Memories, Asymptotic Symmetries and Soft Theorems

EIGHTH CRETE REGIONAL MEETING ON STRING THEORY
NAPFLION 2015

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with help from my collaborators

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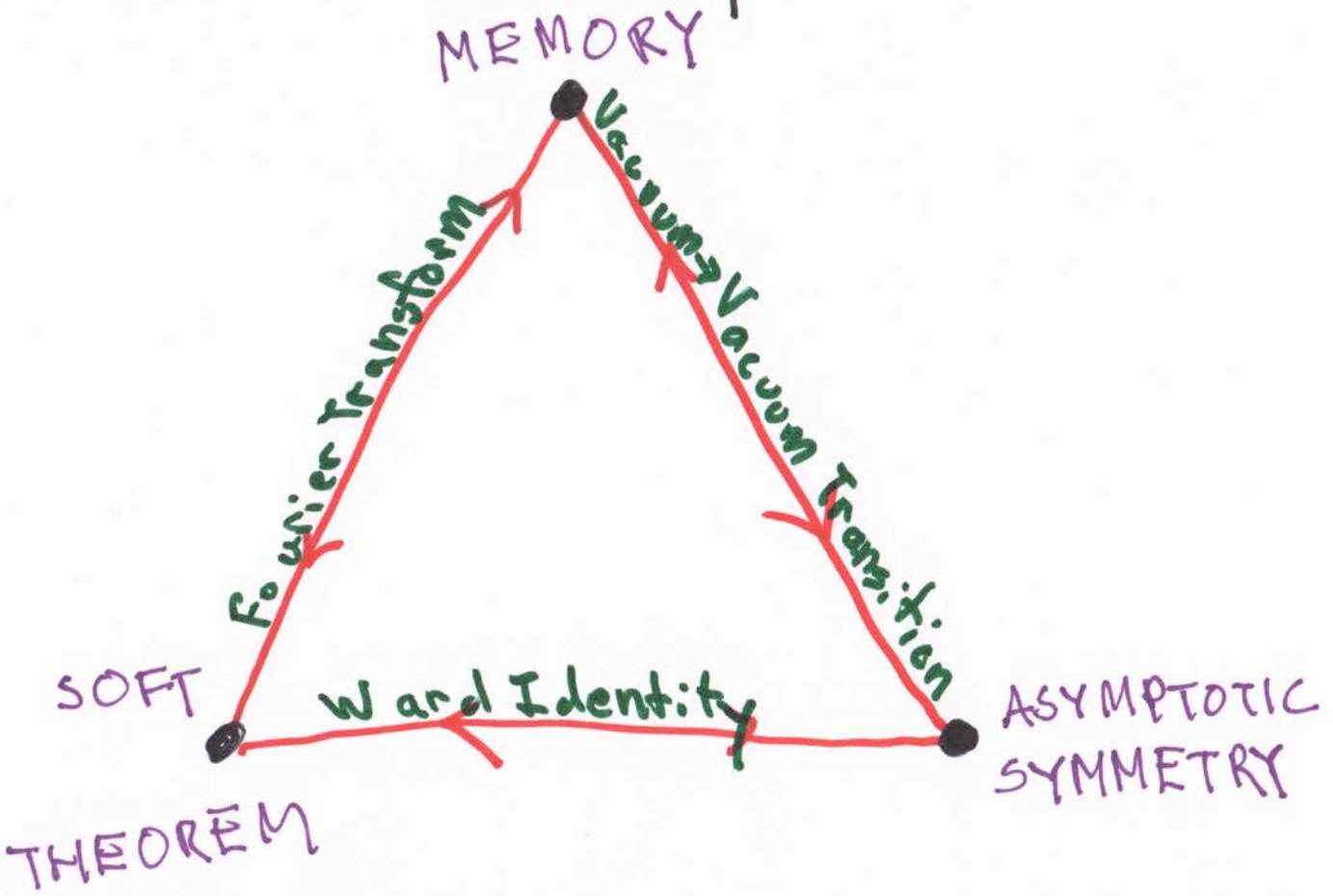
And contributions from:

Casali,Skinner, Lipstein, Mason, Chen, Huang, Wen,Avery,Schwab,Bianchi,Guerrieri, Campiglia, Du, Luo, Zlotnikov, Adamo, Volovich, He,Yaun,DiVecchiia, Marotta, Mojaza, Mohd, Vasquez-Mozo,Bern, Vera, Broedel, Rosso, Plefka,Liu, Lambert, Fu , Wang, Kalousios,Rojas, White, Davies, Nohles,
De Leeuw, Rosso, Davies, Barnich, Banks, Hyun, Park, Yi,…….

This talk considers a **triangle** of exact equivalence relations between three classes of physical phenomena, each studied for for over half a century:



Many copies of the triangle echo throughout physics:

a) QED, Yang-Mills, gravity...

b) leading, subleading, subsubleading...

c) classical, quantum

d) Minkowski, $d=2,3,4,5,\ldots$, deSitter, ...

e) N=0 Susy, N=1 Susy, ...

⋮

Each case is different and interesting. The symmetries are ∞-dimensional, and imply an ∞ of new, physically observable, conserved charges. In most cases, only one corner of the triangle was known prior to a year ago.

MOTIVATIONS

0. Explore/understand rich structure of the deep infrared.

1. Organize soft sectors of QED/QCD, improve jet/collider computations?

2. Minkowski space holography?

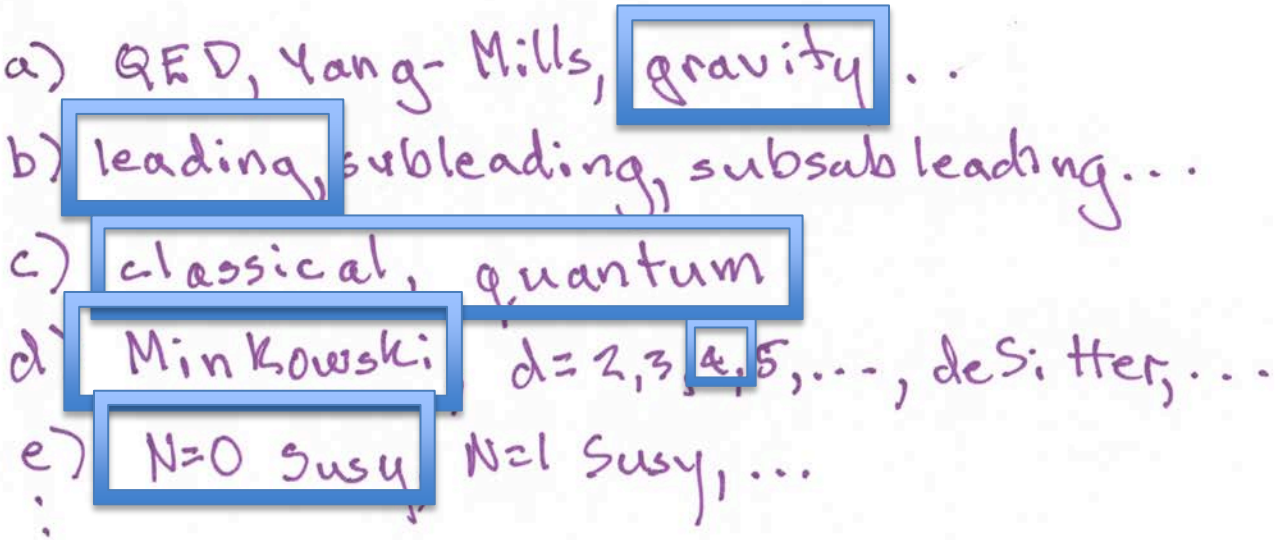
3. Explain "miraculous" structures encountered in amplitudes program?

4. Universality/inevitability of string theory?

The triangle has consequenies for the black hole information puzzle. At the end we will explain that, in constrast to popular beliéf, physical black holes carry an infinite amount of measurable hair.

SPECIFIC EXAMPLE OF THIS TALK

Many copies of the **triangle** echo throughout physics:

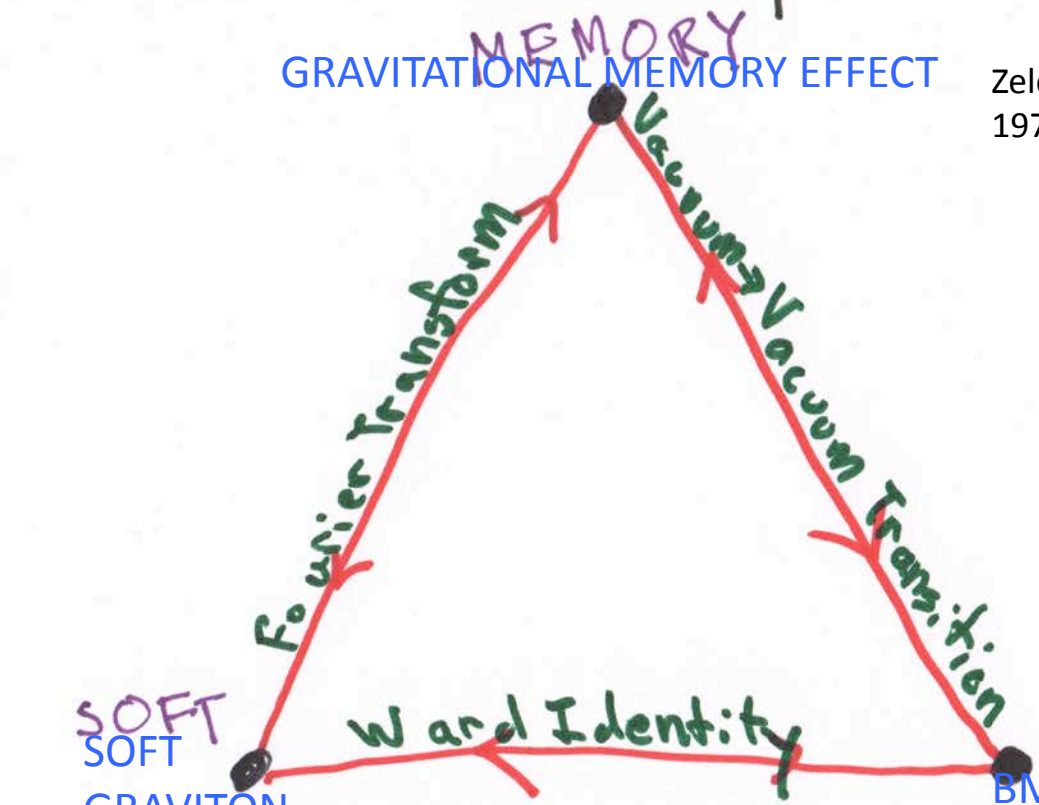


THIS IS ODDLY THE BEST UNDERSTOOD OF ALL CASES!

Each case is different and interesting. The symmetries are ∞-dimensional, and imply an ∞ of new, physically observable, conserved charges. In most cases, only one corner of the **triangle** was known prior to a year ago.

SPECIFIC EXAMPLE

This talk considers a **triangle** of exact equivalence relations between three classes of physical phenomena, each studied for for over half a century:



GRAVITATIONAL MEMORY EFFECT

Zeldovich and Polnarev 1974

SOFT GRAVITON THEOREM

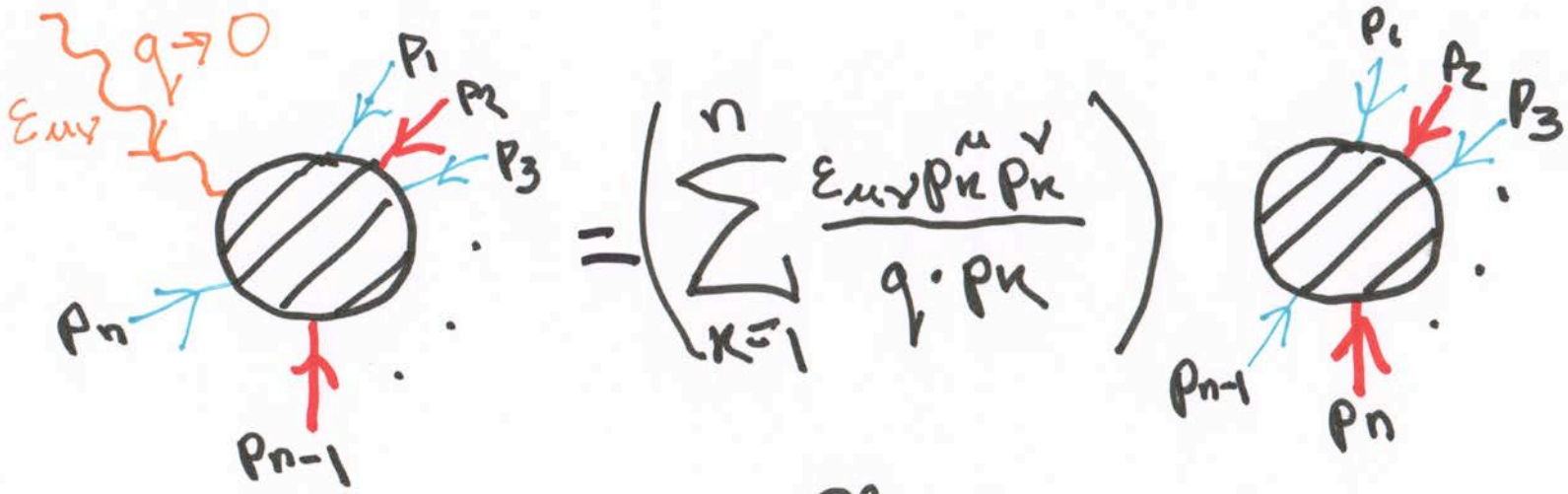
Weinberg 1965

BMS SUPERTRANSLATIONS

Bondi, van der Burgh, Metzner & Sachs 1962

Soft Graviton Theorem

Weinberg 1965

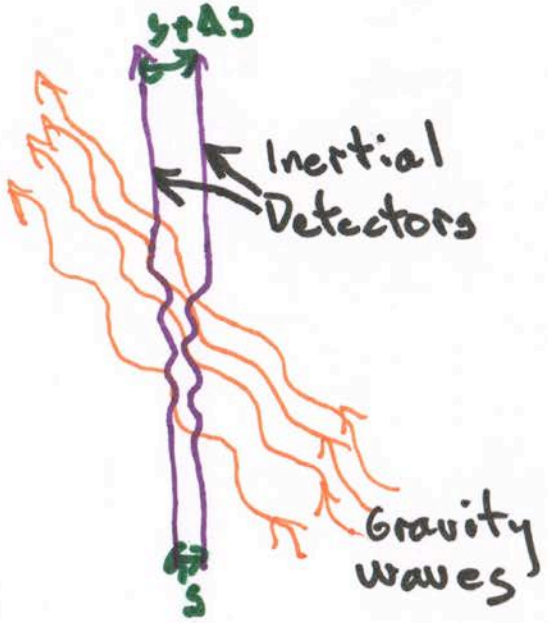


$$+ \mathcal{O}(q^0)$$

Exact & universal formula with simple diagrammatic derivation.

Gravitational Memory

Zeldovich & Polnarev '74
Braginsky & Thorne '87
Christodoulou '91



retarded AF Minkowski metric:

$$ds^2 = -du^2 - 2\,du\,dr + r^2\gamma_{z\bar{z}}\,dz\,d\bar{z} + r\,C_{zz}\,dz^2 + r\,C_{\bar{z}\bar{z}}\,d\bar{z}^2 + \dots$$

gravity waves

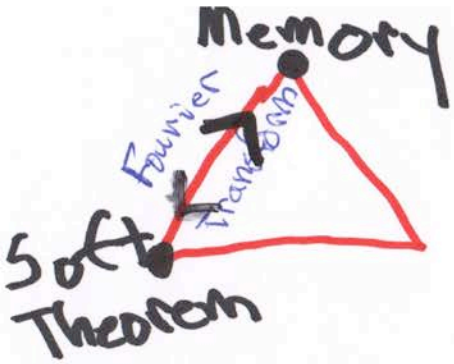
Flatiff $C_{zz} = -2D_z^2(z,\bar{z})$

Integrated geodesic deviation equation:

$$\Delta s^{\bar{z}} = \frac{1}{2r}\gamma^{z\bar{z}}\,\Delta C_{zz}\,s^z$$

final − initial = change in C_{zz}

DC effect. Quite possibly measured in coming decades. Pulsar timing array?



"Infrared Photons & Gravitons"
S. Weinberg, 1965

The dominance of the $1/(p\cdot q)$ pole in (2.5) implies that the effect of attaching one soft-graviton line to an arbitrary diagram is to supply a factor equal to the sum of (2.5) over all external lines in the diagram

$$(8\pi G)^{1/2}\sum_n \eta_n p_n^\mu p_n^\nu/[p_n\cdot q - i\eta_n\epsilon]. \qquad (2.7)$$

$\int dw e^{iwv}$

"Gravitational Wave-Burst with Memory and Experimental Prospects"
V. Braginsky and K.S. Thorne 1987

permanent change in the gravitational-wave field (the burst's memory) δh_{ij}^{TT} is equal to the 'transverse, traceless (TT) part'[36] of the time-independent, Coulomb-type, $1/r$ field of the final system minus that of the initial system. If $\mathbf{P}^A$ is the 4-momentum of mass A of the system and P_i^A is a spatial component of that 4-momentum in the rest frame of the distant observer, and if $\mathbf{k}$ is the past-directed null 4-vector from observer to source, then δh_{ij}^{TT} has the following form:

$$\delta h_{ij}^{TT} = \delta\left(\sum_A \frac{4P_i^A P_j^A}{\mathbf{k}\cdot\mathbf{P}^A}\right)^{TT} \qquad (1)$$

Here we use units with $G=c=1$. In the observer's local Car-

!!!

Changing notations, using $\theta(w) = \int \frac{dw}{w} \frac{e^{iwu}}{2\pi i\delta}$ and elementary particles → black holes, stars!

Memory effect provides physical method to measure soft gravitons.

Asymptotic Supertranslation Symmetry

Bondi vanderBurgh Metzner Sachs 1962

AS 2013 1312.2229

Angle dependent supertranslations

$$u \to u + f(z,\bar{z}) + \dots$$

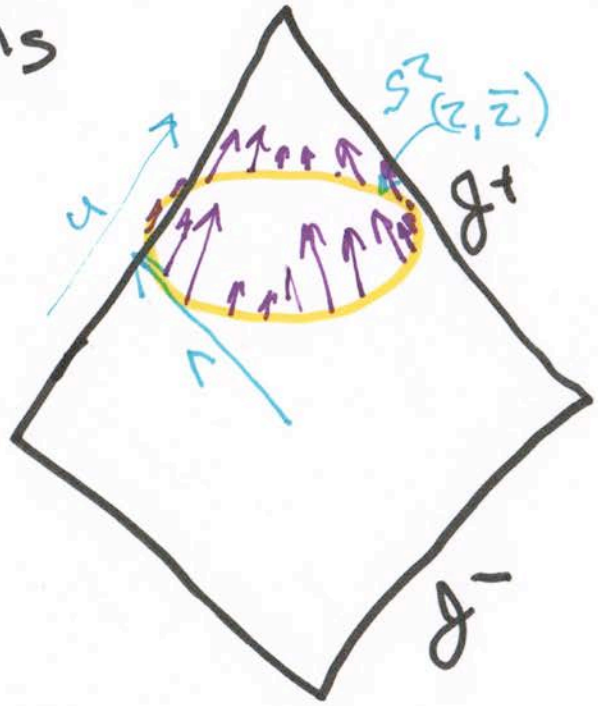
$$z \to z + \frac{1}{r}\gamma^{z\bar{z}}\partial_{\bar{z}} f(z,\bar{z}) + \dots$$

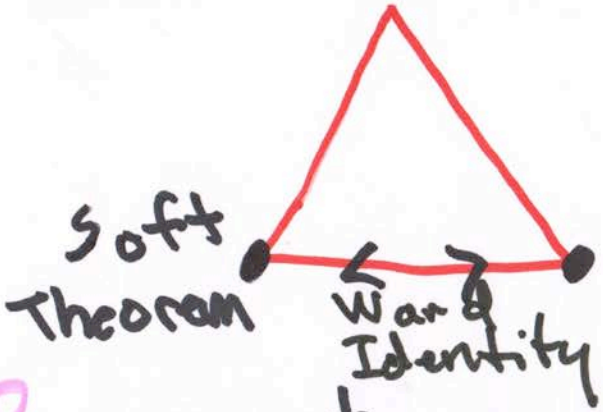
act nontrivially on the physical phase space, while preserving AF form of metric.

$$C_{zz} \to C_{zz} + 2D_z^2 f$$

is the goldstone boson.

Flat metrics not all equivalent. Energy = 0 but angular momentum ≠ 0.





Let B generate supertranslations.

Then

$$BS - SB = 0$$

moreover

$$\langle out | BS - SB | in \rangle$$

is precisely Weinberg's soft graviton theorem. ∞ of associated conserved quantities is total energy at each incoming angle.

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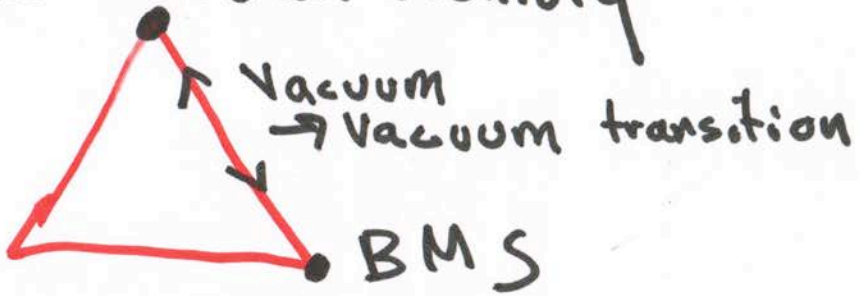
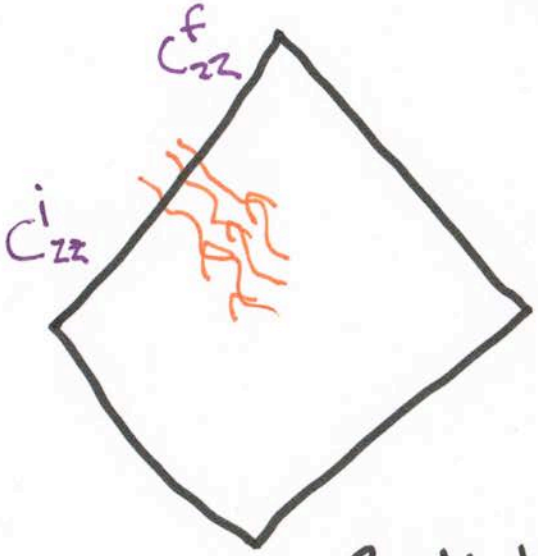
Gravitational Memory





The passage of energy induces a ~~va~~ BMS vacuum transition

$$C^f_{zz} - C^i_{zz} = -2D_z^2 f$$

with

$$f(z,\bar{z}) \sim \int d^2w \ln|z-w|^2 \int du T_{uu}(u)$$

Radiation pulse = domain wall separating BMS equivalent vacuum. Initial & final detector positions differ by BMS diffeo

This is gravitational memory! 1411.5745 1502.06120

Implications for the information puzzle

(i) Black holes carry ∞ BMS hair.

(ii) Hawking radiation is constrained by an ∞ of conservation laws.

(iii) The zero-energy vacuum is ∞ly degenerate and can store ∞ information.

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CONCLUSION

The infrared structure of gauge and gravitational theories is richer than previously realized. We have much to understand.