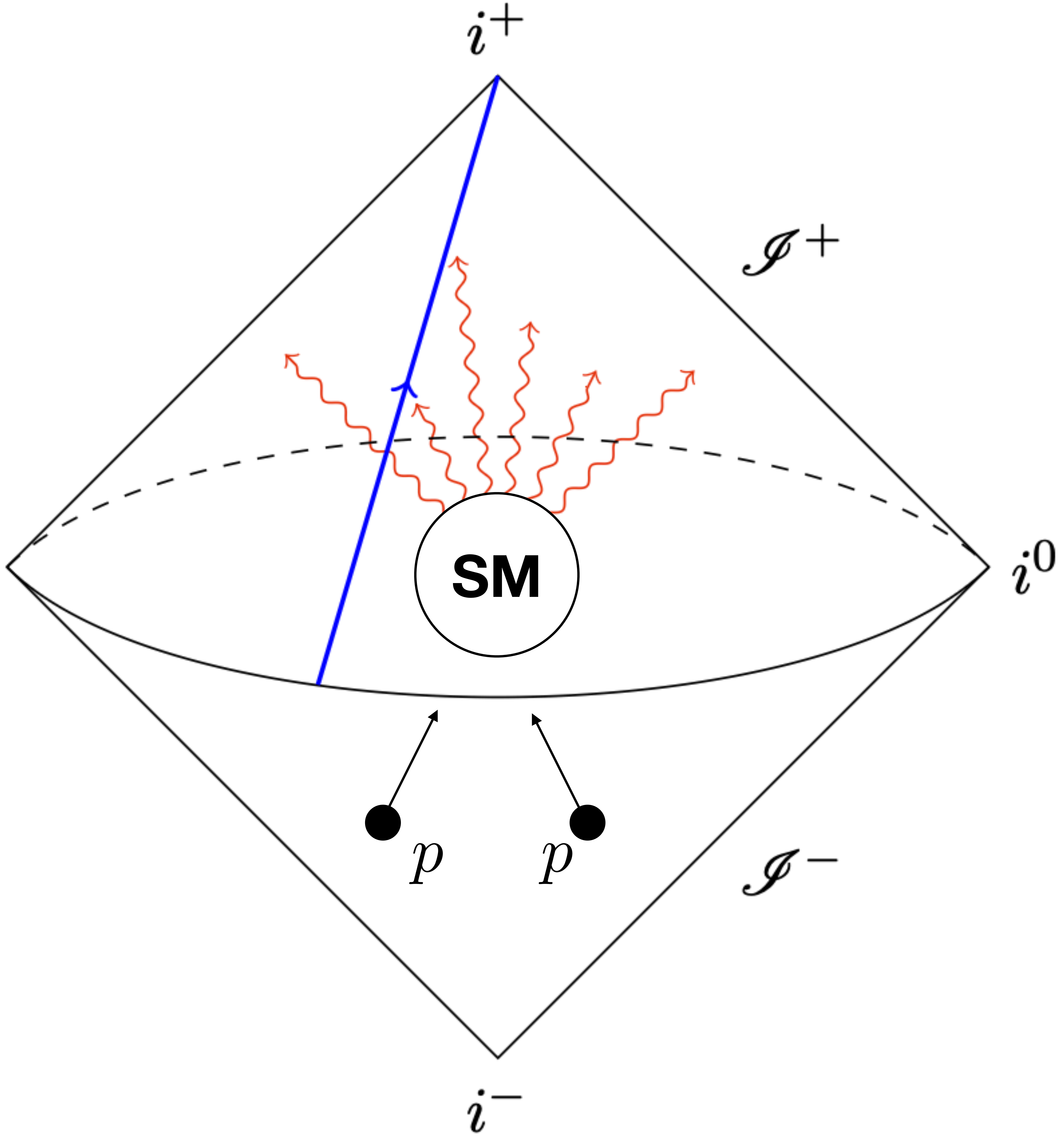
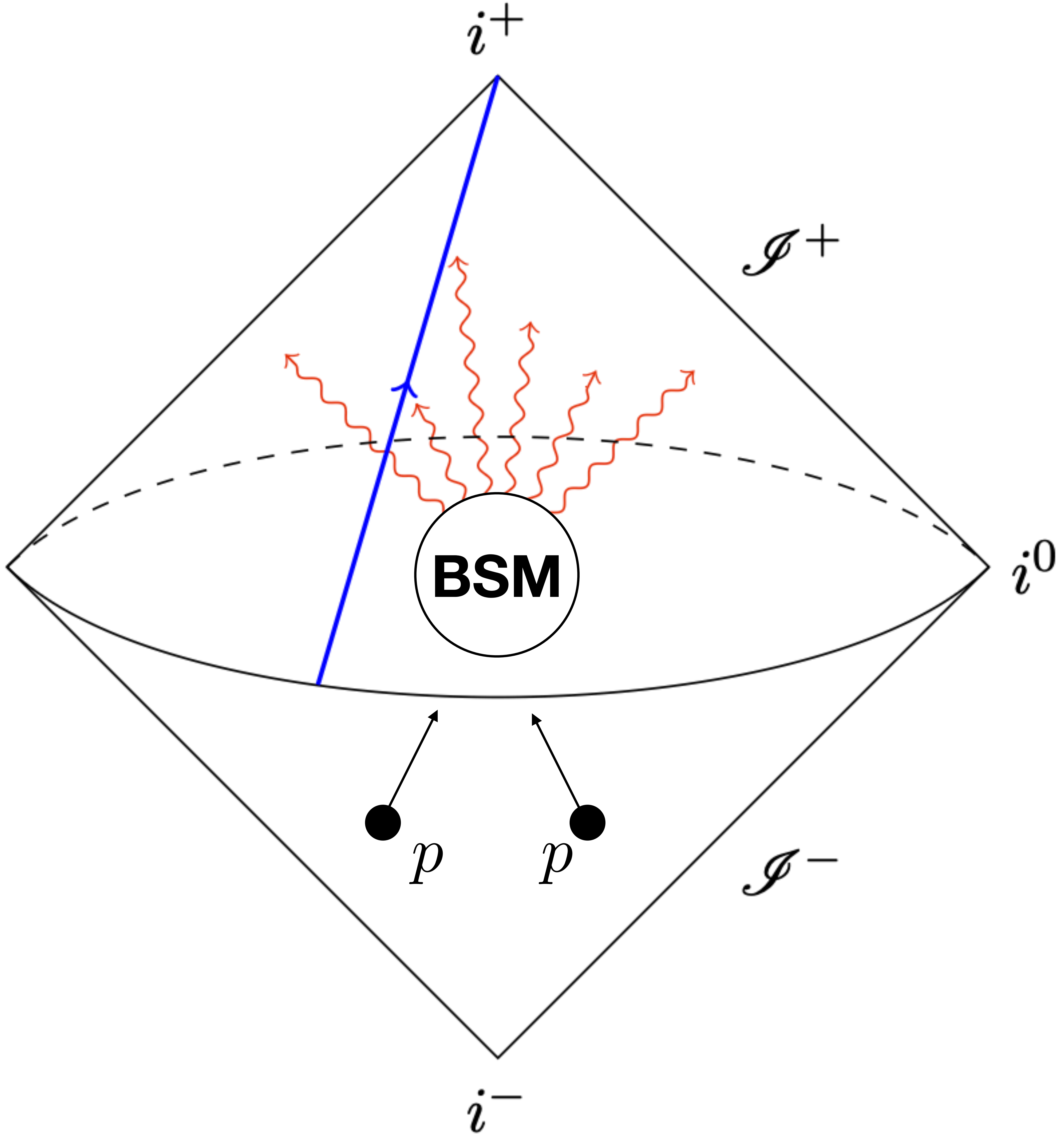
Quantum Field Theory and String Theory
[through the lens of a collider thought experiment]

Alexander Zhiboedov, CERN
EPS-HEP 2025, Marseille

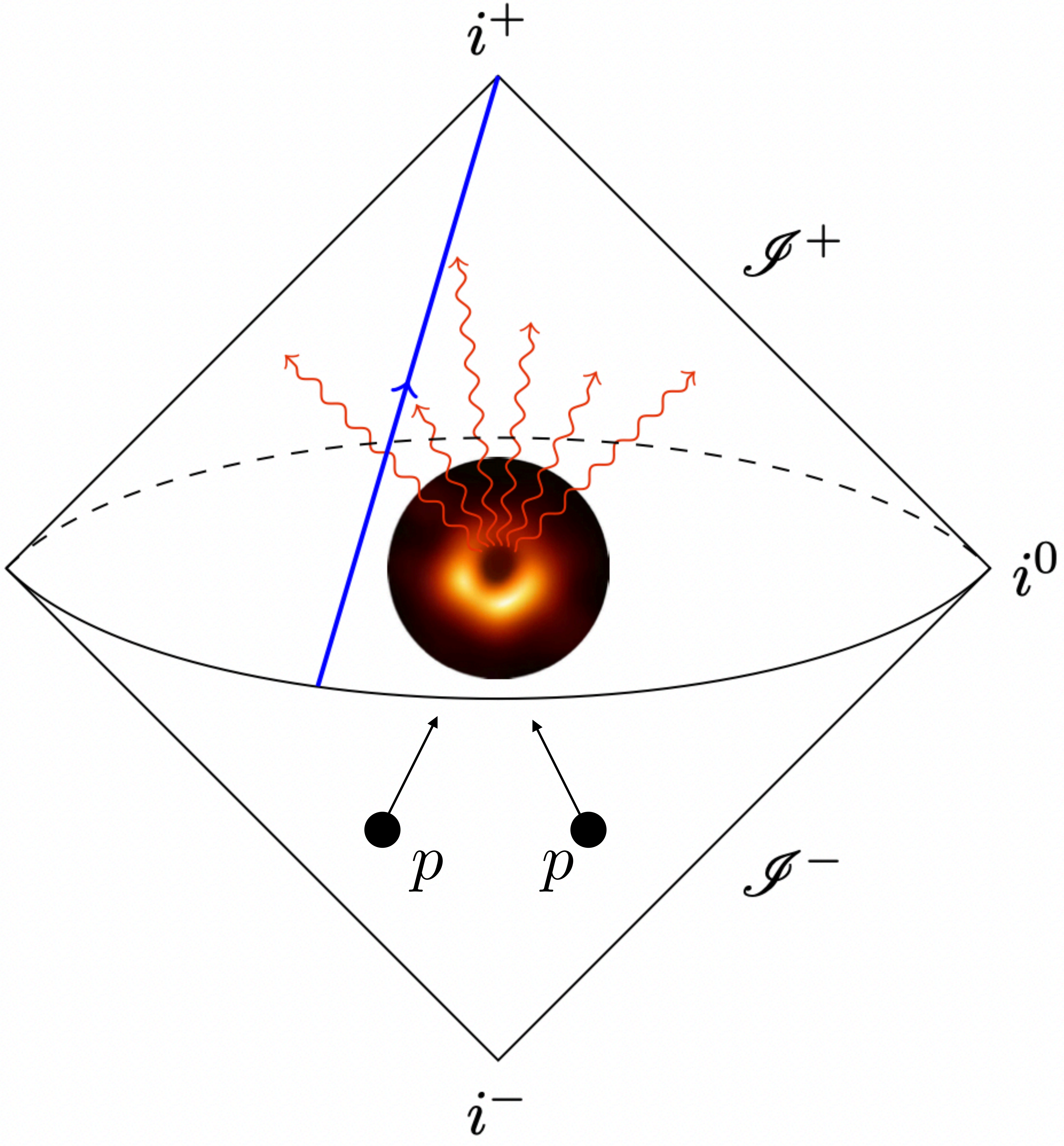
energy frontier

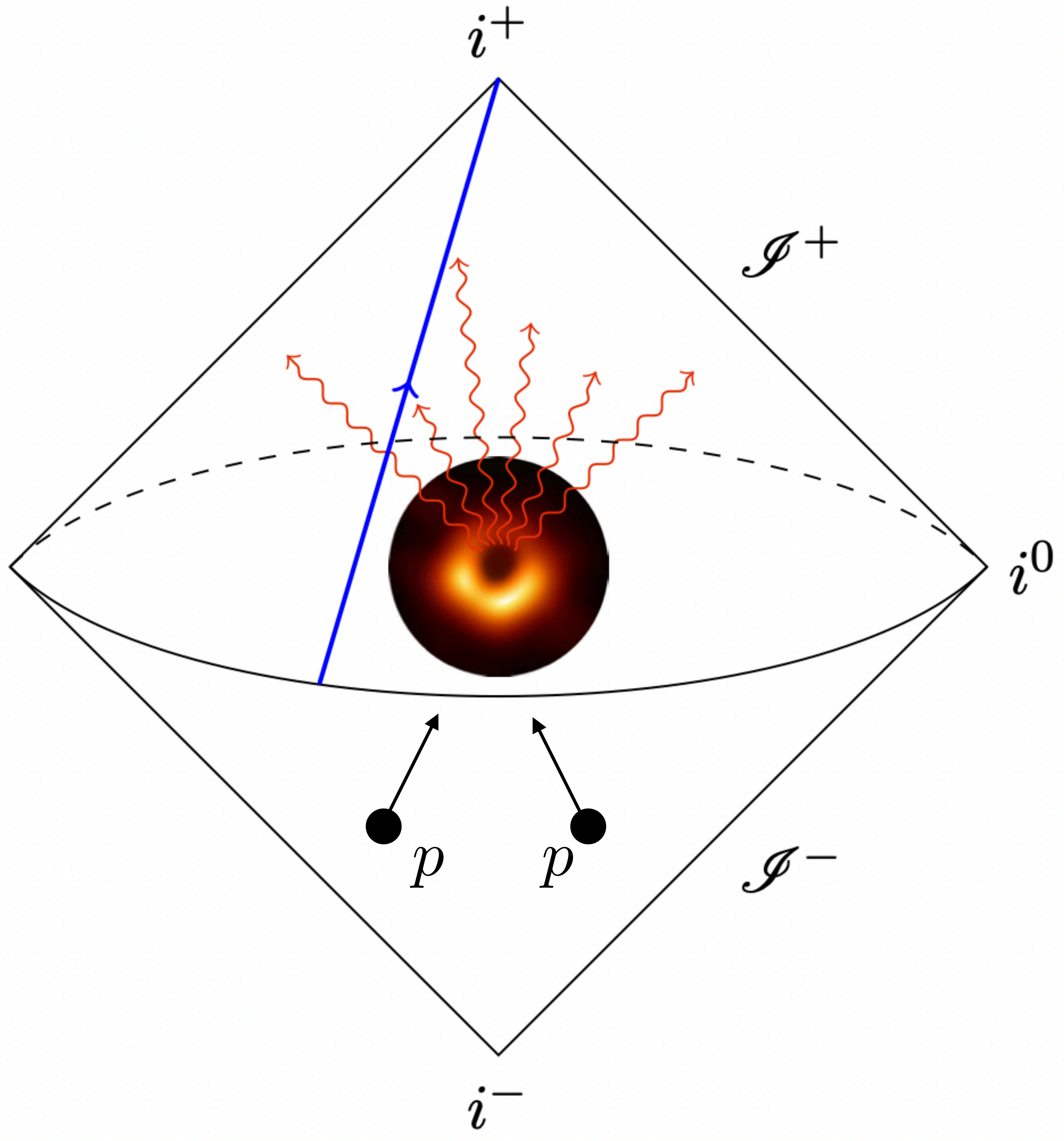


higher energies…



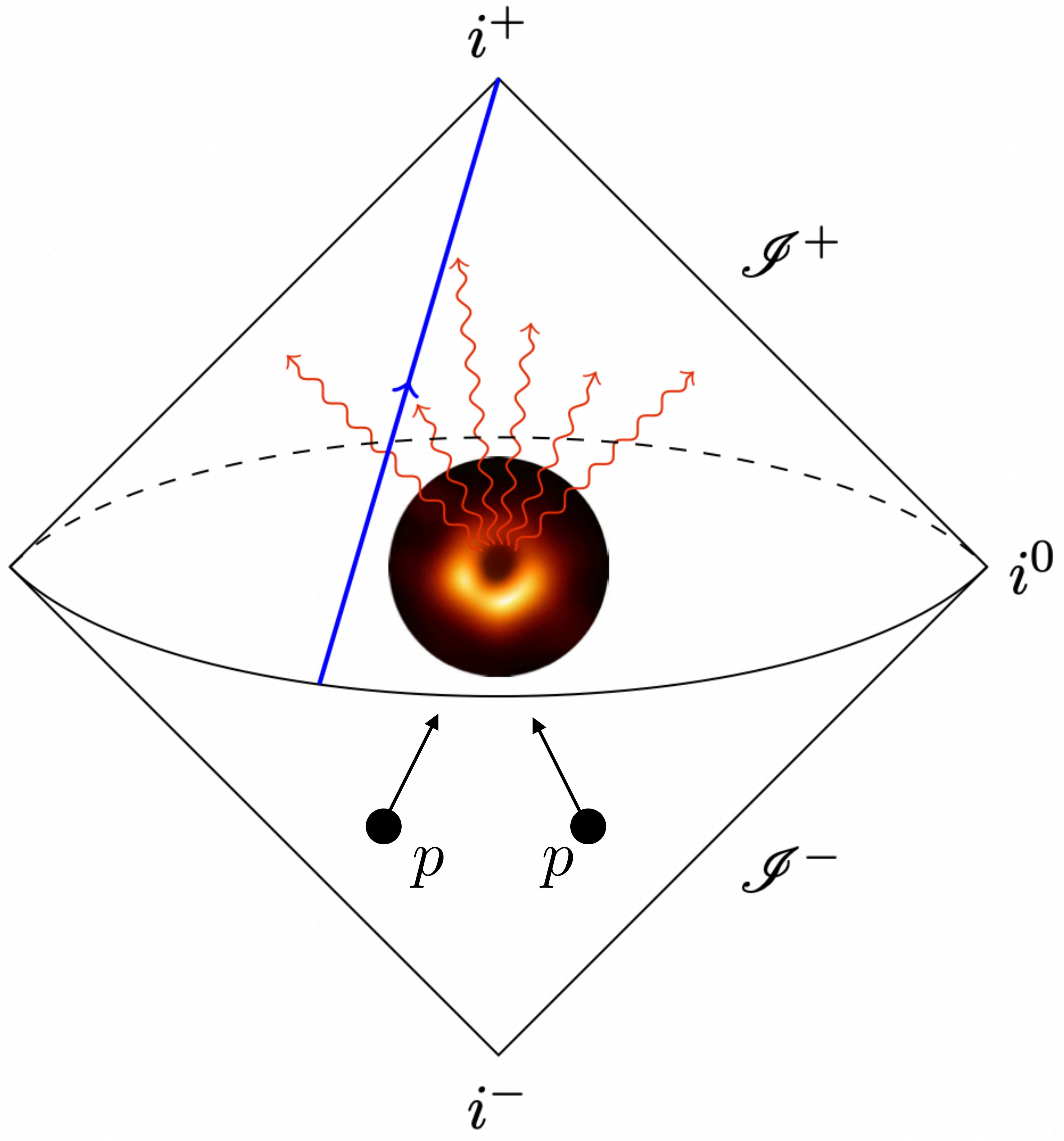
ultimately





1. Theory

[What is the space of consistent theories?]
[What is possible in the UV? How does it manifest in the IR?]



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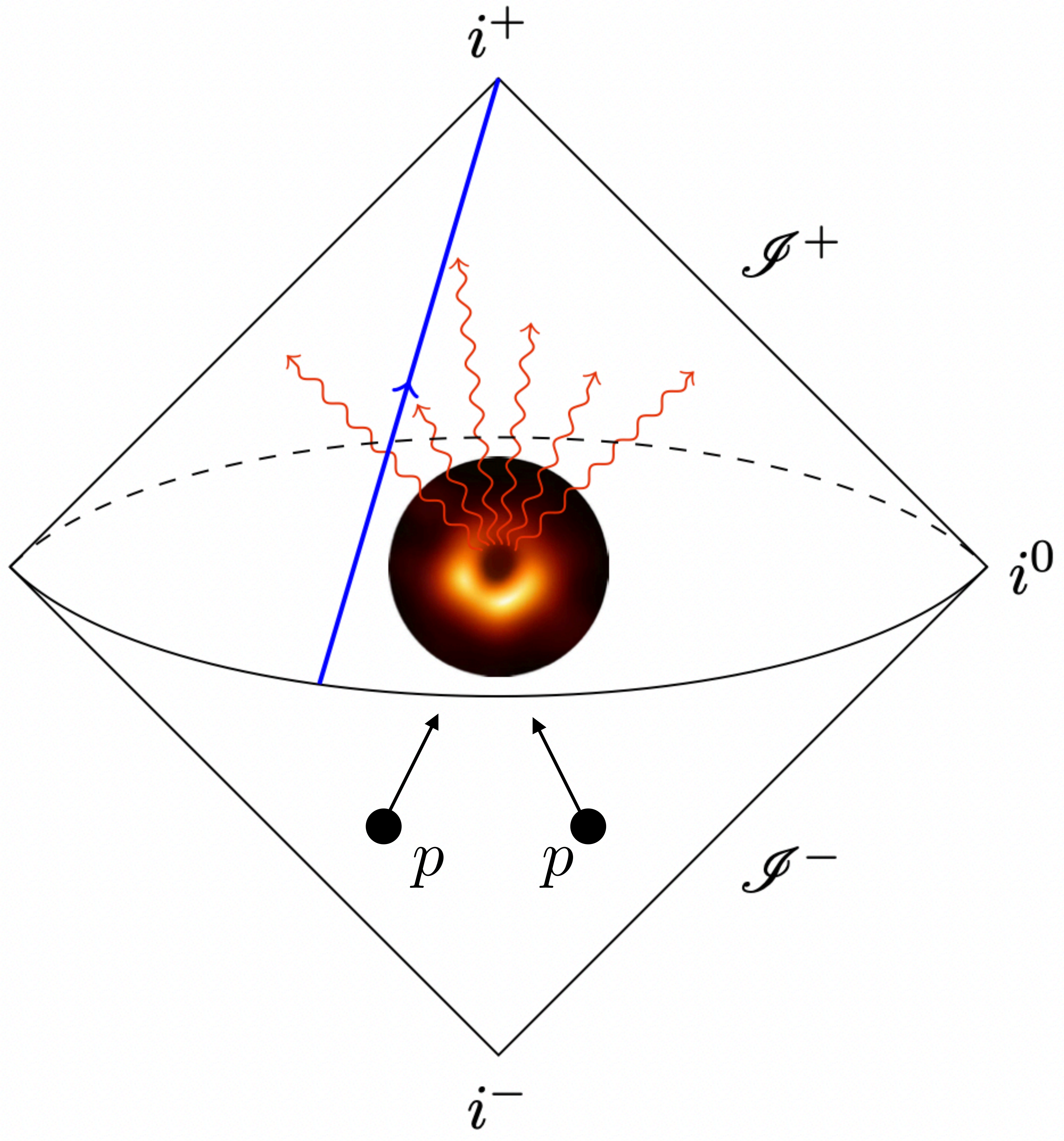
2. Detector

[What is the space of observables?]
[Nonperturbative methods for real-time dynamics]



1. Theory

[What is the space of consistent theories?]
[What is possible in the UV? How does it manifest in the IR?]

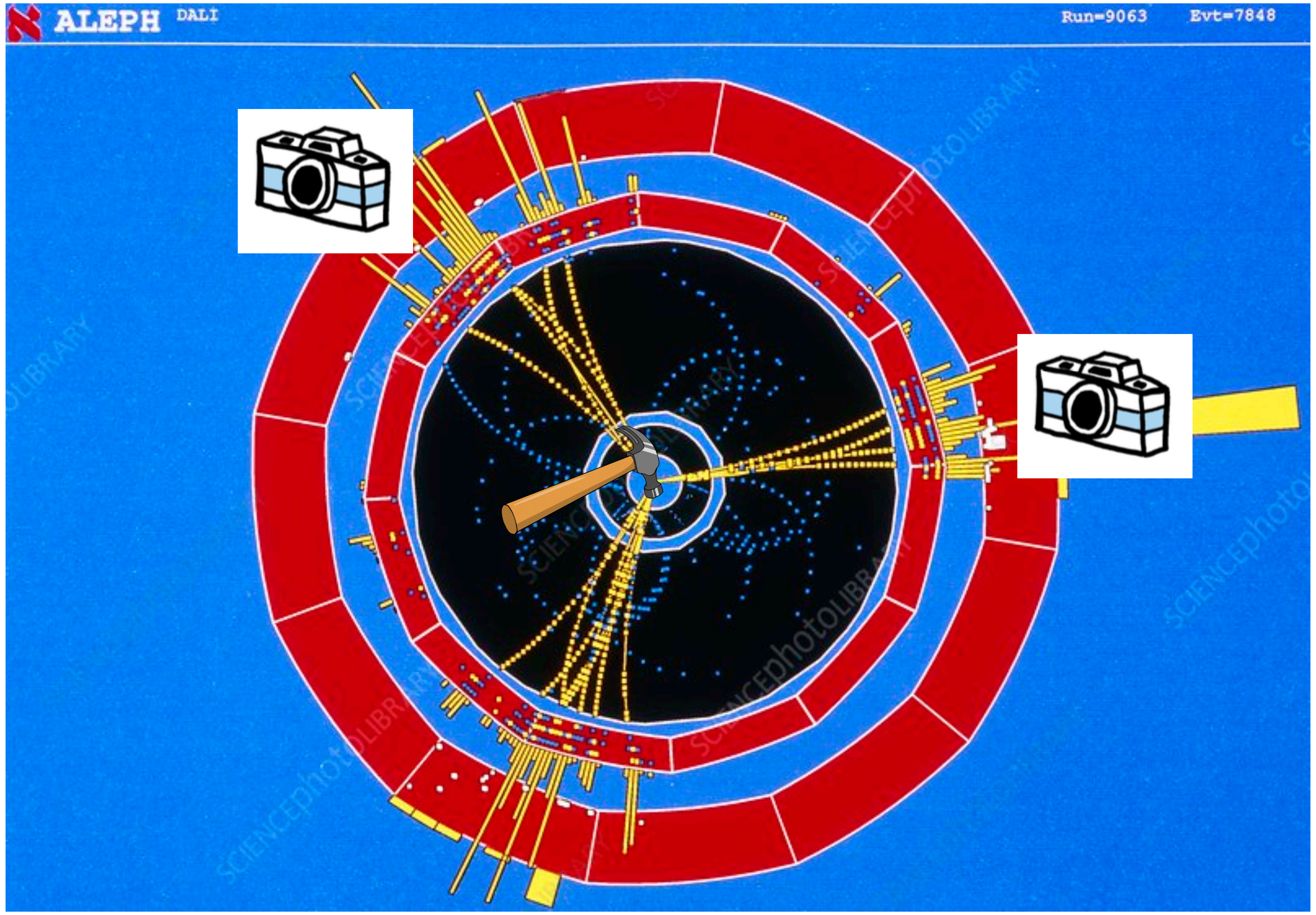
2. Detector

[What is the space of observables?]
[Nonperturbative methods for real-time dynamics]

3. Source

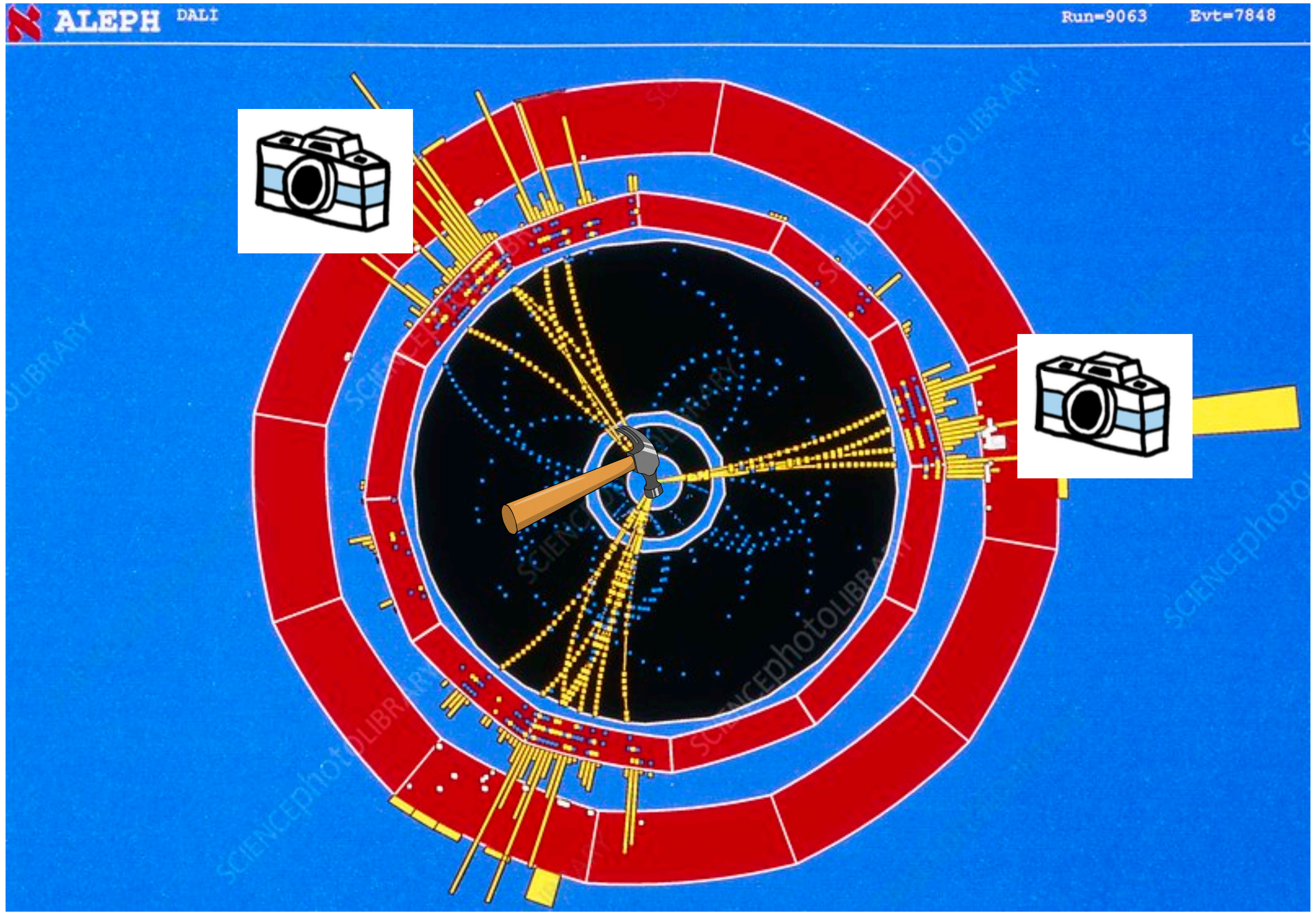
[What is the space of states?]
[Chaos, entanglement, and geometry]

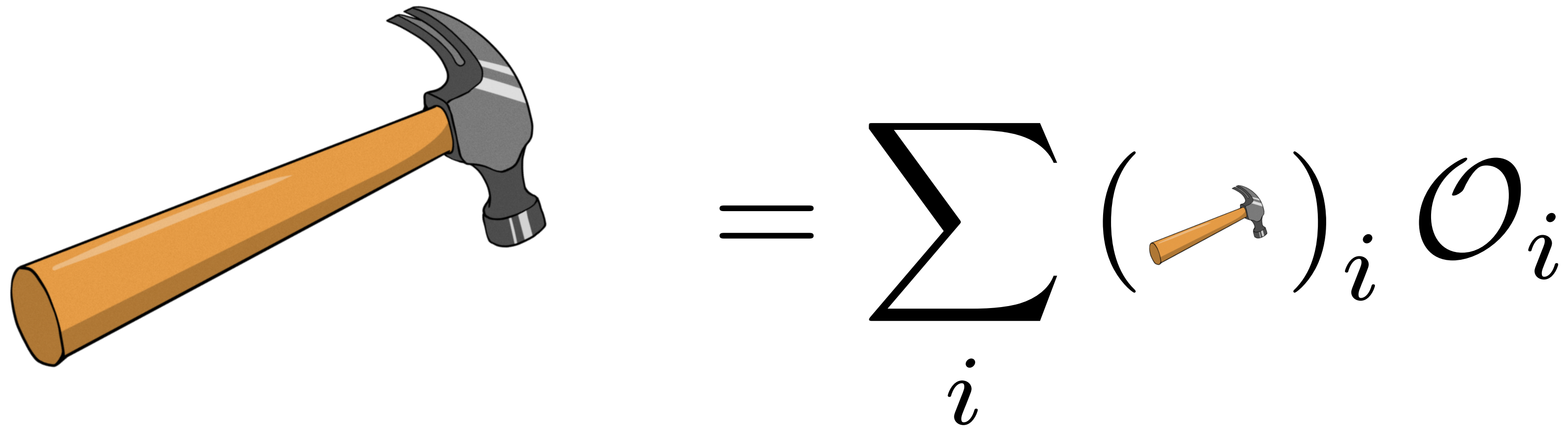
Collider experiment in QFT



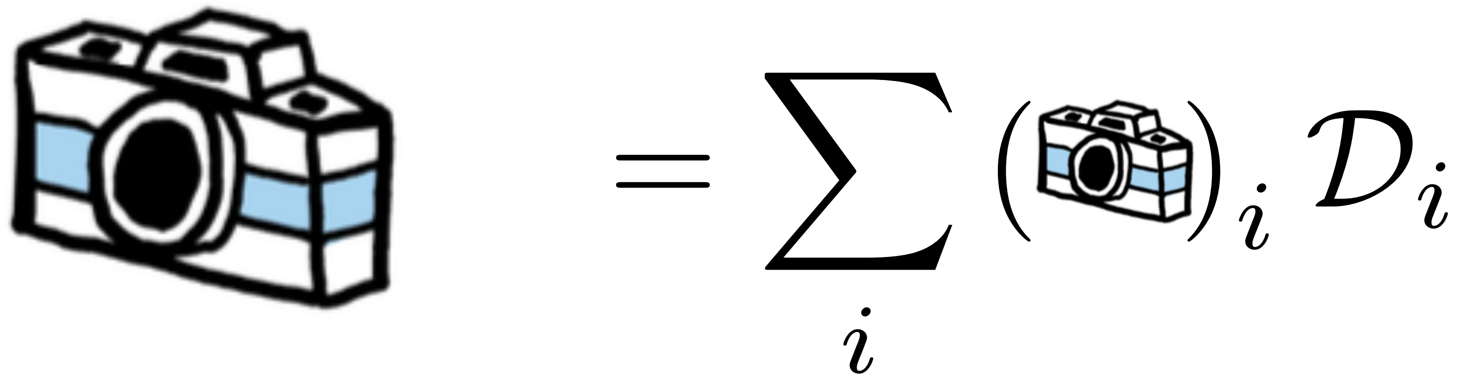
(event shapes)

Collider experiment in QFT





(local operators)



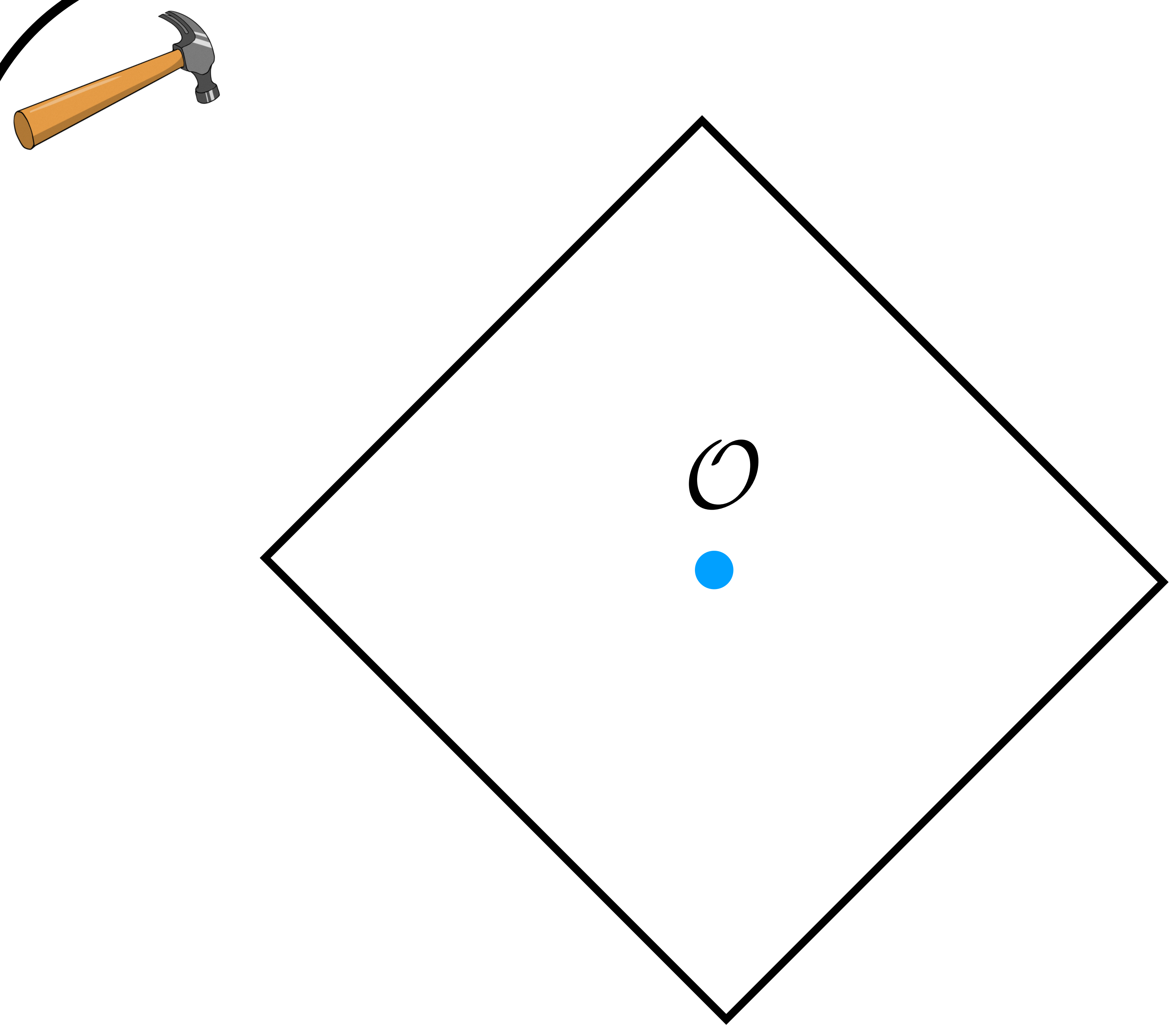
(detector operators)

(event shapes)

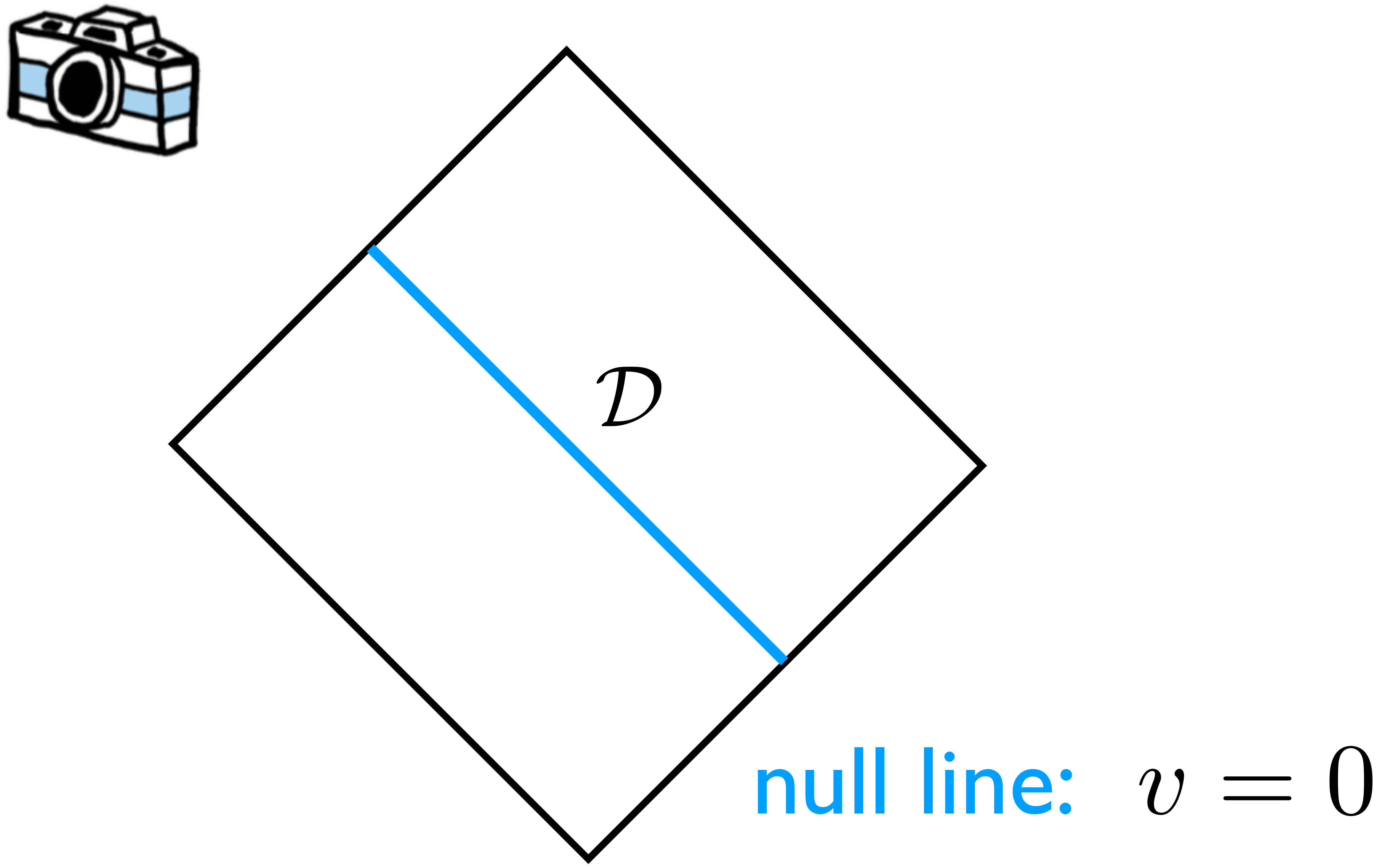
$$\Delta E \Delta t \gtrsim \hbar$$

[non-local in time]

$$ds^2 = -du dv + d\vec{y}^2 \qquad \vec{y} \in \mathbb{R}^{d-2}$$



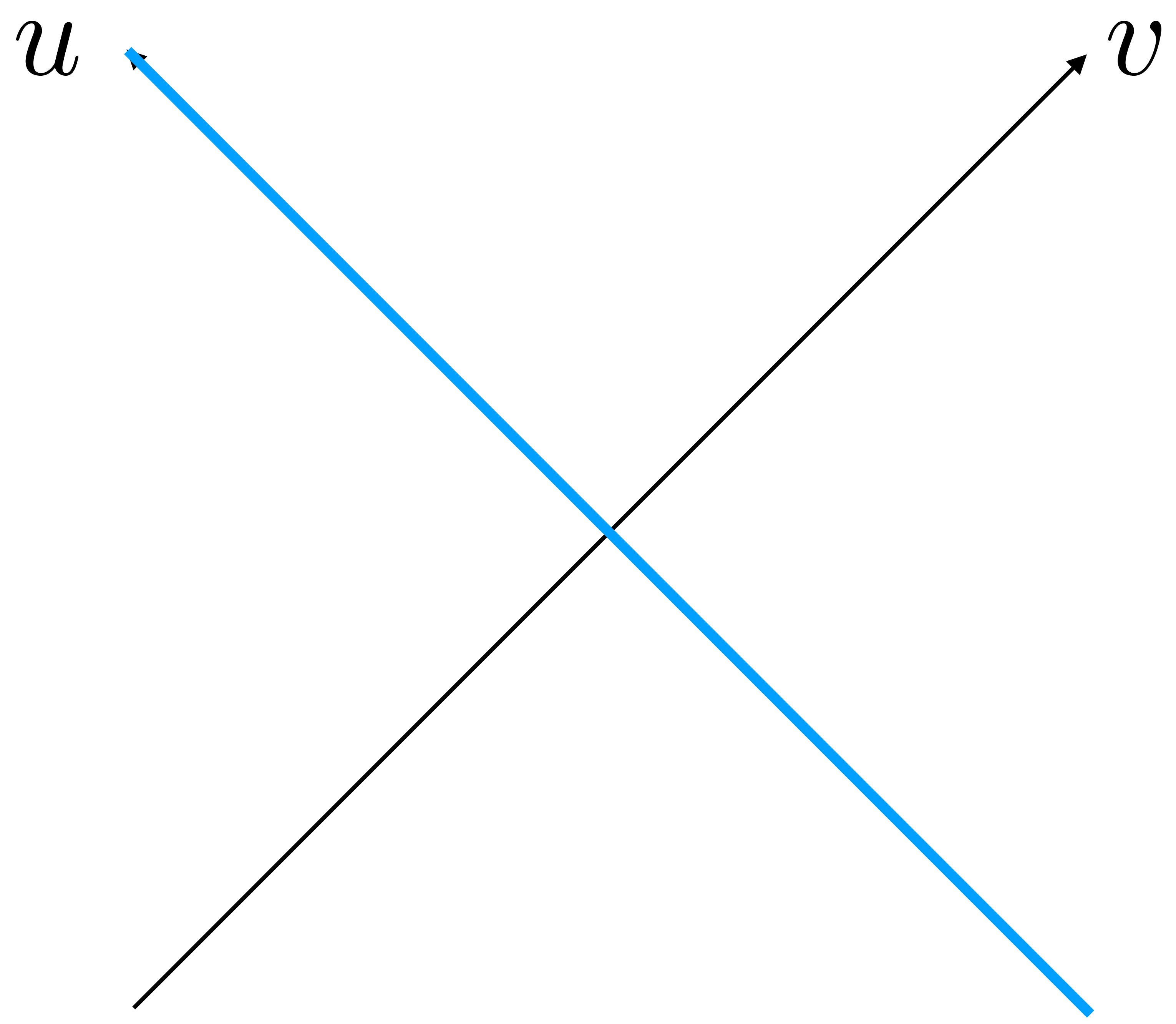
Local operators:
measurements that can be done at a **point**.



Detector operators:
measurements that can be done on a **null line**.

Energy calorimeter (the ANEC operator)

Consider a unitary QFT. The energy-momentum conservation takes the form

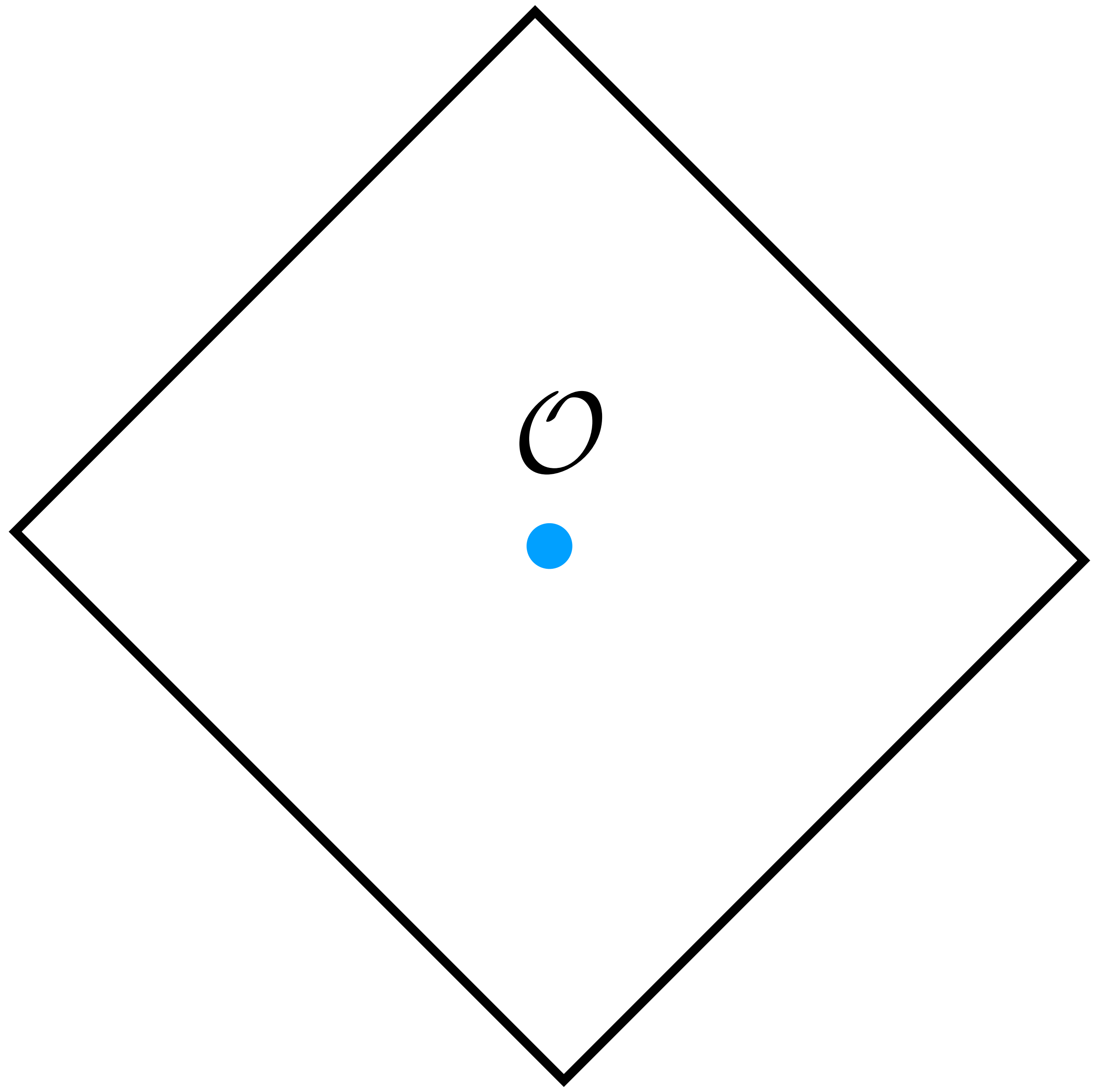


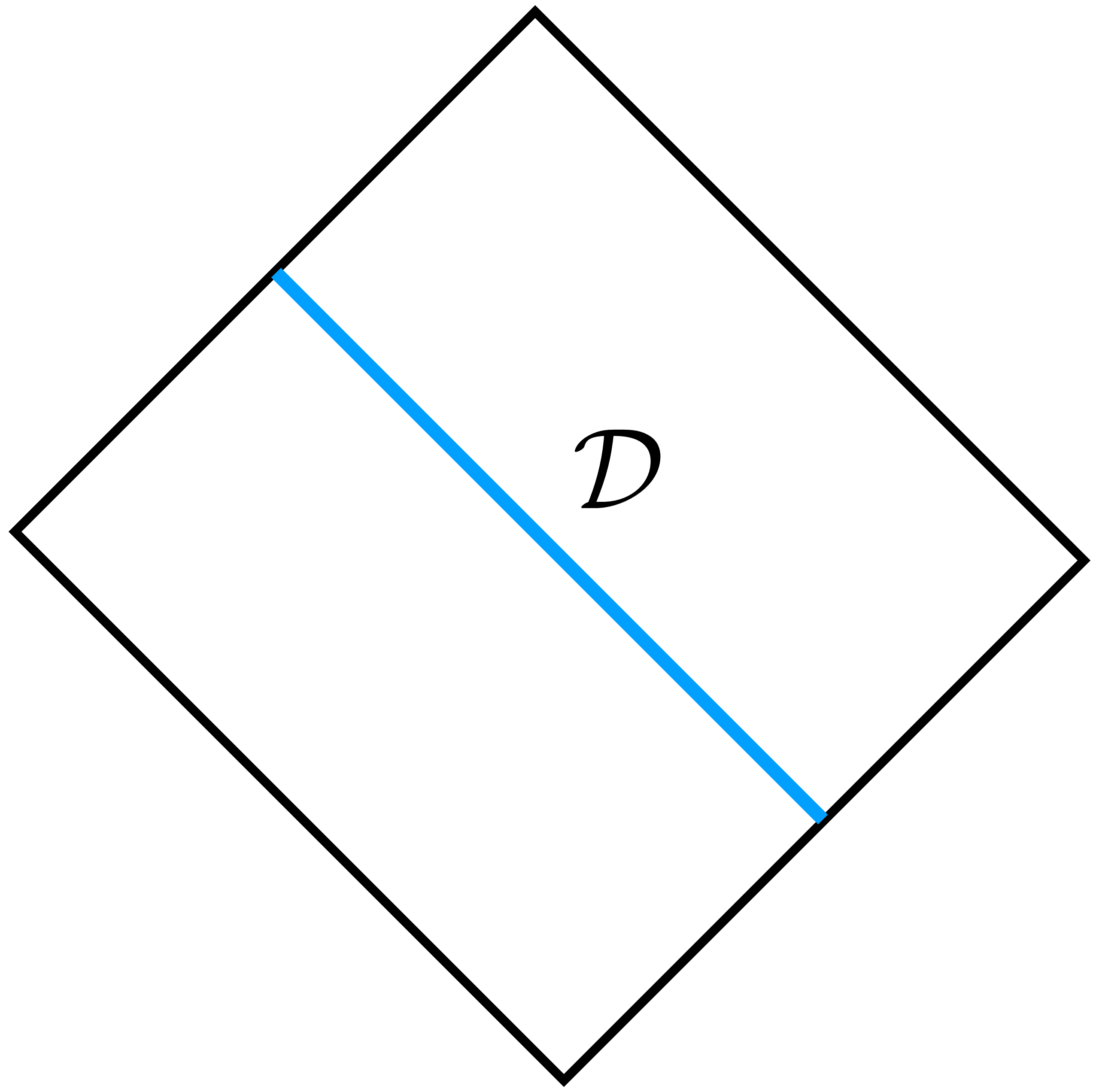
$$\partial_\mu T^{\mu\nu} = 0$$

The **energy calorimeter** operator:

$$\mathcal{E}(\vec{y}) = \int_{-\infty}^{\infty} du T_{uu}(u, 0, \vec{y})$$

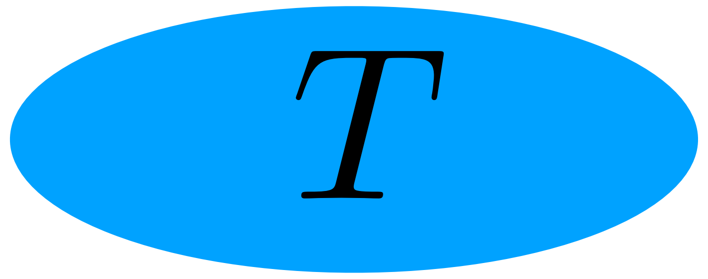
Why is a point different from a null line in QFT?





No positivity in a finite region

[Epstein,Glaser,Jaffe '65]
[Cordova,Maldacena,Turiaci '17]



$$\langle 0|T|0\rangle = 0$$
$$\langle \psi|T|\psi\rangle \geq 0$$

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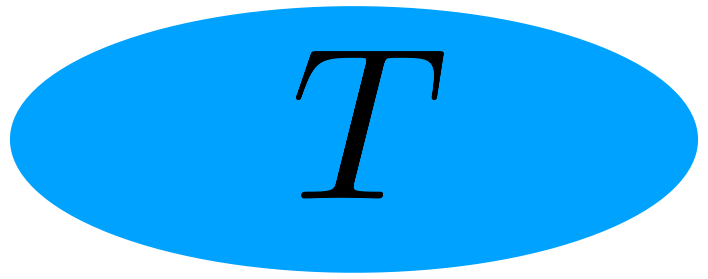

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$$|\langle \psi|T|0\rangle|^2 \leq \langle \psi|T|\psi\rangle\langle 0|T|0\rangle = 0$$

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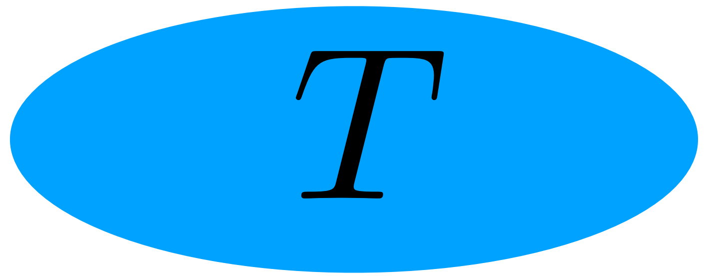
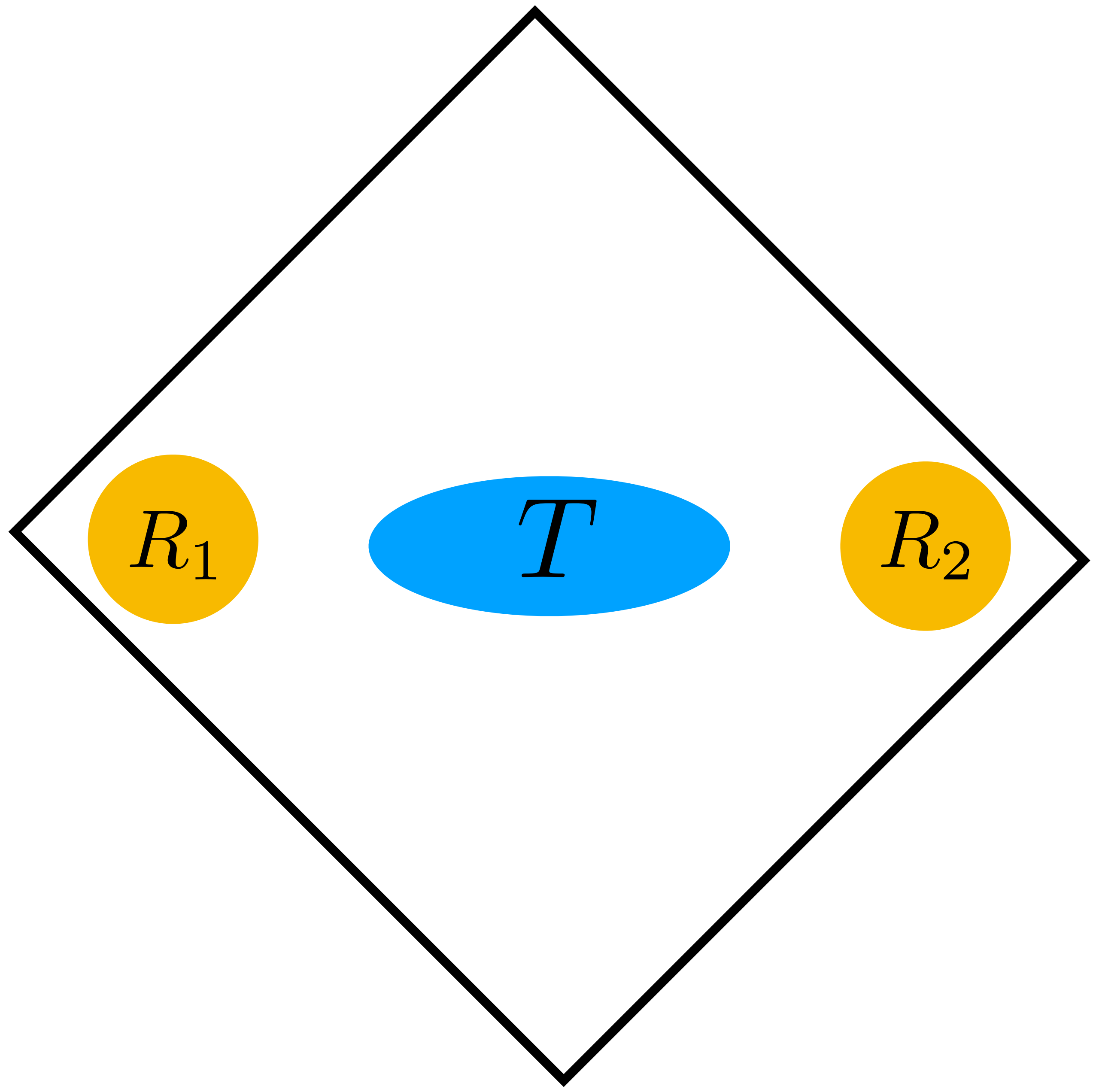


$$\langle 0|T|0\rangle = 0$$
$$\langle \psi|T|\psi\rangle \geq 0$$

$$\Rightarrow \quad |\langle \psi|T|0\rangle|^2 \leq \langle \psi|T|\psi\rangle\langle 0|T|0\rangle = 0$$



$$\begin{aligned} 0 &= \langle \psi|T|0\rangle \\ &= \langle 0|O_{R_1}O_{R_2}T|0\rangle \\ &= \langle 0|O_{R_1}TO_{R_2}|0\rangle \end{aligned}$$

Reeh-Schlieder theorem

$$\langle \psi_1|T|\psi_2\rangle = 0$$

$$\Rightarrow \quad T = 0$$

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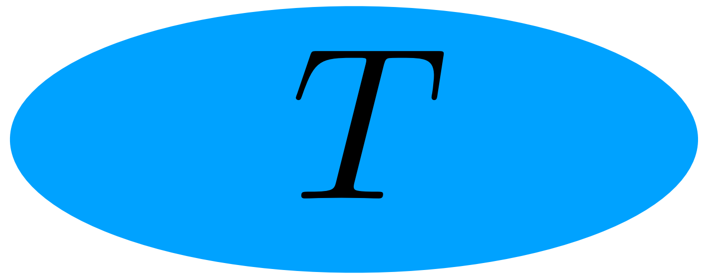

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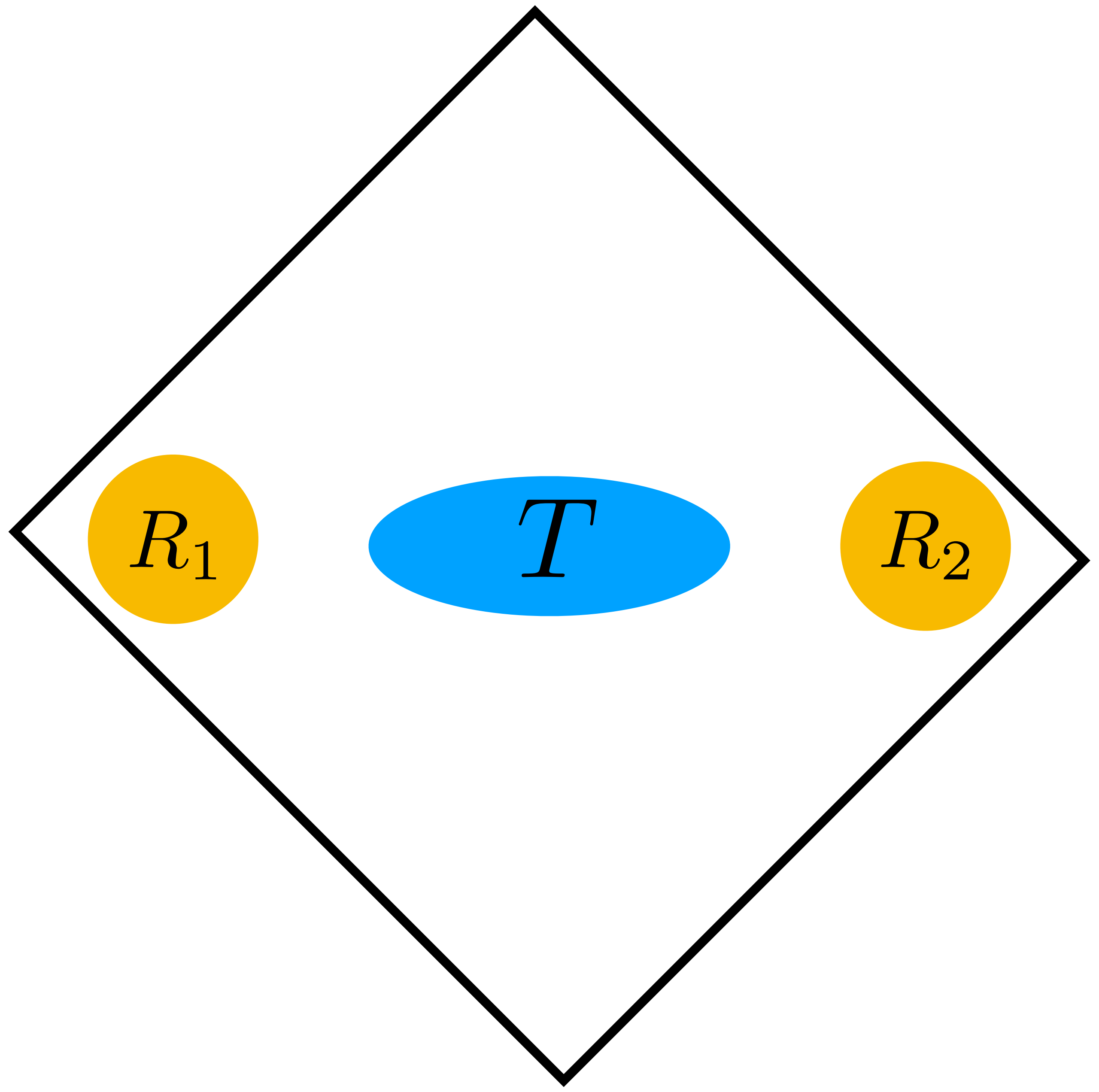


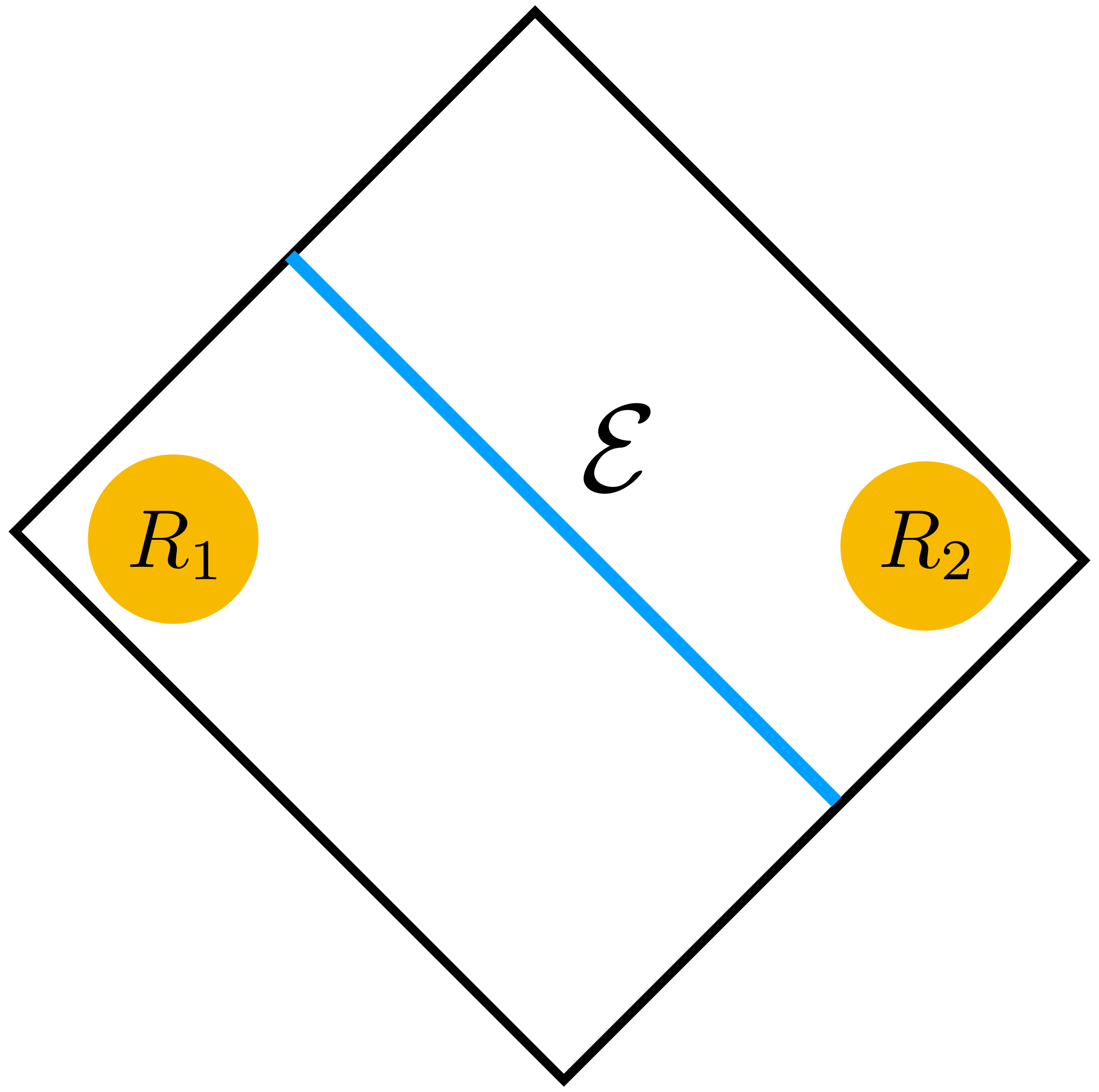
Reeh-Schlieder theorem

$$\langle \psi_1|T|\psi_2\rangle = 0$$

$$\Rightarrow \quad T = 0$$

Positivity on the null line

For the null line, the argument fails



$$\langle 0|O_{R_1}\mathcal{E}O_{R_2}|0\rangle$$
$$\neq \langle 0|O_{R_1}O_{R_2}\mathcal{E}|0\rangle = 0$$

[nothing can hide]

Energy flux is in fact positive!

$$\boxed{\mathcal{E} \geq 0}$$

[unitarity/QM]

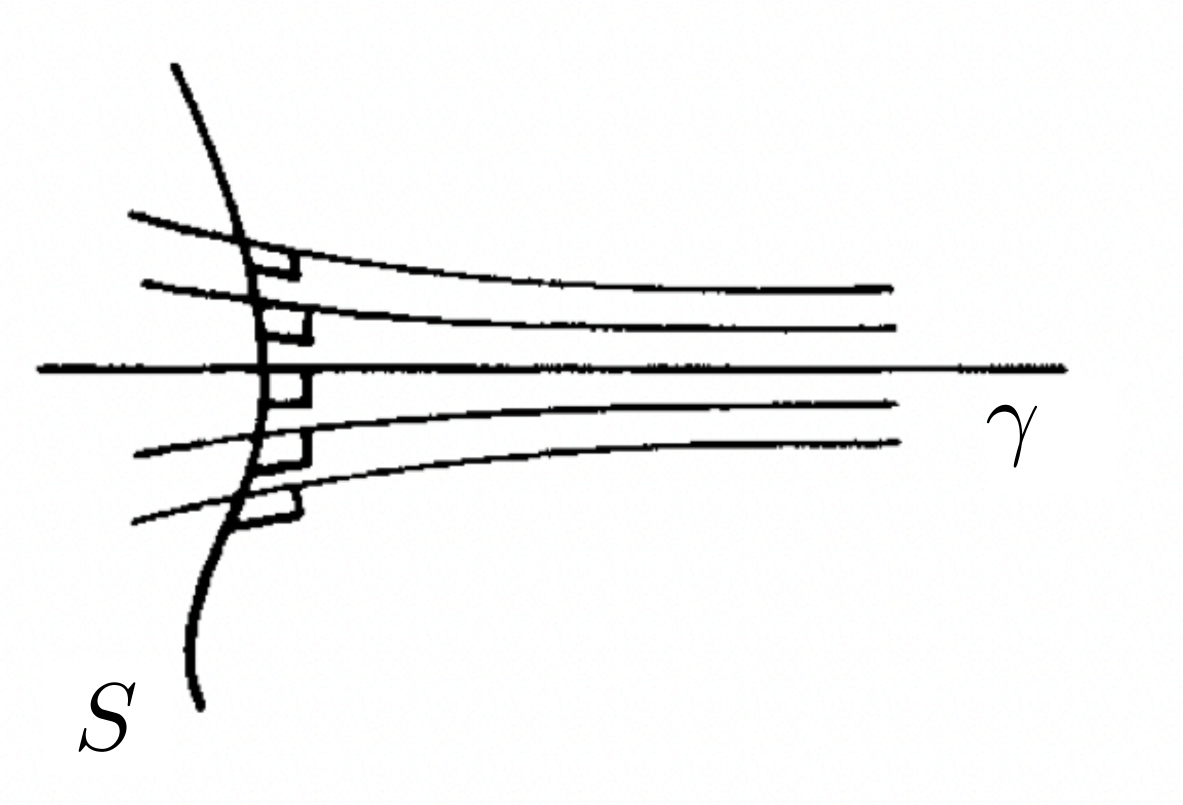
[Faulkner, Leigh, Parrikar, Wang 16']
[Hartman, Kundu, Tajdini 16']

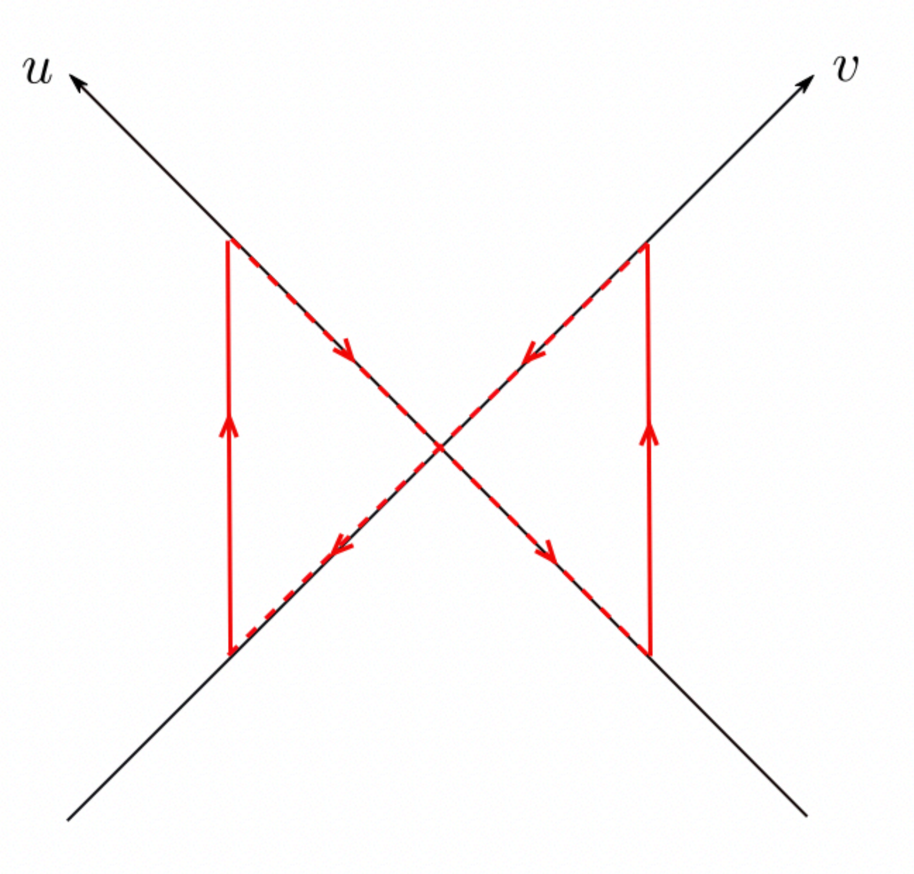
Averaged null energy condition

The fact that $\mathscr{E} \geq 0$ in QFT has many interesting consequences:

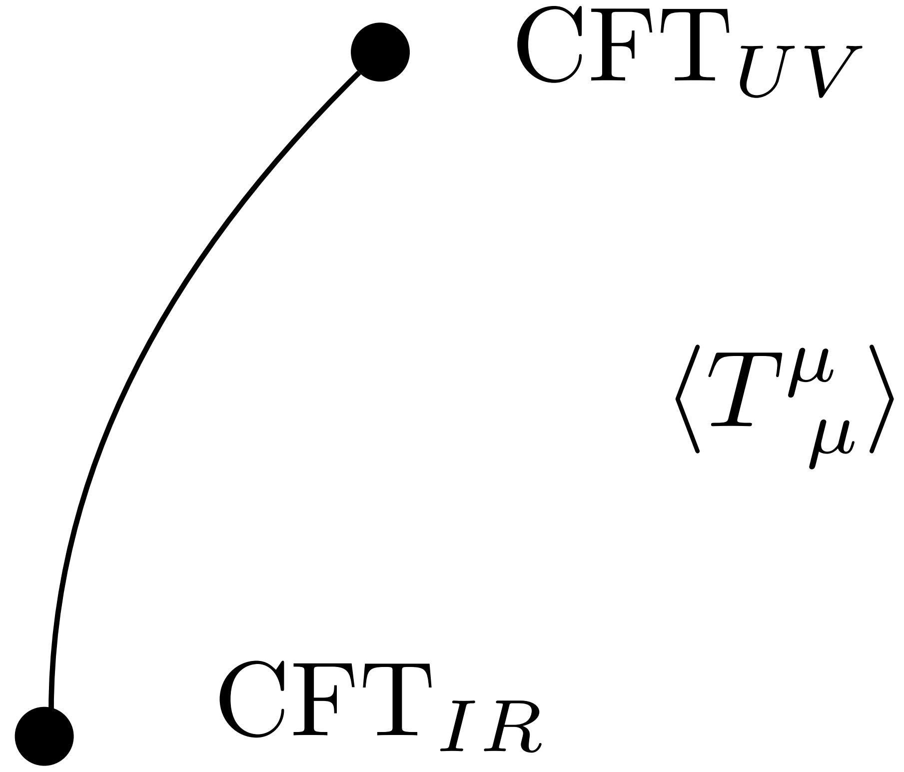
- Classic theorems in general relativity (its violation leads to time machines and violations of the second law of thermodynamics)

[Tipler; Borde '87]
[Morris,Thorne,Yurtsever '88]
[Wall '09]





- Bounds on the RG flows

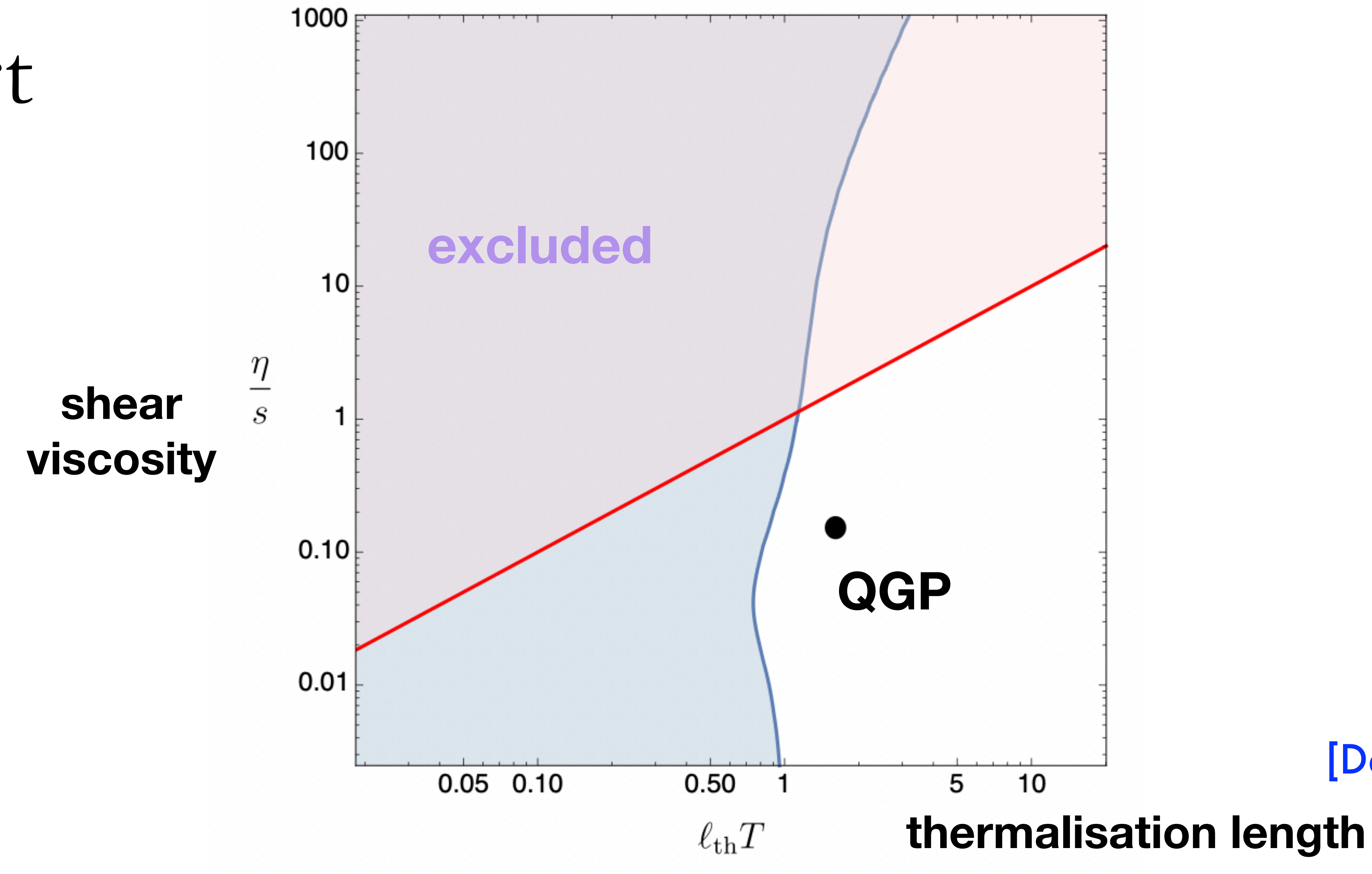


$$a_{UV} - a_{IR} \sim \langle T^{\mu}_{\mu} | \mathcal{E} | T^{\mu}_{\mu} \rangle \geq 0$$

$$\langle T^{\mu}{}_{\mu} \rangle = \frac{c}{16\pi^2} W_{\mu\nu\delta\sigma} W^{\mu\nu\delta\sigma} - \frac{a}{16\pi^2} E$$

[Komargodski,Schwimmer '11]
[Hartman, Mathys '23]

- Bounds on transport



[Hartman,Hartnoll,Mahajan '17]
[Delacretaz,Hartman,Hartnoll,Lewkowycz '18]

- Bounds on CFTs

$$\langle T\cdot\epsilon^*|\mathcal{E}|T\cdot\epsilon\rangle \geq 0 \quad \Rightarrow \quad \frac{31}{18} \geq \frac{a}{c} \geq \frac{1}{3}$$

[Hofman, Maldacena '08,...]

- Connection to quantum information theory:

ANEC →QNEC

$$2\pi\langle T_{uu}\rangle \geq S''_{EE}$$

[Bousso,Fisher,Leichenauer,Wall '16]
[Ceyhan,Faulkner '20]
[Hollands,Longo '25]

What is the space of detector operators?

[e.g measure E^{J-1}]

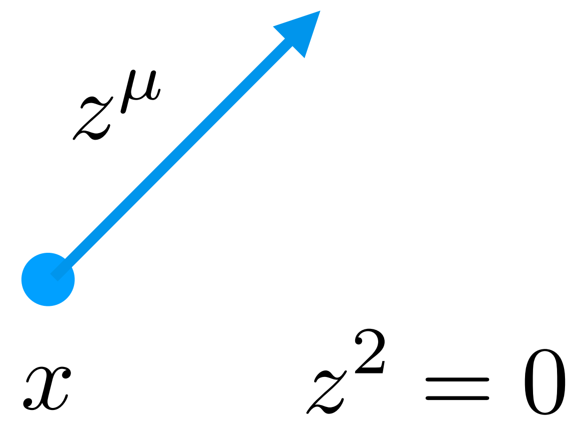
[Caron-Huot,Kologlu,Kravchuk,Meltzer,Simmons-Duffin '22]
[Caron-Huot,Giroux,Hannesdottir,Mizera '23]

What is the space of detector operators?

Local operators

$$\mathcal{O}_{\mu_1 \ldots \mu_J}(x)$$

$$J \in \mathbb{Z}_+$$



Detector operators
(aka lightray operators)

$$\mathbb{O}_J(x, z)$$

$$J \in \mathbb{C}$$

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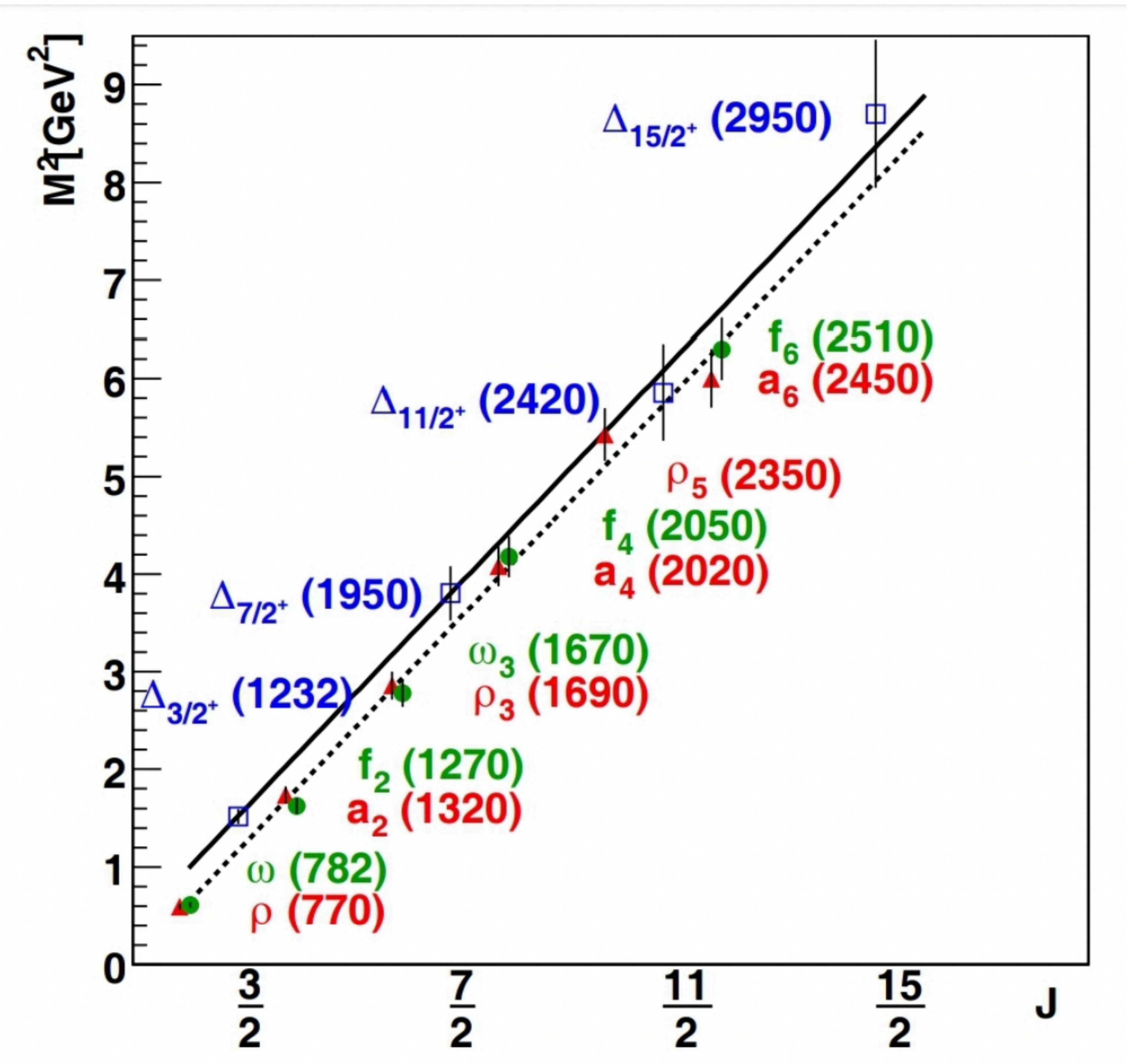
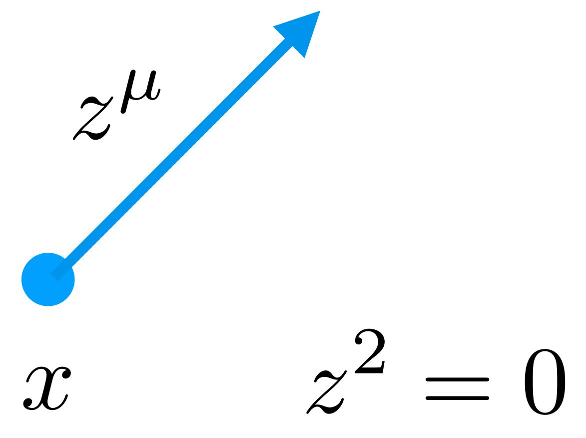


[Klempt,Metsch '12]

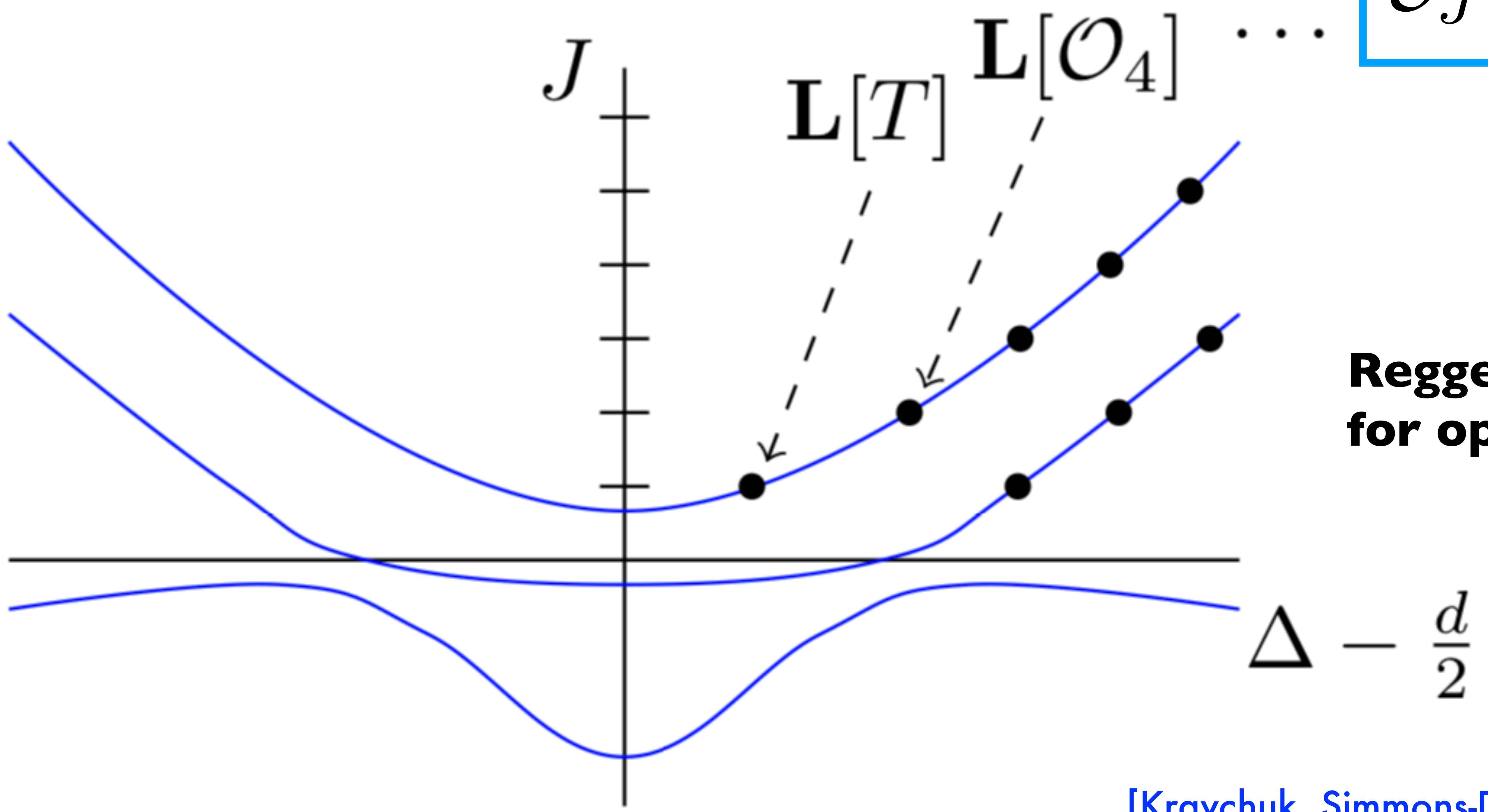


Detector operators
(aka lightray operators)

$$\mathbb{O}_J(x, z)$$

$$J \in \mathbb{C}$$

$$\mathcal{E}_J \geq 0$$

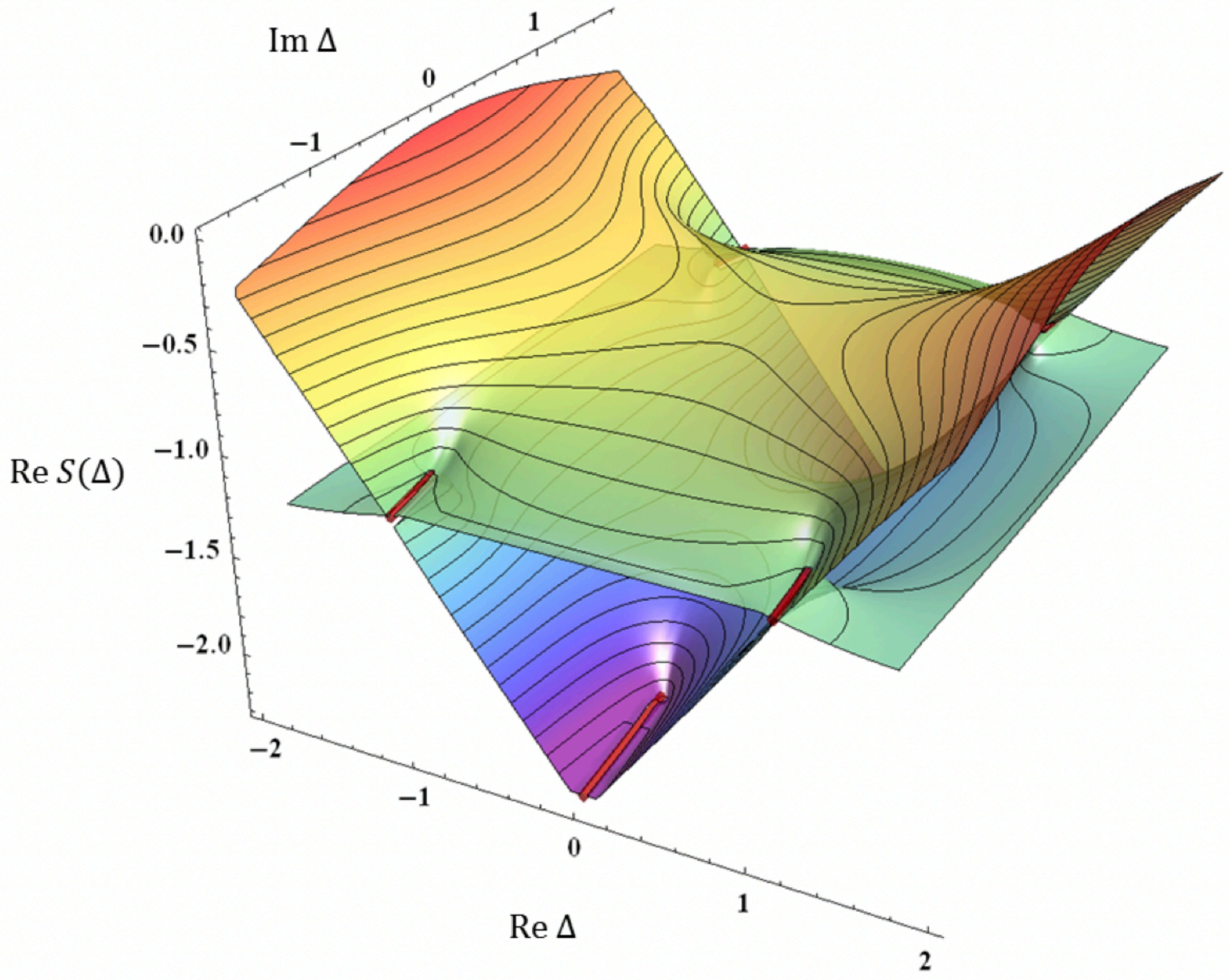


Regge theory for operators

[Kravchuk, Simmons-Duffin '18]

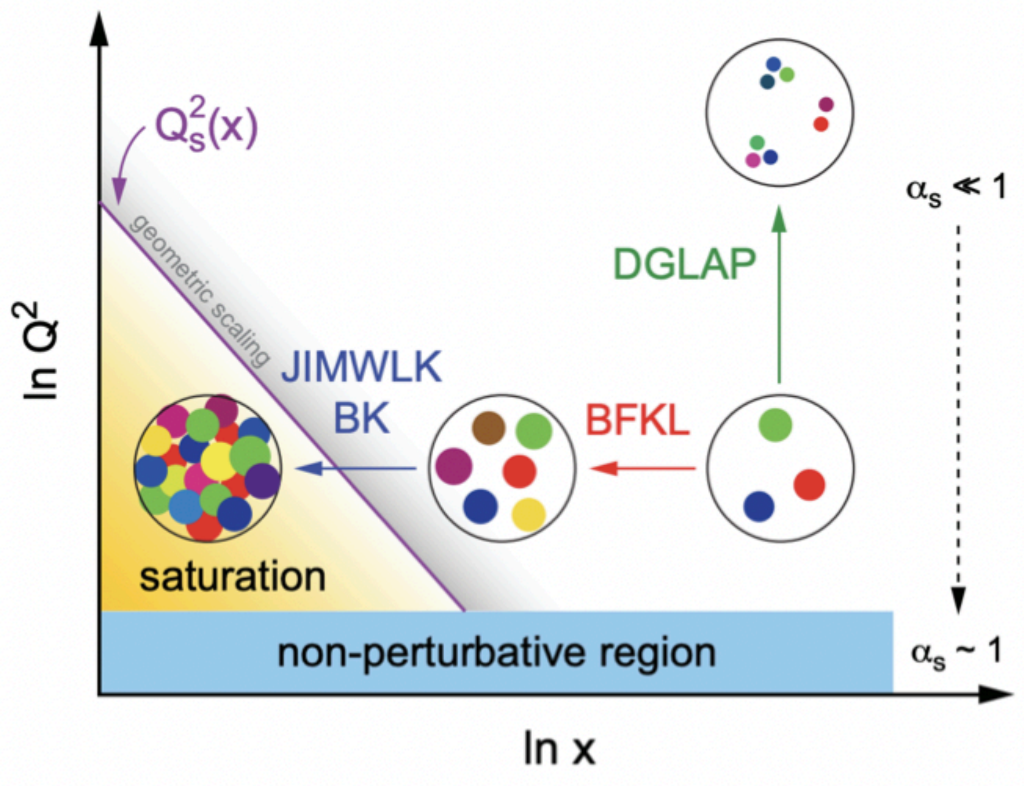
Regge surface

Unified picture for operators on different Regge trajectories.

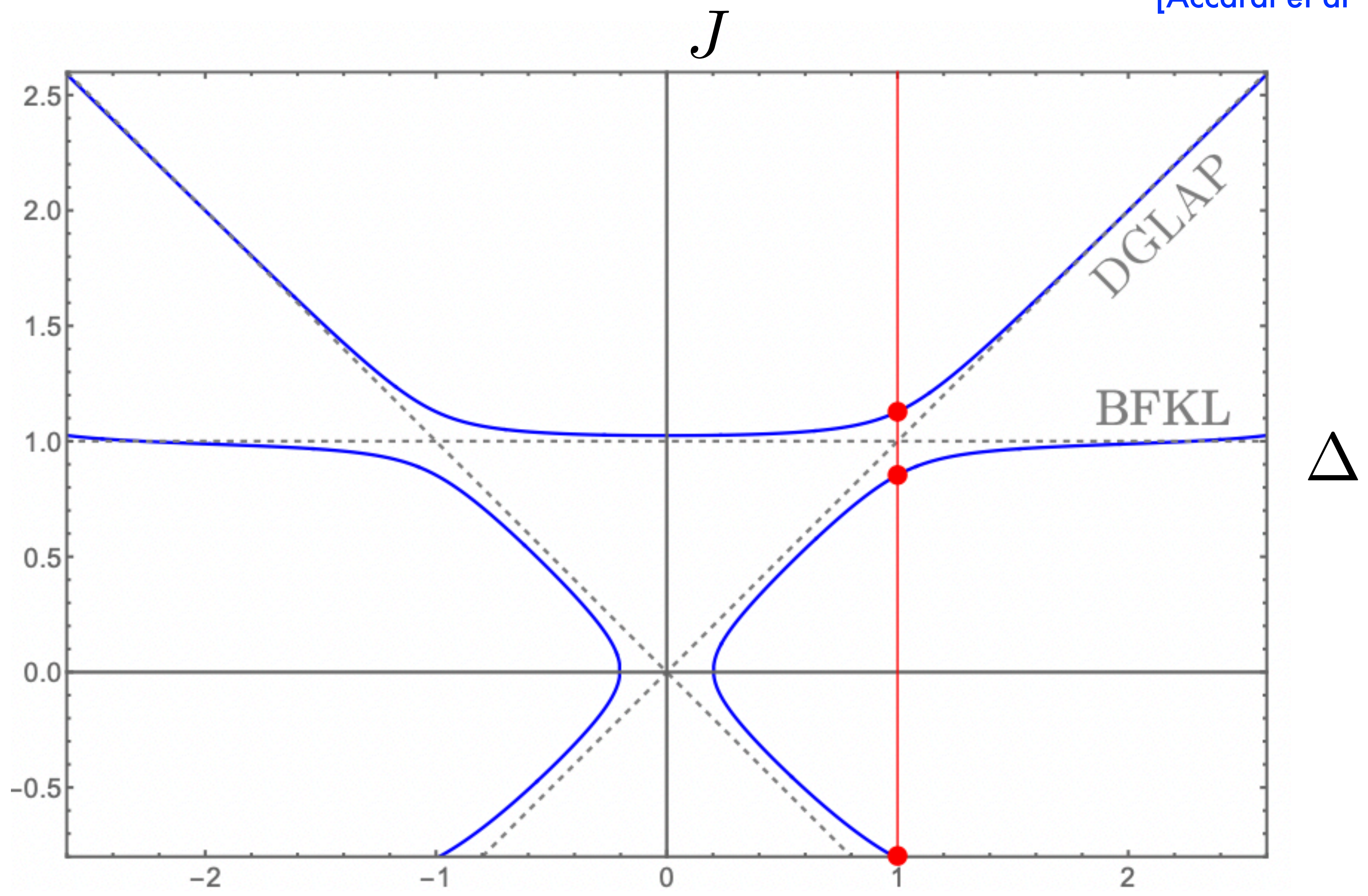


[Gromov,Levkovich-Maslyuk,Sizov '17]

Regge surface for particles?



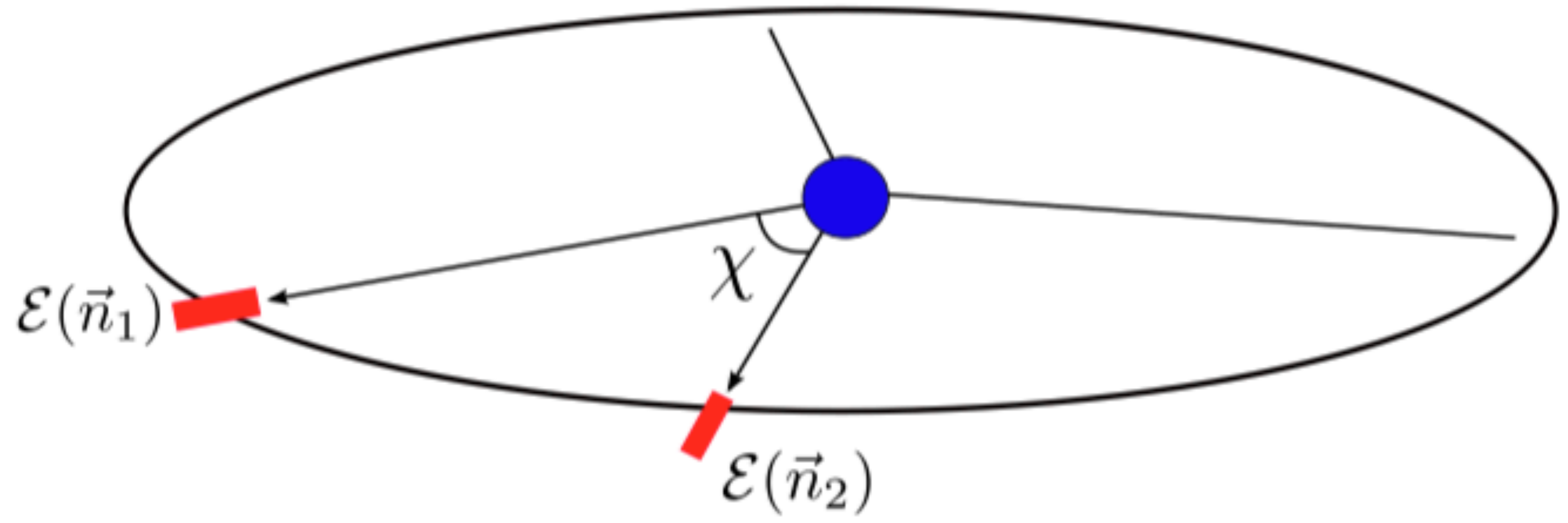
[Accardi et al '12]



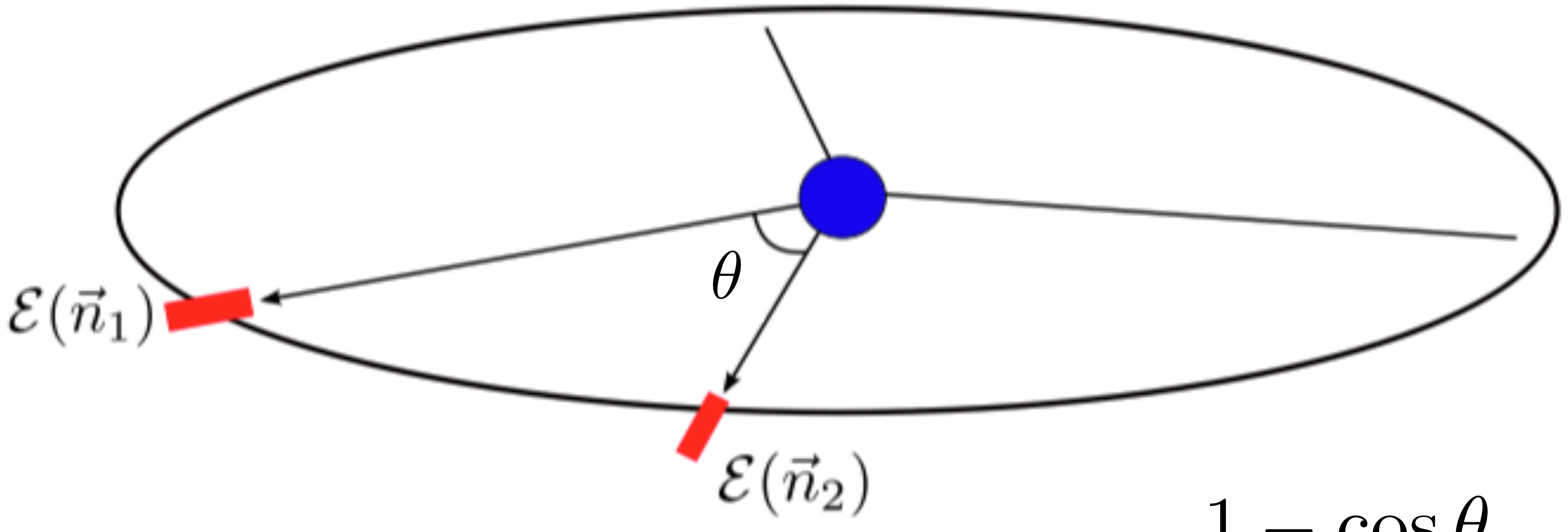
[Ekhammar,Gromov,Preti '24]
[Chang,Chen,Simmons-Duffin,Zhu '25]

In many other theories...

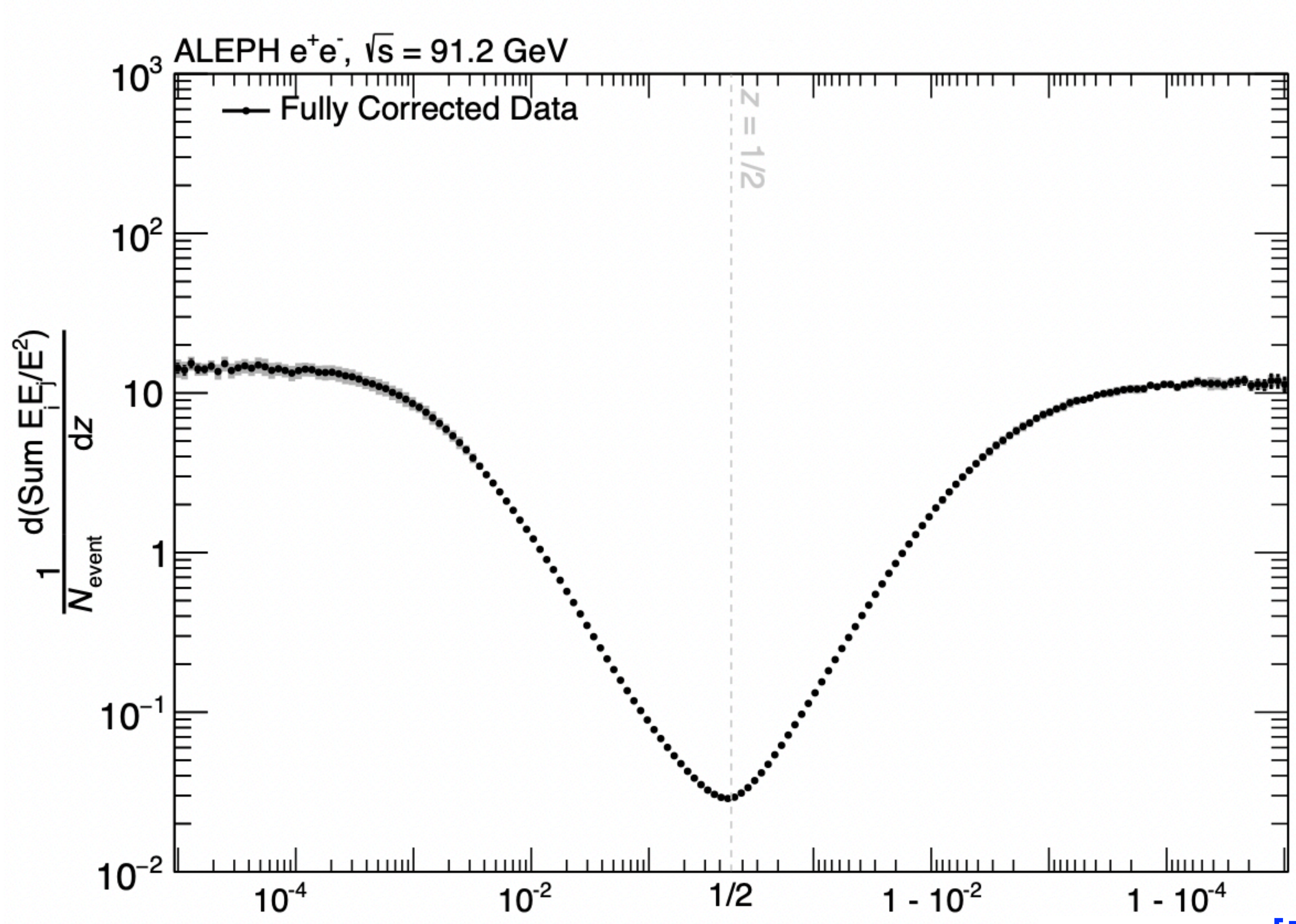
Energy correlators $\langle \mathcal{E}(\vec{n}_1) \ldots \mathcal{E}(\vec{n}_k) \rangle$



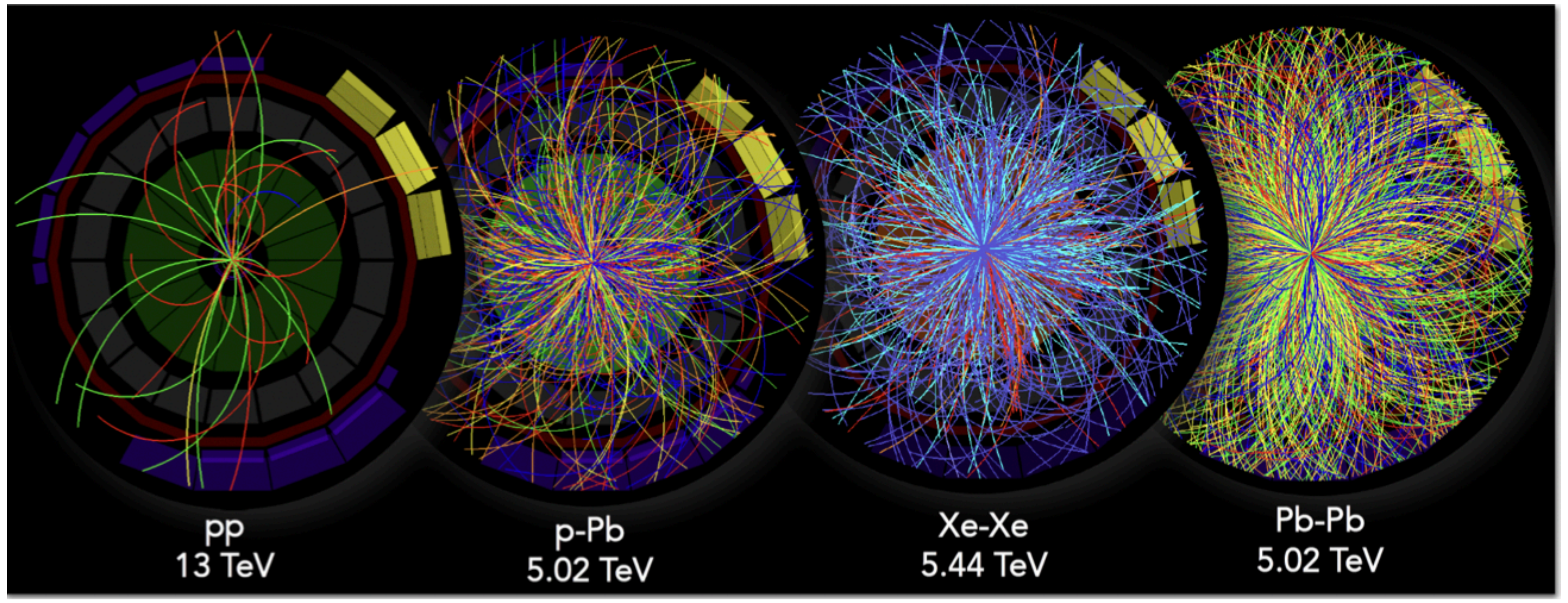
Energy correlators



$$z = \frac{1-\cos\theta}{2}$$



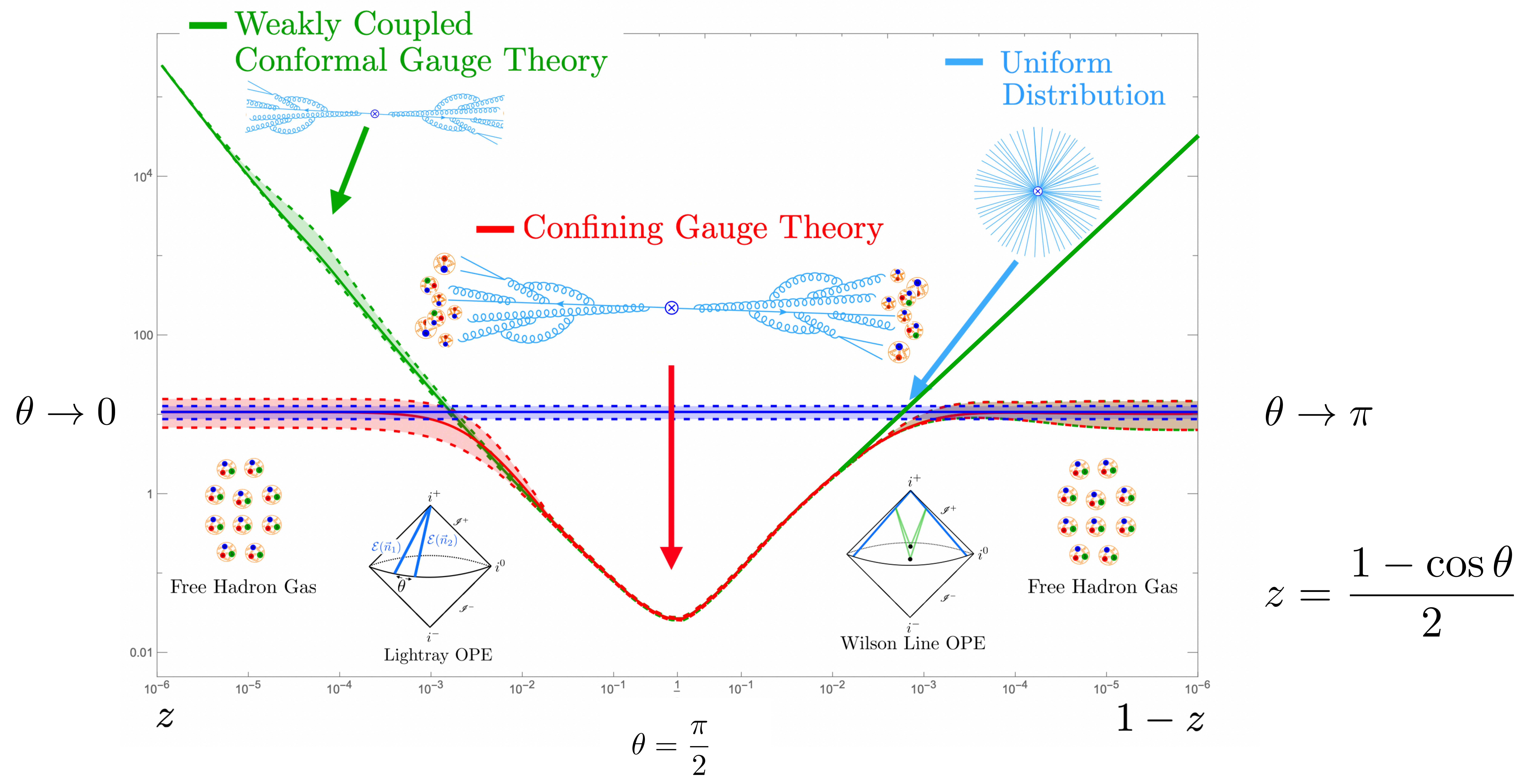
[Bossi et al. '25]



Many new measurements:

- e^+e^- Colliders: Re-analysis using ALEPH archival data (Bossi *et al.*, 2025a,b).
- *ep* Colliders: Measurement by HERA (H1).
- Proton-proton Colliders: Measurements by the CMS (Hayrapetyan *et al.*, 2024a), ALICE (Acharya *et al.*, 2024a, 2025; Hwang) and STAR (Tamis, 2024; STA, 2025; Shen) collaborations.
- Proton-Pb Colliders: Measurement by the ALICE collaboration (Nambrath, a,b).
- Pb-Pb Colliders: Measurements by the ALICE (Rai) and CMS (CMS, 2023, 2025; Chekhovsky *et al.*, 2025) collaborations.

["Energy Correlators: A Journey From Theory to Experiment" Moult, Zhu '25]



[Much richer structure for more than two detectors]

["Energy Correlators: A Journey From Theory to Experiment" Moult, Zhu '25]

Jets: the operator product expansion (OPE)

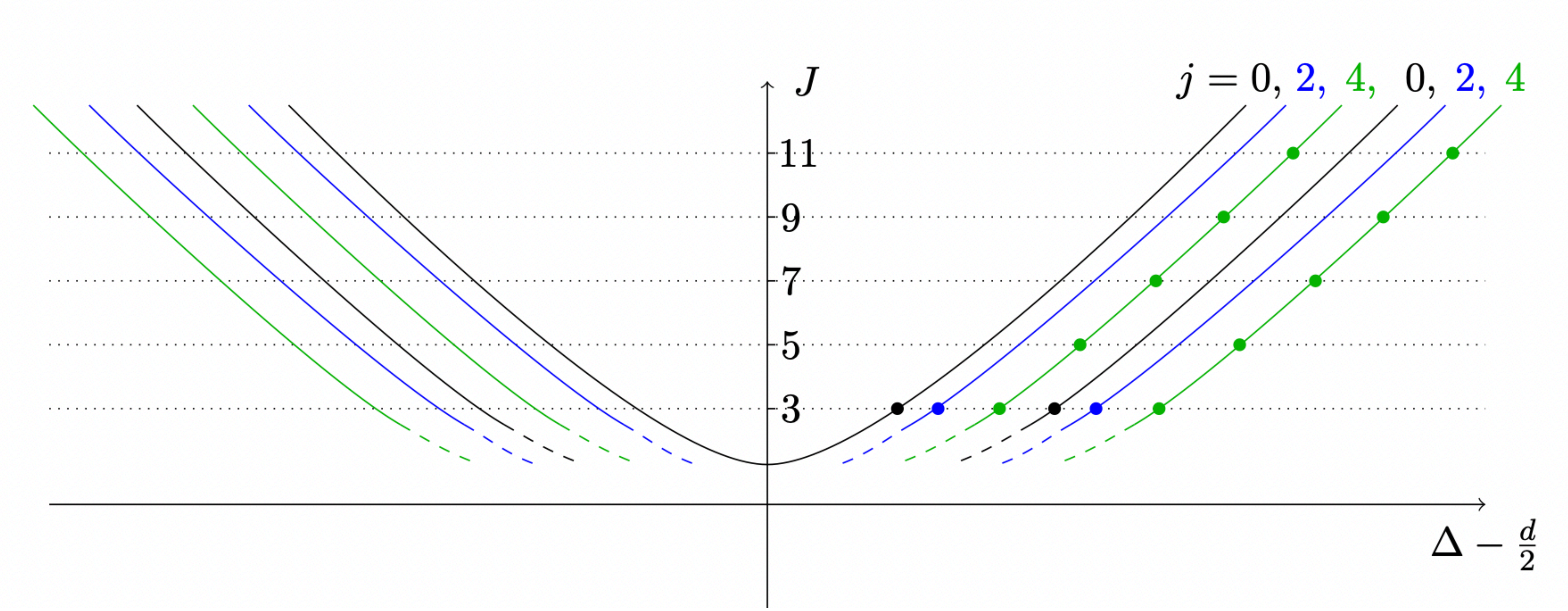
Local operators
(small distances)

Detector operators
(small angles)

$$\mathcal{O}_i(x)\mathcal{O}_j(0) = \sum_k \frac{c_{ijk}}{x^{\Delta_i+\Delta_j-\Delta_k}}\mathcal{O}_k(0)$$

$$\mathcal{E}(\theta)\mathcal{E}(0) = \sum_i \frac{p_i}{\theta^{\tau_i-4}}\mathbb{O}_{i,J=3}(0)$$

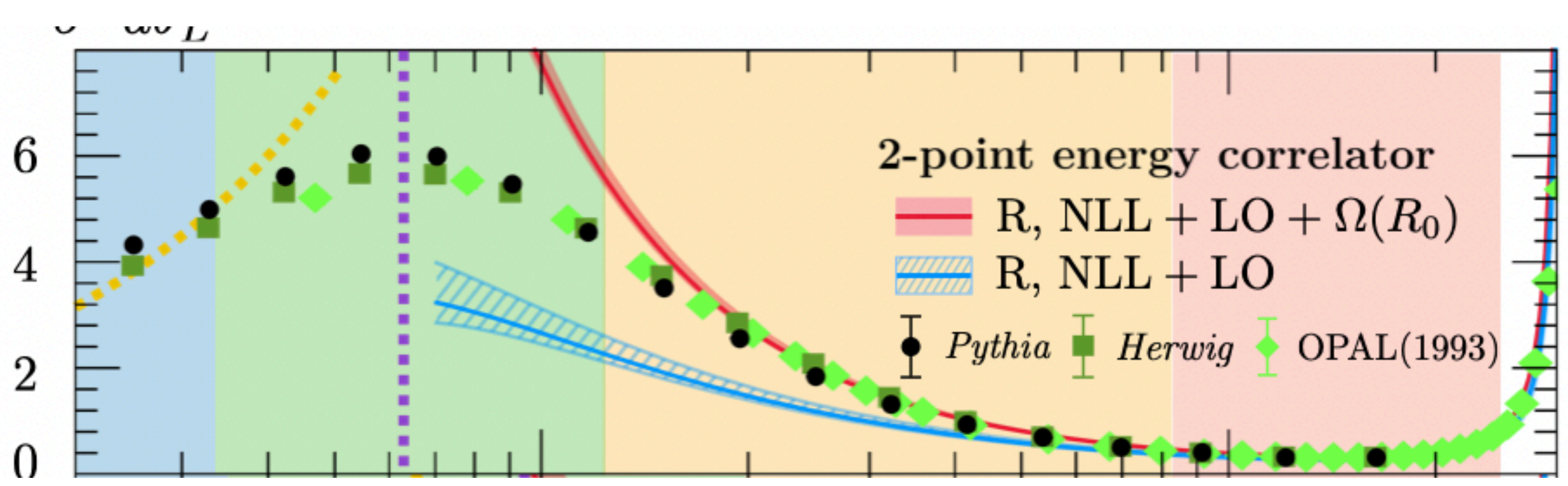
[Hofman, Maldacena '08]



light-ray OPE

[Kologlu, Kravchuk, Simmons-Duffin, AZ '19]
[Chang, Kologlu, Kravchuk, Simmons-Duffin, AZ '20]

QCD: $\mathcal{E}(\theta)\mathcal{E}(0) \sim \frac{\Lambda_{QCD}}{\theta^3} D_i \mathbb{O}_{i,J=2}(0)$



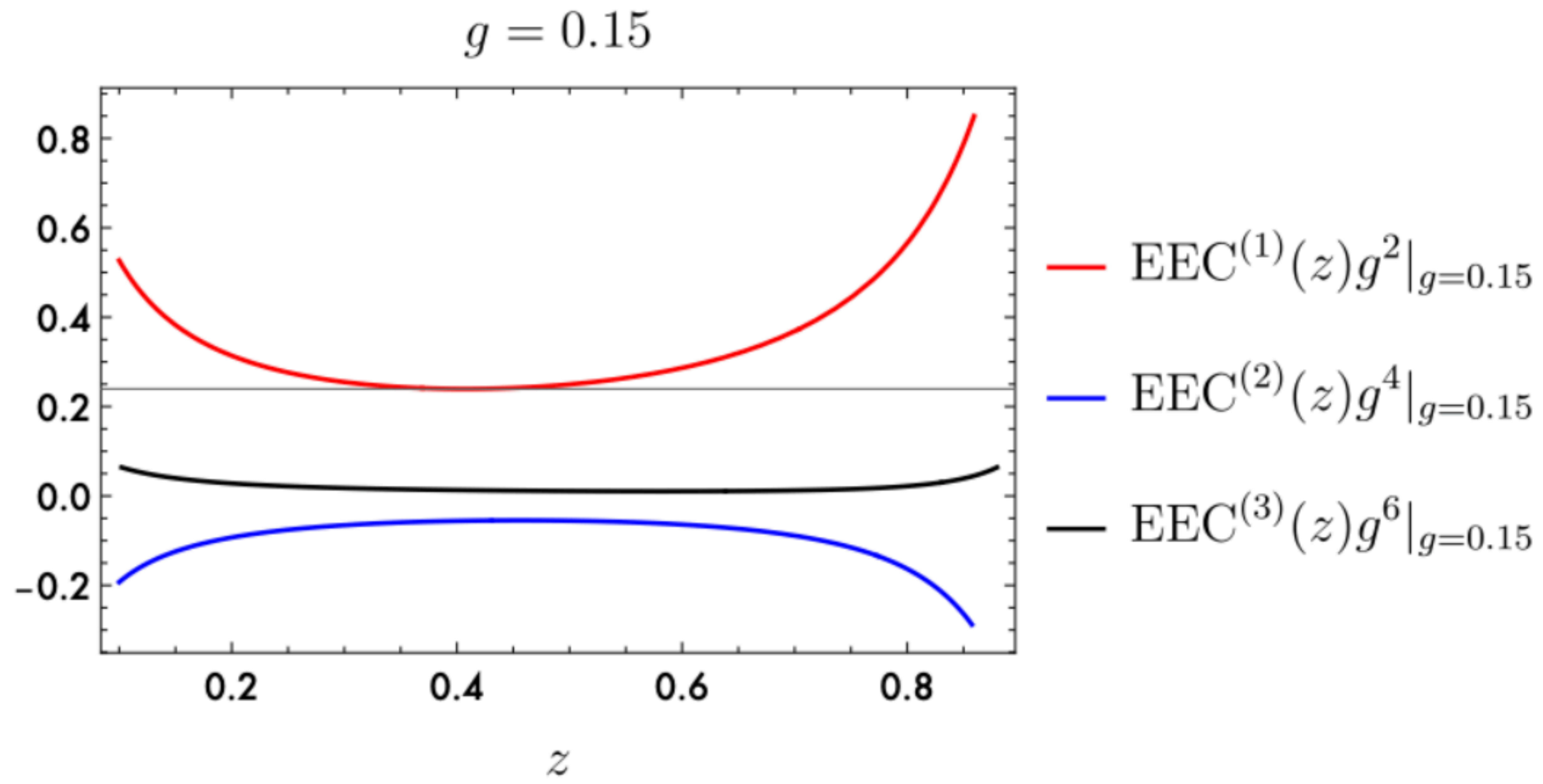
[Korchemsky,Sterman '99]
[Lee,Pathak,Stewart,Sun '24]
[Chen,Monni,Xu,H-X Zhu '24]

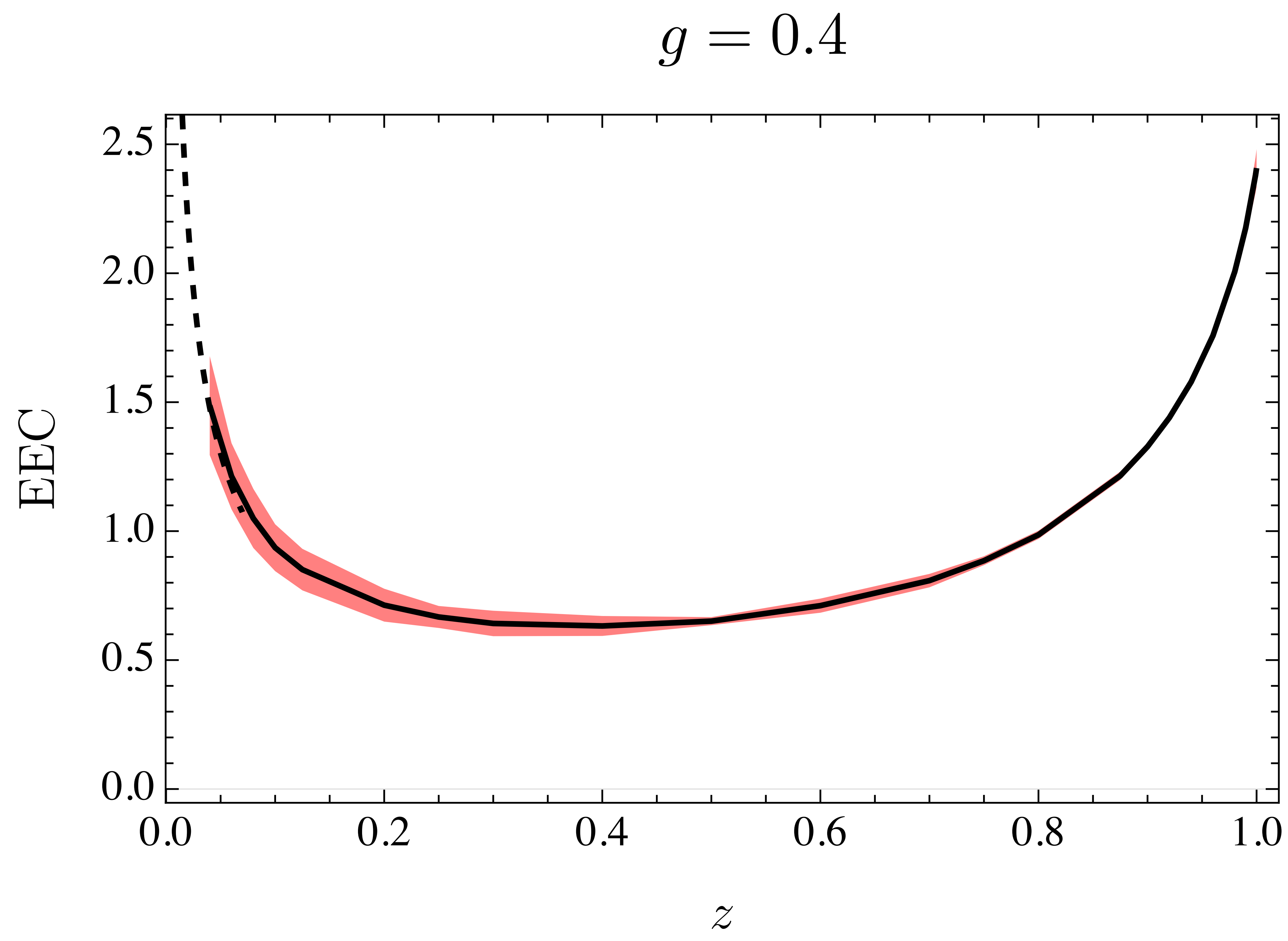
Finite coupling: conformal collider bootstrap (in N=4 SYM)

In $\mathcal{N} = 4$ SYM a comprehensive picture can be achieved by combining dispersion relations, holography, supersymmetric localization, integrability, and the conformal bootstrap.

$$g^2 = \frac{g_{YM}^2 N_c}{(4\pi)^2} \qquad SU(N_c)$$

truly finite coupling calculation!



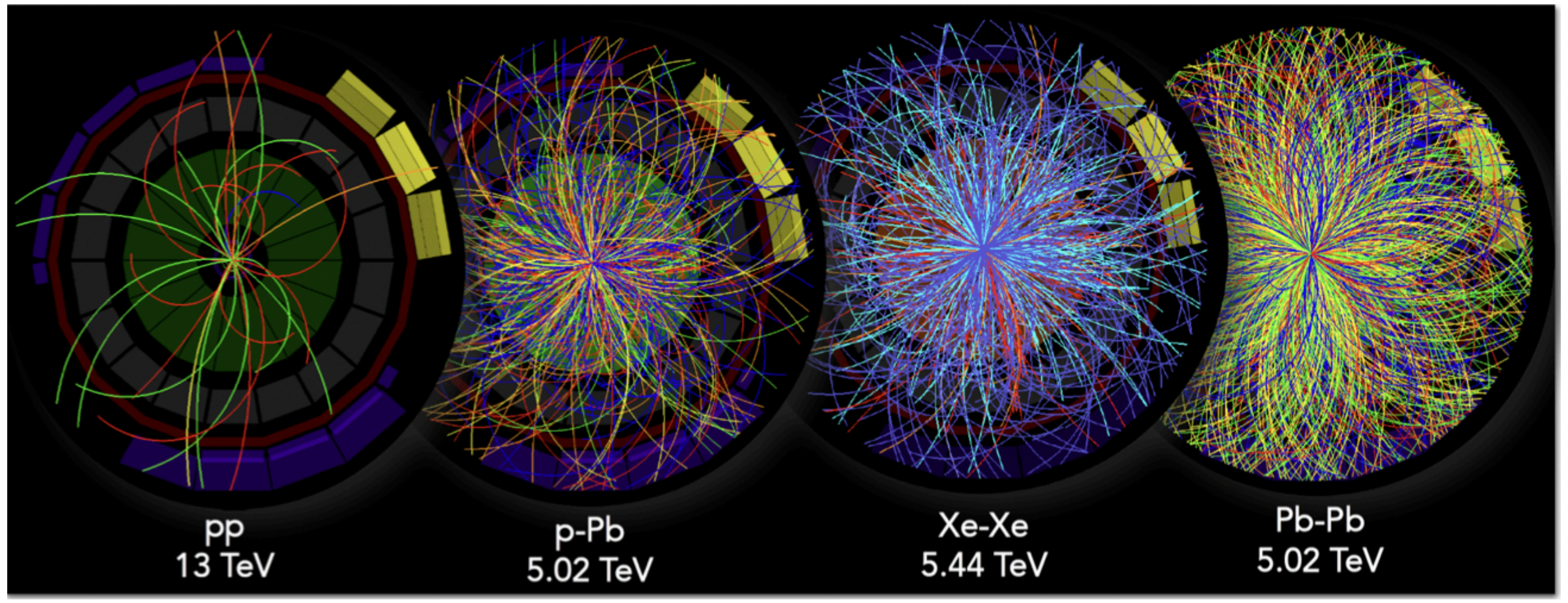


[Belitsky,Henn,Hohenegger,Korchemsky,Sokatchev,Yan,AZ]

[also non-planar] [Dempsey,Karlsson,Pufu,Zahraee,AZ wip]

[Chester, Dempsey, Pufu]
[Caron-Huot, Coronado, Zahraee '24]

What about different sources?



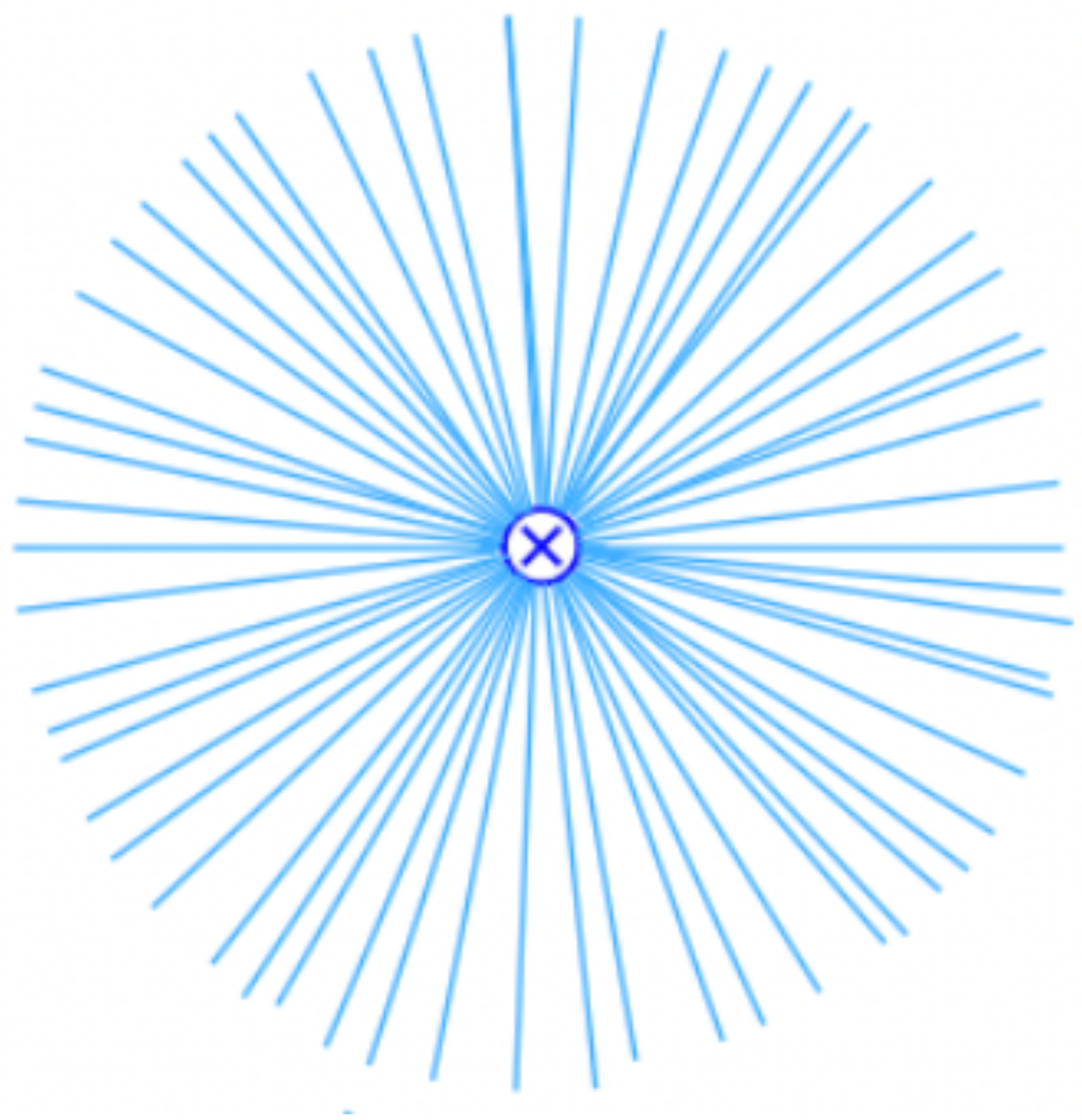
Homogeneous distribution (heavy states, large charge)

To get a homogeneous distribution we could have a multi-particle state (medium), or strongly coupled dynamics (copious production)

$$|\Psi\rangle = \mathrm{Tr}[\phi^K]|\Omega\rangle$$

$$\langle \mathcal{E}(\vec{n}_1)...\mathcal{E}(\vec{n}_k)\rangle = \prod_{i=1}^{k}\langle \mathcal{E}(\vec{n}_i)\rangle + \mathcal{O}\Big(\frac{1}{K}\Big)$$

probe the medium



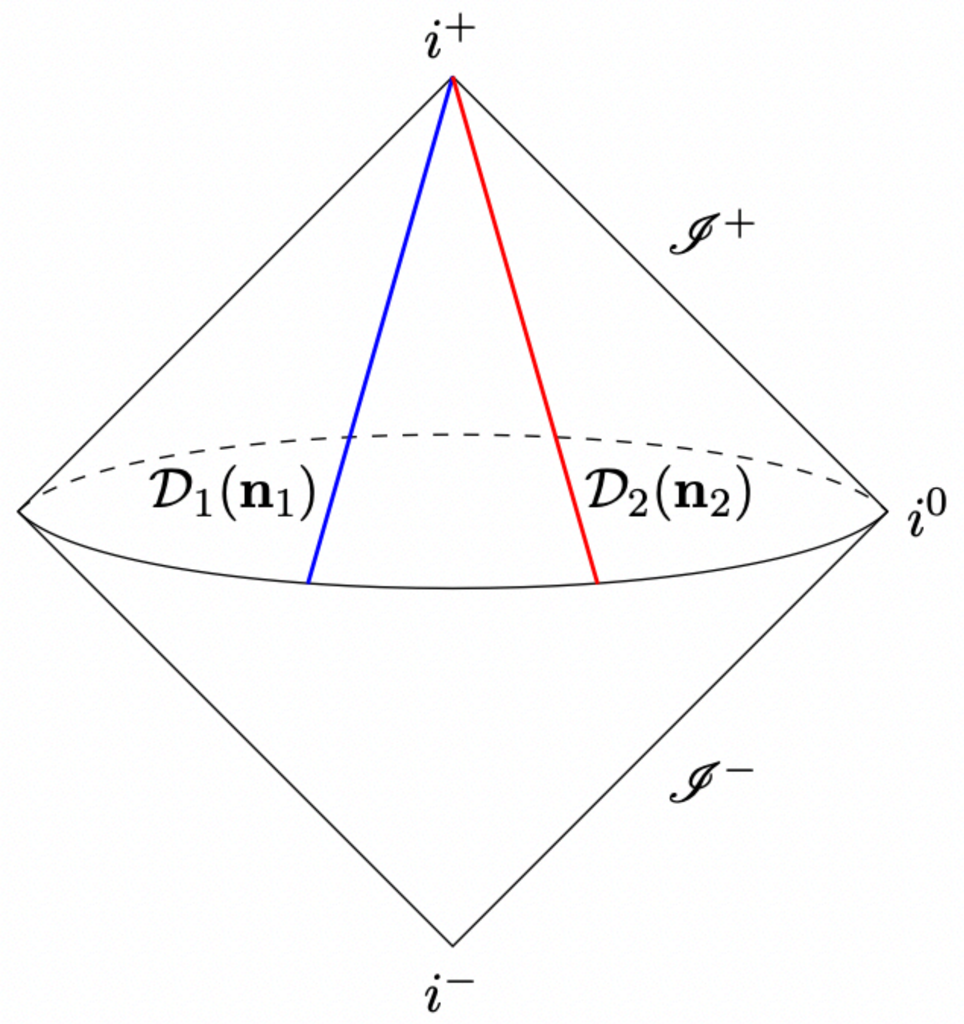
[Chicherin,Korchemsky,Sokatchev,AZ '23]
[Firat,Monin,Rattazzi,Walters '23]

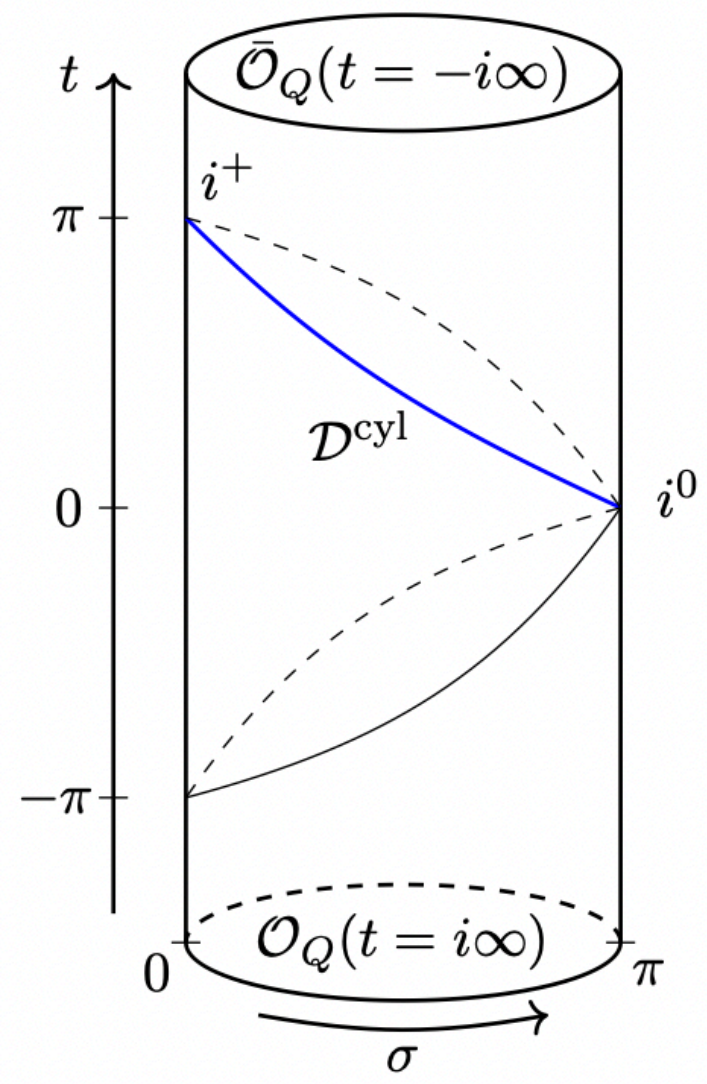
- Large charge EFT

$$S = \frac{c}{d}\int d^dx\sqrt{g}(\partial\chi)^d$$

$$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle \sim -\frac{Q^{-\frac{d}{d-1}}}{\theta^{d-1}} \qquad \frac{1}{Q^{\frac{1}{d-1}}} \ll \theta \ll 1$$

sound jet





[Cuomo,Firat,Nardi,Ricci '25]

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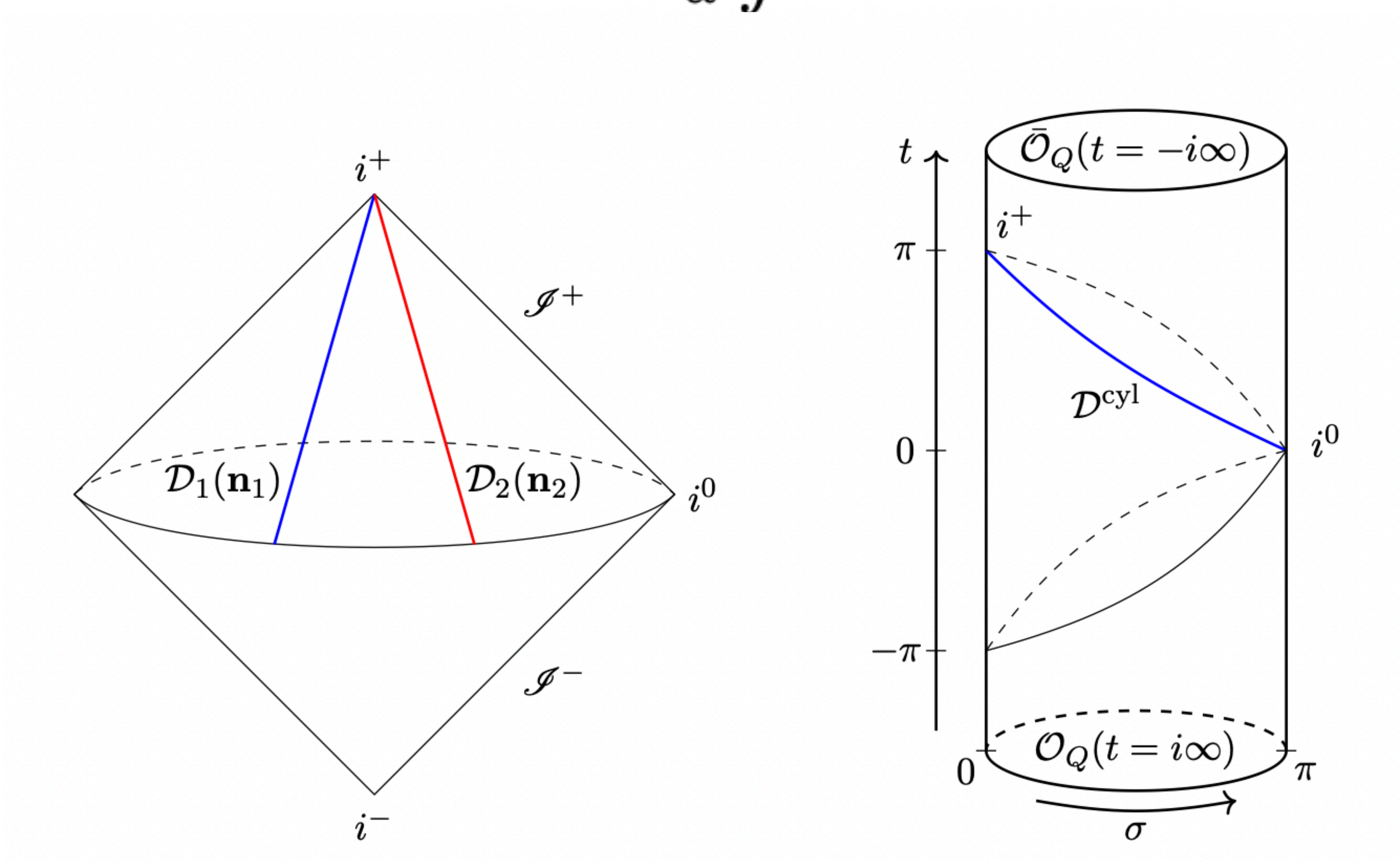
$$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle \sim -\frac{Q^{-\frac{d}{d-1}}}{\theta^{d-1}} \qquad \frac{1}{Q^{\frac{1}{d-1}}} \ll \theta \ll 1$$

sound jet



[Cuomo,Firat,Nardi,Ricci '25]

- Weak coupling (state)

$$|\Psi\rangle = \mathrm{Tr}[\phi^K]|\Omega\rangle$$

$$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle \sim 1 + \frac{1}{K}\frac{1}{\theta^{2-\gamma(3)}}$$

twist-4 (homogeneous)

twist-2 (jet)

- Strong coupling (dynamics)

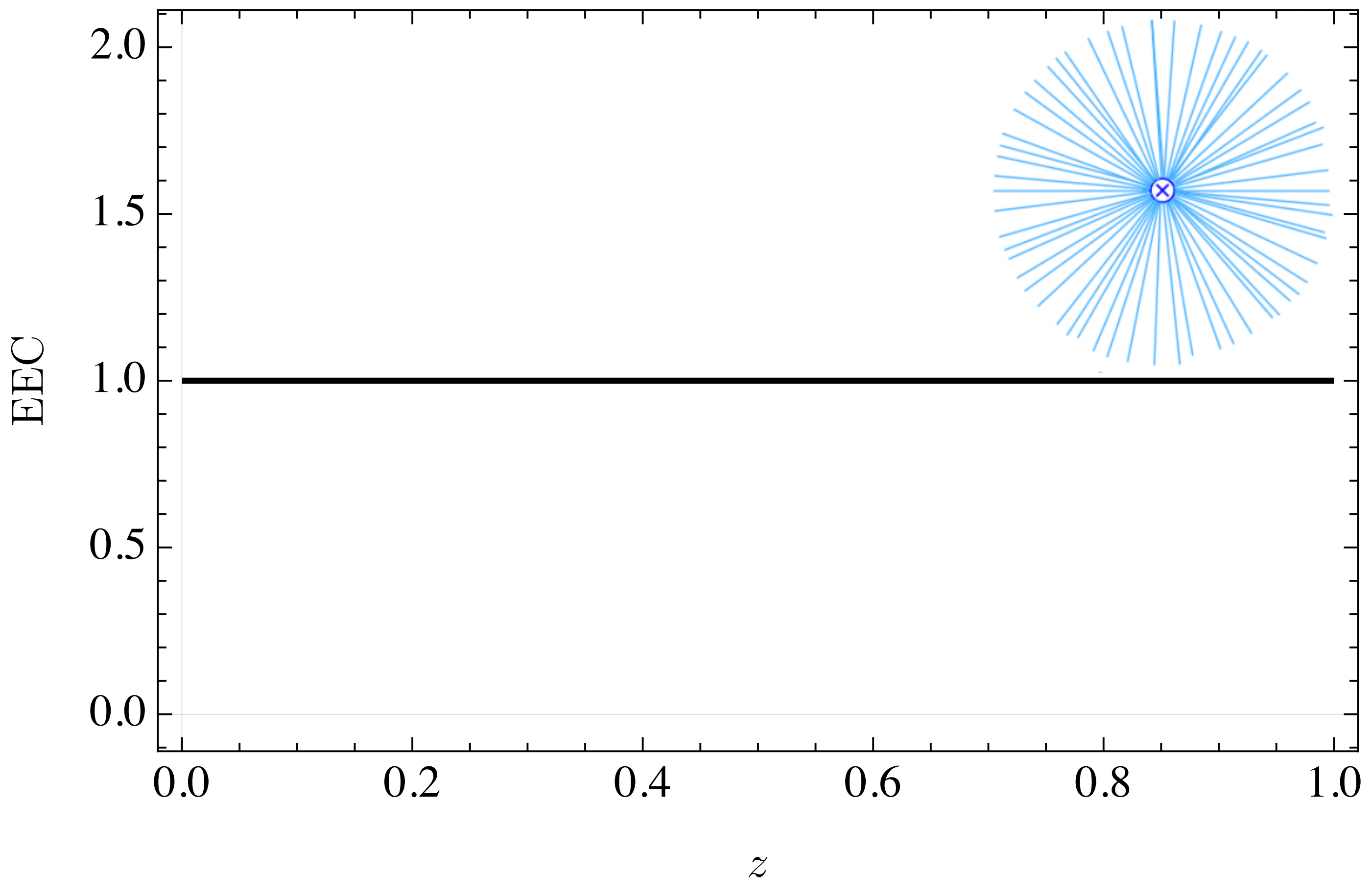
$$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle \sim 1 + \frac{6\pi^2}{\lambda}(\cos^2\theta - \frac{1}{3})$$

gravity

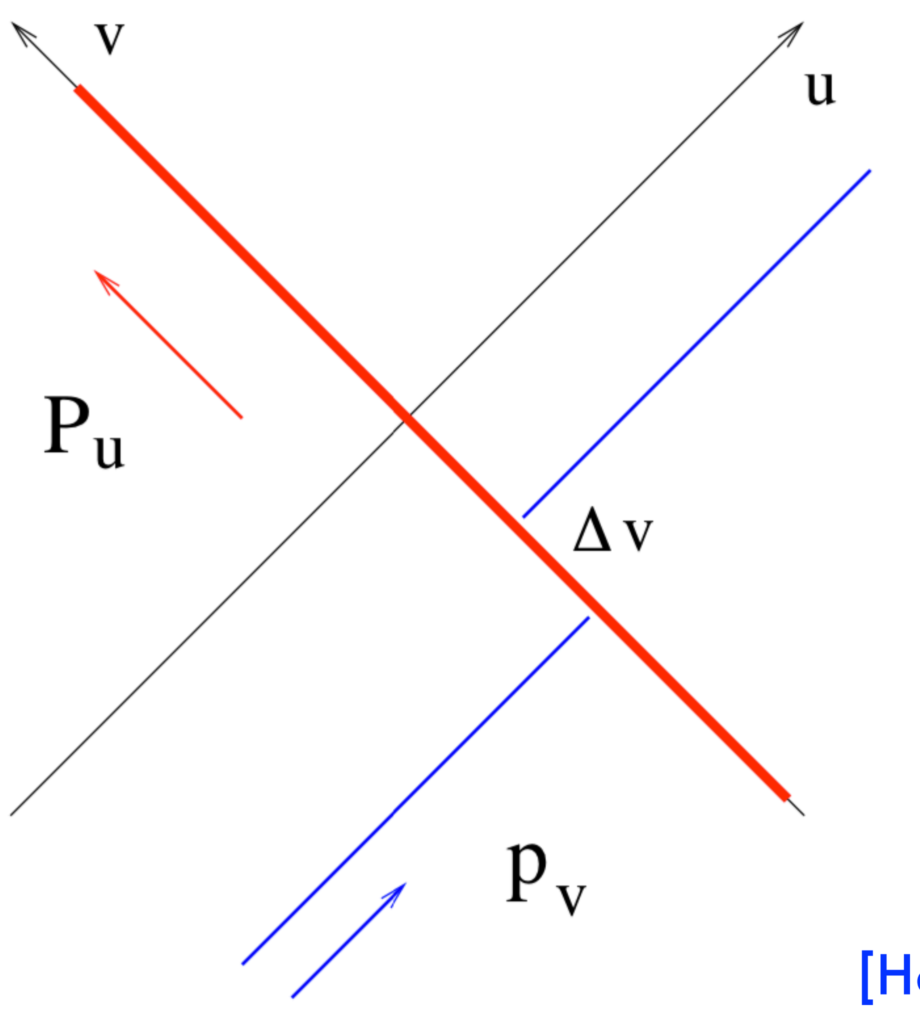
stringy correction

Collider experiment in holography

At strong coupling the energy distribution becomes homogeneous and it is described by **string theory** in the emergent AdS space.



Energy calorimeter	=	Gravitational shockwave
Measuring energy	=	Shapiro time delay
ANEC	=	Causality
$\mathcal{E} \geq 0$		$\Delta v \geq 0$

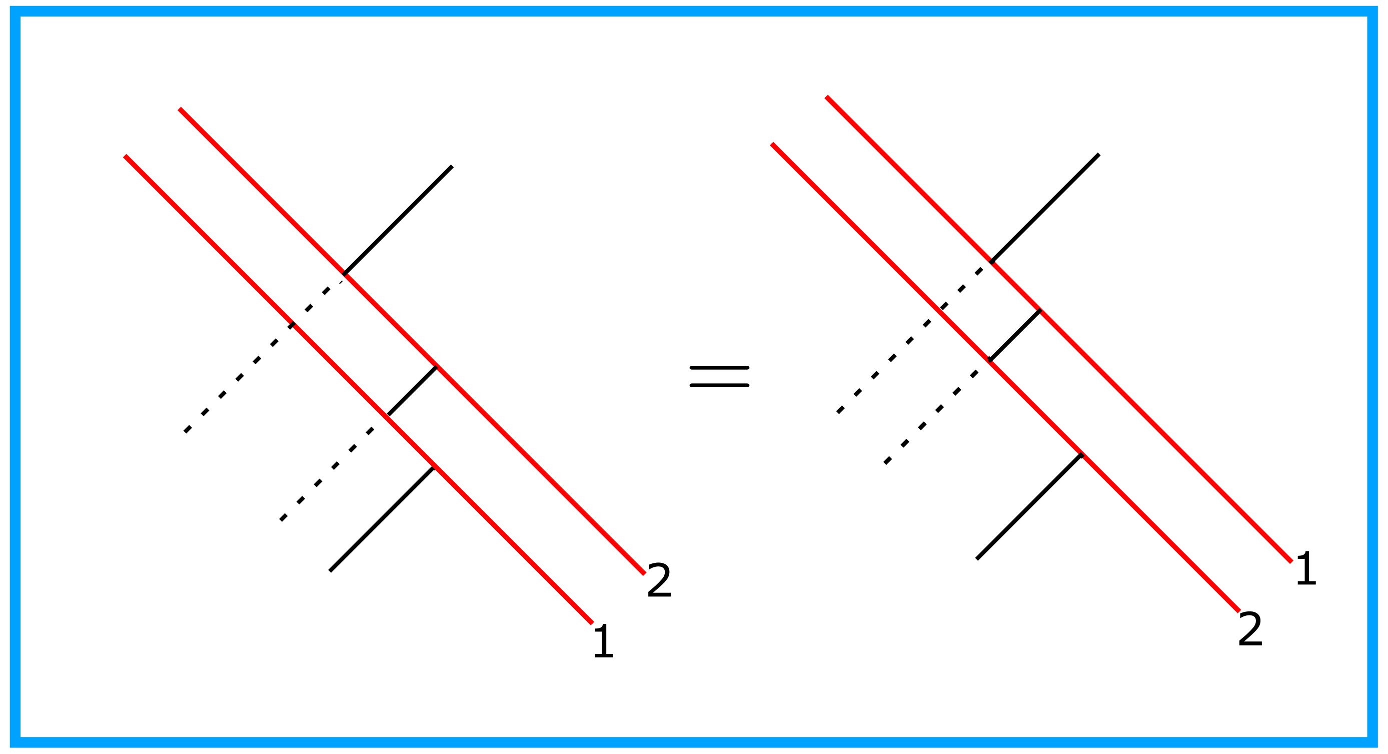


[Hofman, Maldacena, '08]

Measurements commute:

$$[\mathcal{E}(\vec{n}_1), \mathcal{E}(\vec{n}_2)] = 0$$

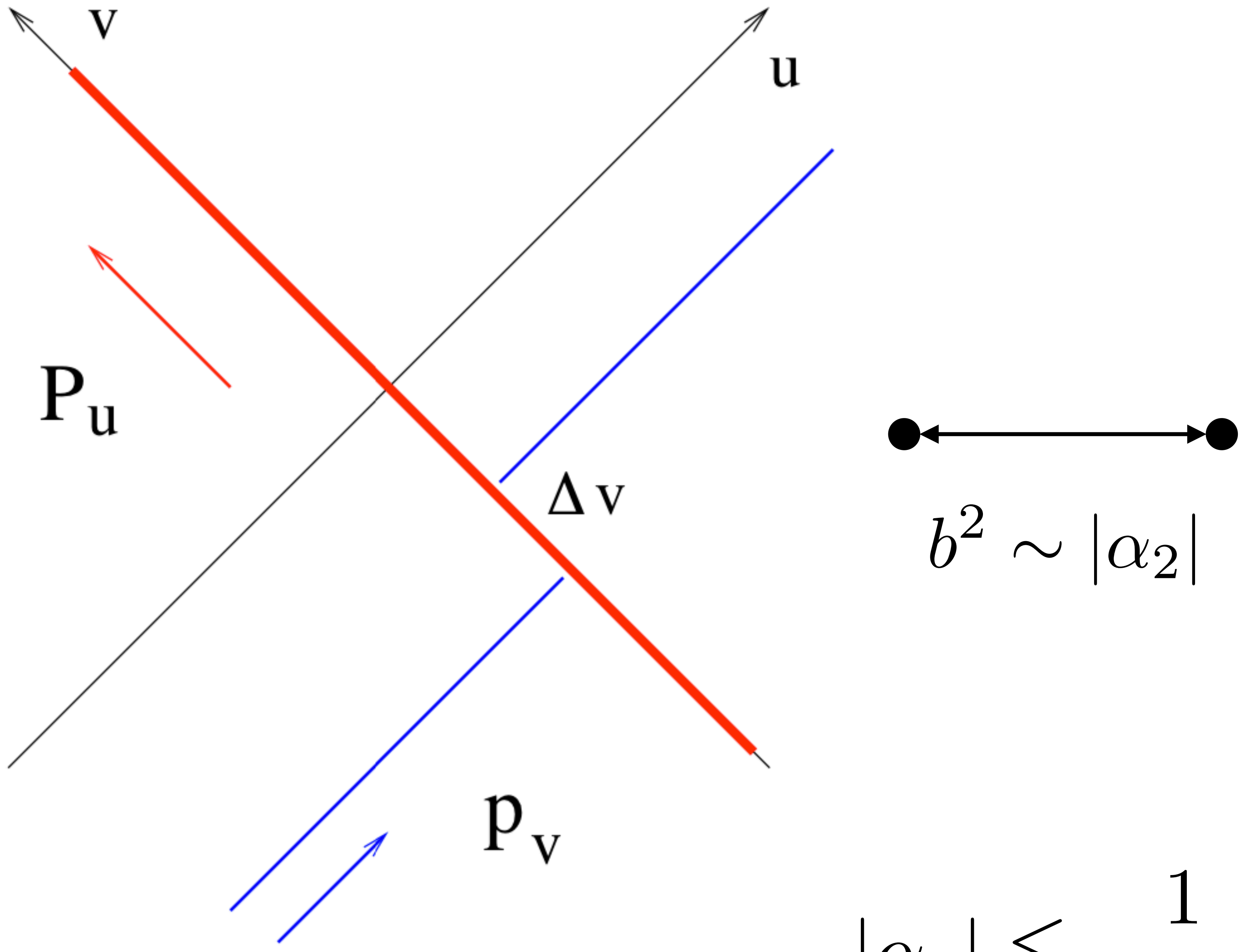
stringy equivalence principle



Corrections to general relativity and causality

By performing more sophisticated versions of this experiment one can systematically derive bounds on the corrections to general relativity

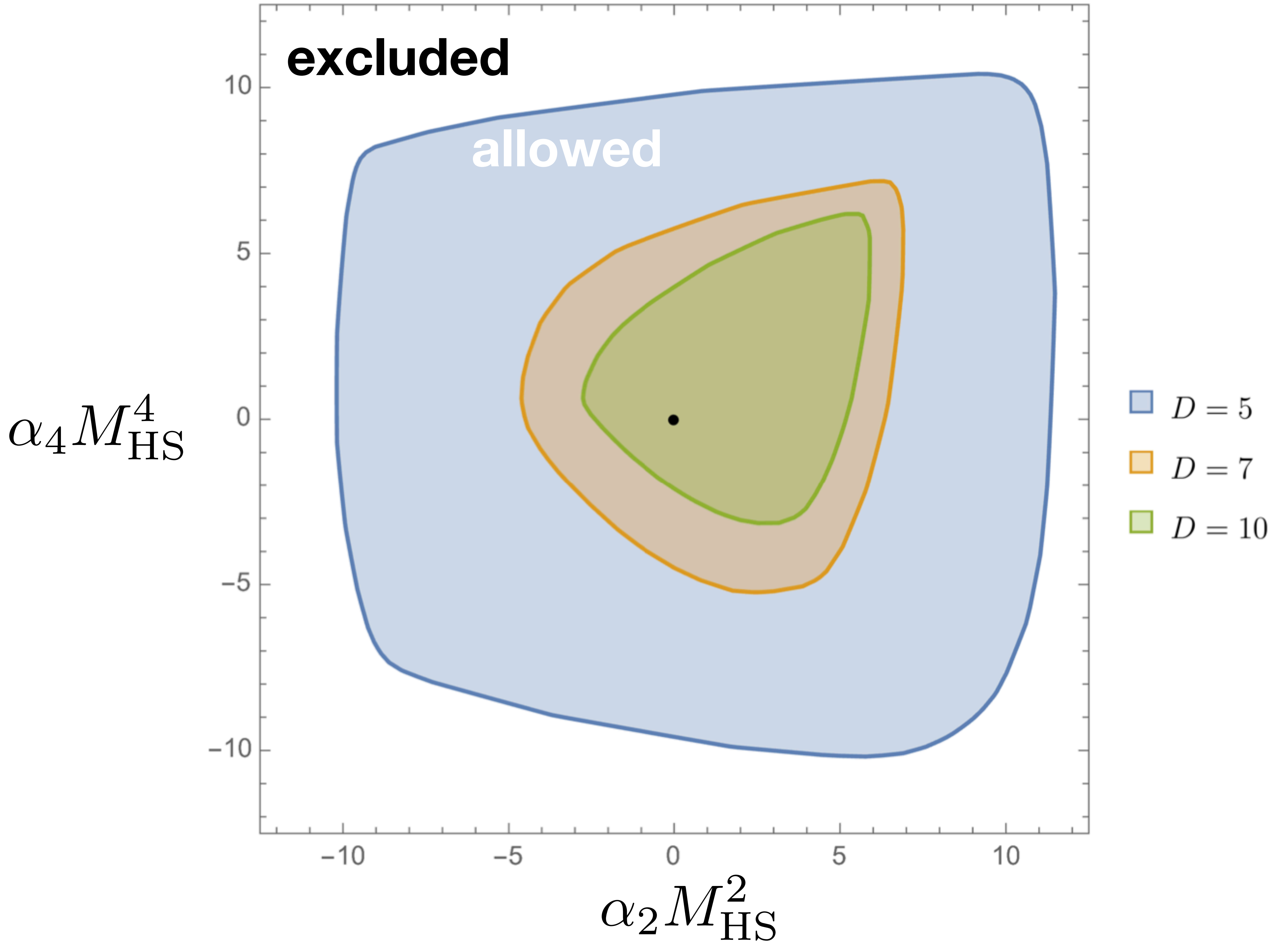
$$S = \int \frac{d^D x \sqrt{-g}}{16\pi G}\left(R + \frac{\alpha_2}{4} C^2 + \frac{\alpha_4}{12} C^3 + \frac{\alpha_4'}{6} C'^3 + \dots\right)$$



$b^2 \sim |\alpha_2|$

$$|\alpha_2| \lesssim \frac{1}{M_{HS}^2}$$

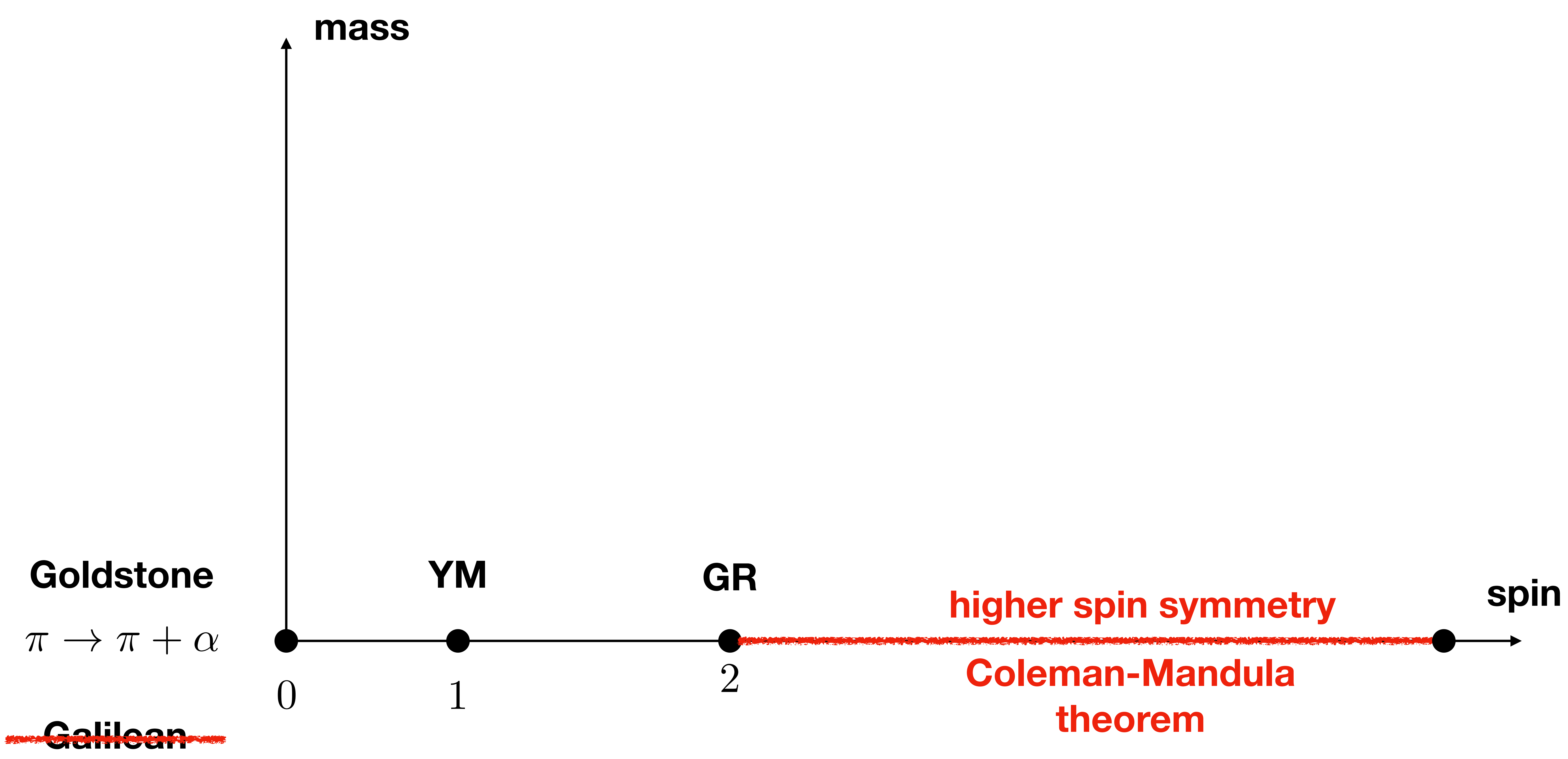
[Camanho, Edelstein, Maldacena, AZ '14]



[Caron-Huot, Li, Parra-Martinez, Simmons-Duffin '22]

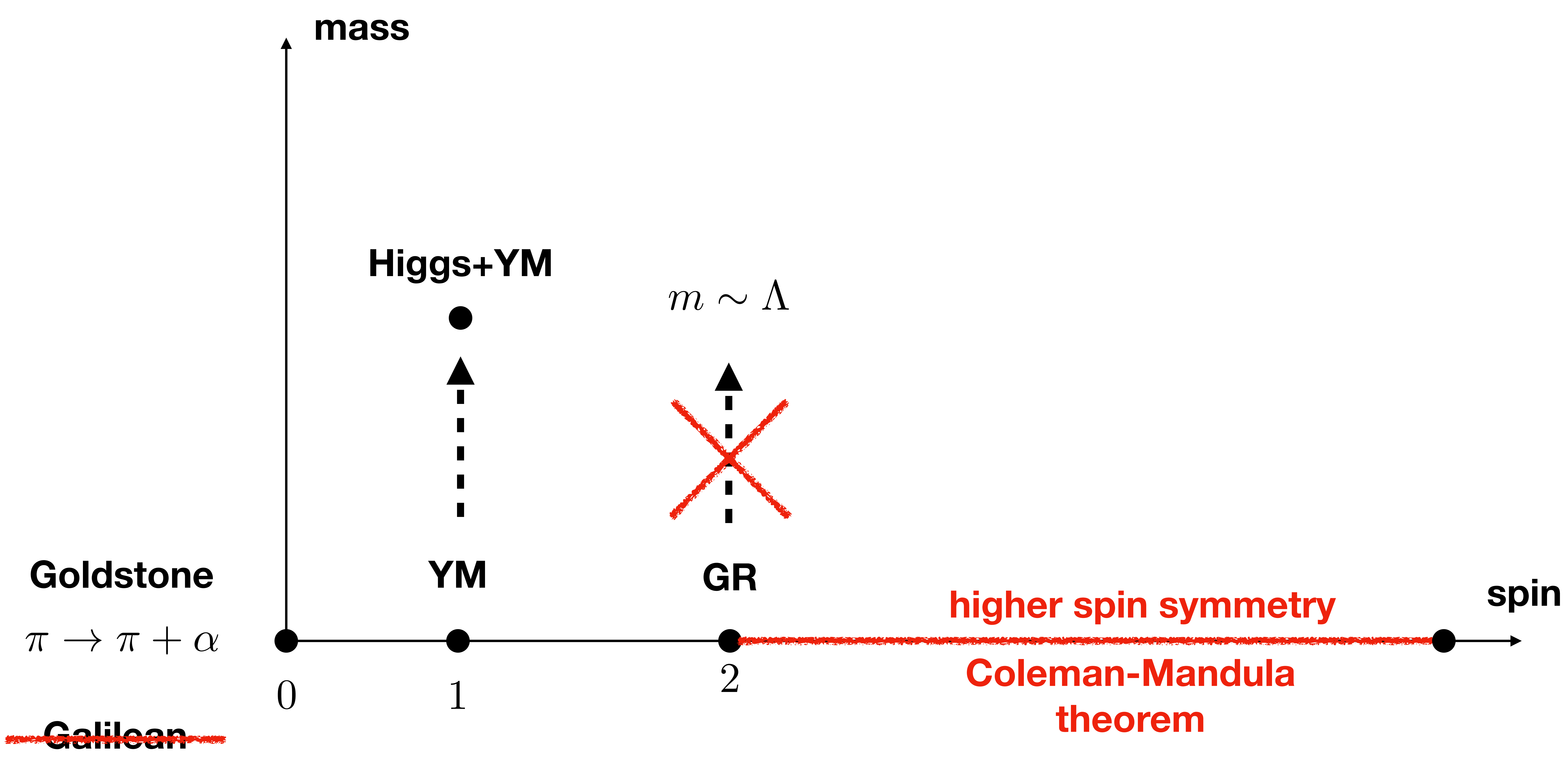
Higher-spin states = budget for higher derivatives

Particle theories at weak coupling + $\Lambda \gg m$



[Bellazzini,Elias-Miro,Rattazzi,Riembau,Riva ’20]

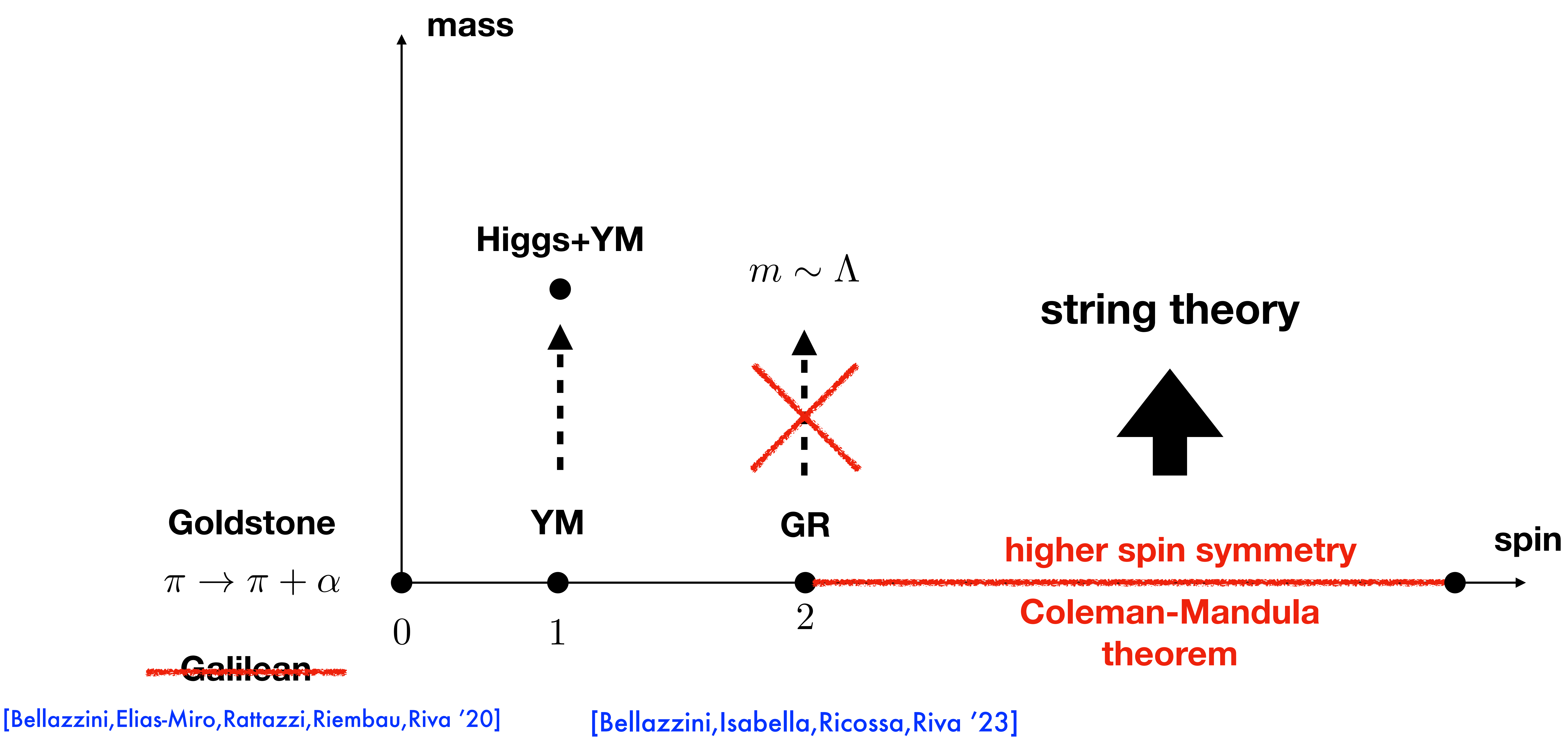
Particle theories at weak coupling + $\Lambda \gg m$



[Bellazzini,Elias-Miro,Rattazzi,Riembau,Riva '20]

[Bellazzini,Isabella,Ricossa,Riva '23]

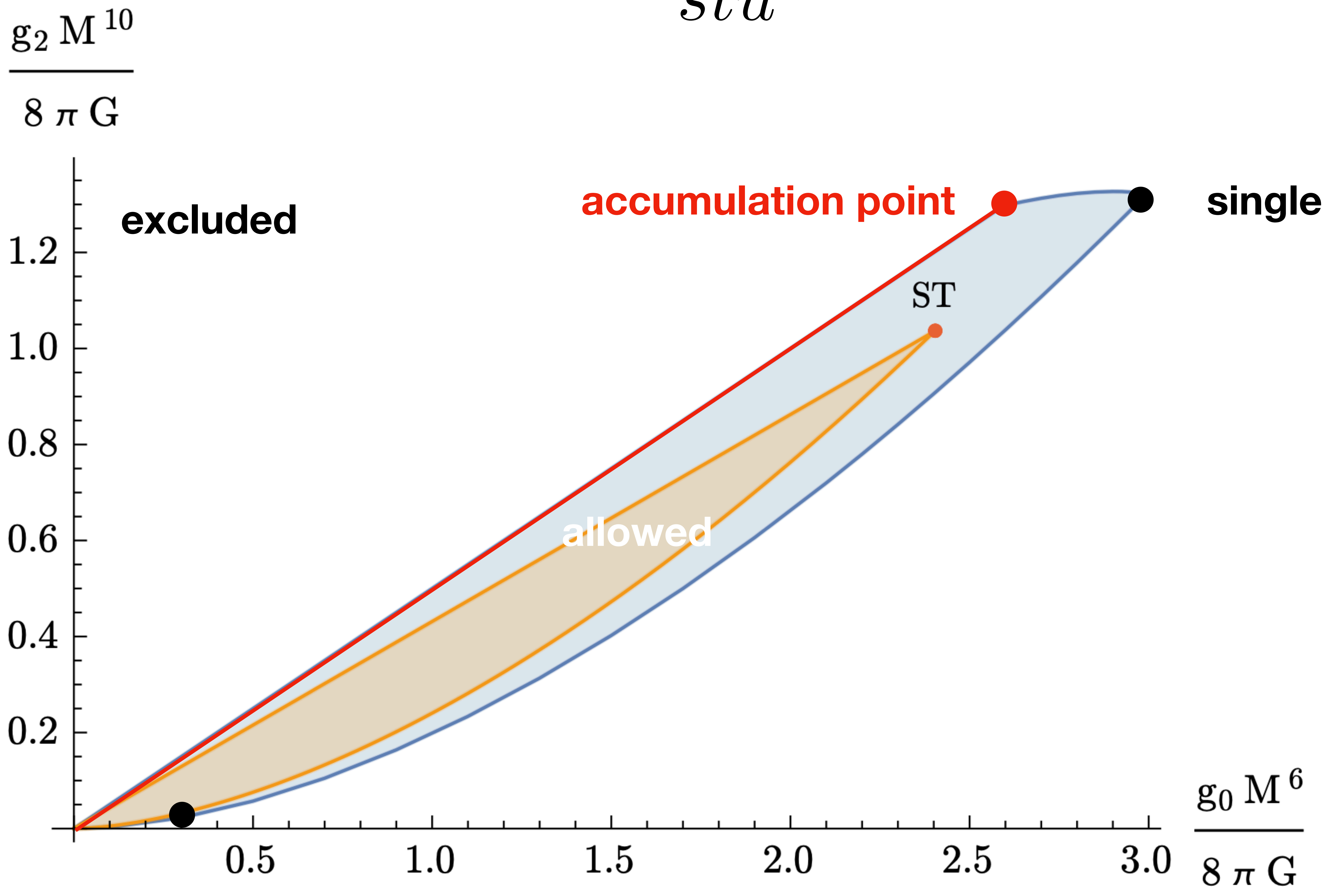
Particle theories at weak coupling + $\Lambda \gg m$

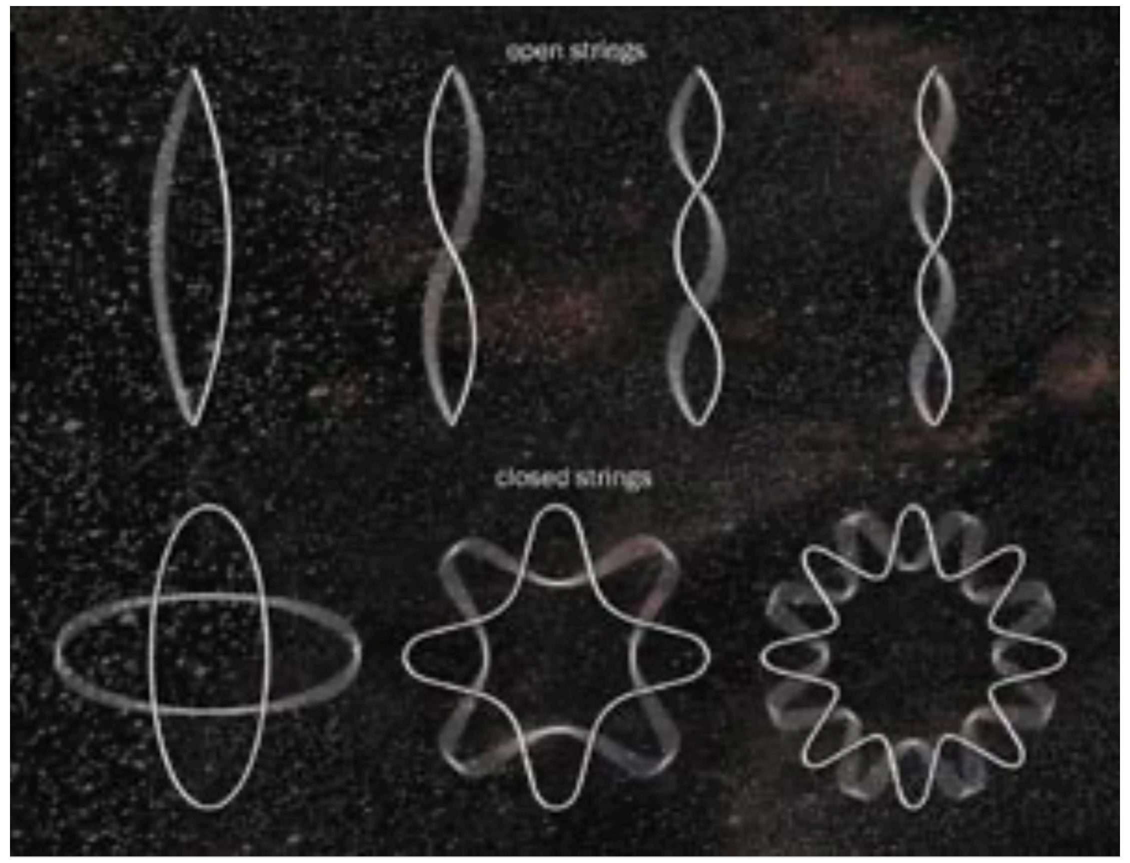


Conjecture: String theory is the **only** way to make higher spin particles massive (s>2) at weak coupling, as the Higgs mechanism is for spin one (s=1) particles.

Is string theory a unique theory of massive HS particles?

$$T(s,t) = \frac{8\pi G_N}{stu} + g_0 + g_2(s^2 + t^2 + u^2) + \dots$$





[Albert, Knop, Rastelli '24]
[Berman, Elvang, Geiser, Lin '24]

There are many threads in the high-energy theory tapestry

[(OpenAI's ChatGPT/DALL·E, 2025)]

Theme 1: Causality, quantum mechanics and Lorentz invariance are powerful principles to chart the space of consistent theories.

[ANEC, dispersion relations, S-matrix/conformal bootstrap]

[nonperturbative approach to 4d gravity; M-theory]

Theme 2: New structures/methods/patterns are being discovered in QFT&QG.

[generalized symmetries, large charge expansion, integrability, localization, swampland program]

[high-energy soft QCD and diffraction; high-energy scattering in gravity]

Theme 3: There is a deep connection between quantum mechanics and quantum gravity (black holes as quantum systems).

[holography, gravitational path integral, operator algebras]

[quantum gravity in dS and inflation]

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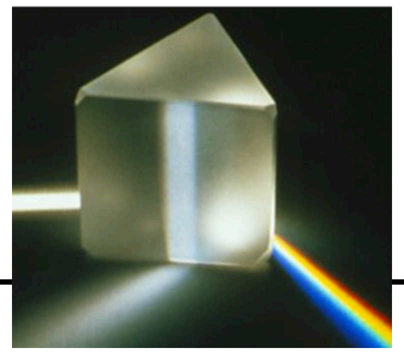
Thank you!

1926-1927



Kronig
Kramers

UV gravity

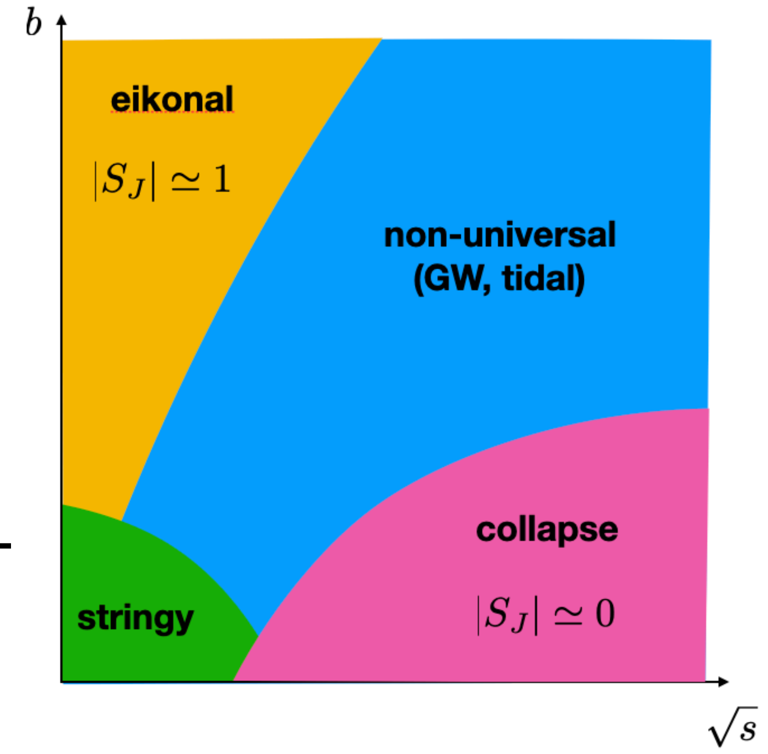
1972

Auberson
Khuri

1987

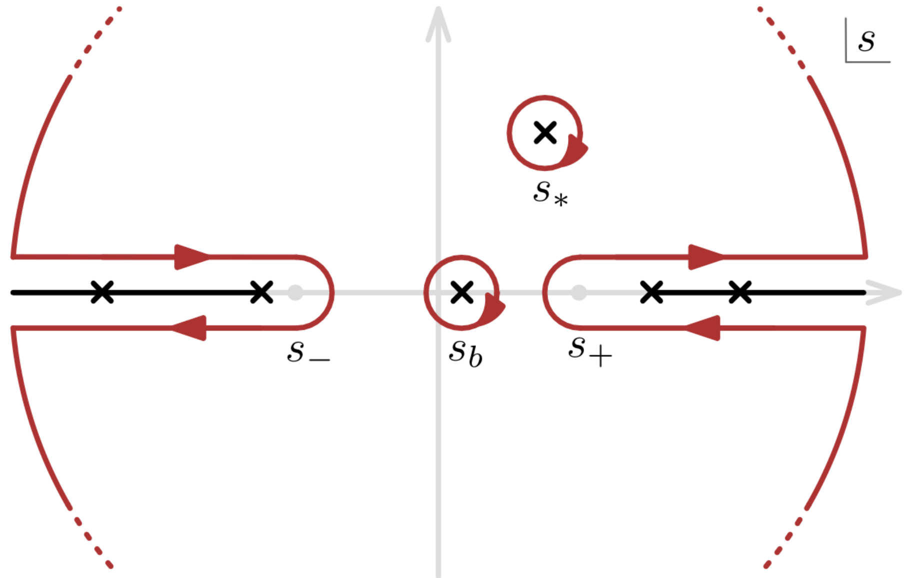
Gross
Mende
't Hooft

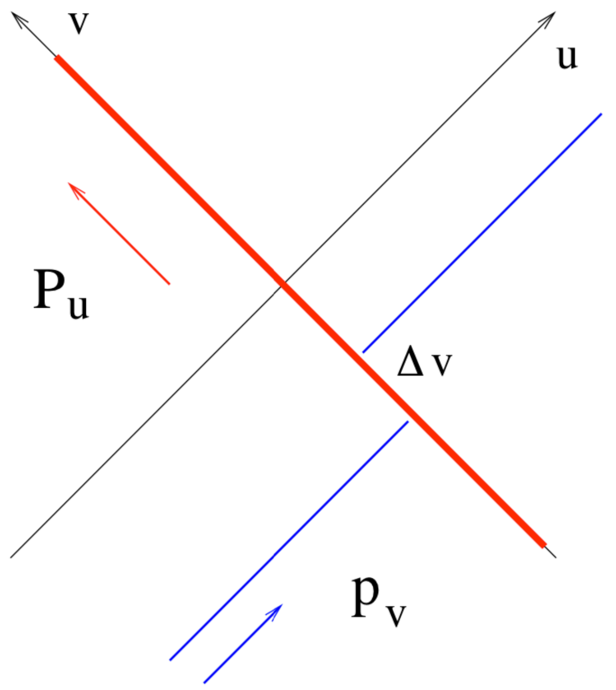
Amati
Ciafaloni
Veneziano



IR

$t = 0$	$t \neq 0$
1954	1956
Gell-Mann Goldberger Thirring	Bogolyubov
2006	2014
Adams et al.	CEMZ
$(\partial\phi)^4$	$\alpha_3(\mathrm{Riem})^3$





2019 — super convergence; AdS DR

2020 — crossing (two-sided b); higher moments

2021 — graviton pole

2022 — four gravitons where is M-theory?; WGC

stringy amplitudes &correlators

where is tree-level string theory?

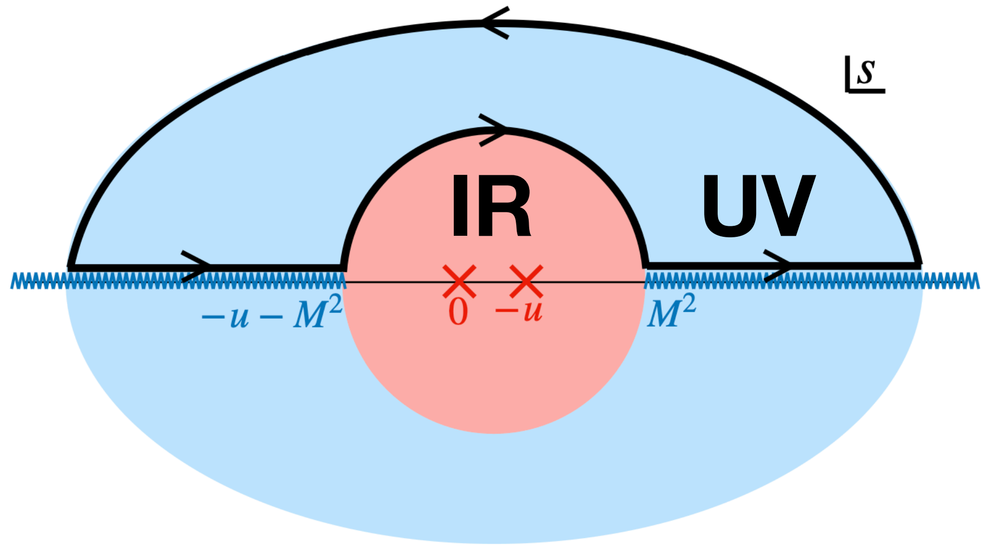
crossing-symmetric disp. rel

loops

species bound/scale

Regge physics

2025 — …



gravitational dispersion relations: IR+UV=0

What is the simplest theory-friendly IR safe quantity in 4d?

$$d\sigma_{\vec{p}_1,\vec{p}_2 \to x+X}$$

- the initial state has an infinite norm
- soft radiation cancels against virtual corrections
- collinear radiation is regular

[Weinberg]
[Akhoury,Saotome,Sterman]

We can then further get rid of of the energies of the final particles by measuring energy fluxes. The simplest thing to try is

$$\langle \vec{p}, -\vec{p} | \mathcal{E}(\vec{n}_1) ... \mathcal{E}(\vec{n}_k) | \vec{p}, -\vec{p} \rangle \overset{?}{<} \infty$$

away from the beam. **[LO manifestly IR finite]**

[Herrmann,Kologlu,Moult '24]
[Kologlu,Parra-Martinez, wip]

For example, we can try to constrain the M-theory S-matrix

$$S = \frac{1}{16\pi G_N}\int d^D x\sqrt{-g}\Big(R + \alpha \ell_{Pl}^6\ t_8 t_8 R^4 + \dots\Big)$$

$$\frac{T(s,t,u)}{8\pi G_N} = s^4\left(\frac{1}{stu} + \alpha\,\ell_P^6 + \dots\right)$$

$$\alpha \ell_P^6 = \frac{2}{\pi}\int_0^\infty \frac{ds}{s^5} T_s(s,0)$$

$$\frac{T(s,t,u)}{8\pi G_N} = s^4\Big(\underbrace{\frac{1}{stu}}_{\texttt{SUGRA}} + \underbrace{\prod_{A=s,t,u}(\rho_A+1)^2 \sideset{}{'}\sum_{a+b+c\le N}\alpha_{(abc)}\rho_s^a\rho_t^b\rho_u^c}_{\texttt{UV completion}}\Big)$$

[Paulos, Penedones, van Rees, Vieira '17]

$$\alpha = \frac{(2\pi)^2}{3\ 2^7} \simeq 0.1028\,.$$

$$\alpha^{\mathrm{IIB}} = \frac{1}{2^6}E_{\frac{3}{2}}(\tau,\bar\tau) \geq \frac{1}{2^6}E_{\frac{3}{2}}(e^{i\pi/3}, e^{-i\pi/3}) \approx 0.1389$$

$$\alpha^{\mathrm{IIA}} = \frac{\zeta(3)}{32 g_s^{3/2}} + g_s^{1/2}\frac{\pi^2}{96} \geq \frac{\pi^{3/2}(\zeta(3))^{1/4}}{24\sqrt{3}} \approx 0.1403$$

Dimension	Bootstrap	String/M–Theory
9	0.223 ± 0.002	0.241752
10	0.124 ± 0.003	0.138949
11	0.101 ± 0.005	0.102808

[Guerrieri, Murali, Penedones, Vieira '22]