Causality, Higher-Spin Particles & Large N QCD

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Based on:

arXiv.org > hep-th > arXiv:2008.05477

High Energy Physics – Theory

[Submitted on 12 Aug 2020]

Closed Strings and Weak Gravity from Higher-Spin Causality

Jared Kaplan, Sandipan Kundu

arXiv.org > hep-th > arXiv:2009.08460

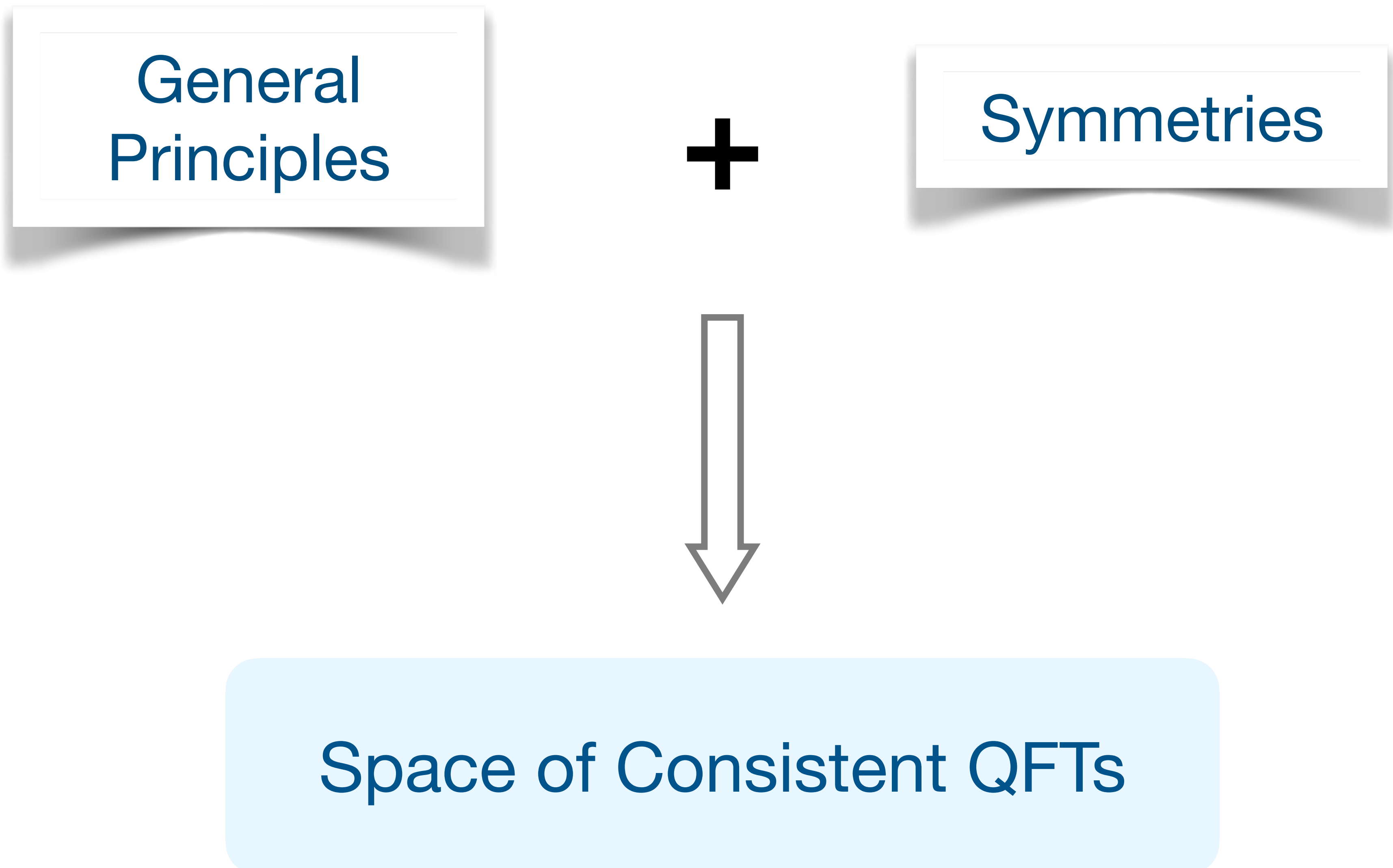
High Energy Physics – Theory

[Submitted on 17 Sep 2020]

Causality Constraints in Large N QCD Coupled to Gravity

Jared Kaplan, Sandipan Kundu

Main Idea



Higher spin particles in nature

Quantum Mechanics + Special Relativity

⇓

Massless particles

Spin $0, \frac{1}{2}, 1, \frac{3}{2}, 2$

Weinberg-Witten (1980), Porrati (2008)

There is a *discrete* difference between massive and massless particles of the same spin.

Massive higher spin particles in general are NOT ruled out!

However, there is a *conflict* between
massive higher spin particles and causality.

Camanho, Edelstein, Maldacena, Zhiboedov (2014)

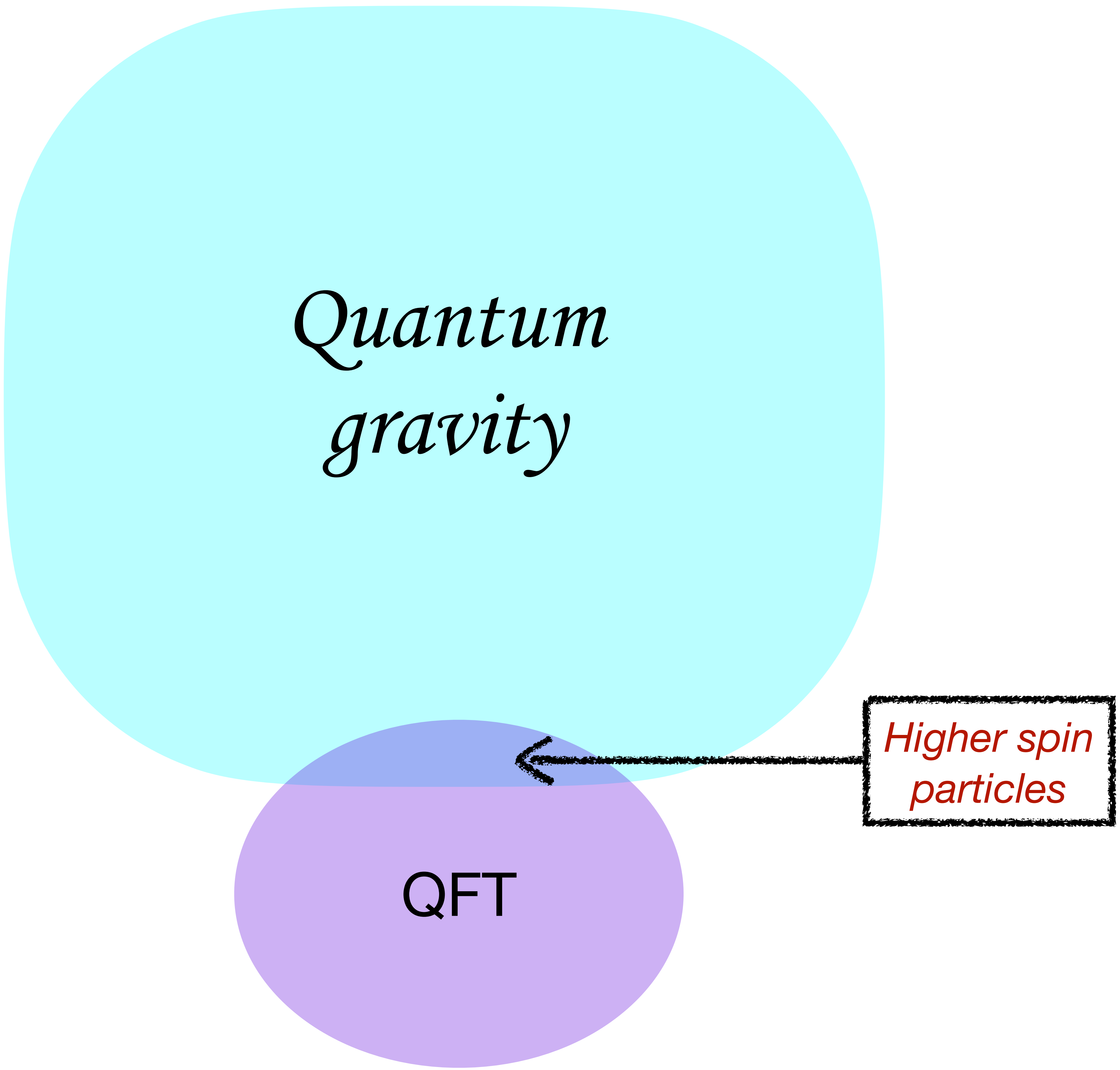
Caron-Huot, Komargodski, Sever, Zhiboedov (2016)

Afkhami-Jeddi, SK, Tajdini (2018)

Large N QCD

Large N confining gauge theories in 4d

Metastable glueballs and mesons of *arbitrarily large spin*


Quantum gravity
Higher spin particles
QFT

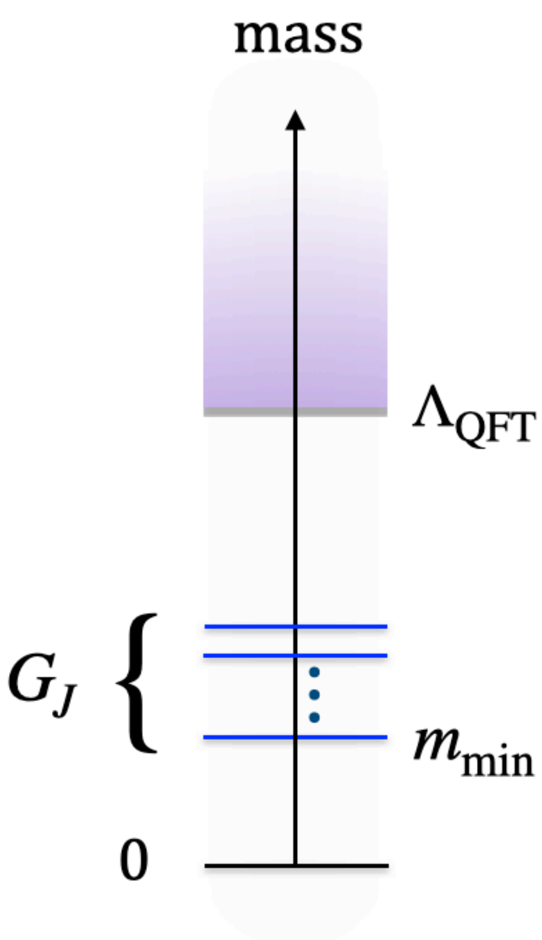
Theories of stable or metastable higher spin particles can be coupled to gravity while preserving causality only when the gravity sector has many of the properties of fundamental strings!

Kaplan, SK (2020)

There is a conflict between causality and large N QCD coupled to gravity!

Kaplan, SK (2020)

Theories of metastable higher spin particles



(a) higher spin QFT

(i) $\{G_J\}$ = all degrees of freedom of the theory below the cut-off scale Λ_{QFT}.

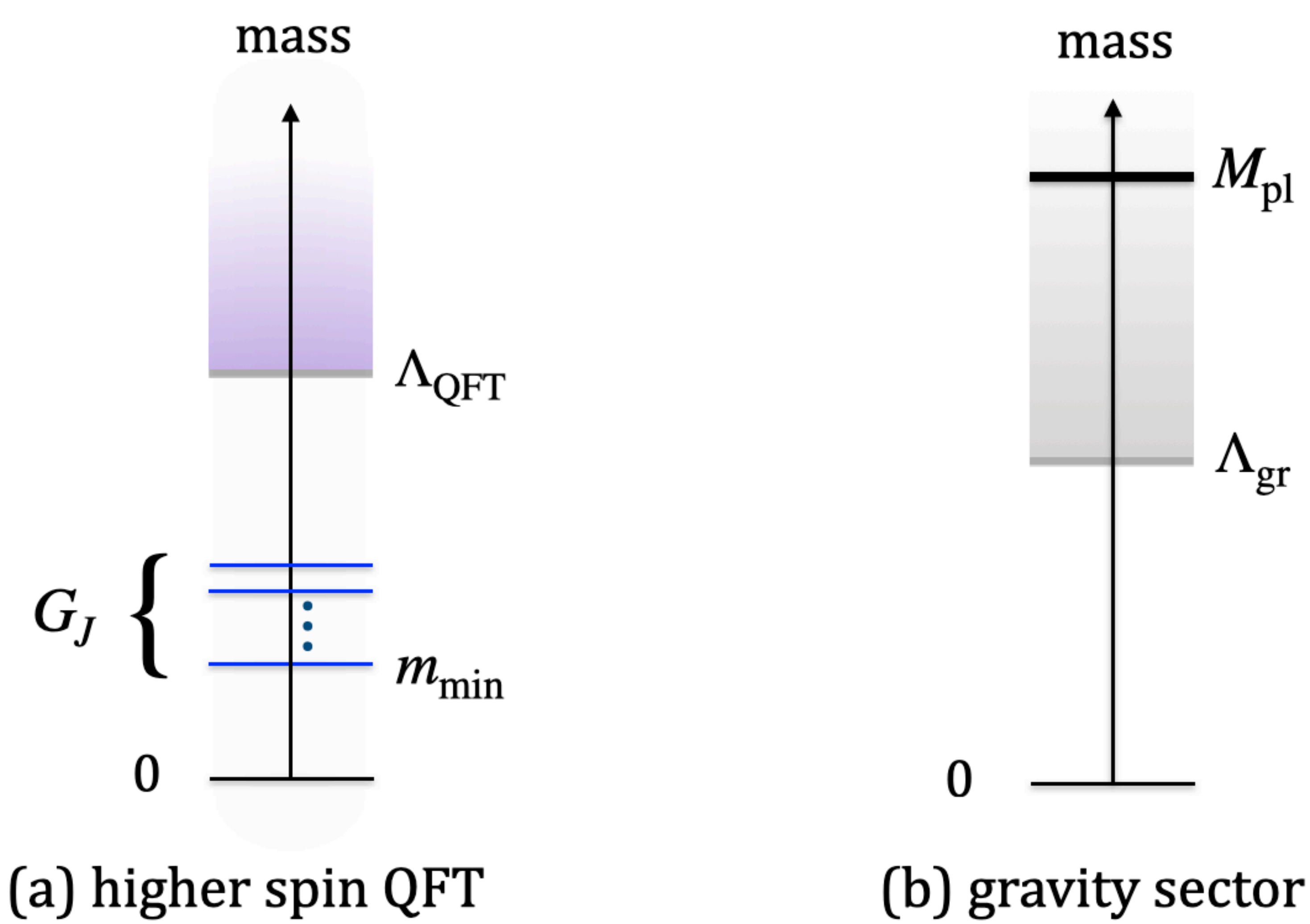
(ii) Metastable: All effective low energy couplings are small

$$\langle G_J G_{J'} G_{J''} \rangle \sim \lambda \qquad |\lambda| \ll 1$$

(iii) Consistent S-matrix.

Kaplan, SK (2020)

Theories of metastable higher spin particles



(iv) Gravitationally metastable: $\langle G_J h_{\mu_1\nu_1} h_{\mu_2\nu_2} \rangle \sim \dfrac{\lambda_G}{M_{\rm pl}^2}$, $|\lambda_G| \lesssim O(1)$

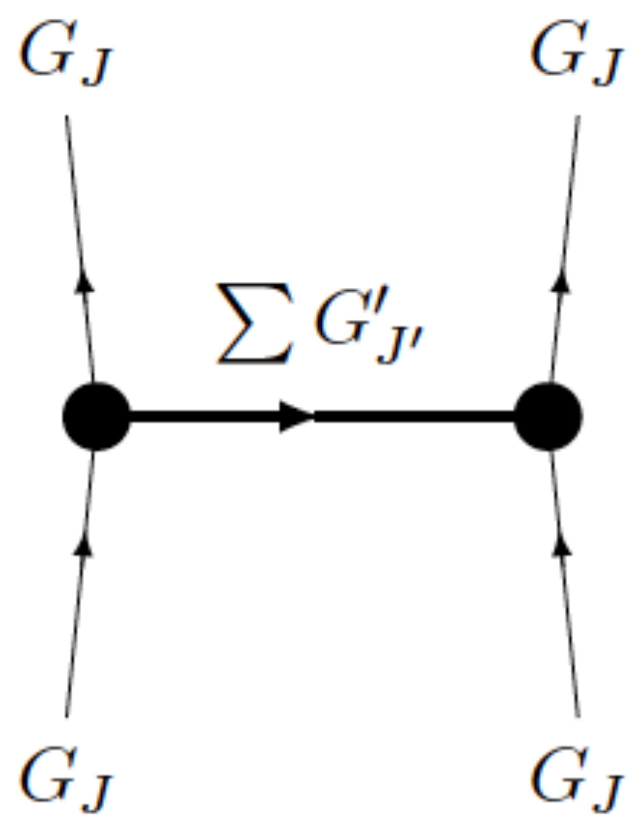
Kaplan, SK (2020)

Theories of metastable higher spin particles

$$G_J G_J \to G_J G_J$$

$M_{\rm pl} \to \infty$

The tree-level scattering amplitude is a meromorphic function with simple poles only at the location of $\{G_J\}$ particles.



Theories of metastable higher spin particles

$$G_J G_J \to G_J G_J$$

$M_{\rm pl} = \text{finite}$

New poles!

⇓

graviton

+

other particles in the gravity sector

These additional gravitational poles are essential to the preservation of causality!

Outline

A. Causality in QFT

B. Causality Constraints on Higher Spin Particles

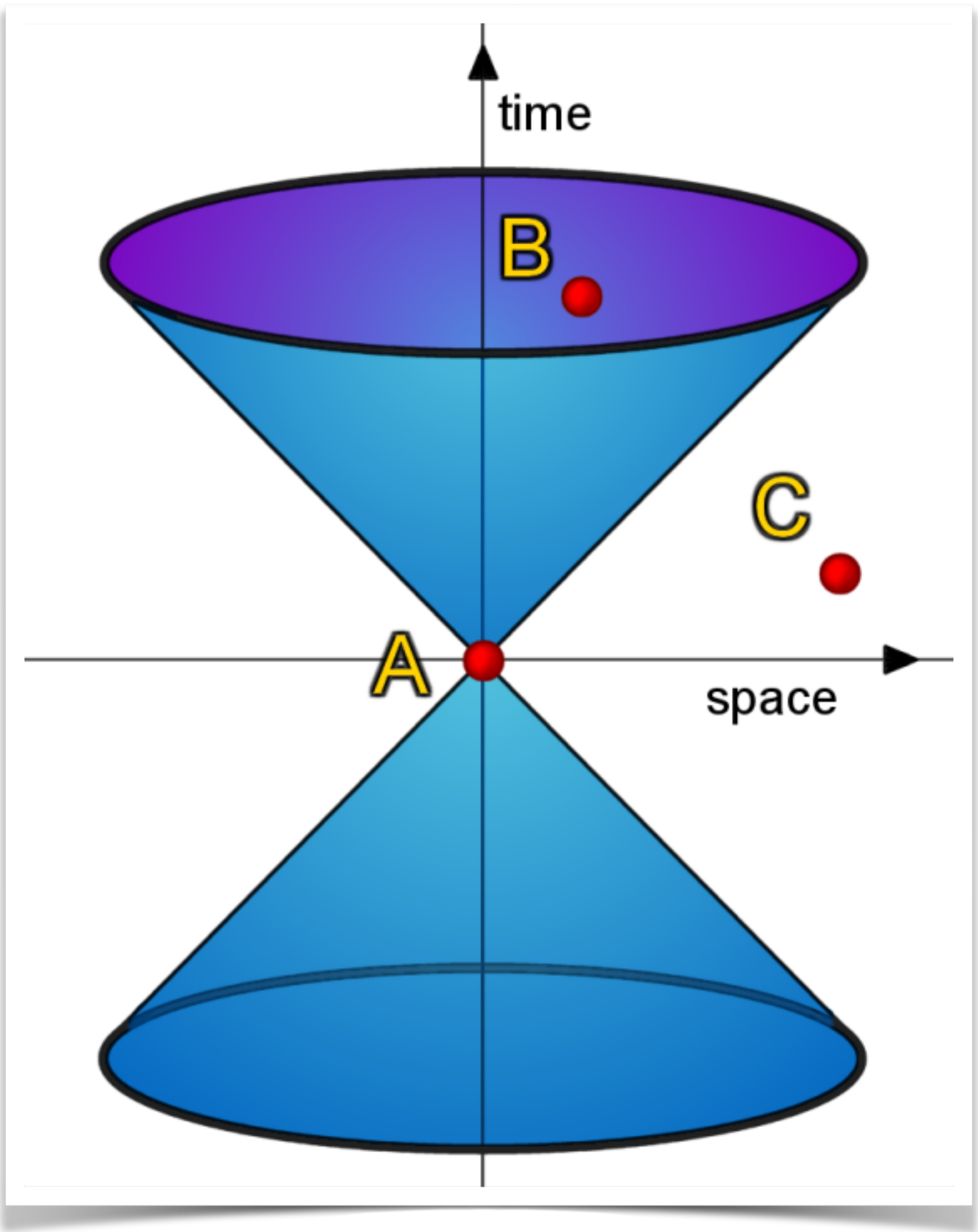
C. Emergence of Closed Strings

D. Large N QCD

E. Conclusions

Causality in QFT

Causality requires commutators of local operators in Minkowski space to vanish outside the lightcone.



$$[O_A, O_C] = 0$$

A non-trivial
operator statement!

Causality in QFT

- Requiring a QFT to be causal in every state of the theory does impose non-trivial constraints on QFTs.
- QFTs that appear to be causal in flat spacetime can violate causality when coupled to gravity.

Causality of position space correlators

ANEC

T. Hartman, SK, A. Tajdini (2016)

QNEC

Balakrishnan, Faulkner, Khandker, Wang (2017)

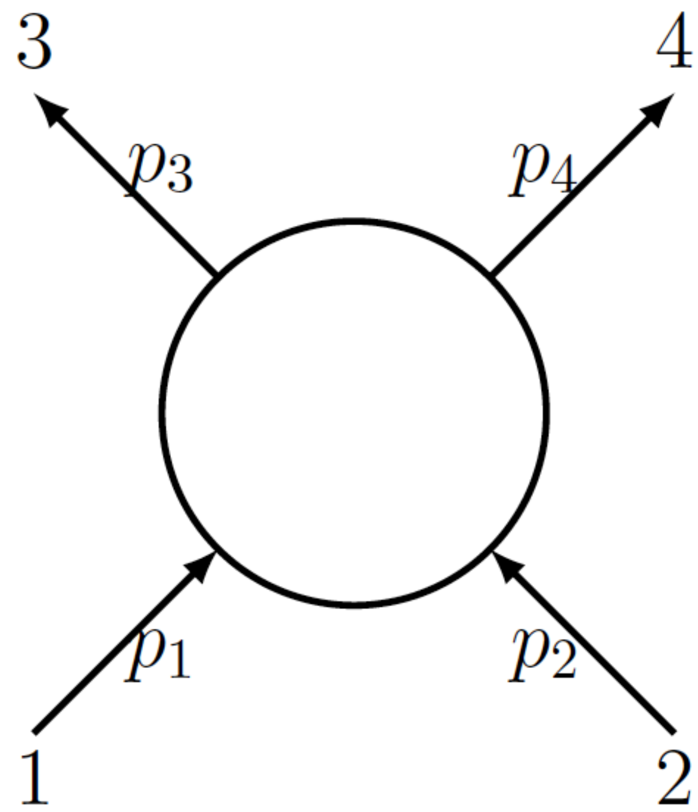
Gravity from CFT

N. Afkhami-Jeddi, T. Hartman, SK and A. Tajdini (2016, 2017)
N. Afkhami-Jeddi, SK and A. Tajdini (2018)

Constrain space of CFTs

Hartman, Jain, SK (2015,2016); Hofman, Li, Meltzer, Poland, Rejon-Barrera (2016); Afkhami-Jeddi, Colville, Hartman, Maloney, Perlmutter (2017); Dutta Chowdhury, David, Prakash (2017); Cordova, Maldacena, Turiaci (2017); Cordova, Diab (2017); SK (2020)

Scattering amplitudes in flat space



$$s = -(p_1 + p_2)^2$$
$$t = -(p_1 - p_3)^2$$
$$u = -(p_1 - p_4)^2$$

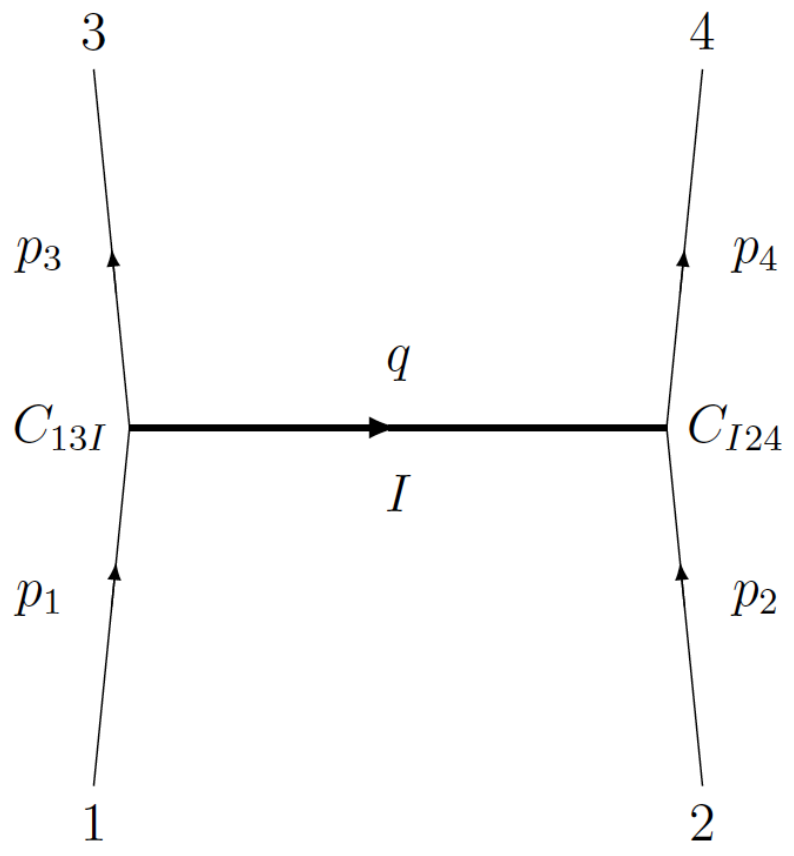
$$|s| \gg |t|, m_i^2$$

Eikonal scattering

The impact parameter space:

$$\delta(s, \vec{b}) = \frac{1}{2s} \int \frac{d^2\vec{q}}{(2\pi)^2} \, e^{i\vec{q}\cdot\vec{b}} M(s, \vec{q}\,)$$

$$= \sum_I \frac{1}{2s} \int \frac{d^2\vec{q}}{(2\pi)^2} \, e^{i\vec{q}\cdot\vec{b}}$$



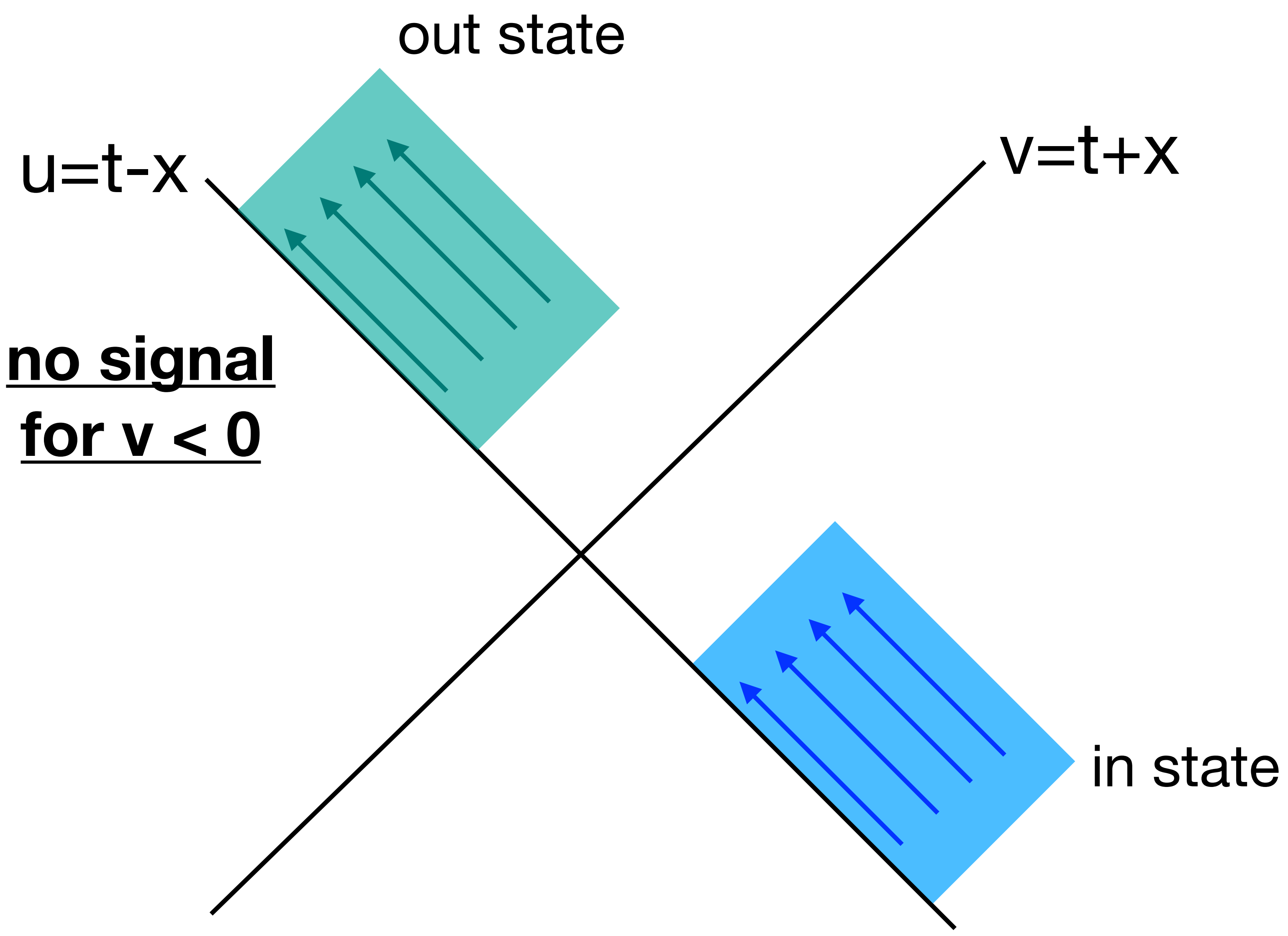
Causality constraints on the phase-shift

$$\delta(s, \overrightarrow{b}) \sim \text{ Shapiro time-delay } \geq 0$$

Camanho, Edelstein, Maldacena, Zhiboedov (2014)

Causality constraints on the phase-shift

For $s \gg \frac{1}{b^2}, m_i^2$ an eikonal scattering can be mapped to a signal transmission problem



Camanho, Edelstein, Maldacena, and Zhiboedov (2014)

Causality constraints on the phase-shift

For $s \gg \frac{1}{b^2}, m_i^2$

- $\delta(s, \overrightarrow{b})$ does not grow faster than s.
- $\delta(s, \overrightarrow{b}) \geq 0$ when it grows linearly with s.

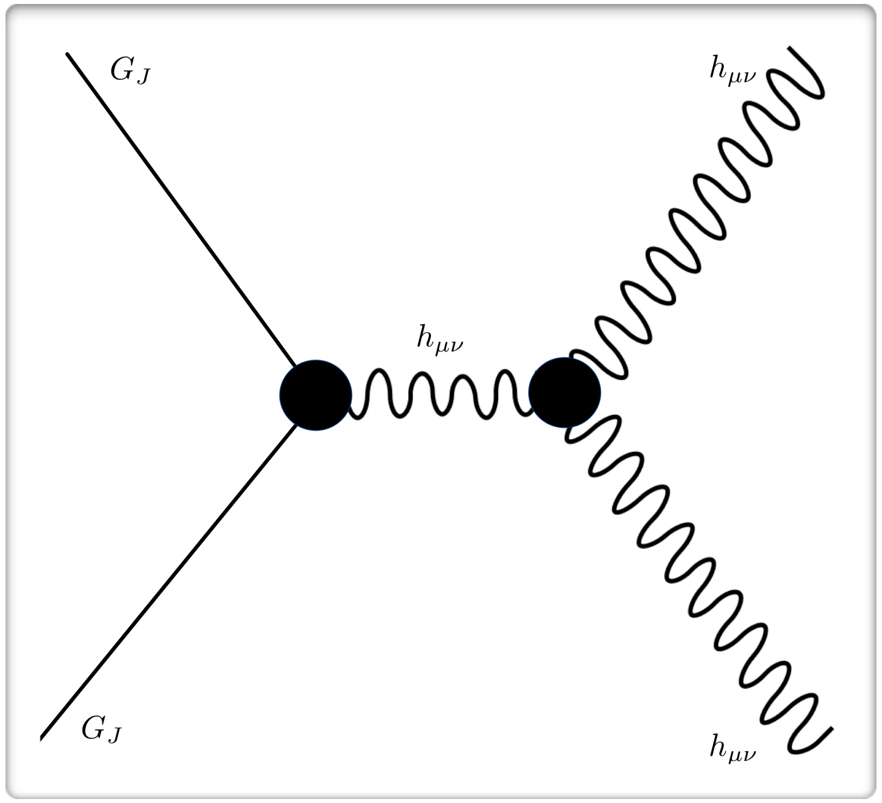
In AdS, this is related to the chaos bound in the dual CFT.

Camanho, Edelstein, Maldacena, and Zhiboedov (2014)

Theories of metastable higher-spin particles coupled to gravity in 4d

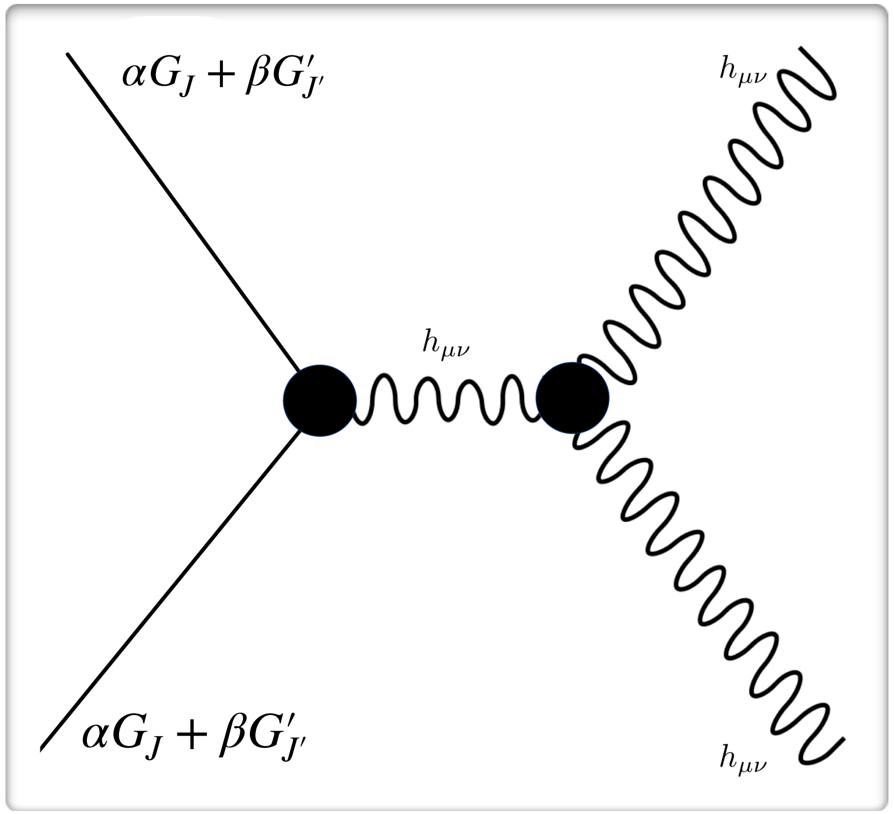
Three thought experiments and a theorem!

1.

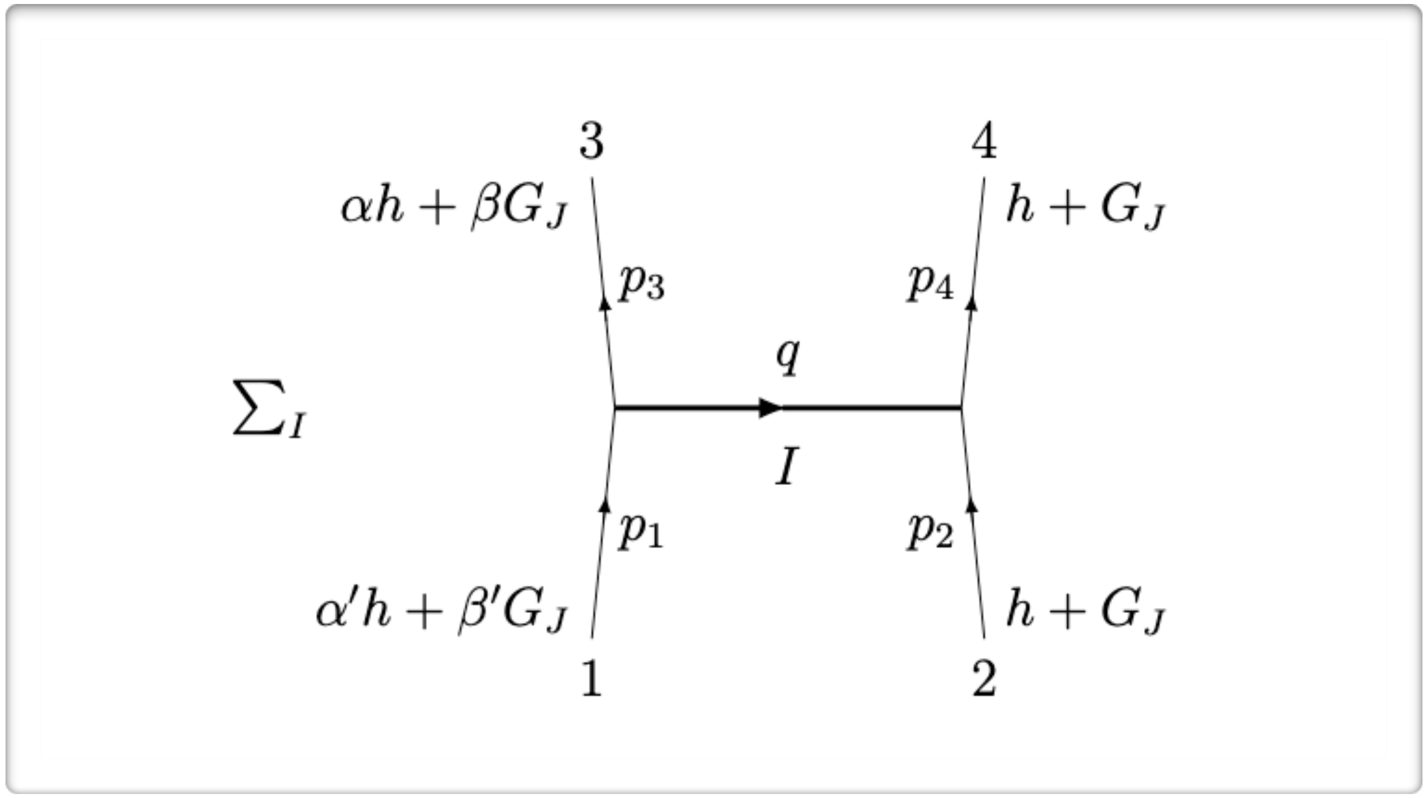


$\delta(s, \overrightarrow{b}) \geq 0$

2.



3.



J. Kaplan, SK (2020)

Three thought experiments and a theorem!

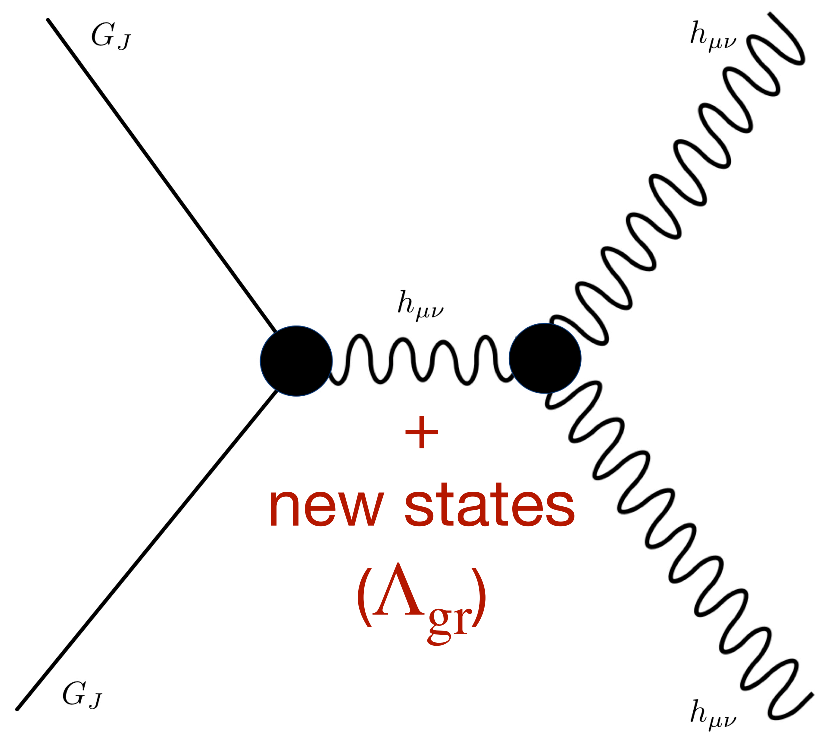
$$\left(s \gg \frac{1}{b^2}, m_i^2\right)$$

$$\delta(s, \vec{b}\,) = \frac{1}{4\pi s}\Gamma_{hhh}(-i\vec{\partial_b})\Gamma_{JJh}(-i\vec{\partial_b})\log\left(\frac{L_{\mathrm{IR}}}{b}\right)$$

on-shell *three-point amplitudes*
(completely fixed by symmetry)

J. Kaplan, SK (2020)

Three thought experiments and a theorem!

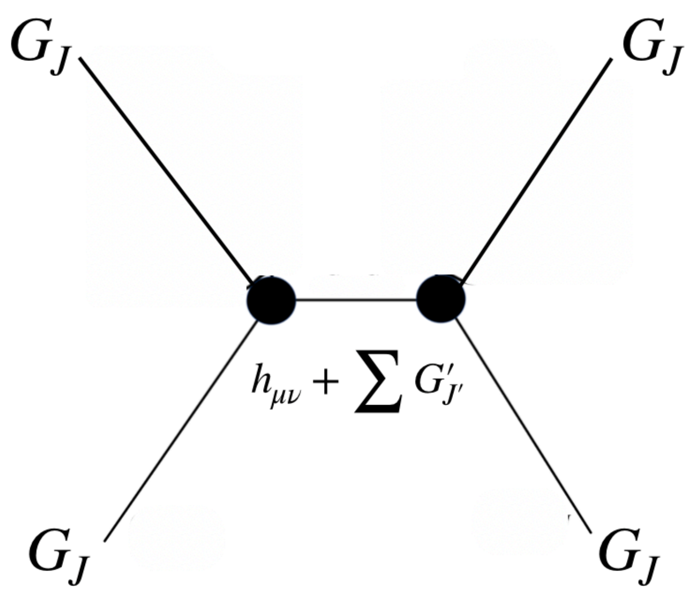


Violates Causality
unless
there are additional states in the gravity sector!

Upper bound on $\Lambda_{\rm gr}$: $\Lambda_{\rm gr} \ll M_{\rm pl}$

J. Kaplan, SK (2020)

$$b = \frac{1}{m_J} \qquad \Lambda_{\rm gr} \gg \sqrt{s} \gg m_J$$



$$\approx \frac{4s}{M_{\rm pl}^2} \ln\left(\frac{L_{\rm IR}}{b}\right) + g_J^2 \left(\frac{s}{m_J^2}\right)^{a_J}$$

gravitational part
$A_{\rm gr}(G_J G_J \to G_J G_J)$

non-gravitational part
$A_{\rm non-gr}(G_J G_J \to G_J G_J)$

Kaplan, SK (2020)

Bound on Λ_{gr}

Causality

$J \geq 3$

$$A_{\text{gr}}(G_J G_J \to G_J G_J) \gg A_{\text{non-gr}}(G_J G_J \to G_J G_J)$$

$$\Lambda_{\text{gr}} \lesssim m_J$$

gravity sector

No QFT description!

Kaplan, SK (2020)

Bound on $\Lambda_{\rm gr}$

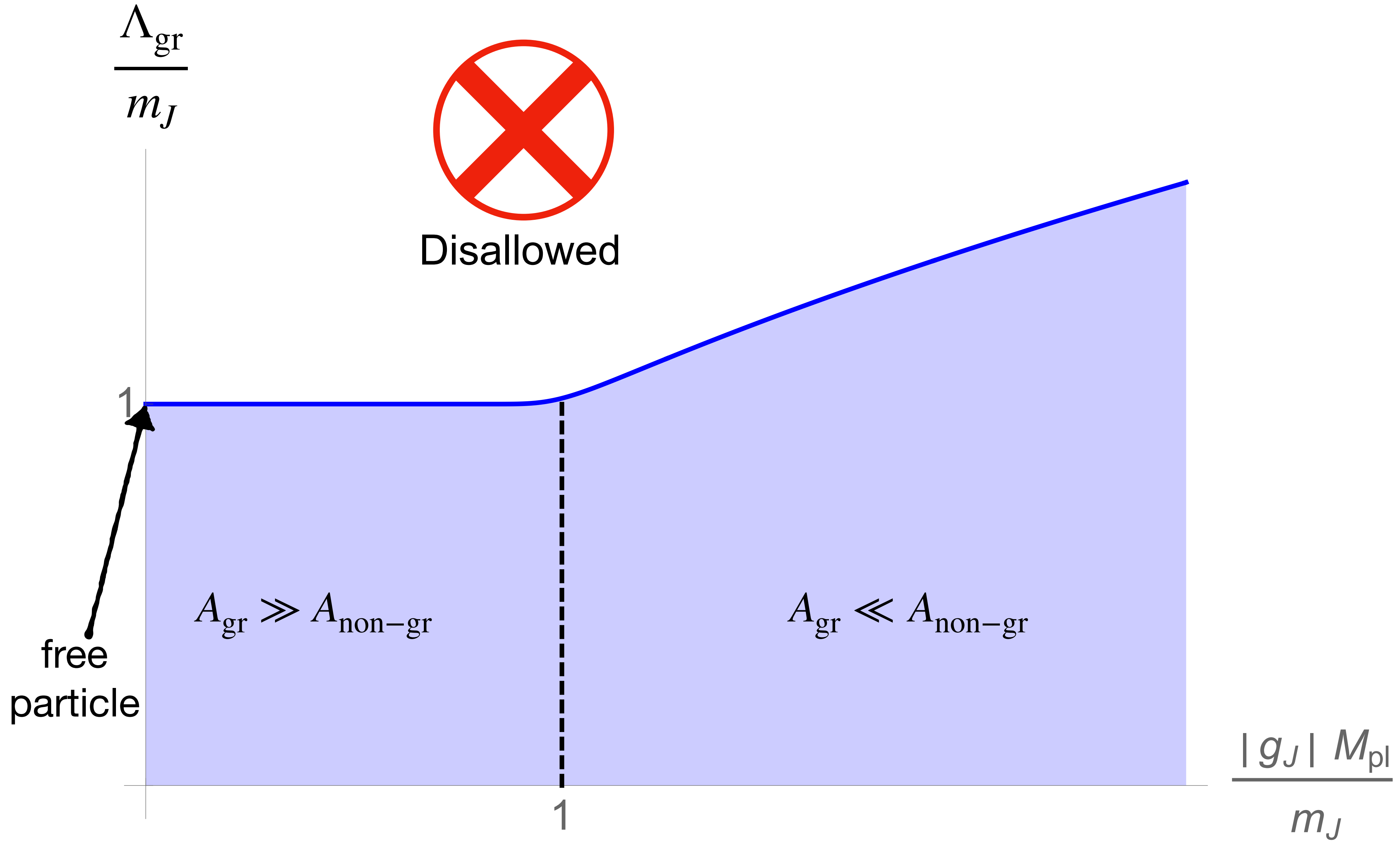
Causality

$J \geq 3$ $\Downarrow$ $A_{\rm gr}(G_J G_J \to G_J G_J) \ll A_{\rm non-gr}(G_J G_J \to G_J G_J)$

$$\Lambda_{\rm gr} \lesssim m_J \left(\frac{|g_J| M_{\rm pl}}{m_J} \right)^{\frac{1}{2(J-2)}} \ll M_{\rm pl}$$

Kaplan, SK (2020)

Bound on $\Lambda_{\rm gr}$



Kaplan, SK (2020)

Theorem: part I

Higher spin (J>2) metastable particles cannot couple to gravity while preserving causality unless there exist ***higher spin states in the gravity sector*** much below the Planck scale.

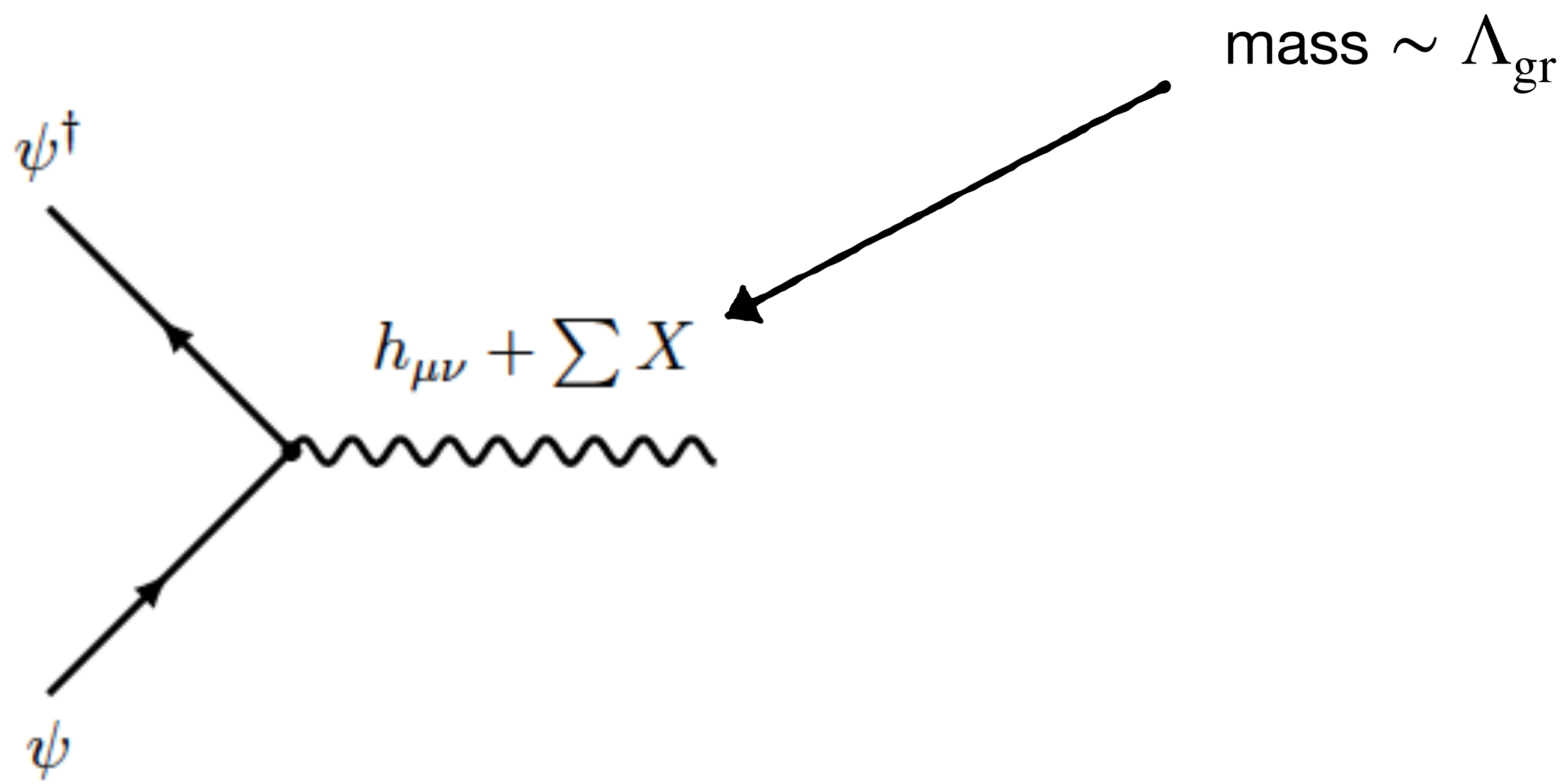
Theorem: part II

Underlying UV complete theory ?

↓

Metastable higher spin particles coupled to gravity

Gravitational scattering in the full theory



Kaplan, SK (2020)

CKSZ uniqueness theorem

arXiv.org > hep-th > arXiv:1607.04253

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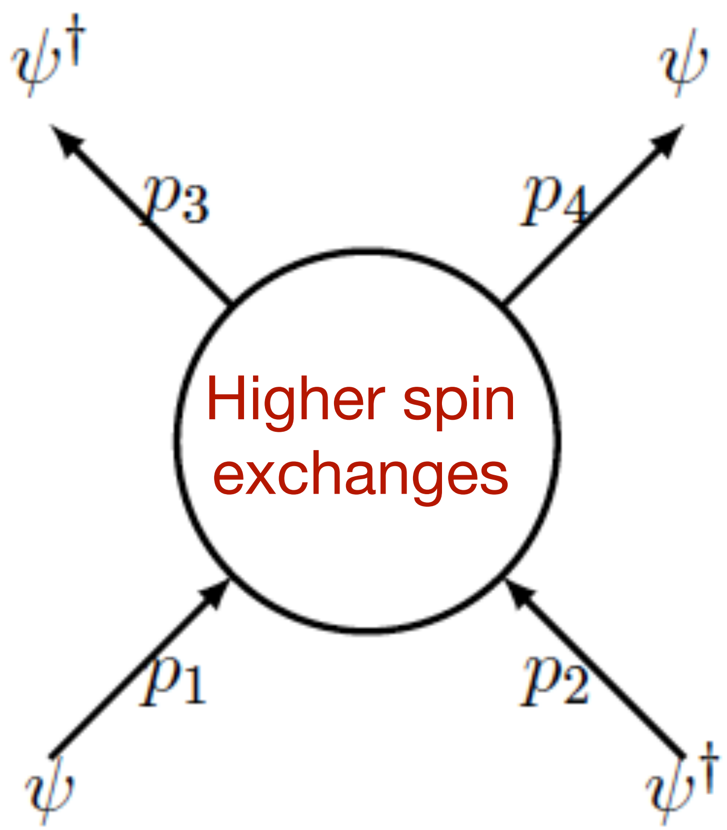
High Energy Physics – Theory

[Submitted on 14 Jul 2016]

Strings from Massive Higher Spins: The Asymptotic Uniqueness of the Veneziano Amplitude

Simon Caron-Huot, Zohar Komargodski, Amit Sever, Alexander Zhiboedov

We consider weakly-coupled theories of massive higher-spin particles. This class of models includes, for instance, tree-level String Theory and Large-N Yang-Mills theory. The S-matrix in such theories is a meromorphic function obeying unitarity and crossing symmetry. We discuss the (unphysical) regime $s, t \gg 1$, in which we expect the amplitude to be universal and exponentially large. We develop methods to study this regime and show that the amplitude necessarily coincides with the Veneziano amplitude there. In particular, this implies that the leading Regge trajectory, $j(t)$, is asymptotically linear in Yang-Mills theory. Further, our analysis shows that any such theory of higher-spin particles has stringy excitations and infinitely many asymptotically parallel subleading trajectories. More generally, we argue that, under some assumptions, any theory with at least one higher-spin particle must have strings.



Asymptotic uniqueness

- *Amplitude is unique for* $t, s \gg 1$

Conditions on the S-matrix of the gravity sector

1. **Weak coupling** — $A_{\text{gravity}}(s,t)$ is a meromorphic function with simple poles

2. **Unitarity** — Positive expansion

3. **Crossing symmetry**

4. **Regge behavior** — $A_{\text{gravity}}(s,t) = F(t)(-s)^{j(t)}$ holds for $|s|, |t| \gg m^2$

5. **No accumulation point in the spectrum**

Emergence Closed Strings

<u>Gravity sector</u> of the <u>full theory</u> must have the following properties:

Asymptotically Linear leading Regge trajectory

$$j(t \to \infty) = \frac{\alpha'}{2} t \qquad \alpha' \sim \frac{1}{\Lambda_{\text{gr}}^2}$$

Kaplan, SK (2020)

Emergence Closed Strings

Gravity sector of the full theory must have the following properties:

Large impact parameter scattering

$$\text{Im}\ A_{gravity}(b,s) \approx e^{-\frac{b^2}{2\alpha' \log(\alpha' s/2)}} \qquad \alpha' \sim \frac{1}{\Lambda_{\text{gr}}^2}$$

Existence of extended objects of size $\sqrt{\alpha' \log(\alpha' s)}$!

Kaplan, SK (2020)

Emergence Closed Strings

Gravity sector of the full theory must have the following properties:

Amplitude in the regime t,s>>1

$$\lim_{s,t\gg 1} A_{gravity}(s,t) = A_0 \exp\left(\frac{\alpha'}{2}\left((s+t)\ln(s+t) - s\ln s - t\ln t\right)\right)$$

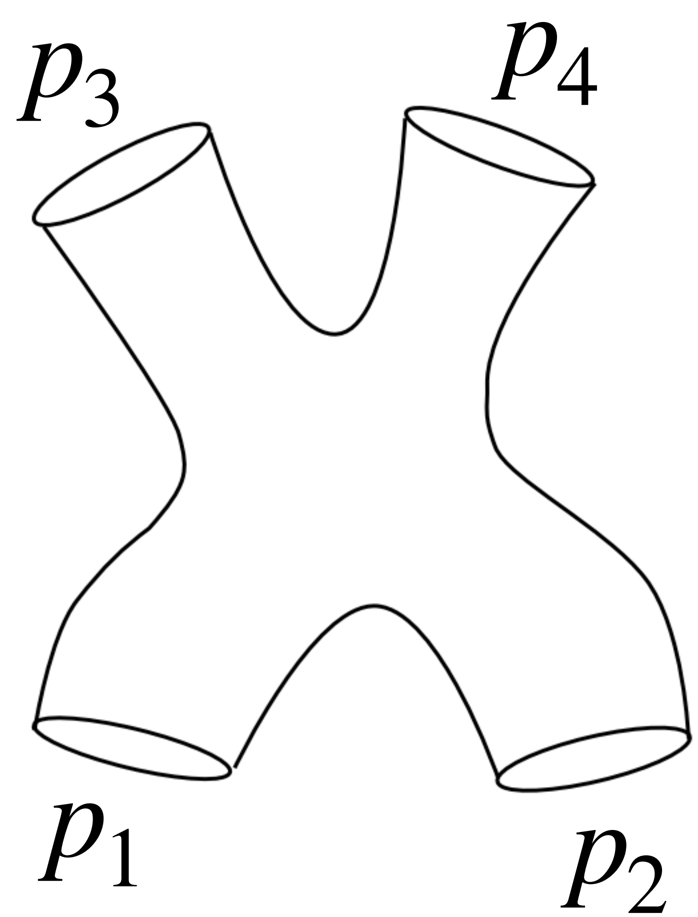
Kaplan, SK (2020)

Emergence Closed Strings

Gravity sector of the full theory must have the following properties:

Amplitude in the regime t,s>>1

$$\lim_{s,t \gg 1} A_{gravity}(s,t) =$$



$$|t|, |s| \to \infty$$

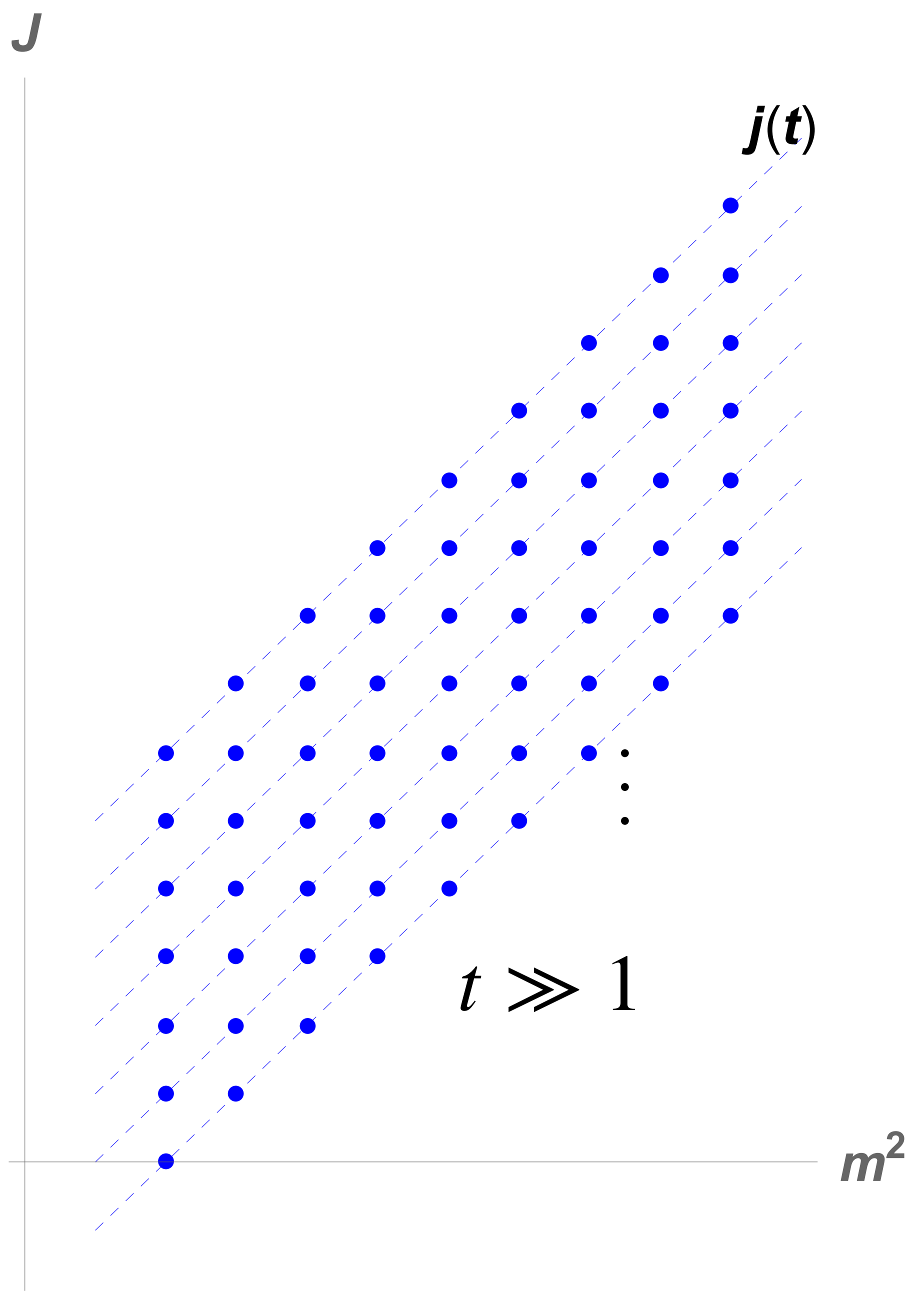
Tree-level Gross-Mende string amplitude!

Gross, Mende (1987)

Kaplan, SK (2020)

Emergence Closed Strings

Gravity sector of the full theory must have the following properties:



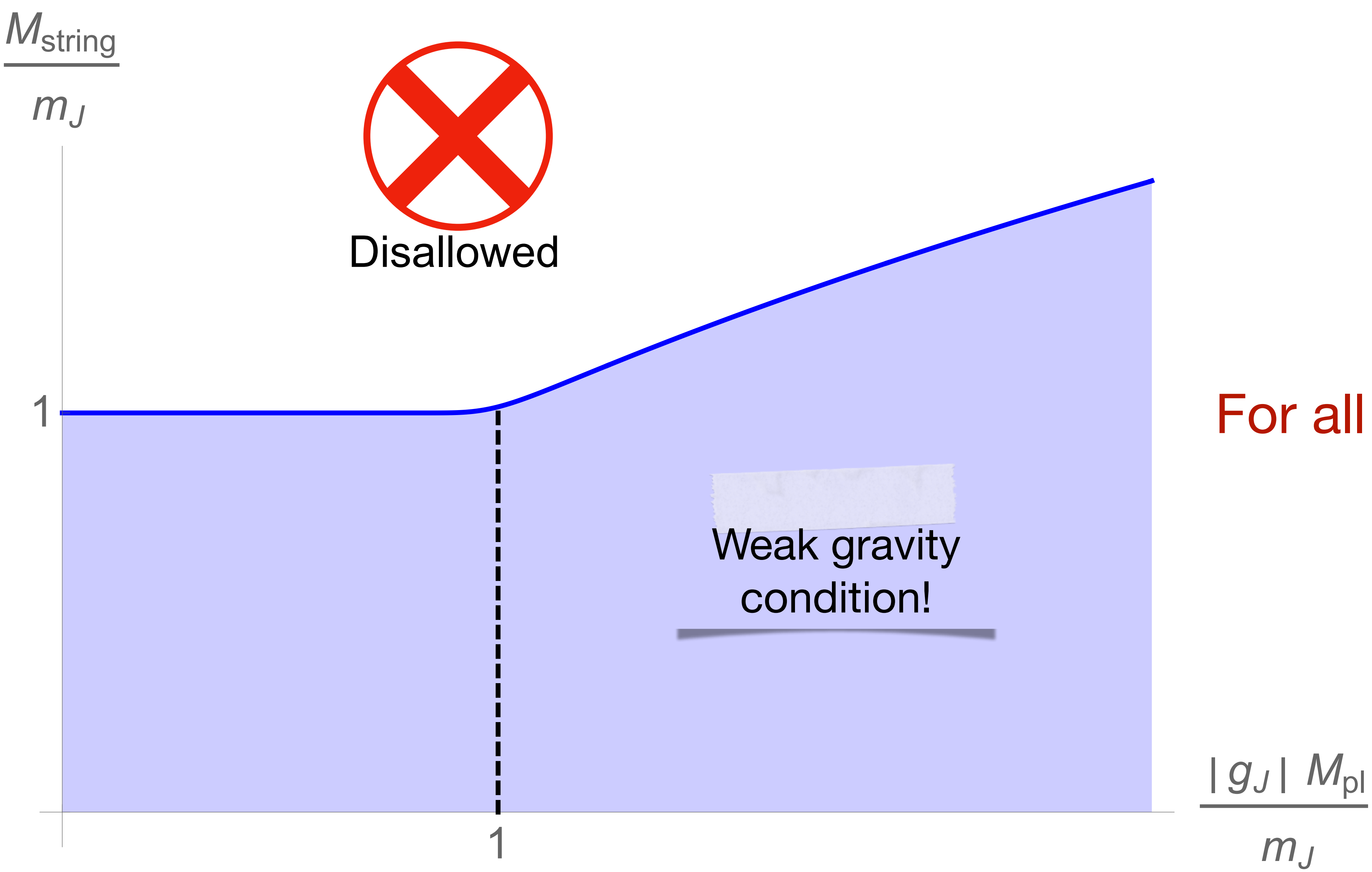
Infinite towers of Regge trajectories

Asymptotically coincide with ***tree-level closed string theory***

Kaplan, SK (2020)

A bound on M_{string}

$$\Lambda_{\text{gr}} \approx M_{\text{string}}$$



For all $\{G_J\}$ with $J \geq 3$

Kaplan, SK (2020)

Theorem

Theories of metastable higher spin particles coupled to gravity

1) Additional gravitational higher spin states are essential to the preservation of causality.

⇓ ***CKSZ theorem***

2) Any weakly coupled UV completion of such a theory must have a stringy gravity sector.

Kaplan, SK (2020)

What about **large N QCD**?

Large N confining gauge theories in 4d

⇓

't Hooft (1974)
Witten (1979)

Metastable glueballs and mesons of arbitrarily large spin

Causality is non-trivial in Large N QCD coupled to gravity!

Kaplan, SK (2020)

Universal scaling at Large N

Scattering amplitudes of glueballs (G) and mesons (π) in the large N limit have universal scaling behavior

$$\langle \pi\pi\pi \rangle \sim \frac{1}{\sqrt{N}}\,, \qquad \langle GGG \rangle \sim \frac{1}{N}\,,$$
$$\langle \pi\pi G \rangle \sim \frac{1}{N}\,, \qquad \langle \pi GG \rangle \sim \frac{1}{N^{3/2}}\,,$$
$$\langle \pi\pi\pi\pi \rangle \sim \frac{1}{N}\,, \qquad \langle GGGG \rangle \sim \frac{1}{N^2}\,.$$

't Hooft (1974)
Witten (1979)

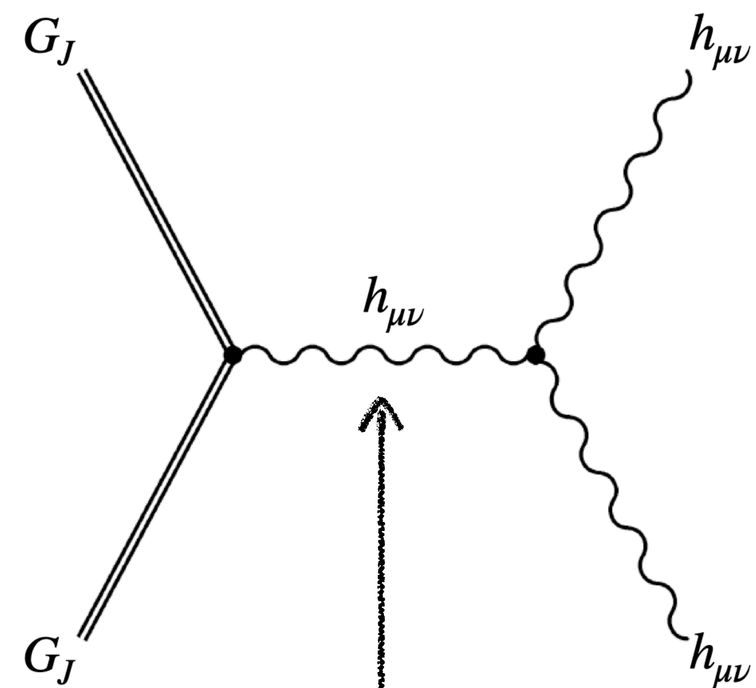
Gravitational coupling

$$\langle \pi\pi h_{\mu\nu} \rangle \sim \frac{1}{M_{\rm pl}}\,, \quad \langle GGh_{\mu\nu} \rangle \sim \frac{1}{M_{\rm pl}}\,,$$

$$\langle \pi\pi\pi h_{\mu\nu} \rangle \sim \frac{1}{\sqrt{N}}\frac{1}{M_{\rm pl}}\,, \quad \langle GGGh_{\mu\nu} \rangle \sim \frac{1}{N}\frac{1}{M_{\rm pl}}\,.$$

Causality Constraints in Large N QCD Coupled to Gravity

Jared Kaplan[1,*] and Sandipan Kundu[1,†]



Glueballs (J>2)

Additional t-channel states are essential to the preservation of causality!

Actually, there are *many variations* of the higher-spin causality argument

⇩

Exactly TWO resolutions!

(I) gauge sector

(II) gravity sector

Kaplan, SK (2020)

(I) Gauge Sector

$$\langle G_J h_{\mu\nu} \rangle \sim \frac{N}{M_{\rm pl}} \ , \quad \langle G_J h_{\mu_1\nu_1} h_{\mu_2\nu_2} \rangle \sim \frac{N}{M_{\rm pl}^2} \ ,$$

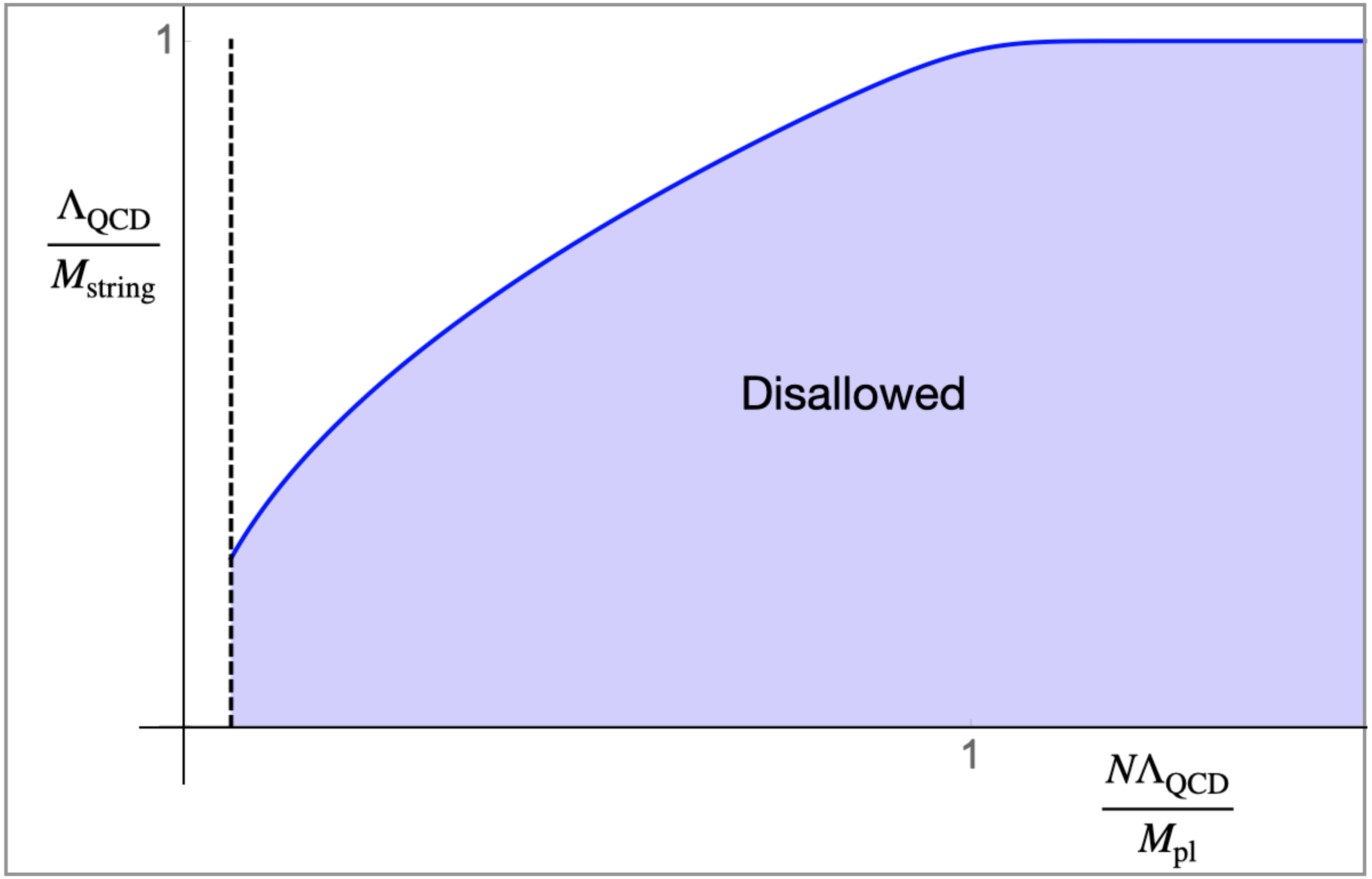
Implications:

1. These interactions are present and highly fine-tuned!
2. Free massless spin 3/2 particles are ruled out.
3. Spectating particles/classical shockwaves are ruled out.

Kaplan, SK (2020)

(II) Gravity Sector

Any weakly coupled UV completion of the gravity-sector must have many stringy features, with an upper bound on the string scale!



Kaplan, SK (2020)

A unifying feature of both scenarios

For weakly coupled gravity, the theory has a stringy description above

$$N \gtrsim \frac{M_{\rm pl}}{\Lambda_{\rm QCD}}$$

Kaplan, SK (2020)

Conclusions

- QFTs that appear to be causal in flat spacetime can violate causality when coupled to gravity.
- Some features of quantum gravity emerges from QFT.
- Theories of metastable higher spin particles can be coupled to gravity while preserving causality only when the gravity sector has many of the properties of closed strings.
- Our argument implies that the gravitational interaction in any confining large N gauge theory must be accompanied by interactions involving other higher spin states well below the Planck scale.
- This has surprising implications for large N QCD coupled to gravity.

Thank You!