Cosmological Collider Physics and an On-Shell Bootstrap



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HL, Qin, and Xianyu, 2407.12299

HL, Qin, Wu, Xianyu, and Zhang, 2606.02686

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Outline

Background

Cosmological collider physics

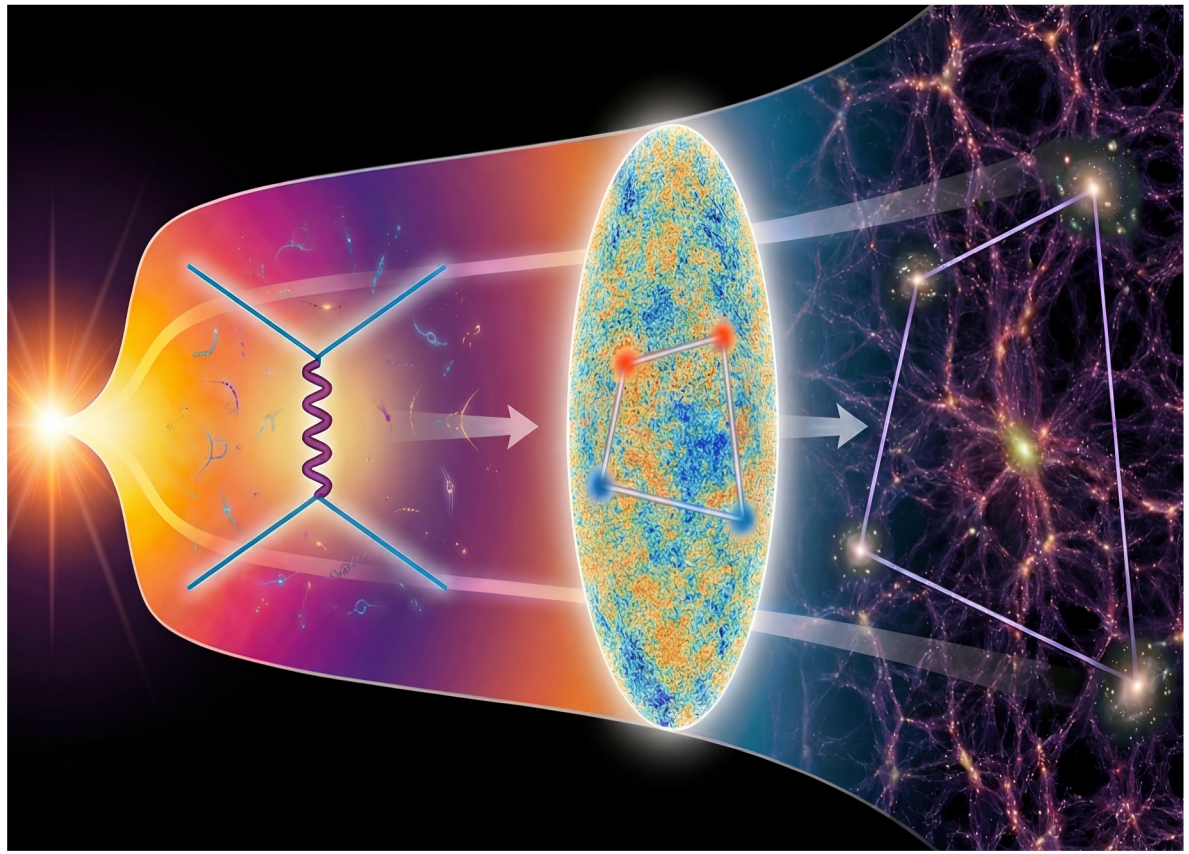
Feynman diagrams in inflation

On-Shell Approach

Loops as sum of trees

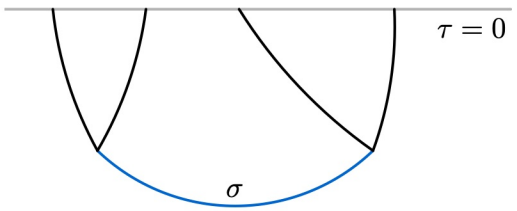
Cosmological collider physics

Chen, Wang, 0911.3380;
Arkani-Hamed, Maldacena, 1503.08043;
and many more

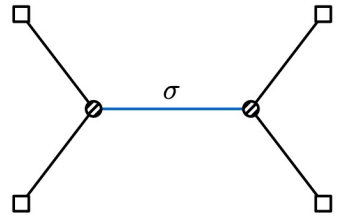


Generated by Gemini, for illustrative purposes only

H up to $10^{14}\mathrm{GeV}$, producing **heavy** particles



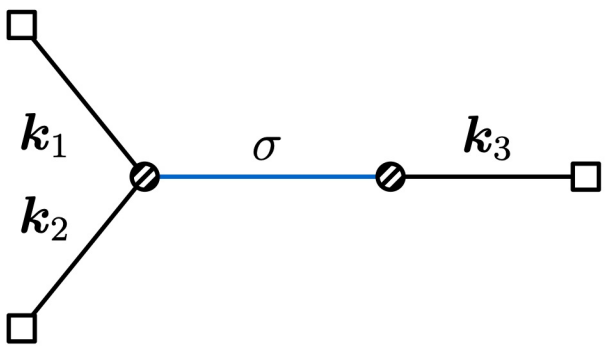
Described by correlation functions of inflaton fluctuations (**inflation correlators**)

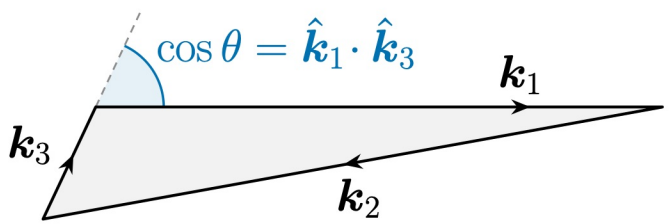


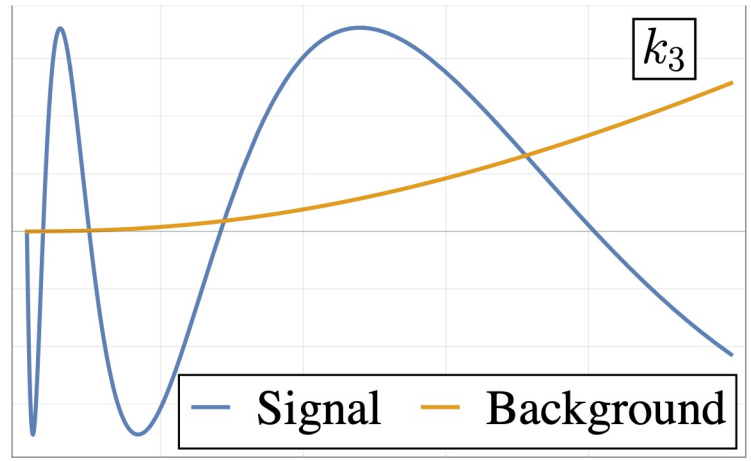
After cosmic expansion & nearly **linear evolution** at large scale, leaving prints at CMB & LSS (& 21-cm line)

Distinct signals

Chen, Wang, 0911.3380;
Arkani-Hamed, Maldacena, 1503.08043;
Lee, Baumann, Pimentel, 1607.03735;
Qin, Xianyu, 2205.01692; and many more







Signal: oscillation in **log** of momentum, and many other properties

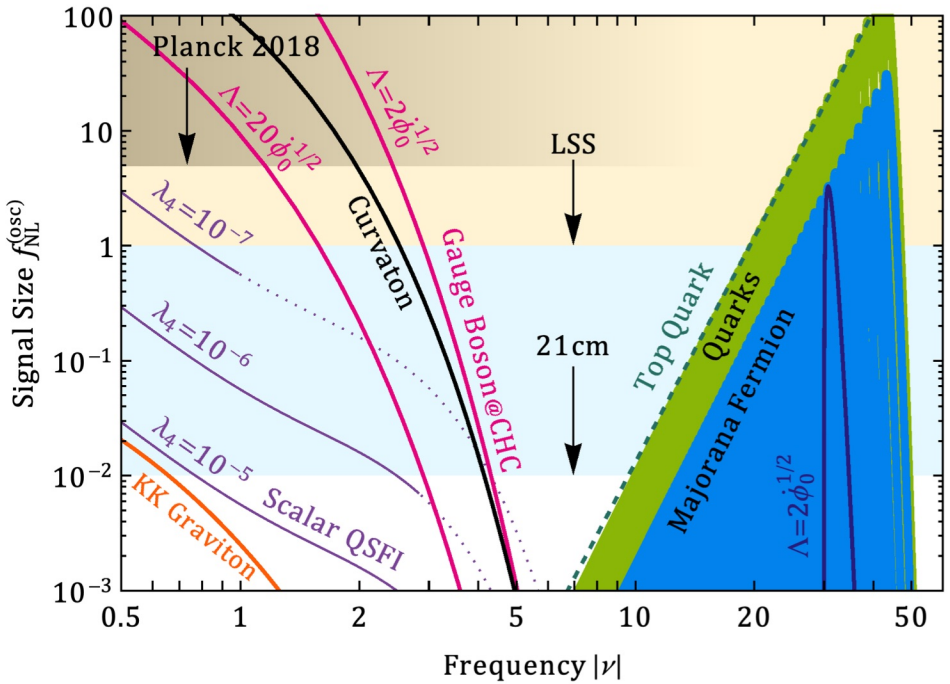
$$\text{Signal} \underset{k_3 \ll k_1 \sim k_2}{\sim} P_s(\hat{\boldsymbol{k}}_1 \cdot \hat{\boldsymbol{k}}_3) \left(\frac{k_3}{k_1}\right)^{\alpha} \cos\left(\omega \log \frac{k_3}{k_1} + \varphi\right)$$

Interaction · Mass · Spin · Spin, interaction, etc.

Background: smooth shape, also encoding rich information

Promising observational prospects

Rich model space with diverse motivations Wang, Xianyu, 1910.12876



Searches and constraints from current data

- CMB Sohn et al., 2404.07203;
  Suman et al., 2512.22085;
  Kumar, Lu, Xianyu, Zhang, 2603.15728 & 2604.07434
- LSS Cabass et al., 2404.01894

Future observations with improved sensitivity

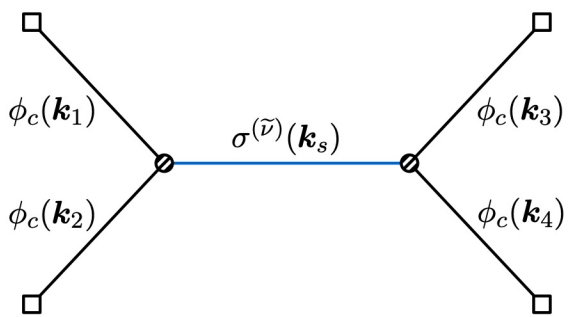
- CMB Abazajian et al., 1610.02743
- LSS Schlegel et al., 2209.03585;
  Schlegel et al., 2209.04322;
  Cai, Huang, Liu, Zhao, and Huang, 2605.10102
- 21-cm line Meerburg et al., 1610.06559;
  Ansari et al., 1810.09572; Bandura et al., 1907.12559

Challenges in computation

Feynman rules are much more complicated than flat-space case

Chen, Wang, Xianyu, 1703.10166 as a review

- Violation of spacetime symmetries: **time-ordered integrals**
- Curvature: **special functions** as mode functions of massive particles
- **Loops** are even harder, but also important!



$$\Rightarrow \quad \mathcal{I} = \sum_{\mathsf{ab}=\pm} -\mathsf{ab}\; k_s^{5+p_{12}} \int_{-\infty}^{0} \mathrm{d}\tau_1 \mathrm{d}\tau_2\, (-\tau_1)^{p_1} (-\tau_2)^{p_2} e^{\mathrm{i}\mathsf{a}k_{12}\tau_1 + \mathrm{i}\mathsf{b}k_{34}\tau_2} D_{\mathsf{ab}}(k_s;\tau_1,\tau_2)$$

where

$$D_{-+}(k;\tau_1,\tau_2) = \frac{\pi}{4} e^{-\pi\widetilde{\nu}} (\tau_1\tau_2)^{3/2} \mathrm{H}^{(1)}_{\mathrm{i}\widetilde{\nu}}(-k\tau_1) \mathrm{H}^{(2)}_{-\mathrm{i}\widetilde{\nu}}(-k\tau_2)$$

$$D_{+-}(k;\tau_1,\tau_2) = \frac{\pi}{4} e^{-\pi\widetilde{\nu}} (\tau_1\tau_2)^{3/2} \mathrm{H}^{(2)}_{-\mathrm{i}\widetilde{\nu}}(-k\tau_1) \mathrm{H}^{(1)}_{\mathrm{i}\widetilde{\nu}}(-k\tau_2)$$

$$D_{\pm\pm}(k;\tau_1,\tau_2) = D^{(\widetilde{\nu})}_{\mp\pm}(k;\tau_1,\tau_2)\theta(\tau_1-\tau_2) + D^{(\widetilde{\nu})}_{\pm\mp}(k;\tau_1,\tau_2)\theta(\tau_2-\tau_1)$$

On-shell part is easier!

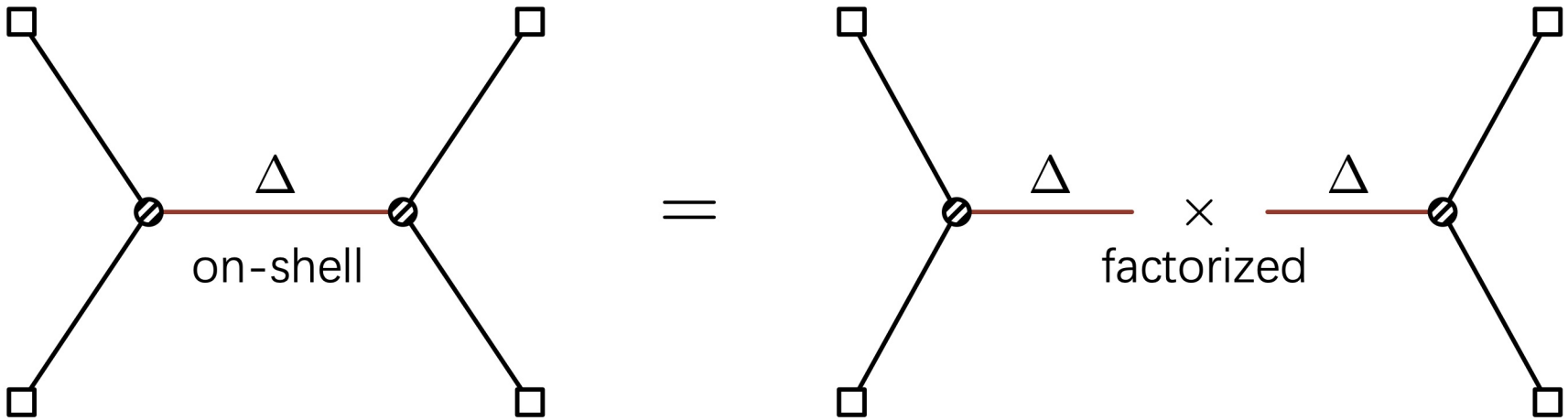
Lessons from tree-level:

On-shell $\Rightarrow$ **Non-local effect** $\Rightarrow$ **Factorized subgraphs**

satisfying EoM
"$p^2 = m^2$"

long separation

two independent processes



Loop level: subtler analysis, but similar conclusions

Everything from on-shell data

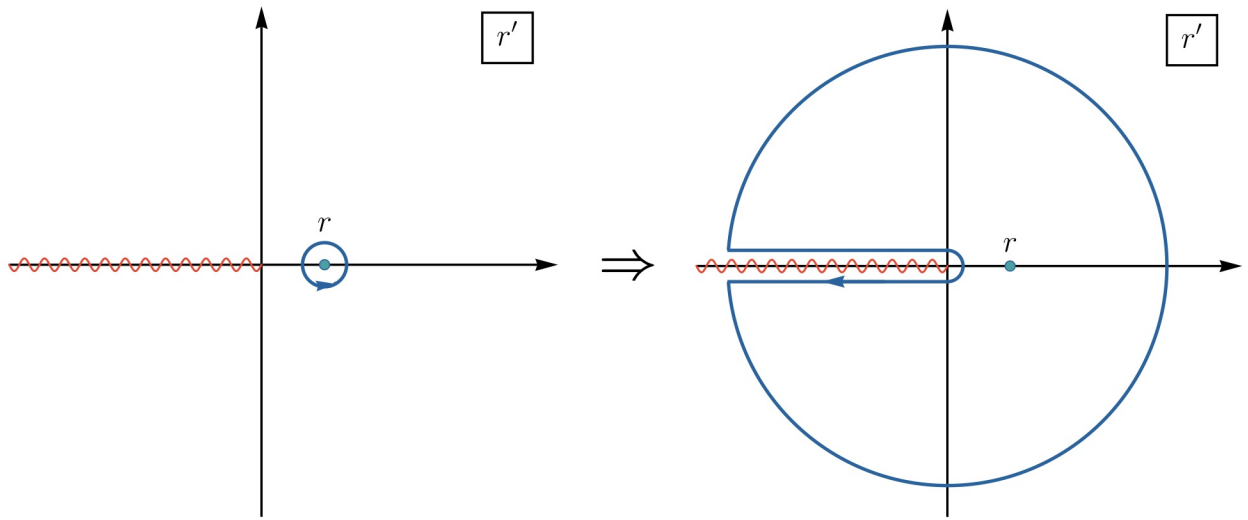
HL, Qin, Xianyu, 2407.12299

$$f(r) = \int_{\mathcal{C}'} \frac{\mathrm{d}r'}{2\pi\mathrm{i}} \frac{f(r')}{r'-r} = \int_{-\infty}^{+\infty} \frac{\mathrm{d}r'}{2\pi\mathrm{i}} \frac{\mathrm{Disc}_{r'}\, f(r')}{r'-r}$$

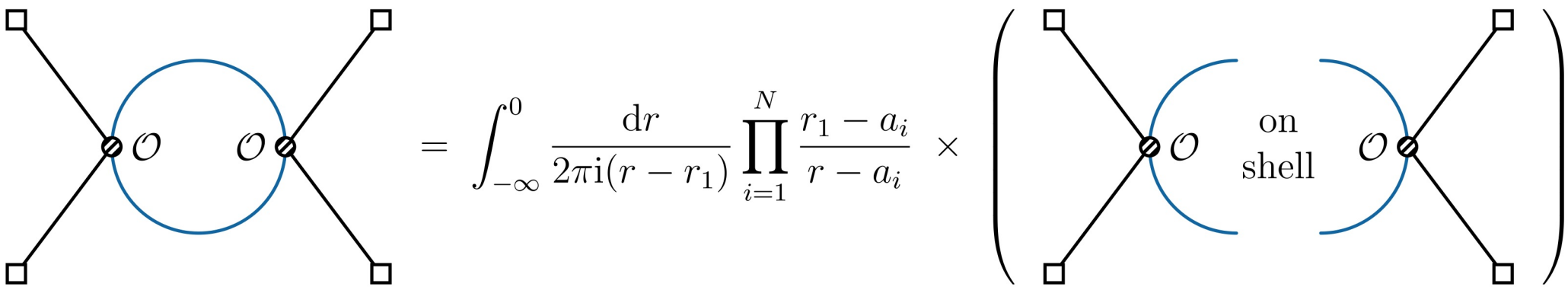
$$\underset{z}{\mathrm{Disc}}\, f(z) \equiv \lim_{\epsilon\to 0^+} \Big[f(z+\mathrm{i}\epsilon) - f(z-\mathrm{i}\epsilon) \Big]$$

$\Uparrow$

Only from on-shell data



Recover bubble diagram from its on-shell data:

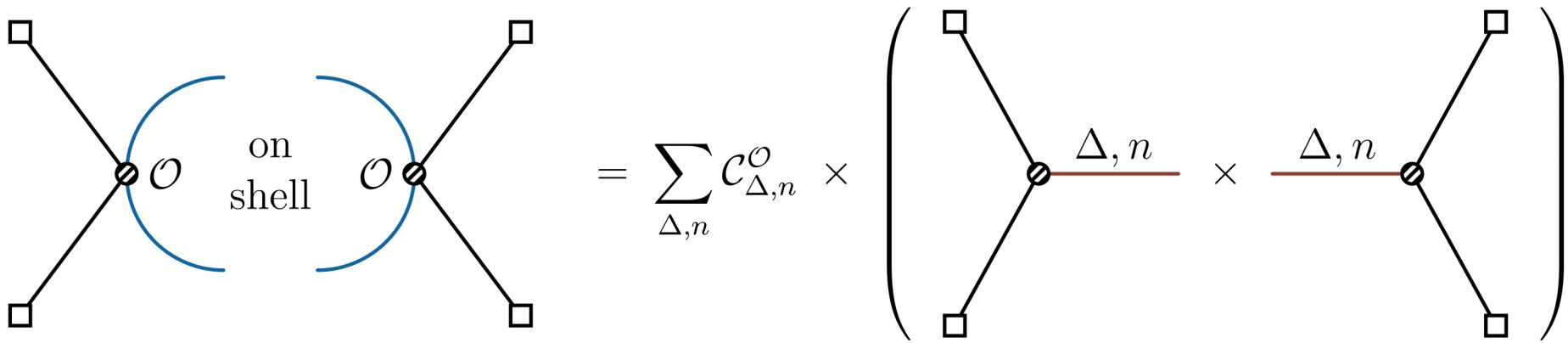


An on-shell bootstrap

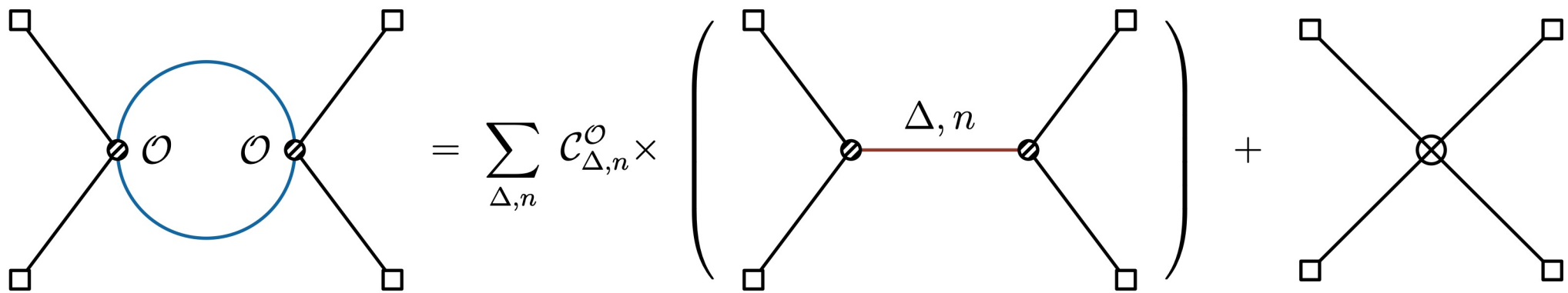
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On-shell data from tree-level processes

Xianyu, Zhang, 2211.03810;
Zhang, 2507.19318



Since everything from on-shell data: **Loop = sum of trees**

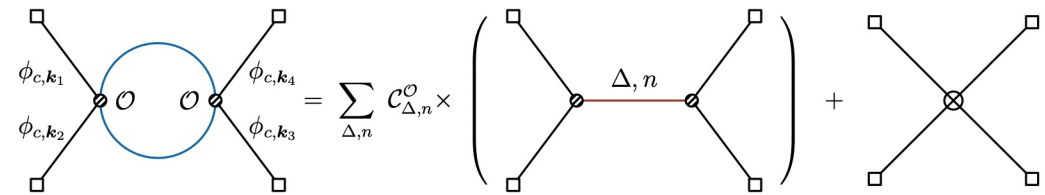


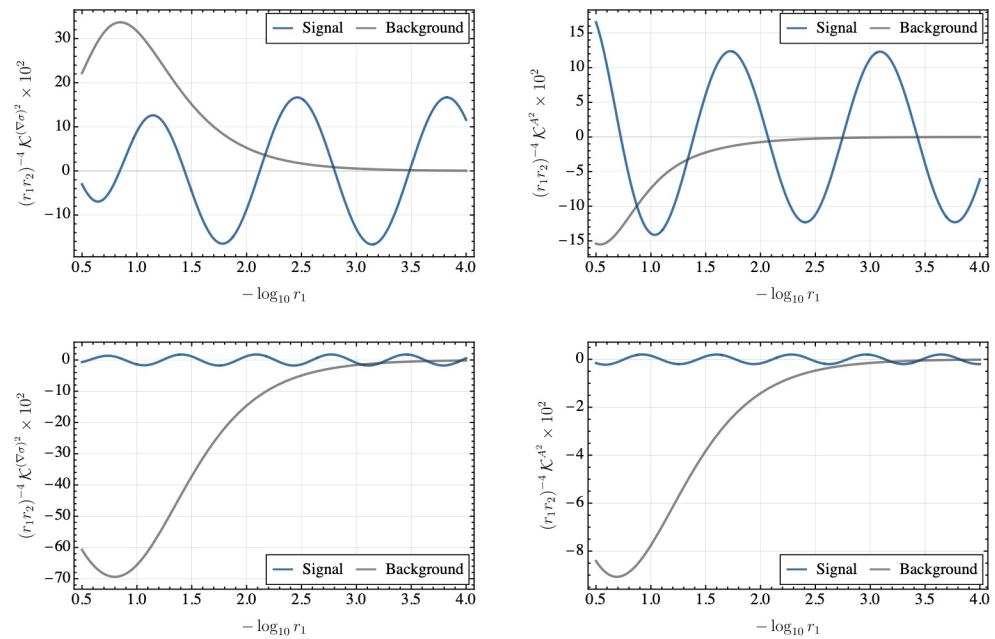
Summary

- Everything from on-shell data
- **Bubble as sum of trees**

Outlooks

- More complicated cases
- Better understand it (perhaps from an AdS perspective)





Thank You!