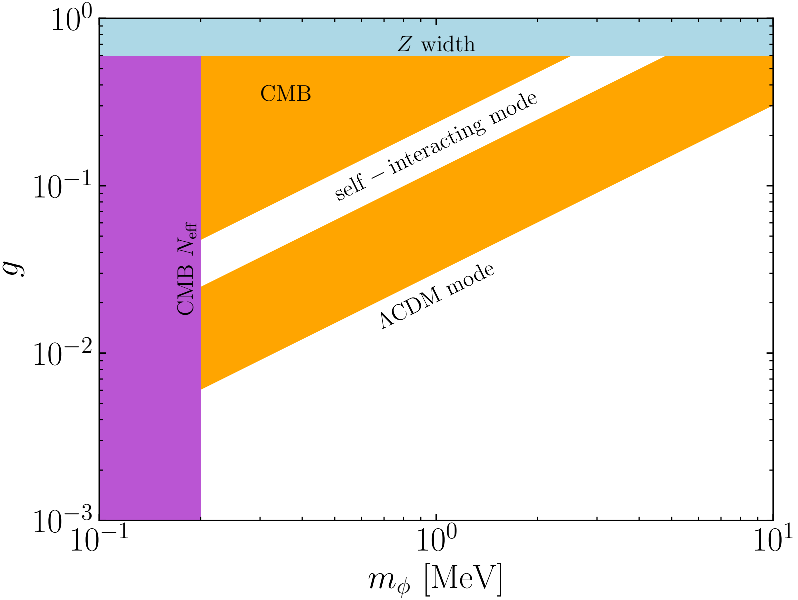
K. Ng, J. Beacom 1404.2288

Triangle



TT+lens

NSSI Parameter Space



Early Universe Physics

Standard picture with neutrinos compared to no neutrinos:

- Free streaming normally pulls the photon-baryon plasma,
- Pushes power to smaller ℓ, and slightly smaller amplitude
- Increases sound horizon slightly

A new interaction $G_{\rm eff} \sim 10^9 G_F$ is compatible with the data.

This delays free streaming from very early to $z_{\nu,\rm dec} \sim 8300$

I. Oldengott, et al. 1706.02123

C. Kreisch, F. Cyr-Racine, O. Doré 1902.00534

Inflation Parameters

Inflaton Lagrangian:

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi)$$

Scalar and tensor perturbations:

$$A_S^2 \equiv \frac{512\pi}{75 m_{\mathrm{P}}^6} \left. \frac{V^3}{V'^2} \right|_{k=aH} \qquad A_T^2 \equiv \frac{4}{25\pi} \left. \frac{H}{m_{\mathrm{P}}^2} \right|_{k=aH} \qquad r = 16 \frac{A_T^2}{A_S^2}$$

$$n_s - 1 \equiv \left. \frac{d \ln A_S^2}{d \ln k} \right|_{k=aH} \qquad n_T \equiv \left. \frac{d \ln A_T^2}{d \ln k} \right|_{k=aH}$$

Inflation Parameters

Slow roll parameters:

$$\epsilon \propto \dot{\phi}^2 \qquad \eta \propto \frac{\ddot{\phi}}{\dot{\phi}}$$

$$\epsilon \equiv \frac{m_{\rm P}^2}{16\pi}\left(\frac{V'}{V}\right)^2 \qquad \eta \equiv \frac{m_{\rm P}^2}{8\pi}\frac{V''}{V}$$

Slow roll ($\ddot{\phi} \ll 3H\dot{\phi}$) requires:

$$n_s - 1 = -6\epsilon + 2\eta \qquad n_T = -2\epsilon$$

Inflation ends when $\epsilon(\phi_e) = 1$ and the number of e-folds is

$$N \simeq -\frac{8\pi}{m_{\rm P}^2}\int_\phi^{\phi_e}\frac{V}{V'}d\phi$$

We know that $45 \lesssim N_{\rm CMB} \lesssim 60$

D. Lyth, A. Riotto hep-ph/9807278

Inflation Models: Natural Inflation

Natural result from a broken shift symmetry → PNGB inflaton (axion)

Potential:

$$V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right]$$

Slow roll parameters:

$$\epsilon(\phi) \simeq \frac{m_{\rm P}^2}{16\pi f^2}\left[\frac{\sin(\phi/f)}{1+\cos(\phi/f)}\right]^2 \qquad \eta(\phi) \simeq -\frac{m_{\rm P}^2}{16\pi f^2}$$

$$N = \frac{16\pi f^2}{m_{\rm p}^2}\ln\left[\frac{\sin(\phi/2f)}{\sin(\phi_e/2f)}\right]$$

Inflation Models: Natural Inflation

Inflation ends when $\phi \to \phi_e$ which is $\epsilon(\phi_e) = 1$:

$$\cos\left(\frac{\phi_e}{f}\right) = \frac{1 - 16\pi(f/m_{\rm P})^2}{1 + 16\pi(f/m_{\rm P})^2}$$

$$\begin{array}{ll} f < m_{\rm P} & n_s \text{ independent of } N \\ f > m_{\rm P} & n_s \text{ independent of } f \end{array}$$

K. Freese, J. Frieman, A. Olinto PRL 65 3233 (1990)

Super-Planckian f naturally leads to observable GWs

Disfavored at $> 1\,\sigma$, will be ruled out if $r <$ few %

Inflation Models: Coleman-Weinberg Inflation

An unavoidable 1-loop contribution

S. Coleman, E. Weinberg, PRD 7 1888 (1973)

Potential:

$$V(\phi) = A\phi^4 \left[\ln\left(\frac{\phi}{f}\right) - \frac{1}{4}\right] + \frac{Af^4}{4}$$

Slow roll parameters:

$$\epsilon(\phi) = \frac{16}{\pi}\frac{m_{\rm P}^2\phi^6}{f^8}\ln^2\left(\frac{\phi}{f}\right) \qquad \eta(\phi) = \frac{m_{\rm P}^2\phi^2}{2\pi f^4}\left[\ln\left(\frac{\phi}{f}\right) + 1\right]$$

$$N(\phi) = \frac{2\pi f^2}{m_{\rm P}^2}\left\{{\rm Ei}\left[-2\ln\left(\frac{\phi}{f}\right)\right] - {\rm Ei}\left[-2\ln\left(\frac{\phi_e}{f}\right)\right]\right\}$$

Inflation Models: Coleman-Weinberg Inflation

Assuming $\phi < f$, then $\epsilon < \eta$ and

$$N \simeq \frac{3}{1-n_s} \quad \rightarrow \quad n_s = 1 - \frac{3}{N}$$

$$r \propto \left(\frac{f}{m_{\mathrm{P}}}\right)^4 \sim 0$$

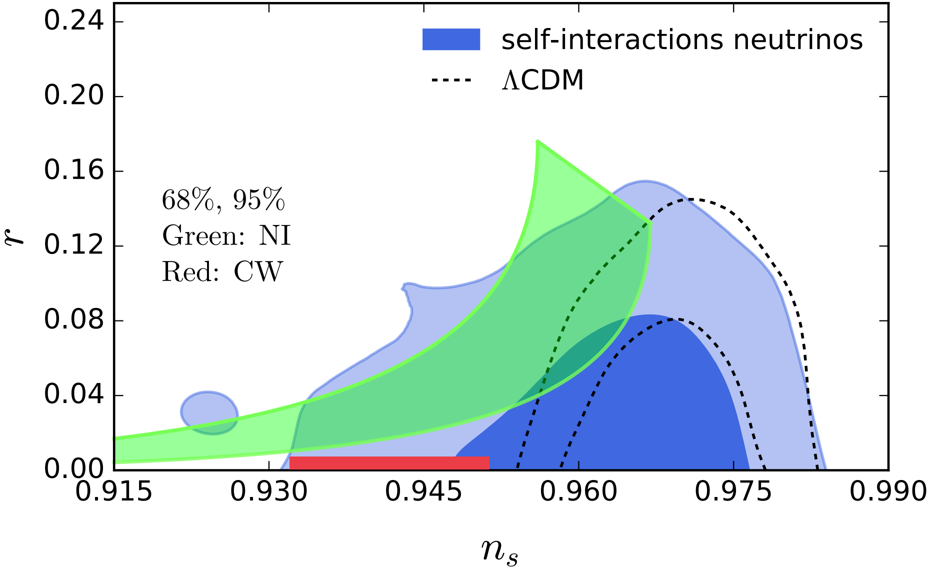
A. Linde PL 108B 389 (1982)

A. Albrecht, et al. PRL 48 1437 (1982)

Ruled out at $\sim 3\,\sigma$

G. Barenboim, E. Chun, H. Lee 1309.1695

Inflation Constraints



CνB Scattering

In the same fashion as the Z-burst at $E_\nu \sim 10^{14}$ GeV...

T. Weiler PRL 49 234 (1982)

HE ν's scatter off CνB leading to a dip due to NSI

A. Difranzo, D. Hooper 1507.03015

I. Shoemaker, K. Murase 1512.07228

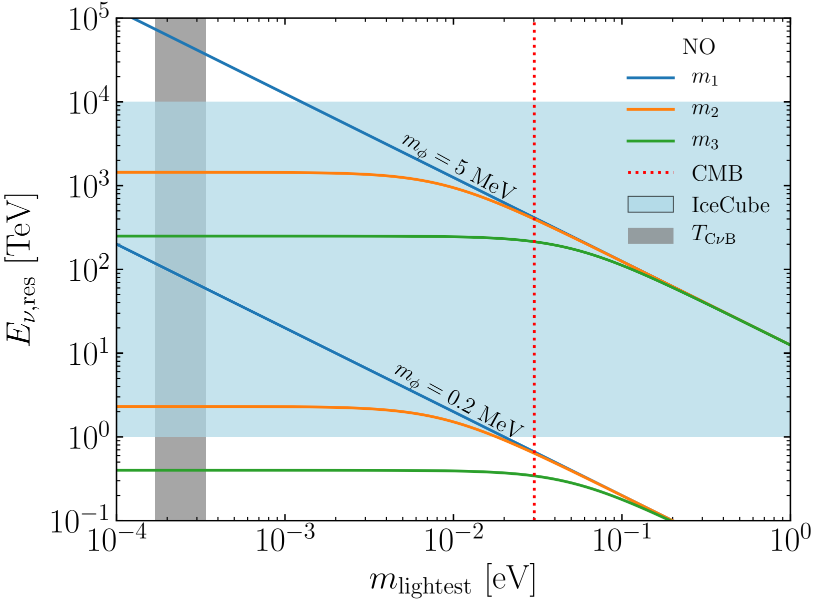
Assuming $p_\nu < m_\nu$

$$E_{\nu_i}^{\rm res} = \frac{m_\phi^2 - m_{\nu_i}^2}{2m_{\nu_i}} \approx \frac{m_\phi^2}{2m_{\nu_i}}$$

Hint of a dip at $E_\nu \sim 500$ TeV?

Dip identification requires:
assuming a known astrophysical spectrum!

IceCube Resonant Absorption



H_0 Tension

More data! More parameters!

1. Also include BAO and local H_0
2. Allow N_{eff} and $\sum m_\nu$ to float

#2 only matters when #1 is included

New results

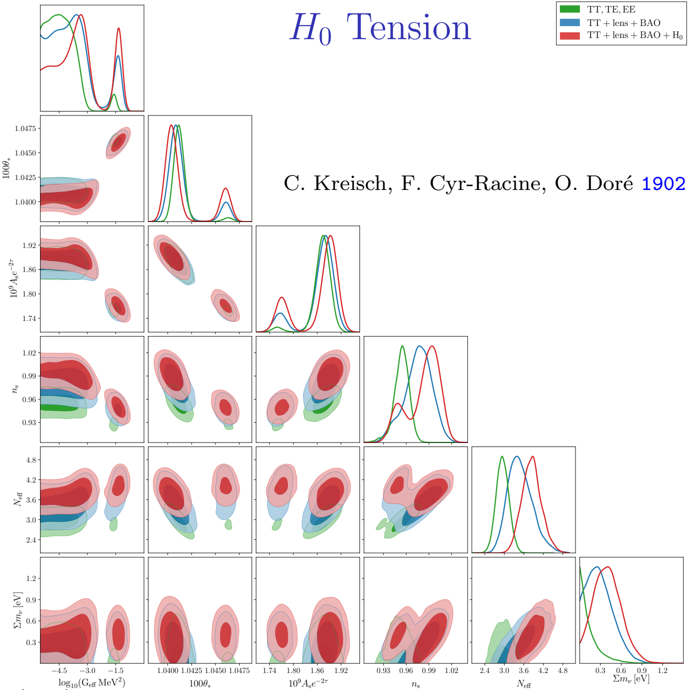
- Data disfavors $G_{\text{eff}} = 0$
- G_{eff} still bimodal
- Driven by H_0
- $N_{\text{eff}} = 4.02 \pm 0.29$ (sterile?)
- Ameliorates σ_8 tension ($\sim 2.6\,\sigma$)

S. Joudaki, et al. 1707.06627

C. Kreisch, F. Cyr-Racine, O. Doré 1902.00534

H_0 Tension

C. Kreisch, F. Cyr-Racine, O. Doré 1902.00534



1903.02036

Other Constraints

To reach large G_{eff}:

What doesn't work:

- Vector mediators are disfavored by BBN
- Dirac neutrinos are disfavored by BBN
- G_{eff} with $\nu_{e,\mu}$ disfavored by K decays

What does work:

- Scalar mediator
- Majorana neutrinos
- Most/all of G_{eff} in the ν_τ sector

N. Blinov, et al. 1905.02727

Conclusions

- Constraints on inflation/ΛCDM need to account for new ν interactions
- Natural and Coleman-Weinberg inflation are allowed
- **Testable** by IceCube (ish)
- H_0 and sterile **tensions** with CMB may be **alleviated**
- Lots of constraints but some parameter space left

Thank You!

Go Blues!