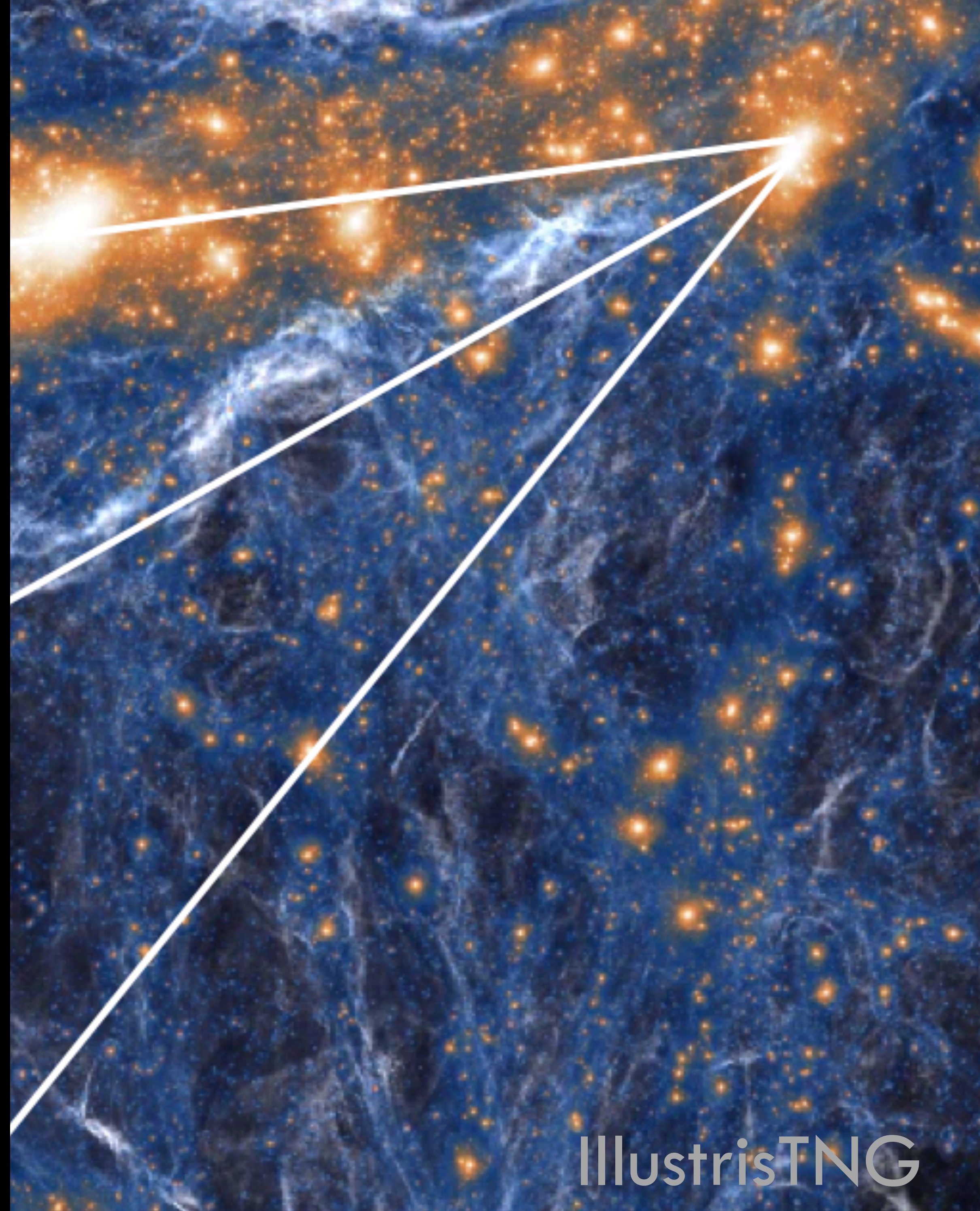
arXiv
2404.01894
2204.01781
2201.07238

with **Giovanni Cabass** & **Misha Ivanov**,
as well as Marko Simonovic, Kaz Akitsu,
Stephen Chen & Matias Zaldarriaga

The Galactic Cosmological Collider

Oliver H. E. Philcox
Columbia University
Simons Foundation

University of Edinburgh, June 2024



What do we Want to Know About Inflation?

Simplest (phenomenological) model

- A *single field* evolving along an almost flat potential with **quantum fluctuations**

$$\text{Simplest Lagrangian} \sim \frac{1}{2}(\partial\phi)^2 - V(\phi)$$

But:

- What is the **energy scale** of inflation? *[Hubble]*

$$H \sim 10^{14}\text{GeV ?}$$

- What sets the **potential**?

$$V(\phi) = \;???$$

- Were there **other fields** during inflation?

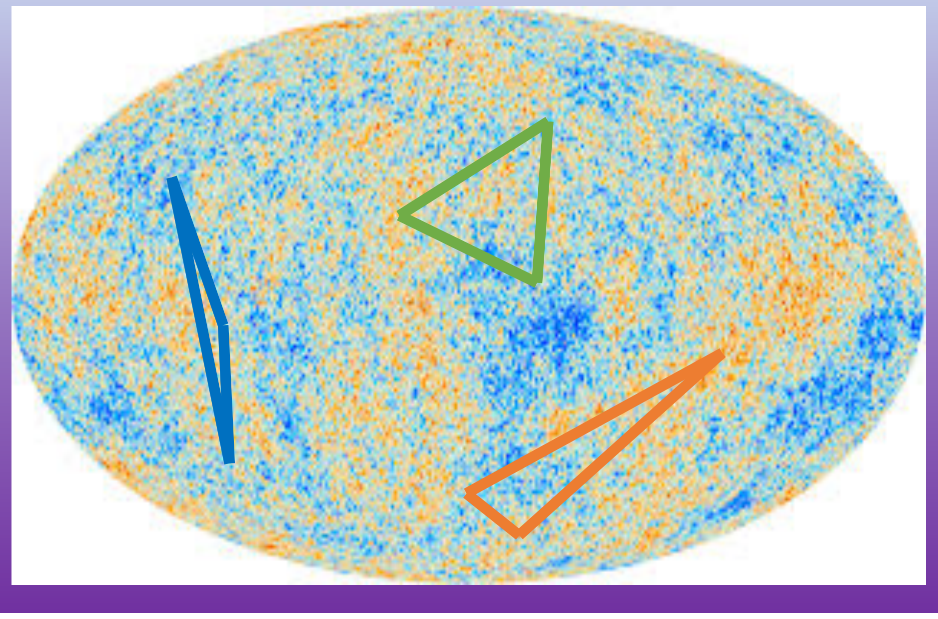
$$\phi \to \phi, \chi, \psi_\mu, \ldots$$

- Did the fields **interact**?

$$\text{Lagrangian} \supset \dot{\phi}^3 + \ldots$$

Linde, Guth, Starobinsky, Lyth, Mukhanov, Sasaki, …

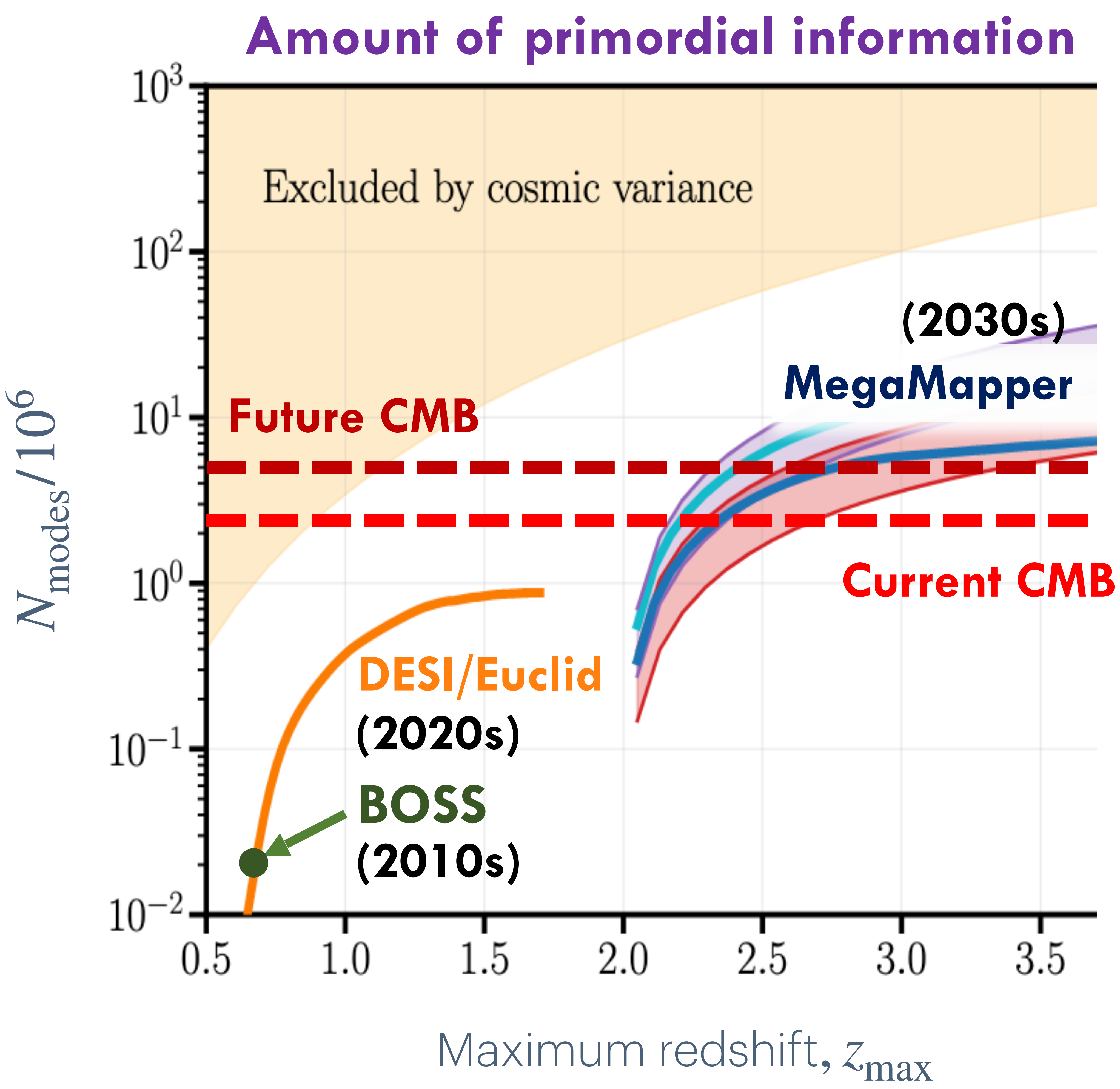
The Future of Non-Gaussianity



- Future **CMB** experiments will improve by $\approx 2\times$
  - This is a **two-dimensional** field
  - We're running out of modes to look at!
  - Small-scales are **hard**

- What about **galaxy surveys**?
  - This is a **three-dimensional** field
  - New surveys will map $\sim 100\times$ more galaxies than Stage-III

[2020s: DESI, Euclid, SPHEREx, LSST, Roman, …]



CMB-S4, Simons Observatory, Sailer+22, Ferraro+22

How to Model Inflation

?

Inflationary Theory

Encodes **inflation model**

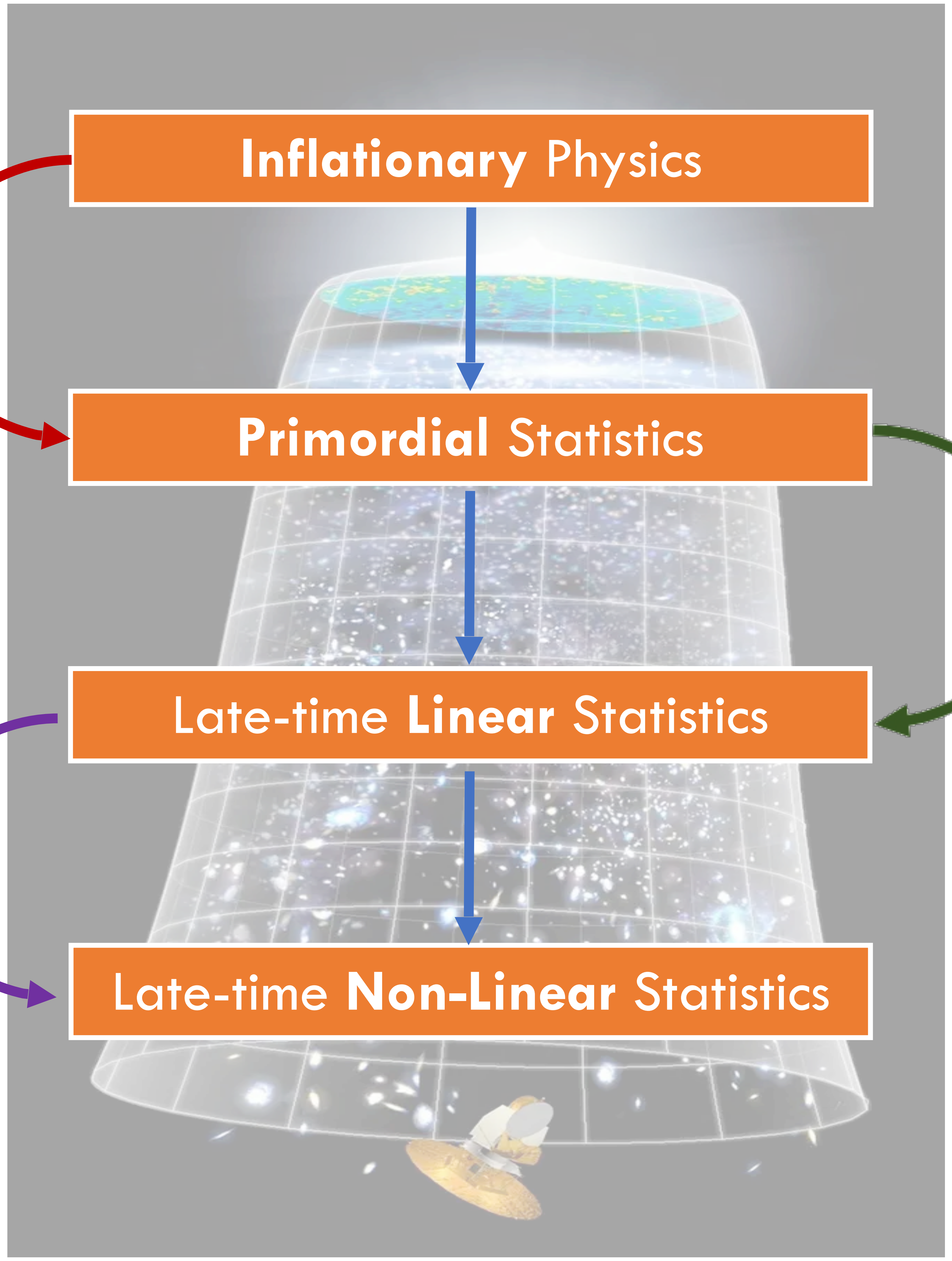
$P_\zeta, B_\zeta, \cdots$

?

Perturbation Theory

Encodes **gravity, hydrodynamics, galaxy formation**

biases, counterterms, etc.



Linear Theory

Encodes **expansion history**

$H_0, \Omega_m, \Omega_b, \Lambda$

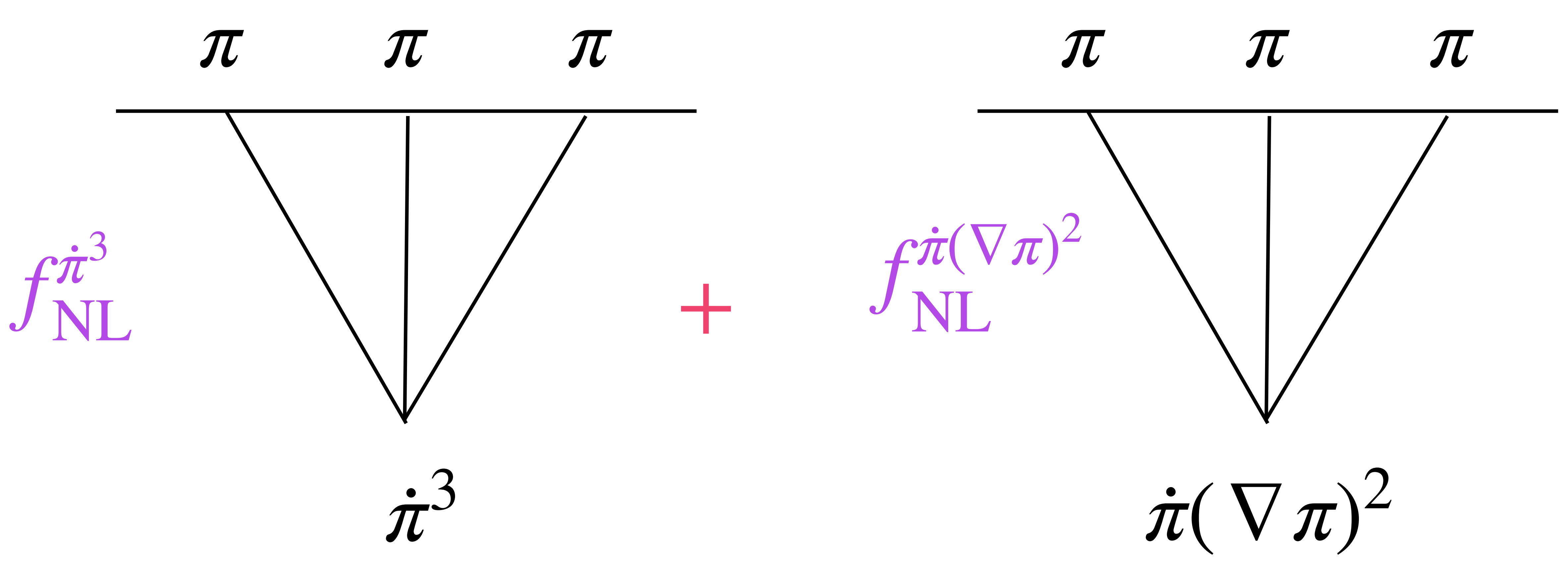
Step 1: Modeling Inflation

- Write down the most-generic **action** for single-field inflation (assuming shift-symmetries)

$$S_{\rm EFT} = \int {\rm d}^4x\sqrt{-g}\left[-\frac{M_{\rm P}^2\dot{H}}{c_s^2}\left(\dot{\pi}^2 - c_s^2\frac{(\boldsymbol{\nabla}\pi)^2}{a^2}\right) + \frac{M_{\rm P}^2\dot{H}}{c_s^2}(1-c_s^2)\left(\frac{\dot{\pi}(\boldsymbol{\nabla}\pi)^2}{a^2} - \left(1+\frac{2}{3}\frac{\tilde{c}_3}{c_s^2}\right)\dot{\pi}^3\right)\right]$$

for Goldstone mode π ($\sim$ inflaton) and sound-speed c_s at $\mathcal{O}(3)$.

- This sources two **bispectra:**



Equivalently: $f_{\rm NL}^{\rm eq}$ & $f_{\rm NL}^{\rm orth}$

Cheung+08, Senatore+09

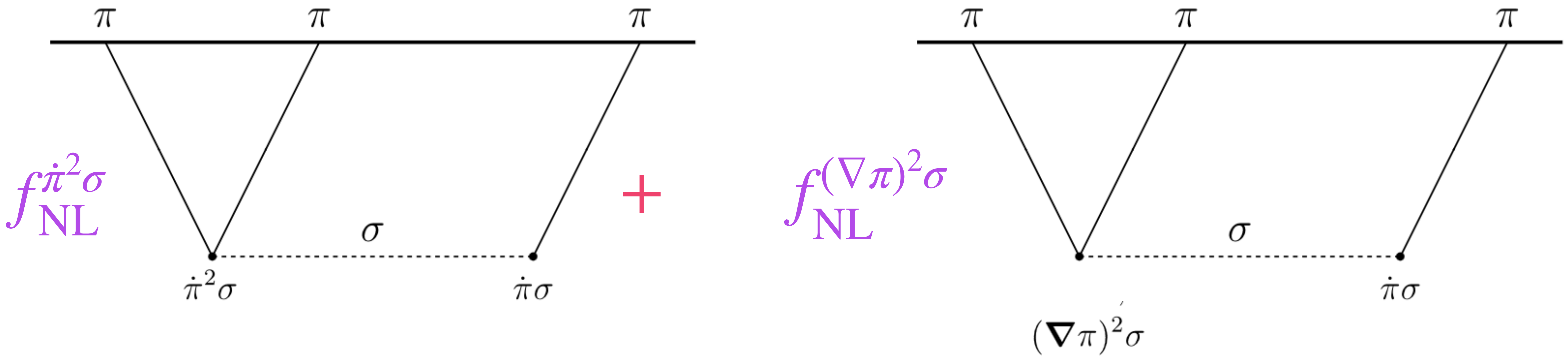
Step 1: Modeling Inflation

- We could also consider multi-field inflation (still assuming shift-symmetries)

$$S_{\rm EFT} \supset \int d^4x\sqrt{-g}\left[A\dot{\pi} + B\dot{\pi}^2 + C\frac{(\nabla\pi)^2}{a^2}\right]\sigma$$

for **scalar-field** σ of mass m_σ and sound-speed c_σ with coupling constants A, B, C (at $\mathcal{O}(3)$).

- This sources two more **bispectra:**



If $m_\sigma \to 0$, this is **local** $f_{\rm NL}$!

If $m_\sigma > 3/2H$, we get **oscillations!**

Lee+16, Pimentel+22, Jazayeri+22, Cabass, **Philcox**+24

Step 2: Modeling Dark Matter

How does **primordial non-Gaussianity** change the theory model?

1. Induces a **late-time bispectrum:**

$$B_{mmm}(k_1, k_2, k_3) = f_{\rm NL}\, T_\zeta(k_1) T_\zeta(k_2) T_\zeta(k_3) B_\zeta(k_1, k_2, k_3)$$

2. Adds new **loop corrections:**

$$P_{mm}(k) \sim \int_{\mathbf{p}_i} \text{kernels}(\mathbf{p}_i, \mathbf{k}) \times \langle \delta_{\rm lin}(\mathbf{p}_1) \cdots \delta_{\rm lin}(\mathbf{p}_n) \rangle$$

e.g., $P_{mm,12}(k) = 2 f_{\rm NL} \int \frac{d\mathbf{p}}{(2\pi)^3} F_2(\mathbf{p}, \mathbf{k}-\mathbf{p}) B_{111}(\mathbf{p}, \mathbf{k}-\mathbf{p})$

This contains **both** P_ζ **and** B_ζ terms!

Assassi+15a

Step 3: Modeling Galaxies

For galaxies, we have **more effects:**

1. Induces a **late-time bispectrum:**

$$B_{ggg}(k_1, k_2, k_3) = f_{\rm NL}\, T_\zeta(k_1)T_\zeta(k_2)T_\zeta(k_3)b_1^3 B_\zeta(k_1, k_2, k_3)$$

2. Adds new **loop corrections:**

$$P_{gg}(k) \sim \int_{\mathbf{p}_i} \text{galaxy kernels}(\mathbf{p}_i, \mathbf{k}) \times \langle \delta_{\rm lin}(\mathbf{p}_1)\cdots\delta_{\rm lin}(\mathbf{p}_n)\rangle$$

e.g., $P_{gg,12}(k) = 2 f_{\rm NL} b_1 \int \frac{d\mathbf{p}}{(2\pi)^3} K_2(\mathbf{p}, \mathbf{k}-\mathbf{p}) B_{111}(\mathbf{p}, \mathbf{k}-\mathbf{p})$

3. Adds new **bias operators**

$$\delta_g \supset b_\phi \phi + b_{\phi\delta}\phi\delta + \cdots$$

(assuming light fields)

$\Rightarrow$ scale-dependent bias!

Assassi+15b, Cabass, **Philcox**+24

Step 3: Modeling Galaxies

We also have to be careful of **renormalization**!

- Look at the **UV dependence** of the loop integrals:

$$P^{\rm UV}_{gg,12}(k) \sim f_{\rm NL} b_1 \int_{p\gg k} \frac{d\mathbf{p}}{(2\pi)^3} K_2(\mathbf{p}, \mathbf{k}-\mathbf{p}) B_{111}(\mathbf{p}, \mathbf{k}-\mathbf{p})$$

  - For **light fields** ($m_\sigma \ll H$): $P^{\rm ct}_{gg,12}(k) \sim f_{\rm NL} k^{-2} P_{\rm lin}(k)$
  - For **massive fields** ($m_\sigma > 3/2H$): $P^{\rm ct}_{gg,12}(k) \sim f_{\rm NL} k^{-1/2} \cos(\mu \log k) P_{\rm lin}(k)$

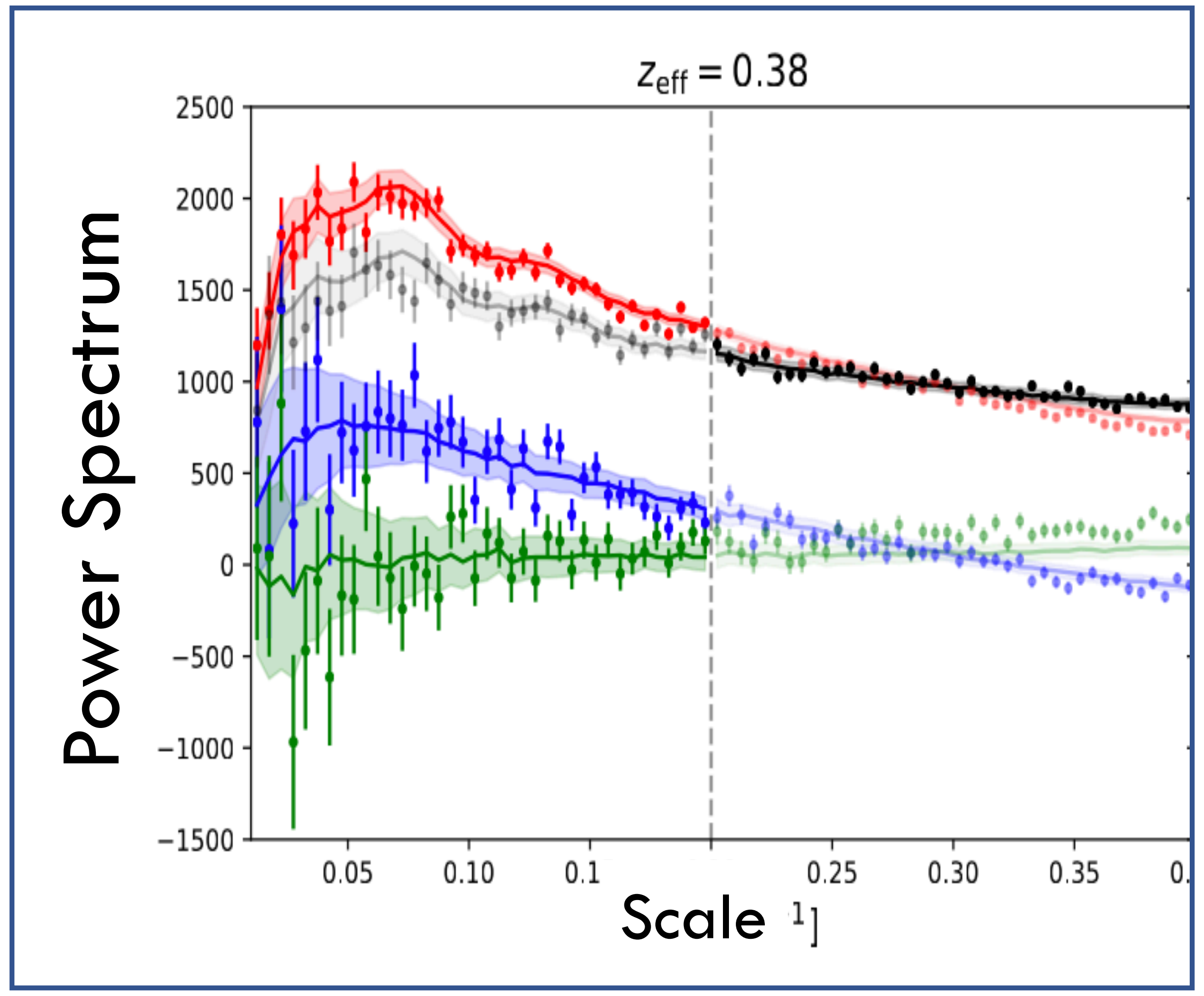
This is exactly degenerate with scale-dependent bias! (as expected…)

$\Rightarrow$ massive particles lead to **weird** scale-dependent bias!

Assassi+15b, Cabass, **Philcox**+24

Constraining Inflation with BOSS Galaxies

Statistics



$$P_\ell(k) + \text{BAO} + P(k_\perp)$$
$$+ B_\ell(k_1, k_2, k_3)$$

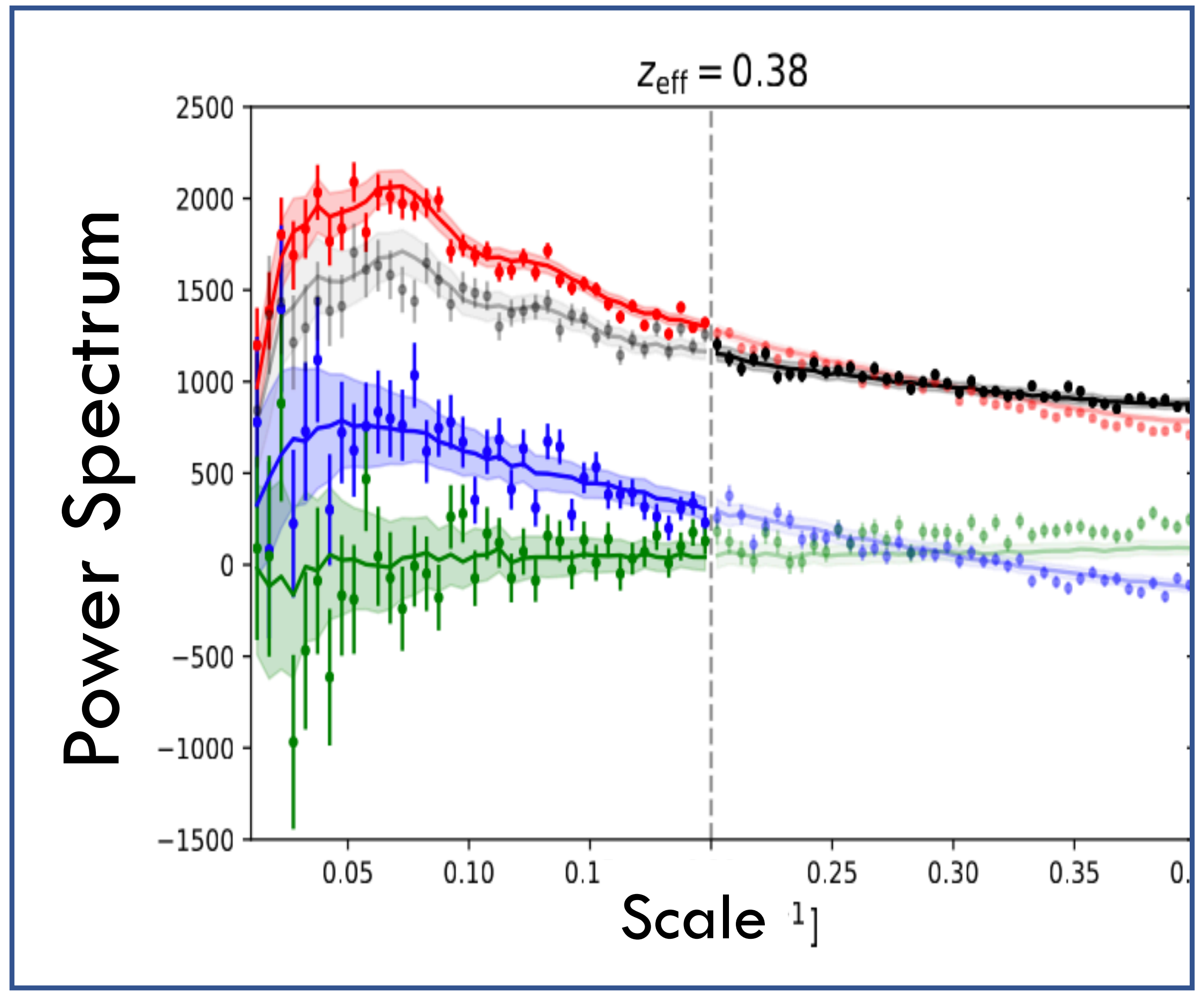
GitHub: **PolyBin3D**

PolyBin

Using (quasi-)**minimum-variance** estimators deconvolving **geometry**

Constraining Inflation with BOSS Galaxies

Statistics



$P_\ell(k) + \mathrm{BAO} + P(k_\perp)$
$+ B_\ell(k_1, k_2, k_3)$

GitHub: **PolyBin3D**

PolyBin

Using (quasi-)**minimum-variance** estimators deconvolving **geometry**

Fast **loop integrals** and flexible **likelihoods**

($\sim$ seconds !)

Gaussian likelihood

$$-2\log L = \left(\hat{P} - P_{\rm theory}\right) C^{-1} \left(\hat{P} - P_{\rm theory}\right)$$

MCMC

$f_{\rm NL}$ constraints (and beyond)

Theory Model

$$\begin{aligned}
Z_1(\boldsymbol{q}_1) &= K_1 + f\mu_1^2, \qquad \text{(A.3)}\\
Z_2(\boldsymbol{q}_1,\boldsymbol{q}_2) &= K_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + f\mu_{12}^2 G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{f\mu_{12}q_{12}}{2} K_1\left[\frac{\mu_1}{q_1} + \frac{\mu_2}{q_2}\right] + \frac{(f\mu_{12}q_{12})^2}{2}\frac{\mu_1}{q_1}\frac{\mu_2}{q_2},\\
Z_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3) &= K_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3) + f\mu_{123}^2 G_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3)\\
&\quad + (f\mu_{123}q_{123})\left[\frac{\mu_{12}}{q_{12}} K_1 G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{\mu_3}{q_3} K_2(\boldsymbol{q}_1,\boldsymbol{q}_2)\right]\\
&\quad + \frac{(f\mu_{123}q_{123})^2}{2}\left[2\frac{\mu_{12}}{q_{12}}\frac{\mu_3}{q_3} G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{\mu_1}{q_1}\frac{\mu_2}{q_2} K_1\right] + \frac{(f\mu_{123}q_{123})^3}{6}\frac{\mu_1}{q_1}\frac{\mu_2}{q_2}\frac{\mu_3}{q_3},\\
Z_4(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3,\boldsymbol{q}_4) &= K_4(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3,\boldsymbol{q}_4) + f\mu_{1234}^2 G_4(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3,\boldsymbol{q}_4)\\
&\quad + (f\mu_{1234}q_{1234})\left[\frac{\mu_{123}}{q_{123}} K_1 G_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3) + \frac{\mu_4}{q_4} K_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3)\right.\\
&\qquad \left. + \frac{\mu_{12}}{q_{12}} G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) K_2(\boldsymbol{q}_3,\boldsymbol{q}_4)\right]\\
&\quad + \frac{(f\mu_{1234}q_{1234})^2}{2}\left[2\frac{\mu_{123}}{q_{123}}\frac{\mu_4}{q_4} G_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3) + \frac{\mu_{12}}{q_{12}}\frac{\mu_{34}}{q_{34}} G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) G_2(\boldsymbol{q}_3,\boldsymbol{q}_4)\right.\\
&\qquad \left. + 2\frac{\mu_{12}}{q_{12}}\frac{\mu_3}{q_3} K_1 G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{\mu_1}{q_1}\frac{\mu_2}{q_2} K_2(\boldsymbol{q}_3,\boldsymbol{q}_4)\right]\\
&\quad + \frac{(f\mu_{1234}q_{1234})^3}{6}\left[3\frac{\mu_{12}}{q_{12}}\frac{\mu_3}{q_3}\frac{\mu_4}{q_4} G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{\mu_1}{q_1}\frac{\mu_2}{q_2}\frac{\mu_3}{q_3} K_1\right]\\
&\quad + \frac{(f\mu_{1234}q_{1234})^4}{24}\frac{\mu_1}{q_1}\frac{\mu_2}{q_2}\frac{\mu_3}{q_3}\frac{\mu_4}{q_4},
\end{aligned}$$

GitHub:
CLASS-PT
&
Full-Shape-Likelihoods

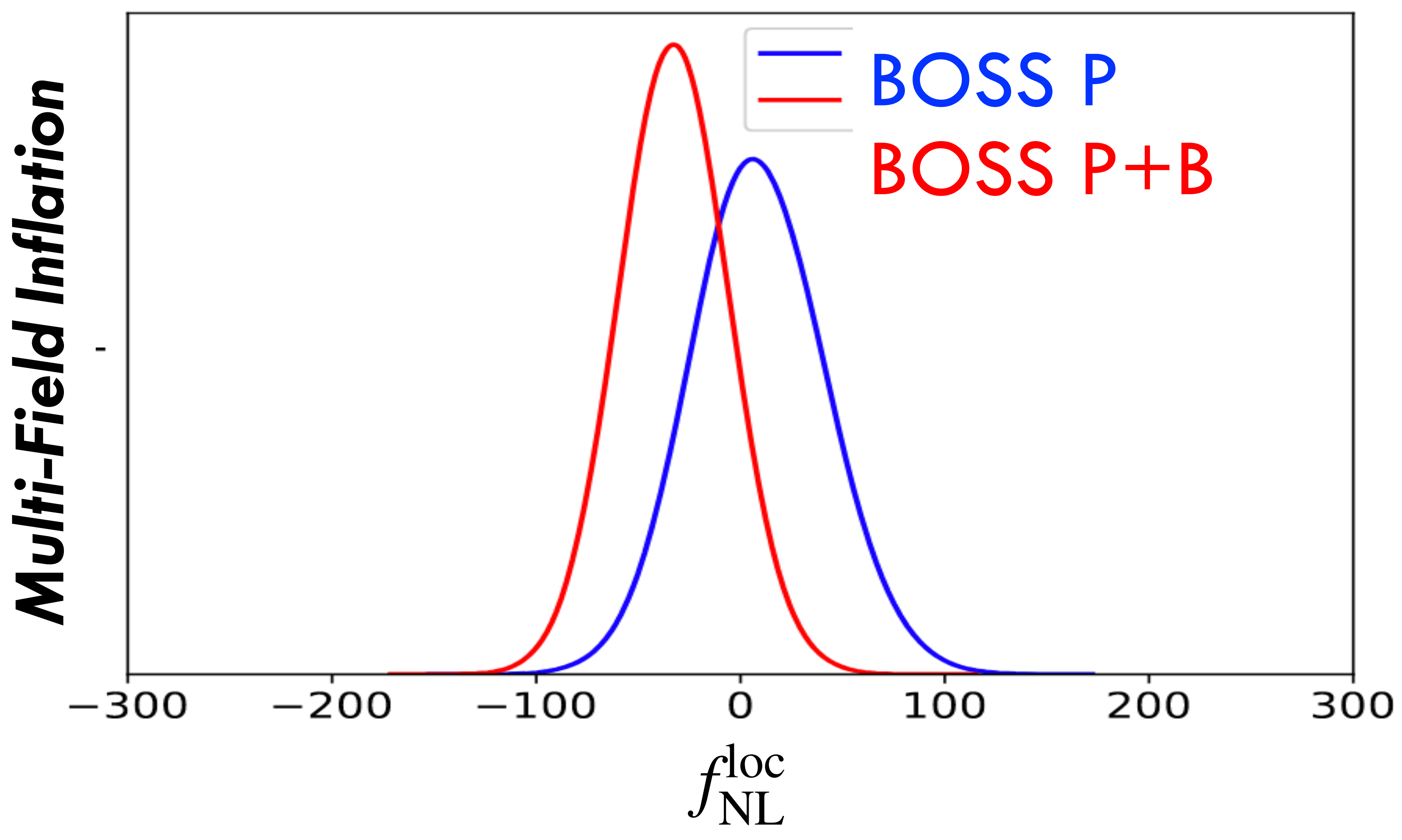
Philcox, Ivanov, Cabass+19-24

Some Recent(ish) Results

1. **Local** non-Gaussianity: $f_{\rm NL}^{\rm loc}$

- Probes **light particles** $(m_\sigma \ll H)$ in multi-field inflation

- **Full** $P_g + B_g$ modeling beats power spectrum **scale-dependent bias** searches by 20%



$$f_{\rm NL}^{\rm loc} = -33 \pm 28 \quad (9 \pm 34 \text{ w/o } B_g)$$

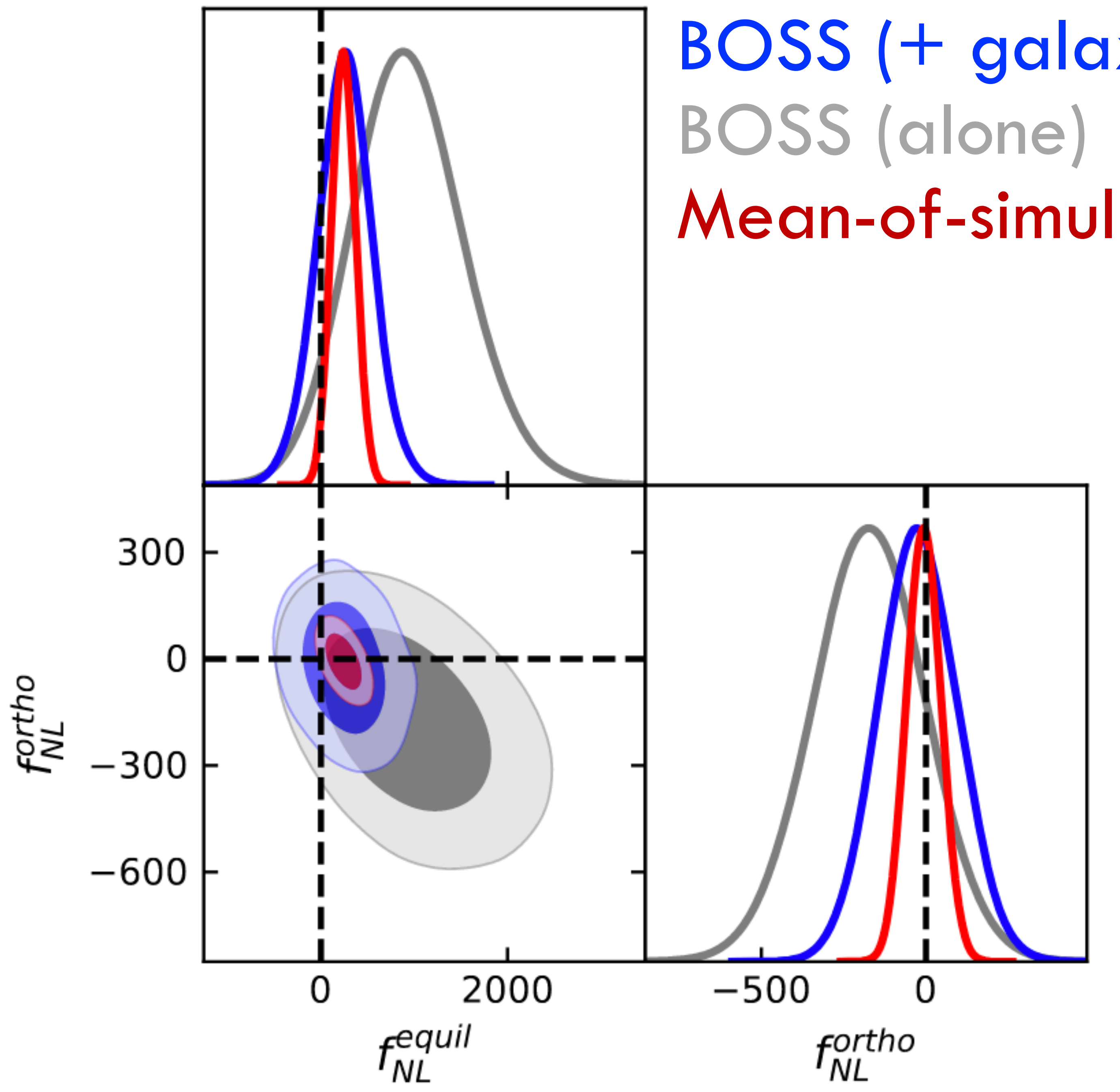
(CMB: ± 5, Target: ± 1)

Cabass, **Philcox**+22b (see also d'Amico+22)

Some Recent(ish) Results

1. **Local** non-Gaussianity: $f_{\rm NL}^{\rm loc}$
2. **Non-local** non-Gaussianity: $f_{\rm NL}^{\rm eq}, f_{\rm NL}^{\rm orth}$

- Probes inflation **interactions** in the single-field EFT of inflation: $10^5 f_{\rm NL} \sim (H/\Lambda)^2$
- **First** non-CMB analysis
- **Hard:**
  - We need to robustly separate **inflation** from **bias** $(b_{\mathcal{G}_2}, b_2)$ [EFTofLSS to the rescue!]
  - **Window functions** are important [use window-deconvolved estimators!]



$f_{\rm NL}^{\rm eq} = 260 \pm 300, f_{\rm NL}^{\rm orth} = -23 \pm 120$

without priors: $f_{\rm NL}^{\rm eq} = 940 \pm 600, f_{\rm NL}^{\rm orth} = -170 \pm 170$

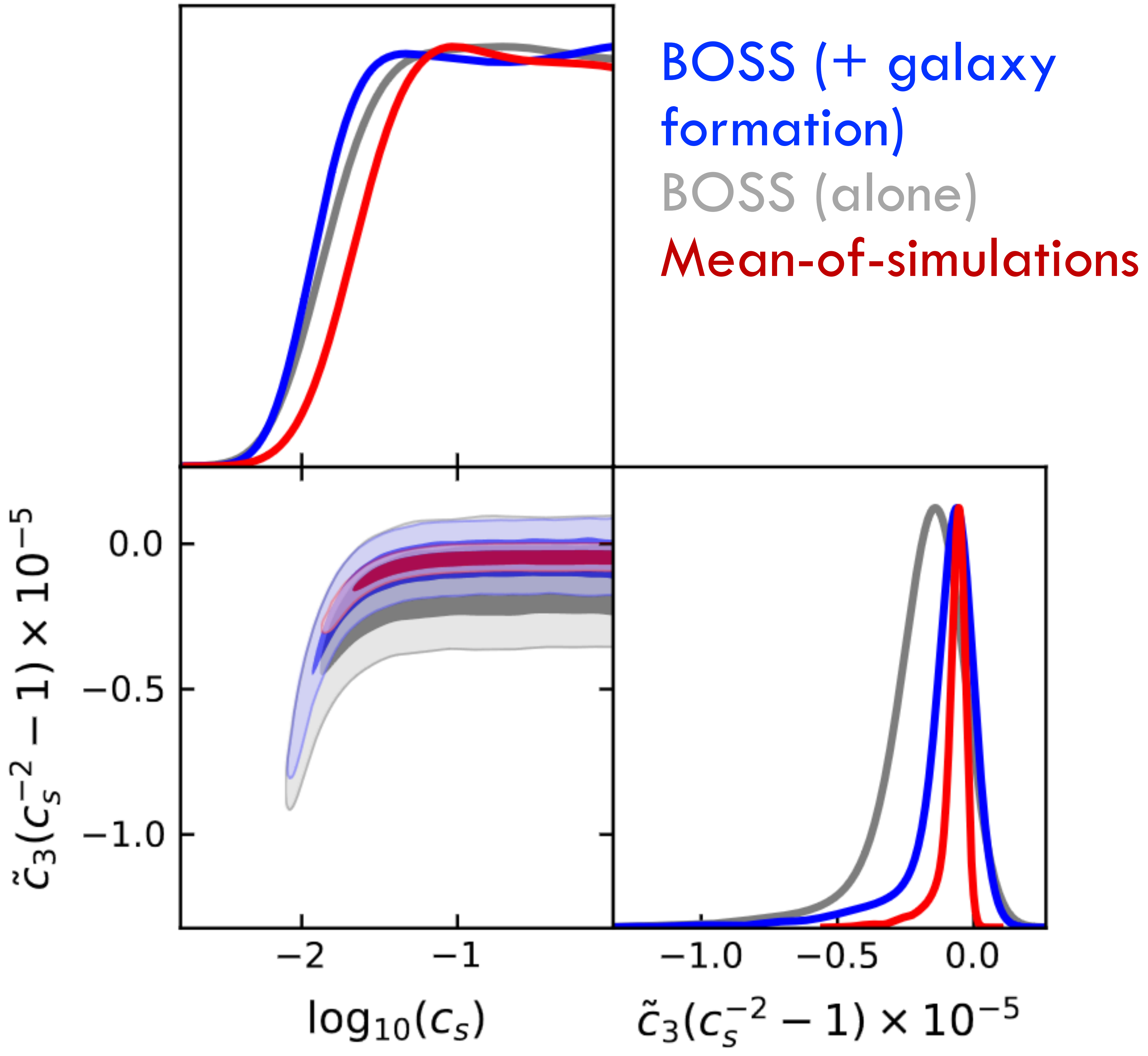
(CMB: $\pm 50, \pm 25$, Target: ± 1)

Cabass, **Philcox**+22a (see also d'Amico+22, Chen+24)

Some Recent(ish) Results

1. **Local** non-Gaussianity: $f_{\mathrm{NL}}^{\mathrm{loc}}$
2. **Non-local** non-Gaussianity: $f_{\mathrm{NL}}^{\mathrm{eq}}, f_{\mathrm{NL}}^{\mathrm{orth}}$

- We can map these onto the EFT of inflation parameters, directly probing **microphysics**!
- We constrain the inflaton sound-speed: $c_s^2 \geq 0.013$ (95% CL)
- This is greatly improved by priors on **bias parameters**



Cabass, **Philcox**+22a

Some Recent(ish) Results

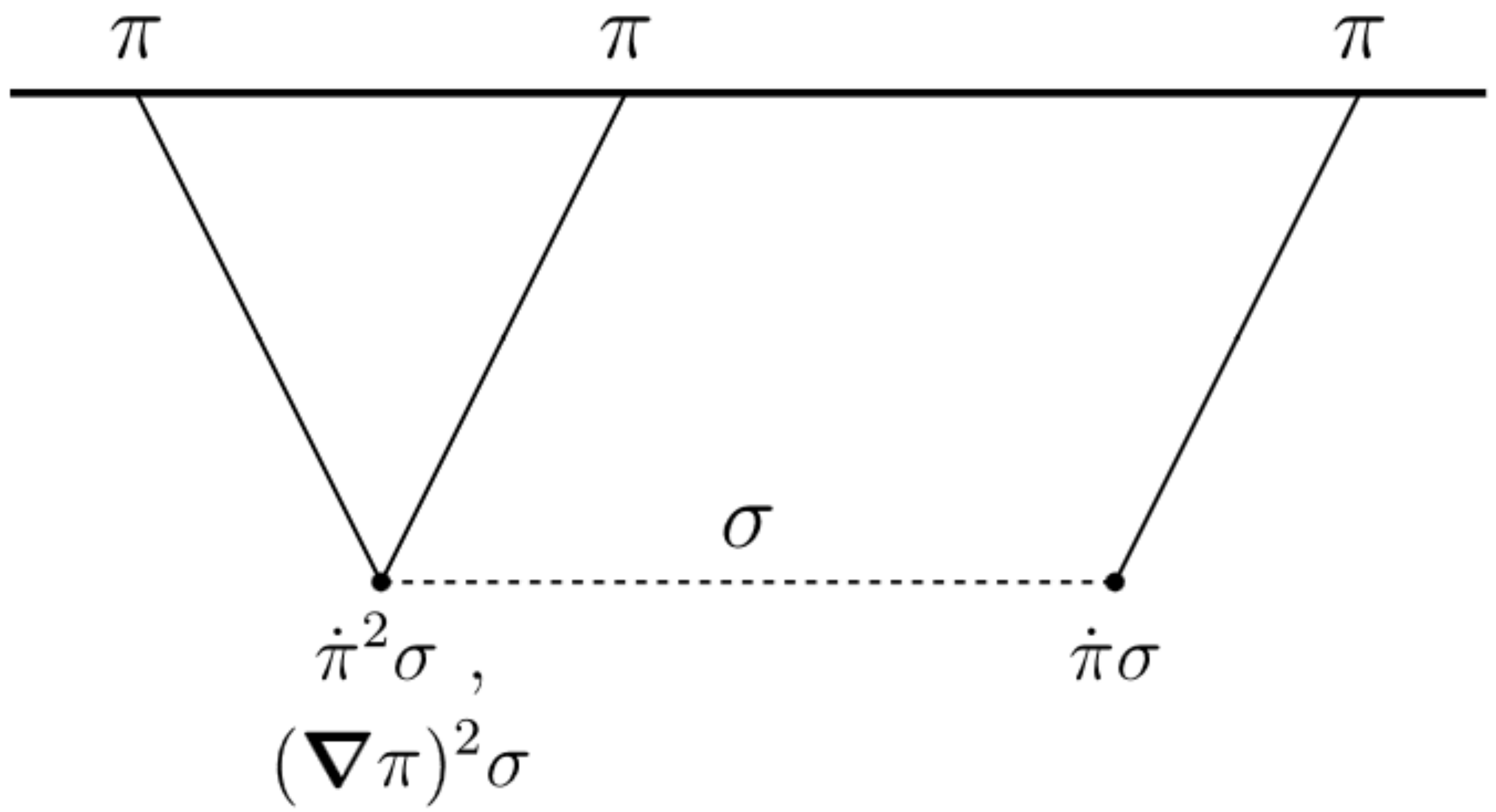
1. **Local** non-Gaussianity: $f_{\rm NL}^{\rm loc}$
2. **Non-local** non-Gaussianity: $f_{\rm NL}^{\rm eq}, f_{\rm NL}^{\rm orth}$
3. **Massive-Particle** non-Gaussianity: $f_{\rm NL}(m_\sigma, c_\sigma)$

- We can probe multi-field inflation with **massive particles** ($m_\sigma > 3/2H$)
- **First** analysis with *either* CMB *or* LSS
- This has more interesting phenomenology including **oscillatory features** and varying **speeds**

$$S(k_1,k_2,k_3) \sim \left(\frac{k_1}{k_3}\right)^{\frac{1}{2}} \cos\left(\mu \ln \frac{c_\sigma k_1}{c_s k_3}\right) \text{ for } k_1 \ll \frac{c_s}{c_\sigma} k_3$$

+ many integrals

$f_{\rm NL}^{\dot\pi^2\sigma}$ $f_{\rm NL}^{(\nabla\pi)^2\sigma}$



Cabass, **Philcox**+24 (see also Sohn+24)

Some Recent(ish) Results

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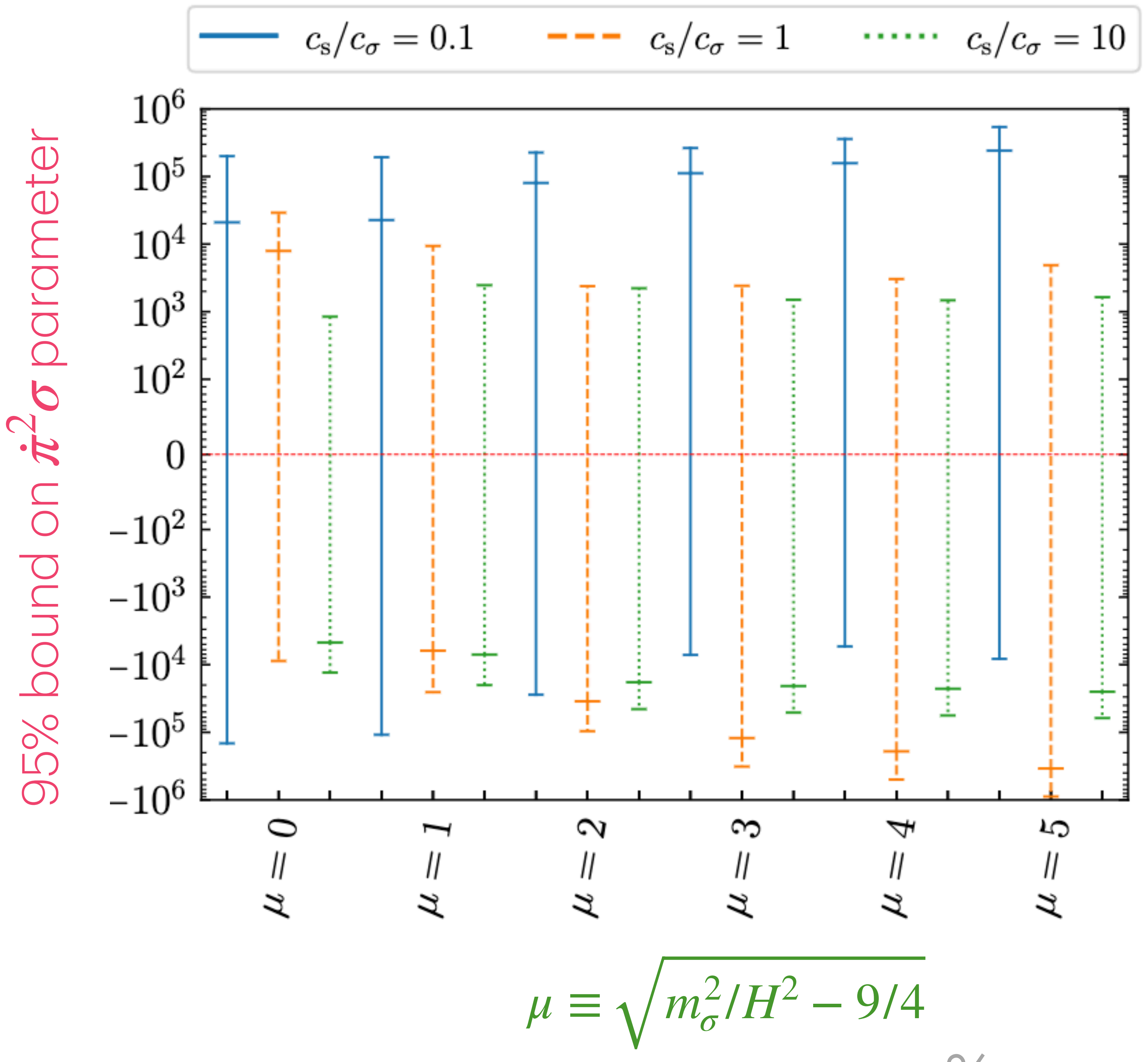
3. **Massive-Particle** non-Gaussianity: $f_{\rm NL}(m_\sigma, c_\sigma)$

- *Very* massive particles look like **self-interactions**
  - Marginalize over $f_{\rm NL}^{\rm eq}, f_{\rm NL}^{\rm orth}$ as well!

- There are several ways to analyze the data:
  1. **Separately** analyze each mass and sound-speed



Cabass, **Philcox**+24 (see also Sohn+24)

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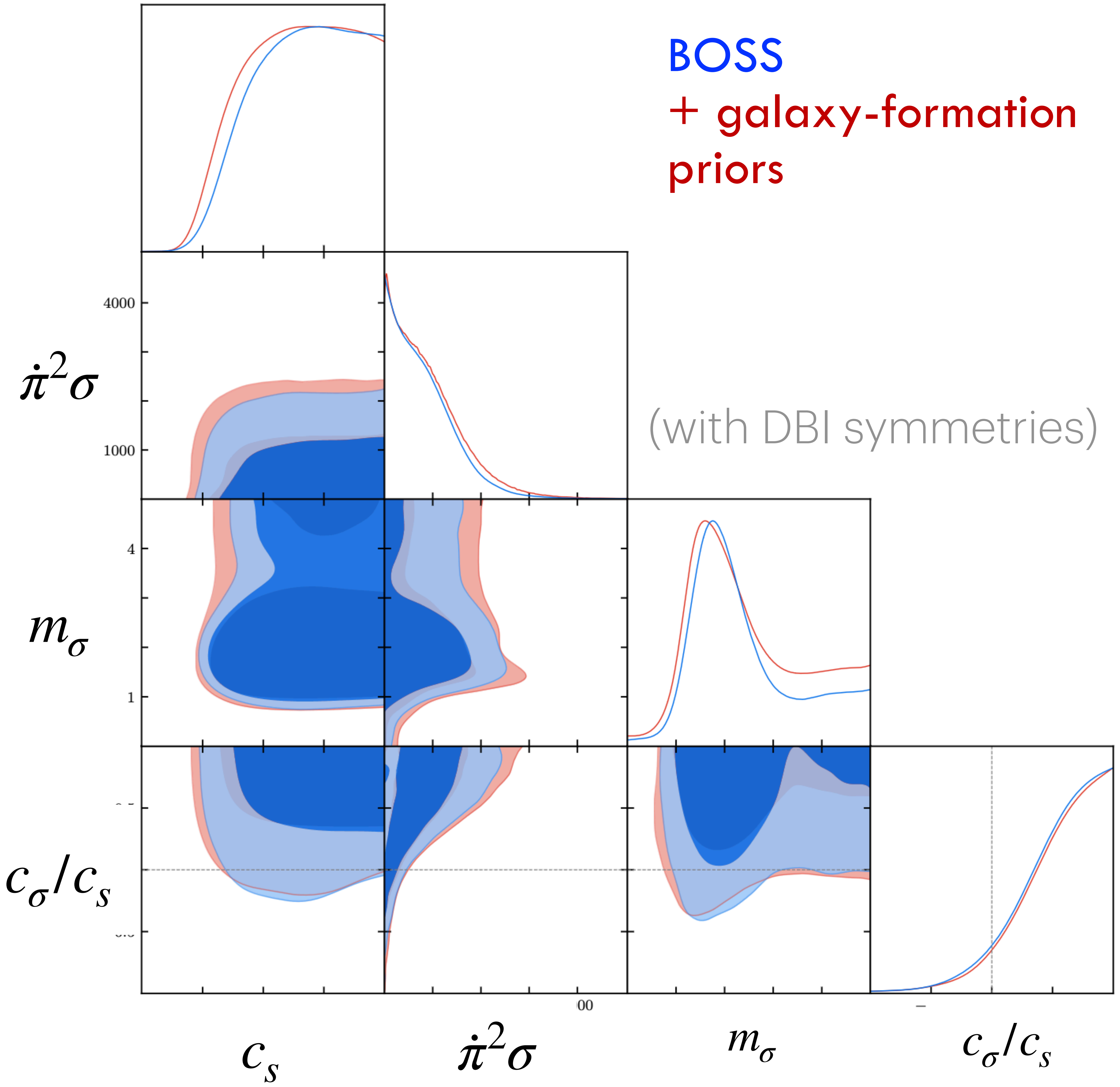
- There are several ways to analyze the data:
  1. **Separately** analyze each mass and sound-speed
  2. **Marginalize** over particle mass



Cabass, **Philcox**+24 (see also Sohn+24)

f_{NL} isn't everything…

Many other things can happen in inflation, e.g.:

- **Massive-ish** particles ($m_\sigma < 3/2H$)

  See upcoming paper with Sam Goldstein!

- Particles with **spin**
- **4-point** interactions
- **Thermal** initial states and **dissipation**
- **Non-perturbative** physics

There's lots to discover in future data!

Cosmological Collider

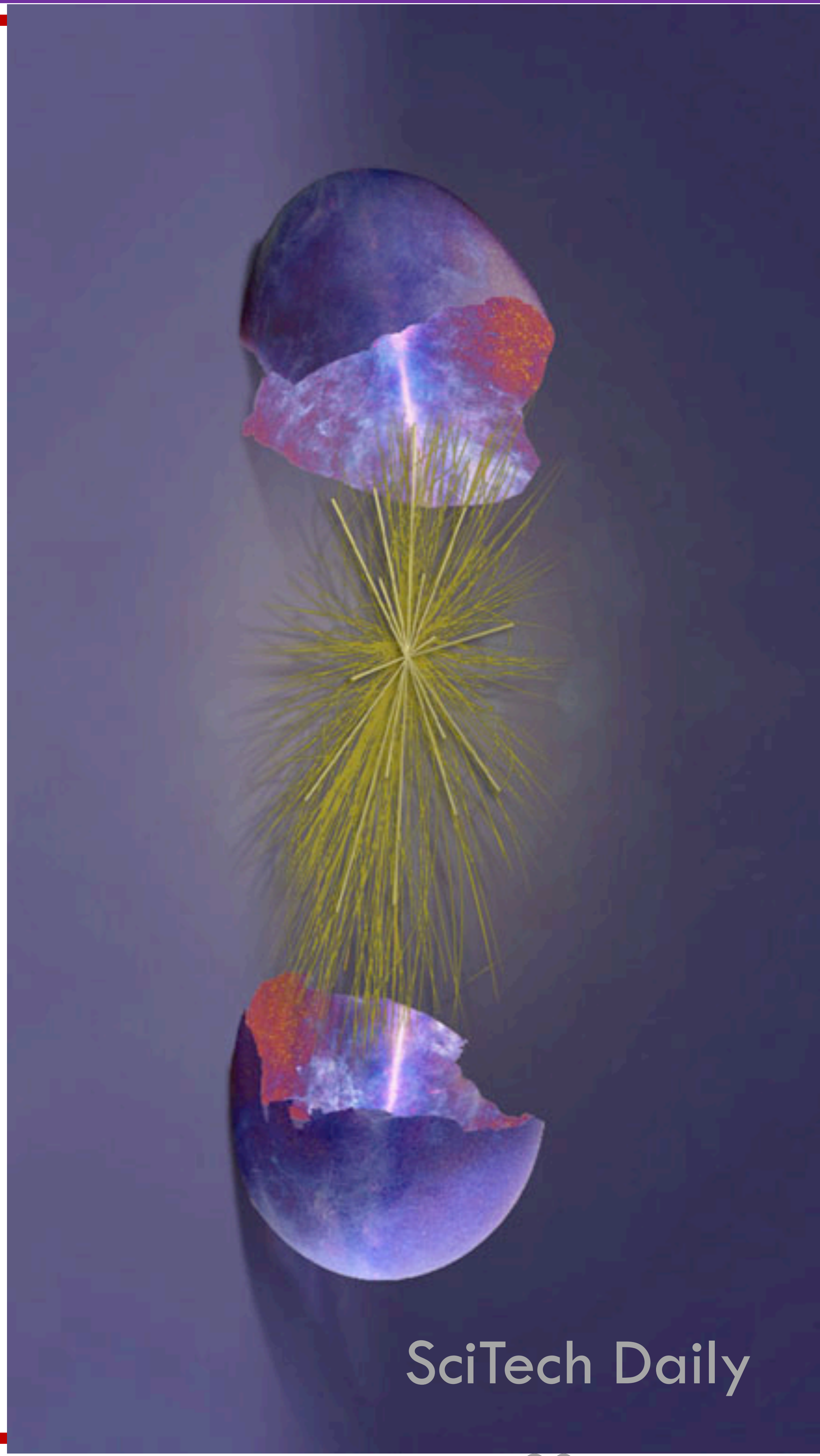
Low-energy remnants
[curvature fluctuations]

↑

High-energy physics
[particle scattering]

↓

Low-energy remnants
[curvature fluctuations]



Cabass, **Philcox**+24, **Philcox**+23, Arkani-Hamed, Pajer, Maldacena, Creminelli, …

Summary

arXiv
2404.01894
2204.01781
2201.07238

- We can robustly probe **primordial non-Gaussianity** with LSS

- So far we have constrained:
  - Self-interactions
  - Light fields
  - Massive fields

- There's lots more to do!!


The Cosmological Collider has been switched on!