



ITP-CAS



新基石科学实验室

Amplitudes

Machine-readable physics → verified research modules → new frontiers

何颂 · 中科院理论物理研究所

particles + strings surfaceology combinatorial / positive geometries
amplitudes $\mathcal{N}=4$ SYM Feynman integrals bootstrap symbols / polylogs QCD + Higgs
cosmology wavefunctions curved backgrounds classical gravity AdS/CFT holography correlators

Amplitudes: intersection of many areas

formal QFT

perturbative strings

mathematics

precision frontier

Amplitudes

AdS/CFT

quantum + classical
gravity

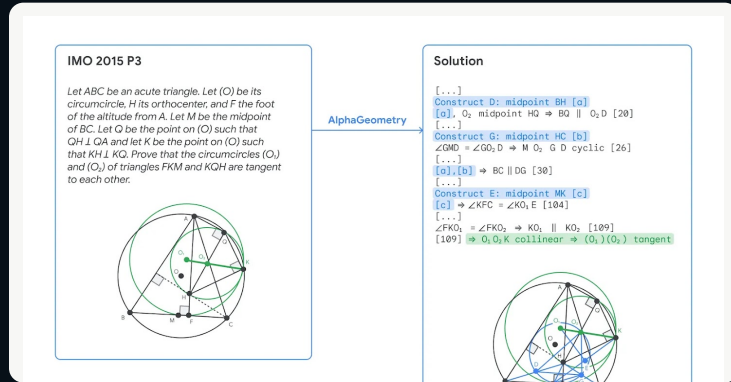
cosmology

exact methods

heroic calculations → simplicity + structures → deep insights + powerful tools

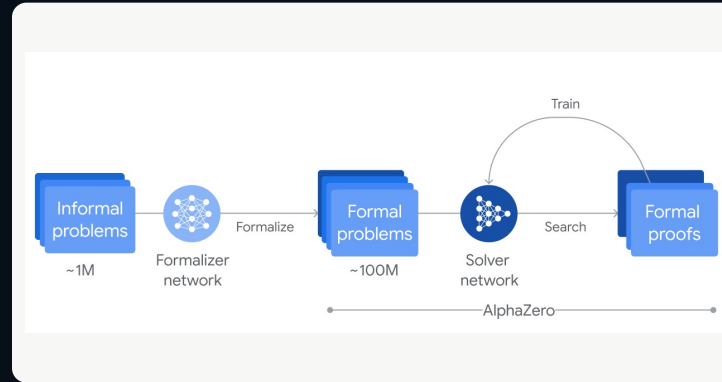
Math: formal language and verification

AI discovery



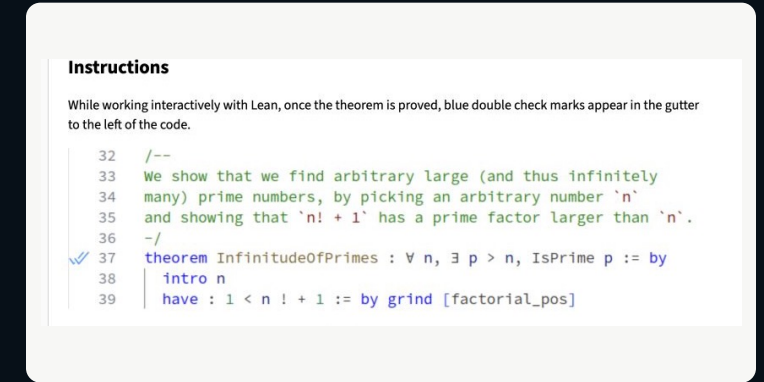
construction + search · patterns beyond brute force

formal proof search



informal statement → formal language → proof search

trusted verification



shared libraries + a small kernel → reusable results

rapid frontier: olympiad reasoning → formal proof search → research mathematics

AI experiments for hep-th research

traditional research module

expert team
× several months

- specialist-only setup
- bespoke code + conventions
- long reproduction cycle

pure AI experiment

non-specialist + AI
× a few days

- machine-readable knowledge
- modules composed by conversation
- expert-verified output

vibe coding + vibe research

ChatGPT · GPT-5.6 — literature / data · coding · automated calculations

exact objects

reusable packages

independent checks

expert responsibility

months → days · a change in who can execute a bounded research workflow.

review + lectures → hands-on research modules: beginners enter quickly · build expertise fast · accelerate the frontier.

Three AI experiments—for now

MAIN OUTPUT — results · packages · databases — all on GitHub: github.com/Amplitude-Lab

I

Combinatorial geometries

strings · particles · wavefunctions

Surfaceology

Cuts → Integrands

Cosmohedra

curves · u -variables · global integrals

II

Automatic Symbol Bootstrap

amplitudes · form factors · singularities

QCD + Higgs Gluing

FI + Landau Toolbox

Auto-Symbol-Bootstrap

alphabets · ansätze · physical constraints

III

Cosmology & dS

wavefunctions · correlators · spinning fields

Cosmological Graph-DE

dS Correlators

Spinning Wavefunctions

graph DEs · recursion · cuts

Combinatorial geometries: particles, strings & wavefunctions

P

particles & loops

associahedra · surfacehedra

positive Grassmannians · amplituhedra

loop geometries · surface cuts

S

strings & worldsheets

worldsheet associahedra

moduli spaces $\mathcal{M}_{g,n}$

stringy / curve integrals

W

wavefunctions & correlators

cosmological polytopes · cosmohedra

correlahedra · correlator polytopes

energy-correlator geometries

kinematics

channels $\leftrightarrow$ curves

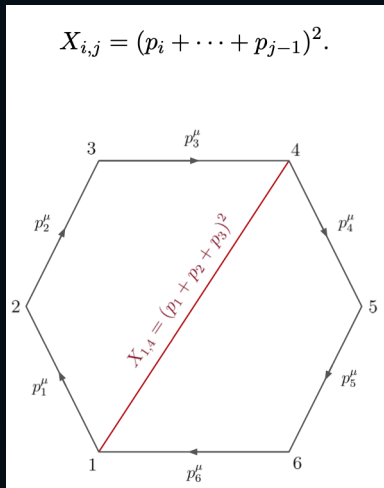
combinatorics

graphs $\leftrightarrow$ triangulations

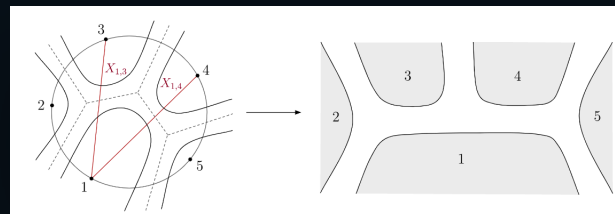
physics

factorization $\leftrightarrow$ boundaries / cuts

Surfaceology: curves on surfaces



diagonals / triangulations



punctures / handles / loops

diagonal $\rightarrow X_{ij} \rightarrow$ curve $\rightarrow$ surface

- **particles** · surfacehedra + shifted theories
- **loops** · punctures / handles + surface cuts
- **strings** · curve integrals + massive levels

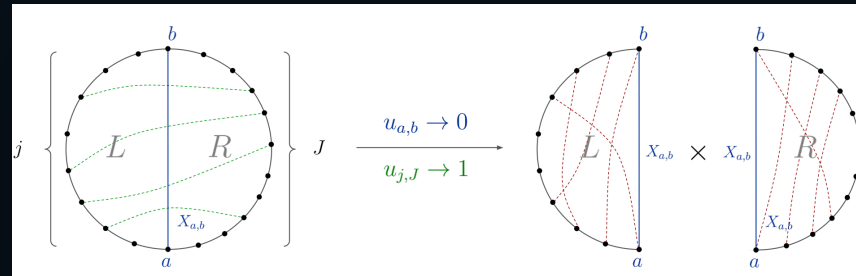
intersection $\leftrightarrow$ compatibility · cutting $\leftrightarrow$ factorization · topology $\leftrightarrow$ loop data

LINEAGE · [ABHY](#) $\rightarrow$ + [Lam](#) $\rightarrow$ + [Thomas](#) / + [Salvatori](#) $\rightarrow$ [Arkani-Hamed et al.](#)

Binary geometries: stringy $\text{Tr } \varphi^3$ amplitudes

$$\text{curve word} \rightarrow F_C(y) \rightarrow u_C$$

$$\mathcal{I}(X) = \int_{\mathbb{R}^{+d}} \prod_i dy_i/y_i \prod_C u_C^{\alpha' X_C}$$



$u_C \rightarrow 0$ forces incompatible crossings to 1

binary u -equations

all curves encoded at once

finite α'

bosonic string amplitudes

tropical limit

tree + loop ϕ^3 amplitudes
without diagrams

Kinematic shifts reveal hidden zeros— and much more

with Nima Arkani-Hamed · 曹趣 · 董晋 · Carolina Figueiredo

FRONTIER — one shifted function · coloured scalars, pions + gluons · hidden zeros + factorization

same function

evaluated on shifted kinematics

- Veneziano zeros → off-shell currents
- the geometric u -data stay fixed

$$\mathcal{I}_{2n}^\delta = \int_{\mathbb{R}_{>0}^{2n-3}} \prod_{I=1}^{2n-3} \frac{dy_I}{y_I} \prod_{(e,e)} u_{e,e}^{\alpha'(X_{e,e}+\delta)} \times \prod_{(o,o)} u_{o,o}^{\alpha'(X_{o,o}-\delta)} \times \prod_{(o,e)} u_{o,e}^{\alpha' X_{o,e}}$$
$$\rightarrow \mathcal{A}_{2n}^{\text{Tr } \phi^3}(X_{e,e} \rightarrow X_{e,e} + \delta, X_{o,o} \rightarrow X_{o,o} - \delta),$$

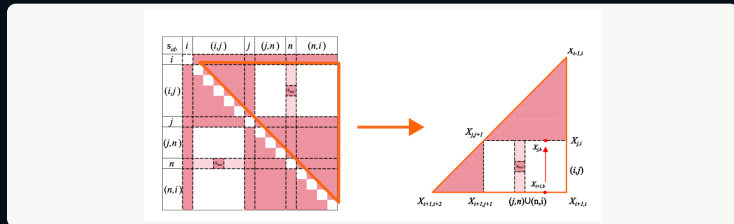
deforming the kinematics, not the underlying function

Universal structures persist from soft limits to loops and strings

with 曹趣 · 董晋 · 施灿欣 · 朱凡

splitting / soft limits

split kinematics
 $\rightarrow J_L \times J_R$



string + particle amplitudes · soft / multi-soft limits

loops

punctures / handles
 $\rightarrow$ all-loop data

shifted curves
 + surface cuts

all-loop NLSM · scaffolded gluons · leading singularities

finite α' strings

curve integrals
 $\rightarrow$ massive levels

$$\mathcal{I}_n^{\text{Tr } \phi^3}(1, 2, \dots, n) = \int_{D(1 \dots n)} \frac{dz_1 \dots dz_n}{\text{vol SL}(2, \mathbb{R})} \frac{1}{\underbrace{z_{1,2} z_{2,3} \dots z_{n,1}}_{\text{PT}(1,2,\dots,n)}} \times \underbrace{\prod_{i < j} z_{i,j}^{2\alpha' p_i p_j}}_{\text{Koba-Nielsen factor}}$$

factorization · asymptotics · superstrings

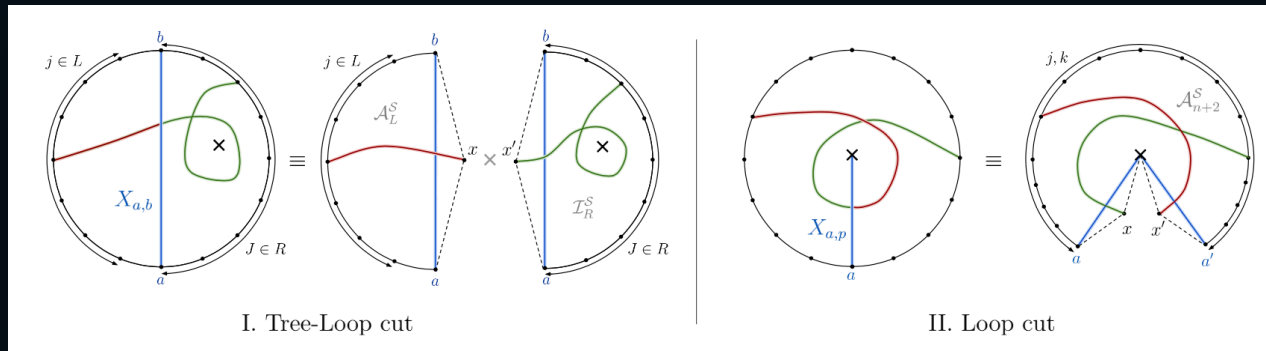
split limits · loop topology · finite α' — one surface language

Surface cuts reconstruct integrands

with 朱凡 · 韩振琦

earlier with 曹趣 · 董晋 · 张勇

FRONTIER — 1L all- n YM + gravity · universal expansion + double copy → compact 2L / 3L integrands



physical cuts organised by surface combinatorics

all- n at one loop

YM ↔ gravity · forward limits
universal expansion · double copy

D-dimensional cuts



refinement poset



Möbius inversion



multi-loop integrand

Exact structures become scalable research engines

ONE AI EXPERIMENT — exact structures across strings · particles · wavefunctions

01

Geometry → integrals

surface → binary u -data
→ curve / stringy integrals
→ tropical limits

generate · mutate · glue · factorize

02

Amplitudes + wavefunctions

Berends–Giele recursion
→ amplitudes + wavefunctions

$n \sim 10^4$ numerically

03

Cuts → integrands

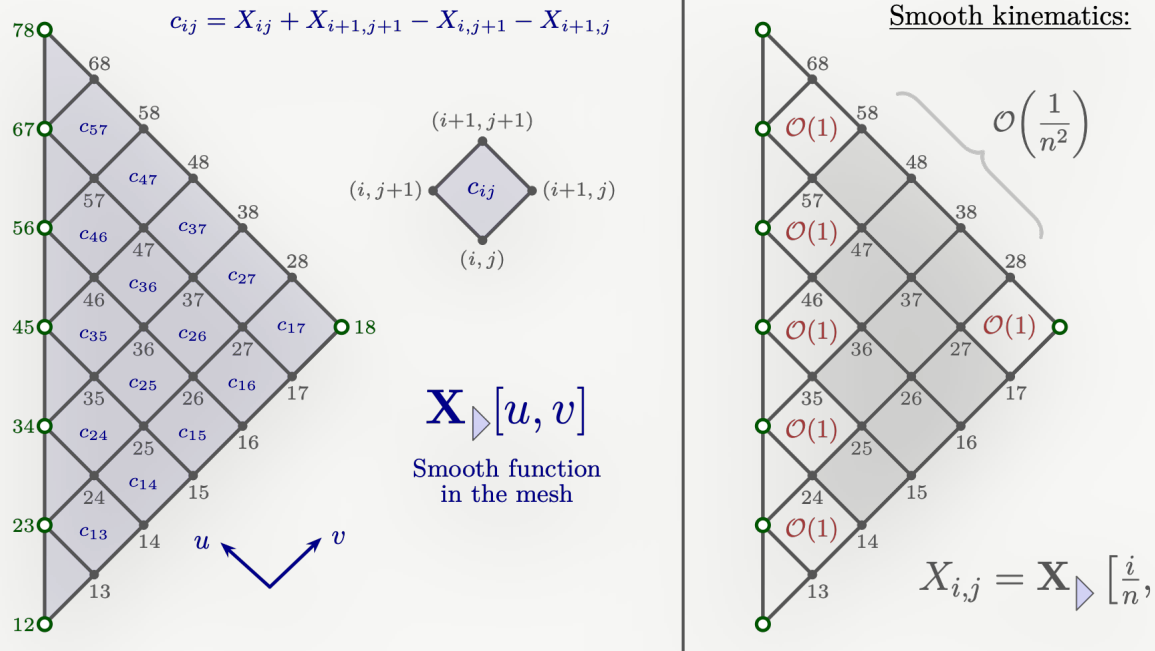
physical cuts → refinement poset
→ global integrands

2L high-multiplicity QCD
new 3L · higher-loop $\mathcal{N}=4$ SYM

Reusable code → a new laboratory for integrands, FIs & precision.

“Smooth kinematics” for large n

MAJOR BREAKTHROUGH — exponentially many diagrams $\rightarrow$ one smooth kinematic profile



Paper 2: chord variables sampled from a smooth triangular profile

$$X_{ij} = \mathbf{X}(i/n, j/n)$$

- **smooth** · bounded curvature across the mesh
- **bulk** $c_{ij} \sim \mathcal{O}(n^{-2})$
- **boundary** $c \sim \mathcal{O}(1)$

$$a_k = X_{1k} \cdot b_k = c_{k-2,k} - X_{1k} \cdot c = c_{1,n-1}$$

Totally new pictures: optimization & transfer matrices

STRUCTURAL RESULT — leading exponent · stringy lift · finite- n composition

FT

optimization

$$\log \mathcal{A}_n / n \rightarrow f[\mathbf{X}]$$

leading exponential
simple kinematic regimes

α'

stringy optimization

positive integral before tropicalization

AM–GM variables
field-theory limit

T

transfer matrix

$$\mathcal{A} \sim \langle L | T_3 \cdots T_{n-1} | R \rangle$$

exact τ -chain seed
prefactor / evolution frontier

APPLICATION · LARGE MULTIPLICITY

Large- n amplitudes become tractable

with Nima Arkani-Hamed · Carolina Figueiredo · 李想 et al.

FRONTIER — exact finite $n \rightarrow$ large- n optimization $\rightarrow$ transfer kernels

PAPER I

New Formalisms for Scattering Amplitudes

exact finite n

PAPER II

Scattering Amplitudes at Large Multiplicity I: An Optimization Problem

optimization

PAPER III

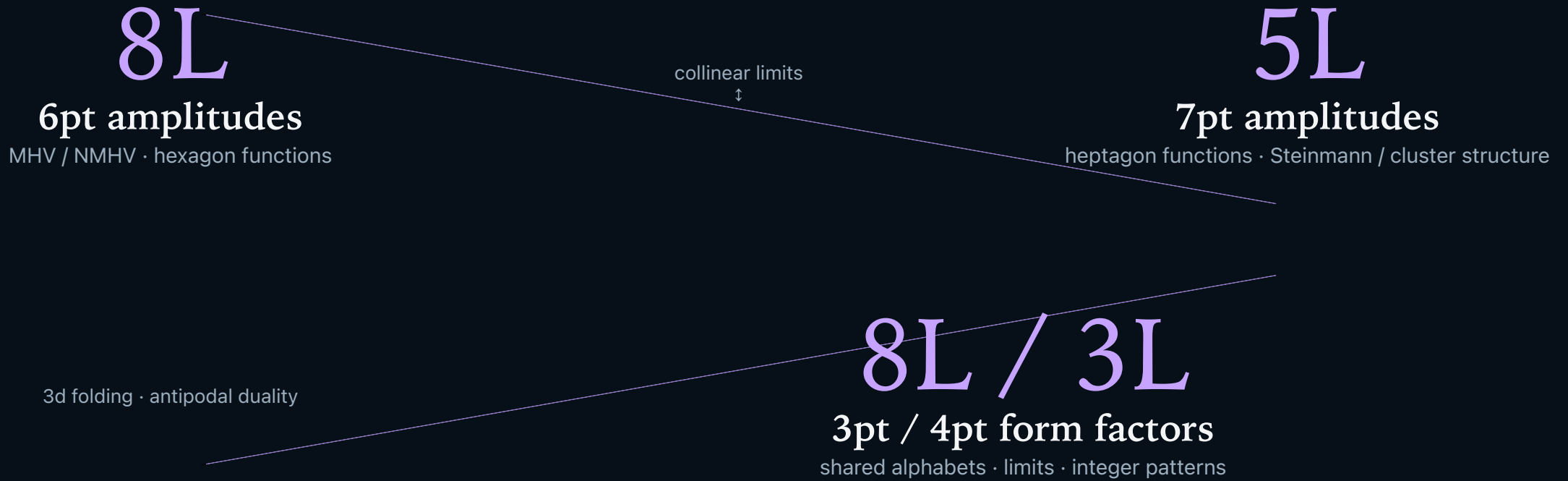
Scattering Amplitudes at Large Multiplicity II: Transfer Matrixology

transfer kernels

TO APPEAR

Bootstrapping amplitudes and form factors in $\mathcal{N}=4$ SYM

earlier work by Lance Dixon et al.



More loops, more legs

earlier work across several groups

high-loop web

6pt amplitudes $\leftrightarrow$ 3pt form factors
limits · foldings · dualities

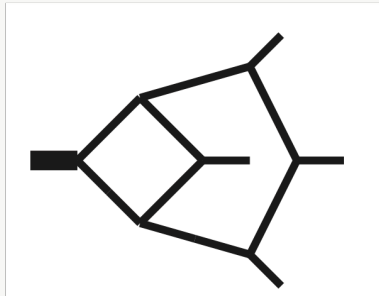
$$\mathcal{A}_{6,7} \leftrightarrow \mathcal{F}_{3,4}$$

limits · foldings · dualities

Lance Dixon et al. · Dixon–Xin

one-mass function space

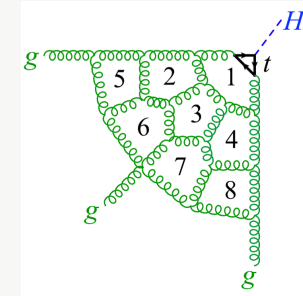
five-point one-mass integrals
 $\rightarrow$ 113-letter function space



Abreu et al. · Chicherin–Sotnikov–Zoia

four-point MHV form factor

2L functions · 88-letter alphabet
 $\rightarrow$ a bridge to $H+4g$

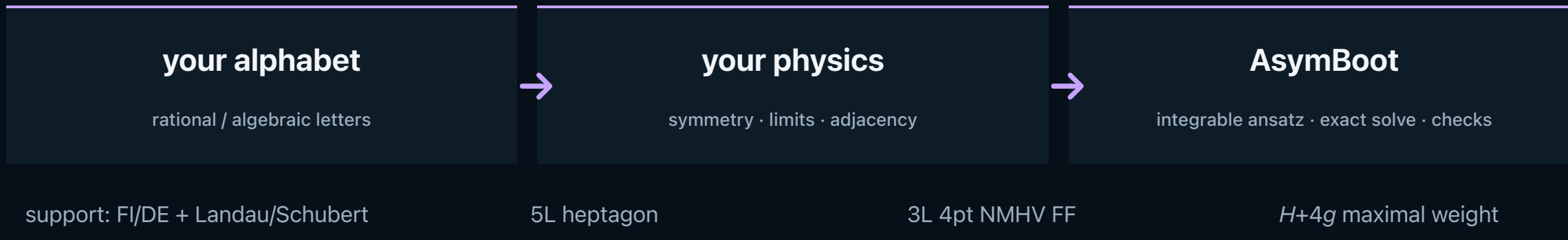


杨刚 et al. · Gopalka–Herrmann · Dixon–Xin

AsymBoot: symbol bootstrap for everyone

with 姜旭航 · 李想

ANYONE CAN USE IT — provide an alphabet + physical conditions → construct · solve · verify the symbol automatically



From a bespoke expert calculation to a portable research module.

The heptagon bootstrap reaches five loops

with 姜旭航 · 李想 · 刘家昊

FRONTIER — unique 5L MHV + NMHV symbols · $>3.1 \times 10^{10}$ integer coefficients · all-loop sequences

7

points
MHV + NMHV

all-loop patterns from exact finite-loop data

5L

complete symbols

integrability · adjacency · collinear data

∞

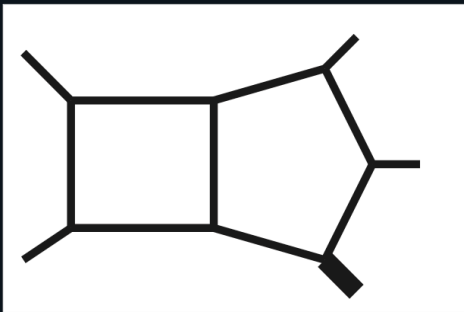
all-loop patterns

sequences from exact finite-loop data

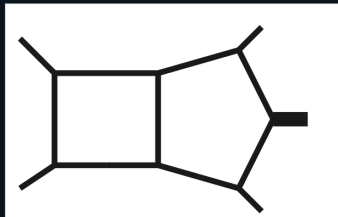
The first multi-loop 4pt NMHV FF

with 刘家昊 · 杨清霖

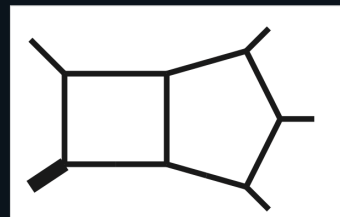
FIRST — multi-loop non-MHV · same 88-letter alphabet across checked MHV / NMHV · unique 3L symbol



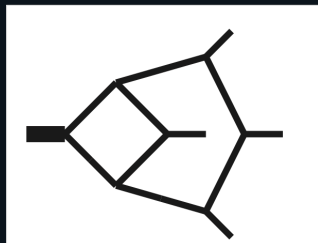
PBmzz



PBzmm



PBzzz



HBzzz



DPzz

- **2L** NMHV leading singularities + one-mass function space
- **3L** same 88 letters + extended Steinmann adjacency
- **(triple) collinear** → new splitting functions + lower-point data
- **checks** soft · double-soft · DDCl

PUBLIC THROUGH 3 LOOPS

FOUR-POINT FORM FACTORS · NEW RESULT

SYM FF $\rightarrow$ max weight of Higgs + gluon amplitudes

with 刘家昊 · 杨清霖

NEW RESULT — the 2L four-point MHV + NMHV form factors determine the maximal-weight functions across Higgs helicity sectors

MHV-like helicities

$++++ \cdot --++ \cdot -+-+$

$\leftrightarrow$ MHV function sectors

helicity-dependent rational prefactors · common pure functions

MAXIMAL-WEIGHT MAP

NMHV-like helicity

$+++ -$

$\leftrightarrow R_i^\pm + S_i$ sectors

rational + three-mass-root prefactors · new functions

RATIONAL + ALGEBRAIC MAP

ONE FORM-FACTOR DATA SET · multiple Higgs helicities · maximal-weight QCD information

[analytic 2L Higgs + 2 jets: 2605.04009](#) · [our 4pt NMHV FF: 2605.28955](#) · our 2L FF $\leftrightarrow$ Higgs maximal-weight map

QCD + HIGGS · NEW PACKAGE

Auto Higgs + QCD prefactors

with 刘家昊

QCD BENCHMARK → HIGGS FRONTIER — reproduce the Henn et al. QCD corpus · generate new Higgs prefactors

QCD · decisive benchmark

Henn et al.
reproduced automatically

years of leading-singularity / prefactor results

Higgs · new discovery

new prefactor families
generated automatically

the maximal-weight helicity map on the previous page

lower-point blocks

Higgs · YM · QCD



enumerate diagrams

helicities · topologies



cut + glue

BCFW · leading singularities



prefactor basis

rational + algebraic sectors

FULLY AUTOMATIC AT MAXIMAL WEIGHT · lower-point data → QCD + Higgs prefactor bases

Automatic bootstrap in a wide context

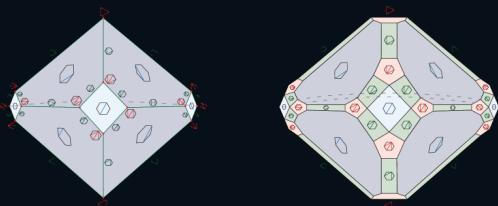
PHYSICS	FRONTIER REACHED	MACHINE-READABLE STRUCTURE
amplitudes	5L heptagon	integrability · adjacency · collinear
form factors → Higgs	3L NMHV FF · 2L $H+4g$	alphabets · helicity sectors · shared functions
reusable tools	AsymBoot · prefactors · FI / Landau	automatic construction + physical checks

AI II FRONTIER — exact spaces → 5L amplitudes → 3L form factors → $H+4g$ · alphabets reveal patterns

Three routes to cosmological observables

wavefunctions / Graph-DE

polytopes + directed graphs
→ integrals / DEs



with 姜旭航 · 刘家昊 · 杨清霖 · 张耀奇

dS correlators

correlator-first recursion
→ smaller checked
alphabets

leaf collapse + graph
fusion

chains · stars · tree families

with Chandramouli Chowdhury · 苏永祥 · 杨东昱

spinning

cuts reconstruct $YM_{4,5,6}$
all-plus → sQED + YM



with 梅嘉杰 · 莫裕宇

wavefunction DEs ↔ correlator recursion ↔ spinning cuts

Edge contractions generate graph differential equations

with 姜旭航 · 刘家昊 · 杨清霖 · 张耀奇

FRONTIER — edge-contraction DEs for arbitrary graph families · trees + loop integrands

$$\begin{aligned}
 d \left[\begin{array}{c} 1 \quad 3 \\ \downarrow \quad \downarrow \\ 2 \quad 4 \end{array} \right] &= d \log \omega_1 \left[\begin{array}{c} 1 \quad 3 \\ \downarrow \quad \downarrow \\ 2 \quad 4 \end{array} - q_1 \begin{array}{c} 1 \quad 3 \\ \downarrow \quad \downarrow \\ 2 \quad 4 \end{array} + i \begin{array}{c} 1+3 \\ \downarrow \quad \downarrow \\ 2 \quad 4 \end{array} + i \begin{array}{c} 1+2 \\ \downarrow \quad \downarrow \\ 3 \quad 4 \end{array} \right] \\
 &+ d \log \omega_2 \left[\begin{array}{c} 1 \quad 3 \\ \downarrow \quad \downarrow \\ 2 \quad 4 \end{array} - q_2 \begin{array}{c} 1 \quad 3 \\ \downarrow \quad \downarrow \\ 2 \quad 4 \end{array} + i \begin{array}{c} 1 \quad 3 \\ \downarrow \quad \downarrow \\ 2+4 \end{array} - i \begin{array}{c} 1+2 \\ \downarrow \quad \downarrow \\ 3 \quad 4 \end{array} \right] \\
 &+ d \log \omega_3 \left[\begin{array}{c} 1 \quad 3 \\ \downarrow \quad \downarrow \\ 2 \quad 4 \end{array} - q_3 \begin{array}{c} 1 \quad 3 \\ \downarrow \quad \downarrow \\ 2 \quad 4 \end{array} + i \begin{array}{c} 1 \quad 3 \\ \downarrow \quad \downarrow \\ 2 \quad 3+4 \end{array} - i \begin{array}{c} 1+3 \\ \downarrow \quad \downarrow \\ 2 \quad 4 \end{array} \right] \\
 &+ d \log \omega_4 \left[\begin{array}{c} 1 \quad 3 \\ \downarrow \quad \downarrow \\ 2 \quad 4 \end{array} - q_4 \begin{array}{c} 1 \quad 3 \\ \downarrow \quad \downarrow \\ 2 \quad 4 \end{array} - i \begin{array}{c} 1 \quad 3 \\ \downarrow \quad \downarrow \\ 2 \quad 3+4 \end{array} - i \begin{array}{c} 1 \quad 3 \\ \downarrow \quad \downarrow \\ 2+4 \end{array} \right]
 \end{aligned}$$

$$d\mathcal{J}_G \sim \sum_{e \in E(G)} \omega_e \mathcal{J}_{G/e}$$

- directed graphs
- terminal data closes the system

Correlator recursion shrinks the dS alphabet

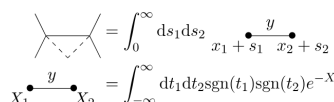
with Chandramouli Chowdhury · 苏永祥 · 杨东昱

FRONTIER — correlator-first recursion · smaller alphabets for checked chains and stars

correlator block → collapse a leaf · fuse lower-point graphs

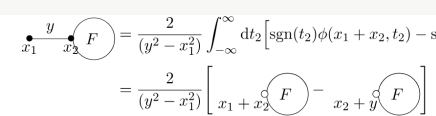
direct representation

dressing rules → time integrals


$$\begin{aligned} \text{Diagram} &= \int_0^\infty ds_1 ds_2 \text{Diagram} \\ &= \int_{-\infty}^\infty dt_1 dt_2 \text{sgn}(t_1) \text{sgn}(t_2) e^{-X_1|t_1|} e^{-X_2|t_2|} G_F(t_1, t_2; y) \end{aligned} \tag{2.14}$$

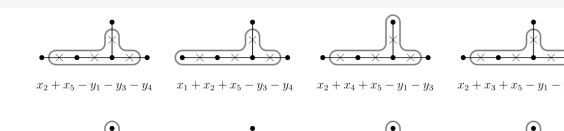
leaf recursion

local collapse → lower-point graphs


$$\begin{aligned} \text{Diagram} &= \frac{2}{(y^2 - x_1^2)} \int_{-\infty}^\infty dt_2 \left[\text{sgn}(t_2) \phi(x_1 + x_2, t_2) - \text{sgn}(t_2) \phi(x_2 + y, t_2) \right] F(t_2) \\ &= \frac{2}{(y^2 - x_1^2)} \left[\text{Diagram} - \text{Diagram} \right] \end{aligned} \tag{3.6}$$

smaller alphabets

missing letters ↔ tubing data


$$\text{Diagram} = \text{Diagram} \tag{4.13}$$

From cosmological cuts to all-plus bootstraps

with 梅嘉杰 · 莫裕宇

PUBLISHED SEED → NEW RESULTS — YM_{4,5,6} from cuts · all-plus simplicity → sQED + YM laboratories

cuts → YM wavefunctions

$$\Psi_{4,5,6}^{\text{YM}} = \text{cut data} + \text{local completion}$$

projectors · current conservation · flat-space limit

DIRECT FEYNMAN MATCH

all-plus laboratory

$$\text{Res}_{E_T=0} \Psi_n^{+\cdots+} = \mathcal{A}_n^{+\cdots+} = 0$$

the vanishing flat residue fixes nontrivial completion data

RECURSIVE FRONTIER

sQED 6pt · 66 histories

YM 5pt · 11 root sectors

towards 7pt / all- n

Three experiments share one research protocol

MACHINE-READABLE OBJECTS	OPERATIONS	INDEPENDENT CHECKS	FRONTIER
I · geometry curves · graphs · polytopes	generate · cut · optimize	factorization · residues	integrands · large- n · cosmohedra
II · symbols alphabets · functions · singularities	ansatz · bootstrap · reconstruct	integrability · physical limits	5L heptagon · 3L NMHV FF · $H+4g$
III · cosmology directed graphs · cuts	DE · recurse · complete	terminal data · conservation	correlators · spinning wavefunctions

expert design → AI orchestration → independent physics checks

MATURE RESULTS → NEXT AI EXPERIMENTS

A web of particle + string amplitudes

with 曹趣 · 董晋 · 张勇 · 朱凡 et al.

MATURE CORPUS — one-loop modules · years of exact relations and data

biadjoint / scalars
cubic graphs · color ordering

CHY representations
scattering equations

open / heterotic strings
disk integrals · Z-theory

NLSM · YMS · YM
universal expansions

all-n tree amps

gravity
double copy · KLT

KK · BCJ · transmutation
relations across theories

field-theory limit
 $\alpha' \rightarrow 0$

selected one loop
forward limits · partial integrands

AI EXPERIMENT · navigate the web · reconstruct relations · test new theories and representations

[local project map](#) · [CHY · 1307.2199](#) · [strings ↔ field theory · 1812.03369](#) · [one-loop universal expansions · 2412.19629](#)

MATURE RESULTS → NEXT AI EXPERIMENTS

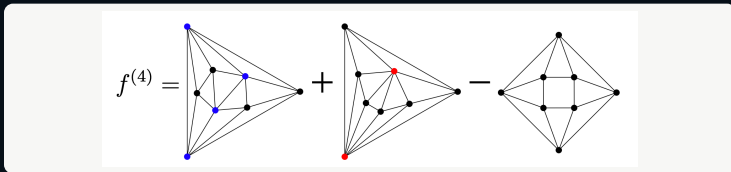
Half-BPS + giant-graviton correlators

with 施灿欣 · 唐一朝 · 张耀奇 · Jacob L. Bourjaily · Congkao Wen

RESULTS — planar 12L · giant gravitons 3L · ABJM 4pt / 6L · 6pt / 2L · 8pt / tree

planar correlators

12L
22M+ coefficients



cusp → double-triangle → triangle

giant gravitons

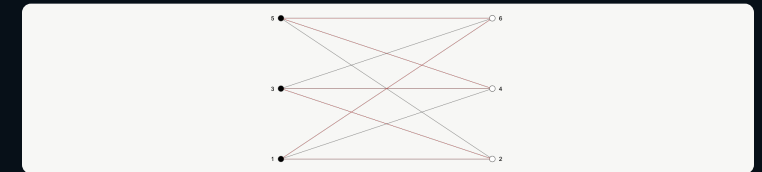
3L
labelled non-planar f -graphs

localisation
+ hidden 10d symmetry

3L non-planar correlator

ABJM

4pt / 6L · 6pt / 2L
8pt / tree



with 张耀奇 et al. · bipartite geometry

AI EXPERIMENT · amplituhedra · correlahedra · f -graph geometries: boundaries → canonical forms → observables

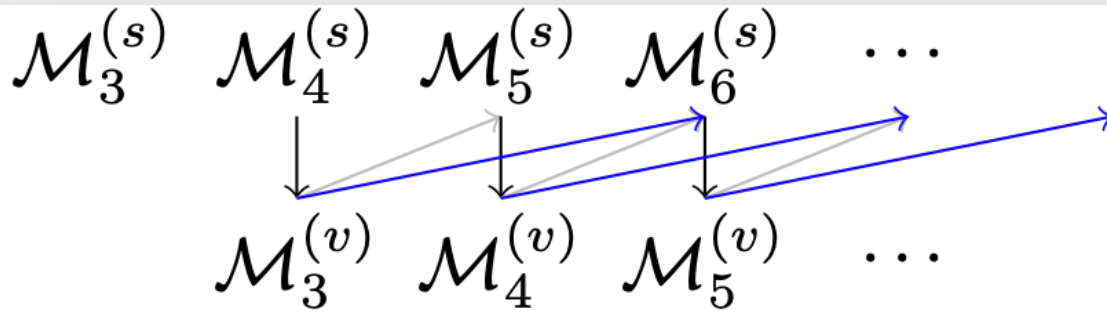
[12L planar · 2503.15593](#) · [giant gravitons · 2605.14281](#) · [ABJM · 2601.21980](#) · [positive geometries · 2505.09808](#)

MATURE RESULTS → NEXT AI EXPERIMENTS

All- n spinning AdS Mellin amplitudes

with 曹趣 · 唐一朝 · 李想 · 莫裕宇 · 杨东昱

FRONTIER — all-multiplicity AdS constructibility · $2n$ scalars → n spinning fields



scalar seeds ↔ spinning Mellin amplitudes

$2n$ scalars → n spinning fields

- factorization / OPE + flat-space limit
- recursive all-multiplicity supergluons
- $2n \rightarrow n$ all-multiplicity scaffolding

AI EXPERIMENT · OPE / factorization + recursion + scaffolding + flat-space checks → systematic AdS observables

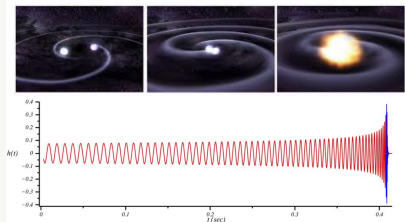
Further horizons

OUTLOOK — classical observables · mathematics beneath amplitudes · precision frontier

C

Classical gravity

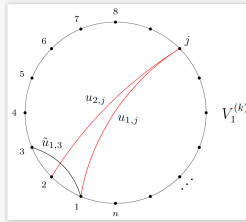
amplitudes → impulse · radiation · waveform



M

New math structures

combinatorics · number theory · geometries etc.
behind particle & string amps



P

Precision frontier

beyond amps: EECs · event shapes
FIs · numerics · precision observables

