Hydrodynamic response on the celestial sphere

New Opportunities in Particle and Nuclear Physics with Energy Correlators

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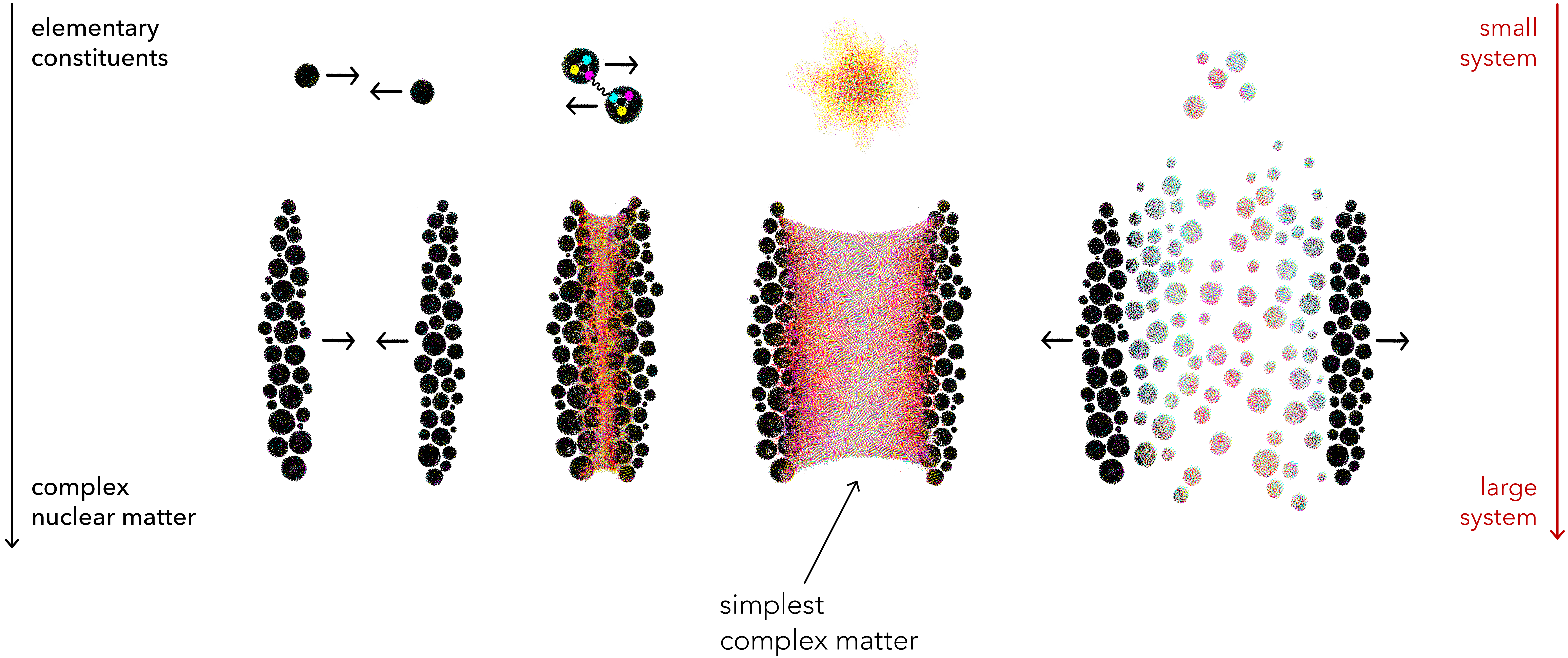
LIP, Lisbon

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

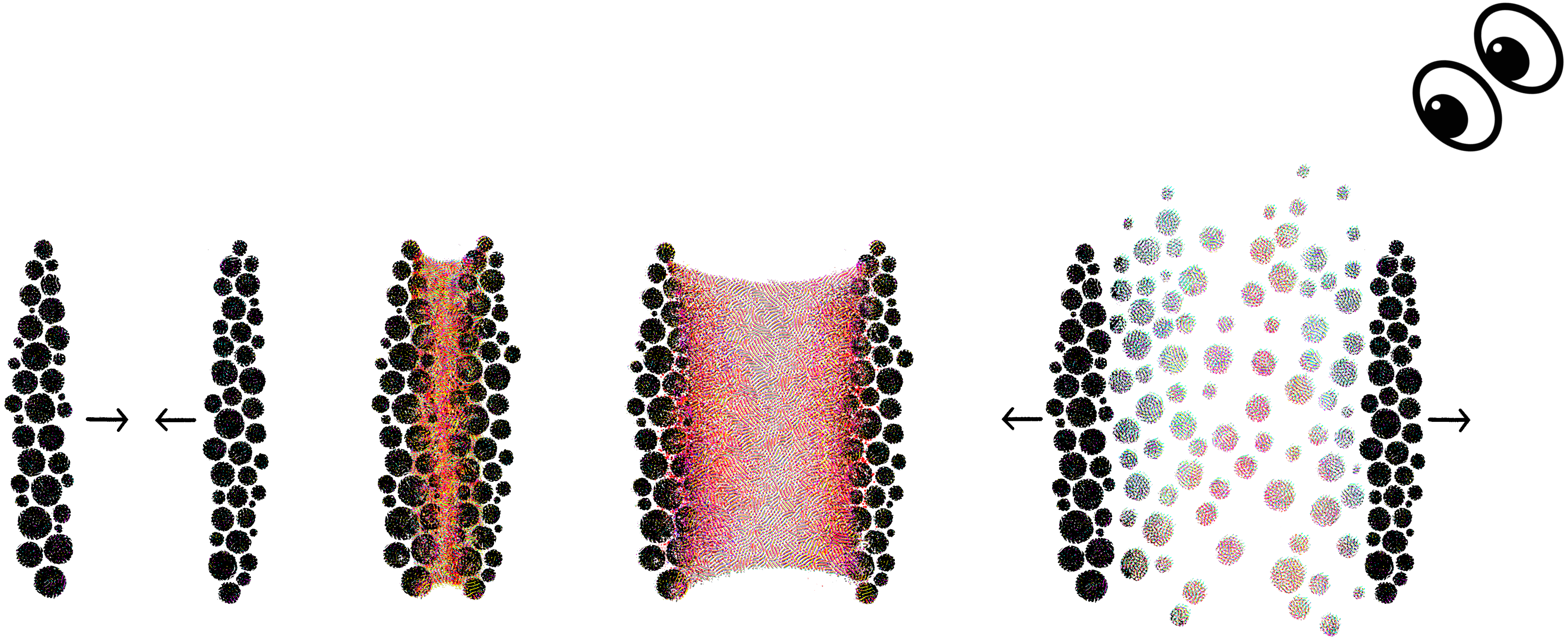
The origin of complex matter



Some motivation

- Learning about QCD in Early Universe ("Big Bang" matter)
- Probing QCD phase diagram (extreme conditions)
- Understanding matter formation (and its evolution)
- Probing nuclear structure (probing partons)
- …
- Add your favorite option here

Probes of matter in HIC



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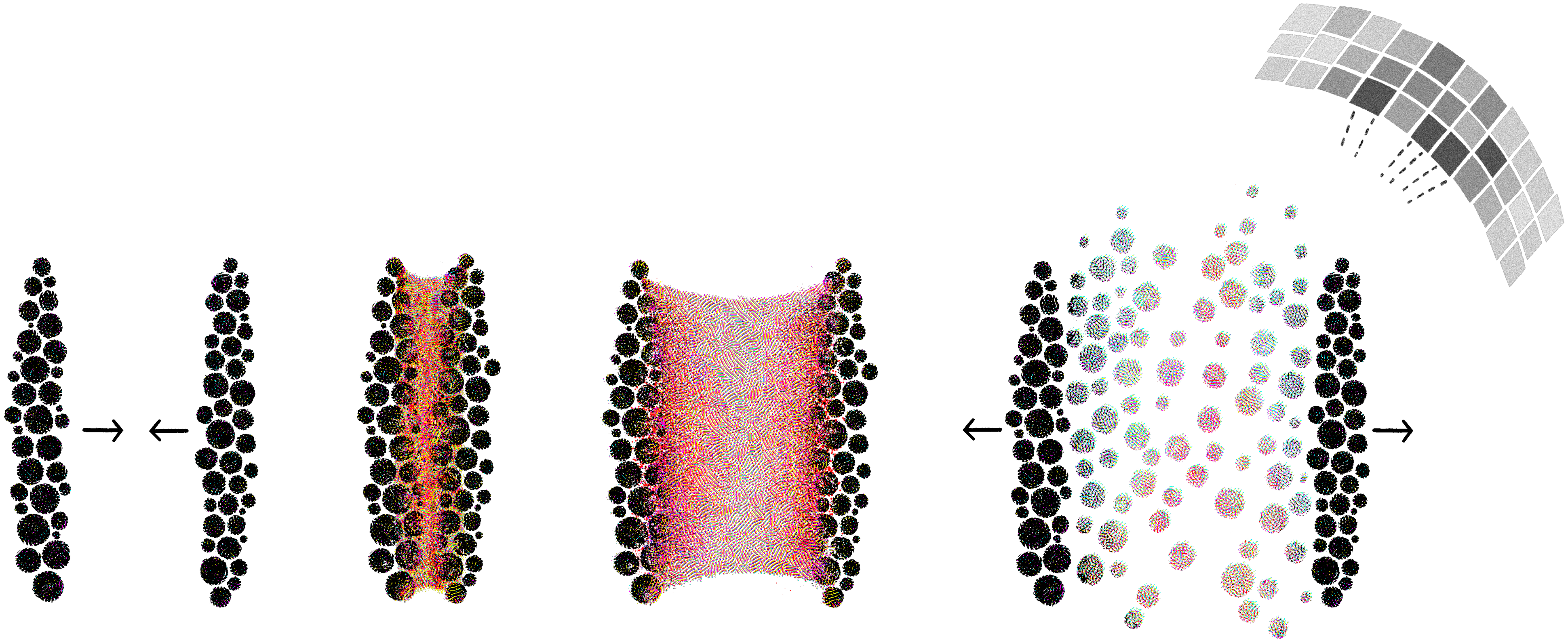

Probes of matter in HIC

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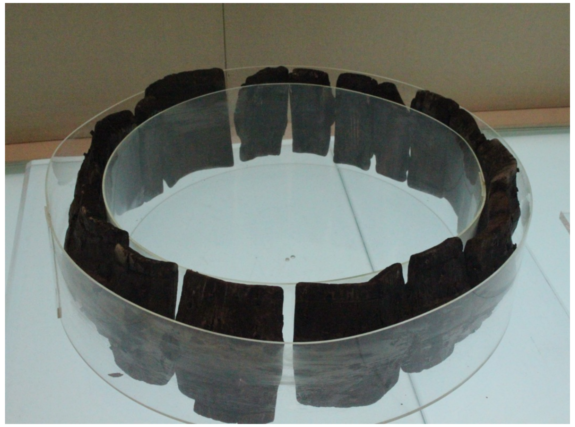
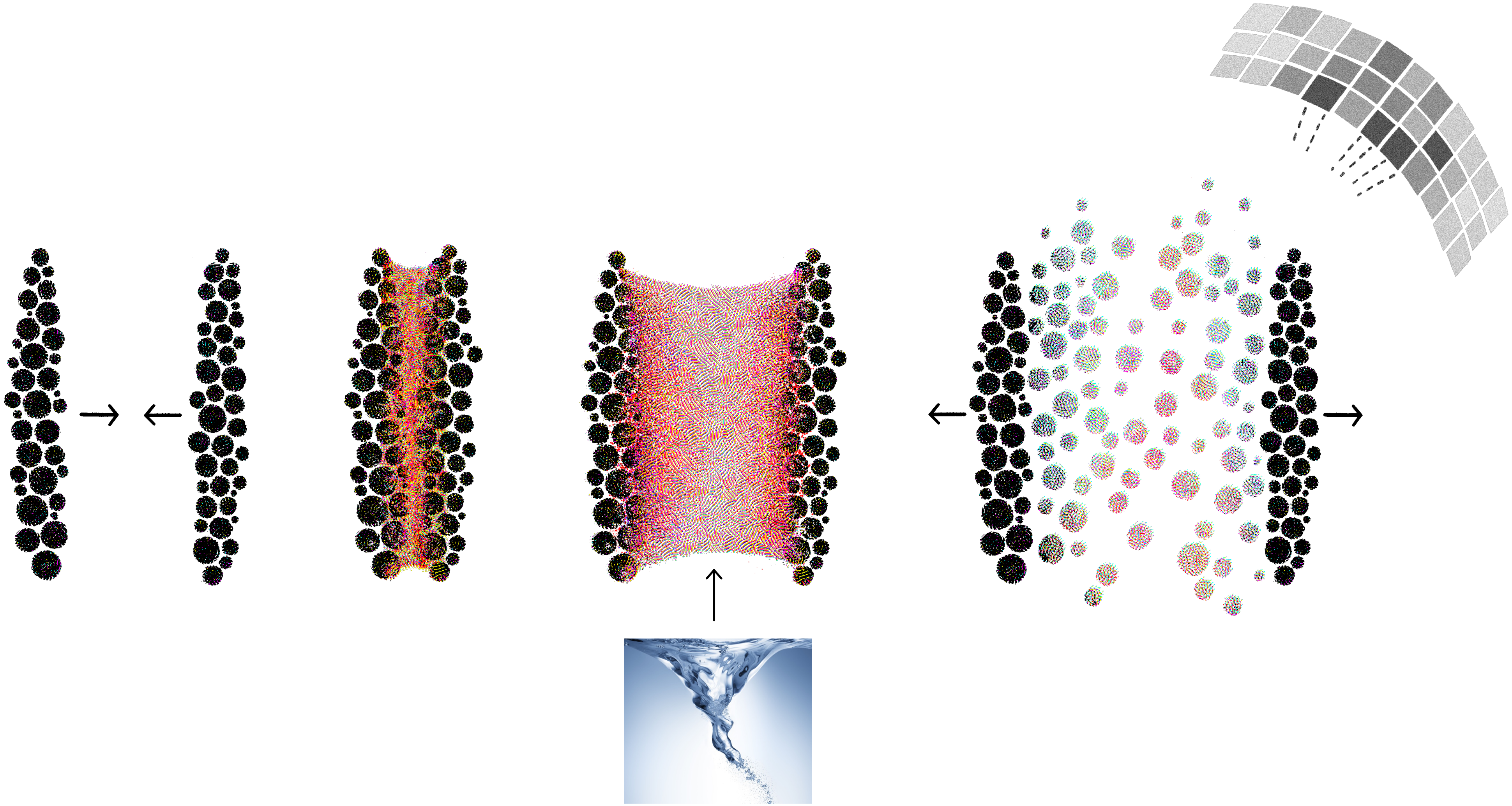


Probes of matter in HIC



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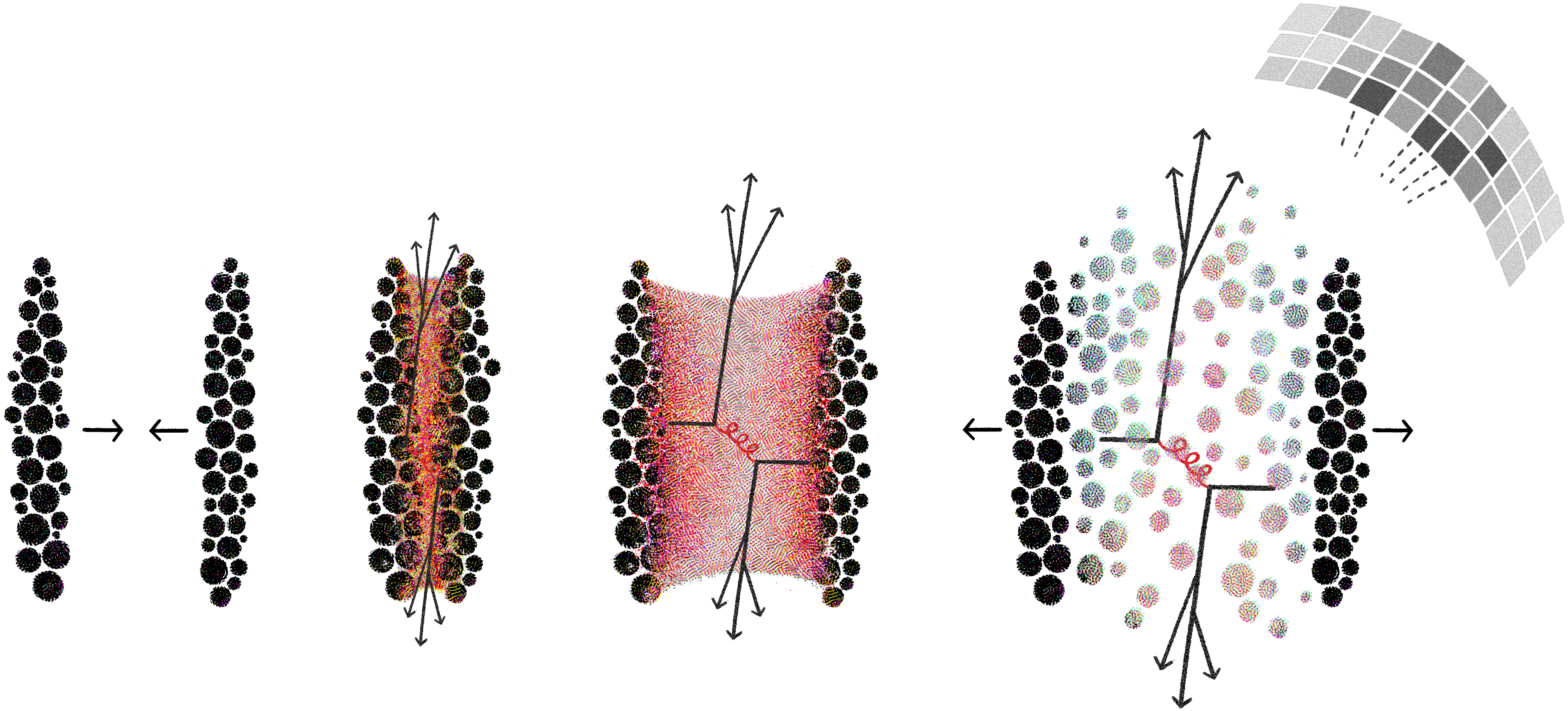
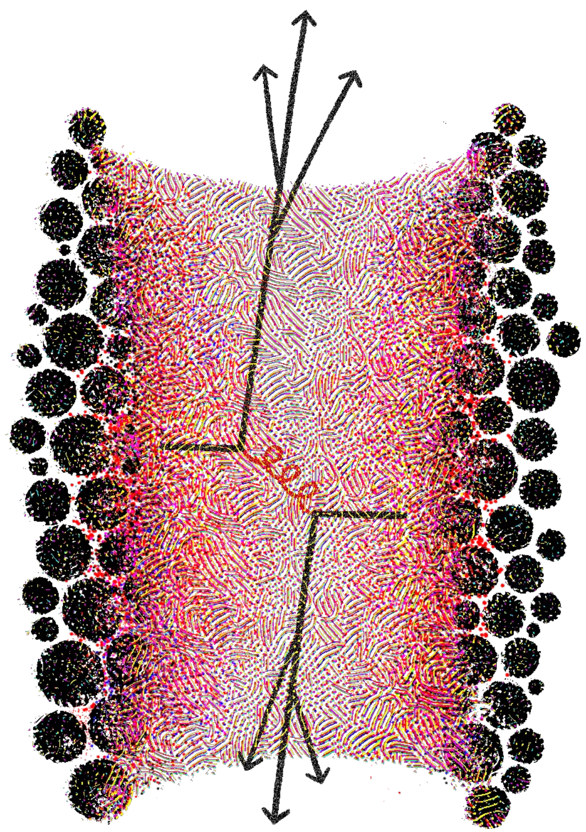


Jet quenching



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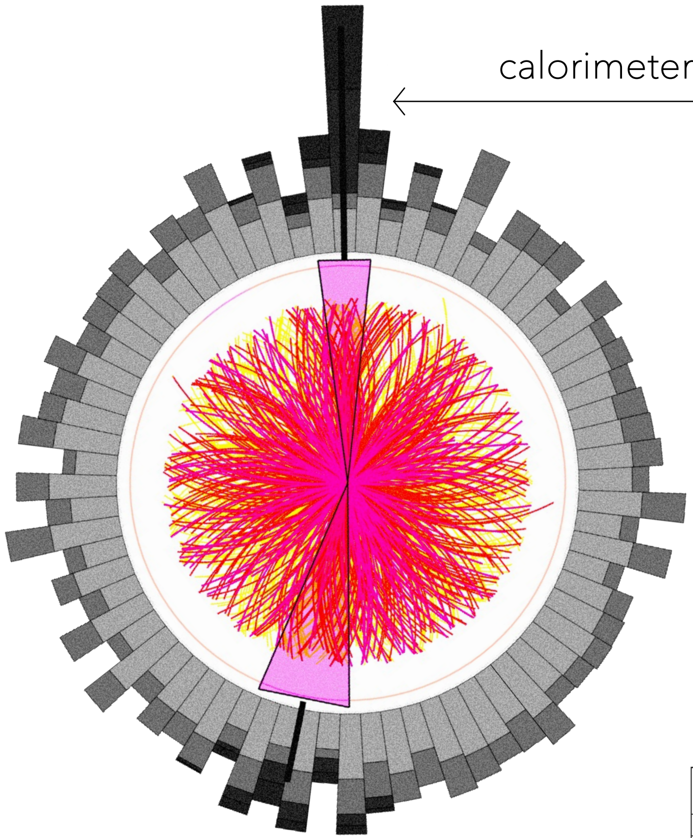
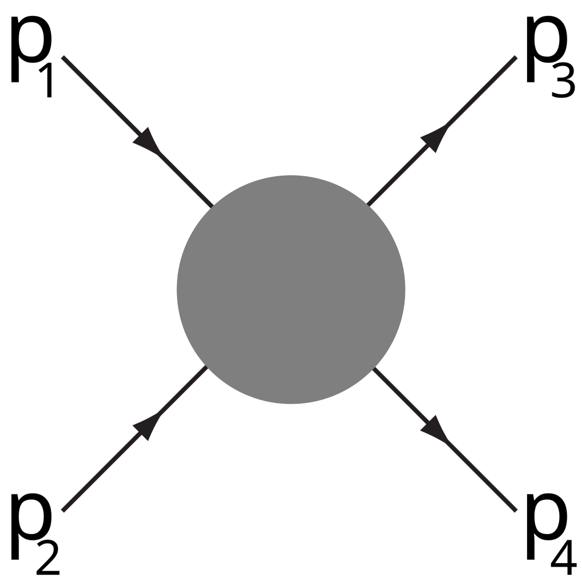


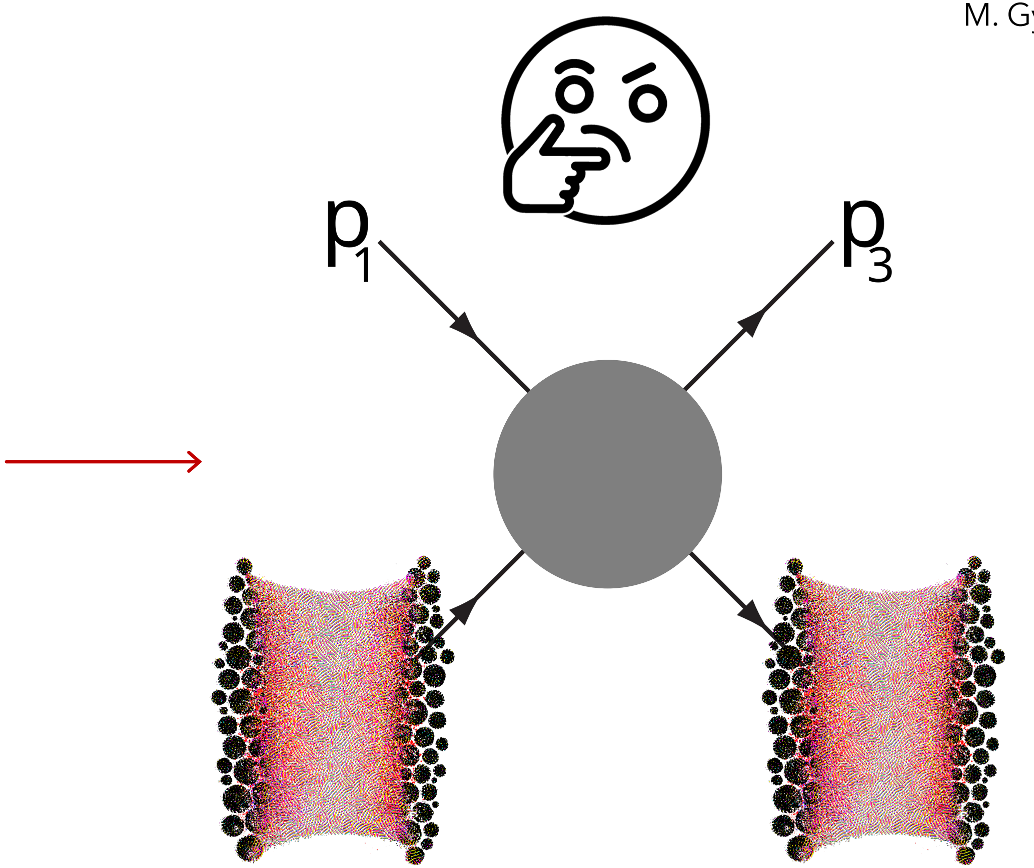
CMS

jets lose energy as they propagate through nuclear matter

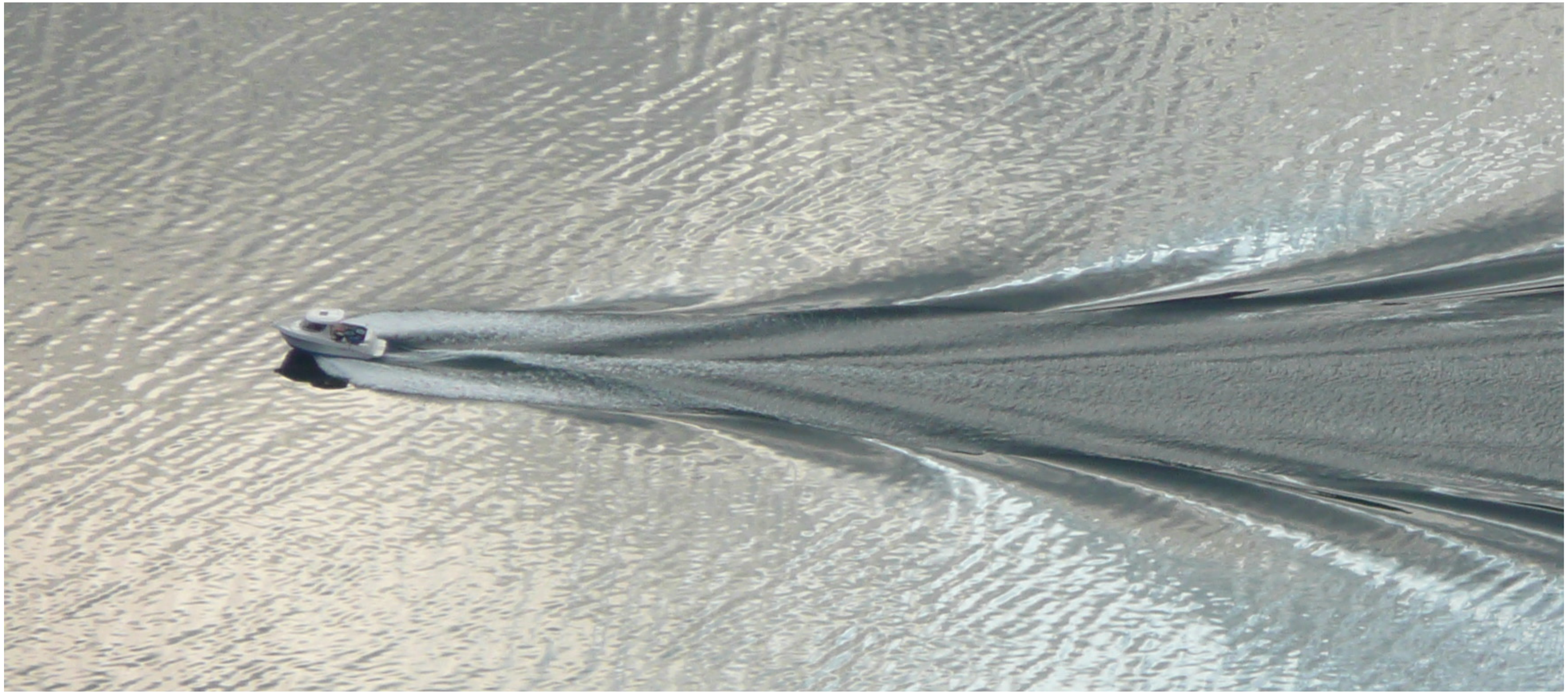
M. Gyulassy , X.-N. Wang, NPB, 1994
R. Baier et al, NPB, 1997
B. G. Zakharov, JETP, 1997
R. Baier et al, NPB, 1998
M. Gyulassy et al, NPB, 2000
X.-F. Guo, X.-N. Wang, PRL, 2000
M. Gyulassy et al, NPB, 2001
AMY, JHEP, 2002

Jet quenching



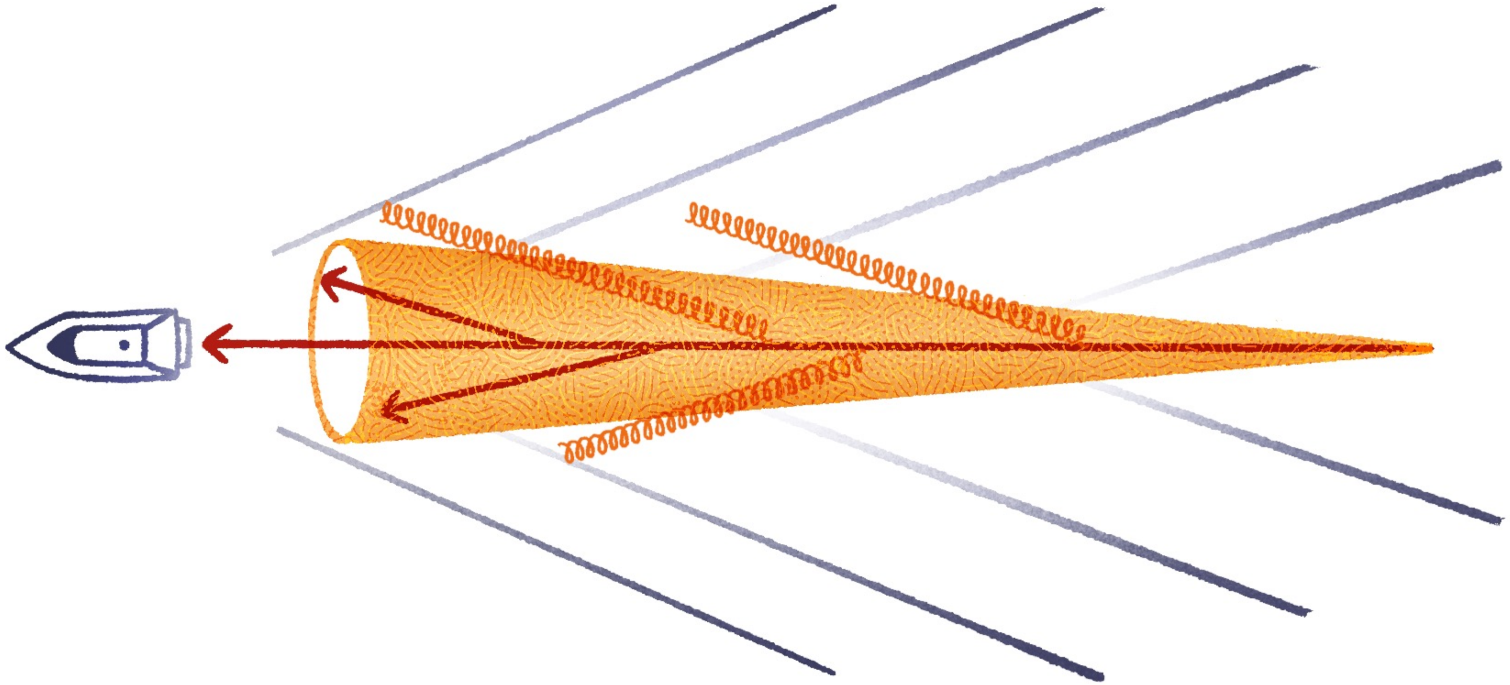


Medium response



J. Casalderrey-Solana et al, 2004
L.M. Satarov et al, PLB, 2005
J. Ruppert et al, PLB. 2005
A. K. Chaudhuri et al, PRL, 2006
J. Casalderrey-Solana et al, 2006
R Neufeld et al, PRL, 2009
G.-Y. Qin, PRL, 2009

Medium response



Probes of matter in HIC

- Matter modifies the probes
- Matter responses to the probes and mixes with them
- We generally need a better description
- We generally need a better way to look into that system

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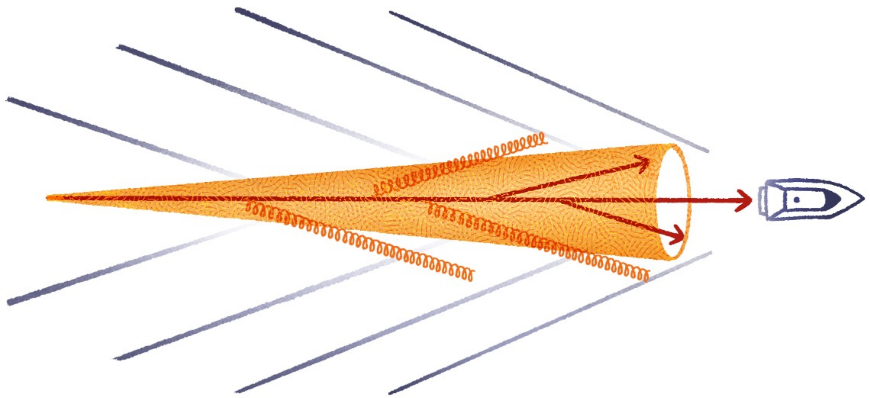
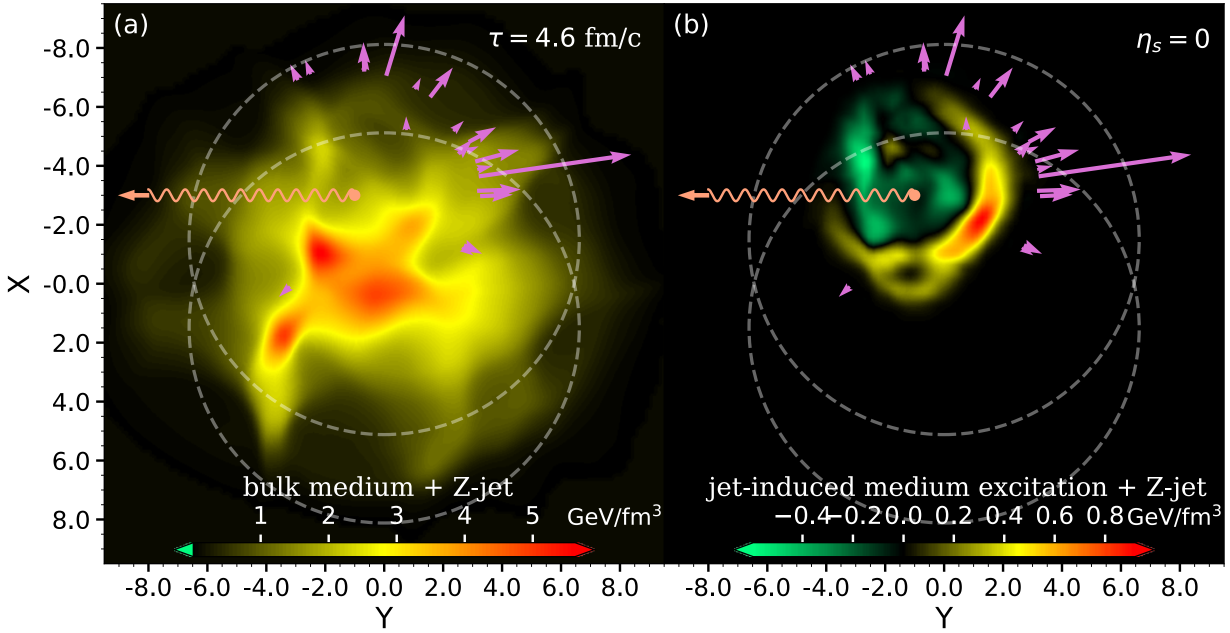
Y. He, T. Luo, X.-N. Wang, Y. Zhu, PRC, 2015
Y. Tachibana, N.-B. Chang, G.-Y. Qin, PRC, 2017
J. Casalderrey-Solana et al, JHEP, 2021
W. Chen, Z. Yang, Y. He, W. Ke, L. Pang, X.-N. Wang, PRL, 2021
Z. Yang, T. Luo, W. Chen, L.-G. Pang, X.-N. Wang, PRL, 2023

Probing the response

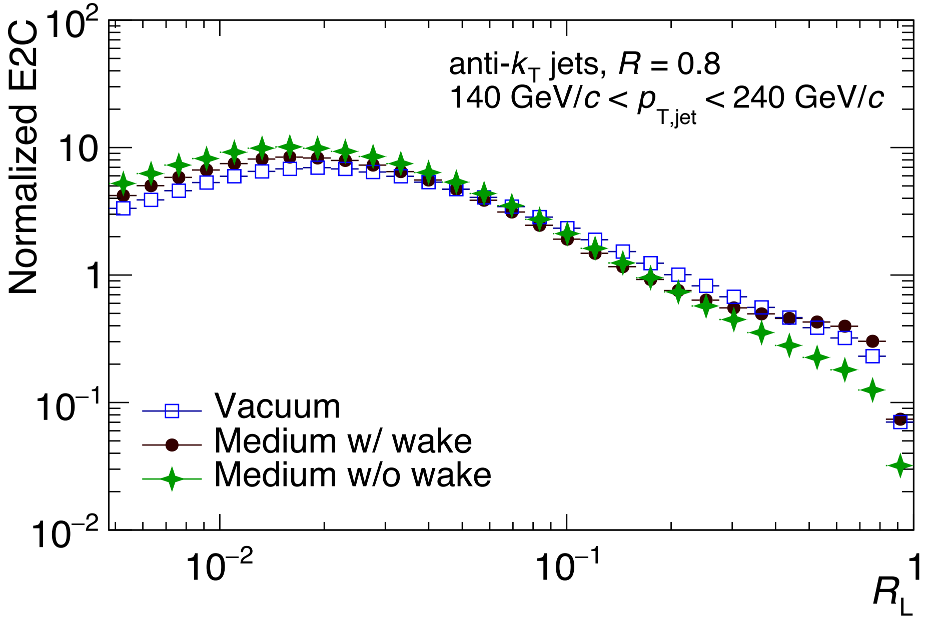


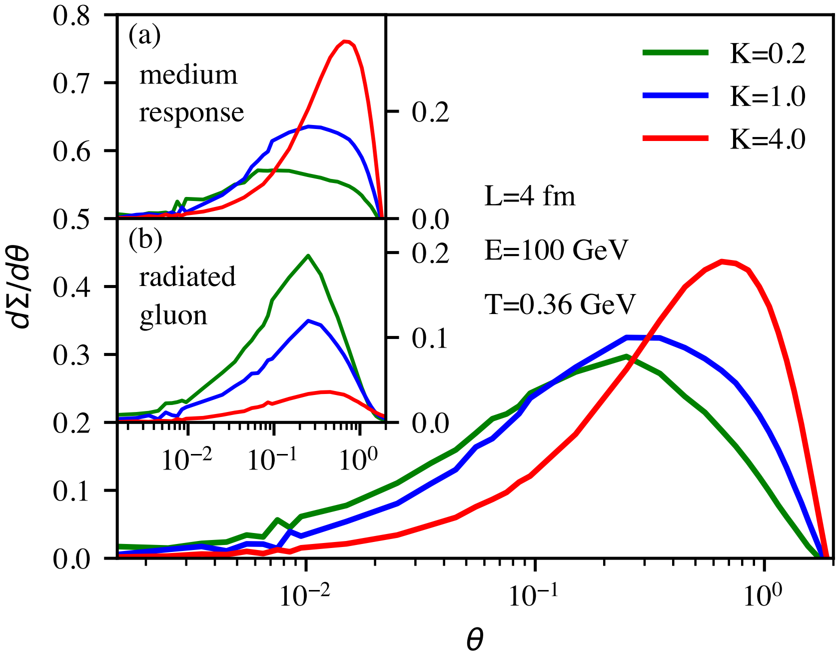


- Renewed interest in the medium response: recent consideration e.g. within CoLBT, JEWEL, Hybrid model
- Experimental needs, see e.g. ALICE, PRC, 2023; ATLAS, PRC, 2025; CMS, 2025

Probing the response

see also sides by Ian and Zhong

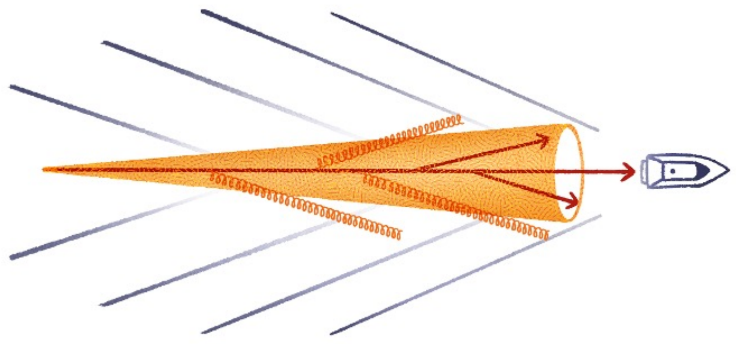


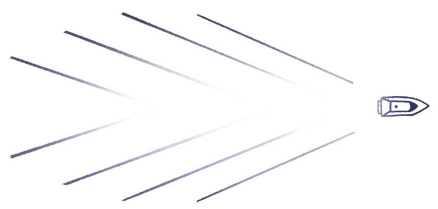


- Renewed interest in the medium response: recent consideration within CoLBT, JEWEL, and Hybrid model
- Experimental needs, see e.g. ALICE, PRC, 2023; ATLAS, PRC, 2025; CMS, 2025
- **EEC as a new way to look into the details?**

Probing the response

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



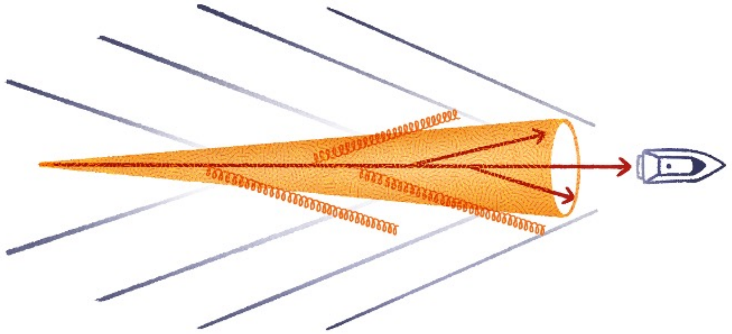


Probing the response

An illustration: static background

$$J^\mu(\mathbf{x},t) = \left(\frac{dE}{dt}, \frac{d\mathbf{p}_\perp}{dt}, \frac{dE}{dt}\right)\delta^{(2)}(\mathbf{x}_\perp)\delta(t-z)$$

$$\int_0^\infty dt\,\delta T^{0i}(t,\mathbf{k}) = -\frac{ik^i}{\mathbf{k}^2}\int_0^\infty dt\,J_0(t,\mathbf{k}) + \left(\delta^{ij} - \frac{k^i k^j}{\mathbf{k}^2}\right)\frac{1}{\Gamma_\eta \mathbf{k}^2}\int_0^\infty dt\,J^j(t,\mathbf{k})$$



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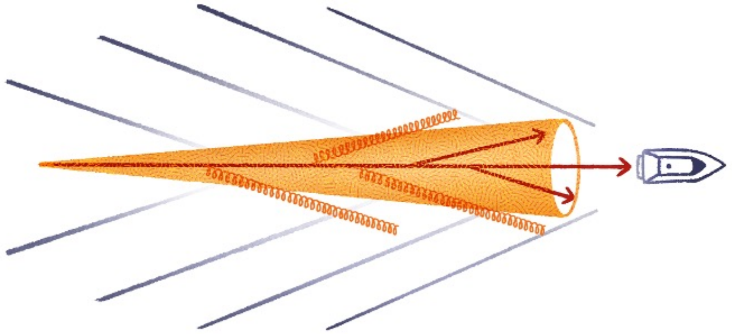

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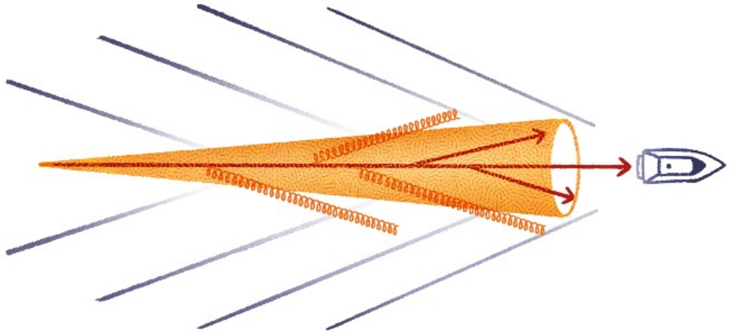
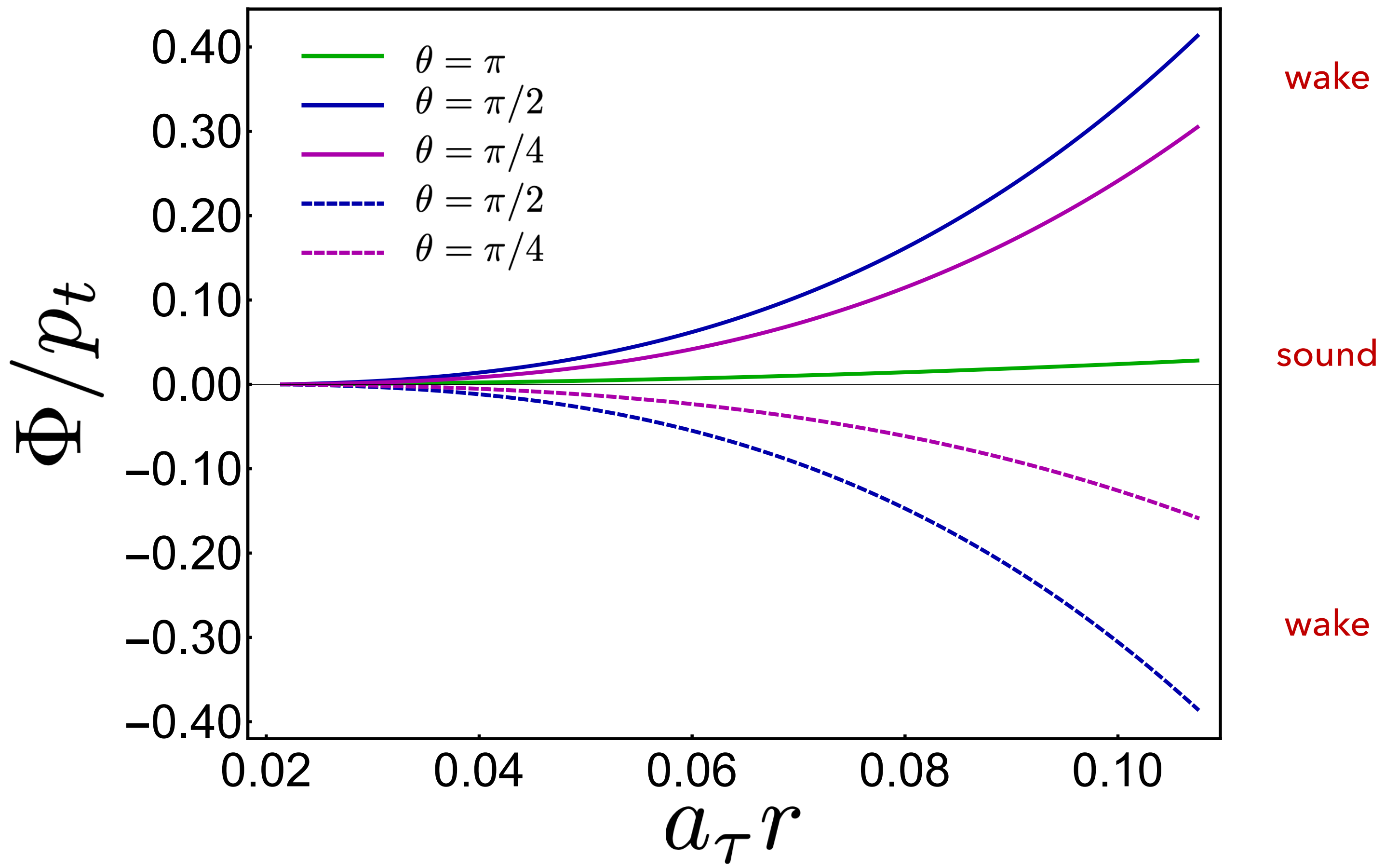


$$r^2 \int_t \int_{\mathbf{n}} n^i\, T^{0i} = \left(r\cos\psi\,\frac{1-\cos^2\theta}{4\Gamma_\eta} + \frac{1-\cos\theta}{2}\right)\int_s \frac{dE}{ds} + \mathcal{O}\left(\frac{1}{r}\right)$$

diffusive modes (wake) sound modes

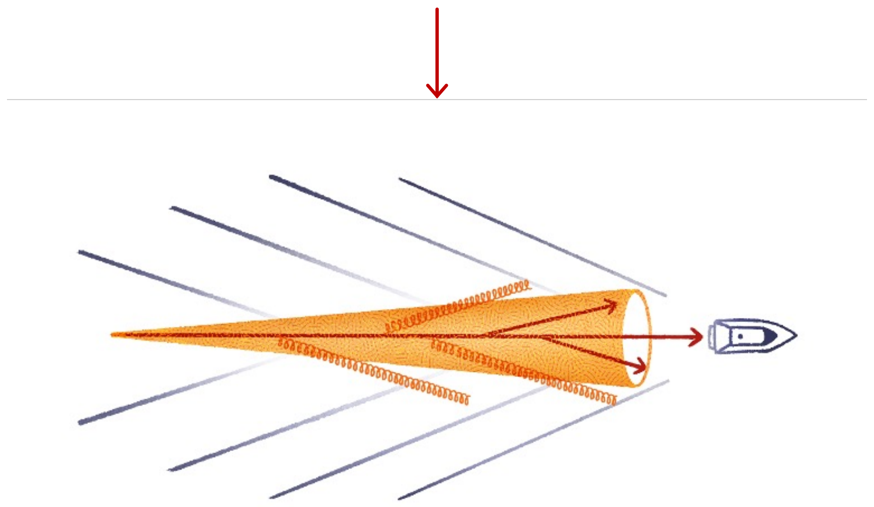
Probing the response



Probing the response

An approximate in-medium evolution of the single gluon inclusive distribution:

$$\partial_\tau D(x,\tau) = \int d\zeta\, \mathcal{K}(\zeta) \left[\sqrt{\frac{\zeta}{x}} D\left(\frac{x}{\zeta}, \tau\right) - \frac{\zeta}{\sqrt{x}} D(x,\tau) \right]$$



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↓

$$\frac{1}{p_t}\frac{dE}{dt} \equiv -\partial_t \int_{x_0}^{1} dx\, D(x,t)$$

↓

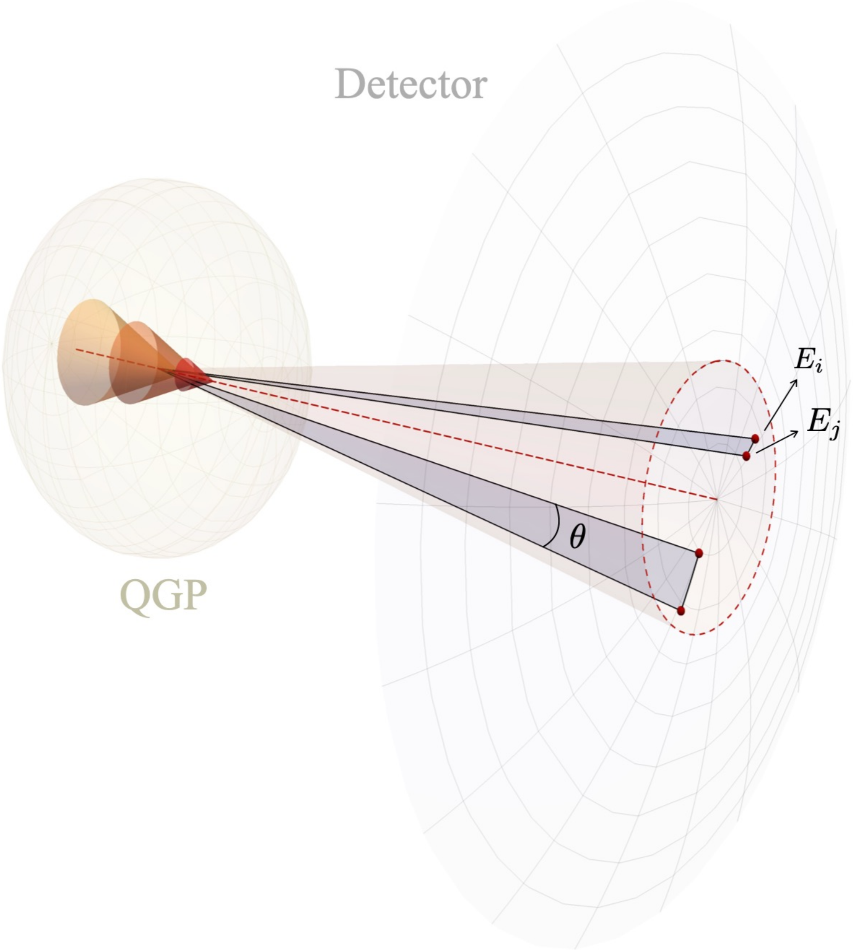
$$\frac{\pi x_0}{1-x_0}$$

$$\frac{1}{p_t}\frac{dE}{dt} = \frac{2}{a_\tau\sqrt{\pi}} e^{-(\gamma+\pi)\tau^2} \left(\sqrt{\gamma} + e^{\gamma\tau^2} \pi^{\frac{3}{2}}\, \tau\, \mathrm{erfc}(\sqrt{\gamma}\tau) \right) \Theta(t)\Theta(L-t)$$

$$(\alpha_s C_A/\pi)\sqrt{\hat{q}/p_t}$$

Probing the response

- The hydrodynamic description of a flowing medium is classical



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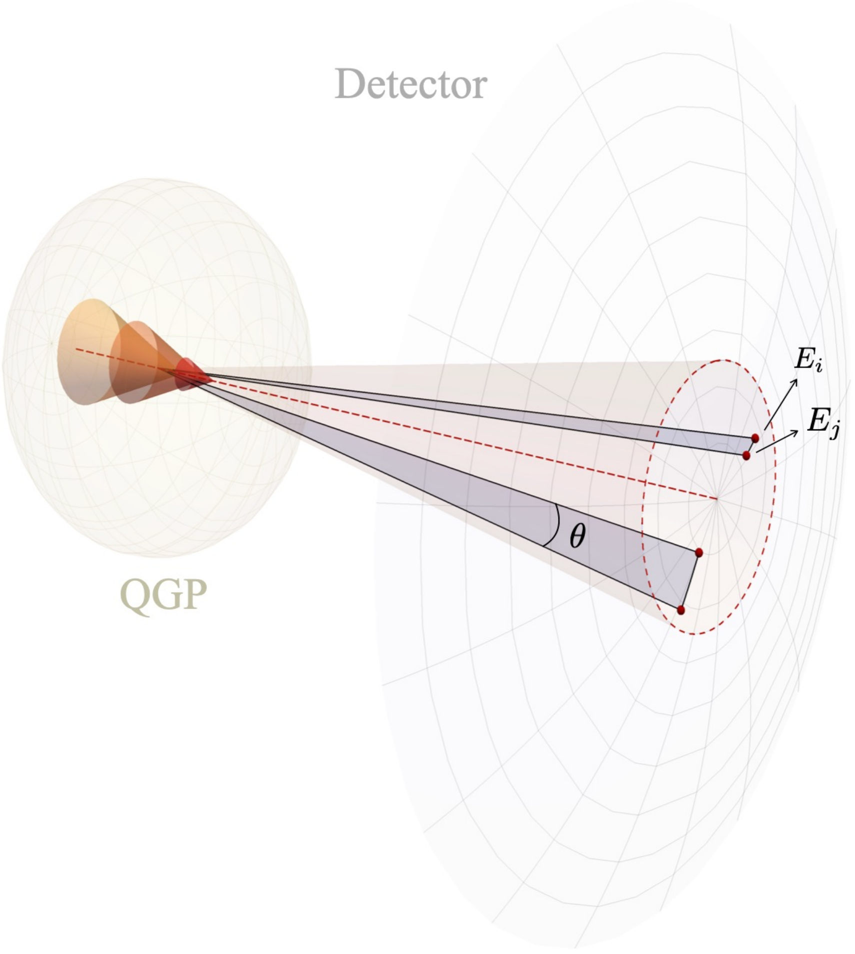

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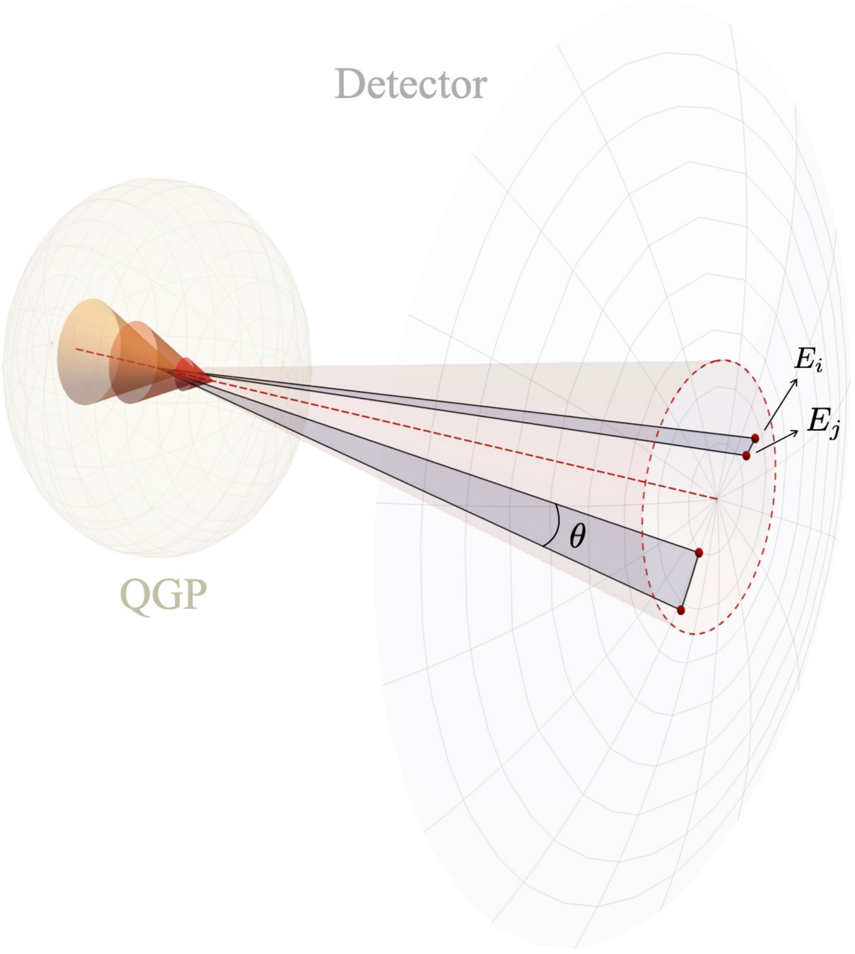
- **But what would happen if a classical flow were plugged into the ECs?**



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$$\langle \mathcal{E}(\mathbf{n}_1)\mathcal{E}(\mathbf{n}_2)\rangle$$

$$\downarrow$$

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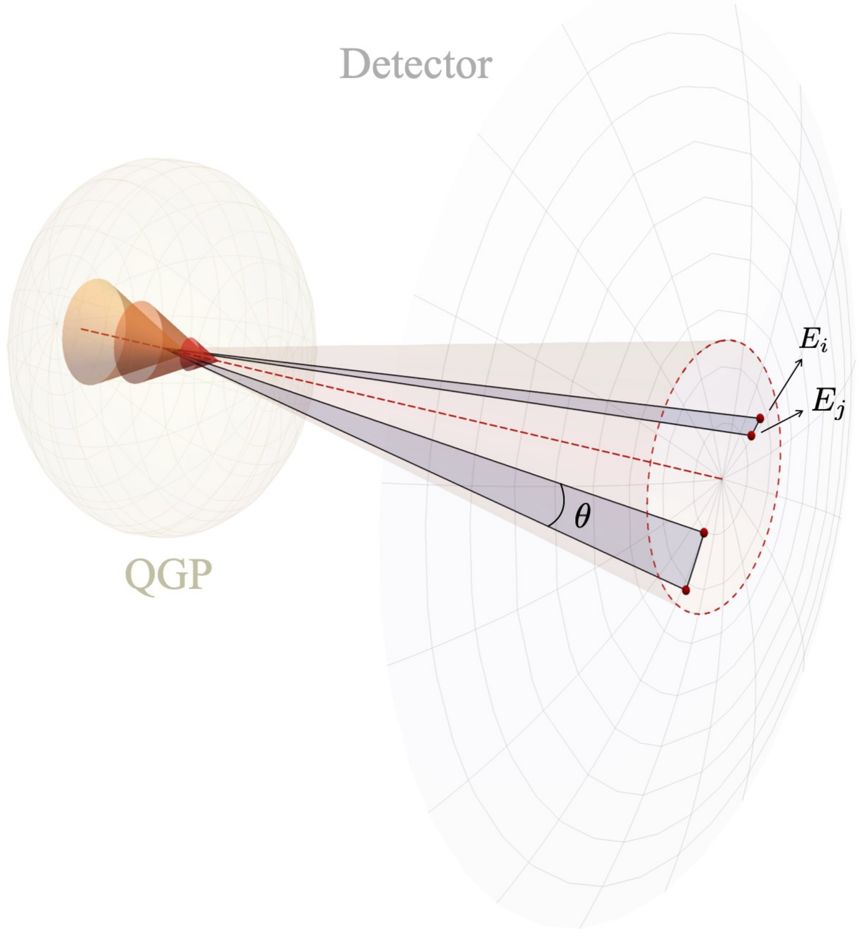

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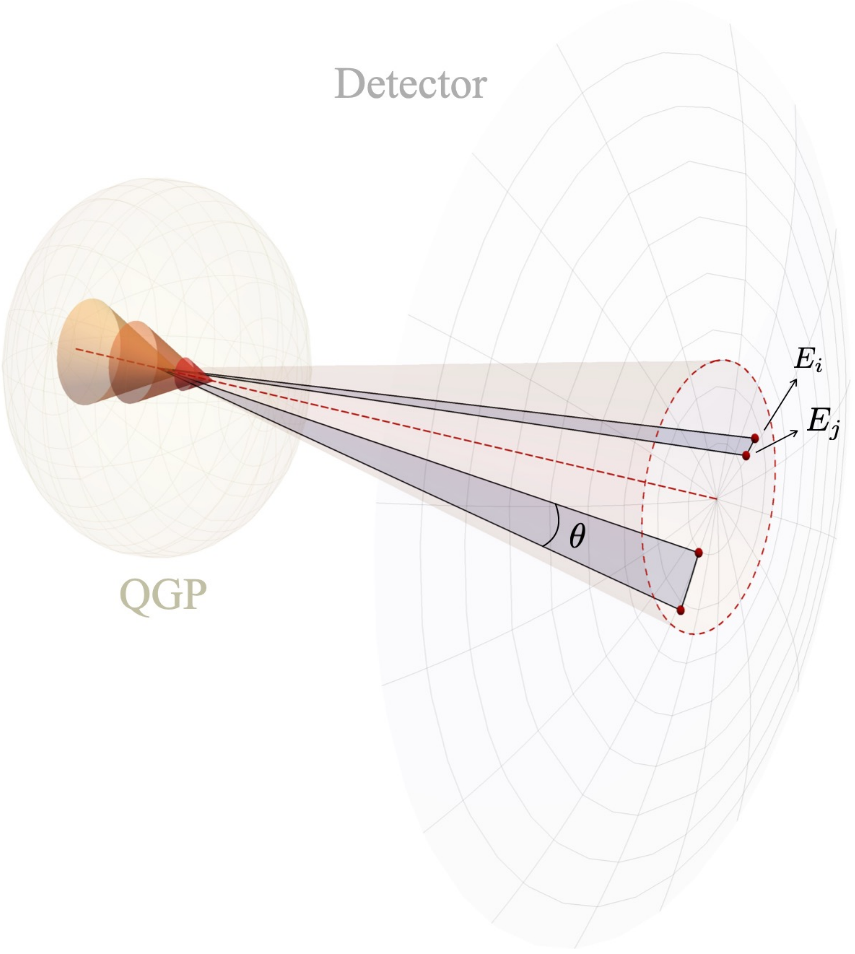
- **Uncorrelated energy flux contributes through geometric correlations**

$$\frac{d\Sigma^{(2)}}{d\theta} \simeq \sum_{k=2} c_k^{(2)} \theta^{2k-3}$$

↑

$$c_2^{(2)} = \hat{\sum_{\text{events}}} \frac{(2\pi)^2}{p_t^2} \int_\Theta \mathcal{E}^2(\Theta) \sin\Theta$$



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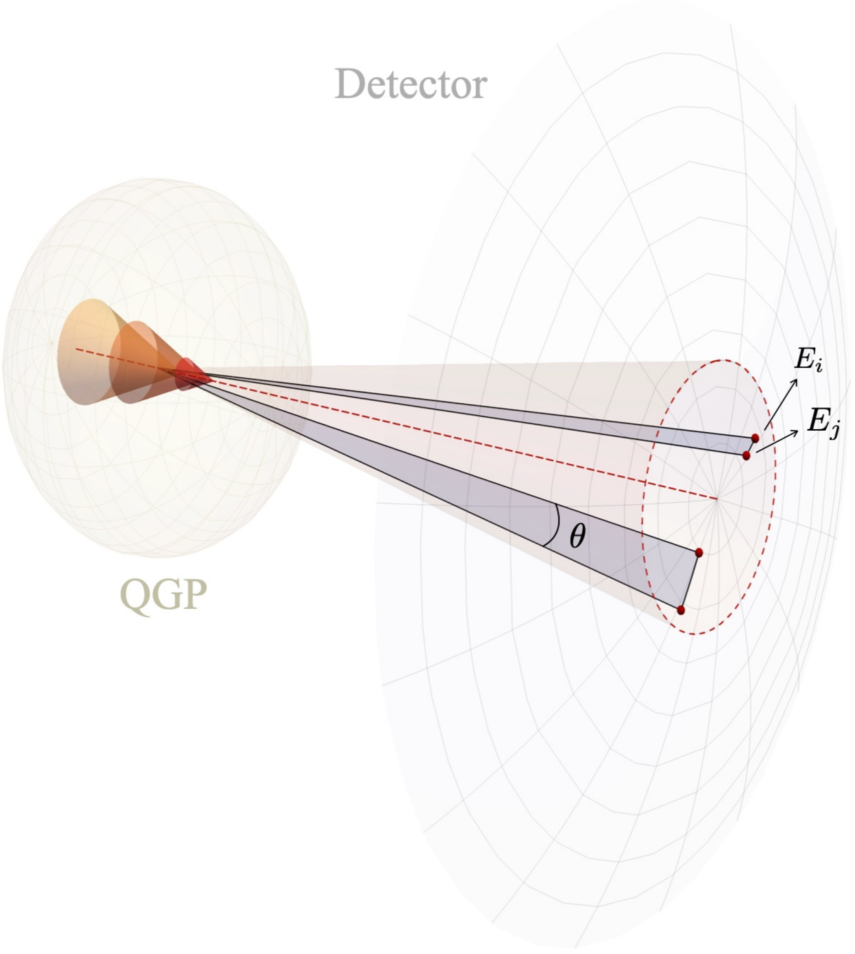
the leading structure is unmodified by the stochastic contribution



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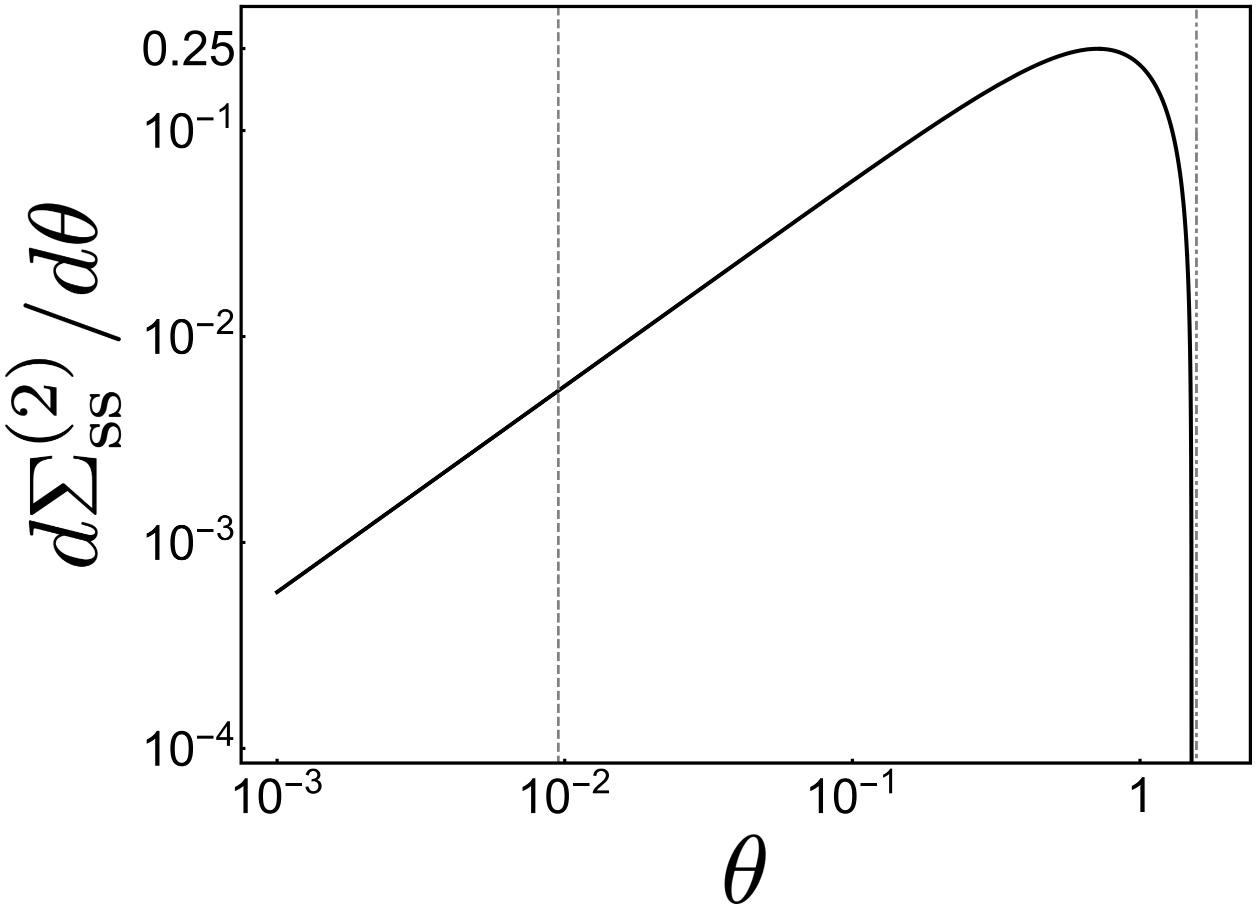
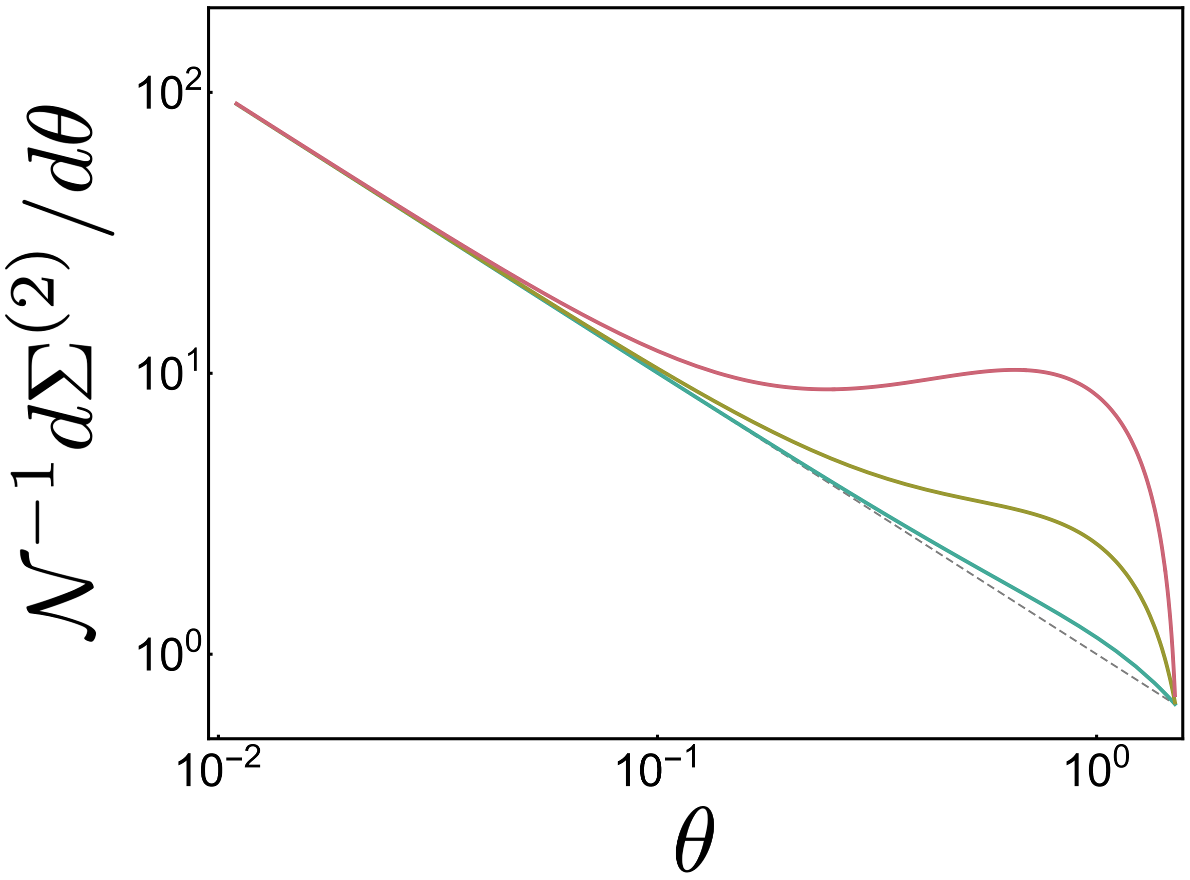


Probing the response

$$\mathcal{E}(\mathbf{n}) = \hat{\mathcal{E}}_h(\mathbf{n}) + \mathcal{E}_c(\mathbf{n})$$

$$\downarrow$$

$$\frac{d\Sigma^{(2)}}{d\theta} = \mathcal{N}\left[\frac{1}{\theta} + \mathsf{c}\,\frac{d\Sigma^{(2)}_{cc}}{d\theta}\right]$$



- Specific model is needed to fix the factors (cannot be done at this level)
- Classical flux leads to universal features (e.g. positivity of the leading term)
- The same behavior for different descriptions (hydro, EKT, etc)

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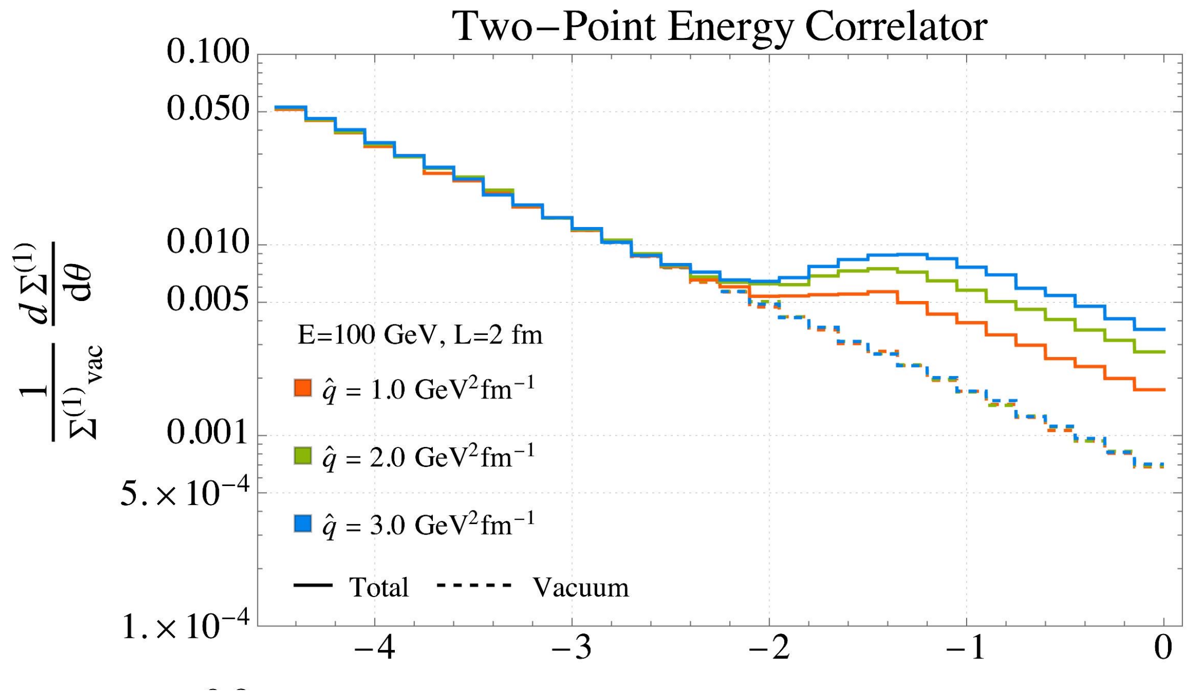

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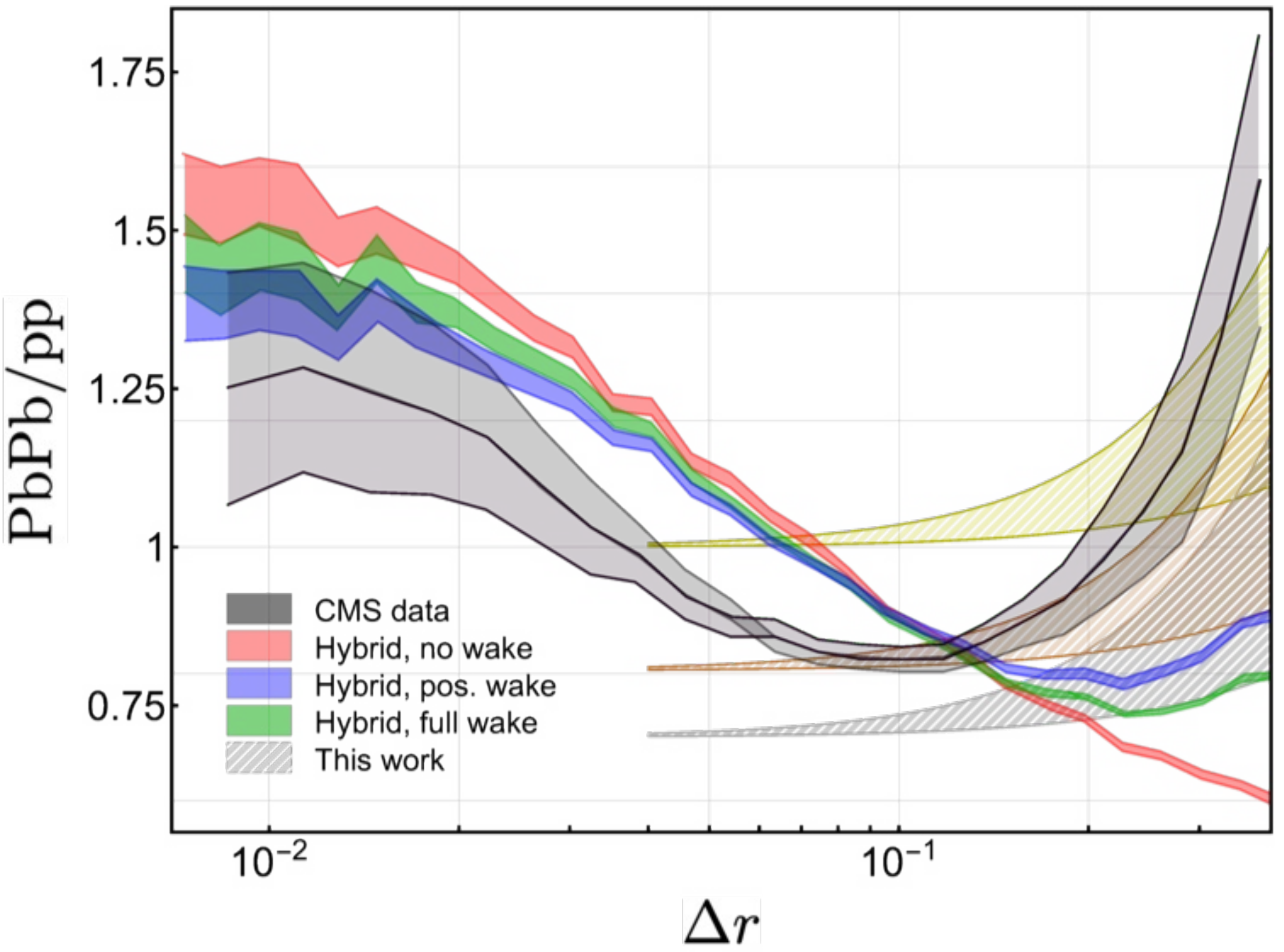
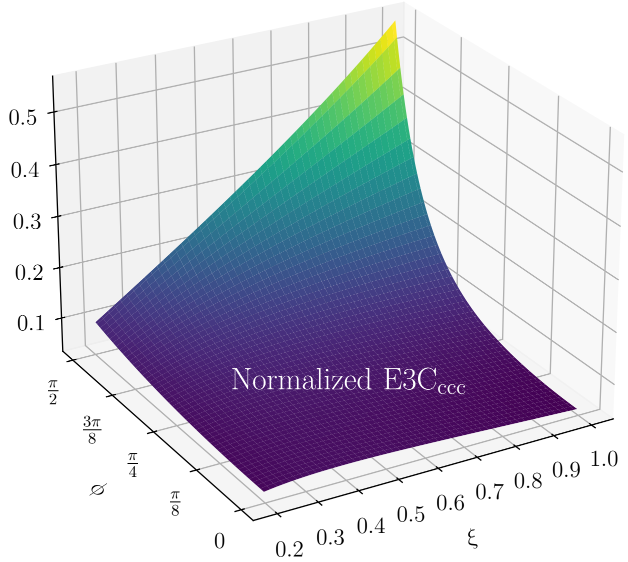


Probing the response

$$\langle \mathcal{E}_c(\mathbf{n}_1)\mathcal{E}_c(\mathbf{n}_2)\mathcal{E}_c(\mathbf{n}_3)\rangle = \mathcal{E}_c(\mathbf{n}_1)\mathcal{E}_c(\mathbf{n}_2)\mathcal{E}_c(\mathbf{n}_3)$$

↓

$$\frac{d\Sigma^{(3)}_{ccc}}{dR_L d\xi d\phi} = \frac{4\pi^2 p_t^{-2} R_L^3 \int_\Theta \mathcal{E}^3(\Theta)\sin\Theta}{(1+\xi\cos\phi)^3\sqrt{4+4\xi\cos\phi-\xi^2\sin^2\phi}}$$



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$$R_L > R_M > R_S$$

$$\xi = R_S/R_M$$

$$\sin^2\phi = 1 - (R_L - R_M)^2/R_S^2$$

Probing the response

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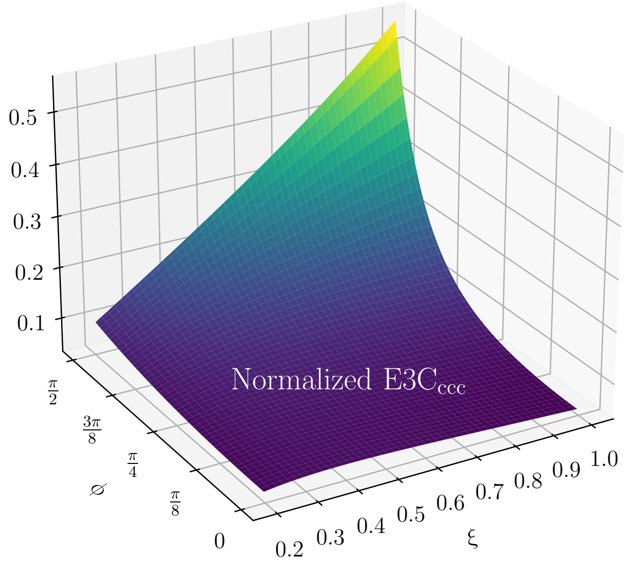

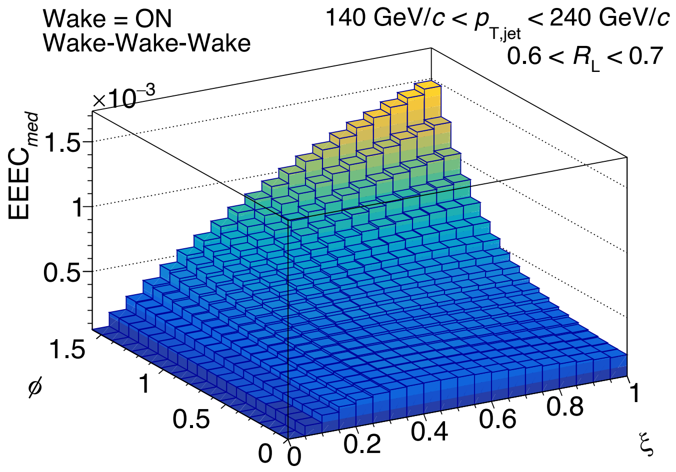

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Probing the response

An illustration: $\mathcal{E}_c(\mathbf{n}) = \frac{\Delta}{\pi\theta_0} e^{-\theta^2/\theta_0^2}$ and no perturbative medium modification

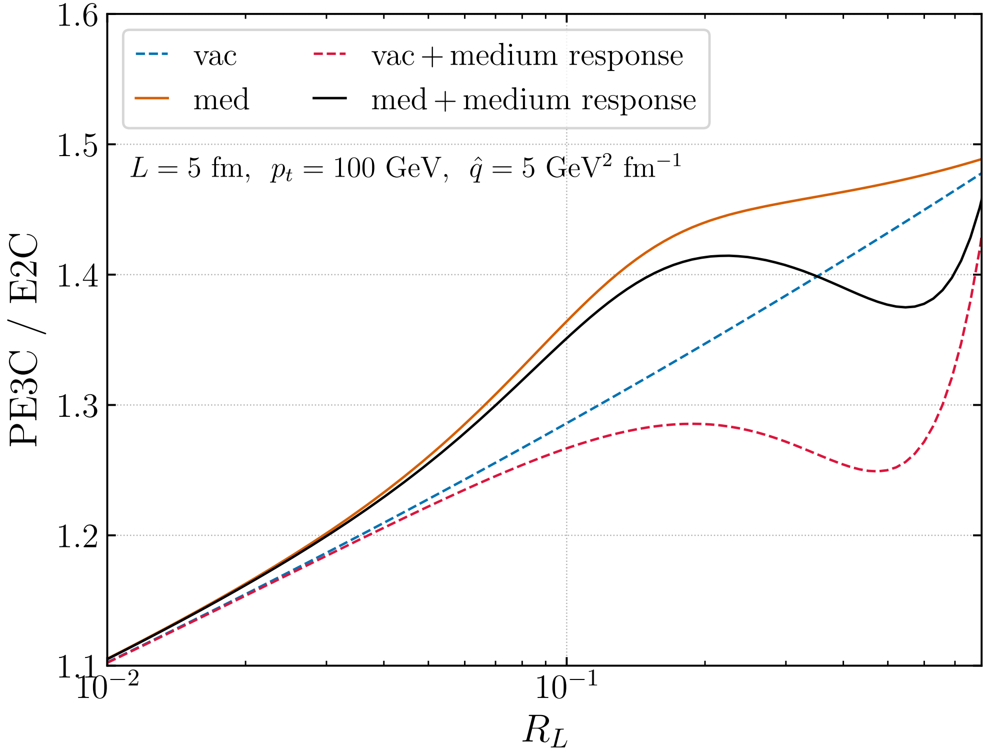
$$\frac{d\Sigma^{(2,3)}_{\rm P,vac}}{dR_L} \simeq a_{2,0}^{P(2,3)} R_L^{\gamma(3,4)-1}$$

$$\left.\frac{\rm PE3C}{\rm E2C}\right|_{\rm v+r} = \left(\frac{a_{2,0}^{P(3)}}{R_L^{1-\gamma(4)}} + \frac{a_{2,0}^{P(3)}\Delta}{6\pi p_t}\,\mathcal{C}\,R_L^{1+\gamma(3)} + \frac{\Delta^3}{\theta_0^2 p_t^3}\left(\frac{2}{9} - \frac{\sqrt{3}}{6\pi}\right) R_L^3\right)\left(\frac{a_{2,0}^{P(2)}}{R_L^{1-\gamma(3)}} + \frac{\Delta^2 R_L}{p_t^2\theta_0^2}\right)^{-1}$$

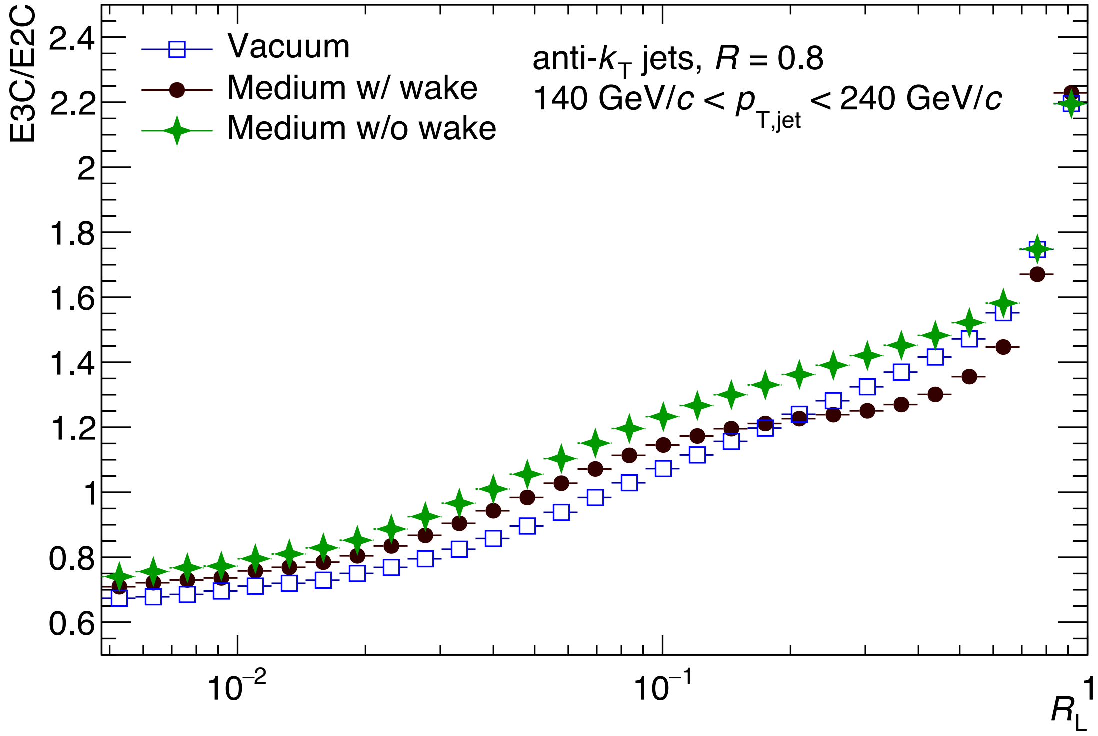
chh, regularized

Probing the response

An illustration: $\mathcal{E}_c(\mathbf{n}) = \frac{\Delta}{\pi\theta_0} e^{-\theta^2/\theta_0^2}$



see João's talk for more details



Universality of the geometric ECs

- The vac. PENC in the OPE limit:

$$\frac{d\Sigma^{(N)}_{\mathrm{P,vac}}}{dR_L} = \sum_{k=1} a^{\mathrm{P}(N)}_{\tau,0} R_L^{\tau-3}\Big|_{\tau=2k}$$

- The medium-induced part of PENC: (for a static and homogeneous matter)

$$\frac{d\Sigma^{(N)}_{\mathrm{P,\,med\,(no\,vac)}}}{dR_L} = \sum_{k=2} b^{\mathrm{P}(N)}_{\tau,0}(\omega_c/p_t,\theta_c) R_L^{\tau-3}\Big|_{\tau=2k}$$

- The medium response contribution: (no azimuthal structure, leading terms)

$$\frac{d\Sigma^{(N)}_{\mathrm{P,\,response}}}{dR_L} = \sum_{k=2} c^{\mathrm{P}(N)}_{\tau}\Big[\mathcal{E}_c\Big] R_L^{\tau-3}\Big|_{\tau=2k}$$

Summary and outlook

- The “uncorrelated” energy fluxes lead to geometric ECs
- These contributions have highly universal structure, allowing to understand their qualitative feature
- Only accounting for all the types of contributions one can systematically study the medium properties with ECs in HIC
- PECs suggest an alternative way to access the anisotropy of the medium properties (azimuthal structure leads to even powers)
- The geometric contributions to E3C closely follows the pattern set by the celestial block decomposition