Second EuCAPT Symposium
May 2022, 25th

Based on: **[Lucas Pinol 2020]**
J. Cosm. & Astro. Phys. 04(2021)048
[Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi 2021]
ArXiv:2112.05710

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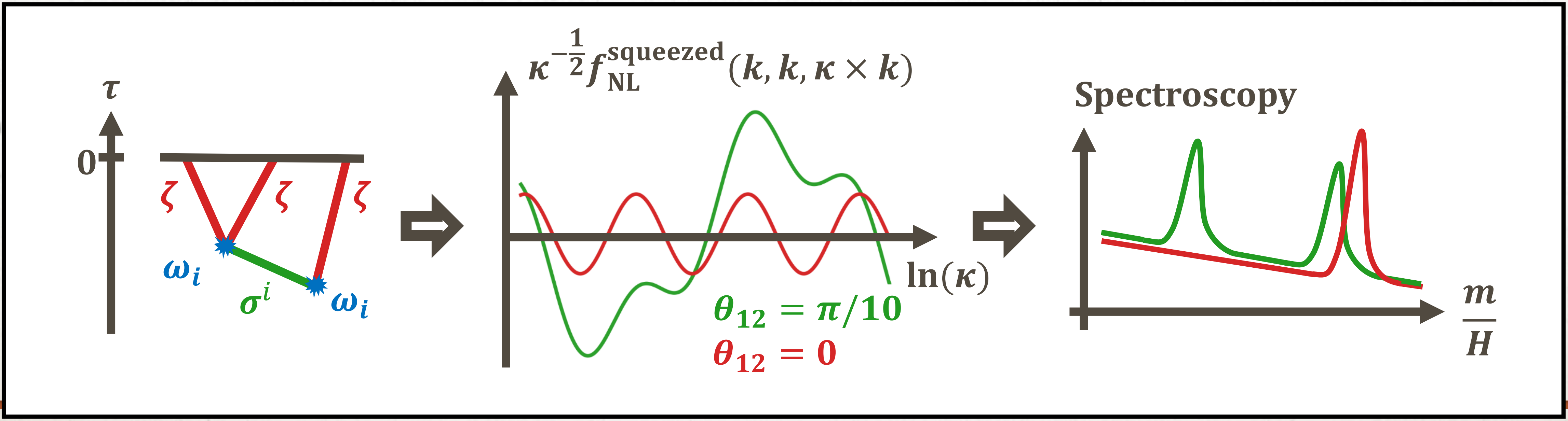
INFLATIONARY FLAVOR OSCILLATIONS
AND THE COSMIC SPECTROSCOPY

PS: it will be 6 min long sorry

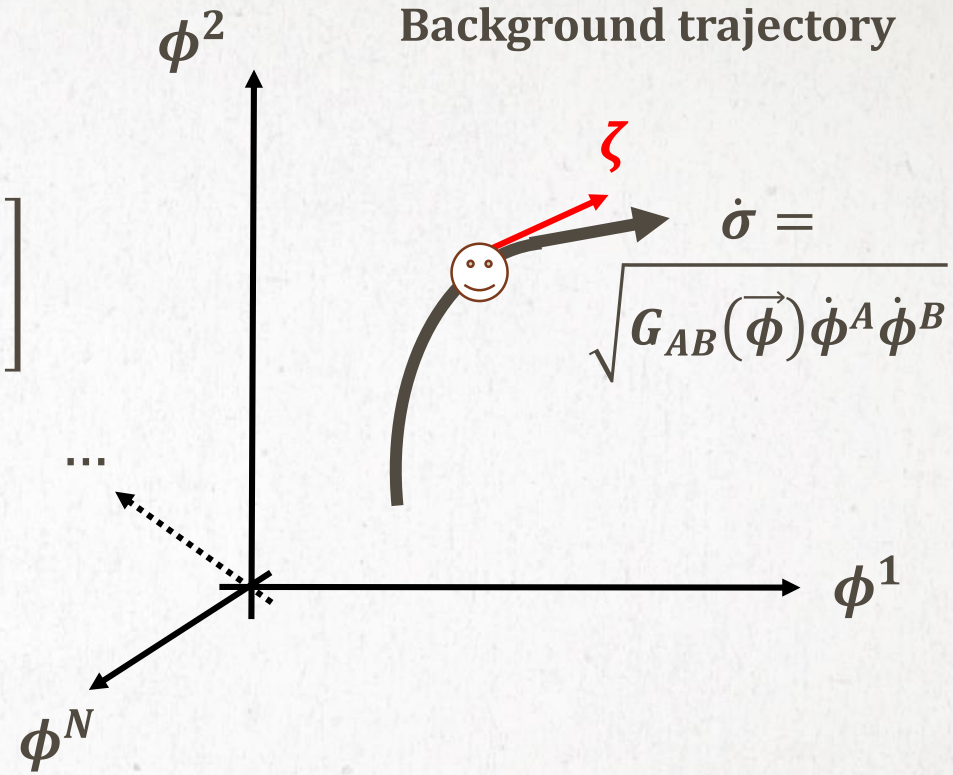


Other topics of research: Multifield stochastic inflation in phase space, multi-species reheating, anisotropies of the SGWB…

INFLATIONARY FLAVOR AND MASS BASES

Multifield inflation with non-canonical kinetic terms:

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{2} - \sum_{A,B} g^{\mu\nu} \boldsymbol{G_{AB}(\vec{\phi})}\partial_\mu\phi^A\partial_\nu\phi^B - \boldsymbol{V(\vec{\phi})}\right]$$



- Both **potential** and **kinetic** interactions: **very generic**
- Any number N of scalar fields
- Perturbation theory: $\phi^A(t,\vec{x}) = \bar{\phi}^A(t) + \delta\phi^A(t,\vec{x}) + \cdots$

To compute non-Gaussianities: define gauge-invariant variables, expand the action at cubic order, make IBPs, etc.

INFLATIONARY FLAVOR AND MASS BASES

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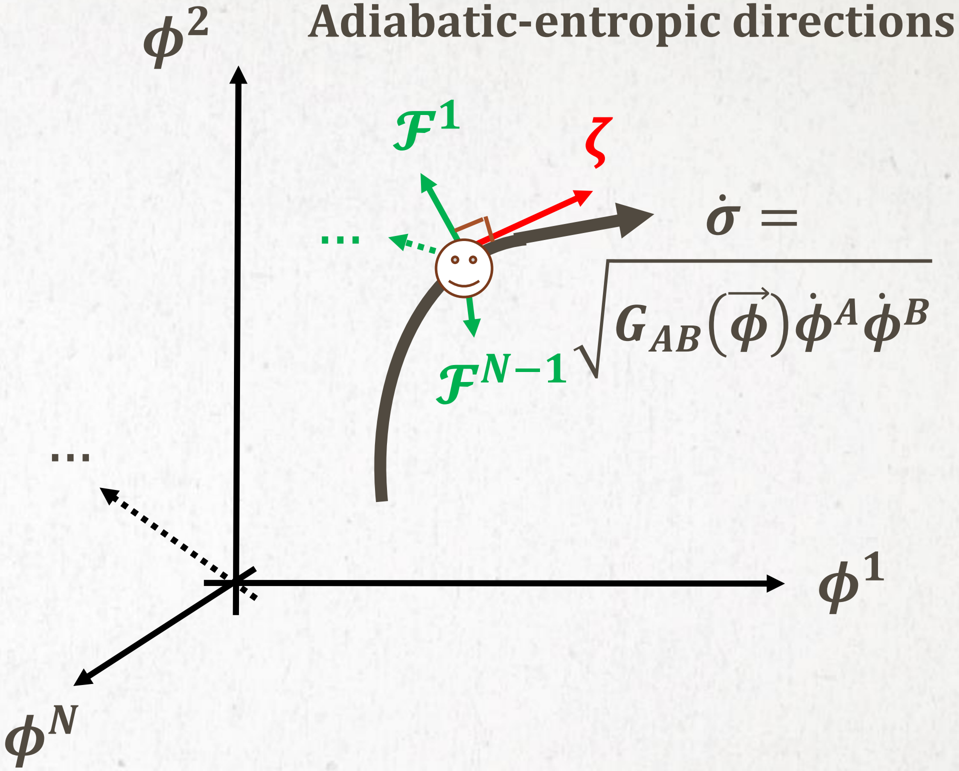
Quadratic action for the extra fluctuations:
(Also the cubic action is computed)

ζ	The curvature perturbation
$\mathcal{F}^1, \dots \mathcal{F}^{N-1}$	The entropic/isocurvature perturbations

Adiabatic-entropic directions



INFLATIONARY FLAVOR AND MASS BASES

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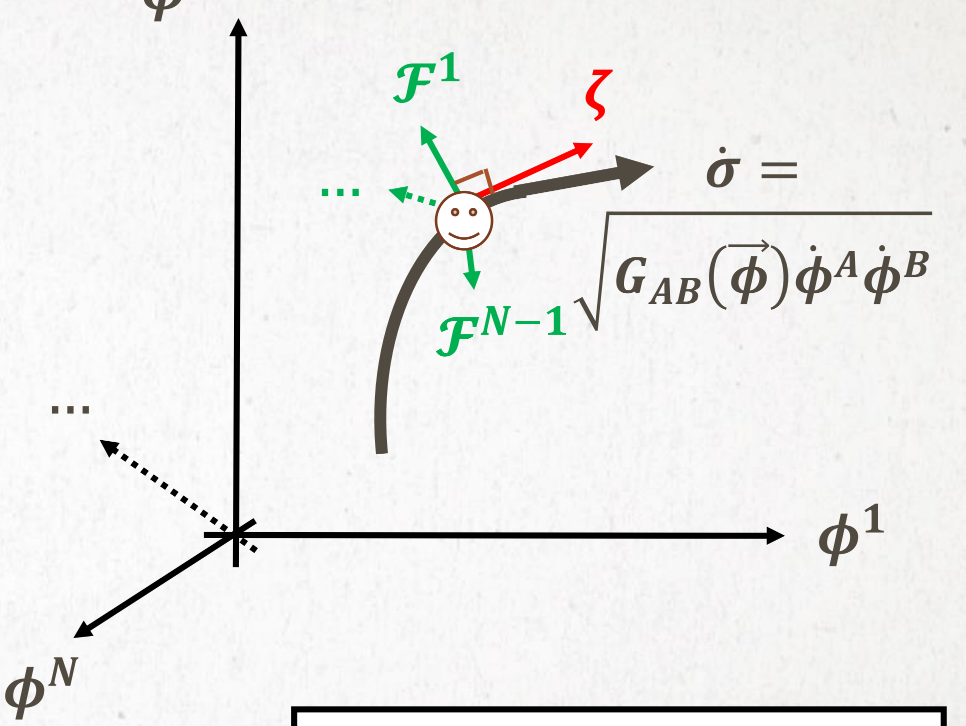
Adiabatic-entropic directions



Quadratic action for the extra fluctuations:

$$\mathcal{L}^{(2)}_{\text{flavor}} = \frac{a^3}{2}\left[\delta_{\alpha\beta}\left(\dot{\mathcal{F}}^\alpha\dot{\mathcal{F}}^\beta - \frac{\partial\mathcal{F}^\alpha\partial\mathcal{F}^\beta}{a^2}\right) - M^2_{\alpha\beta}\mathcal{F}^\alpha\mathcal{F}^\beta\right]$$

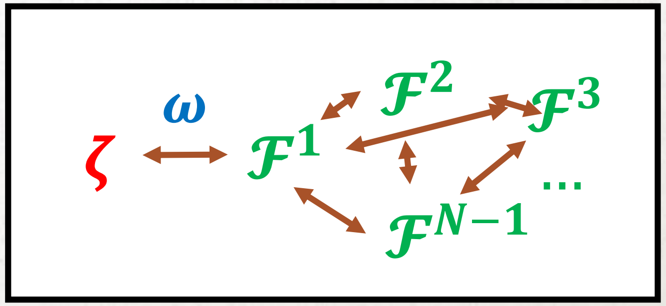
$$+ 4\sqrt{2\epsilon}M_{\text{Pl}}\omega\delta_{\alpha 1}\mathcal{F}^\alpha\dot{\zeta}$$

- **Non-trivial mass matrix mixing**

- **Only the first extra field $\mathcal{F}^1$ is coupled to ζ:**

  portal field + sterile sector

Flavor basis: the one in which interactions are specified



Diagonalization: $M_{\alpha\beta} = \left(OmO^T\right)_{\alpha\beta}$ and $\mathcal{F}^\alpha = O^\alpha{}_i\,\sigma^i$

INFLATIONARY FLAVOR AND MASS BASES

[Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi 2021]

ArXiv:2112.05710

Quadratic action for the extra fluctuations:

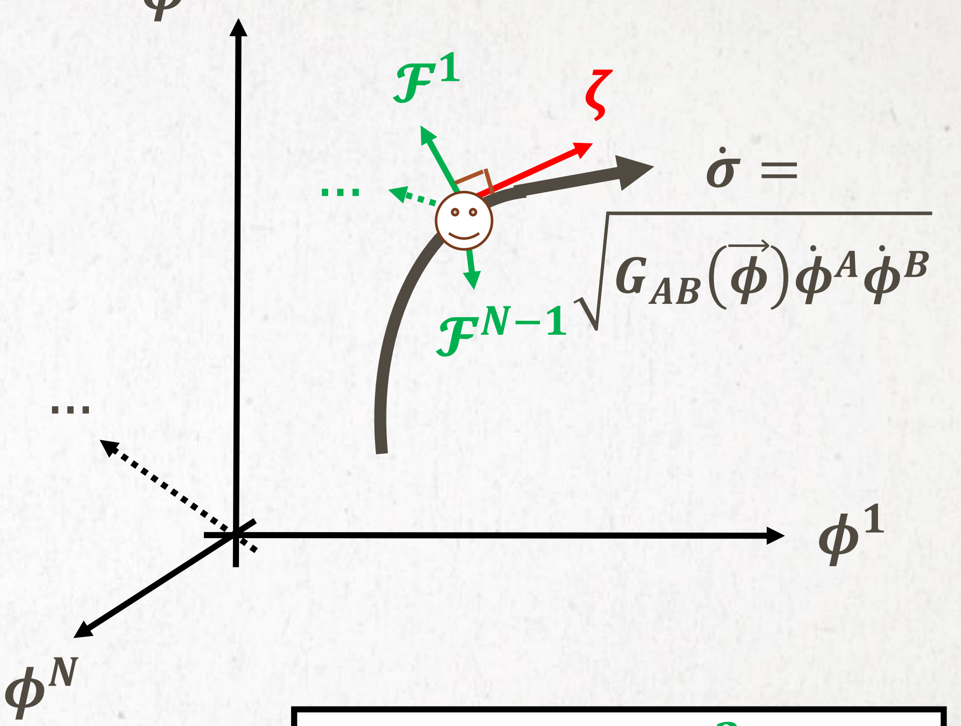
$$\mathcal{L}^{(2)}_{\rm mass} = \frac{a^3}{2}\left[\delta_{ij}\left(\dot\sigma^i\dot\sigma^j - \frac{\partial\sigma^i\partial\sigma^j}{a^2}\right) - \sum_i \underline{m_i^2\sigma_i^2}\right]$$

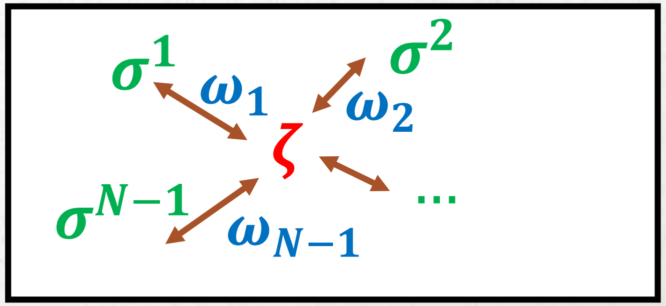
$$+\,4\sqrt{2\epsilon}M_{\rm Pl}\,\underline{\omega O^1{}_i\,\sigma^i\dot\zeta}$$

- **Well-defined masses**
- **All mass eigenstates are coupled to ζ with:**

$$\boldsymbol{\omega_i = \omega O^1{}_i \ \text{ with } \mathcal{F}^1 = O^1{}_i\sigma^i}$$

Adiabatic-entropic directions

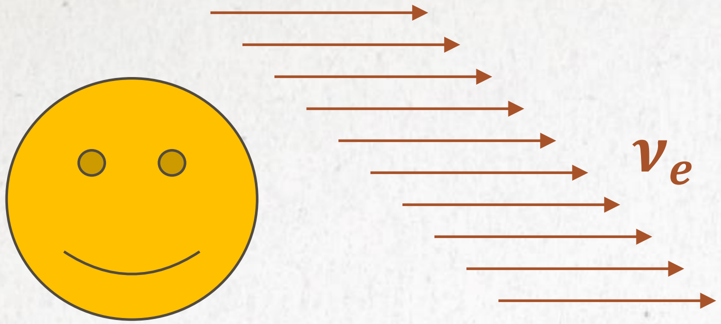




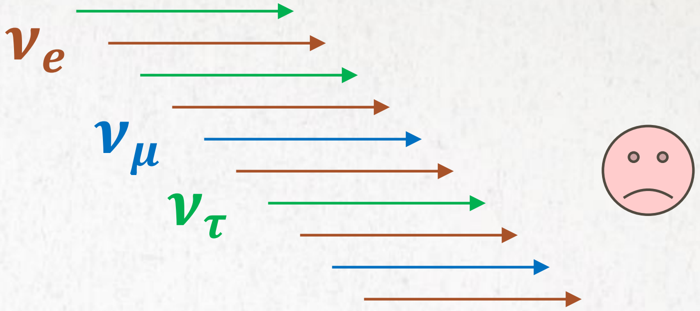
Mass basis: the one in which masses are specified

Diagonalization: $M_{\alpha\beta} = \left(OmO^T\right)_{\alpha\beta}$ and $\mathcal{F}^\alpha = O^\alpha{}_i\,\sigma^i$

ANALOGY WITH NEUTRINO OSCILLATIONS



NO INTERACTIONS



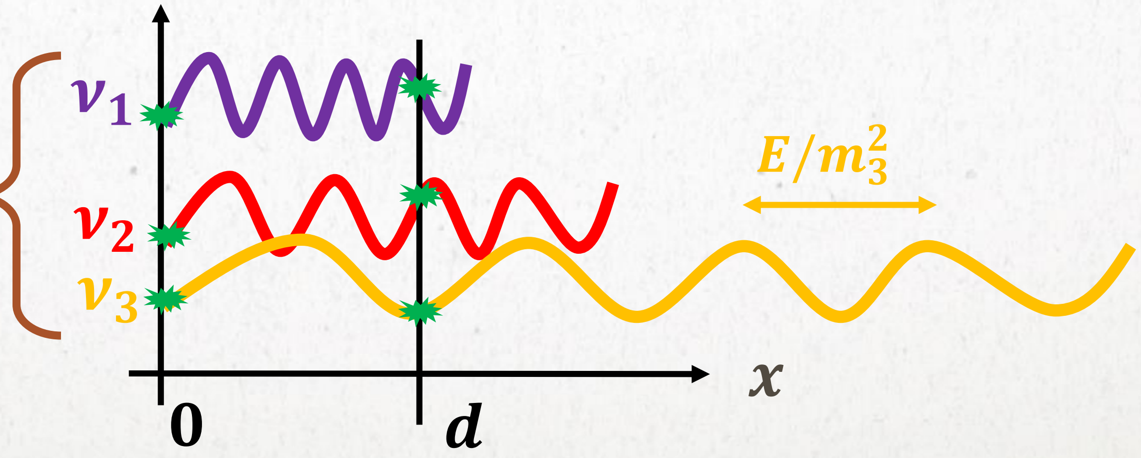
This is the Sun

It is emitting electronic neutrinos

This is me

I am seeing many less electronic neutrinos

$$\nu_e = \sum_i U_{ei}\, \nu_i$$



Entries of the PMNS matrix: mixing angles

PMNS stands for Pontecorvo-Maki-Nakagawa-Sakata: try to pronounce it ten times in a row

ANALOGY WITH NEUTRINO OSCILLATIONS

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For us, $\mathcal{F}^\alpha$ are the flavor eigenstates and σ_i the free fields: the mass eigenstates.

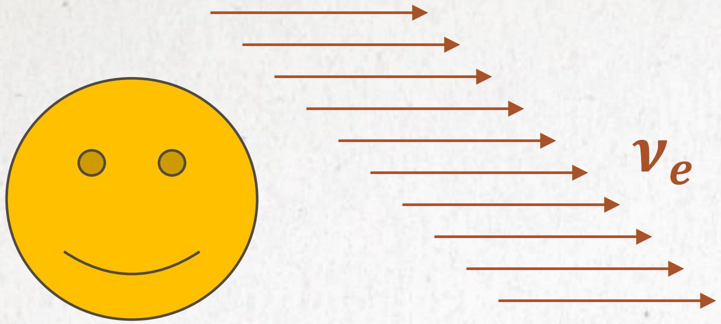
In particular: $\mathcal{F}^1 = \sum_i O^1{}_i\, \sigma_i$ with $O^1{}_i = [\cos(\underline{\theta_{12}})\cos(\underline{\theta_{13}}), \sin(\theta_{12})\cos(\theta_{13}), \sin(\theta_{13})]_i \;, \quad (3)$

if $N_{\text{flavor}} = 3$

Mixing angles

Maybe called the PARY matrix one day?

ANALOGY WITH NEUTRINO OSCILLATIONS



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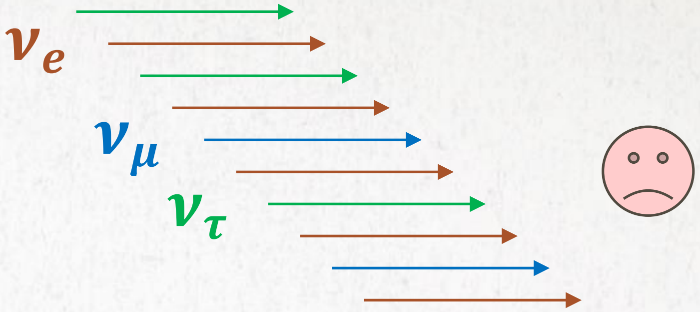

This is the Sun

It is emitting electronic neutrinos

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What process equivalent to the missing solar neutrinos may hint towards inflationary flavor oscillations?

BISPECTRUM IN MULTIFIELD INFLATION

The squeezed limit as a cosmological collider

Single-field result:

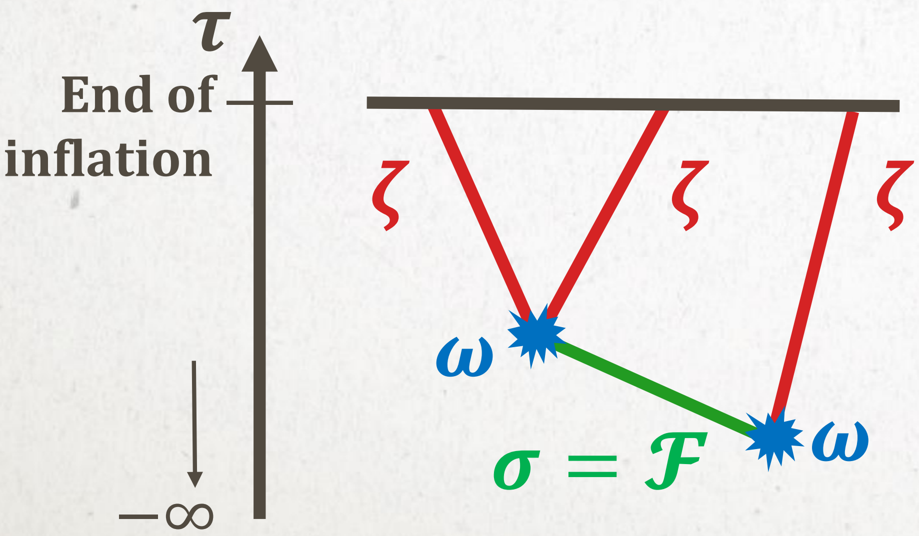
$$\boxed{f_{\mathrm{NL}}^{\text{squeezed}} \propto 1 - n_s \ll 1}$$

consistency relation

[Maldacena 2003]

Two-field result: Usual curvature perturbation ζ + one extra field $\sigma = \mathcal{F}$

[Chen, Wang 2009]
[Noumi, Yamaguchi, Yokoyama 2013]
[Arkani-Hamed, Maldacena 2015]



$$f_{\mathrm{NL}}^{\text{squeezed}} \sim \left(\frac{\omega}{H}\right)^2 e^{-\pi\mu} \cos\left[\boldsymbol{\mu} \log\left(\frac{k_l}{k_s}\right) + \varphi(\boldsymbol{\mu})\right]$$

Oscillatory pattern: massive particle

$\boldsymbol{\mu} = \sqrt{\frac{m_\sigma^2}{H^2} - \frac{9}{4}}$ **the reduced mass**

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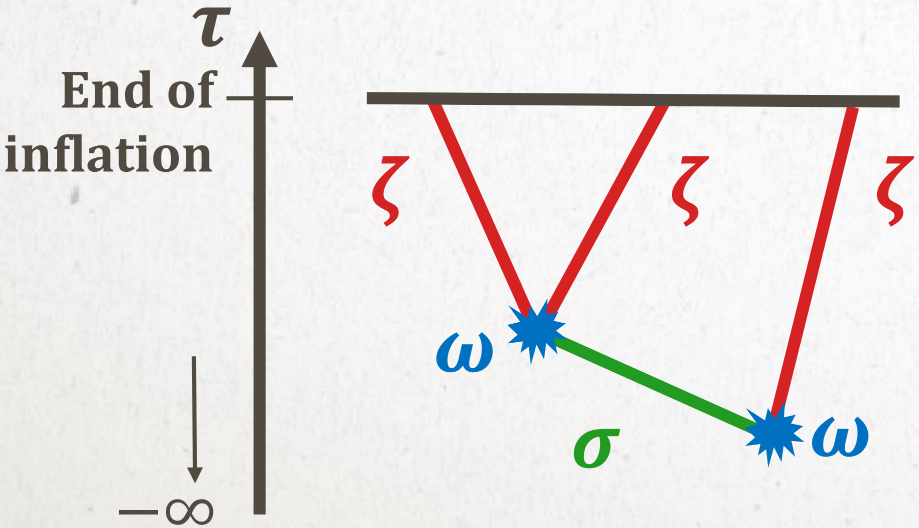

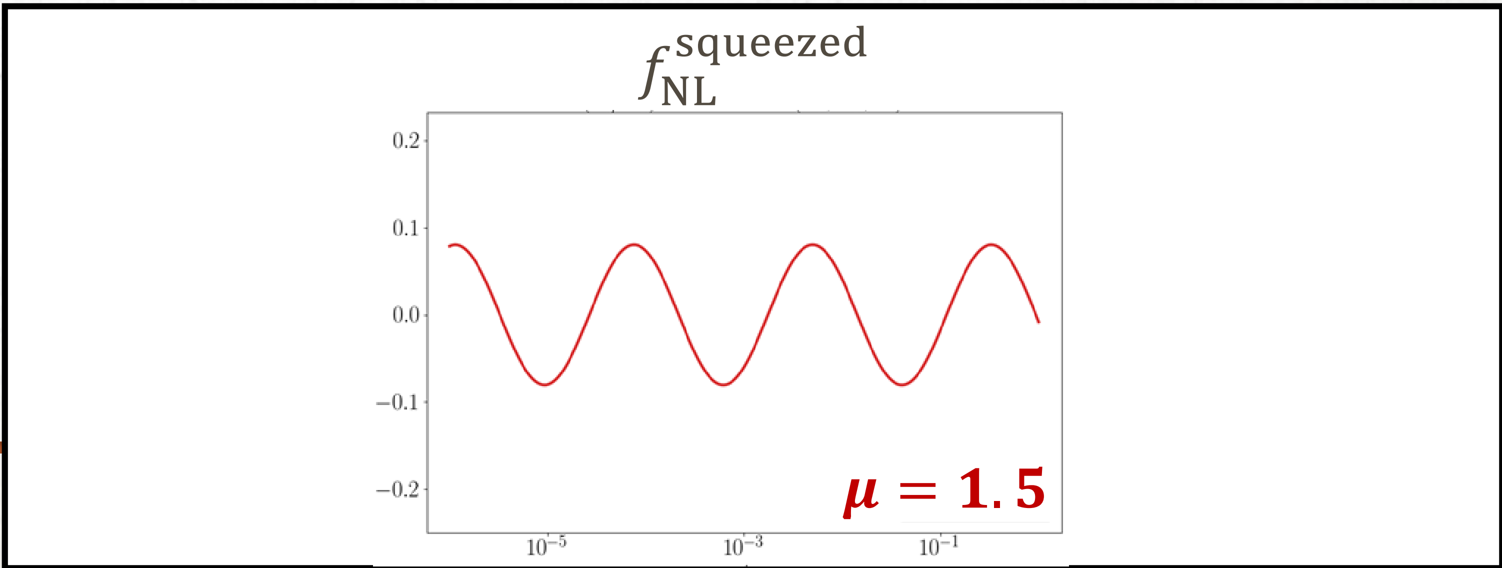

BISPECTRUM IN MULTIFIELD INFLATION

The squeezed limit as a cosmological collider

[Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi 2021]

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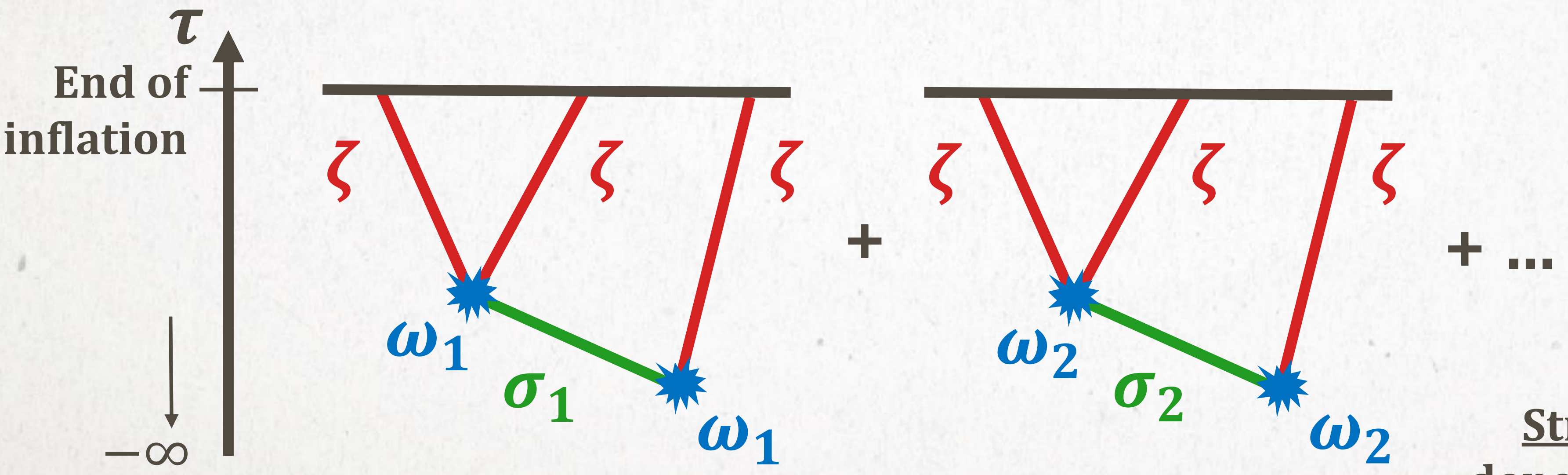
N-field result



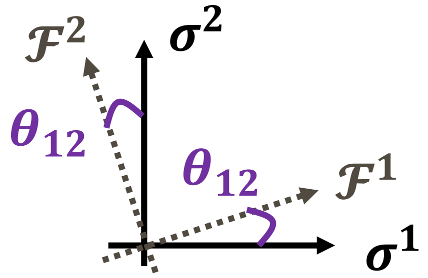
Strength of interactions depend on the mixing angles

$$\omega_i = O^1{}_i \times \omega$$

BISPECTRUM IN MULTIFIELD INFLATION

- Three fields: ζ and 2 flavors $(\mathcal{F}^1, \mathcal{F}^2)$

  Only one **mixing angle $\boldsymbol{\theta_{12}}$**



- If $\theta_{12} \in \{0, \pi/2\}$: no mixing

- If $0 < \theta_{12} < \pi/2$: mixing

[Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi 2021]

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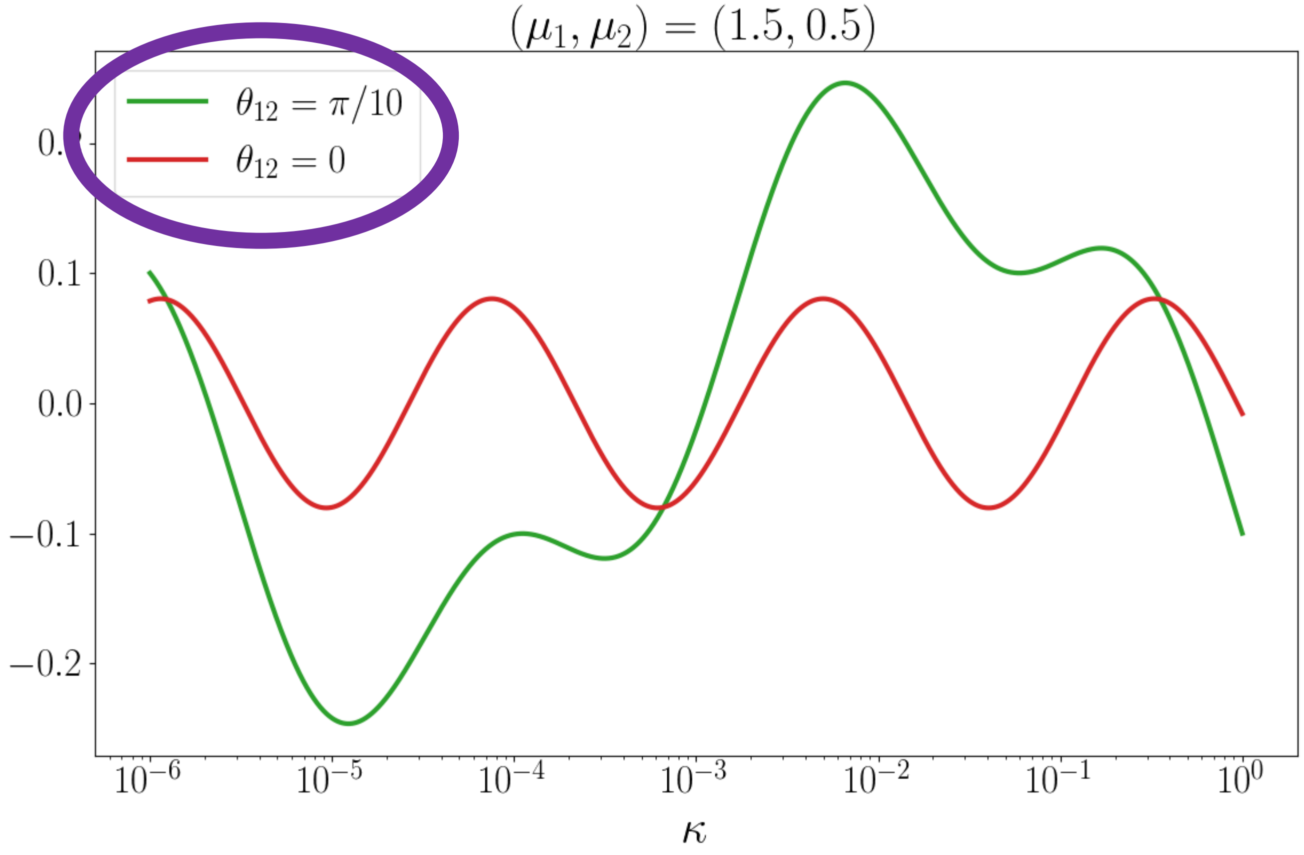
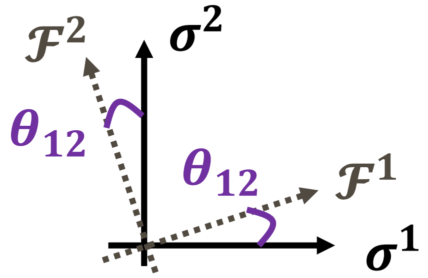
BISPECTRUM IN MULTIFIELD INFLATION



- Three fields: ζ and 2 flavors $(\mathcal{F}^1, \mathcal{F}^2)$
  - Only one **mixing angle $\boldsymbol{\theta_{12}}$**



- If $\theta_{12} \in \{0, \pi/2\}$: no mixing
  - **Oscillations** with frequency $\mu_{1,2}$
- If $0 < \ \theta_{12} < \pi/2$: mixing
  - **Modulated oscillations** with frequencies $\dfrac{\mu_1 \pm \mu_2}{2}$

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CONCLUSION

Depending on **the mass spectrum and mixing angles**, the squeezed limit of the bispectrum provides a **cosmic spectroscopy**: