Heavy Ions theory review

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IGFAE - Santiago de Compostela

Yocto/LHC
Yoctosecond imaging of QCD collectivity using jet observables
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QCD and collectivity

Standard Model built/discovered looking for the **highest possible degree of simplicity**

All particle content and interactions of the Standard Model discovered using this principle
— greatest success of the reductionistic approach in Physics

Also very successful — **Complex systems with emerging behavior**

[Strongly-coupling many body systems; quantum entanglement with many d.o.f…]

Region of transition — largely unknown

QCD — rich dynamical content, with emerging dynamics
that happens at scales easy to reach in collider experiments

Best available tool to study the first levels of complexity

Equilibrium AND non-equilibrium dynamics

QCD phase diagram

QCD — rich dynamical content, with emerging dynamics
that happens at scales easy to reach in collider experiments — e.g. EoS

Experimental tools

High-energy heavy-ion coll. [high T, low n_B]

LHC — pp, pPb, PbPb, XeXe, (other lighter ions under study)

RHIC — pp, dAu, AuAu, CuCu, UU,…

Medium energies HIC [moderate T, high n_B]

RHIC Beam Energy Scan

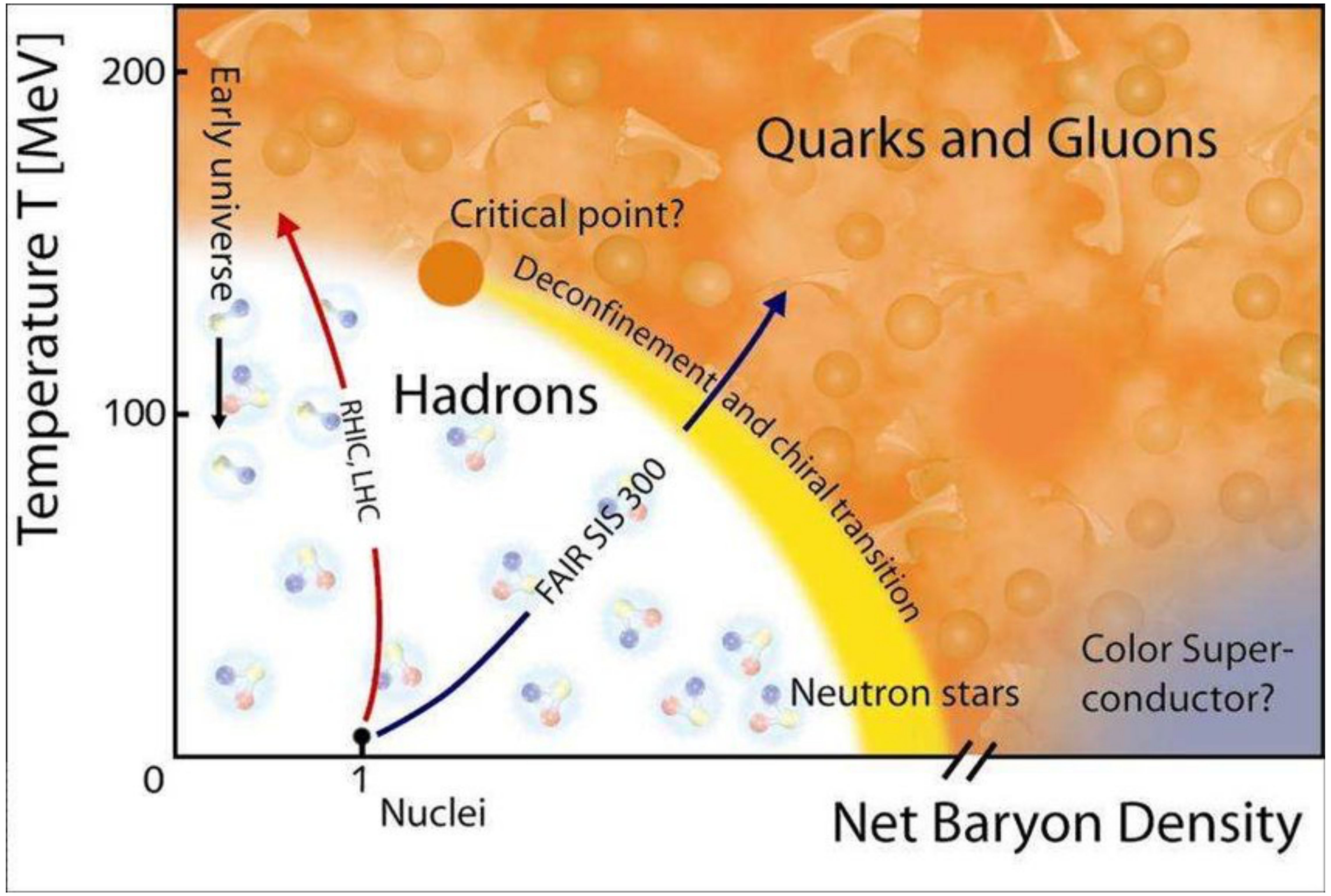
FAIR at GSI

NICA at Dubna

Cosmological observations — notably GWs

Neutron star coalescence - **low T, high n_B**

Future — access to QCD transition in early Universe?



[See talks by Pasztor and Philipsen]

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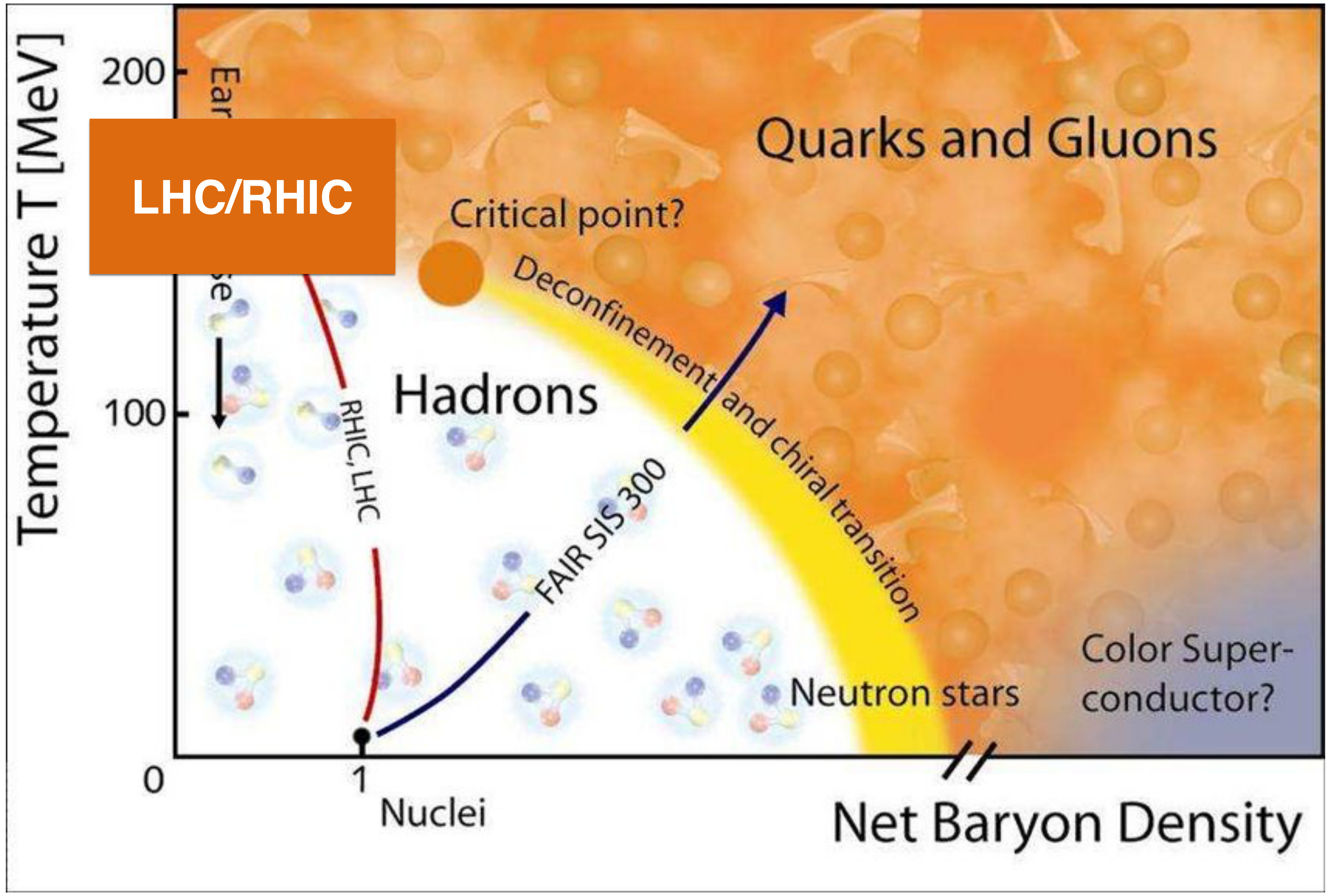

[See talks by Pasztor and Philipsen]

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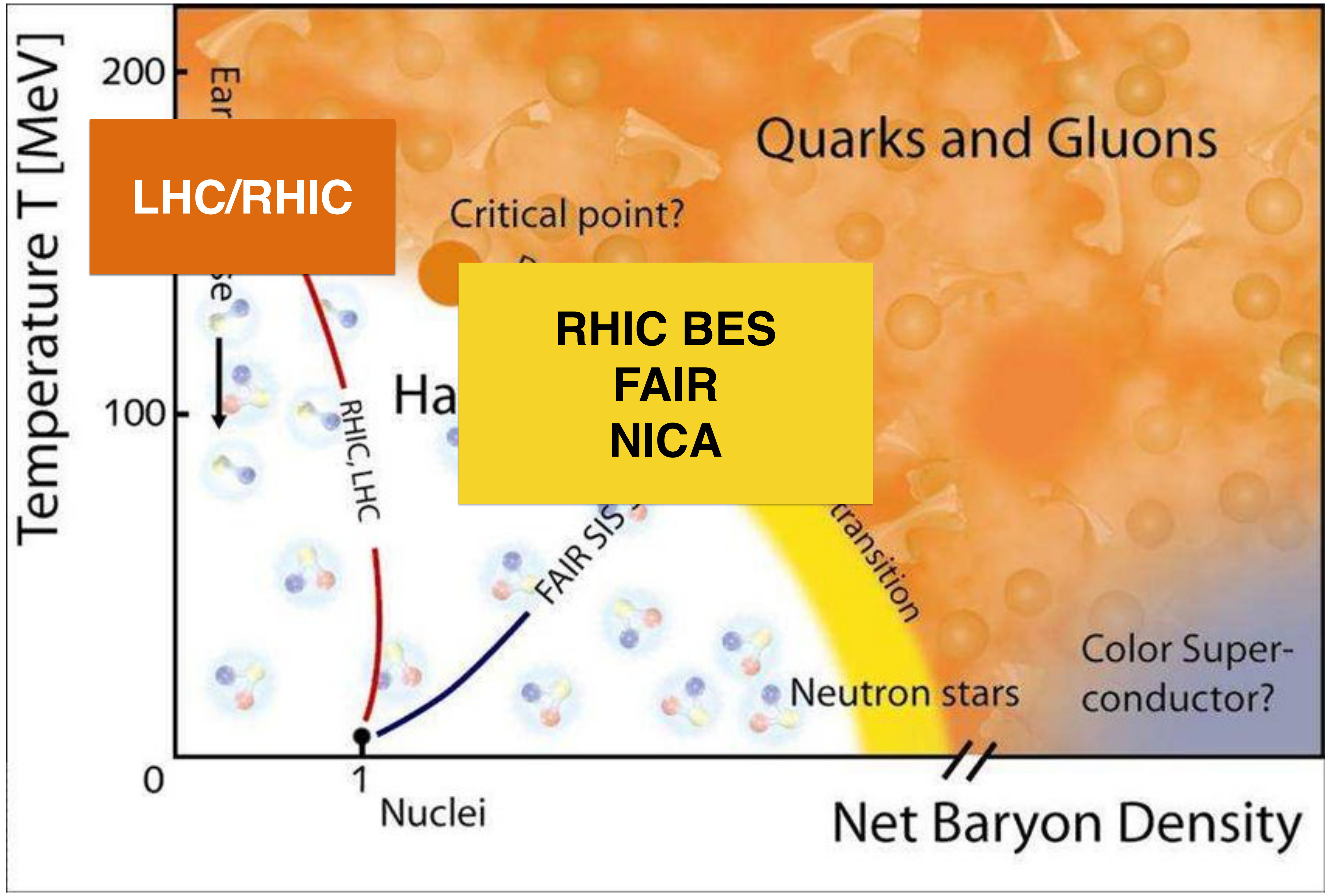

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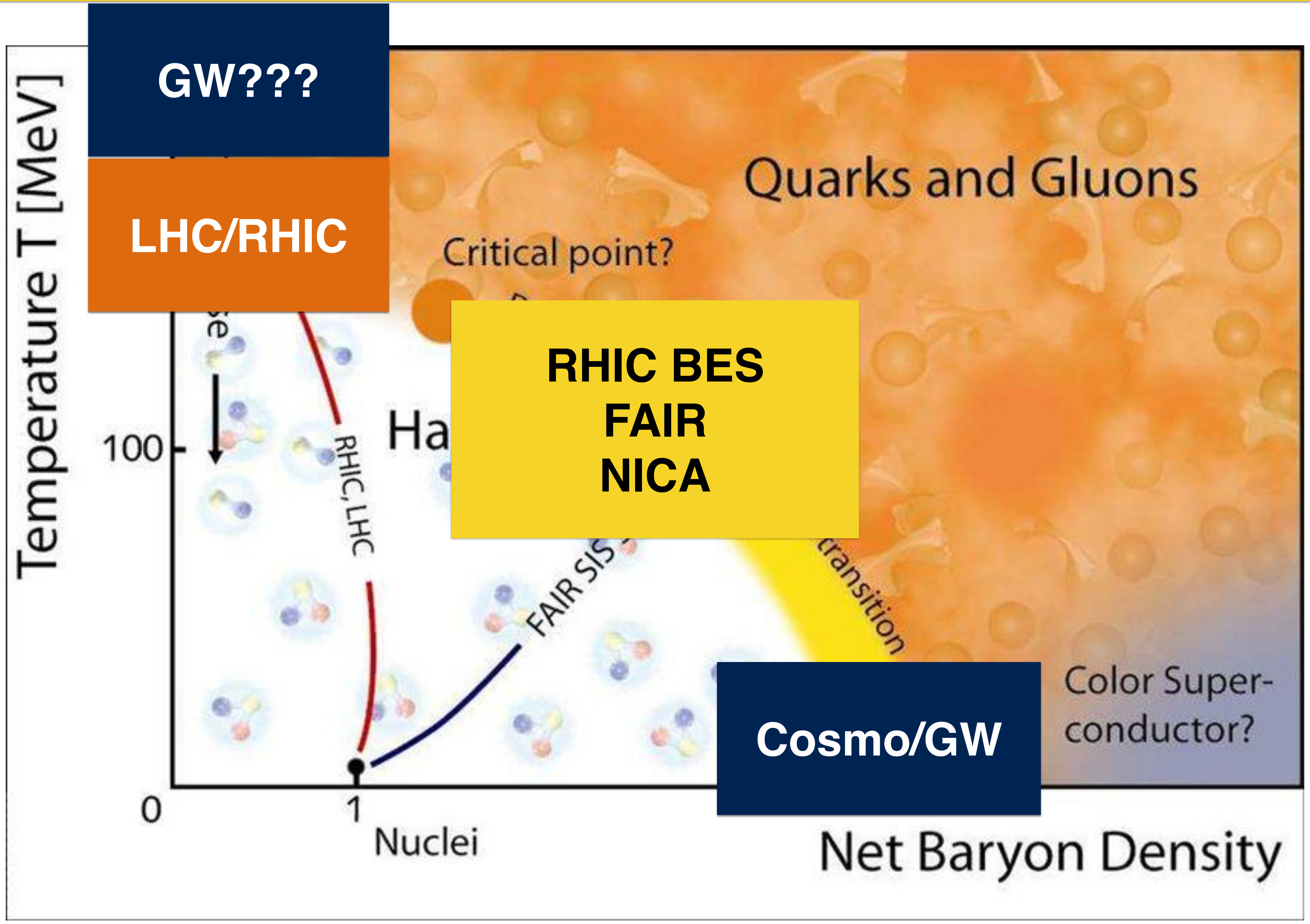
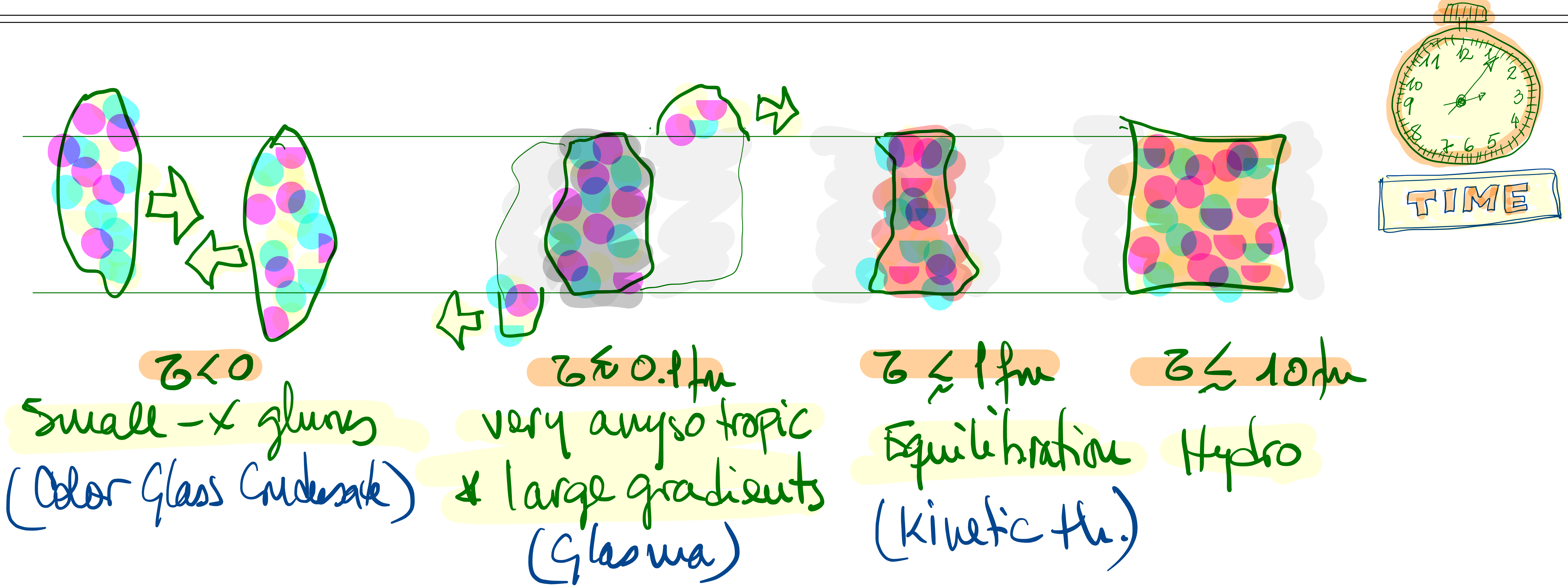


[See talks by Pasztor and Philipsen]

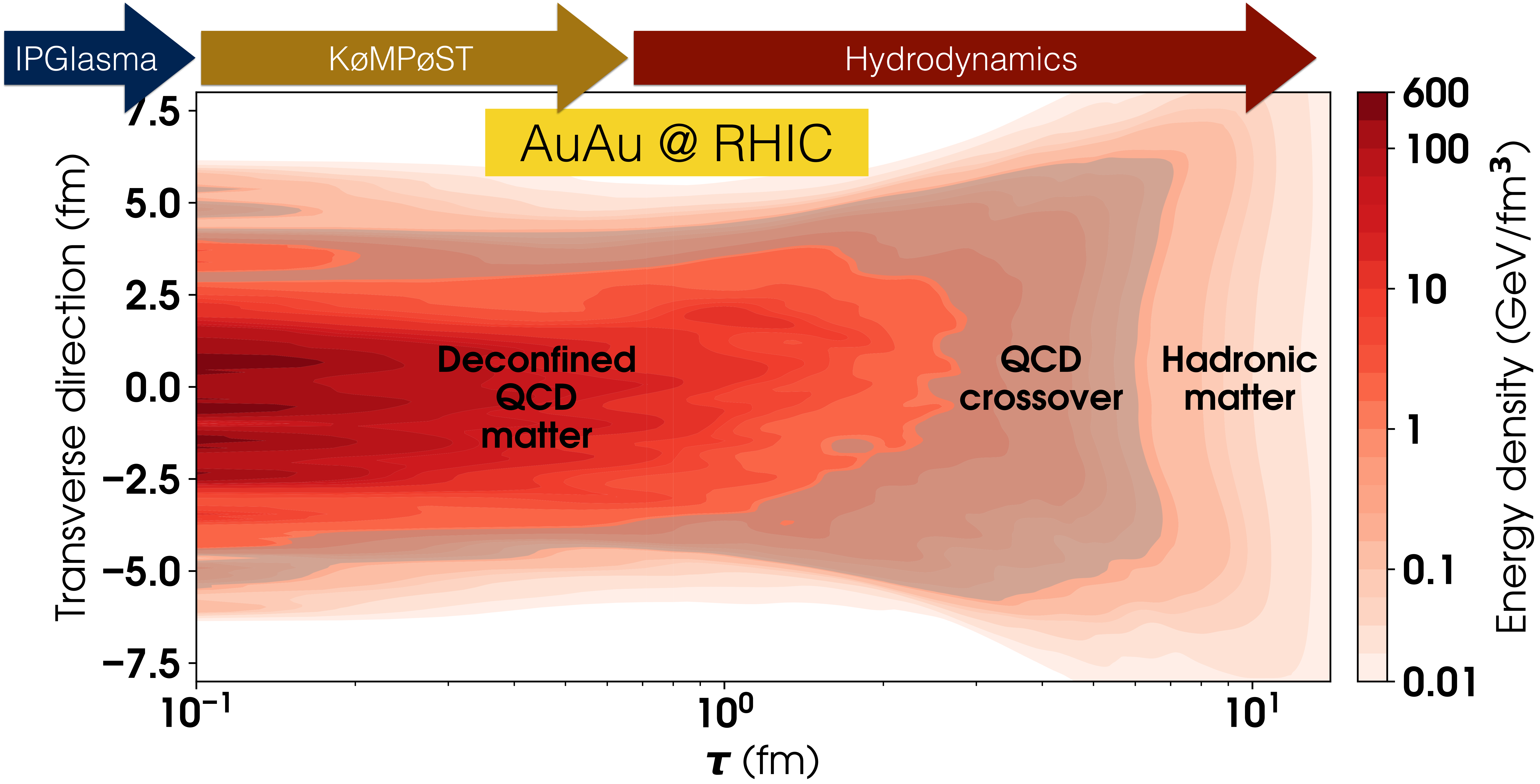
(A possible) Time evolution of a HIC



In contrast to usual HEP, **time and distance are relevant variables** in heavy-ion collisions

Building collectivity in extended (macroscopic) systems

(A possible) Time evolution of a HIC



[Jean-François Paquet - talk at Initial Stages 2021]

Questions accessible in HIC

What is the structure of the colliding objects?

- Small-x region of the nuclear (hadron) wave function
- Fix out-of-equilibrium initial stages with well-controlled theoretical framework

What is the dynamics at the initial stages after the collision?

- Mechanism of isotropization/equilibration/thermalization — classical/quantum
- When/how/why hydrodynamics apply?

What are the properties of the produced medium?

- identify signals to characterize the medium with well-controlled observables
- what are the building blocks and how they organize?
- is it strongly-coupled? quasiparticle description? phases?

Out of equilibrium

Towards equilibrium

Local equilibrium

Questions accessible in HIC

First ~5 yoctoseconds or 1.5fm/c

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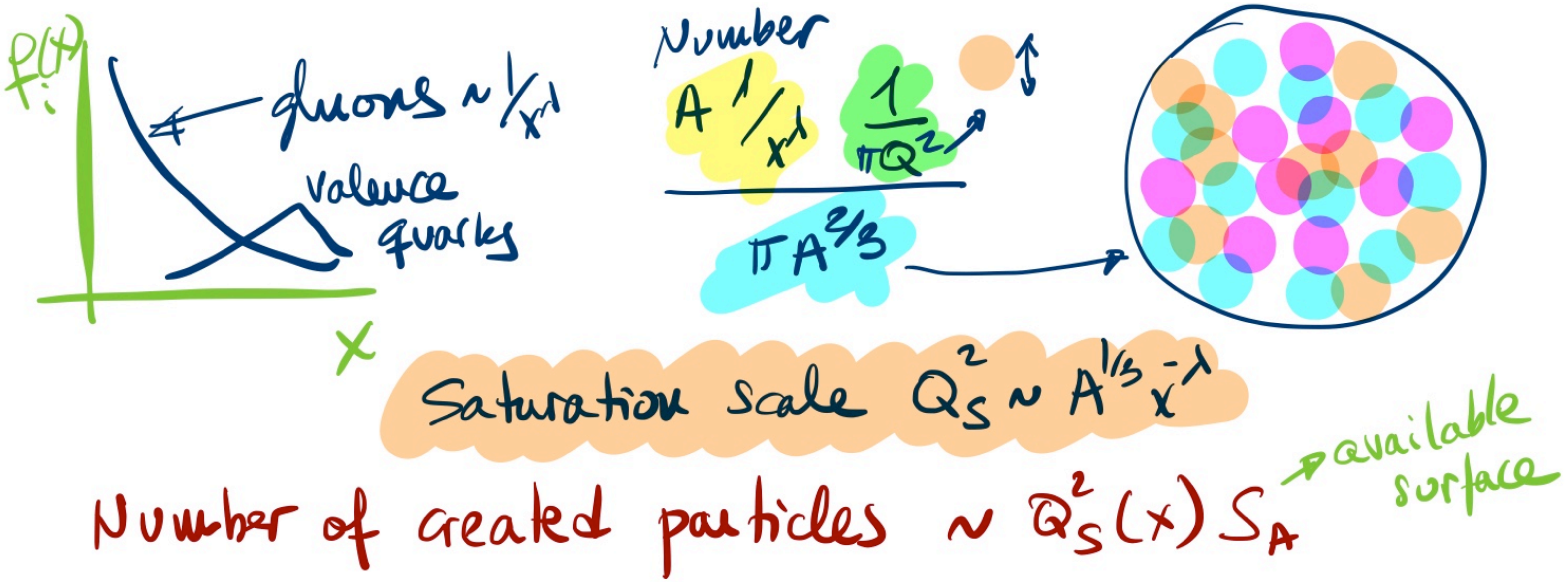
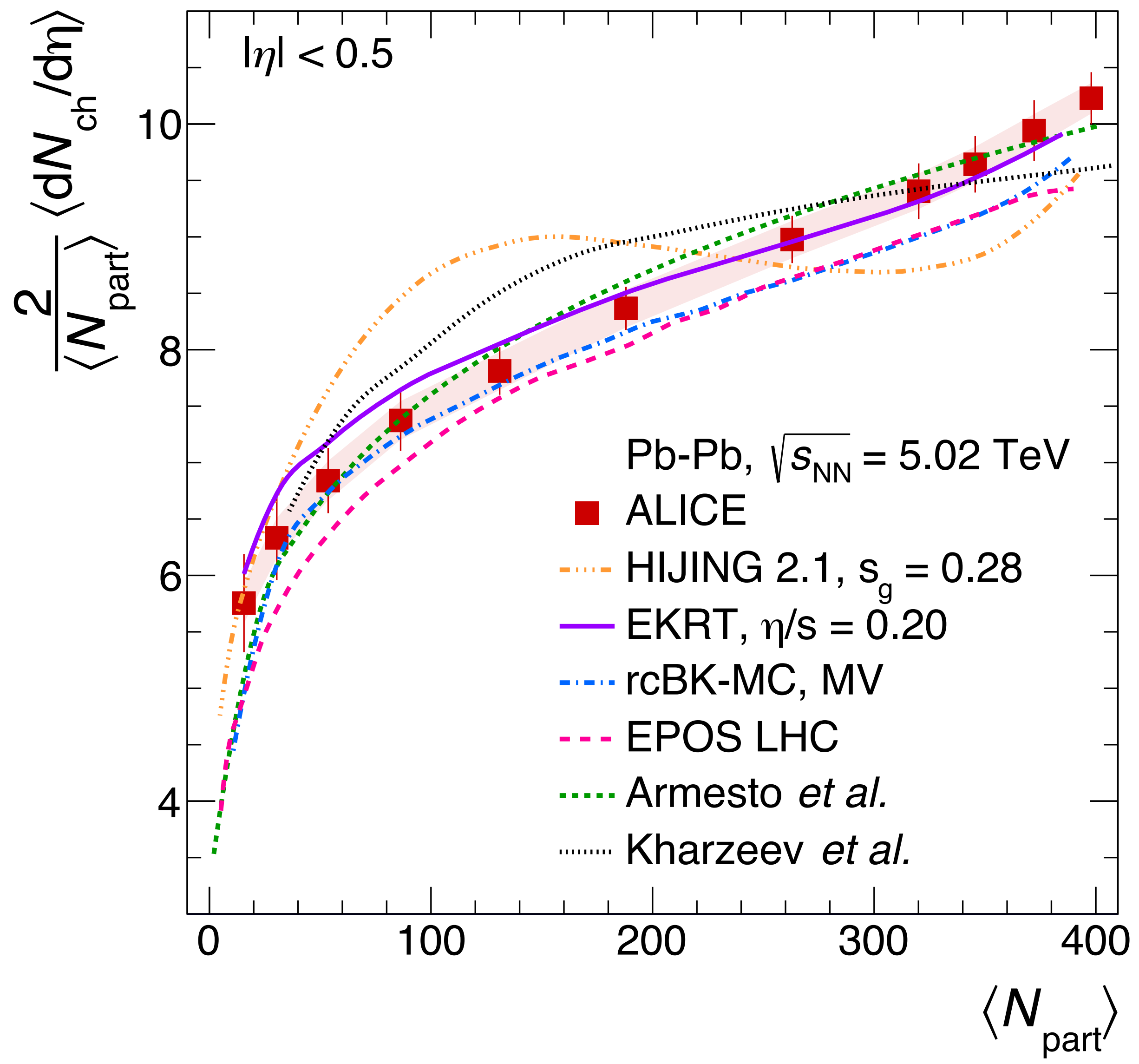
Out of equilibrium

Towards equilibrium

Local equilibrium

Saturation - Color Glass Condensate



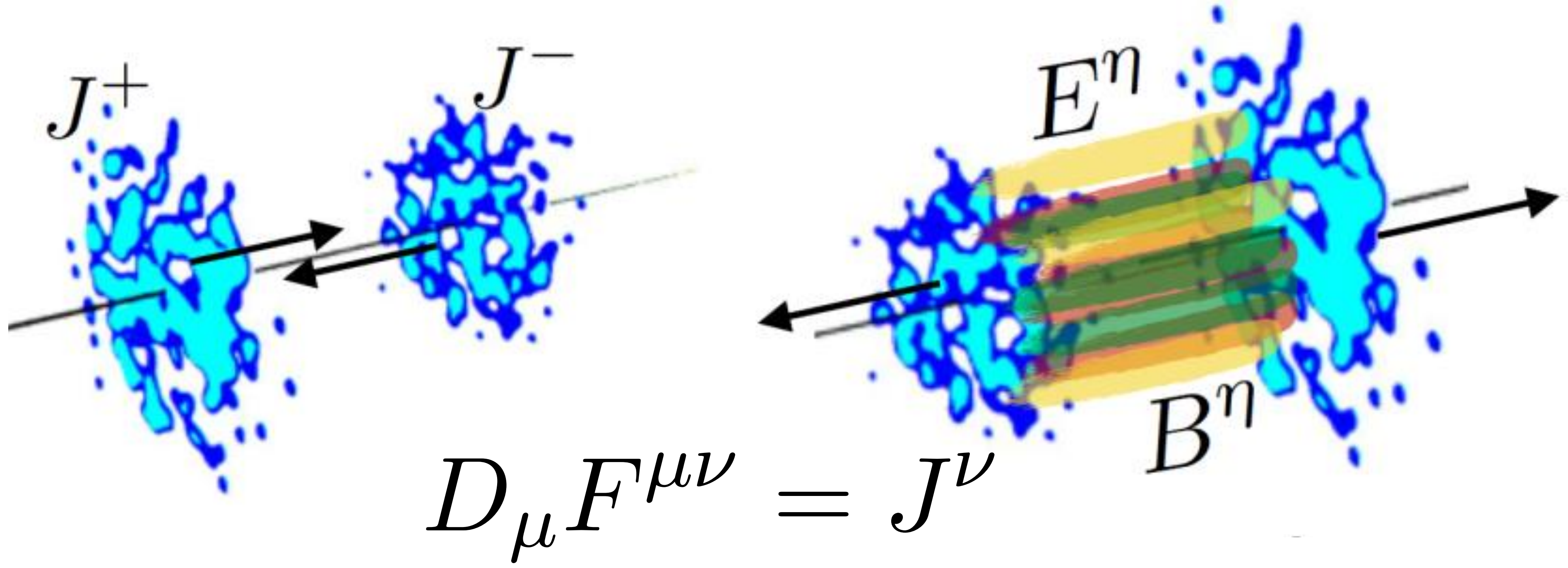


Color Glass Condensate

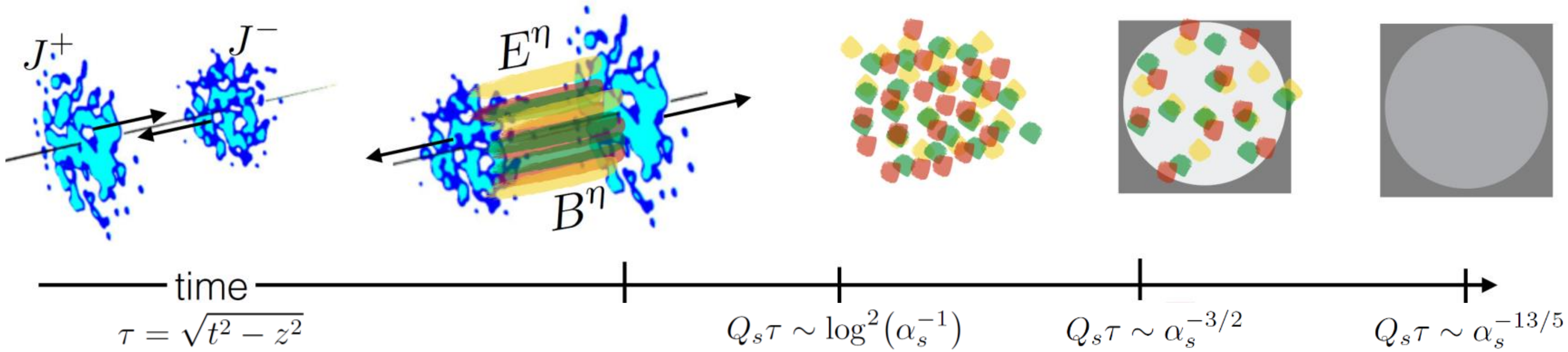
Large occupation numbers - classical fields

Quantum Corrections - evolution eqs.

Color Glass Condensate provides a general framework to compute initial stages



A picture for equilibration



Sören Schlichting

[Classical statistical/lattice gauge theory…]

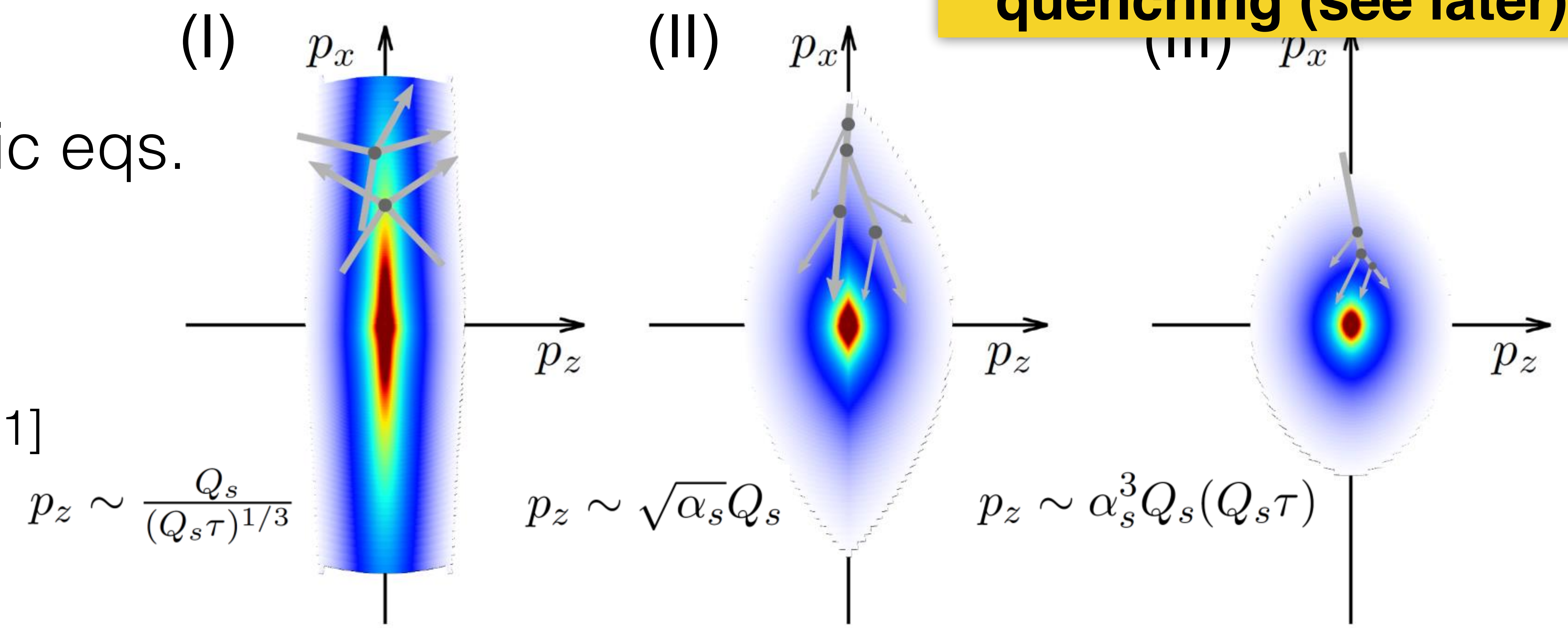
Notice: similar to jet quenching (see later)

Evolution of boost-invariant system with kinetic eqs.

$$p^\mu \partial_\mu f(x,p) = \mathcal{C}_{2\leftrightarrow 2}[f] + C_{1\leftrightarrow 2}[f]$$

[Bottom-up thermalization — Baier, Mueller, Schiff, Son 2001]

[Arnold, Moore, Yaffe 2001; Kurkela, Zhu 2015; Keegan, Kurkela, Mazeliauskas, Teaney 2016; Kurkela Mazeliauskas, Paquet, Schlichting, Teaney 2019…]



Hydrodynamics

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

$$T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu} + \text{viscosity corrections}$$

(+ Equation of State)

+ initial time
+ freeze-out temperature

Far from equilibrium initial state needs to equilibrate fast (~1 fm or less)

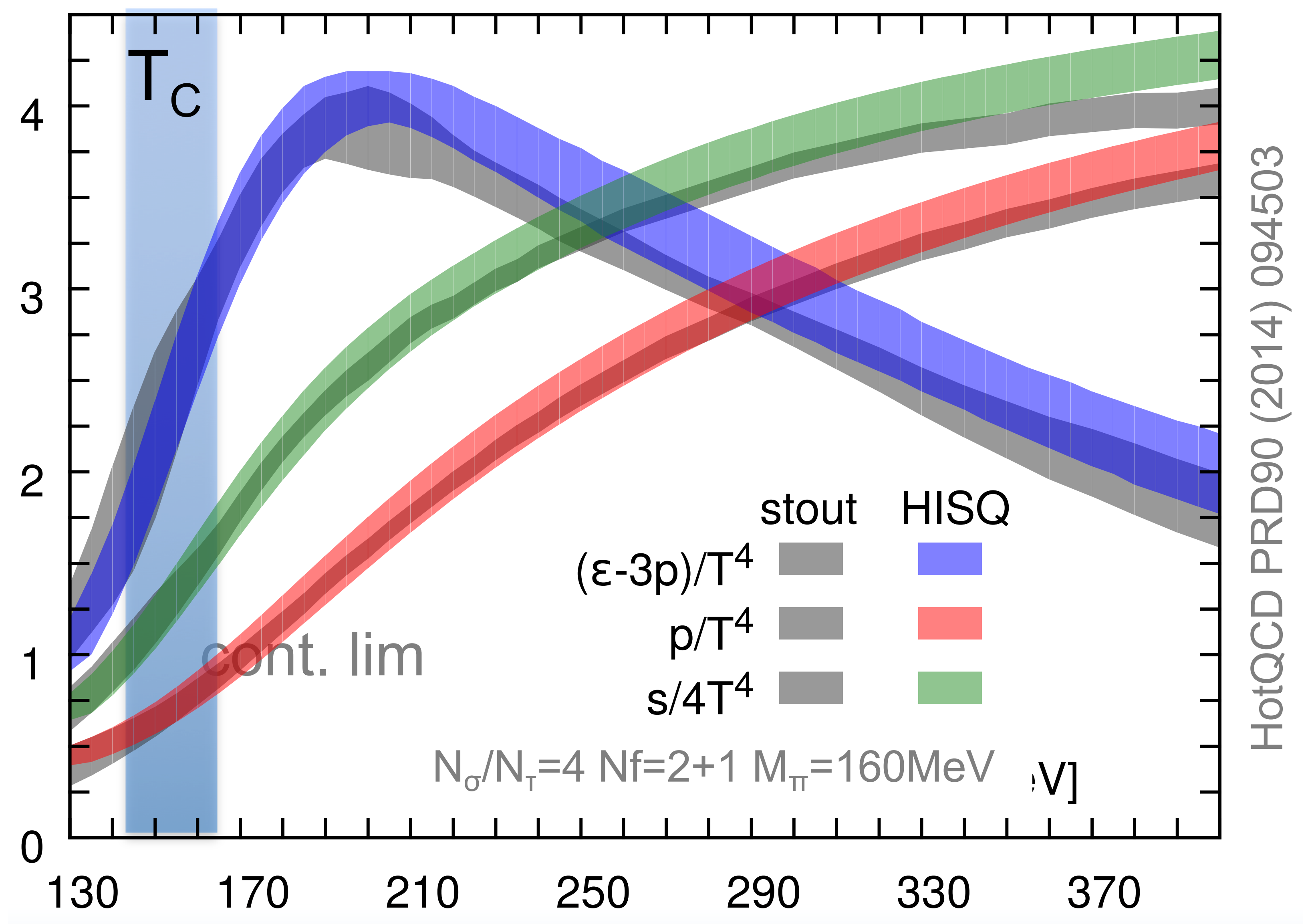
Most of the theoretical progress in the last years:

- Viscosity corrections and consistency
- Fluctuations in initial conditions
- Emergence of hydro from kinetic eqs, holography, etc…

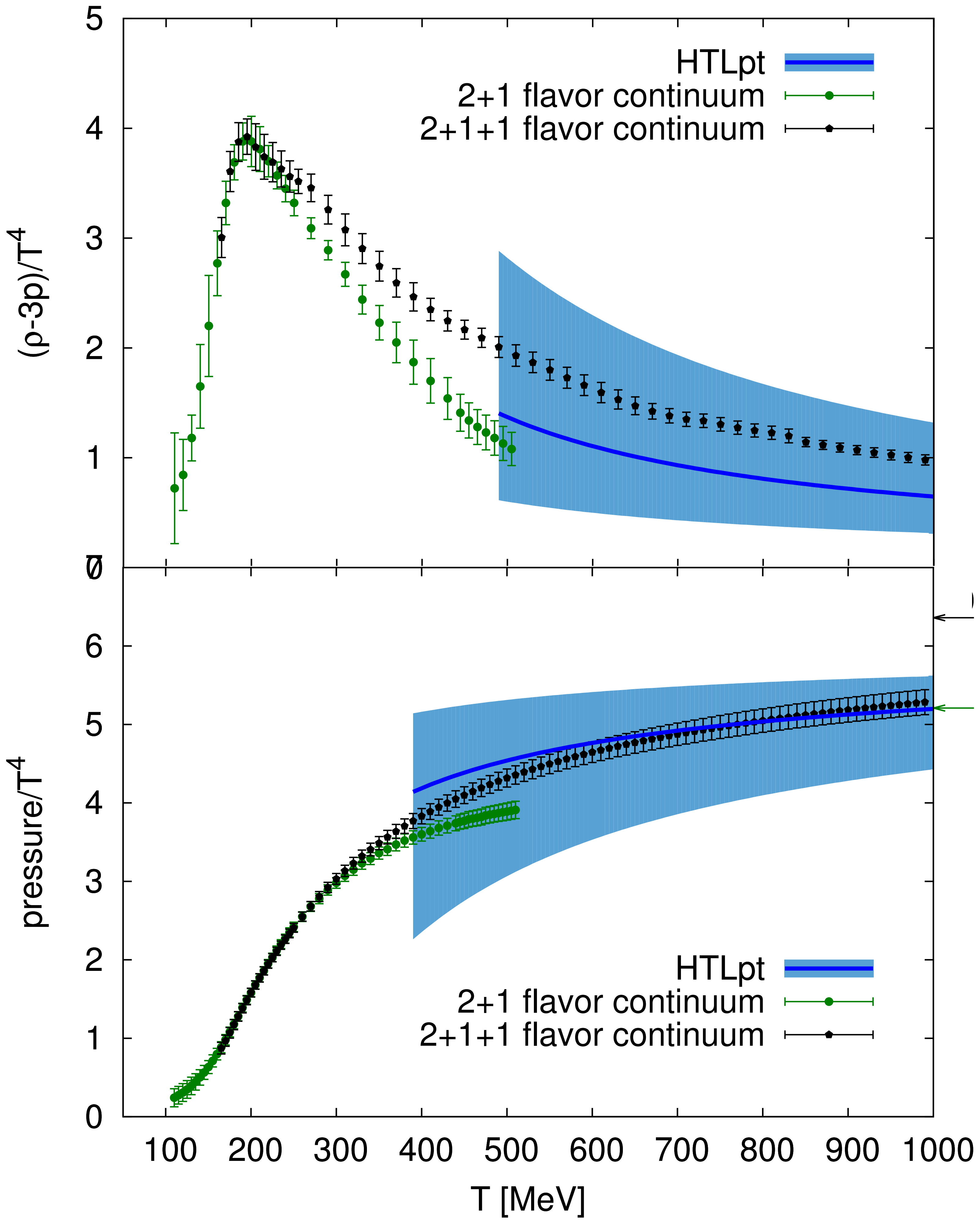
[See talk by Giacalone]

EoS — high temperature

Equation of state at μ_B=0 is rather well known by lattice at moderate temperature — reasonably good matching with perturbative at $T \lesssim 1 GeV$



[Included in hydro simulations]



[Borsanyi et al Nature 539 (2016) no.7627, 69-71]

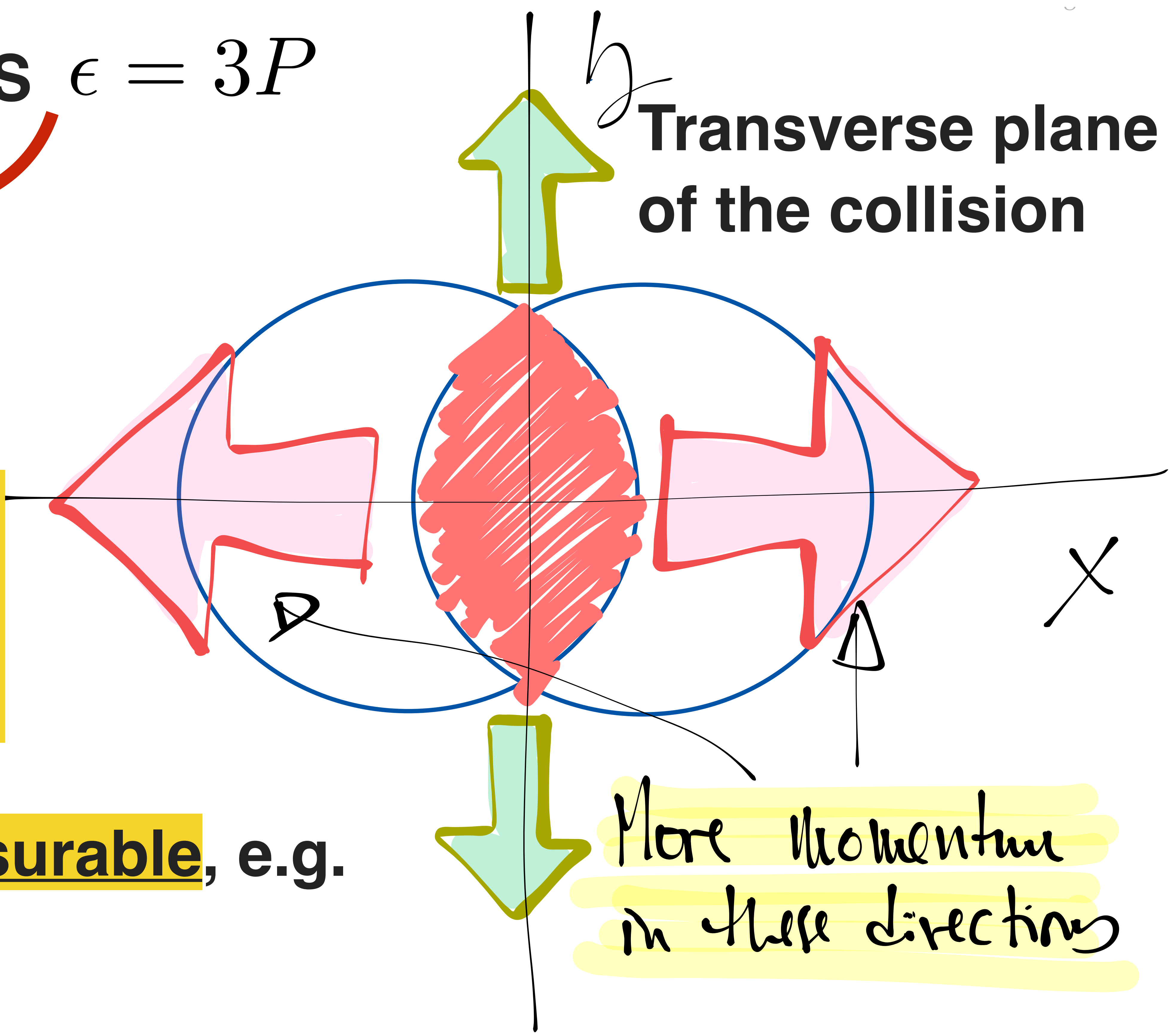
Harmonics: the golden measurement

[simplified discussion]

Remember the Euler eqs. — and use conformal EoS $\epsilon = 3P$

$$\frac{\partial \beta}{dt} = -\frac{c^2}{\epsilon + P}\nabla P \propto -\nabla \epsilon$$

Initial state <u>spatial</u> anisotropies	→	**Final state <u>momentum</u> anisotropies**



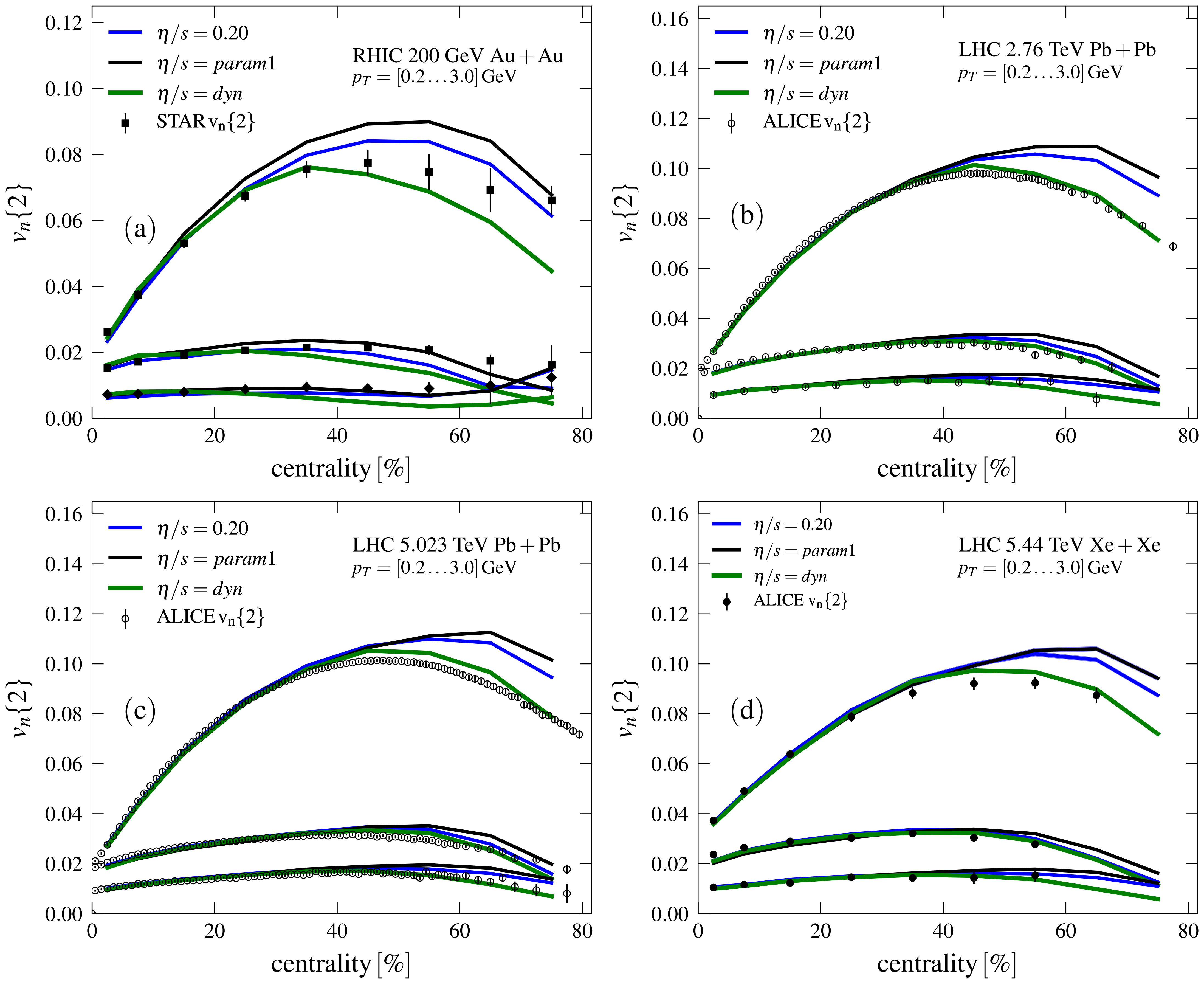
These final state momentum anisotropies are <u>measurable</u>, e.g.

$$\frac{dN}{d\phi} \propto 1 + 2 v_2 \cos 2\phi$$

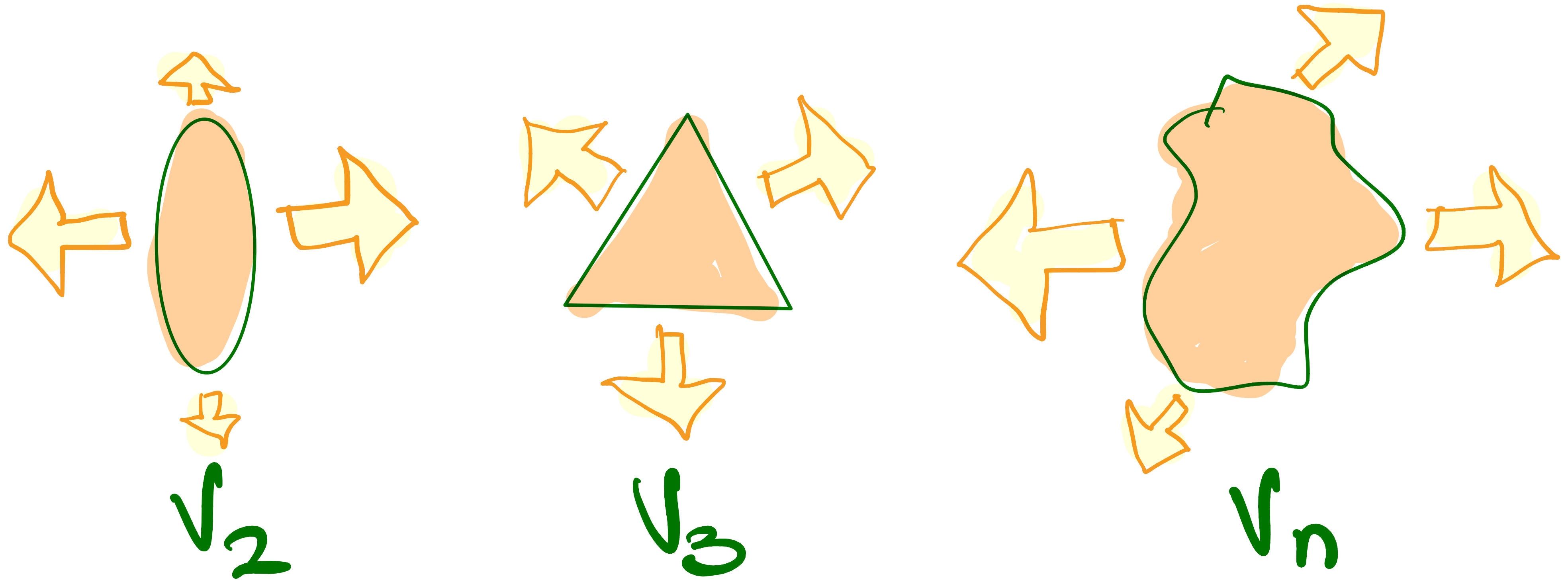
v_2 → Elliptic Flow

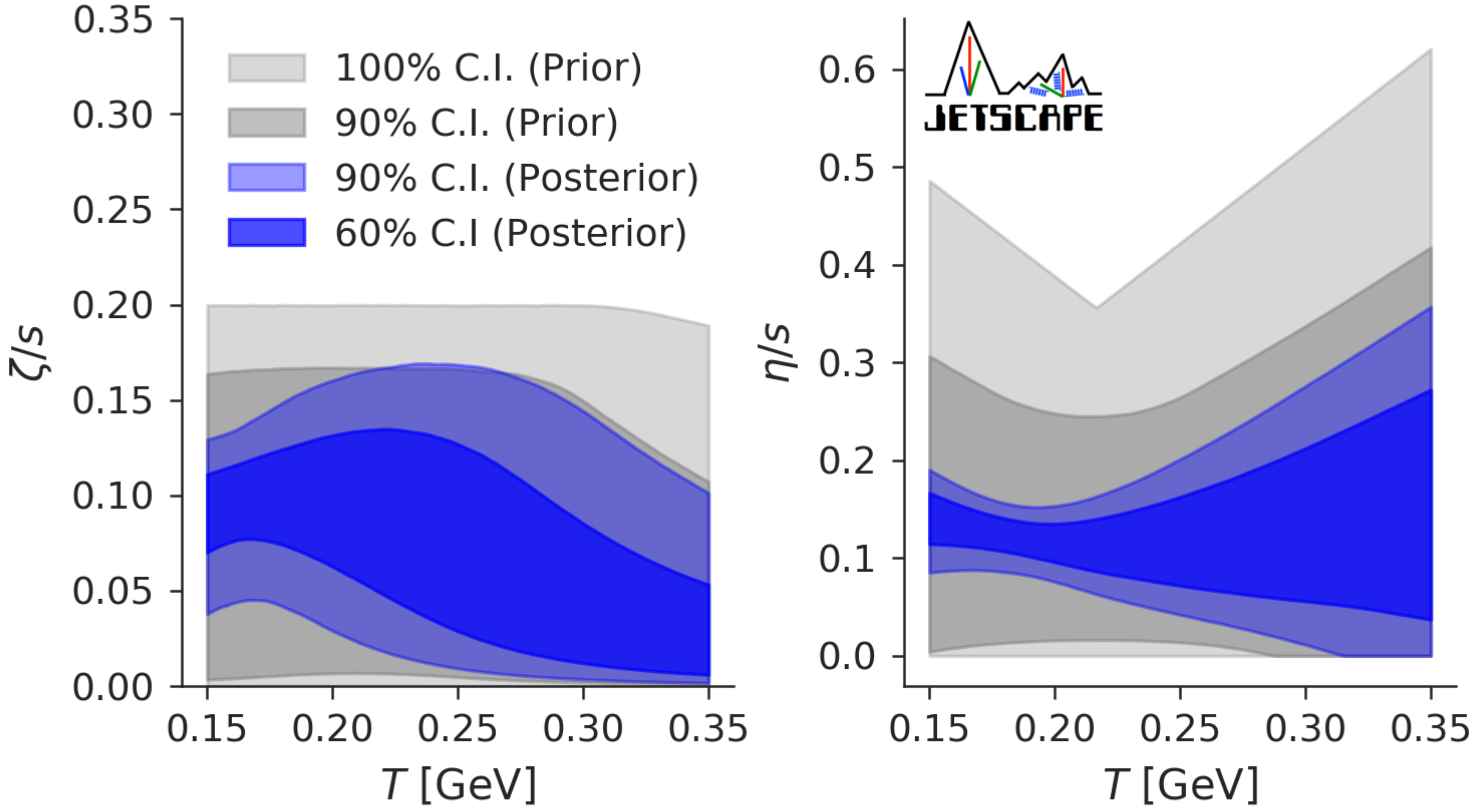
Description of data and viscosity

[Hirvonen, Eskola, Niemi 2022]



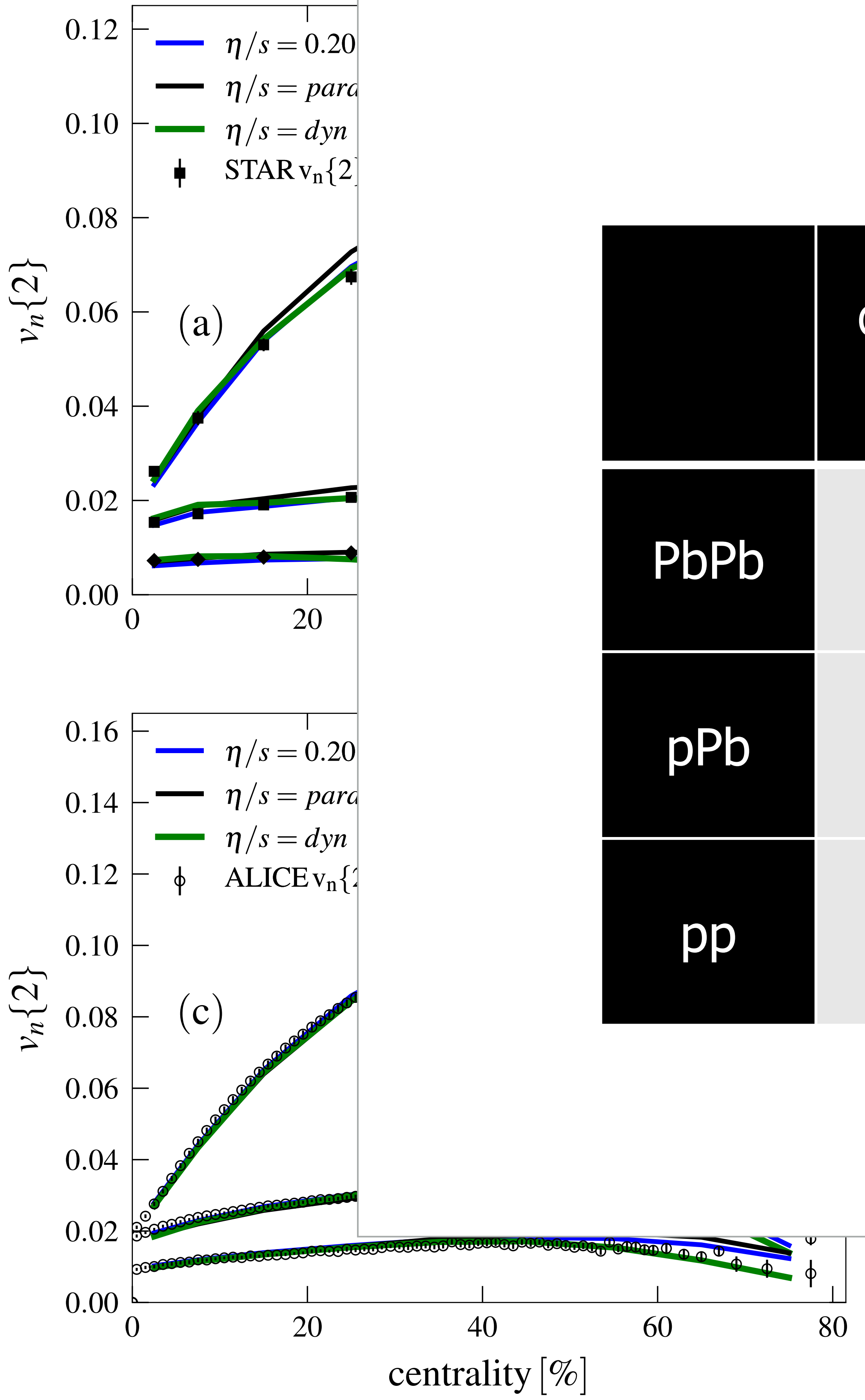
Fluctuation in I.C. generate higher harmonics

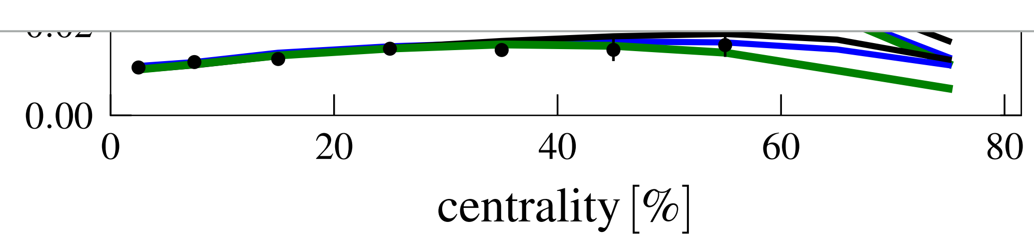




[Everett et al. 2021]

Description of data and viscosity



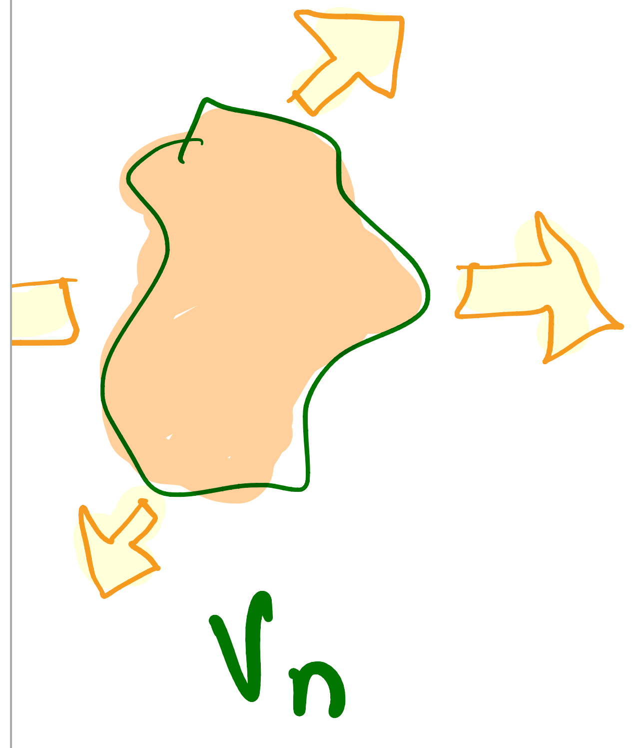


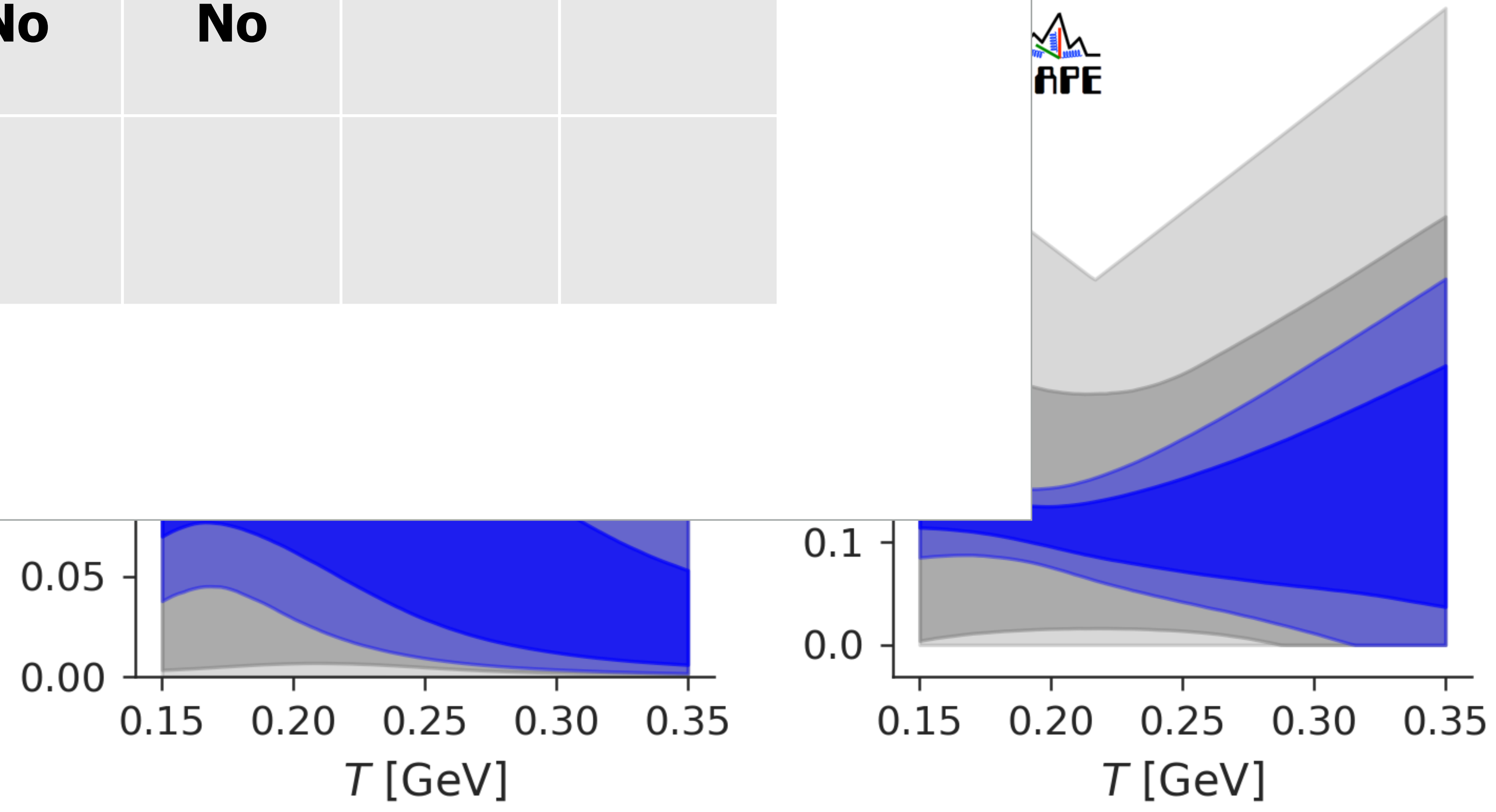
Shengquan Tuo ICHEP 2022

Do we see flow signals?

	Charged hadron	Strange	Prompt J/Ψ	b→ J/ψ	Prompt D^0	b→ D^0	Y(1S/2S)	Dijet	Z boson
PbPb	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**Yes**	**No**
pPb	**Yes**	**Yes**	**Yes**		**Yes**	**No**	**No**		
pp	**Yes**	**Yes**			**Yes**				

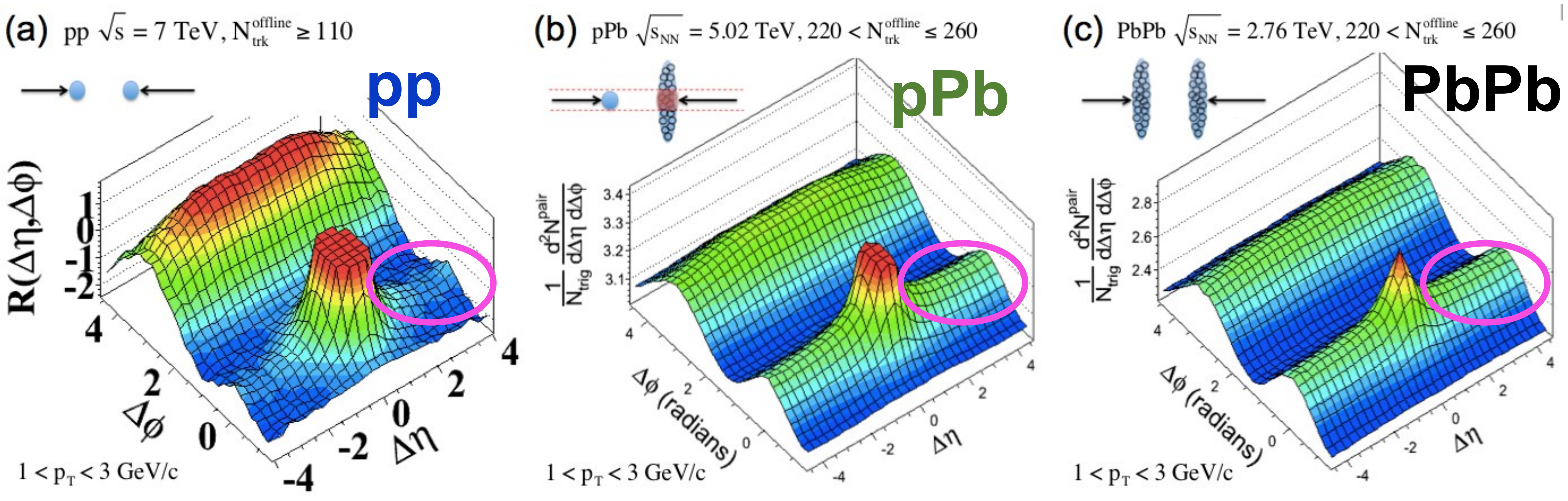
her harmonics

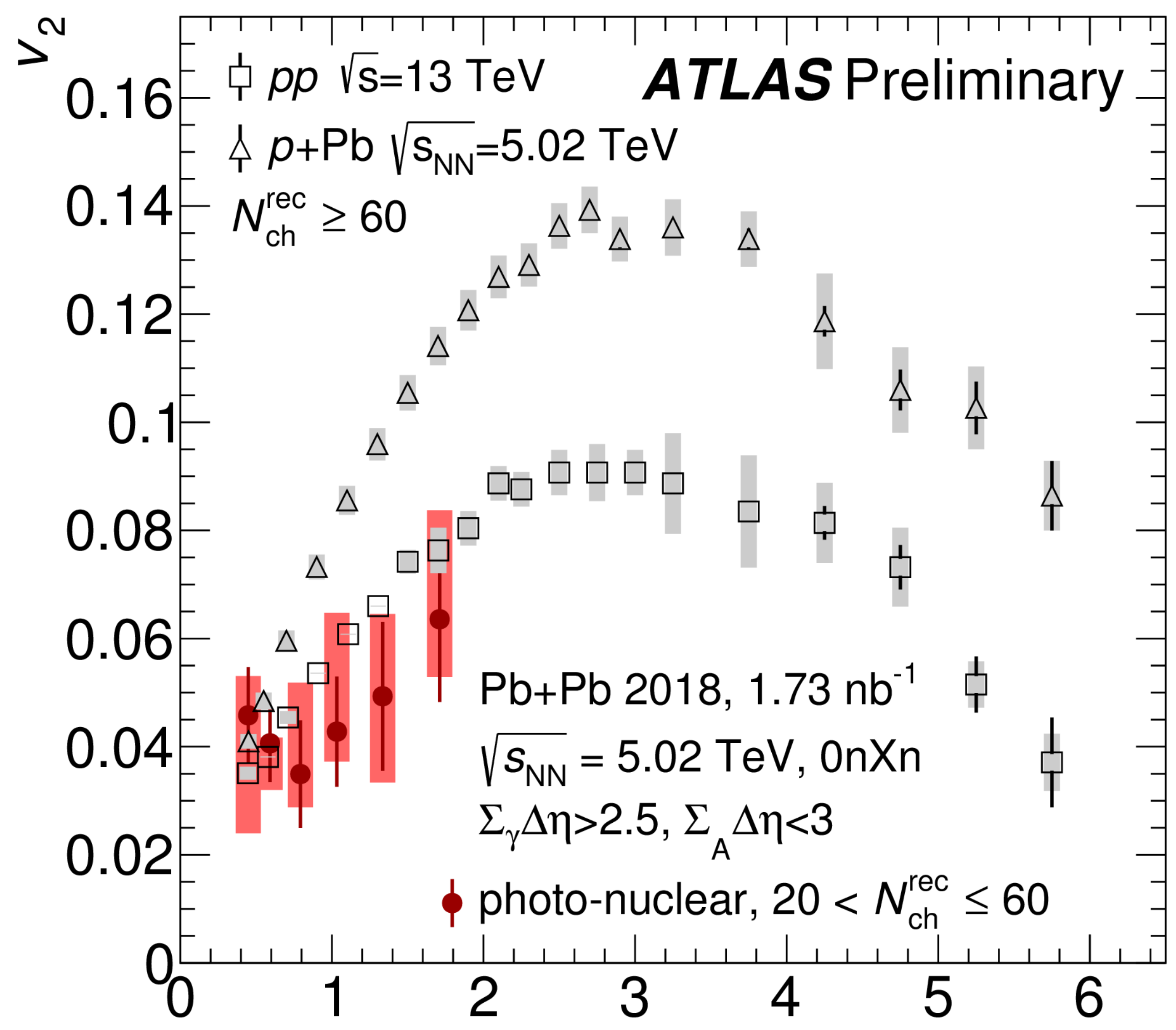




[Everett et al. 2021]

Hydro works in all systems from small to large ??





Hydro models able to describe the harmonics from these data

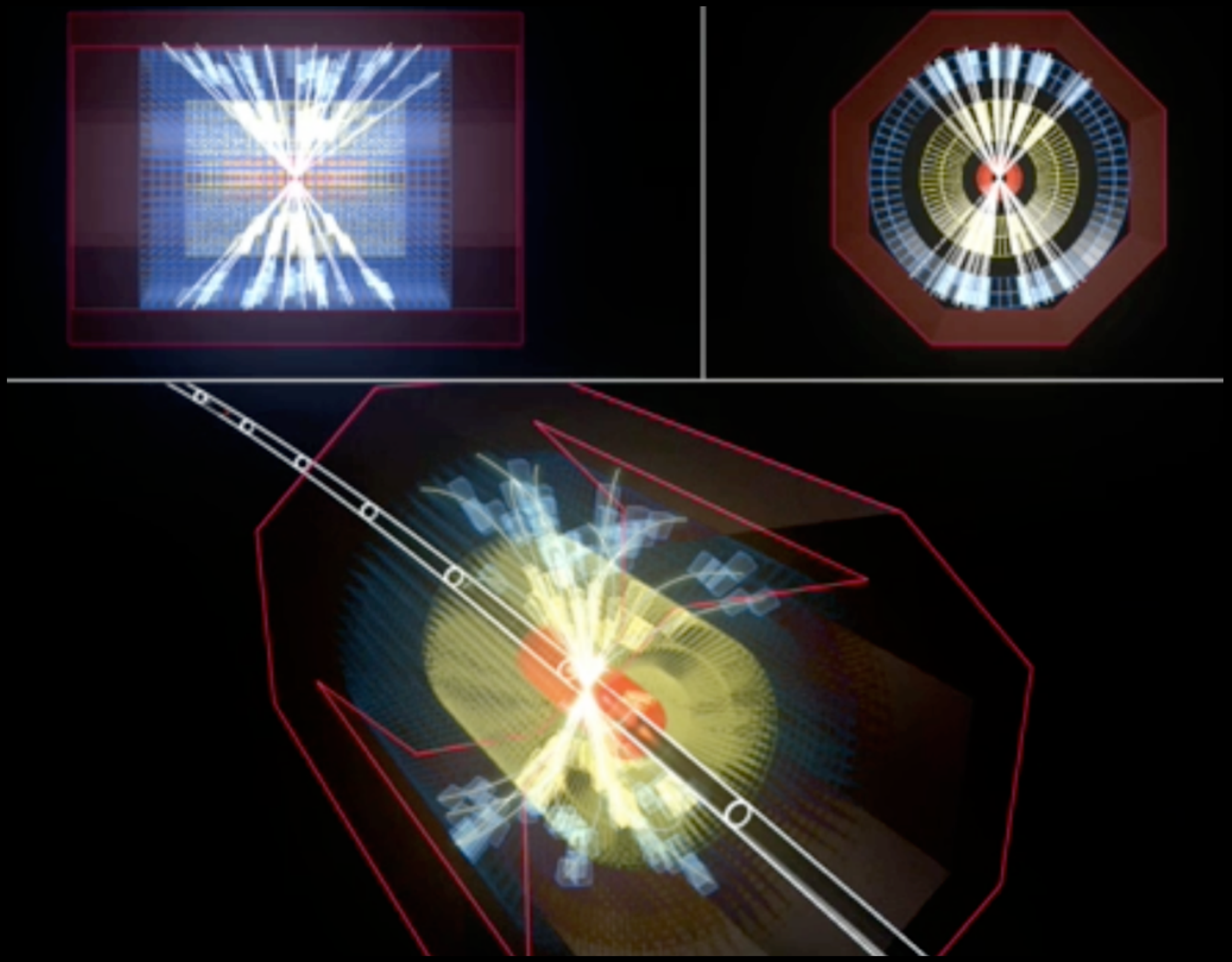
Hydrodynamics seem to work (too) well in all colliding systems for large multiplicities

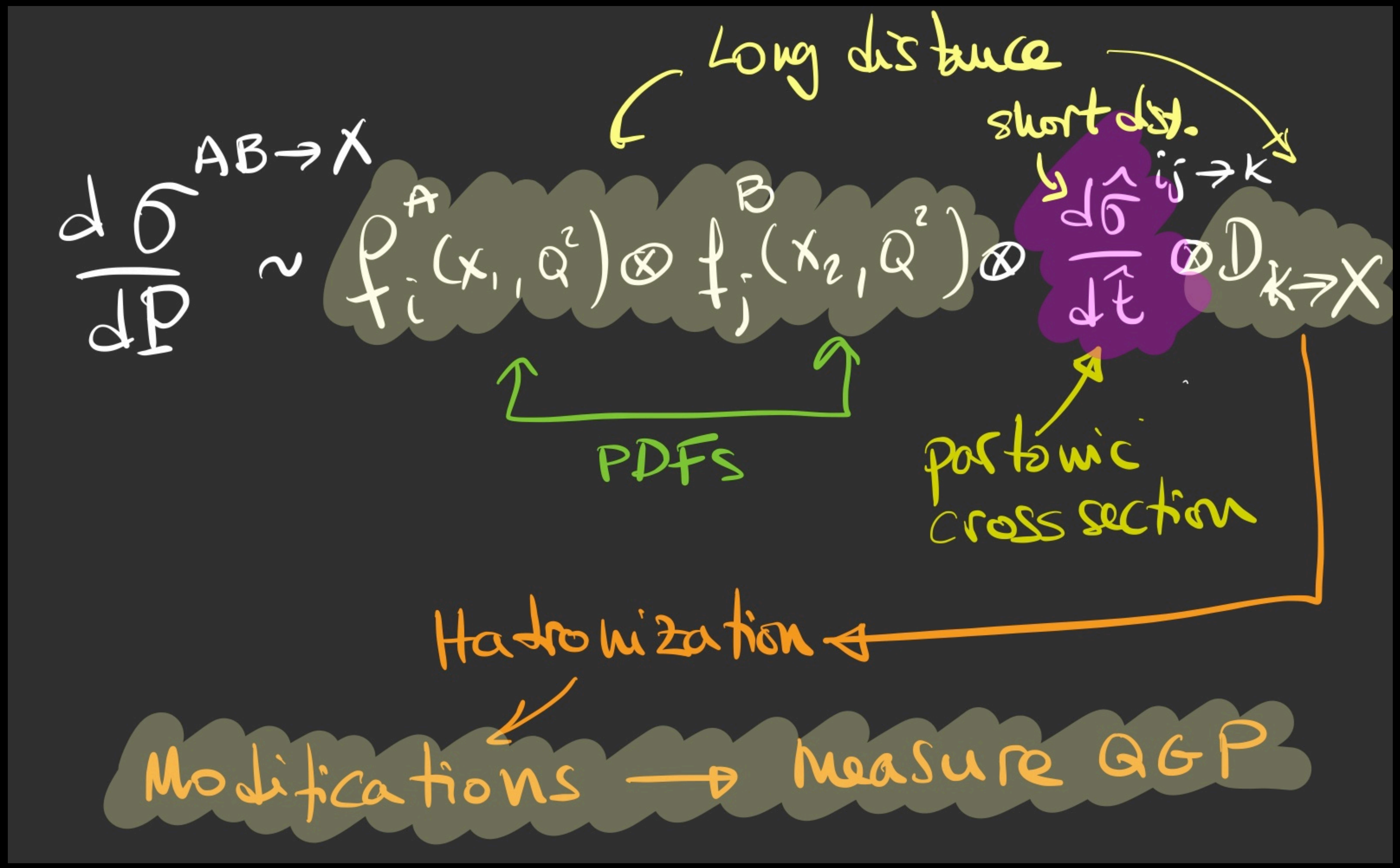
But time scales and occupancies in small systems are small

For some classes of problems hydro equations have attractors

[universal solutions, independent on initial conditions]

HARD PROBES





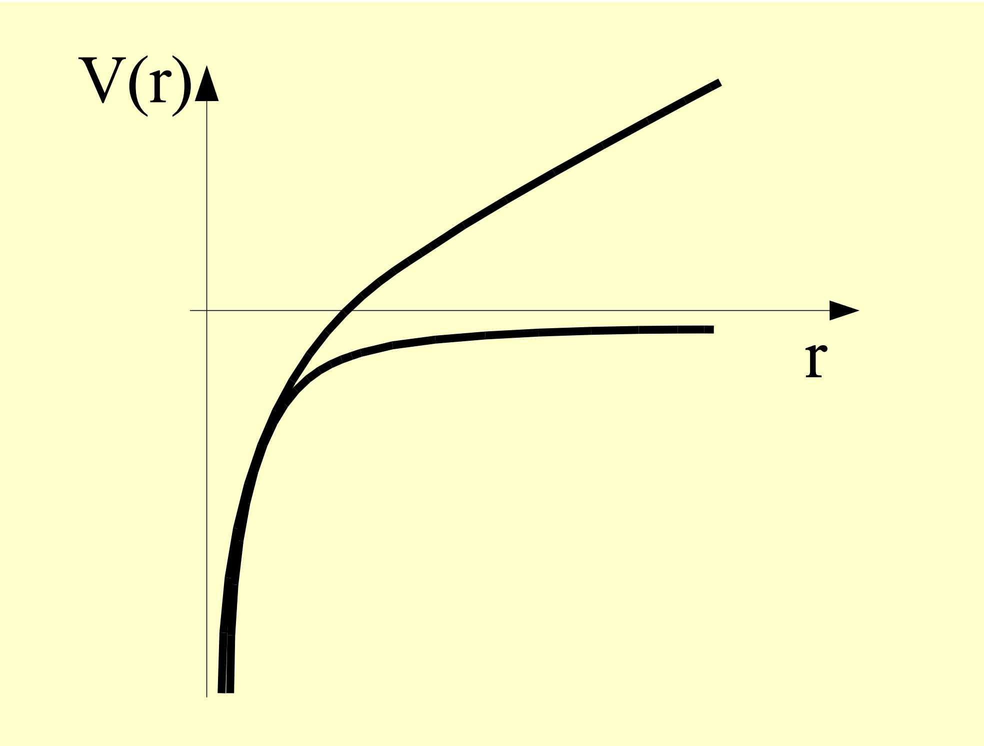
- ☐ Jet quenching
- ☐ Quarkonia suppression
- ☐ Open heavy flavor
- ☐ EW probes

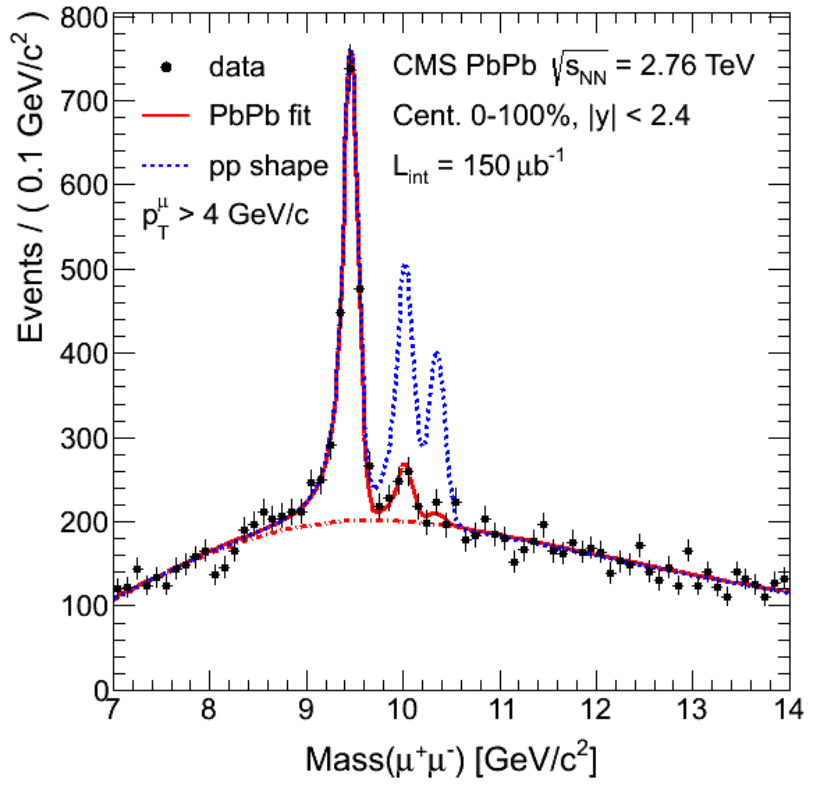
[See talk by Bin Wu]

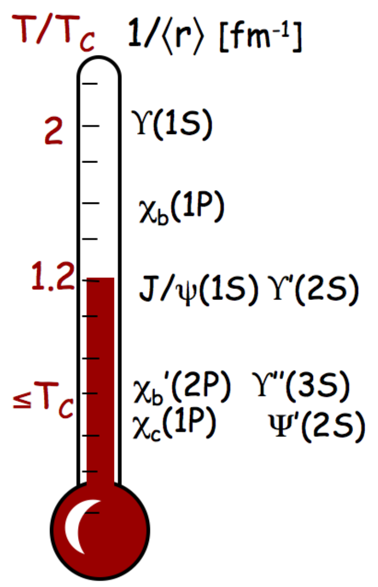
Quarkonia suppression

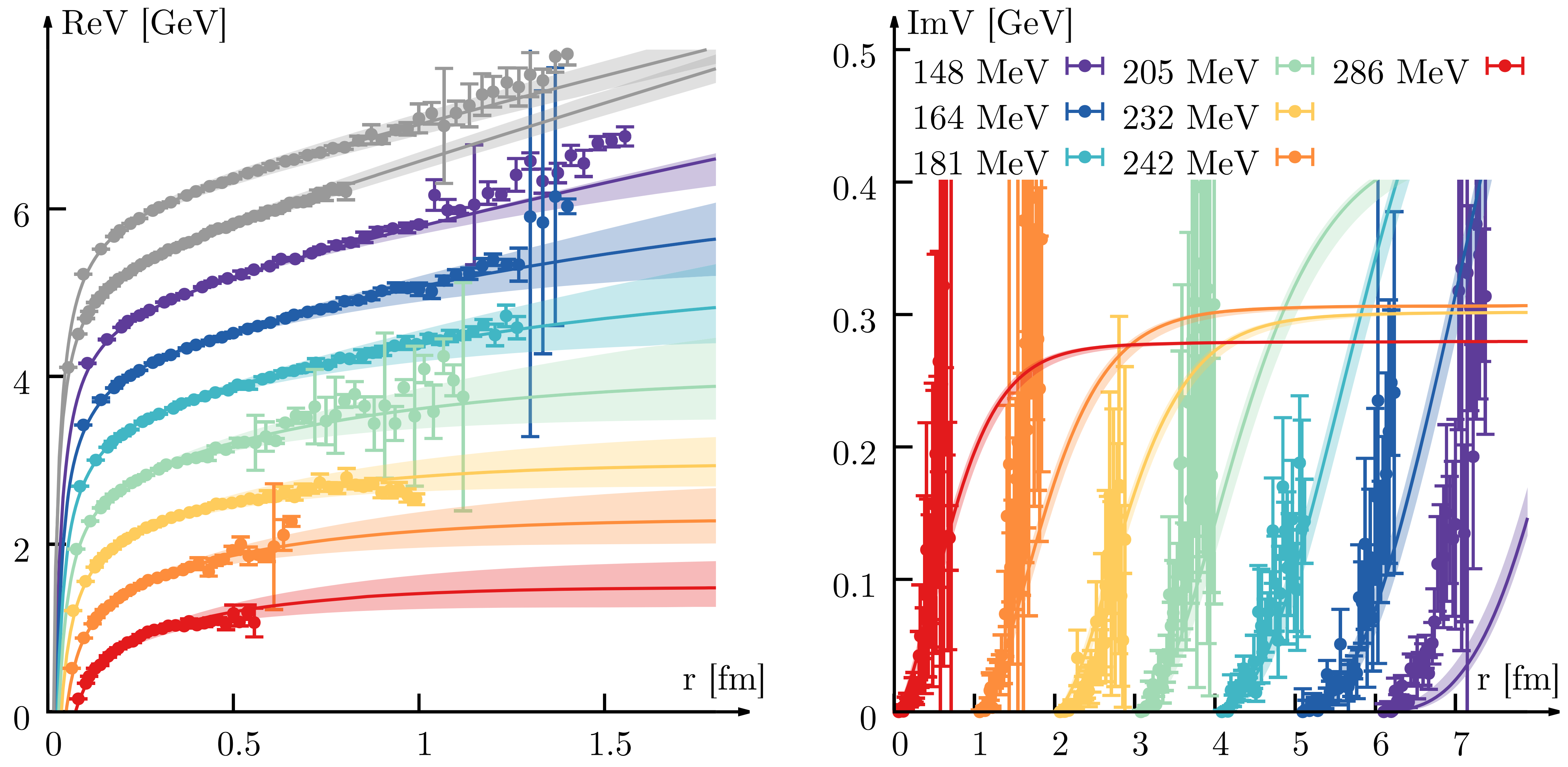
Simple intuitive picture [Matsui & Satz 1986]

- Potential screened at high-T
- Quarkonia suppressed
- Sequential suppression of excited states
- **Quarkonia as a thermometer**









[Lafferty, Rothkopf 2020]

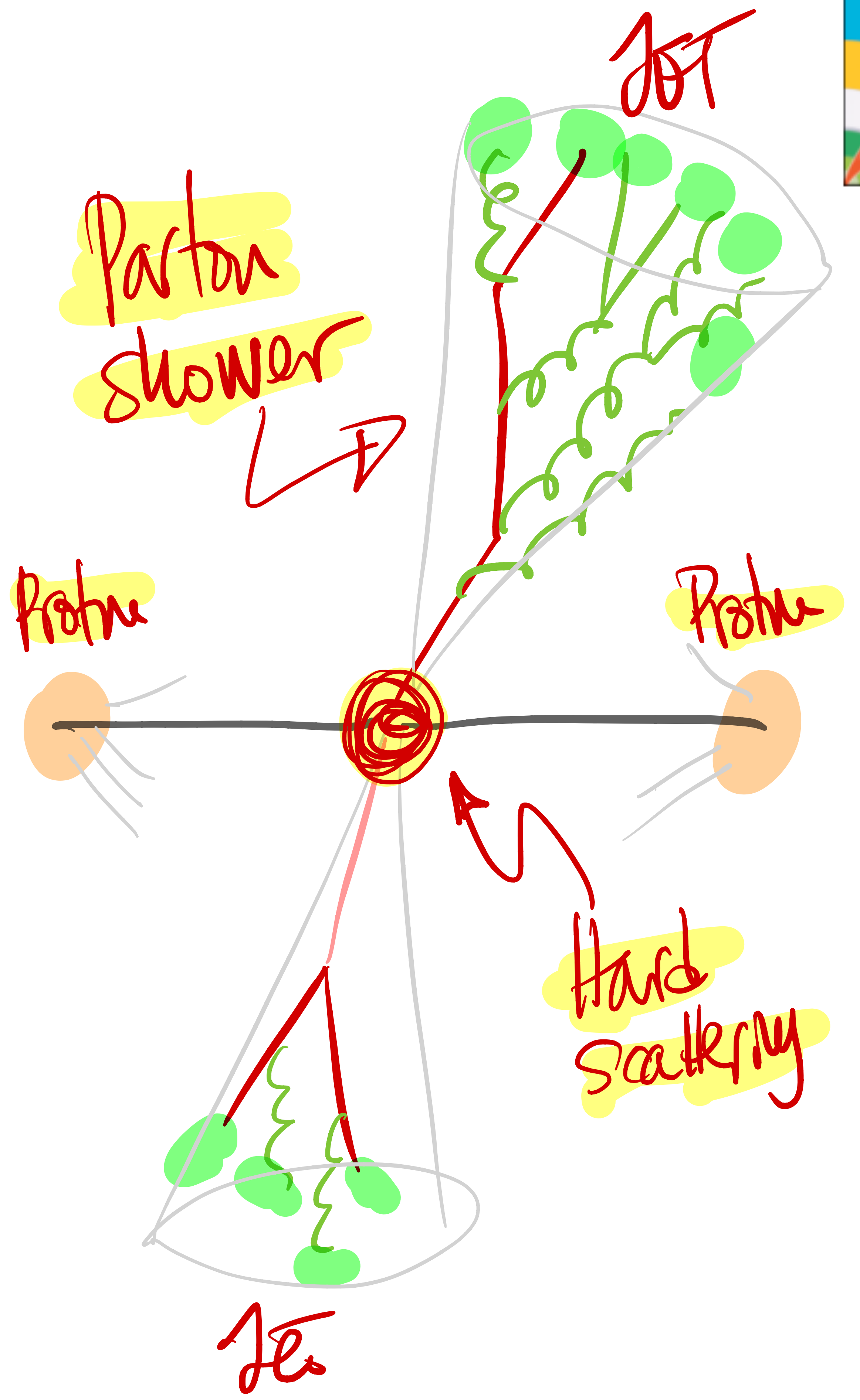
Dynamical picture:

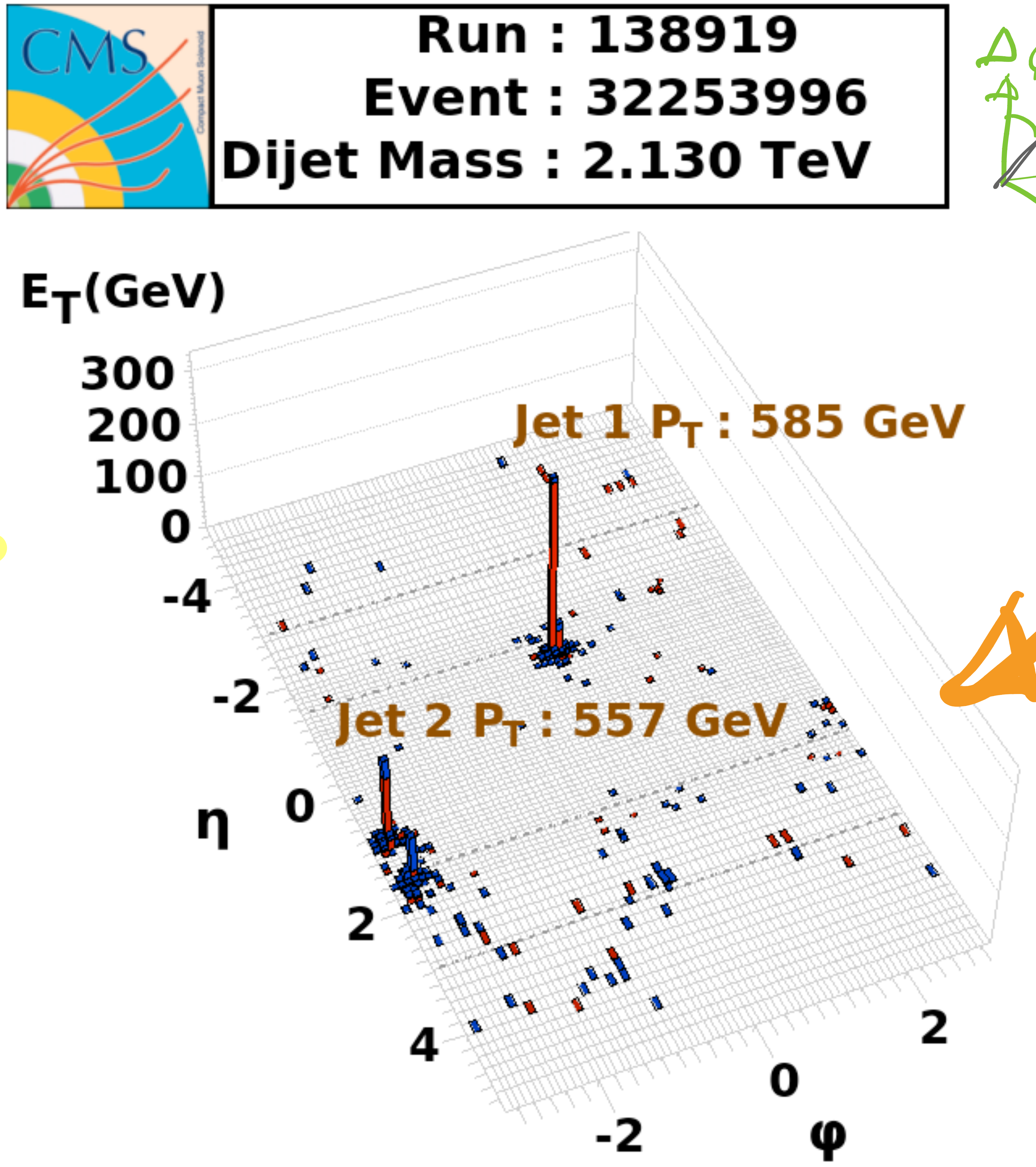
- different effects:
  - screening / rescattering / recombination
- Induced transition between quarkonia states

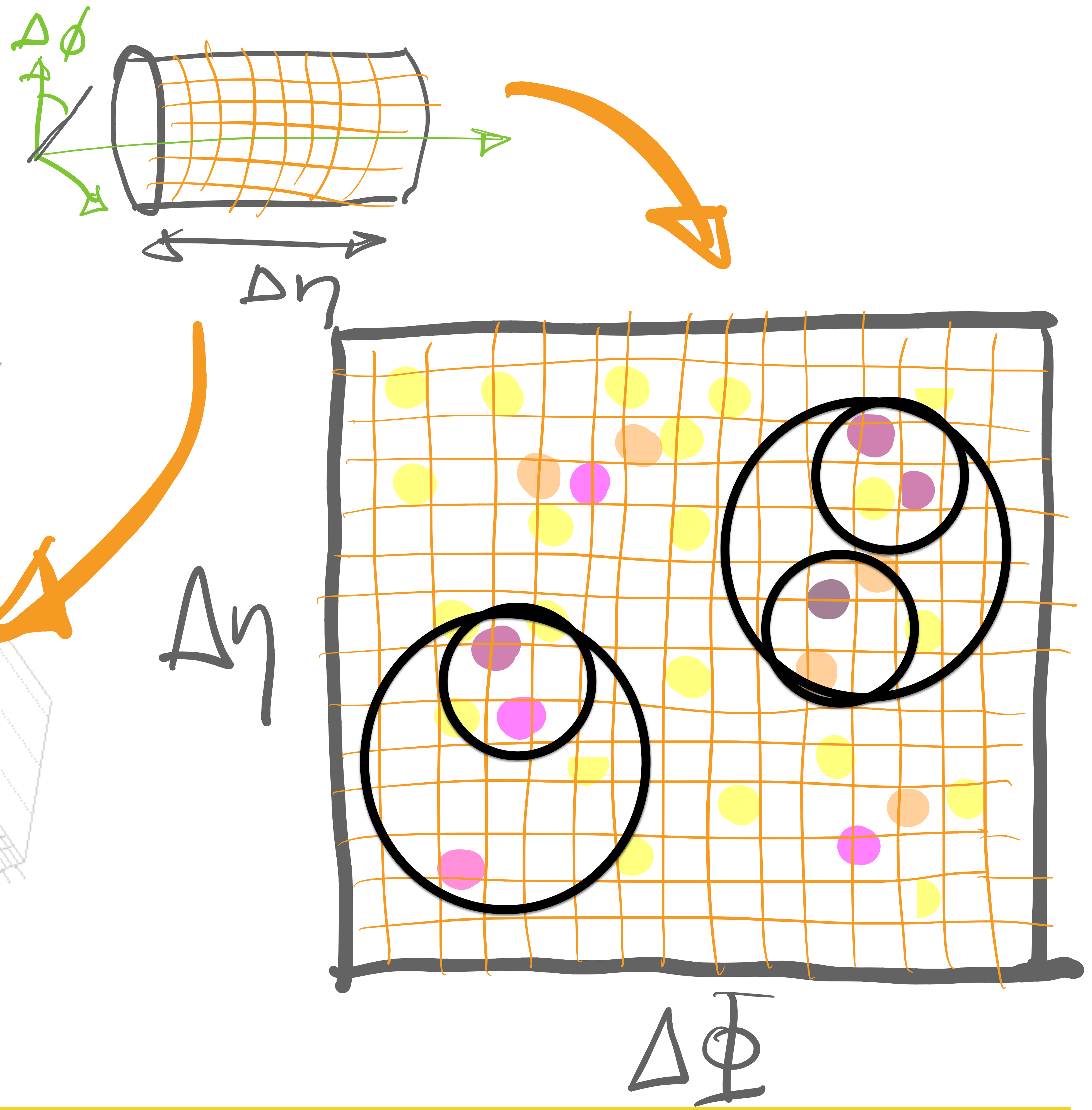
Quarkonia as an open quantum system

[Bambrilla, Soto, Escobedo, Vairo, Ghiglieri, Petreczky, Strickland, Blaizot, Rothkopf, Kaczmarek, Asakawa, Katz, Gossiaux, Kajimoto, Akamatsu, Borghini …]

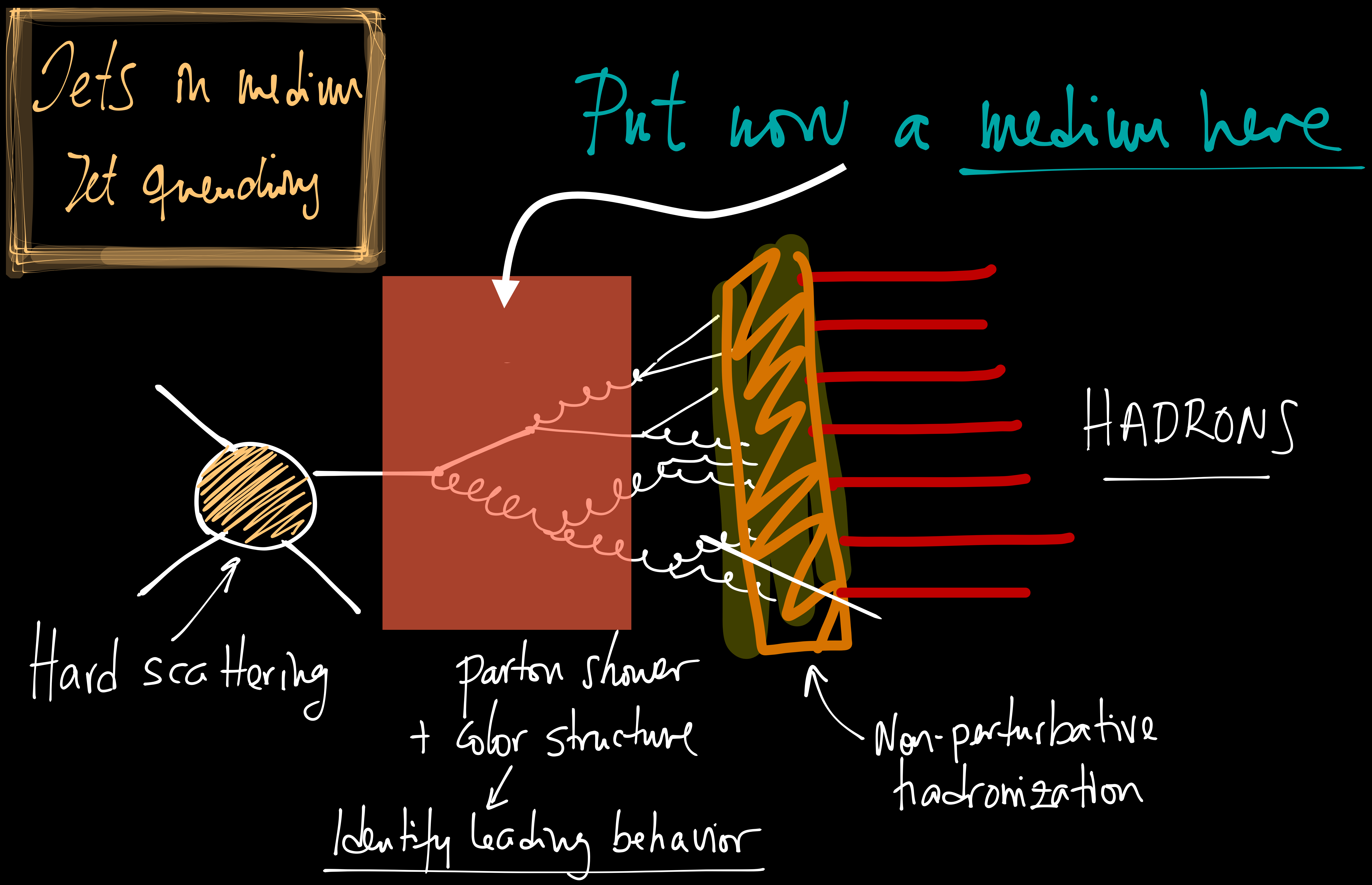
How to identify jets?





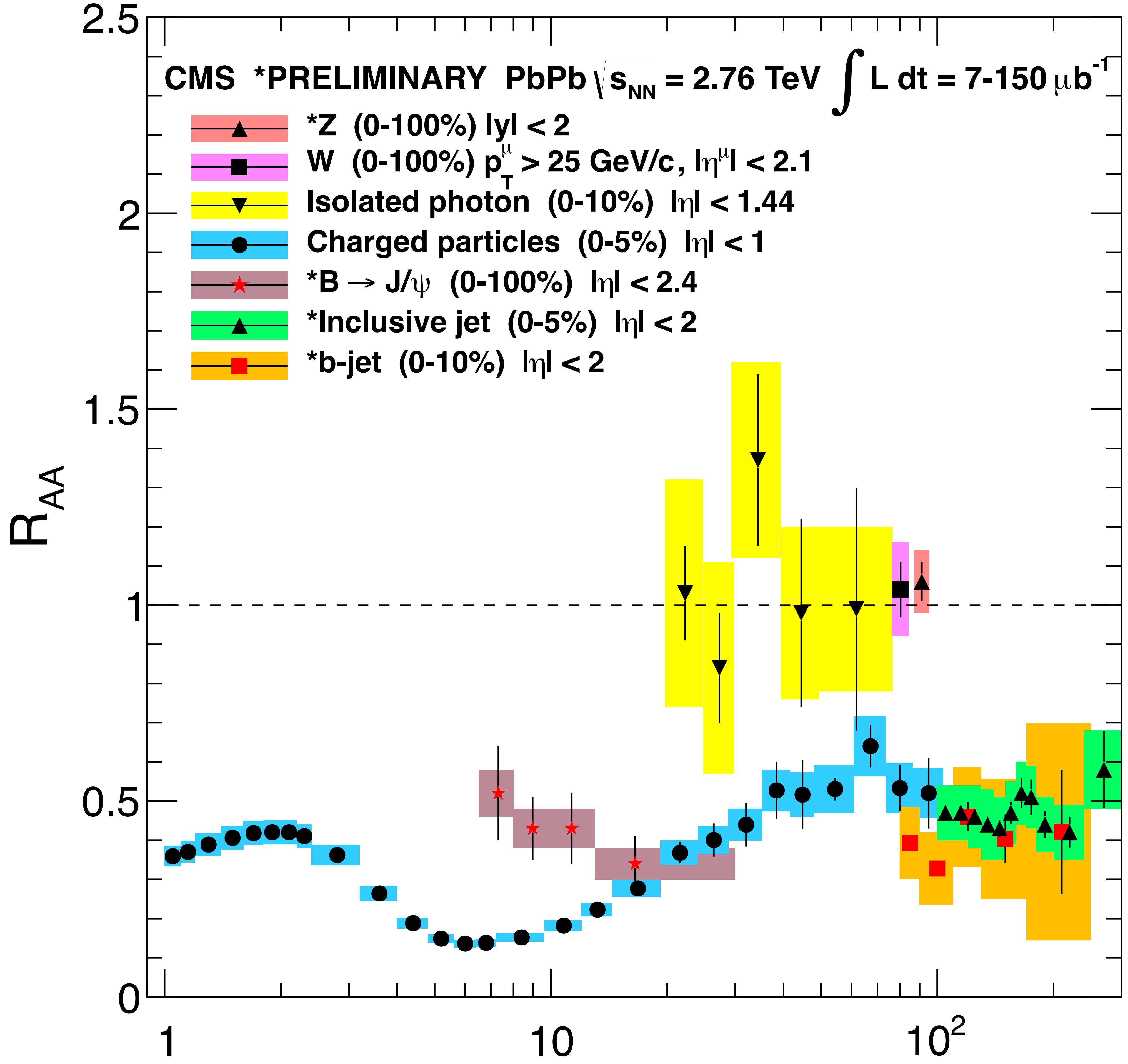


Jets are proxies to quarks and gluons produced in elementary QCD processes



Jets are extended objects - ideal to study space-time evolution

Particles traversing the QGP

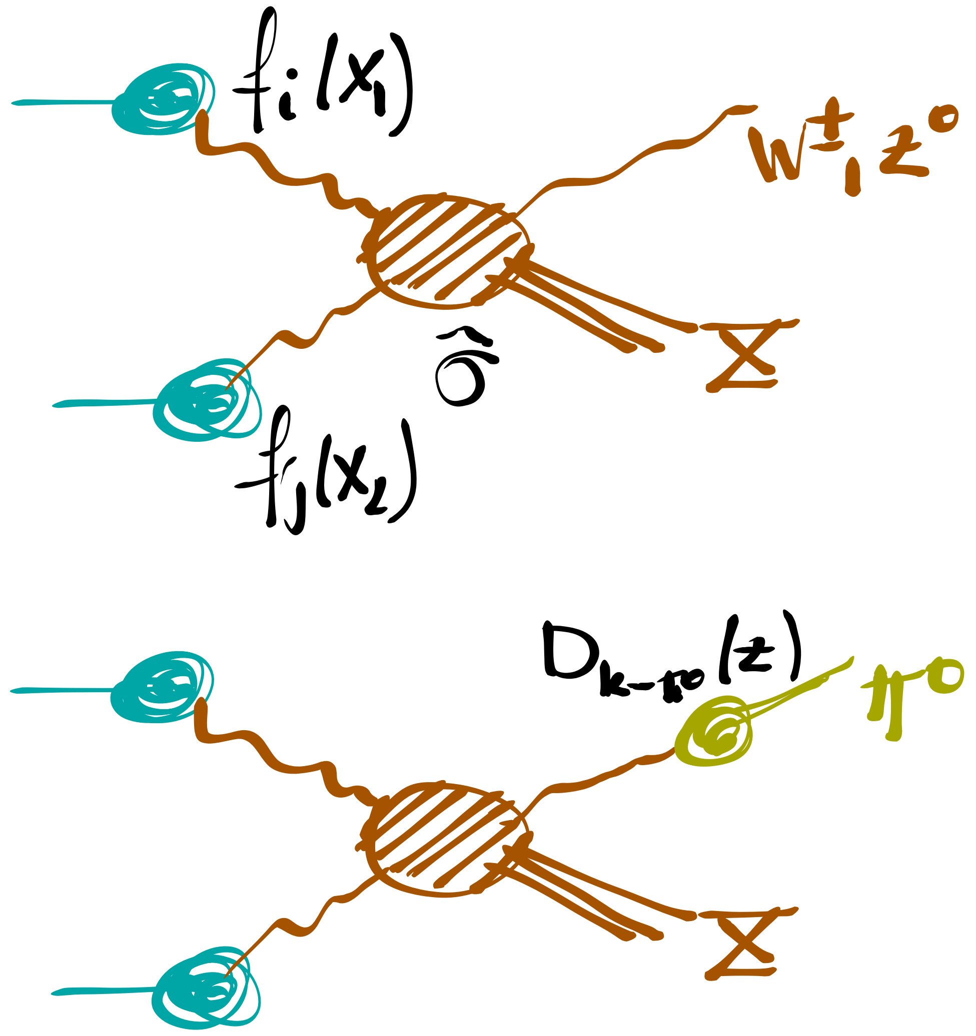


[A. Florent - Hard Probes 2013]

Medium-modification factor

$$R_{AA} = \frac{dN^{AA}/dp_t}{\langle N_{coll}\rangle dN^{pp}/dp_t}$$

$R_{AA} \to 1$ — no effect



Color-less particles

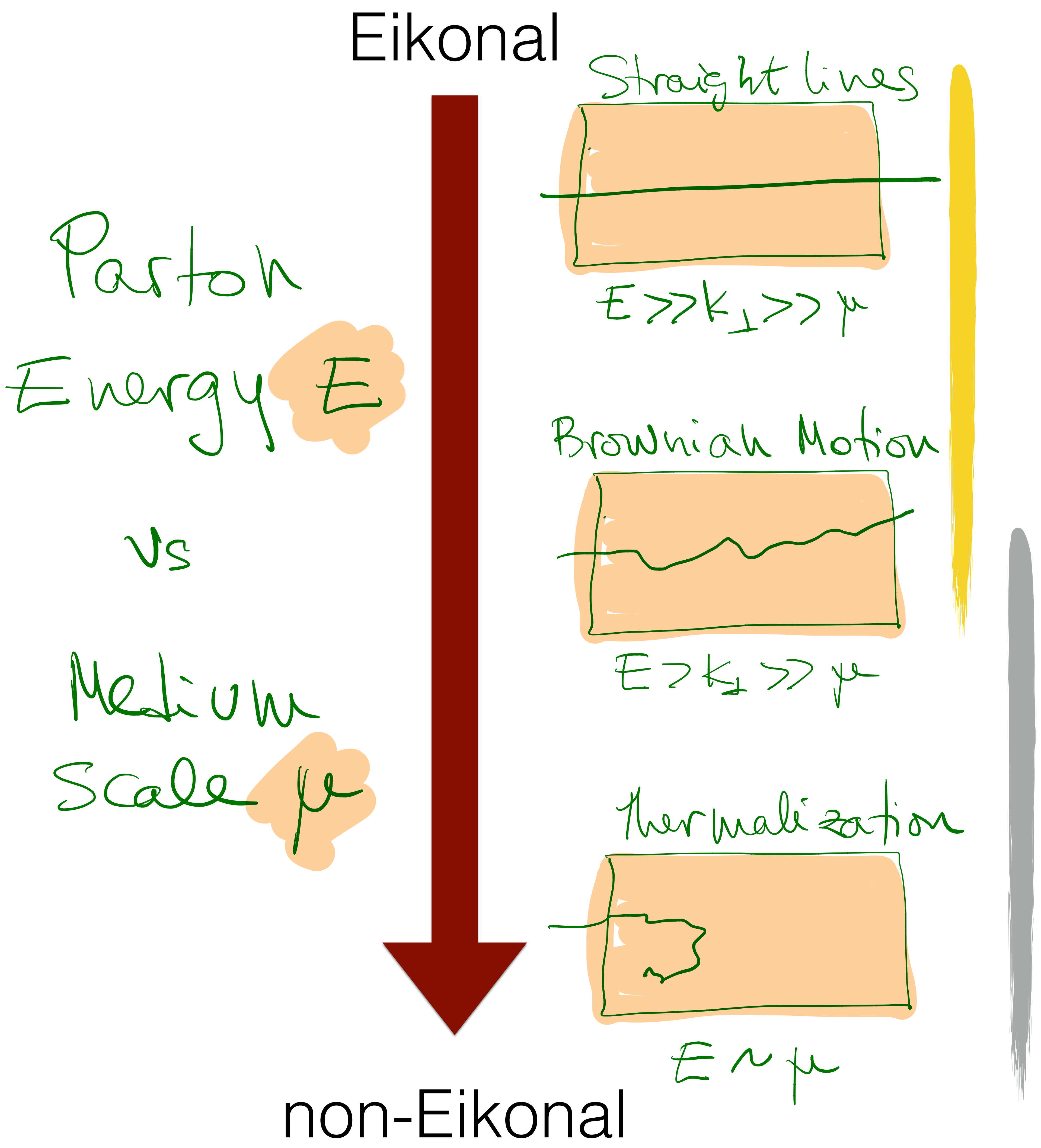
$R_{AA} \sim 1$

Colored particles

$R_{AA} < 1$

Energy-loss (mainly radiation)

In-medium parton propagation

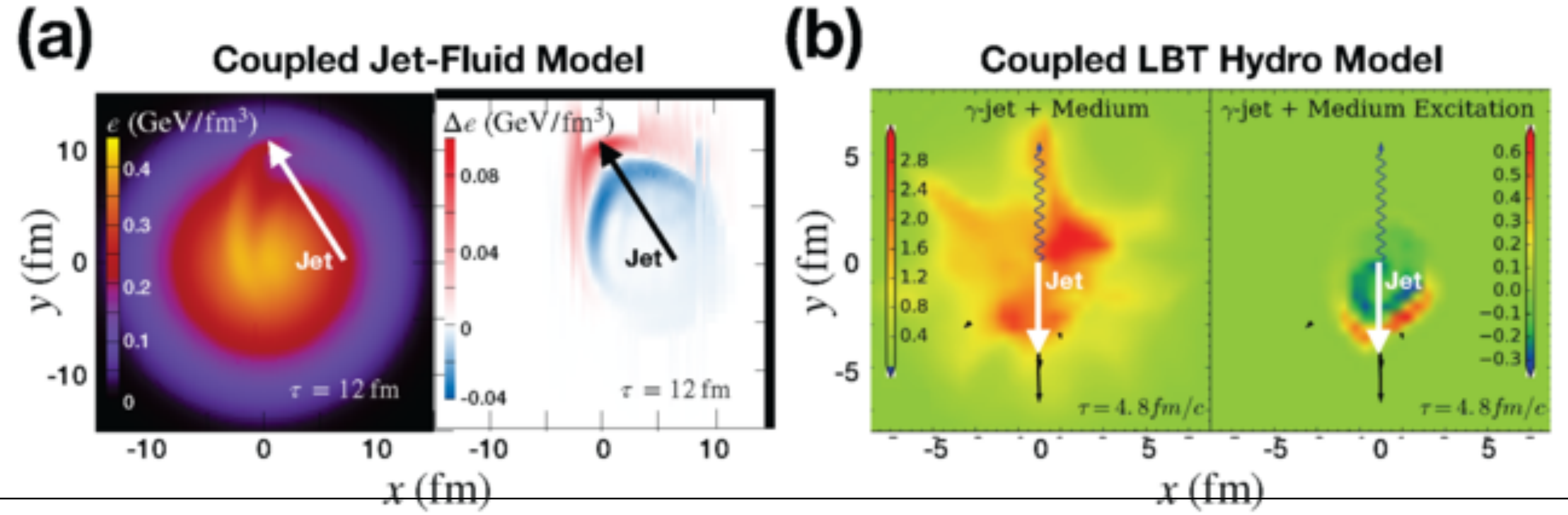


Medium is a background field: color rotation
[Energy of the parton unmodified]

$$W(x_\perp) = \mathcal{P} \exp\left\{ ig \int d\xi \, n \cdot A(\xi, x_\perp) \right\}$$

$$G(x_\perp; y_\perp) = \mathcal{P} \int \mathcal{D}\mathbf{r} \exp\left\{ i\frac{E}{2} \int d\xi \left[\frac{d\mathbf{r}}{d\xi}\right]^2 + ig \int d\xi \, n \cdot A(\xi, \mathbf{r}) \right\}$$

Medium is **dynamical**
[Energy exchanged with the medium]

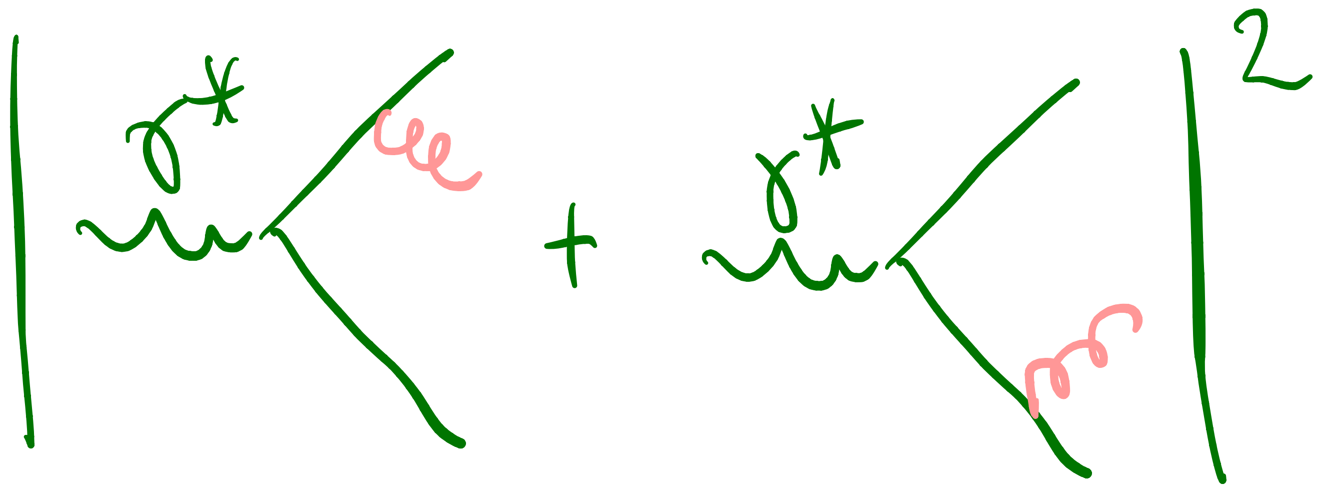


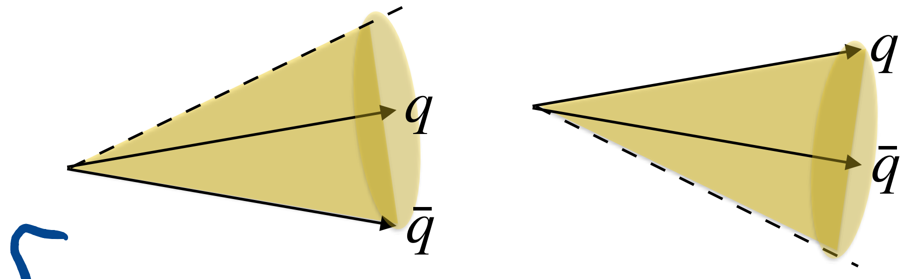
[Tachibana 2019]

Intra-jet color coherence

[Mehtar-Tani, Salgado, Tywoniuk; Iancu, Casalderrey-Solana, … 2010-]

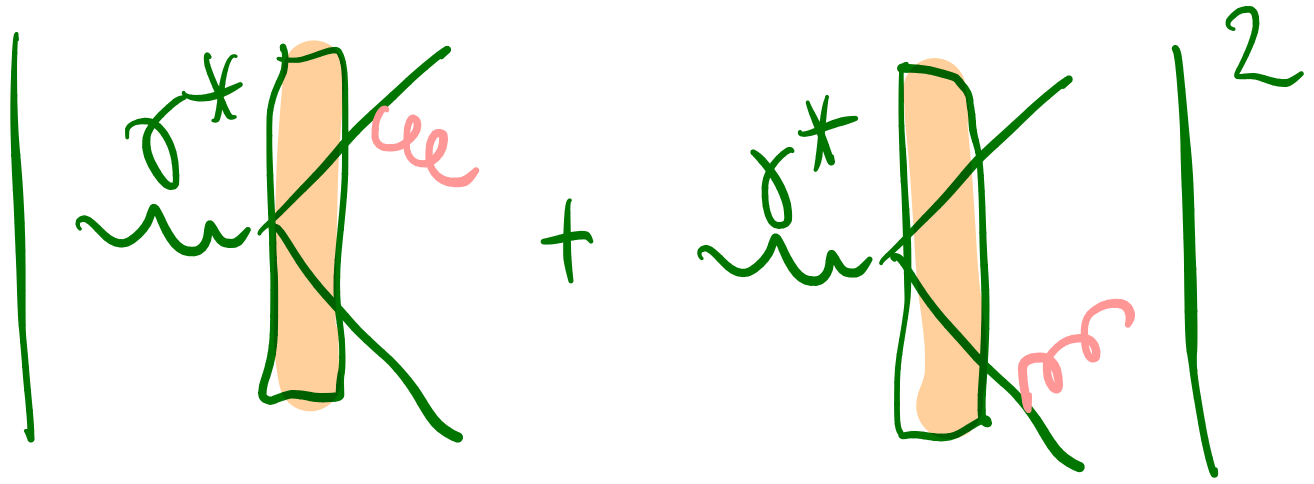
QCD antenna - classical calculation including color coherence *[angular ordering]*





$$\omega \frac{dN}{d\omega\, d\theta} \sim \alpha_s C_F \left[R_q - J + R_{\bar{q}} - J \right]$$

The QCD medium can break color coherence - independent color rotation of q and qbar



$$\omega \frac{dN}{d\omega\, d\theta} \sim \alpha_s C_F \left[R_q - S_{q\bar{q}} J + R_{\bar{q}} - S_{q\bar{q}} J \right]$$

$$S(x_\perp, y_\perp) \equiv \frac{1}{N_c^2 - 1} \mathrm{Tr} \left\langle W(x_\perp) W^\dagger(y_\perp) \right\rangle_{\mathrm{med}} \simeq \exp\left\{ -\frac{1}{4} \hat{q}\, \theta_{q\bar{q}}^2\, L^3 \right\}$$

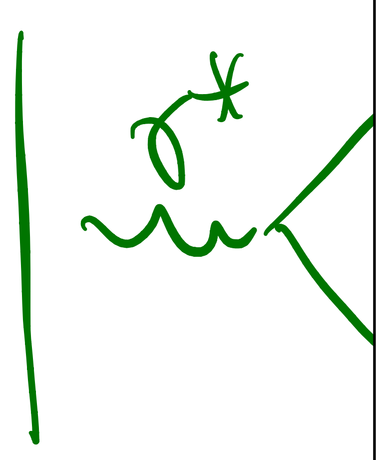
Survival probability

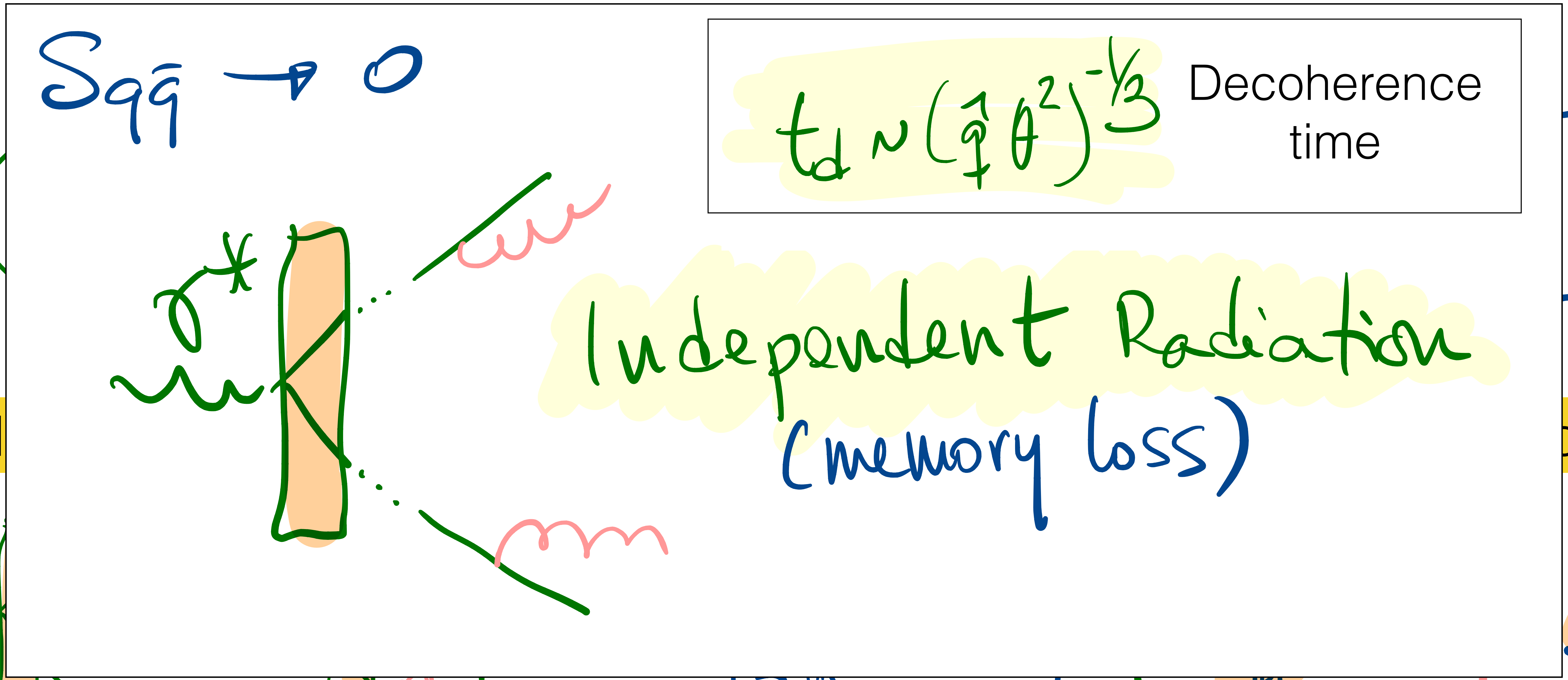
$\hat{q}$ - jet quenching parameter

Intra-jet color coherence

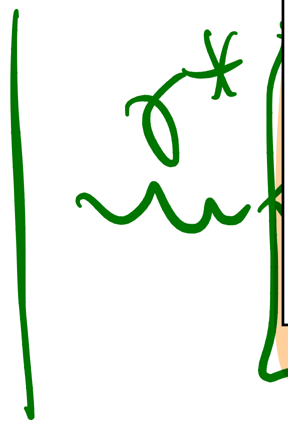
[Mehtar-Tani, Salgado, Tywoniuk; Iancu, Casalderrey-Solana, … 2010-]

QCD antenna - classical calculation including color coherence *[angular ordering]*





The QCD med… of q and qbar



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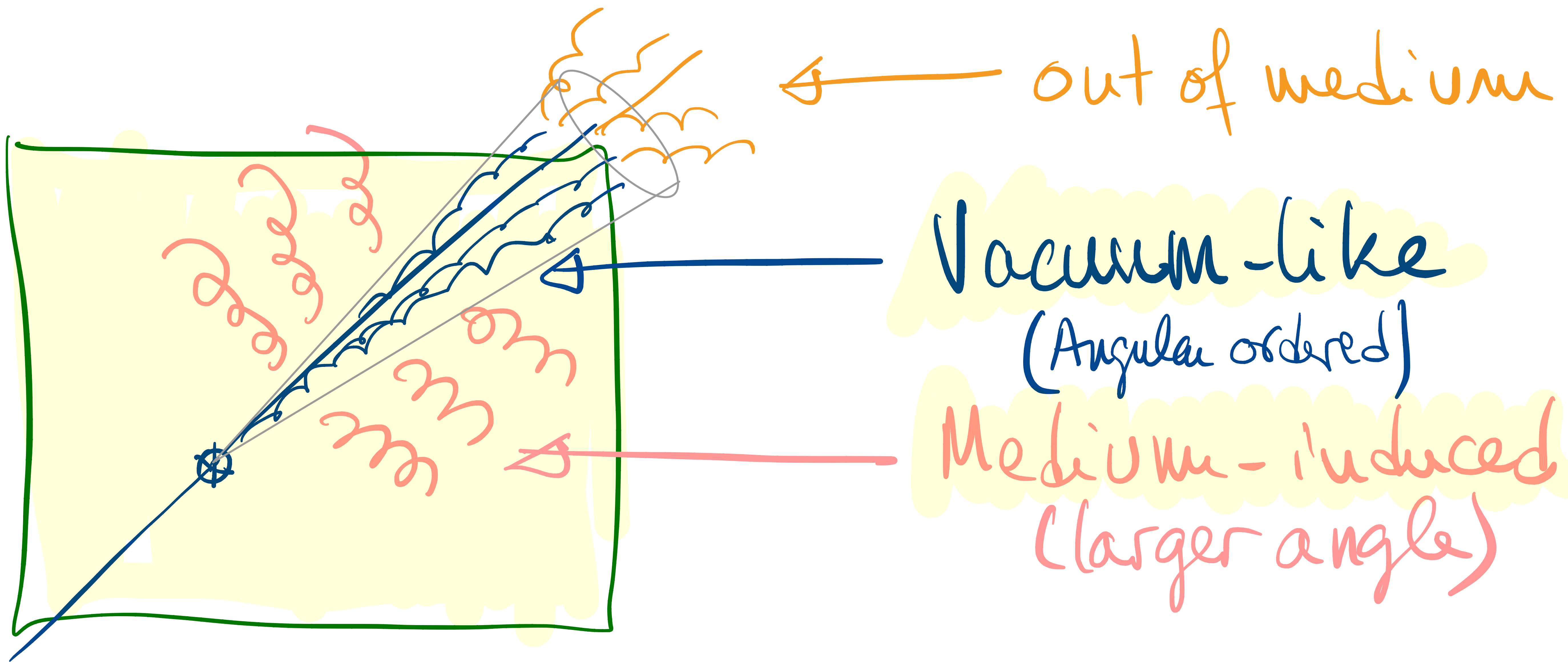
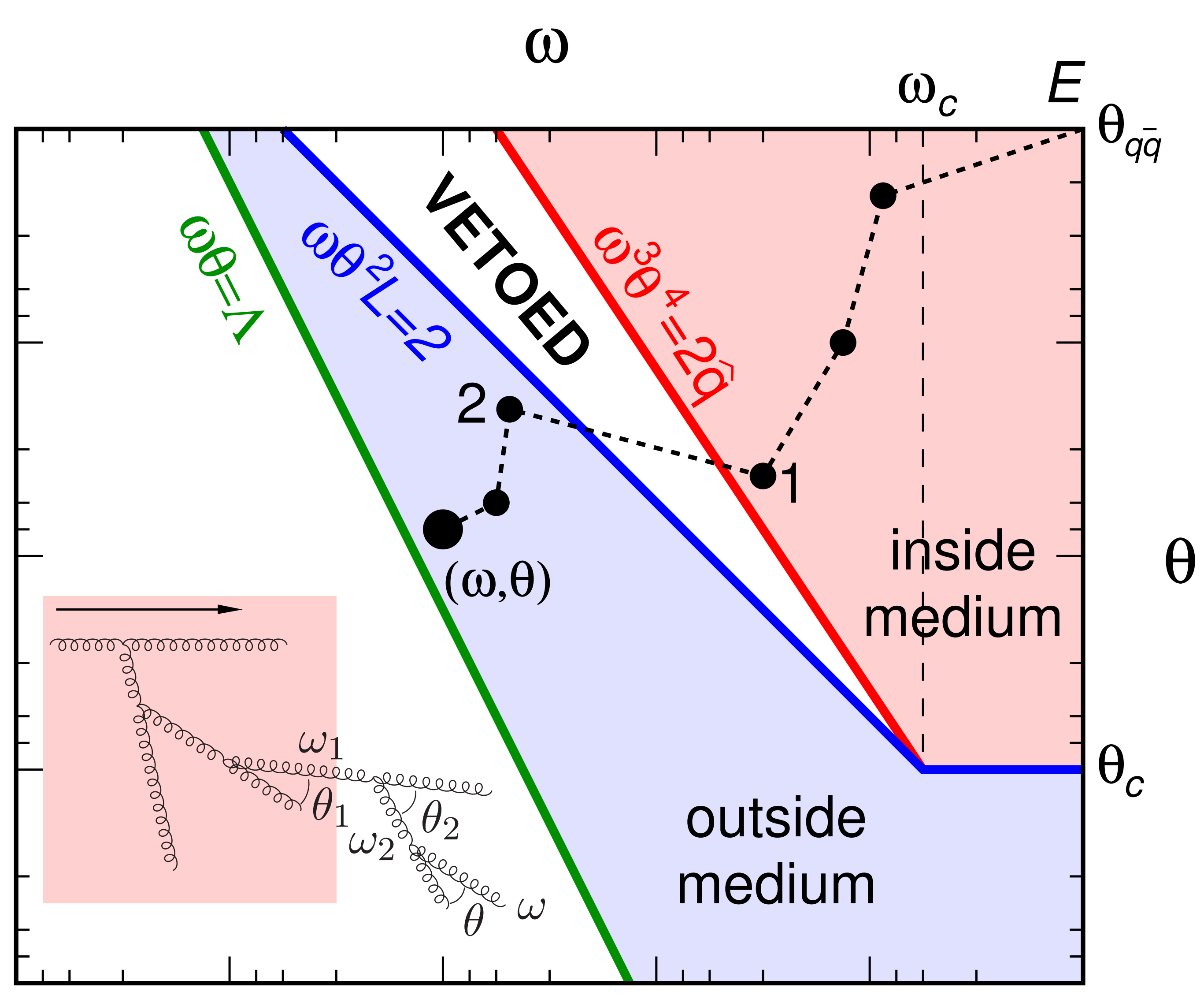
Survival probability
$\hat{q}$ - jet quenching parameter

Vacuum-like emissions

Hard splittings with small formation time $t_f \ll t_d$ cannot be resolved by the medium

First hard splitting + DLA — **most of the cascade is vacuum-like** (with energy loss on top)



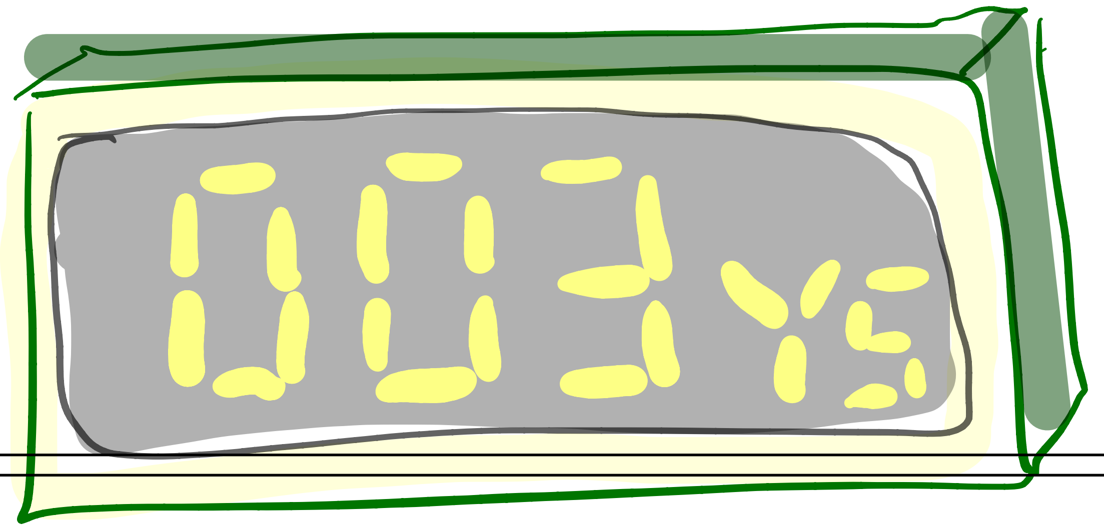


[Caucal, Iancu, Mueller, Soyez 2018]

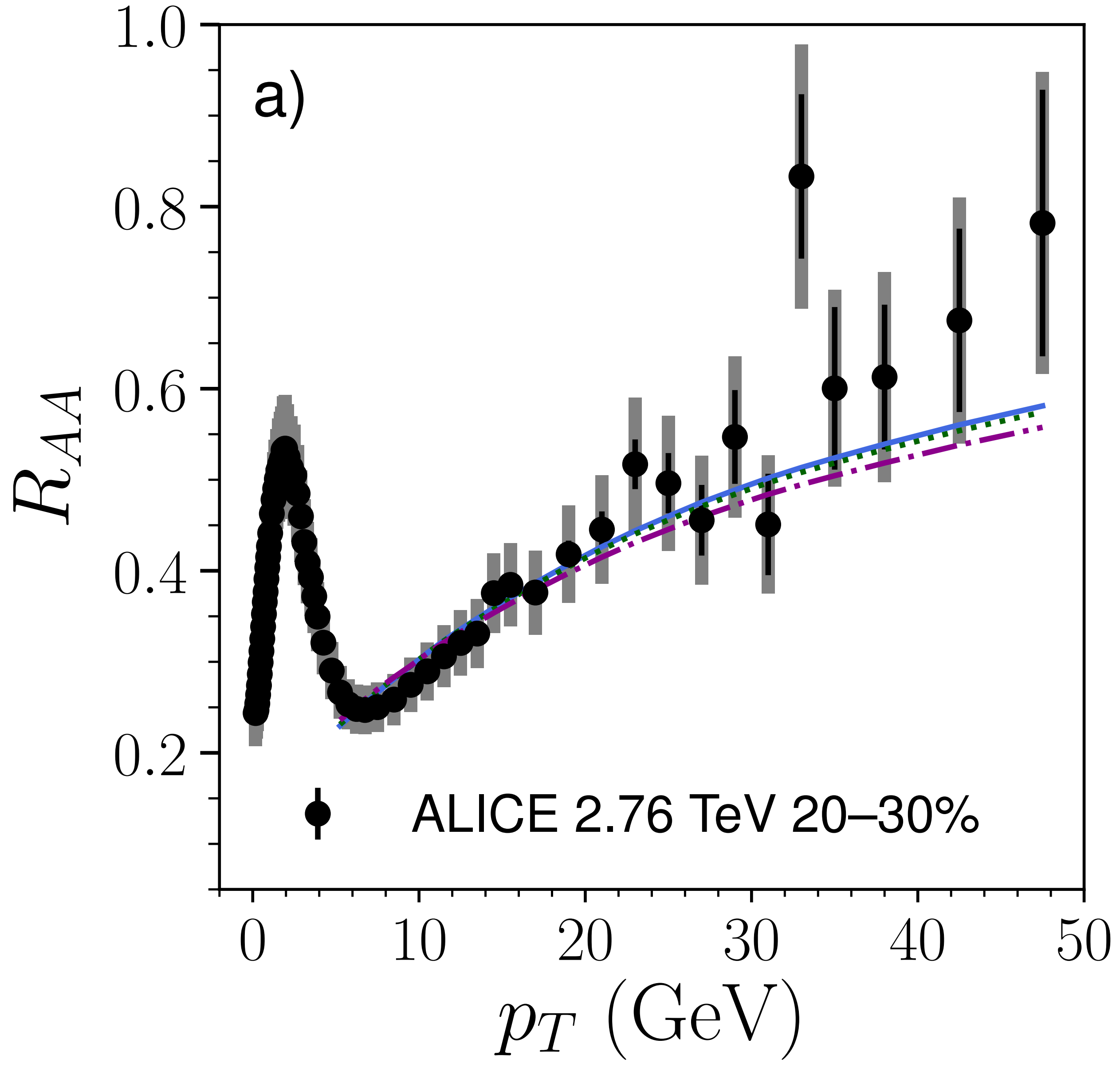
Color coherent sub-jets provide organizational principle for in-medium cascade

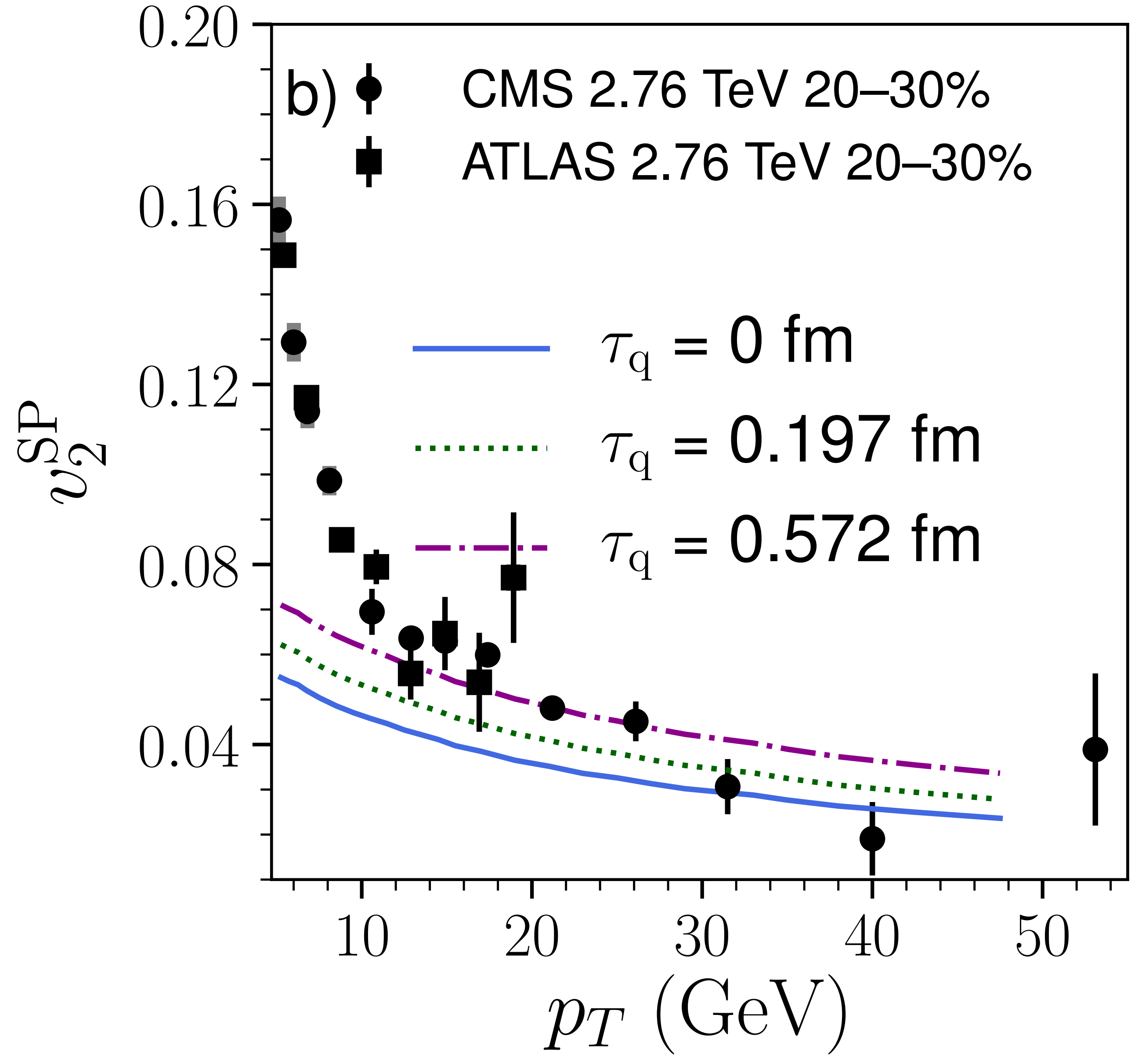
[Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk 2012]

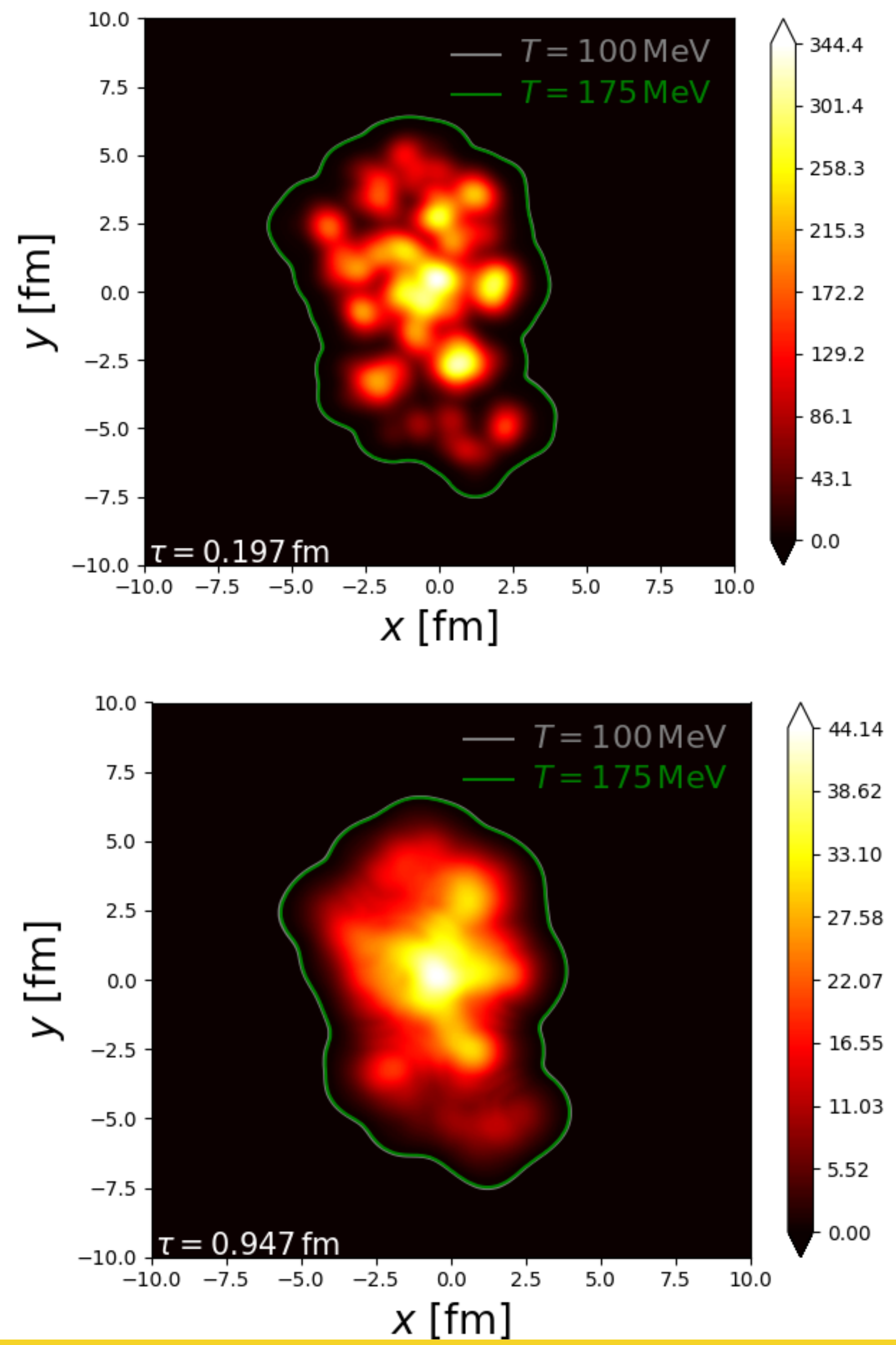
First ~3ys…



Main question - can we access the initial stages with jet quenching?







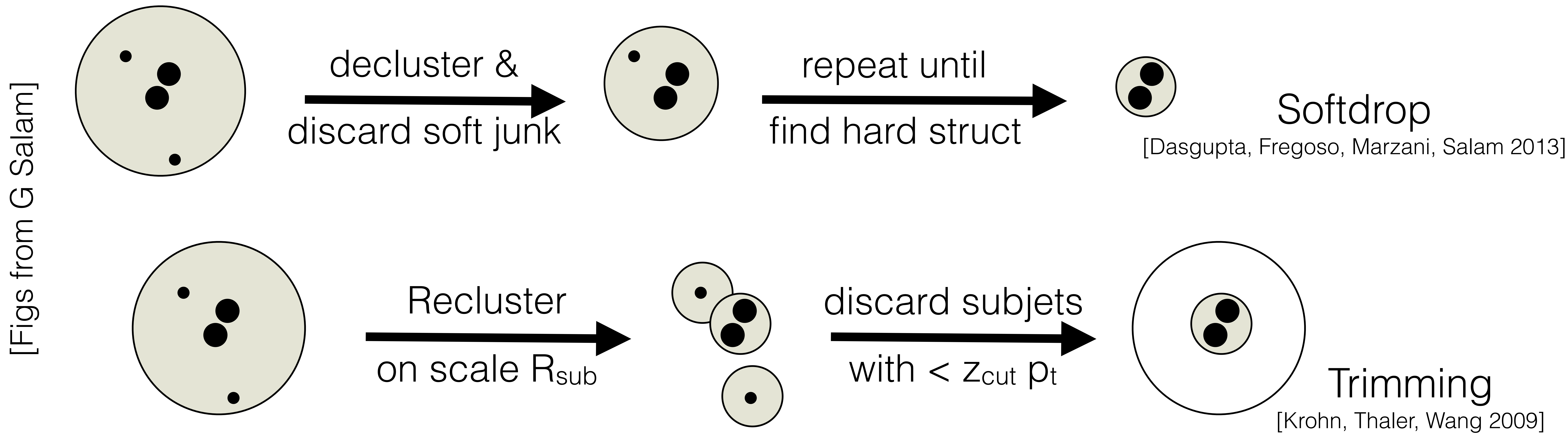
[Andres, Armesto, Niemi, Paatelainen, Salgado 2019]

Initial stages (thermalisation period) affect jet quenching -
Opens completely new possibilities - study early times with jet observables

Jet substructure and time evolution

Find different substructures in identified jets

[very active area, lots of results in the last years]



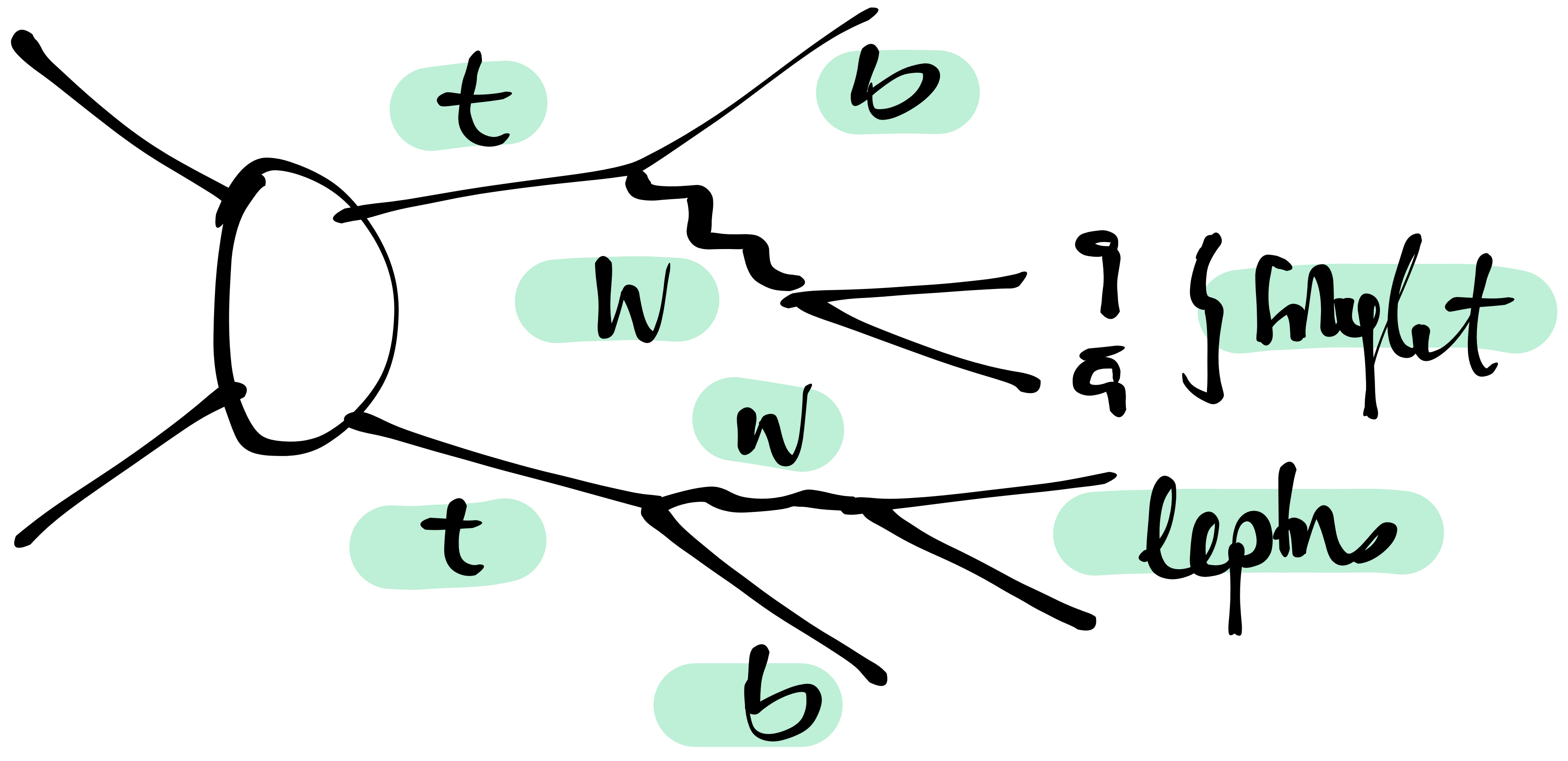
Also to identify two-pronged jet structures - boosted H/W/Z

A yoctosecond chronometer

[late times]

Can we **more directly measure the space-time development with jet observables?**

[Apolinario, Milhano, Salgado, Salam 2019]



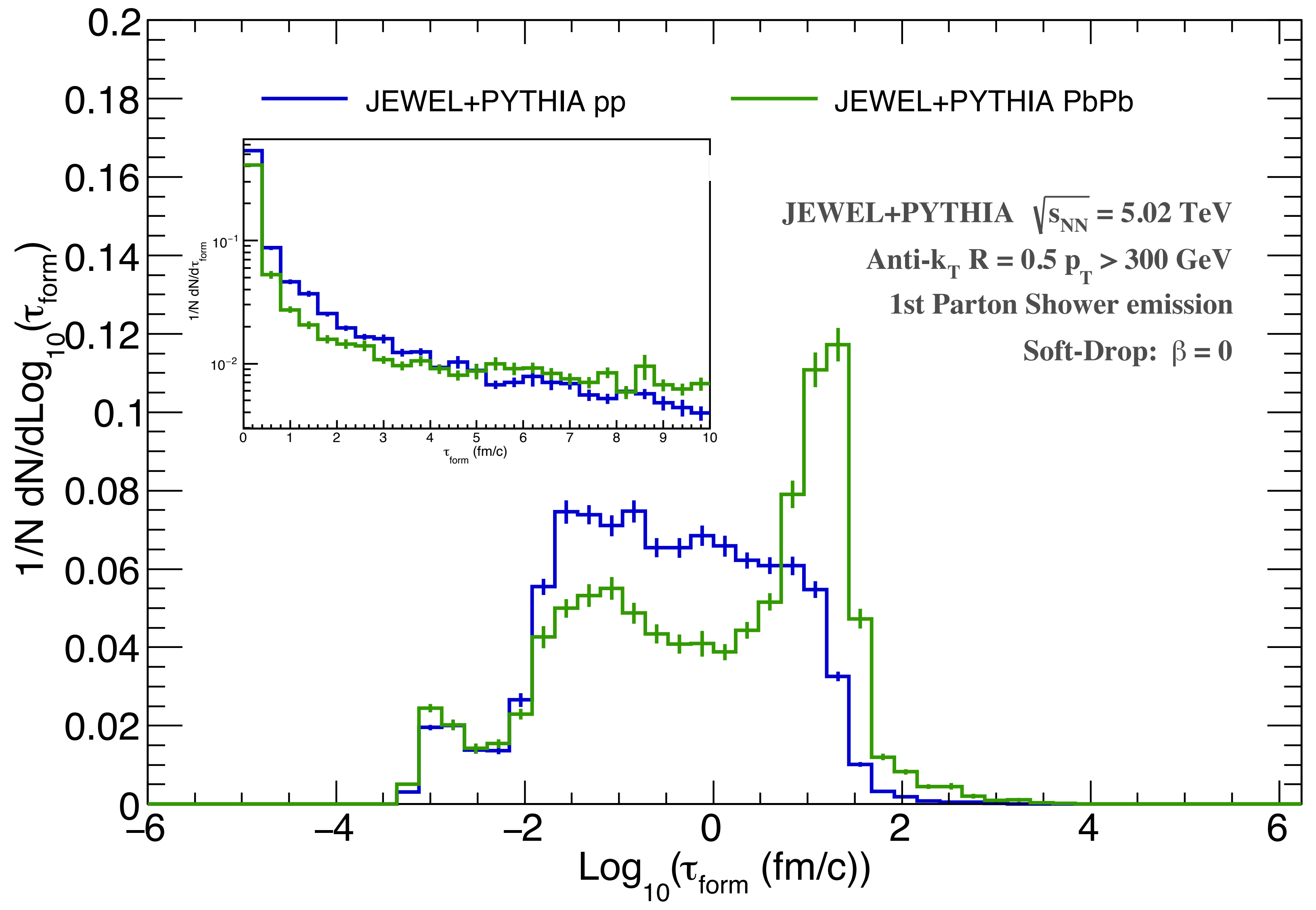
Boosted tops

Difficult with LHC PbPb luminosity - lighter ions?

Charm/Bottom quarks? [Attems, et al 2022]

New time reclustering algorith

Very promising

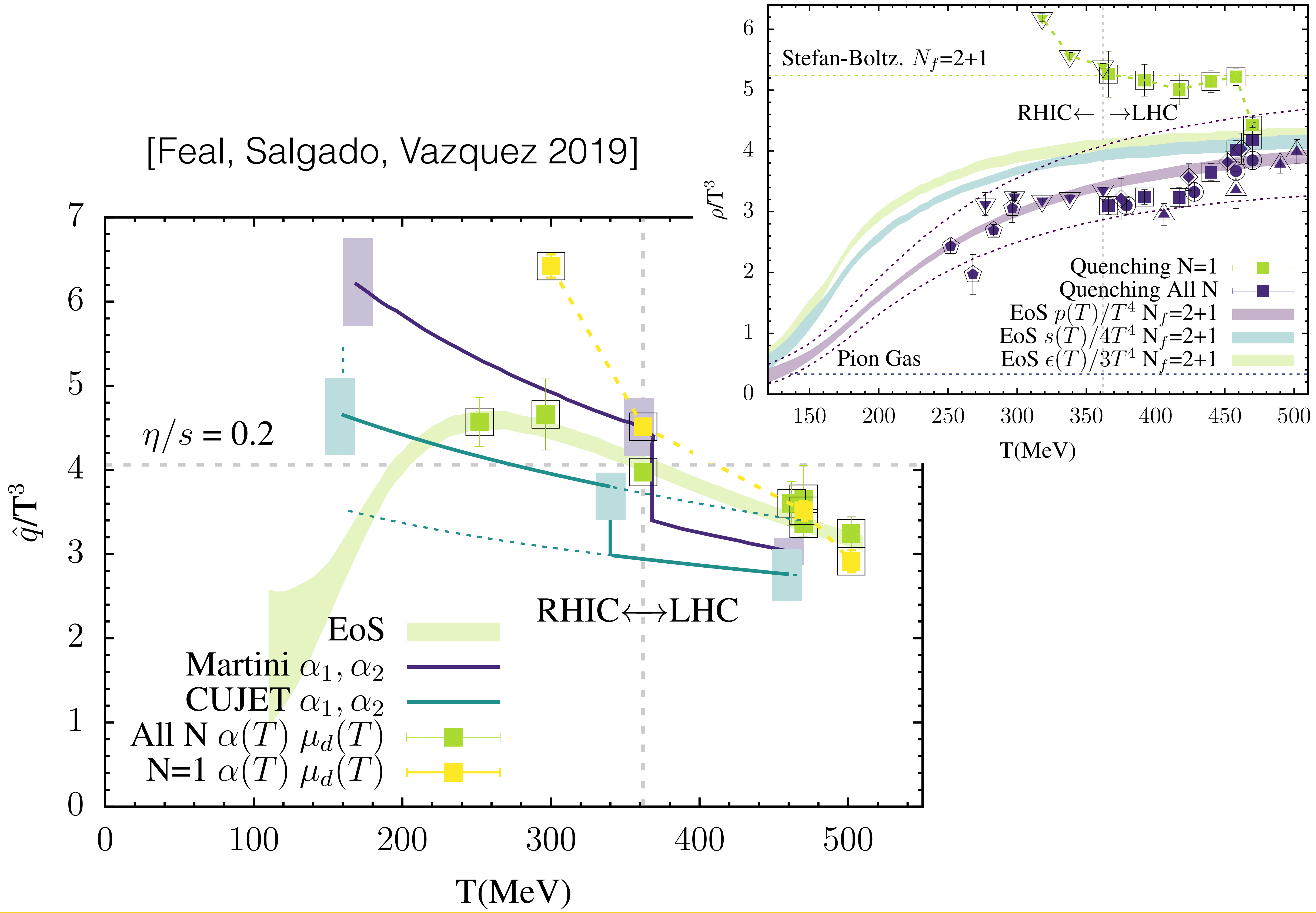


[Apolinario, Cordeiro, Zapp 2021]

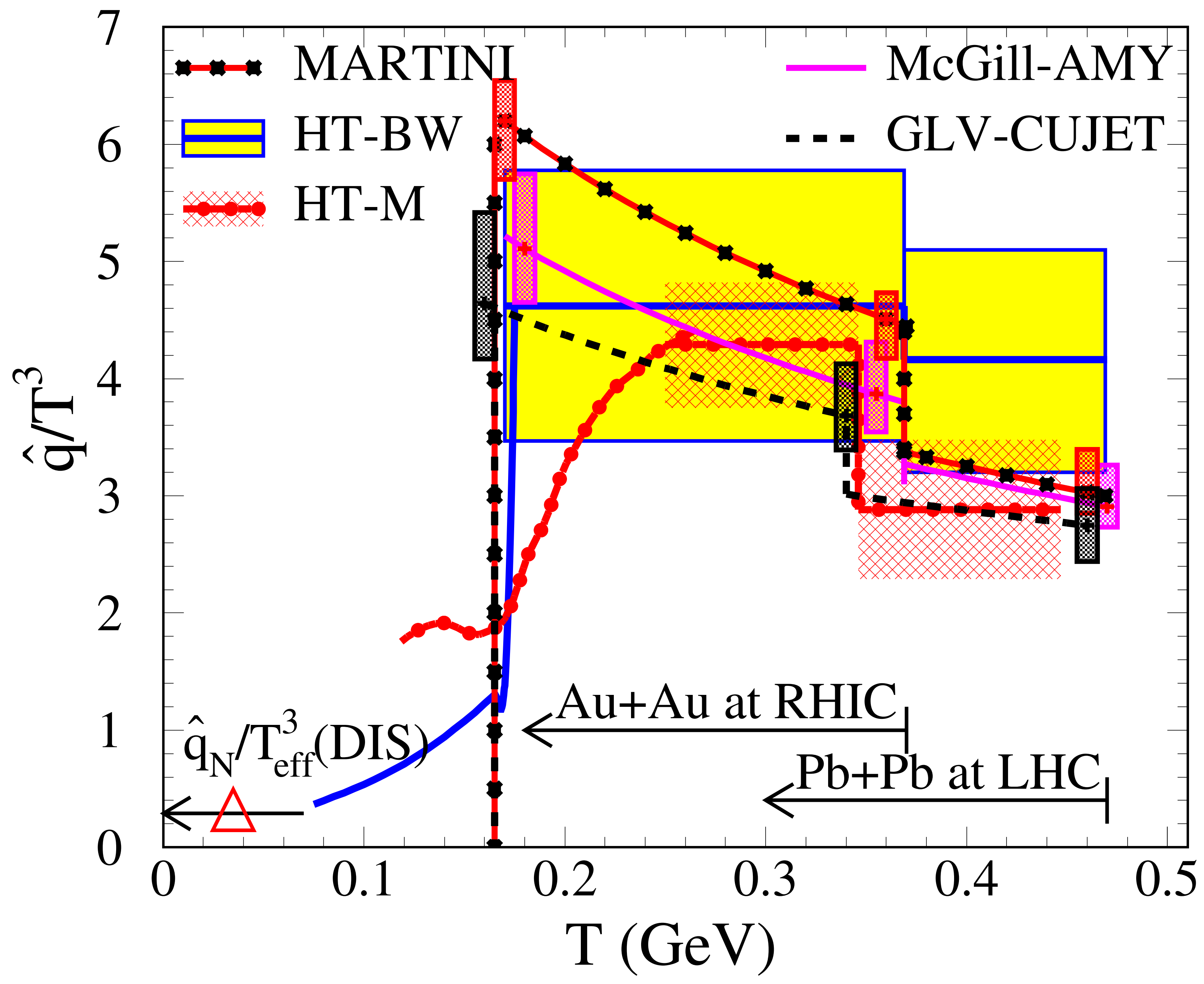
Jet quenching parameter

Information about the medium properties usually encoded in the jet quenching parameter $\hat{q}$

[Feal, Salgado, Vazquez 2019]



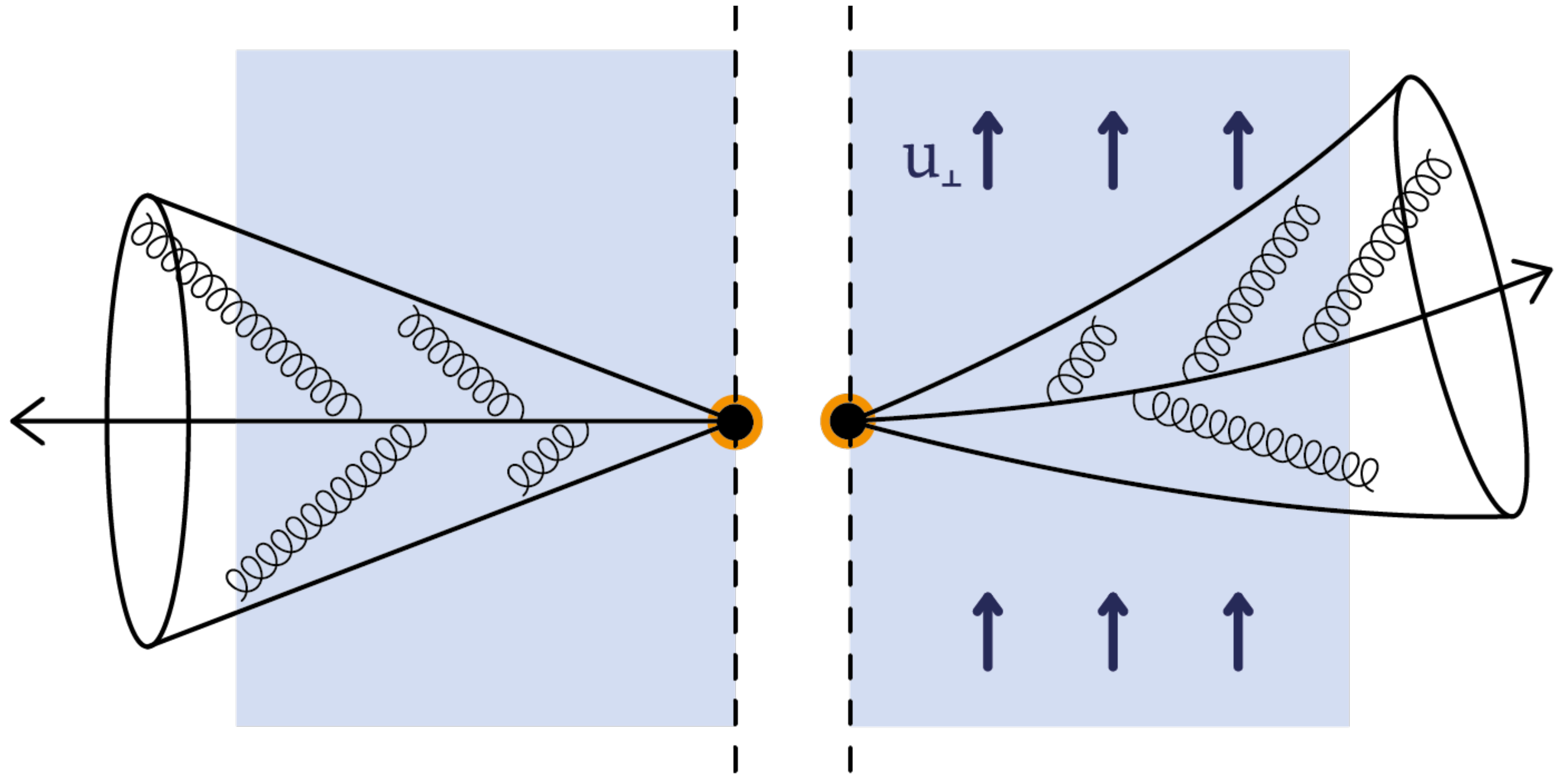
[Burke et al - Jet Collaboration 2013]



Agreement with cross sections from thermal-QCD — resummation of multiple scatterings needed

Coupling to hydro

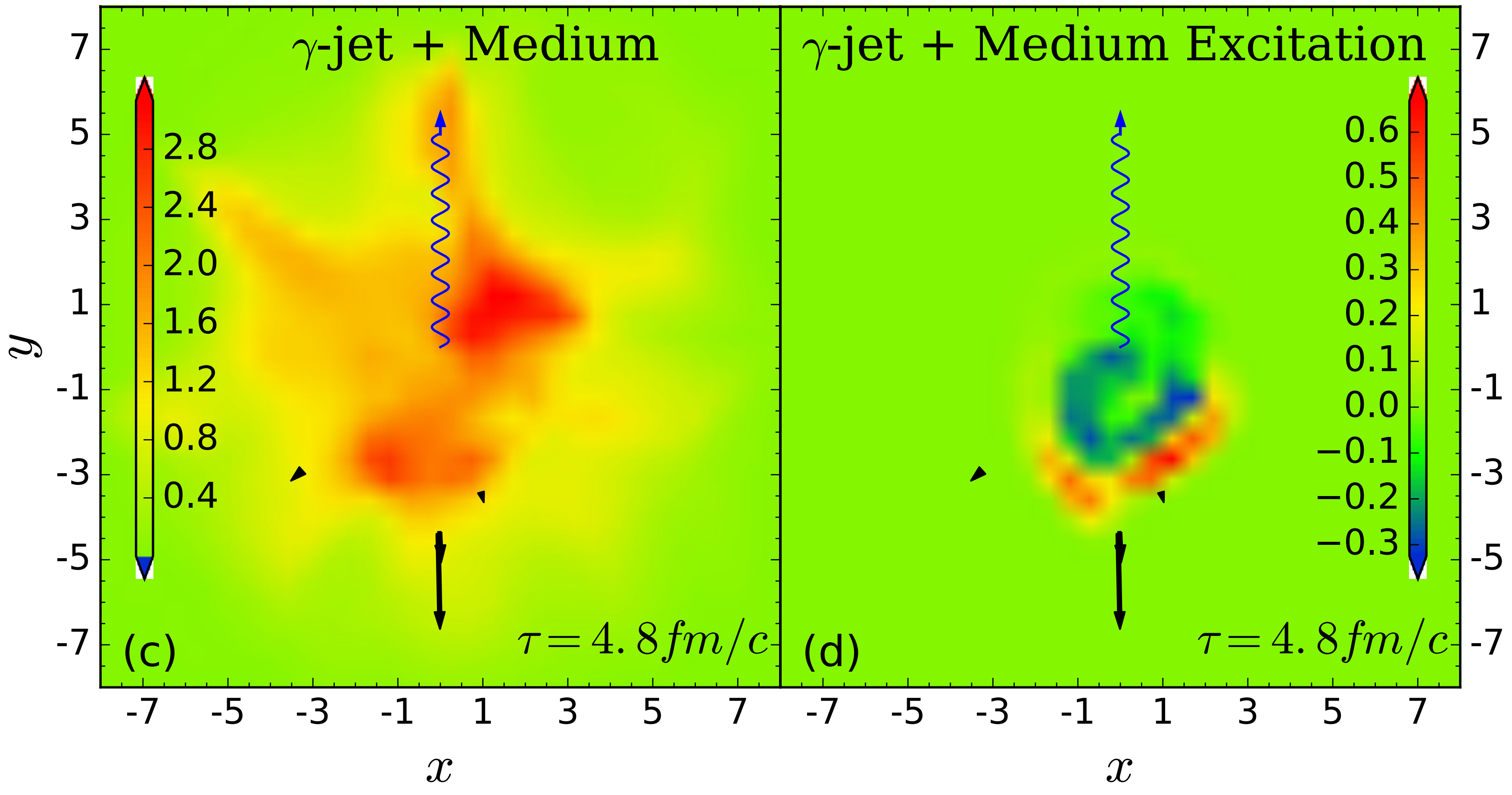
Rigorous jet-medium coupling - include gradients and velocity fields in background field

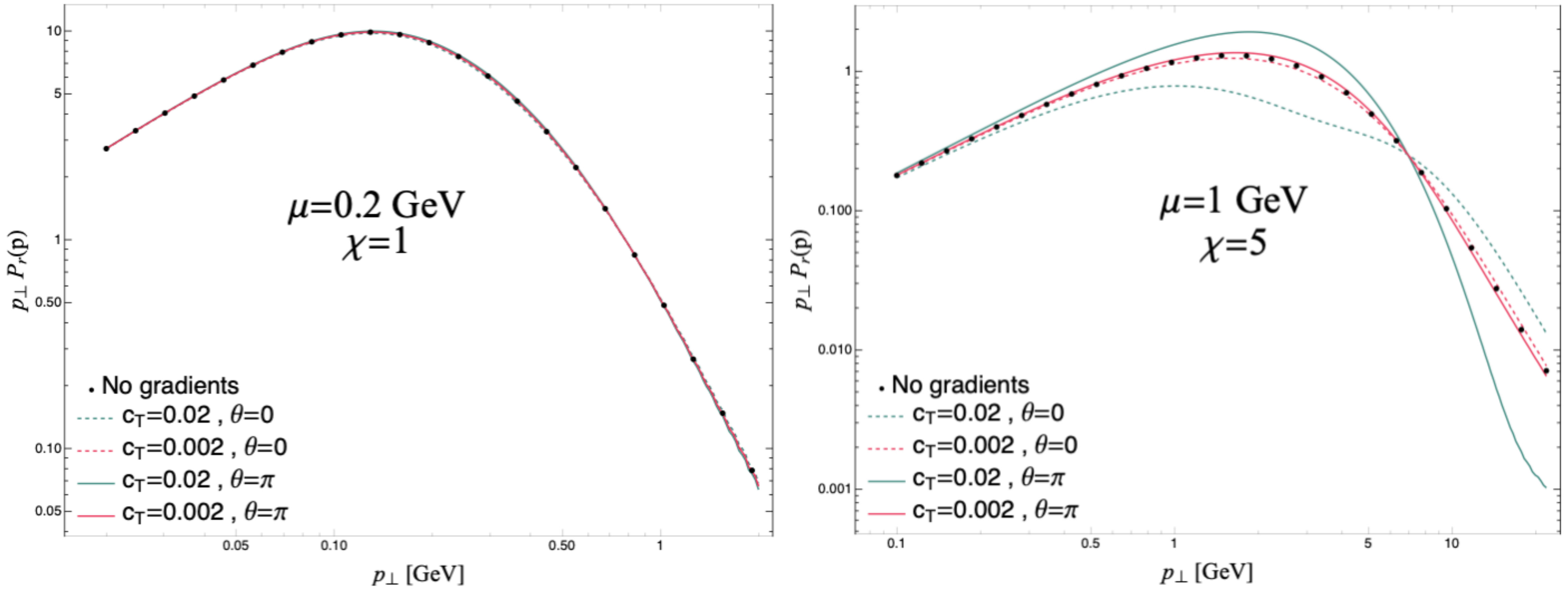


[Sadofyev, Sievert, Vitev 2021; Antiporda, Bahder, Rahman, Sievert 2022; Barata, Sadofyev, Salgado 2022; Fu, Casalderrey, Wang 2022; Andres, Dominguez, Sadofyev, Salgado 2022; Ipp, Muller, Schuh 2022 — Previous: Armesto, Salgado, Wiedemann 2004]

$$gA^{a\lambda}(q) = u^{\lambda}\, v(q) \left[\int d^2\boldsymbol{x}\, dz\, e^{-i(\boldsymbol{q}\cdot\boldsymbol{x}+q_z z)}\hat{\rho}^a(\boldsymbol{x},z)\right] (2\pi)\,\delta(q^0-\boldsymbol{u}\cdot\boldsymbol{q})$$

[Chen, Cao, Luo, Pang, Wang 2018]





Conclusions

QCD provides a very powerful laboratory to understand how the first levels of complexity emerge from a fundamental (and non-abelian) theory

- **QCD has a rich dynamical content well within experimental reach**
- Branches to other very active fields in Physics, including Cosmology or Condense Matter - equilibration, role of quantum entanglement, etc…

Impressive progress in several theoretical areas of heavy ion collisions

- Initial stages, parton saturation and thermalization
- Hydrodynamics
- Hard Probes: jet quenching and quarkonia (also heavy-flavor)
- … **and connections between them**

New data from LHC and RHIC

- Continuous progress on the characterization of the QGP and Yoctosecond Chronometer
- **Completely new opportunities — initial stages / small systems — directly access time evolution**