Color Memory and Novel Global Symmetries of Scattering Amplitudes

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Why do we find universal phenomena?

Explanations for Universality

1. **Infrared physics**

   Low-energy probes are **insensitive** to non-universal microscopic details.

2. **Symmetries**

   Observables are **protected** from non-universal specifics of the system.

Are these related? If so, how?

A hint…

$$Q \sim \int d^3\vec{x}\ \rho(\vec{x}) \sim \lim_{|\vec{p}|\to 0} \int d^3\vec{x}\ e^{i\vec{p}\cdot\vec{x}}\rho(\vec{x})$$

Conserved charges involve long-wavelength data.

Why should we care?

Affords more precise control of when to expect observables to be universal and how to measure them.

Disclaimer: will not fully deliver today!

Today's application:

In the context of scattering problems, there is an **equivalence**

Universality in the **infrared** $\Longleftrightarrow$ Universality due to **Symmetry**

Crux of the equivalence

Soft theorems in quantum field theory $\Longleftrightarrow$ **Conservation laws** for an infinite number of (global) symmetries

Outline:

Soft theorems $\Longleftrightarrow$ **Conservation laws**

Gravity

1. **Establish the equivalence**
   - Formally reinterpret soft theorems as statements of symmetry (conservation laws).
2. **Identify physical interpretation of symmetry**
   - Compare with familiar conservation laws.
3. **Determine an observable signature → "memory effect"**
   - Identify good observables for measuring conserved quantities → verify conservation law

Non-abelian gauge theory

1. Soft gluon theorem as a conservation law
2. Infinite-dimensional enhancement of color rotation symmetry
3. Color memory

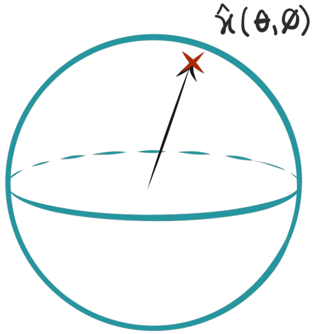
Weinberg's Soft Graviton Theorem

The scattering amplitude for the **emission of a soft graviton** has a **pole in the energy** of that graviton with a **universal residue**.

$$\lim_{\omega \to 0} \omega \langle \text{out} | a_+(\omega \hat{x}) \mathcal{S} | \text{in} \rangle = \sum_{k=1}^{n} S_k(\hat{x}) \langle \text{out} | \mathcal{S} | \text{in} \rangle$$

Graviton momentum:

$$q^\mu = \omega \hat{q}^\mu = \omega \big(1, \hat{x}(\theta, \phi)\big)$$



Soft factor: $S_k(\hat{x}) = \dfrac{\kappa}{2} \dfrac{\varepsilon^+_{\mu\nu} p_k^\mu p_k^\nu}{\hat{q} \cdot p_k}$

[Weinberg 1965]

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- **Infrared:** *low-energy graviton* probes long-distance properties of scattering process.
- **Universality:** soft factor only depends on momenta of external particles
  - *Insensitive* to precise particle content
  - *Insensitive* to most details of particle interactions
- **Symmetry?** exact relationship between scattering amplitudes

[Weinberg 1965]

Symmetry in Scattering

- To rigorously establish the soft theorem as consequent of symmetry, must first recall how symmetries are realized in the context of scattering.

Symmetries of the Scattering Problem

- Transformations of initial and final states that *preserve the S-matrix*

$$\langle \text{out}'|\mathcal{S}|\text{in}'\rangle = \langle \text{out}|U^\dagger \mathcal{S} U|\text{in}\rangle = \langle \text{out}|\mathcal{S}|\text{in}\rangle$$

Continuous symmetries:

$$U \sim 1 + iQ, \quad Q|\Psi\rangle \sim \delta|\Psi\rangle$$

$$\Rightarrow \langle \text{out}|[Q, \mathcal{S}]|\text{in}\rangle = 0$$

$\Rightarrow$ To establish soft theorems as statements of symmetry, simply need to show that they can be put in this form!

Soft Theorems Imply Symmetries

- **Goal:** write soft theorem in the form $\langle \mathrm{out}|[Q,\mathcal{S}]|\mathrm{in}\rangle = 0$.

$$\lim_{\omega\to 0} \omega \langle \mathrm{out}|a_+(\omega\hat{x})\mathcal{S}|\mathrm{in}\rangle = \sum_{k=1}^{n} S_k(\hat{x})\langle \mathrm{out}|\mathcal{S}|\mathrm{in}\rangle \qquad S_k(\hat{x}) = \frac{\kappa}{2}\frac{\varepsilon^+_{\mu\nu}p_k^\mu p_k^\nu}{\hat{q}\cdot p_k}$$

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$$S_k(\hat{x}) = \frac{\kappa}{2}\frac{\varepsilon^+_{\mu\nu}p_k^\mu p_k^\nu}{\hat{q}\cdot p_k}$$

- Regard soft factor S_k as eigenvalue of single particle state under operator Q_H

$$S_k(\hat{x})|p_k\rangle = Q_H(\hat{x})|p_k\rangle = -i\delta_{(\hat{x})}|p_k\rangle$$

- RHS gives total transformation of all single particle states under $\delta_{(\hat{x})}$

$$\underbrace{\sum_{k=1}^{n} S_k\langle \text{out}|\mathcal{S}|\text{in}\rangle} = \langle \text{out}|[Q_H, \mathcal{S}]|\text{in}\rangle$$

- Soft theorem implies that the $\mathcal{S}$-matrix is invariant under $\delta_{(\hat{x})}$ provided that *a soft particle is added.*

[He, Lysov, Mitra, Strominger, hep-th/1401.7026; Strominger, hep-th/1703.05448]

Soft Theorems Imply Symmetries

- **Goal:** write soft theorem in the form $\langle \text{out}|[Q,\mathcal{S}]|\text{in}\rangle = 0$.

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- Denote operator which **adds soft particles** Q_S

$$Q_S(\hat{x}) \sim -\lim_{\omega\to 0}\omega\left[a_+(\omega\hat{x}) + a_-^\dagger(\omega\hat{x})\right]$$

- Then, the LHS can be written as

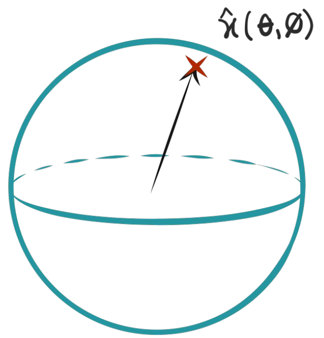
$$\lim_{\omega\to 0}\langle \text{out}|\omega a_+(\omega\hat{x})\mathcal{S}|\text{in}\rangle = -\langle \text{out}|[Q_S,\mathcal{S}]|\text{in}\rangle$$

- Soft theorem can be rearranged to take the form

$$\langle \text{out}|[Q,\mathcal{S}]|\text{in}\rangle = 0, \qquad Q = Q_H + Q_S$$

[He, Lysov, Mitra, Strominger, hep-th/1401.7026; Strominger, hep-th/1703.05448]

Summary



$$\lim_{\omega\to 0} \omega\langle \text{out}|a_+(\omega\hat{x})\mathcal{S}|\text{in}\rangle = \sum_{k=1}^{n} S_k(\hat{x})\langle \text{out}|\mathcal{S}|\text{in}\rangle$$

$$S_k(\hat{x}) = \frac{\kappa}{2}\frac{\varepsilon^+_{\mu\nu}p_k^\mu p_k^\nu}{\hat{q}\cdot p_k}$$

- Soft theorem can be put in the form $\langle \text{out}|[Q,\mathcal{S}]|\text{in}\rangle = 0$.
- Implies that the $\mathcal{S}$-matrix is **invariant under symmetry** generated by Q.
- Q is parametrized by $\hat{x}$

$\Rightarrow$ Soft theorems imply the $\mathcal{S}$-matrix is invariant under an **infinite** number of **symmetries**, one for each point on the sphere!

Outline:

Soft theorems $\Longleftrightarrow$ **Conservation laws**

Gravity

✔ **Establish equivalence**

- Formally reinterpret soft theorems as statements of symmetry (conservation laws).

2. **Identify physical interpretation of symmetry**
   - Compare with familiar conservation laws.
3. **Determine an observable signature → "memory effect"**
   - Identify good observables for measuring conserved quantities → verify conservation law.

Physical Interpretation of the Symmetries

- To facilitate an interpretation, parametrize charges by **functions** $f(\theta,\phi)$ rather than **points** $\hat{x}(\theta,\phi)$.

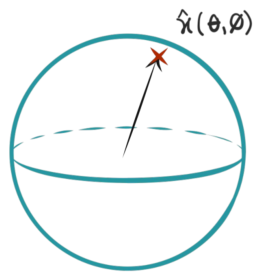
$$Q[f] = \int d^2\hat{x}\ f(\hat{x})\mathcal{D}_{(\hat{x})}Q(\hat{x})$$

- Obtain charges with **local** action

$$-i\delta_{(\hat{x})}|p_k\rangle = Q_H(\hat{x})|p_k\rangle = S_k(\hat{x})|p_k\rangle$$

$$\Downarrow$$

$$-i\delta_f|p_k\rangle = Q_H[f]|p_k\rangle = \omega_k f(\hat{x}_k)|p_k\rangle$$



$$p_k^\mu = \omega_k(1,\hat{x}_k)$$

[He, Lysov, Mitra, Strominger, hep-th/1401.7026; Strominger, hep-th/1703.05448]

Physical Interpretation of the Symmetries

$$-i\delta_f|p_k\rangle = Q_H[f]|p_k\rangle = \omega_k f(\hat{x}_k)|p_k\rangle$$

- When $f = 1$, find total energy

$$-i\delta_{f=1}|p_k\rangle = \omega_k|p_k\rangle$$

Q[f = 1] generates *ordinary* time translations

- Generic $f = f(\theta, \phi)$:

$$-i\delta_f|p_k\rangle = \omega_k f(\hat{x}_k)|p_k\rangle$$

f parametrizes *amount* of translation at every angle

Arbitrary $f \Rightarrow$ identify symmetry as **independent** time translations at **every angle**.

[He, Lysov, Mitra, Strominger, hep-th/1401.7026; Strominger, hep-th/1703.05448]

Why *infinitely* many?

To gain intuition, let’s reevaluate the transformations that observers could *possibly* perform on the system…

Why *infinitely* many?

In scattering, *only* observe initial & final states

Interactions between particles are negligible

Observers at different angles must be sufficiently far apart.

Formally implemented by assuming observers populate a sphere of infinite radius

“The Celestial Sphere”

Observers at different angles are *out of causal contact* with one another.

The Celestial Sphere

Why *infinitely* many?

Observers at different angles are *out of causal contact* with one another.

$\Downarrow$

Cannot synchronize transformations across different points on the celestial sphere

$\Downarrow$

Independent time translational symmetry at each point

$\Downarrow$

Infinite-dimensional enhancement of the translation group

Supertranslations

[Bondi, Metzner, van der Burg & Sachs, 1962]

The Celestial Sphere

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How do we know when a system admits a **symmetry**?

We observe that it respects a **conservation law**!

(Noether's theorem)

Constraints from Supertranslations

- Recall conserved charge:

$$Q = Q_H + Q_S$$

$$Q_H \sim \sum_k \omega_k f(\hat{x}_k)$$

Q_H characterizes local energy flux at every angle

$$Q_S(\hat{x}) \sim -\lim_{\omega \to 0} \omega \left[a_+(\omega \hat{x}) + a_-^\dagger(\omega \hat{x}) \right]$$

How do we measure Q_S?

Observable Signatures of Supertranslations

- Rewrite soft charge in terms of position-space field:

$$Q_S(\theta,\phi) \sim \lim_{\omega\to 0} \omega \left[a(\omega\hat{x}) + a^\dagger(\omega\hat{x})\right] \sim \lim_{\omega\to 0} \int dt\ \varepsilon^{\mu\nu} e^{i\omega t} \partial_t h_{\mu\nu}^{\mathrm{rad}}$$

Q_S captures the **zero-frequency component** of the **radiative gravitational field**.

- But also…

$$Q_S(\theta,\phi) \sim \varepsilon^{\mu\nu} \underbrace{\Delta h_{\mu\nu}}_{h_{\mu\nu}(t_f) - h_{\mu\nu}(t_i)}$$

Follows from

$$\int d\omega\ \frac{e^{i\omega t}}{\omega} \sim \Theta(t)$$

Q_S captures a **permanent net shift** in the **asymptotic metric**.

[Strominger & Zhiboedov, hep-th/1411.5745]

Are there observables that are sensitive to a permanent shift in the asymptotic metric?

Soft Charges and Vacuum Transitions

- Revisit Q_S from yet another angle:

$$Q_S(\hat{x}) \sim -\lim_{\omega\to 0} \omega \left[a_+(\omega\hat{x}) + a_-^\dagger(\omega\hat{x}) \right]$$

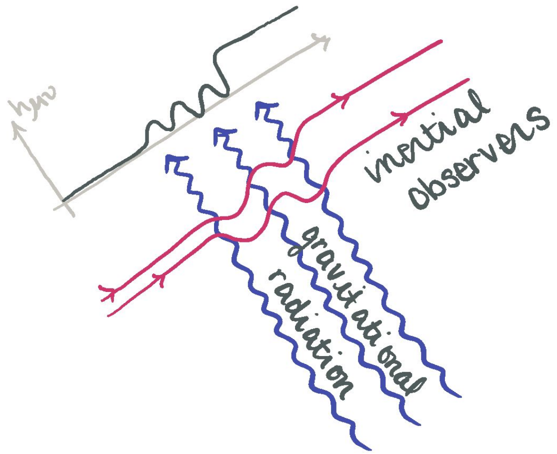
Q_S carries zero energy

- Acting with Q_S does not change the energy of a state.
- In particular, Q_S maps a **vacuum** state **to** a **vacuum** state.
- Suggests objects **charged under the symmetry** might be sensitive to **vacuum transitions**
  - In a theory of gravity, consider a **pair of inertial detectors**.

[Strominger, hep-th/1703.05448 and references therein]

Gravitational Memory

Permanent shift in metric induces permanent change in relative displacement between inertial observers



Geodesic Deviation Equation

$$\Delta s^i \sim \Delta h^{ij} s_j$$
$$\sim \lim_{\omega \to 0} \int dt\ e^{i\omega t} \partial_t h^{ij} s_j$$

[Zel'dovich & Polnarev 1974]

NATURE VOL. 327 14 MAY 1987

Gravitational-wave bursts with memory and experimental prospects

Vladimir B. Braginsky* & Kip S. Thorne†

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:

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

Conservation law relating change in asymptotic metric to soft factor $\leftrightarrow Q_H \leftrightarrow$ local energy flux

Gravitational Memory & Supertranslations

Relative displacement of inertial observers:

$$\Delta s^i \sim \Delta h^{ij} s_j$$
$$\sim \lim_{\omega \to 0} \int dt \; e^{i\omega t} \partial_t h^{ij} s_j$$

- Measures net shift in asymptotic metric!
- How to measure soft radiation!
  - ⇒ Tile the celestial sphere with inertial observers and measure the change in their relative displacements.

[Strominger & Zhiboedov, hep-th/1411.5745]

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Non-abelian gauge theory

1. Soft gluon theorem as a conservation law
2. Infinite-dimensional enhancement of color rotation symmetry
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Novel Global Symmetries in Gauge Theory

Tree-level Soft Gluon Theorem:

$$\underbrace{\lim_{\omega\to 0} \omega\langle \text{out}|a_+^a(\omega\hat{x})\mathcal{S}|\text{in}\rangle}_{-\langle \text{out}|[Q_S^a(\hat{x}),\mathcal{S}]|\text{in}\rangle} = \underbrace{\sum_{k=1}^{n} gT_k^a \frac{\varepsilon^+\cdot p_k}{\hat{q}\cdot p_k}\langle \text{out}|\mathcal{S}|\text{in}\rangle}_{\langle \text{out}|[Q_H^a(\hat{x}),\mathcal{S}]|\text{in}\rangle}$$

- Soft theorem can be put in the form

$$\langle \text{out}|\,[Q(\hat{x}),\mathcal{S}]\,|\text{in}\rangle = 0, \qquad Q = Q_H + Q_S$$

- Implies that the $\mathcal{S}$-matrix is **invariant under symmetry** generated by Q, parametrized by $\hat{x}$.

⇒ Soft gluon theorem implies the $\mathcal{S}$-matrix is invariant under an **infinite** number of **symmetries**, one for each point on the sphere!

[He, Mitra & Strominger, hep-th/1503.02663]

Physical Interpretation of the Symmetries

$$-i\delta_\varepsilon|p_k\rangle = Q_H[\varepsilon]|p_k\rangle = g\varepsilon(\hat{x}_k)|p_k\rangle$$

Parametrize by (Lie algebra-valued) **functions** $\varepsilon(\theta,\phi) = T^a\varepsilon^a(\theta,\phi)$, rather than **points** $\hat{x}(\theta,\phi)$

- When $\varepsilon = T^a$, find total color charge

$$-i\delta_{\varepsilon=T^a}|p_k\rangle = gT^a_k|p_k\rangle$$

Q[$\varepsilon = T^a$] generates *ordinary* color rotations

- Generic $\varepsilon = T^a\varepsilon^a(\theta,\phi)$

$$-i\delta_\varepsilon|p_k\rangle = gT^a_k\varepsilon^a(\hat{x}_k)|p_k\rangle$$

ε parametrizes *amount* of color rotation at every angle

Arbitrary $\varepsilon \Rightarrow$ identify symmetry as **independent** color rotations at **every angle**.

[He, Lysov, Mitra, Strominger, hep-th/1401.7026; Strominger, hep-th/1703.05448]

Verifying the Conservation Law

- Recall in gravity, subtlety involved measuring Q_S

$$Q_S(\hat{x}) \sim \lim_{\omega \to 0} \omega \left[a^a(\omega \hat{x}) + a^{a\dagger}(\omega \hat{x}) \right] \sim \lim_{\omega \to 0} \int dt\ \varepsilon^\mu e^{i\omega t} \partial_t A_\mu^{a\,\mathrm{rad}} \sim \varepsilon^\mu \Delta A_\mu^a$$

Q_S captures the **zero-frequency component** of the **radiative gluon field**
or equivalently, a **permanent net shift** in the **radiative gluon field**.

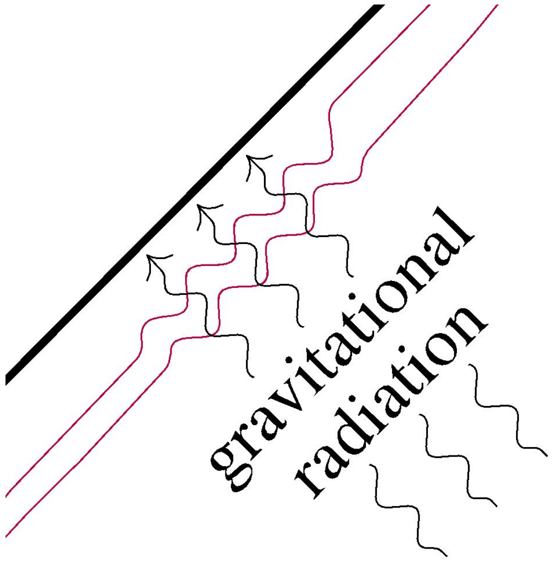
- Recall the resolution was to study the effect on objects **charged under the symmetry**
  - In gauge theory, consider **test quarks**

[**MP**, Raclariu, & Strominger hep-th/1707.08016]

Color Memory by Analogy

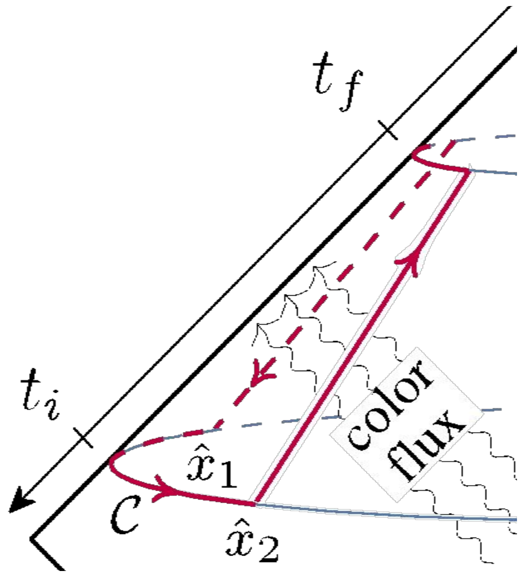
Gravitational Memory

Permanent shift in the **metric** induces permanent shift in the **relative displacement** of a pair of **inertial observers**.



Color Memory

Permanent shift in the **gluon field** induces permanent shift in the **relative color** of a pair of **test quarks**.



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Color Memory by Analogy

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Permanent shift in the **metric** induces permanent shift in the **relative displacement** of a pair of **inertial observers**.

Color Memory

Permanent shift in the **gluon field** induces permanent shift in the **relative color** of a pair of **test quarks**.

Geodesic Deviation Equation

$$\Delta s^i \sim \Delta h^{ij} s_j$$
$$\sim \lim_{\omega \to 0} \int dt\ e^{i\omega t} \partial_t h^{ij} s_j$$

Wong's Equation

$$\frac{dx^\mu}{d\tau} (\partial_\mu q - igA_\mu q) = 0$$

$$\mathcal{W}_\mathcal{C} = \mathcal{P} \exp \left(ig \oint_\mathcal{C} A \right)$$

[**MP**, Raclariu, & Strominger hep-th/1707.08016]

Is color memory accessible by experiment?

Obvious objection: confinement obstructs our ability to access long-wavelength modes of the gluonic field by experiment…

Color Memory in Experiment

- There exists a regime in scattering in which the physics is dominated by a classical color memory effect.

Regge limit

$$t \text{ fixed}, \qquad s \to \infty$$

(momentum transfer) (center of mass energy)

- Heavy ion scattering in the Regge limit is argued to admit a classical description.

"Color Glass Condensate"

(Effective Field Theory)

[Iancu & Venugopalan, hep-ph/0303204; Gelis, Iancu, Jalilian-Marian & Venugopalan, hep-ph/1002.0333]

DIS in the Regge Limit

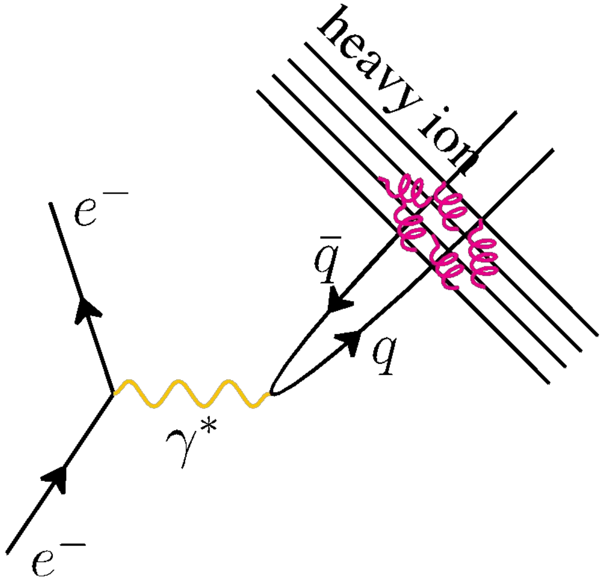
- For concreteness, consider deep inelastic scattering in the Regge limit.

Two-stage Process:

1. Photon fluctuates into quark dipole
2. Quark dipole interacts with heavy ion

Pair of test quarks

Color shockwave sourcing permanent shift in gluon field



Inclusive DIS virtual photon-heavy ion cross section:

$$\sigma_{\gamma^* \mathrm{ion}}(x, Q^2) = \int_0^1 dz \int d^2\vec{r}\ \underbrace{\left|\Psi_{\gamma^* \to q\bar{q}}(z, \vec{r}, Q)\right|^2}_{\text{QED}}\ \underbrace{\sigma_{\mathrm{dipole}}(x, \vec{r})}_{\text{QCD}}$$

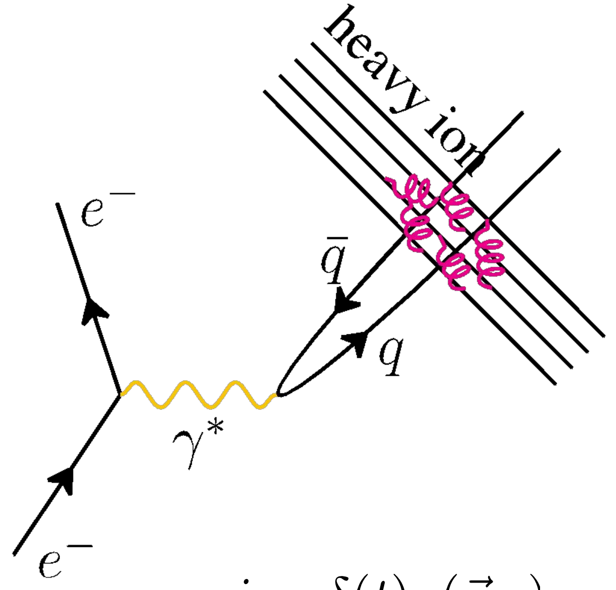
Color Memory in DIS

- The QCD process is dominated by a color memory effect

[Ball, **MP**, Raclariu, Strominger & Venugopalan, hep-ph/1805.12224]

QCD process cross section

$$\sigma_{\text{dipole}}(x, \vec{r}_\perp) = 2 \int d\vec{b}_\perp \, [1 - \langle \text{Re}\, \mathcal{S}(\vec{x}_{1\perp}, \vec{x}_{2\perp}) \rangle$$



$$\mathcal{S}(\vec{x}_{1\perp}, \vec{x}_{2\perp}) = \frac{1}{N_c} \text{Tr}\left[\mathcal{P} \exp\left(ig \oint_{\mathcal{C}} A\right)\right]$$

$$j \sim \delta(t)\rho(\vec{x}_\perp)$$

Color memory

(Relative color rotation)

$$\partial_i \Delta A_i \sim \partial_i \lim_{\omega \to 0} \omega \left[a + a^\dagger\right] \sim \int_{t_i}^{t_f} dt \; j$$

Identify low-frequency mode of the gluon field as responsible for non-trivial dipole scattering.

Observables in the Color Glass Condensate

- Non-trivial physics of the heavy ion is captured by averaging over **an ensemble** of sources.

$$\langle \mathcal{O} \rangle = \int [\mathcal{D}\rho] W_{\Lambda^+}[\rho] \mathcal{O}[\rho] \qquad j \sim \delta(t)\rho(\vec{x}_\perp)$$

⇒ Ensemble of shockwave profiles
⇒ Ensemble of "permanent shift" field config.

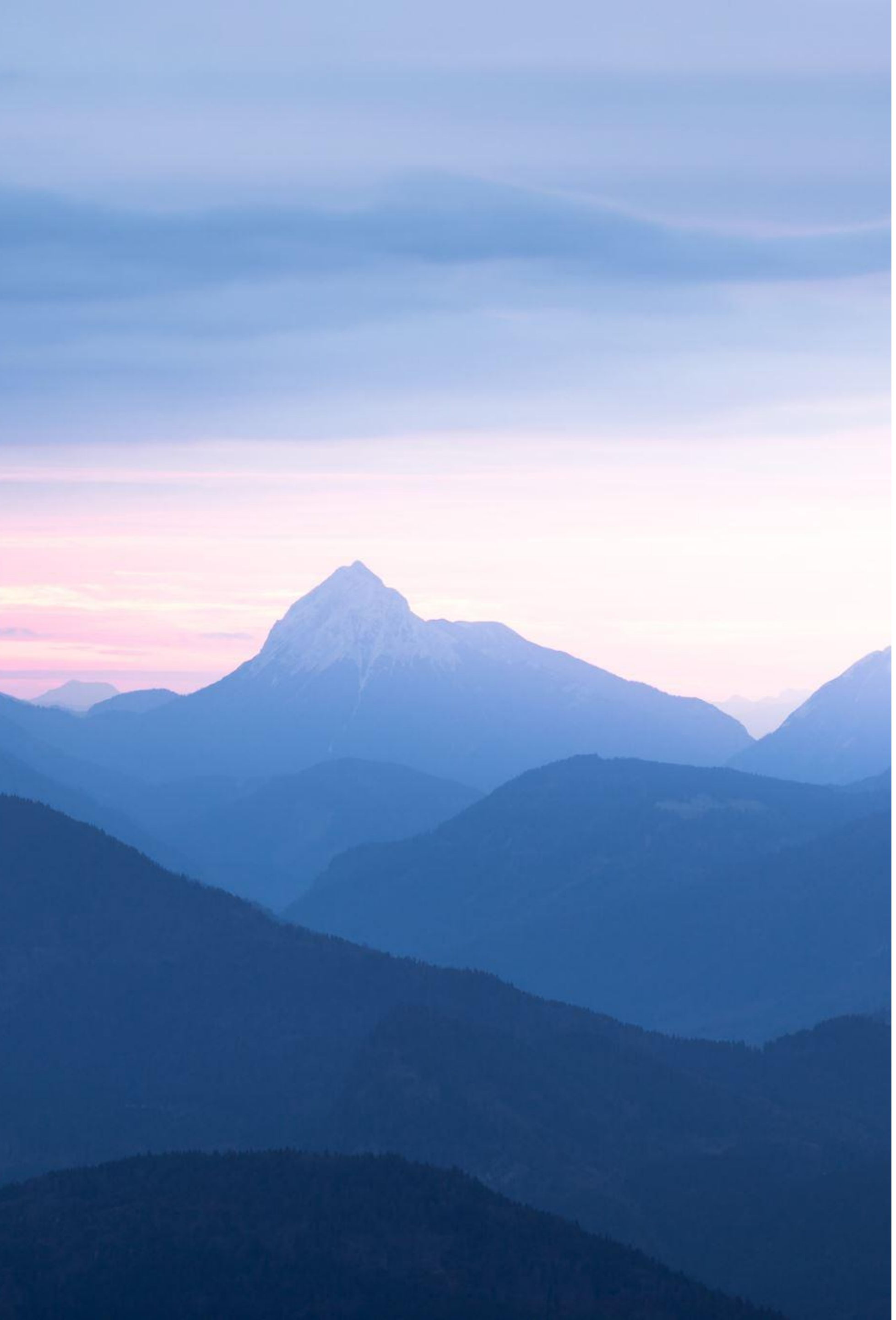
⇒ Generates **systematic dependence** on transverse momentum scale a.k.a. **"saturation scale"**.

Characteristic distance for large color fluctuations $\quad Q_S^2 \sim A^{1/3}$

CGC predicts systematic dependence of observables on this scale.

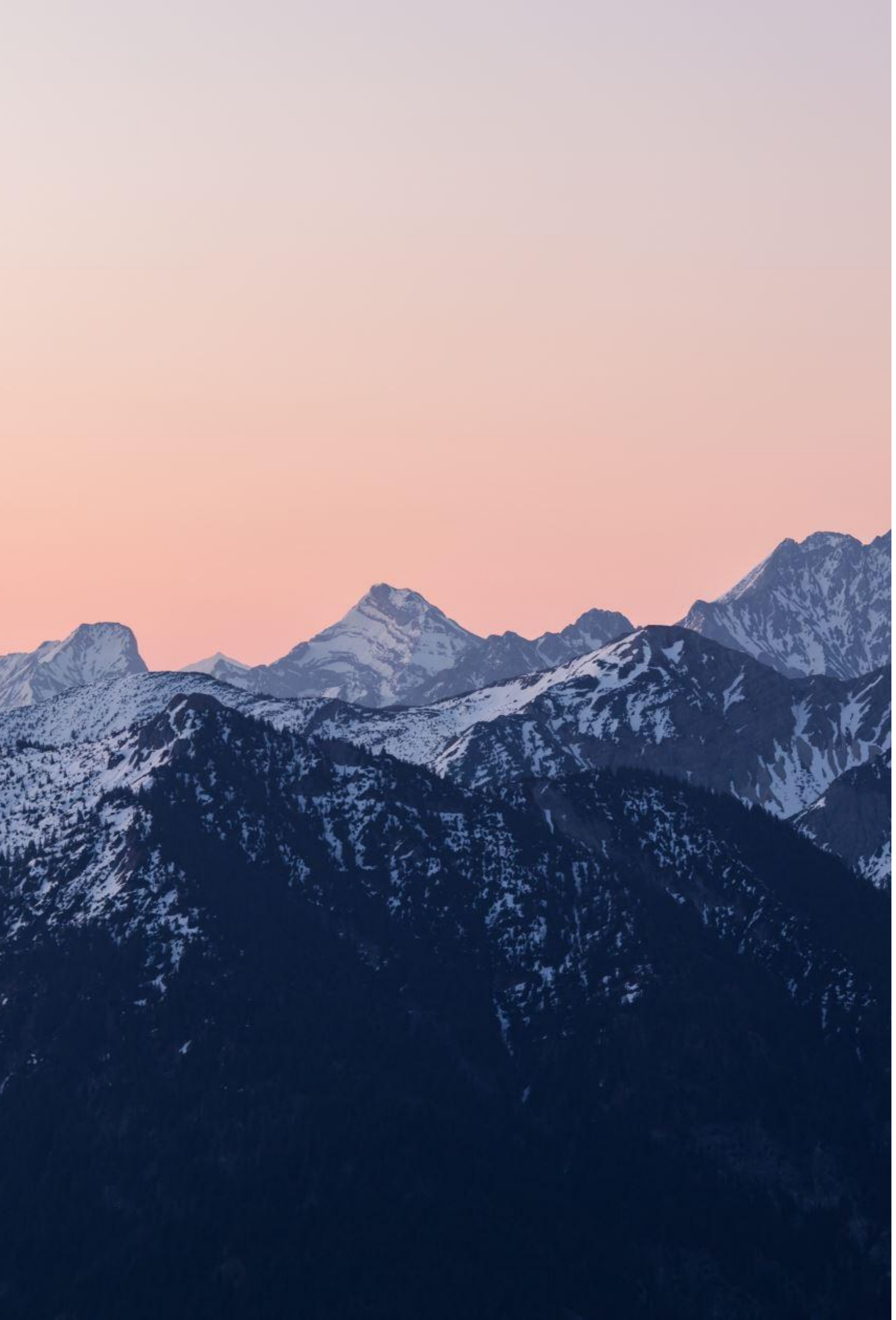
While the full low-frequency field configuration is not captured by observables, can experimentally verify whether physics is governed by the saturation scale: **characteristic** (transverse) **distance** for **fluctuations** in the **low-frequency mode**.

[Ball, **MP**, Raclariu, Strominger & Venugopalan, hep-ph/1805.12224]



Summary

- Presented formal argument that **soft theorems** imply the $\mathcal{S}$-matrix is **invariant** under an **infinite-dimensional symmetry**
- Identified symmetry as **enhancement** of **translations** and **color rotations** in theories of **gravity** and **gauge**, respectively.
- Established **"memory effects"** as observables with **simple dependence** on associated **conserved quantities**,
  - Necessary to verify conservation laws, a natural observable signature of symmetry
- Described context in which a **classical color memory** is relevant to **experiment**



Outlook

- Additional infinite-dimensional symmetries in gauge and gravitational theories from other known soft theorems:
    - **Subleading soft theorems**
    - Soft theorems with **fermionic soft particles**

- Exploit developments concerning **universal features** of generic theories of gauge and gravity to

1. Determine the theory of **quantum gravity**
2. Identify/design **robust observables** for particle colliders

Thank You!

Saturation Scale Effects

- The saturation scale is predicted to control the transverse momentum kick received by a probe quark propagating through a target.
- Larger saturation scales lead to larger momentum kicks.
- E.g. predicts diminished likelihood that hadron pairs in deuteron-gold collisions are azimuthally correlated back-to-back as compared with those in proton-proton collisions

[C. Marquet, Nucl. Phys. A 796, 41 (2007); T. Lappi and H. Mantysaari, Nucl. Phys. A 908, 51 (2013)]