On the cosmological bootstrap

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Based on work with

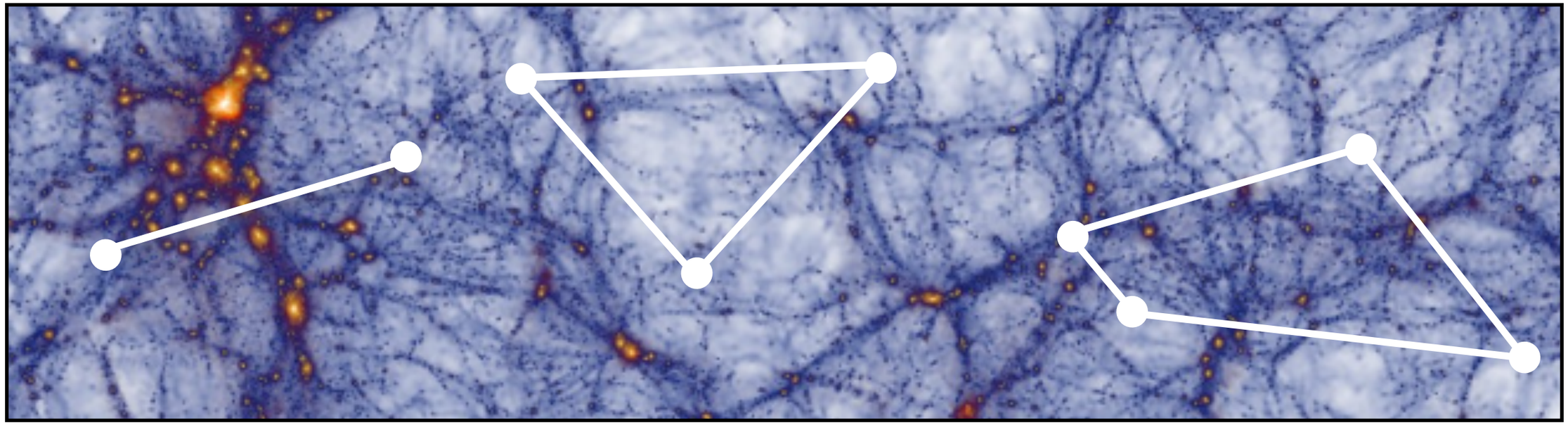
Nima Arkani-Hamed
Daniel Baumann
Wei-Ming Chen
Carlos Duaso Pueyo
Austin Joyce
Hayden Lee
Juan Maldacena

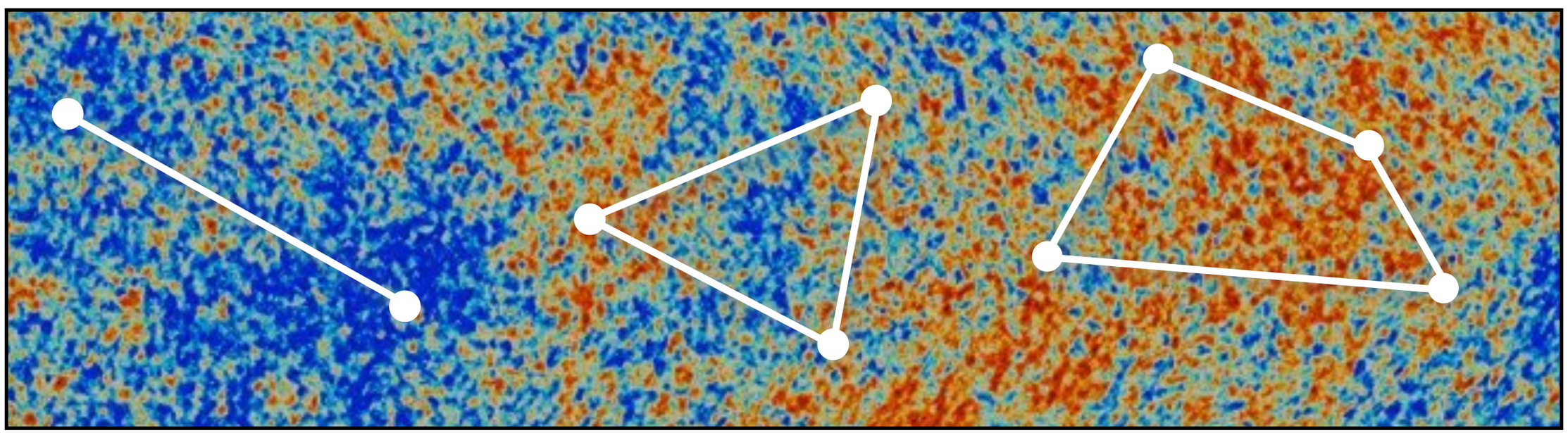
Related work by

P. Benincasa, X. Chen, A. Hillman, K. Hinterbichler, M. Trodden, J. Bonifacio, R. Rosen, C. Sleight, M. Taronna, J. Farrow, A. Lipstein, P. McFadden, G. Cabass, A. Bzowski, K. Skenderis, H. Goodhew, S. Jazayeri, A. McLeod, C. Vergu, E. Silverstein, L. Senatore, V. Gorbenko, R. Sundrum, S. Kumar, S. Kharel, Y. Urakawa, D. Meltzer, P. Creminelli, Y. Wang, E. McDonough, T. Grall, S. Melville, G. Shiu, L. Bordin, T. Noumi, S. Zhou, K. Takeuchi, S. Kim, S. Albayrak, S. Kharel, H. Isono, H. Liu, D. Stefanyszyn, J. Supel, A.-C. Davis, S. Céspedes, A. Sivaramakrishnan, S. Jain, D. Green, T. Cohen, R. R. John, V. Malvimat, D. Ponomarev, Y. Neiman, R. Porto, A. Premkumar, C. Dvorkin, B. Nagaraj, P. Mazur, E. Mottola, I. Antoniadis, S. Raju, A. Riotto, A. Kehagias, G. Franciolini, M. Shiraishi, V. De Luca, T. Anous, D. Anninos, S. Alexander, G. Palma, S. Sypsas, R. Bravo, L. Jenks, Z-Z. Xianyu, L. Hui, S. Wong, T. Hartman, …

What is the origin of structure in the universe?

Cosmological Correlators





All of the information about the **<u>origin of structure</u>** and the dynamics of the early universe is encoded in cosmological correlations!

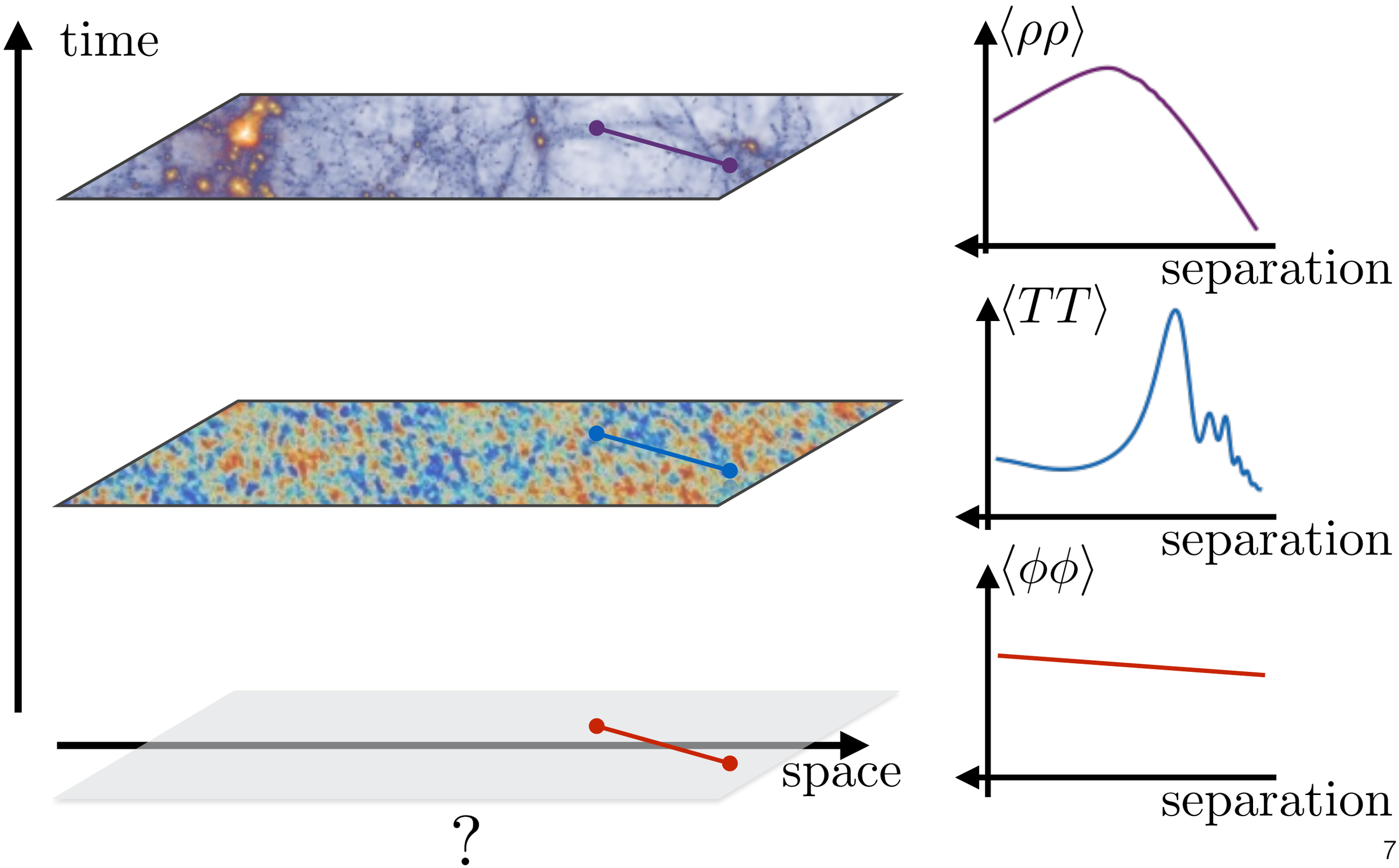
I will show that the early universe can be thought of as a collider experiment run at high energies.

Cosmological correlators are the scattering amplitudes of this experiment.

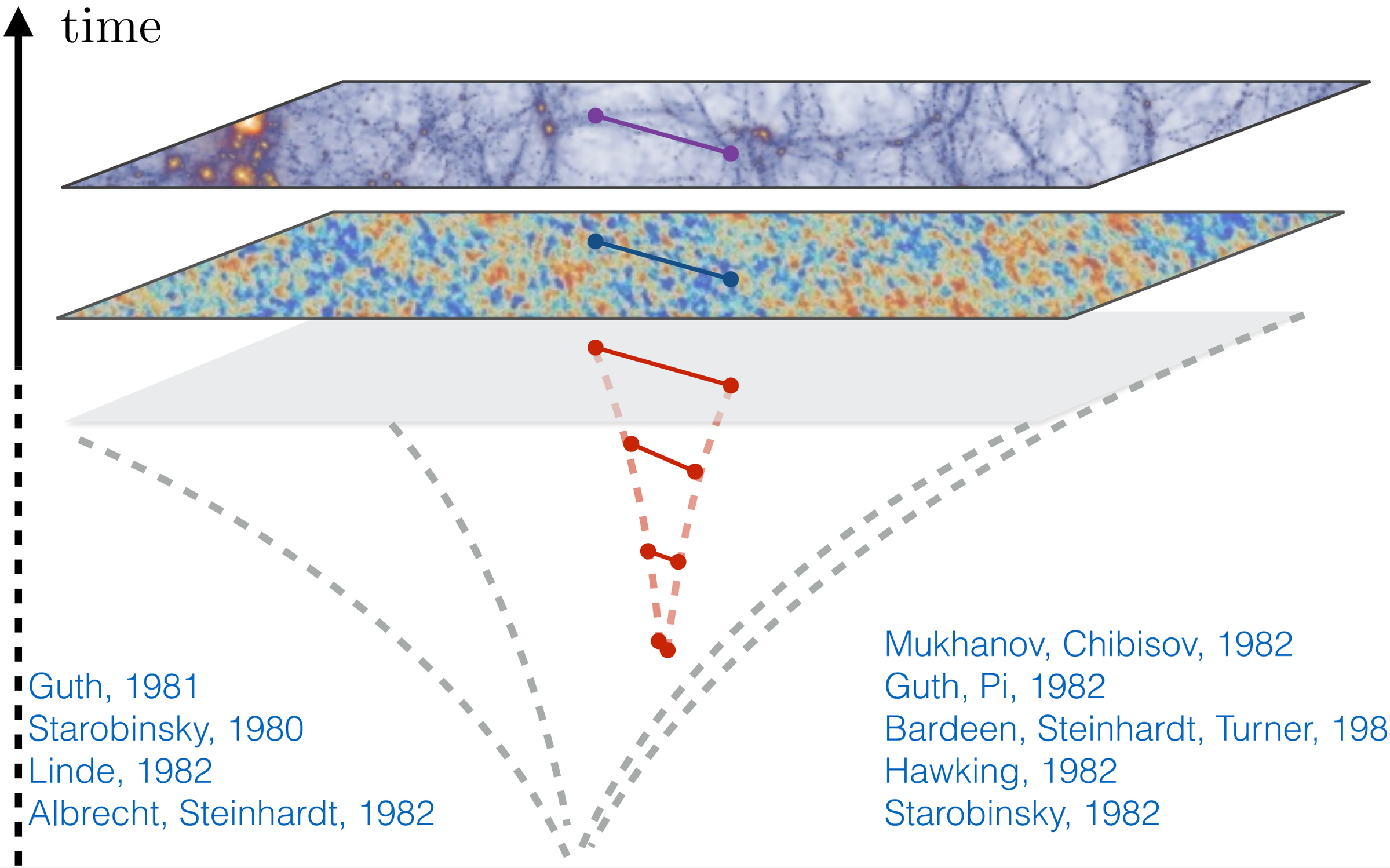
Cosmological correlators contain scattering amplitudes in a precise sense.

We can use new tools to bootstrap and decode the physics of cosmological correlators.

Primordial Fluctuations



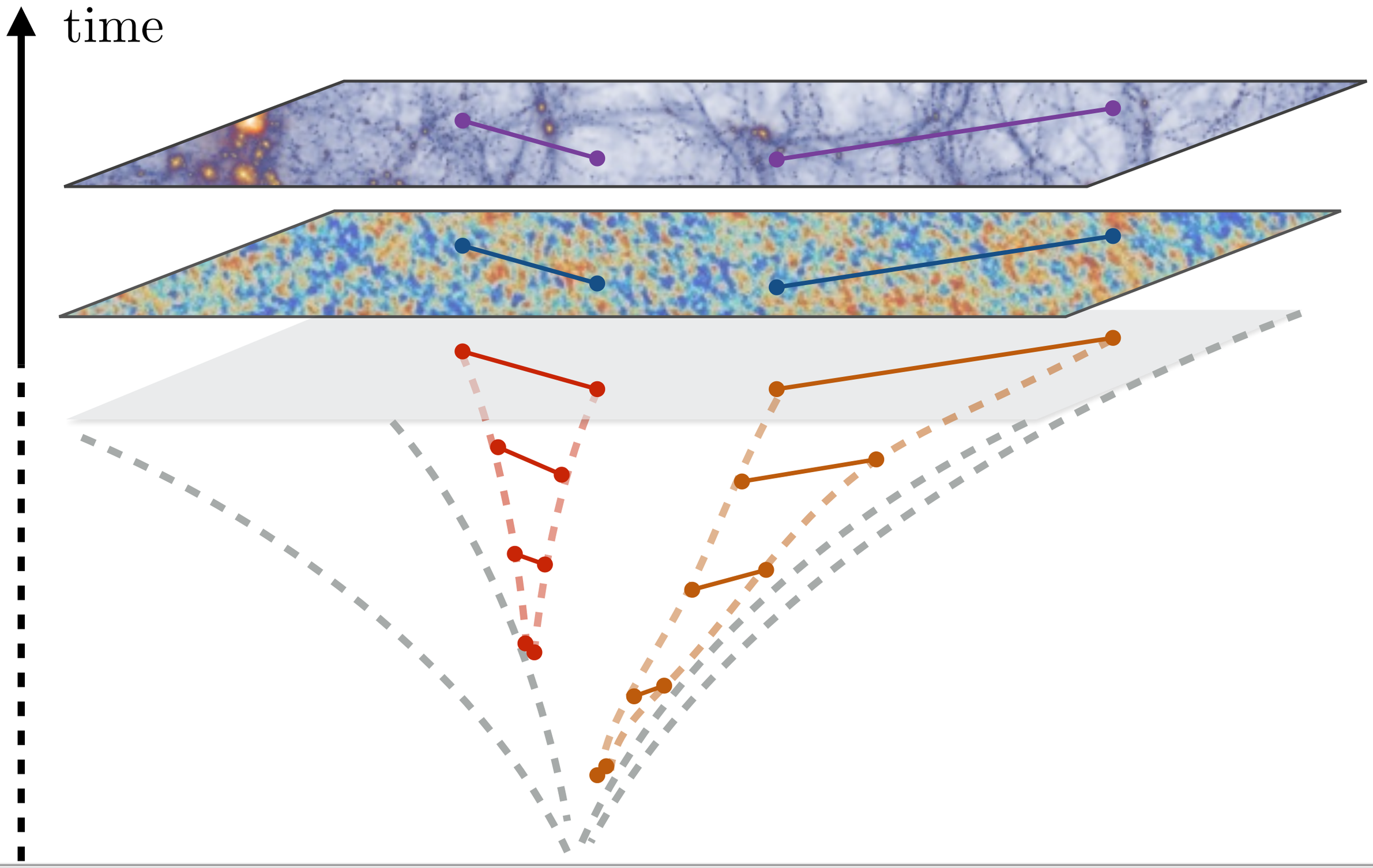
Inflation



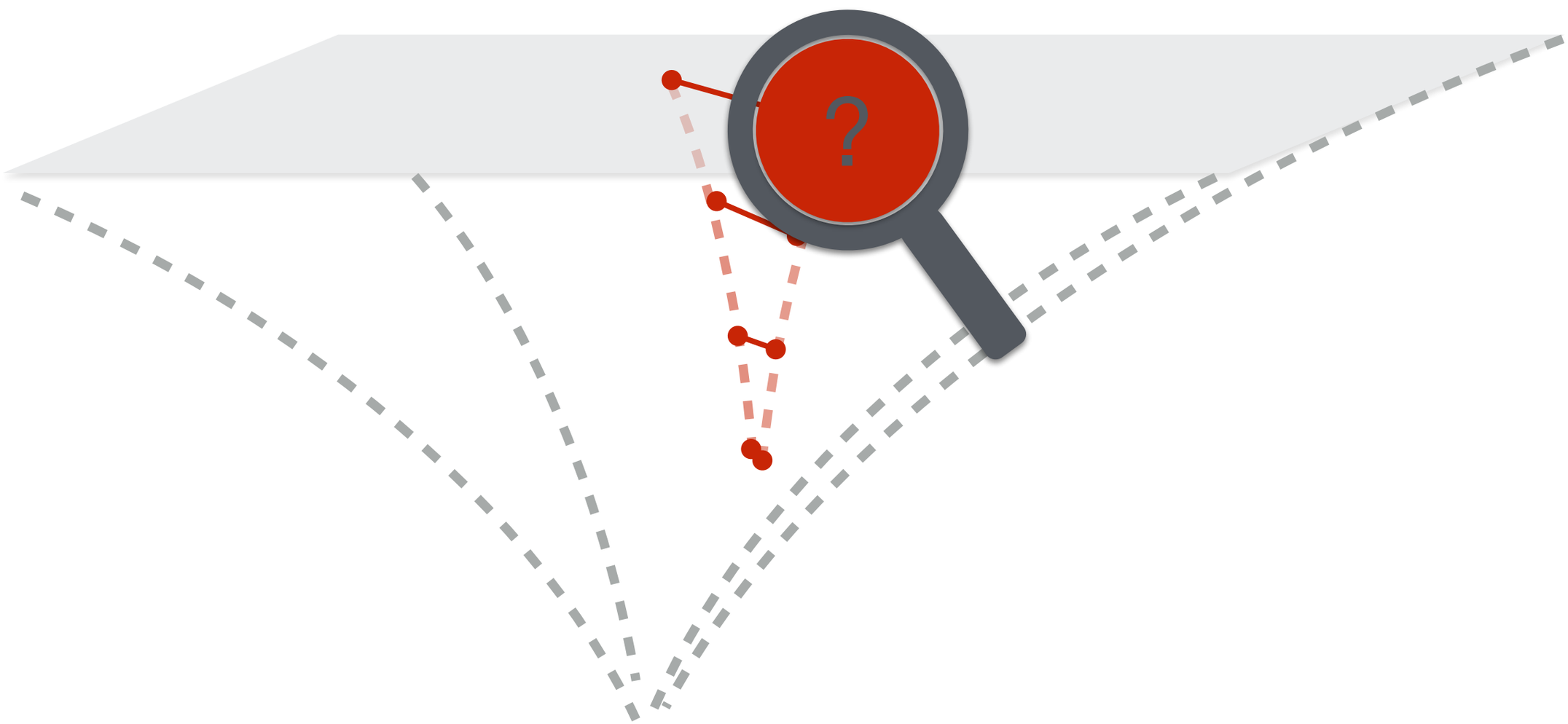
Guth, 1981
Starobinsky, 1980
Linde, 1982
Albrecht, Steinhardt, 1982

Mukhanov, Chibisov, 1982
Guth, Pi, 1982
Bardeen, Steinhardt, Turner, 1983
Hawking, 1982
Starobinsky, 1982

Time without Time



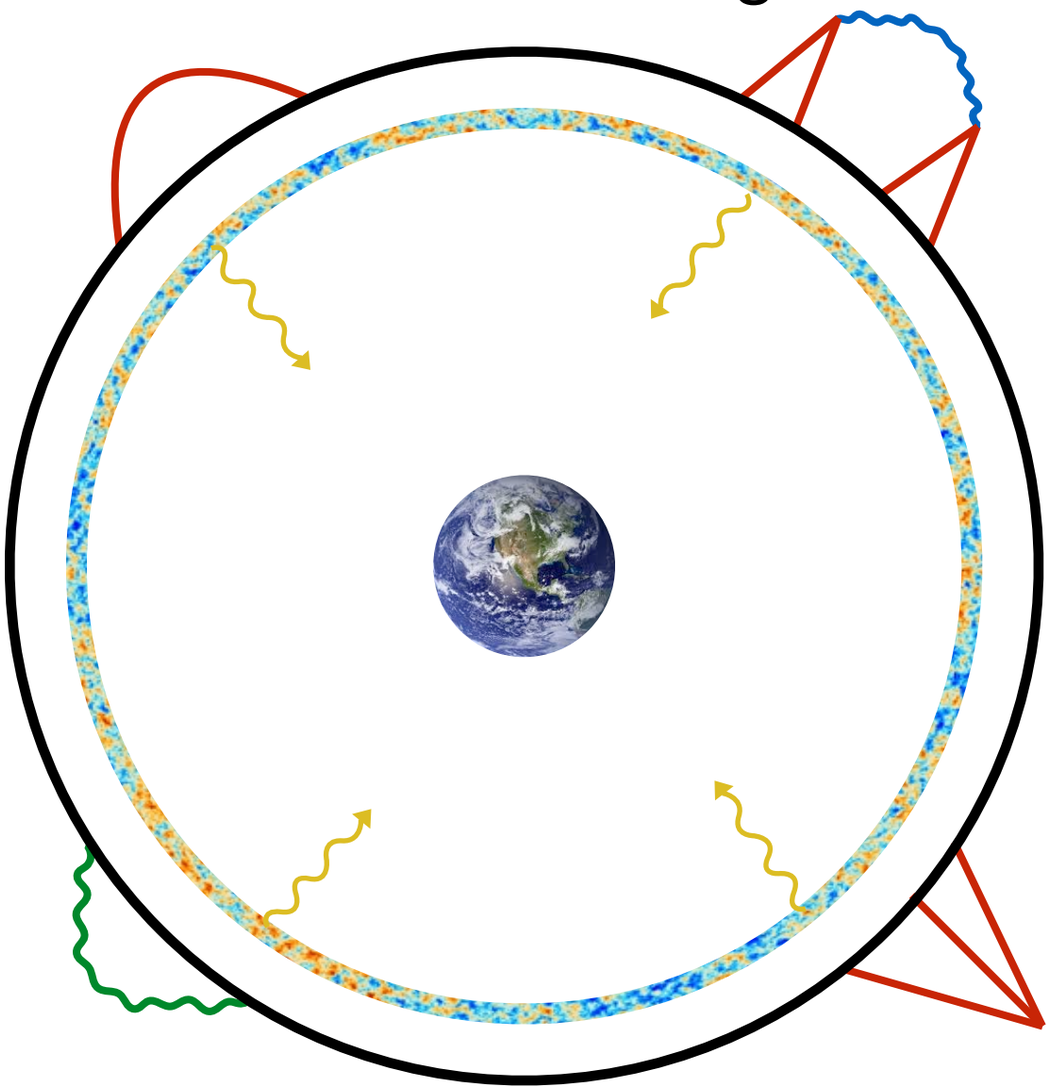
Inflaton ?

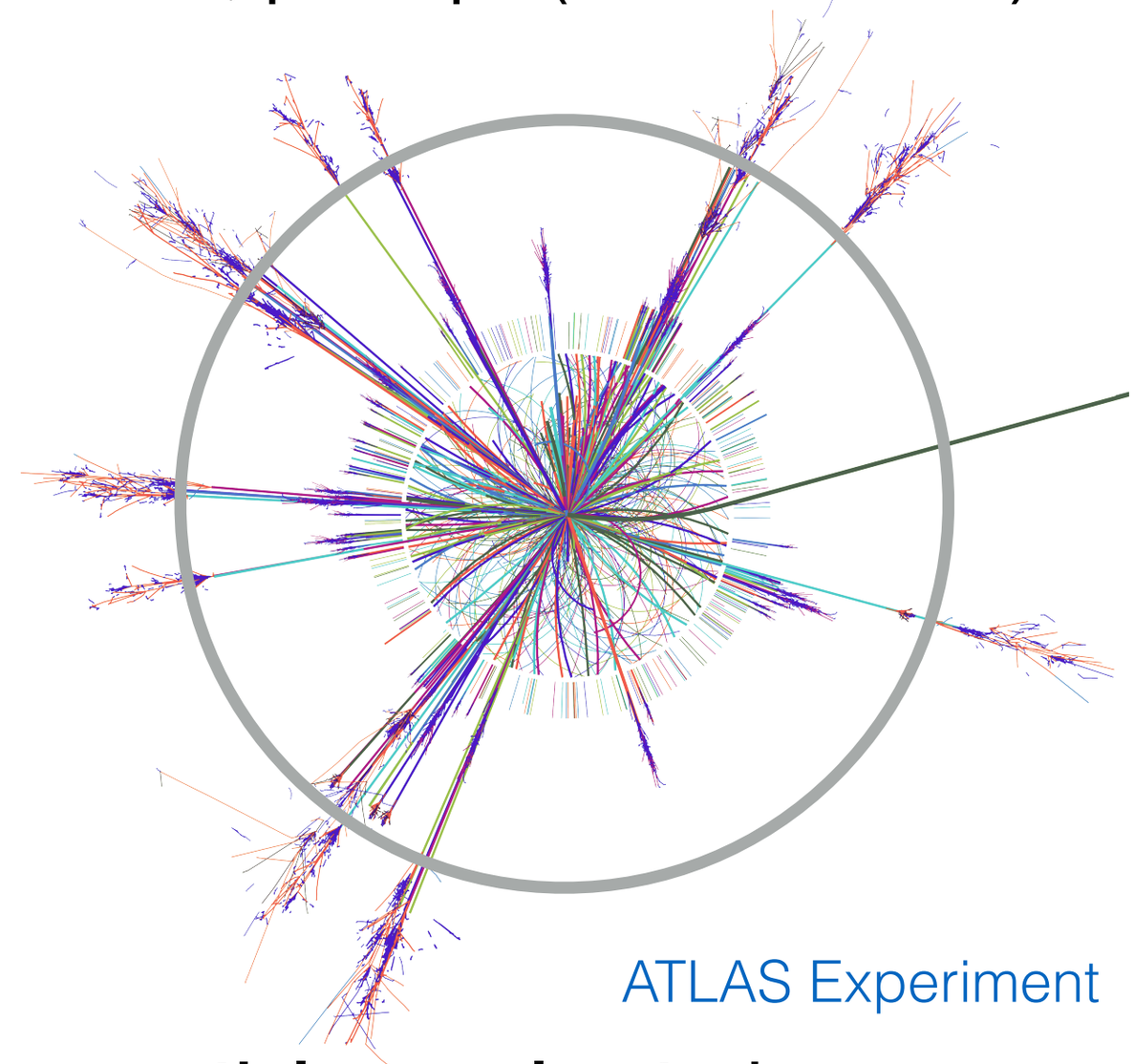


Inflationary Microscopy

Inflation as a Collider

Inflation is most energetic event in nature, perhaps (LHC x billions)!





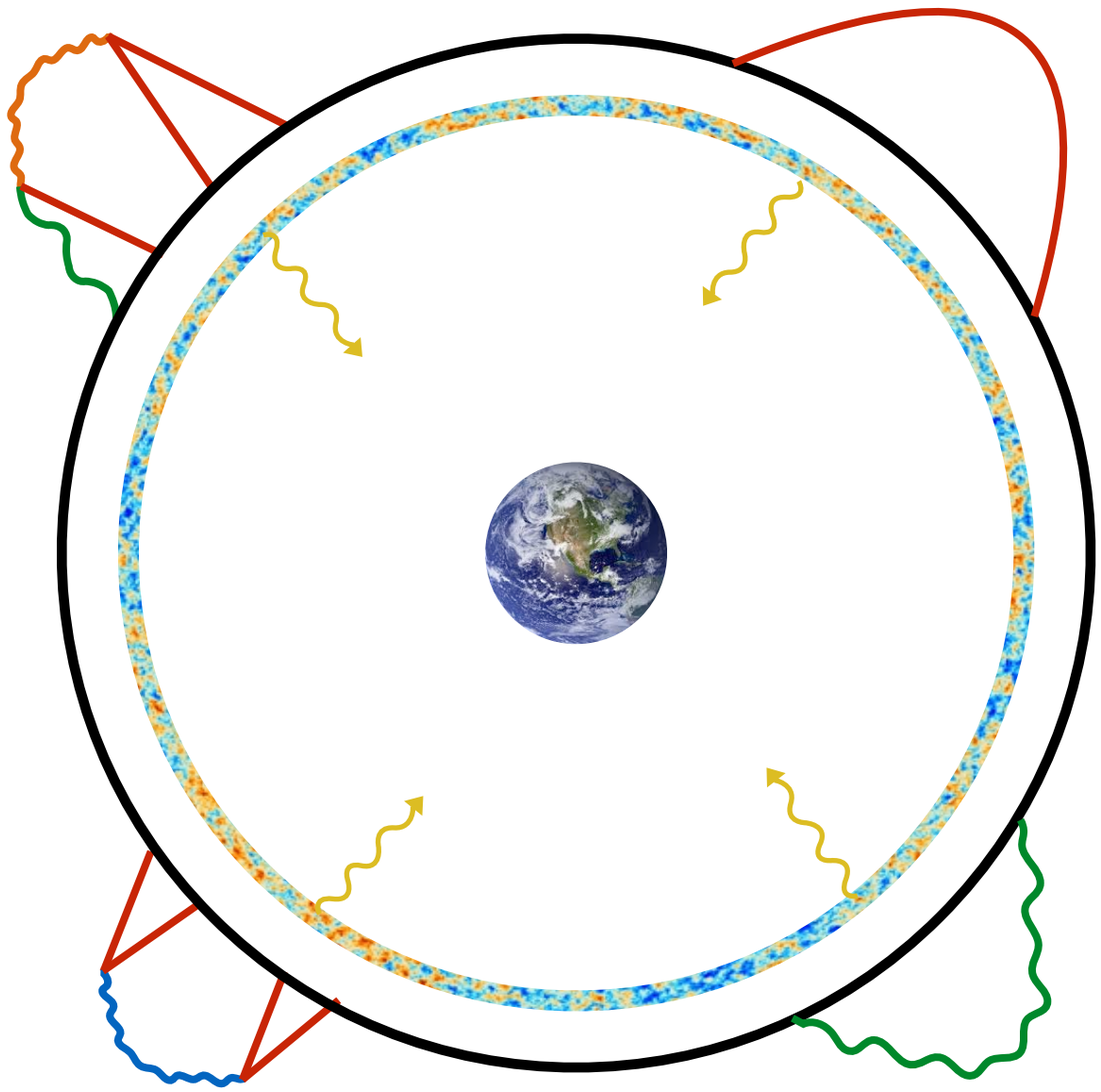
ATLAS Experiment

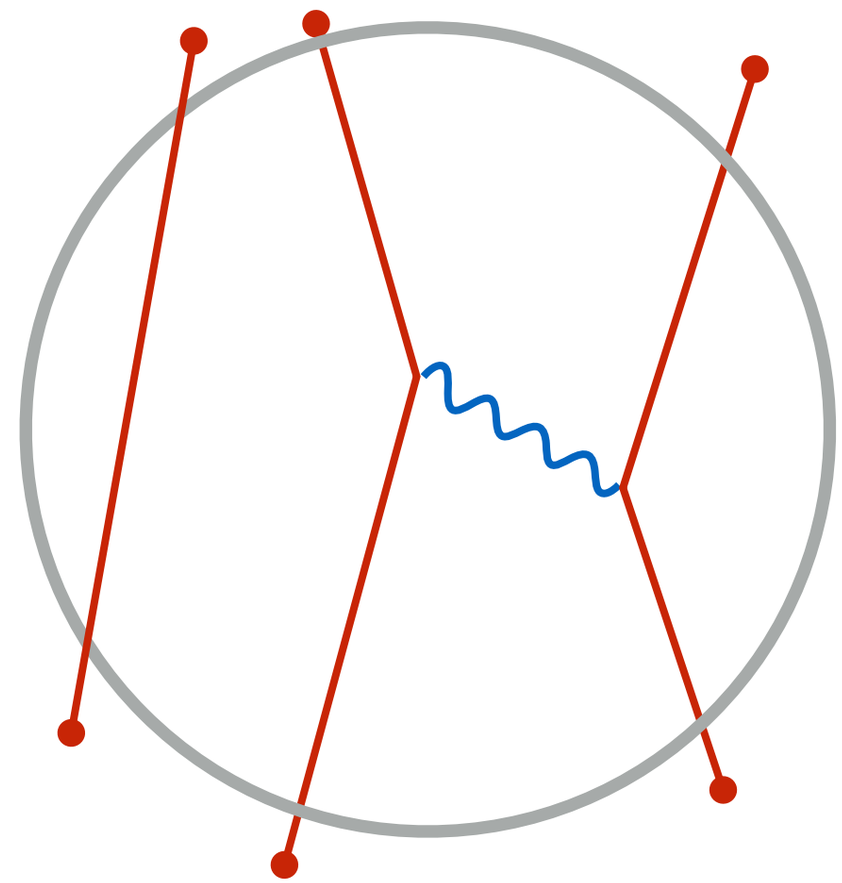
The early universe acts as a **particle accelerator**!

Arkani-Hamed, Maldacena, 2015
Chen, Wang, 2009
Baumann, Green, 2010
Noumi, Yamaguchi, Yokoyama, 2012

Lee, Baumann, GLP, 2016
Baumann, Goon, Lee, GLP, 2017
Arkani-Hamed, Baumann, Lee, GLP, 2018

What collides? How?



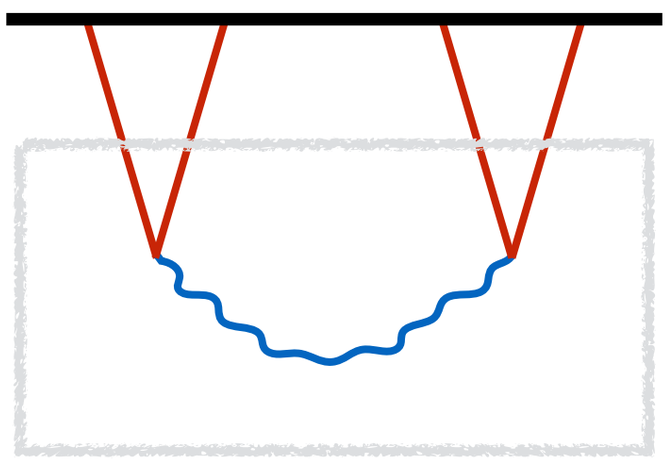


What — large two-point functions!
How — Higher-point functions!
The dynamics is encoded in those correlations.

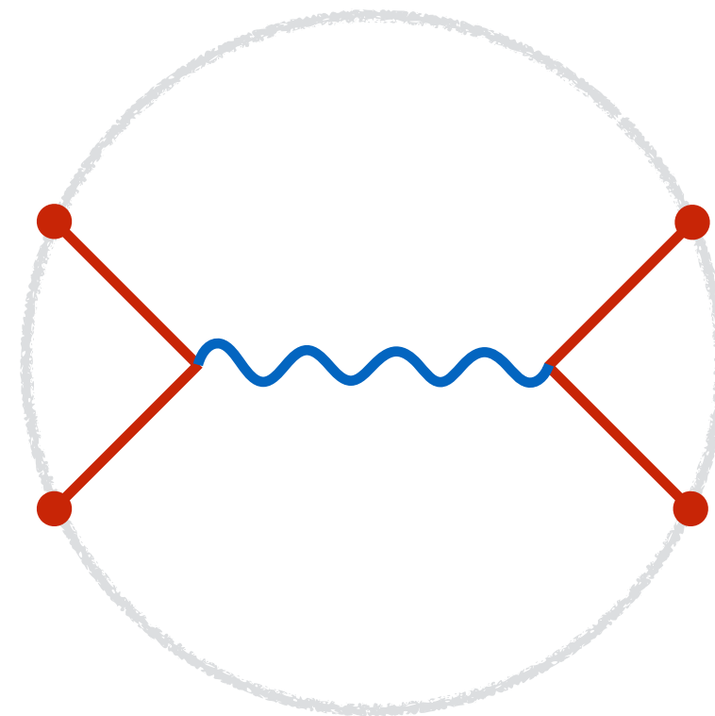
Cosmology & Scattering

$$|\mathbf{k}_1| + |\mathbf{k}_2| + |\mathbf{k}_3| + |\mathbf{k}_4| = E$$ "Total Energy"

$$\lim_{E \to 0}$$



$$= \frac{1}{E\#}$$

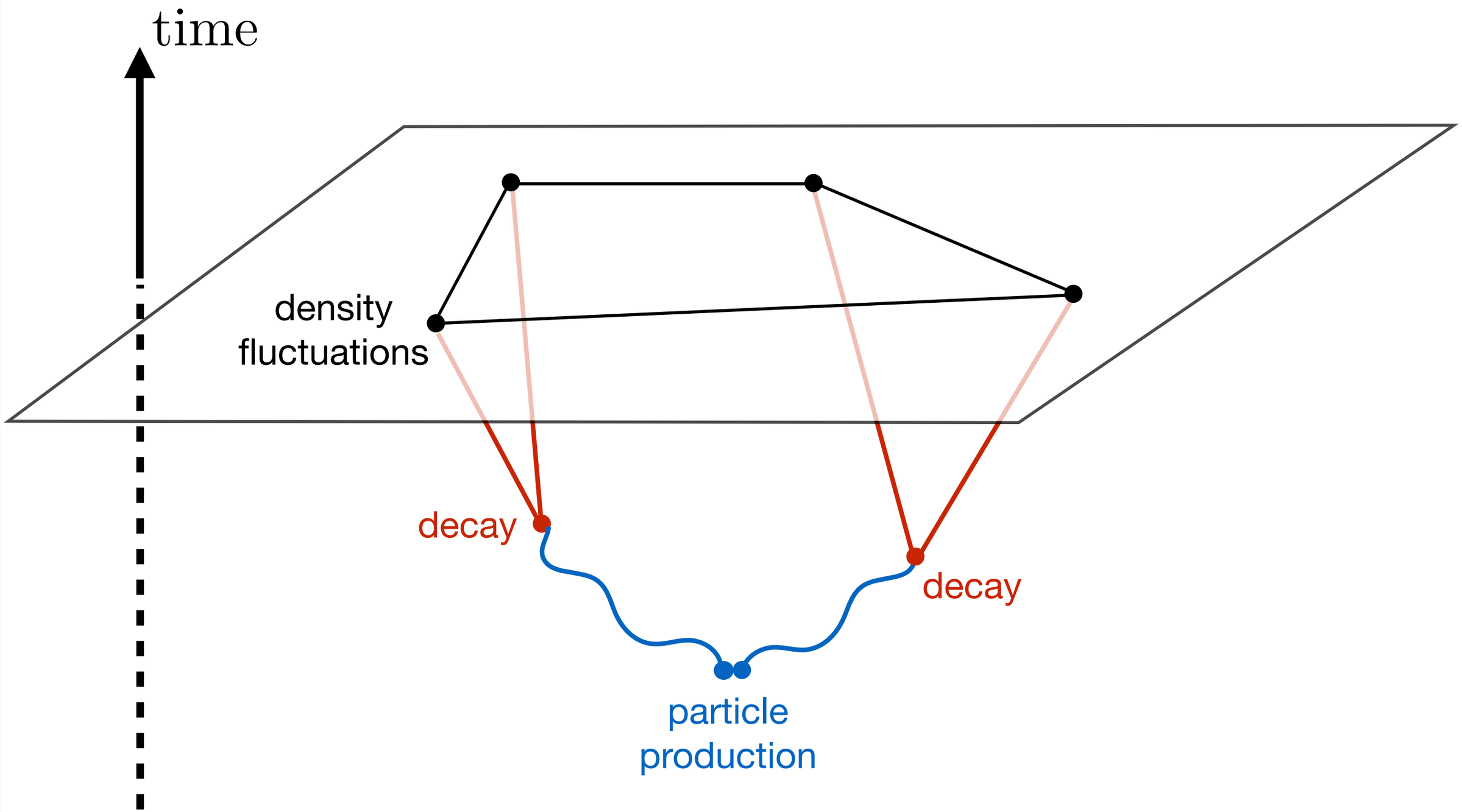


The S-matrix is **<u>contained</u>** in the analytic structure of Cosmological Correlators!

Maldacena, GLP, 2011
Raju, 2012

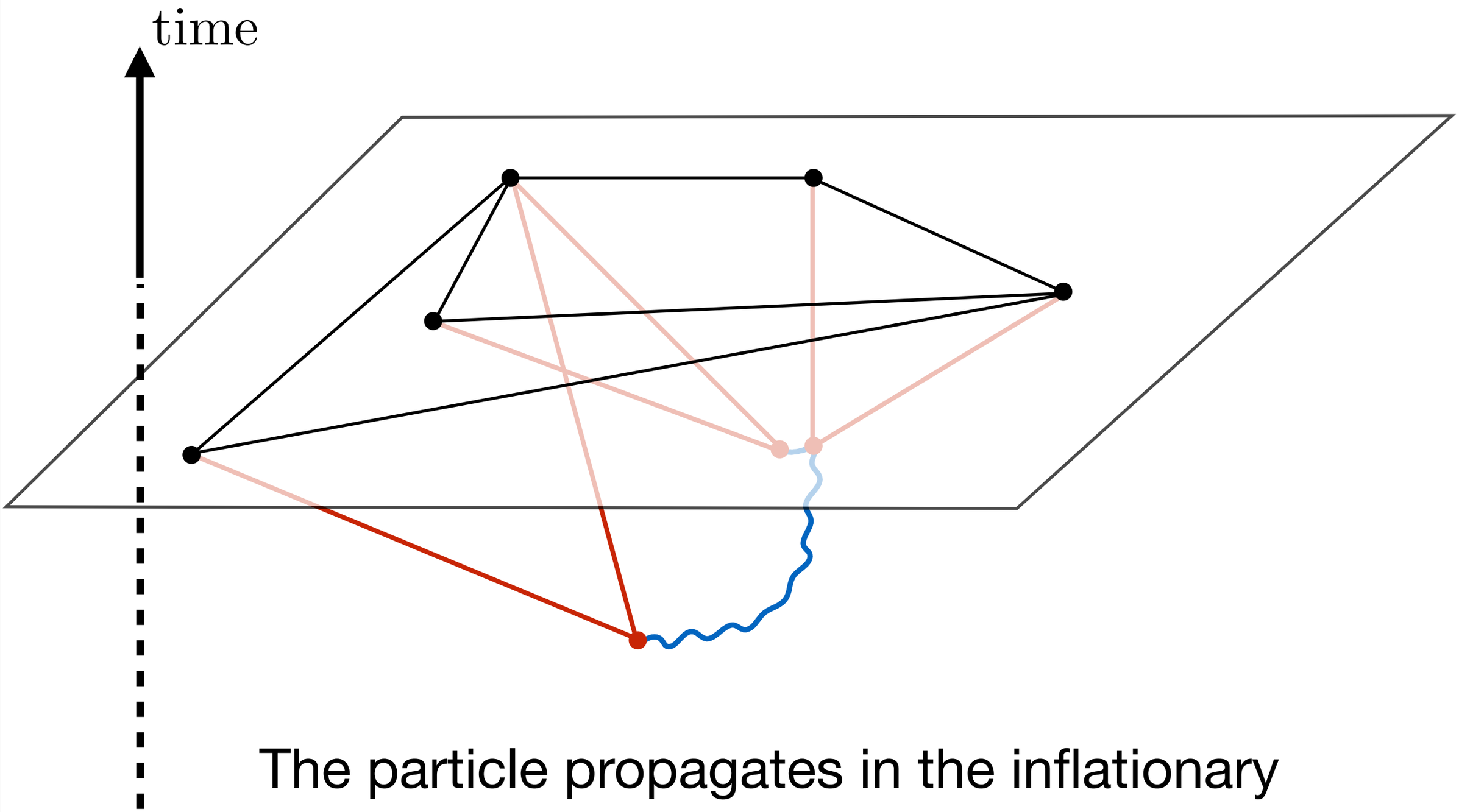
What are all the possible correlators?

Structure of Correlator



Inferring which particles are created
will tell us about the microphysics of inflation.

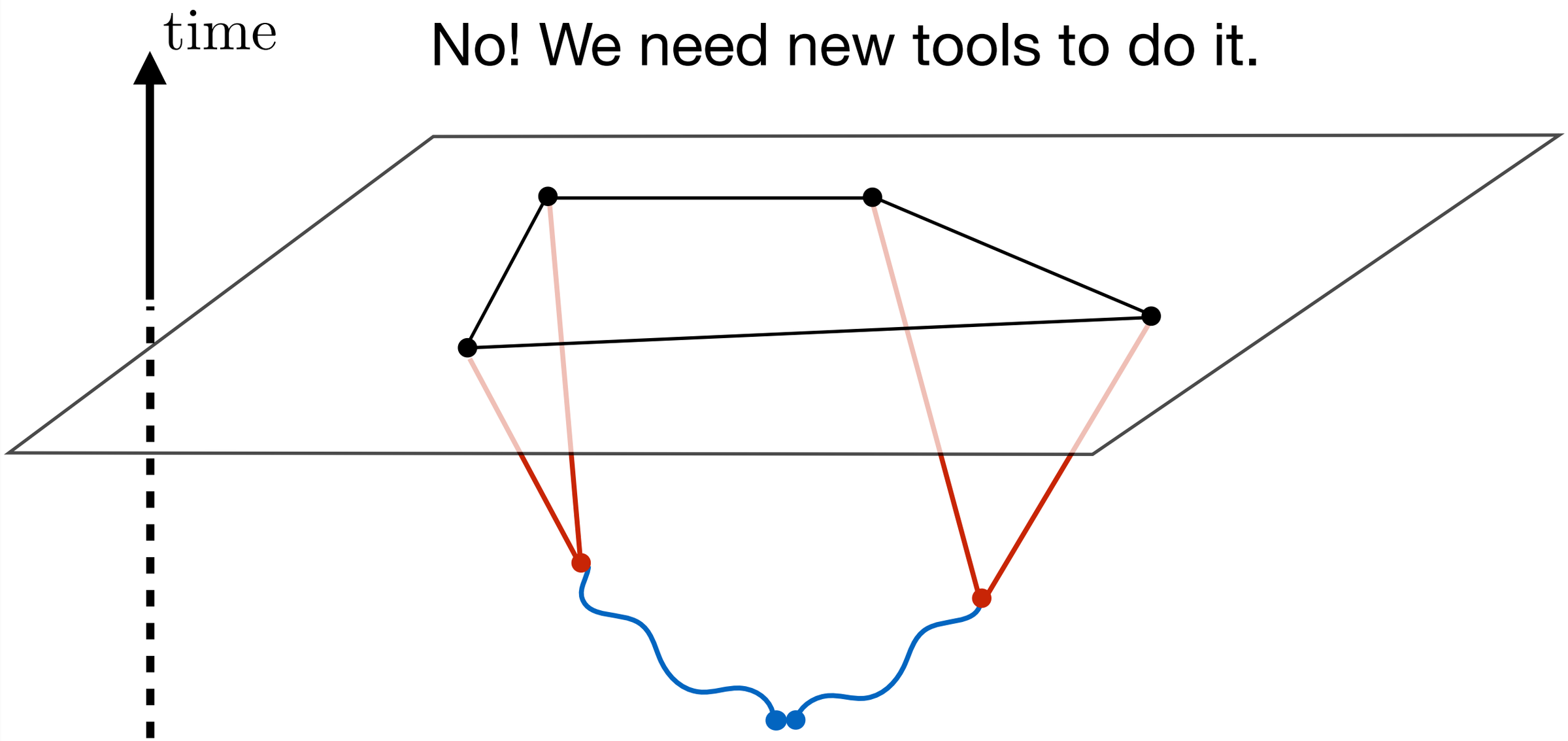
Particles as Tracers



The particle propagates in the inflationary background, tracing and imprinting it in the correlator, as we change the shape in the sky.

Easy to Calculate?

No! We need new tools to do it.



$$\int \mathrm{d}t\,\mathrm{d}t'\; e^{i(k_1+k_2)t} e^{i(k_3+k_4)t'}\; G(|k_1+k_2|, t, t')$$

External Mode Functions

Lots of special (Hankel) functions

Bootstrap

Physical Principles
(Symmetry, Locality, Unitarity)

→

~~Lagrangian~~
~~equations of motion~~
~~spacetime evolution~~
~~Feynman diagrams~~

→

Observables

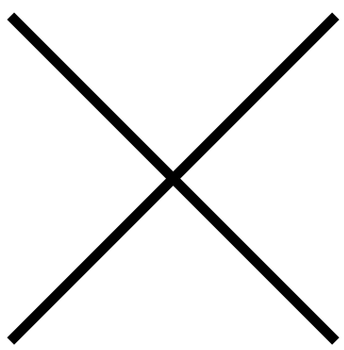
Bootstrap

- **Scattering amplitudes,**
- **Conformal field theories,**
- **Cosmological correlators?**

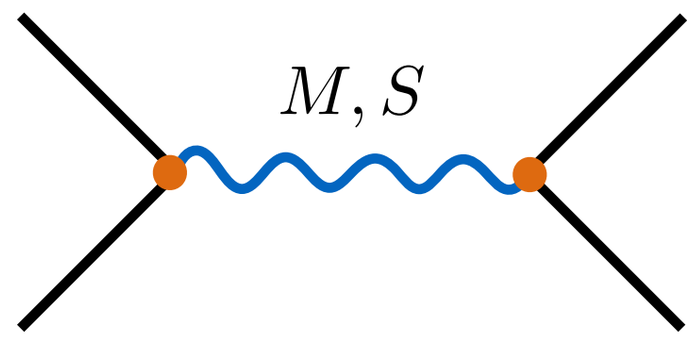
The S-matrix Bootstrap

Weakly coupled four-particle amplitude:

$$A(s,t) = \sum a_{nm} s^n t^m + \frac{g^2}{s - M^2} P_S \left(1 + \frac{2t}{M^2}\right)$$



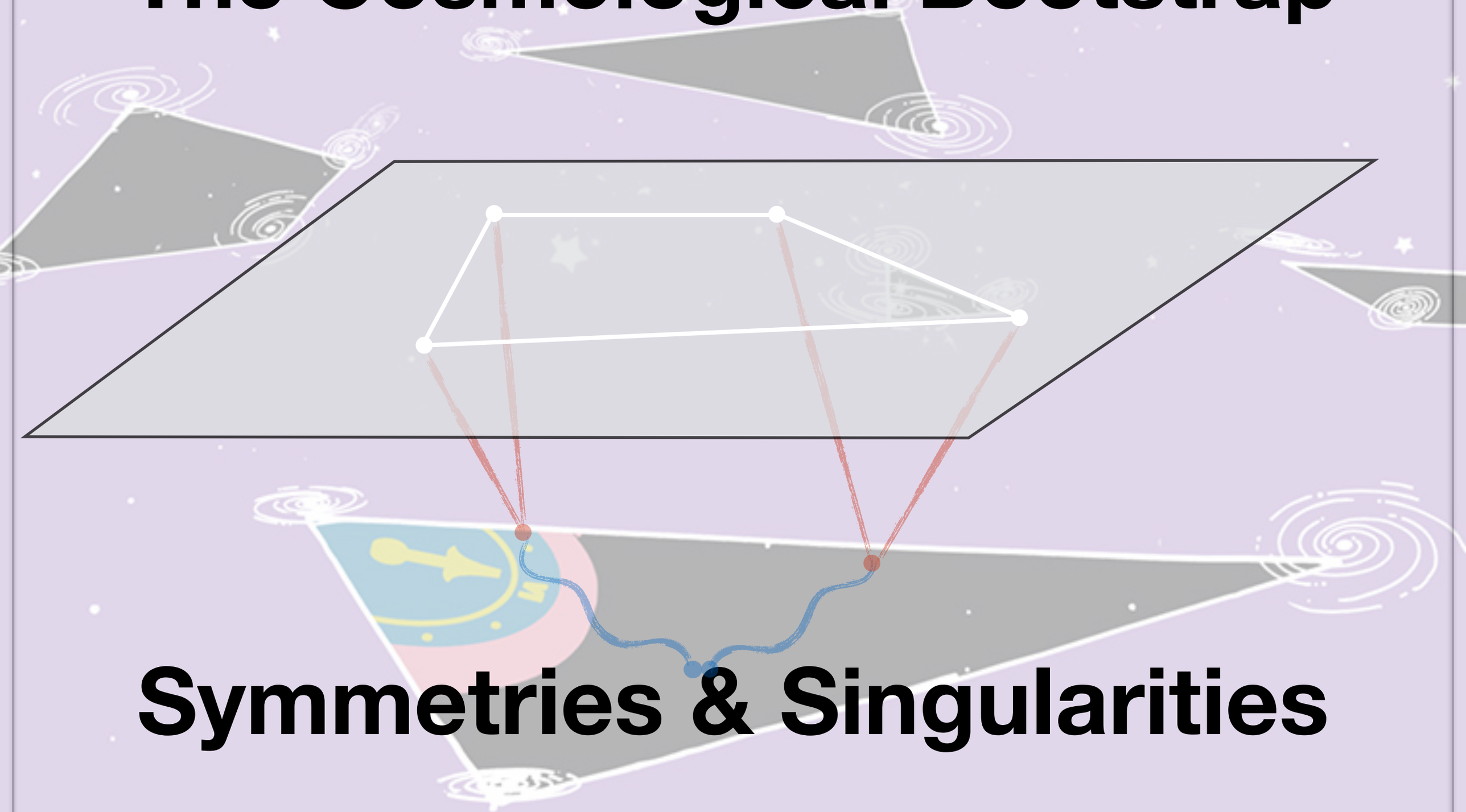
contact interactions



exchange interactions

No Lagrangian or Feynman diagrams.
Basic principles (symmetry, locality, unitarity)
allow only a small menu of possibilities.

The Cosmological Bootstrap



Symmetries & Singularities

Arkani-Hamed, Baumann, Lee, GLP, 2018
Baumann, Duaso Pueyo, Joyce, Lee, GLP, 2019
Baumann, Duaso Pueyo, Joyce, Lee, GLP, 2020

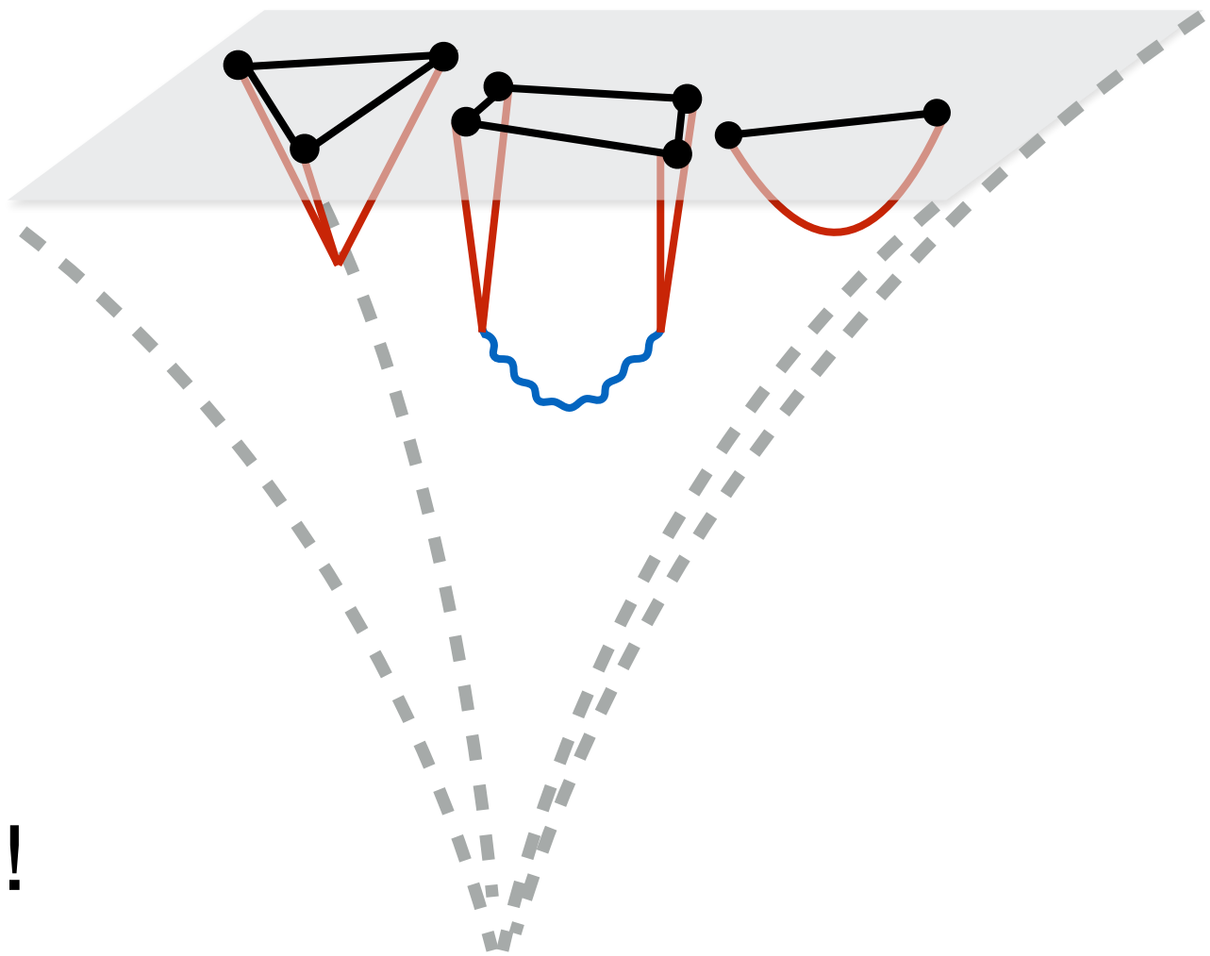
Olena Shmahalo (*Quanta* magazine)

Symmetries

Key feature: conformal symmetry of fluctuations.

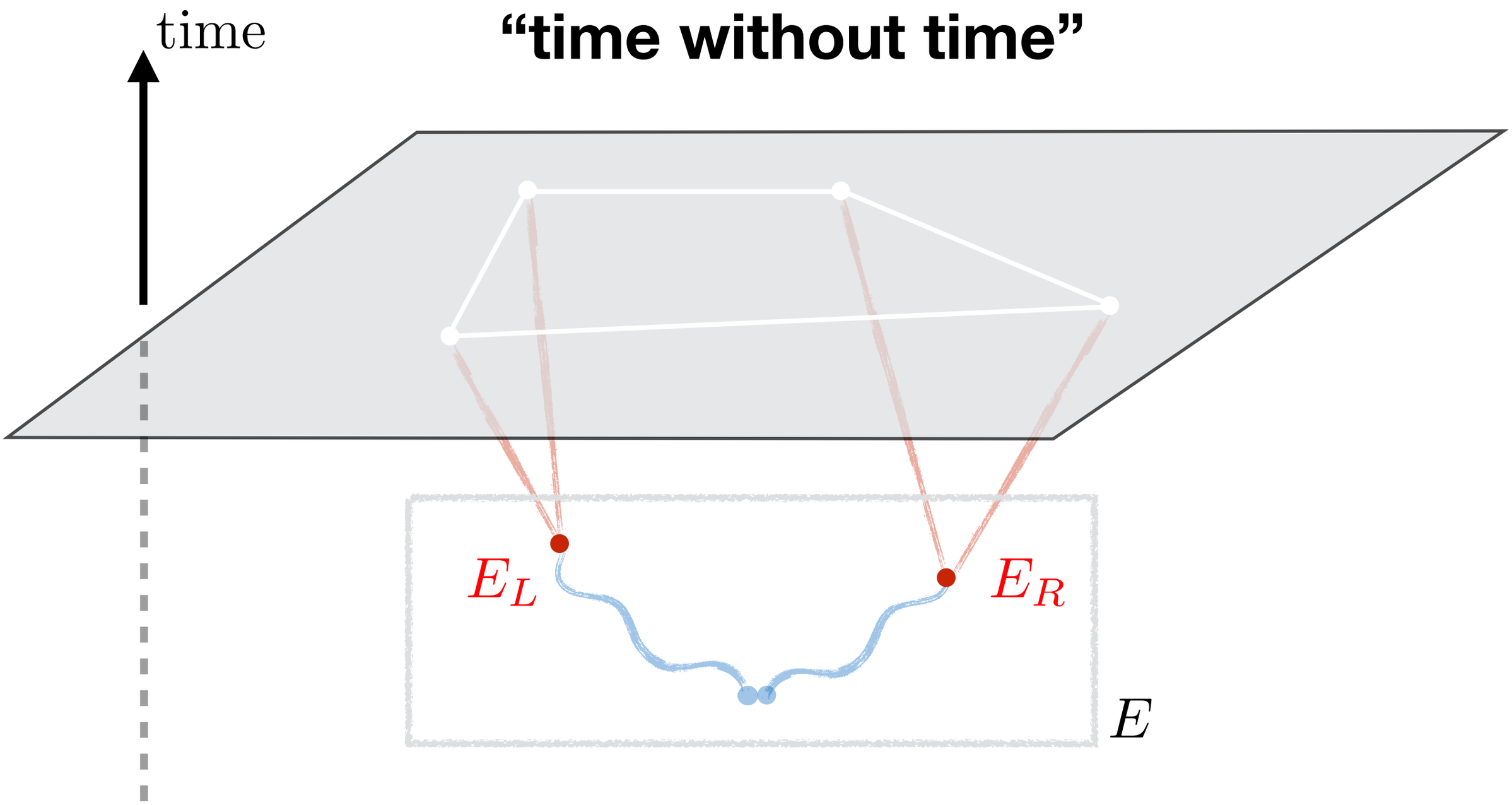
Spatial momentum conserved.

Rotations + Dilations + Boosts — very constraining!



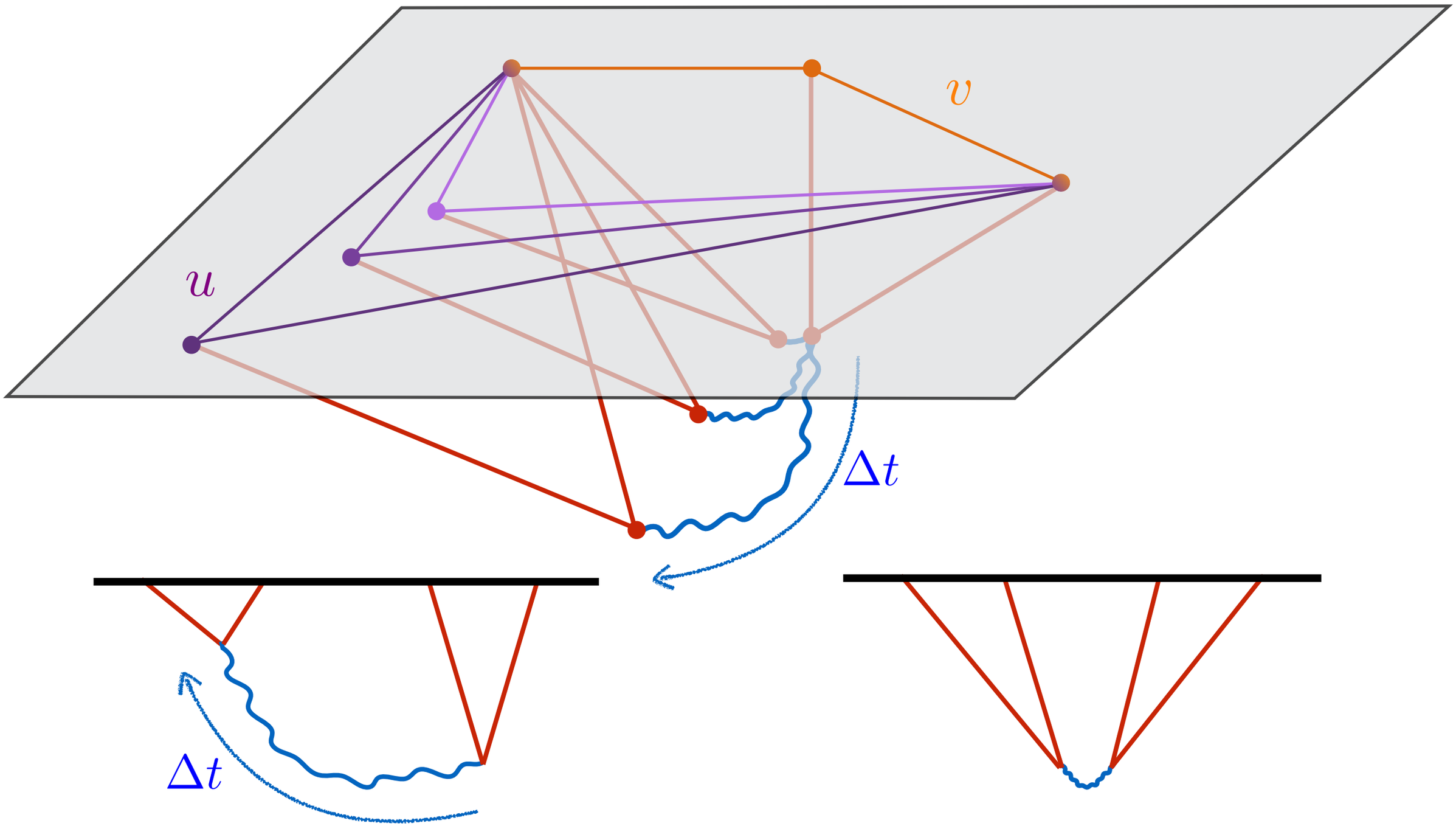
Singularities

“time without time”



Result — simple, solvable differential equation

Equation Appetizer



Particle Production

Contact Interaction

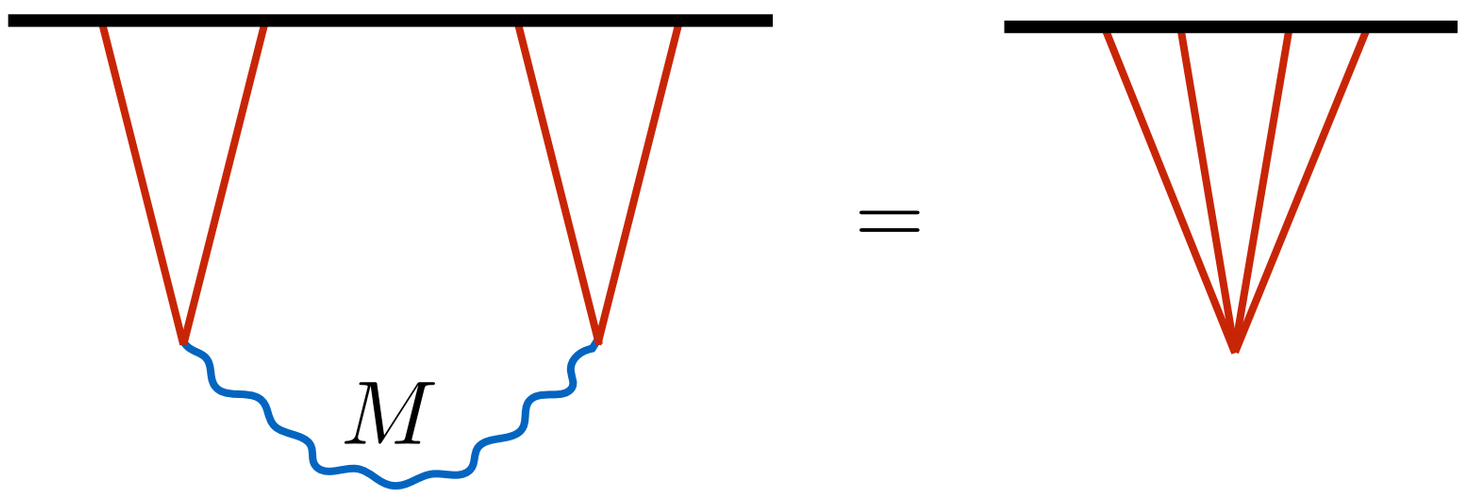
Exchange Dynamics

$$(\Delta_u + M^2)F = F_c$$

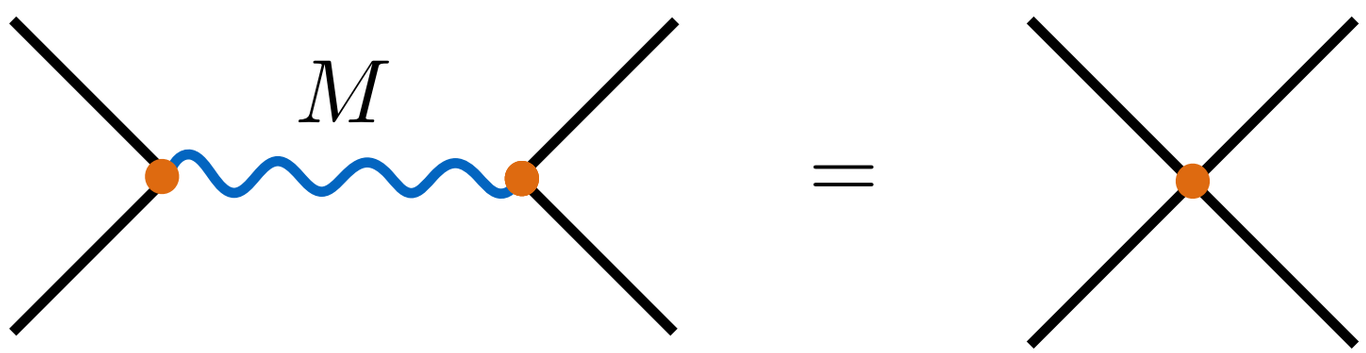
Contact correlator

Mass of exchanged particle

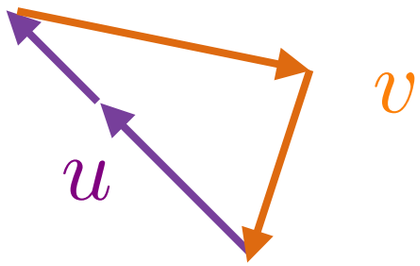
$(\Delta_u + M^2)$
$(\Delta_v + M^2)$



$(s - M^2)$

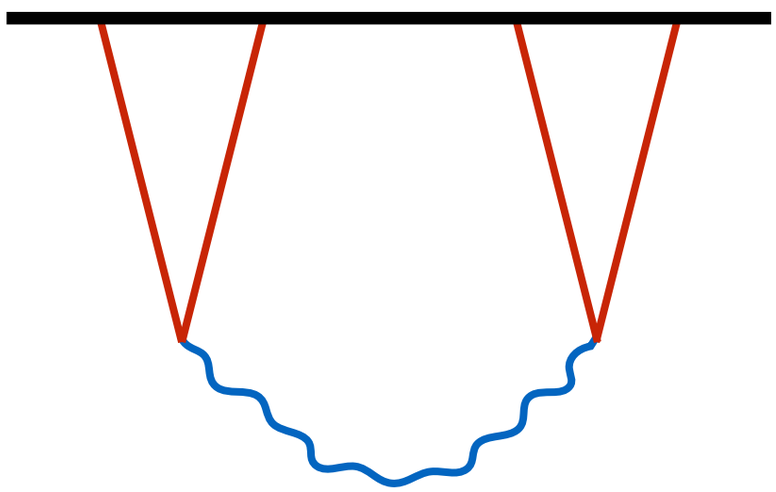


Boundary Conditions



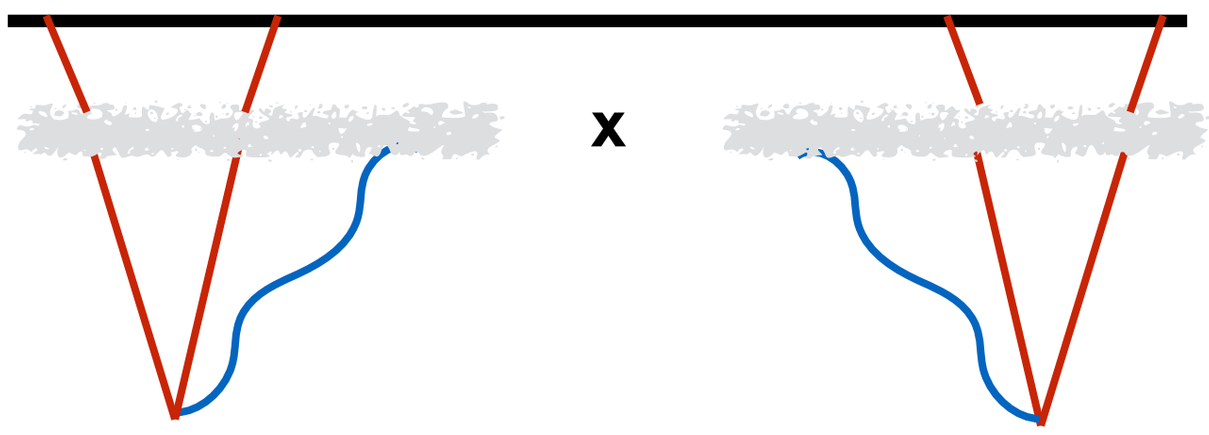
1.Smooth in "folded" limit

$$u \to +1$$

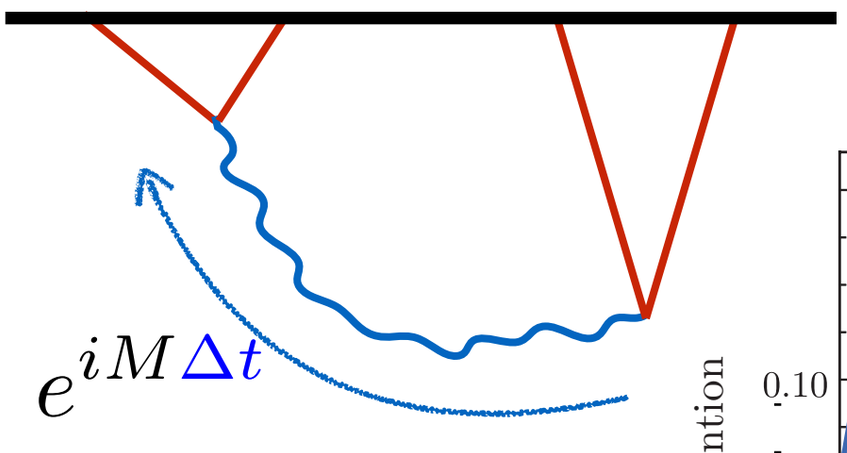


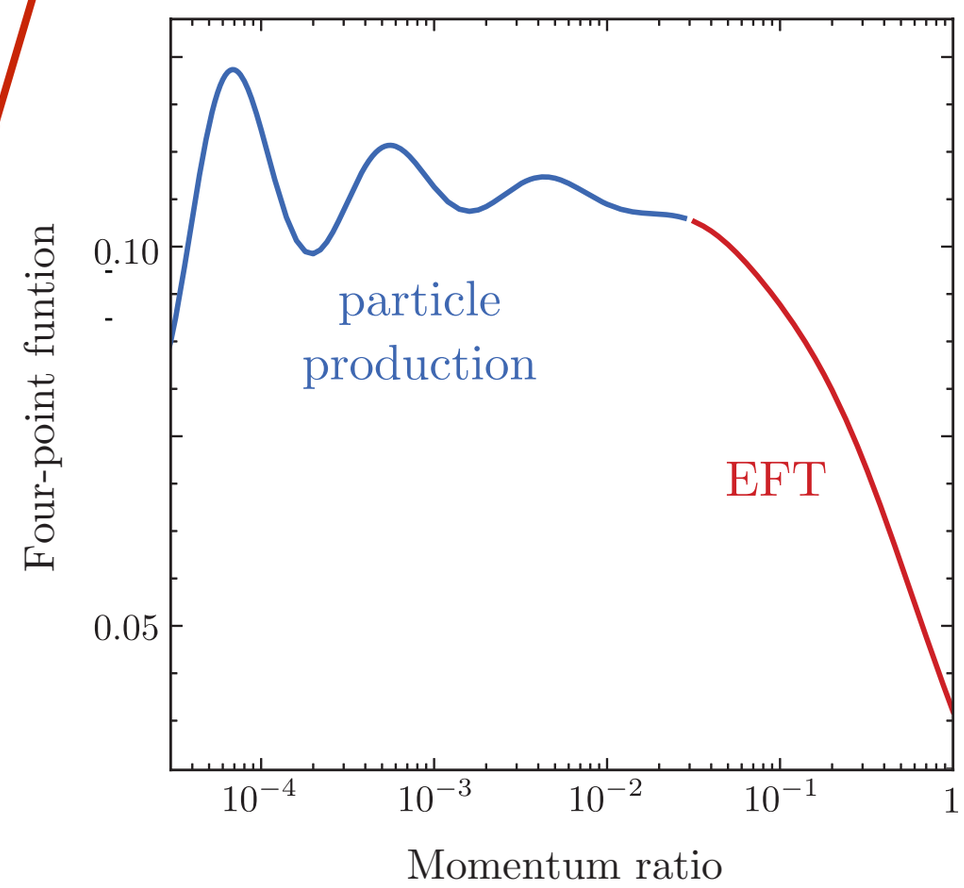
2.Factorizes in "early times" limit

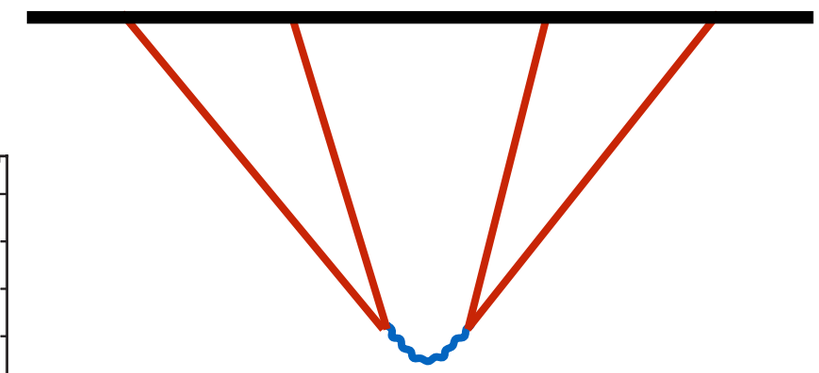
$$u \to -1$$



Solution

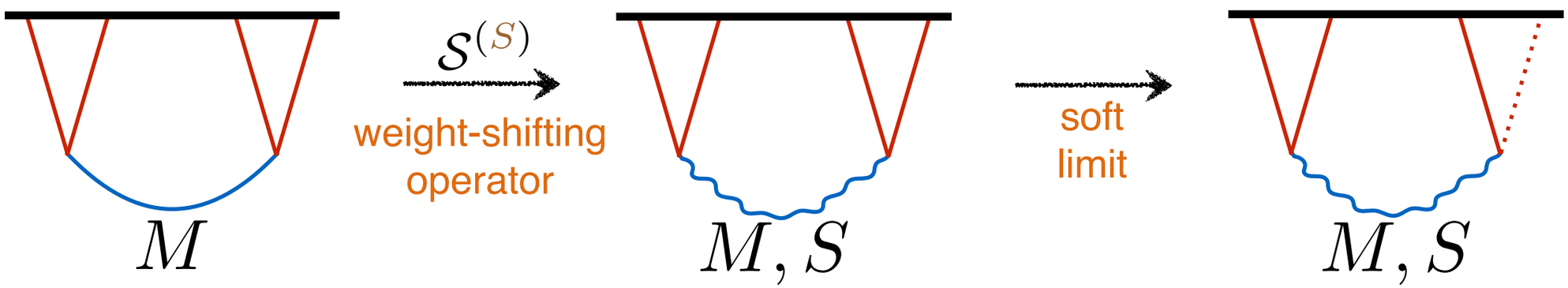






The result is general! (thanks to **symmetry**)

General Result

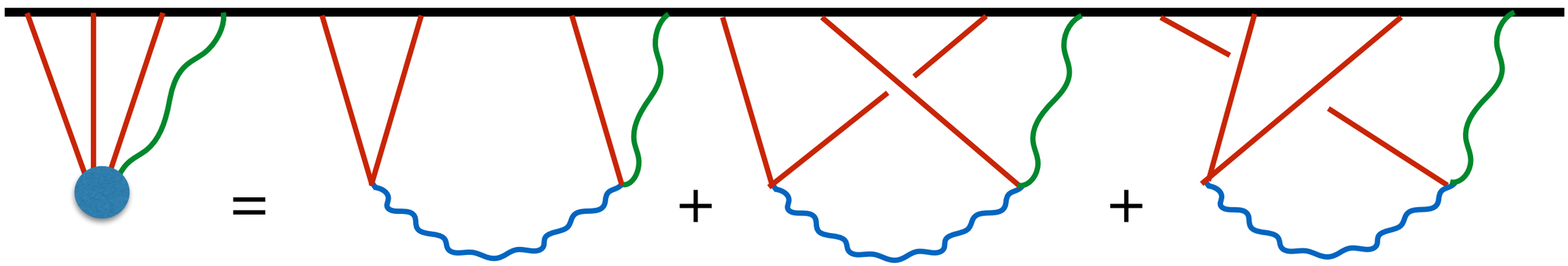


$$F_{M,S,g} = g^2\, \mathcal{S}^{(S)} F_{M,0}$$

Parametrized by mass, spin, & coupling.

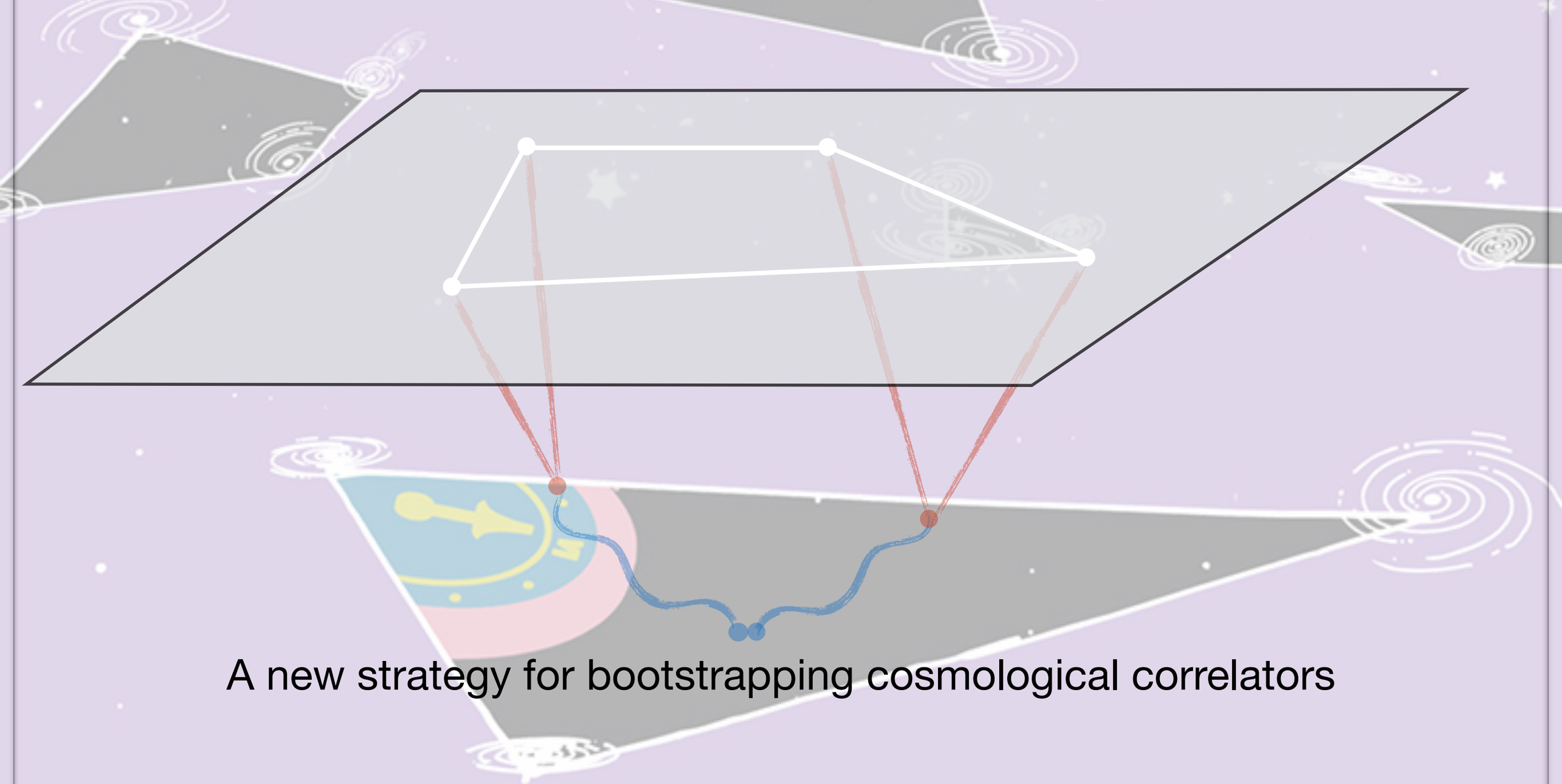
Gravitons in the Sky

(or, how to bootstrap the equivalence principle)



Baumann, Duaso Pueyo, Joyce, Lee, GLP, 2020

Cutting, Gluing, Lifting

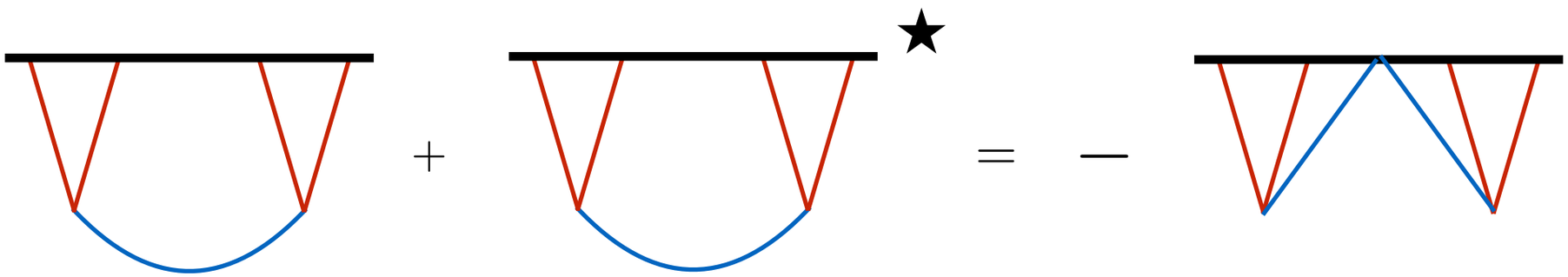


A new strategy for bootstrapping cosmological correlators

Olena Shmahalo (*Quanta* magazine)

Baumann, Chen, Duaso Pueyo, Joyce, Lee, GLP, 2021

Cutting



Follows from

locality (structure of propagator)

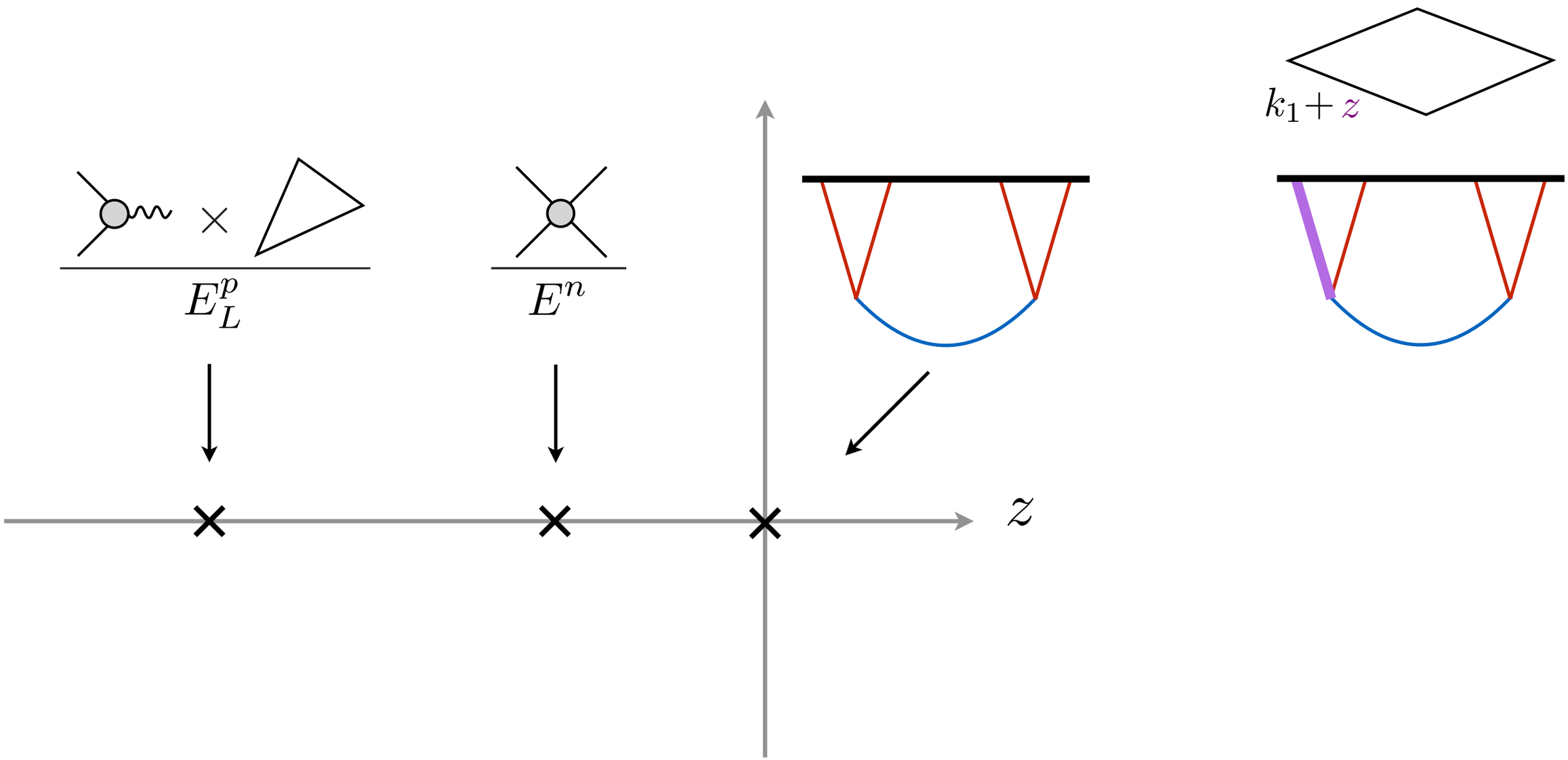
+

unitarity (real Hamiltonian)

Goodhew, Jazayeri, Pajer, 2020
Céspedes, Davis, Melville, 2020
Meltzer, Sivaramakrishnan, 2020
Jazayeri, Pajer, Stefanyszyn, 2021
Melville, Pajer, 2021
Goodhew, Jazayeri, Lee, Pajer, 2021
Baumann, Chen, Duaso Pueyo, Joyce, Lee, GLP, 2021

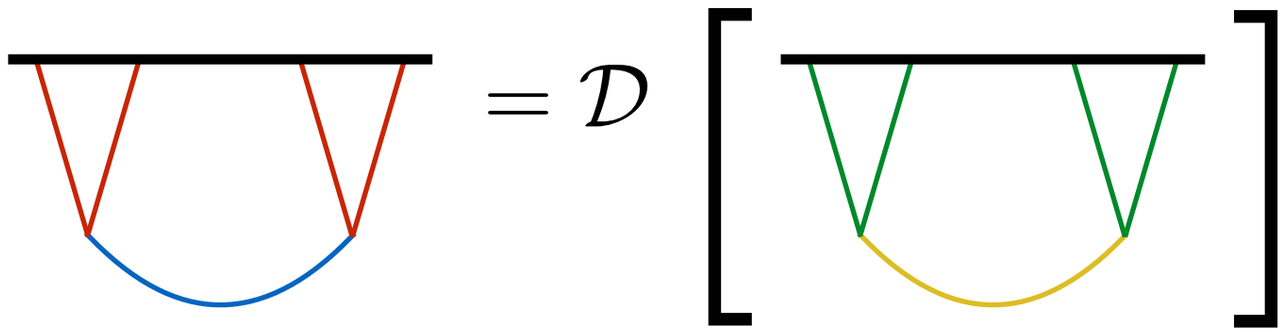
★ complex conjugation + “energy” flips

Gluing



Arkani-Hamed, Benincasa, Postnikov, 2017
Jazayeri, Pajer, Stefanyszyn, 2021
Baumann, Chen, Duaso Pueyo, Joyce, Lee, GLP, 2021

Lifting



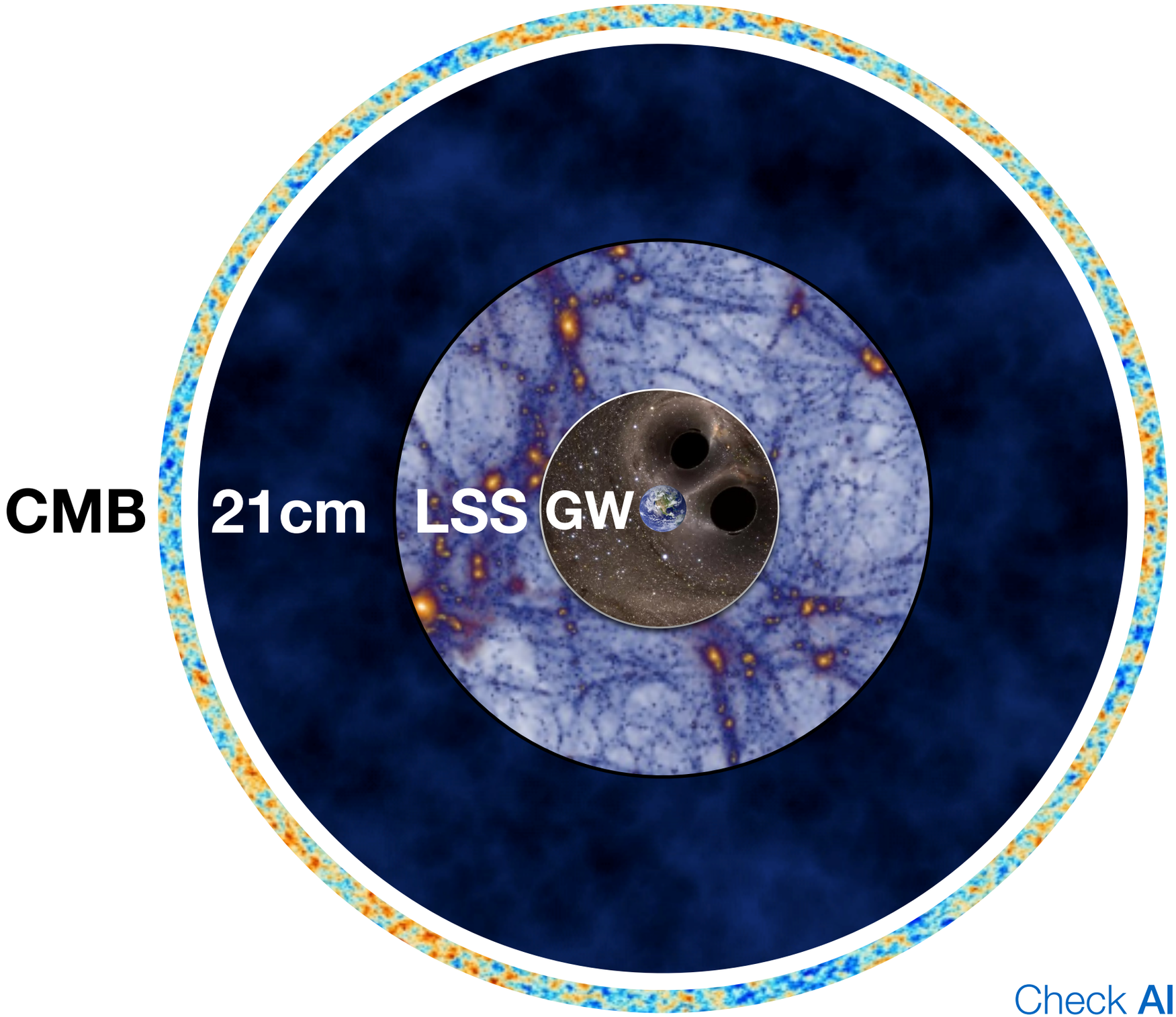
de Sitter Flat

$$f_k^{(\mathrm{dS})} = (1 - k\partial_k) f^{(\mathrm{flat})}$$

Benincasa, 2019
Baumann, Chen, Duaso Pueyo, Joyce, Lee, GLP, 2021

Future

Detection

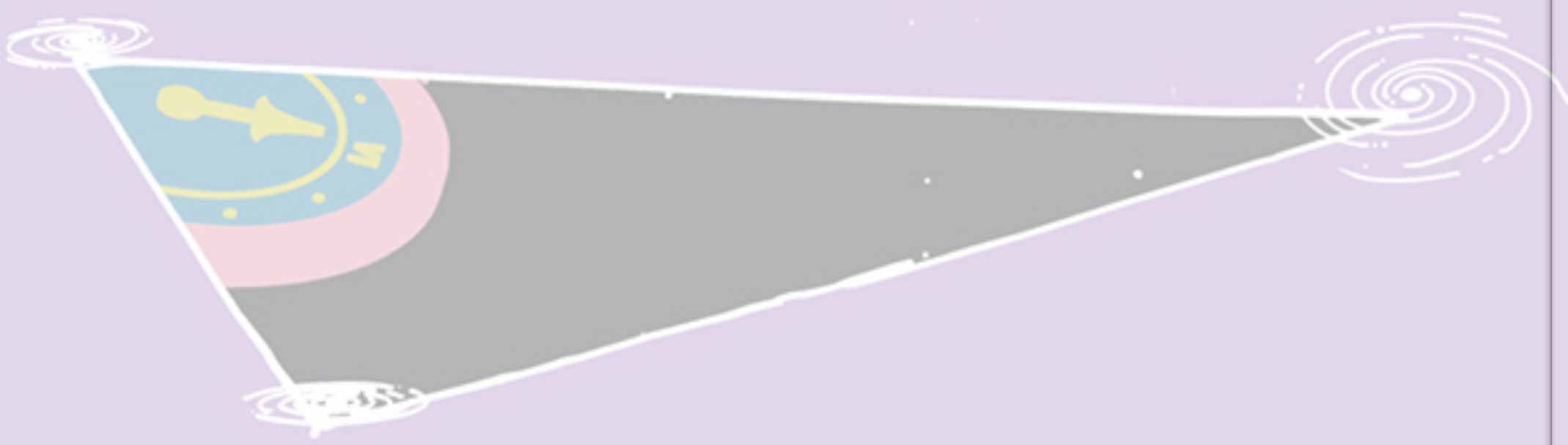


Check **Alba Kalaja**'s talk!

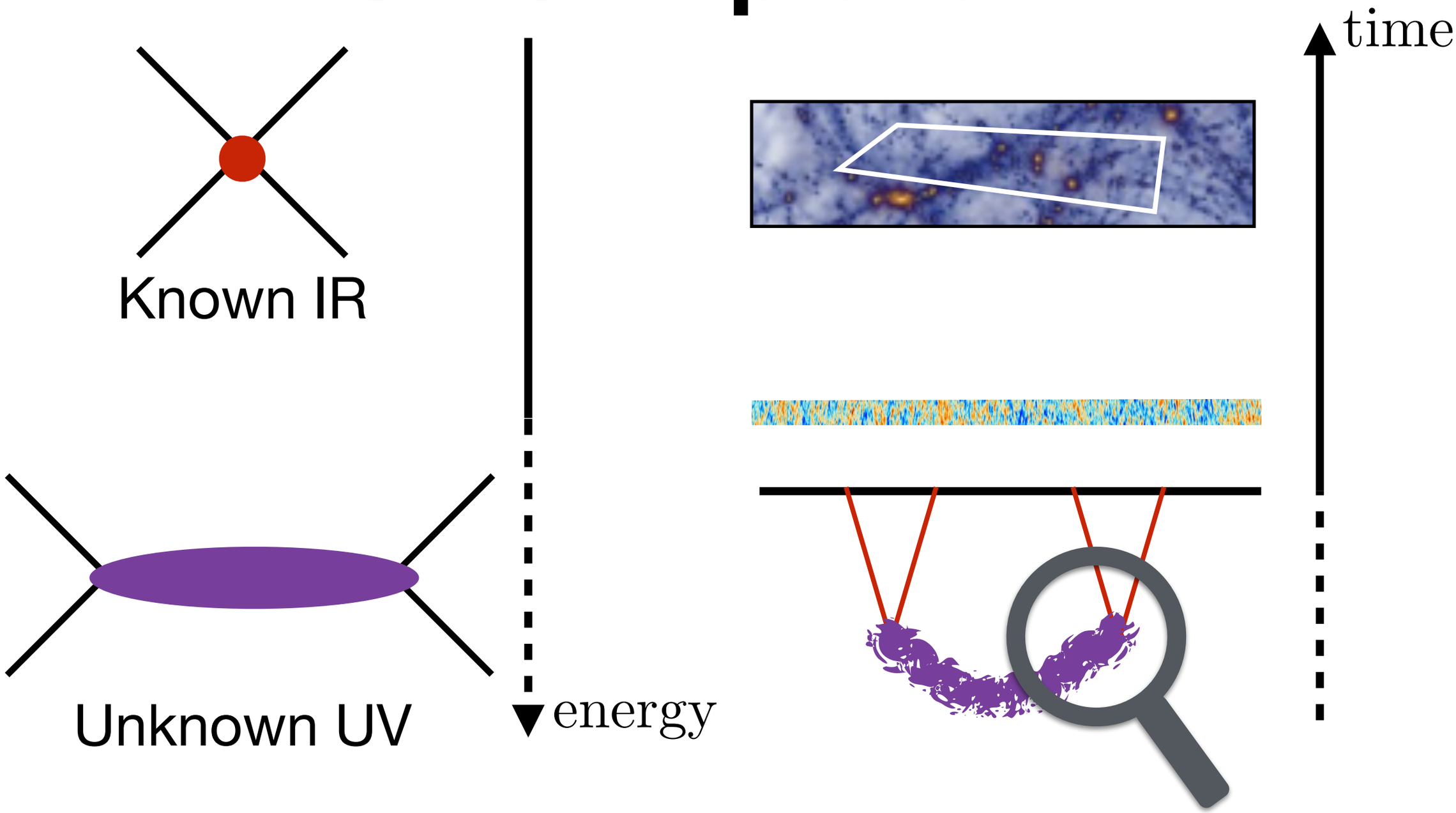
Broken

Other

Symmetries & Singularities

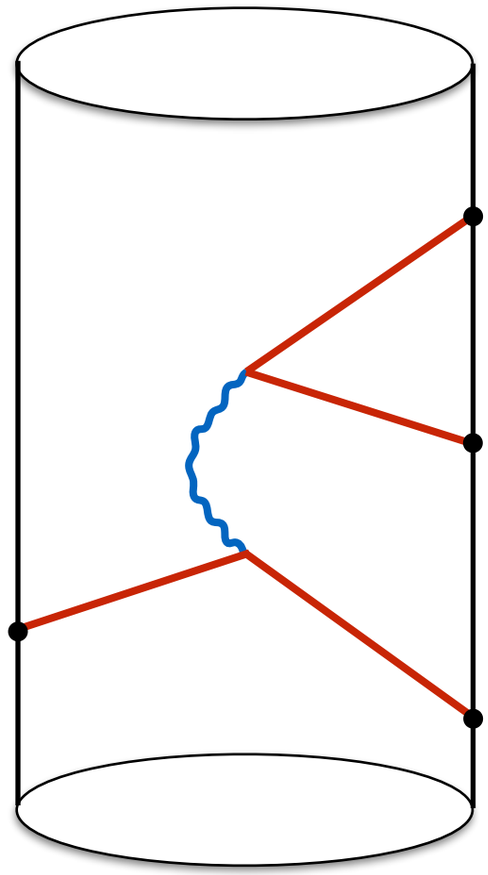


UV Completion

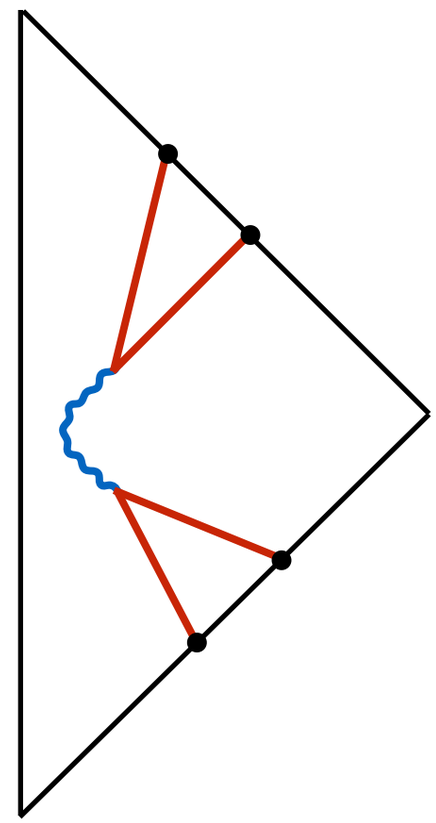


How does unitarity and causality constrain space of theories?

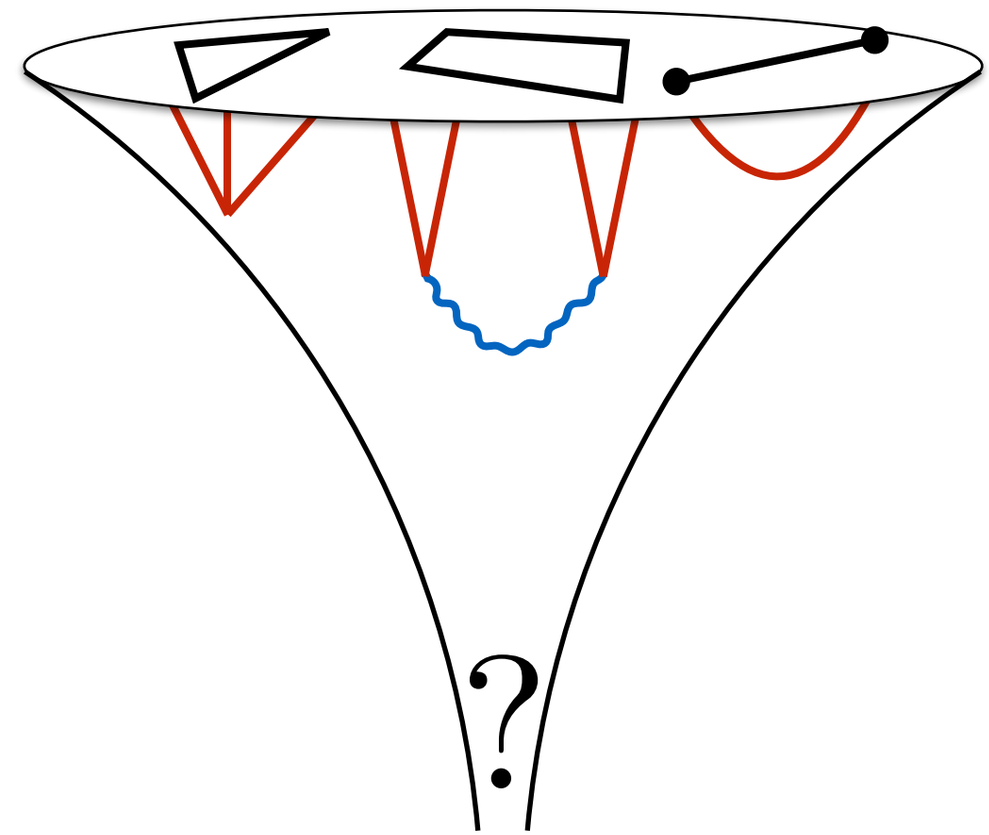
Cosmology & Holography



$\Lambda < 0$



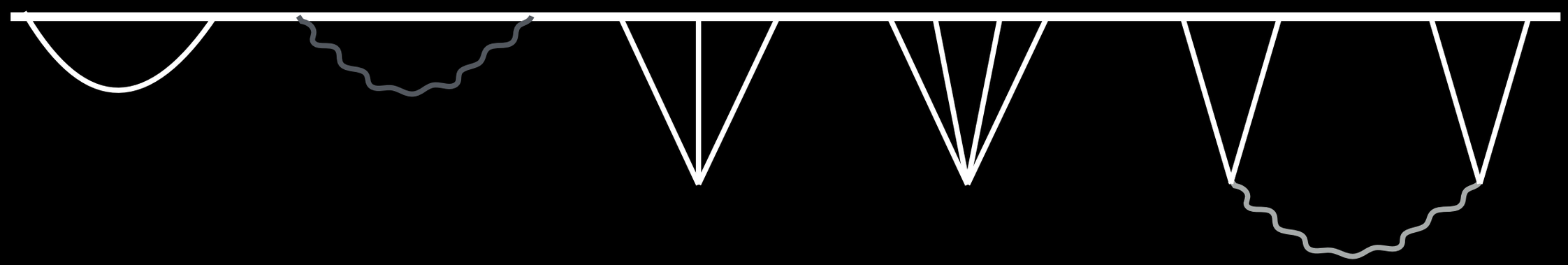
$\Lambda = 0$



$\Lambda > 0$

Understanding

Pressing in Cosmology — **Big Bang Singularity**!



Primordial fluctuations probe **particle collisions** in the sky at ultra high energies!

Bootstrap gives **new perspective** on cosmological correlators.

Time evolution is **encoded** in spatial patterns.

Bootstrap is a new toolbox to decode primordial non-Gaussianity.