Cosmology From Home 2023
July 2023

Based on: **[Lucas Pinol. 2021]**
JCAP 04(2021)048
[Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi. 2022]
PRD Letters (2023) 2, L021301

Lucas Pinol
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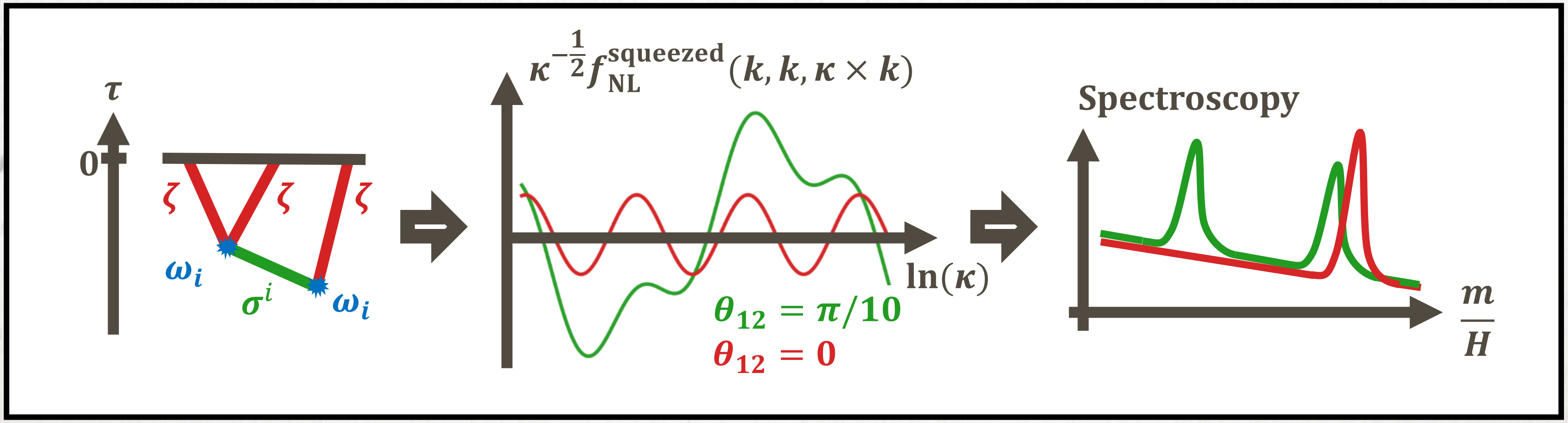
INFLATIONARY FLAVOR OSCILLATIONS
AND THE COSMIC SPECTROSCOPY

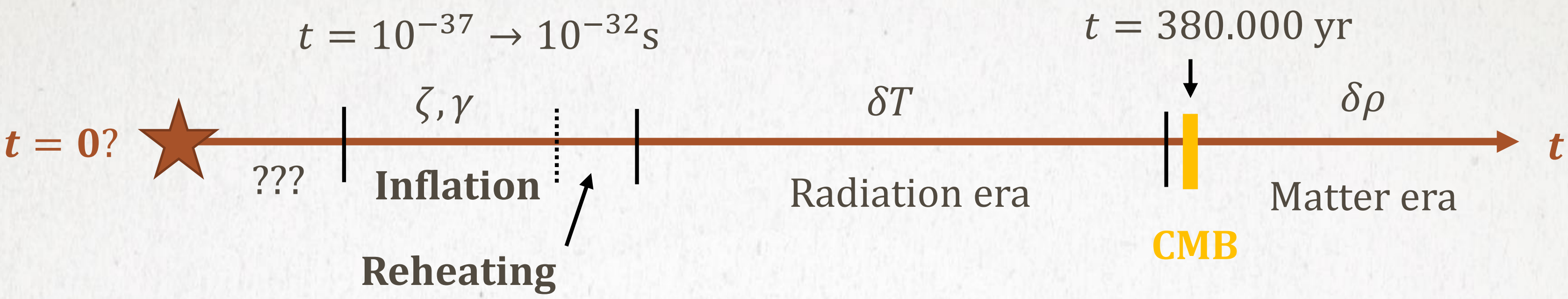


Other topics of research: Multifield stochastic inflation in phase space, multi-species reheating, primordial gravitational waves… Visit my website: lucaspinol.wordpress.com

I. INFLATION

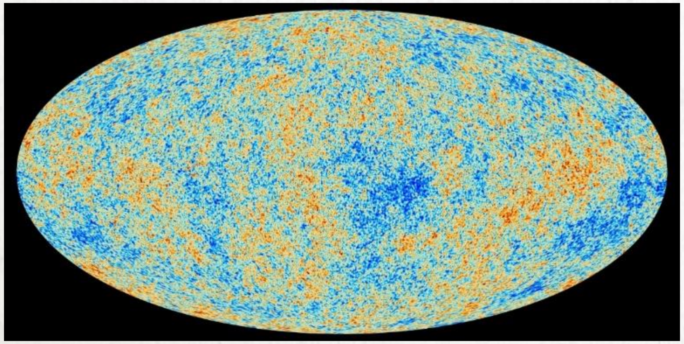
From cosmology to high-energy physics

Early universe: the big picture



Scalar fluctuations ~ density fluctuations → $\zeta(t, \vec{x})$

Tensor fluctuations ~ gravitational waves → $\gamma(t, \vec{x})$



Cosmic Microwave Background

motivates →

← predicts

Inflation

Solves several conceptual issues of the Hot Big Bang scenario

and correctly predicted CMB anisotropies that had yet to be observed in the 1980's

UV-sensitivity of inflation

Unique framework: general relativity + quantum field theory + precision data

$\langle \zeta^2 \rangle = (2.09 \pm 0.03) \times 10^{-9}$

$\log(E/\text{GeV})$ Natural units: $\hbar = c = 1$ and the only dimension is energy (or mass)

19 — M_{Pl} Planck mass

M_s String theory, quantum loop gravity etc.

16 — M_{GUT} : Grand Unified Theories (GUT):

Unification of the fundamental non-grav. forces

14 —

??? — **H, inflation**

Scale of inflation is unknown

Particle content is unknown

3 — Standard Model, LHC

} Accessible experiments on Earth

Inflation sensitive to high energies

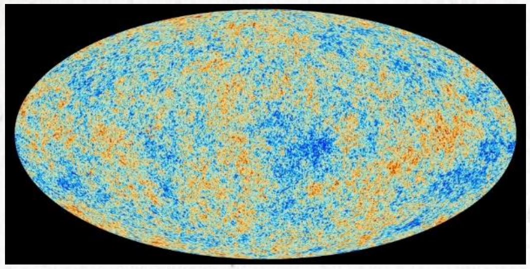
+

Precision data (current and future)

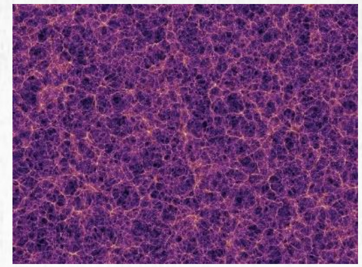
=

Formidable opportunity to test high-energy physics beyond the reach of terrestrial experiments

Observational probes of the early universe

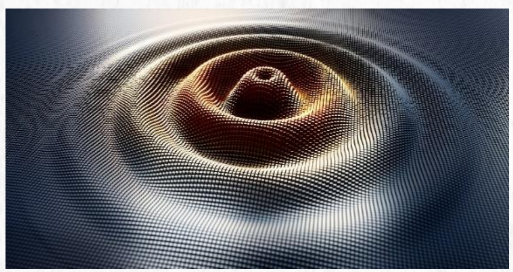
Current $=$ 

Cosmic Microwave Background

$+$ 

Large-Scale Structures

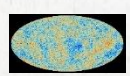
(scalars)

Future $=$ 

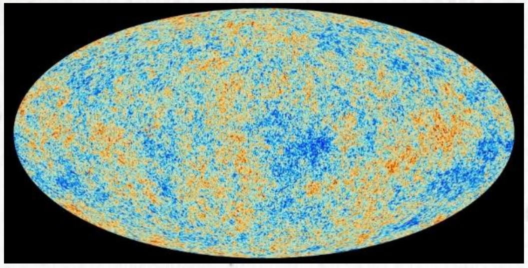
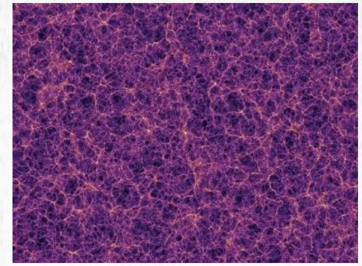
Primordial Gravitational Waves

(tensors) ?

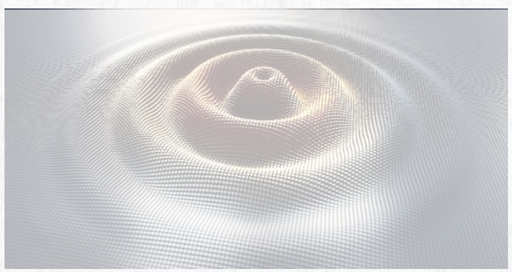
Objects of study $=$ **primordial correlations functions**

e.g. $\langle \zeta^2 \rangle \rightarrow \Big\langle$  $^2 \Big\rangle$; $\langle \gamma^2 \rangle \rightarrow \Big\langle$  $^2 \Big\rangle$; $\langle \zeta^3 \rangle \rightarrow \Big\langle$  $^3 \Big\rangle$; etc.

Observational probes of the early universe

Current $=$  $+$  **(scalars)**

Cosmic Microwave Background **Large-Scale Structures**

Future $=$  **(tensors) ?**

Primordial Gravitational Waves

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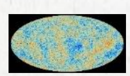
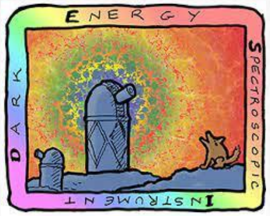
e.g. $\langle \zeta^2 \rangle \rightarrow \Big\langle$  $^2 \Big\rangle$; $\langle \gamma^2 \rangle \rightarrow \Big\langle$  $^2 \Big\rangle$; $\langle \zeta^3 \rangle \rightarrow \Big\langle$  $^3 \Big\rangle$; etc.

At the dawn of a new era for cosmological data



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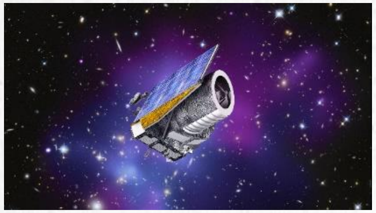
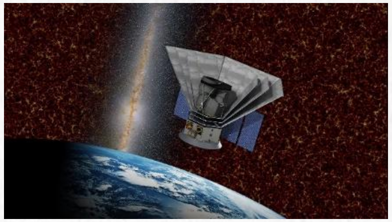


Euclid



SphereX

(and many others)

All these experiments will bring valuable information about early universe physics…

… only if our theoretical understanding is mature enough to interpret them correctly!

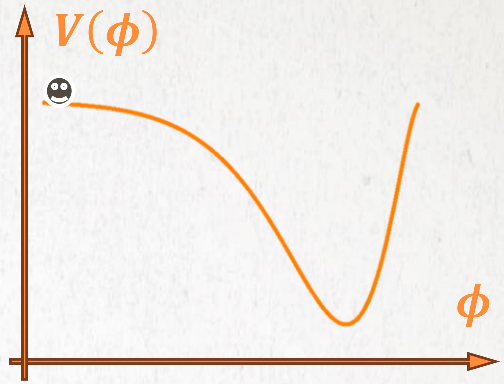
II. MULTIFIELD INFLATION

The inflationary flavor and mass eigenstates

Inflationary mechanism

Single-field slow-roll inflation with canonical kinetic terms:

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



- Simplest model that explains cosmological observations
- A large variety of **flat** scalar potentials do the job…
- … but **flat** scalar potentials are not natural in high-energy theories!

Multifield inflation with non-canonical kinetic terms:

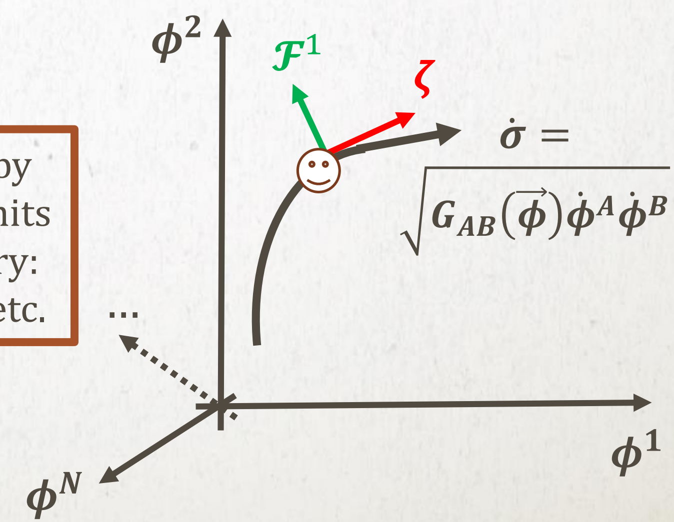
$$\mathcal{L} = -\frac{1}{2} \sum_{A,B} g^{\mu\nu} G_{AB}(\vec{\phi}) \partial_\mu \phi^A \partial_\nu \phi^B - V(\vec{\phi})$$

- Both **potential** and **kinetic** interactions
- Any number N of scalar fields
- Scalar potential needs not be flat

as predicted by low-energy limits of string theory: supergravity, etc.

- Inflation generically happens along a **curved** trajectory
- Adiabatic (ζ) and entropic ($\mathcal{F}^\alpha$) fluctuations

Background trajectory



Inflationary mechanism

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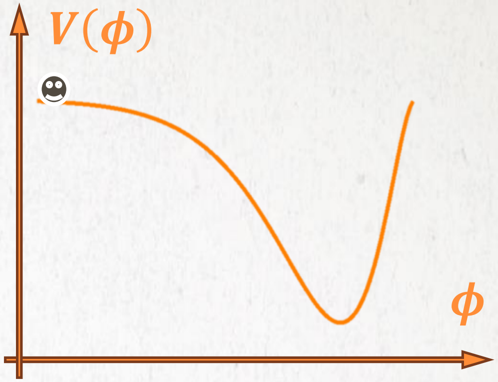

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Multifield inflation with non-canonical kinetic terms:

$$\mathcal{L} = -\frac{1}{2} \sum_{A,B} g^{\mu\nu} \boldsymbol{G_{AB}(\vec{\phi})} \partial_\mu \phi^A \partial_\nu \phi^B - \boldsymbol{V(\vec{\phi})}$$

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Do we absolutely have to think in terms of *covariant models*?

No!

↓

"Effective field theories of inflationary fluctuations"

From covariant models to multifield fluctuations

Technical steps:

- Multifield perturbation theory: $\phi^A(t,\vec{x}) = \bar{\phi}^A(t) + \delta\phi^A(t,\vec{x}) + \cdots$
- Identify covariant fluctuations: $Q^A = \delta\phi^A + \Gamma^A{}_{BC}\,\delta\phi^B\,\delta\phi^C/2 + \cdots$
- Define adiabatic and entropic fluctuations: $Q_\sigma = e_{\sigma A}\,Q^A$; $Q_s^\alpha = e_{sA}^\alpha\,Q^A$
- Fix the gauge freedom (comoving gauge): $Q_\sigma^{\mathrm{com}} = 0$; $g_{ij}^{\mathrm{com}} = a^2\exp[2\,\zeta]\,\delta_{ij}$

$$Q_s^{\alpha,\mathrm{com}} = \mathcal{F}^\alpha$$

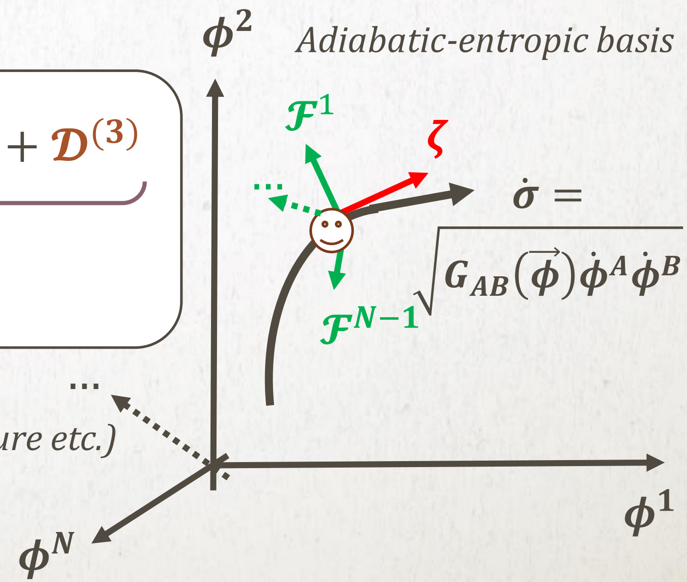
- Expand the action (up to cubic order for bispectrum calculations)

$$\mathcal{L}(\zeta,\mathcal{F}^\alpha) = \underbrace{\mathcal{L}^{(2)}(\zeta,\mathcal{F}^\alpha)}_{\text{Dictating the power spectrum}} + \underbrace{\mathcal{L}^{(3)}_{\mathrm{Maldacena}}(\zeta) + \mathcal{L}^{(3)}_{\mathrm{new}}(\zeta,\mathcal{F}^\alpha) + \mathcal{D}^{(3)}}_{\text{Dictating the bispectrum}}$$

Dictating the power spectrum

Dictating the bispectrum

Involves covariant derivatives of $V(\vec{\phi})$ and of $G_{AB}(\vec{\phi})$ (Riemann curvature etc.)



[Lucas Pinol. 2021]
JCAP 04(2021)048

Flavor and mass bases

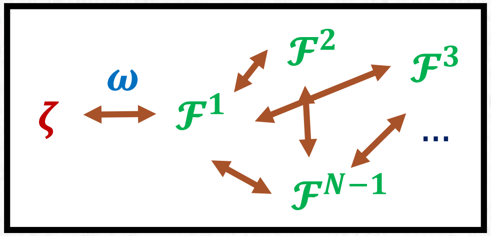
$$\mathcal{L}^{(2)}_{\text{flavor}} = \frac{a^3}{2}\left[\delta_{\alpha\beta}\left(\dot{\mathcal{F}}^{\alpha}\dot{\mathcal{F}}^{\beta} - \frac{\partial\mathcal{F}^{\alpha}\partial\mathcal{F}^{\beta}}{a^2}\right) - \boldsymbol{M^2_{\alpha\beta}}\mathcal{F}^{\alpha}\mathcal{F}^{\beta}\right] + 4\sqrt{2\epsilon}M_{\text{Pl}}\,\boldsymbol{\omega\delta_{\alpha 1}}\mathcal{F}^{\alpha}\dot{\zeta}$$

- **Non-trivial mass matrix mixing**
- **Only the first extra field $\mathcal{F}^1$ is coupled to ζ: portal field + sterile sector**

Flavor basis: interactions are specified

$\mathcal{F}^1$ *portal* to ζ

$\mathcal{F}^{2,\dots,N-1}$ *sterile* sector



[Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi. 2022]

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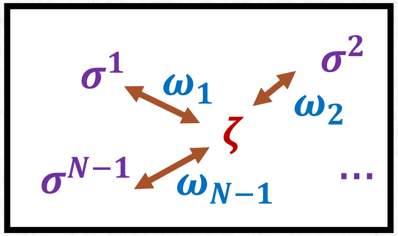
Flavor and mass bases

$$\mathcal{L}^{(2)}_{\rm flavor} = \frac{a^3}{2}\left[\delta_{\alpha\beta}\left(\dot{\mathcal{F}}^\alpha \dot{\mathcal{F}}^\beta - \frac{\partial \mathcal{F}^\alpha \partial \mathcal{F}^\beta}{a^2}\right) - \boldsymbol{M}^{\boldsymbol{2}}_{\boldsymbol{\alpha\beta}} \mathcal{F}^\alpha \mathcal{F}^\beta\right] + 4\sqrt{2\epsilon} M_{\rm Pl}\, \boldsymbol{\omega \delta_{\alpha 1}} \mathcal{F}^\alpha \dot{\zeta}$$

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



Mass basis:
masses are specified

All $\boldsymbol{\sigma_i}$ are coupled to ζ with $\boldsymbol{\omega_i}$

$$\mathcal{L}^{(2)}_{\rm mass} = \frac{a^3}{2}\left[\delta_{ij}\left(\dot{\sigma}^i \dot{\sigma}^j - \frac{\partial \sigma^i \partial \sigma^j}{a^2}\right) - \sum_i m_i^2 \sigma_i^2\right] + 4\sqrt{2\epsilon} M_{\rm Pl}\, \overbrace{\boldsymbol{\omega\, O^1{}_i}}\, \sigma^i \dot{\zeta}$$

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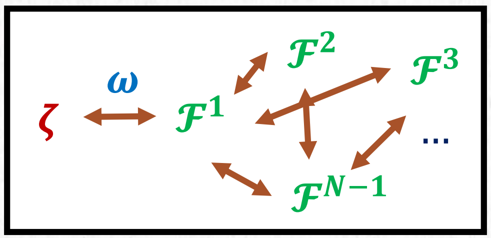

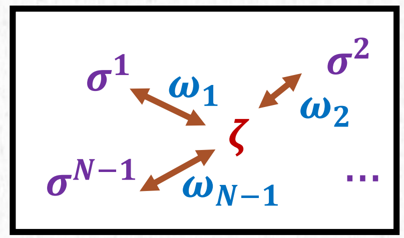

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[Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi. 2022]

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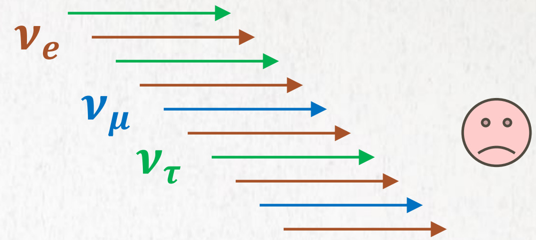
Analogy with neutrino oscillations

NO INTERACTIONS



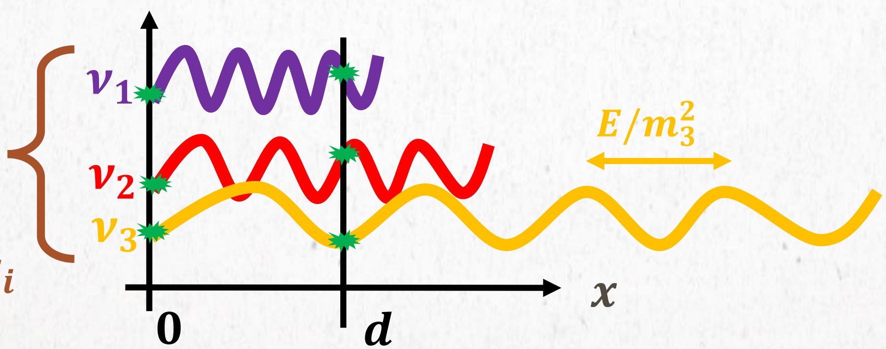
This is the Sun

This is me

It is emitting electronic neutrinos*

I am seeing many less electronic neutrinos

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



*Entries of the PMNS** matrix: mixing angles, due to the mass matrix $M_{\alpha\beta}$ of neutrino flavors*

*also some ν_τ from MSW

***Pontecorvo-Maki-Nakagawa-Sakata*

Analogy with neutrino oscillations

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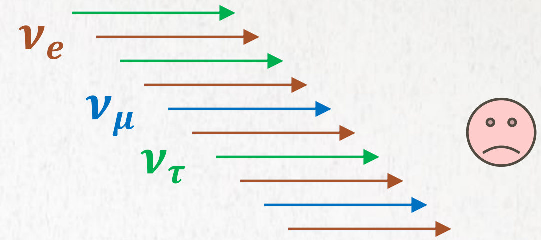

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It is emitting electronic neutrinos

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I am seeing many less electronic neutrinos

ζ is the "detector"

$\mathcal{F}^\alpha$ are the flavor eigenstates and σ_i the freely propagating ones: the mass eigenstates

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

Mixing angles *if* $N_{\rm flavor} = 3$

Inflationary flavor oscillations due to the misalignment between flavor and mass eigenstates

Analogy with neutrino oscillations

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

It is em… …inos

ζ is the "detector"

$\mathcal{F}^\alpha$ are the flavor eigenstates and σ_i the freely propagating ones: the mass eigenstates

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

Mixing angles *if* $N_{\text{flavor}} = 3$

→ Inflationary flavor oscillations due to the misalignment between flavor and mass eigenstates

III. THE COSMIC SPECTROSCOPY

Masses, couplings… and mixing angles!

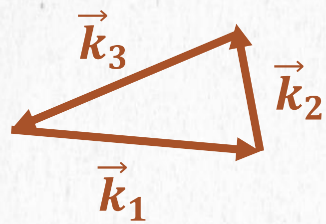
Bispectrum in single-field inflation

Power spectrum $= 2.10 \times 10^{-9}$

ζ the primordial curvature perturbation

$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle = (2\pi)^7 \, \delta^{(3)}\left(\overrightarrow{k_1} + \overrightarrow{k_2} + \overrightarrow{k_3}\right) \frac{A_s^2}{(k_1 k_2 k_3)^2} \times S(k_1, k_2, k_3)$$

Shape function



Probes interactions during inflation

Observable in the CMB, large-scale structures → so far no detection, only constraints

Bispectrum in single-field inflation

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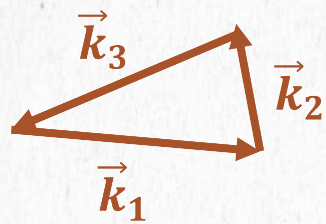


Shape function

$f_{\mathrm{NL}}^{\mathrm{equilateral}} < \mathbf{0.0035}$ (from $r < 0.056$)

(attractor, canonical kinetic terms)

Ex: Single-field inflation

$$S = \frac{5}{12}(1 - n_s) S_{\mathrm{loc}} + \frac{\epsilon}{8} S_{\mathrm{eq}} + \cdots = \textbf{VERY SMALL}$$

[Maldacena. 2003]

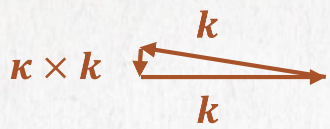
$f_{\mathrm{NL}}^{\mathrm{squeezed}} = \mathbf{0.015}$

Actually, residual gauge freedom $\rightarrow S^{\text{squeezed, observable}} \propto \left(\frac{k_l}{k_s}\right) \ll 1$

[Tanaka, Urakawa. 2011] [Pajer, Schmidt, Zaldarriaga. 2013]

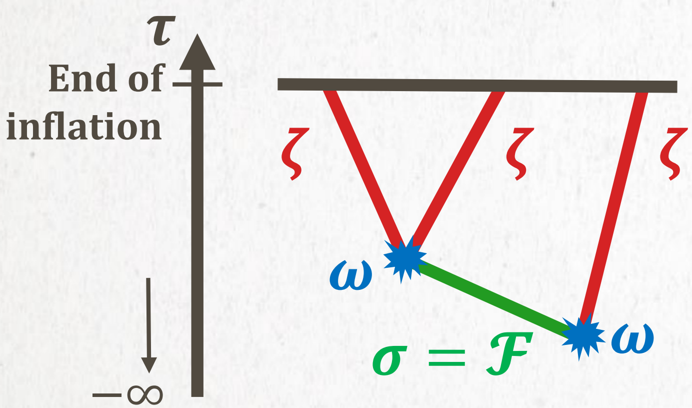
Bispectrum in two-field inflation

The squeezed limit as a cosmological collider



Squeezing: $\kappa = k_3/k_{1,2}$

Usual curvature perturbation ζ + one heavy field $\sigma = \mathcal{F}$ (no flavor oscillation)



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

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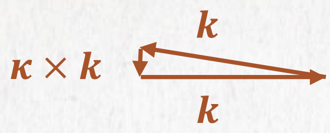

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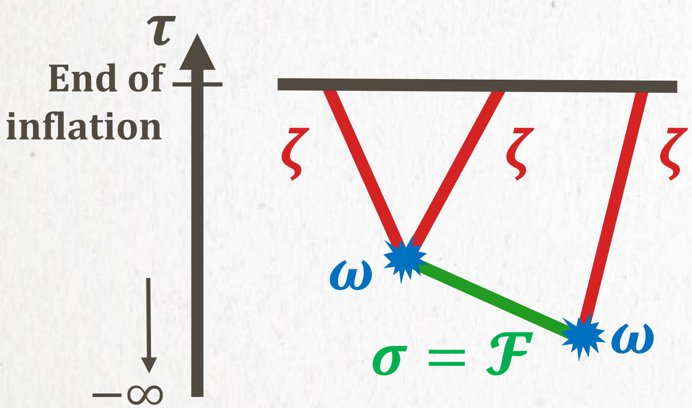


$$S^{\text{squeezed}} \sim \left(\frac{\omega}{H}\right)^2 \kappa^{-\frac{1}{2}} e^{-\pi\mu} \cos[\mu \ln(\kappa) + \varphi(\mu)]$$

Oscillatory pattern: massive particle

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

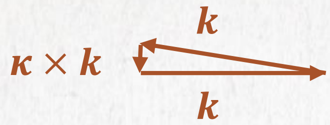
[Chen, Wang 2009]
[Noumi, Yamaguchi, Yokoyama 2013]
[Arkani-Hamed, Maldacena 2015]

- ❖ **Amplitude proportional to coupling constants**
- ❖ **Scaling law advantageous compared to single field**
- ❖ **Oscillations with frequency = mass of the heavy field**

→ Distinctive non-single-field signature, but pinpointing m/H requires care!

Bispectrum in many-field inflation

The cosmic spectroscopy



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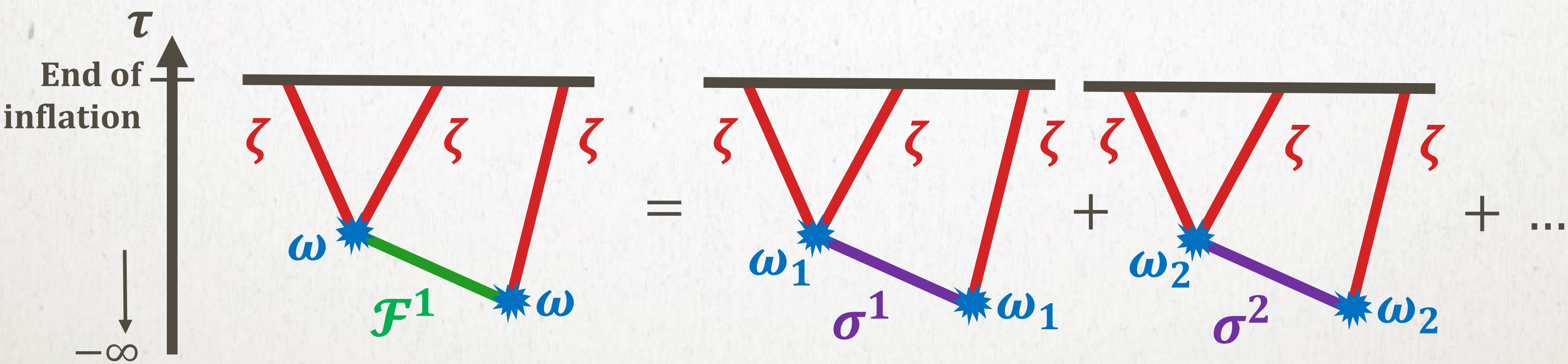

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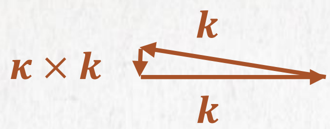
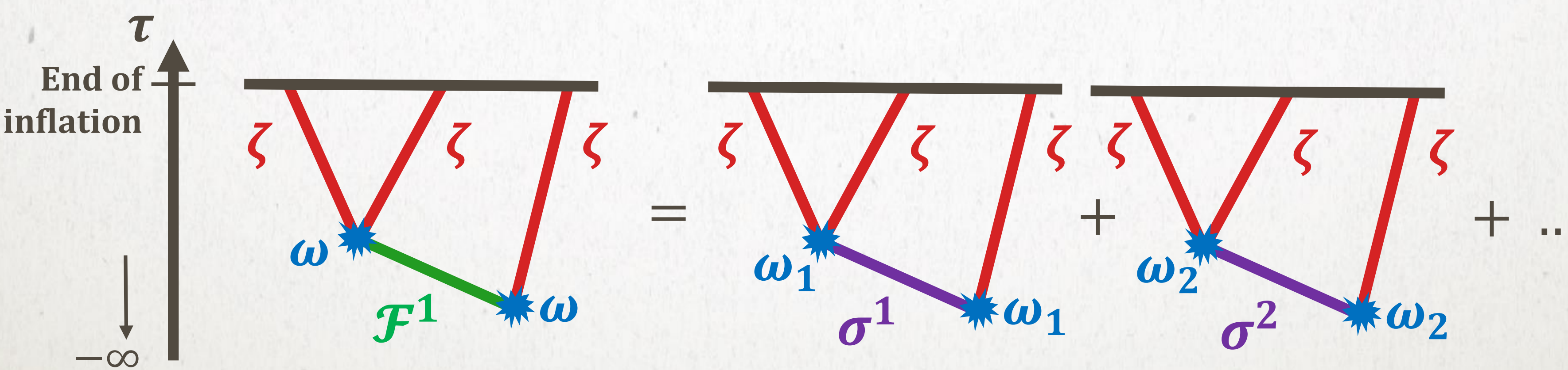


Squeezing: $\kappa = k_3/k_{1,2}$

$$\mu_i = \sqrt{\frac{m^2_{\sigma_i}}{H^2} - \frac{9}{4}}$$

N-field $$S^{\text{squeezed}} \sim \left(\frac{\omega}{H}\right)^2 \kappa^{1/2} \sum_{i=1}^{N-1} f(\theta_i) e^{-\pi\mu_i} \cos[\,\mu_i \ln(\kappa) + \varphi(\mu_i)\,]$$

- Modulated oscillations with frequencies = combinations of ALL the masses
- Relative amplitudes depend on the mixing angles of the theory: $\theta_i \subset \omega_i$

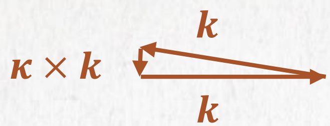


[Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi. 2022]

PRD Letters (2023) 2, L021301

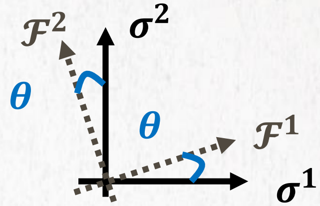
Bispectrum in many-field inflation

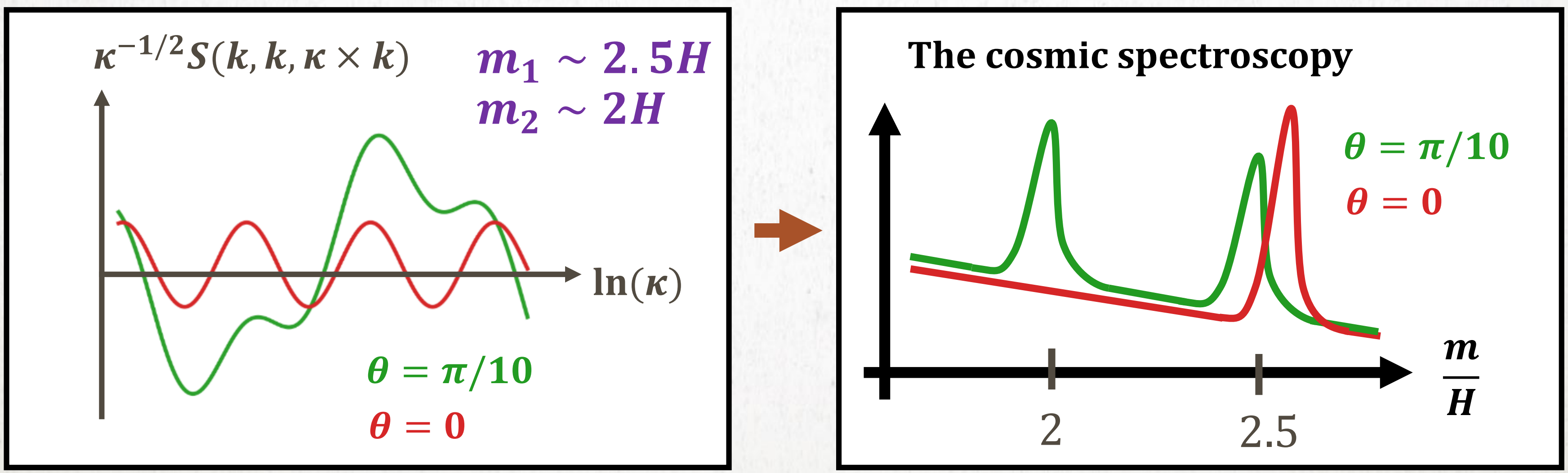
The cosmic spectroscopy



Squeezing: $\kappa = k_3/k_{1,2}$

$N = 3 \rightarrow N - 1 = 2$ flavors: $\{\zeta, \mathcal{F}^1, \mathcal{F}^2\} \leftrightarrow \{\zeta, \sigma^1, \sigma^2\}$



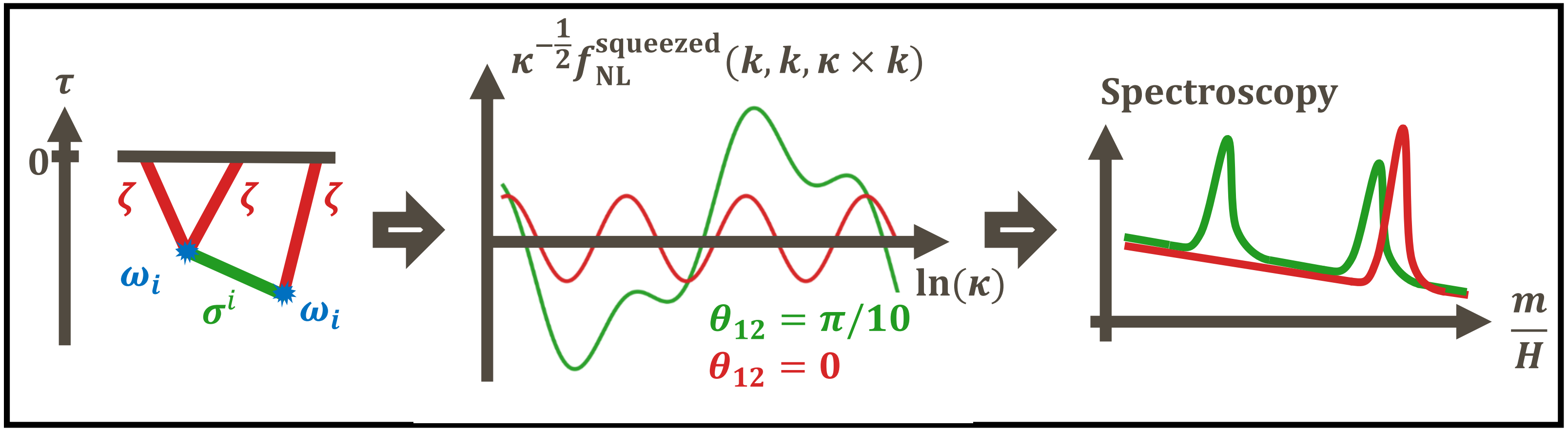


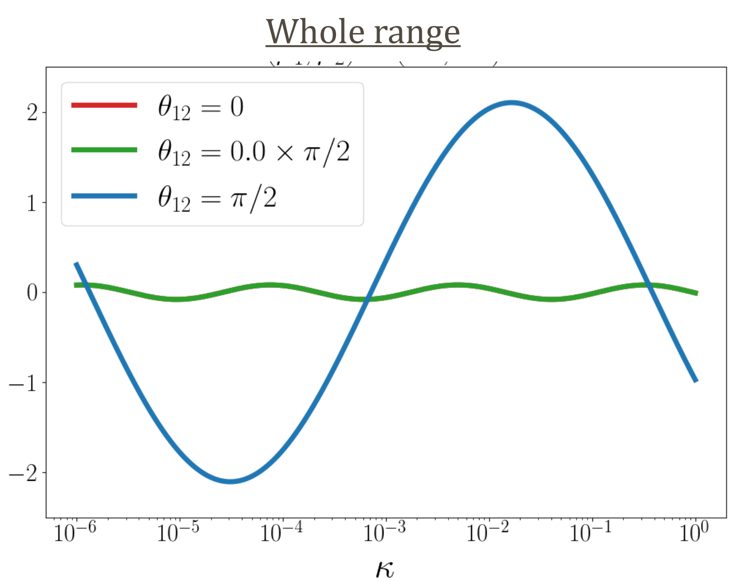
[Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi. 2022]

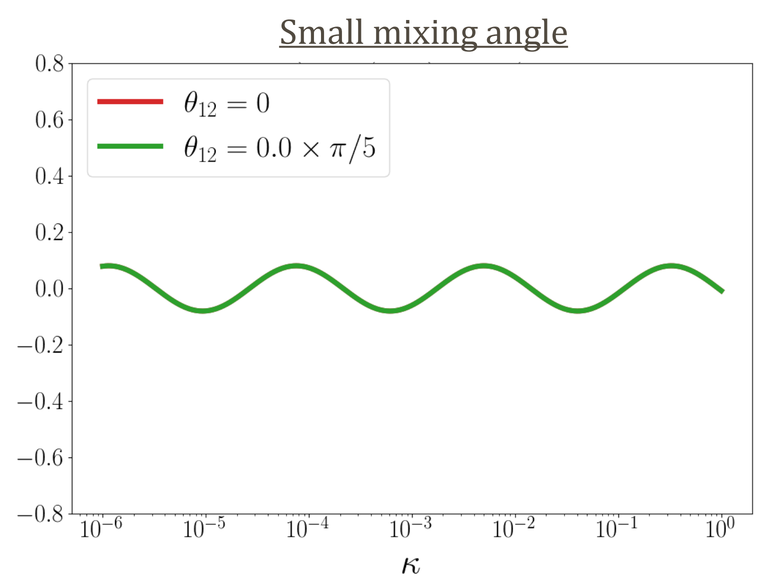
PRD Letters (2023) 2, L021301

Conclusion

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







Outlook, and directions beyond

- Not only heavy fields $\left(\frac{m}{H} > \frac{3}{2}\right)$ but also light ones, for any number of fields

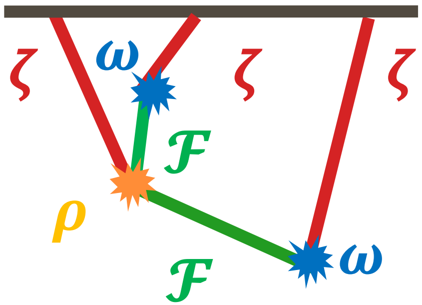
  [Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi. 2022]
  PRD Letters (2023) 2, L021301

- Cosmological colliders at strong mixing $\left(\frac{\omega}{H} > 1\right)$, with features $(\omega(t))$

  [Werth, Lucas Pinol, Renaux-Petel. 2023]
  ArXiv:2302.00655

- Cosmological colliders with several-particle exchanges

  [Werth, Lucas Pinol, Renaux-Petel. 2023]
  ArXiv:2302.00655



- Systematics description of cosmological colliders

  [Werth, Lucas Pinol, Renaux-Petel. To come in fall 2023]

- Cosmic spectroscopy of string-inspired inflation, etc.

CORRELATION FUNCTIONS: CMB CONSTRAINTS

[Planck 2018]
[BICEP-Keck 2022]

- Power spectra: $\langle \zeta^2 \rangle = A_s \left(\frac{k}{k_{\rm CMB}} \right)^{n_s - 1}$

  $\langle \gamma^2 \rangle = r \times A_s \left(\frac{k}{k_{\rm CMB}} \right)^{n_t}$

  → $A_s = (2.09 \pm 0.03) \times 10^{-9}$

  $n_s = 0.9649 \pm 0.0042$

  $r < 0.035$

- Scalar bispectrum: $\langle \zeta^3 \rangle$ →

  $f_{\rm NL}^{\rm loc} = -0.9 \pm 5.1$

  $f_{\rm NL}^{\rm eq} = -26 \pm 47$

  $f_{\rm NL}^{\rm ortho} = -38 \pm 24$

all are compatible with zero

OTHER CONSTRAINTS

Bounds at CMB scales

- Higher-order correlation functions:

$\langle\zeta^4\rangle \xrightarrow{\text{squeezed}} g_{\rm NL} = (-5.8 \pm 6.5)10^4$ **[Planck 2018]**

$\langle\zeta^4\rangle \xrightarrow{\text{collapsed}} \tau_{\rm NL} = 400 \pm 1300$ **[Marzouk, Lewis, Carron 2022]**

from theory…

$\tau_{\rm NL} \geq \left(\frac{6}{5} f_{\rm NL}^{\rm loc}\right)^2$ **(= for single-field)**

[Suyama, Yamaguchi 2007]
[Smith, LoVerde, Zaldarriaga 2011]

- Tensor and mixed scalar-tensor PNG

$\langle\zeta^2\gamma\rangle \xrightarrow{\text{squeezed}} f_{\rm NL,loc}^{\zeta\zeta\gamma} = -48 \pm 28$ **[Shiraishi, Liguori, Fergusson 2017]**

$\langle\zeta\gamma^2\rangle \xrightarrow{\text{squeezed}} f_{\rm NL,loc}^{\zeta\gamma\gamma} = \;???$

$\langle\gamma^3\rangle \xrightarrow{\text{squeezed}} f_{\rm NL,loc}^{\gamma\gamma\gamma} = 220 \pm 170$ **[WMAP 2013]**

} **GW anisotropies**

… and nothing else…

Please tell me if these are outdated

FUTURE CONSTRAINTS

- Power spectra: precision n_s and features

  $\sigma_r \sim 10^{-3}$

  [LiteBIRD, CMB-S4, SO]

- Primordial non-Gaussianities: $\sigma_{f_{\rm NL}^{\rm loc}} \sim 2$

  $\sigma_{f_{\rm NL}^{\rm eq}} \sim 10$

  [DESI, Euclid]

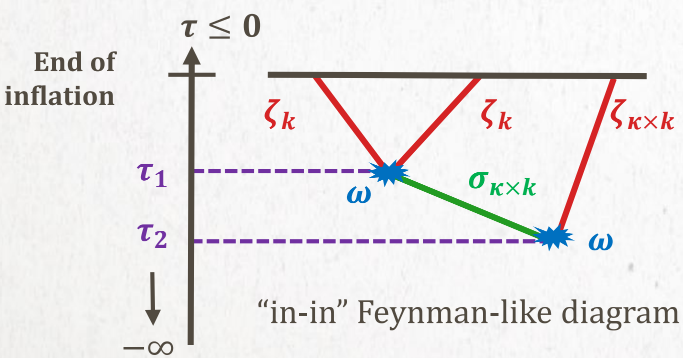
  $\sigma_{f_{\rm NL}^{\rm loc}} \sim 1$ **[SphereX]**

The cosmological collider

ζ the massless curvature perturbation

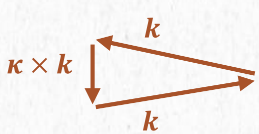
σ a heavy fluctuation ($m \gtrsim H$) as motivated, e.g., by supersymmetry

Two-field



"in-in" Feynman-like diagram:

single-exchange channel



iscosceles triangles

The cosmological collider

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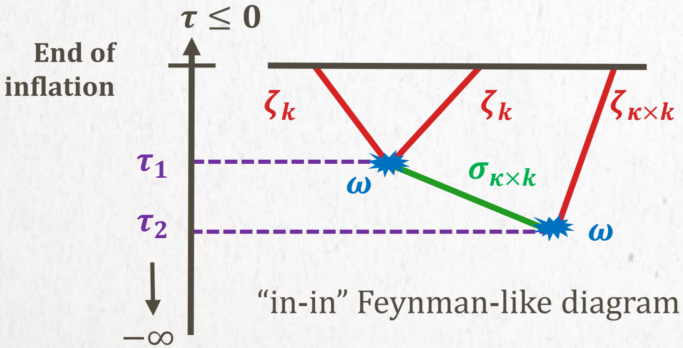
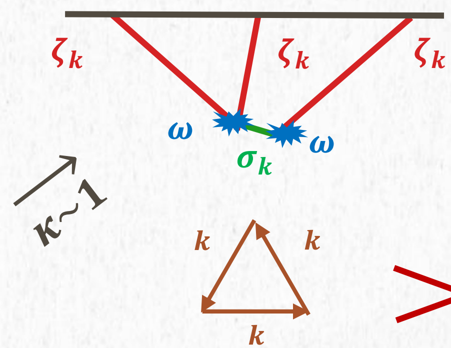
Two-field



"in-in" Feynman-like diagram:

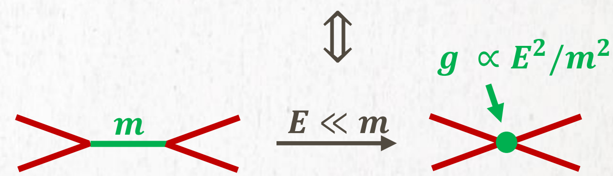
single-exchange channel



Single characteristic time: $|\tau_2| \sim |\tau_1| \sim 1/k$

Contact-like:

effectively single-field



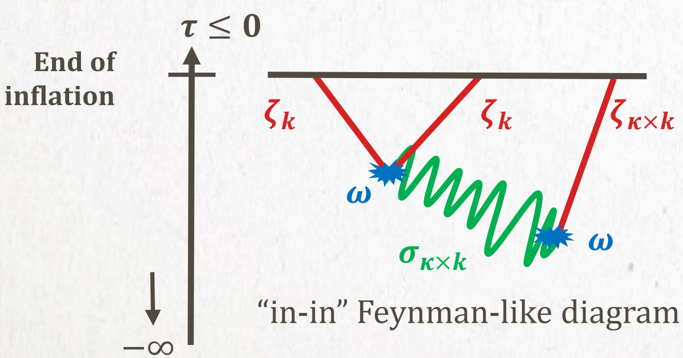
The cosmological collider

ζ the massless curvature perturbation

σ a heavy fluctuation ($m \gtrsim H$) as motivated, e.g., by supersymmetry

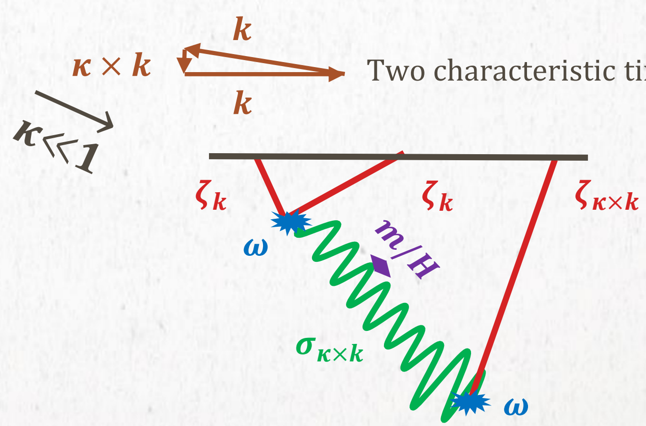
$$\textbf{Two-field:} \quad S(k,k,\kappa\times k) \xrightarrow[\kappa\ll 1]{} \left(\frac{\omega}{H}\right)^2 e^{-\pi(m/H)}\,\kappa^{1/2}\cos[m/H\,\mathrm{Log}(\kappa)+\varphi(m/H)]$$

Oscillations with frequency = mass of the heavy field



"in-in" Feynman-like diagram:

single-exchange channel



Two characteristic times: $|\tau_2| \sim |\tau_1|/\kappa \gg |\tau_1|$

<u>Particle-exchange</u>:

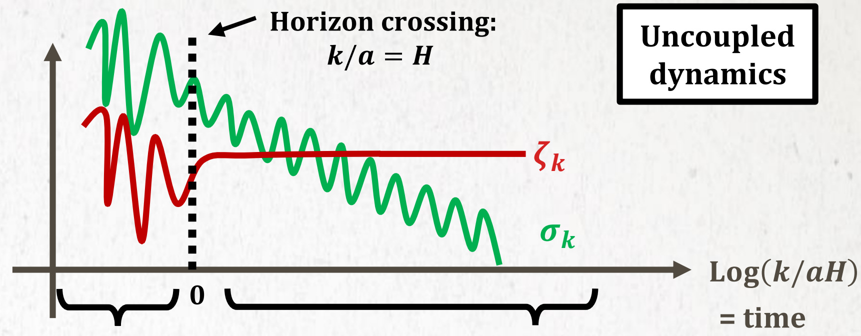
resonance

The cosmological collider

Uncoupled dynamics

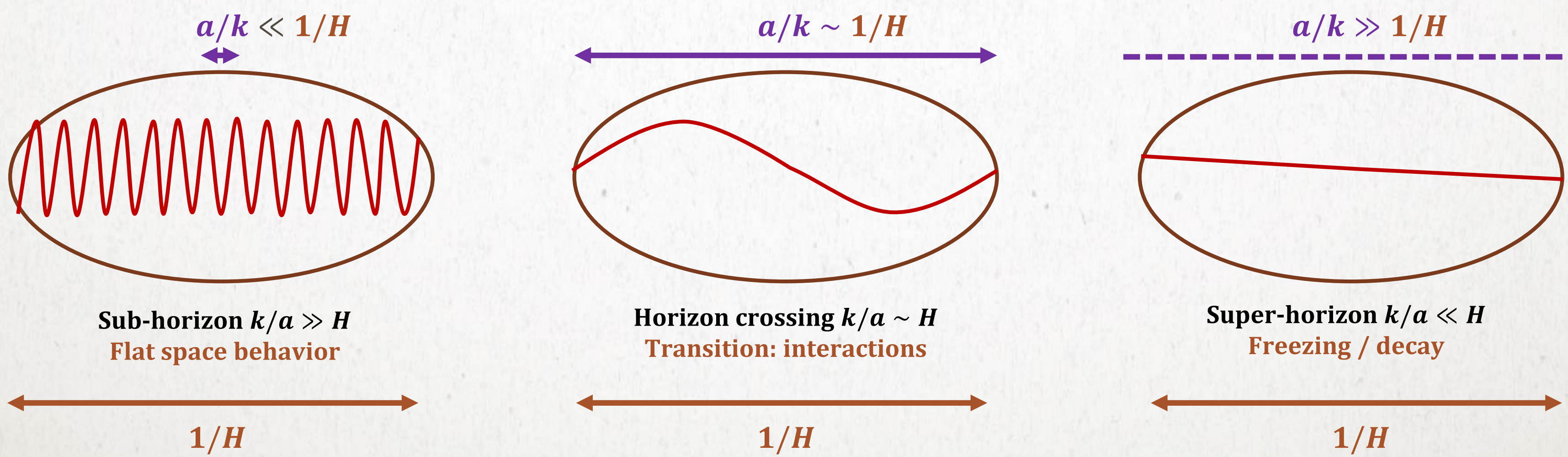
ζ the massless curvature perturbation

σ a heavy field ($m \gtrsim H$)



Sub-horizon:
Vacuum oscillations

Super-horizon:
massless field freezes
heavy field decays $\propto a^{-3/2}\cos[(m/H)\mathrm{Log}(k/aH)]$
massive oscillations

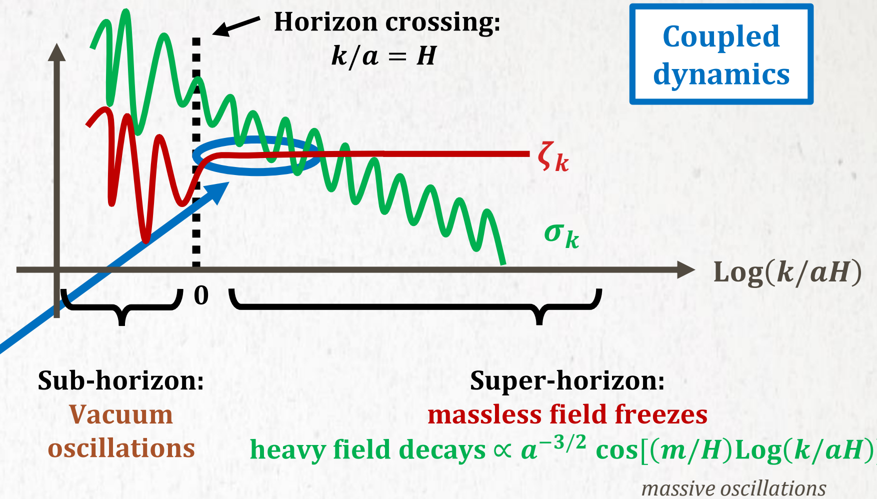


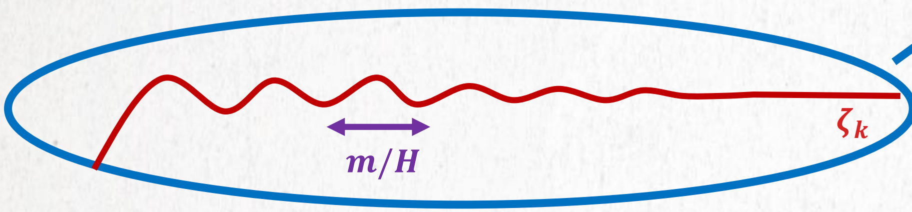
The cosmological collider

ζ **the massless curvature perturbation**

σ **a heavy field** ($m \gtrsim H$)

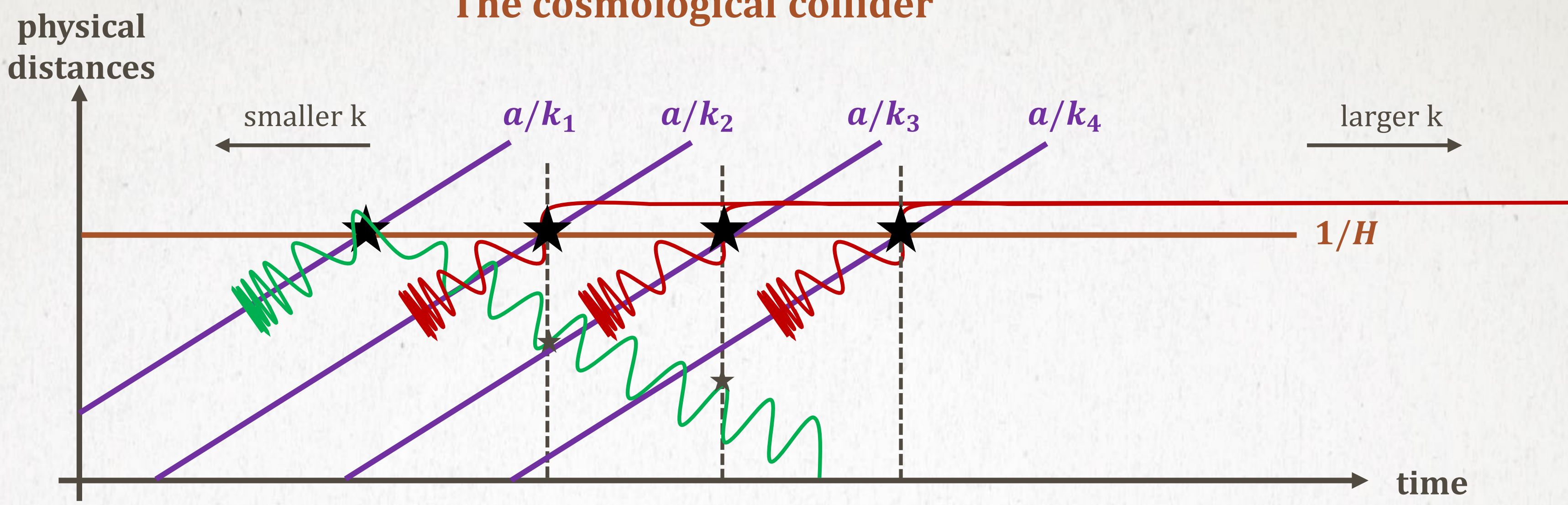
Coupled by ω





Interactions $\propto \omega \rightarrow \zeta_k$ **develops a transient phase**$[m/H, \text{Log}(k/aH)]$

The cosmological collider



Clean probe = soft limits of primordial NG, e.g. squeezed bispectrum:

$$f_{NL}^{\text{squeezed}} = \lim_{k_1=k_2=k_3/\kappa} S(k_1,k_2,k_3) \sim \left(\frac{\omega}{H}\right)^2 e^{-\pi(m/H)} \cos[m/H \,\text{Log}(\kappa) + \varphi(m/H)]$$

Oscillatory pattern: imprint from massive particle production