Progress and Questions in SOFT PHYSICS

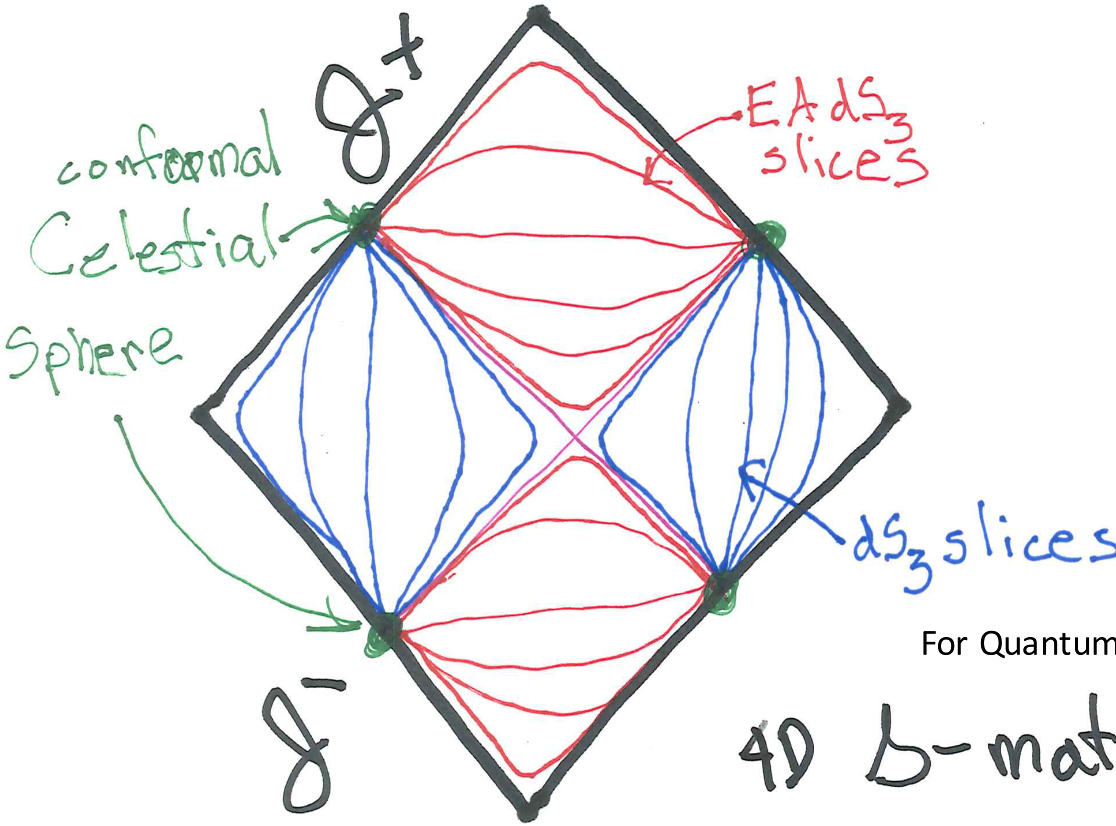
In Memory of Stephen Hawking
1942-2018

Andy Strominger
Strings 2018
Okinawa

I am going to give a sampler of topics in soft physics that I have been working on with others and also present some interesting open questions concerning flat space holography, soft hair on black holes, color memory measurement in QCD.....

Flat Space Holography

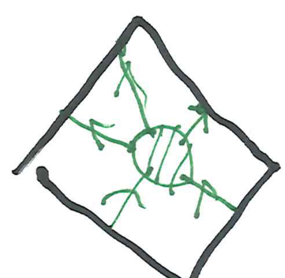
De Boer, Solodukhin 0303006; AS 13122229; He, Mitra, AS 150302663; Cheung, Fuente, Sundrum 160900732



4D MINKOWSKI SPACE

For Quantum Gravity

4D S-matrix = CFT_2 correlators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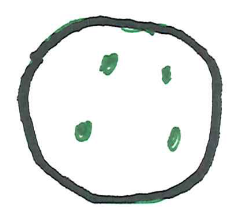

FREE PARTICLES

Complete orthonormal basis ~~$e^{ip\cdot X}$~~ supplied by unitary principle series

$$L_0\,\psi_{h\bar{h}}(x) = h\,\psi(x), \quad \bar{L}_0\,\psi(x) = \bar{h}\,\psi(x)$$

$$L_1\psi = \bar{L}_1\psi = 0, \qquad L_{\pm 1}, L_0, \bar{L}_{\pm 1}, \bar{L}_0 \sim SL(2,C)$$

Lorentz

·Scalar

Pasterski, Shao, AS 170100049 ; Pasterski, Shao 170501027; Donnay, Puhm, AS in progress

$$(h,\bar{h}) = (1+i\lambda,\ 1+i\lambda)$$

$\lambda \in R^+$ (massive)

$\in R$ (massless)

Photon (+helicity)

$$(h,\bar{h}) = (1+i\lambda,\ i\lambda),\ \lambda \in R$$

Special treatment needed at $\lambda = 0$. $\exists$ symplectic pair

J_z conformally soft photon $(h,\bar{h}) = (1,0)$

S_z goldstone boson for large gauge symmetry

Already interested

$$J_z J_w \sim 0, \quad J_z S_w \sim \frac{1}{z-w^2}, \quad S_z S_w \sim \frac{\Gamma_{cusp}}{(z-w)^2} \qquad \Gamma_{cusp} = \frac{e^2}{4\pi^2}$$

Graviton

$(h,\bar{h}) = \left(\frac{3}{2}+i\lambda,\ -\frac{1}{2}+i\lambda\right)$ complete basis

$\lambda \leftrightarrow -\lambda$ symplectic pairs

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special analysis of $\lambda \to 0 \Rightarrow$ pair of modes $(h,\bar{h}) = \left(\frac{3}{2}, -\frac{1}{2}\right)$

Goldstone mode for broken supertranslations

+ Soft graviton supertranslation generator

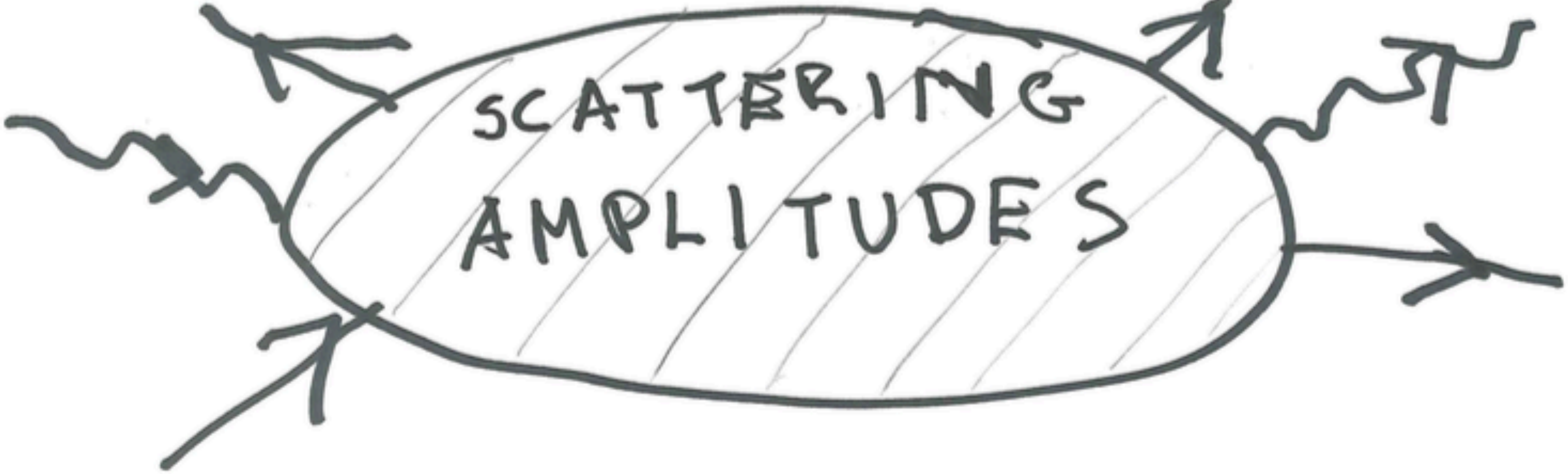
$\lambda = -\frac{i}{2} \Rightarrow (h,\bar{h}) = (2,0)$

gives

$$T_{zz} = 2i \int du\, d^2w \frac{u\, \gamma^{w\bar{w}}}{(z-w)^4} \hat{N}_{\bar{w}\bar{w}}$$

= generator of conformal trans. on the celestial sphere

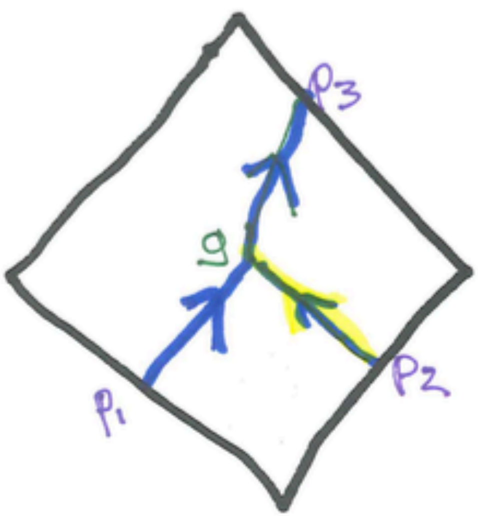
Kapec, Mitra, Raclariu, AS
160900282
Cheung, Fuente, Sundrum
160900732



Massive scalar

$m_1 + m_2 + \varepsilon = m_3$

Pasterski, Shao, AS 17010049;
Cardona,Huang, 170203283;
Shao,Tam 171106138;
Banerjee,Banerjee,Bhatkar and Jain, 171106690;Banerjee 180406646



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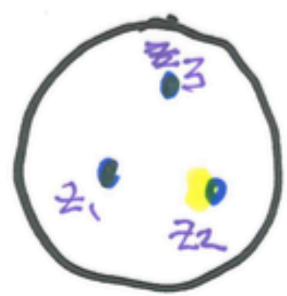


$$\simeq g \frac{\text{constant}}{|z_1-z_2|^{h_1+h_2-h_3}\,|z_2-z_3|^{h_2+h_3-h_1} \times |z_1-z_3|^{h_1+h_3-h_2}}$$

QED

Amplitudes factorize (soft factorization theorem)

Schwartz ``Quantum Field Theory'' 2014.

$$\mathcal{A}_{total} = \mathcal{A}_{soft} \times \mathcal{A}_{hard}$$

This is familiar from CFT2 with current algebra

$$\langle J_{z_1} J_{z_2} \mathcal{O}_3 \mathcal{O}_4 \dots \rangle$$

$$= \underbrace{\langle S_{z_1} S_{z_2} e^{iq_3\phi} e^{iq_4\phi} \dots \rangle}_{\text{current algebra}} \underbrace{\langle \hat{\mathcal{O}}_3 \hat{\mathcal{O}}_4 \dots \rangle}_{\text{parafermions}}$$

These are the same statement!

$$J_z J_w \sim 0, \quad J_z S_w \sim \frac{1}{(z-w)^2} \qquad S_z S_w \sim \frac{\Gamma_{cusp}}{(z-w)^2}$$

$$\Rightarrow \mathcal{A}_{soft} = \prod_{k \neq \ell}^{n} e^{-\frac{e_k e_\ell}{4\pi^2}[\gamma_{k\ell} \coth \gamma_{k\ell} - 1]} \dots$$

all matches!

$$\cosh \gamma_{k\ell} \equiv \frac{p_k \cdot p_\ell}{m_k m_\ell}$$

Nande, Pate, AS 1705000608

MHV amplitudes have been computed for any number N gluons at tree level and are given by Aomoto-Gelfand generalized hypergeometric functions on the Grassmannian Gr(4, N). Loop corrections were also found. A salient feature is the vanishing of the total imaginary part of the conformal weights $\Sigma \lambda_j = 0$. It would be interesting to relate conformally soft limit to G Kac-Moody on the celestial sphere.

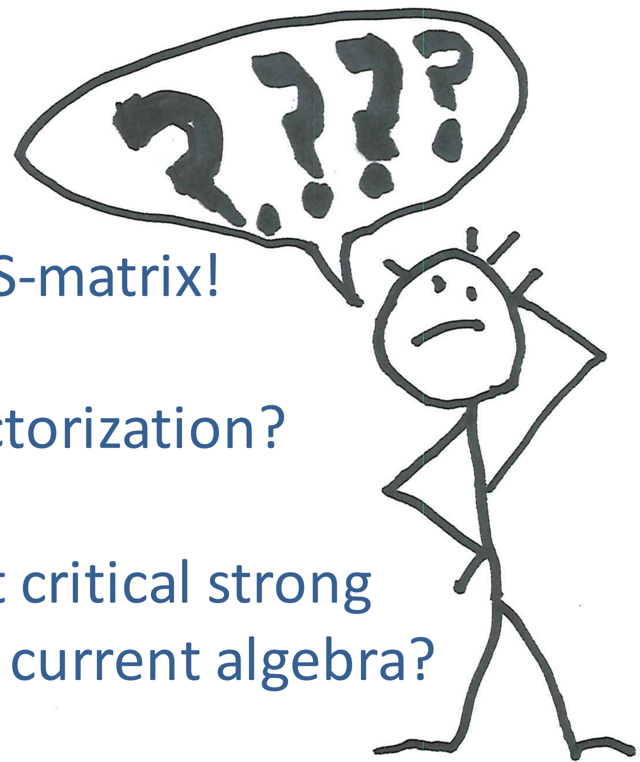
Schreiber, Volovich, Zlotnikov 171108435; Pasterski, Shao, AS 170603917.

SOME OPEN QUESTIONS

1. Is there a simple (free field theory?) example of Minkowski/CFT2 duality?

2.What good properties of the CFT2 are implied by 4D unitarity, crossing,……?

3. What is the relation
between the celestial CFT2
And the string worldsheet CFT2?
Both compute the 4D Minkowski S-matrix!
Steiberger Taylor 180605688



4. Gravity—celestial MHV, soft factorization?

5. Does QED U(1) get enhanced at critical strong coupling to SU(2) as suggested by current algebra?

Black Hole Entropy & Soft Hair

In progress: Haco, Hawking, Perry and AS

Generic Kerr BHs have a conformal symmetry emergent in the near-horizon region of phase space (not spacetime)

$\omega R \ll 1$

For ex. the near region contribution to soft scalar absorption is

$$P_{abs} \sim T_L^{2h_L-1} T_R^{2h_R-1} \sinh\left(\frac{\omega_L}{2T_L} + \frac{\omega_R}{2T_R}\right) \left|\Gamma\left(h_L + \frac{i\omega_L}{2\pi T_L}\right)\right|^2 \left|\Gamma\left(h_R + \frac{i\omega_R}{2\pi T_R}\right)\right|^2$$

$$T_L = \frac{r_+ + r_-}{4\pi a}, \quad T_R = \frac{r_+ - r_-}{4\pi a}; \quad \longleftrightarrow \quad \omega_L = \frac{2M^2}{a}\omega, \quad \omega_R = \frac{2M^2}{a}\omega - m$$

thermodynamically conjugate

$h_L = h_R = \ell$

$\sim$ thermal CFT_2

Castro, Maloney, AS 10040996; Larsen

CS can also be seen from the near-region wave equation.

Motivated by this, we found a pair of diffeos

$[\xi_n, \bar{\xi}_m] = 0$; $[\xi_n, \xi_m] = (m-n)\xi_{m+n}$; $[\bar{\xi}_n, \bar{\xi}_m] = (m-n)\bar{\xi}_{m+n}$

realizing this hidden conformal action on the horizon. Using the Ayer-Lee-Wald formalism, & fixing counterterm ambiguity with charge integrability, the ALW surface term gives

$c_L = c_R = 12J$

The Cardy formula then gives

$$\boxed{S_{BH} = \frac{\pi^2}{3}(c_L T_L + c_R T_R) = 2\pi M r_+ = \frac{Area}{4}} \; !$$

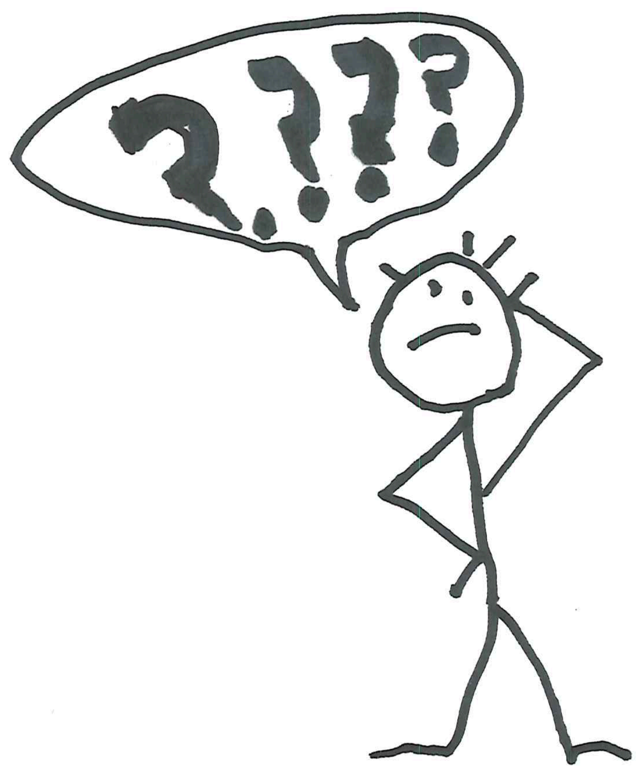
See also Carlip, Setare, Adami, Sheik Jabbari, Donnay Giribet Grumiller Wurbis Afshar

suggesting that, similar to stringy examples, S_{BH} can be inferred from the action of nontrivial diffeos on the black hole.

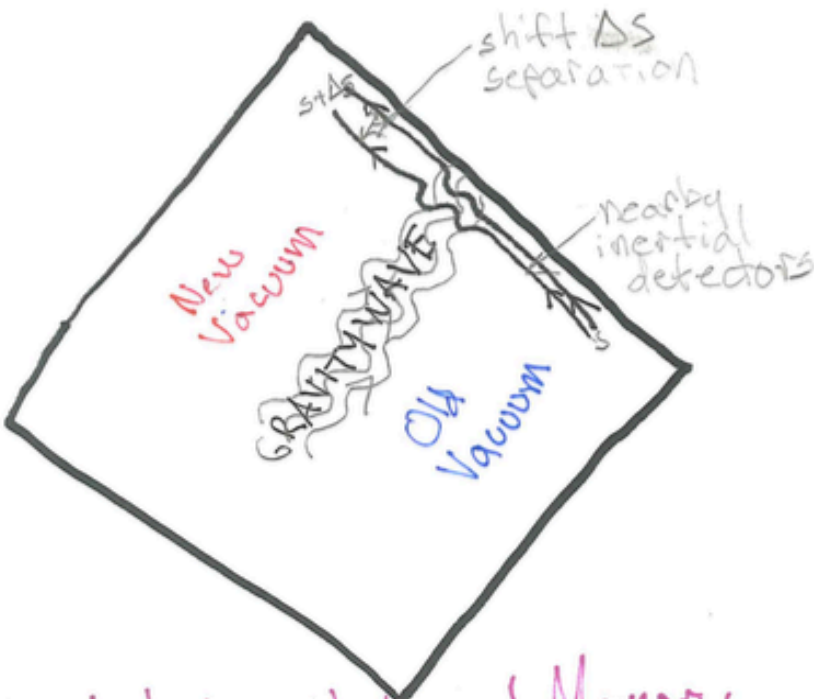
Stephen's last expression was a huge smile at this result.

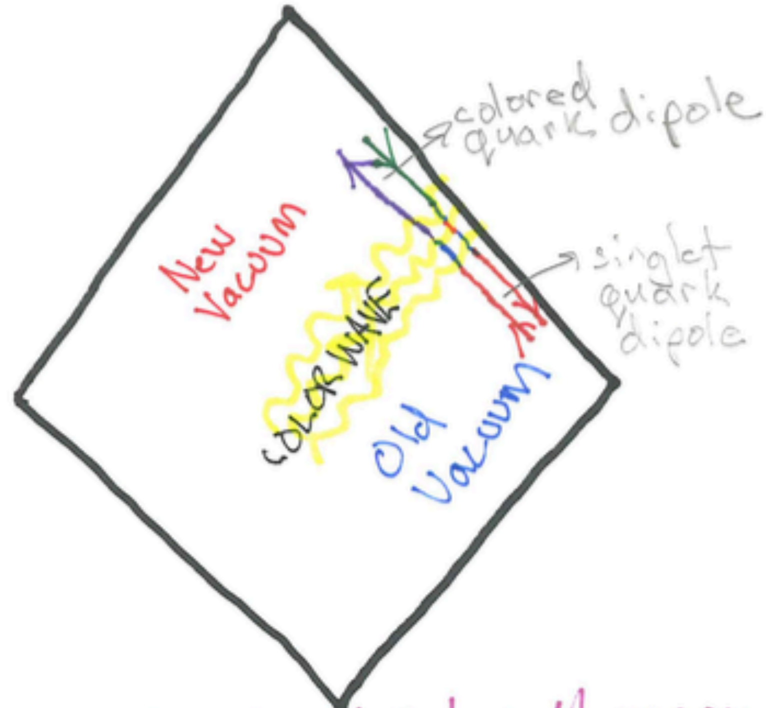
SOME OPEN QUESTIONS

Very many!!!!!



Color Memory at Electron-Ion Colliders





Classical Gravitational Memory

$\frac{\Delta s}{s}(z,\bar{z}) = \int d^2w \, G(z,\bar{z};w,\bar{w}) \int du \, T_{uu}$

= soft graviton theorem

likely to-be-measured LIGO

Classical Color Memory

$W(C) = \mathrm{Tr} \, P \, e^{i g_{ym} \oint A}$

closed $q\bar{q}$ worldline

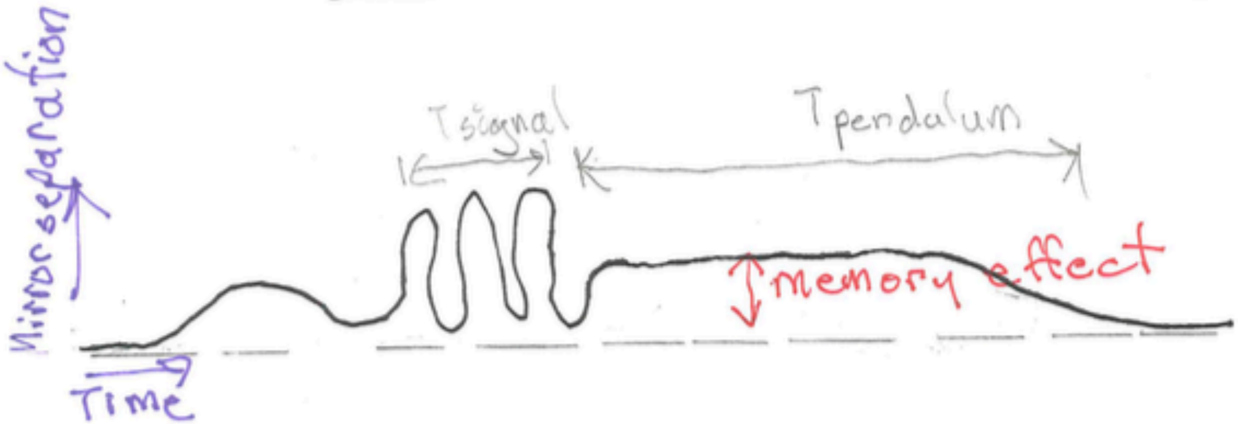
$D \cdot A \sim j_{\text{color flux}}$

= soft gluon theorem

Why measurable in QCD?

Pate, Raclariu, AS 170708016

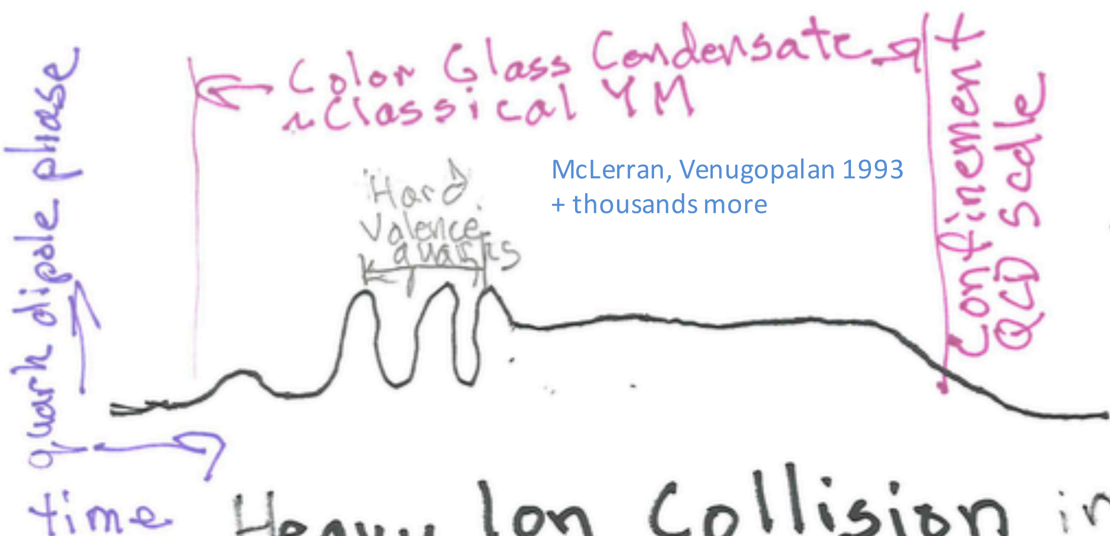
Scale separation

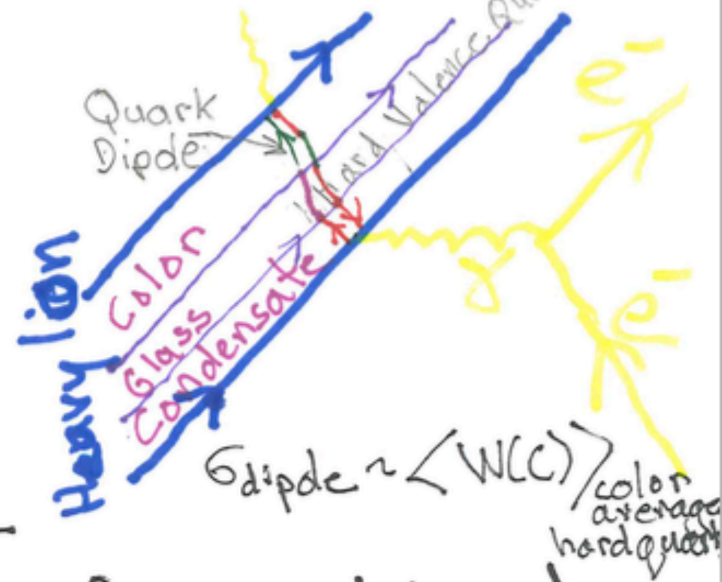


GW150914

To measure memory need $\frac{T_{signal}}{T_{pend}} < 1$

Not so small at h160 but still hope to measure.





Heavy Ion Collision in Regge Limit

Ball, Pate, Raclariu, AS, Venugopalan 180512224

In the Regge limit, it is argued that the inclusive virtual photon - ion cross section factorizes

$$\sigma_{\gamma^* \mathrm{Ion}} \sim \sigma_{\gamma^* \to q\bar{q}}\, \sigma_{\mathrm{dipole}} \quad \propto 1 - \langle W(C) \rangle_{\substack{\text{color}\\ \text{averaged}}}$$

and is proportional to the memory effect. The current situation is fluid as to whether or not color memory has been observed. Definitive measurement should be possible at the currently planned Future Electron- Ion collider!

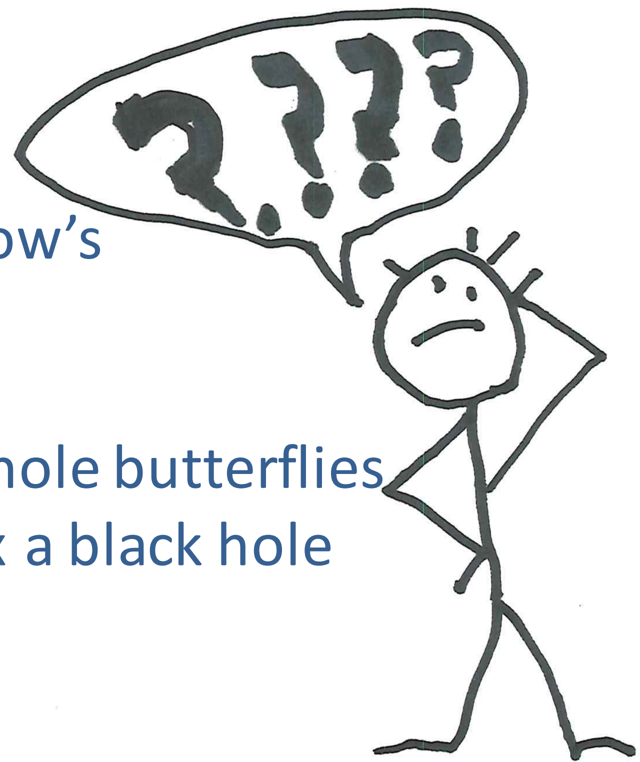
SOME OPEN QUESTIONS

1. Are there better ways to measure gravitational memory? Subleading `spin memory”?

2.How do we measure electromagnetic memory -in QED? (Change in net dipole time derivative is large at colliders!)

3. What is the observable memory effect associated to Low’s subleading soft theorem?

4. Are Shenker-Stanford black hole butterflies or `tHooft’s black hole S-matrix a black hole memory effect?



Conclusions

There is much yet-to-be understood about the deep IR in Minkowskispace. It is relevant both to ongoing experiments and to fundamental issues in holography, black holes and quantum gravity.


THANK YOU!