The Cosmological Collider

An Observational Perspective

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Inflationary Q&A

Big Unanswered Questions:

- What is the **energy scale** of inflation? ⟶ $E \lesssim 10^{13}\text{TeV}$
- What sets the **potential**? ⟶ $V(\phi) = ???$
- Were there **other fields** during inflation? ⟶ $\phi \to \phi, \chi, \psi_u, \cdots$
- Did the fields **interact**? ⟶ Lagrangian $\supset \dot{\phi}^3 + \cdots$

Primordial non-Gaussianity: $\zeta \sim e^{-\frac{1}{2}\zeta^2/P_\zeta}\left(1 + \zeta^3 B_\zeta + \zeta^4 T_\zeta + \cdots\right)$

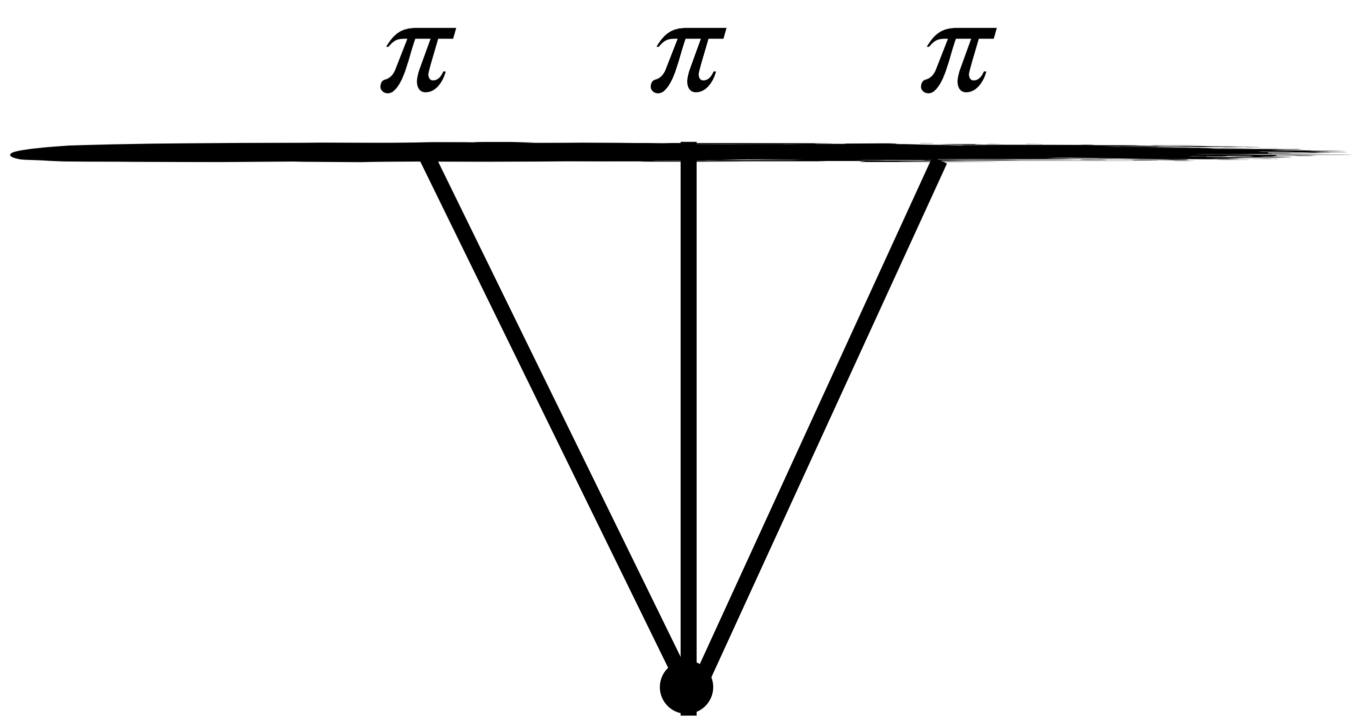
Linde, Guth, Starobinsky, Lyth, Mukhanov, Sasaki, …

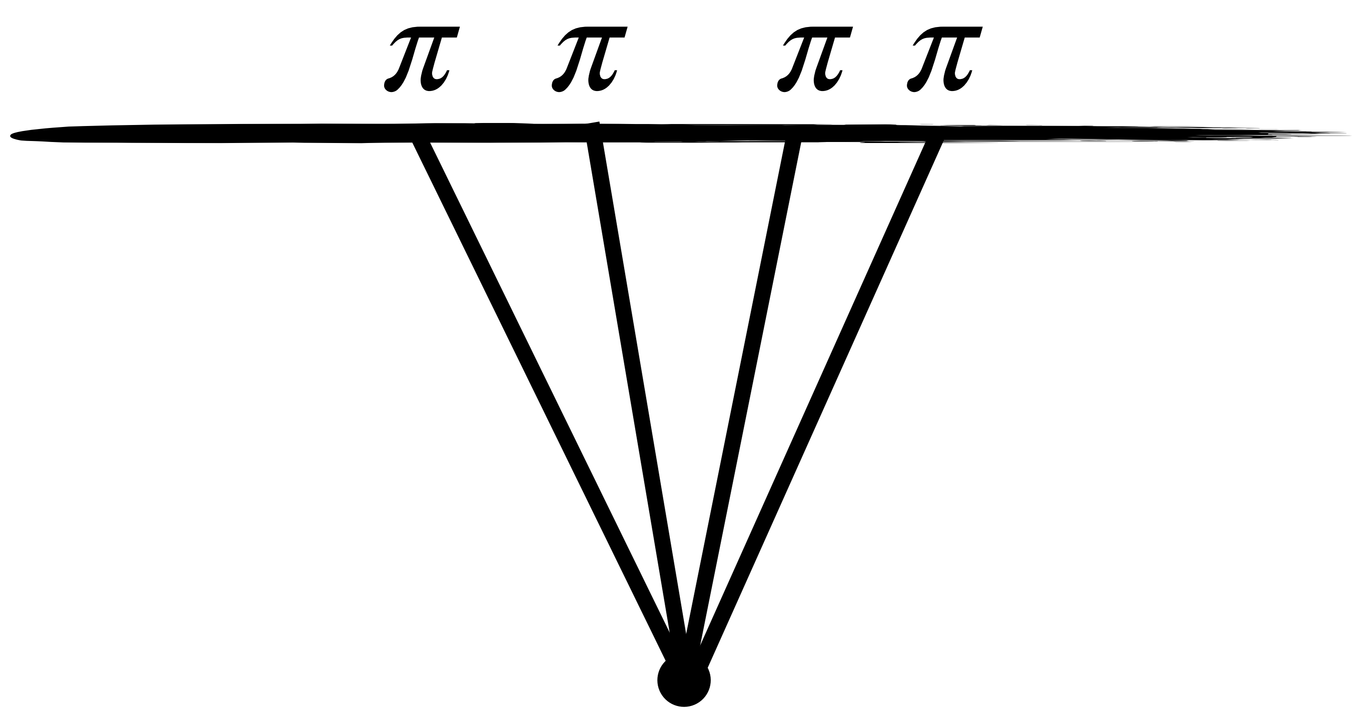
Self-Interactions

- Many models of inflation feature **self-interactions:**

$$\mathscr{L} \supset \delta\dot{\pi}^3, \quad \delta\dot{\pi}(\partial\pi)^2, \quad \delta\dot{\pi}^4, \quad \cdots$$

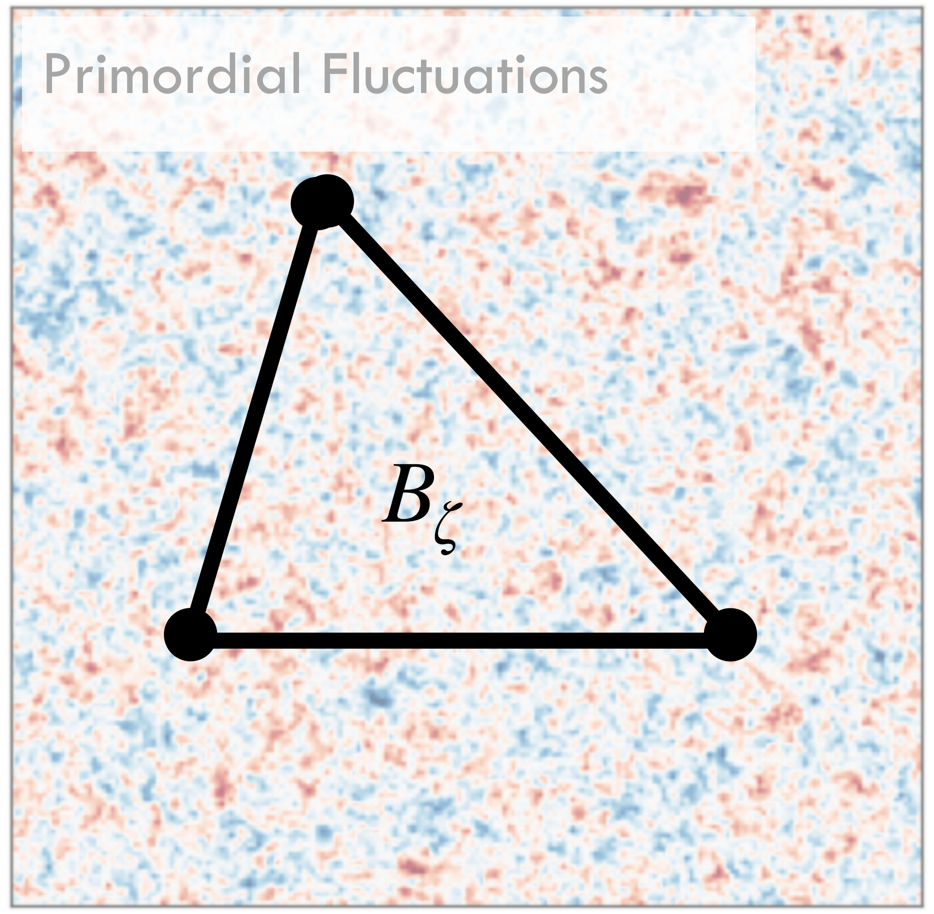
(π = Goldstone of broken time-translation)

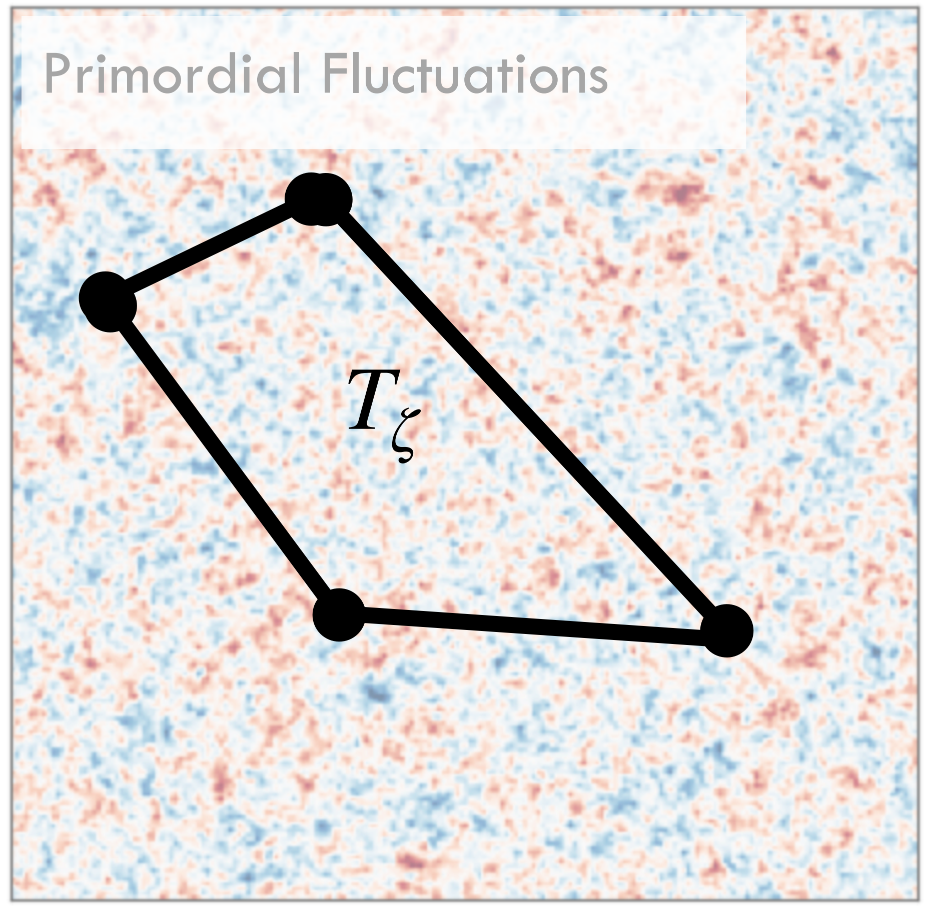




Cubic $\sim f_{\rm NL}^{\rm eq}, f_{\rm NL}^{\rm orth}$

Quartic $\sim g_{\rm NL}^{\rm eq}$





- These lead to **three**- and **four**-point functions at the end of inflation

- The **shape** encodes the vertex, the **amplitude** encodes the microphysics

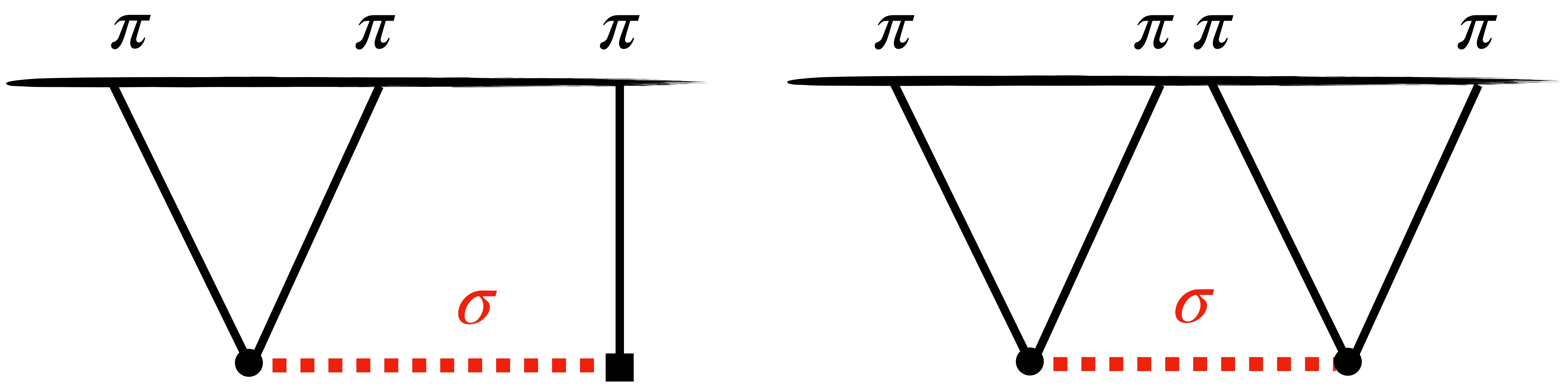
e.g. $\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle \sim f_{\rm NL}^{\rm eq} \times$ shape

Senatore, Zaldarriaga, Creminelli, Baumann, …

New Degrees of Freedom

- Other models feature **new particles**, σ:

$$\mathscr{L} \supset \dot{\pi}\sigma, \quad \dot{\pi}^2\sigma, \quad (\partial_i\pi)^2\sigma, \quad \cdots$$



Linear-Quadratic $\sim f_{\rm NL}^{\rm loc}$ *Quadratic*^{2} $\sim \tau_{\rm NL}^{\rm loc}$

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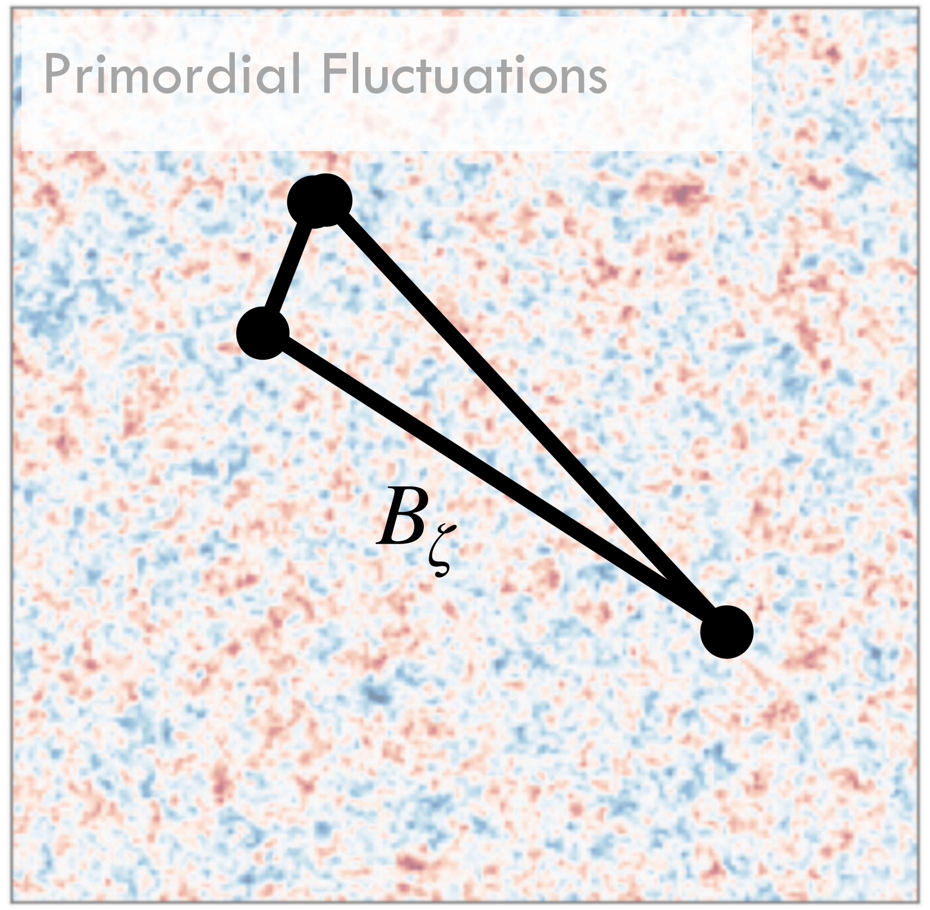
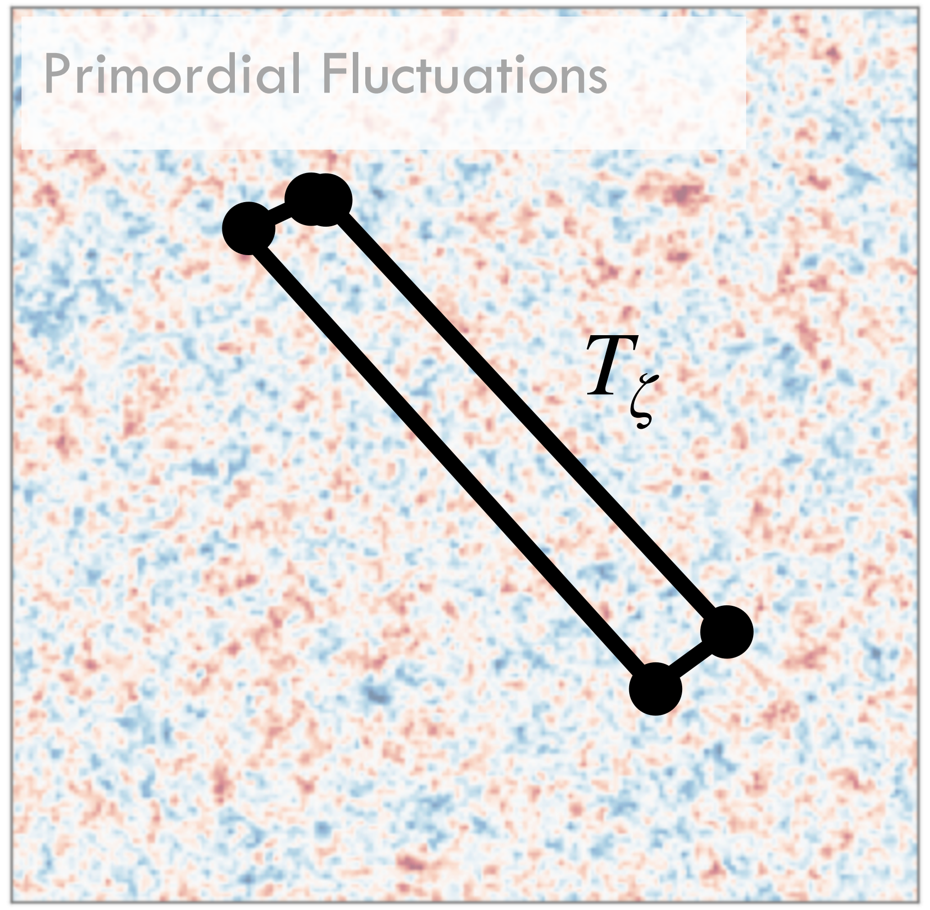




Arkani-Hamed, Maldacena, Lee, Moradinezhad, Cabass, Pajer, Jazayeri, Baumann…

The Cosmological Collider

see Qianshu's talk!

- In the **squeezed limit** (low exchange momentum), the inflationary signatures are set by **symmetry**

- They depend **only** on the mass m_σ, the spin, s, and the speed c_σ *not* on the microphysical model!

- For the **bispectrum:**

$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle_{k_1 \ll k_3} \sim f_{\rm NL}(m_\sigma, s, c_\sigma)$$

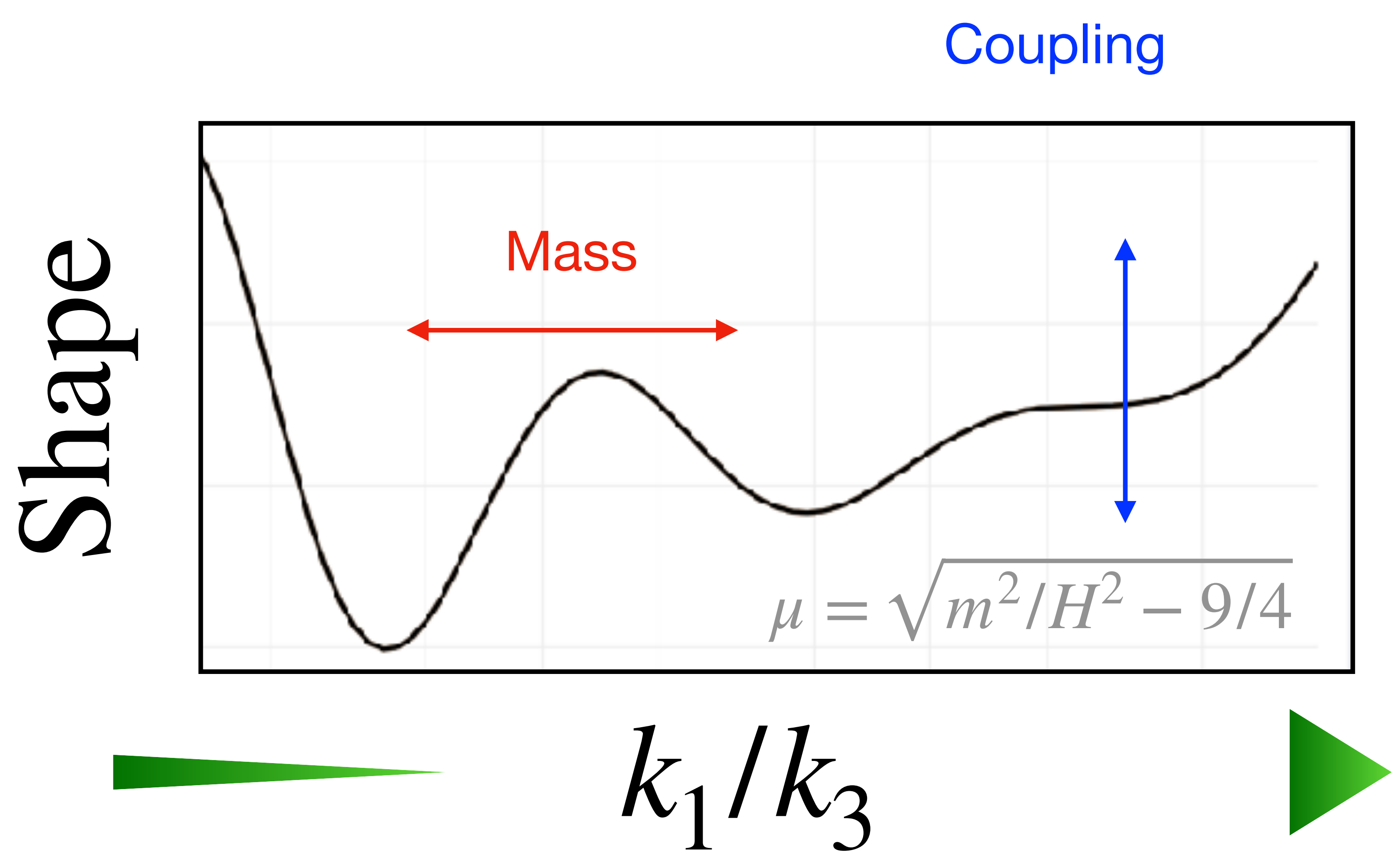
Amplitude $\sim e^{-\pi m_\sigma/H}$

$$\times \frac{1}{k_1^3 k_3^3}\left[\left(\frac{k_1}{k_3}\right)^{3/2+i\mu} + \left(\frac{k_1}{k_3}\right)^{3/2-i\mu}\right]$$

Shape (mass dependent)

$$\times \mathscr{L}_s(\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_3)$$

Angle (spin-dependent)

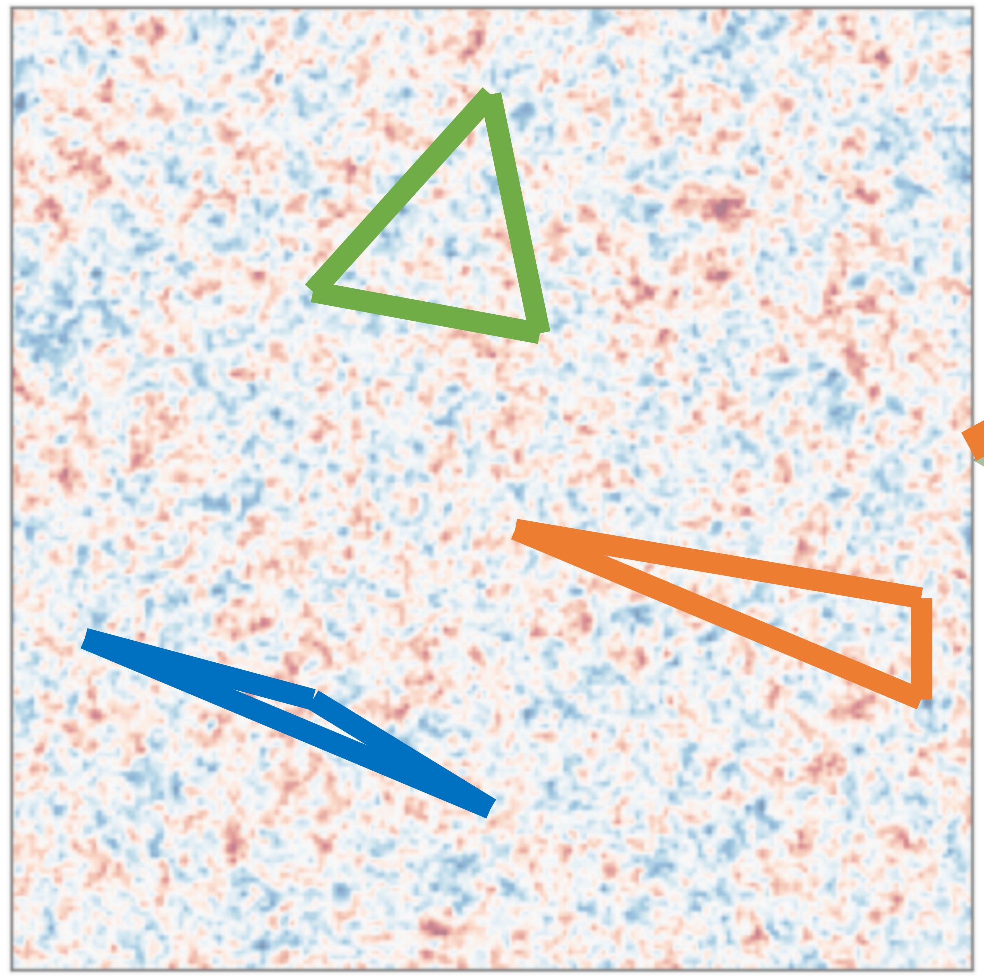


- These **oscillations** are a **smoking-gun** for new physics

Maldacena, Arkani-Hamed, Jazayeri, Pajer, Zaldarriaga, Lee, Moradinezhad, Cabass, Baumann, …

How to Constrain Inflation

The **curvature perturbation** ζ sets the **initial conditions** for the late Universe!

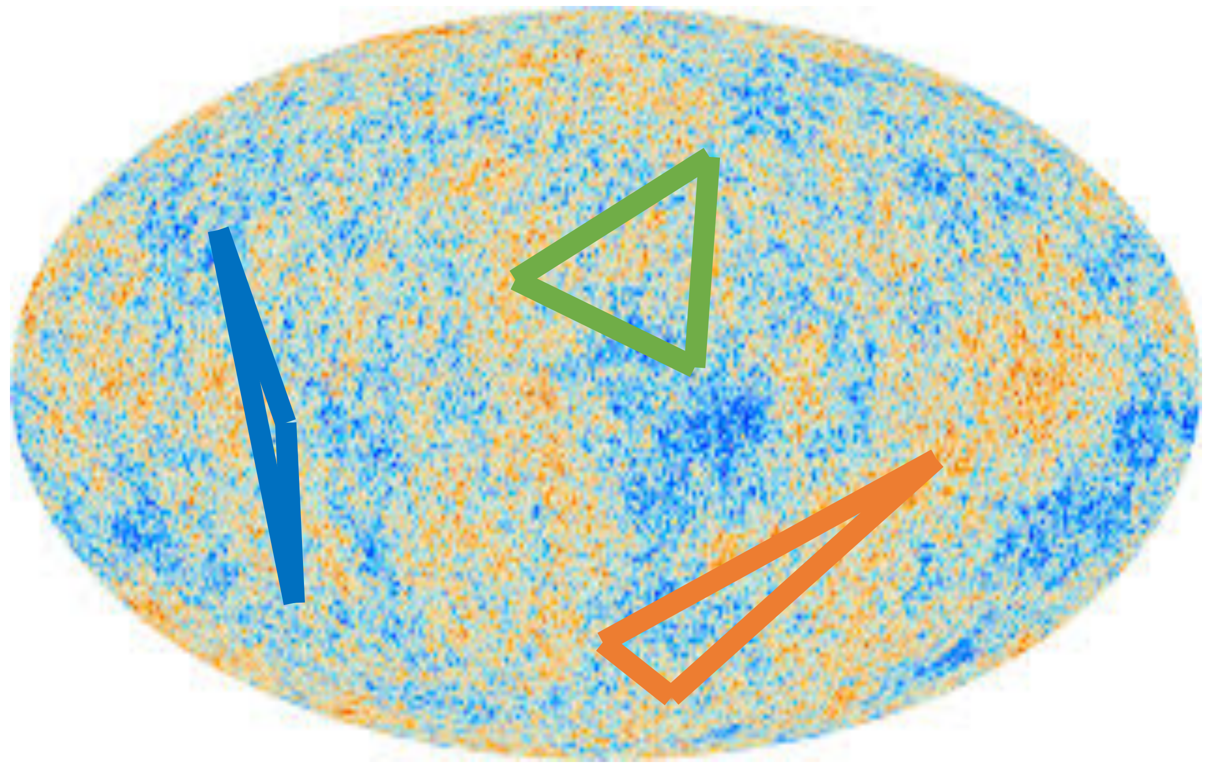


Primordial Curvature

$\langle \zeta^n \rangle \neq 0?$

Linear Physics

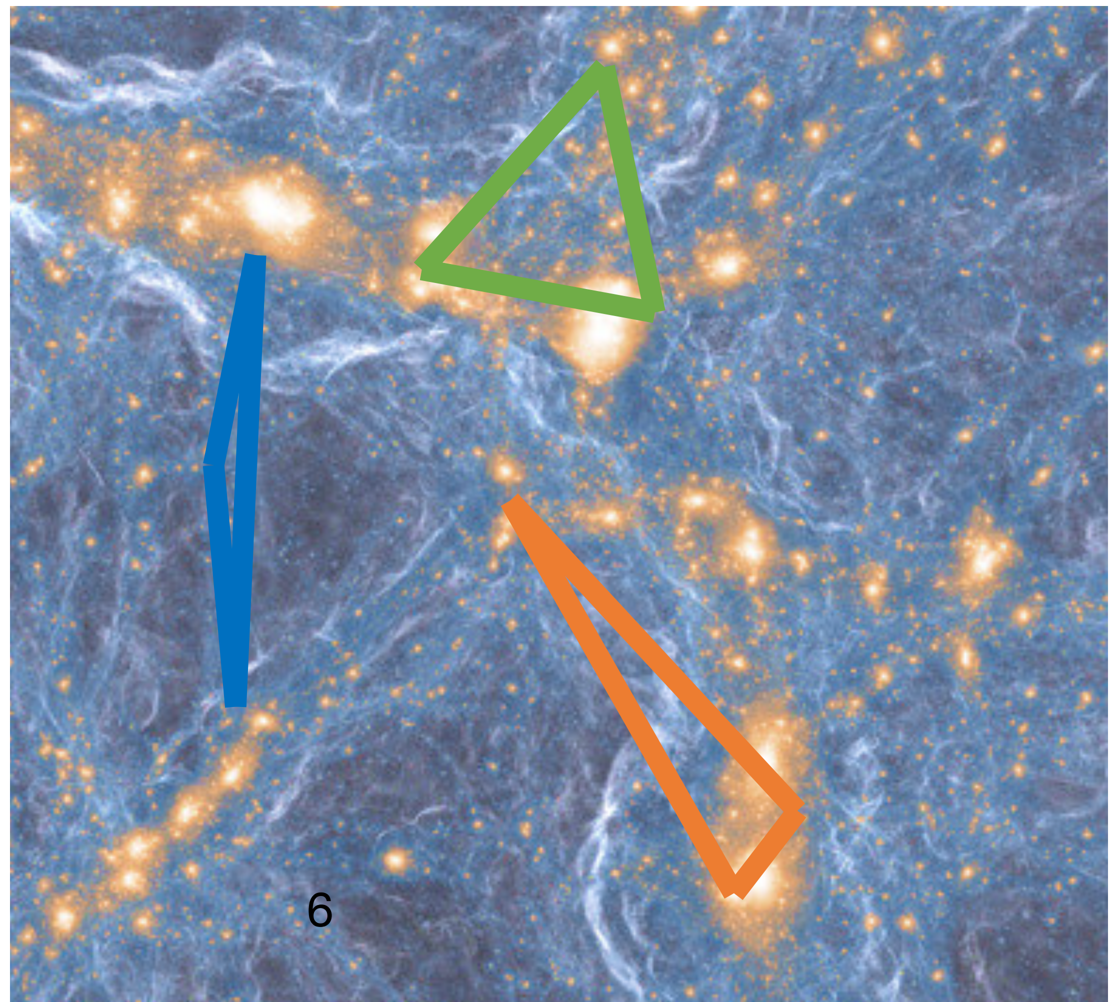
Non-Linear Physics



Cosmic Microwave Background fluctuations

$\langle \delta T^n \rangle \neq 0?$

*(tracing **photon energies**)*



Galaxy Number Density Fluctuations

$\langle \delta n^n_{\rm galaxy} \rangle \neq 0?$

*(tracing **dark matter**)*

Planck, IllustrisTNG

How to Constrain Inflation

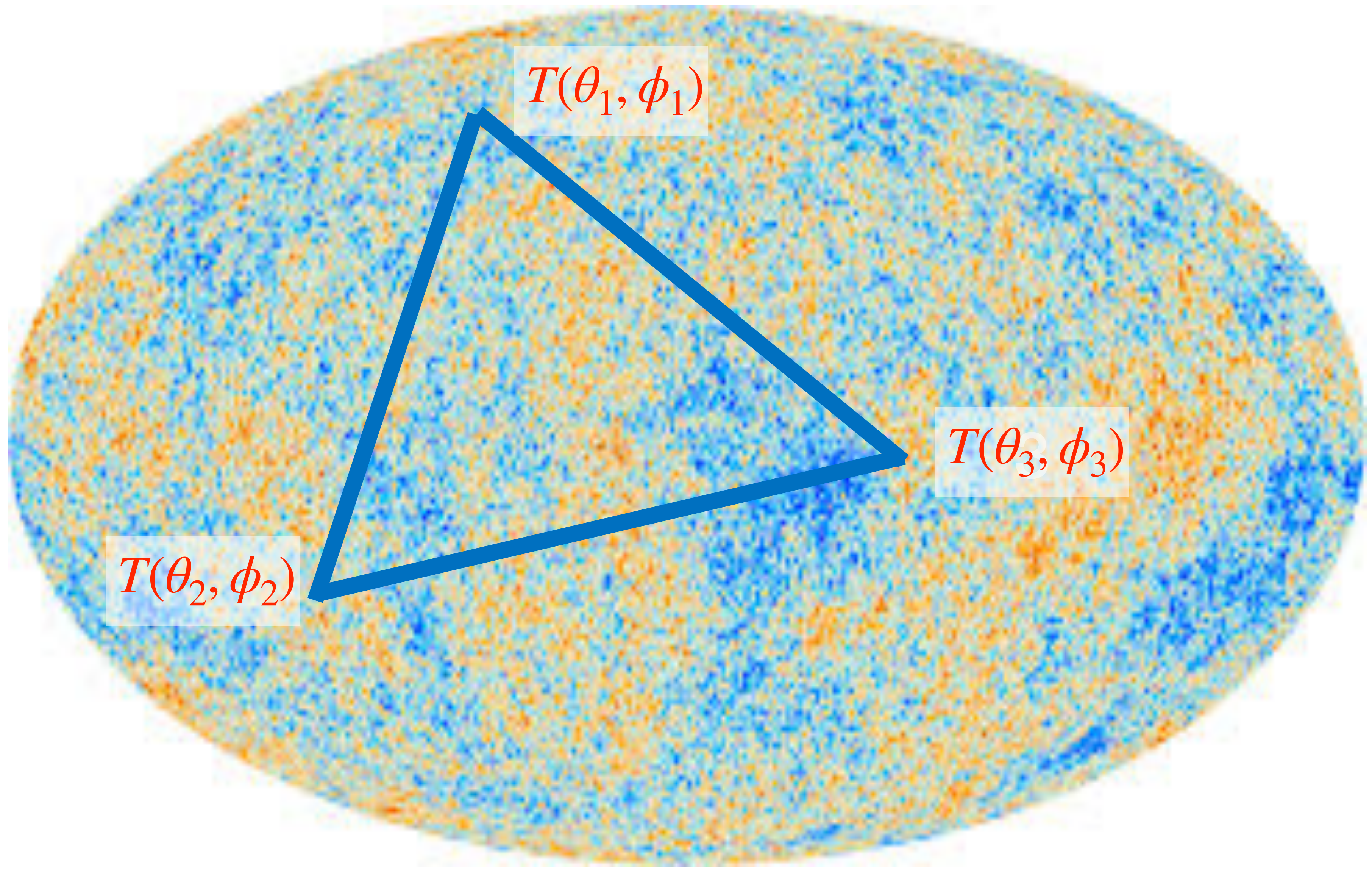
- CMB experiments measure the **temperature** and **polarization** across (part of) the whole sky

$$T(\theta,\phi), \quad E(\theta,\phi) \quad \leftrightarrow \quad a^T_{\ell m}, \quad a^E_{\ell m}$$

- Since the physics is **linear** we just need to correlate the CMB at **three** angles

$$\langle T(\theta_1,\phi_1)T(\theta_2,\phi_2)T(\theta_3,\phi_3)\rangle \leftrightarrow \langle a^T_{\ell_1 m_1} a^T_{\ell_2 m_2} a^T_{\ell_3 m_3}\rangle$$

- This is computationally **expensive:**
  - The bispectrum is **3-dimensional** [after symmetries]
  - There's $N^3_{\rm pix} \sim 10^{21}$ combinations of points!



Planck 2018

How to Constrain Inflation

Most CMB analyses use two tricks:

1. **Compression:**

   - We compress all 10^{21} elements into a single number, encoding the amplitude of a **specific** model, e.g., **self-interactions**

$$\widehat{f_{\rm NL}} \sim \sum_{\ell_1 m_1 \ell_2 m_2 \ell_3 m_3} \underset{\text{Model}}{\langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3}\rangle^{\dagger}_{\rm theory}} \times \underset{\text{Data}}{(C^{-1}a)_{\ell_1 m_1}(C^{-1}a)_{\ell_2 m_2}(C^{-1}a)_{\ell_3 m_3}}$$

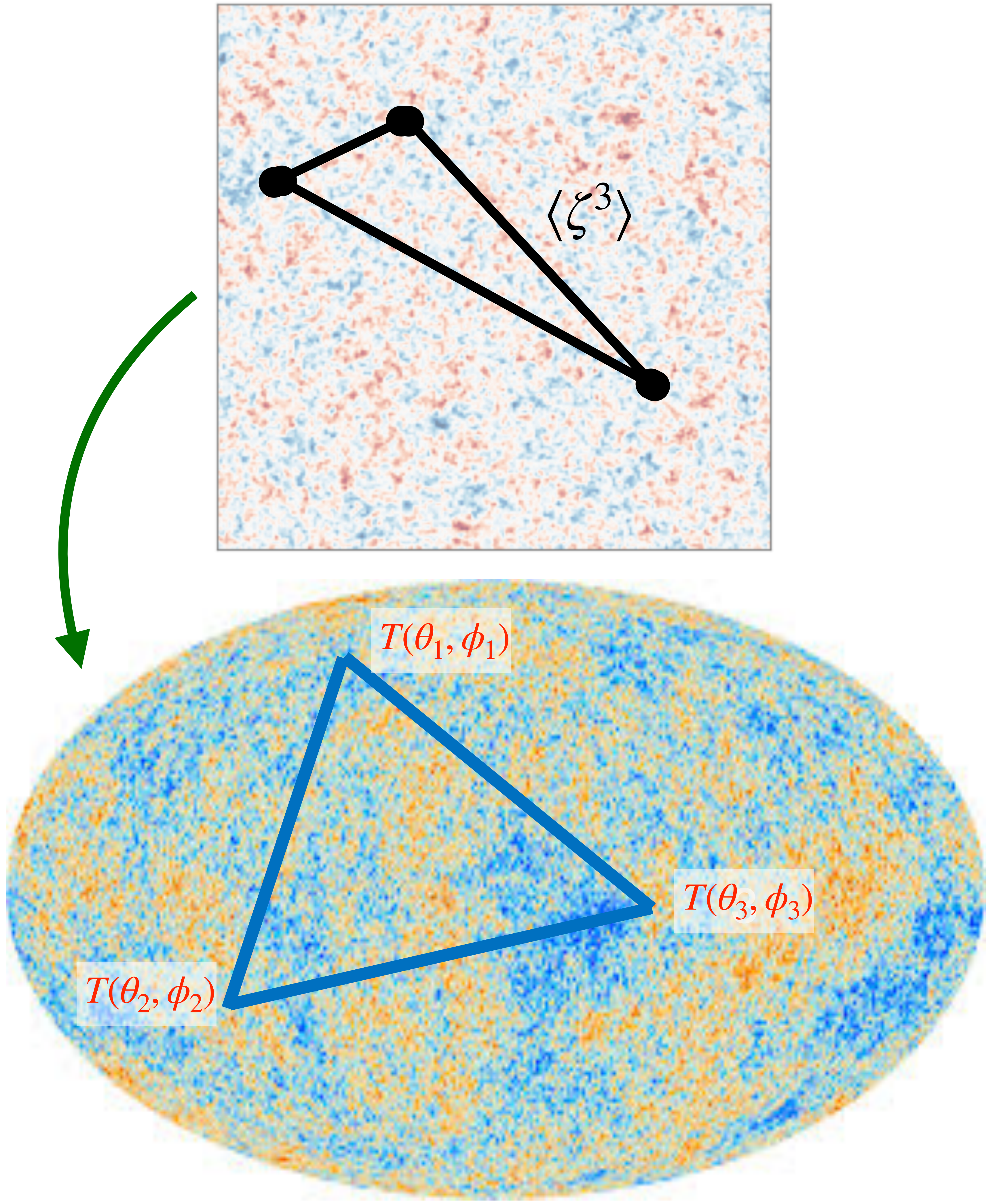
   - This is an **optimal estimator** for $f_{\rm NL}$, *i.e.* it is **lossless**

2. **Factorizable:**

   - If the **theory model** is **factorizable**, we can rewrite the ℓ, m sum using spherical harmonic transforms!

$$\boxed{B_\zeta(k_1, k_2, k_3) \to a(k_1)b(k_2)c(k_3)}$$

   - This reduces the complexity from $\mathcal{O}(N_{\rm pix}^3)$ to $\mathcal{O}(N_{\rm pix} \log N_{\rm pix})$

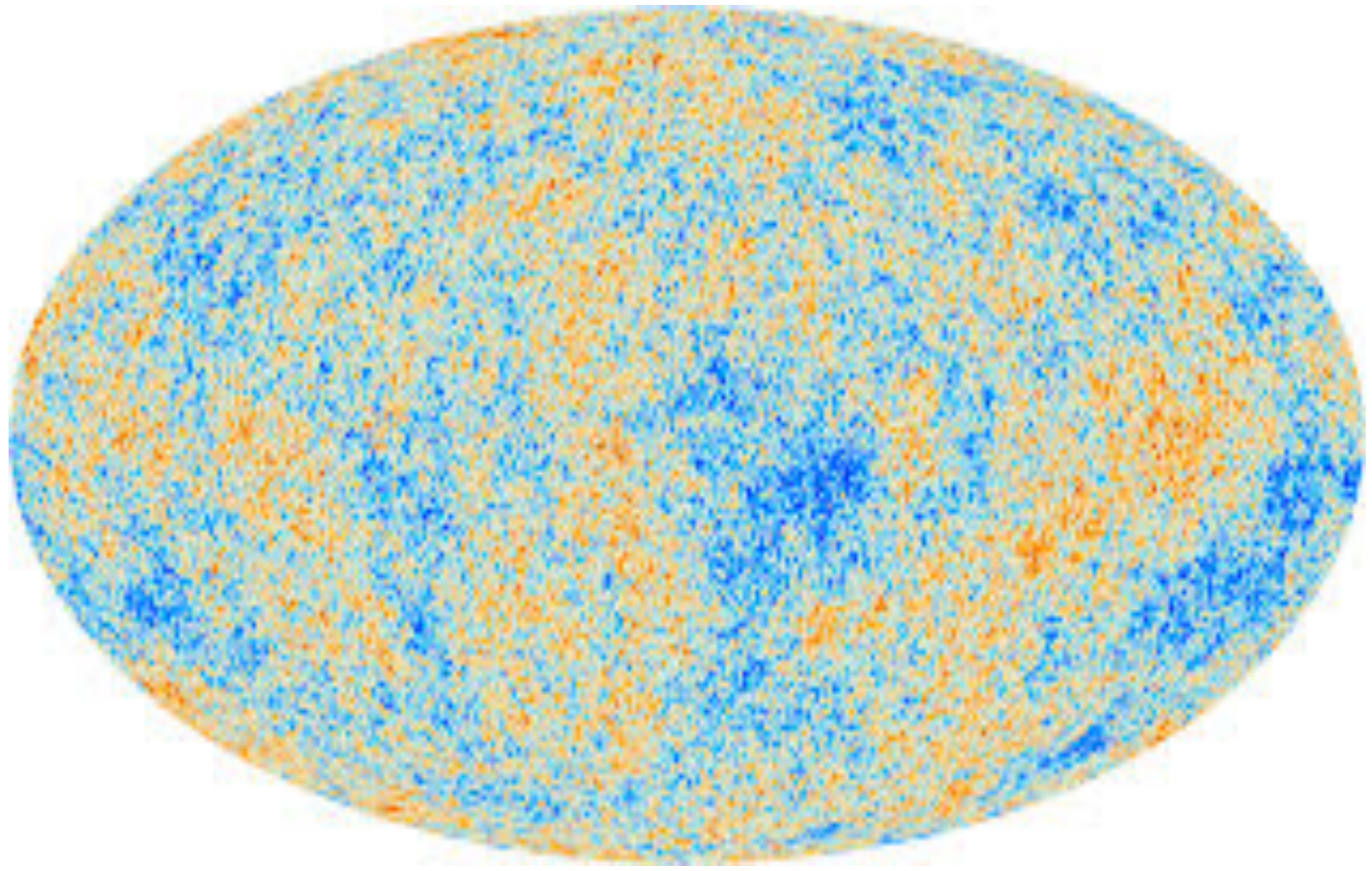


(See also modal / binned estimators)

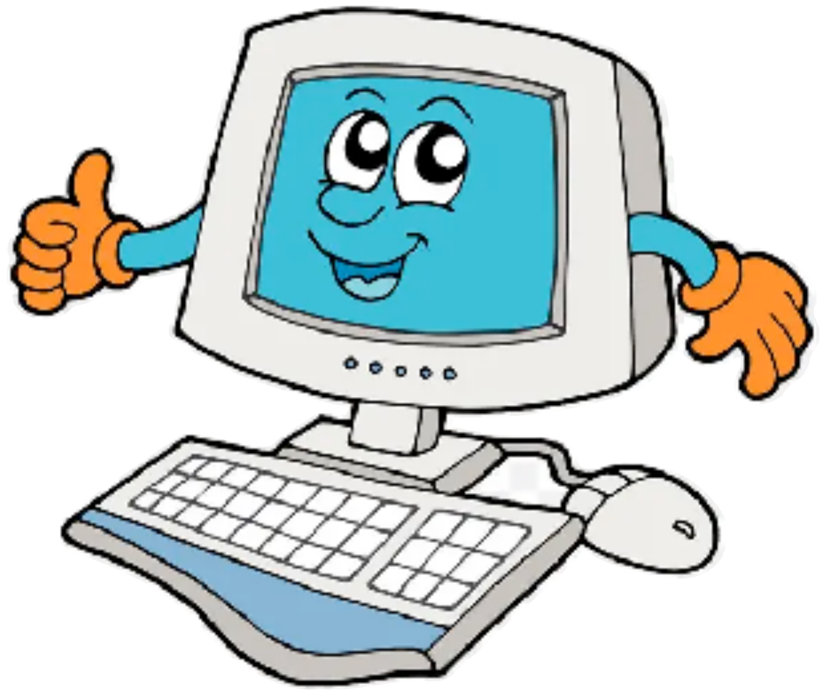
Komatsu, Spergel, Wandelt, Smith, Senatore, Zaldarriaga, …

How to Constrain Inflation

Data



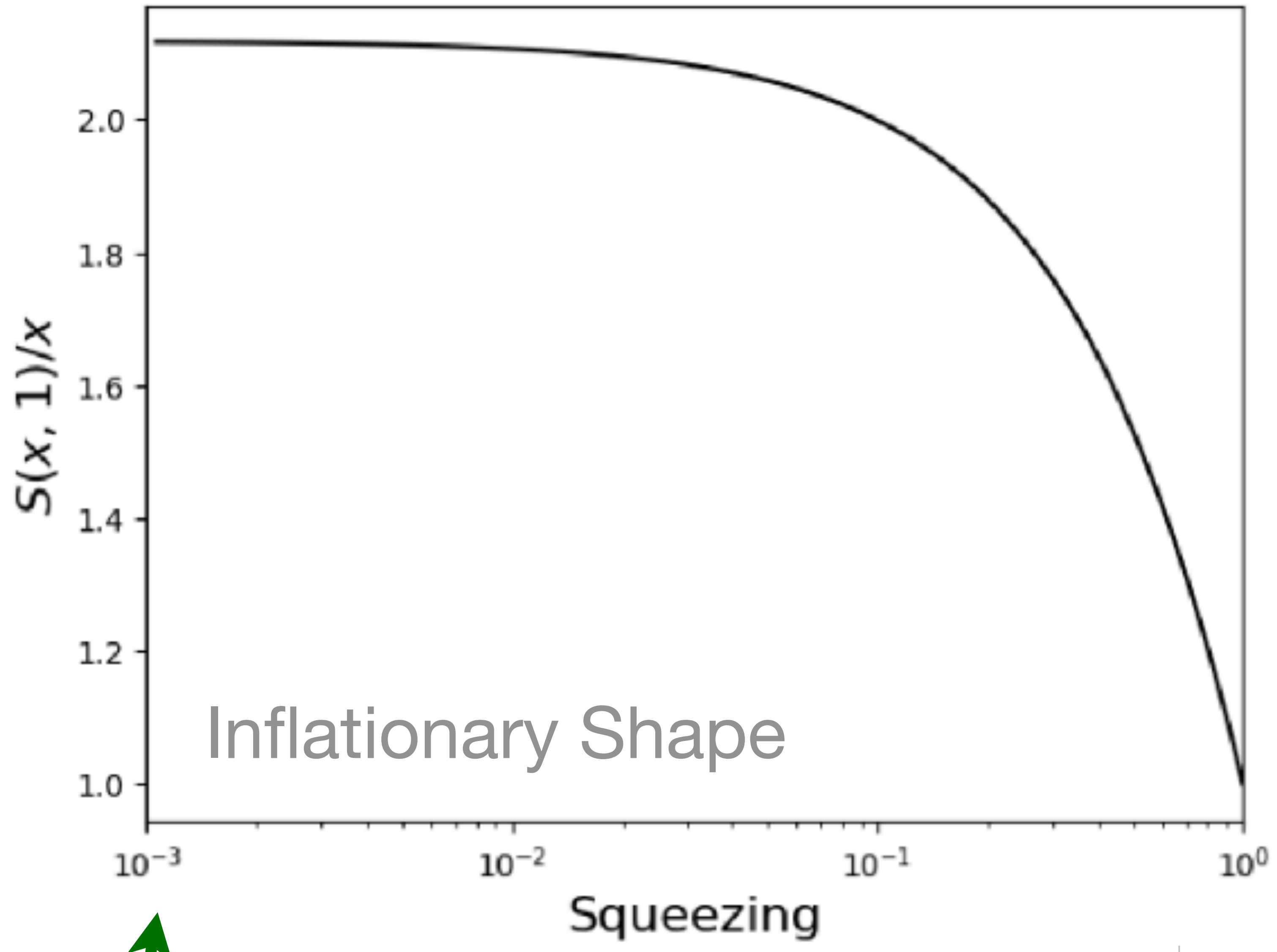
CMB Fluctuations

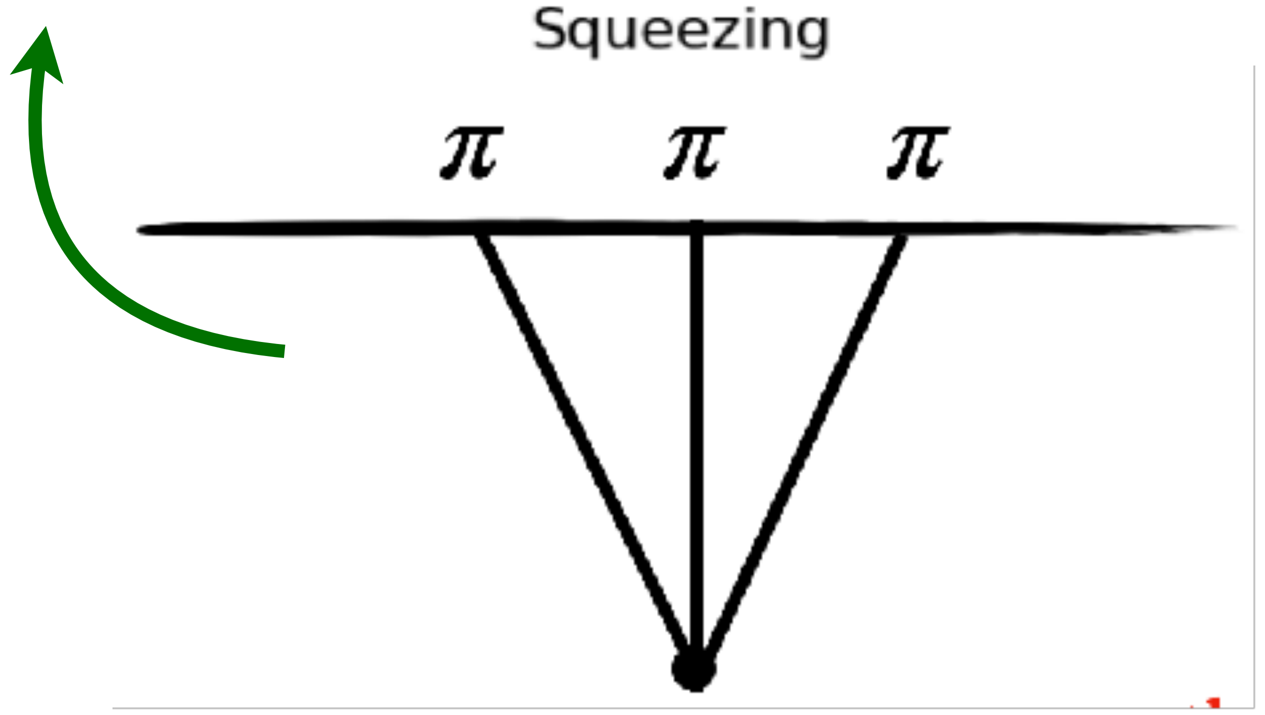


f_{NL}

Amplitude

Theoretical Template





This is **hard**

- We need a **factorizable** template
- Every shape needs its **own** analysis

Komatsu, Spergel, Wandelt, **Philcox**, Zhong, Sirletti, Smith, Zaldarriaga, Senatore, …

Constraining Factorizable Templates

- Previous CMB experiments have placed **strong** constraints on factorizable **three-point** functions

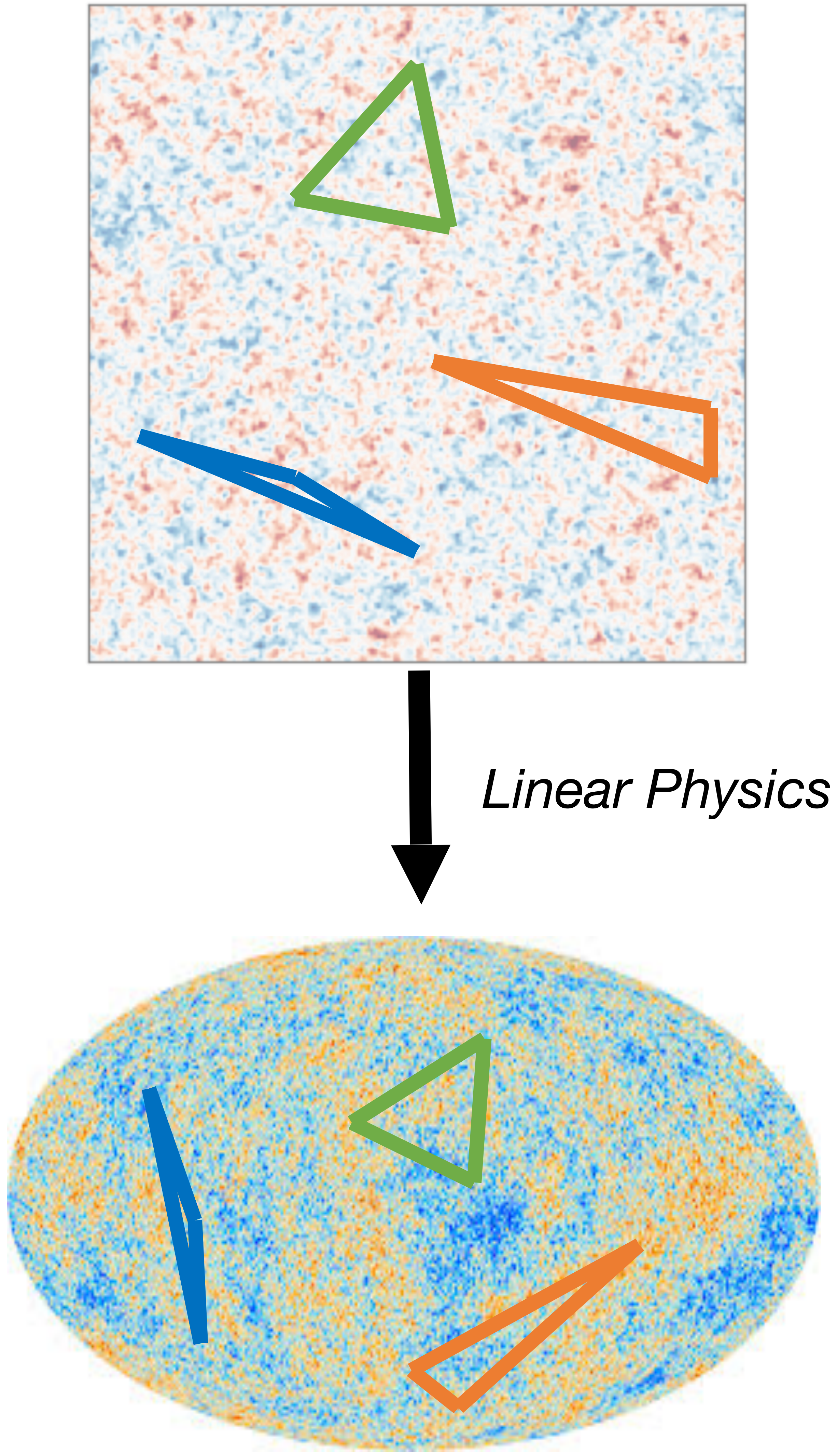
see Jo's talk!

$$\langle \delta T^3 \rangle \sim \langle \zeta^3 \rangle \sim f_{\rm NL} \times \text{Shape}$$

Planck 2018		
	Local	-0.9 ± 5.1
	Equilateral	-26 ± 47
	Orthogonal	-38 ± 24

Light field exchange

Self interactions



Conclusion: Primordial non-Gaussianity is **small!**

$$10^{-5}\,|f_{\rm NL}| \ll 1$$

*W*e are still far from the (vaguely defined) theory targets:

$$f_{\rm NL} \sim 1$$

Planck 2018, Smith+, Senatore+, Maldacena, Creminelli, Fergusson, Shellard

Constraining Non-Factorizable Templates

General inflationary models are not factorizable so how do we analyze them?

$$\boxed{B_\zeta(k_1, k_2, k_3) \neq a(k_1)b(k_2)c(k_3)}$$

1. Measure the <u>binned</u> bispectrum

$$B(\overline{\ell}_1, \overline{\ell}_2, \overline{\ell}_3) \sim \int dk_1 dk_2 dk_3 dr\, B_\zeta(k_1, k_2, k_3) j_{\ell_1}(k_1 r) j_{\ell_2}(k_2 r) j_{\ell_3}(k_3 r) \cdots$$

Expensive to compare theory and data

2. Measure the <u>compressed</u> **modal** bispectrum

$$B_\zeta(k_1, k_2, k_3) \sim \sum_{abc} \omega_{abc}\, k_1^a k_2^b k_3^c \quad \Leftrightarrow \quad \omega_{abc} \sim \int dk_1 dk_2 dk_3\, k_1^a k_2^b k_3^c\, B_\zeta(k_1, k_2, k_3)$$

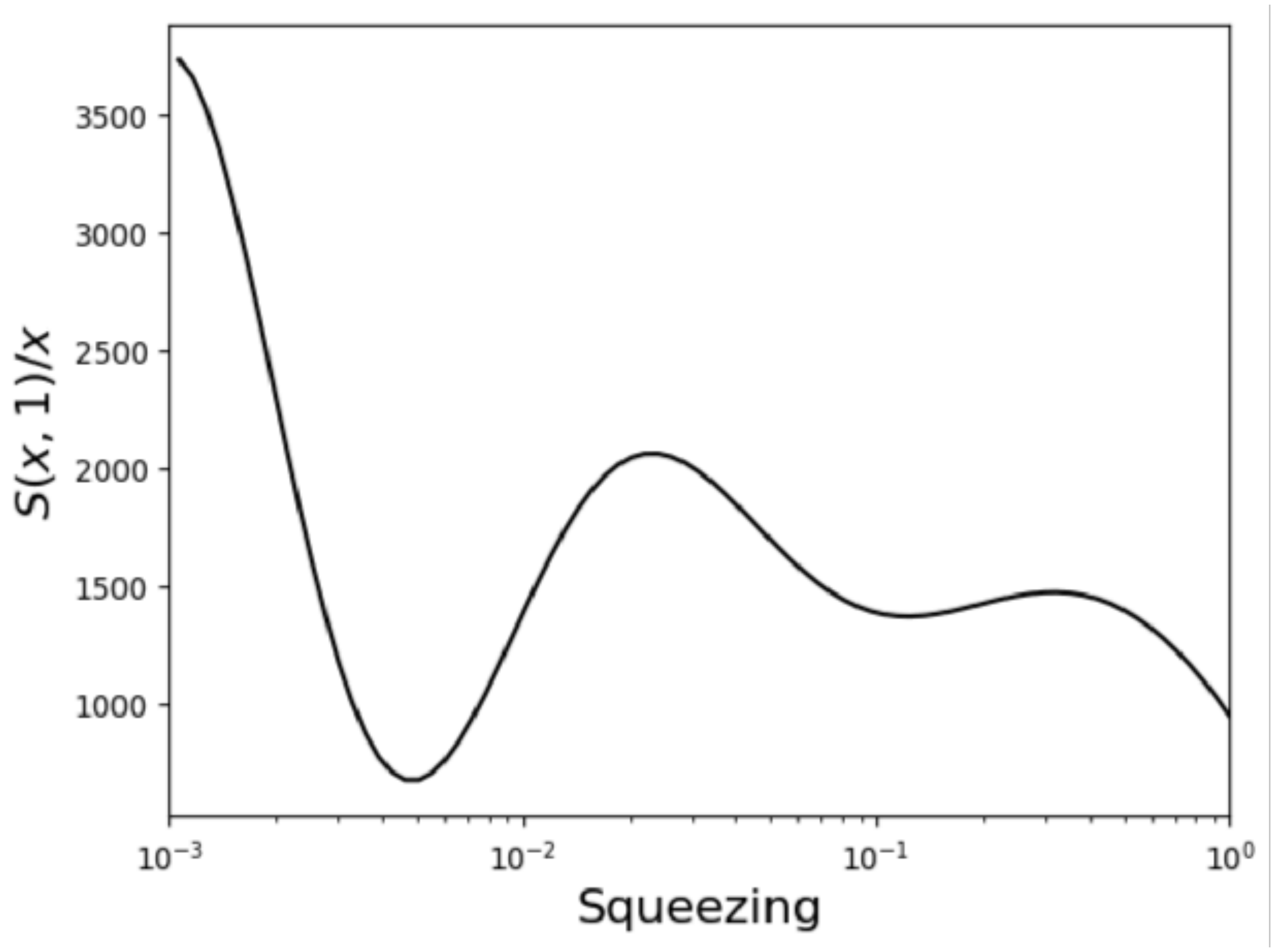
Powerful but **high-dimensional** and only as good as the **basis**

3. Measure the <u>compressed</u> bispectrum using **machine learning**

$$B_\zeta(k_1, k_2, k_3) \sim f_{\rm NL} \sum \mathrm{Neural}_1(k_1)\mathrm{Neural}_2(k_2)\mathrm{Neural}_3(k_3)$$

Easy to find the **best basis** for a particular model

Massive particle exchange (non-factorizable)



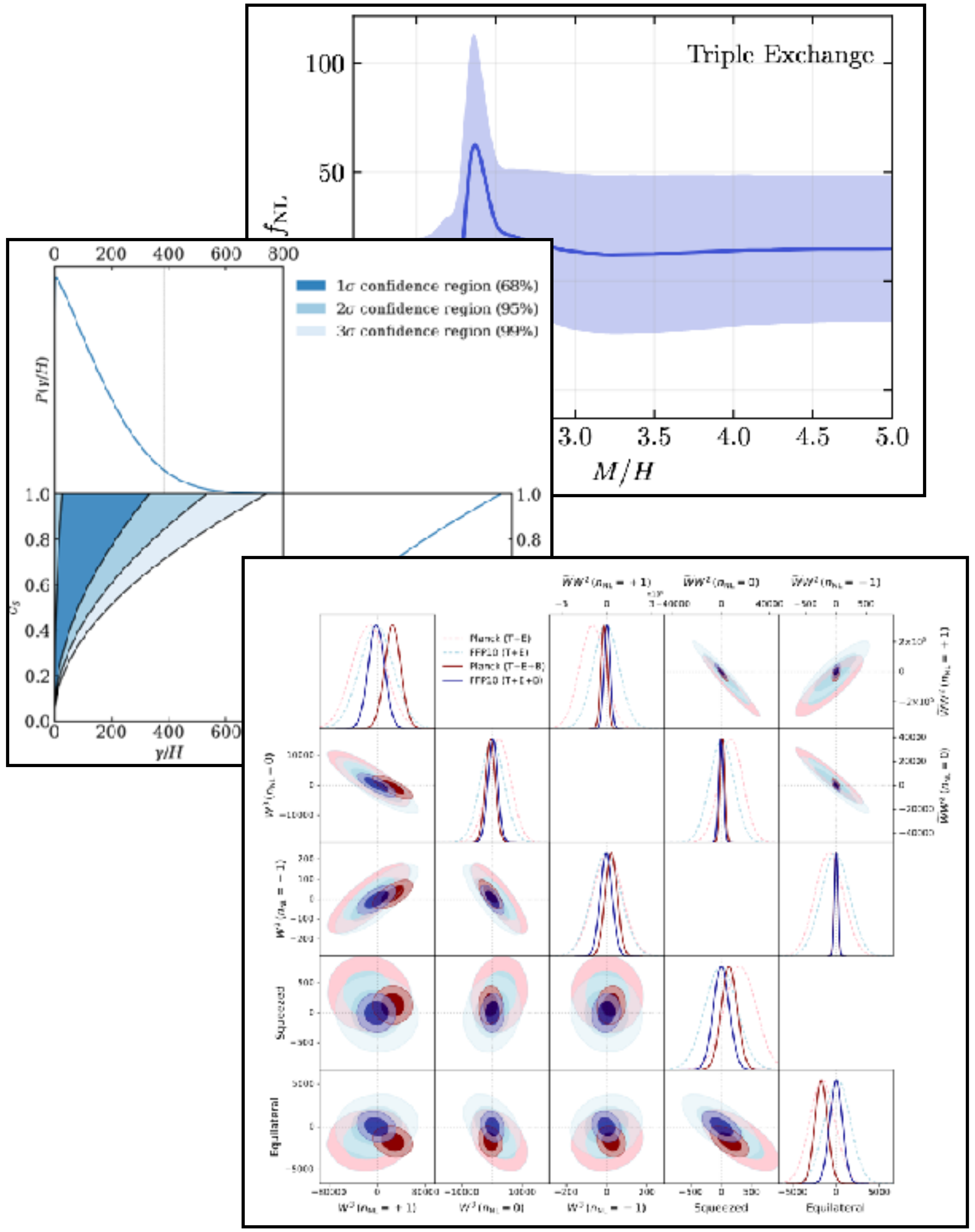
Shellard, Fergusson, Sohn, Suman, Wang, Bucher, Racine, van Tent, **Philcox**, Sirletti, Zhong…

CMB Bispectrum Constraints

These have placed strong constraints on novel physics

1. Measure the <u>binned</u> bispectrum
   - Correlations with **gravitational waves** ($\langle\zeta\zeta h\rangle + \cdots$)
2. Measure the <u>compressed</u> **modal** bispectrum
   - Oscillations and approximate shape of **massive particles** with $m_\sigma \sim H$
   - Extensions with **triple-exchange**, **dissipation** and **chemical potential** (exact shapes)
3. Measure the <u>compressed</u> bispectrum using **machine learning**
   - **Strongly-coupled** systems (“unparticles”)

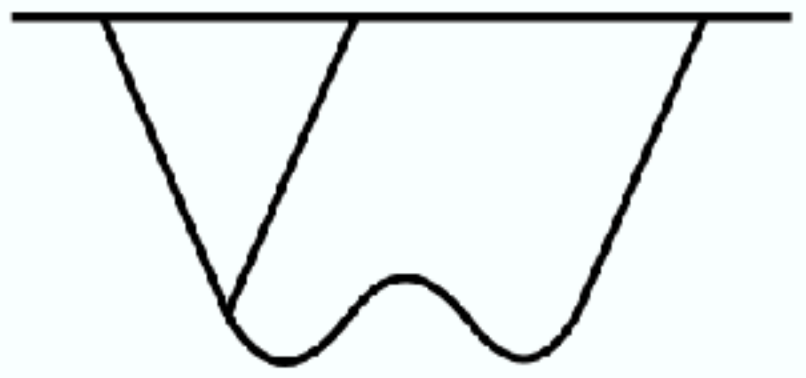
So far, there have been no detections



Salcedo, Lu, Kumar, Shiraishi, Colas, Xianyu, Sohn, Suman, Wang, Yang, Shellard, Fergusson, Pimentel, Zhang, **Philcox**…

CMB Bispectrum Constraints

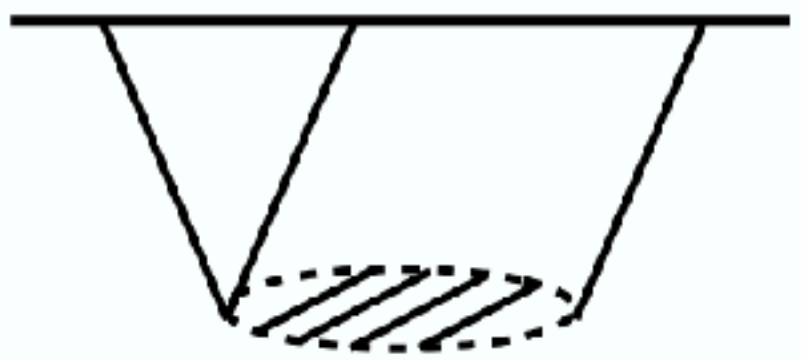
Models $\Rightarrow$ Pipeline $\Rightarrow$ Constraints



Weakly coupled (M, J)

Massive particle exchange

$$\mathscr{L} \sim \dot{\pi}\sigma + (\partial_\mu \pi)^2 \sigma$$



Strongly coupled (M, Δ)

Conformal Field Theory exchange

(Unparticles)

$$\mathscr{L} \sim \dot{\pi}\mathcal{O} + (\partial_\mu \pi)^2 \mathcal{O}$$

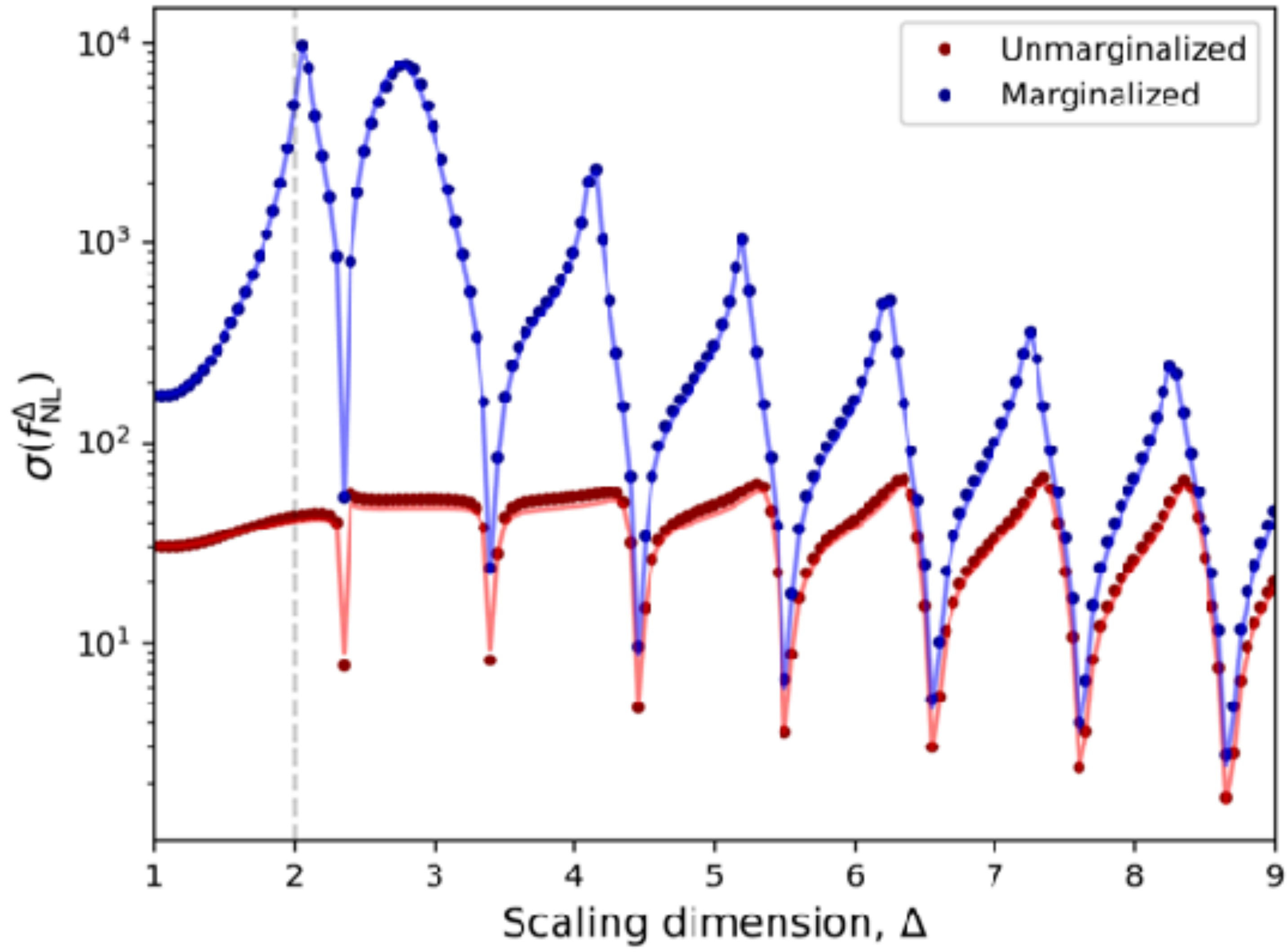
$$\langle \tilde{\mathcal{O}}_\Delta(\eta_1, \mathbf{x}) \tilde{\mathcal{O}}_\Delta(\eta_2, \mathbf{y}) \rangle_{\mathrm{dS}_4} = \frac{(H^2 \eta_1 \eta_2)^\Delta}{\left(-(\eta_1 - \eta_2)^2 + (\mathbf{x} - \mathbf{y})^2 \right)^\Delta}$$

Theoretical Model
$S_\Delta(x, y)$

Orthogonal Components
$S^{(i)}(k_1, k_2, k_3)$

Separable Basis
$\alpha_n^{(i)}(k), \beta_n^{(i)}(k), \gamma_n^{(i)}(k)$

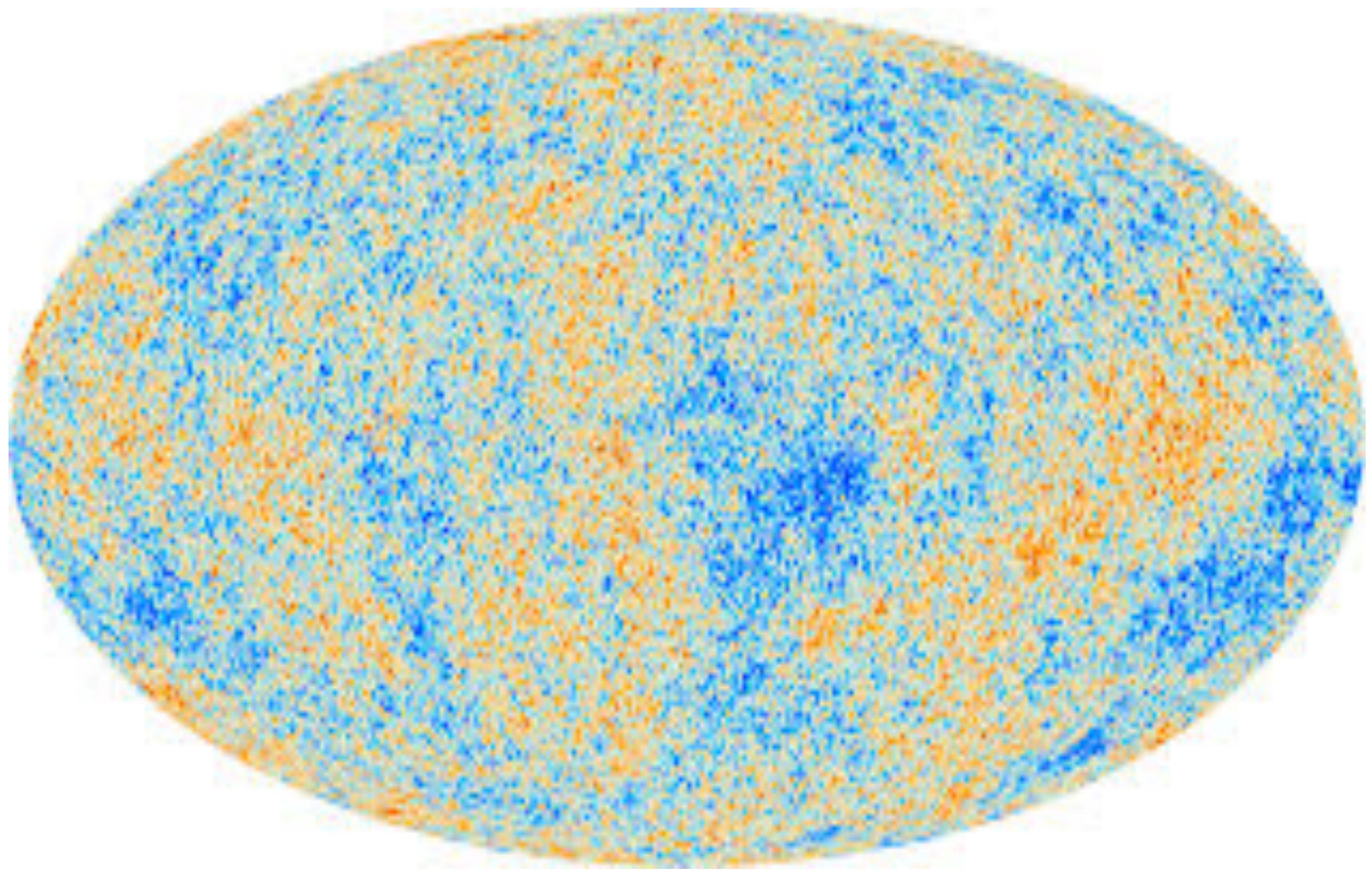
PNG Constraints
f_{NL}^{Δ}



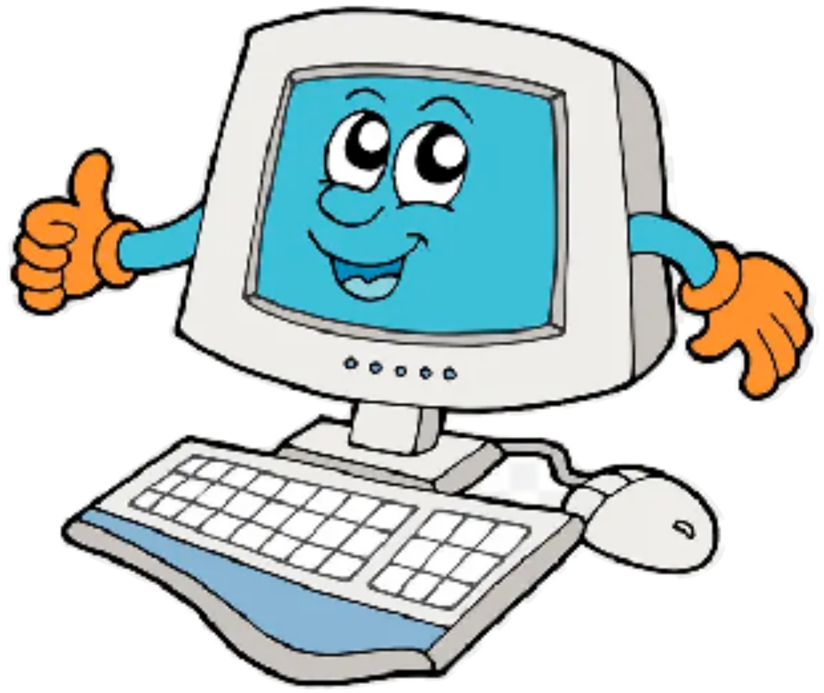
Philcox, Pimentel, Wang 26 (also Green, Lewandowski, Zaldarriaga, Senatore, Silverstein)

How to Constrain Inflation

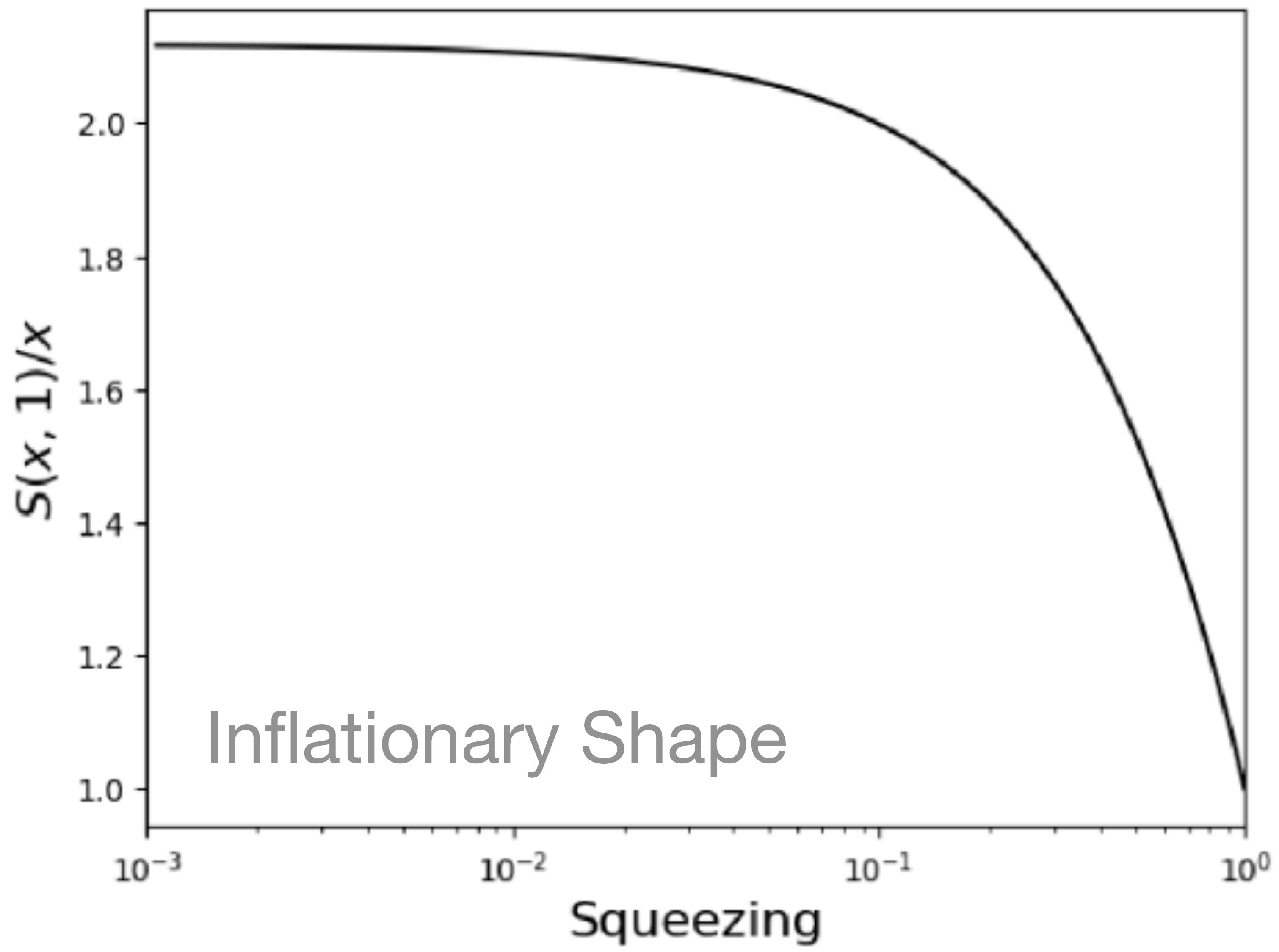
Data



CMB Fluctuations



Theoretical Template



f_{NL}

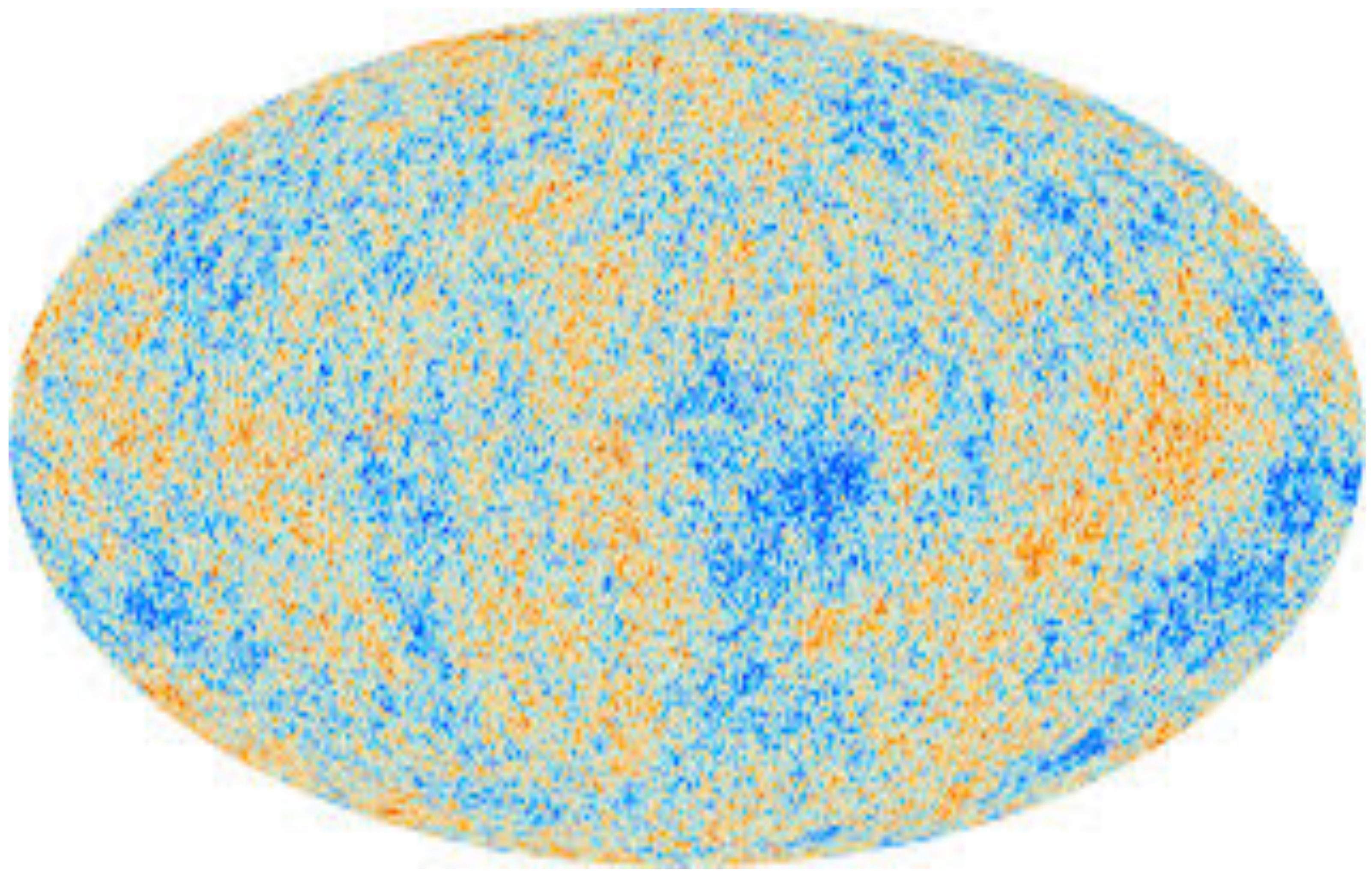
Amplitude

This is **hard**

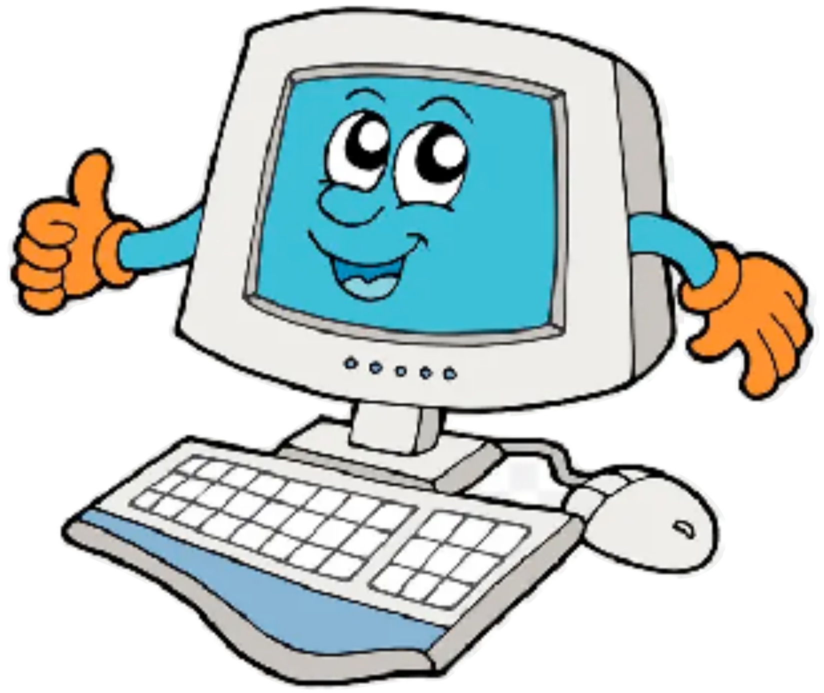
- We need a **factorizable** template
- Every shape needs its **own** analysis

How to Constrain Inflation

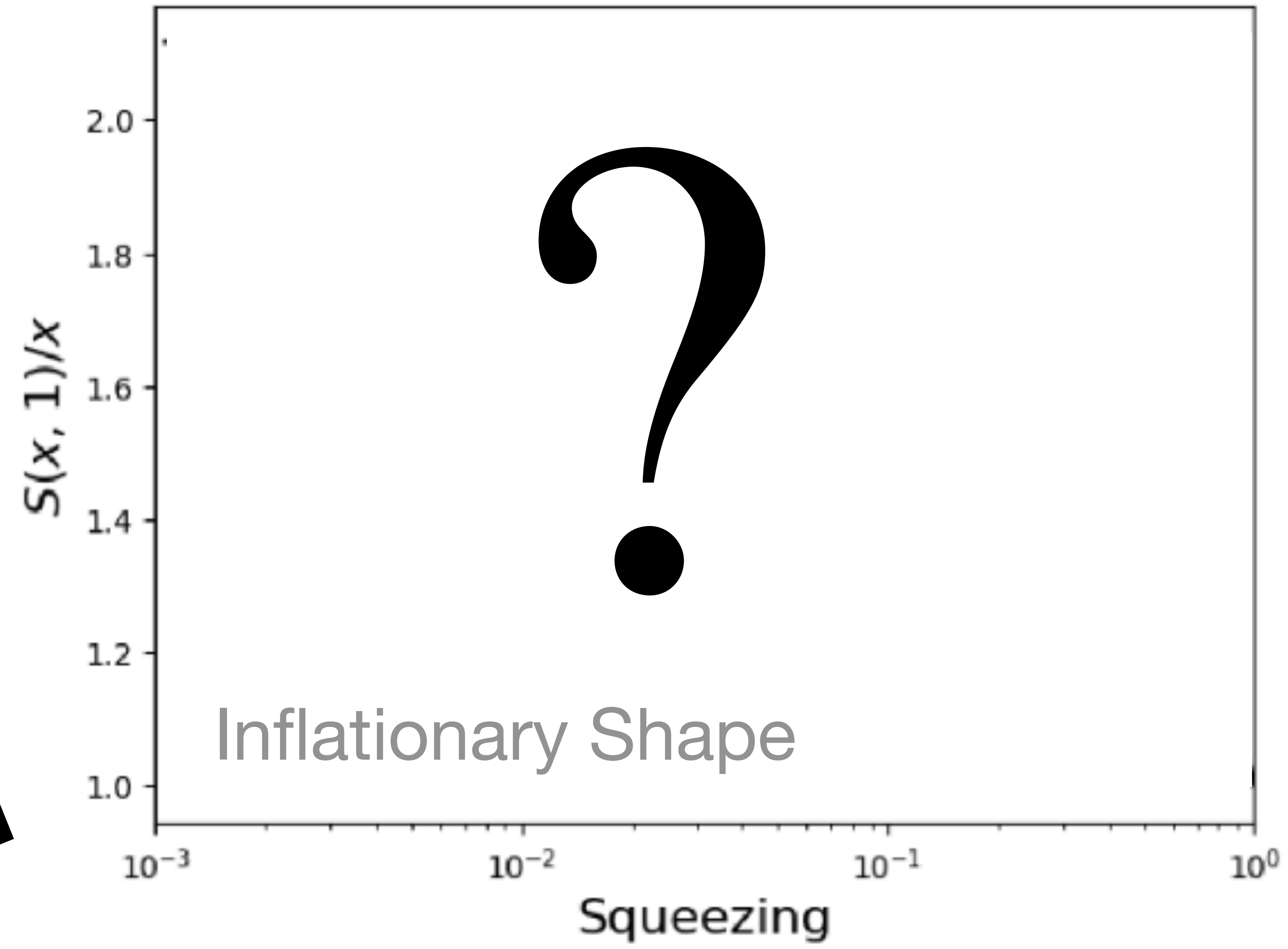
Data



CMB Fluctuations



Observed Shape



f_{NL}

Amplitude

This is **easy**

- We can analyze *any* shape
- The analysis is (almost) **free**

Philcox 26

What Shape is the Bispectrum?

Can we **reconstruct** the inflationary bispectrum?

$$B(\ell_1,\ell_2,\ell_3) \sim \int dk_1 dk_2 dk_3 dr\, B_\zeta(k_1,k_2,k_3) j_{\ell_1}(k_1 r) j_{\ell_2}(k_2 r) j_{\ell_3}(k_3 r)\cdots$$

Observer-friendly *Theory-friendly*

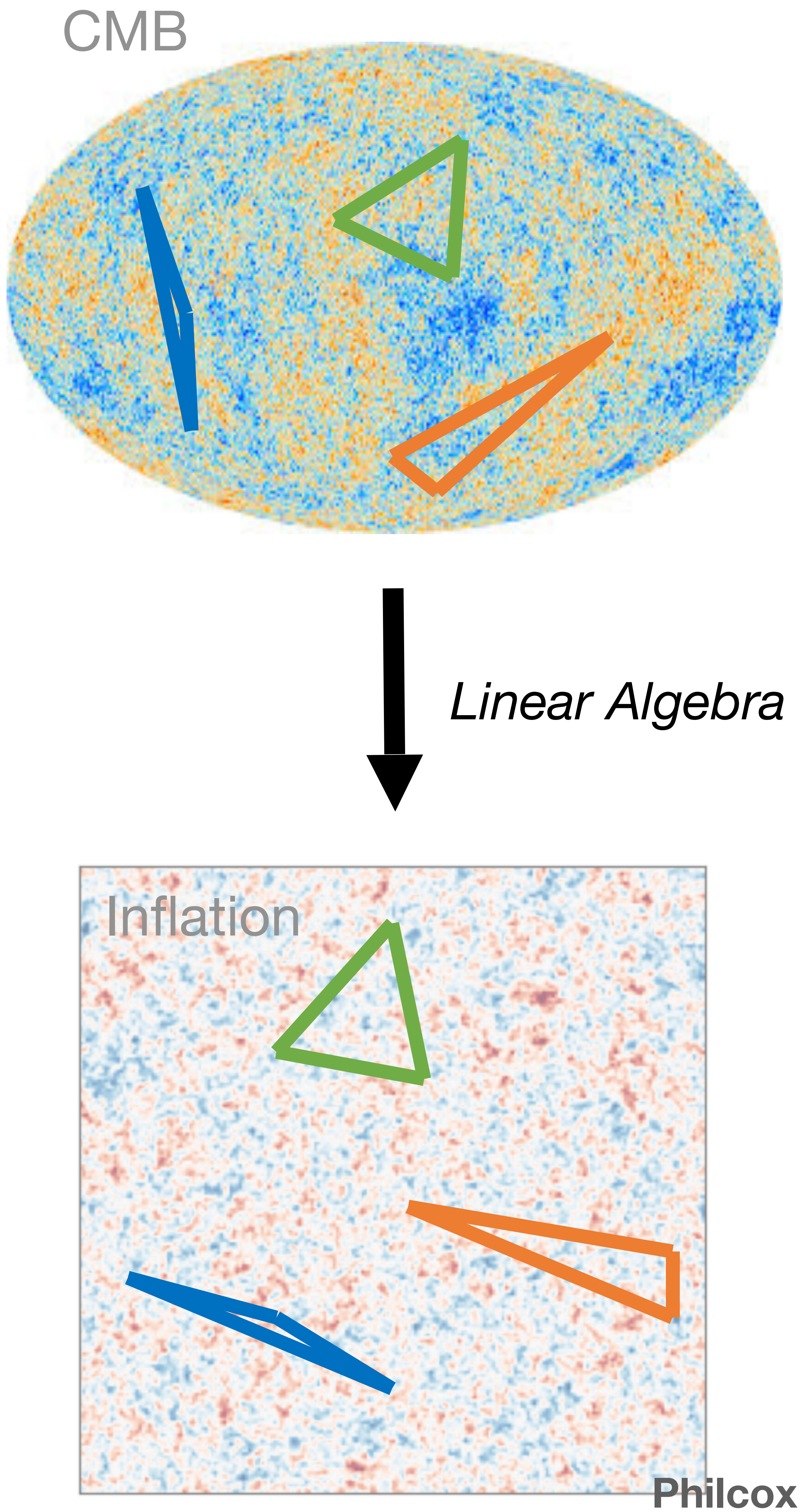
- Let's assume **scale-invariance** (*i.e.* dilatation invariance) ⇒ we have a 2D **shape function**

$$B_\zeta(k,k,k) \sim k^{-6} \qquad S(x = k_1/k_3, y = k_2/k_3) \propto (k_1k_2k_3)^2 B_\zeta(k_1,k_2,k_3)$$

- Build a **binned estimator** for $S(x,y)$ from the CMB!

$$\widehat{S(x,y)} \sim \sum_{\ell_1 m_1 \ell_2 m_2 \ell_3 m_3} \frac{\partial \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3}\rangle^\dagger_{\text{theory}}}{\partial S(x,y)} \times (C^{-1}a)_{\ell_1 m_1}(C^{-1}a)_{\ell_2 m_2}(C^{-1}a)_{\ell_3 m_3}$$

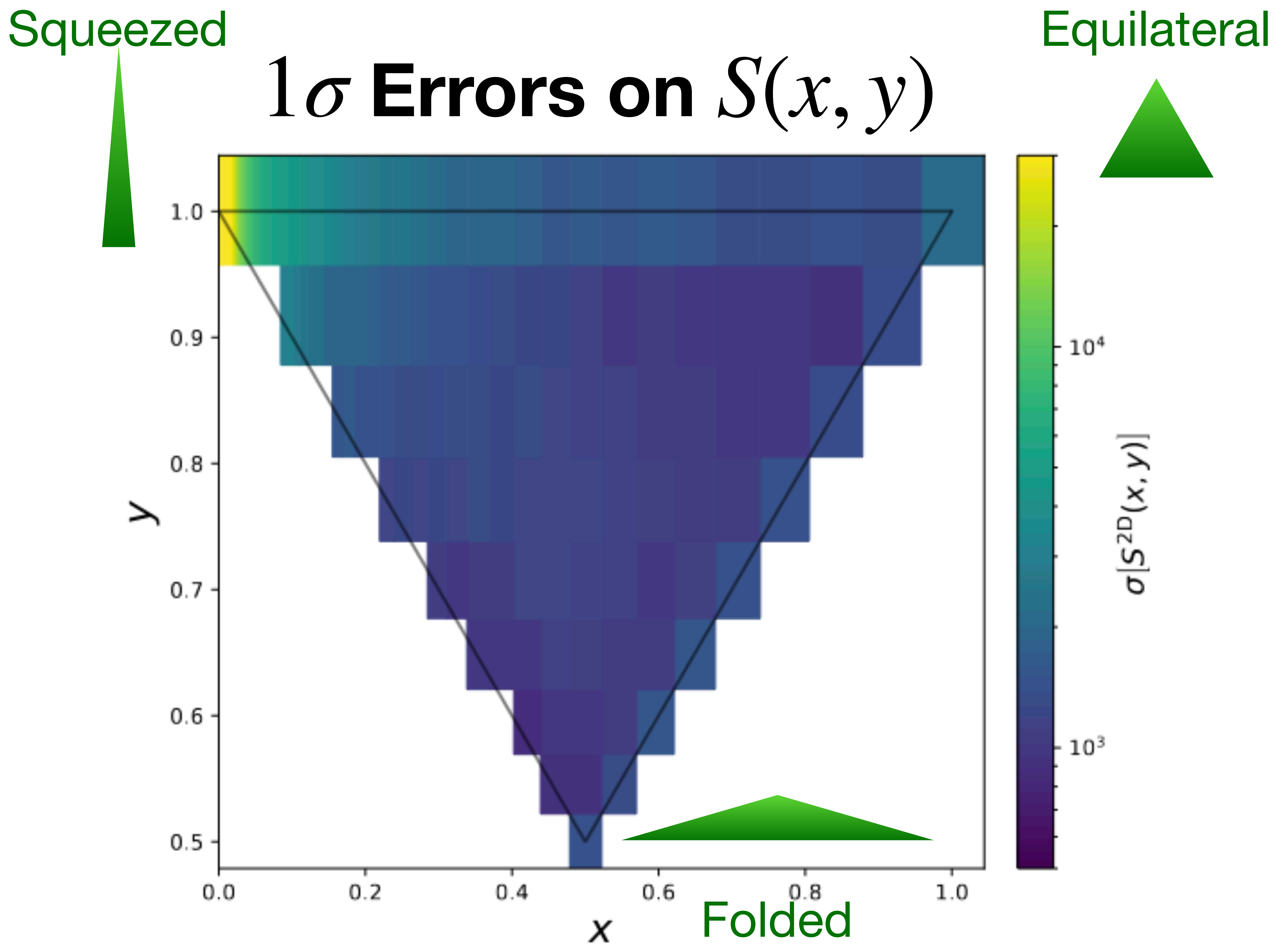
(In practice, build a 3D estimator binned in $\log k$, then linearly transform to $\log x/\log y$ bins)

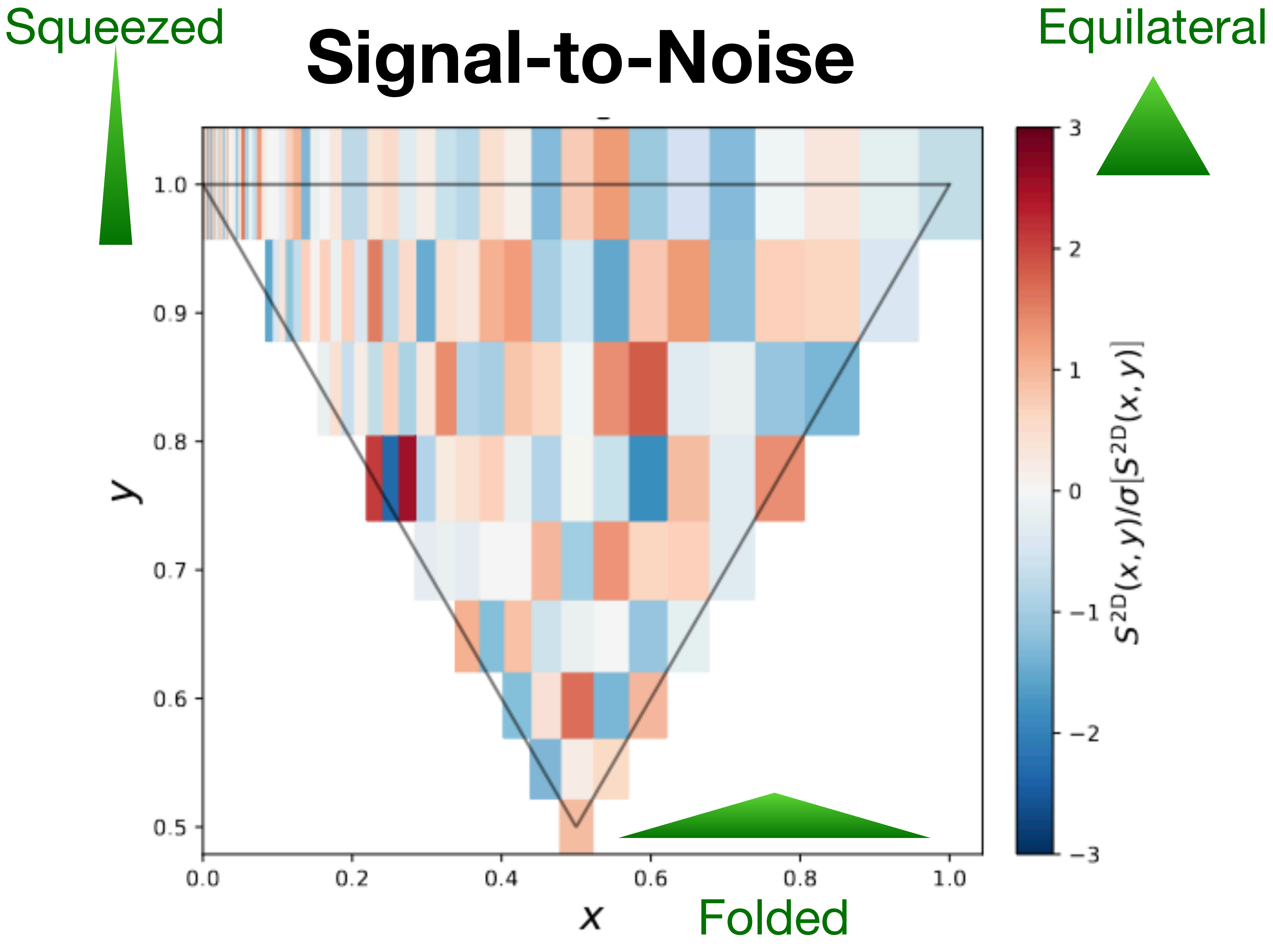


Philcox 26

The *Planck* Bispectrum Shape

We build **efficient**, quasi-**optimal**, mask/beam-corrected, **cubic estimators** for the underlying primordial shape

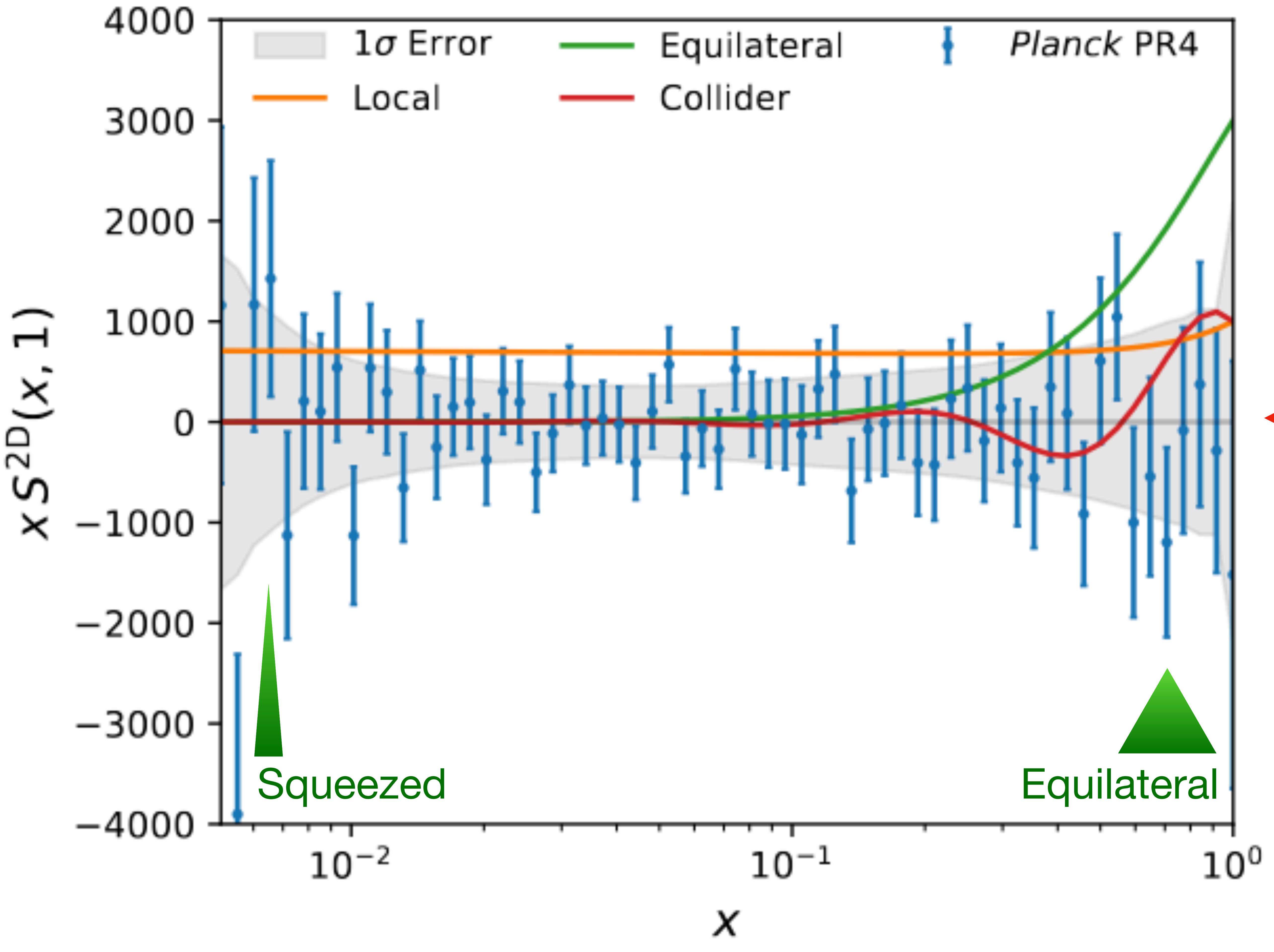




Planck PR4, T+E, $\ell \in [2{,}2048]$, $\chi^2/\mathrm{dof} = 174/171$

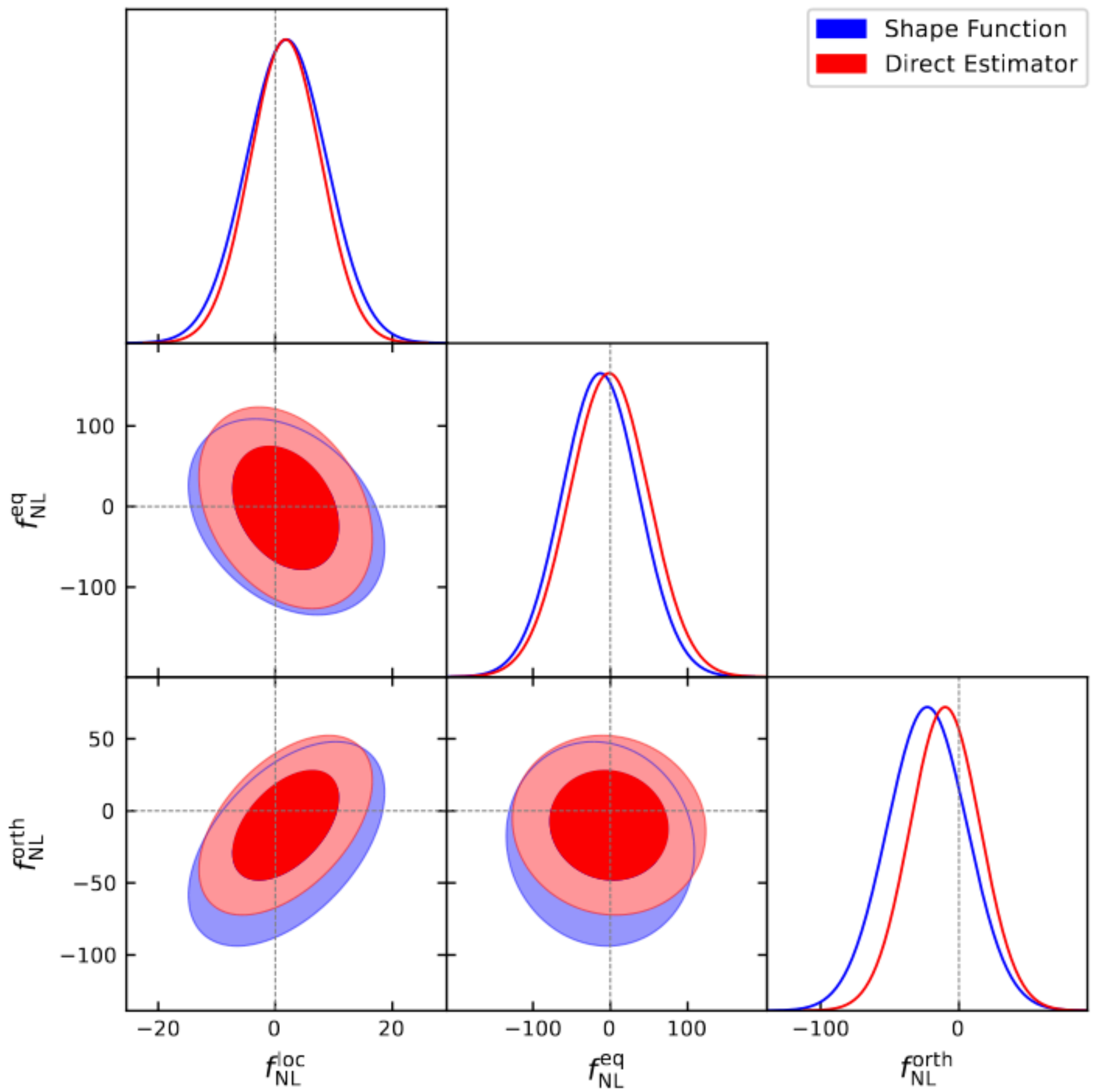
The *Planck* Bispectrum Shape

We can directly probe the **squeezed limit** to **directly** compare to models!



Collider oscillations are hard to detect!

Does this actually work?



We are **compressing** the full bispectrum into a set of **binned** $S(x, y)$ measurements.

Is this a sensible approach?

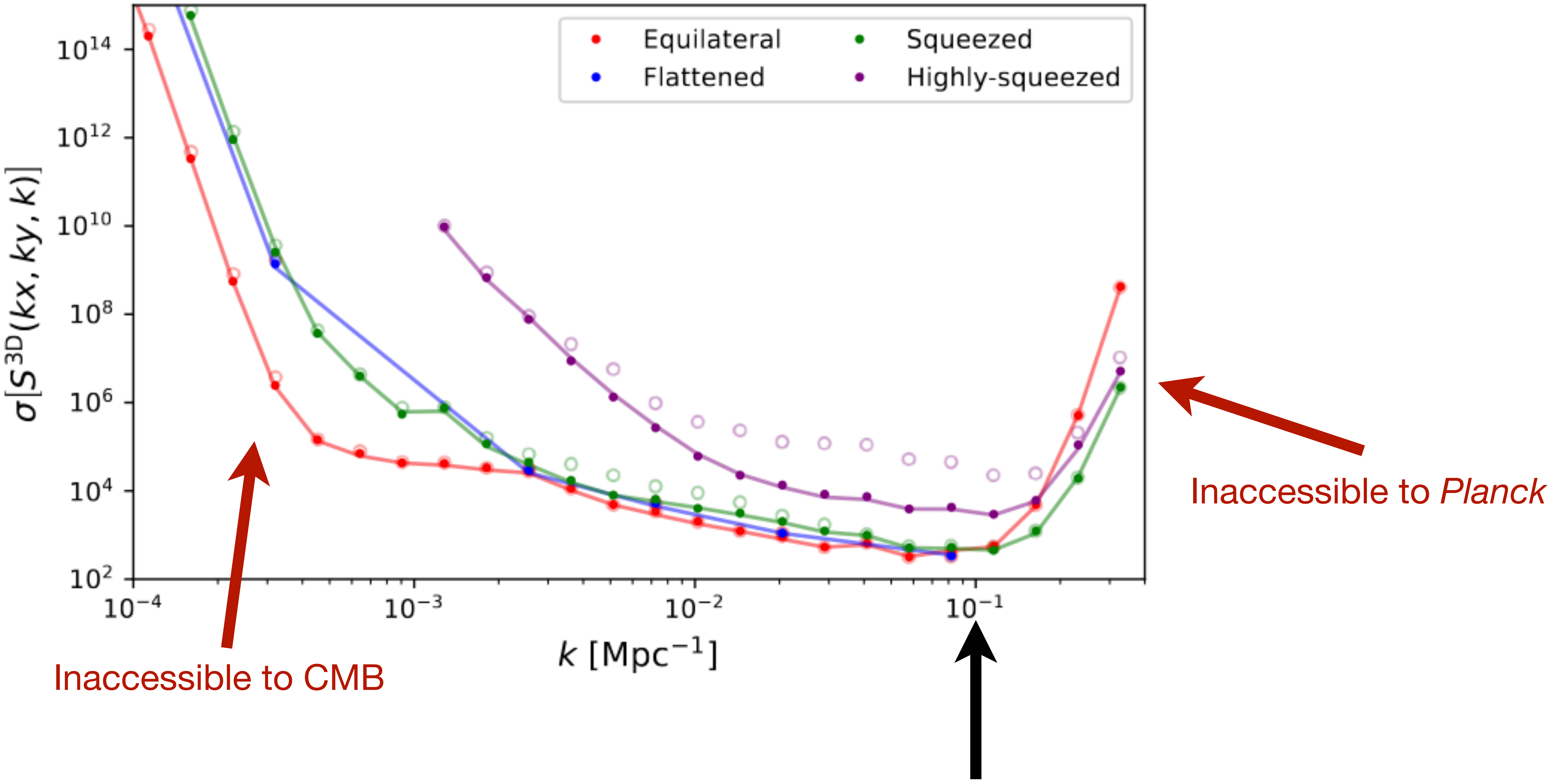
Yes!

We get the f_{NL} amplitudes and errors correct to $\mathcal{O}(10\%)$

Where does the information come from?

Using the binned **three-dimensional** bispectrum $S(kx, ky, k)$ we can probe the **information content** with respect to k

~ 6 e-folds accessible to PNG

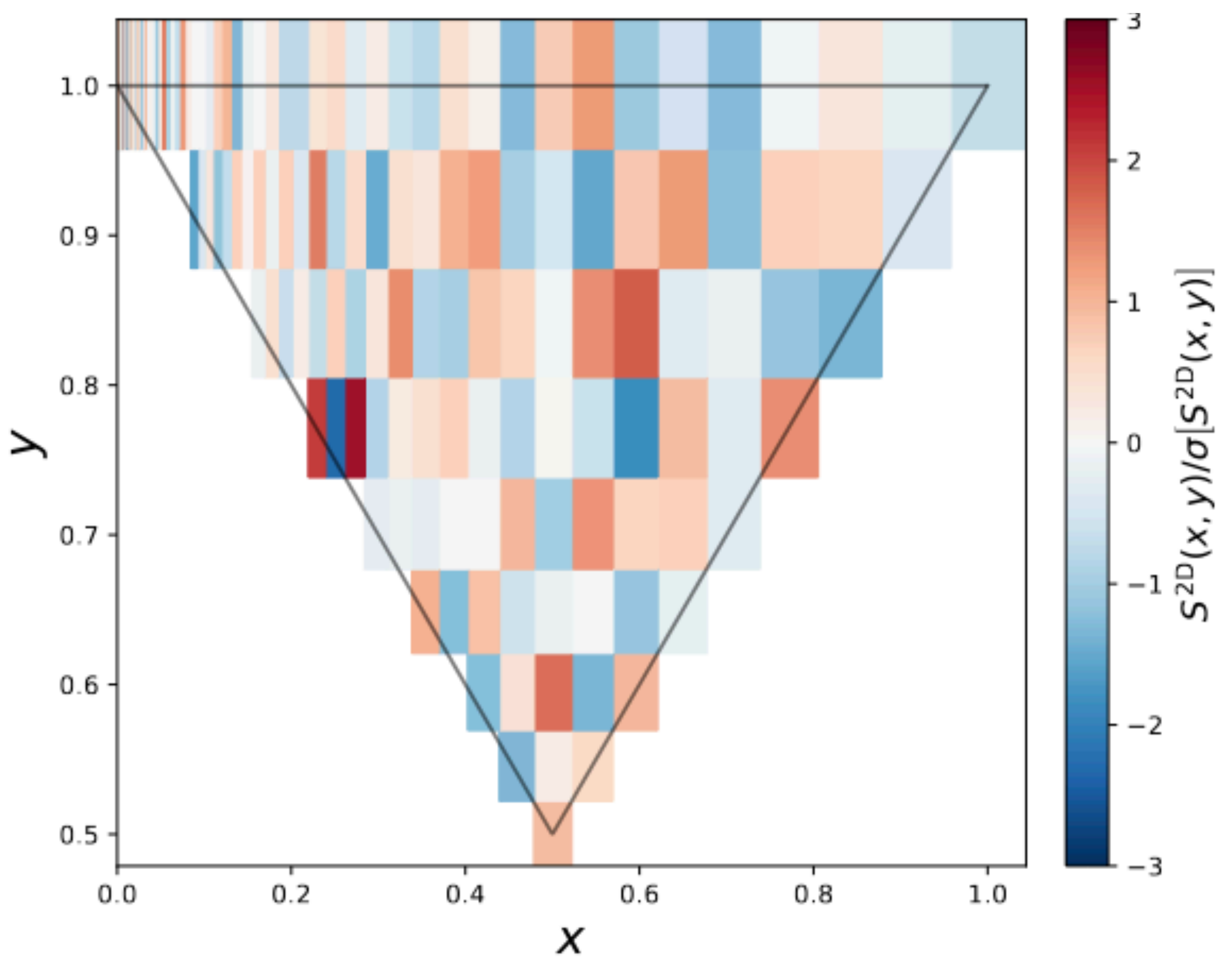


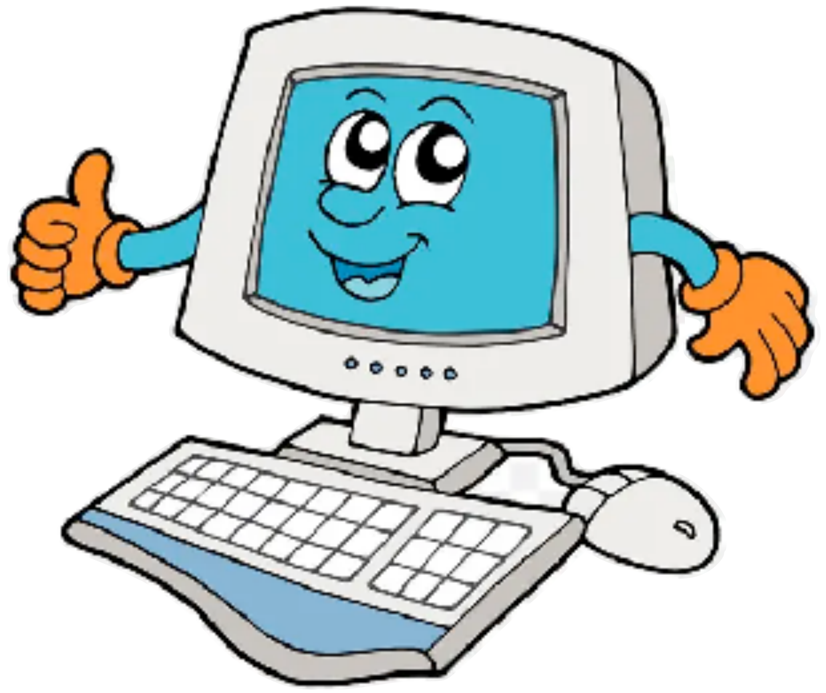
Philcox 26

How to Constrain Inflation

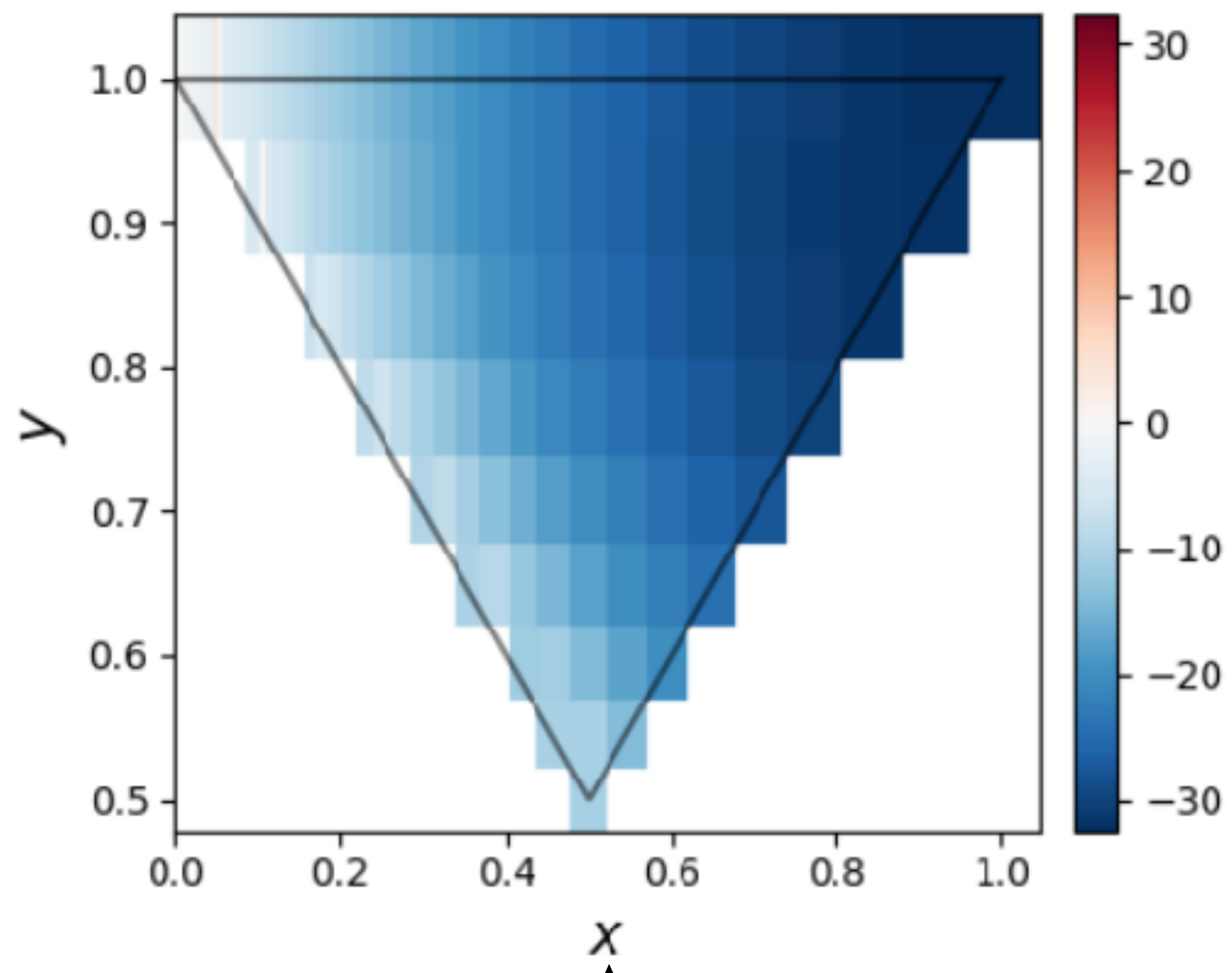
We can analyze (scale-invariant) bispectrum templates **<u>much faster</u>** **(**$\mathcal{O}(\mathrm{ms})$ **not** $\mathcal{O}$(lots of hours)**)**

Observed Shape





Theoretical Shape

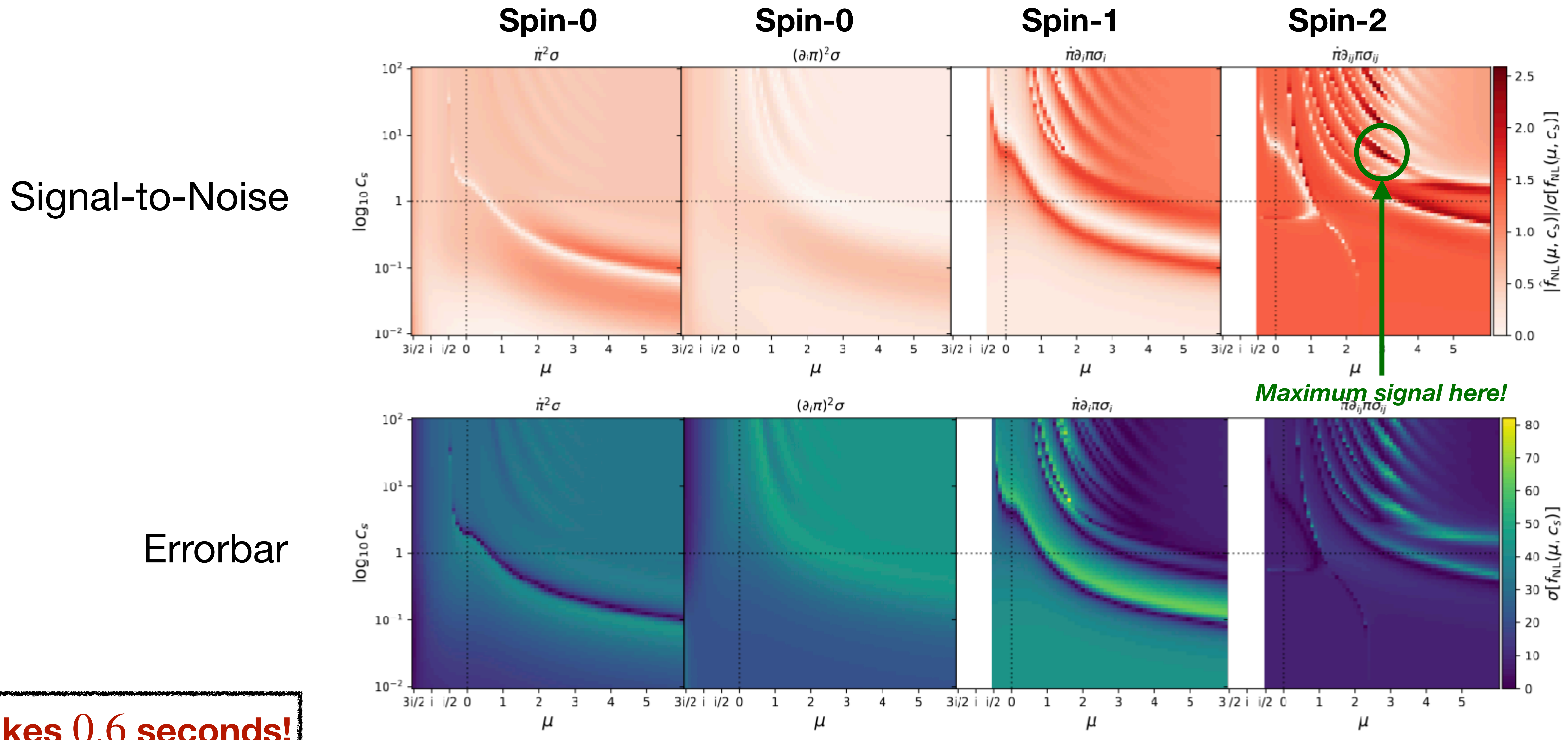


Signal-to-Noise

Model Parameters

Searching for the Cosmological Collider

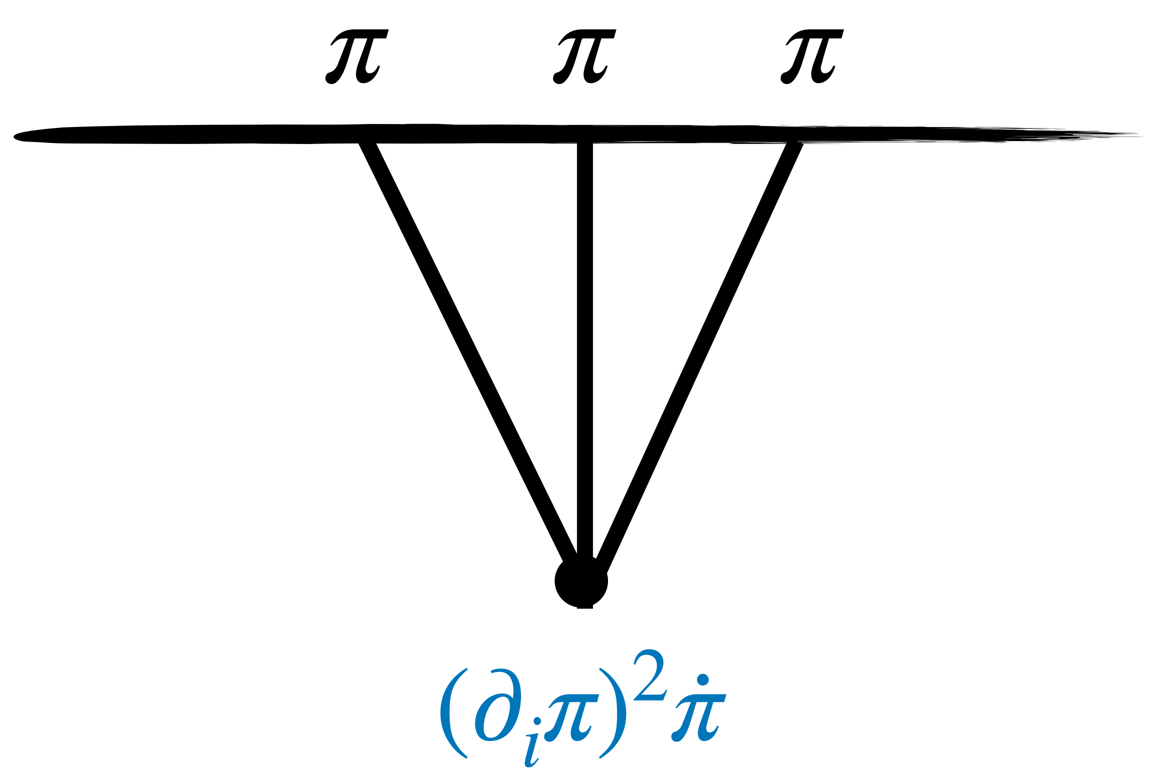
We can use this to constrain **massive** particle (single)-exchange, as a function of **mass**, **spin**, and **sound-speed** by coupling to (exact) **bootstrap** codes



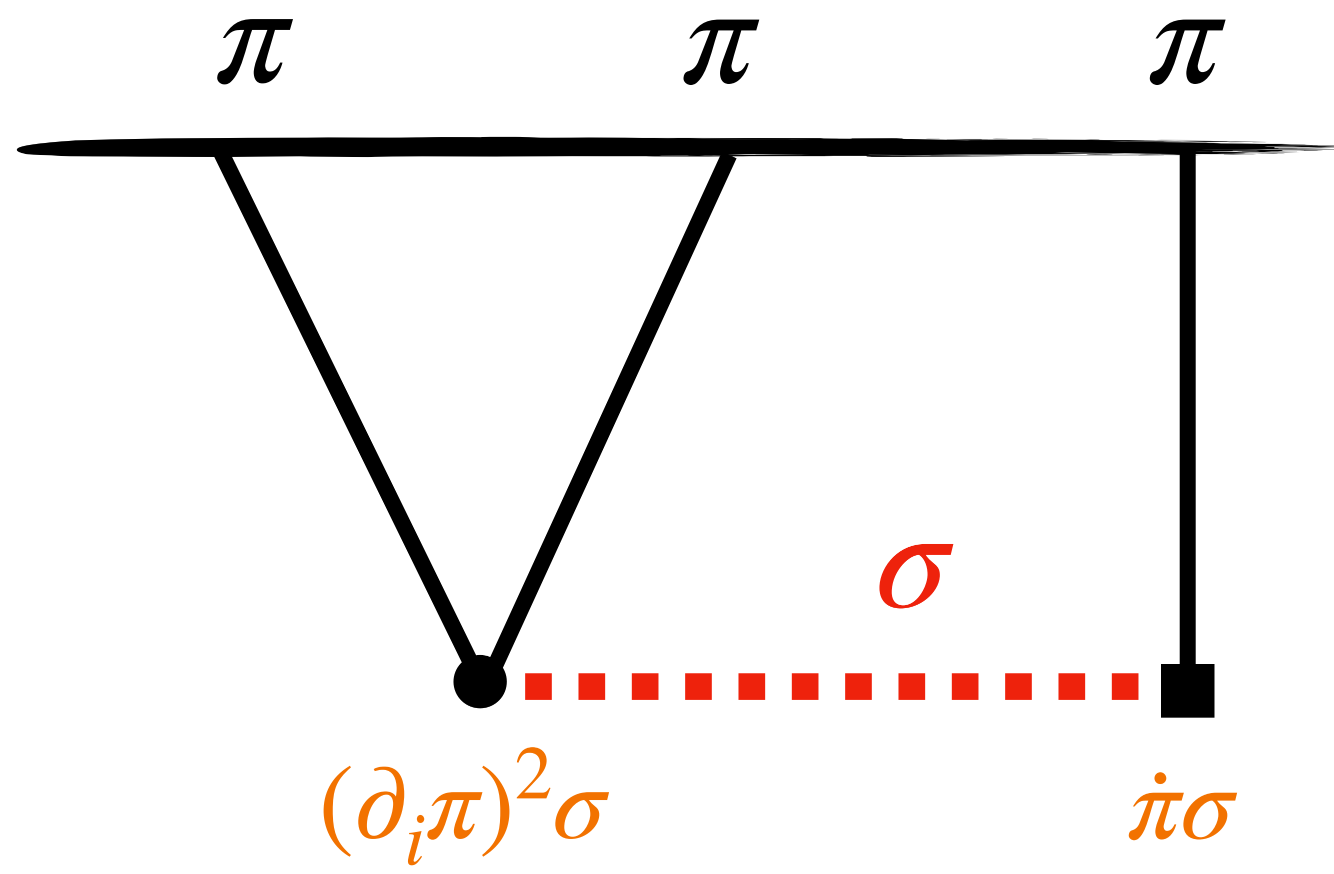
This takes 0.6 seconds!

Beyond Template Analyses

- Various terms in the model are **non-linearly** related, e.g.,
  - low-sound speed ⇒ large $(\partial_i\pi)^2\sigma$ 😀 ⇒ large $(\partial_i\pi)^2\dot{\pi}$ 😭
  - large collider signal ⇒ large $(\partial_i\pi)^2\sigma$ 😀 ⇒ large quadratic mixing $\dot{\pi}\sigma$ 🤔



- **Template** analyses ignore this information!
  - (e.g., no correlations imposed between $f_{\rm NL}^{\rm eq}$ and $f_{\rm NL}^{\rm collider}$)



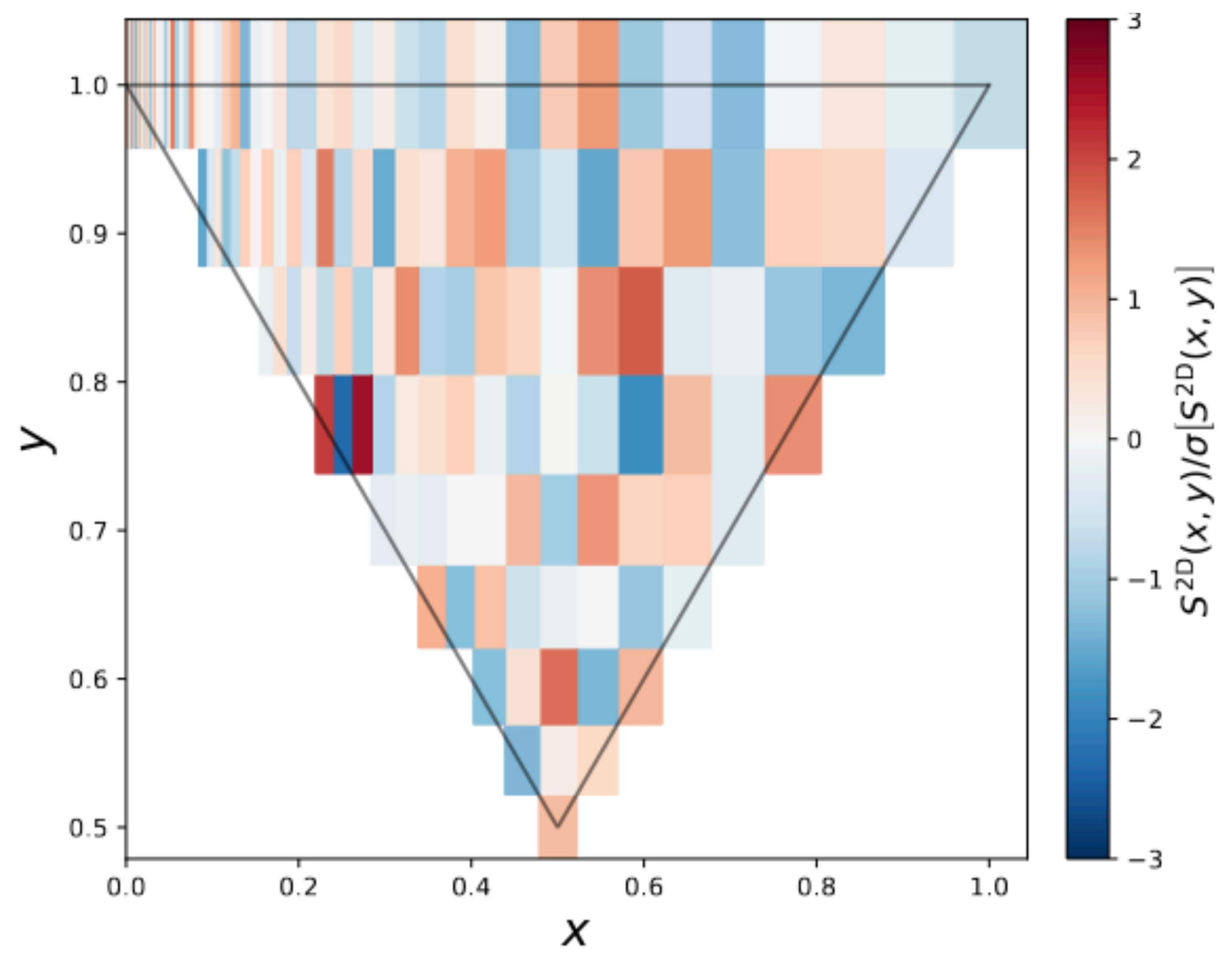
- **Solution**: analyze the full cubic Lagrangian self-consistently!

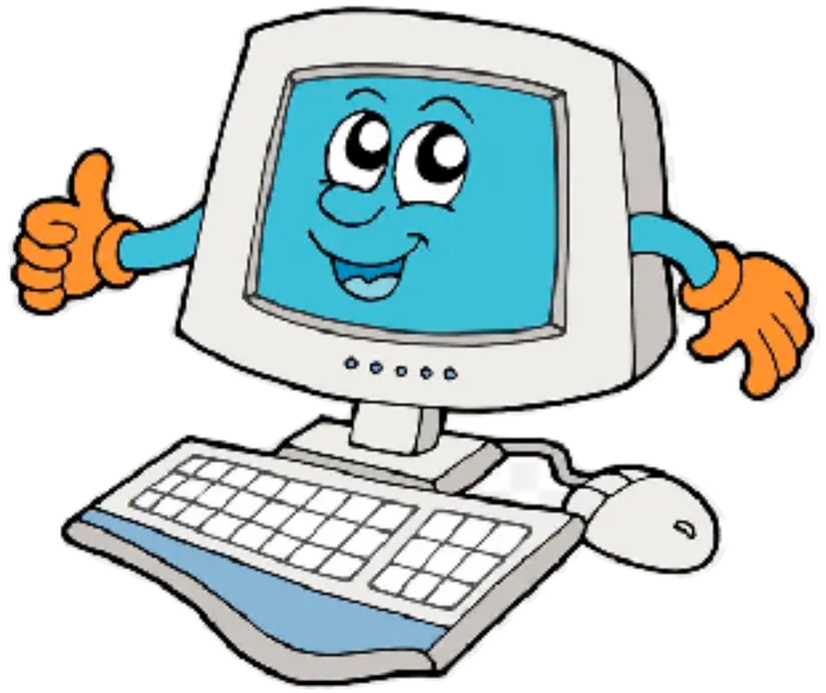
Philcox (in prep.)

How to Constrain Inflation

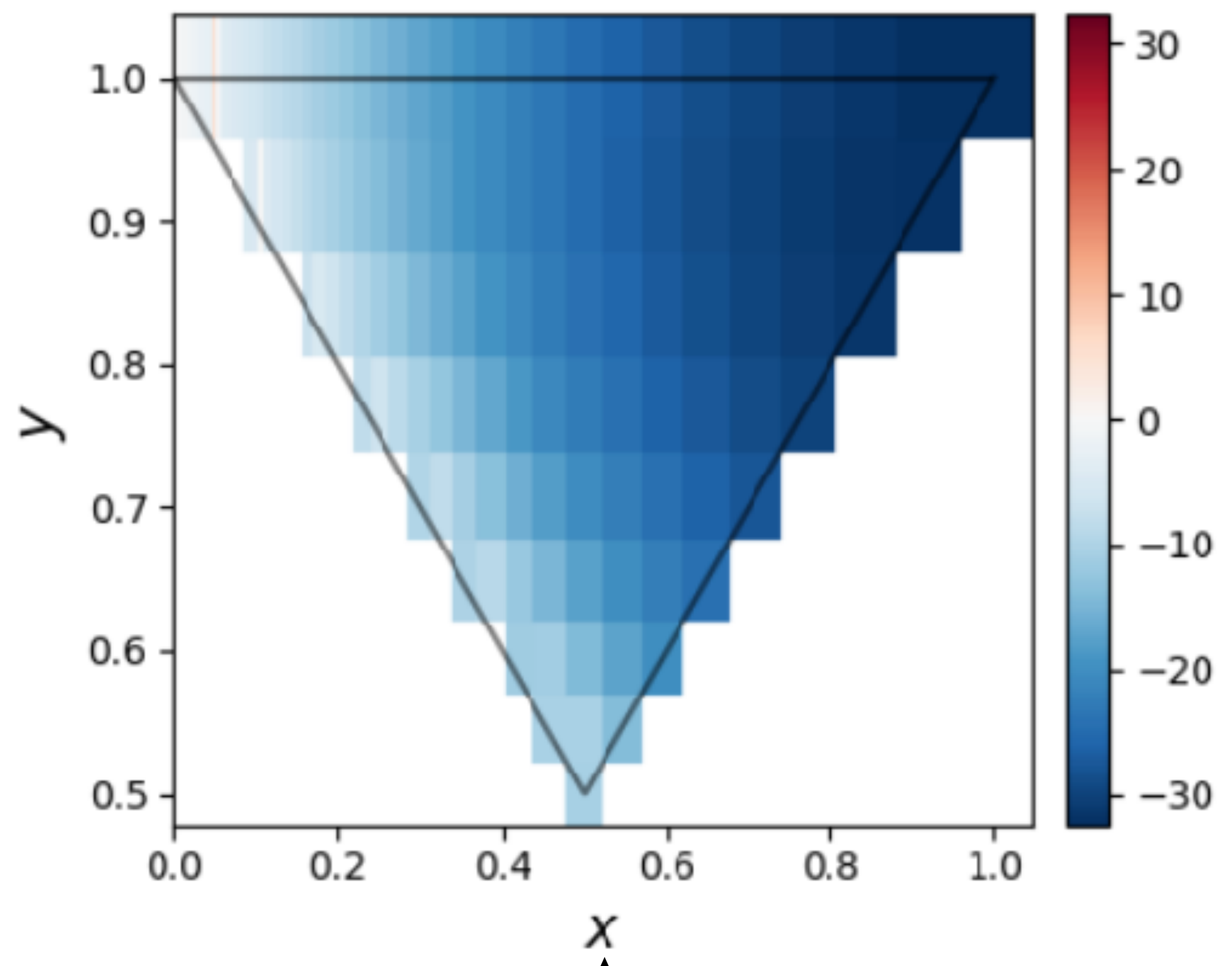
We can **consistently** analyze the full tree-level bispectrum!

Observed Shape





Theoretical Shape

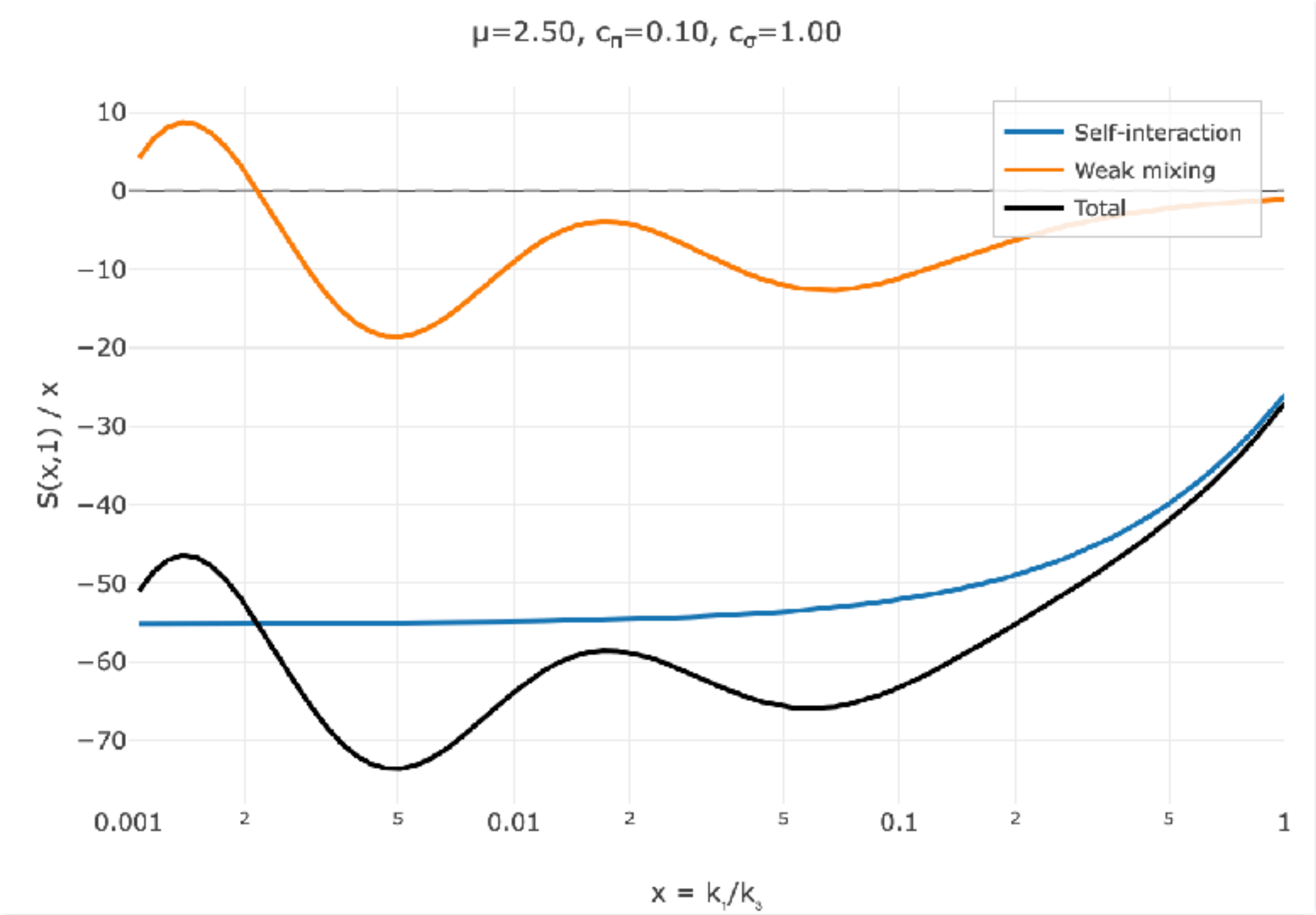


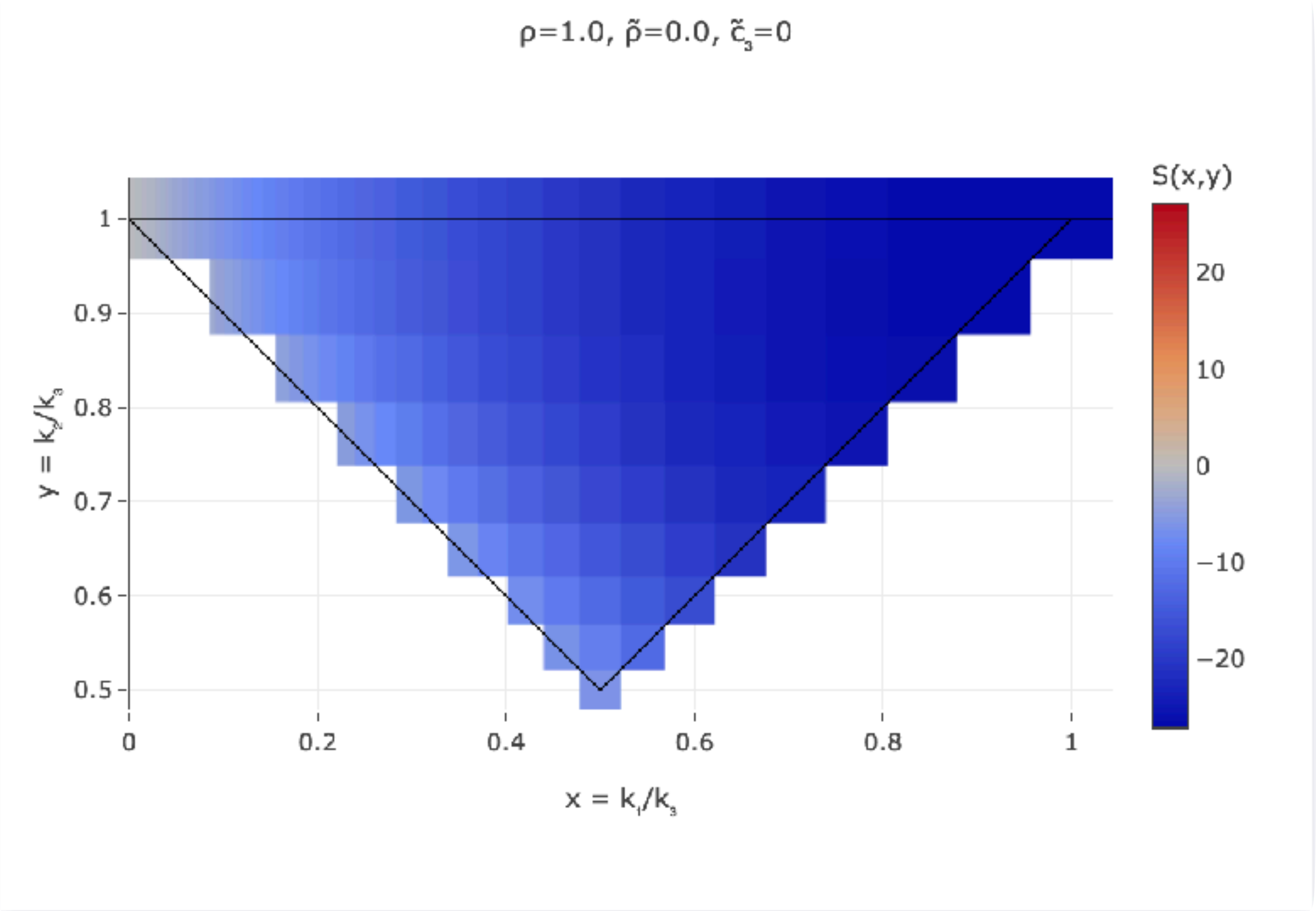
Constraints on Couplings

$$\frac{\mathcal{L}}{a^3} = \frac{1}{2}\left[\dot{\pi}_c^2 - c_{\rm rel}^2\frac{(\partial_i\pi_c)^2}{a^2}\right] + \frac{1}{2}\left[\dot{\sigma}_c^2 - \frac{(\partial_i\sigma_c)^2}{a^2} - m^2\sigma_c^2\right] + \rho\,\dot{\pi}_c\sigma_c$$
$$- \lambda_1\frac{(\partial_i\pi_c)^2}{a^2}\dot{\pi}_c - \lambda_2\,\dot{\pi}_c^3 - \frac{\kappa_1}{2}\frac{(\partial_i\pi_c)^2}{a^2}\sigma_c - \frac{\kappa_2}{2}\dot{\pi}_c^2\sigma_c$$

Philcox (in prep.)

Weakly-Mixed Spin-Zero Colliders





Interactive Demo!

Log y-axis | Divide by x | Reset

Self-Interactions

Sound Speed	$\log_{10} c_\pi$	-1.00
π^3 Interaction	$\tilde{c}_3(c_\pi^{-2}-1)$	0

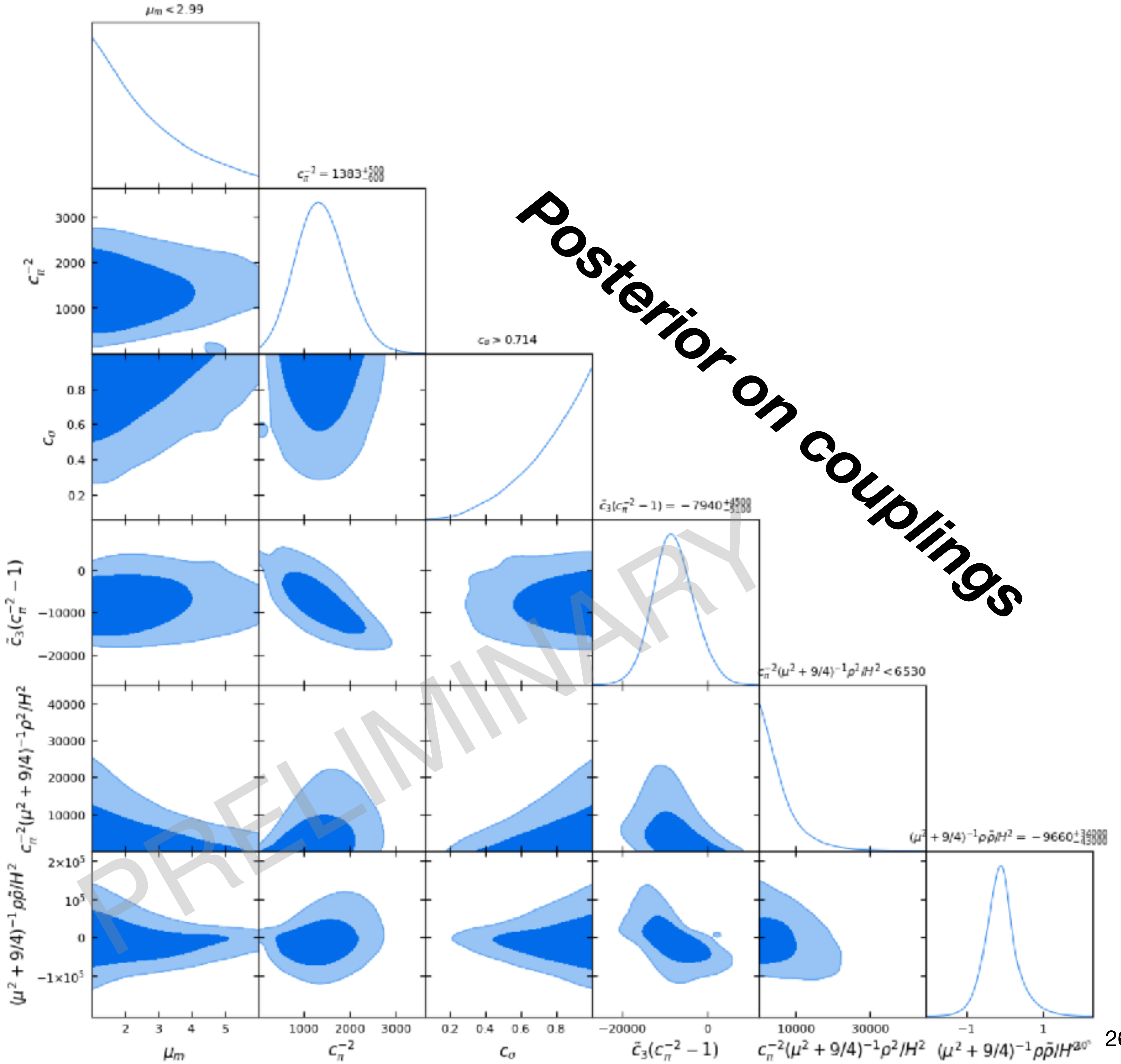
Weak Mixing

Scalar Mass	μ	2.50
Sound Speed	$\log_{10} c_\sigma$	0.00
$\dot{\pi}\sigma$ Mixing	ρ	1.00
$\pi^2\sigma$ Interaction	$\tilde{\rho}$	0.0

Interactive Demo!

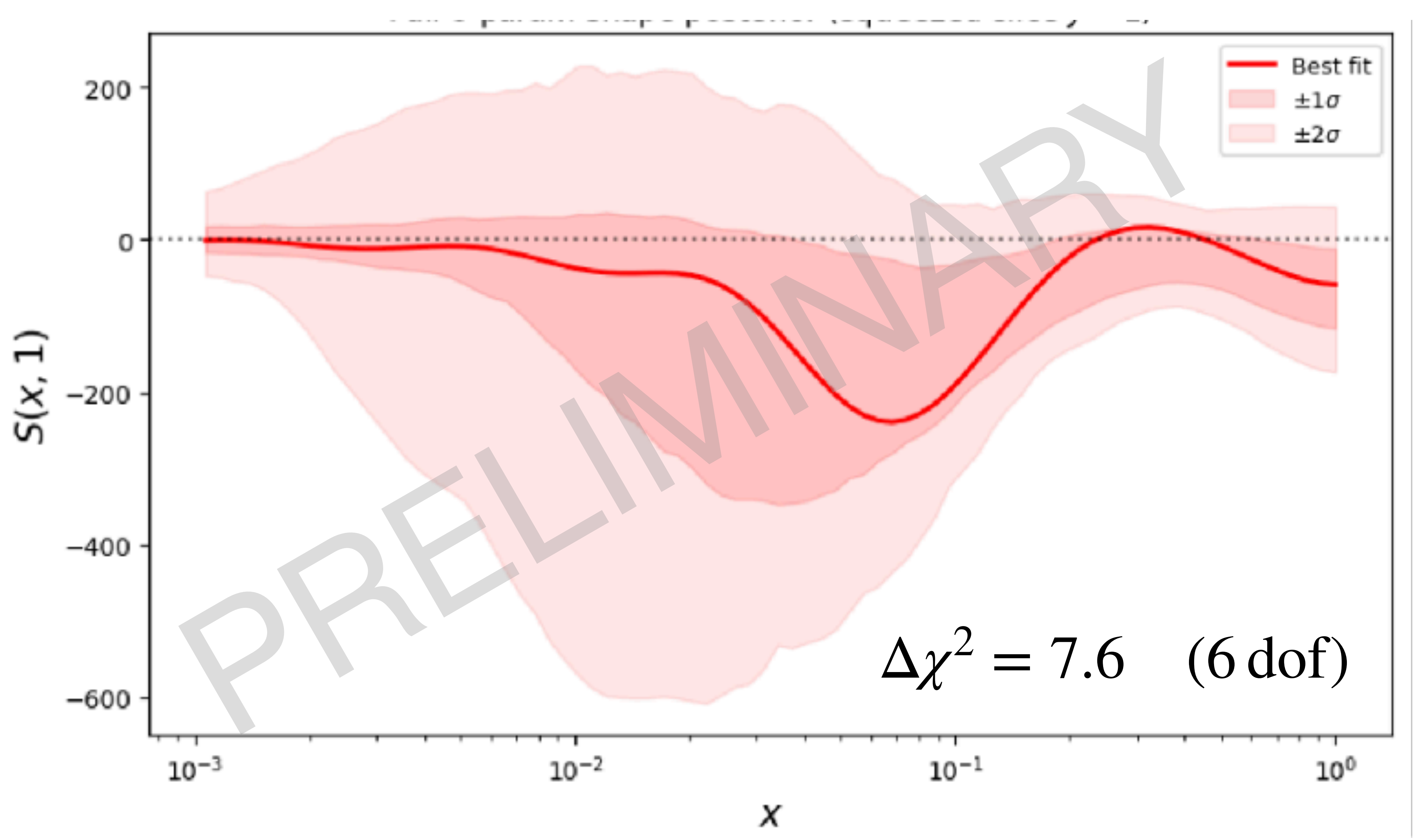
Philcox (in prep.)

Weakly-Mixed Spin-Zero Colliders



Posterior on couplings

Maximum *a posteriori* solution



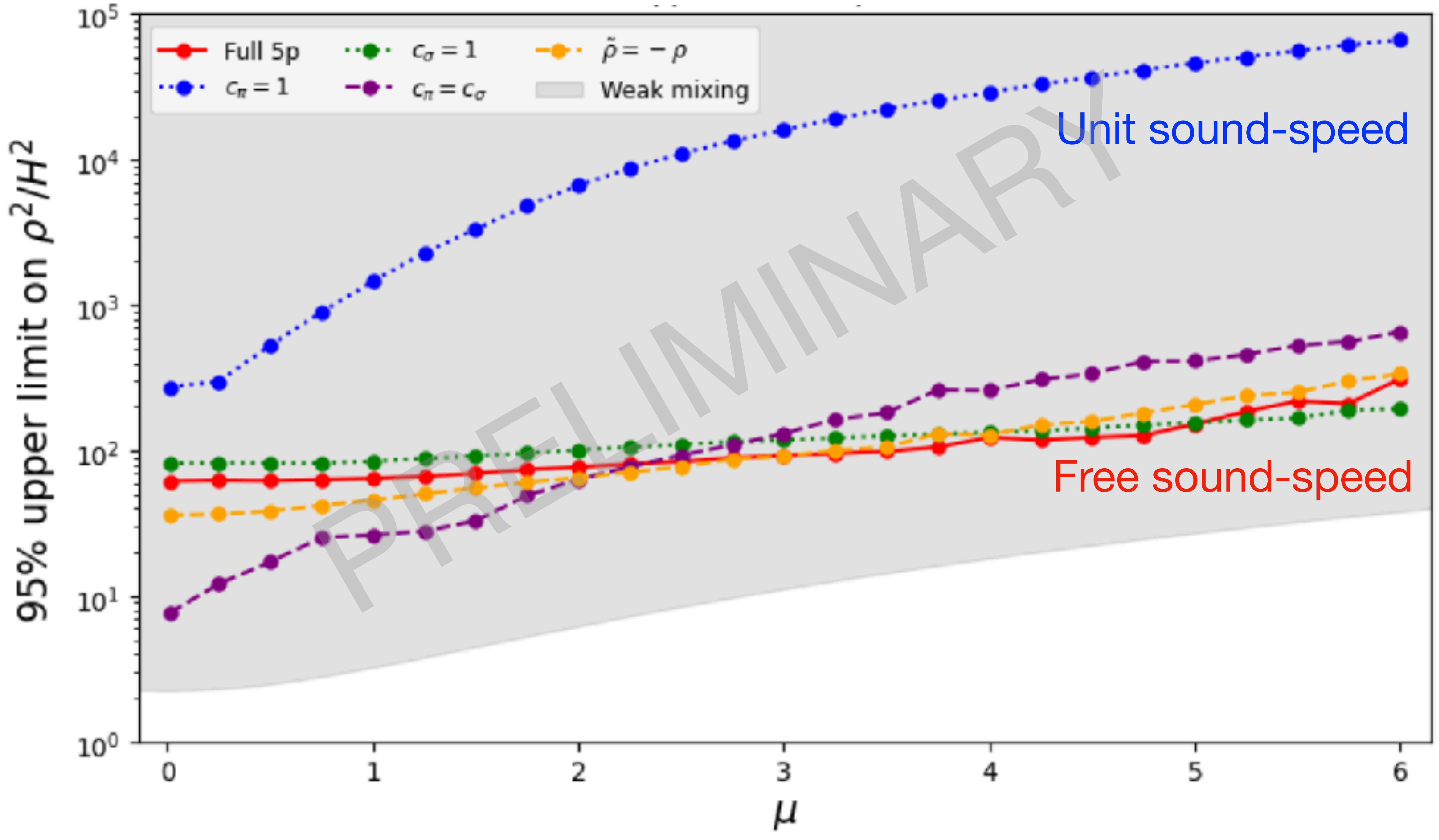
Interactive Demo!

Philcox (in prep.)

Weakly-Mixed Spin-Zero Colliders

"large collider signal ⇒ large $(\partial_i \pi)^2\sigma$ 😀 ⇒ large quadratic mixing $\dot{\pi}\sigma$ 🤔"

Upper limit on quadratic mixing



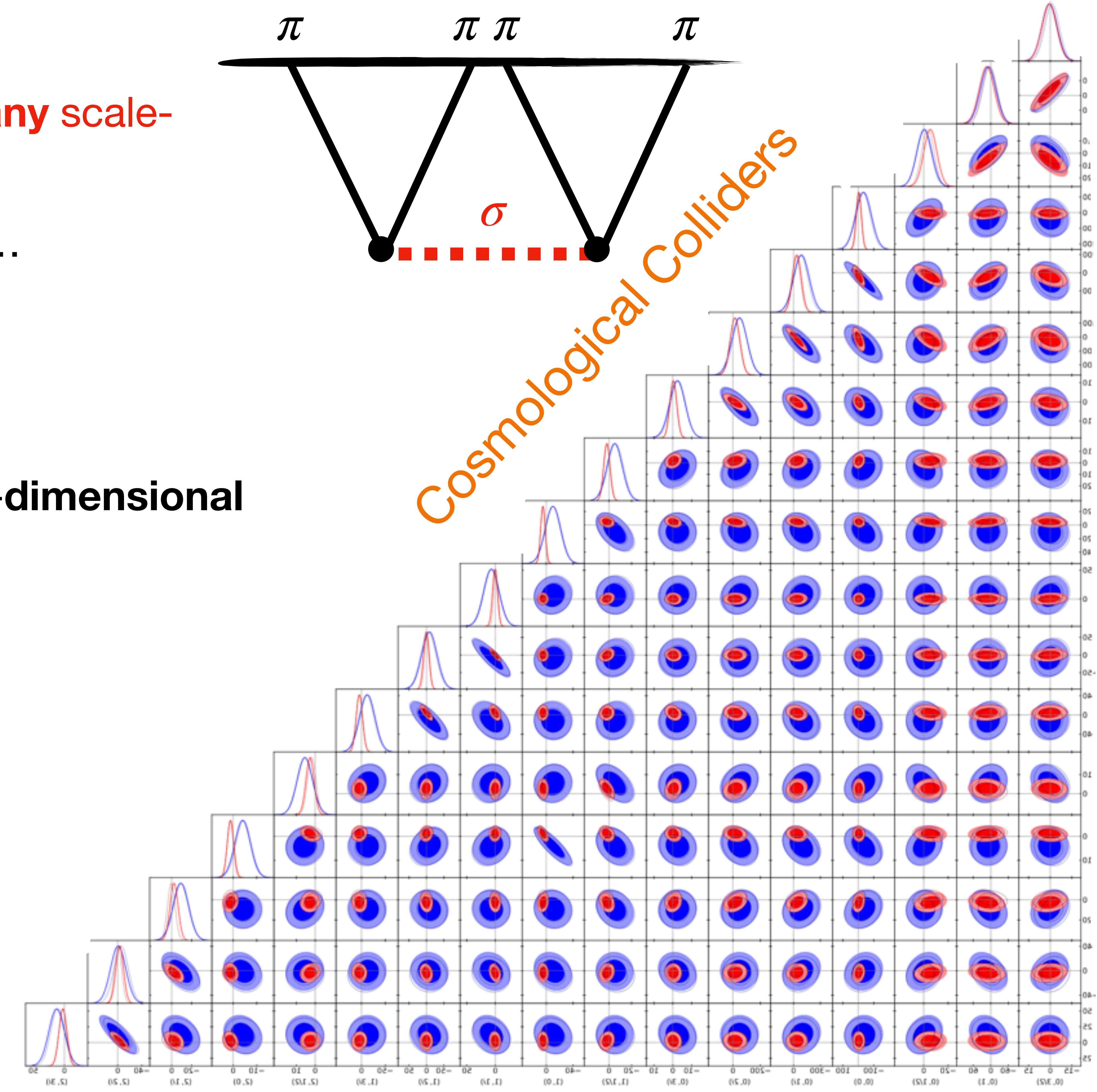
Conclusion: detectable single-exchange diagrams must be **strongly-mixed**

Philcox (in prep.)

What's Next for the CMB?

- With the binned **shape function** estimators, we can constrain **any** scale-invariant primordial bispectrum
  - Bootstraps, Cosmological Flows, Mellin transforms, loops, …

- What about **trispectra**?
  - This is **hard** — the scale-invariant four-point function is four-**dimensional** $S^{(3)}(x,y) \to S^{(4)}(x,y,u,v)$
  - There has been work searching for **factorizable shapes**
    - Self-interactions
    - Oscillatory **cosmological collider** signals
    - Modifications to $\tau_{\rm NL}$
  - **No detections yet!** (except CMB lensing)



Regan, Shellard, Fergusson, Smith, Senatore, Zaldarriaga, **Philcox** 25abc, …

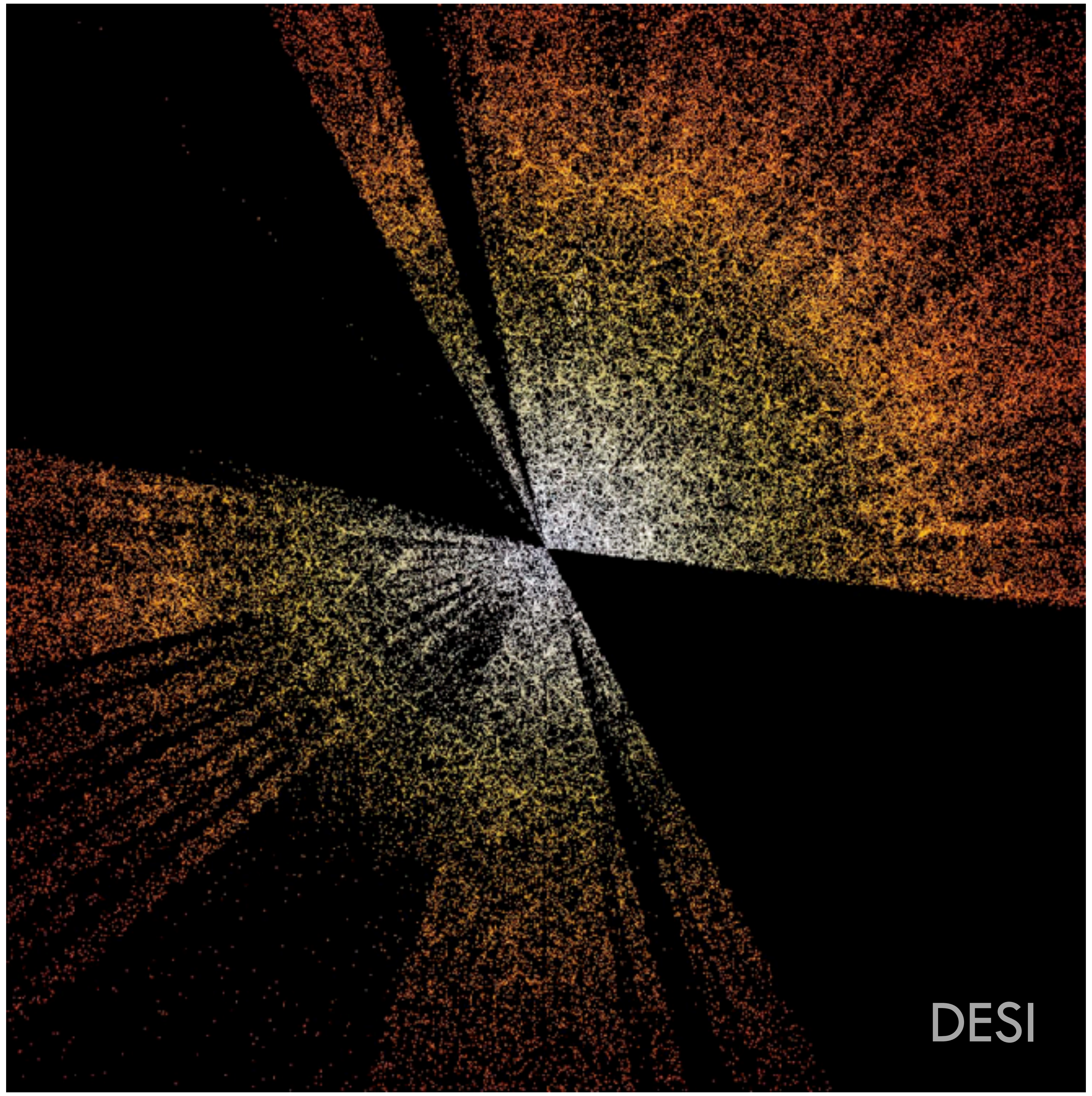
The Future of Non-Gaussianity

- **CMB experiments** have provided a precise **two-dimensional** map of the Universe at age $400{,}000\,\mathrm{yr}$
  - Their **primordial** constraining power is saturating!

- **Galaxy surveys** will map the Universe in **three-dimensions** at age $\sim 10^9 - 10^{10}\mathrm{yr}$
  - Legacy surveys have mapped a **million** galaxies [BOSS]
  - New surveys map $\sim \mathbf{100}\times$ more! [DESI, Euclid, Rubin, Roman, …]

see Uros's talk!

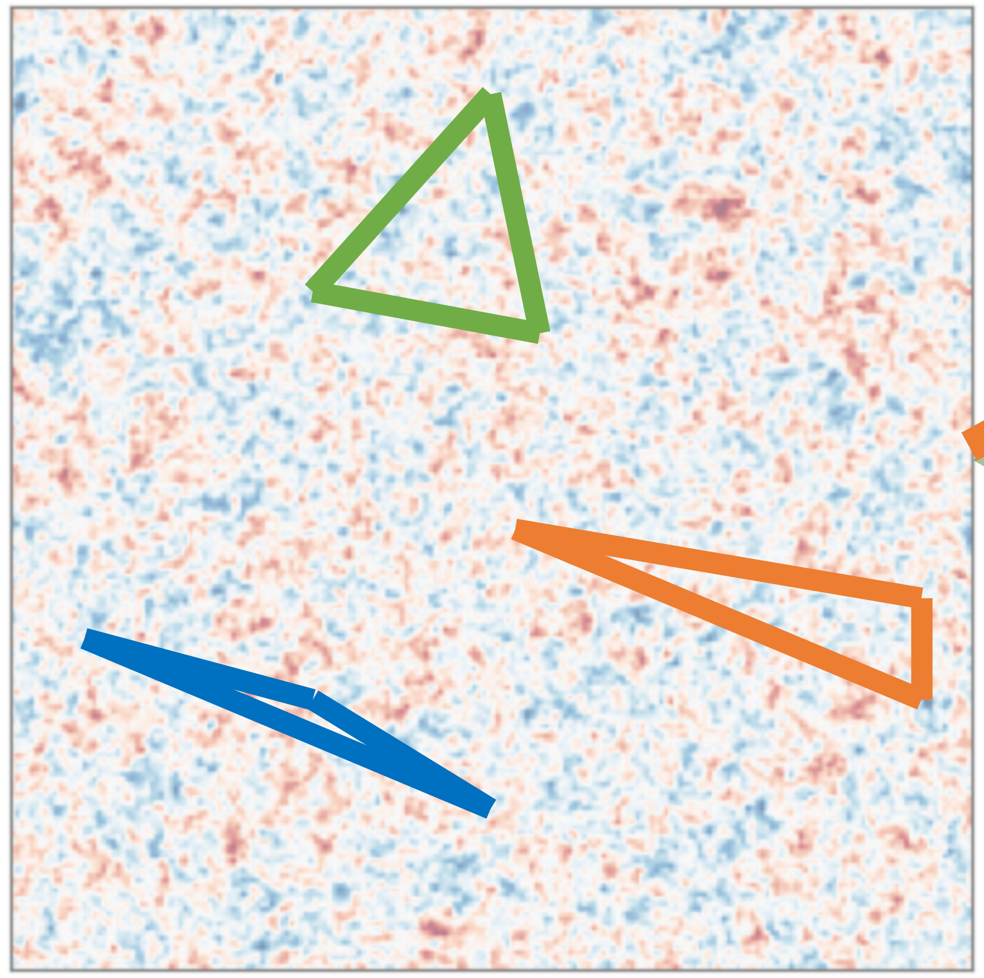
Density of galaxies, n_{gal}



Can we use **galaxy surveys** to learn about **inflation**?

How to Measure Primordial Non-Gaussianity

The **curvature perturbation** ζ sets the **initial conditions** for the late Universe!

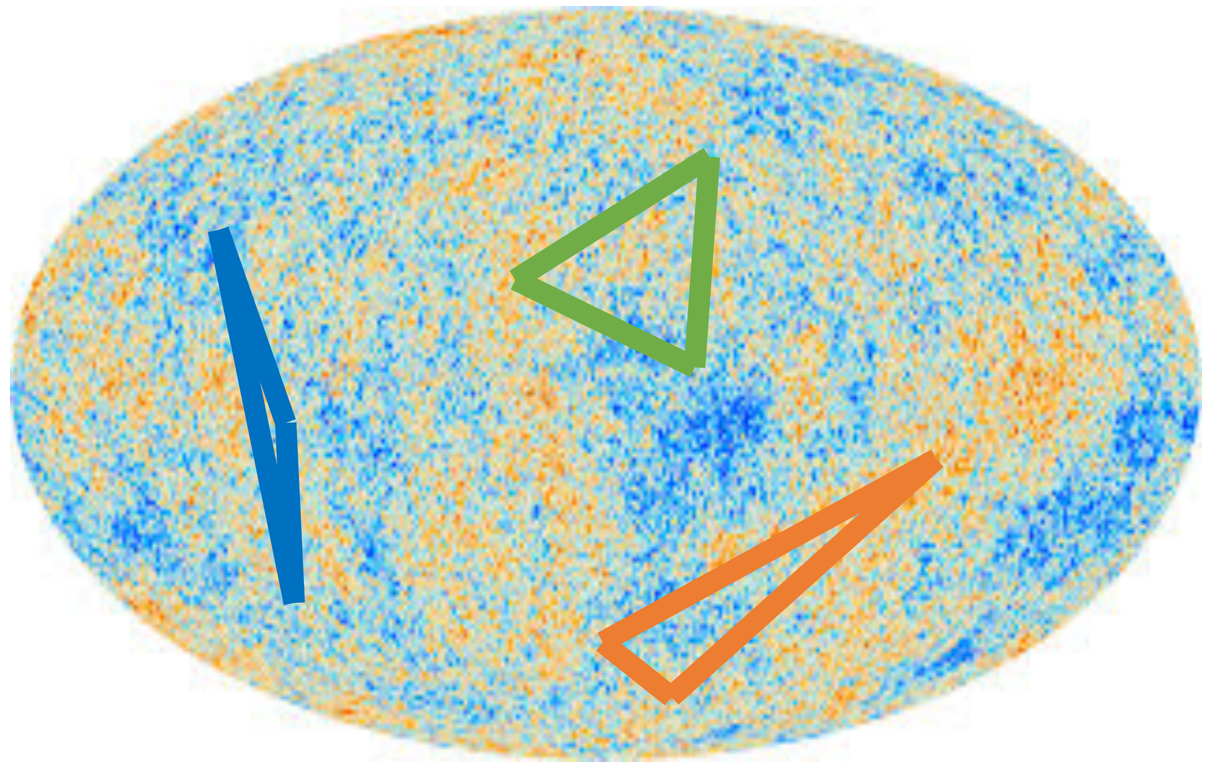


Primordial Curvature

$$\langle \zeta^n \rangle \neq 0?$$

Linear Physics

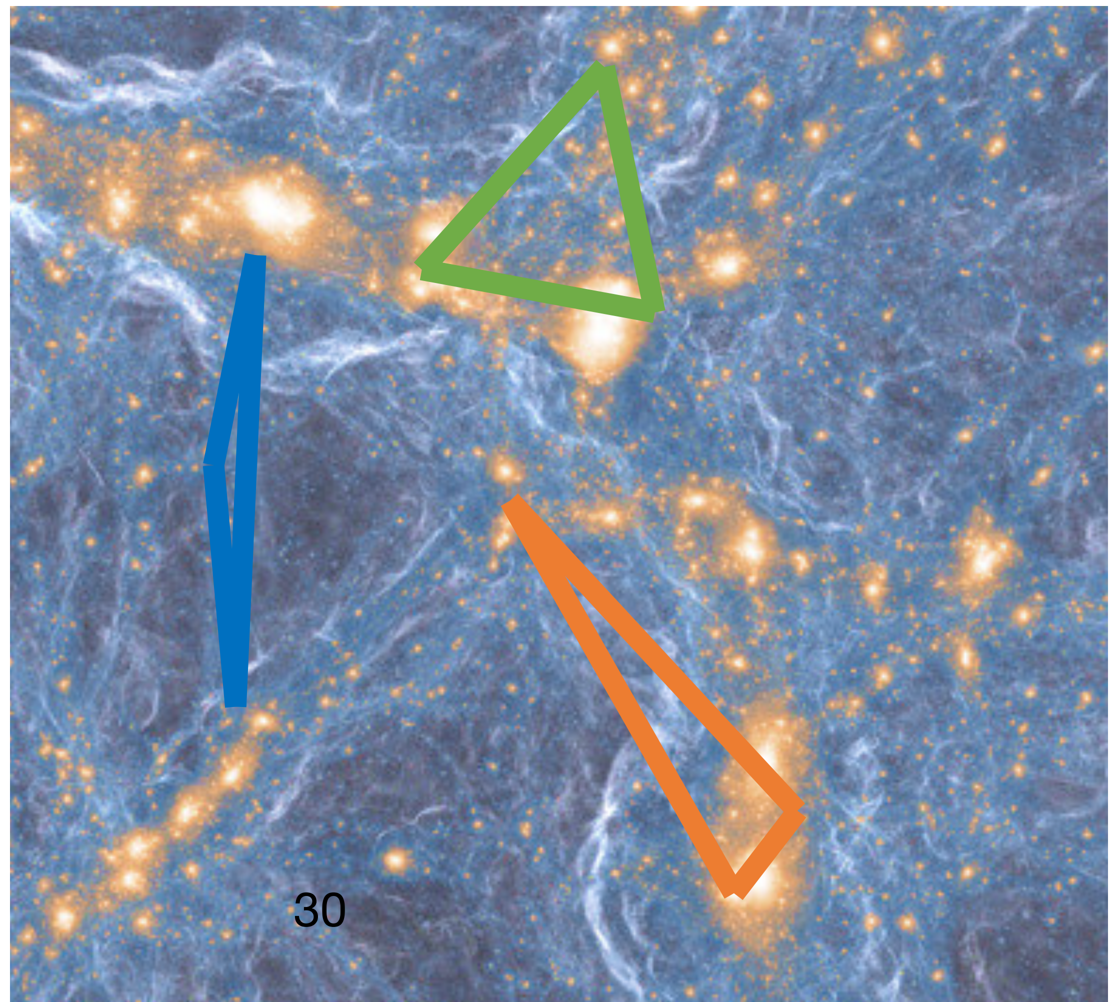
Non-Linear Physics



Cosmic Microwave Background fluctuations

$$\langle \delta T^n \rangle \neq 0?$$

*(tracing **photon energies**)*



Galaxy Number Density Fluctuations

$$\langle \delta n^n_{\mathrm{gal}} \rangle \neq 0?$$

*(tracing **dark matter**)*

Planck, IllustrisTNG

Inflation from DESI

The first year of DESI data is now public!

- We have developed an **independent** pipeline for analyzing the **galaxy two-** and **three-point** functions based on **Effective Field Theory** methods

- This has been used to constrain: ΛCDM (Ω_m, H_0, σ_8), dark energy ($w_0 w_a$), curvature (Ω_k), neutrino masses ($\sum m_\nu$), both **alone** and in combination with the **CMB** and **gravitational lensing**

Excerpt from DESI Data Release 1

TARGETID int64	Z float64	NTILE int64	RA float64	DEC float64	...
39627540901396844	0.42060841162467566	1	159.30684159361635	-10.155757636765902	...
39627546836338876	0.8668980715716706	1	158.44667596279407	-9.962760066342906	...
39627546840531340	0.9348172077800124	1	158.4799294702238	-9.880343166939232	...
39627546840533707	0.7646678553759423	1	158.65071160360105	-9.900898173028425	...
39627546840534067	0.88129590000311	1	158.67878216902403	-9.91791308567385	...
39627546840534396	0.6646155566176719	1	158.70027052890555	-9.885818986284596	...
39627546844725593	0.7619120932610688	1	158.72751630870823	-10.011383569041937	...
39627546844726132	0.8129116729090922	1	158.75343950179967	-9.912671320450734	...
39627546844726593	0.835471640017949	1	158.79898500886574	-9.952788127324665	...
39627546848921194	0.8148312339778753	1	159.052157885943	-9.992428612452807	...
39627546848922139	0.7200341373651288	1	159.10202657806508	-9.938566366253578	...
39627546848922621	0.7606337242857438	1	159.1309146297404	-10.02377942401391	...
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39627546848923415	0.8891288789150124	1	159.18008439182032	-10.072752528866118	...
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39627546848923519	0.7212784017696859	1	159.1860701777553	-9.944737378735352	...
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39627546853115470	0.7147216867384578	1	159.2970230990033	-10.012836906791499	...
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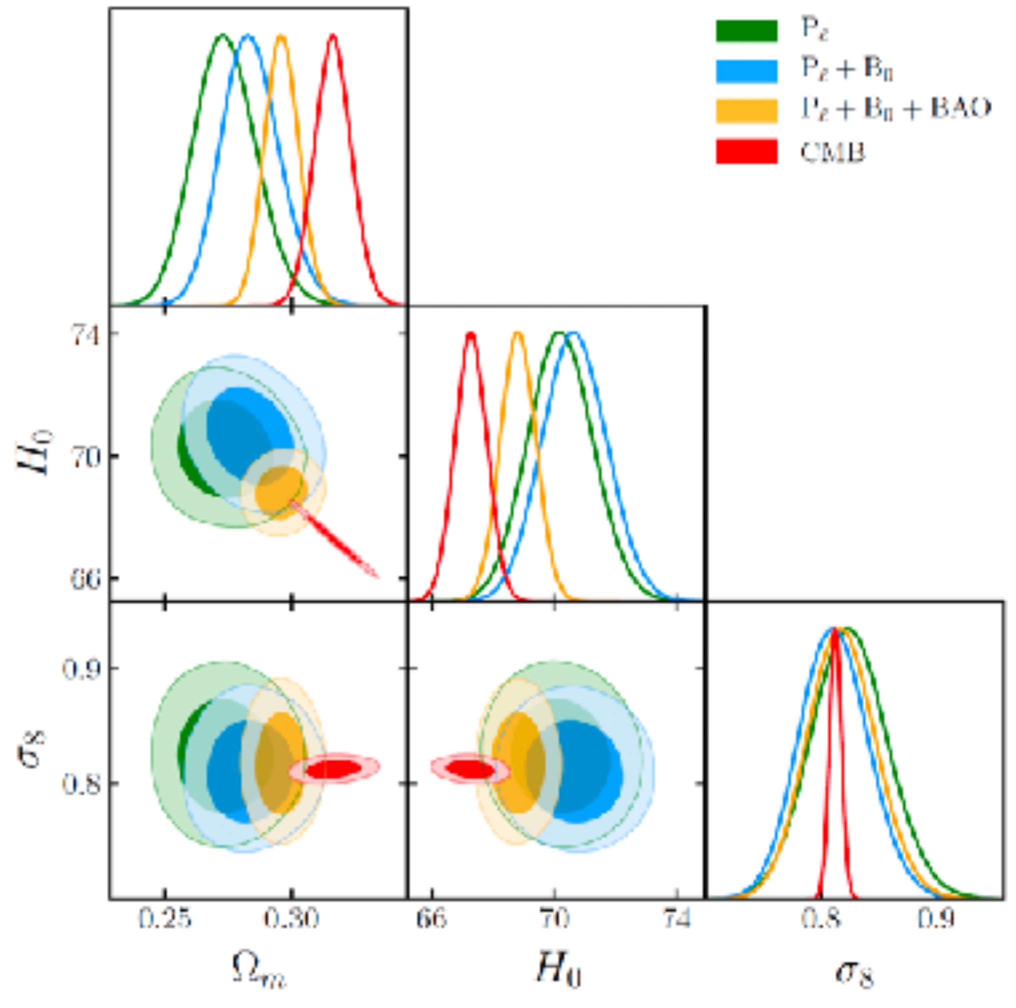
...	...	...	...	...	...



ΛCDM Constraints

Chudaykin, Ivanov, **Philcox** 2025abc / 2026ab, DESI, Chaussidon+24

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- This has been used to constrain: ΛCDM (Ω_m, H_0, σ_8), dark energy ($w_0 w_a$), curvature (Ω_k), neutrino masses ($\sum m_\nu$), both **alone** and in combination with the **CMB** and **gravitational lensing**

New constraints on inflation!

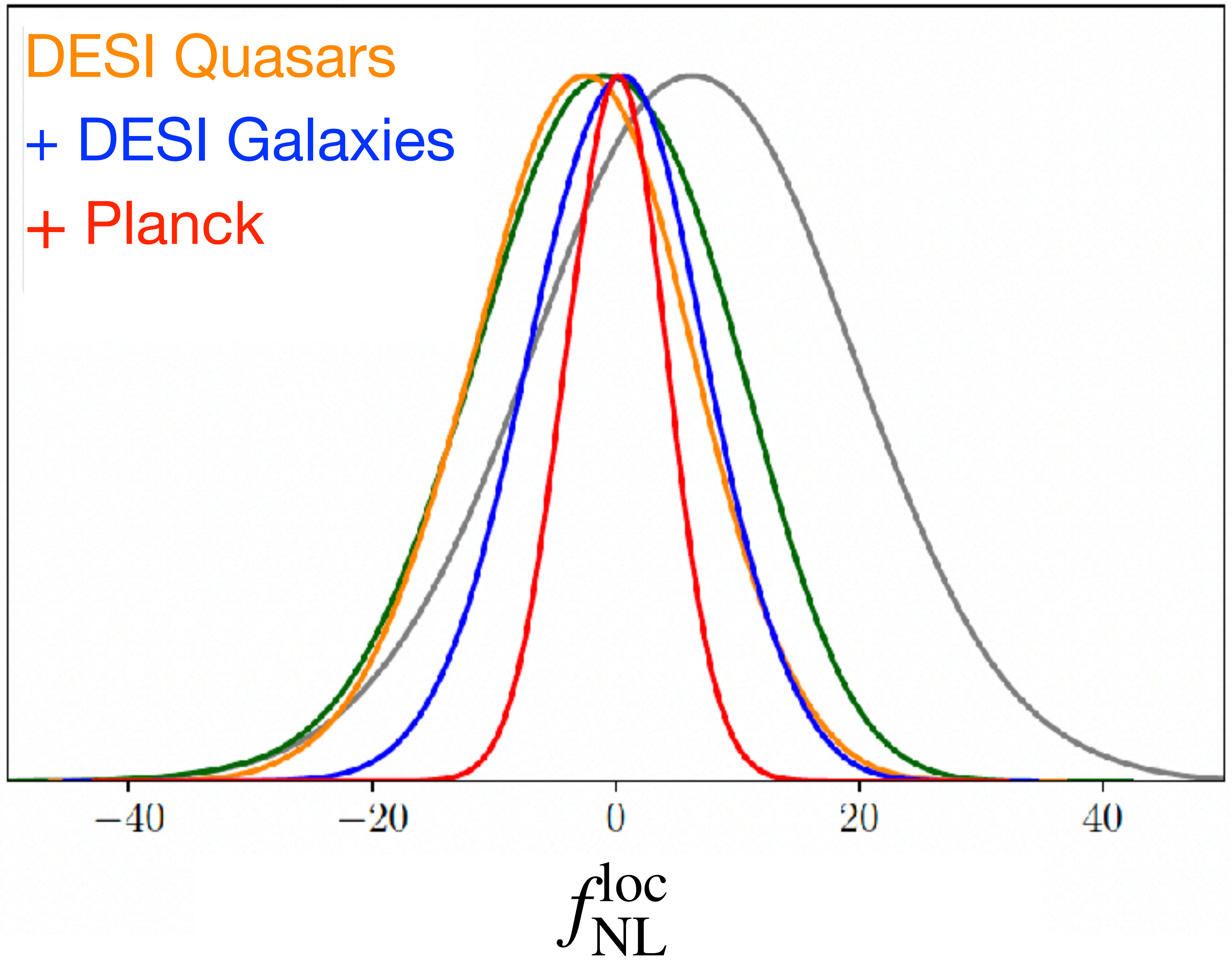
- **Multi-field**: $f_{\rm NL}^{\rm loc} = -0.1 \pm 7.4$
- **Single-Field**: $f_{\rm NL}^{\rm eq} = 200 \pm 230, \;\; f_{\rm NL}^{\rm orth} = -24 \pm 86$

Compare to official DESI results:
$f_{\rm NL}^{\rm loc} = -2 \pm 10$

(Many more models to explore!)

- Adding **Planck**, we obtain the **tightest** constraint on local PNG yet!!

$$\boxed{f_{\rm NL}^{\rm loc} = 0.0 \pm 4.1}$$



Chudaykin, Ivanov, **Philcox** 2025abc / 2026ab, DESI, Chaussidon+24

Summary

- Extracting **inflationary physics** from CMB data is challenging

- New methods reconstruct the underlying **inflationary shape** allowing a wide range of **new tests** of inflation

- Galaxies are the next frontier for primordial non-Gaussianity

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