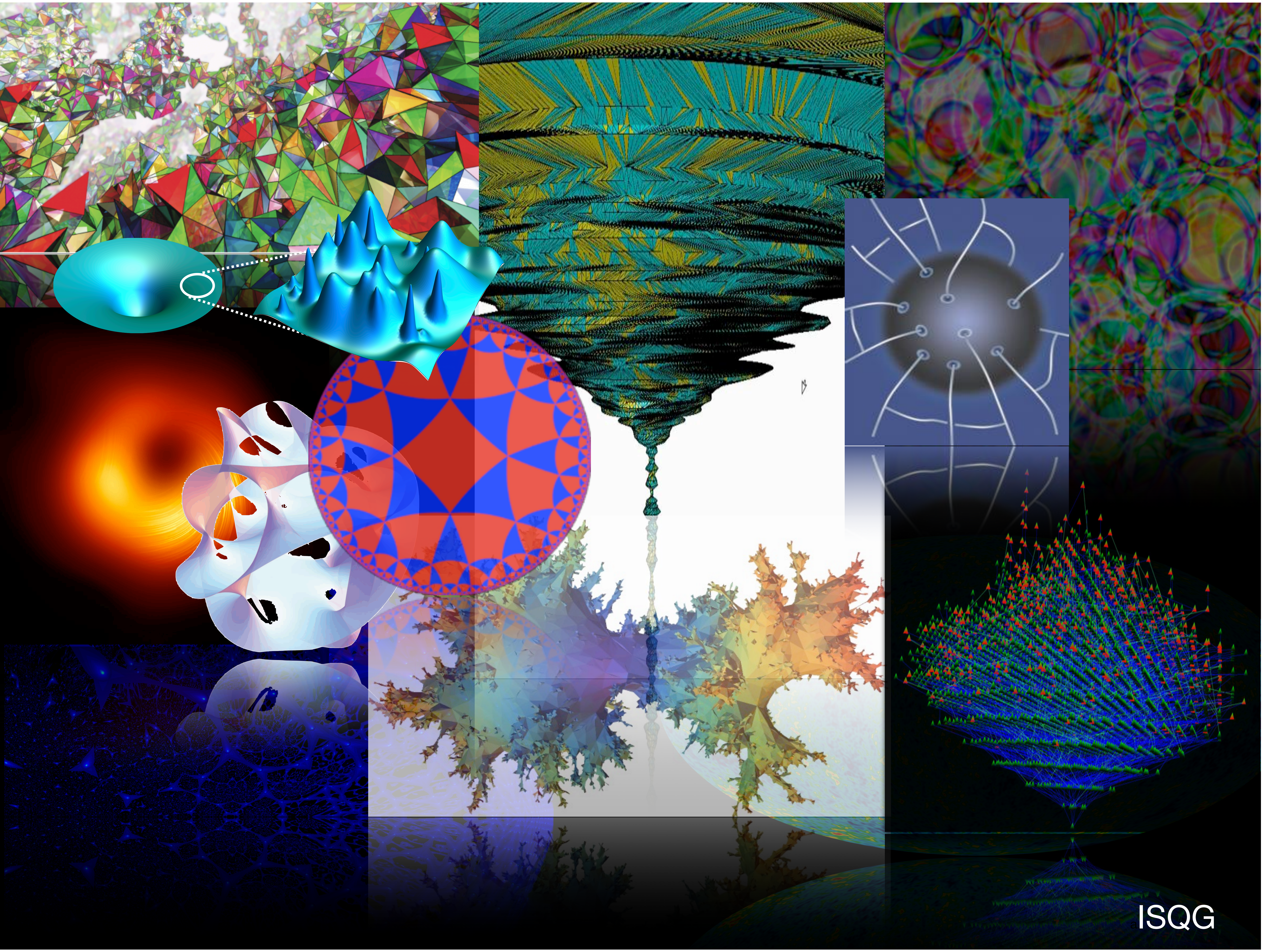
Common challenges in quantum gravity

Bianca Dittrich,
Perimeter Institute

Quantum Gravity 2023, Radboud University Nijmegen

Diversity of ideas



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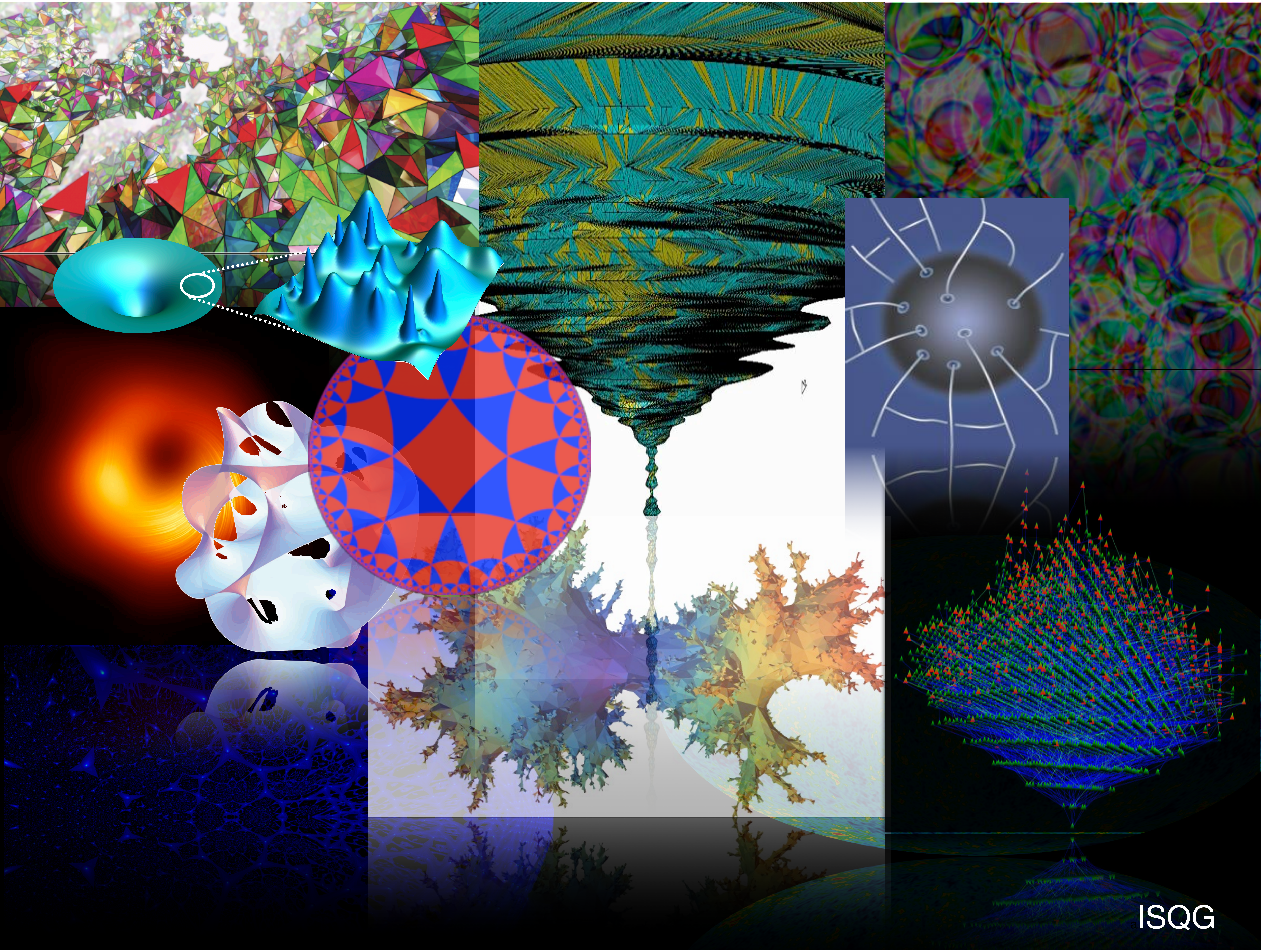


Important to learn from each other,
and to look for shared challenges and principles.

I will present a biased selection of challenges.

[de Boer et al: Frontiers of quantum gravity, shared challenges, converging directions (Snowmass 2021)]

Our universe is Lorentzian

… most of the times.

Euclidean Quantum Gravity

Why???

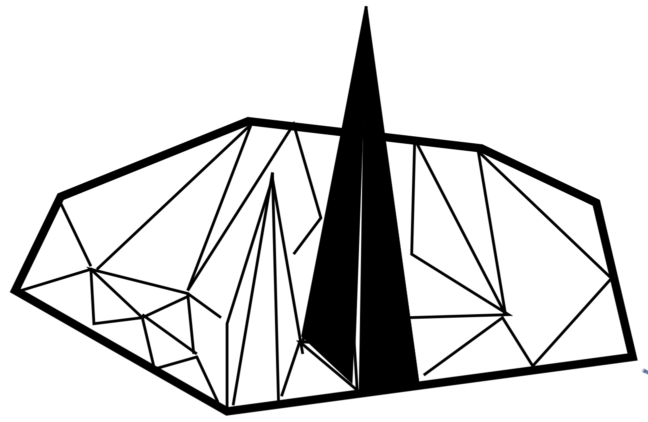
Euclidean Quantum Gravity

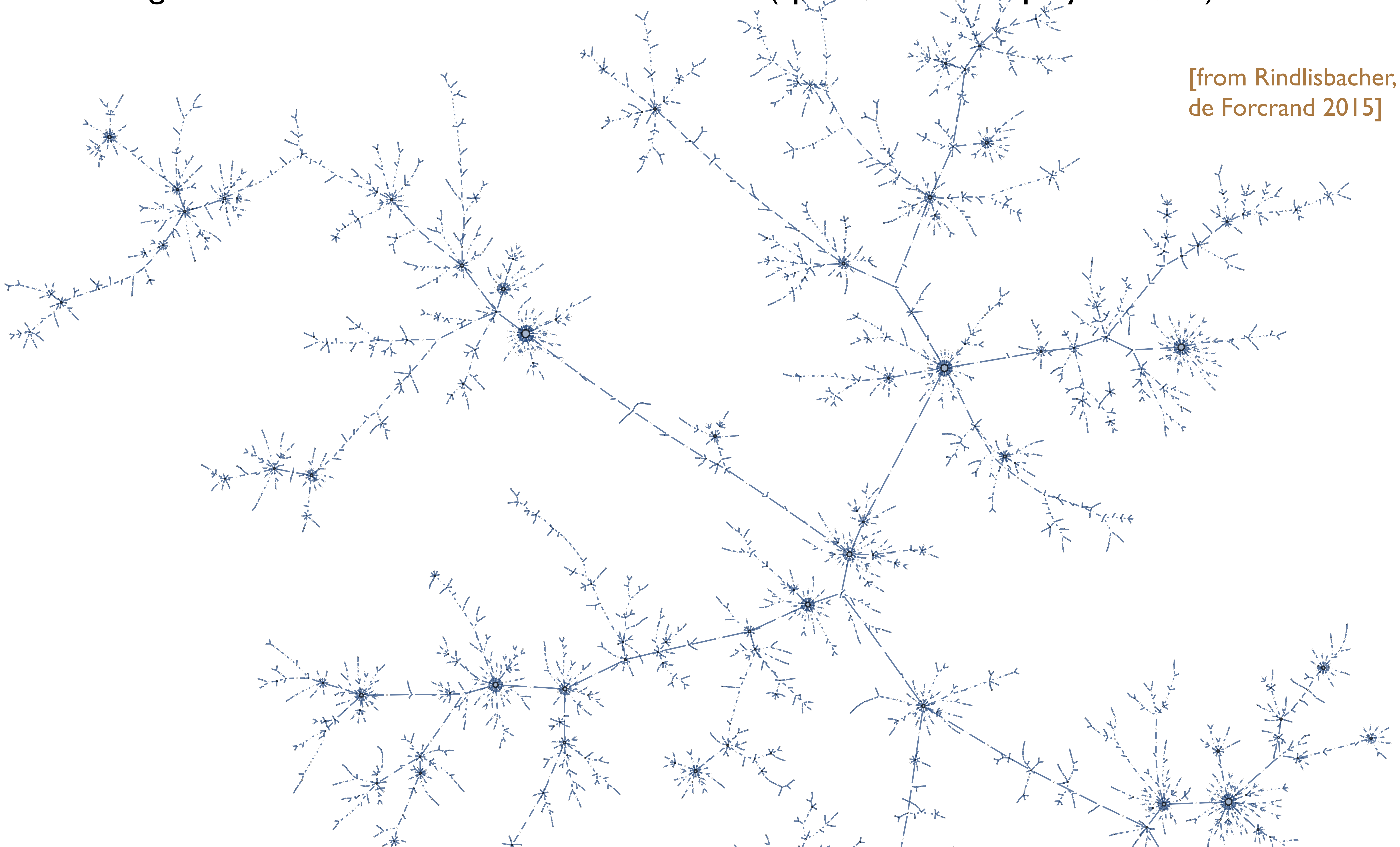
Why did/do we do Euclidean quantum gravity? $Z_E = \int \mathscr{D}\mathrm{geom_E} \;\; \exp(-\mathrm{S}(\mathrm{geom_E}))$ Vs $Z_L = \int \mathscr{D}\mathrm{geom_L} \;\; \exp(\imath \mathrm{S}(\mathrm{geom_L}))$

- Wick rotation: successful strategy in QFT
- Computational techniques: Monte Carlo vs. few techniques for complex amplitudes
- Thermodynamic interpretation

Drawbacks of Euclidean Quantum Gravity

- Conformal factor problem: Action is not bounded from below.
- Lattice simulation: tends to drive system into region where conformal factor is maximized (spikes, branched polymers, …)





[from Rindlisbacher, de Forcrand 2015]

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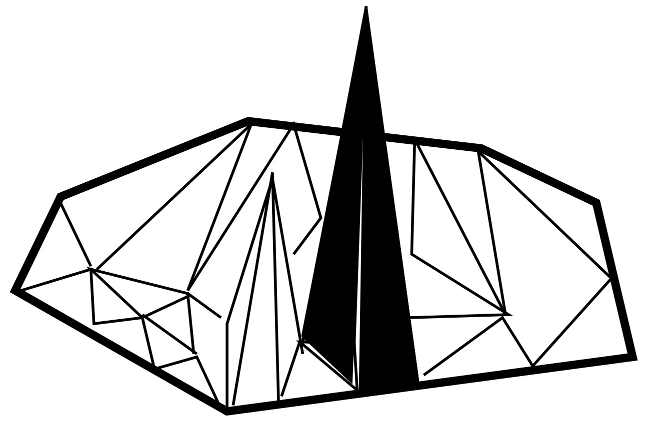

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- Lorentzian configuration space very different from Euclidean configuration space:
  No well-defined Wick rotation. [Ambjorn, Loll, Jurkiewicz et al. 98+: Causal Dynamical Triangulations]

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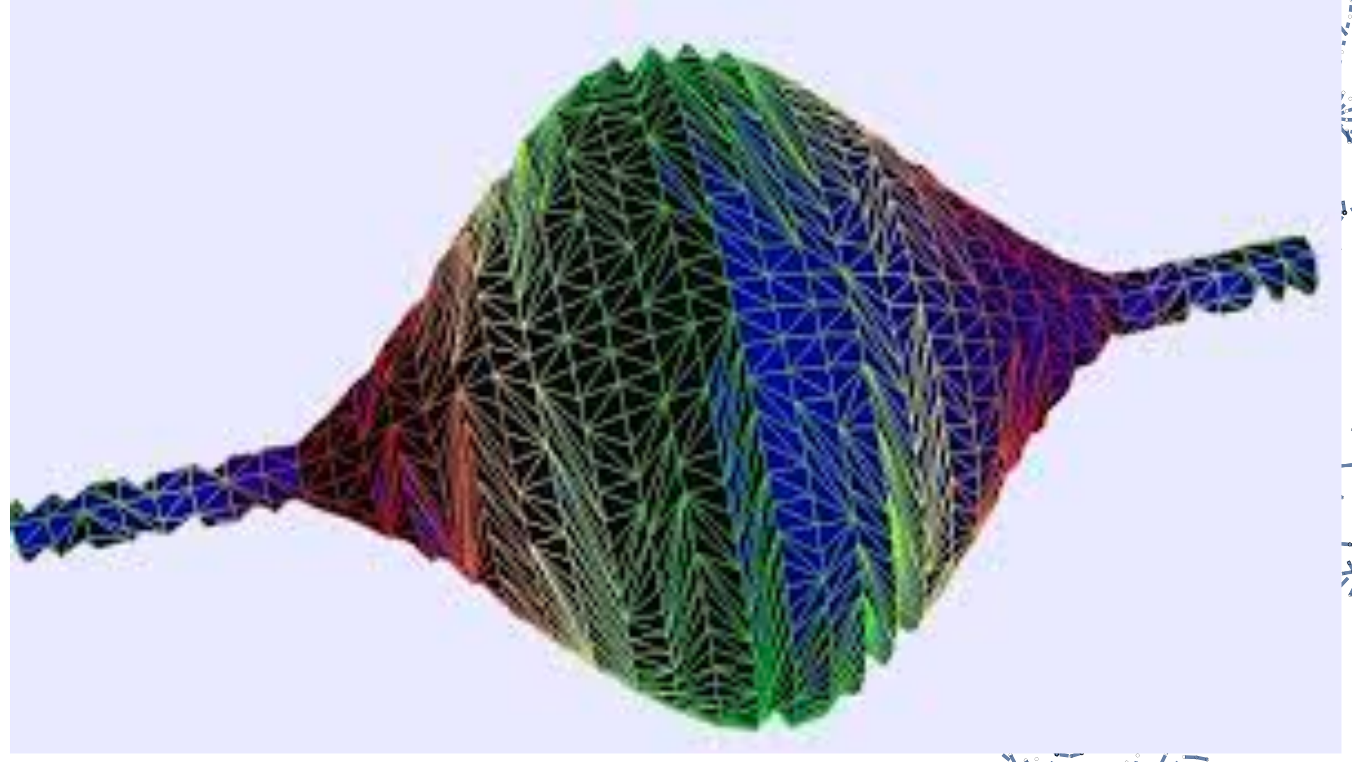
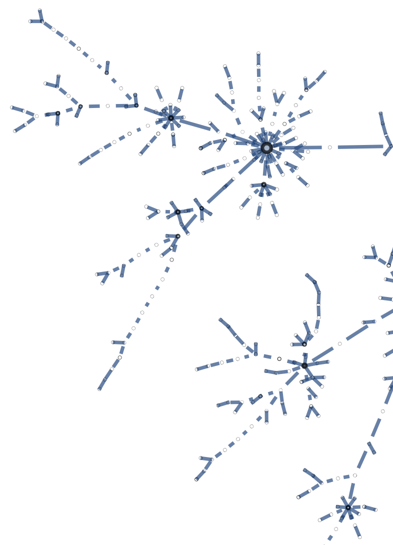


[Goerlich]



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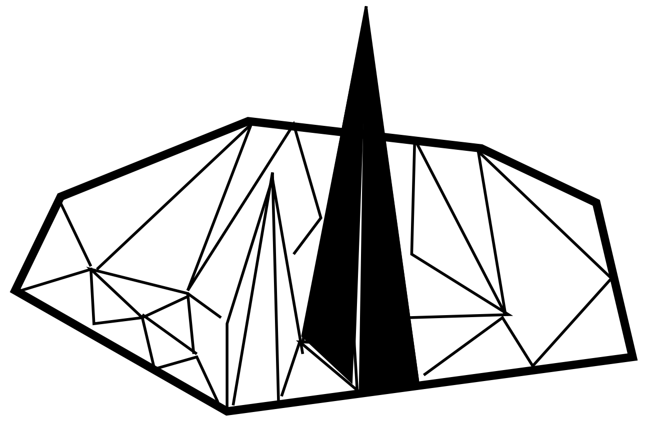

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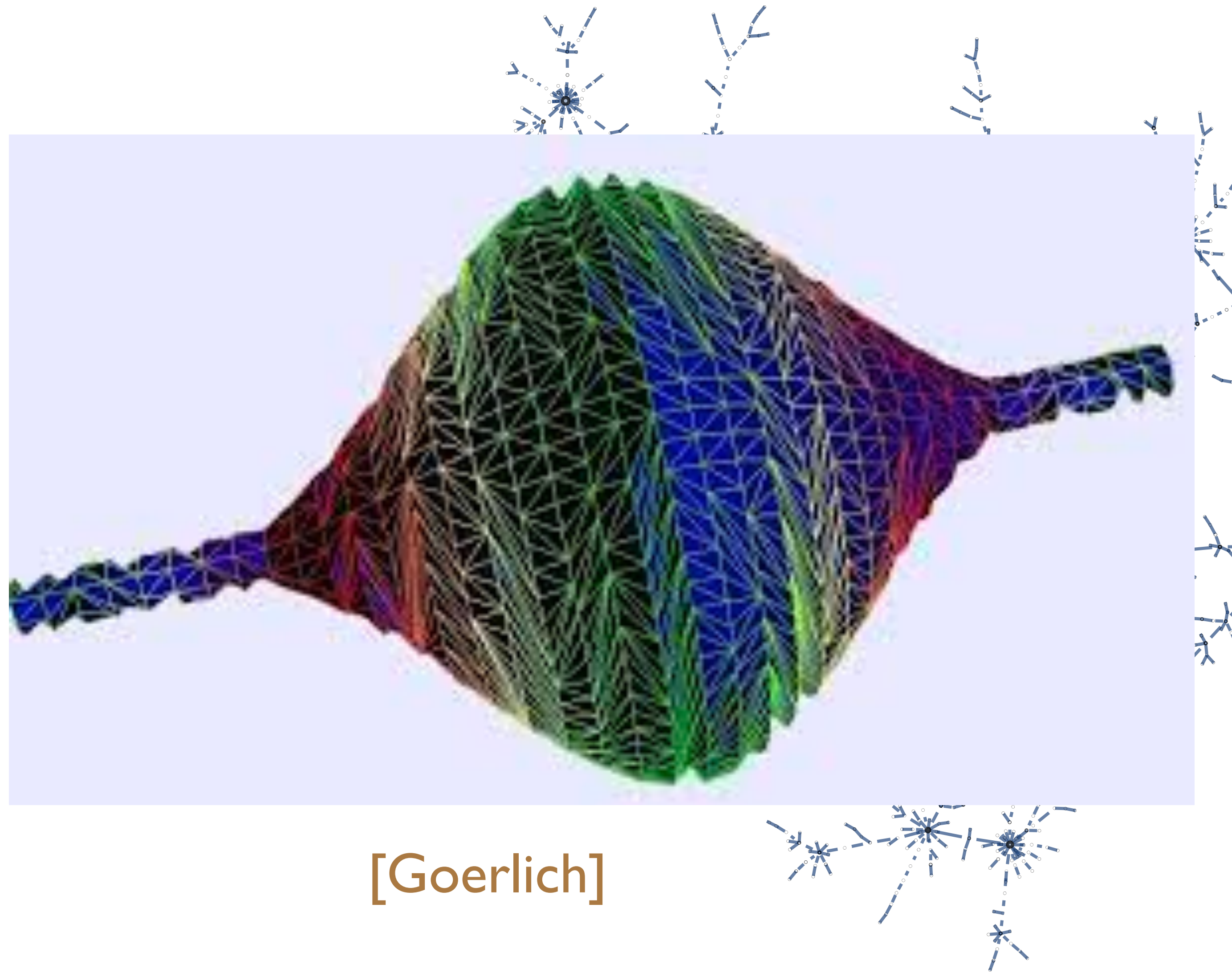
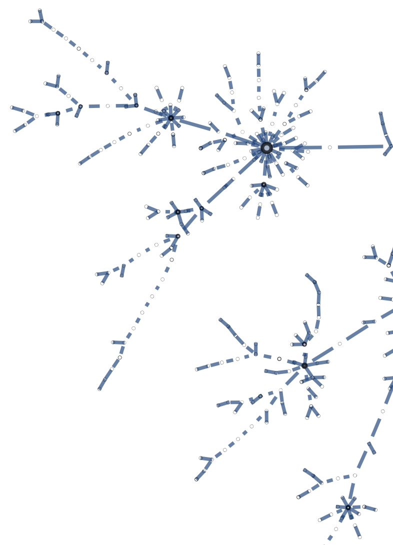


[Goerlich]

- No destructive interference which might cancel out unwanted configurations

[Carlip, Carlip, Surya 22: Causal Sets]   [Talks by Carlip, Surya]



Computational techniques for complex amplitudes

[Talks by Asante, Feldbrugge]

- deformation of integration contour, possible choice - Lefschetz thimbles
  (Semi-classical and numerical)

  [Witten; Turok, Feldbrugge, Lehners et al ; Asante, BD, Padua-Arguelles, …]

- Holomorphic gradient flow / Monte Carlo on Lefschetz thimbles
  (Numerical, "experimental")

  [QCD: Alexandru et al, Spin foams: Han et al, Regge: Jia]

- Acceleration operators for series convergence (for sums and integrals)
  (Numerical)

  [Effective Spin foam cosmology: BD, Padua-Arguelles 23]

- Tensor network renormalization
  (Numerical, so far up to three dimensional systems)

  [Cunningham, Delcamp, BD, Martin-Benito, Mizera, Steinhaus; Ito, Kadoh, Sato]

- Asymptotic Safety
  (Lorentzian configuration space, Lorentzian renormalization flow)

  [Biemans, Platania, Saueressig; Knorr, Platania, Schiffer; Fehre, Litim, Pawlowski, Reichert; Rejzner et al]

  [Talk by Rejzner]

- Machine learning, quantum simulations, ….
  (To be explored: Scaling?)

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Challenge: Methods for large scale systems.

Acceleration techniques for series convergence

[Schmidt 41,   Shanks 55,   Wynn 56, …]   [BD, Padua-Arguelles 23]

A quite simple technique that allows to treat oscillating sums and integrals.
Contour deformation not necessary.   But reproduces results for integrals treated via contour deformation.

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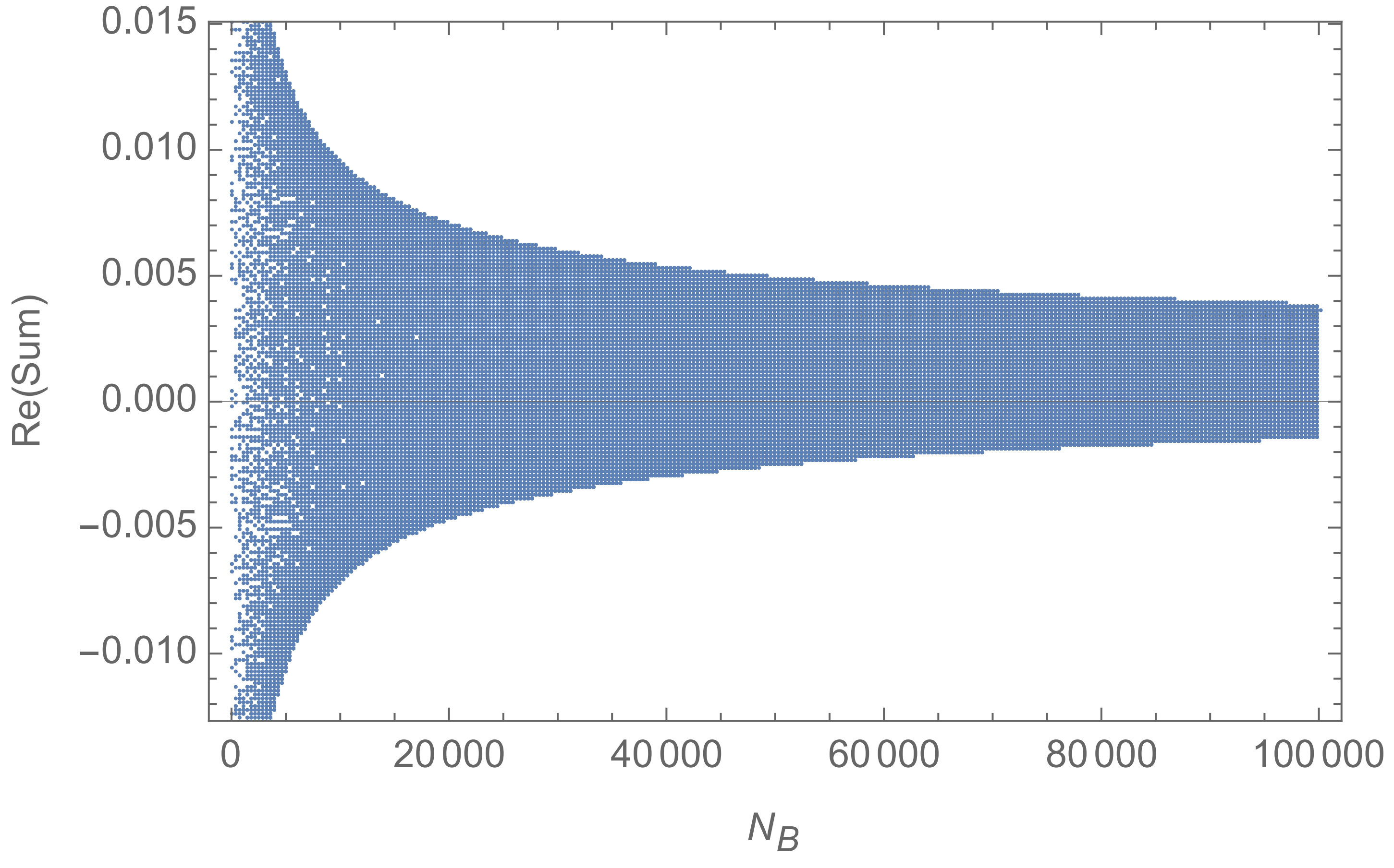

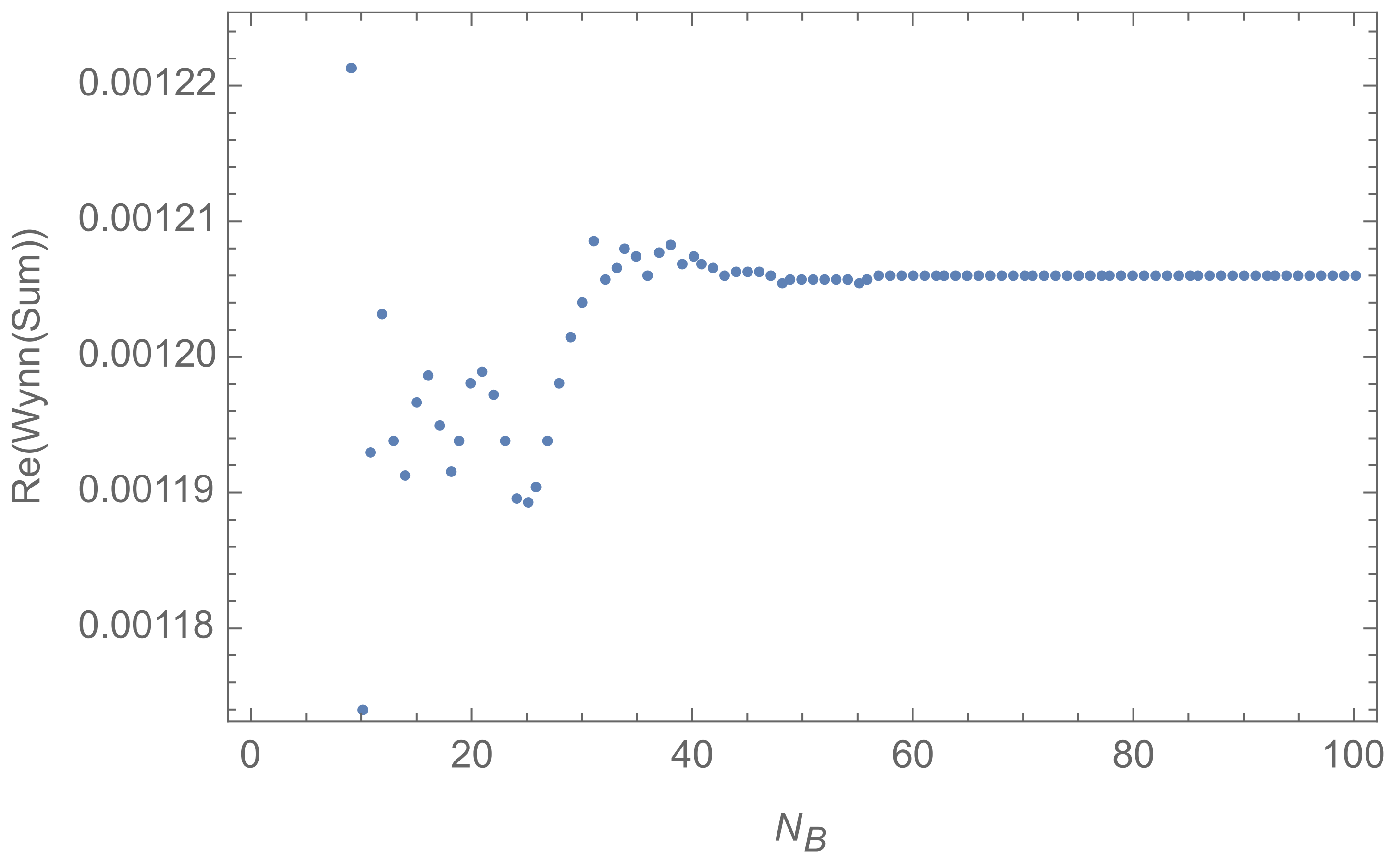

Rel. Error$\sim 10^{-11}$

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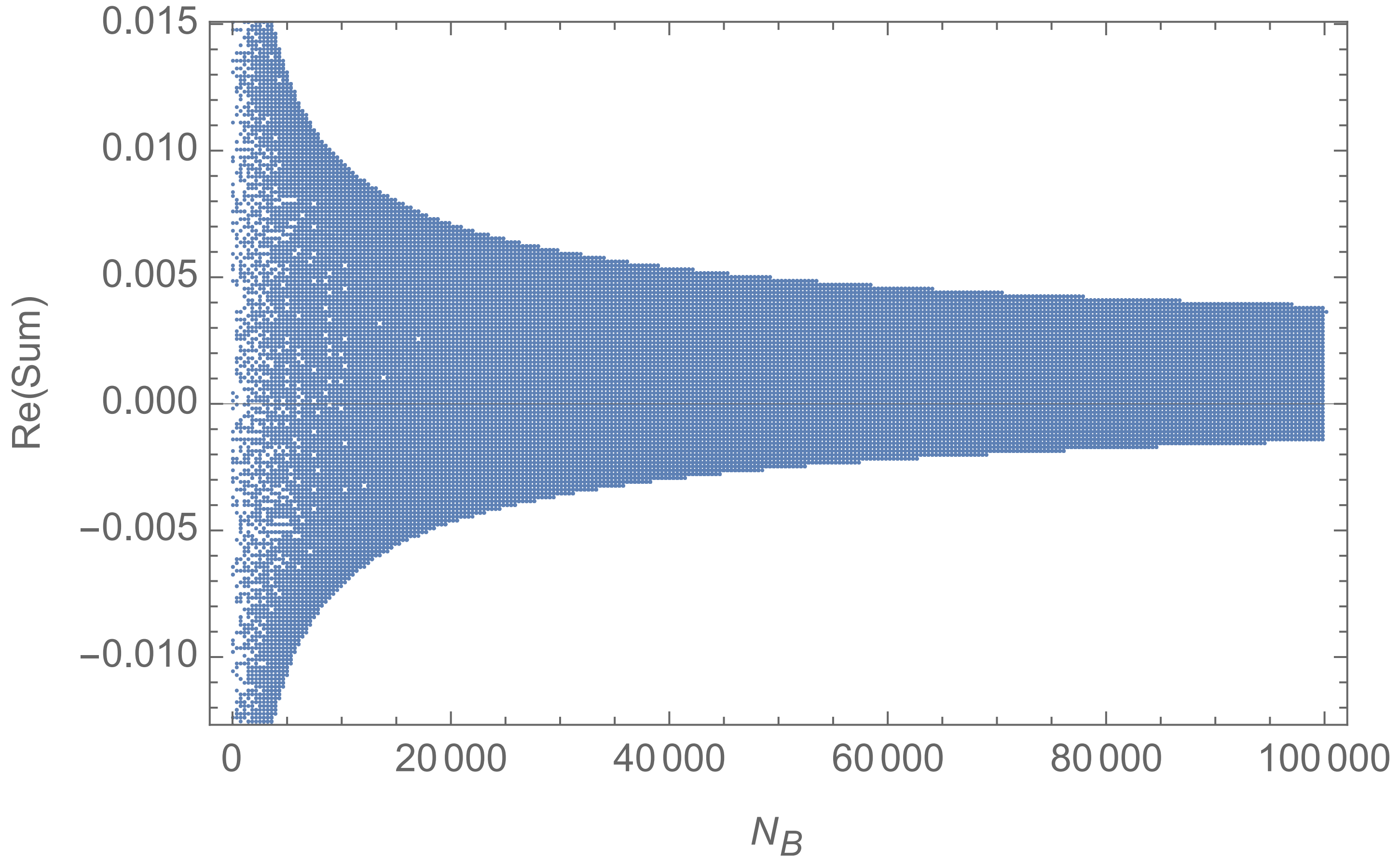

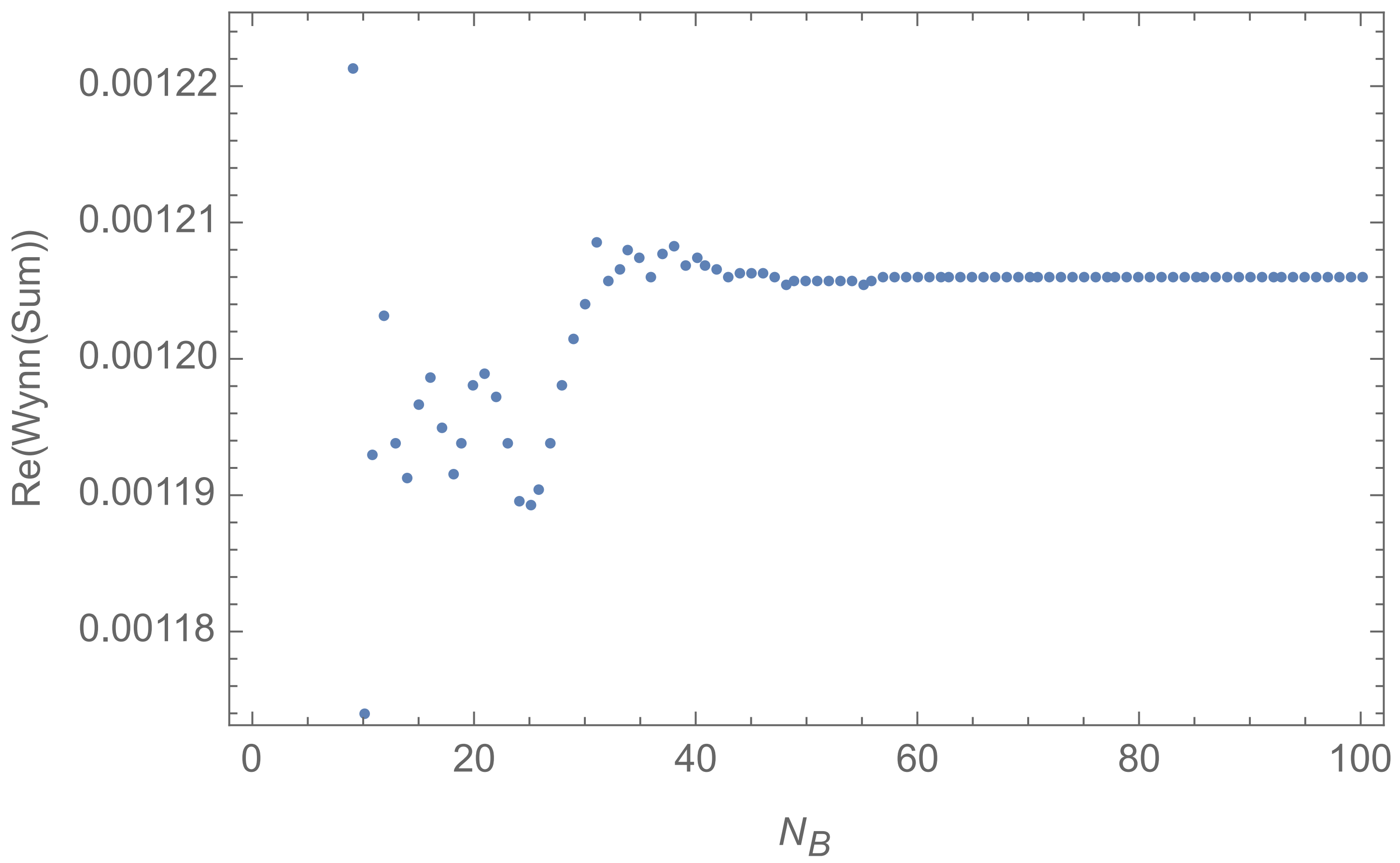

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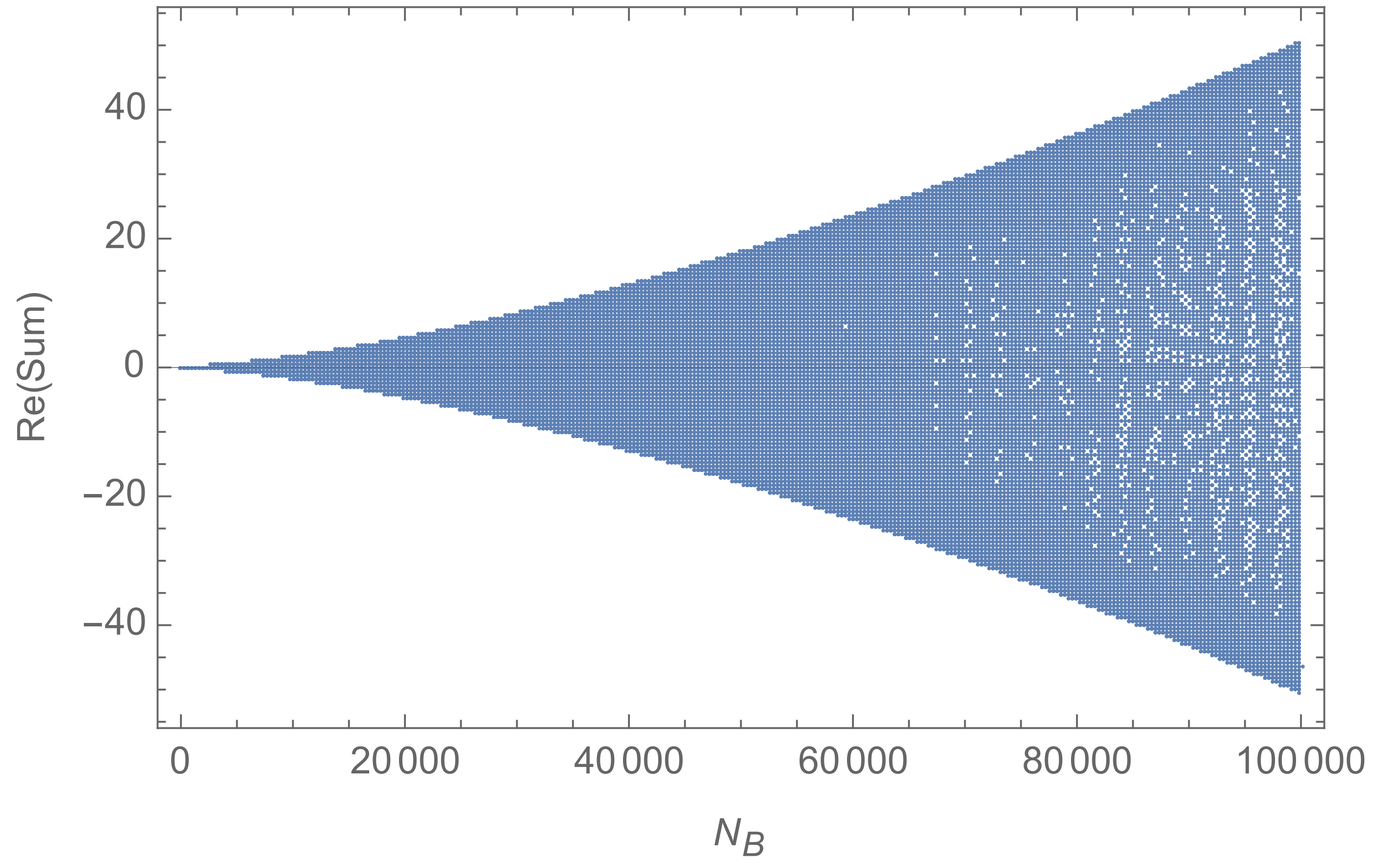
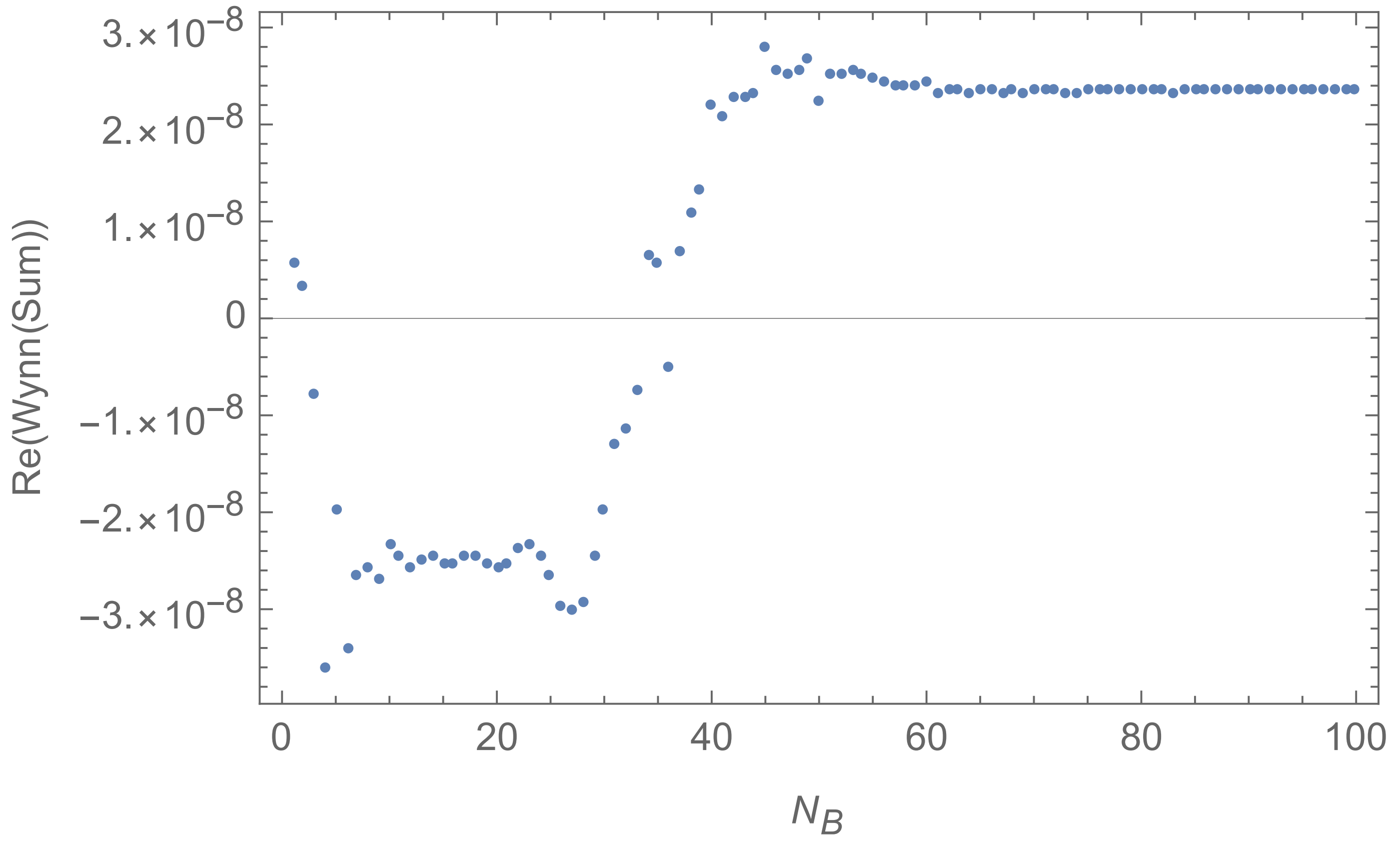
For computation of expectation value:
(Remember this plot)



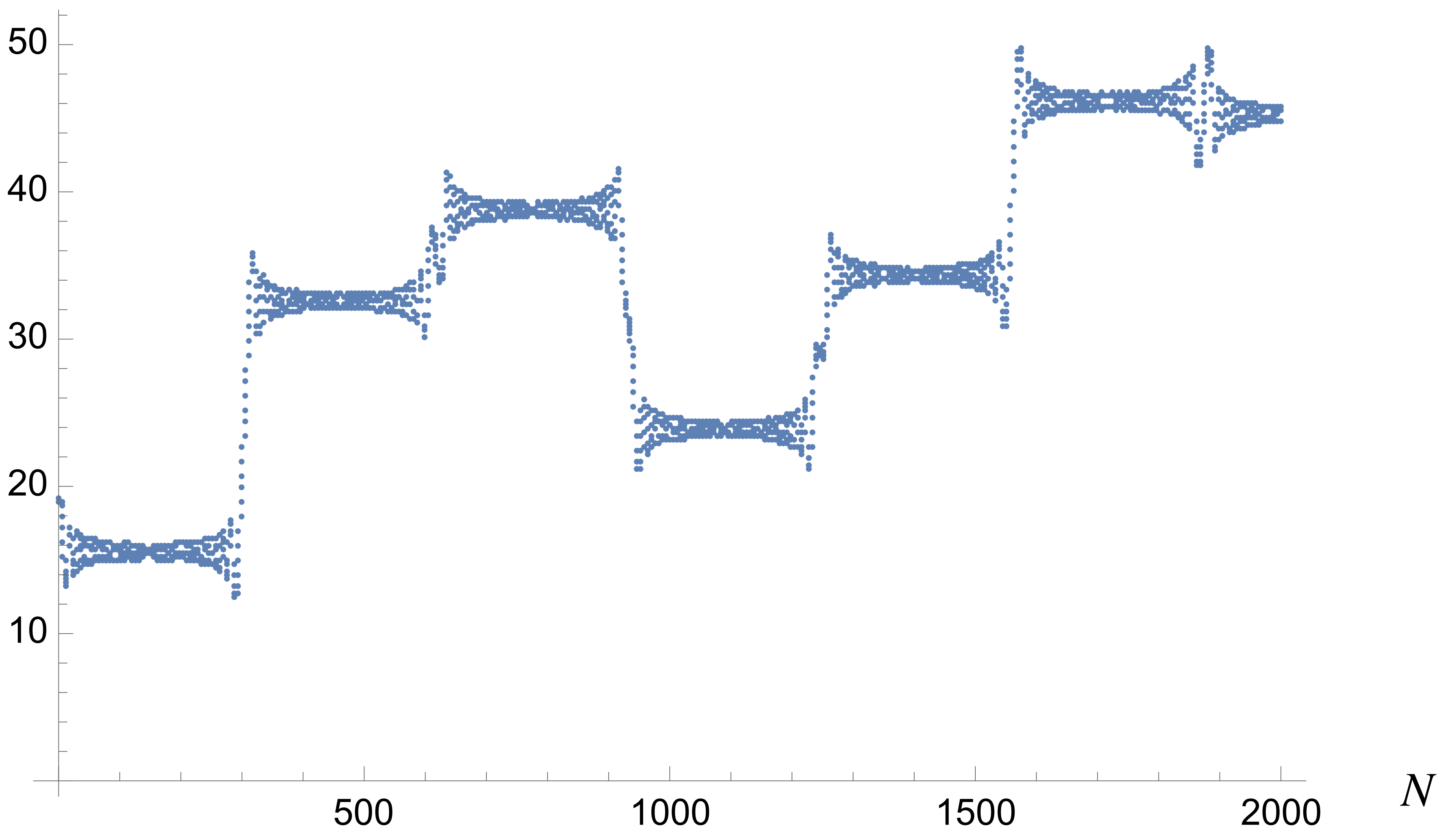


Rel. Error$\sim 10^{-8}$

Works well for sums with actions that are at most linear in the summation variable.
Consistent with quantum mechanics (Bohr quantization).

Action quadratic in discrete variable

$$Re\,@\sum_{k}^{N}\exp(\imath(\frac{x}{10}-1)^2)$$



Partial sums for an action quadratic in the summation variable

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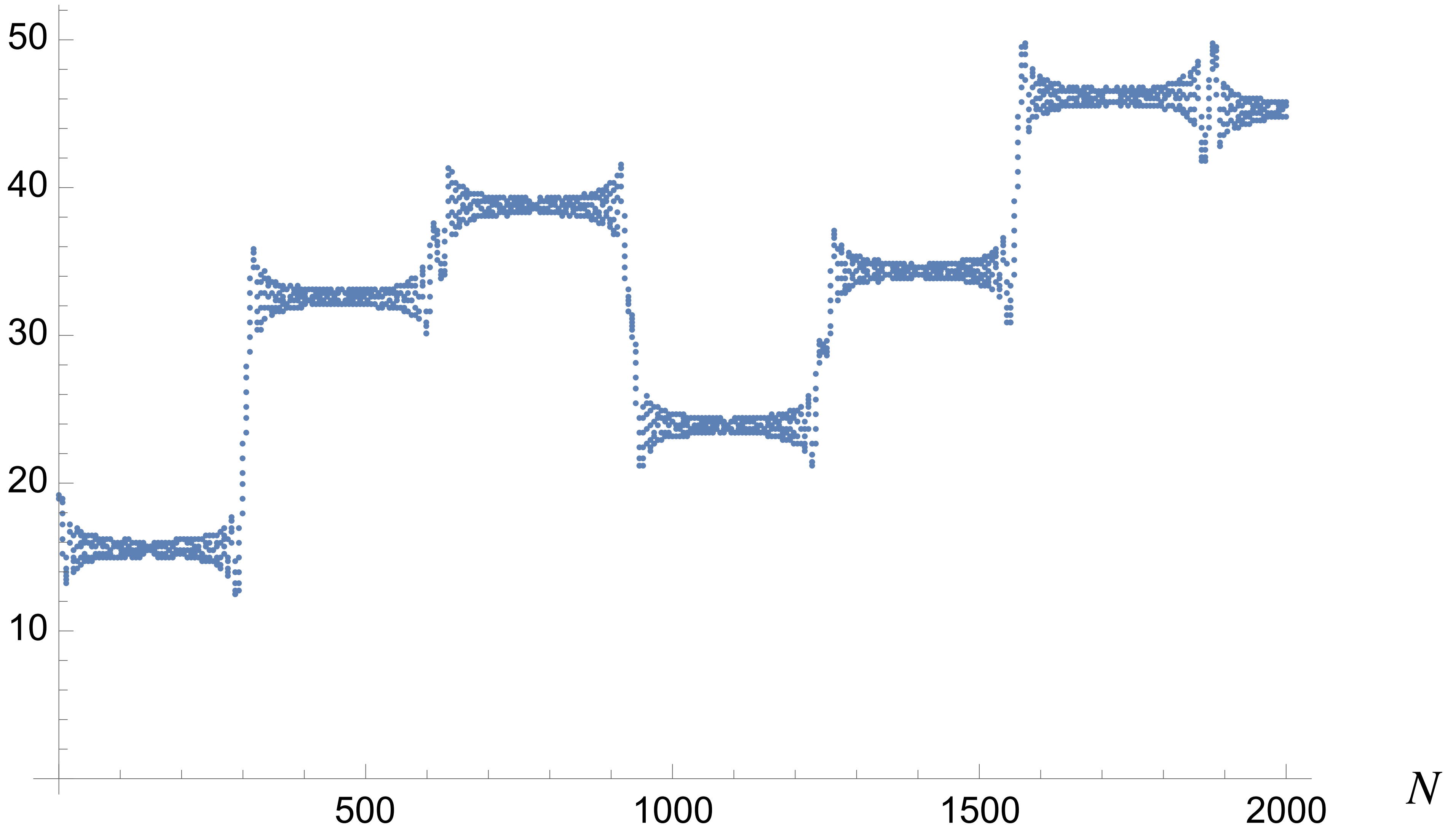

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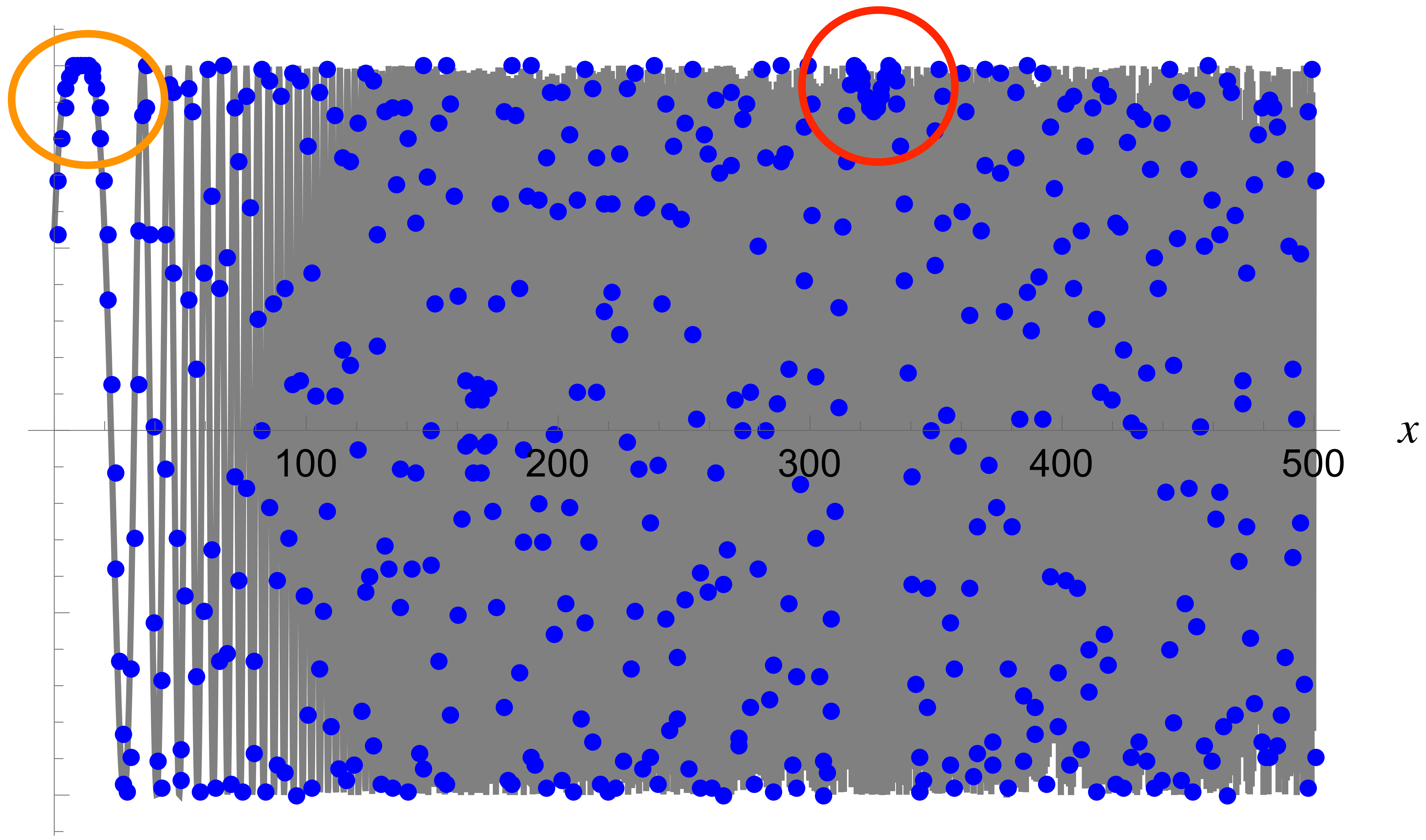

True saddle point

Pseudo saddle point

Conformal factor problem?

Euclidean quantum gravity: rotate conformal factor by hand (if you can)

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Lorentzian path integral: deformation of contour/ Picard-Lefschetz

- Convergence criterium automatically selects 'right' contour

[Mini-superspace: Feldbrugge, Lehners, Turok 17, …
Lorentzian Regge: Asante, BD, Padua-Arguelles 21,
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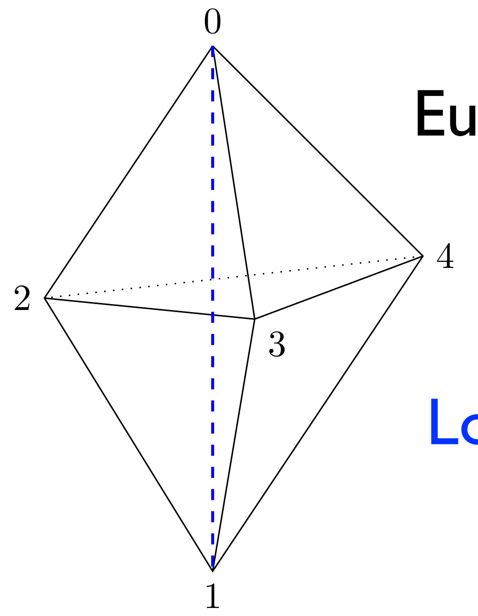

Eucl: $$\sim \int \exp(-p_{3-2}\lambda^2)\ \mathrm{d}\lambda$$

Lor: $$\sim \int \exp(+ip_{3-2}\lambda^2)\ \mathrm{d}\lambda$$

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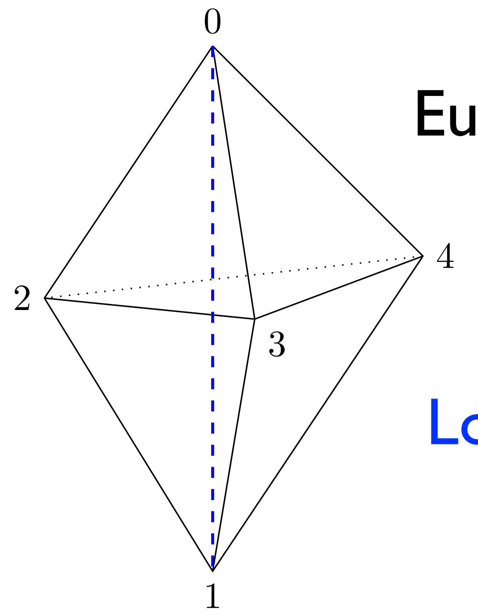

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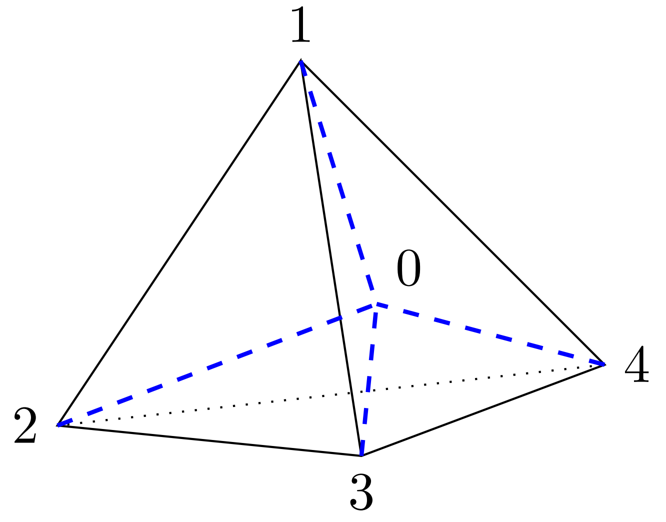

Conformal and gauge modes

$\sim \int \exp(+p_{4-1}\lambda^2)\, \mathrm{d}\lambda$

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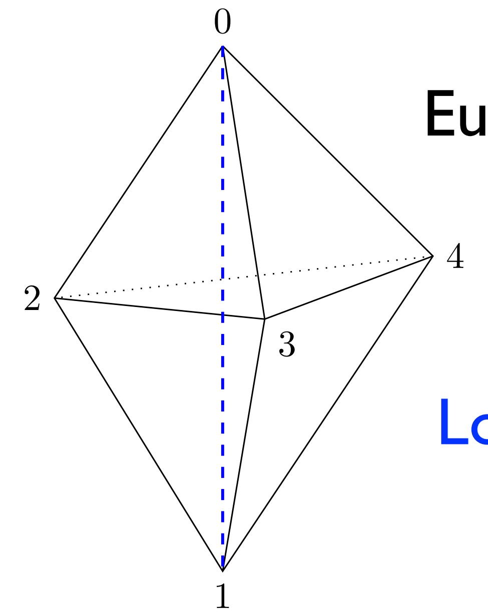

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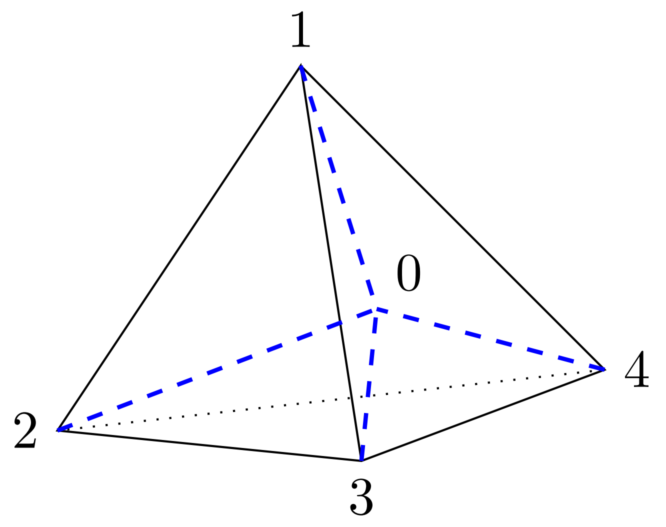

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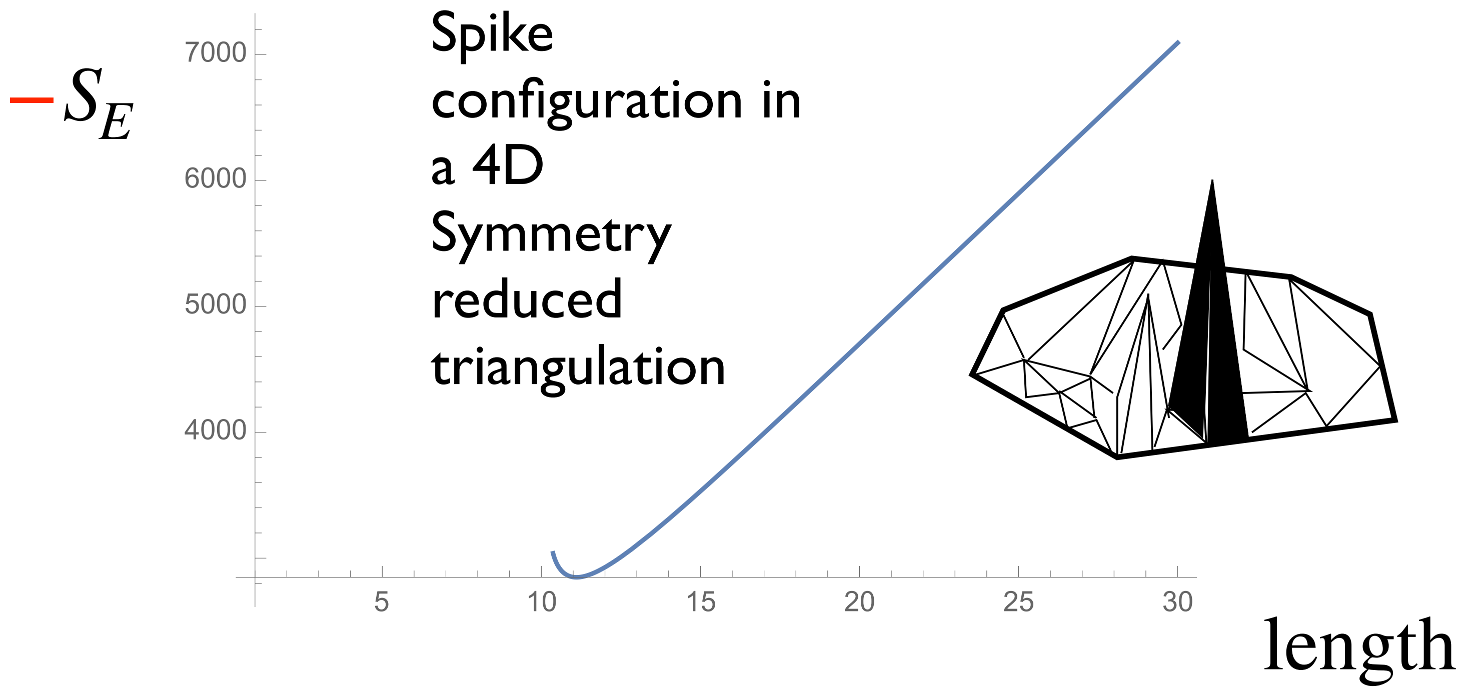

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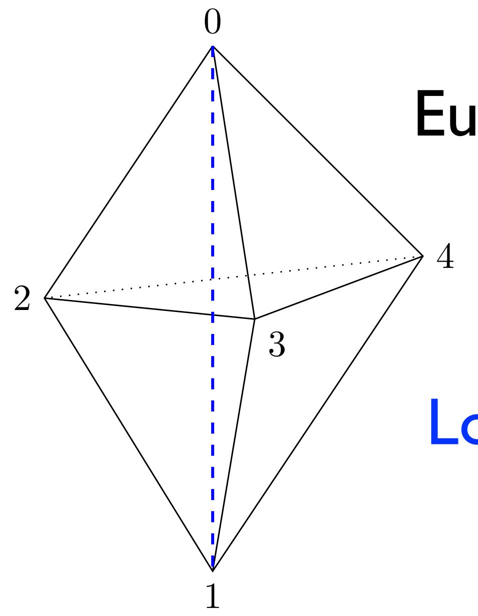

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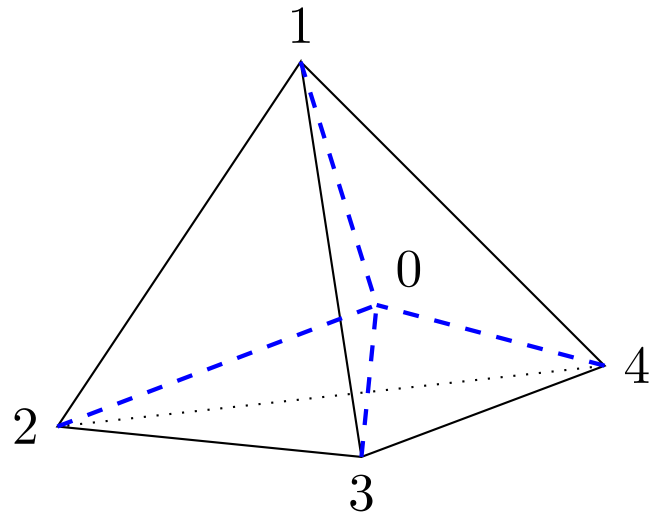

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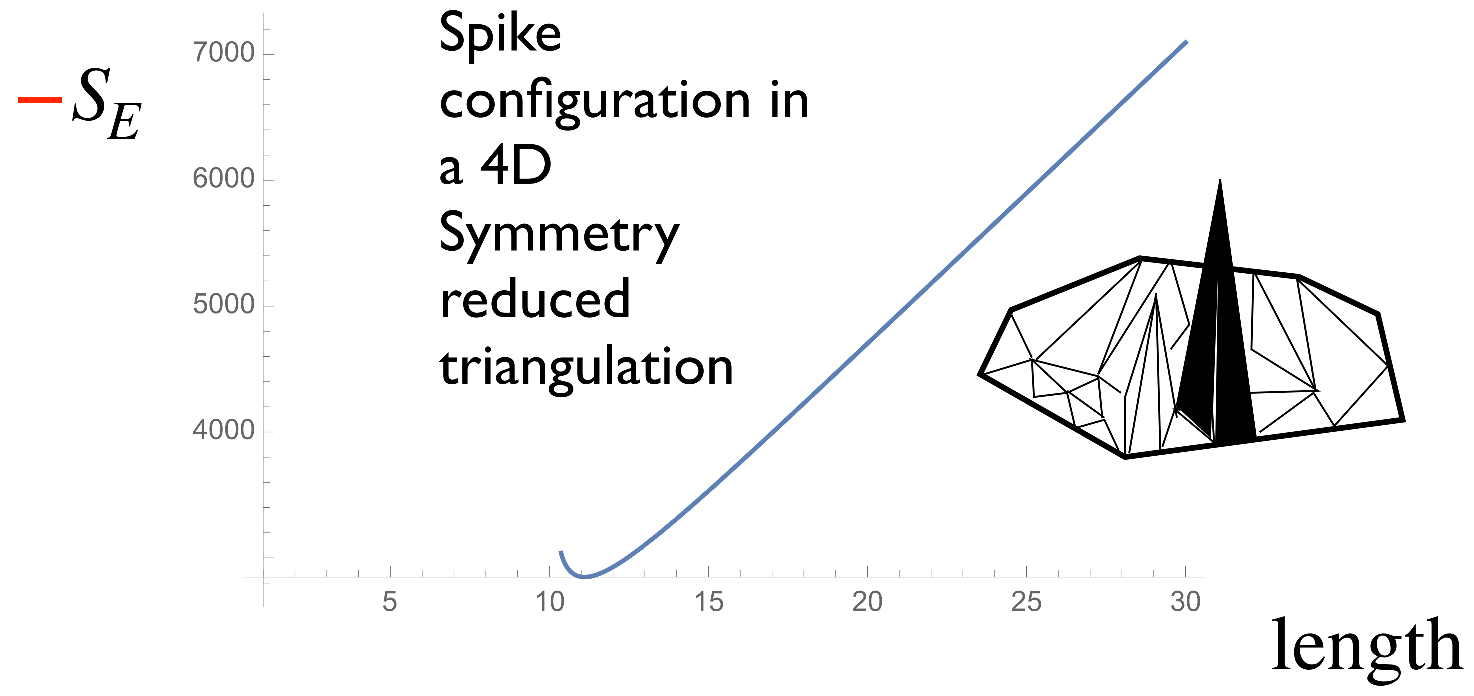

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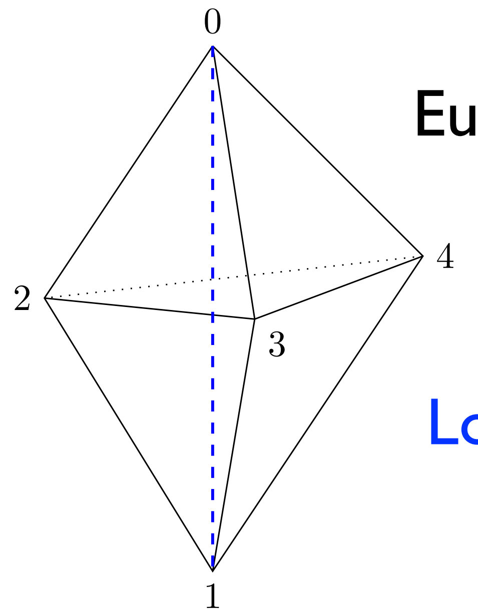

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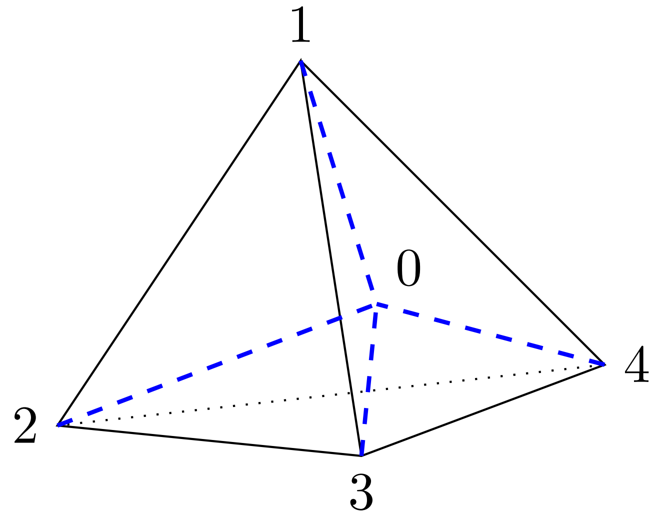

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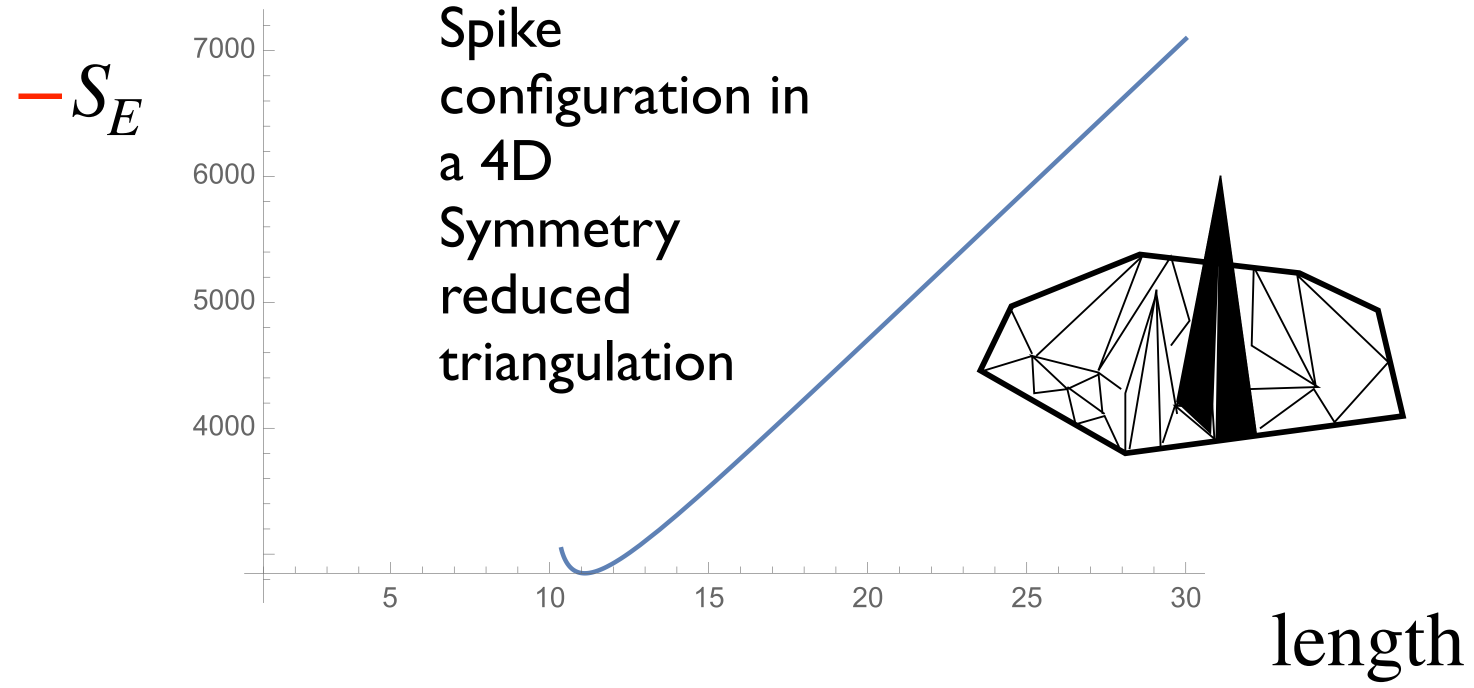

Challenge: Which kind of Euclidean simulations/ calculations to trust?

Lorentzian vs Euclidean configuration space

What kind of Lorentzian configurations to sum over?

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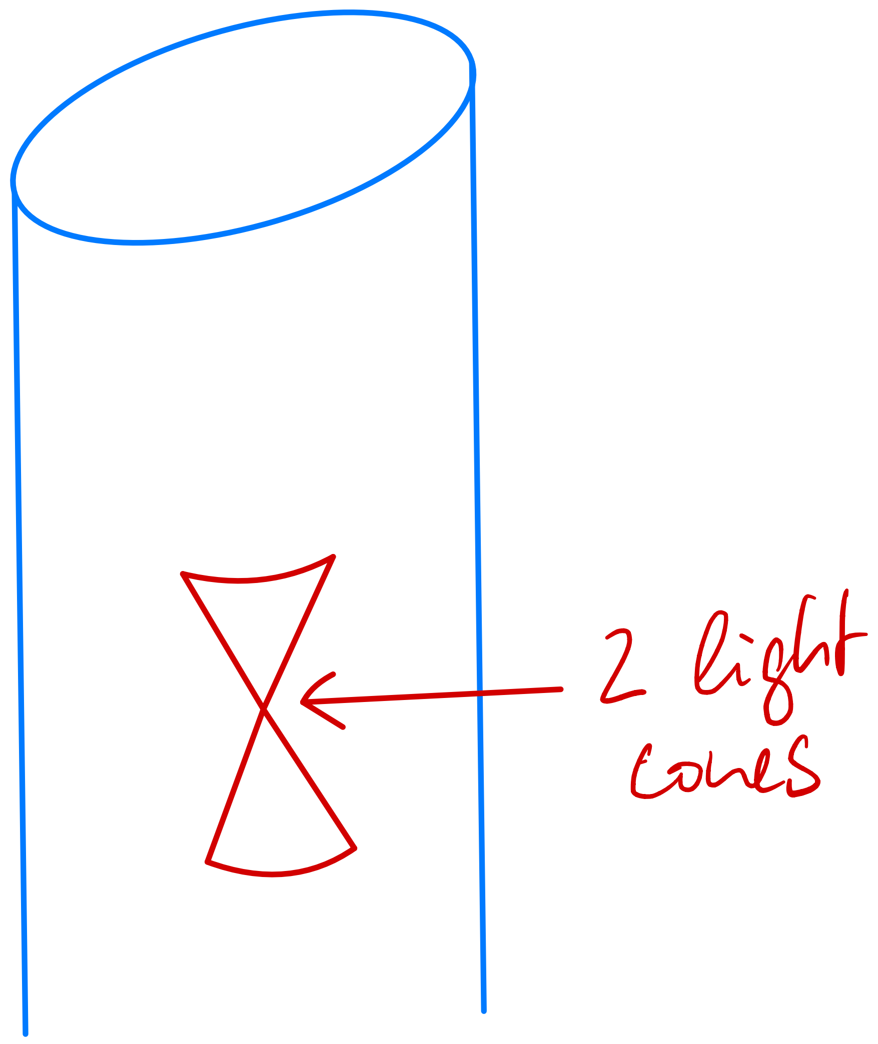

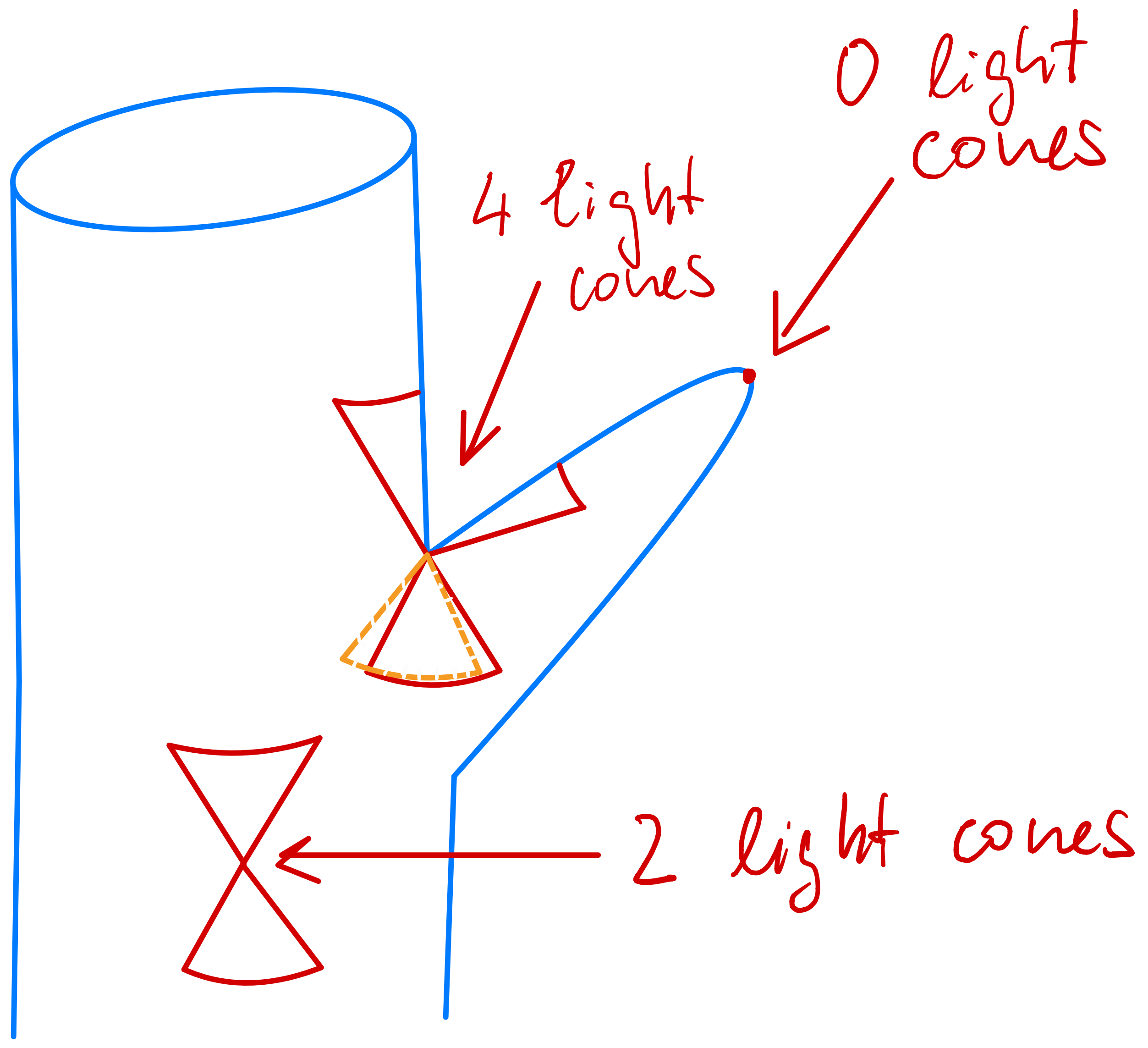

Lorentzian space time with regular light cone structure.

Lorentzian space time with irregular light cone structure.

Lorentzian vs Euclidean configuration space

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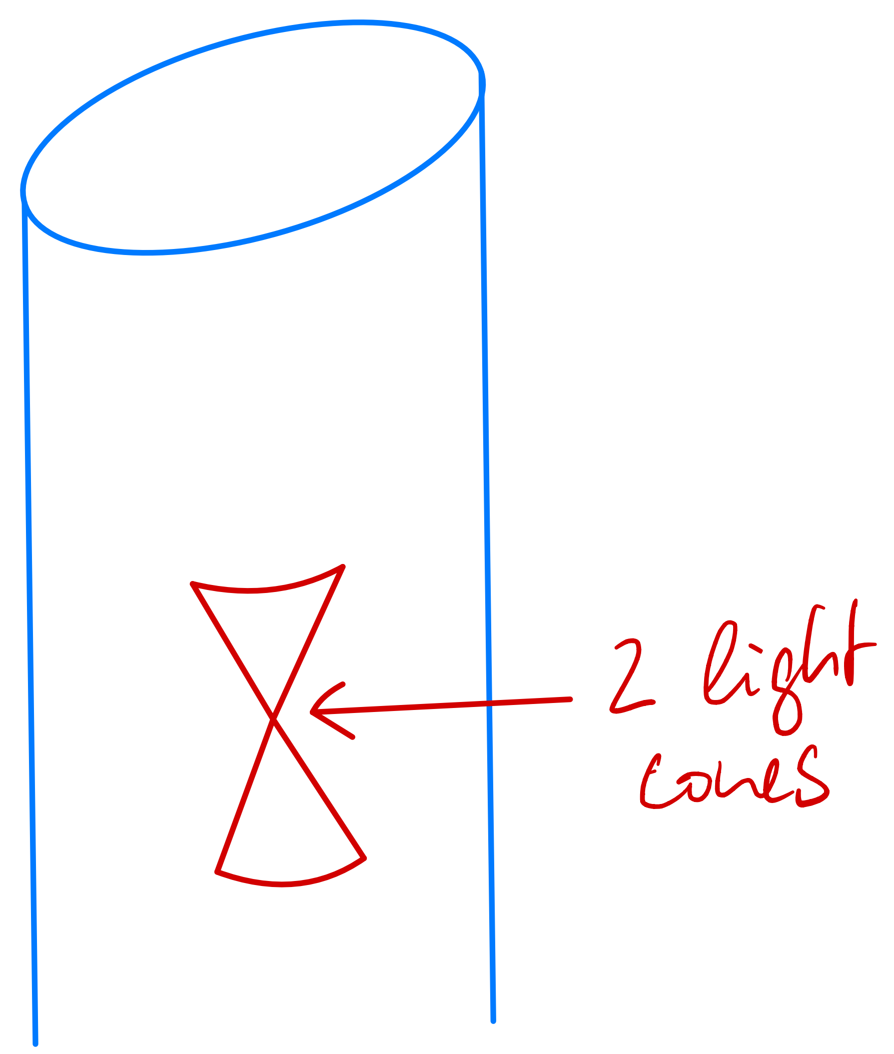

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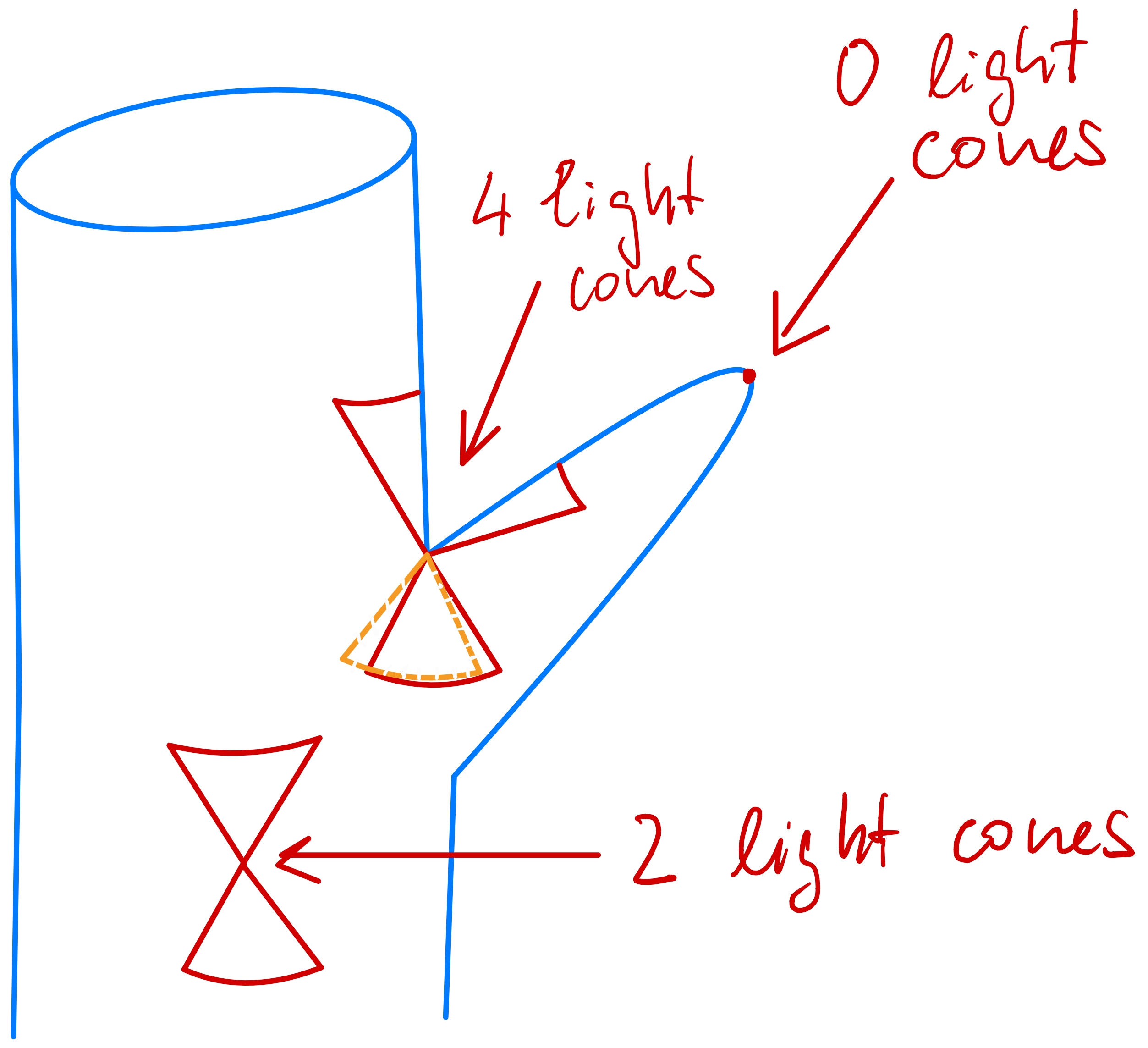

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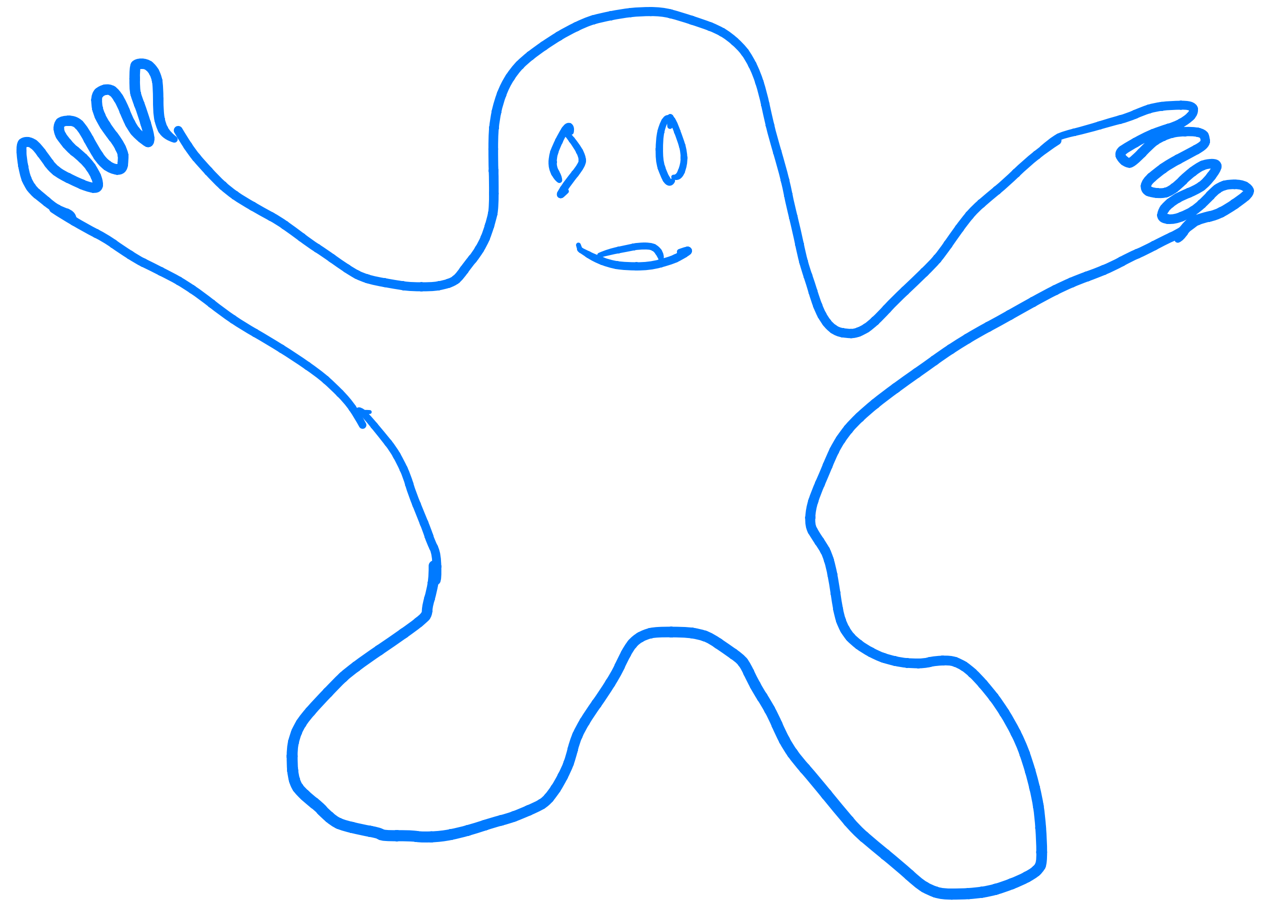

Valid Euclidean space time.

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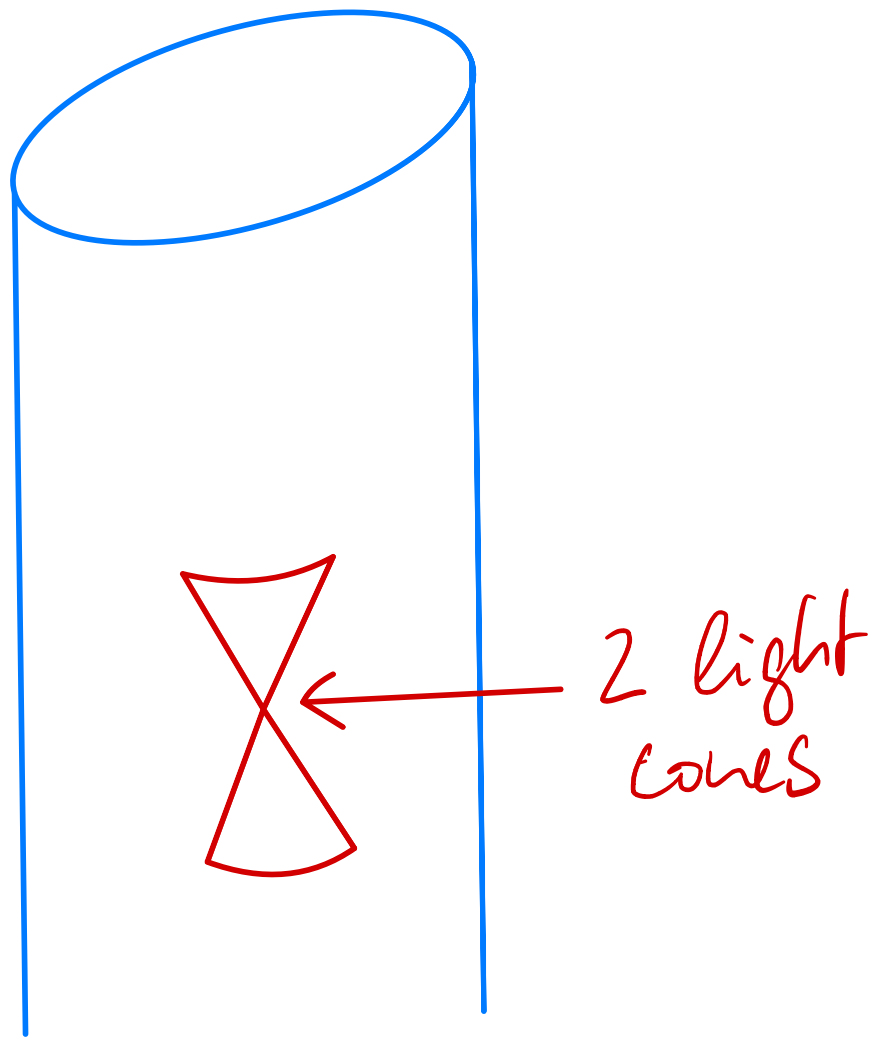

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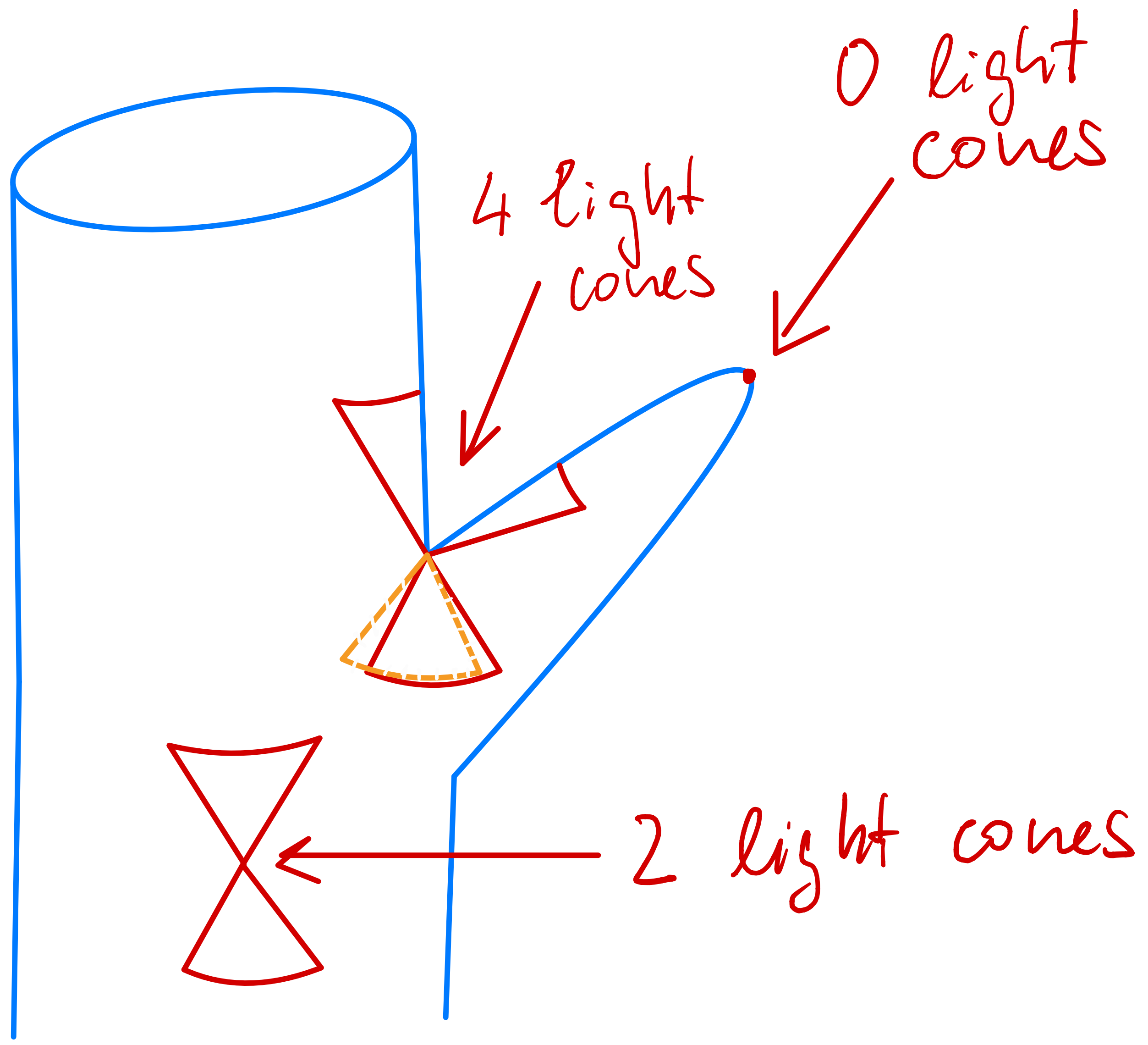

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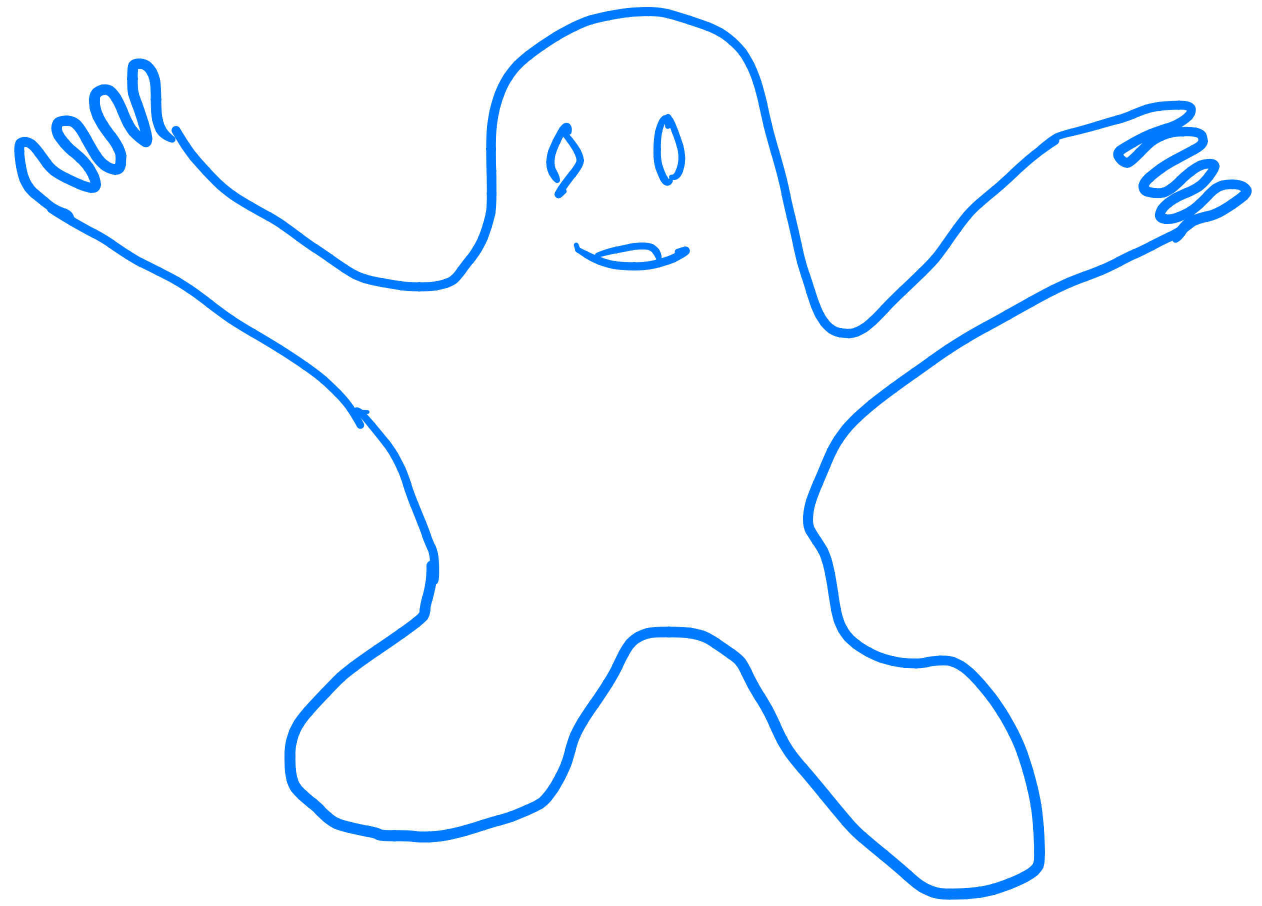

Valid Euclidean space time.

Causal Dynamical Triangulations
does forbid such configurations.
Leads to a new universality class of random triangulations
and an interesting continuum limit in 4 dimensions.
[Ambjorn, Loll 1998+] [without preferred slicing: Jordan, Loll 2013]

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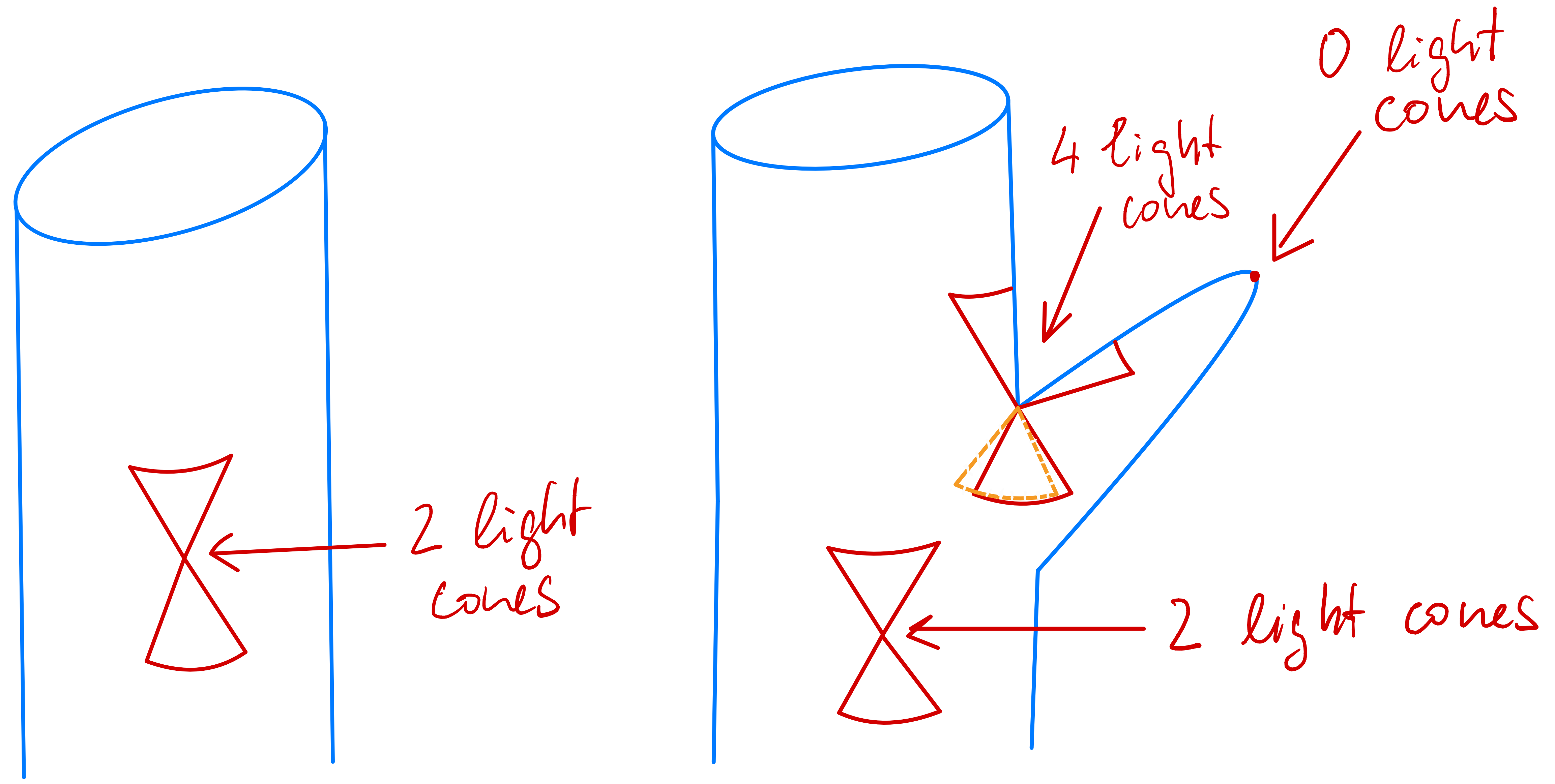

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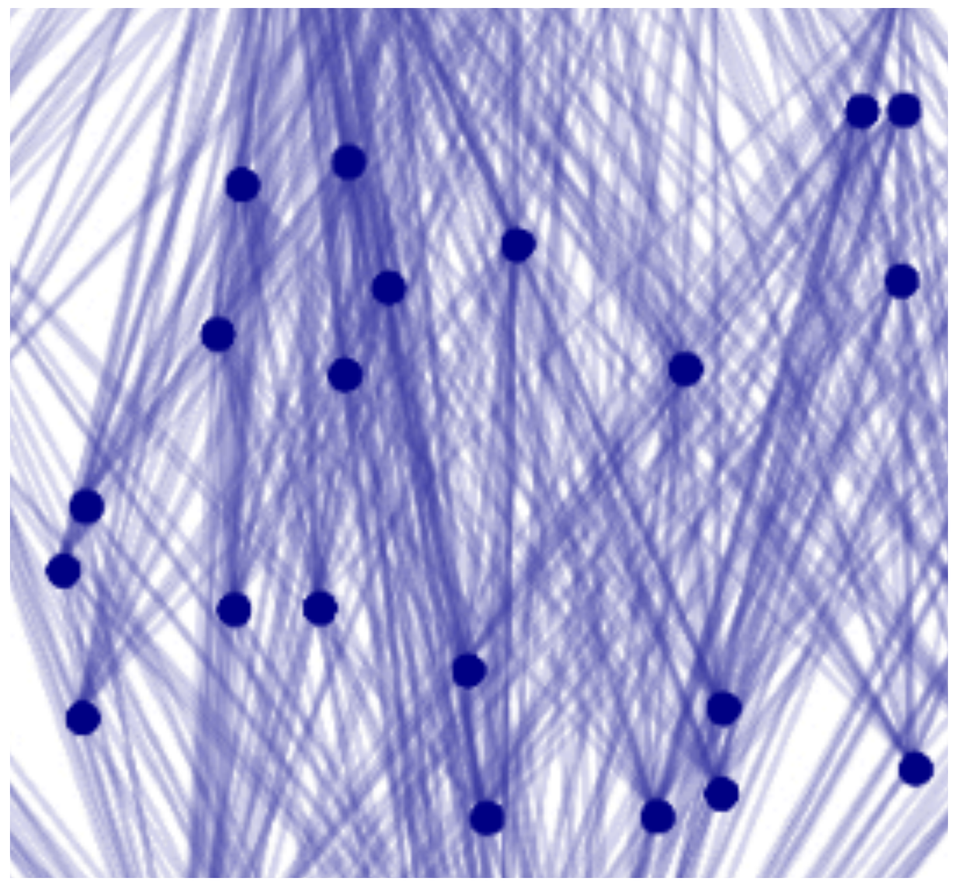

Lorentzian geometry fully encoded in causal relations and volume=number of points.

[from Surya 2019]

Causal sets:
Configurations with irregular light cone structure are allowed.

[Talks by Carlip, Surya]

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Lorentzian vs Euclidean configuration space

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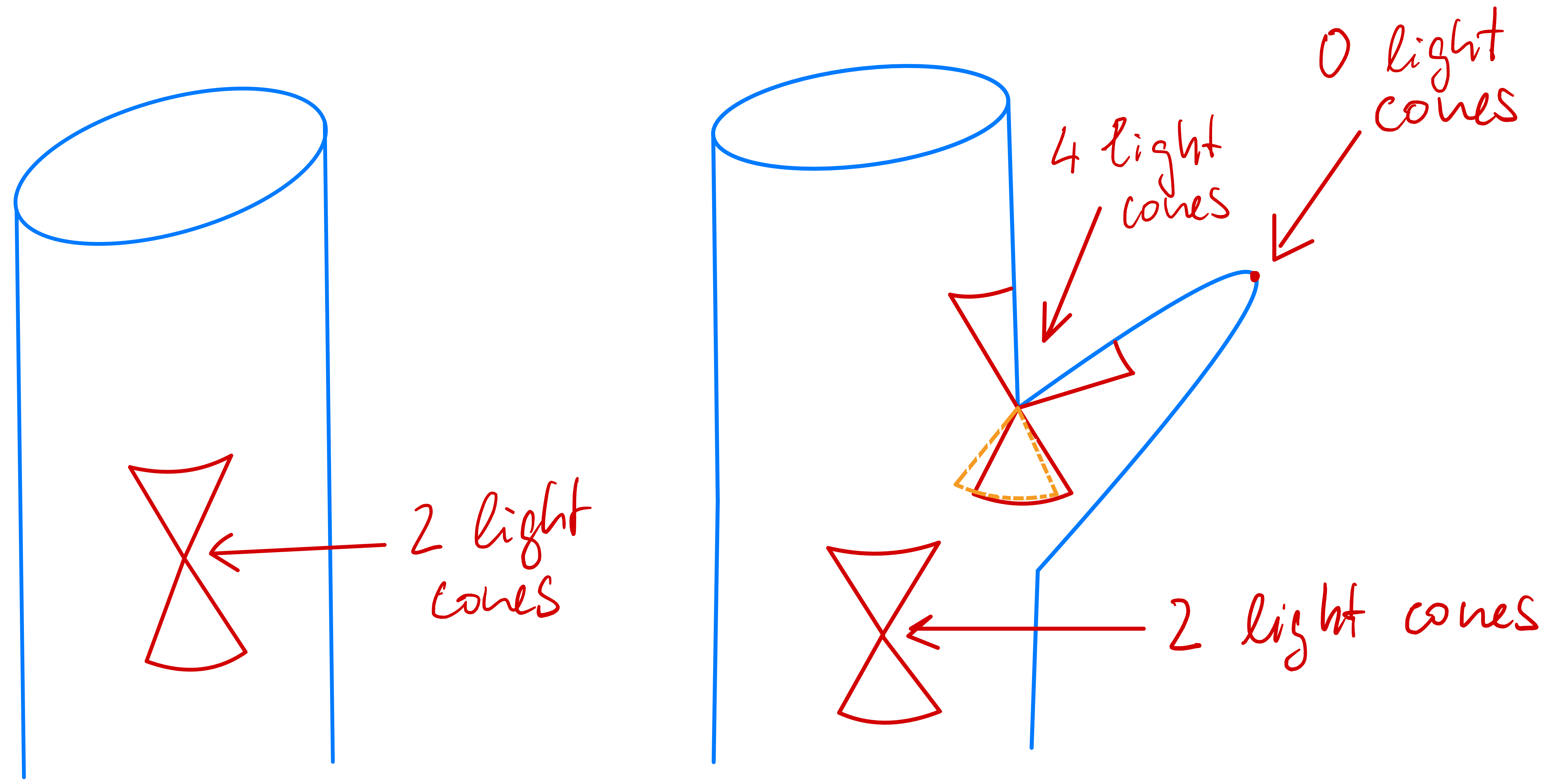

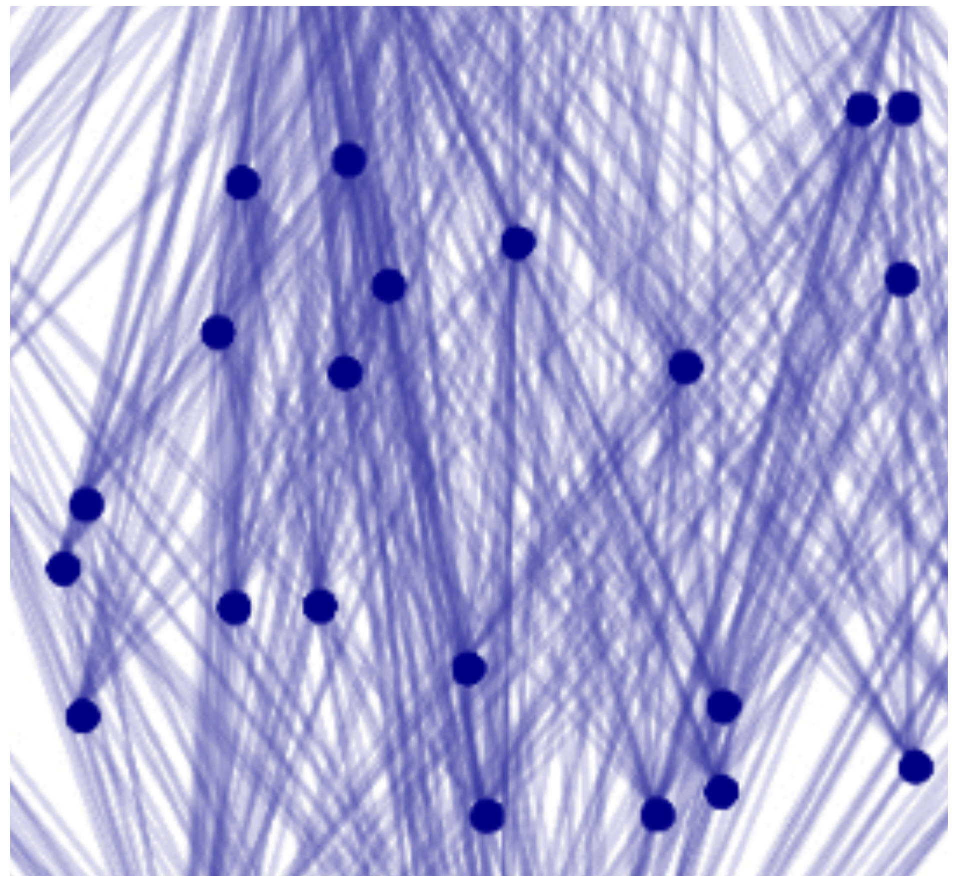

Lorentzian geometry fully encoded in causal relations and volume=number of points.

[from Surya 2019]

Lorentzian space time with regular light cone structure.

Lorentzian space time with irregular light cone structure.

Causal sets: [Talks by Carlip, Surya]
Configurations with irregular light cone structure are allowed.

Causal Dynamical Triangulations
does forbid such irregular configurations.
Leads to a new universality class of random triangulations and an interesting continuum limit in 4 dimensions.
[Ambjorn, Loll 1998+] [without preferred slicing: Jordan, Loll 2013]

Imaginary terms in action?

Regge gravity (and spin foams)

Configuration space: lengths (or other geometric quantities) associated to edges of triangulation.

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Allowed Lorentzian triangulations,
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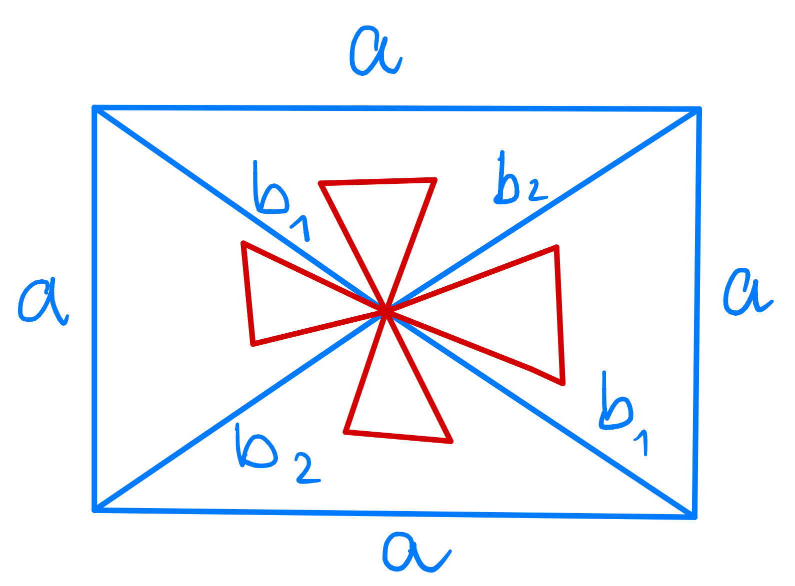
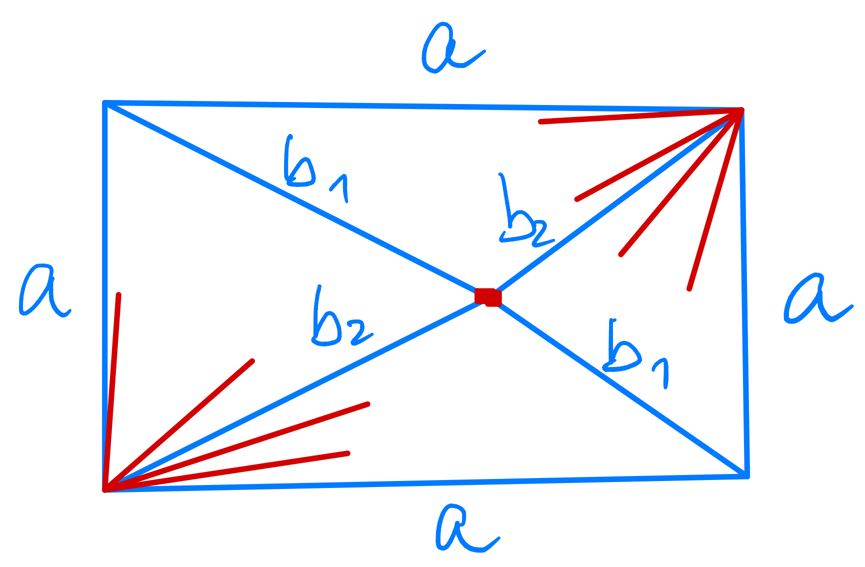
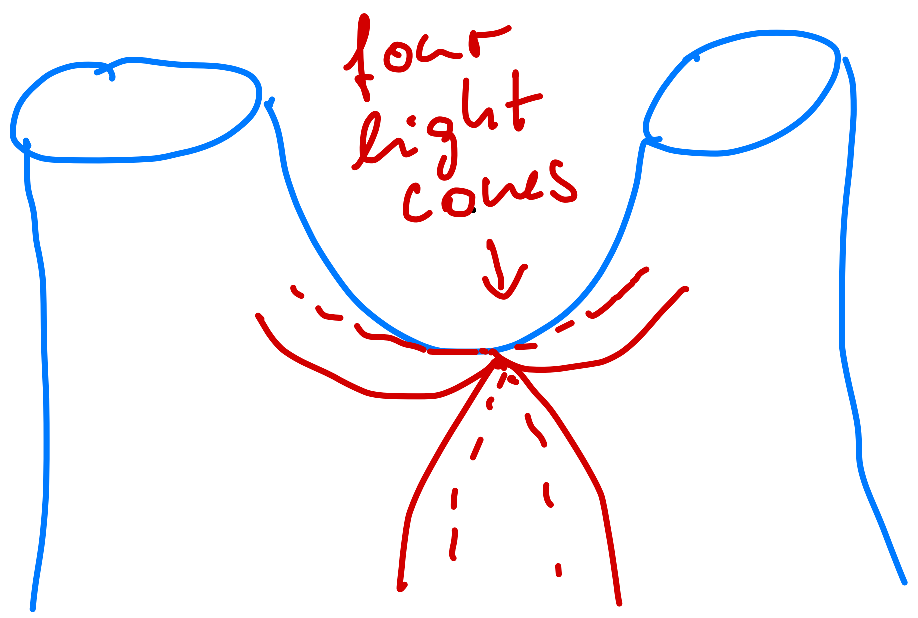
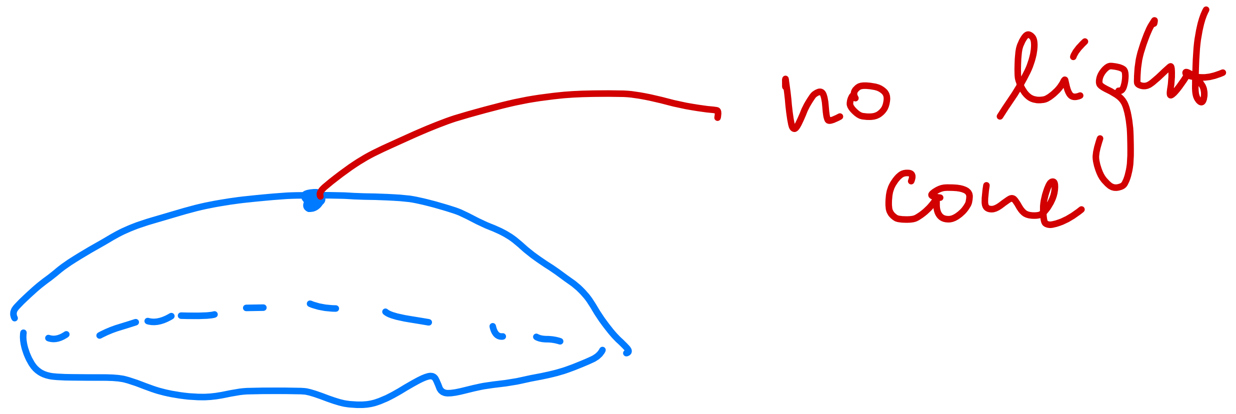


$a > 2b_1 = 2b_2$



$b_1 > b_2 + a$





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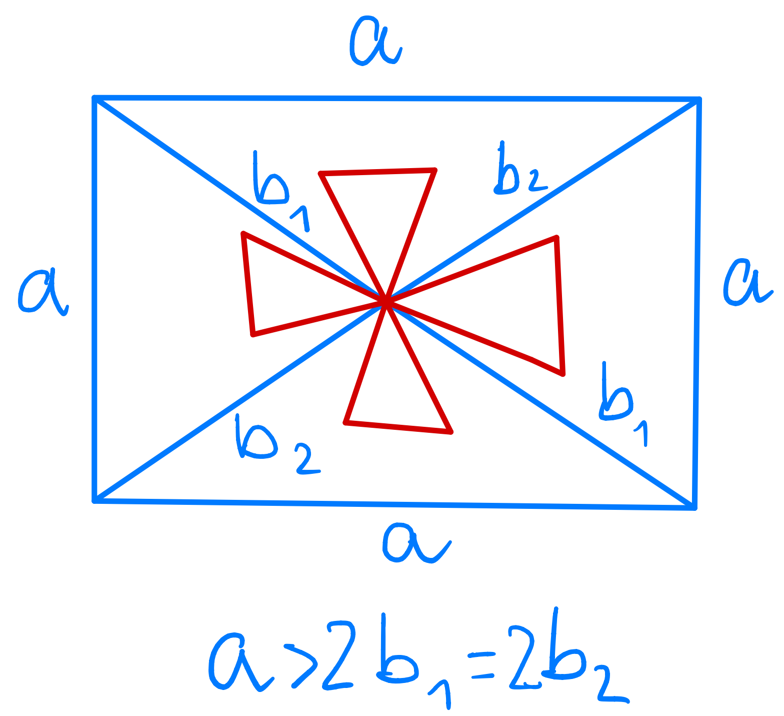

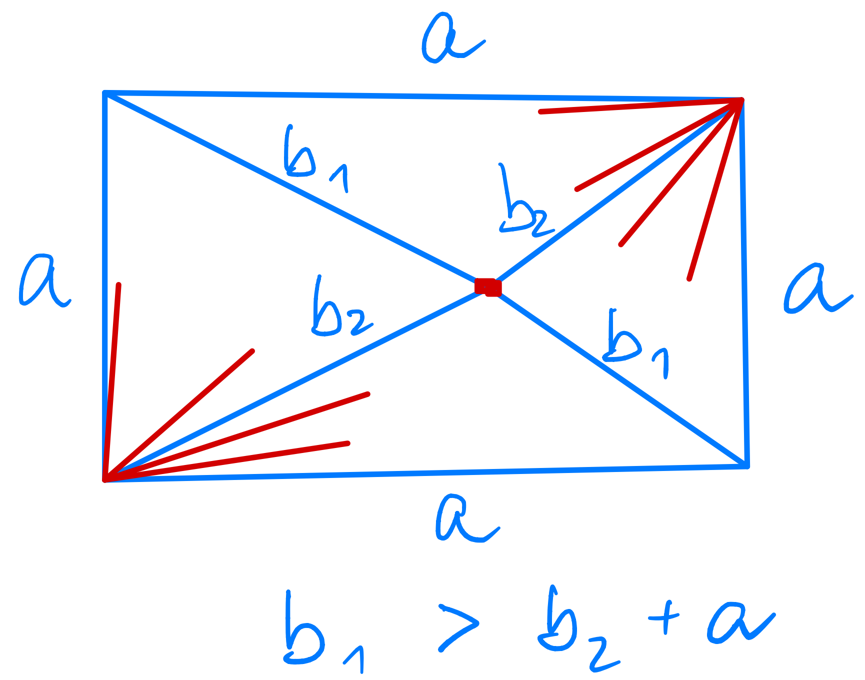

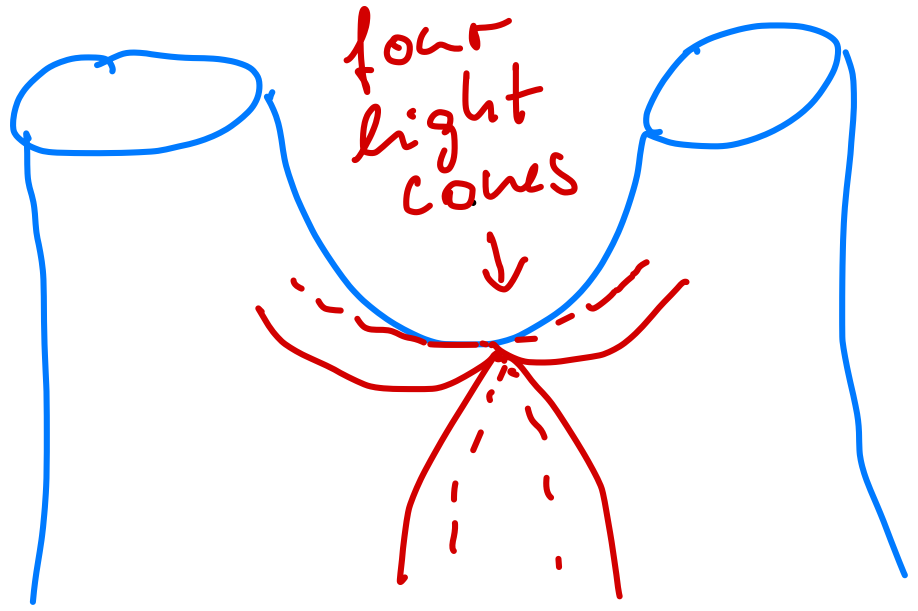

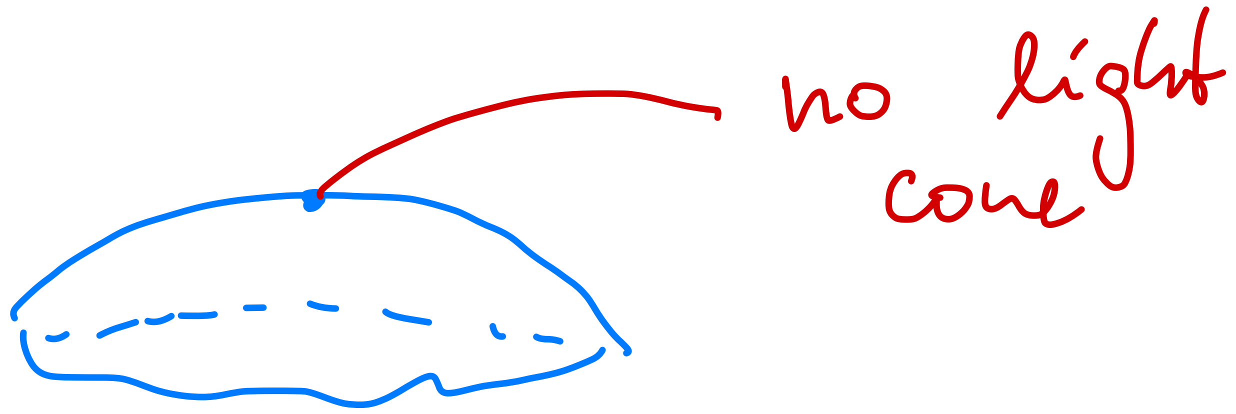

Configurations with irregular light cone structure appear to be generic.
Appear even in configurations describing mini-superspace cosmology.
Results indicated that such configurations should be included in the path integral. [Asante, BD, Padua-Arguelles 2022]

Complex Regge action

Consider Regge action as function of complexified (time-like) length variables.

[Sorkin 1974, Sorkin 2019]
[Jia 2022]
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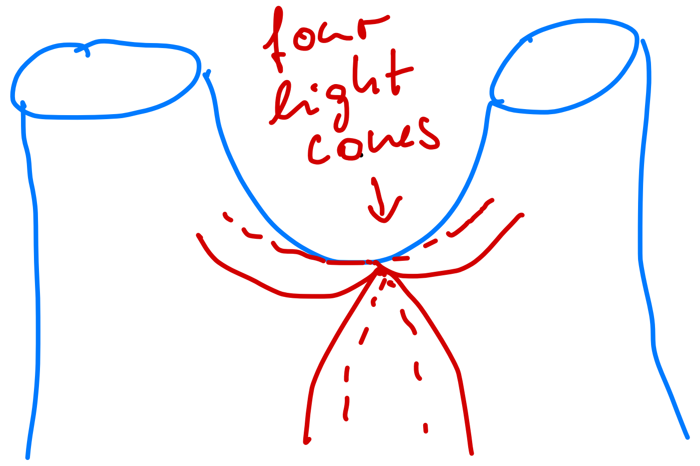

Irregular light cone configurations (of co-dimension 2) lead to branch cuts for the complex Regge action and imaginary contributions with opposite signs. [Asante, BD, Padua-Arguelles 2021]

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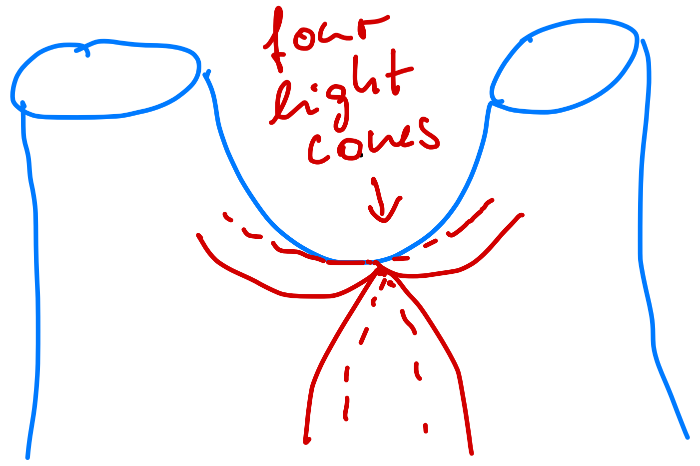

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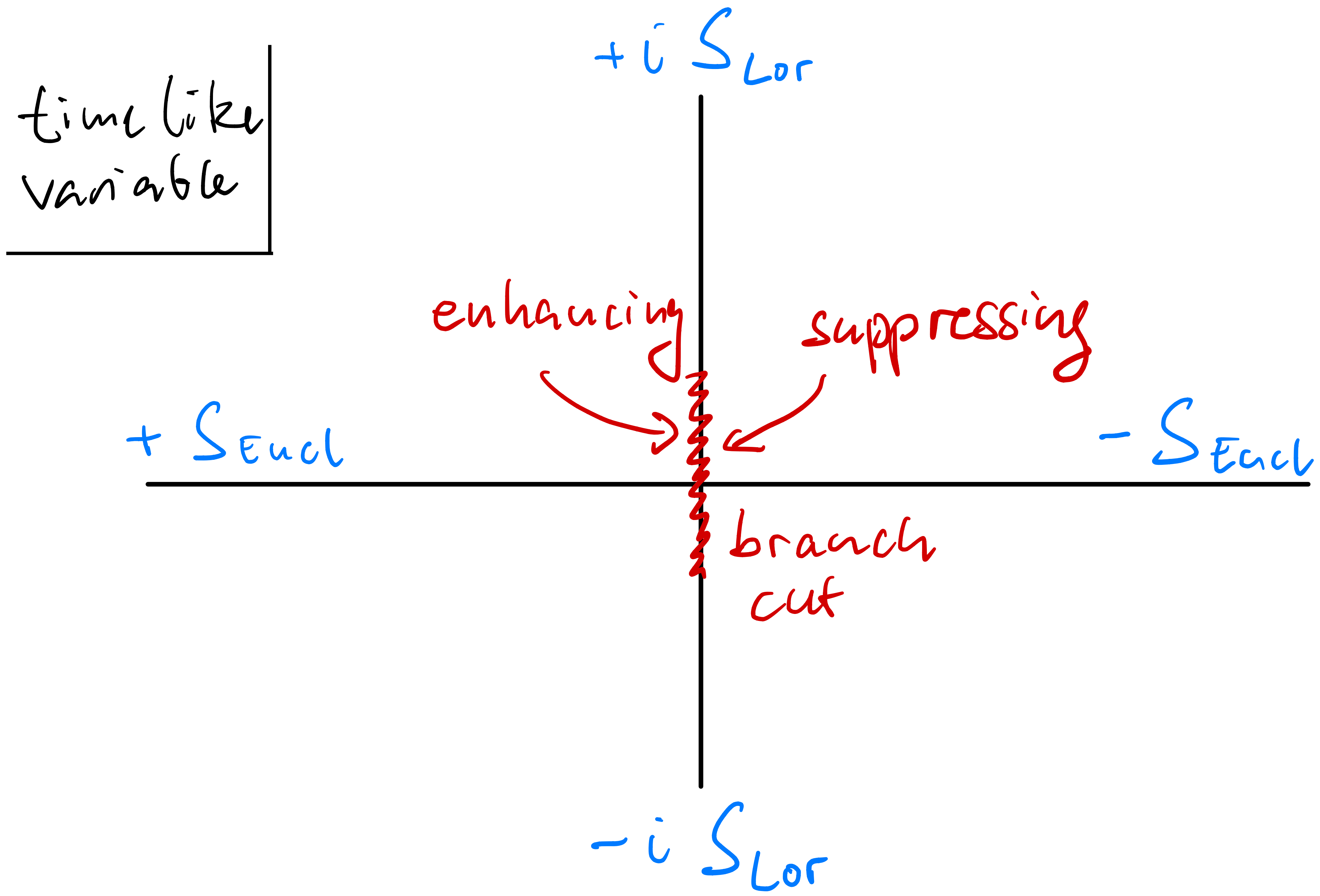

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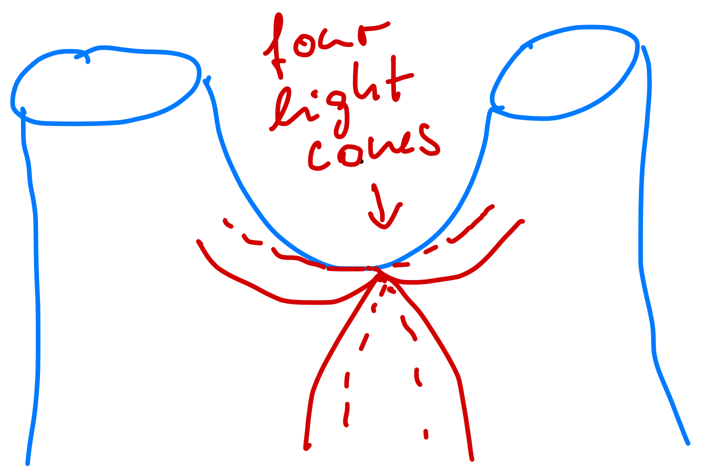

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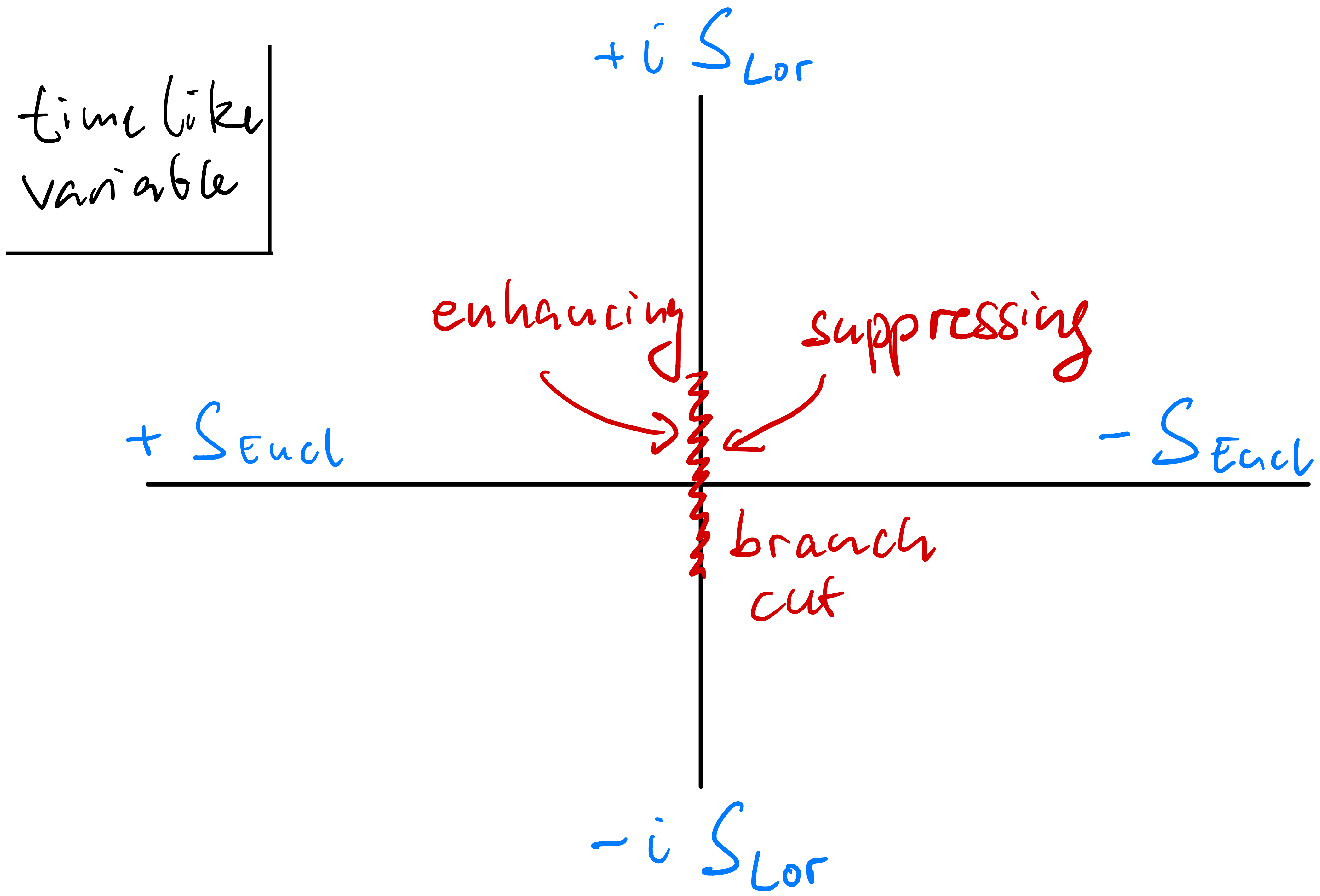


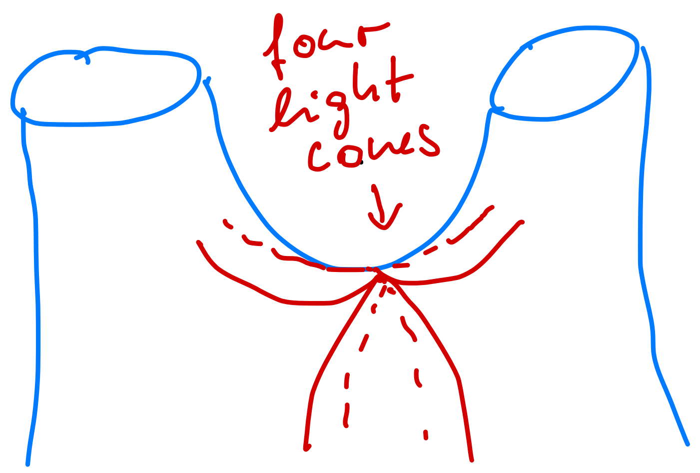
Which choice of sign for the path integral?

Suppressing sign:
Mechanism for suppressing light cone irregular configurations.

Possibility to reconcile CDT and Causal Sets positions?

Continuum and thermodynamic interpretation

Do such imaginary terms appear in the continuum?



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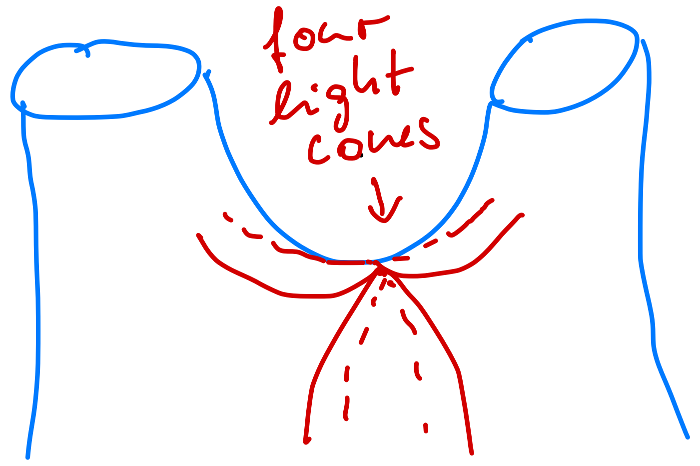

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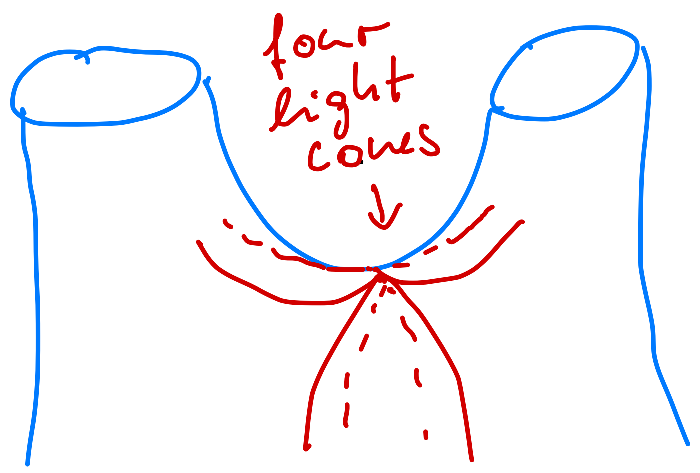

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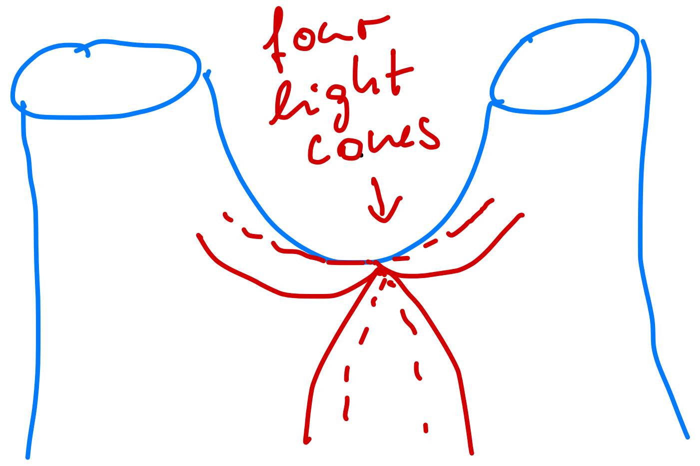

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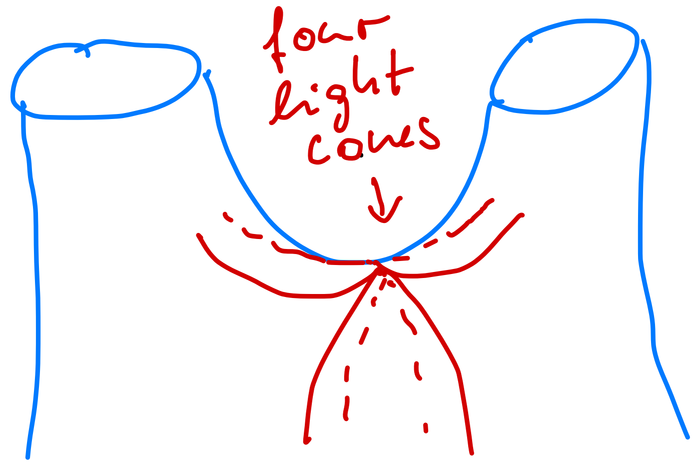

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Challenges: Understand better role of complex structures for Lorentzian gravitational path integral.
Canonical Formalism?
Should we include configurations describing topology change?
Complex actions for sum over topologies?

Lorentzian quantum gravity

- More techniques for Lorentzian path integrals
- Lorentzian configurations have additional light cone structure: can be (often) irregular
- Irregular light cone structure leads to branch cuts for the gravitational action and imaginary terms
- Which Lorentzian configurations to include in the path integral?   Which side of the branch cut?
- Thermodynamical interpretation?

What is the structure of quantum space time?

Observables, (non-) locality and quantum space-time

How much can we resolve space-time?

Quantum Field Theory: Fields $\phi(x, t)$ are observables. n-point functions allow to reconstruct full theory.

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Relational observables [Einstein, …] $\phi(\psi_1, \psi_2, \psi_3, \psi_4)$ [Talks by Kiefer, Ferrero, Giacomini, Hoehn, Menendez-Pidal, Rastgoo, Ruf, …]

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But there seem to be no perfect clocks in our (relativistic) universe. [Giddings, Marolf, Hartle 05; BD, Tambornino 06, Giddings, Donnely 15; Hoehn et al 20+]

Chaos and other aspects: [Bojowald, Hoehn, et al. 12+, BD, Hoehn, Kosolowski, Nelson 17]

End of time: [Talks by Gielen, Menendez-Pidal]

Observables, (non-) locality and quantum space-time

How much can we resolve space-time?

Bound on resolution with relativistic clocks: $$\left[\phi(\psi),\phi(\psi+\epsilon)\right] = G(\psi,\psi+\epsilon)\left(1+\frac{\text{Energy}(\phi)}{\text{Energy}(\psi))}\right)$$

[Giddings, Marolf, Hartle 05, BD, Tambornino 06]

Increasing energy (and size) of clock field leads to black holes.

$\Rightarrow$Locality Bounds

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⇒Locality Bounds

A new uncertainty principle?

New uncertainty for Time of arrival operator $\Delta t > 1/\overline{E}$. [Aharanov et al 97]

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High energy scattering leading to black holes: "The end of short distance physics".
UV-IR mixing.

[Banks,Fischler 99;
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Challenge: Better understanding of type and algebra of observables.

Structure of quantum space-time

Quantum field theory: space-time is an index set.

Quantum gravity: this index set is dynamical and quantum. [Talks by Freidel, Giacomini, Hoehn, …]

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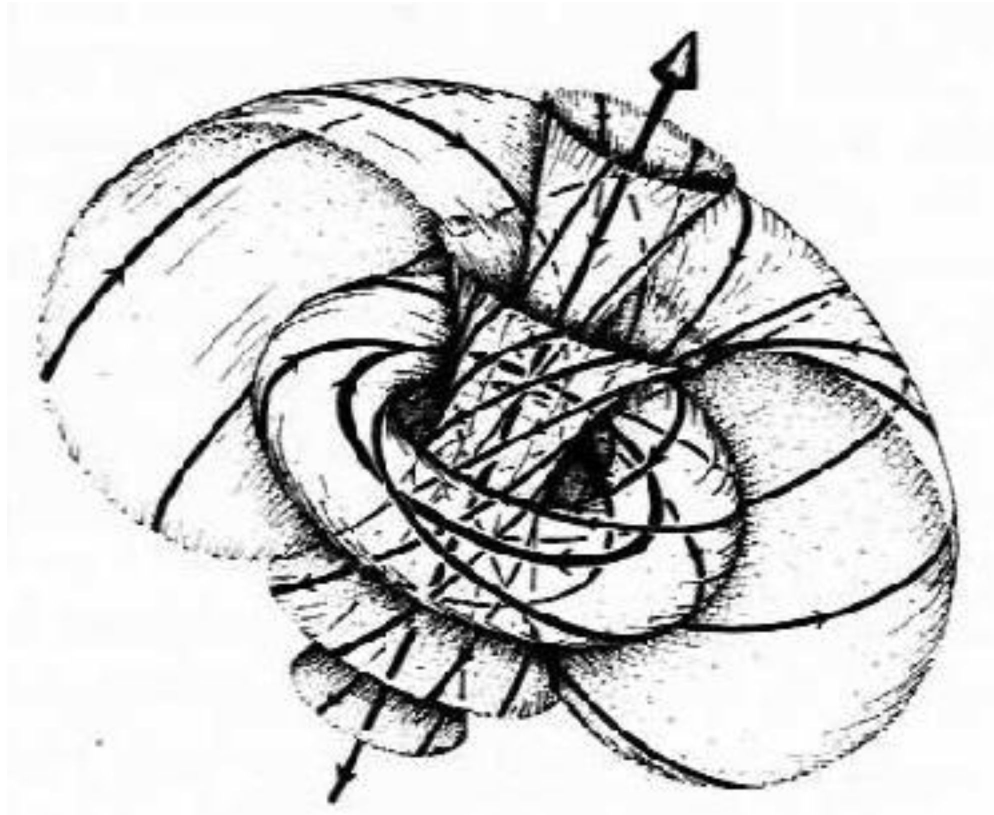
What is the resulting structure of quantum space time?

- fractal dimensions/ space-times
- non-commutative space-time
- geometric operators (with discrete spectra)

- holography
- local holography
- matrix and tensor models
- group field theories
- strings
- area metrics
- twistor space
- relative locality and Born duality
- …

Space time emergent



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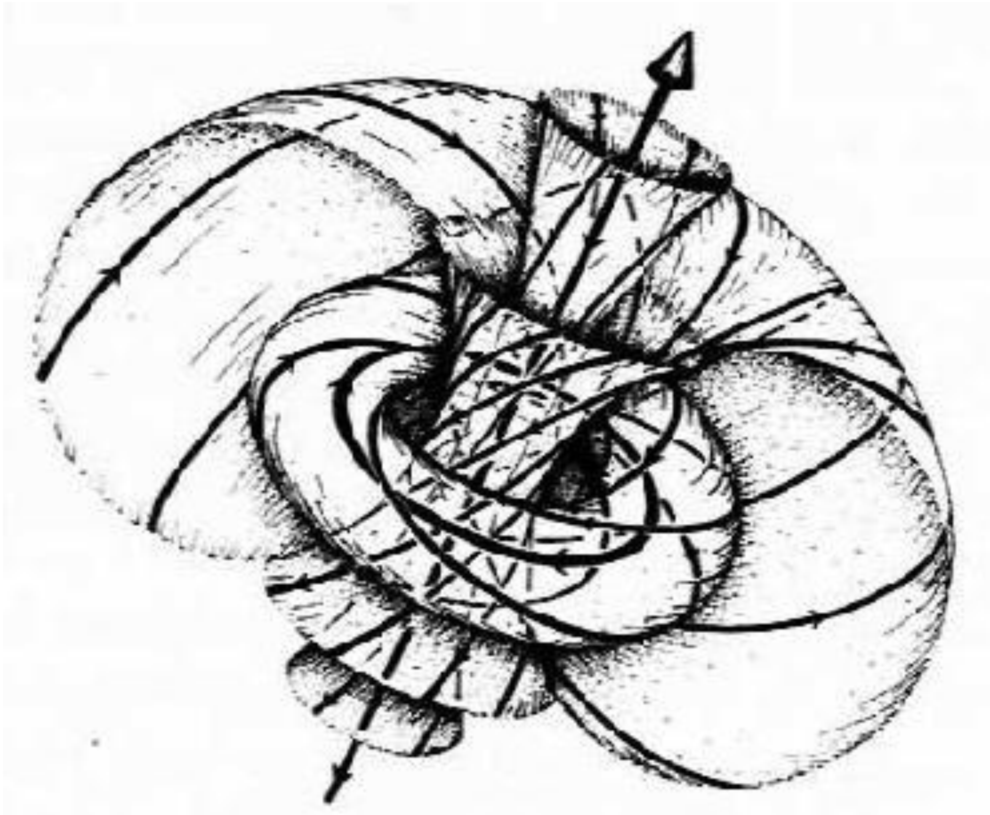
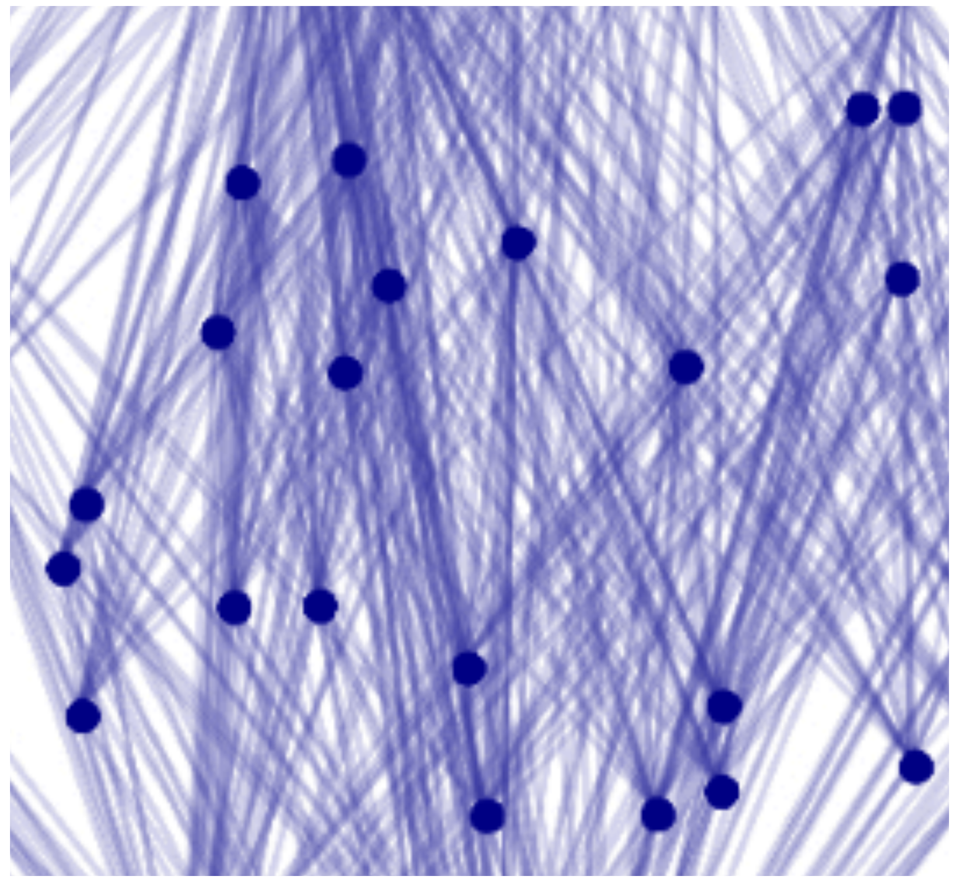
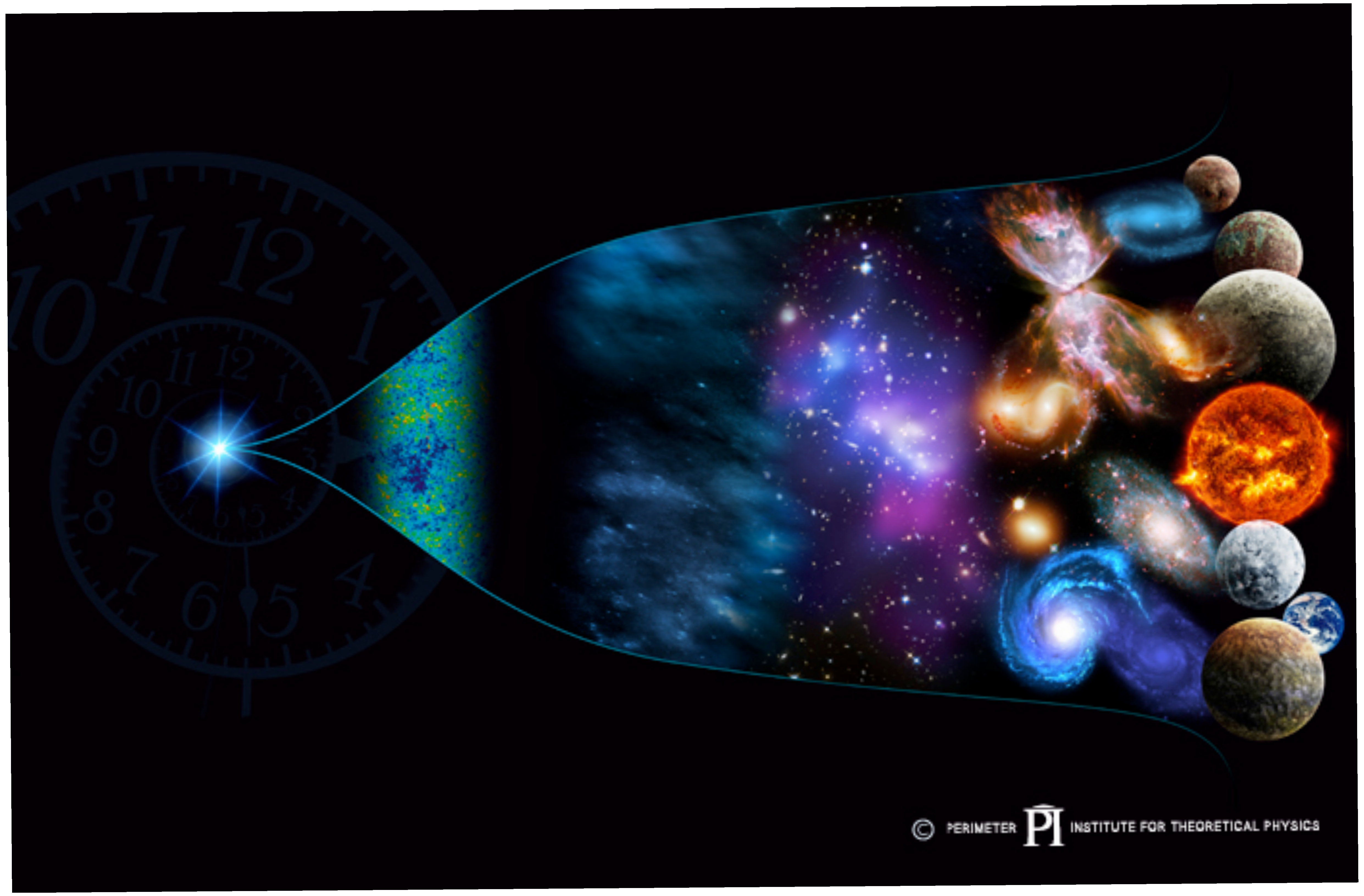


Challenge: Observable algebra and symmetries ↔ Structure of quantum space-time

Reconstructing our universe





Challenge: Bridge enormous number of scales.
Understand renormalization and develop (common) language for ‘emergence’ of space-time.

Understanding our universe

“So far we have not seen any signatures of quantum gravity.”

“Are we now really at the dawn of quantum gravity phenomenology?” [Talk by Amelino-Camelia]

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But there are many features of our universe asking for explanation:

- Quantum theory?
- (Macroscopic) four-dimensional smooth space-time
- Lorentzian signature
- Gravitational dynamics
- Small and positive cosmological constant

[Talk: Yasaman]

- Inflation?
- (Simple) initial conditions
- Matter
- Dark Matter
- Types of matter and values of matter couplings

[Talk: Wetterich]


Happy
re- and de-constructing!