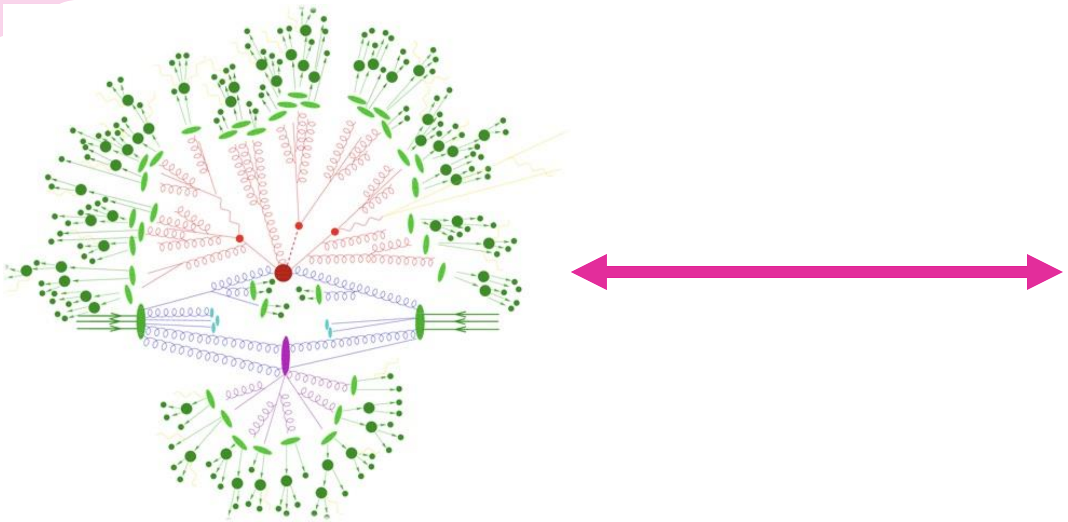
Can we disentangle collectivity-like signals by separating few-scattering effects from QGP formation?

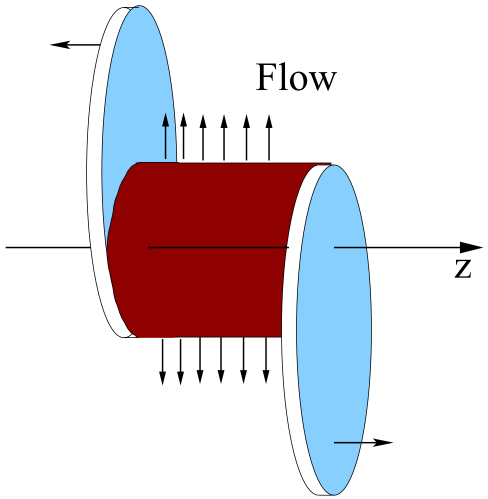
ALEKSI KURKELA

The VIIITH International Conference on the INITIAL STAGES of High-Energy Nuclear Collisions

Taipei, Taiwan

Introduction:

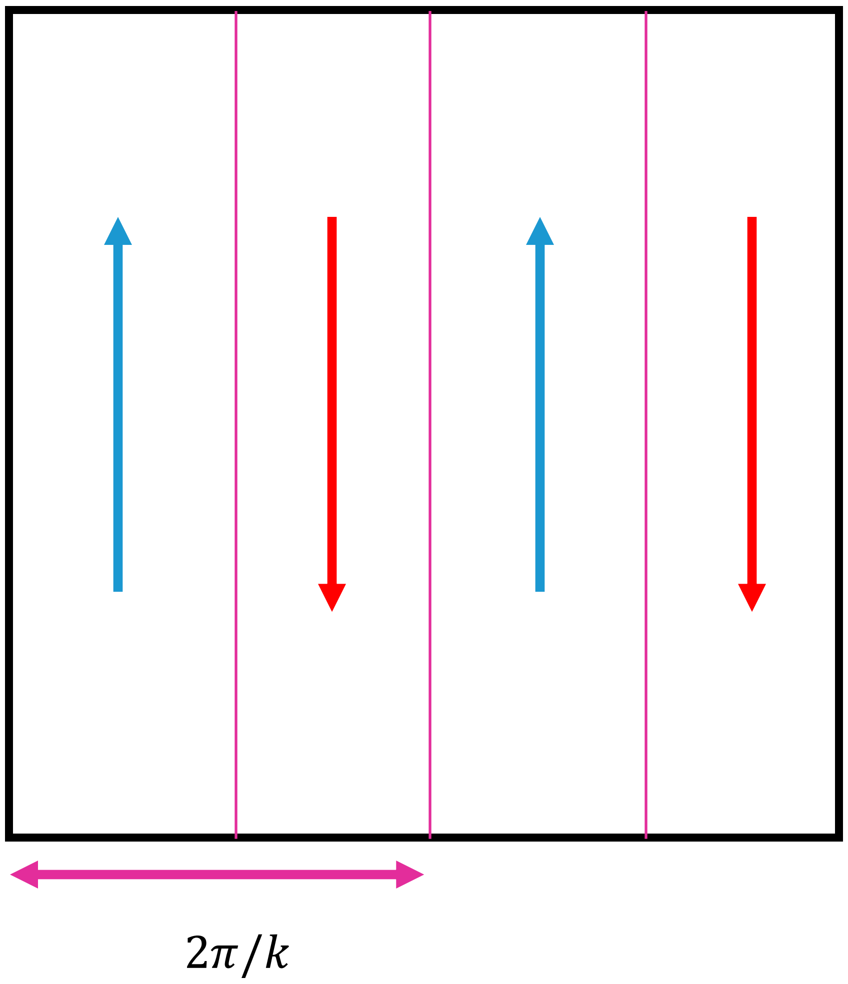




- **Experiment:** Signs of collectivity ($v_n' s$) extend all the way to smallest hadronic collision systems
- **Pheno:** Hydrodynamics-based models give a quantitative account of v_n's down to small systems
- **Theory:** **hydrodynamics** must break at microscopic scales, $\mathrm{Kn}^{-1} \sim L_{macro}/L_{micro} \sim 1$
- **Opportunity:** When hydrodynamics breaks, gain access to **microscopic structure** of QGP
- **Challenge:** No clear demarcation line between few-scatterings and hydro, but qualitative differences…

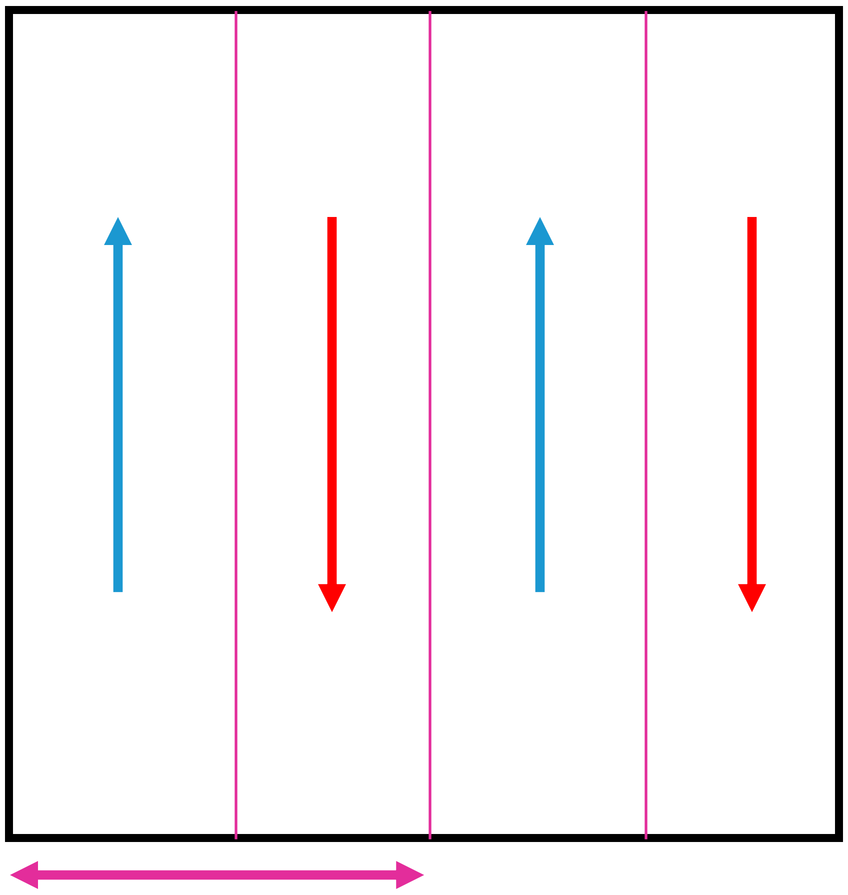
How can we separate few-scattering physics from QGP in an ideal world

Disentangling hydro from few scatterings:



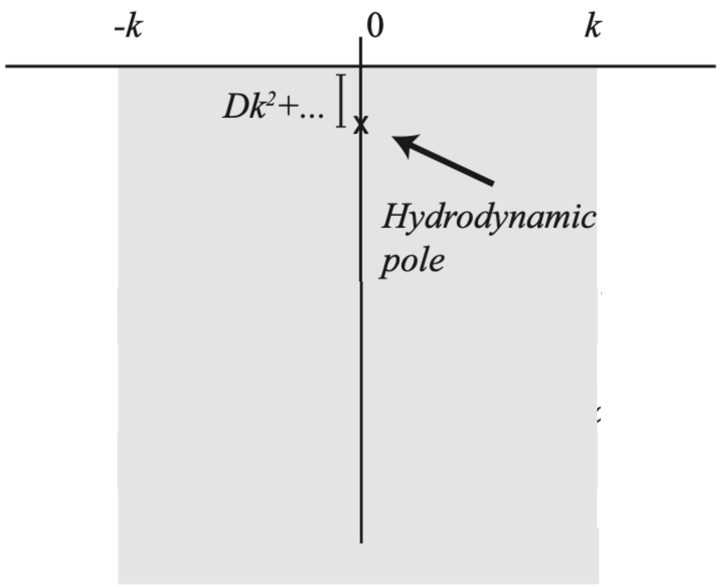
- Matter in thermal equilibrium
- Impose shear flow with wavevector $\boldsymbol{k}$
- The response depends on the wavevector $\boldsymbol{k}$

Disentangling hydro from few scattering:



- For **large** system (small ***k***), hydrodynamic response:

$$\langle T_{0x}(-\omega)T_{0x}(\omega)\rangle_R = \frac{\eta k^2}{i\,\omega - \eta\, k^2/(s\,T)}$$



- Exponential decay of shear due viscosity: $e^{-\frac{\eta\, k^2}{s\,T}t}$

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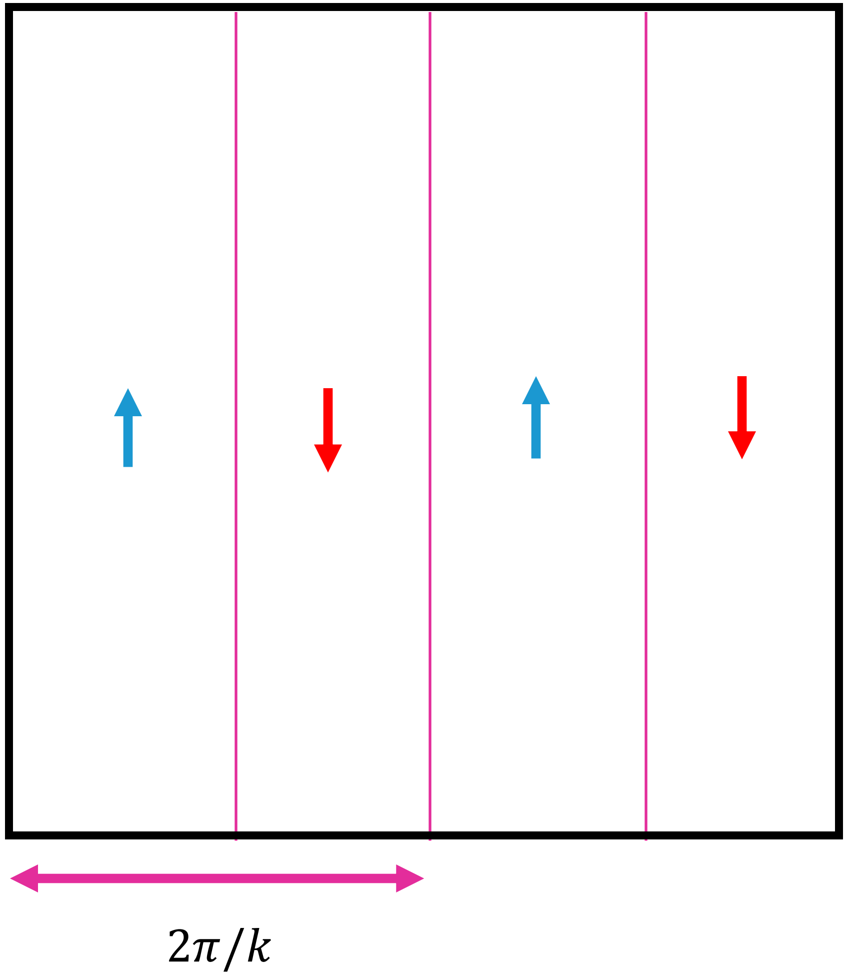

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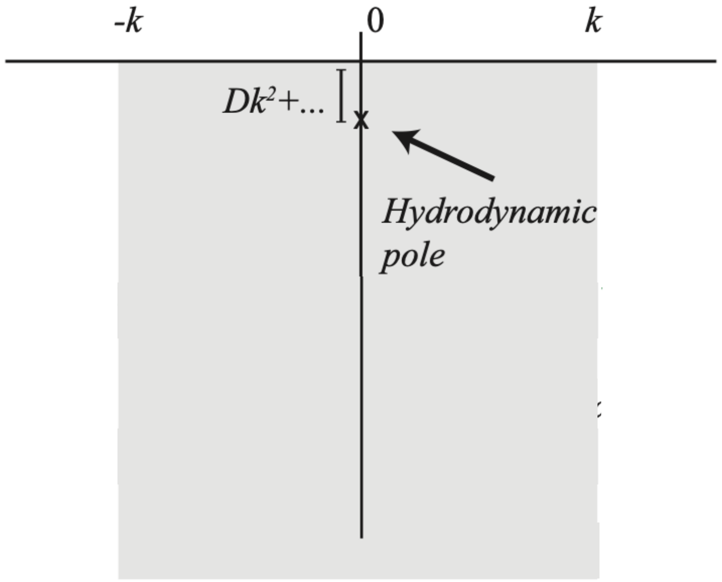

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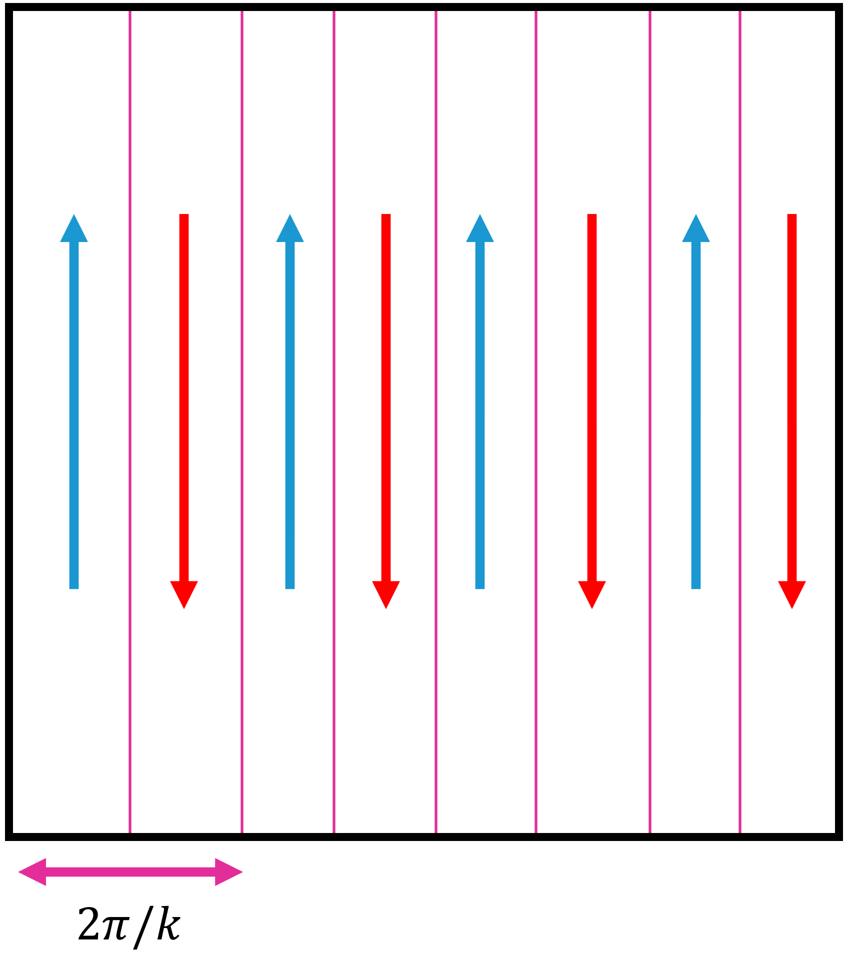

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$$\langle T_{0x}(-\omega)T_{0x}(\omega)\rangle_R \sim sT \int \frac{d\vec{v}}{i\omega - \vec{v}\cdot\vec{k}} \sim sT \log\left(\frac{\omega+k}{\omega-k}\right)$$

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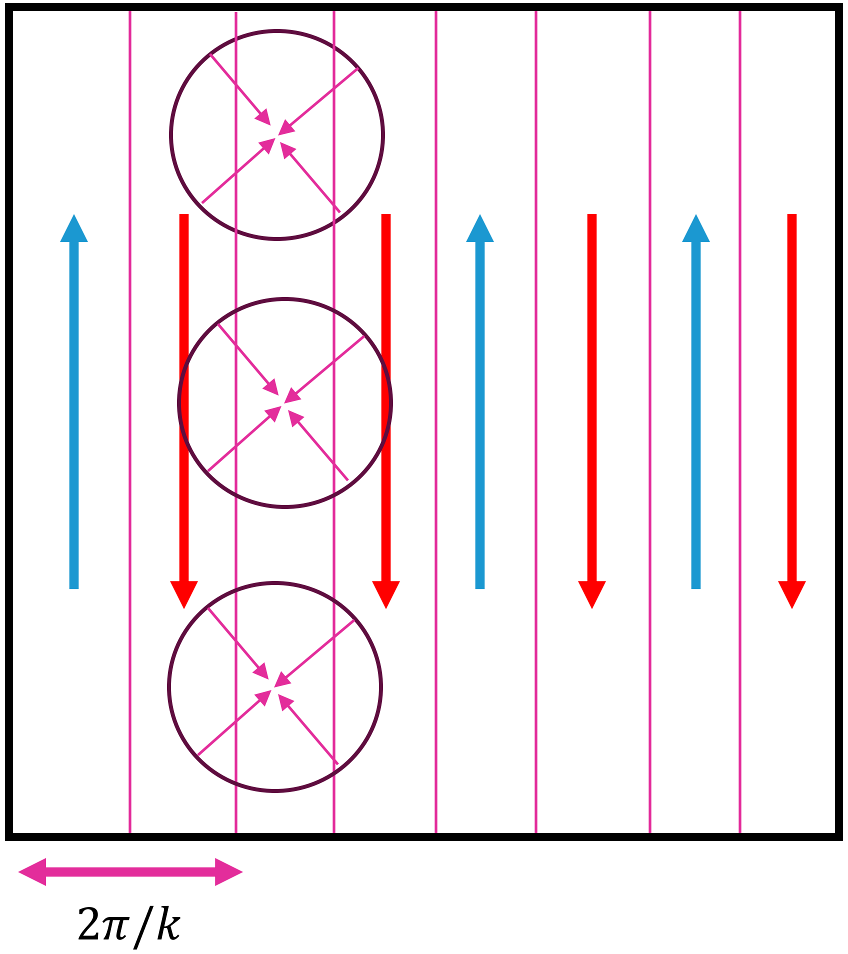

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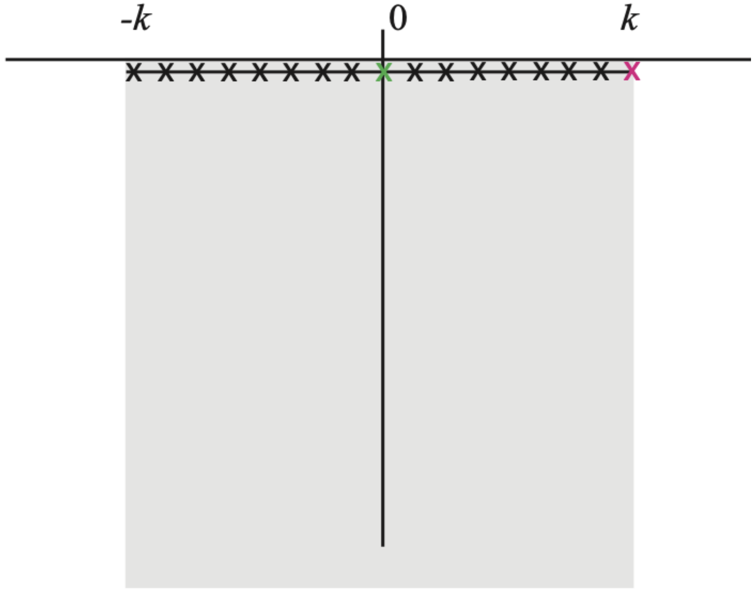

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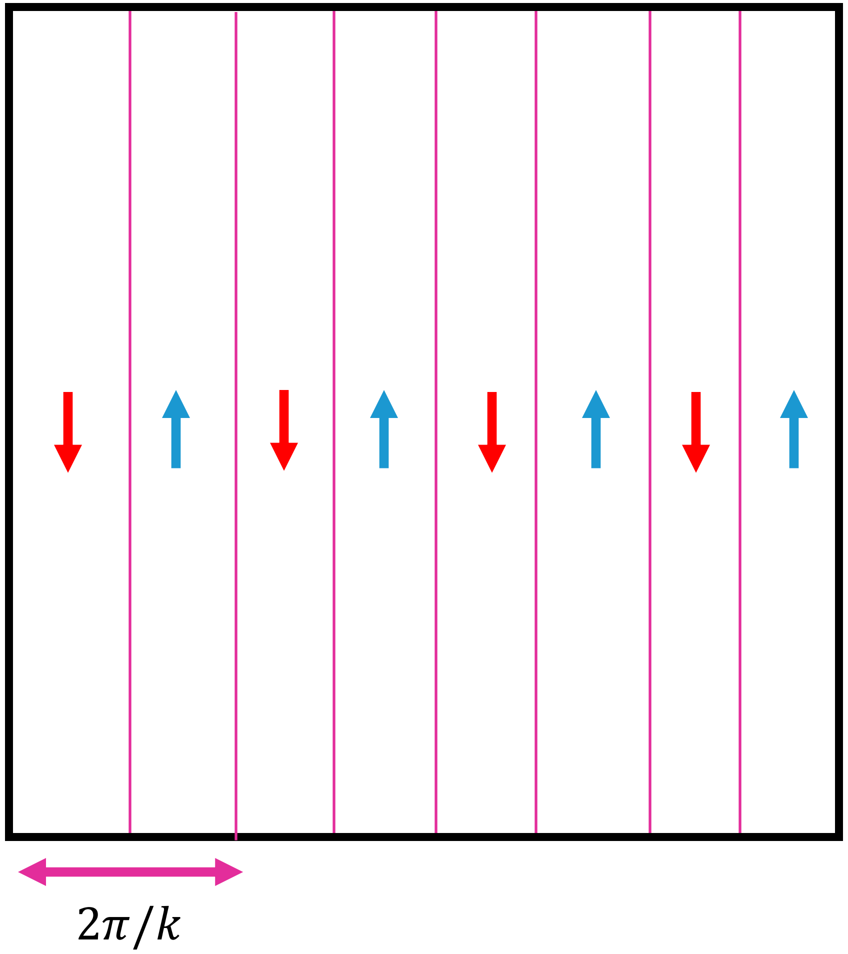

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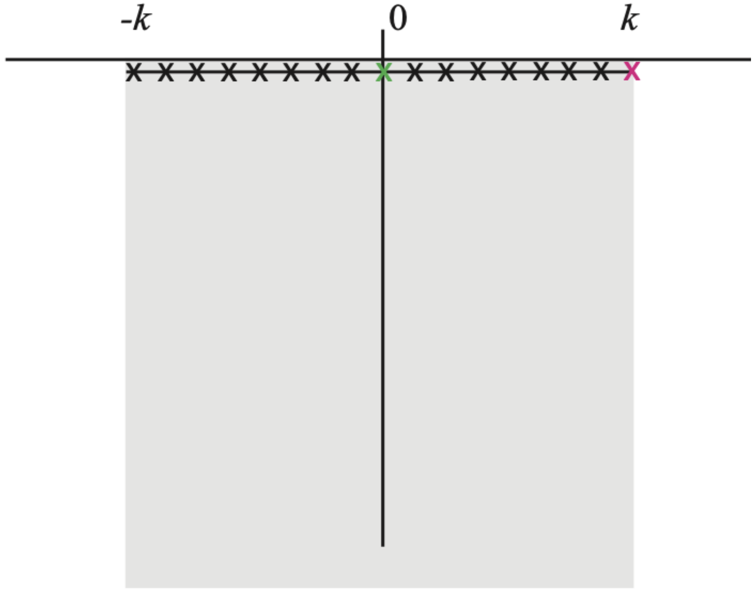

- Polynomial decay with **real frequency**: $\frac{1}{t^2}\sin(kt)$

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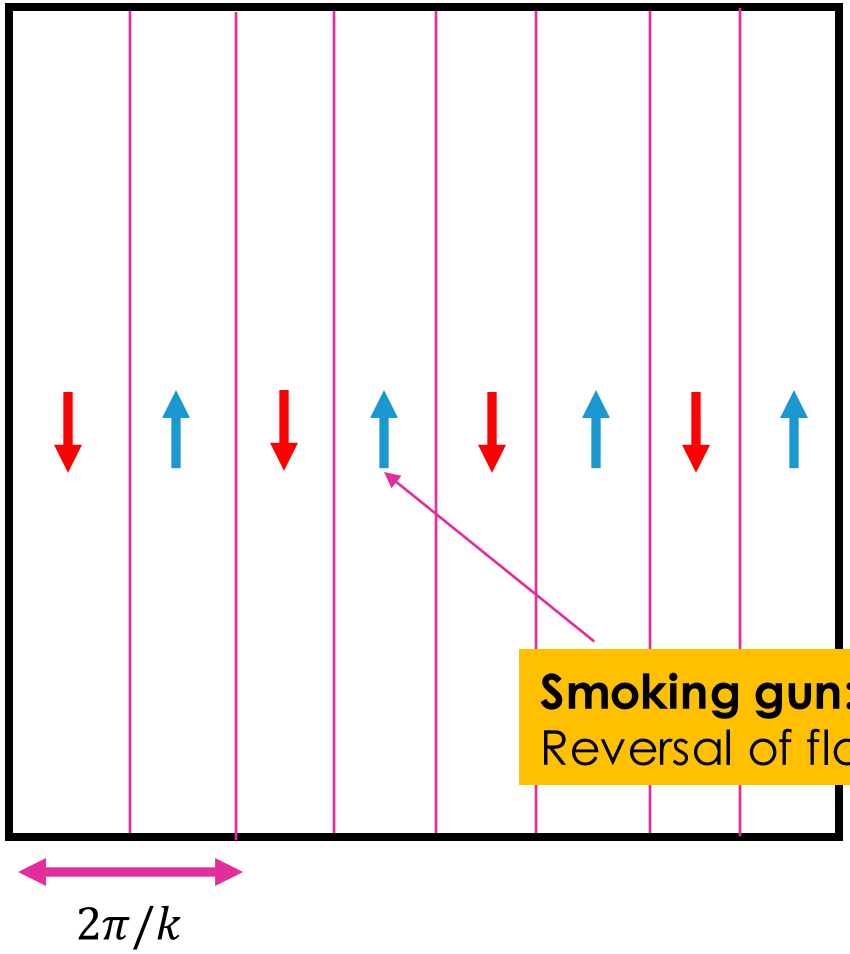

Smoking gun:
Reversal of flow direction

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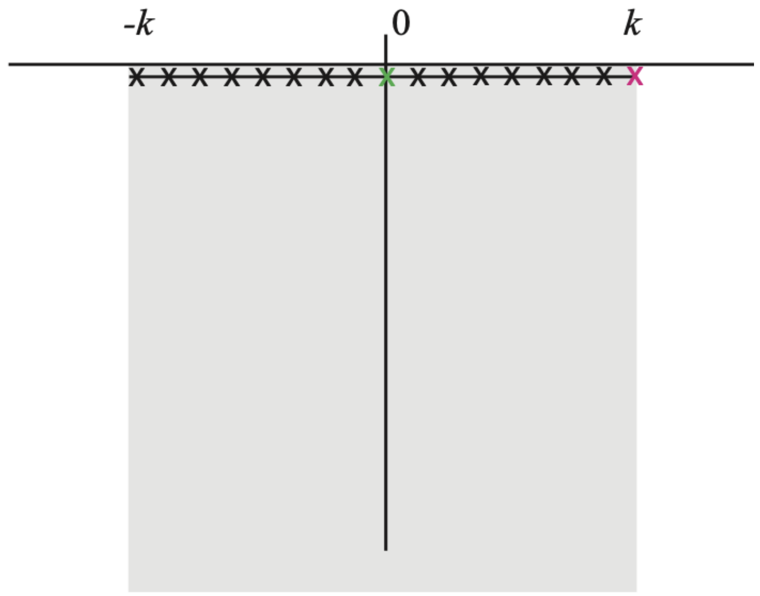

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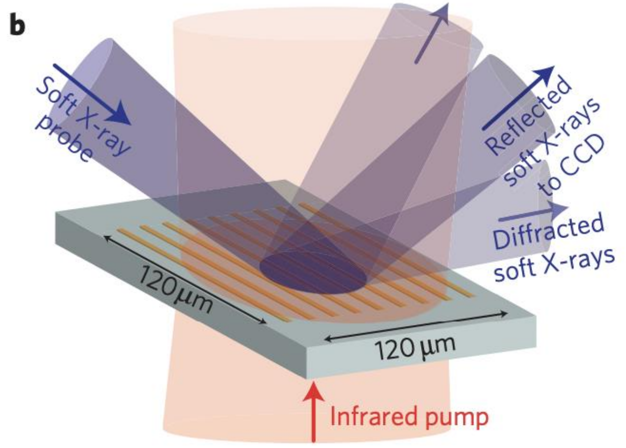
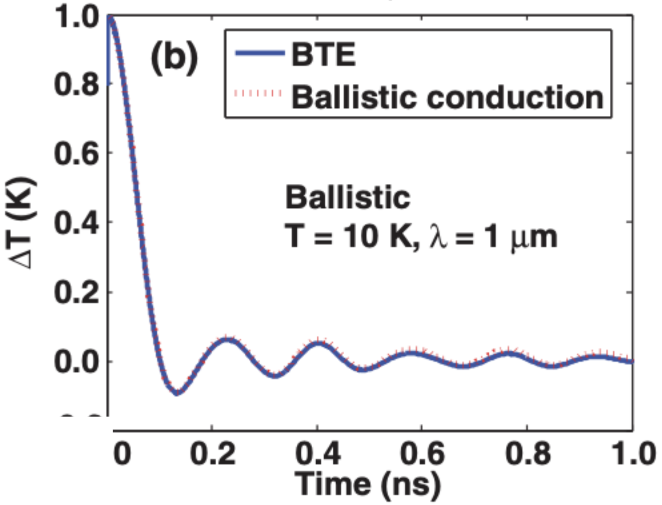
Transient Grating Spectroscopy:

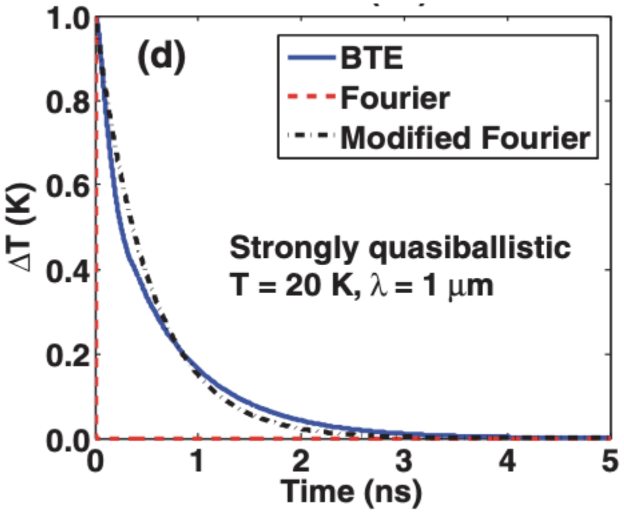


- *Quasi-ballistic thermal transport from nanoscale interfaces observed using ultrafast coherent soft X-ray beams* Siemens et al. Nature Materials 9 (2010)
  - Heat carried by ballistic phonons, described by (RTA) kinetic theory

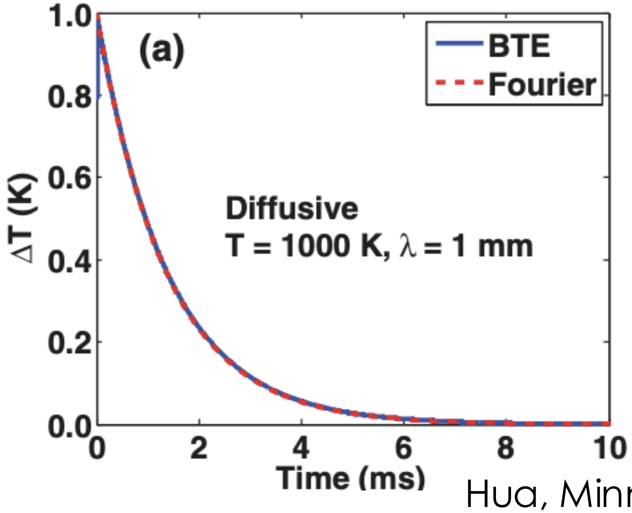
Small system: free streaming, $k\tau_D \gg 1$



Mesoscopic system, $k\tau_D \sim 1$



Large system: Hydrodynamics, $k\tau_D \gg 1$



Hua, Minnich PRB 89 (2014)

RTA: Romatschke EPJC76 (2016)

Onset of hydrodynamics:

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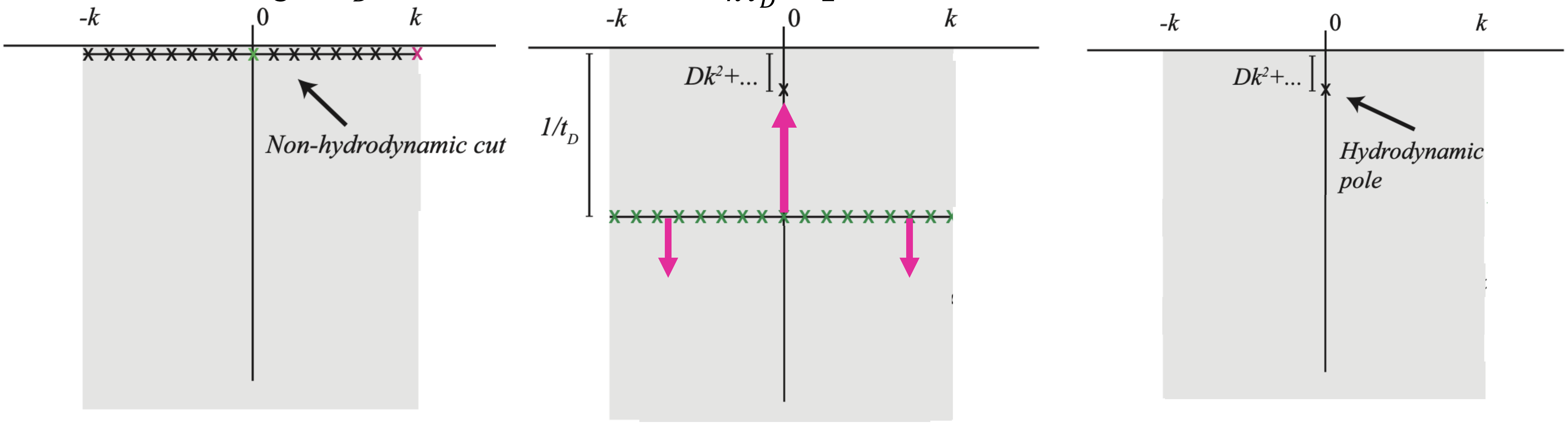

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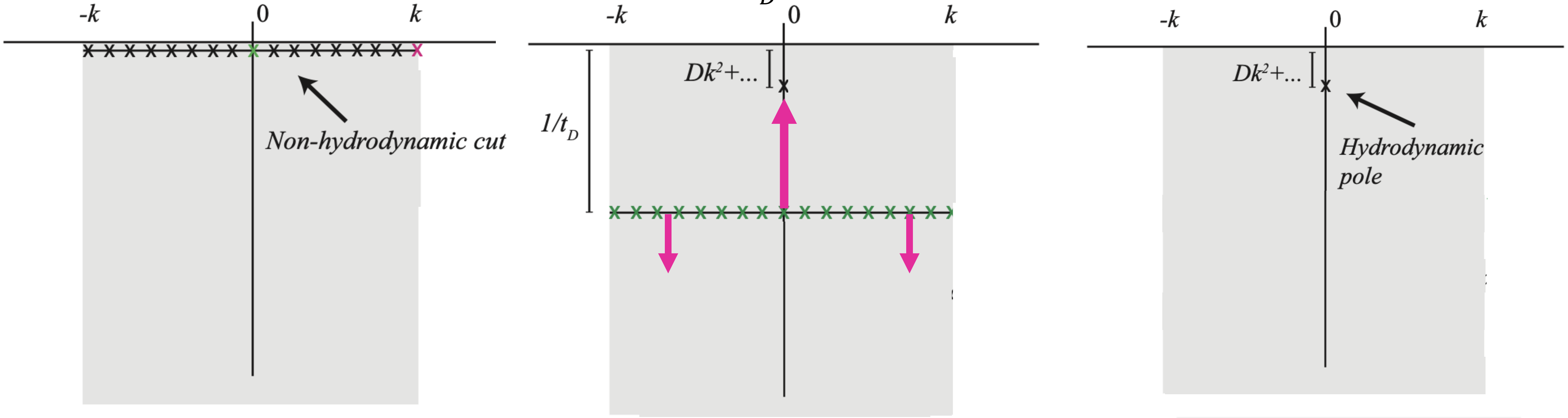
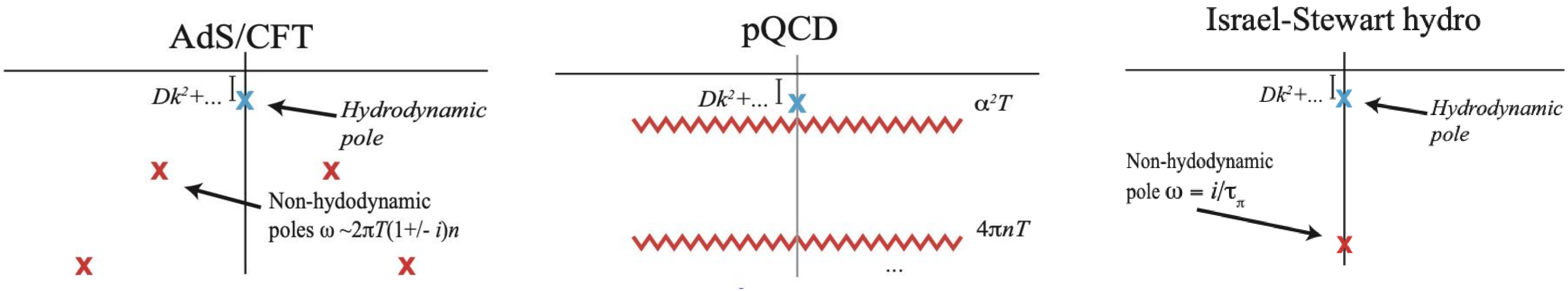


- Picture more **complicated**, but remains **qualitatively similar** for more complex kinetic theories

Momentum dependent RTA: Kurkela, Wiedemann EPJC 79 (2019)
$\boldsymbol{\phi^4}$ **– Theory**: Moore, *JHEP* 05 (2018), Ochsenfeld Schlichting *JHEP* 09 (2023)
EKT: Hong, Teaney PRC 82 (2010), Du, Ochsenfeld, Schlichting PLB 845 (2023)
Massive RTA: Katz, Kurkela, Soloviev JCAP 08 (2019) Bajec , Soloviev 2506.15531, Lin, Sun Wu 2505.04444
RTA Beyond LO in BBBGKY: Grozdanov Soloviev 2501.00099

Non-hydrodynamic modes:

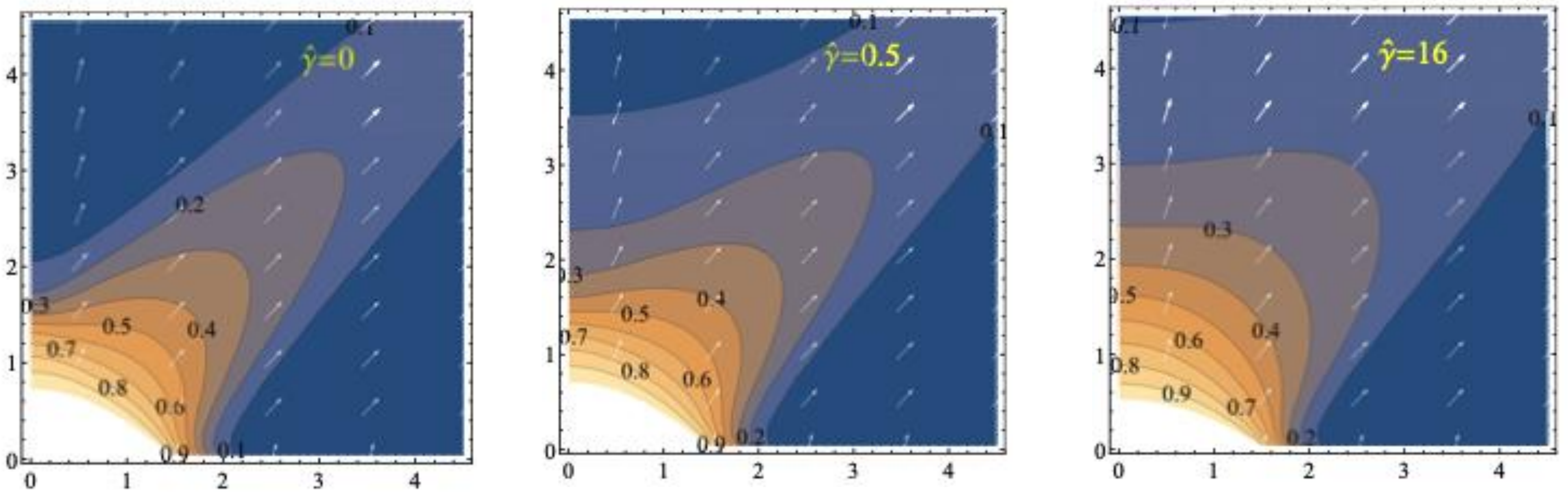


- Different models of Quark-Gluon plasma have different **non-hydrodynamic modes**

How can we separate few-scattering flow from QGP in HIC

From free-streaming to hydrodynamics

Small system: free streaming, $k\tau_D \gg 1$ | Mesoscopic system, $k\tau_D \sim 1$ | Large system: Hydrodynamics, $k\tau_D \gg 1$

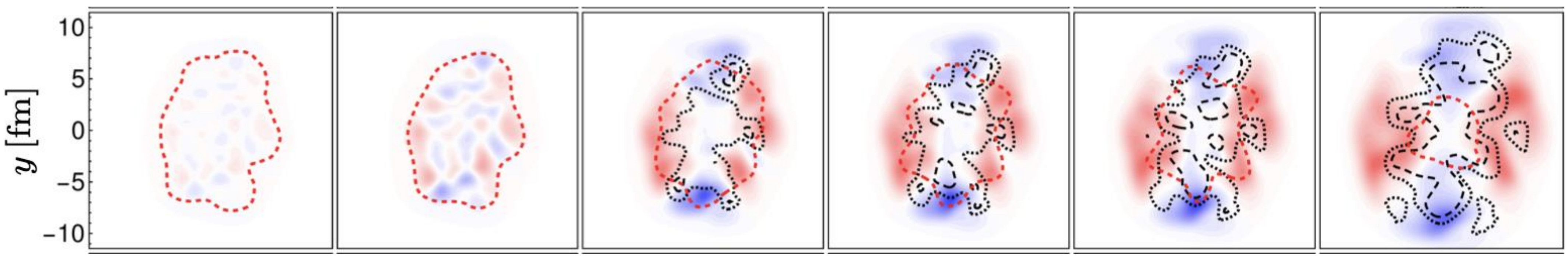


Time τ

Radial position r

RTA: Kurkela, Wiedemann, Wu EPJC 79 (2019) 11; Kurkela, Van der Schee, Wiedemann, Wu PRL 124 (2020);
EKT: Kurkela, Mazeliauskas, Törnkvist JHEP 11 (2021), Talk by Fabian Zhou
Full transverse dynamics: Kurkela, Taghavi, Wiedemann, Wu PLB 811 (2020); Ambrus Schlichting Werthmann PRL 130 (2023) Taghavi, Mehr, Taghinavaz 2504.17707
Full 3D dynamics in 2 ↔ 2 KT: Nugara, Borghini, Greco, Plumari 2509.05495

From free-streaming to hydrodynamics



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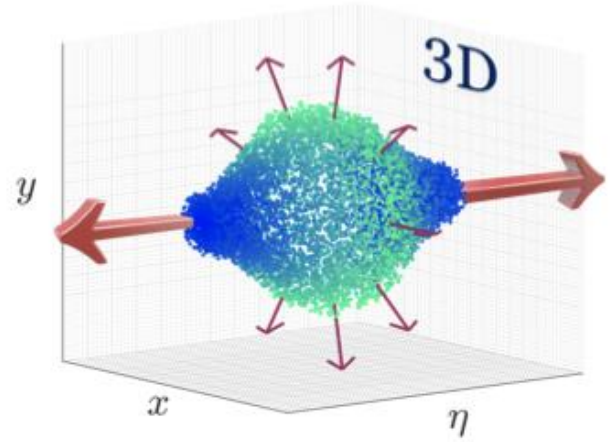

Nugara, Borghini, Greco, Plumari 2509.05495

124 (2020);
EP 11 (2021)
L 130 (2023)
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Kurkela, Wiedemann PLB 783 (2018)

From wavevector to opacity $\hat{\gamma}$:

- In **RTA** kinetic theory, system size encoded in **opacity** $\hat{\gamma}$

$$p^{\mu}\partial_{\mu}f(x,p) = -\frac{u^{\mu}(x)p_{\mu}}{\tau_R(x)}\left[f(x,p) - f_{iso}(x,p)\right]$$

$$\hat{\gamma} = \frac{1}{5\eta/s}\left(\frac{R}{\pi a}\frac{dE_{\perp}^{0}}{d\eta}\right)^{1/4}$$

- $\hat{\gamma} \sim$ Transverse size in terms of the scattering length, depending on, interaction strength and density

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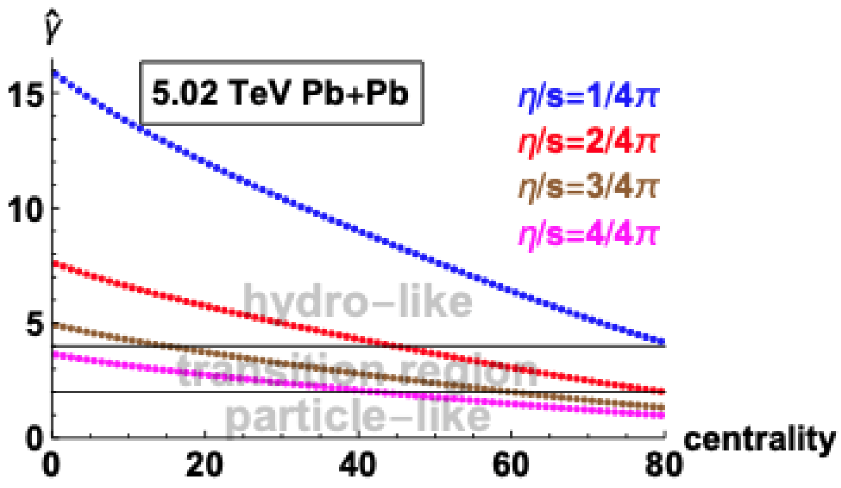
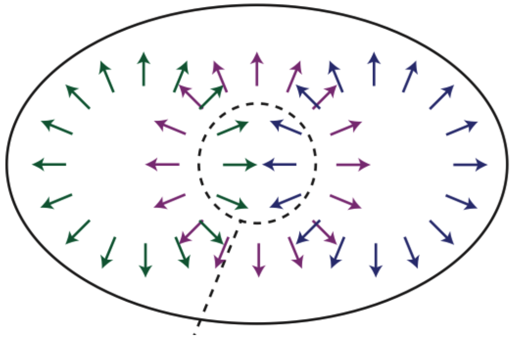


Opacity $\hat{\gamma}$	Collision system at LHC
≈ 8	Central Pb-Pb
≈ 4	Peripheral Pb-Pb
$\lesssim$ 3-4	O-O
$\lesssim$ 1.5	p-Pb

Kurkela, Wiedemann,Wu EPJC 79 (2019) 11
Ambrus, Schlichting, Werthmann PRD 111 (2025)

Kurkela, Wiedemann, Wu EPJC 79 (2019) 9

Linear flow response to geometry:

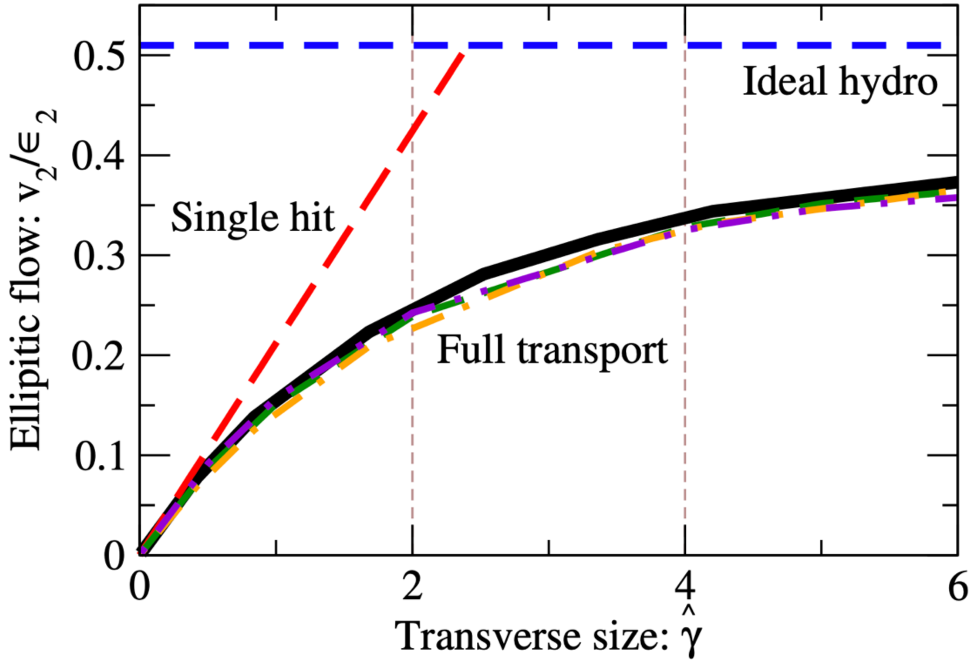


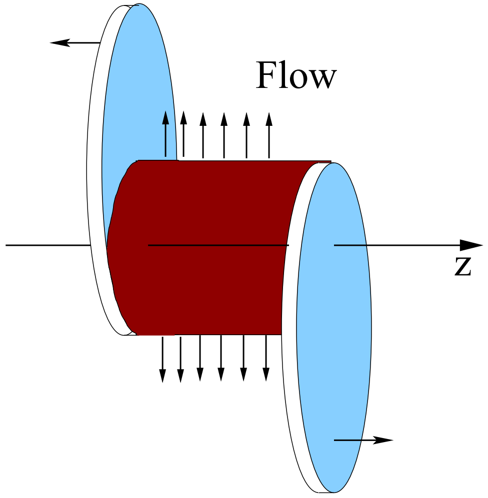
Single-hit regime:

- Free-streamin leads to local anisotropy
- Isotropizing scattering leads to global momentum anisotropy
- Solution perturbation on free-streaming $f = f_{free} + \delta f$

⇒**Response linear in** $\hat{\gamma}$

Energy-weighted elliptic flow





Hydro flow:

- Pressure gradient drives flow
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Kurkela, Wiedemann PLB 783 (2018)

Kurkela, Wiedemann, Wu EPJC 79 (2019) 9

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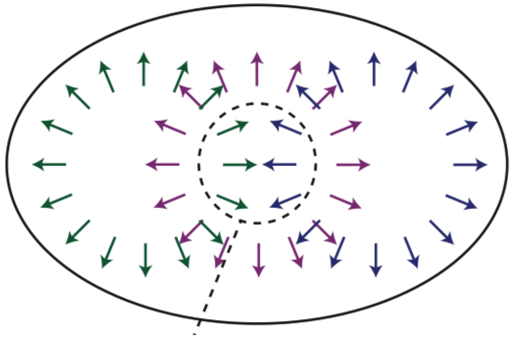

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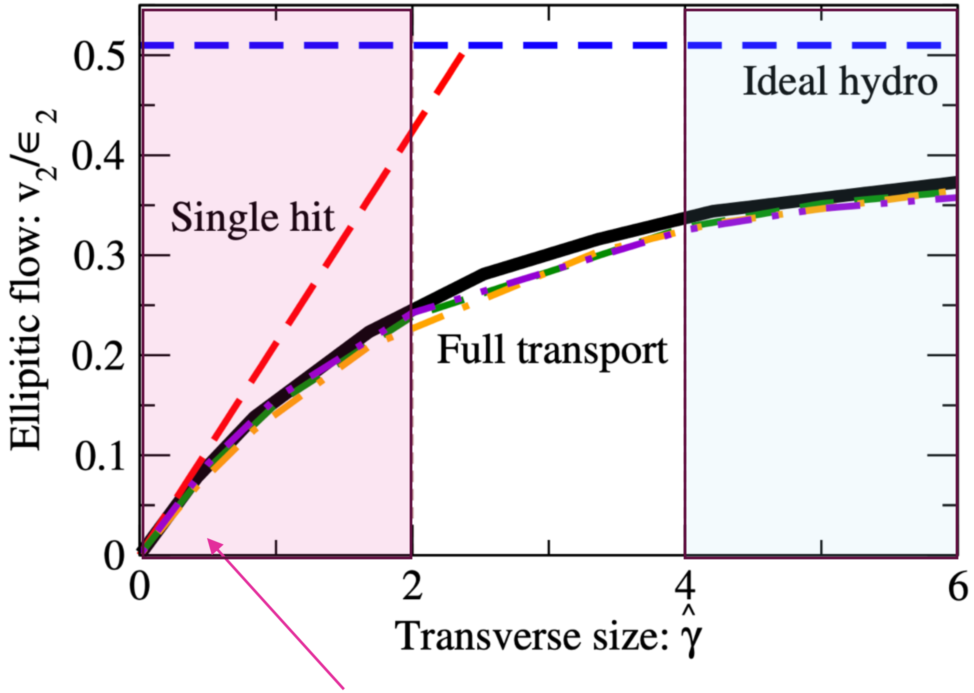
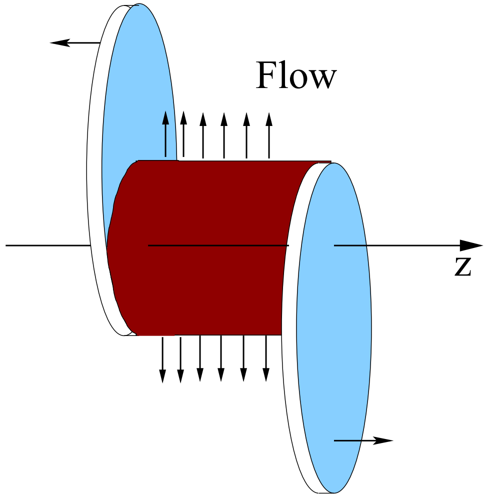


Smoking gun:
Linear dependence on opacity



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Kurkela, Wiedemann, Wu EPJC 79 (2019) 9

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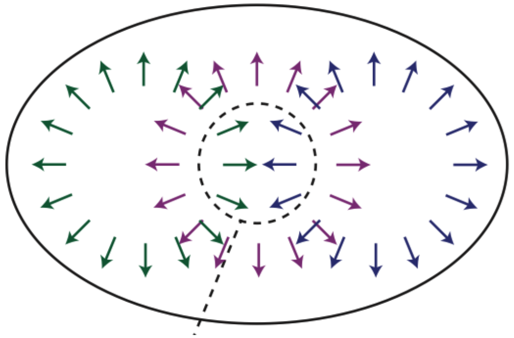

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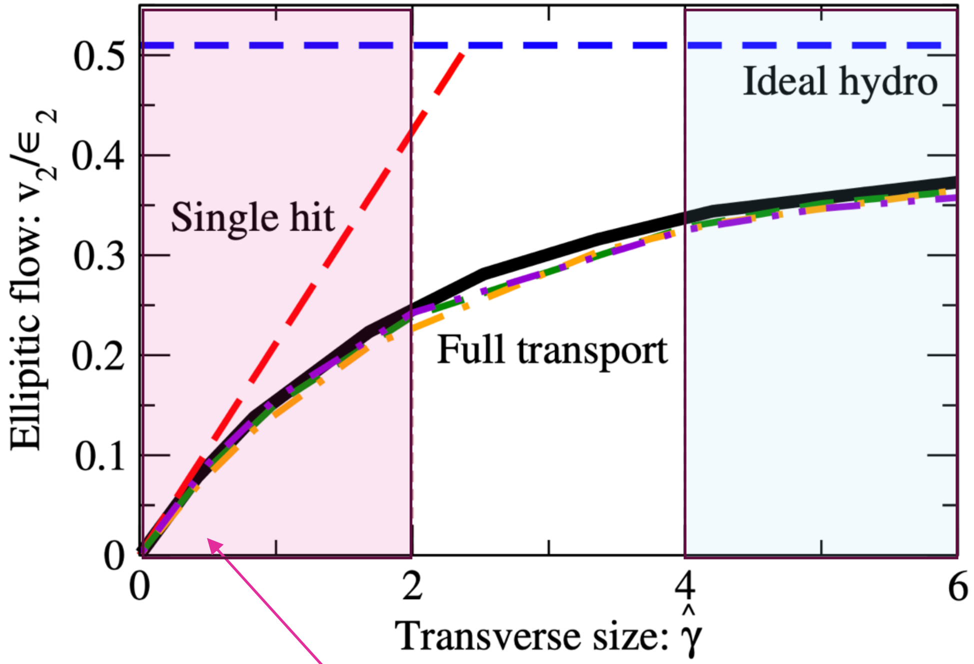

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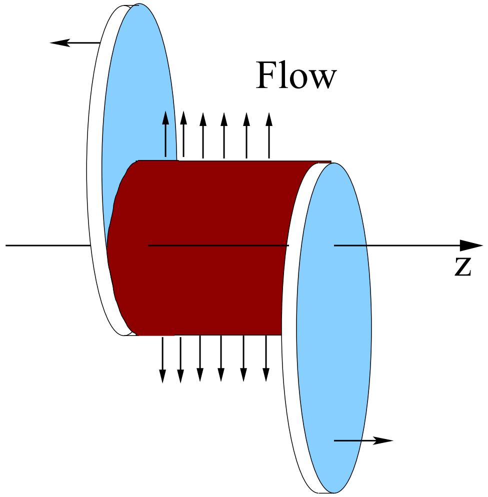

Hydro flow:
- Pressure gradient drives flow
- Response weakly dependent of $\hat{\gamma}$

- Other kinetic theories may have different scaling parameters

Cf. Nugara, Borghini, Greco, Plumari 2509.05495, talk by Nugara

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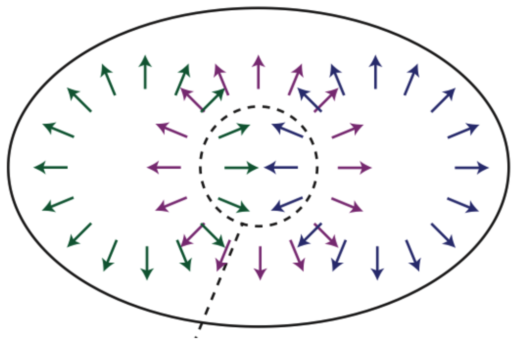

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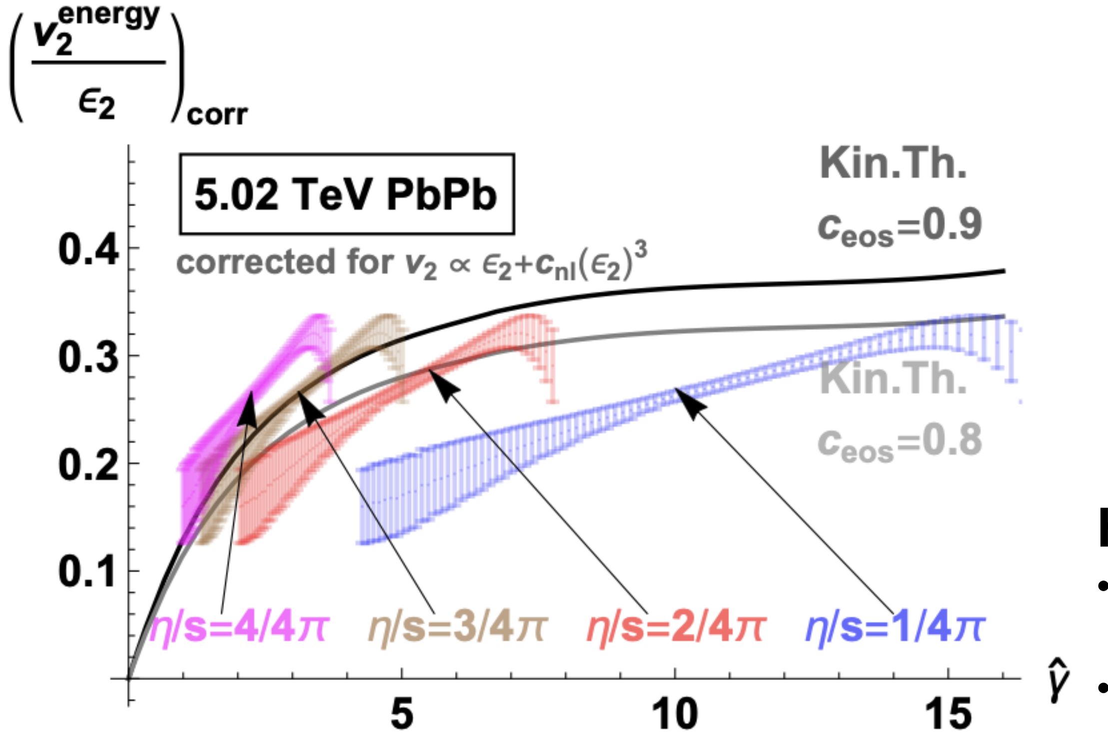

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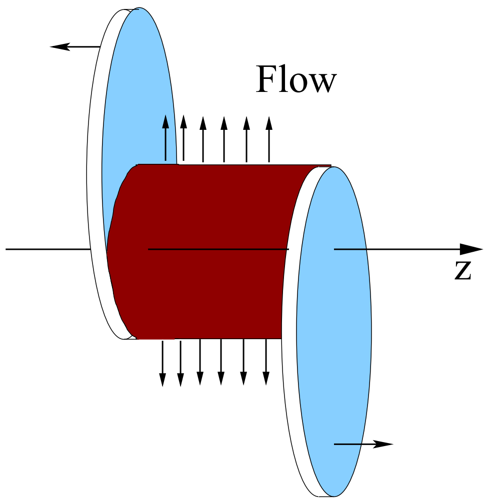

Hydro flow:

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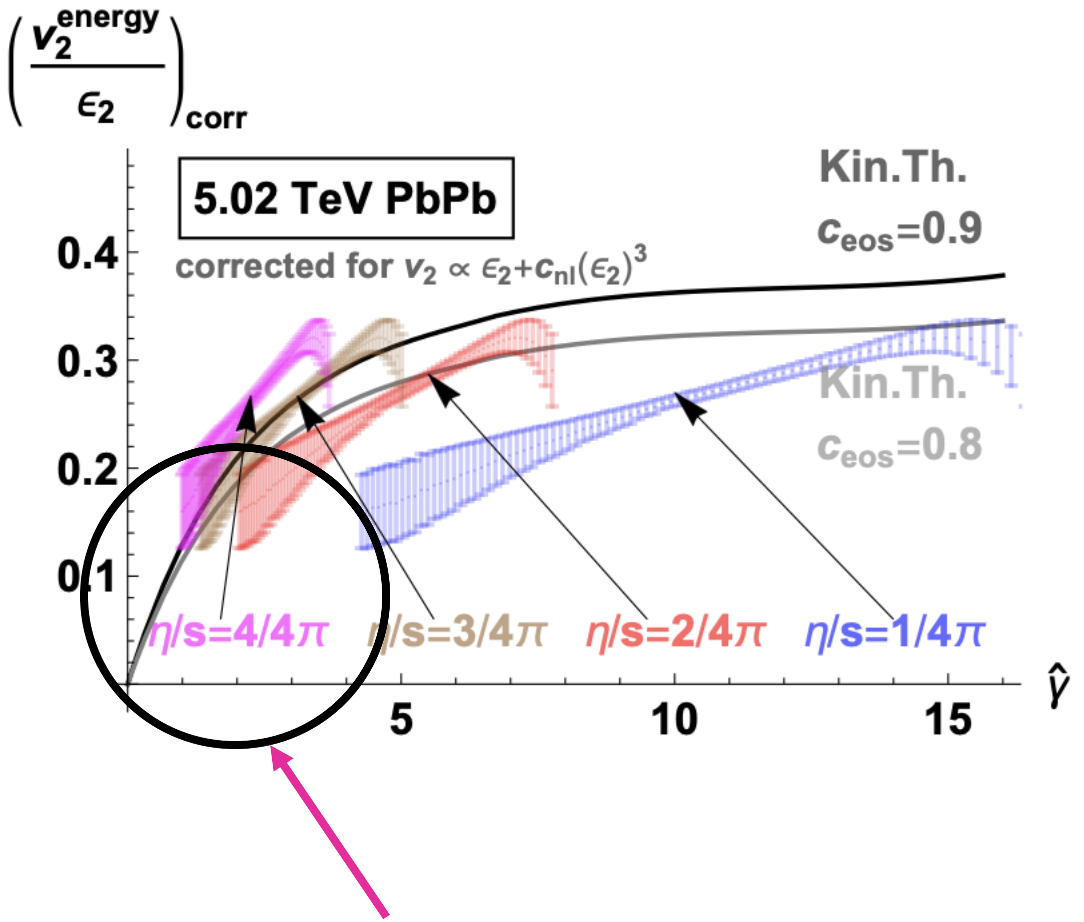
Challenges and opportunities:

- Difficult extend to pp, pPb as geometry $\{\epsilon_n\}$ poorly constrained.



OO and Ne extend to the most interesting $\hat{\gamma}$ –range

Challenges and opportunities:

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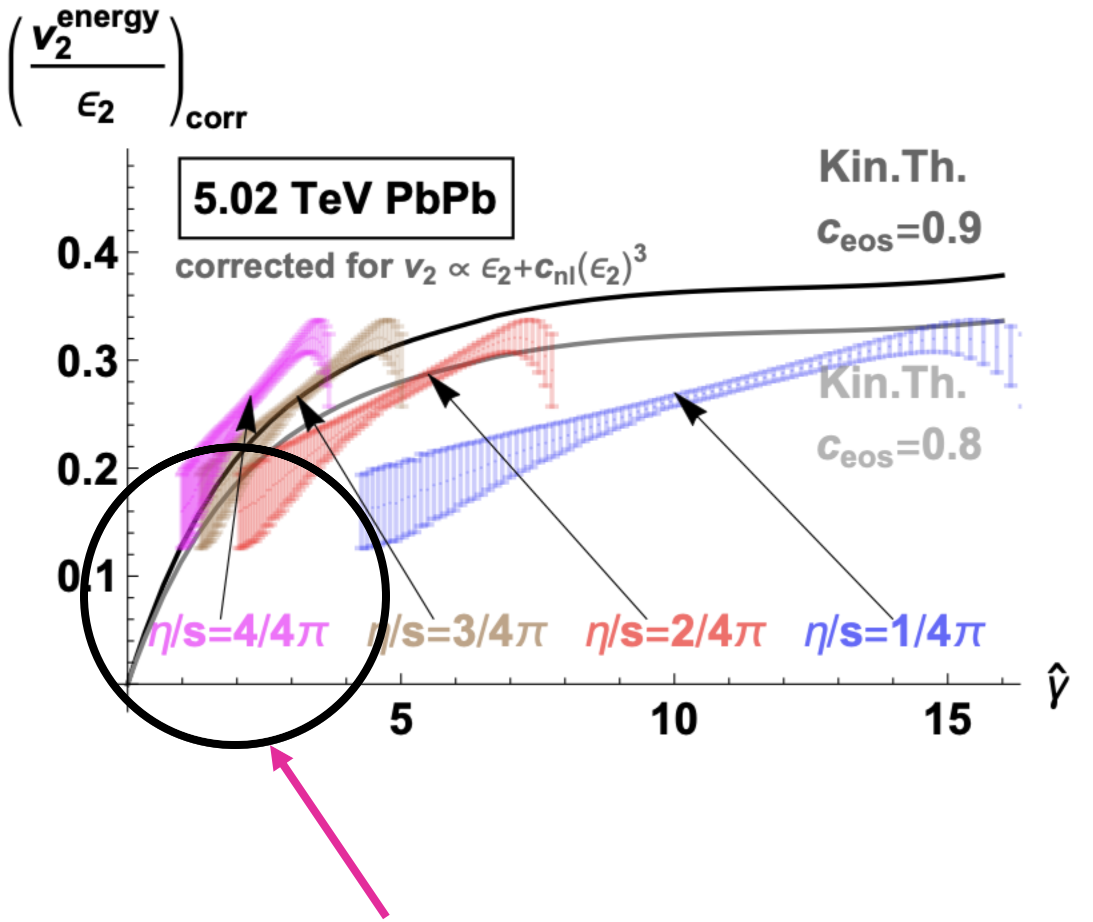
- OO, NeNe geometry better understood and testable

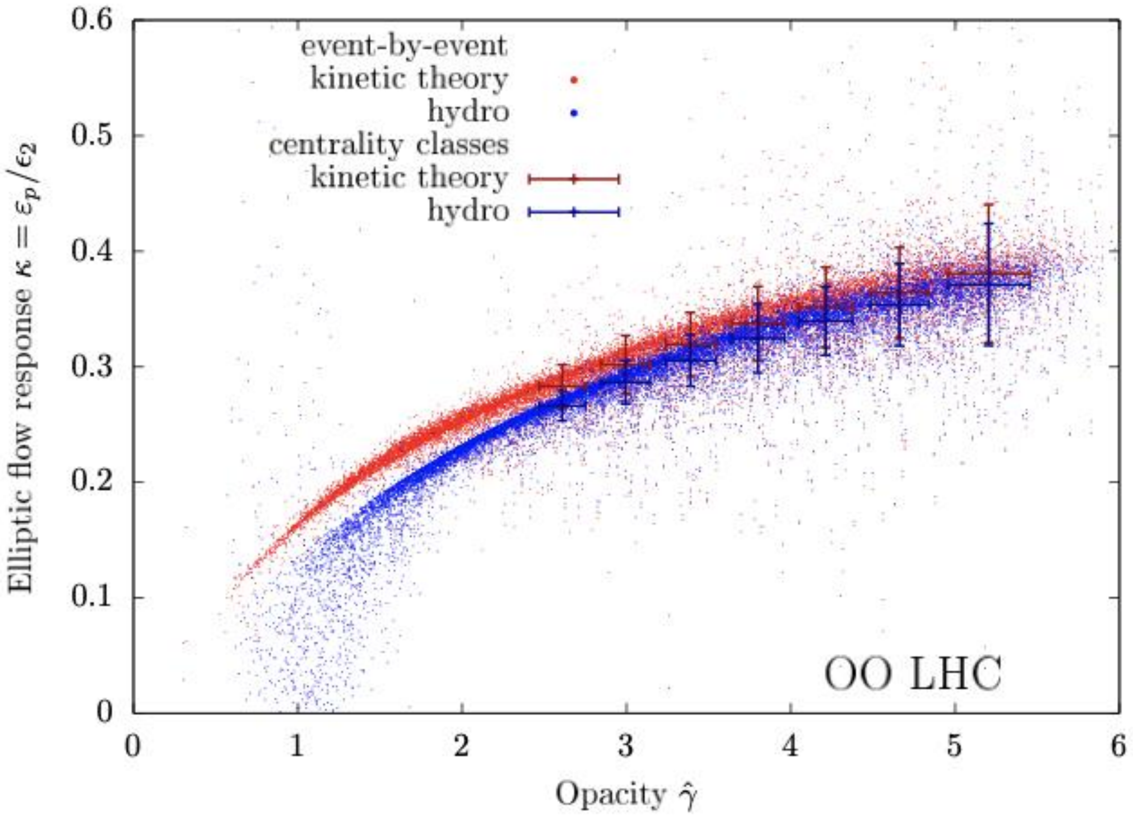
Giacalone et al. 2402.05995, Talk by Gajdosoba



OO and Ne extend to the most interesting $\hat{\gamma}$ –range

Challenges and opportunities:

- **Viscous corrections** and **hydro resummations** (Israel-Stewart, aHydro etc.) mimic the kinetic theory response



Ambrus, Schlichting, Werthmann PRD 111 (2025)

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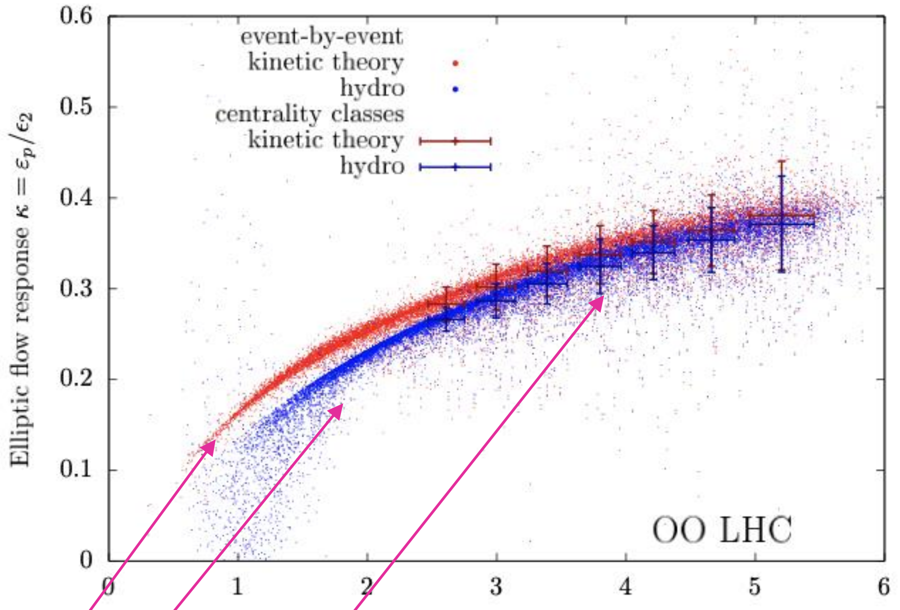
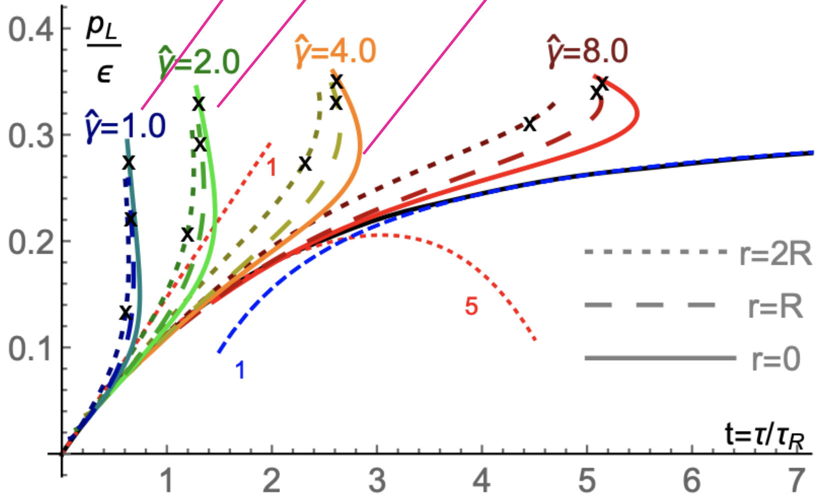


- **Hydrodynamics** never reached during the time evolution for $\hat{\gamma} \lesssim 4$

- Success of **hydrodynamic-based models** based on non-hydrodynamic properties of the models?



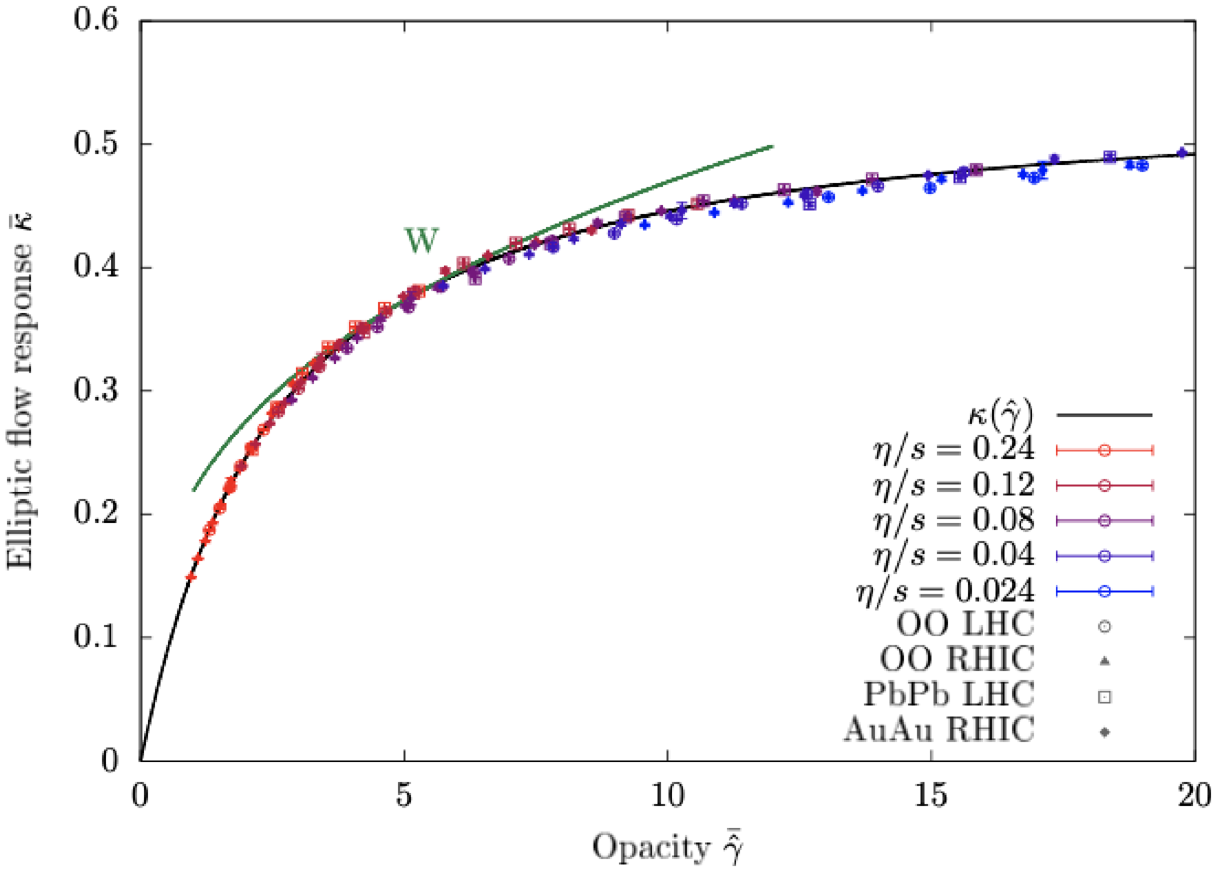
Kurkela, Van der Schee, Wiedemann, Wu PRL 124 (2020);

Challenges and opportunities:

- Data-driven observable related to flow-coefficient and opacity.
  - Avoids need for modelling of ϵ_2
  - Two systems (A, B) with same geometry

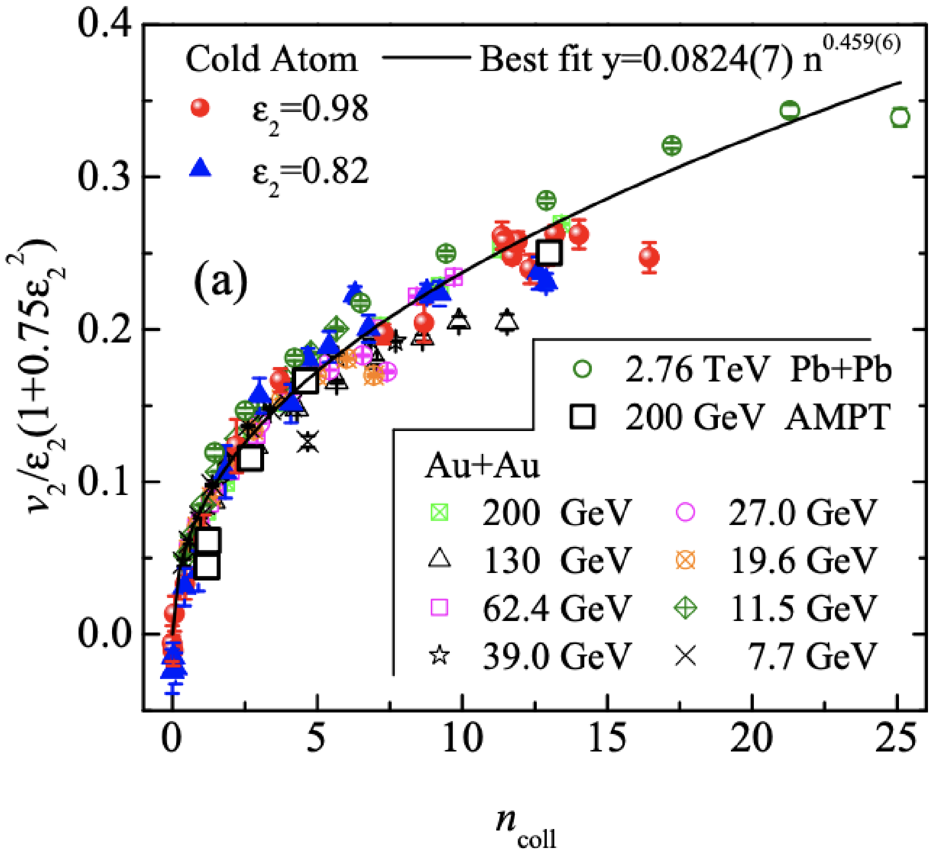
$$W = \frac{2}{k} \frac{\log(c_2\{2k\}_A / c_2\{2k\}_B)}{\log\left(\left\langle\frac{dE}{d\eta}\right\rangle_A / \left\langle\frac{dE}{d\eta}\right\rangle_B\right)} \approx \frac{d\log(v_2/\epsilon_2)}{d\log\hat{\gamma}}$$

W = 1: Single-hit, W = 0: Hydrodynamics

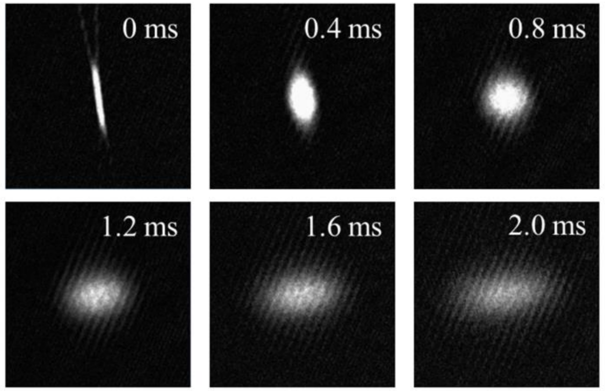


Ambrus, Schlichting, Werthmann PRD 111 (2025)

Linear response in cold atoms:



- Qualitative similarity in flow response between HIC and cold ^{6}Li atoms
   - $n_{coll} = \frac{\sigma}{c\tau\sqrt{\pi S_{\perp}}}\frac{dN}{dy} \neq \hat{\gamma}$
- Scaling variable different for non-conformal systems with fixed cross-section
- Establishing scaling variable may give access to microphysics



Li, Song, Xu, Sun, Wang 2405.02847, Talk by Wang

Conclusion:

Key question:

"How can we access physics beyond standard **hydrodynamic** model?"

Smoking gun: Linear dependence of response coefficients on opacity

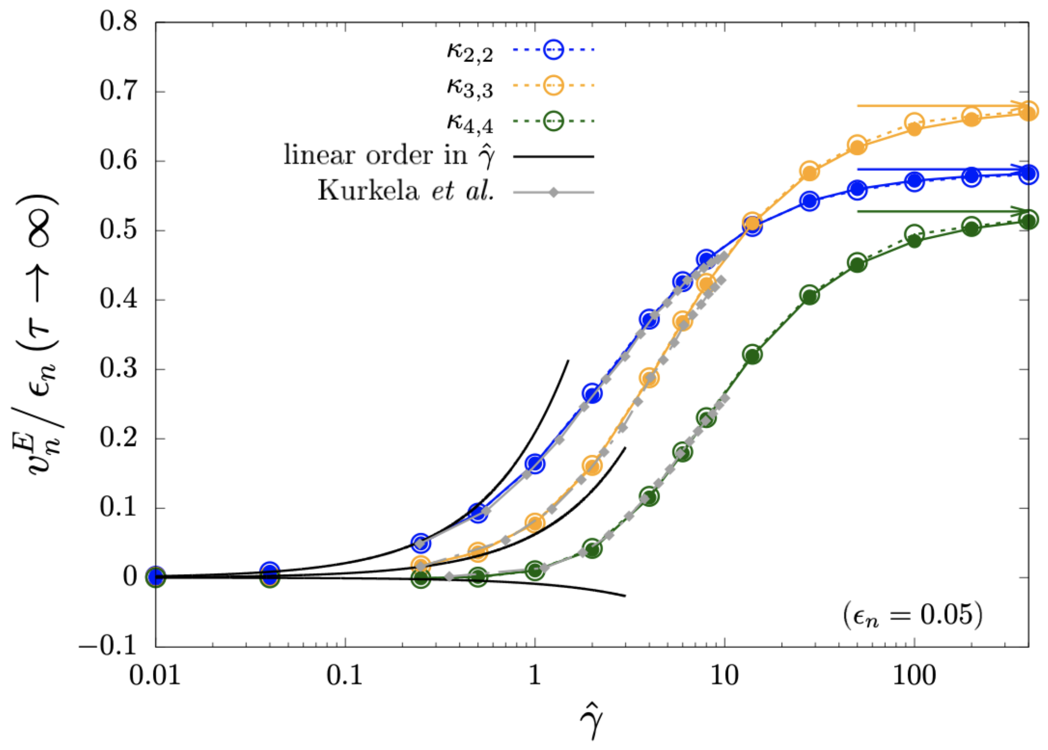
OO: Enough reach to extend clearly to single-hit regime?

Hierarchies in response coefficients:

Single-hit:

$$\frac{v_2}{\epsilon_2} > \frac{v_3}{\epsilon_3}$$

Energy weighted



Hydro flow:

$$\frac{v_2}{\epsilon_2} < \frac{v_3}{\epsilon_3}$$

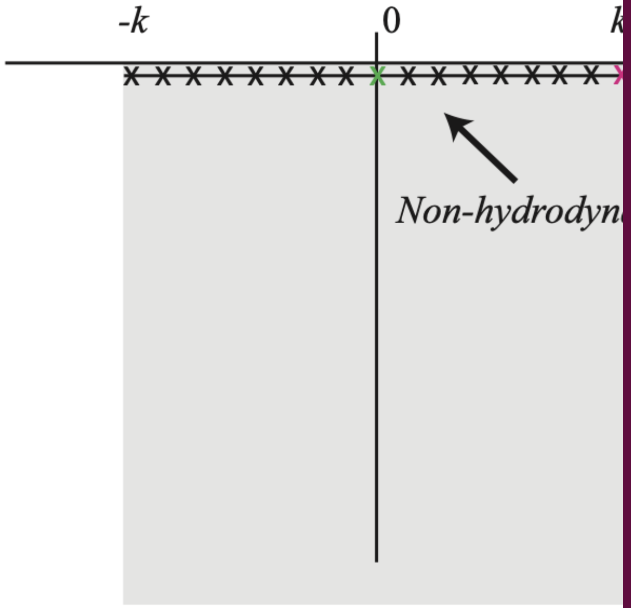
Energy weighted

RTA: Kurkela, Taghavi, Wiedemann, Wu PLB 811 (2020), Ambrus, Schlichting, Werthmann PRD 105 (2022)
2↔2 KT: Alver, Gombeaud, Luzum, Ollitrault PRC 82 (2010) ; Bachmann, Borghini, Feld, Roch EPJC 83 (2023)
EKT: Kurkela, Mazeliauskas, Törnkvist JHEP 11 (2021) 216

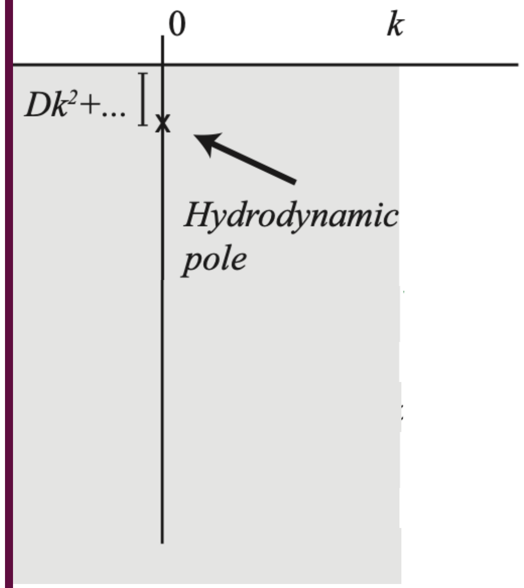
RTA: Romatschke EPJC76 (2016)

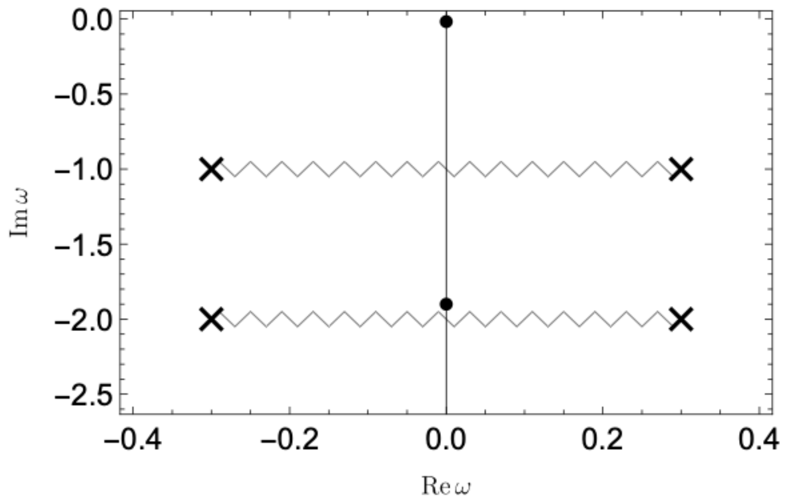
Onset of h

Small system:
free streaming, $k\tau_D \gg$



arge system:
dynamics, $k\tau_D \gg 1$





$$\left(\partial_t + \mathbf{v}_1 \cdot \frac{\partial}{\partial \mathbf{r}_1} + \mathbf{F}_1 \cdot \frac{\partial}{\partial \mathbf{p}_1}\right) f_1 = -\frac{f_1 - f_1^{\text{eq}}}{\tau_R} - \int d^3r_2 d^3p_2 \frac{\partial U_{\text{L}}(\mathbf{r}_1 - \mathbf{r}_2)}{\partial \mathbf{r}_1} \cdot \frac{\partial g_{12}}{\partial \mathbf{p}_1},$$

$$\left(\partial_t + \mathbf{v}_a \cdot \frac{\partial}{\partial \mathbf{r}_a} + \mathbf{F}_a \cdot \frac{\partial}{\partial \mathbf{p}_a}\right) g_{12} = -\frac{g_{12} - g_{12}^{\text{eq}}}{\tau_C},$$

RTA Beyond LO in BBGKY: Grozdanov Soloviev 2501.00099

- Picture more **compli** mplex kinetic theories

kela, Wiedemann EPJC 79 (2019)
enfeld Schlichting *JHEP* 09 (2023)
enfeld, Schlichting PLB 845 (2023)
)6.15531, Lin, Sun Wu 2505.04444
Grozdanov Soloviev 2501.00099

Mass