Signals of a Quantum Universe

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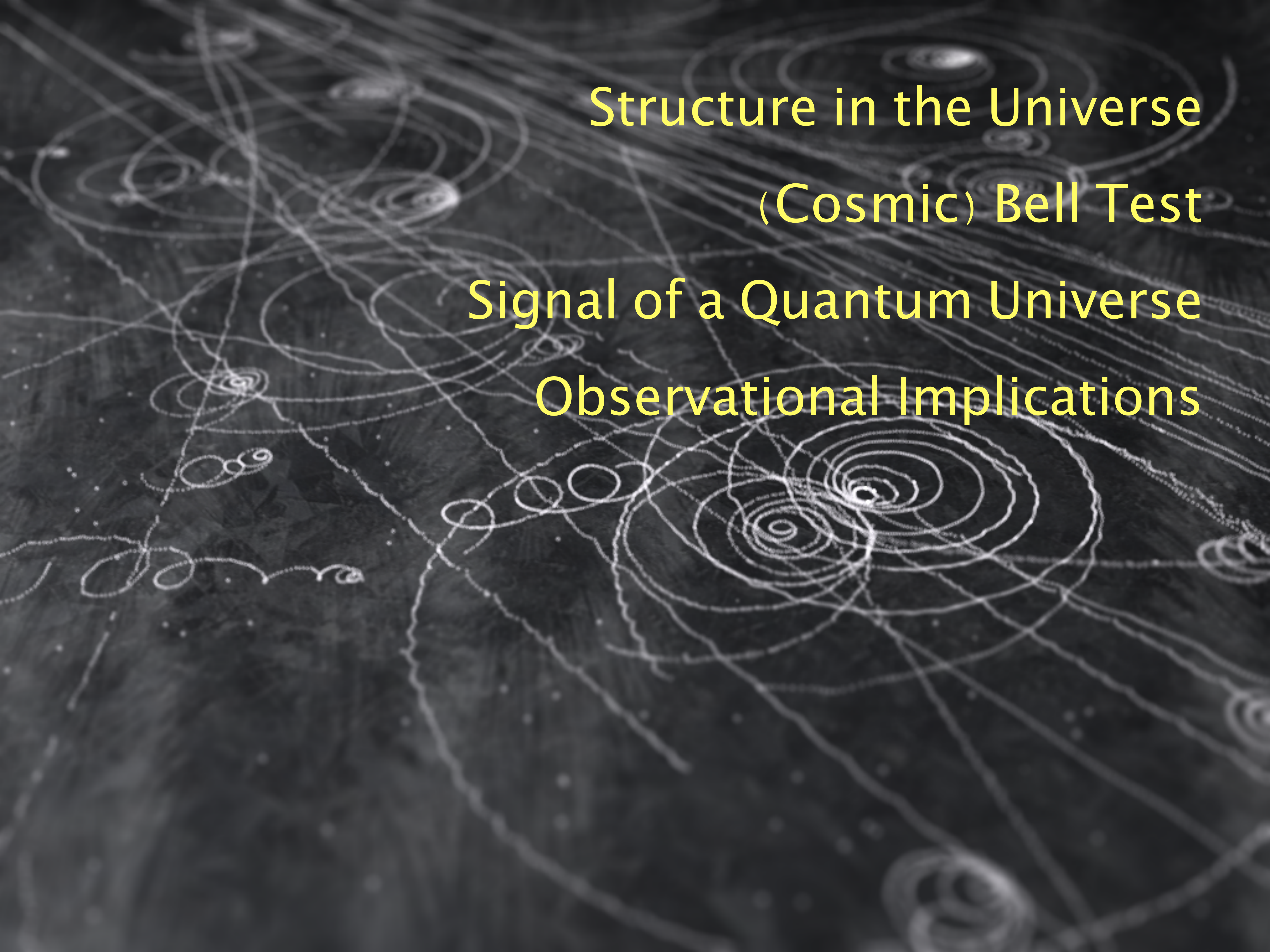
with Rafael Porto
arXiv:2001.09149 [Phys. Rev. Lett. 124, 25]



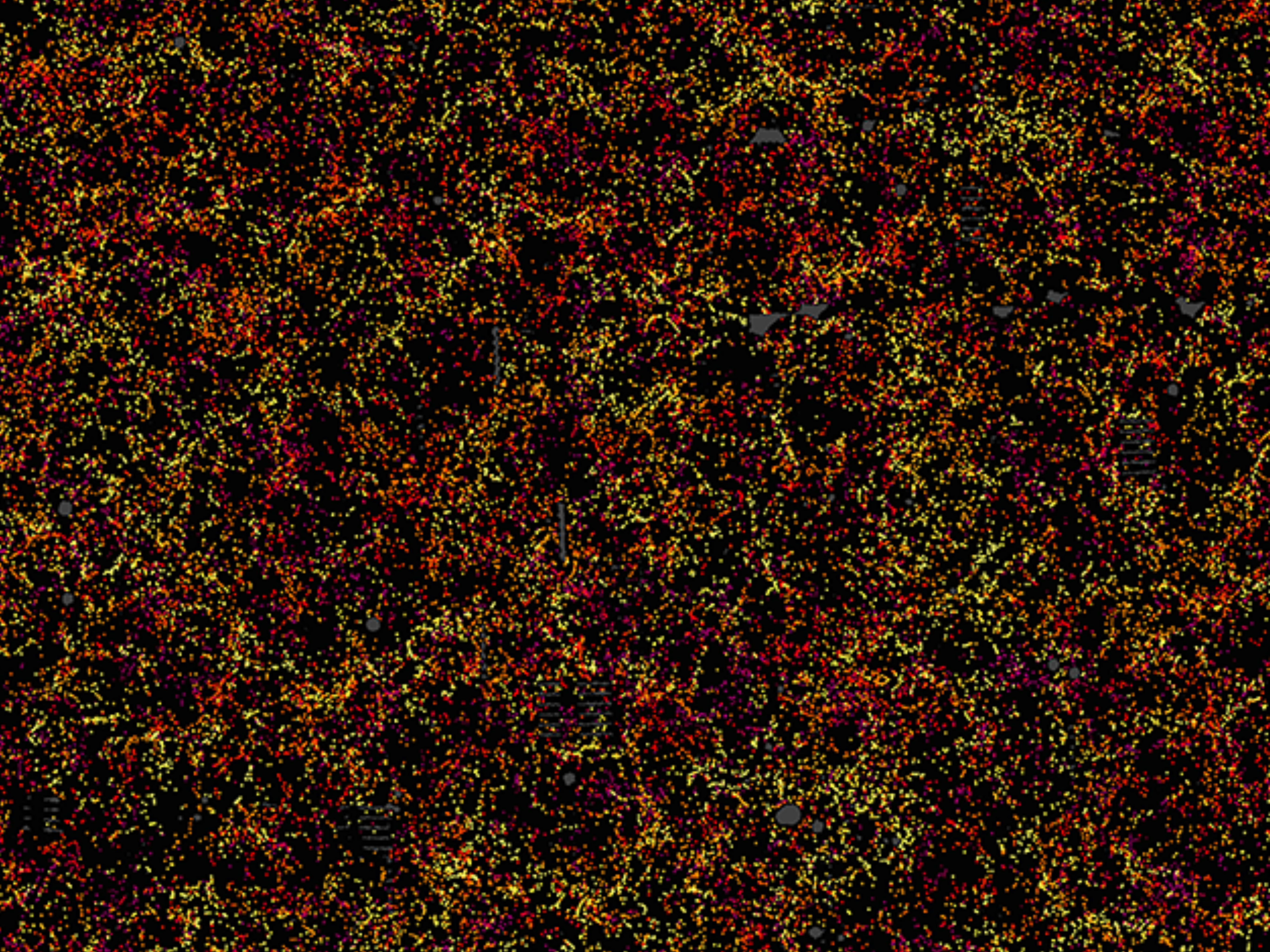
Structure in the Universe

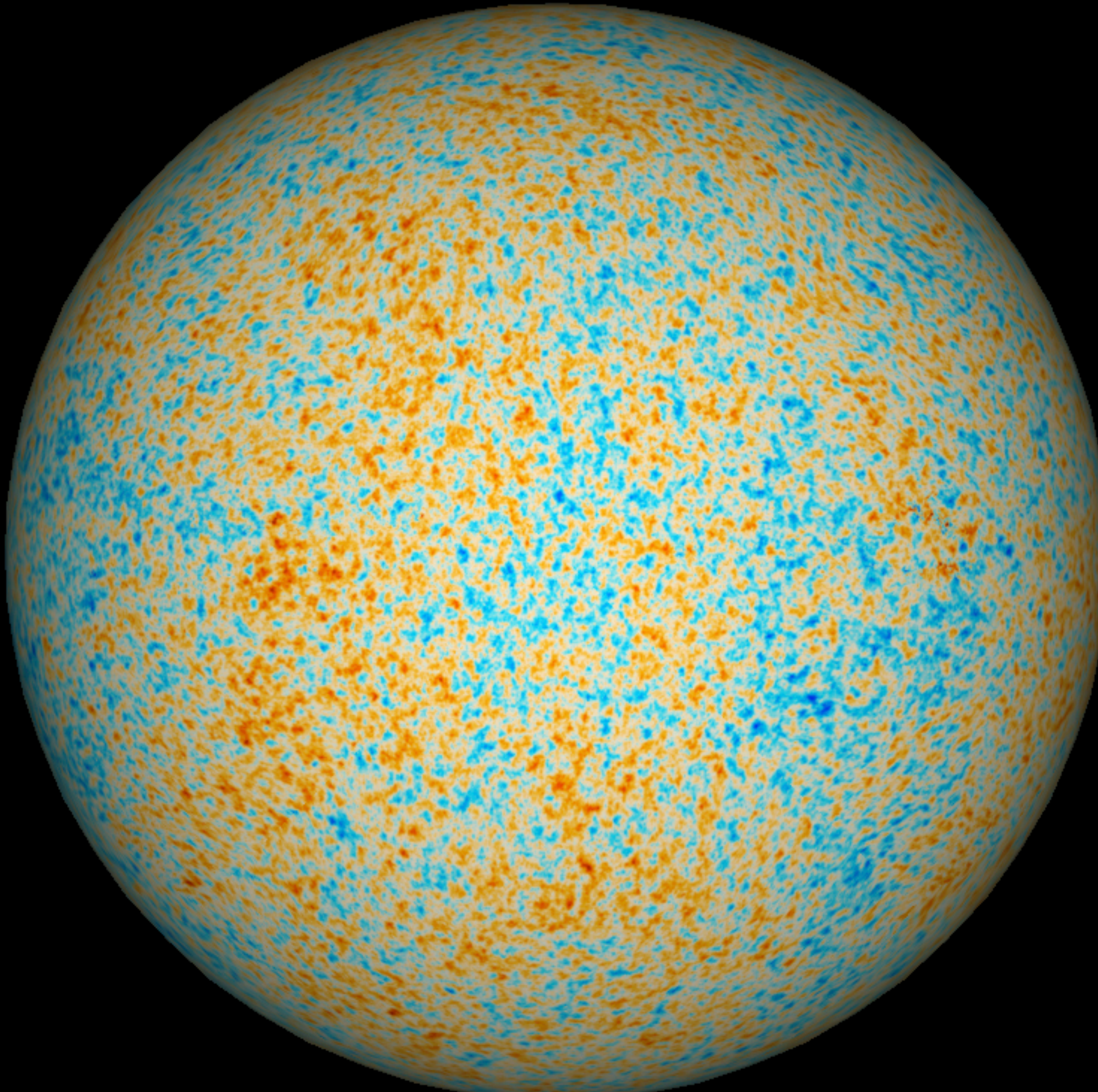
(Cosmic) Bell Test

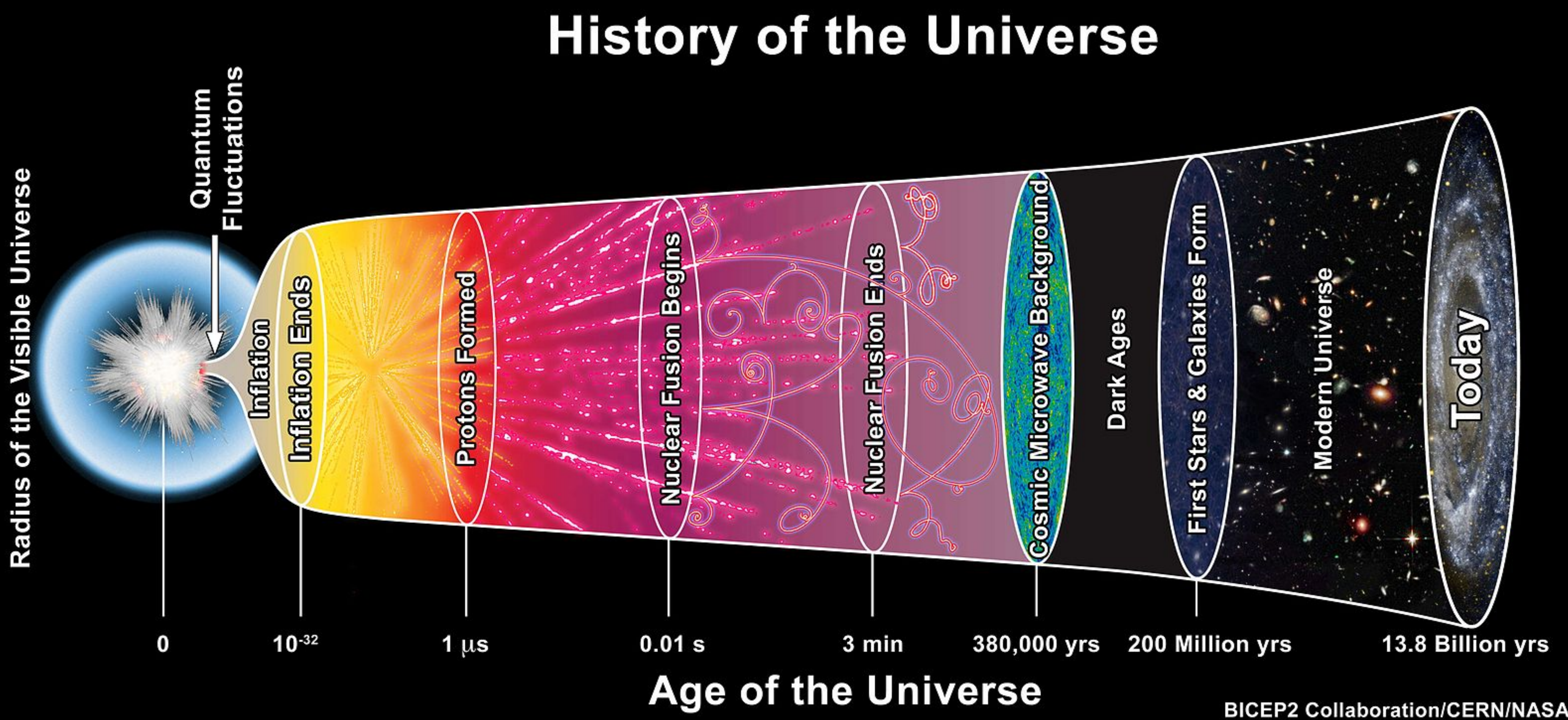
Signal of a Quantum Universe

Observational Implications

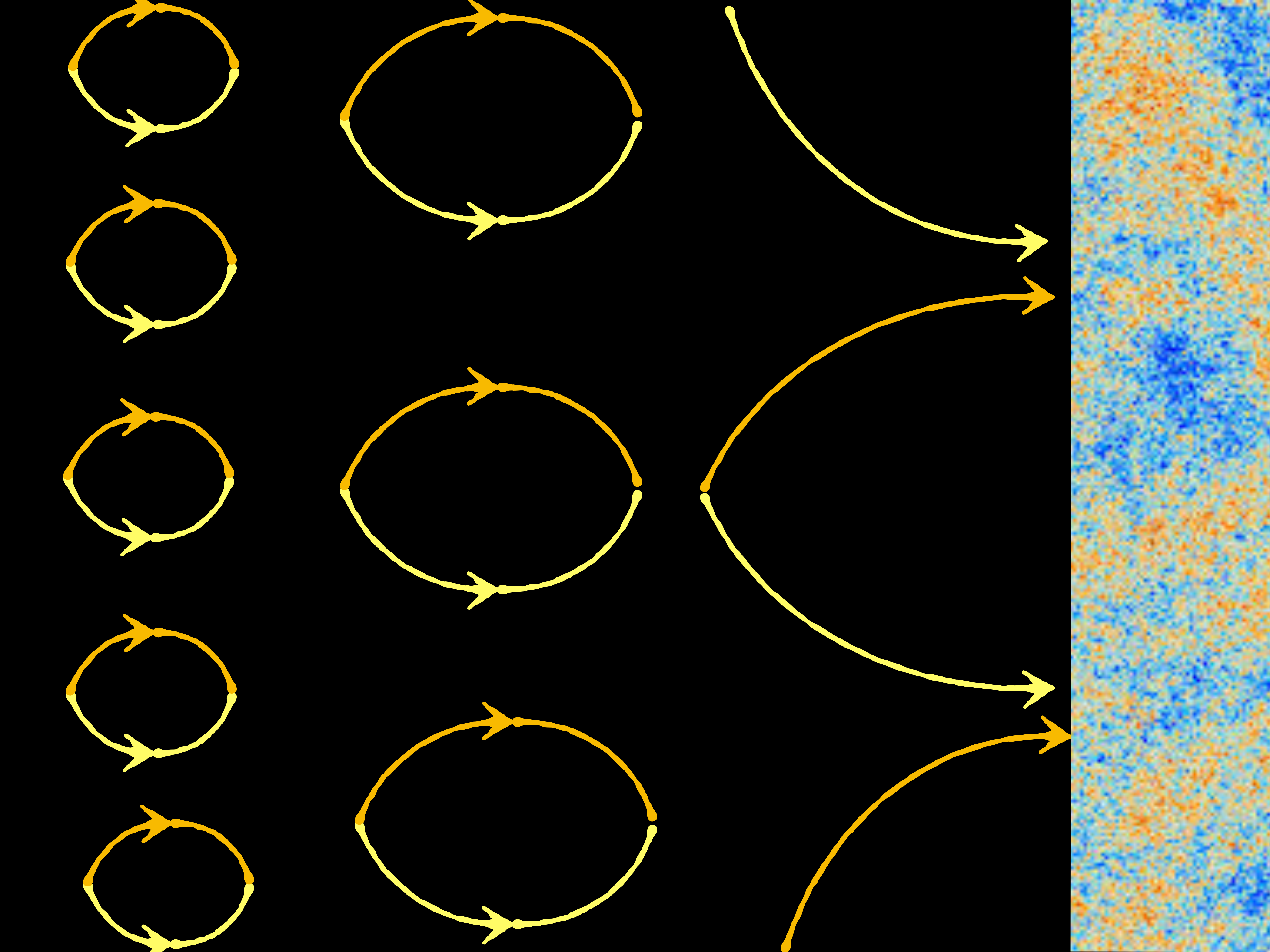
Structure in the Universe



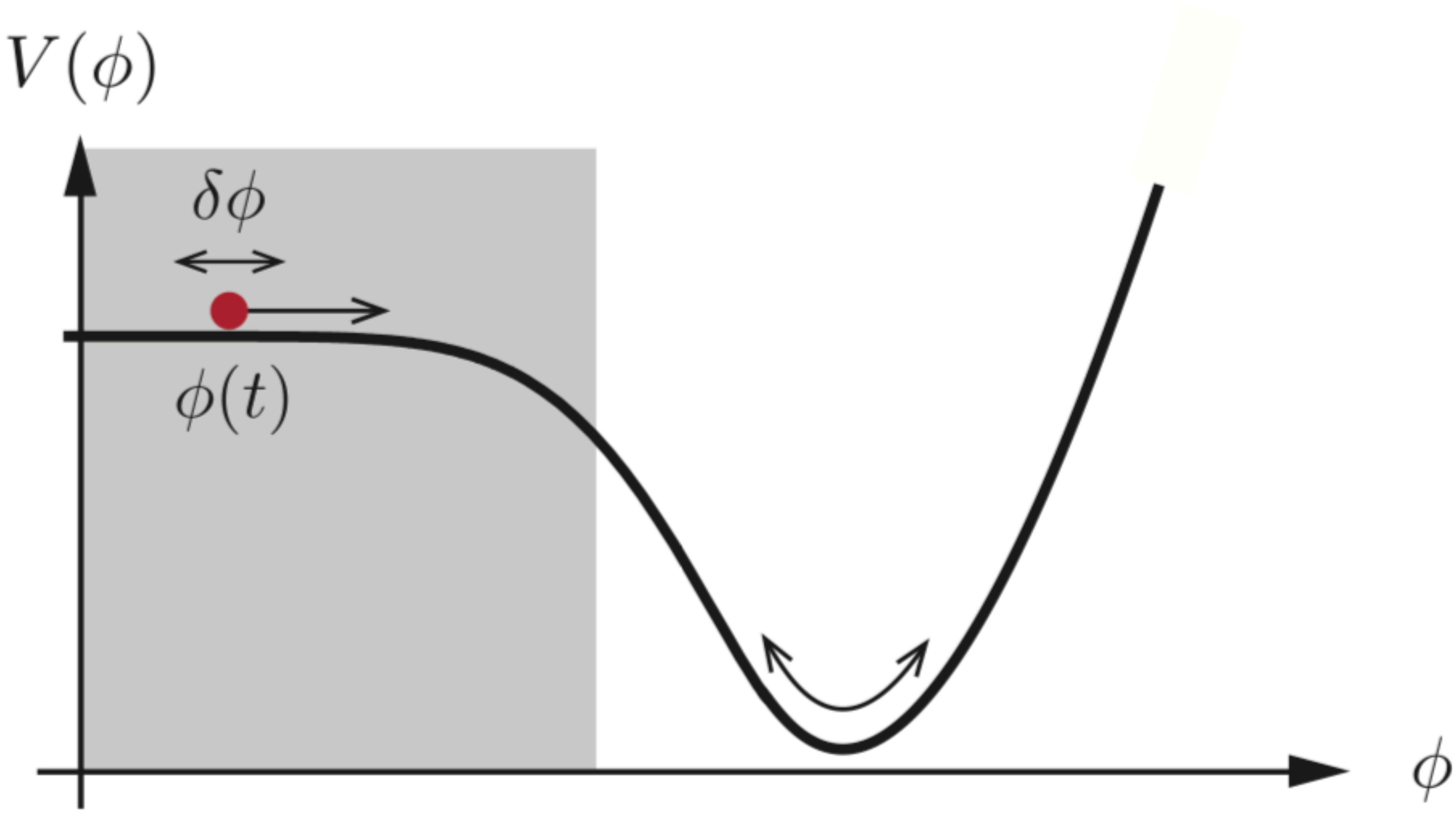




History of the Universe
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10-32
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe
BICEP2 Collaboration/CERN/NASA



Quantum Origin of Structure



From Baumann & McAllister

Quantum Origin of Structure

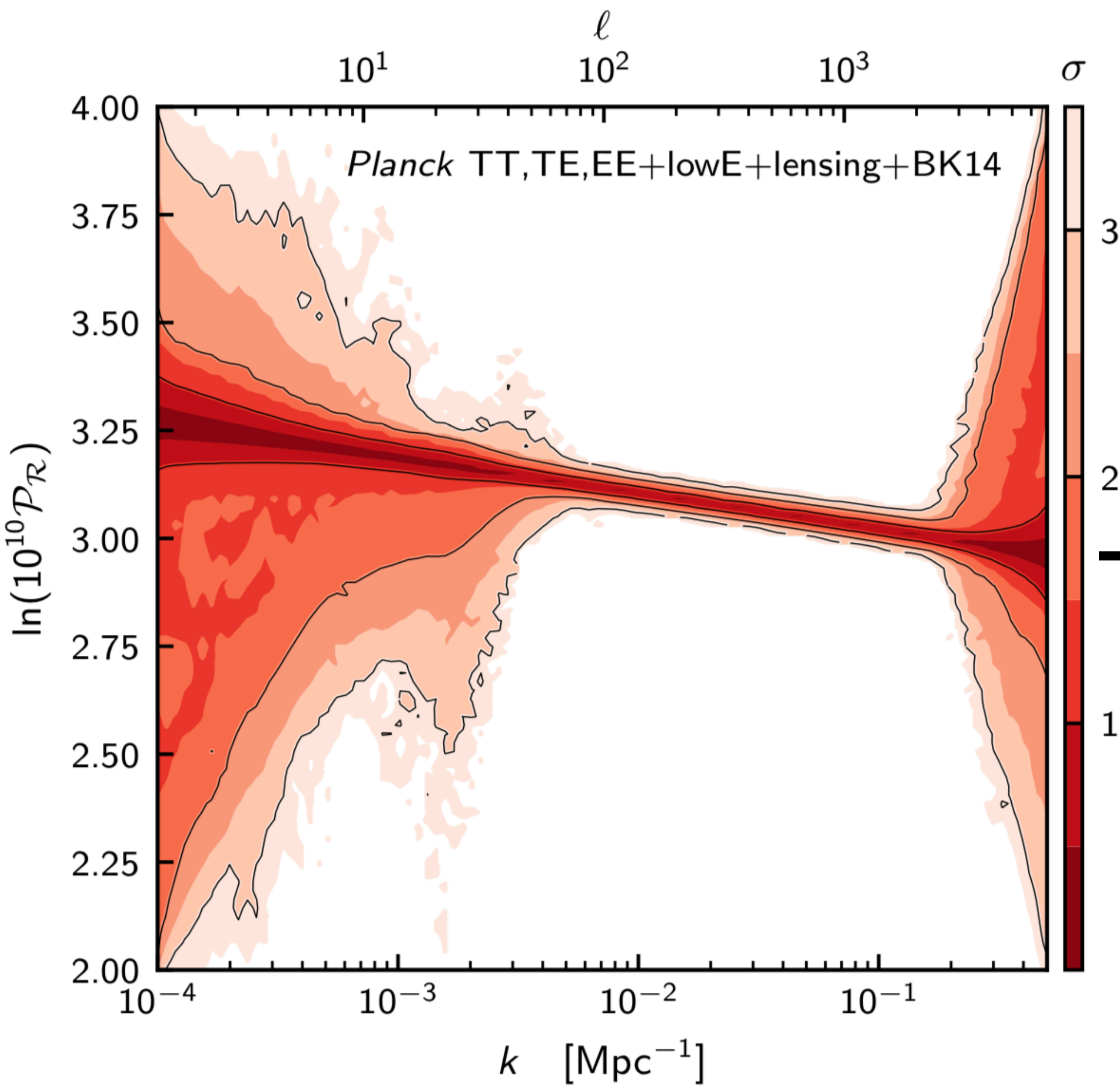
Vacuum fluctuations can explain origin of structure

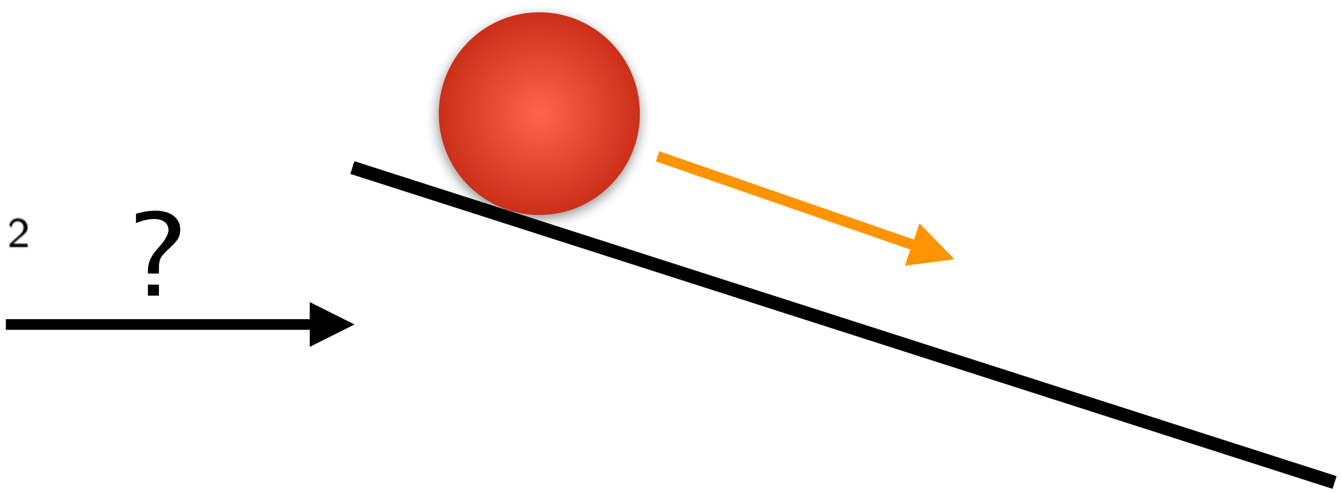
This explanation captures the imagination:

The largest objects in the universe are explained by the unusual phenomena of the smallest scales

But is this how the universe works?

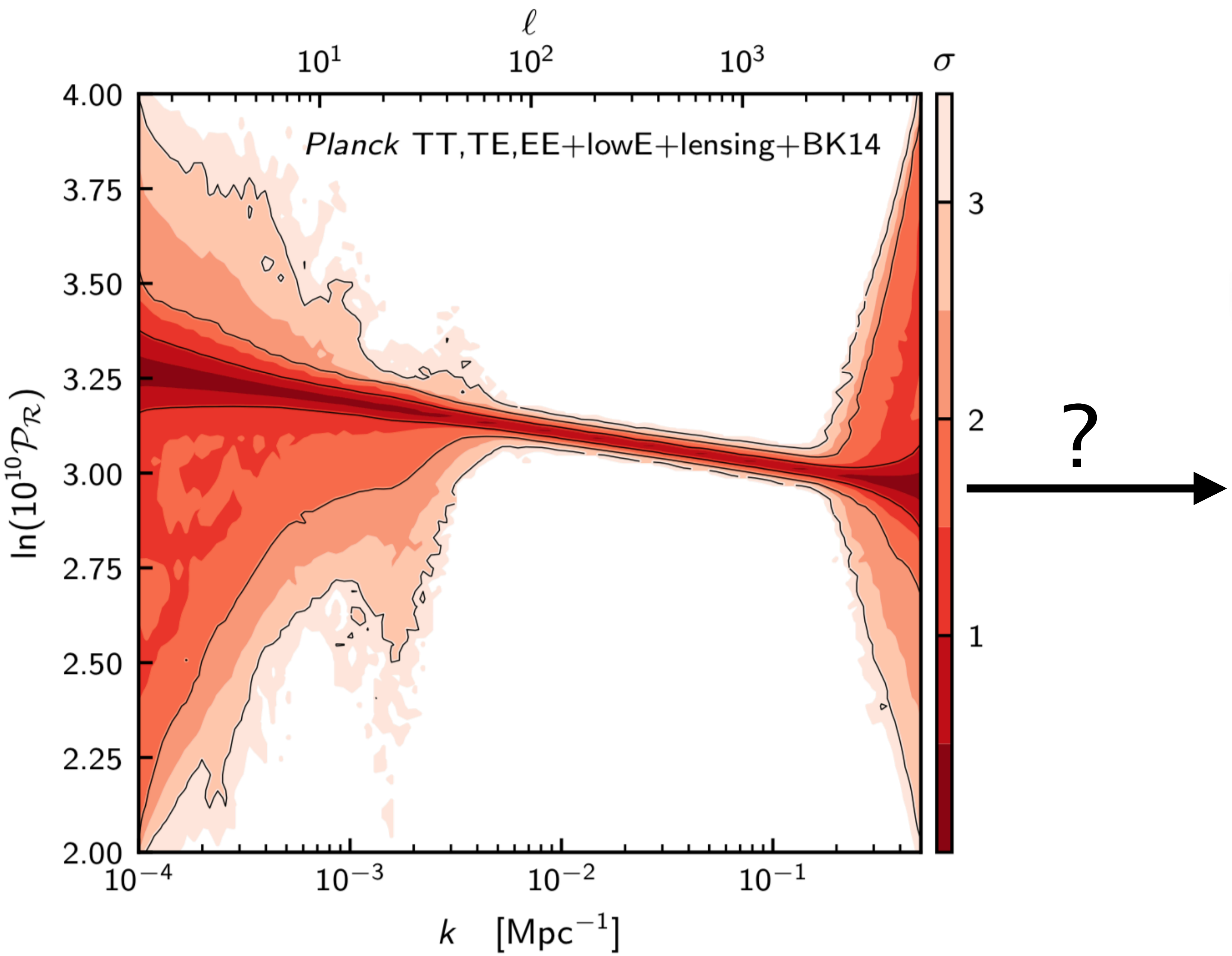
Quantum Origin of Structure





Planck 2018

Quantum Origin of Structure



Planck 2018

Quantum Origin of Structure

Classical physics gives rise to structures too!

[e.g. thermal fluctuations]

Bell gives a definitive way to tell a state <u>IS</u> quantum

Unfortunately, the universe we observe is classical

We need a way to tell is <u>WAS</u> in a quantum

Cosmic Bell's Inequalities

Review of Bell's Inequalities

Really just a reflections of two kinds of probability

Quantum: given $\mathcal{A}_{if} \in \mathbb{C}$ for each path

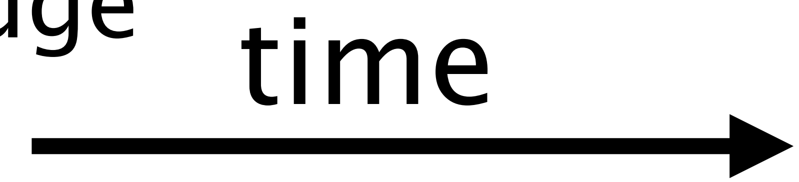
$$P_f = \left| \sum_i \mathcal{A}_{if} \right|^2 \qquad \sum_f P_f = 1$$

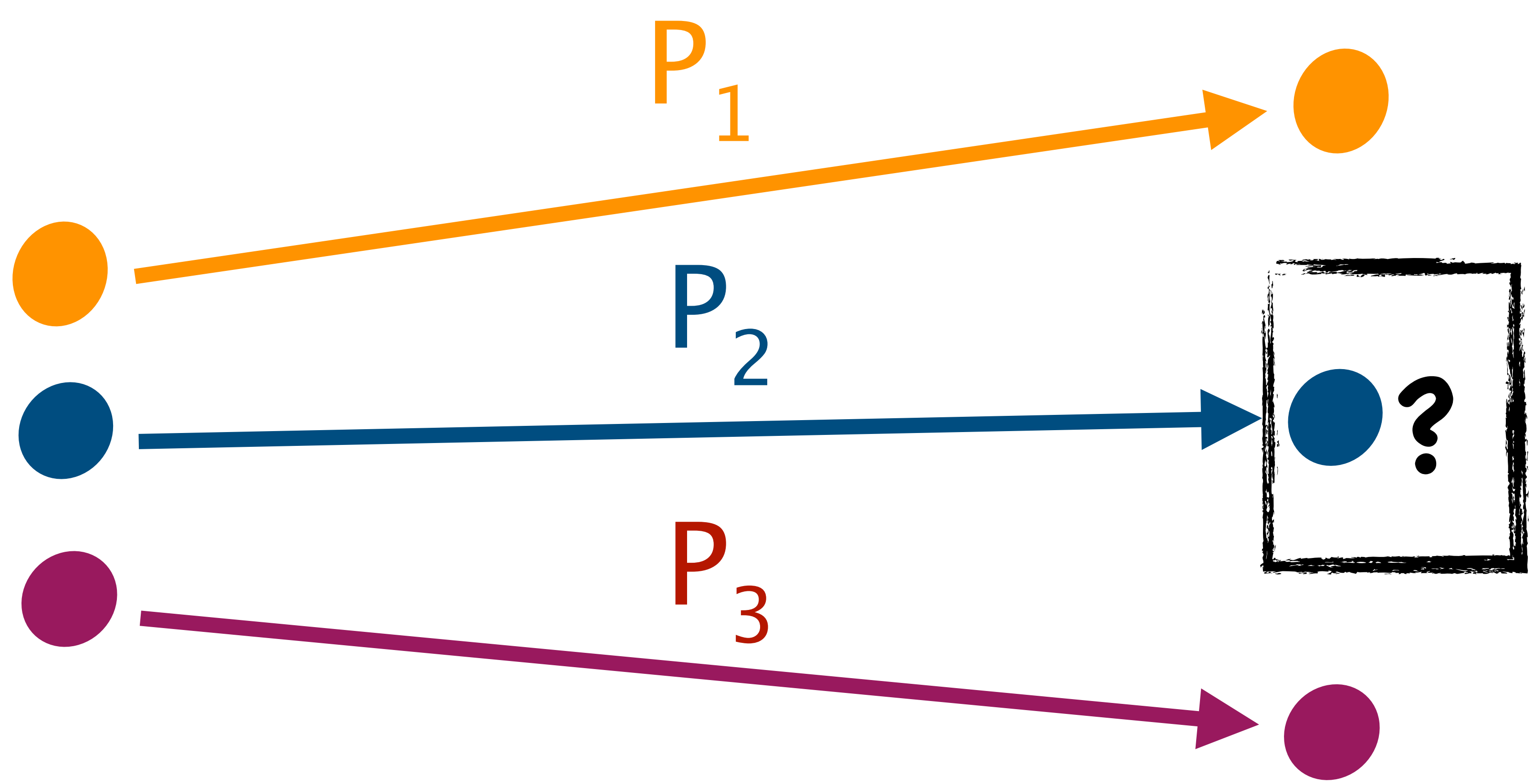
Classical: given $p_{if} \in [0,1]$ for each path

$$P_f = \sum_i p_{if} \qquad \sum_f P_f = 1$$

Review of Bell's Inequalities

Classical Probably = lack of knowledge



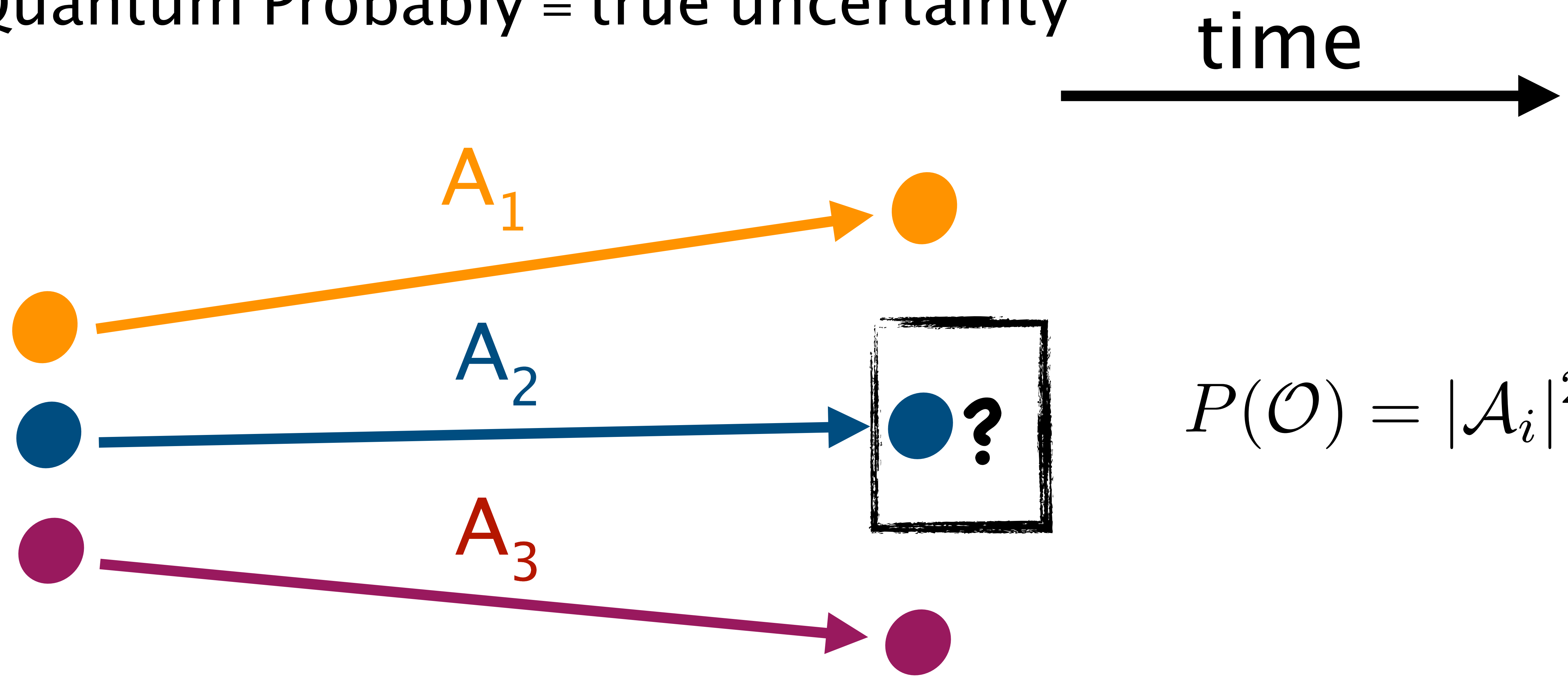


$$P(\mathcal{O}) = P_i$$

The universe picks one trajectory

Review of Bell's Inequalities

Quantum Probably = true uncertainty

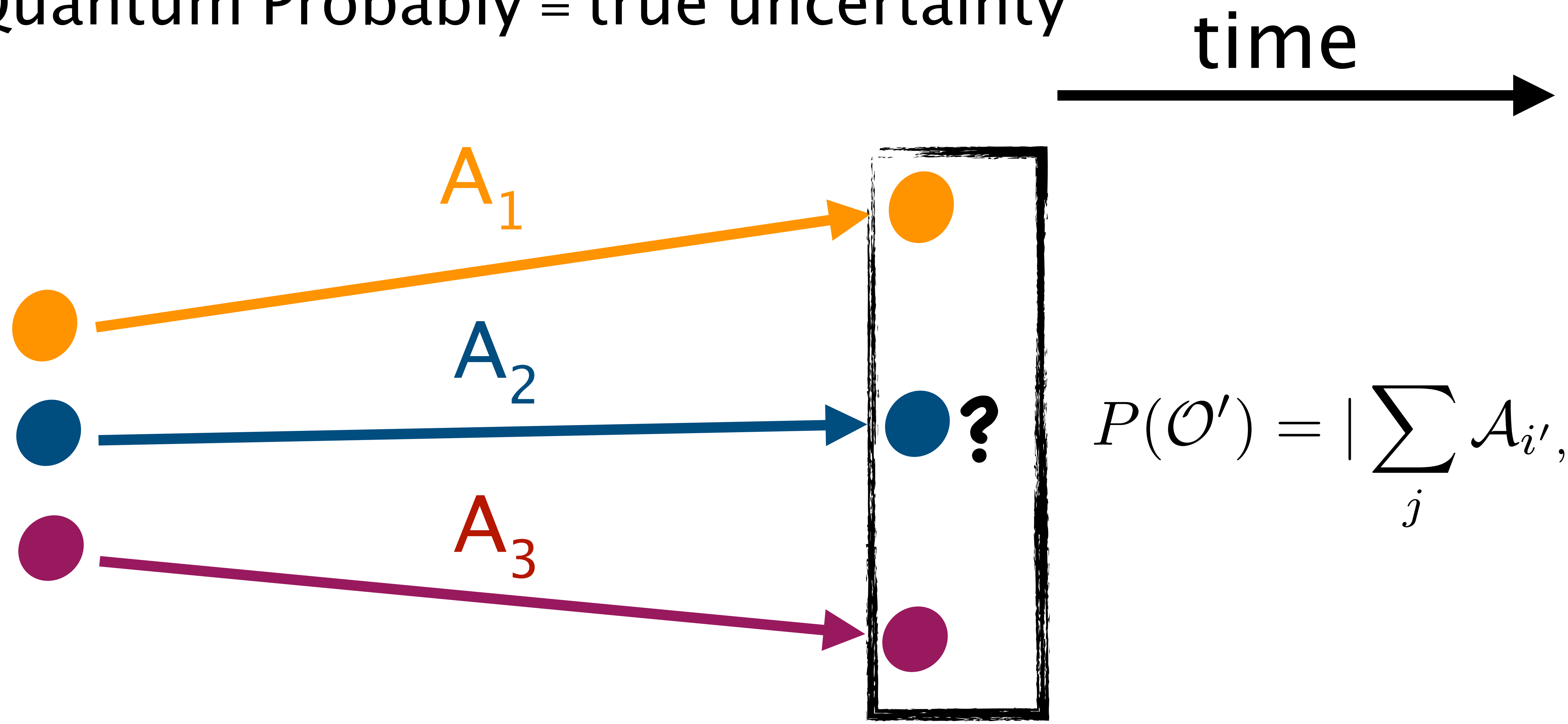


$$P(\mathcal{O}) = |\mathcal{A}_i|^2$$

It might even look classical if $[H, \mathcal{O}] = 0$

Review of Bell's Inequalities

Quantum Probably = true uncertainty

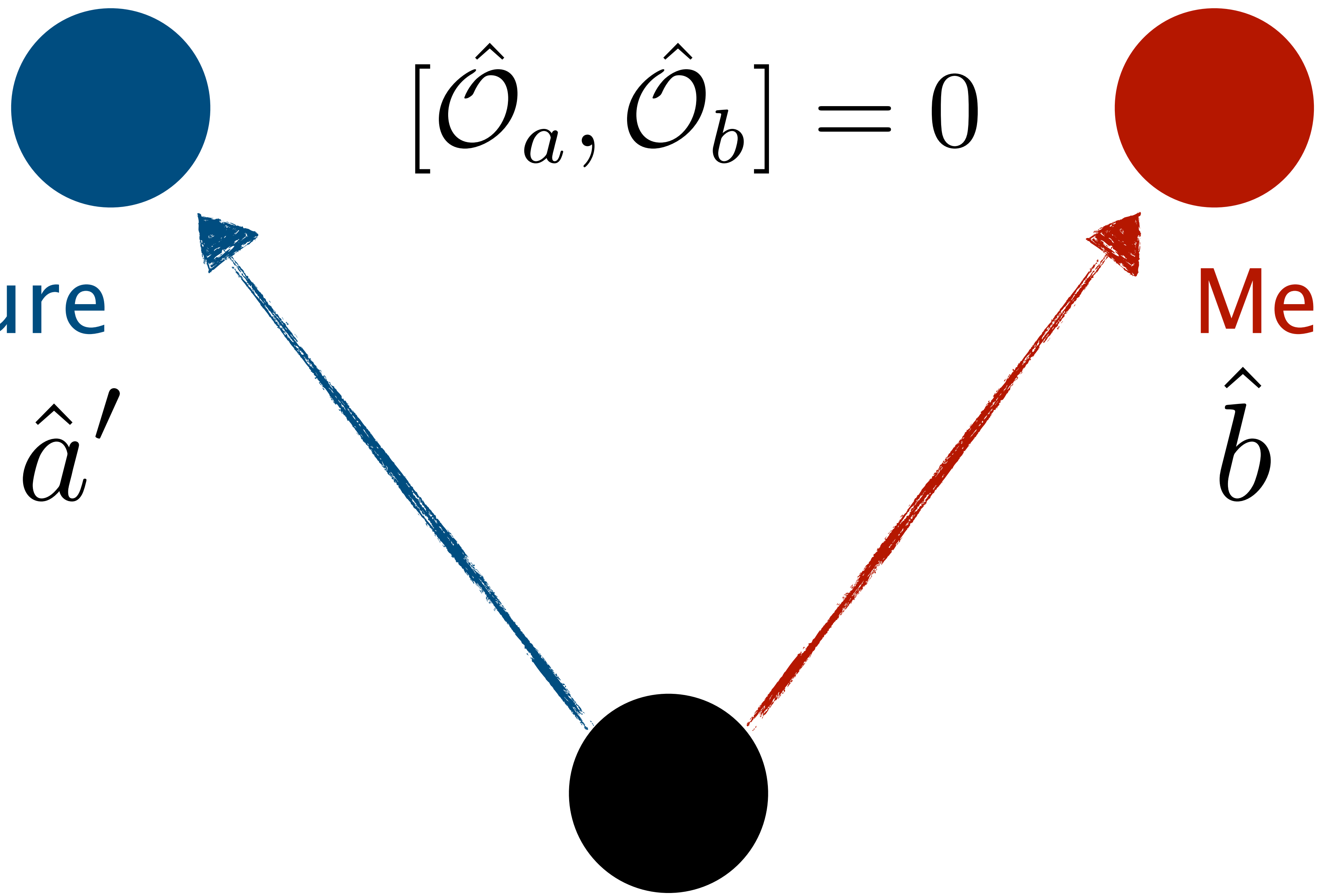


$$P(\mathcal{O}') = |\sum_j \mathcal{A}_{i',j}|^2$$

But not if we measure in basis $[\mathcal{O}', \mathcal{O}] \neq 0$

Review of Bell's Inequalities

$$[\hat{\mathcal{O}}_a, \hat{\mathcal{O}}_b] = 0$$



Measure $\hat{a}$ or $\hat{a}'$

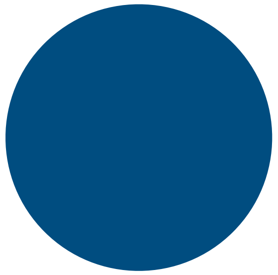
Measure $\hat{b}$ or $\hat{b}'$

$$\hat{a}^2 = \hat{a}'^2 = \hat{b}^2 = \hat{b}'^2 = 1$$

Review of Bell's Inequalities

Key idea: I can choose what I measure locally

$$\hat{a}|\psi_a\rangle$$



$$\hat{a}'|\psi_a\rangle$$

[pure or mixed state]

Do not have to commute $[\hat{a}, \hat{a}'] \neq 0$

But both will only return ± 1

Q vs C distinguished by $\hat{C} = \hat{a}\hat{b} + \hat{a}'\hat{b} + \hat{a}'\hat{b}' - \hat{a}\hat{b}'$

Challenge for Cosmology

The central challenge in cosmology is that

$$[\zeta(\vec{x},t),\dot{\zeta}(\vec{x}',t)] \propto \frac{1}{\sqrt{-g}}\delta(\vec{x}-\vec{x}') = \frac{1}{a^3}\delta(\vec{x}-\vec{x}')$$

e.g. Grishchuk & Sidorov

Suppressed by the volume of the universe

$$\langle\hat{\zeta}(\vec{x},t)\dots\rangle = \int d\zeta\,(\zeta(\vec{x},t)\dots)\,|\Psi[\zeta]|^2$$

This is completely equivalent to classical statistics

$$|\Psi[\zeta]|^2 \to P[\zeta]$$

A Signal of a Quantum Universe

Key Ideas

Our only hope is to use statistics. Since

$$\langle\hat{\zeta}(\vec{x},t)\ldots\rangle = \int d\zeta\,(\zeta(\vec{x},t)\ldots)\,|\Psi[\zeta]|^2$$

We must ask whether

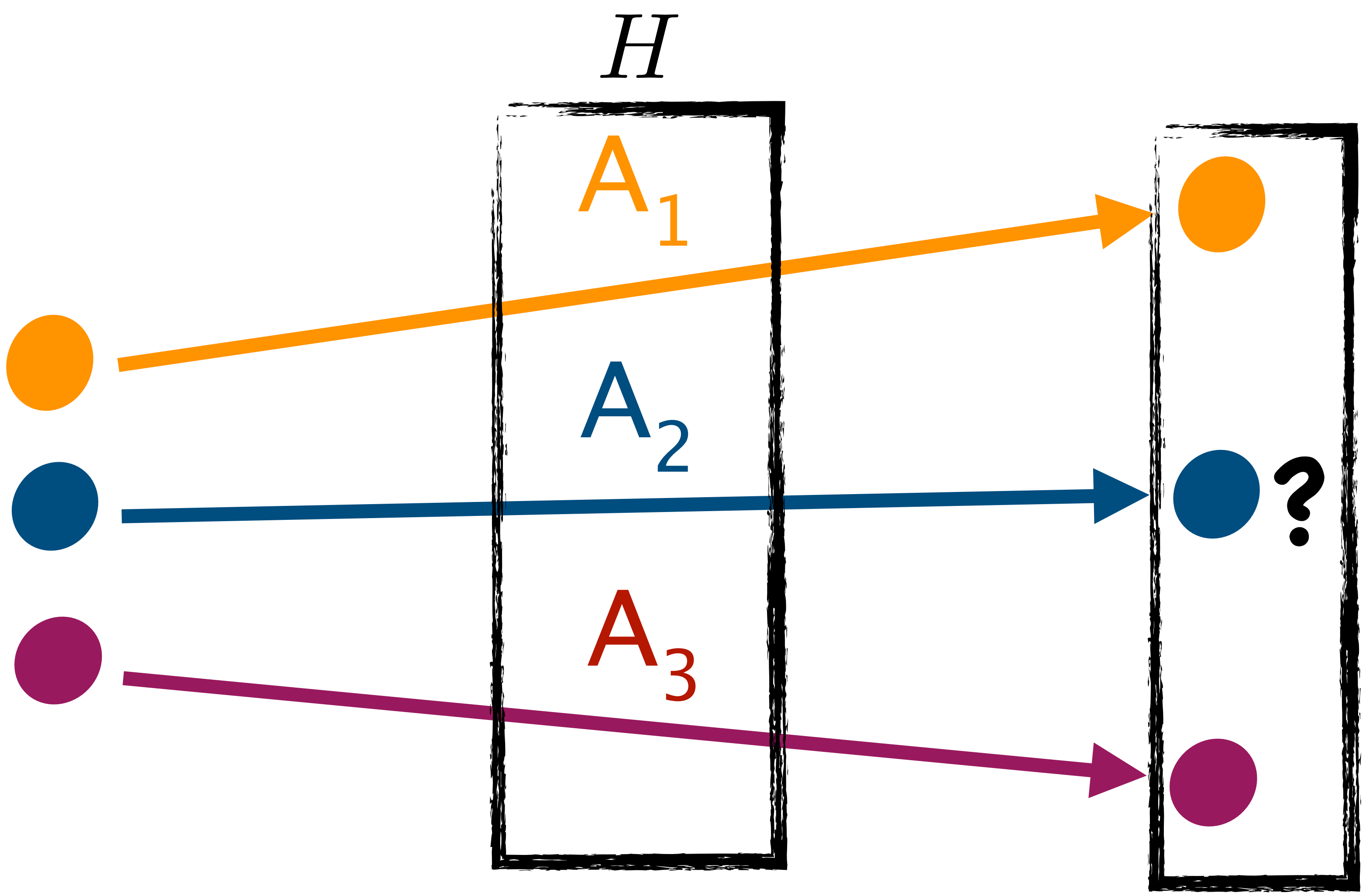
$$|\Psi[\zeta]|^2 \to P[\zeta] \neq P_{\mathrm{classical}}[\zeta]$$

I.e. possible final probably distribution different

Need to understand of how we generate $P[\zeta]$

Key Ideas

Can the evolution itself act as a Bell measurement



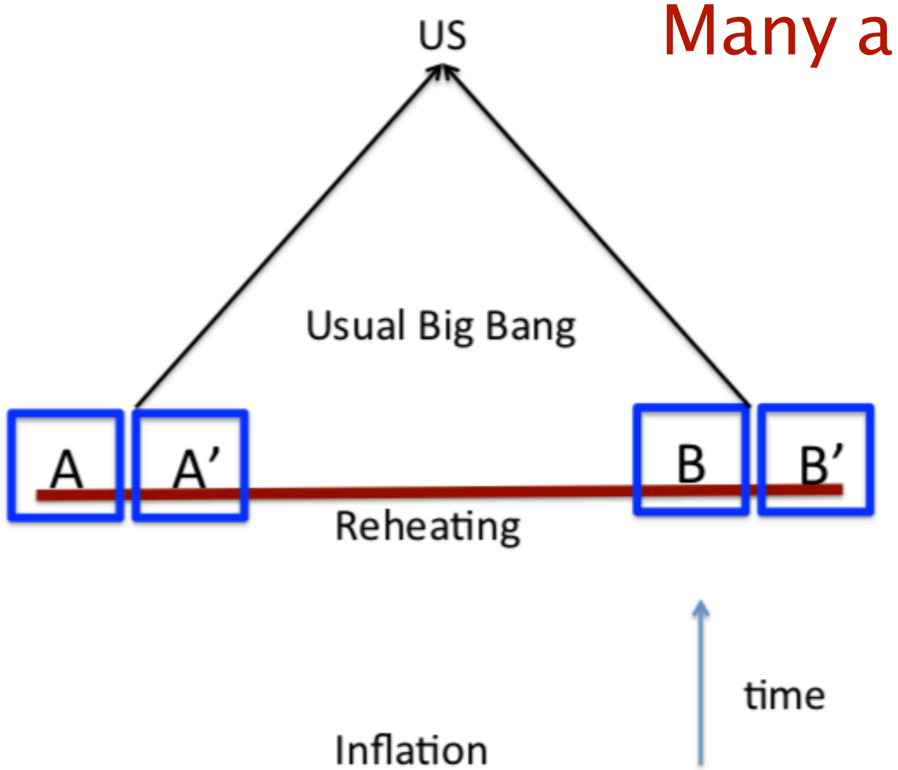
$$P(\mathcal{O}) = |\sum_j \mathcal{A}_i|^2$$

Not obviously classical when $[H, \mathcal{O}] = \mathcal{O}' \neq 0$

Key Ideas

Bell measurement

Many authors

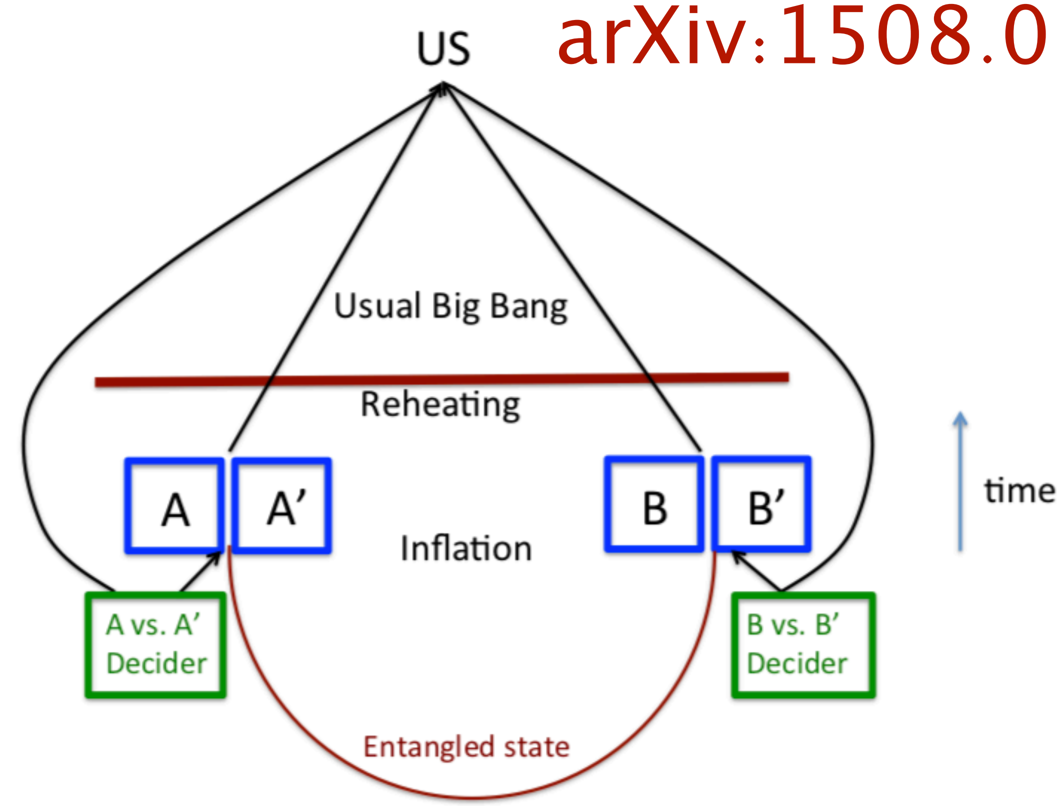


Suppressed by 10^{-115}

E.g. Martin & Vennin, arXiv:1706.05001
de Putter & Doré, arXiv:1905.01394

Maldacena's Model

arXiv:1508.01082



This works, but only in this highly contrived model

We want something more generic

Key Ideas

Classical fluctuations are always real/physical

Classical statistics just represents our uncertainty

Classical modes are sines and cosines

Quantum (vacuum) fluctuations become physical

Quantum modes are positive / negative frequencies

Direct reflect of quantum vs classical statistics

Gaussian Fluctuations

Gaussian modes described as

$$ds^2 = \frac{1}{H^2\tau^2}(-d\tau^2 + d\mathbf{x}^2)$$

$$\zeta(\mathbf{x},\tau) = \int \frac{d^3k}{(2\pi)^3}\frac{\Delta_\zeta}{\sqrt{k^3}} e^{i\mathbf{k}\cdot\mathbf{x}}\left[a^\dagger_{\mathbf{k}}(1-ik\tau)e^{ik\tau} + a_{-\mathbf{k}}(1+ik\tau)e^{-ik\tau}\right]$$

Quantum: $\langle 0|a_{\mathbf{k}'}a^\dagger_{\mathbf{k}}|0\rangle = \delta\left(\mathbf{k}-\mathbf{k}'\right), \quad \langle 0|a^\dagger_{\mathbf{k}}a_{\mathbf{k}'}|0\rangle = 0$

Classical: $\langle a^\dagger_{\mathbf{k}}a_{\mathbf{k}'}\rangle_c = \frac{1}{2}\delta\left(\mathbf{k}-\mathbf{k}'\right) = \langle a_{\mathbf{k}'}a^\dagger_{\mathbf{k}}\rangle_c$

Gaussian Fluctuations

Equal-time correlators are identical

$$\langle \zeta_{\mathbf{k}}(\tau)\zeta_{\mathbf{k}'}(\tau)\rangle_{q,c} = \frac{\Delta_\zeta^2}{k^3}\left(1+k^2\tau^2\right)(2\pi)^3\delta\left(\mathbf{k}+\mathbf{k}'\right)$$

Non-equal times differ, reflecting $[\zeta,\dot{\zeta}]_q \neq 0$

$$\langle \zeta_{\vec{k}}(0)\zeta_{\vec{k}'}(\tau)\rangle_q' = \frac{\Delta_\zeta^2}{k^3} e^{ik\tau}(1-ik\tau)$$

$$\langle \zeta_{\vec{k}}(0)\zeta_{\vec{k}'}(\tau)\rangle_c' = \frac{\Delta_\zeta^2}{k^3}\left(\cos(k\tau)+k\tau\sin(k\tau)\right)$$

Non-Gaussian Fluctuations

What about non-Gaussian correlators?

We will assume NG arises from nonlinear evolution

I.e. no non-local correlations in the initial state

We do not want to assume special interactions

E.g. not allowed to arrange a Bell measurement

Key difference between cosmology and computing

Quantum NG

Let us work out a simple example

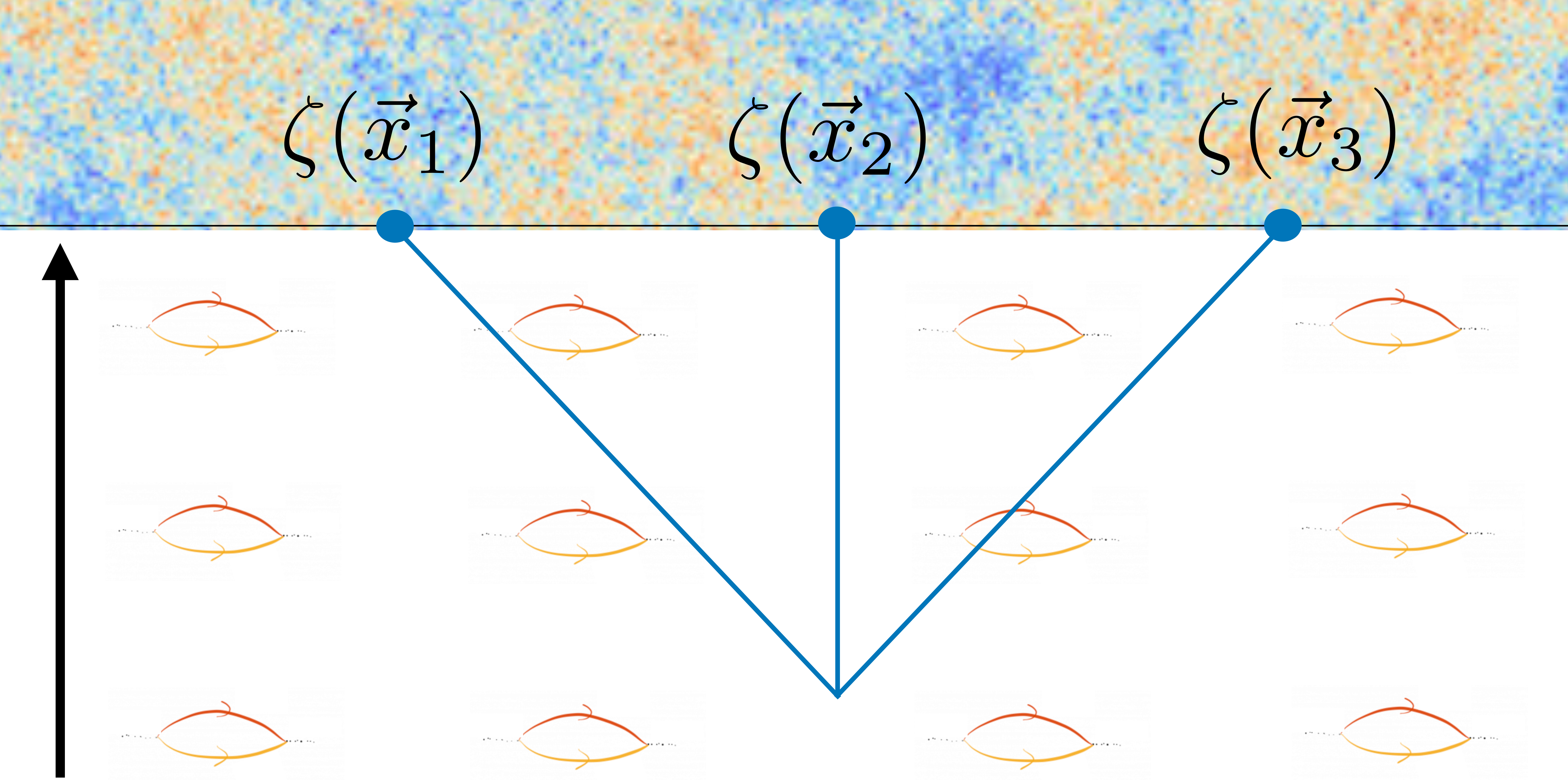
$$H_{\text{int}} = -\frac{\lambda}{3!}\dot{\zeta}^3$$

Standard in-in perturbation theory

$$\langle \zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle'_q = i\int d\tau' \, \langle [H_{\text{int}}(\tau'), \zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}(0)]\rangle$$

$$= \frac{4\lambda H^{-1}\Delta_\zeta^6}{\boxed{(k_1+k_2+k_3)^3}\,k_1k_2k_3}$$

"total energy pole"



Time

Creation of three particles from vacuum

$$\delta(E_1 + E_2 + E_3) \to \frac{1}{(E_1+E_2+E_3)^n}$$

Scattering Uncertainty Principle

Residue is the related to the S-matrix

Maldacena & Pimentel; Raju

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle_q' = \frac{4\lambda H^{-1} \Delta_\zeta^6}{\boxed{(k_1 + k_2 + k_3)^3} k_1 k_2 k_3}$$

"total energy pole"

$$\propto \frac{\mathcal{A}_{\text{on-shell}}(\vec{k}_1, \vec{k}_2, \vec{k}_3)}{(k_1 + k_2 + k_3)^3 \, k_1^2 k_2^2 k_3^2}$$

The pole itself is just signaling energy conservation

Classical NG

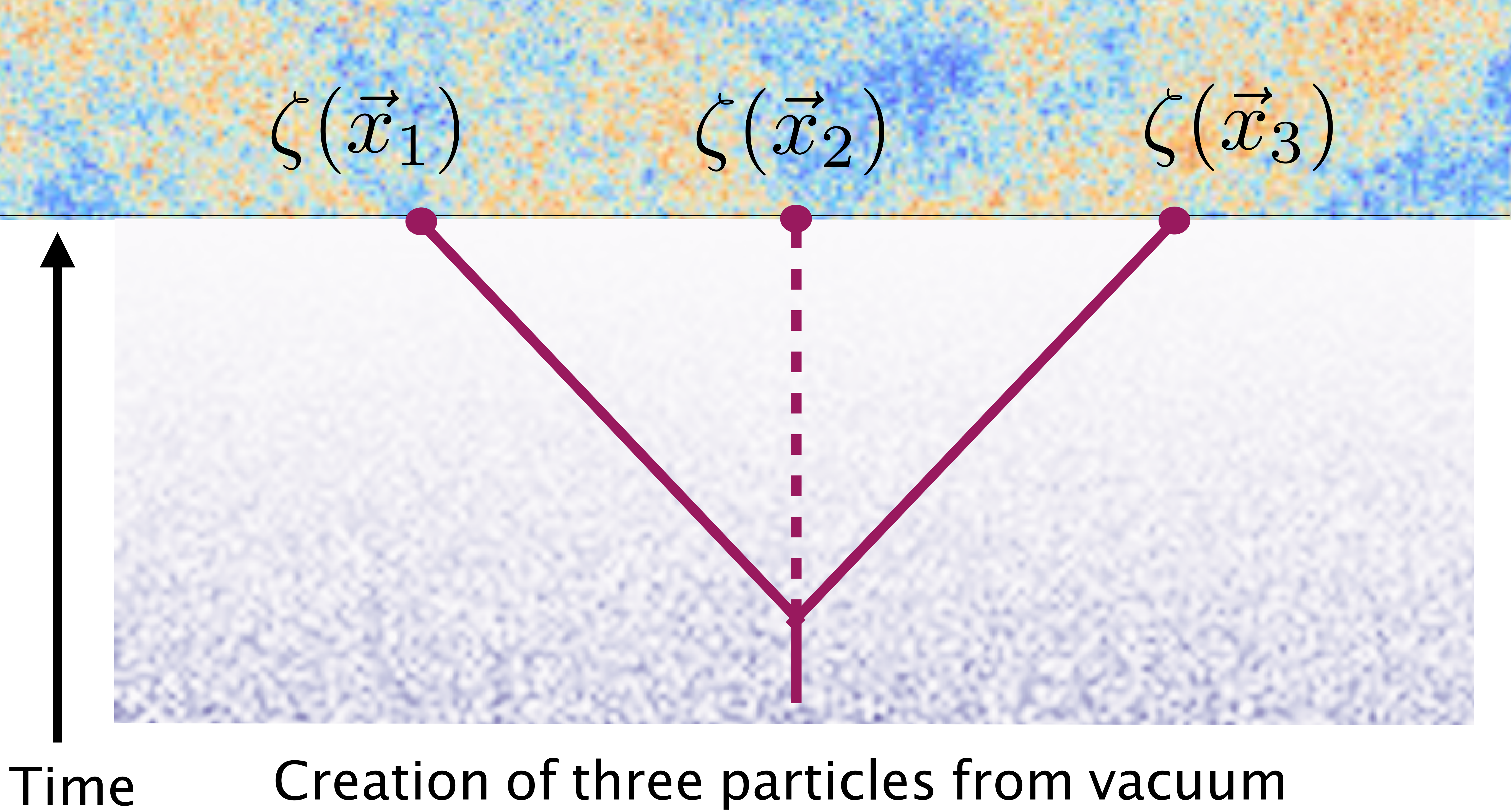
Classical analogue: solve EoM perturbatively

$$\zeta^{(2)}_{\mathbf{k}}(\tau) = \lambda \int \frac{d\tau' d^3p}{(2\pi)^3} \left(-H\tau'\right)^{-1} \left(\partial_{\tau'} G_{\mathbf{k}}(\tau,\tau')\right) \partial_{\tau'} \zeta^{(1)}_{\mathbf{p}}(\tau')\, \partial_{\tau'} \zeta^{(1)}_{\mathbf{k}-\mathbf{p}}(\tau')$$

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle'_c = \frac{\lambda H^{-1} \Delta_\zeta^6}{3k_1k_2k_3} \left[\boxed{\frac{3}{(k_1+k_2+k_3)^3}} \right.$$ "total energy pole"

$$\left. + \boxed{\frac{1}{(k_1+k_2-k_3)^3}} + \boxed{\frac{1}{(k_1-k_2+k_3)^3}} + \boxed{\frac{1}{(k_2-k_1+k_3)^3}} \right]$$

On-shell pole or "Folded Shape"



Creation of three particles from vacuum

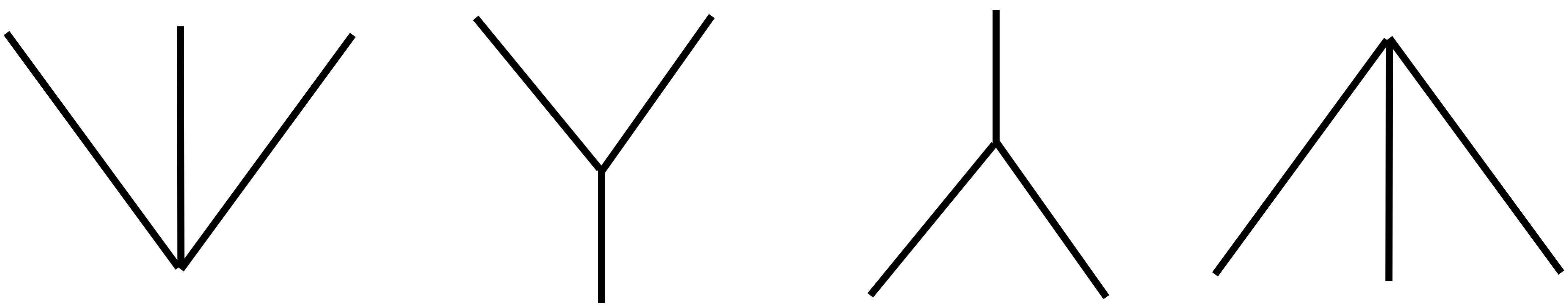
$$\delta(E_1 - E_2 - E_3) \to \frac{1}{(E_1 - E_2 - E_3)^n}$$

Scattering　　　On-Shell Decay

Classical NG

A result of crossing symmetry of the S-matrix

LSZ formula shows that you must have all processes



$0 \to 3$ $\quad$ $1 \to 2$ $\quad$ $2 \to 1$ $\quad$ $3 \to 0$

Only differ by number of particles in the initial state

Classical NG

Classical fluctuations = particles in the initial state

Fluctuations always includes negative frequencies

$$\zeta(\mathbf{x},\tau) = \int \frac{d^3k}{(2\pi)^3} \frac{\Delta_\zeta}{\sqrt{k^3}} e^{i\mathbf{k}\cdot\mathbf{x}} \left[a_{R,\mathbf{k}}(\cos(k\tau) + k\tau\sin(k\tau)) + a_{I,\mathbf{k}}(\sin(k\tau) - k\tau\cos(k\tau))\right]$$

$$a_{\vec{k}} = \frac{1}{2}[a_{R,\vec{k}} + i a_{I,\vec{k}}]$$

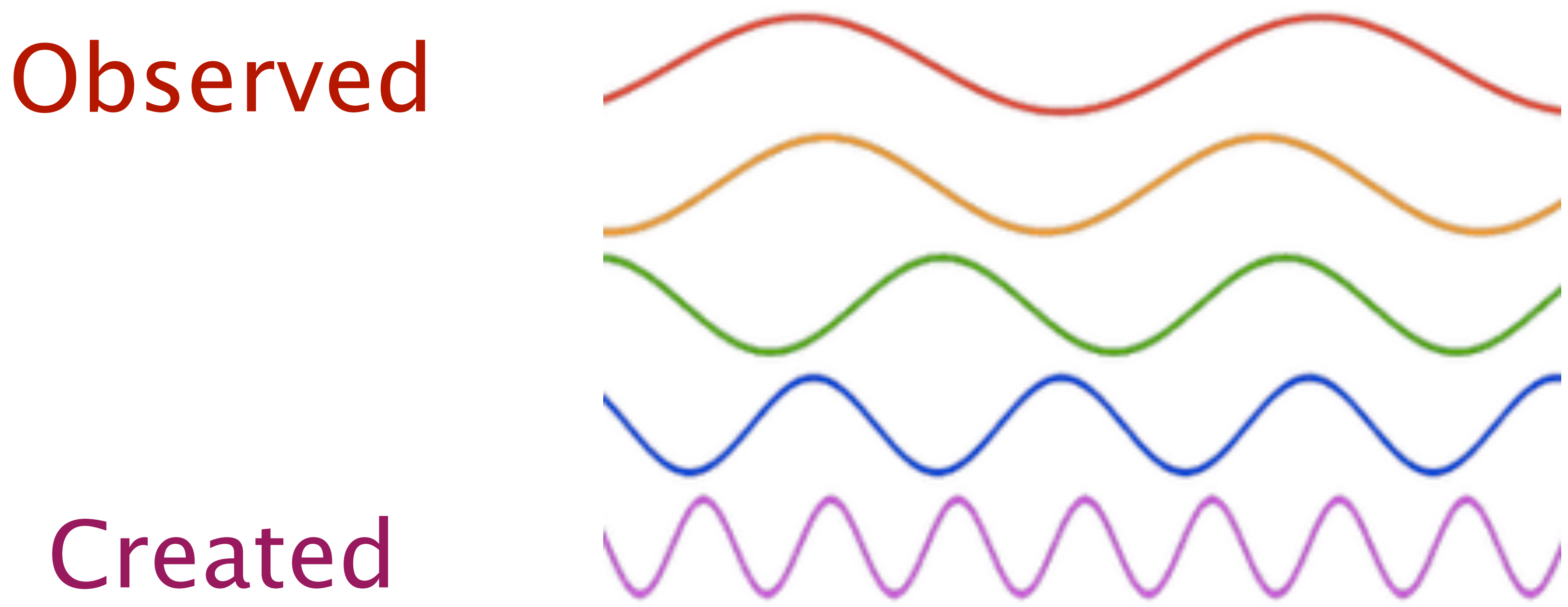
$$\langle a_{R,\mathbf{k}} a_{R,\mathbf{k}'} \rangle_c = \delta\left(\mathbf{k} + \mathbf{k}'\right) = \langle a_{I,\mathbf{k}} a_{I,\mathbf{k}'} \rangle_c$$

Classical probability is just lack of knowledge

Classical NG

Classical fluctuations = particles in the initial state

Observed fluctuations exist in the far past

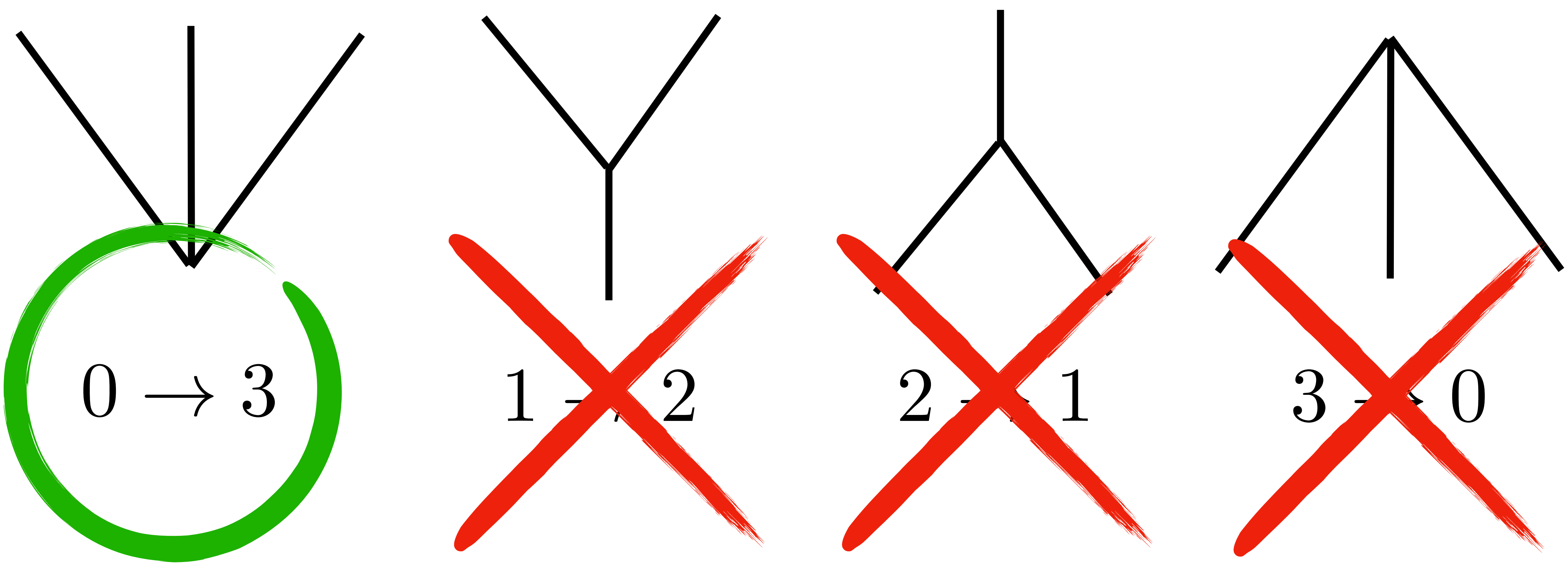


Classical probability is just lack of knowledge

Quantum vs Classical

No classical analogue of vacuum fluctuations

Quantum vacuum has no initial particles



In detail: compare quantum In-In to classical EoM

$$\langle \zeta(\mathbf{x}_1,\tau)\,\zeta(\mathbf{x}_2,\tau)\,\zeta(\mathbf{x}_3,\tau)\rangle_q = -i\int_{-\infty}^{\tau} d\tau' d^3\mathbf{x}' a^4(\tau')\left[\langle[H_{\rm int},\zeta(\mathbf{x}_1,\tau)]\,\zeta(\mathbf{x}_2,\tau)\,\zeta(\mathbf{x}_3,\tau)\rangle\right.$$

$$\left.+\langle\zeta(\mathbf{x}_1,\tau)\,[H_{\rm int}(\mathbf{x}',\tau'),\zeta(\mathbf{x}_2,\tau)]\,\zeta(\mathbf{x}_3,\tau)\rangle+\langle\zeta(\mathbf{x}_1,\tau)\,\zeta(\mathbf{x}_2,\tau)\,[H_{\rm int}(\mathbf{x}',\tau'),\zeta(\mathbf{x}_3,\tau)]\rangle\right]$$

$$= \lambda\int_{-\infty}^{t} dt' d^3x' a^3(t')\left[\dot G(t,t';\mathbf{x}_1-\mathbf{x}')\boxed{\left\langle\dot\zeta^2(\mathbf{x}',t')\,\zeta(\mathbf{x}_2,t)\,\zeta(\mathbf{x}_3,t)\right\rangle}\right.$$

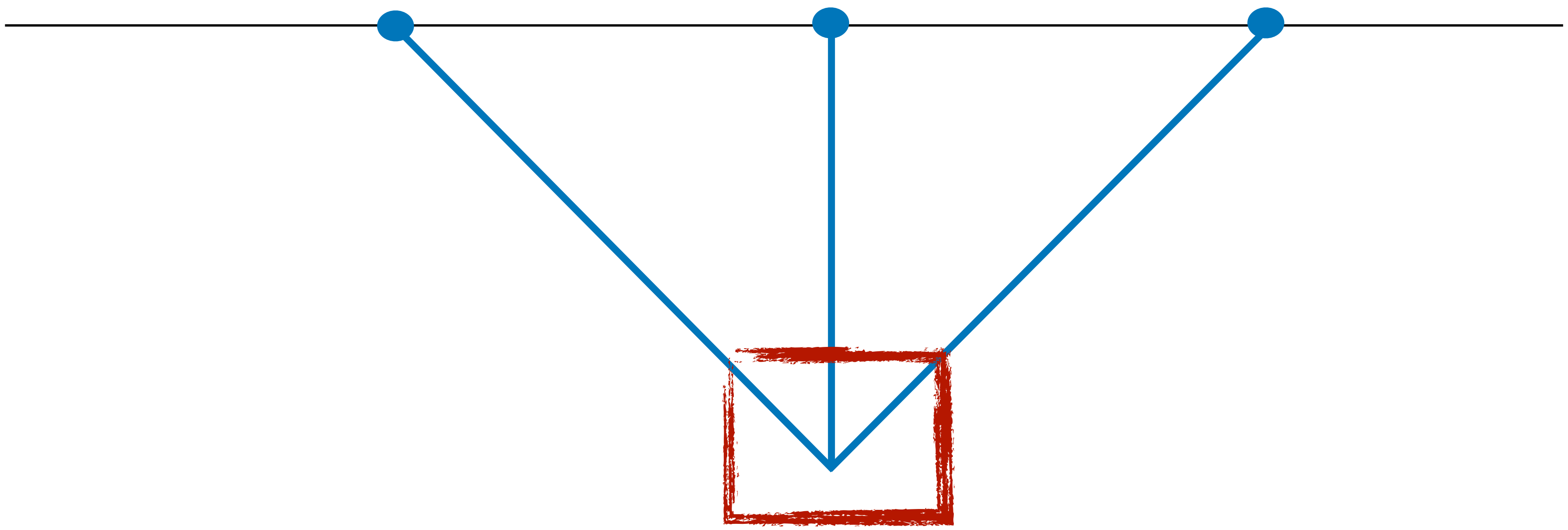
$$\left.+\dot G(t,t';\mathbf{x}_2-\mathbf{x}')\boxed{\left\langle\zeta(\mathbf{x}_1,t)\,\dot\zeta^2(\mathbf{x}',t')\,\zeta(\mathbf{x}_3,t)\right\rangle}+\dot G(t,t';\mathbf{x}_3-\mathbf{x}')\boxed{\left\langle\zeta(\mathbf{x}_1,t)\,\zeta(\mathbf{x}_2,t)\,\dot\zeta^2(\mathbf{x}',t')\right\rangle}\right.$$

Terms differ by operator ordering

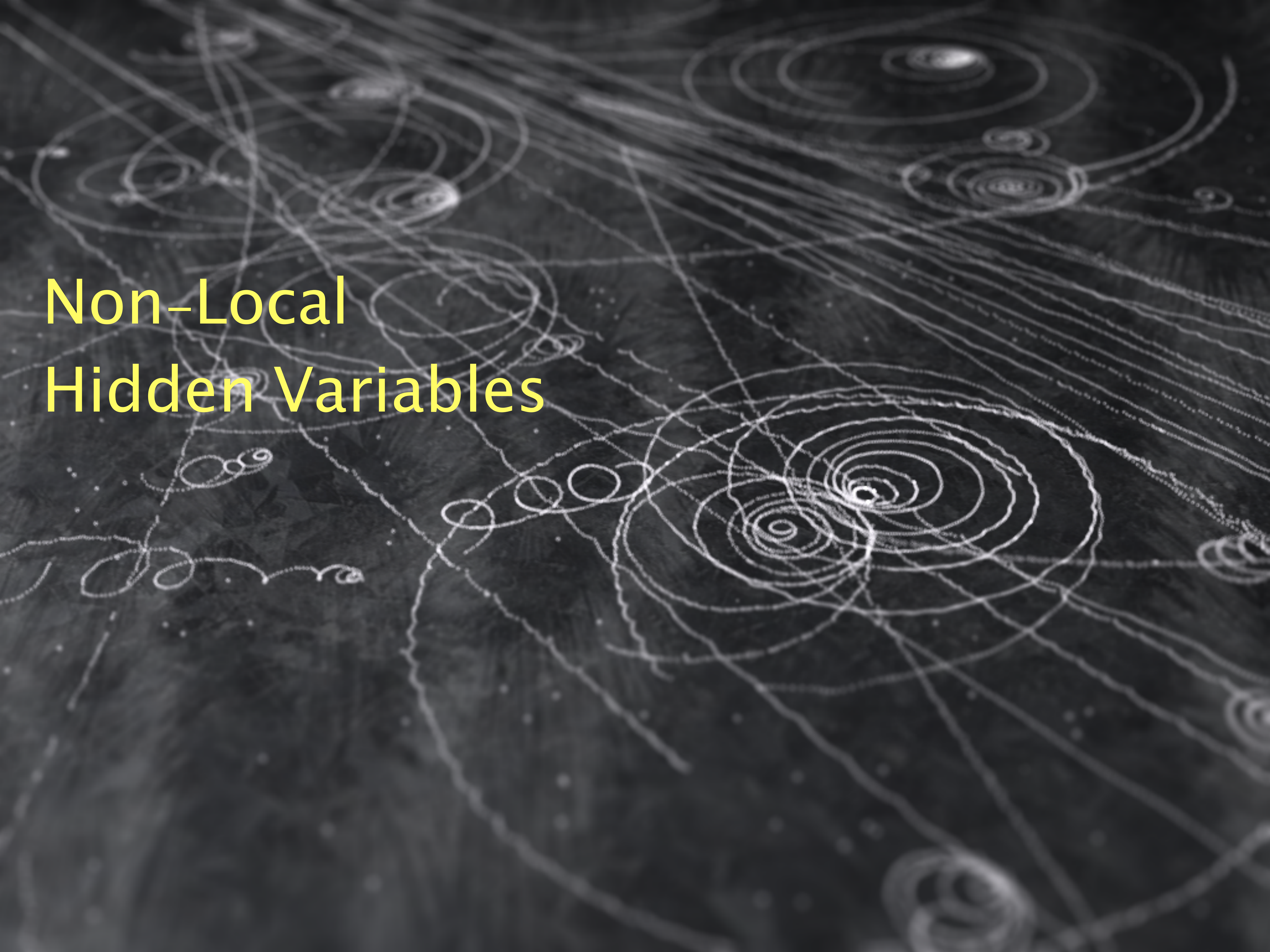
Removing ordering with commutators

$$\langle\zeta(\mathbf{x}_1,\tau)\,\zeta(\mathbf{x}_2,\tau)\,\zeta(\mathbf{x}_3,\tau)\rangle_q - \langle\zeta(\mathbf{x}_1,\tau)\,\zeta(\mathbf{x}_2,\tau)\,\zeta(\mathbf{x}_3,\tau)\rangle_c =$$

$$+\frac{i\lambda}{4}\int_{-\infty}^{\tau} d\tau' d^3x' a^4(\tau')\left[\zeta(\mathbf{x}_1,\tau),\dot{\zeta}(\mathbf{x}',\tau')\right]\left[\zeta(\mathbf{x}_2,\tau),\dot{\zeta}(\mathbf{x}',\tau')\right]\left[\zeta(\mathbf{x}_3,\tau),\dot{\zeta}(\mathbf{x}',\tau')\right]$$



Commutator non-zero at the intersection of past light-cones


Non-Local
Hidden Variables

Hidden Variables

We can evade Bell's inequality if we give up locality

Is there a similar result in cosmological signature?

Idea: Classical theory prefers positive frequencies

Use a complex scalar

$$\phi_{\mathbf{k}}(\tau) = \frac{\Delta_\phi}{k^{3/2}}\left[a^\dagger_{\mathbf{k}}(1 - ik\tau)e^{ik\tau} + b_{-\mathbf{k}}(1 + ik\tau)e^{-ik\tau}\right]$$

Only excite the positive frequencies

$$\left\langle a^\dagger_{\mathbf{k}} a_{\mathbf{k}'} \right\rangle_c = \left\langle a_{\mathbf{k}'} a^\dagger_{\mathbf{k}} \right\rangle_c = \delta\left(\mathbf{k} - \mathbf{k}'\right), \quad \left\langle b_{\mathbf{k}} b^\dagger_{\mathbf{k}'} \right\rangle_c = 0$$

Hidden Variables

Now we will simply invent a "Green's function"

$$\dot{G}_{\mathbf{k}} \to G^{\mathrm{eff}}_{\mathbf{k}}\left(\tau \to 0, \tau'\right) = \frac{1}{k} e^{-ik\tau'}$$

By analogy with an interaction $\mathcal{L}_{\mathrm{int}} = \lambda_\phi \dot{\phi}^3 + \lambda_\phi^* \dot{\phi}^{*3}$

$$\phi_{\mathbf{k}}(\tau \to 0) = \frac{i}{3}\lambda_\phi \int \frac{d^3p}{(2\pi)^3} \int d\tau' \frac{1}{k} e^{-ik\tau'} \dot{\phi}^*_{\mathbf{p}}\left(\tau'\right) \dot{\phi}^*_{\mathbf{k}-\mathbf{p}}\left(\tau'\right)$$

Describes 1 particle decaying to 2 anti-particles

Hidden Variables

Using this to compute the bispectrum gives

$$\langle \phi_{\mathbf{k}_1} \phi_{\mathbf{k}_2} \phi_{\mathbf{k}_3} \rangle' = i\lambda_\phi H^{-1} \frac{\Delta_\phi^6}{k_1 k_2 k_3} \int_{-\infty}^{0} d\tau' \tau'^2 e^{-i(k_1+k_2+k_3)\tau'}$$

$$= \frac{2\lambda_\phi H^{-1} \Delta_\phi^6}{(k_1 + k_2 + k_3)^3 \, k_1 k_2 k_3}$$

Only net creation of three antiparticles

Only a total energy pole

Hidden Variables

This theory is non-local

$$G^{\rm eff}_{\mathbf{k}}\left(\tau \to 0, \tau' \to 0\right) = \frac{1}{k}$$

Non-zero at space-like separations

$$G^{\rm eff}\left(\vec{x}, \tau \to 0, \tau' \to 0\right) \propto \frac{1}{x^2}$$

In a local theory, must vanish outside the light-cone

$$G^{\rm eff}_{\mathbf{k}} \sim \frac{1}{k}\sin(k\tau) \to G^{\rm eff}(\vec{x}) \propto \delta(\vec{x})$$

Hidden Variables

In this local theory

$$\phi_{\mathbf{k}}(\tau \to 0) = \frac{i}{3}\lambda_\phi \int \frac{d^3p}{(2\pi)^3} \int d\tau' \frac{1}{k} \sin(k\tau')\dot{\phi}^*_{\mathbf{p}}(\tau')\,\dot{\phi}^*_{\mathbf{k}-\mathbf{p}}(\tau')$$

and

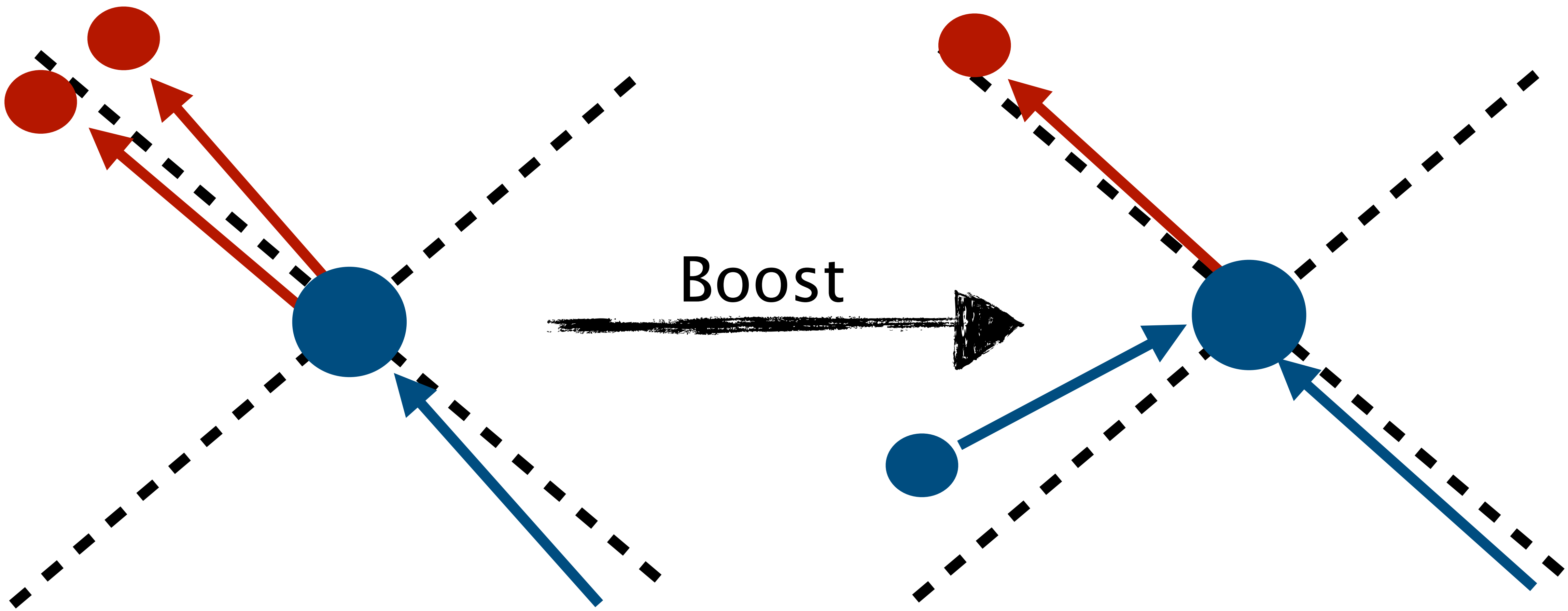
$$\langle \phi_{\mathbf{k}_1}\phi_{\mathbf{k}_2}\phi_{\mathbf{k}_3}\rangle' \supset \frac{\lambda_\phi H^{-1}\Delta_\phi^6}{(k_1 - k_2 + k_3)^3\, k_1 k_2 k_3}$$

Include 2 particles annihilating to 1 anti-particle

Non-trivial relation between crossing and causality

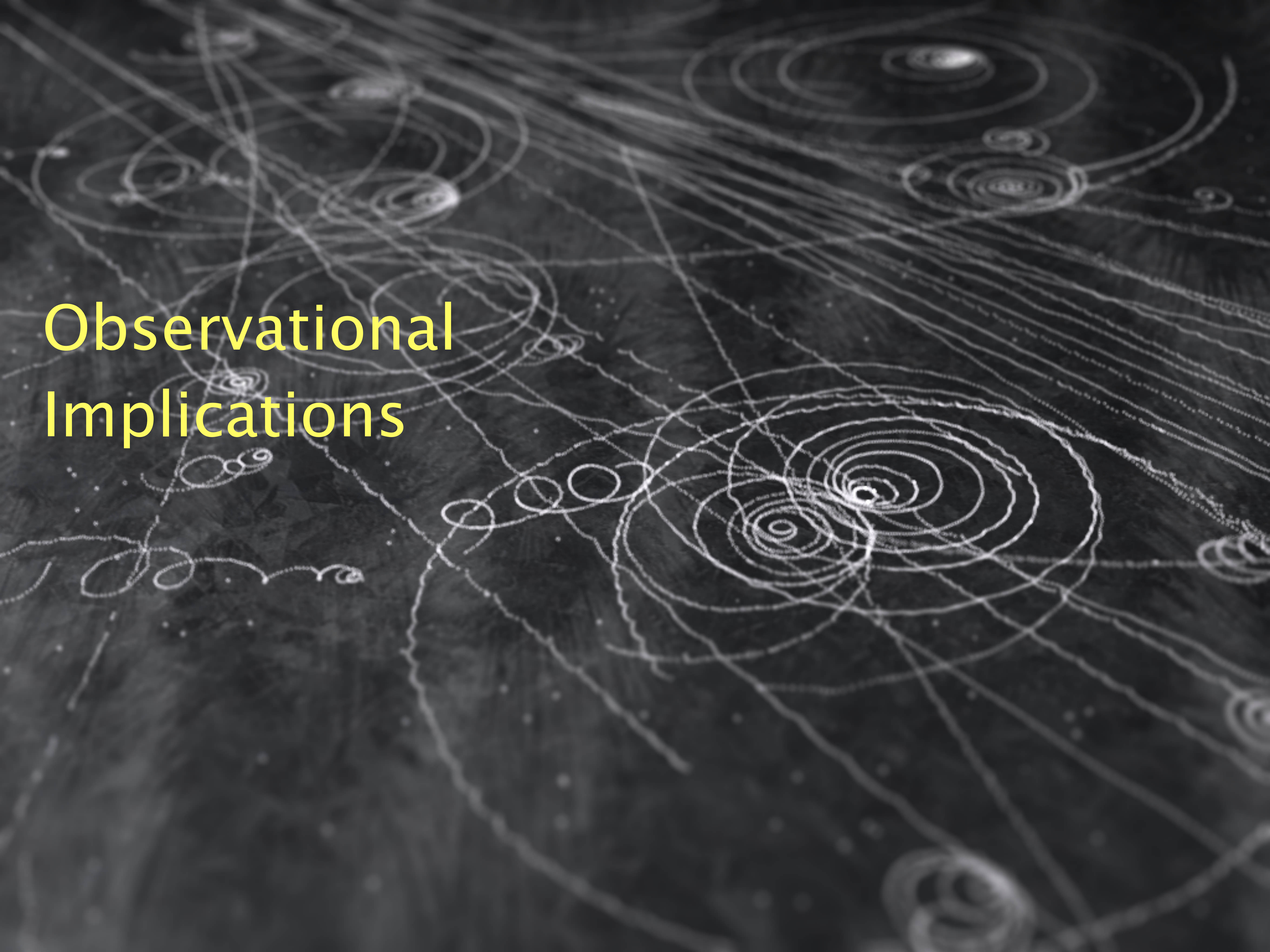
Hidden Variables

This is the same as the need for antiparticles

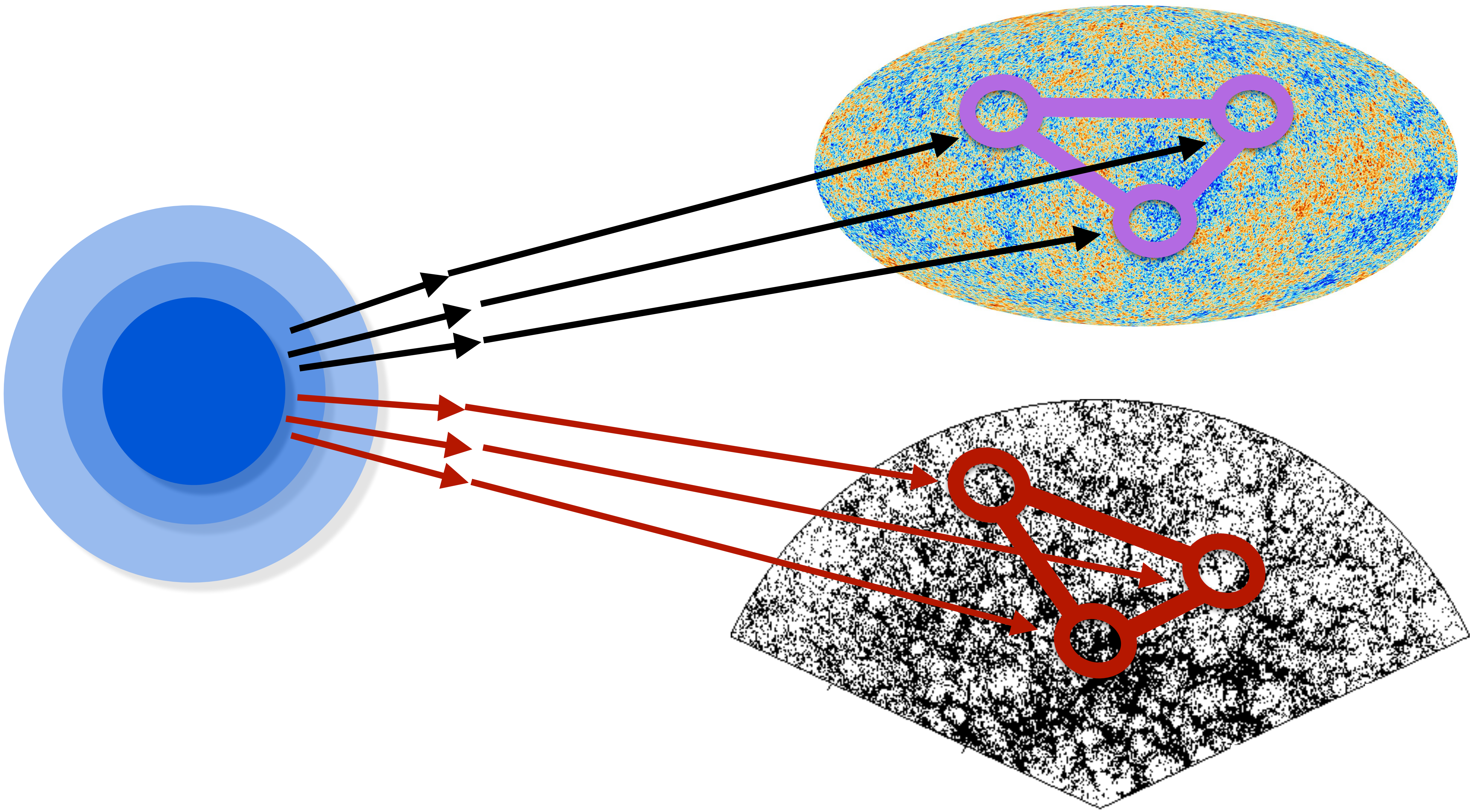


Lorentz invariance requires they come together

Observational Implications



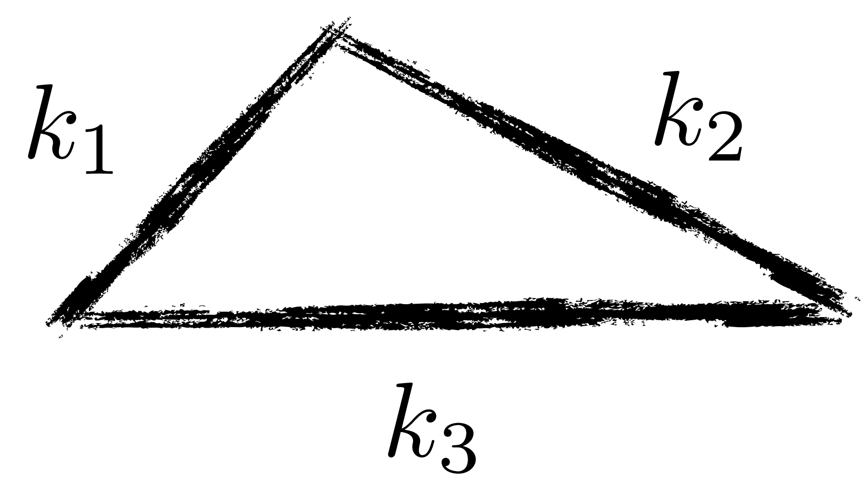
Primordial Non-Gaussianity



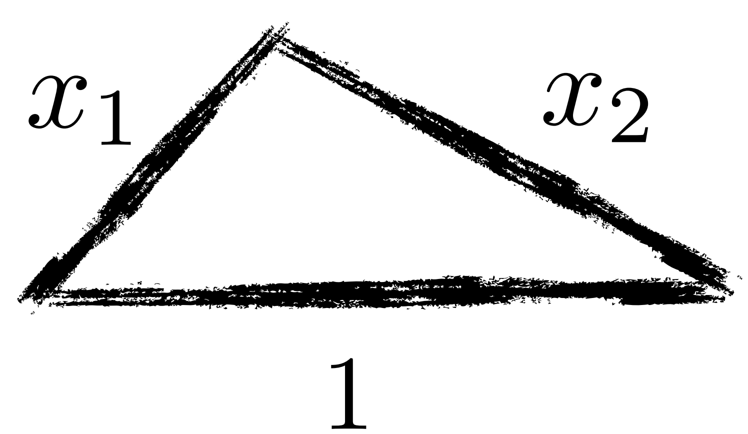
On general groups, bispectra take the form

$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_1} \zeta_{\vec{k}_1} \rangle = B(k_1, k_2, k_3)(2\pi)^3 \delta(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)$$

Momentum conservation:



Scale invariance:



$$\times \frac{1}{k_3^6}$$

Primordial Non-Gaussianity

Defined by amplitude and “shape”

$$B(k_1, k_2, k_3) = \boxed{f_{\rm NL}} \frac{18}{5} \frac{\Delta_\zeta^4}{k_3^6 x_1^2 x_2^2} \boxed{S(x_1, x_2)}$$

The shapes live in a basis of orthogonal functions

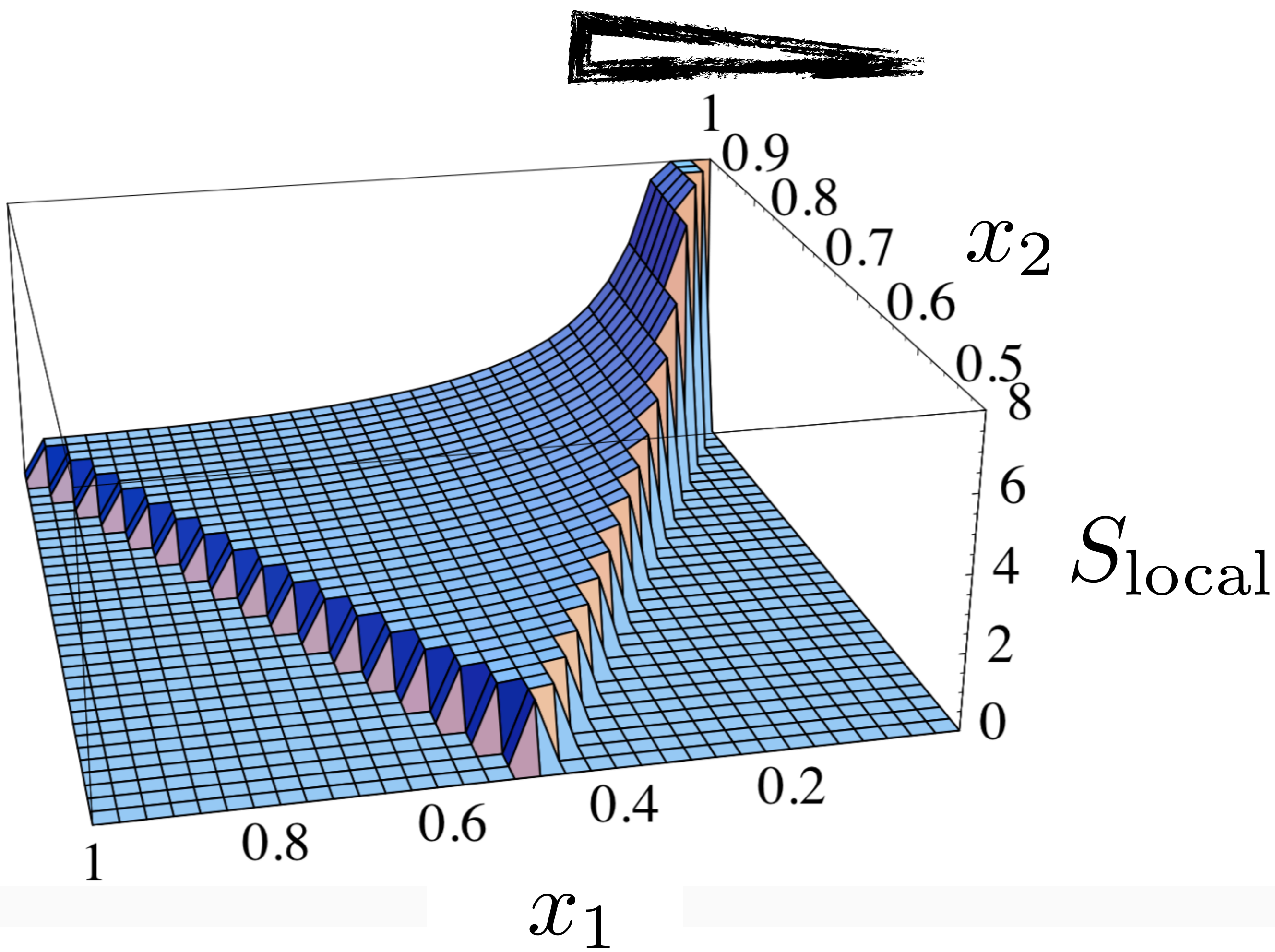
$$\int dx_1 dx_2 S_1(x_1, x_2) S_2(x_1, x_2) = S_1 \cdot S_2 = \cos_{12}$$

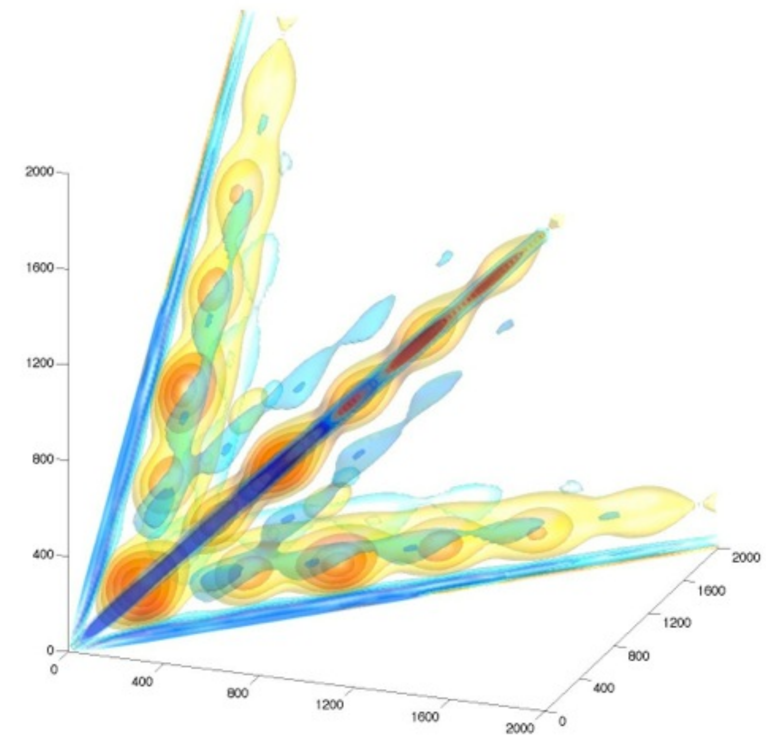
Cosine is how easily they are distinguish (in 3pt)

The "Local Shape"

$$f_{\mathrm{NL}}^{\mathrm{local}} = -0.9 \pm 5.1$$

Planck 2018





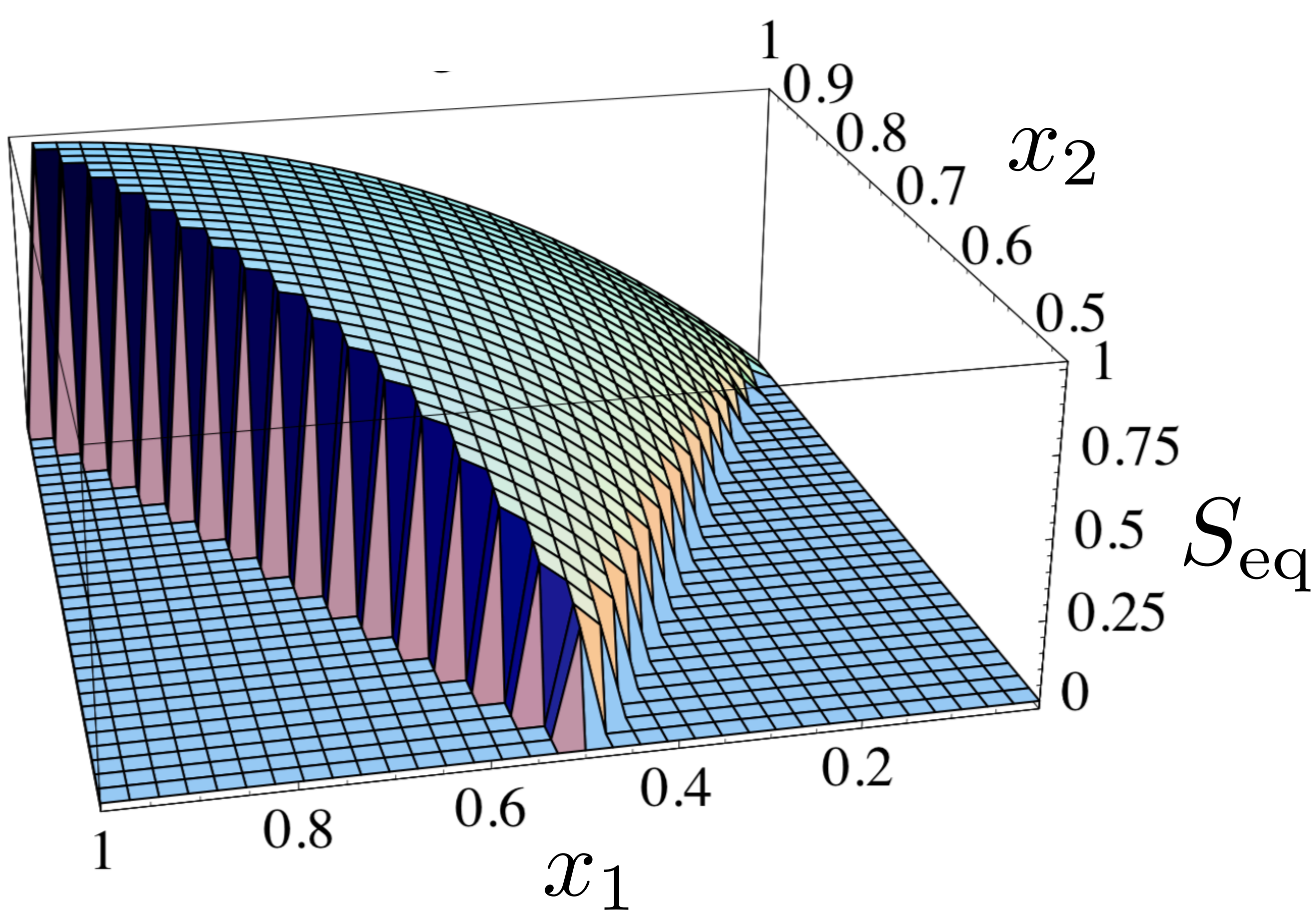
Courtesy of Fergusson & Shellard

Babich et al.

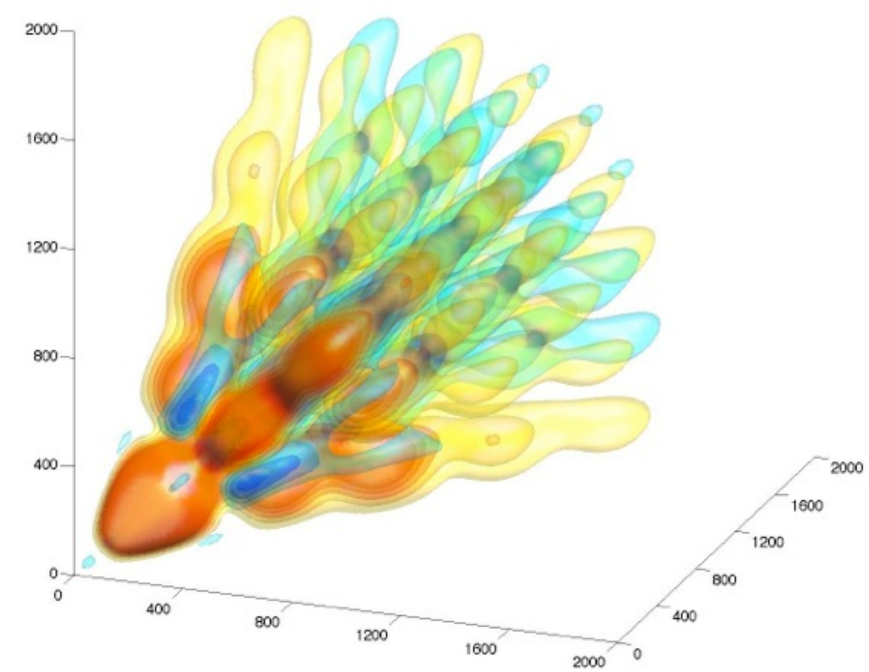
The "Equilateral Shape"

$$f_{\mathrm{NL}}^{\mathrm{equil}} = -26 \pm 47$$

Planck 2018



Babich et al.



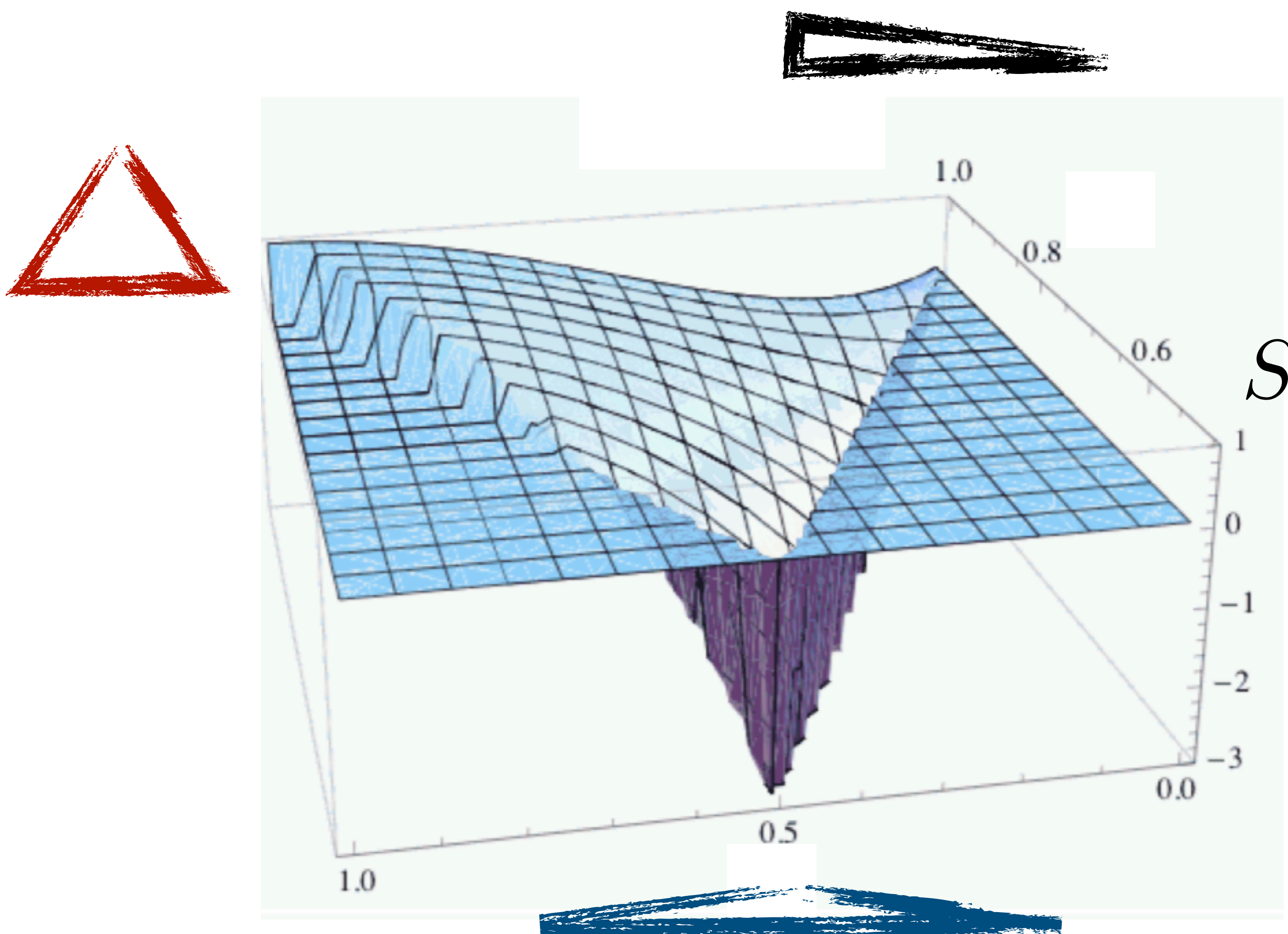
Courtesy of Fergusson & Shellard

Current Limits

The “Orthogonal Shape”

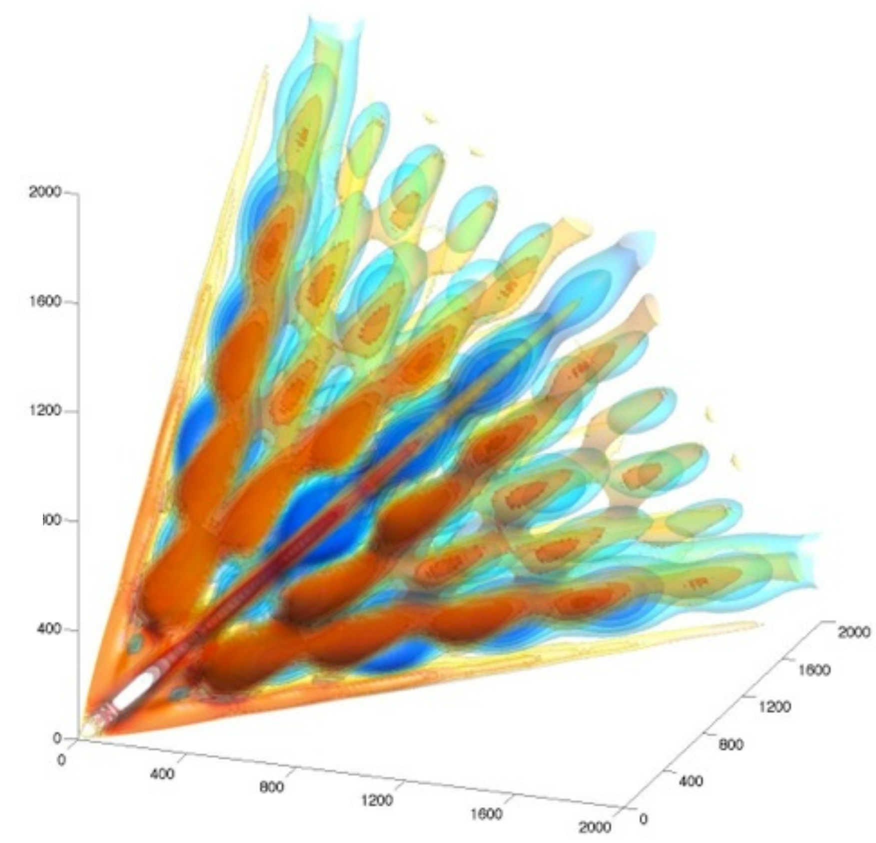
$$f_{\mathrm{NL}}^{\mathrm{ortho}} = -38 \pm 24$$

Planck 2018



S_{ortho}

Smith et al.



Courtesy of Fergusson & Shellard

Observational Implications

Quantum NG = Equilateral NG

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle'_q = \frac{4\lambda H^{-1} \Delta_\zeta^6}{(k_1 + k_2 + k_3)^3 \, k_1 k_2 k_3}$$

Classical NG = Pole in folded limit

$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_1} \zeta_{\vec{k}_1} \rangle'_c \supset \frac{\lambda H^{-1} \Delta_\zeta^6}{(k_1 - k_2 + k_3)^3 k_1 k_2 k_3}$$

Observational Implications

As written, classical shape has $S/N \to \infty$

Pole resolved into a bump (finite S/N) by loops

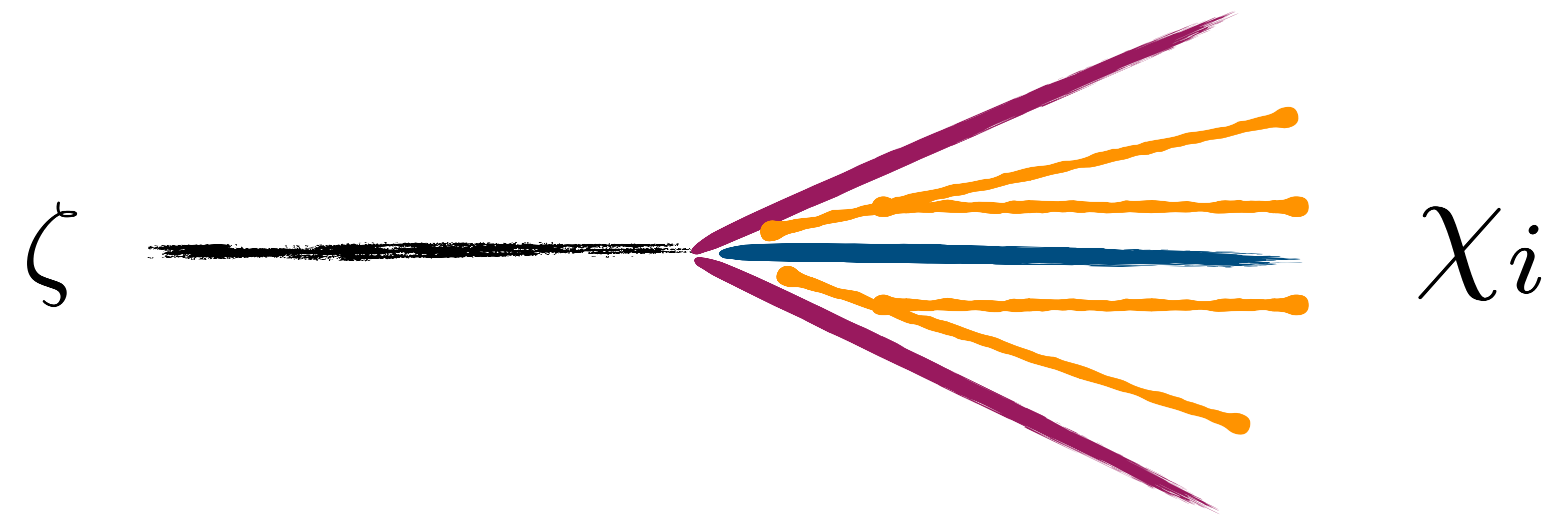
$$\frac{1}{(k_1 - k_2 + k_3)^3} \to \frac{1}{(k_1 - k_2 + k_3 + k_\Gamma)^3}$$

If perturbative, S/N is still enhanced

$$(\mathrm{S/N})_{\mathrm{class}} \approx \frac{1}{\lambda}(\mathrm{S/N})_{\mathrm{quantum}} \gg (\mathrm{S/N})_{\mathrm{quantum}}$$

Observational Implications

Suppressed S/N with non-perturbative dissipation



Increasing decay rate is tied to amplitude of NG

$$k_\Gamma \propto \log \Gamma \qquad\qquad f_{\mathrm{NL}} \propto \Gamma$$

Hard to hide the classical signal given current limits

Observational Implications

Conclusions:

(1) We need to detect equilateral NG

(2) Check for enhanced folded pole

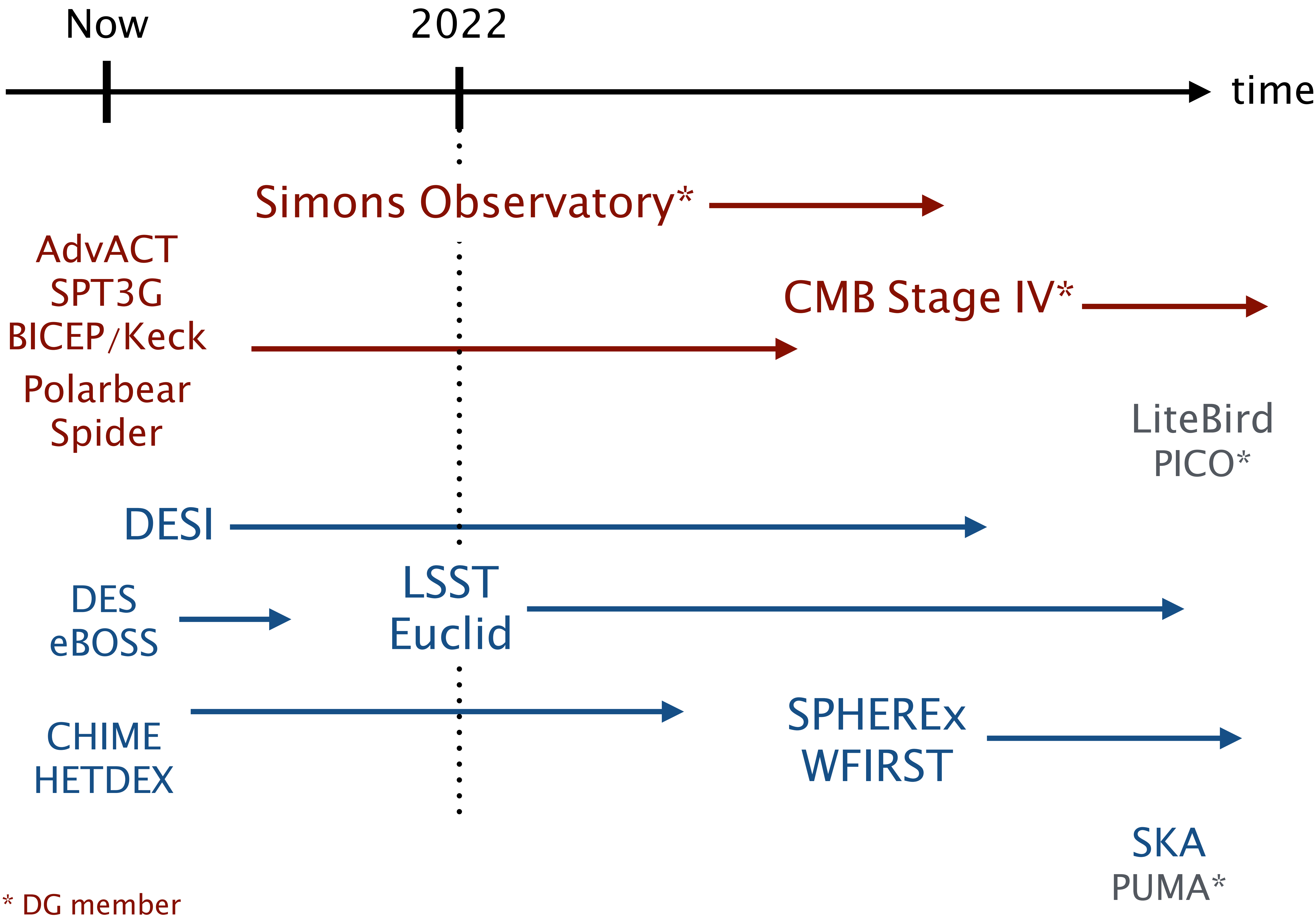
i. Most classical models would have large S/N

ii. Extreme dissipation might (just) be excluded

(3) Check squeezed/soft limit (local shape)

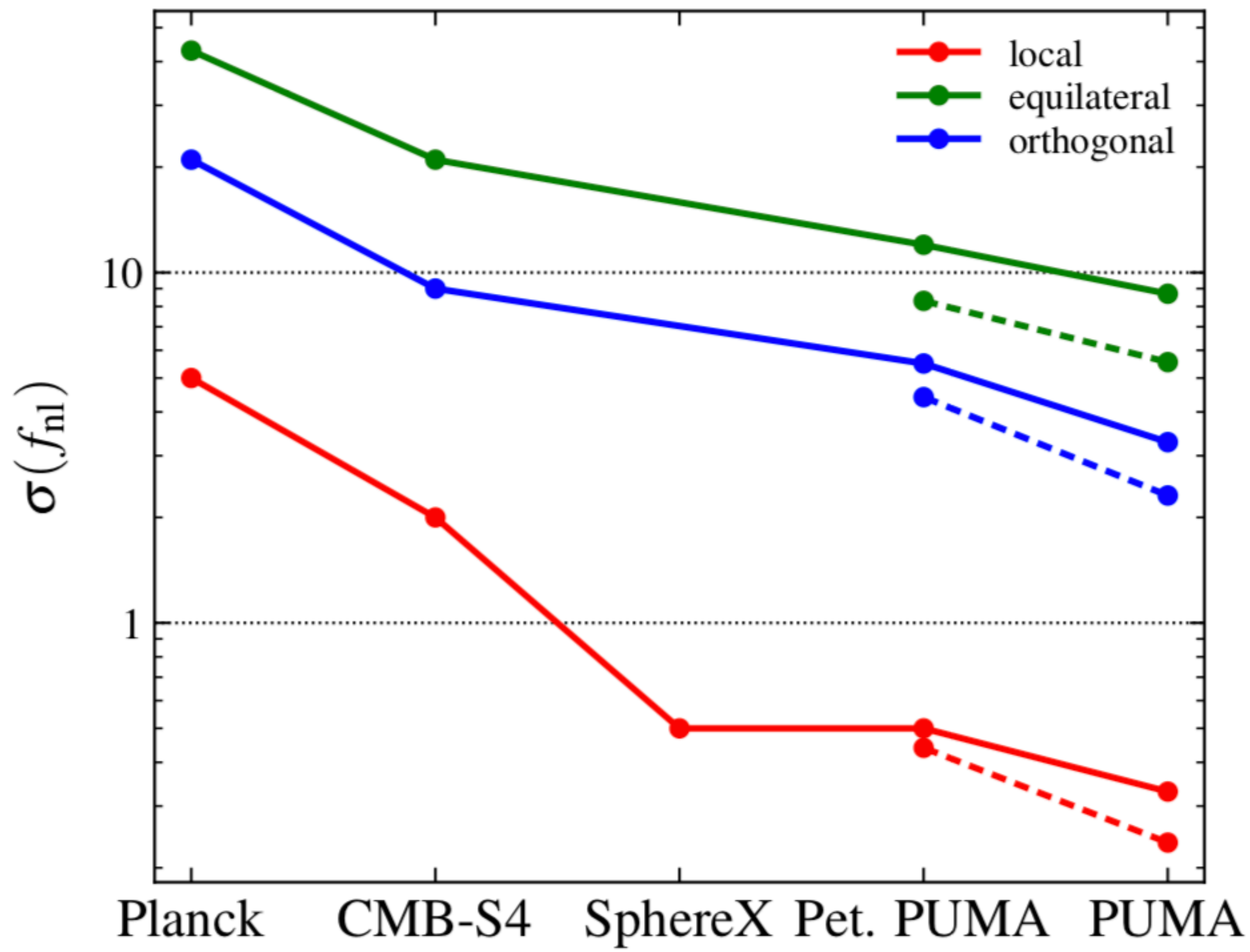
i. Test of single / multi-field 

ii. Sensitive to excited states / extra particles


Now
2022
time
Simons Observatory*
AdvACT
SPT3G
BICEP/Keck
Polarbear
Spider
CMB Stage IV*
LiteBird
PICO*
DESI
DES
eBOSS
LSST
Euclid
CHIME
HETDEX
SPHEREx
WFIRST
SKA
PUMA*
* DG member

Future Limits

Forecasted improvements on current limits:



Summary

Summary

The “total energy pole” is a generic feature of NG

- The cosmological analogue of energy conservation
- Quantum vacuum fluctuations only have these
- Classical fluctuations also have physical poles

This result is a consequence of locality

Can only be avoided with non-local hidden variables


Thank you