New theoretical developments

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Initial Stages 2021
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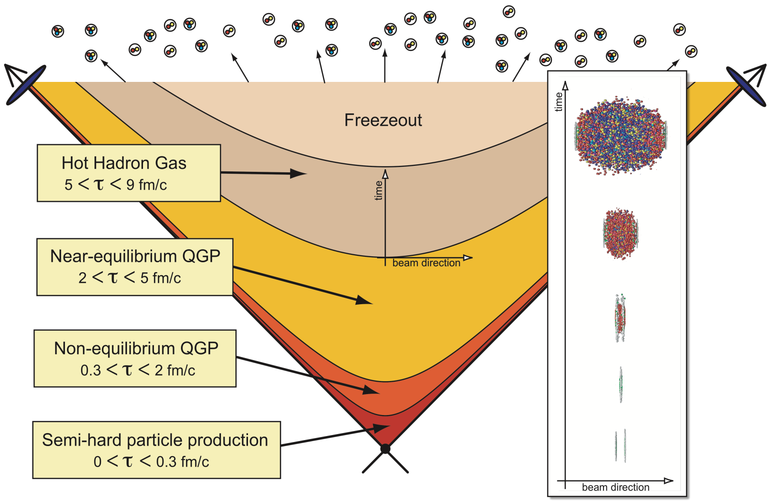
IS2021 raison d'etre

- What is the right way to model the early-time dynamics of the QGP?
- How can we compare our models to experimental measurements?
- Fluctuations in initial geometry at $\tau = \tau_{\text{hydro}}$ are encoded in observed v_n; has allowed us to better understand the spatial structure of the fluctuating initial conditions generated in HIC.
- How does pre-equilibrium evolution modify things?
- Can we learn more detailed information about the initial conditions from experiment? Can we "measure" T_0, initial chemical composition (quarks vs gluon), and/or early-time LRF pressure anisotropy?
- How can we better understand high-multiplicity pp and pA collisions which possess short lifetimes and are farther from equilibrium at freeze-out?

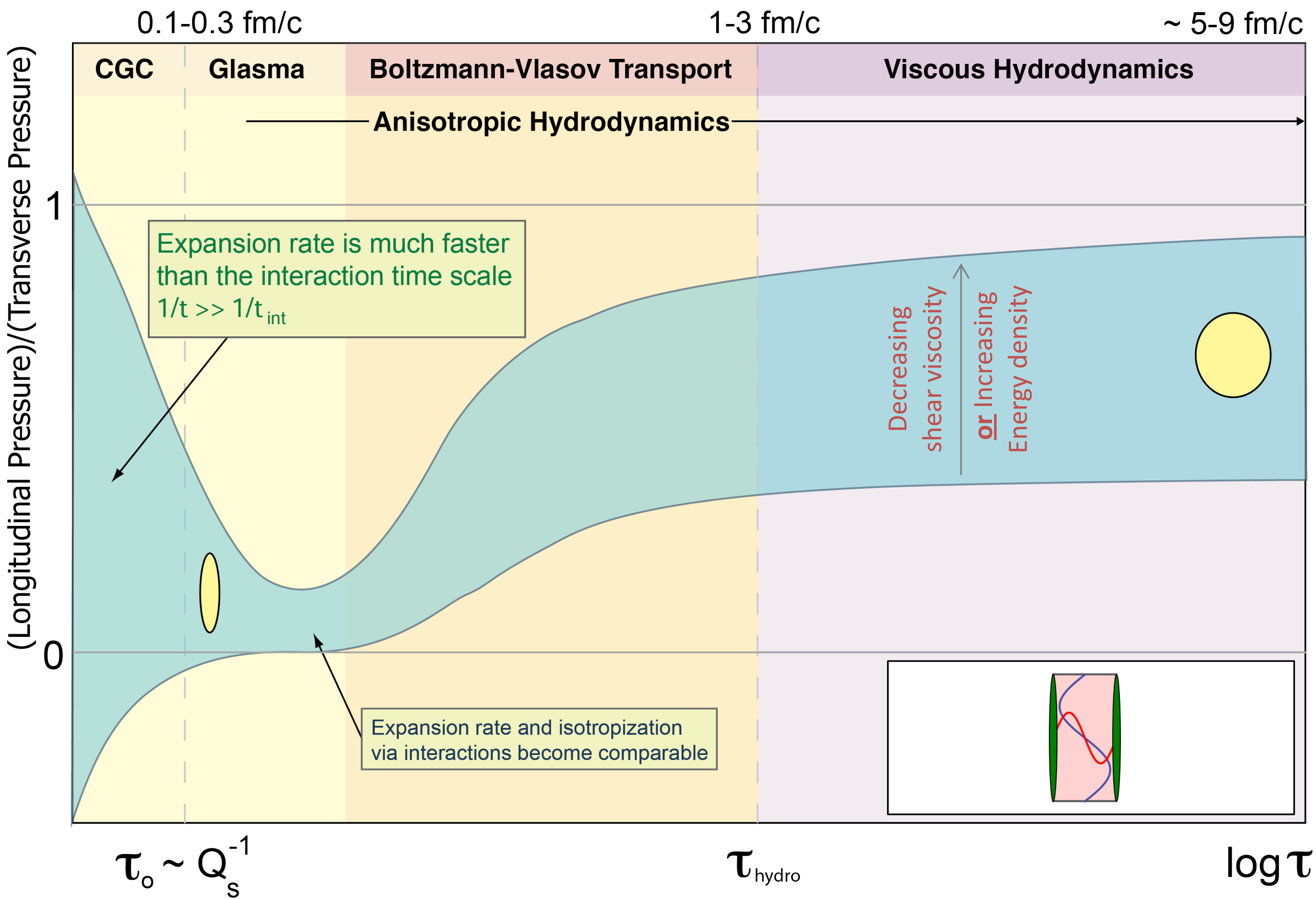
Variety of probes

- In AA collisions, soft-hadronic production (e.g. pions) occurs at "late" times; part of the information about the initial state is lost during the hydrodynamical evolution.
- When studying initial state physics **hard probes** are very important
  - high-energy jet suppression
  - heavy quarkonium suppression
  - electromagnetic radiation



- **Electromagnetic radiation** is particularly appealing, since these probes do not experience significant interactions after their production.
- **How do we reliably compute <u>non-equilibrium</u> particle production and transport from first principles QCD?**

QGP momentum anisotropy cartoon



Enter the attractors

Work over the course of the last decade has shown that there exist three dynamical attractors for the non-equilibrium dynamics of the QGP:

1. An **early-time non-thermal attractor** associated with **Classical Yang-Mills (CYM) evolution**; never thermalizes and system generates ever growing momentum anisotropy; however, can be used as IC for the next stage o evolution

   Berges, Boguslavski, Schlichting, Venugopalan, …

2. A **QCD effective kinetic theory (QCD EKT) attractor** that can be matched onto both the early-time CYM non-thermal and late-time hydrodynamical attractors; numerical realization of bottom-up thermalization

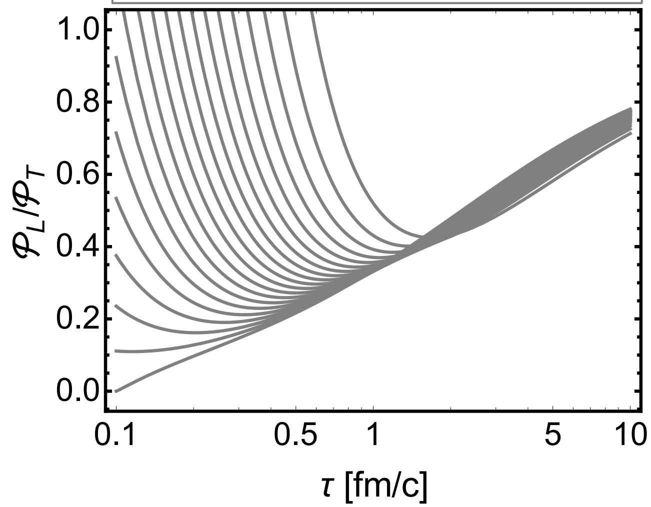
   Kurkela, Zhu, Keegan, Romatschke, van der Schee, Mazeliauskas, Almaalol, MS, Schlicting, Du, Arnold, Moore, Yaffe, Baier, Mueller, Son, Schiff, …

3. A “late time” **universal dissipative hydrodynamical attractor**

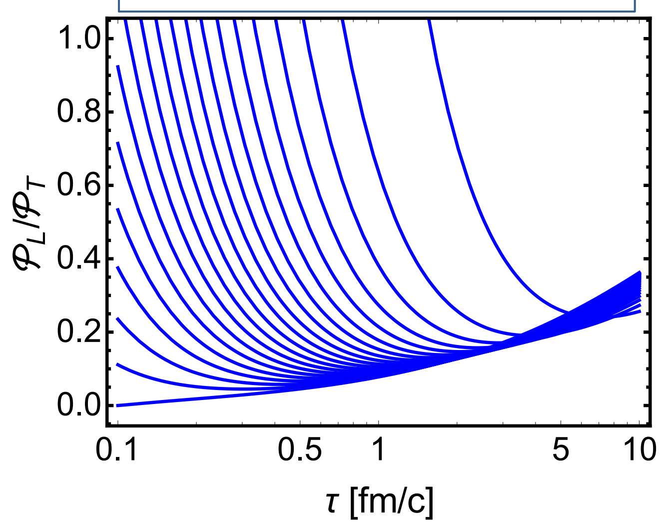
   Heller, Spalinski, Romatschke, Kurkela, Svensson, Denicol, Noronha, MS, Almaalol, Martinez, Brewer, Blaizot, Yan, …

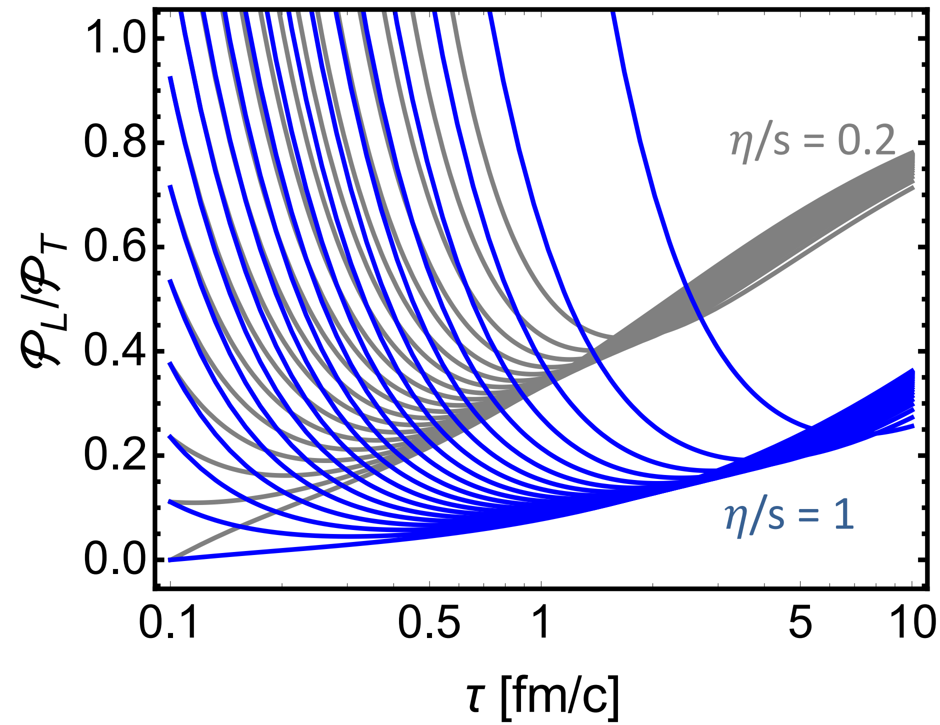
The exact RTA kinetic attractor

Assuming $\eta/s = 0.2$ and $T_0 = 500$ MeV



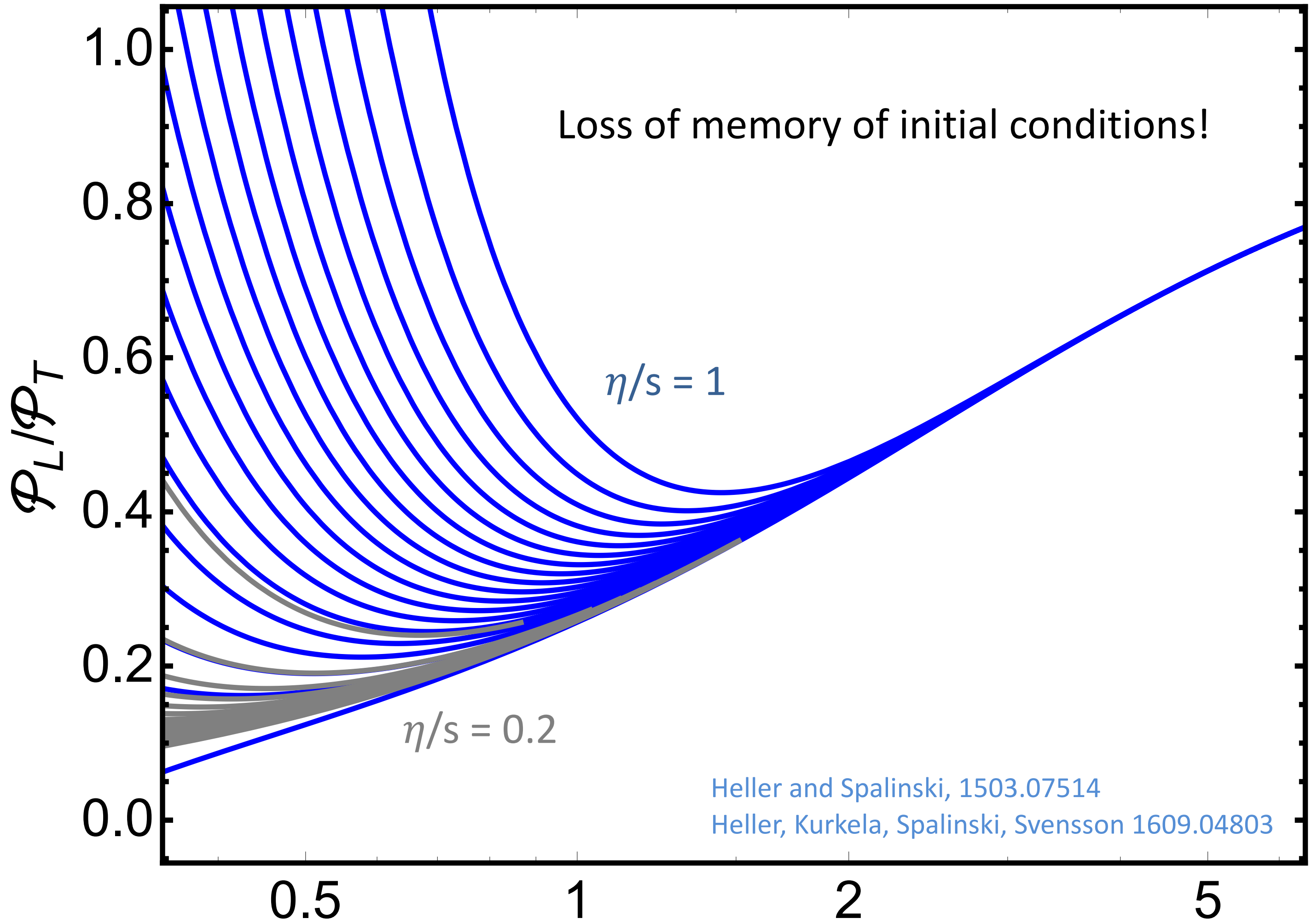
Assuming $\eta/s = 1$ and $T_0 = 500$ MeV





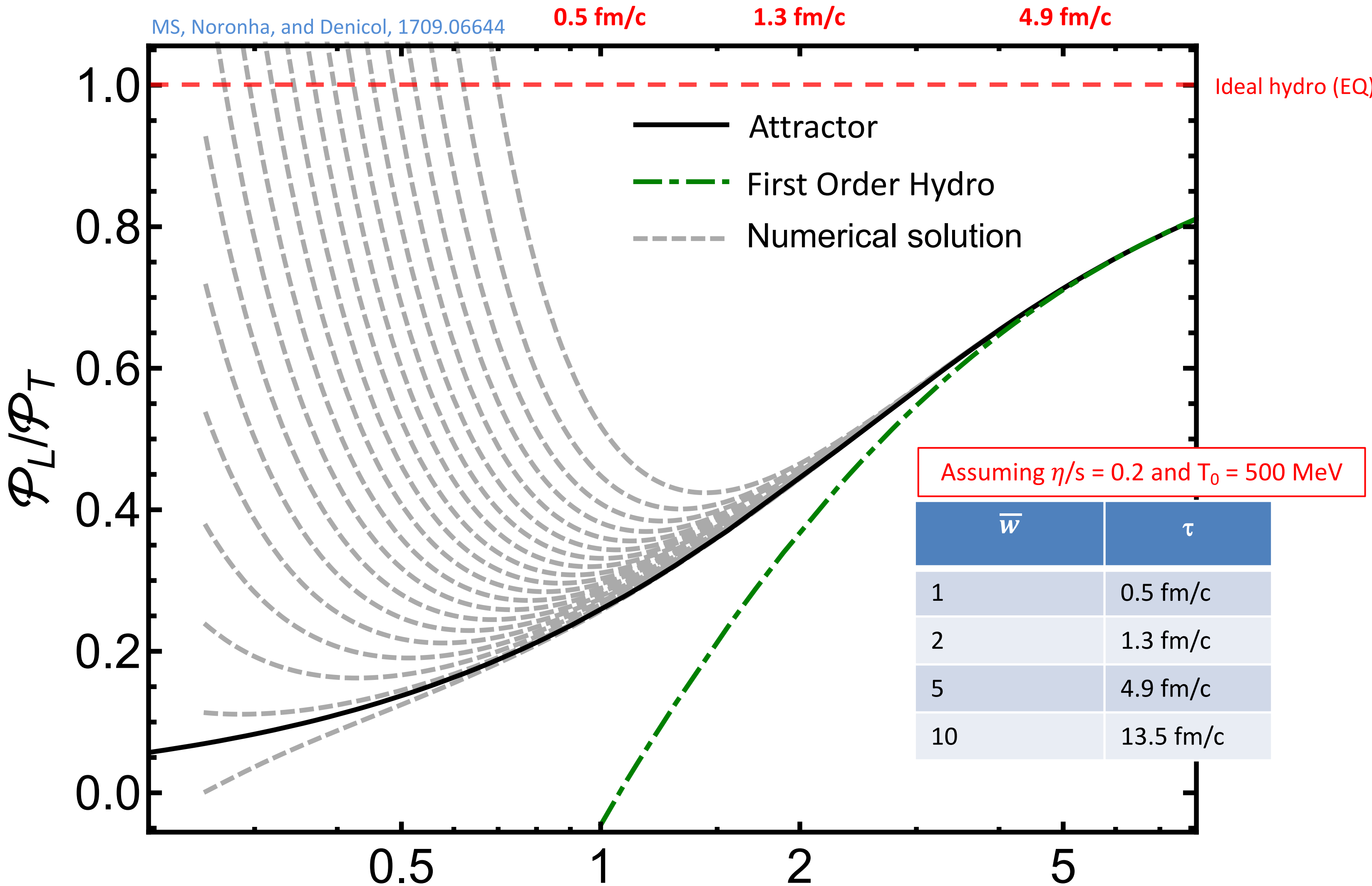
- Keep it simple: Björken 0+1D dynamics.
- Solve dynamical equations for different initial conditions and different values of the shear viscosity (gray vs blue)

Collapsing the results to the attractor



$$\overline{w} = \frac{\tau}{\tau_{\rm eq}(\tau)} = \frac{\tau T(\tau)}{5\bar{\eta}} = \text{Inverse Knudsen \#}$$

The attractor concept



Assuming $\eta/s = 0.2$ and $T_0 = 500$ MeV

$\overline{w}$	τ
1	0.5 fm/c
2	1.3 fm/c
5	4.9 fm/c
10	13.5 fm/c

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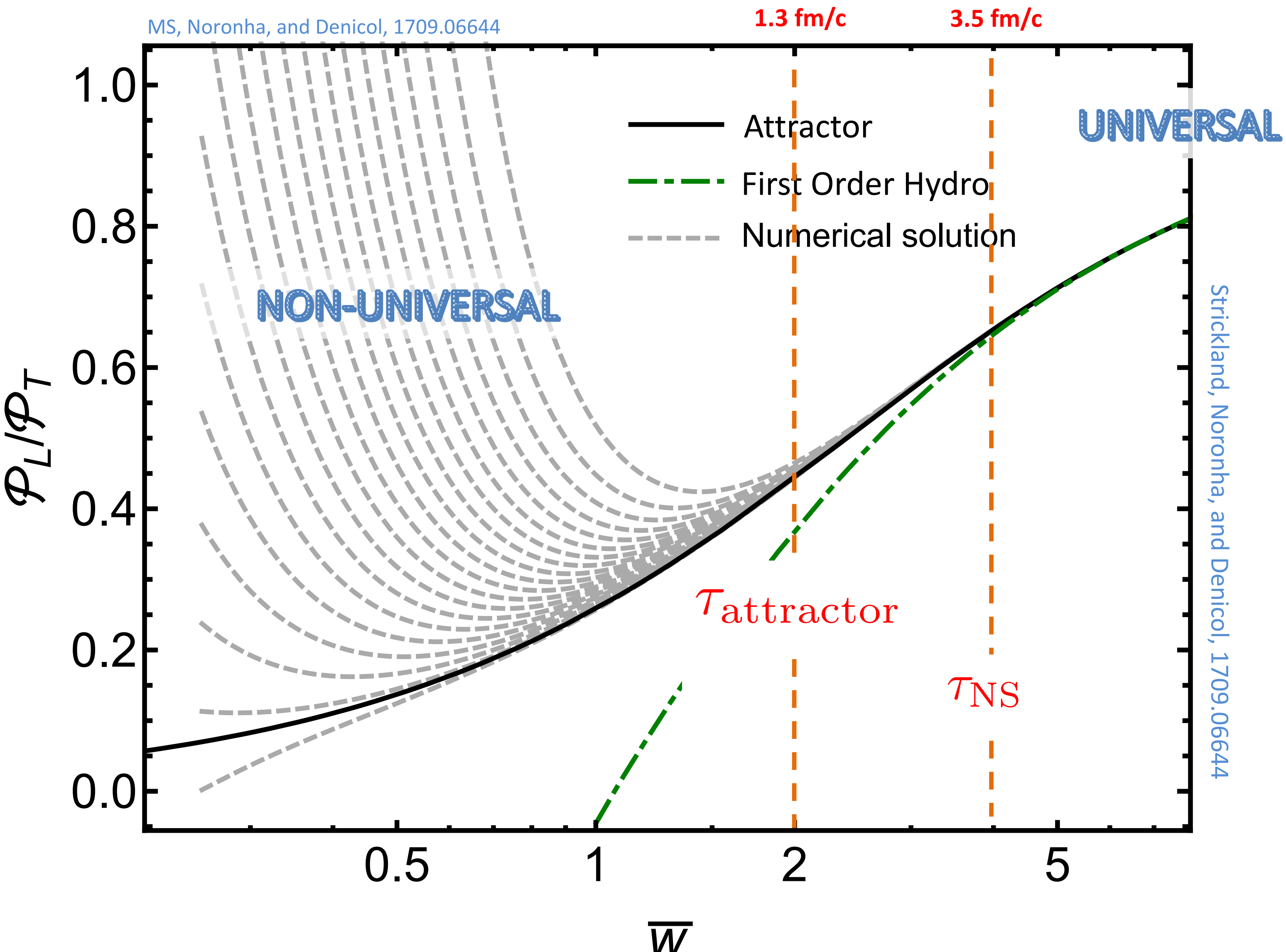
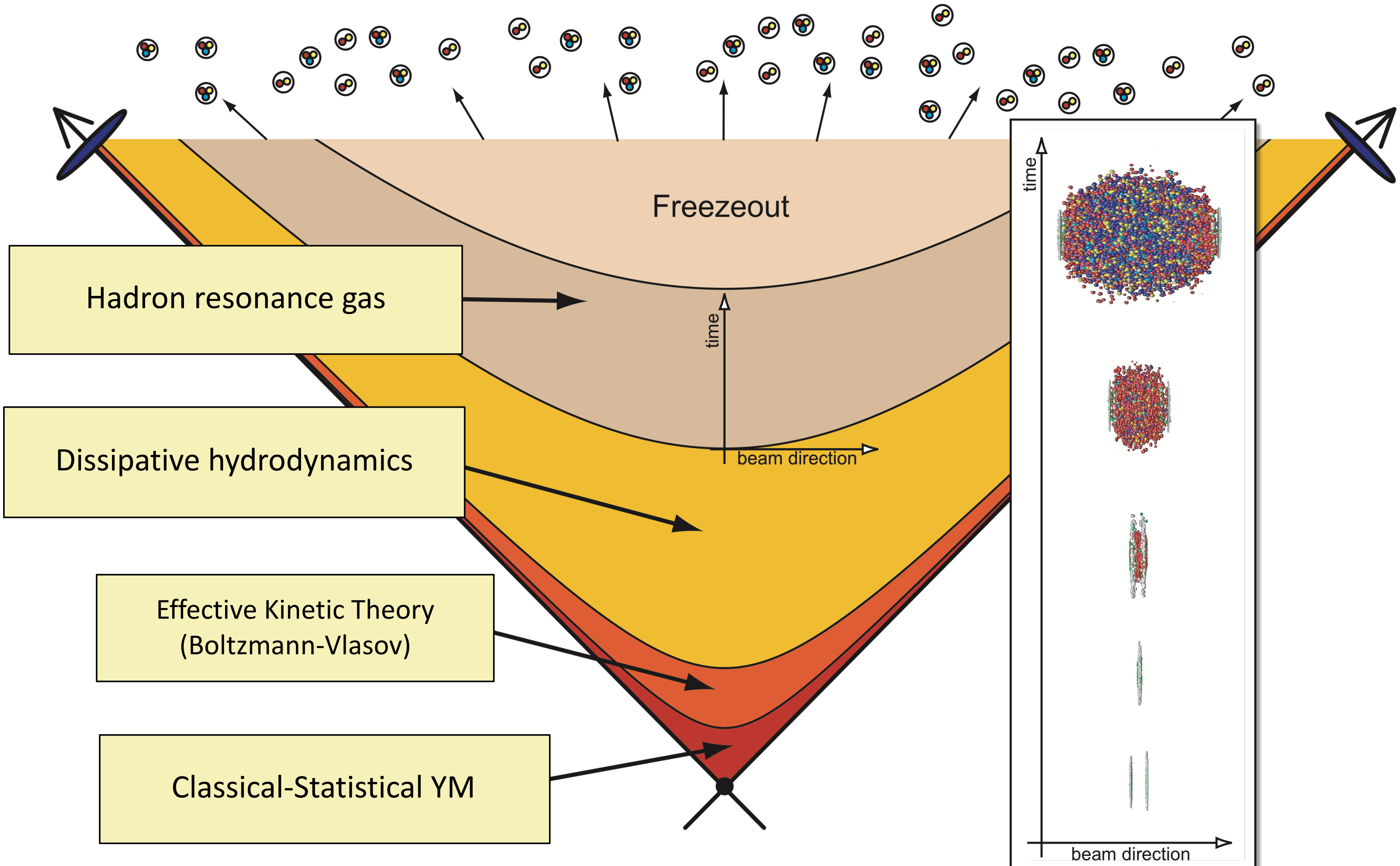


How does this work in practice?



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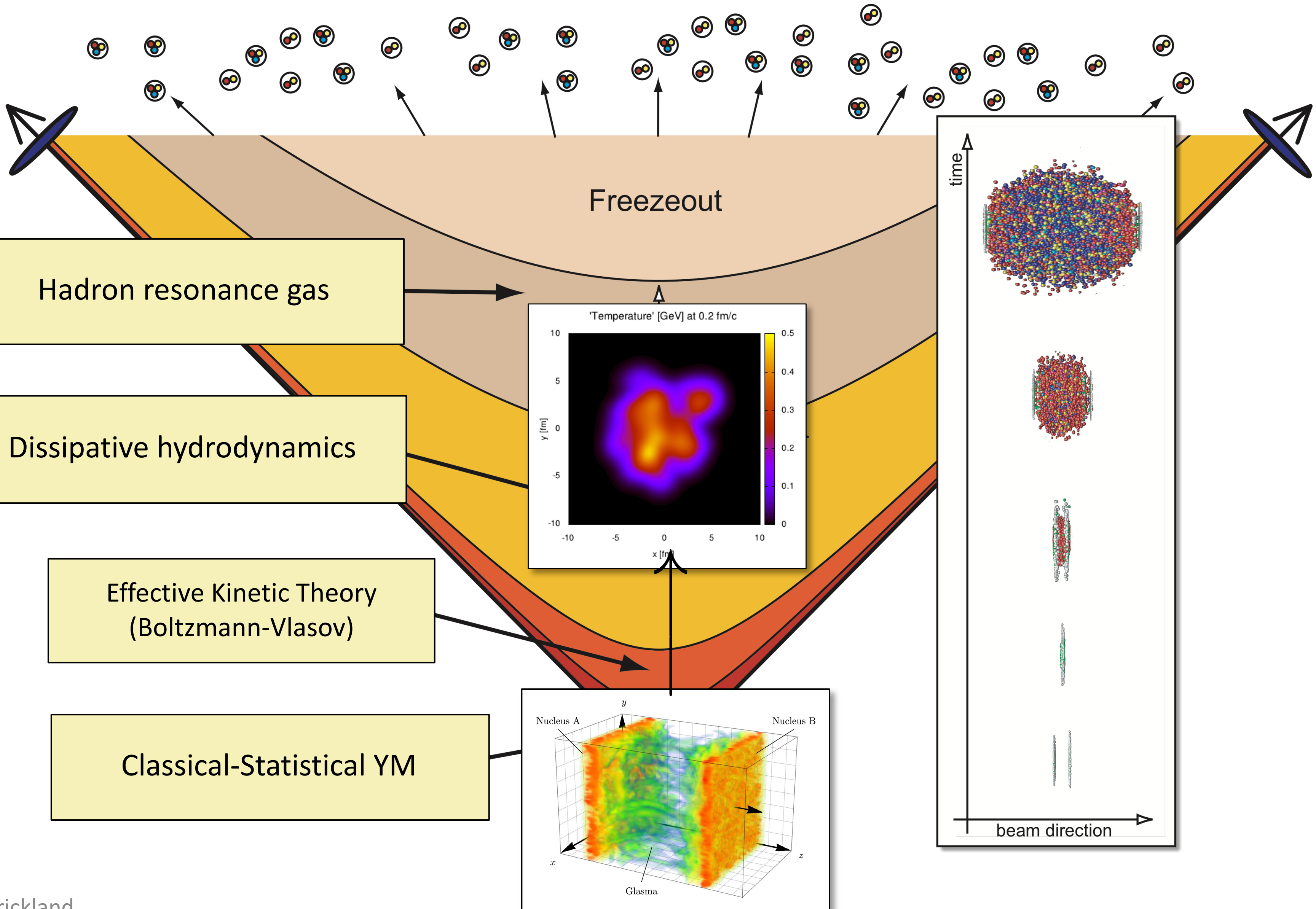
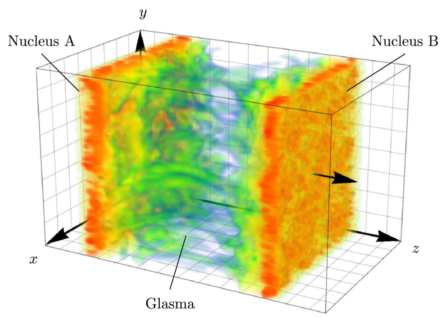
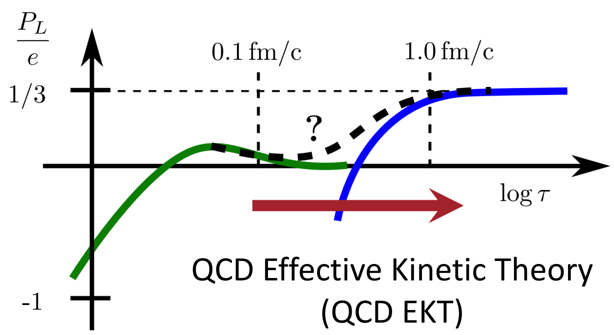
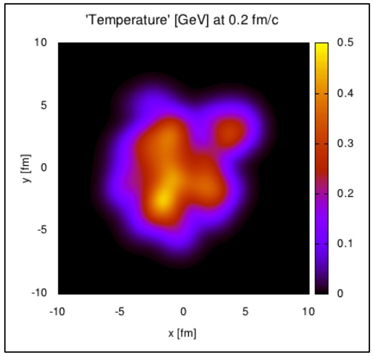


Connecting the dots using QCD EKT

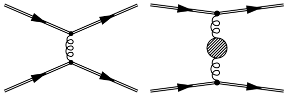






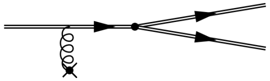
Kurkela, Mazeliauskas, Paquet, Schlichting and Teaney, arXiv:1805.01604, 1805.00961 (KøMPøST)

- Includes elastic 2 ↔ 2 and inelastic 1 ↔ 2 scatterings with LPM suppression
- Based on weak-coupling treatment (HTL quasiparticles)
- Allows for high occupation numbers



$$\partial_\tau f + \frac{\mathbf{p}}{|p|} \cdot \nabla f - \frac{p_z}{\tau} \partial_{p_z} f = -\left(C_{2\to 2}[f] + C_{1\to 2}[f]\right)$$

Baier, Mueller, Schiff, and Son (2001)
Arnold, Moore, Yaffe (2003)



Related IS2021 talks

Glasma

Evolution of energy density correlations in the Glasma
Pablo Guerrero Rodríguez
11/01/2021, 19:40

Non-perturbative renormalization of the average color charge and multi-point correlators of color charge from a non-Gaussian small-x action
André Giannini
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Transverse momentum broadening of jets in the weak field limit of the glasma
Daniel Schuh
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Heavy quark diffusion in an overoccupied gluon plasma
Jarkko Peuron
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Heavy quarks traversing glasma
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Nonperturbative properties of overoccupied gluonic plasmas
Kirill Boguslavski
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Jet momentum broadening in real-time lattice simulations of the glasma
David Mueller
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Kinetic Theory

Emergence of prescaling in far-from-equilibrium quark-gluon plasma
Bruno Sebastian Scheihing Hitschfeld
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Hydrodynamic attractors, initial state energy and particle production in relativistic nuclear collisions
Soeren Schlichting
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Non-equilibrium attractors of QCD kinetic theory at zero and finite density
Xiaojian Du
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New developments in QCD-based kinetic transport theory
Dekrayat Almaalol
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Adiabatic hydrodynamization
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Emergence of slow modes: the governing degrees of freedom in rapidly-expanding quark--gluon plasma
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Application to E&M observables

Preequilibrium dilepton production: concepts, estimates and feasibility
Maurice Louis Coquet
12/01/2021, 17:00

Accessing the initial stages of heavy ion collisions with photons
Bjoern Schenke
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Photon emission in initial and hydrodynamic stages of nuclear collisions
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Beyond hydrodynamics?

- Can the concept of a non-equilibrium attractor be extended beyond the 14 degrees of freedom described using the energy-momentum tensor, number density, and diffusion current?
- In kinetic theory we describe things in terms of a one-particle distribution function **f(x,p)** and the energy-momentum tensor is obtained from low-order moments:

$$T^{\mu\nu} = \int dP \, p^{\mu} p^{\nu} f(x,p) \qquad dP = \int \frac{d^3p}{(2\pi)^3 E}$$

- What about more general moments of f? Particularly ones that are sensitive to higher momenta?

Beyond hydrodynamics?

- For a conformal (massless) system it suffices to consider

$$\mathcal{M}^{nm}[f] \equiv \int dP \, (p \cdot u)^n \, (p \cdot z)^{2m} \, f(x,p)$$

- This encompasses the moments necessary to construct the energy momentum tensor, e.g. below, and <u>more</u>

$$\varepsilon = \mathcal{M}^{20} = \int dP \, (p \cdot u)^2 \, f(\tau, w, p_T) = T^{00}_{\rm LRF}$$

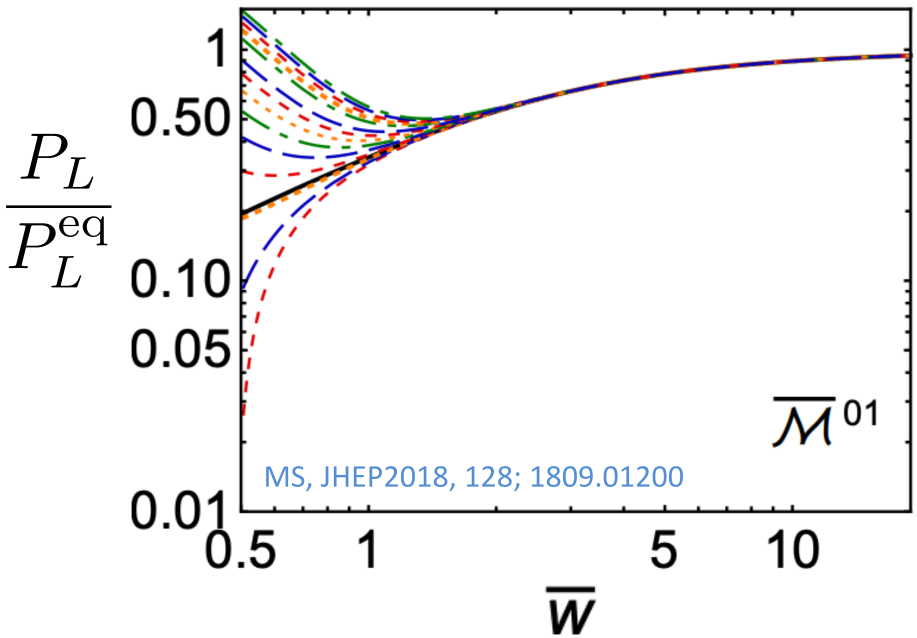
$$P_L = \mathcal{M}^{01} = \int dP \, (p \cdot z)^2 \, f(\tau, w, p_T) = T^{zz}_{\rm LRF}$$

Evidence for a QCD EKT attractor

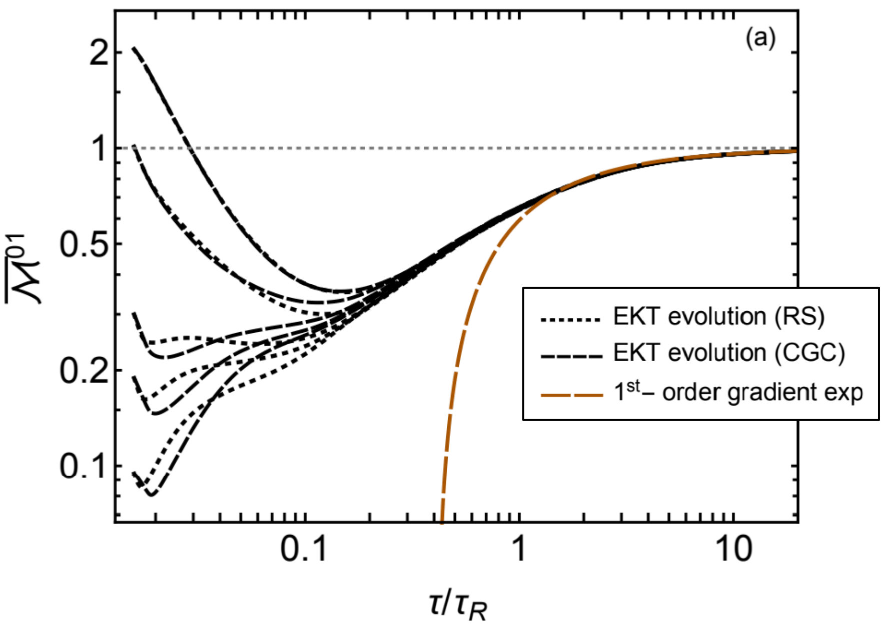
D. Almaalol, A. Kurkela, and MS, PRL 125, 122302 (2020)

- Numerical implementation of pure glue AMY effective kinetic theory (EKT)
- Includes **elastic gluon scattering** and **inelastic gluon splitting** with LPM suppression and detailed balance.
- We use the "pure glue" EKT code of Kurkela and Zhu PRL 115, 182301 (2015)
- 250 x 2000 x 1 grid in momentum space (n_p x n_θ x n_ϕ)

RTA



EKT QCD



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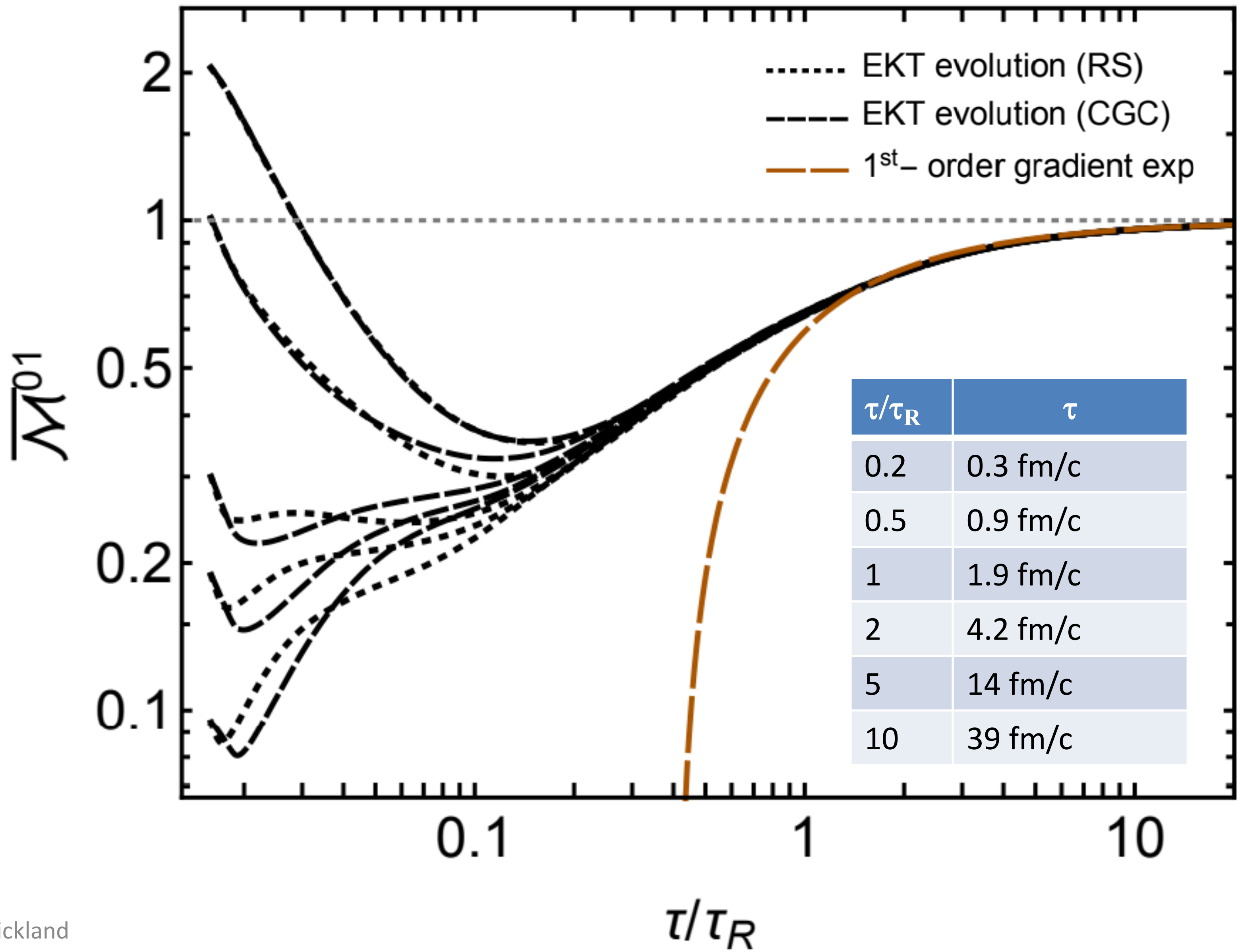
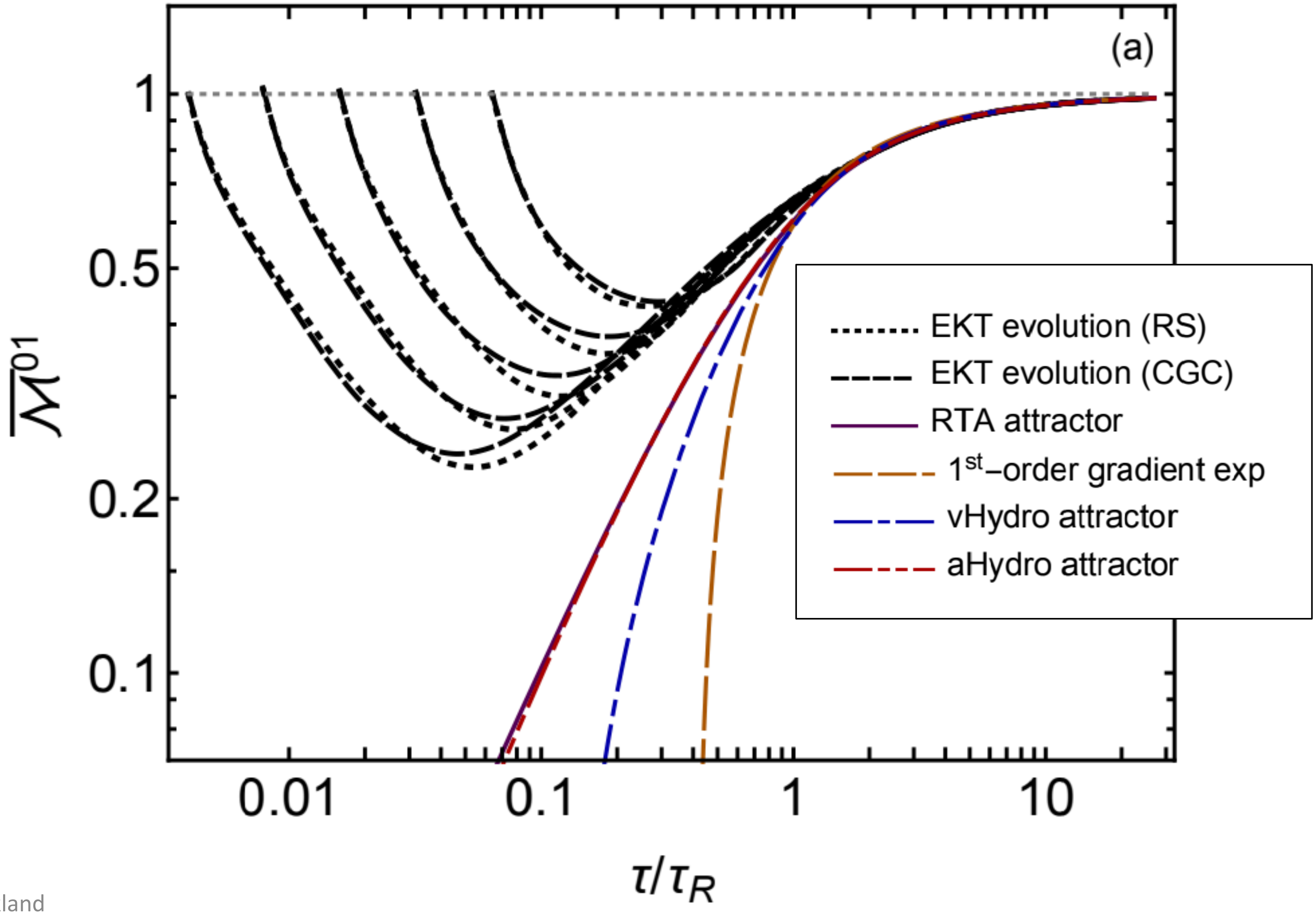


τ/τ_R	τ
0.2	0.3 fm/c
0.5	0.9 fm/c
1	1.9 fm/c
2	4.2 fm/c
5	14 fm/c
10	39 fm/c

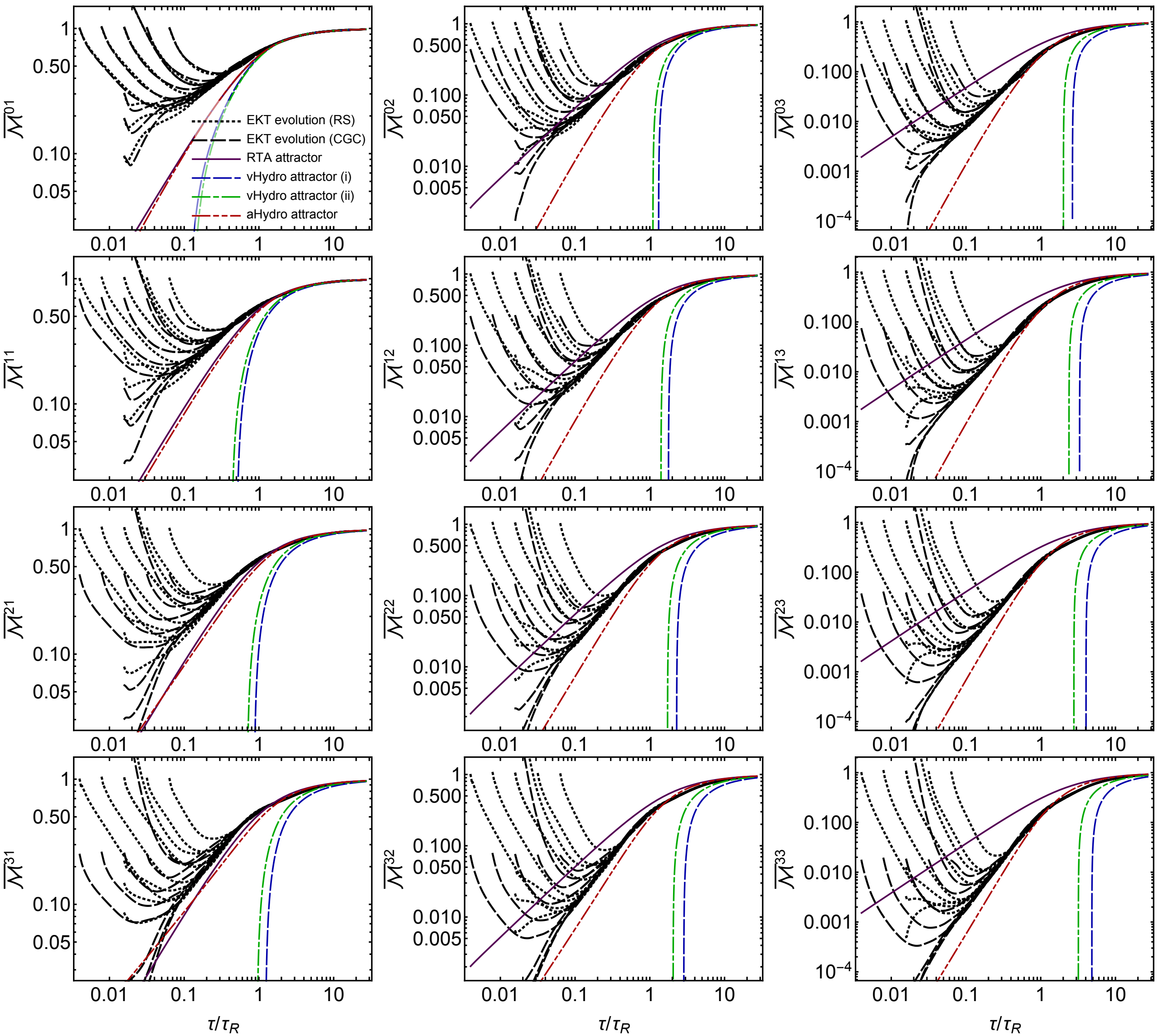
Is there an early-time attractor?

D. Almaalol, A. Kurkela, and MS, PRL 125, 122302 (2020)



Varying initial anisotropy and τ_0

D. Almaalol, A. Kurkela, and MS, PRL 125, 122302 (2020)



- **Attractor seen in all moments and is the same for both types of initial conditions.**
- For low order moments, EKT QCD is closer to EQ than RTA and hydro predictions.
- For high order moments the opposite is true.
- **Can be used to constrain freeze-out f (see poster and talk by D. Almaalol)**
- Suggests that there is an attractor for the entire one-particle distribution function!

Conclusions

- Initial state of QGP is not in equilibrium.
- In order to understand it and potentially measure its properties we must understand non-equilibrium dynamics and fold this together with, e.g. electromagnetic production calculations.
- Existence of attractors helps to simplify the calculation: Leading-order approximation is to flow along attractor.
- Helps to remove ambiguities in the calculation.
- Can also use attractors to test different hydrodynamic approximations, both evolution and freeze-out (see poster and talk by D. Almaalol)