Dense QCD Matter in Heavy Ion collisions and Neutron Stars [Theory]

Carlos A. Salgado
IGFAE - Santiago de Compostela

EPS-HEP 2019 — Ghent July 2019

[Disclaimer — too broad for 25m, **many** important results not shown — see also three previous talks by Marco, Jan Fiete and Dennis]

IGFAE Instituto Galego de Física de Altas Enerxías
USC
XUNTA DE GALICIA
EXCELENCIA MARÍA DE MAEZTU

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

<u>Equilibrium</u> AND <u>non-equilibrium dynamics</u>

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

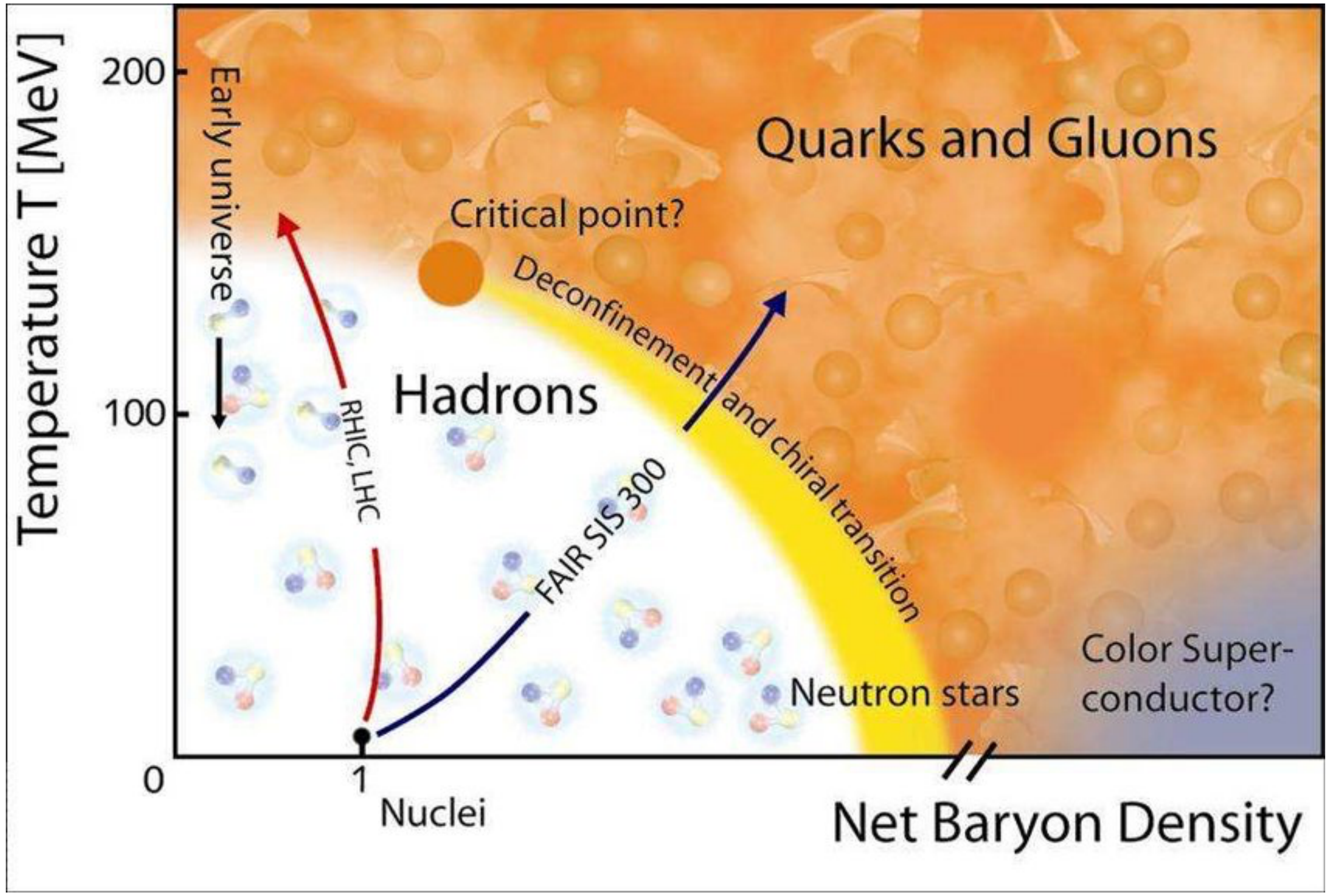
FAIR at GSI

NICA at Dubna

Cosmological observations — notably GWs

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

Future — access to QCD transition in early Universe?



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

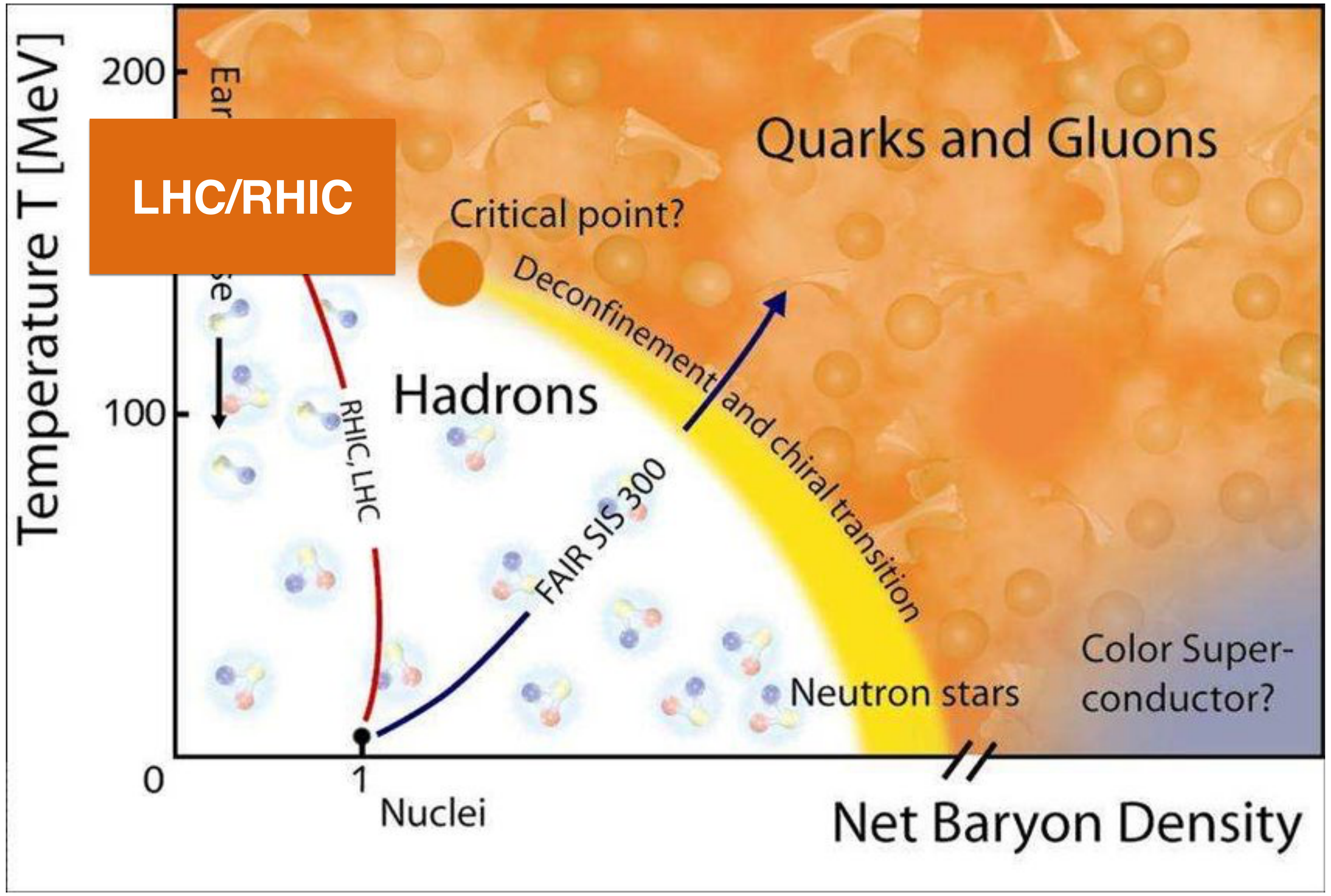
FAIR at GSI

NICA at Dubna

Cosmological observations — notably GWs

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

Future — access to QCD transition in early Universe?



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

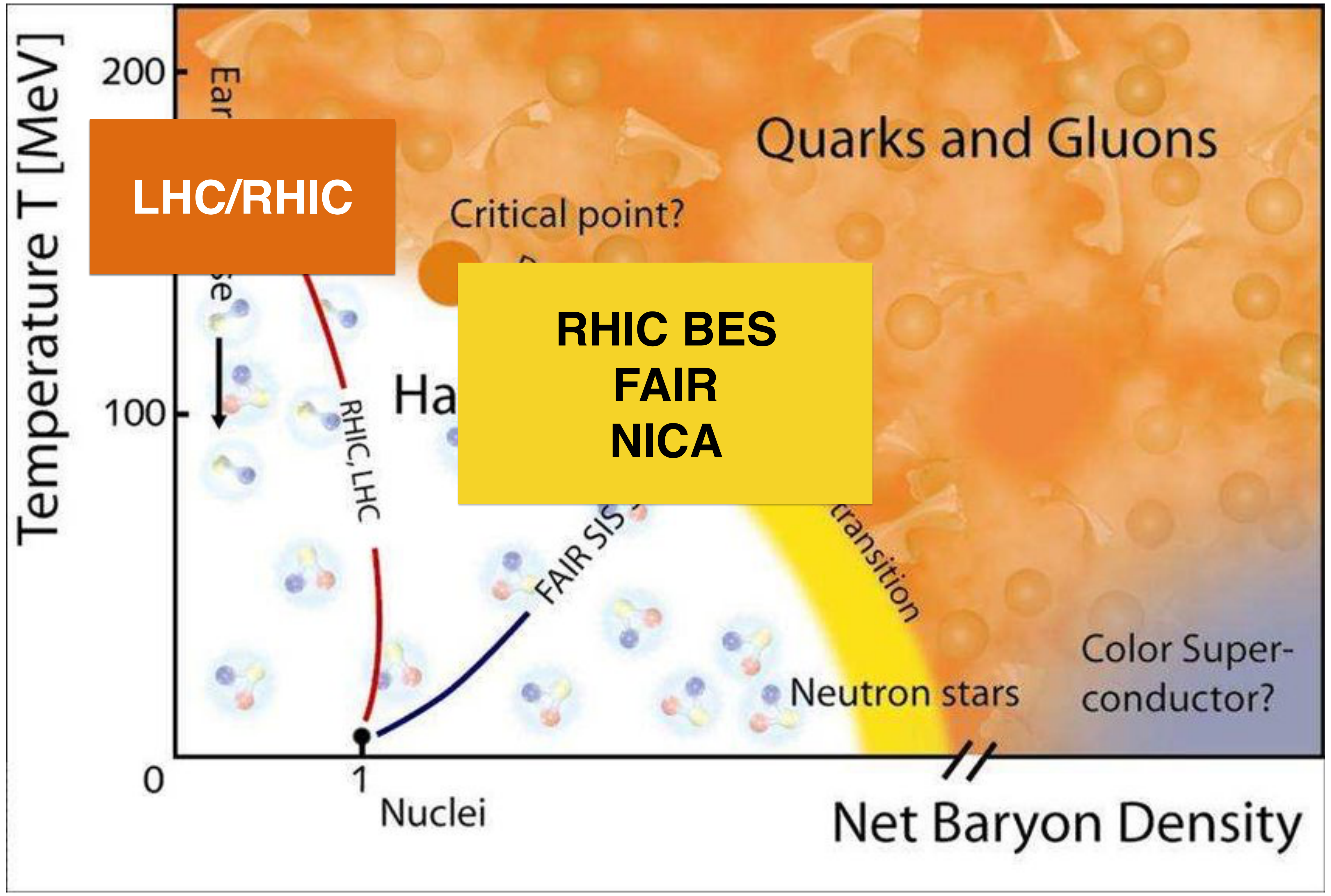
FAIR at GSI

NICA at Dubna

Cosmological observations — notably GWs

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

Future — access to QCD transition in early Universe?



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

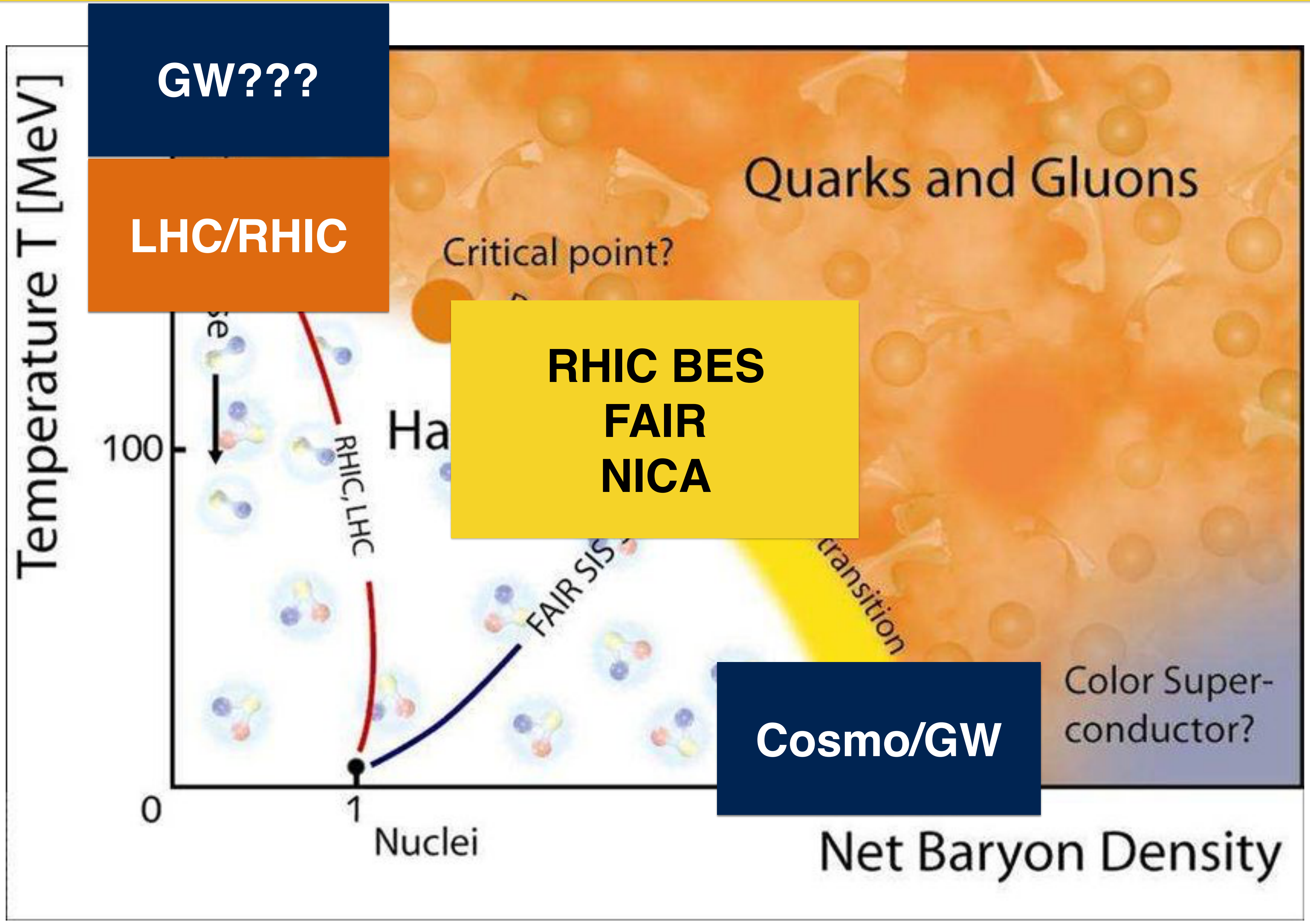
FAIR at GSI

NICA at Dubna

Cosmological observations — notably GWs

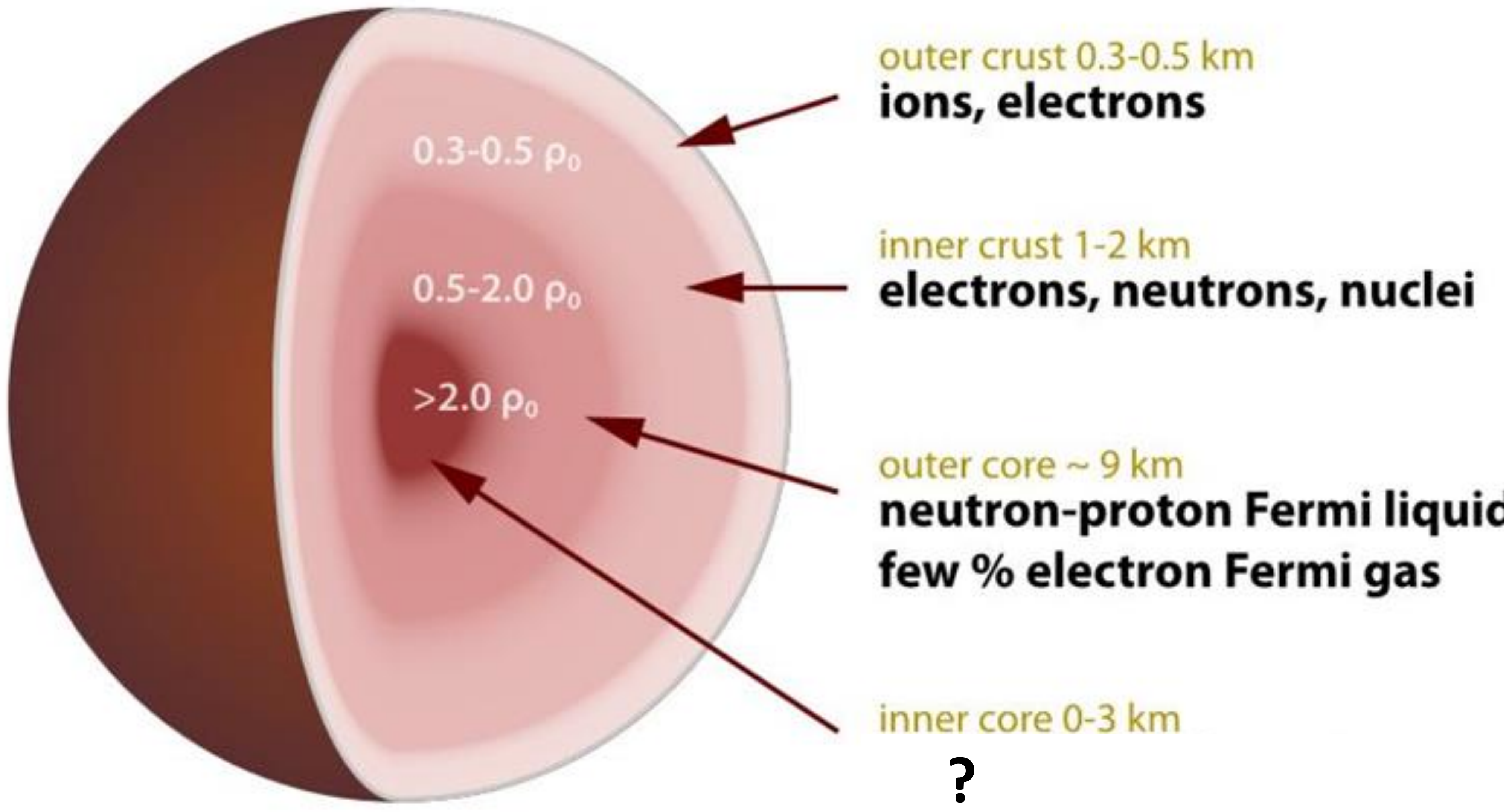
Neutron star coalescence - **low T, high n_B**

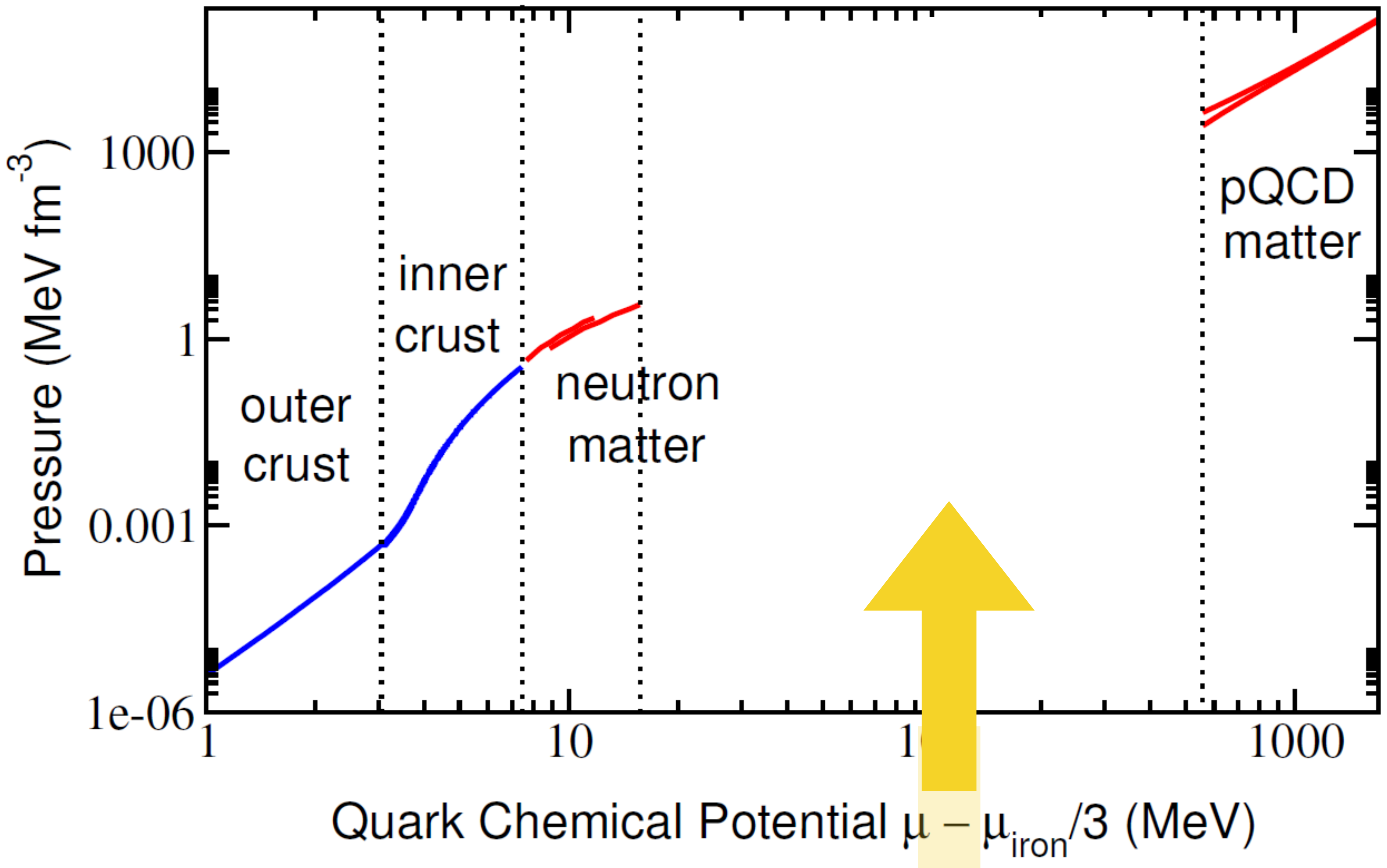
Future — access to QCD transition in early Universe?



Neutron stars

EoS determines neutron star structure





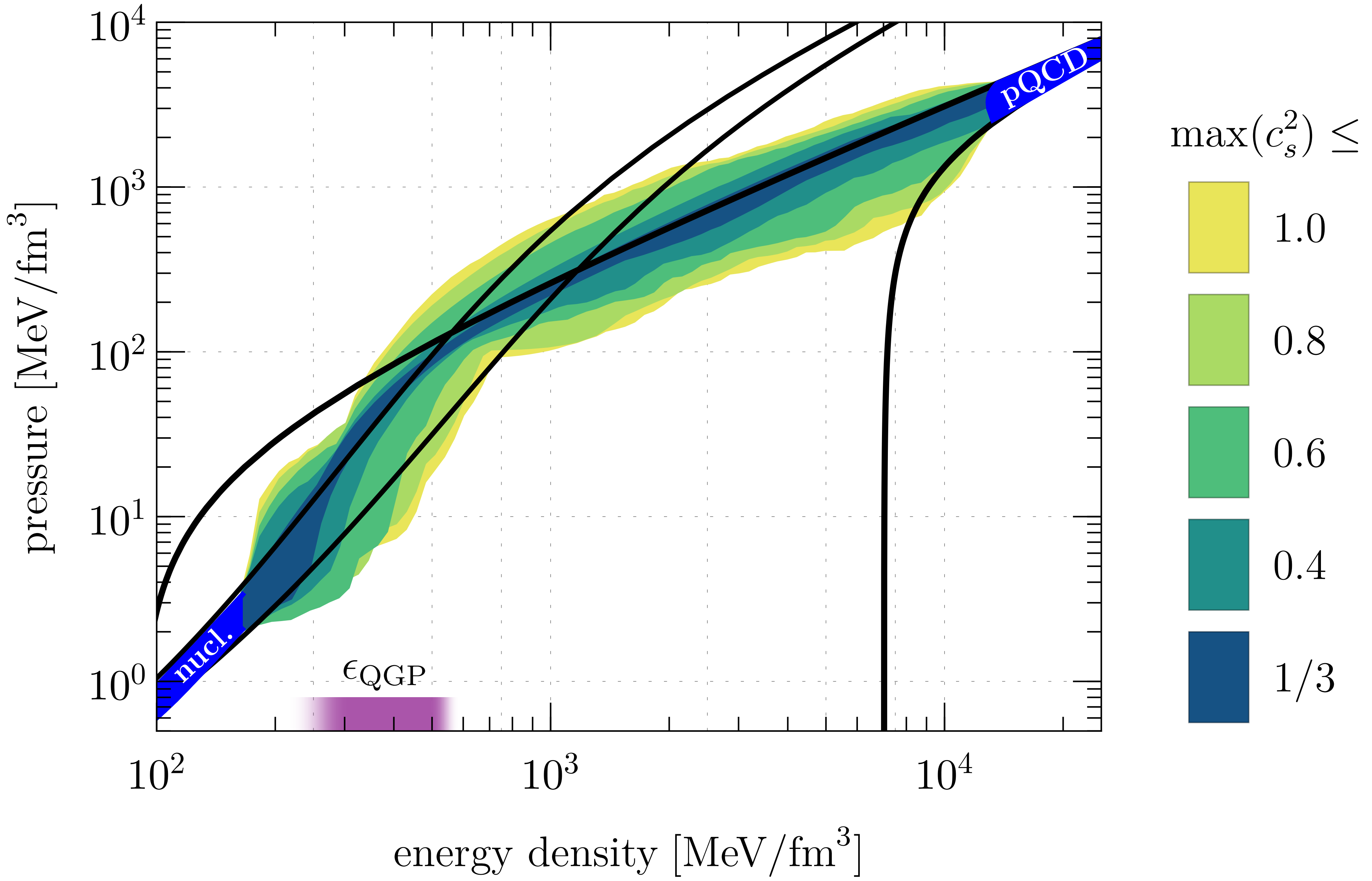
[A Vuorinen QM2018]

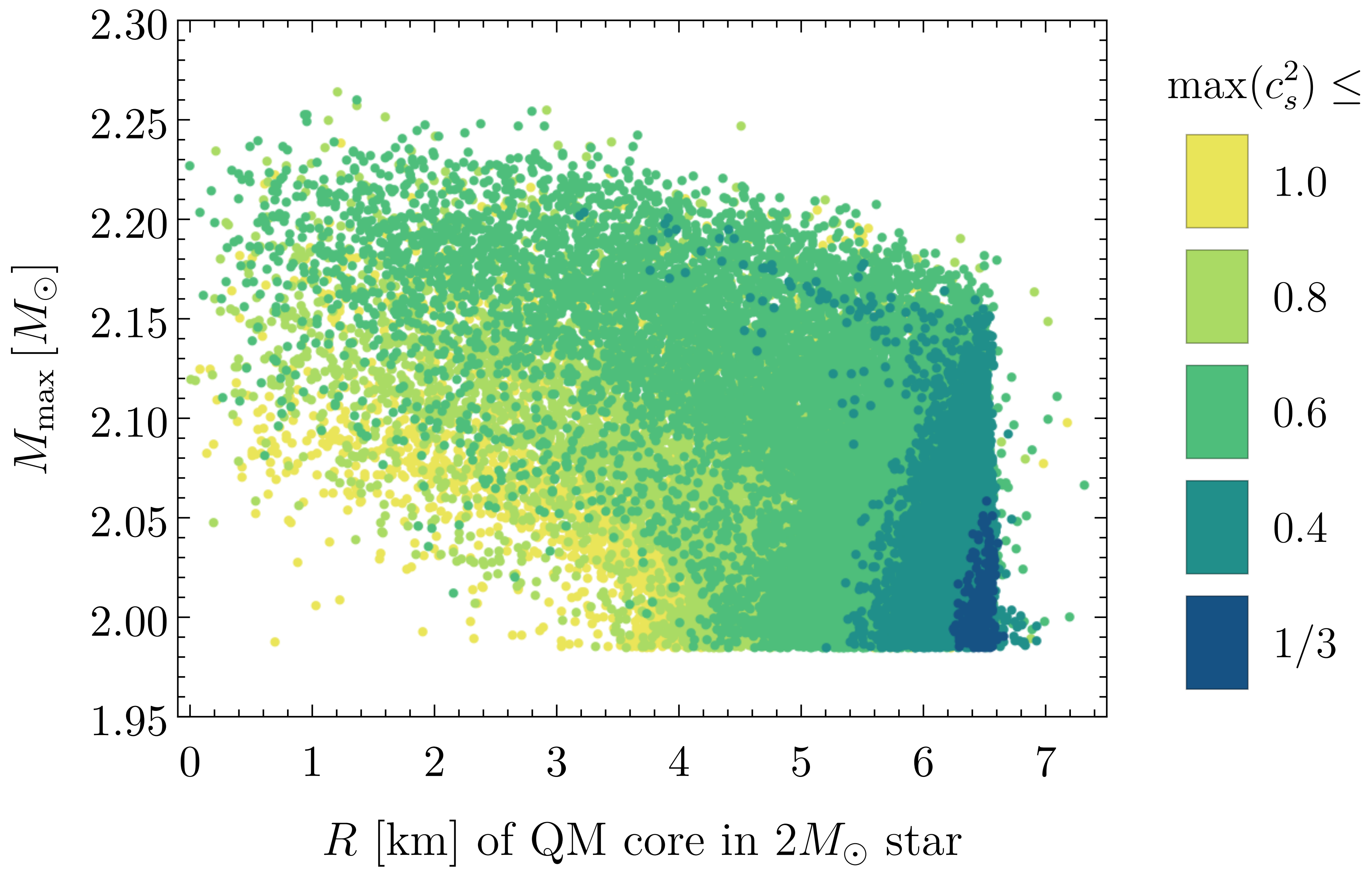
6

Lattice QCD
very challenging at finite μ_B

Region relevant for neutron star structure largely unknown

EoS constraints from GW





[Annala, Gorda, Kurkela, Vuorinen 2018; Annala, Gorda, Kurkela, Nattila, Vuorinen 2019; also Most et al. 2018; Dexheimer et al. 2019]

The existence of quark-matter core found to be a common feature of the allowed EoS

Further constraints for the EoS at higher and higher baryon density in future experiments FAIR, NICA

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?

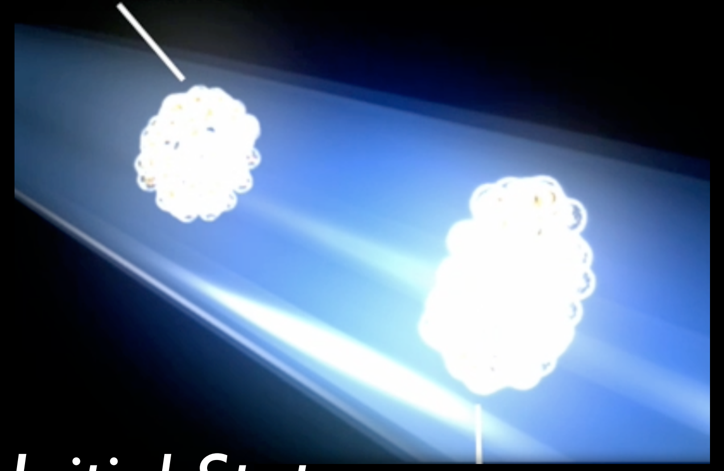
- identify signals to characterize the medium with well-controlled observables
- what are the building blocks and how they organize?
- is it strongly-coupled? quasiparticle description? phases?

Out of equilibrium

Towards equilibrium

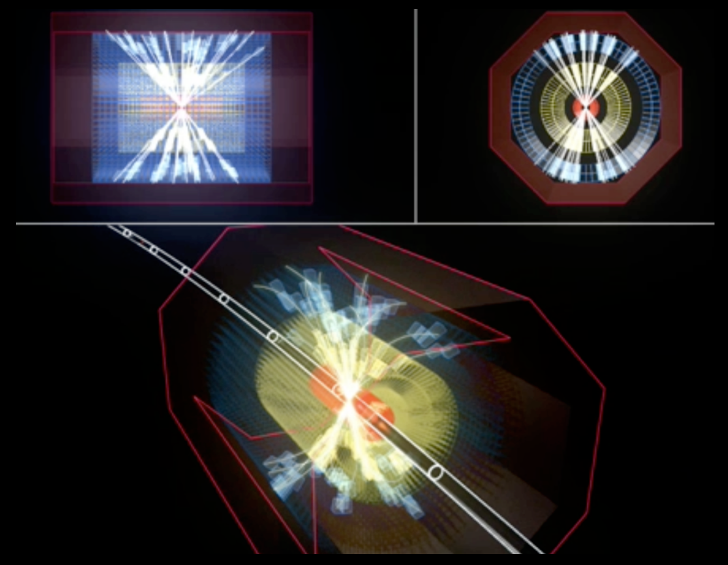
Local equilibrium

Questions accessible in HIC



Initial State

Final State



First ~5 yoctoseconds or 1.5fm/c

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

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

[Melo - parallel talk]

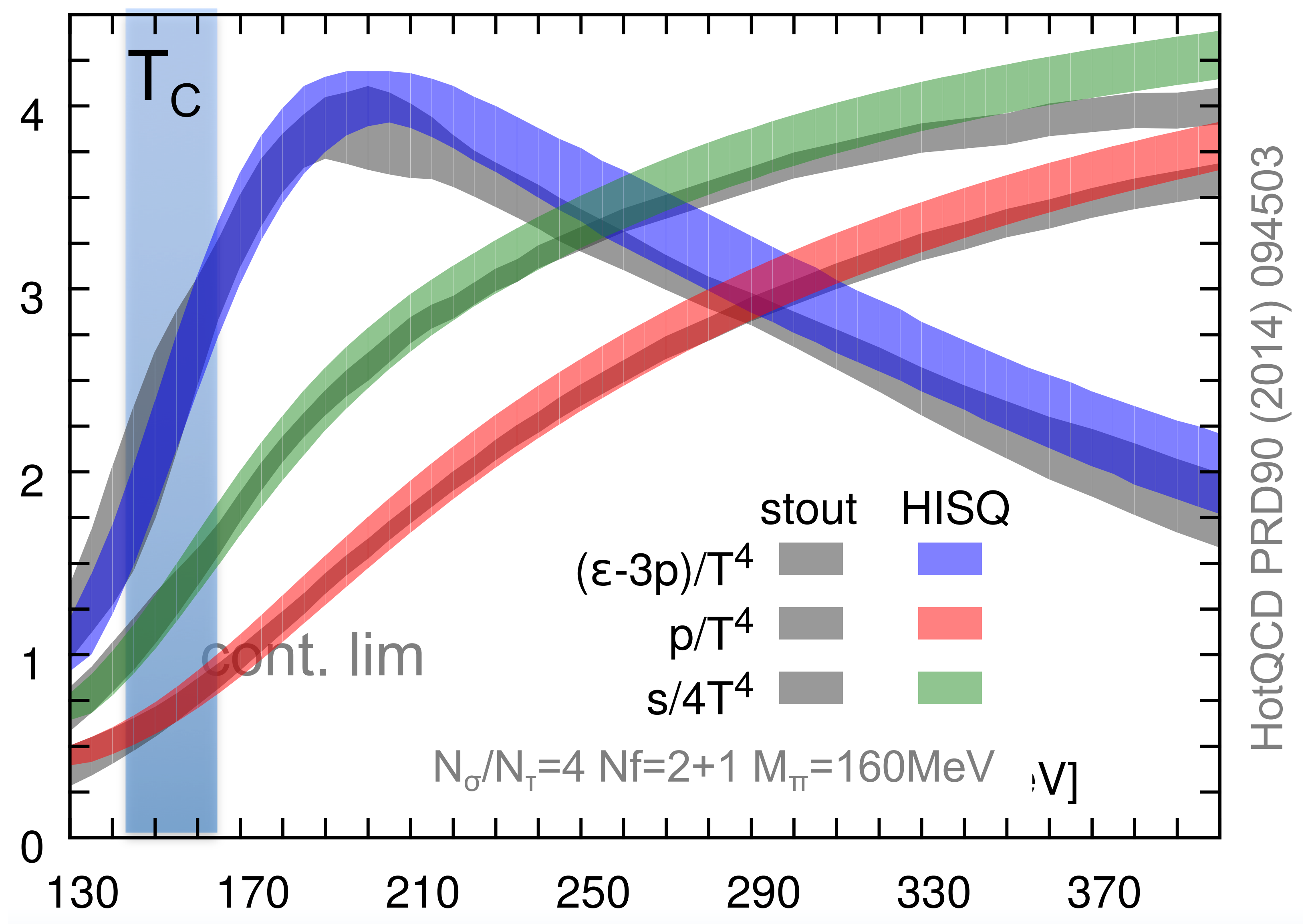
Far from equilibrium initial state needs to equilibrate fast (~1 fm or less)

Most of the theoretical progress in the last years:

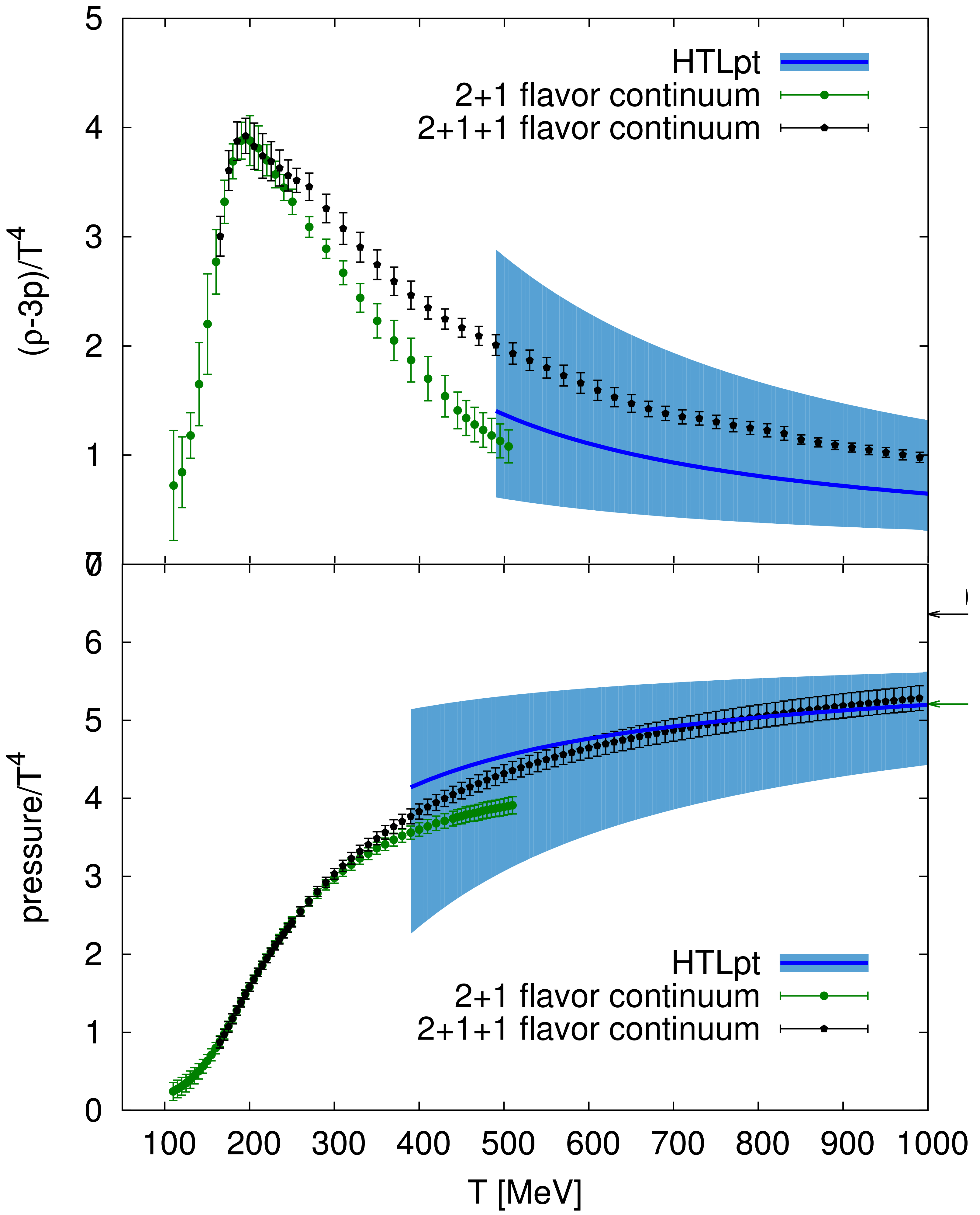
- Viscosity corrections
- Fluctuations in initial conditions
- Emergence of hydro from kinetic eqs, holography, etc…

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]



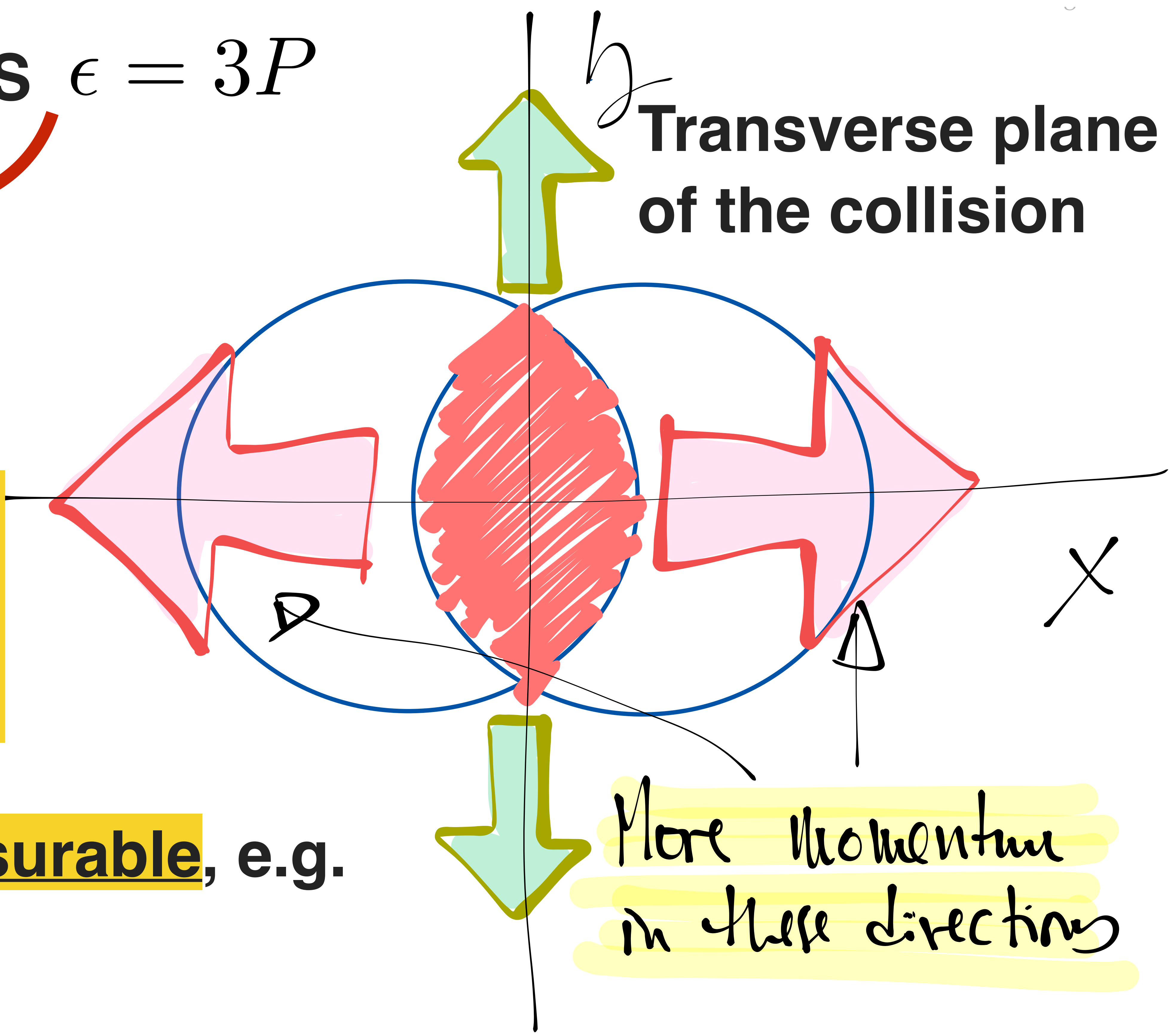
[Borsanyi et al Nature 539 (2016) no.7627, 69-71]

Harmonics: the golden measurement

[simplified discussion]

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

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



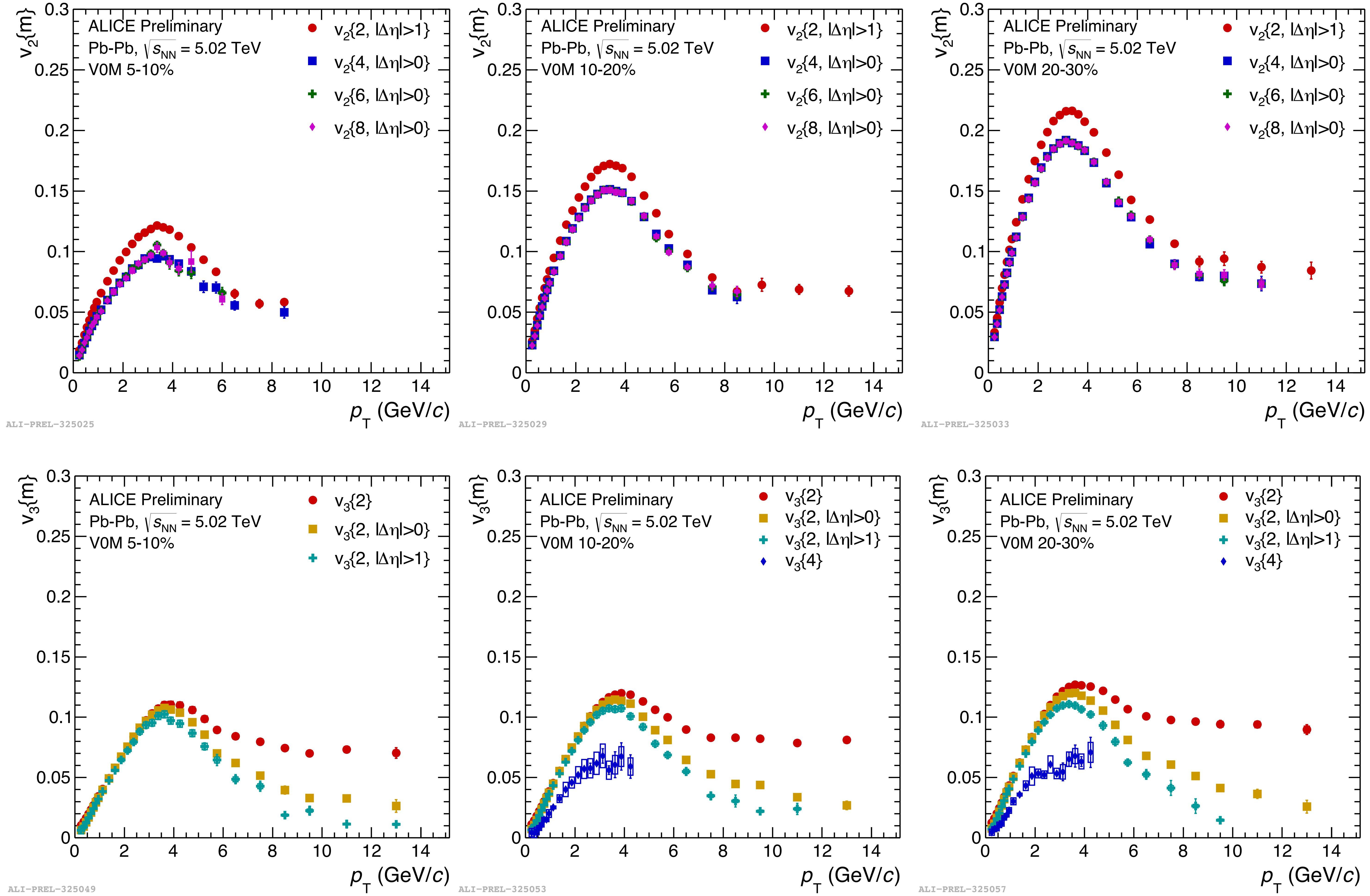
Initial state spatial anisotropies → **Final state momentum anisotropies**

These final state momentum anisotropies are measurable, e.g.

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

↳ Elliptic Flow

Some experimental results for PbPb

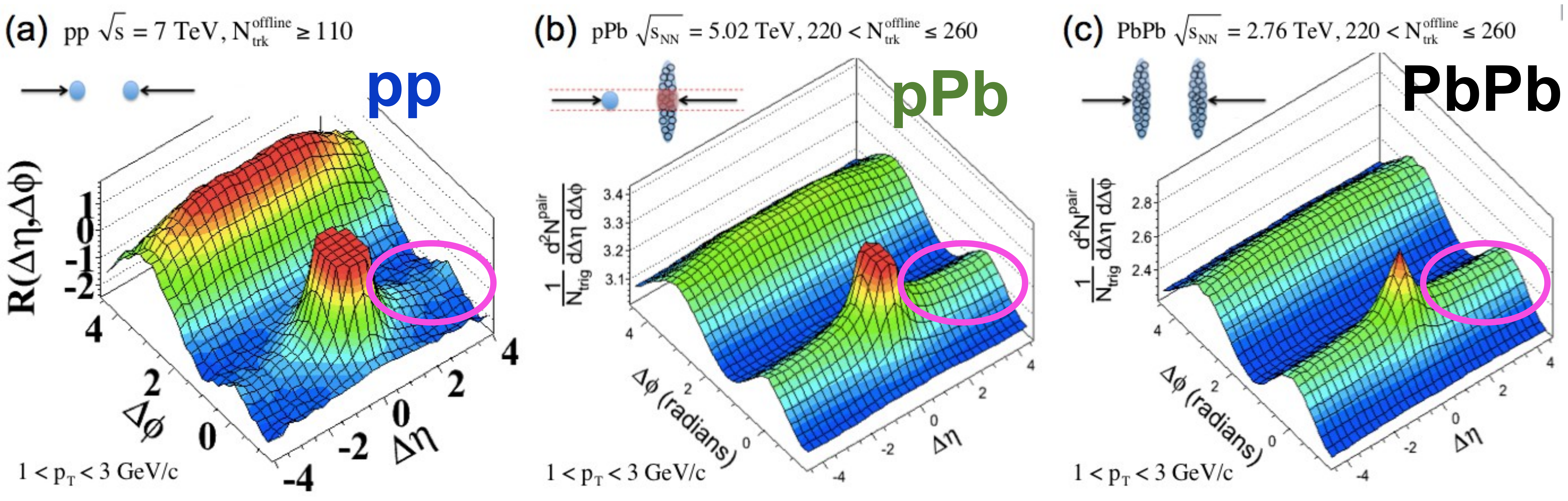


[Vytautas Vislavicius parallel talk]

[Plenty of other data in previous talks]

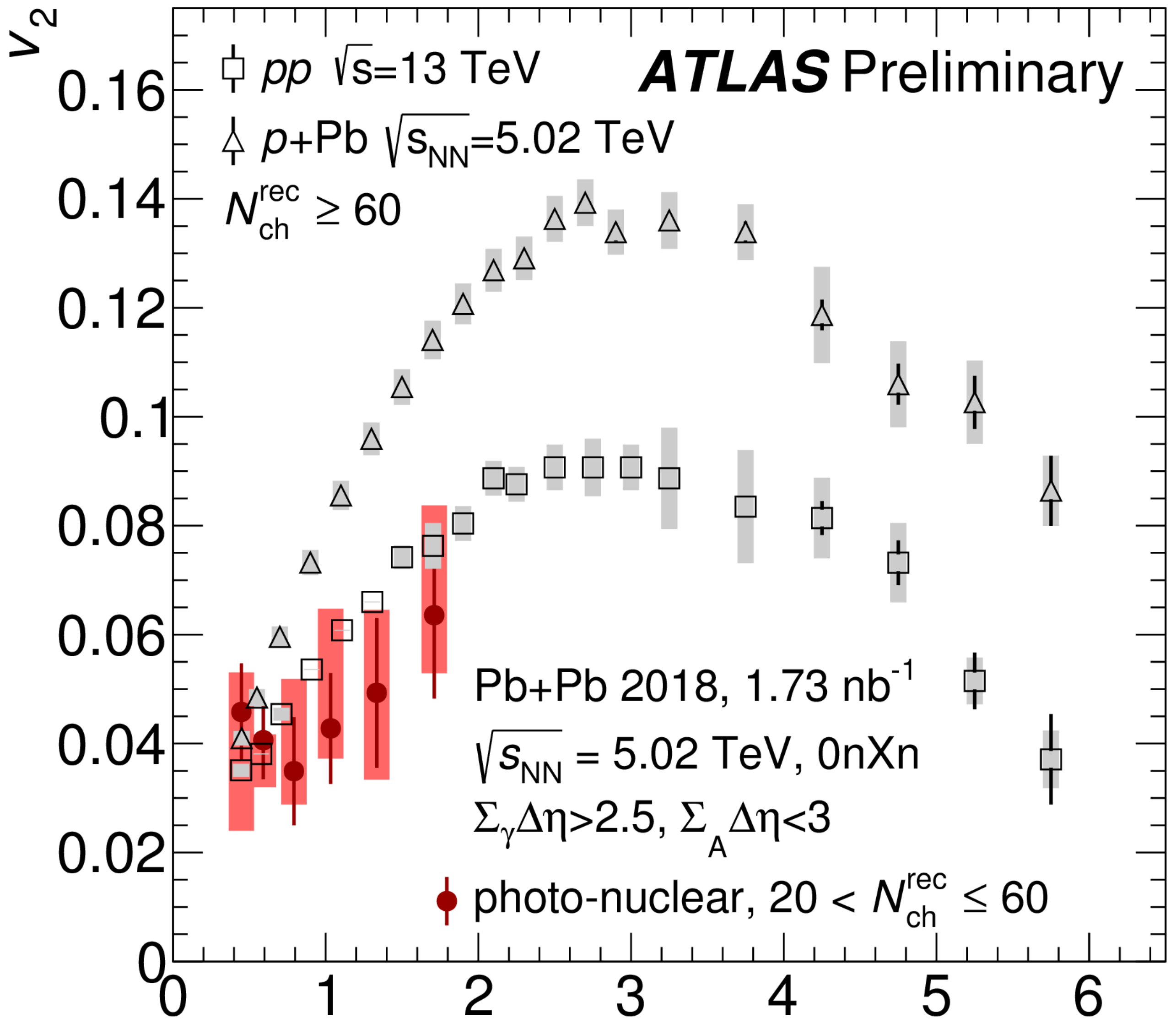
Hydro works in all systems from small to large ??

[Also plenary — Jan Fiete Grosse-Oetringhaus]



Hydro models able to describe the harmonics from these data

[Tayalati parallel talk]



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

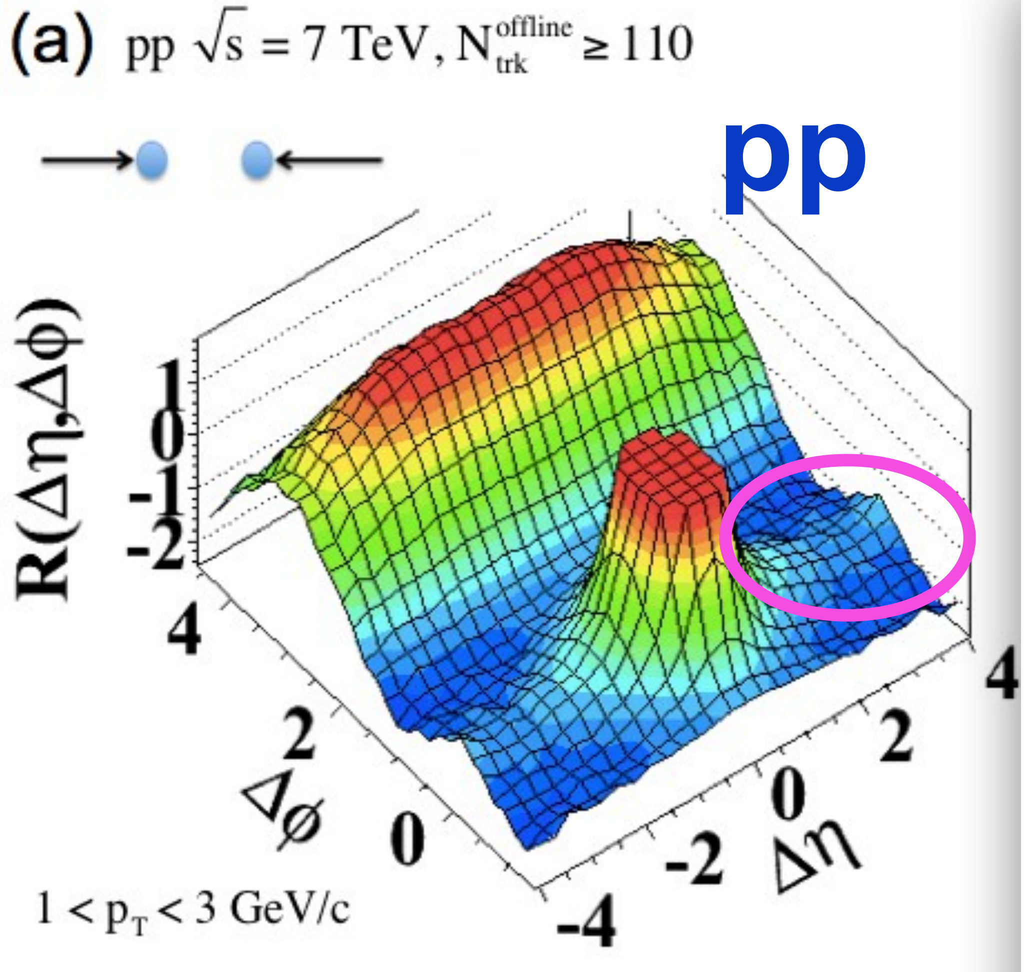
But time scales and occupancies in small systems are small

For some classes of problems hydro equations have attractors

[universal solutions, independent on initial conditions]

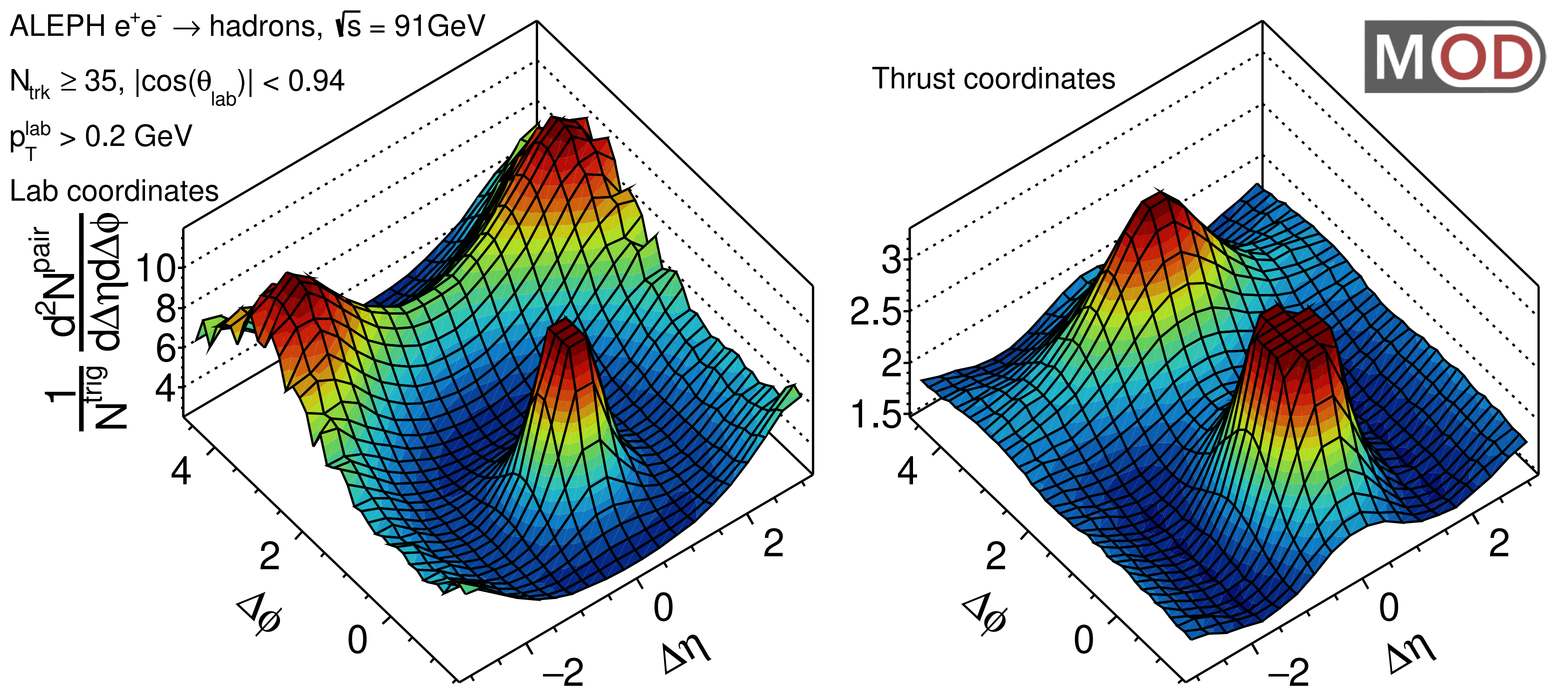
Hydro works in all systems from small to large ??

[Also plenary — Jan Fiete Grosse-Oetringhaus]



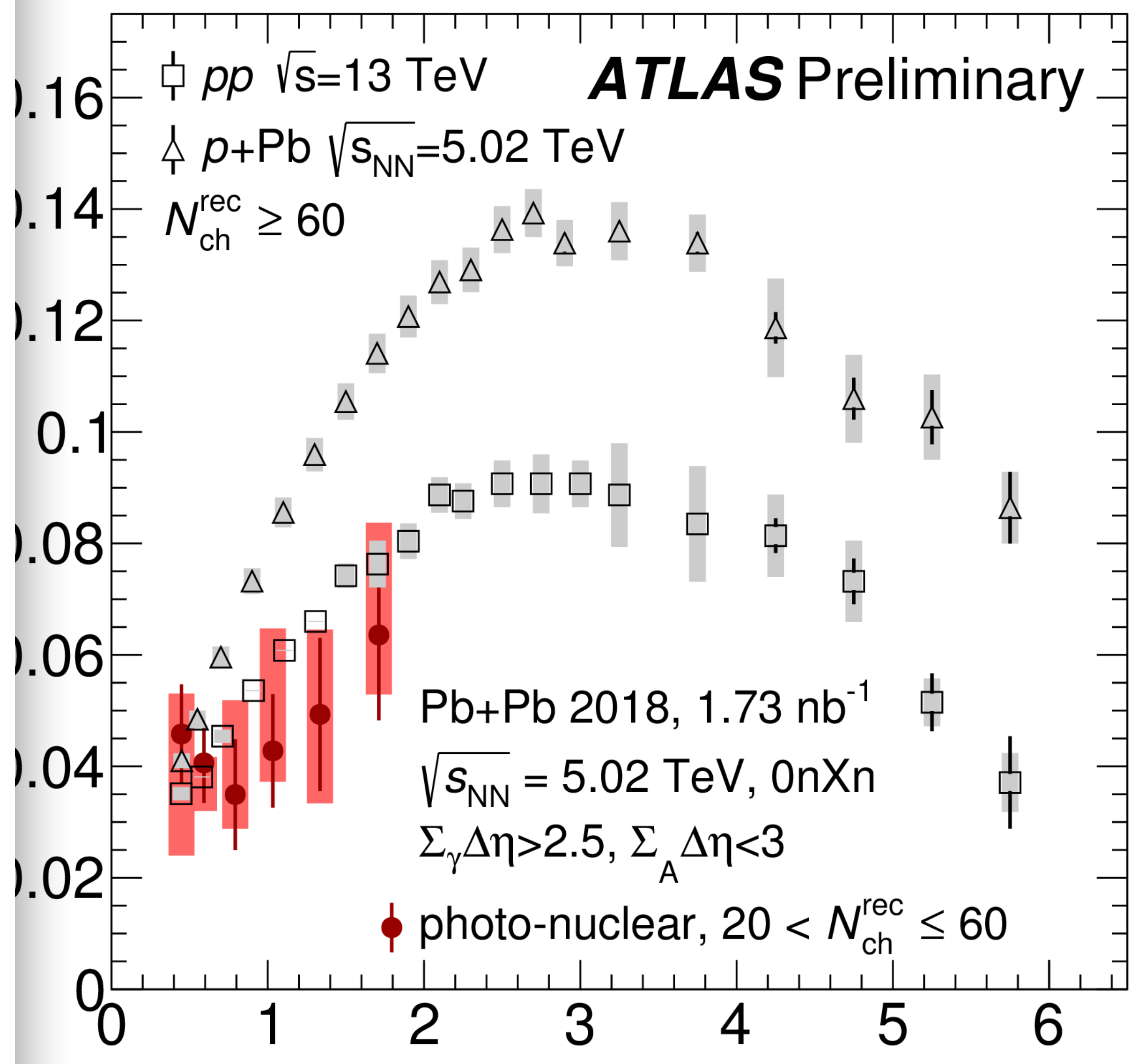
Hydro models able

Reanalyzed ALEPH data do not show signs of collectivity



[Badea et al. 2019]

[Tayalati parallel talk]



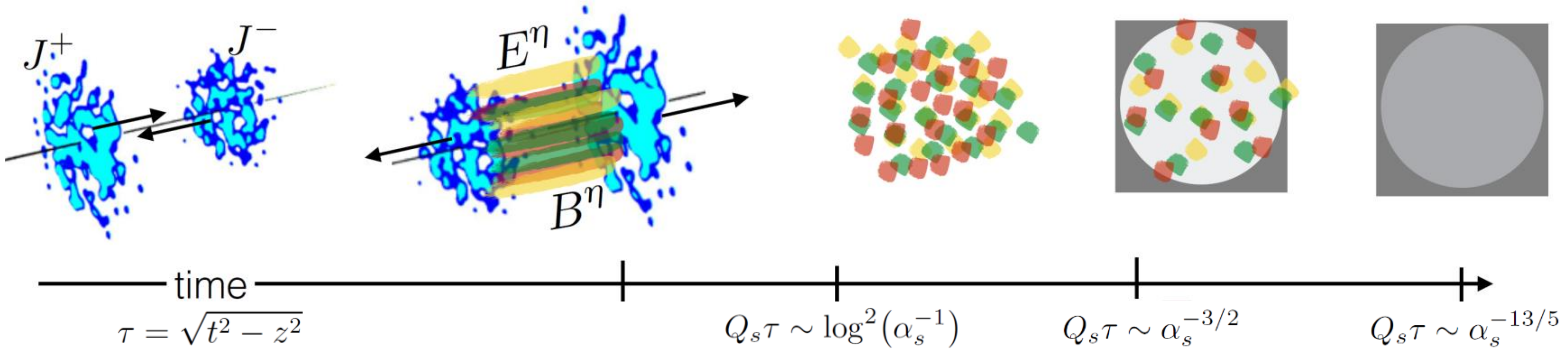
Hydrodynamics seem to work (too) well in all colliding systems for large multiplicities

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]

A picture for equilibration



Sören Schlichting

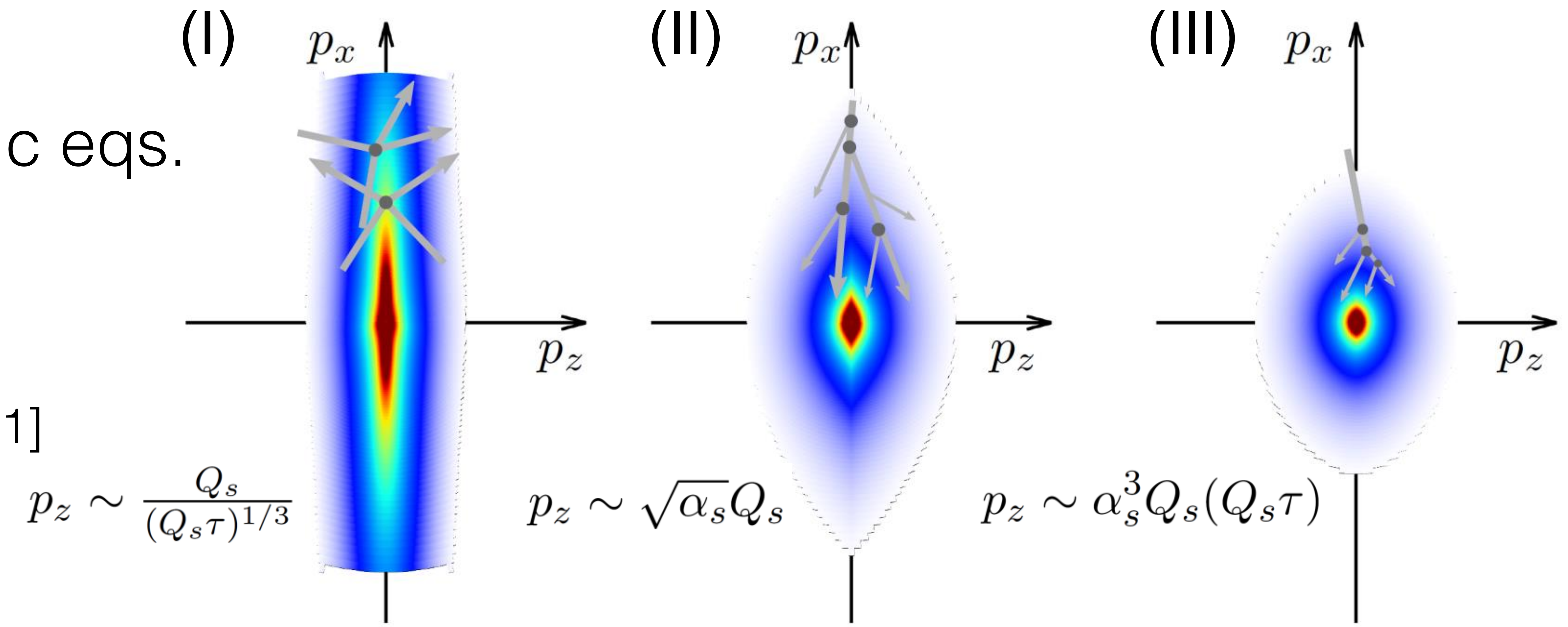
[Classical statistical/lattice gauge theory…]

Evolution of boost-invariant system with kinetic eqs.

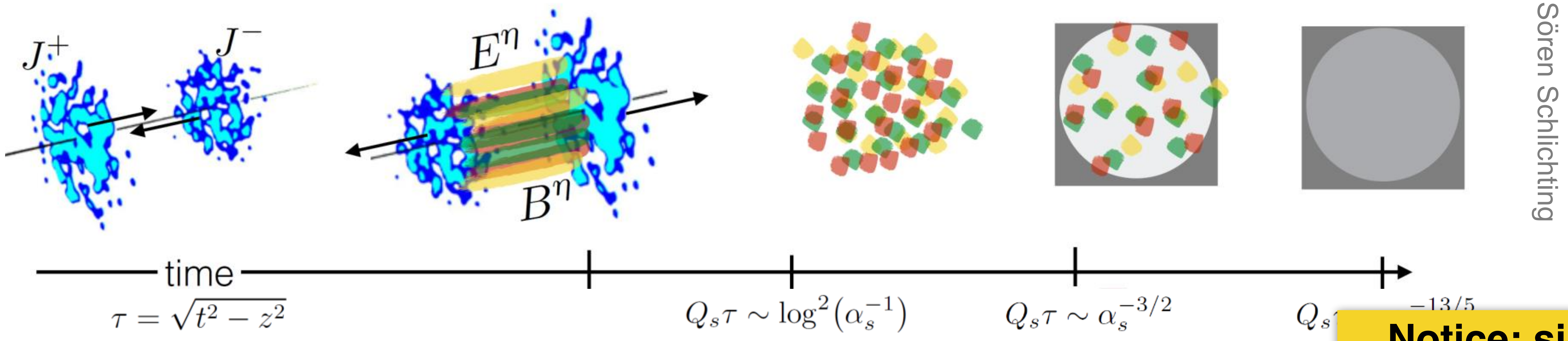
$$p^\mu \partial_\mu f(x,p) = \mathcal{C}_{2\leftrightarrow 2}[f] + C_{1\leftrightarrow 2}[f]$$

[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…]



A picture for equilibration



Notice: similar to jet quenching (see later)

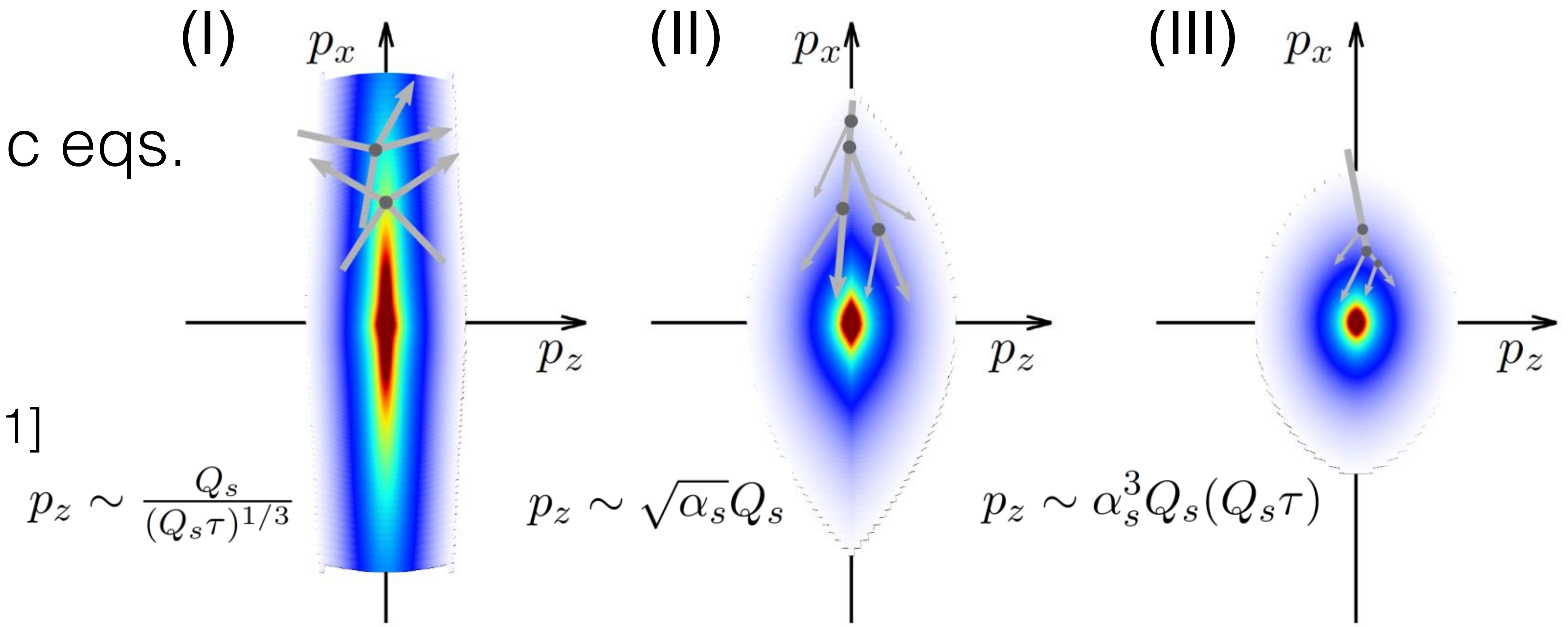
[Classical statistical/lattice gauge theory…]

Evolution of boost-invariant system with kinetic eqs.

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

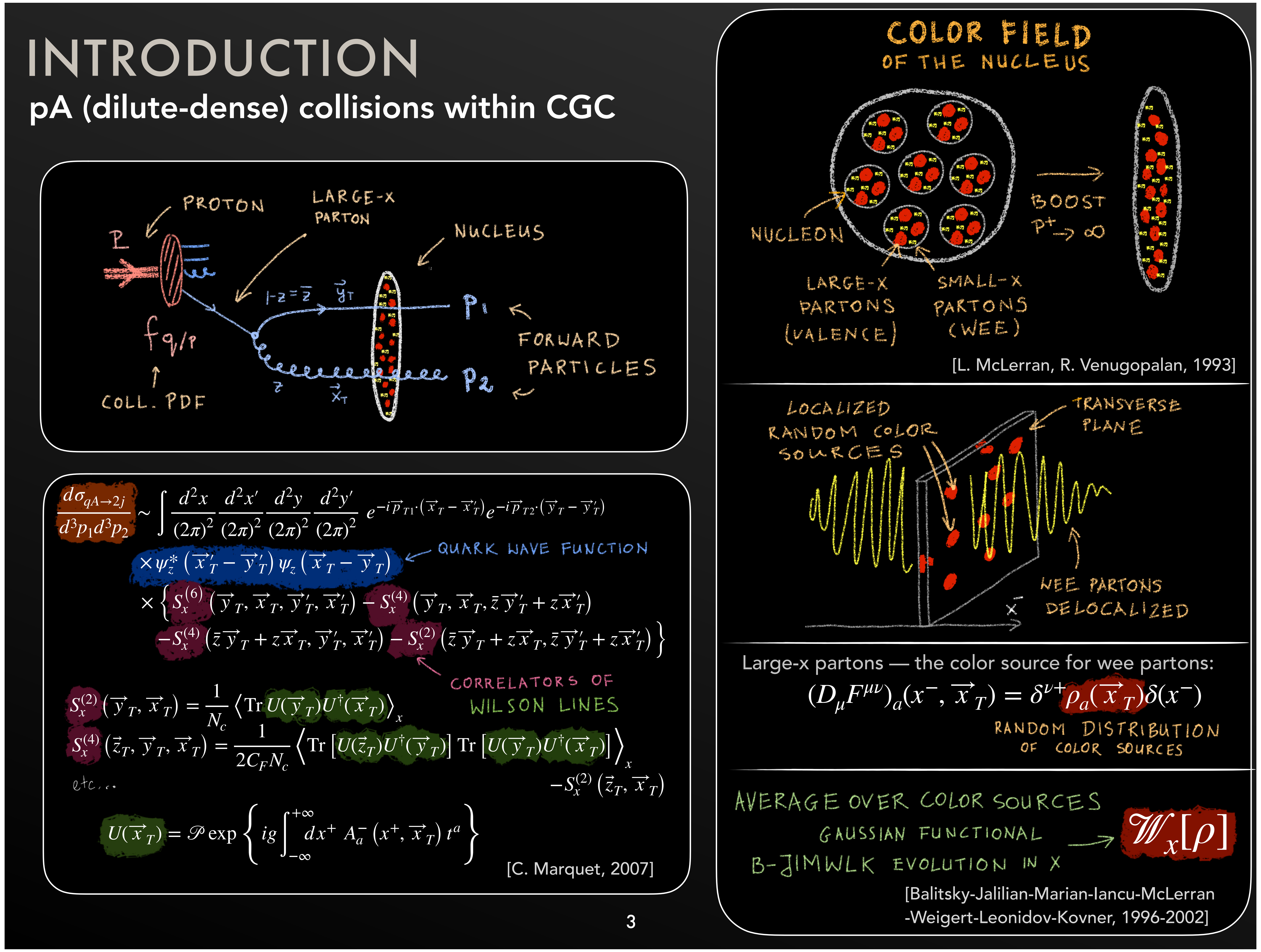
[Bottom-up thermalization — Baier, Mueller, Schiff, Son 2001]

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

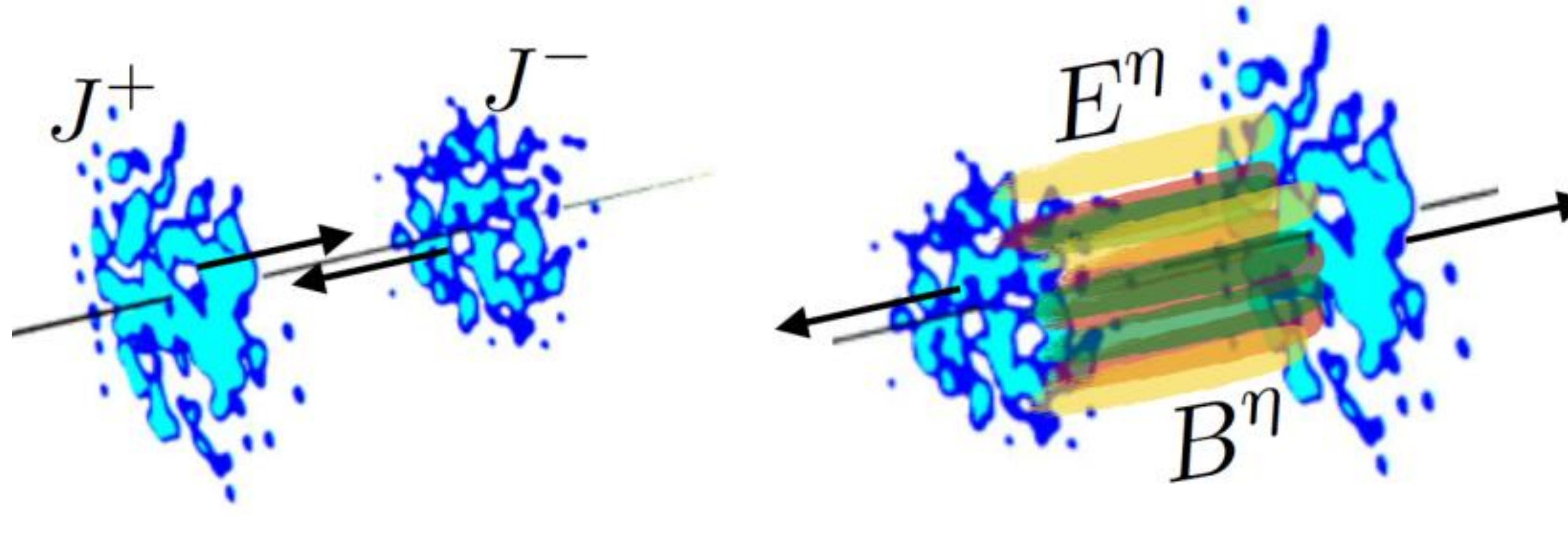


Initial conditions and CGC

[Piotr Kotko - parallel talk]



Color Glass Condensate provides a general framework to compute initial stages in dilute-dense or dense-dense regimes

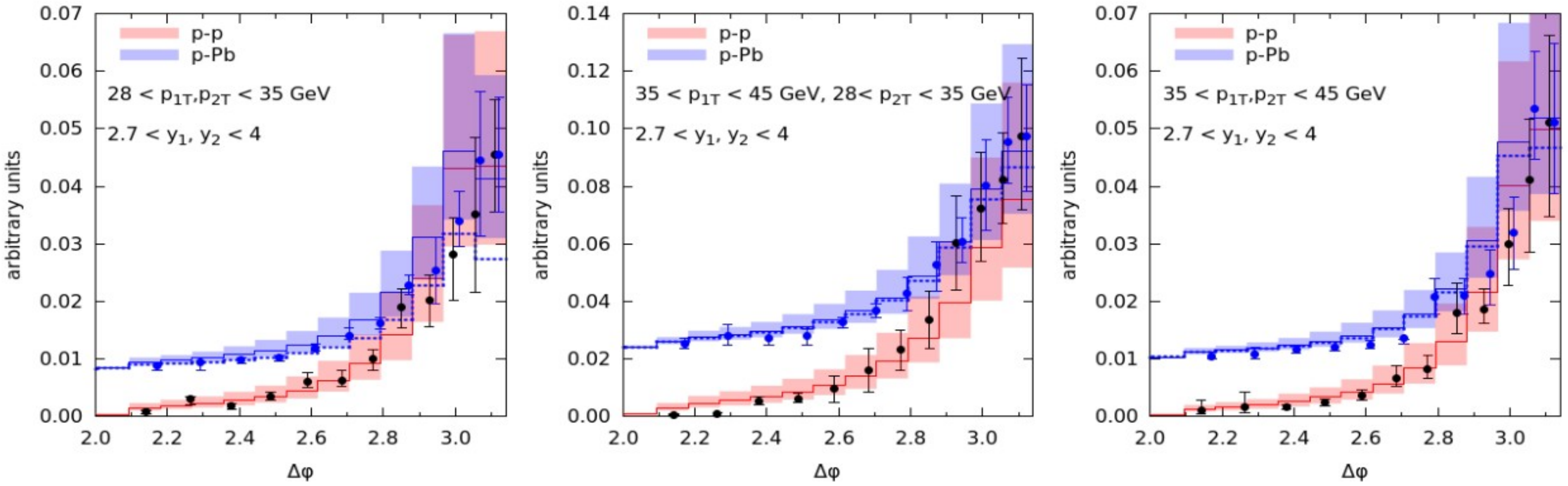


In dense-dense I.C. usually computed by solving the Color YM equations with classical sources

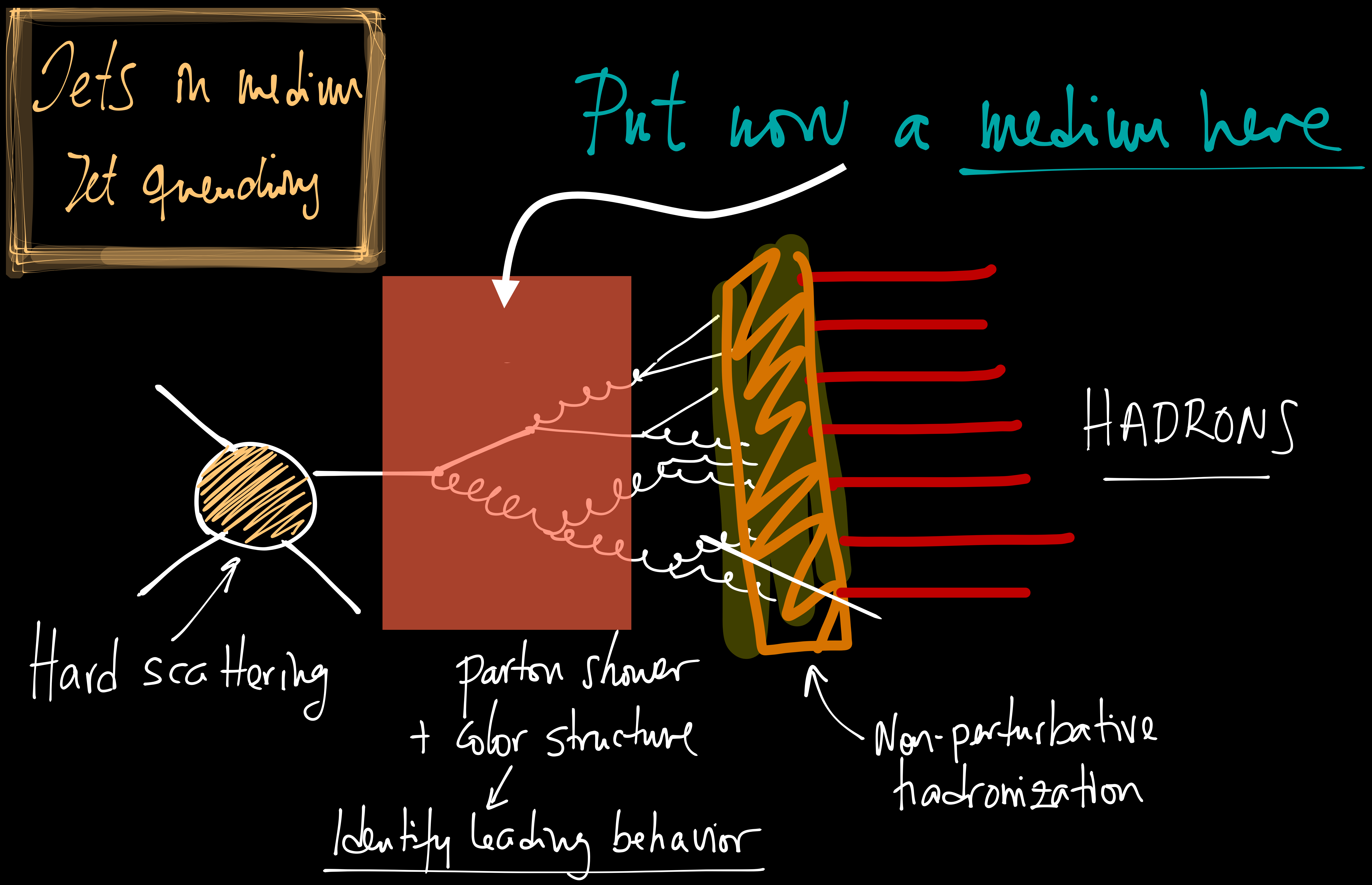
Forward-forward jets

Checks of CGC the relevance/presence of dynamics of utmost importance

One generic prediction of CGC dynamics is **broadening** —
proposal: best seen in forward-forward jets



[Krzysztof Kutak - parallel talk
See Marat Siddikov for predictions on J/Psi]



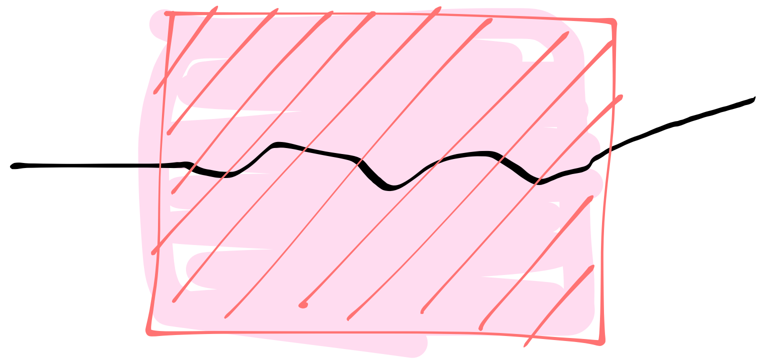
Jets are extended objects - ideal to study space-time evolution

In-medium parton propagators

[A complete set of Feynman rules can be written]

Medium is extended — space-time needed [purely momentum not suitable]

Eikonal approximation, the medium is a background classical field $A^a_\mu(x)$



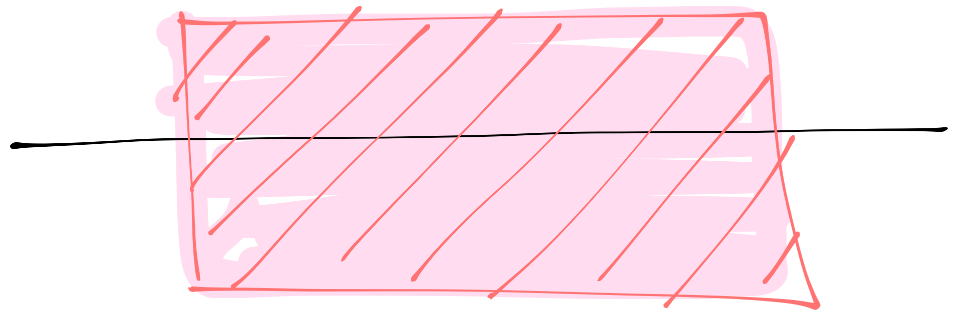
$E > k_\perp >> \mu$

Brownian motion in $\perp$-plane (Broadening)

$$G(t_2, x_{\perp,2}; t_1, x_{\perp,1} \,|\, E) = \mathscr{P} \int \mathscr{D}\mathbf{r} \exp \left\{ i \frac{E}{2} \int d\xi \left[\frac{d\mathbf{r}}{d\xi} \right]^2 + ig \int d\xi \, n \cdot A(\xi, \mathbf{r}) \right\}$$

The dynamics in the transverse plane is described by usual Quantum Mechanics (Feynman path integral)

$E \to \infty$



$E >> k_\perp >> \mu$

Straight lines

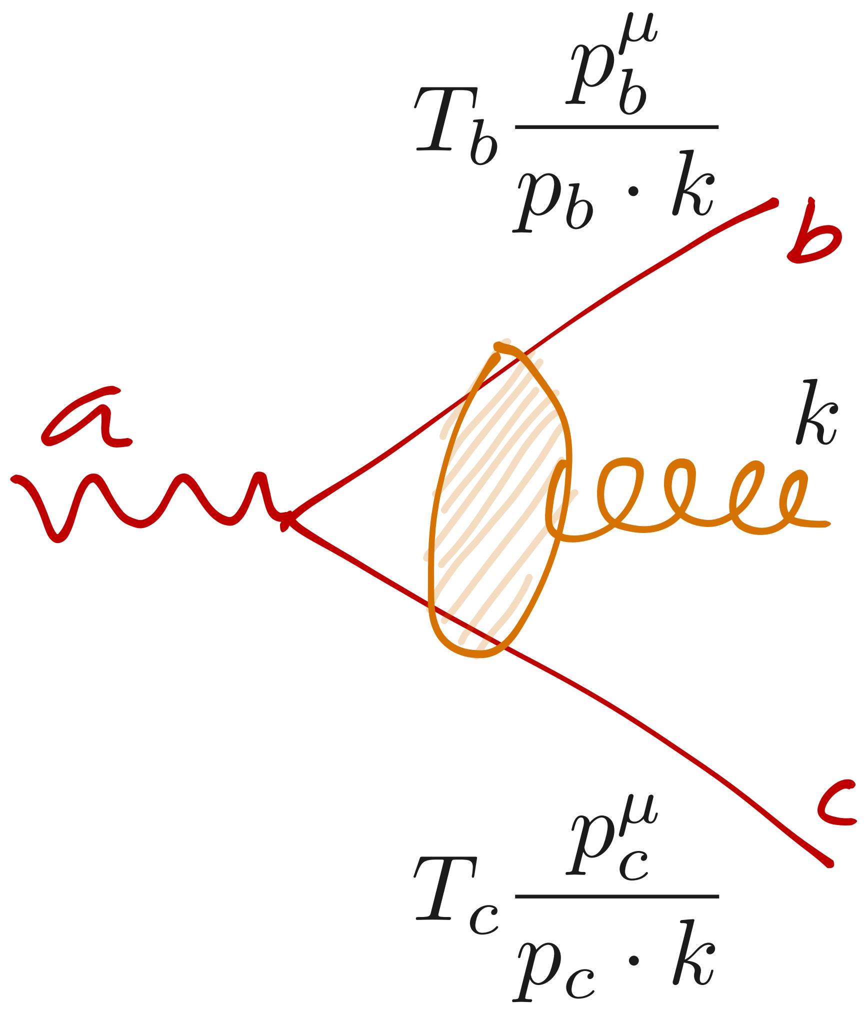
$$W(x_\perp) = \mathscr{P} \exp \left\{ ig \int d\xi \, n \cdot A(\xi, x_\perp) \right\}$$

Color rotation — Wilson line

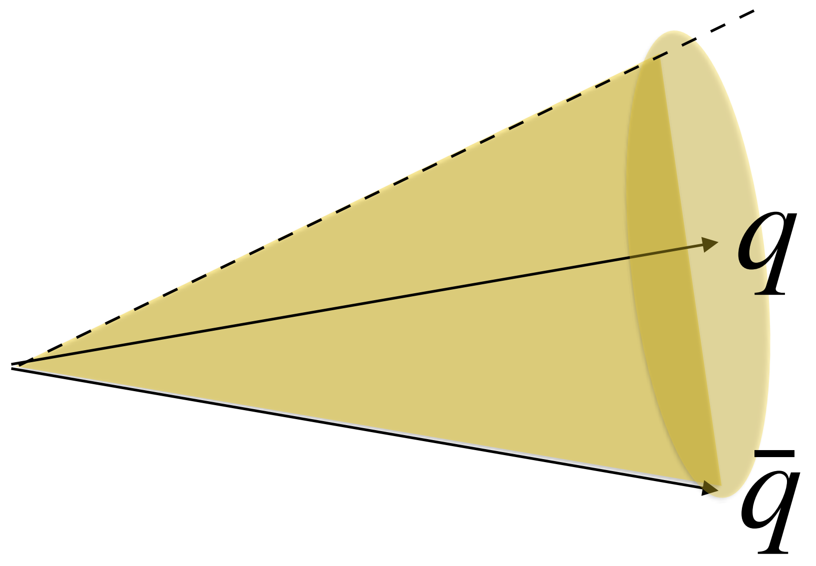
$W(x_\perp) \simeq 1$ **No color rotation (color survival)**

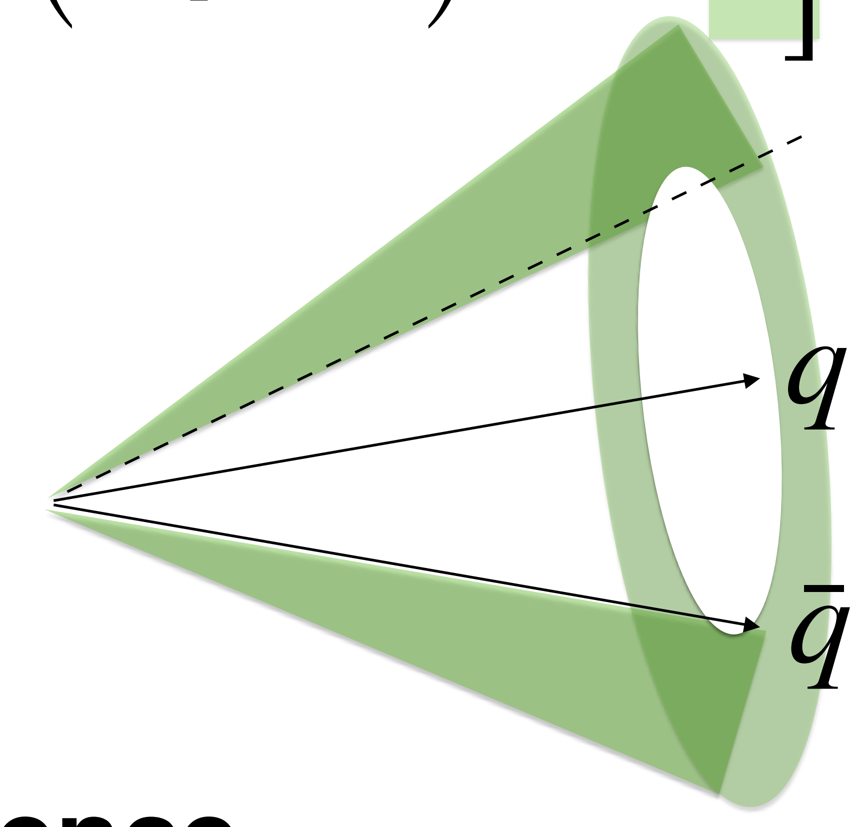
Intra-jet color coherence

Color coherence - number of effective emitters for soft gluon radiation



$$\omega \frac{dN}{d^3k} \sim \frac{\alpha_s}{\omega^2}\left[C_F\left(\mathscr{R}_q - \mathscr{J}\right) + C_F\left(\mathscr{R}_{\bar{q}} - \mathscr{J}\right) + C_a \mathscr{J}\right]$$





Known vacuum result — antenna radiation — angular ordering…

Radiation by total charge when the pair cannot be resolved

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

A medium rotates color and can break color coherence

$$\omega \frac{dN}{d^3k} \sim \frac{\alpha_s}{\omega^2}\left[C_F\left(\mathcal{R}_q - S(x_\perp, y_\perp)\mathcal{J}\right) + C_F\left(\mathcal{R}_{\bar{q}} - S(x_\perp, y_\perp)\mathcal{J}\right) + C_a S(x_\perp, y_\perp)\mathcal{J}\right]$$

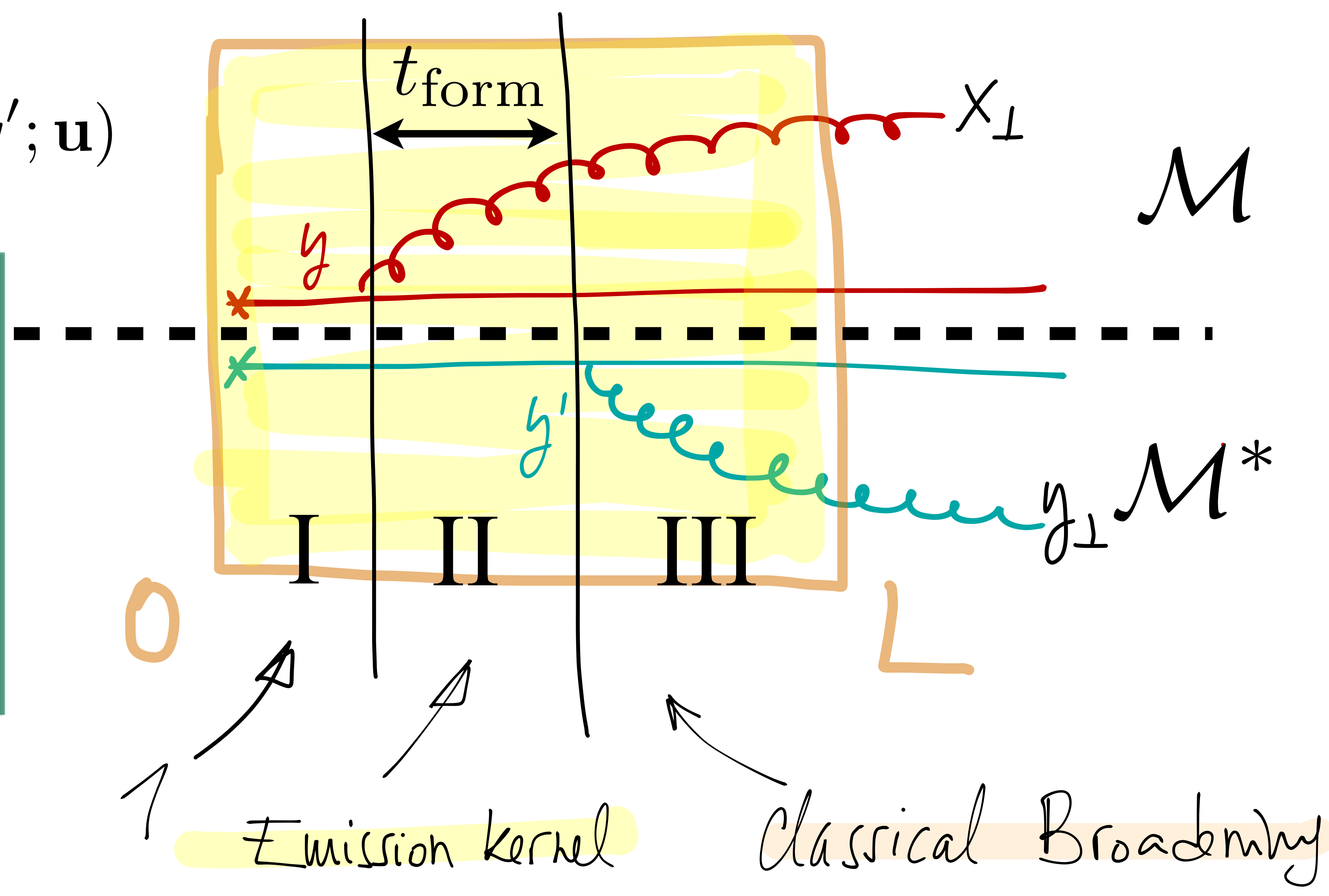
$$S(x_\perp, y_\perp) \equiv \frac{1}{N_c^2 - 1}\mathrm{Tr}\left\langle U(x_\perp)U^\dagger(y_\perp)\right\rangle_{\mathrm{med}} \simeq \exp\left\{-\frac{1}{4}\hat{q}\, t\, (x_\perp - y_\perp)^2\right\}$$

Survival prob — medium cannot resolve distances smaller than $1/\sqrt{\hat{q}t}$

Medium-induced radiation

[Zakharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others… starting in the mid-90's]

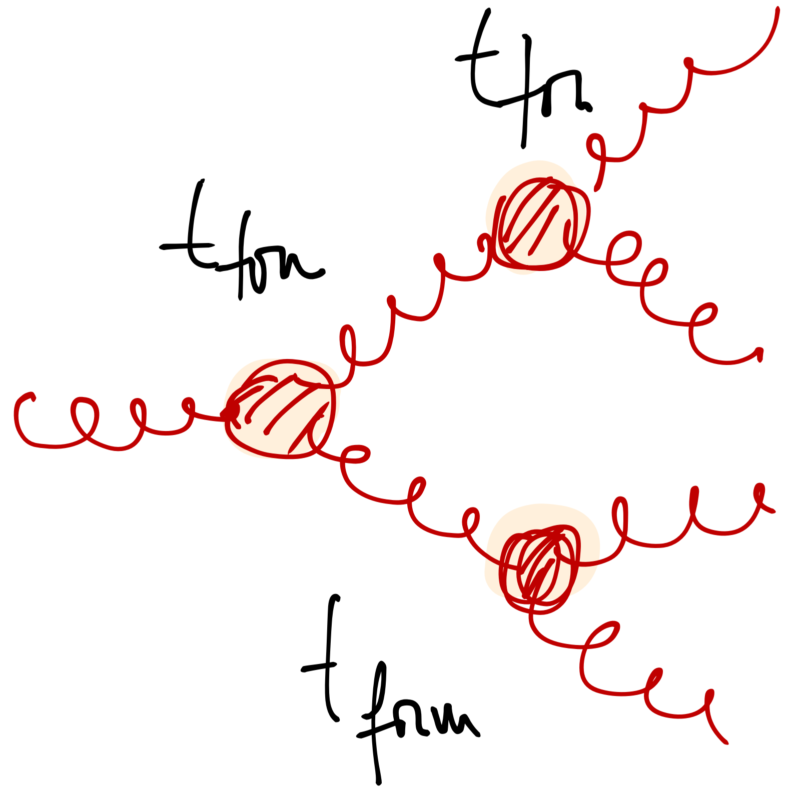
$$\omega \frac{dI}{d\omega d\mathbf{k}} \sim \alpha_s C_R \int dy \int dy' \int d\mathbf{u}\, e^{i\mathbf{k}\cdot\mathbf{u}}\, \partial_{\mathbf{u}} \cdot \partial_{\mathbf{y}} \mathcal{K}(y', \mathbf{u}; y, \mathbf{y})\Big|_{\mathbf{y}=0} \tilde{\mathcal{P}}(L, y'; \mathbf{u})$$



Where the Kernel is given by the path integral

$$\mathcal{K}(y', \mathbf{u}; y, \mathbf{y}) = \int_{\mathbf{y}(y)}^{\mathbf{u}(y')} \mathcal{D}\mathbf{r} \exp\left\{ i\frac{\omega}{2} \int d\xi \left(\frac{d\mathbf{r}(\xi)}{d\xi}\right)^2 \right\} \tilde{\mathcal{P}}(y', y, \mathbf{r})$$

During formation time $k_\perp^2 \sim \hat{q}\, t_{\rm form} \implies t_{\rm form} \sim \sqrt{\omega/\hat{q}}$



Factorization for soft gluons

Rate equations

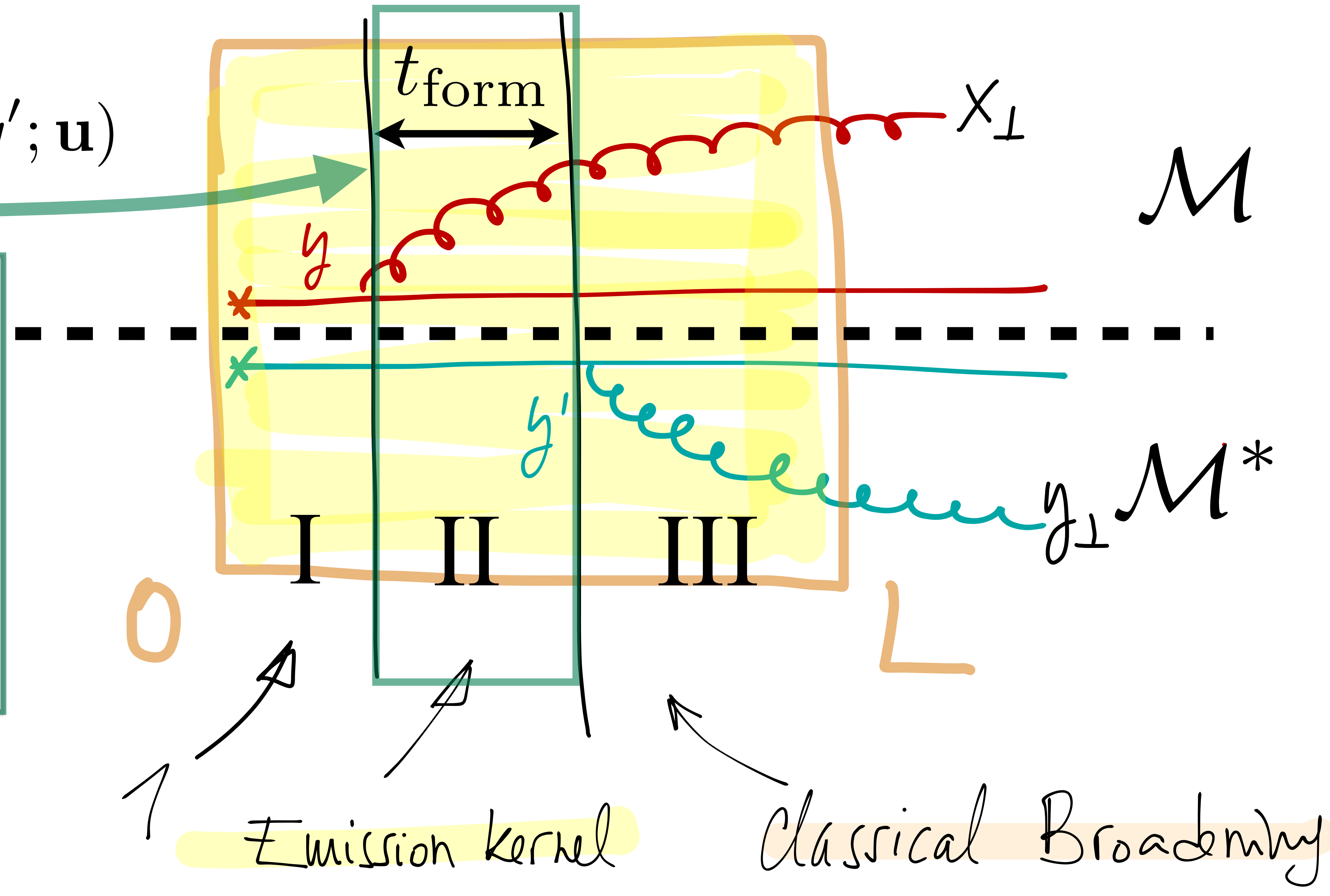
$$\frac{\partial}{\partial L} D_i^{\rm med}(x, p_\perp, L) = \int_0^1 dz\, \mathcal{K}_{ij}\left(z, \frac{x}{z} p_\perp; L\right) \times \left[D_j^{\rm med}\left(\frac{x}{z}, p_\perp, L\right) - z\, D_j^{\rm med}(x, p_\perp, L)\right],$$

[Balizot, Dominguez, Iancu, Mehtar-Tani 2013; Jeon, Moore 2005]

Medium-induced radiation

[Zakharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others… starting in the mid-90's]

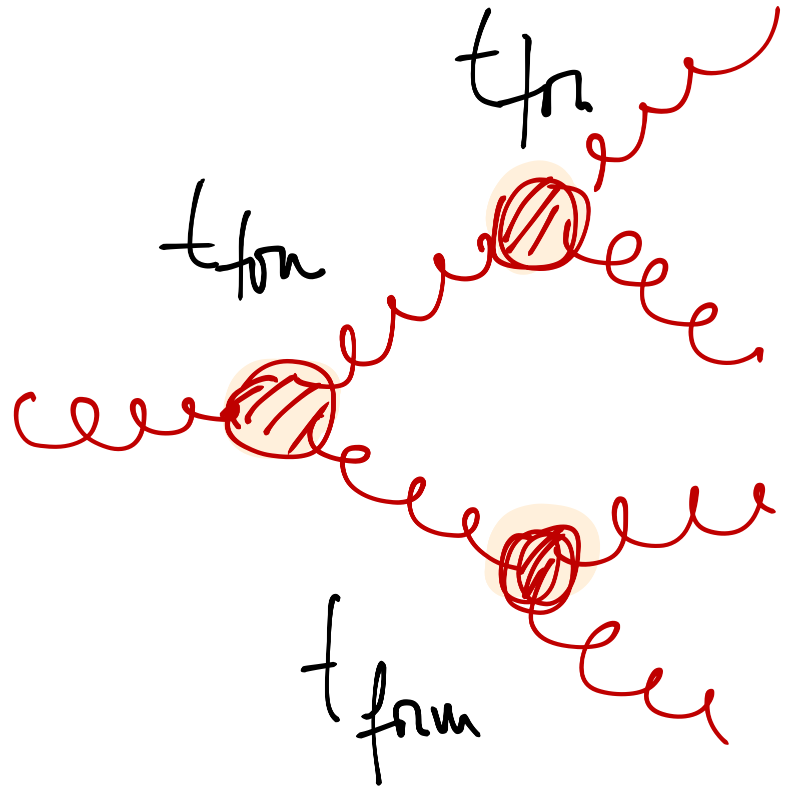
$$\omega \frac{dI}{d\omega d\mathbf{k}} \sim \alpha_s C_R \int dy \int dy' \int d\mathbf{u}\, \mathrm{e}^{i\mathbf{k}\cdot\mathbf{u}}\, \partial_{\mathbf{u}} \cdot \partial_{\mathbf{y}} \mathcal{K}(y', \mathbf{u}; y, \mathbf{y})\Big|_{\mathbf{y}=0} \tilde{\mathcal{P}}(L, y'; \mathbf{u})$$



Where the Kernel is given by the path integral

$$\mathcal{K}(y', \mathbf{u}; y, \mathbf{y}) = \int_{\mathbf{y}(y)}^{\mathbf{u}(y')} \mathcal{D}\mathbf{r} \exp\left\{ i\frac{\omega}{2} \int d\xi \left(\frac{d\mathbf{r}(\xi)}{d\xi}\right)^2 \right\} \tilde{\mathcal{P}}(y', y, \mathbf{r})$$

During formation time $k_\perp^2 \sim \hat{q}\, t_{\text{form}} \implies t_{\text{form}} \sim \sqrt{\omega/\hat{q}}$



Factorization for soft gluons

Rate equations

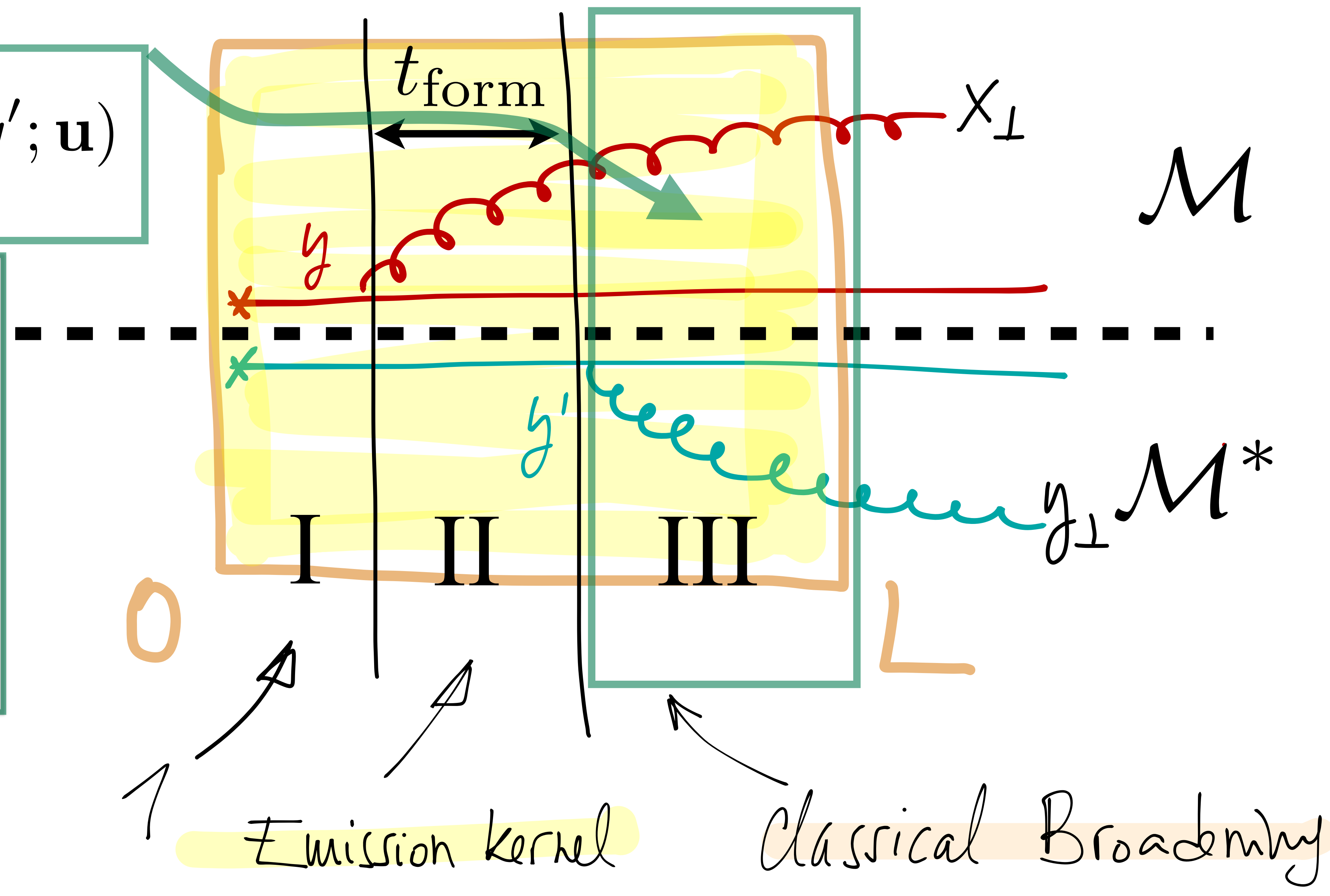
$$\frac{\partial}{\partial L} D_i^{\text{med}}(x, p_\perp, L) = \int_0^1 \mathrm{d}z\, \mathcal{K}_{ij}\left(z, \frac{x}{z} p_\perp; L\right) \times \left[D_j^{\text{med}}\left(\frac{x}{z}, p_\perp, L\right) - z\, D_j^{\text{med}}(x, p_\perp, L) \right],$$

[Balizot, Dominguez, Iancu, Mehtar-Tani 2013; Jeon, Moore 2005]

Medium-induced radiation

[Zakharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others… starting in the mid-90's]

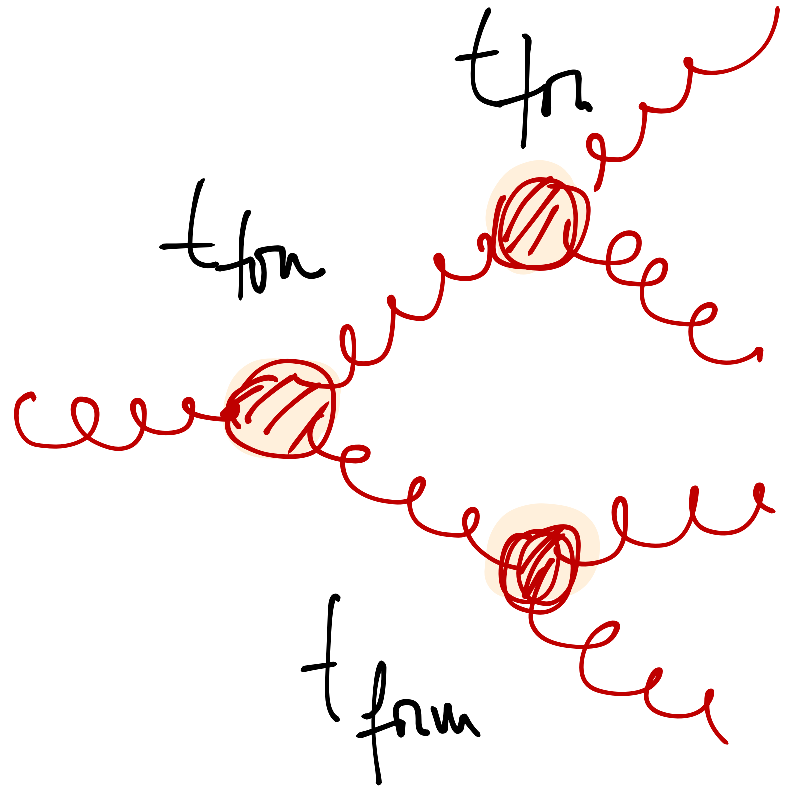
$$\omega \frac{dI}{d\omega d\mathbf{k}} \sim \alpha_s C_R \int dy \int dy' \int d\mathbf{u}\, e^{i\mathbf{k}\cdot\mathbf{u}}\, \partial_{\mathbf{u}} \cdot \partial_{\mathbf{y}} \mathcal{K}(y', \mathbf{u}; y, \mathbf{y})\Big|_{\mathbf{y}=0} \tilde{\mathcal{P}}(L, y'; \mathbf{u})$$



Where the Kernel is given by the path integral

$$\mathcal{K}(y', \mathbf{u}; y, \mathbf{y}) = \int_{\mathbf{y}(y)}^{\mathbf{u}(y')} \mathcal{D}\mathbf{r} \exp\left\{ i\frac{\omega}{2} \int d\xi \left(\frac{d\mathbf{r}(\xi)}{d\xi}\right)^2 \right\} \tilde{\mathcal{P}}(y', y, \mathbf{r})$$

During formation time $k_\perp^2 \sim \hat{q}\, t_{\rm form} \implies t_{\rm form} \sim \sqrt{\omega/\hat{q}}$



Factorization for soft gluons

Rate equations

$$\frac{\partial}{\partial L} D_i^{\rm med}(x, p_\perp, L) = \int_0^1 {\rm d}z\, \mathcal{K}_{ij}\left(z, \frac{x}{z} p_\perp; L\right) \times \left[D_j^{\rm med}\left(\frac{x}{z}, p_\perp, L\right) - z\, D_j^{\rm med}(x, p_\perp, L) \right],$$

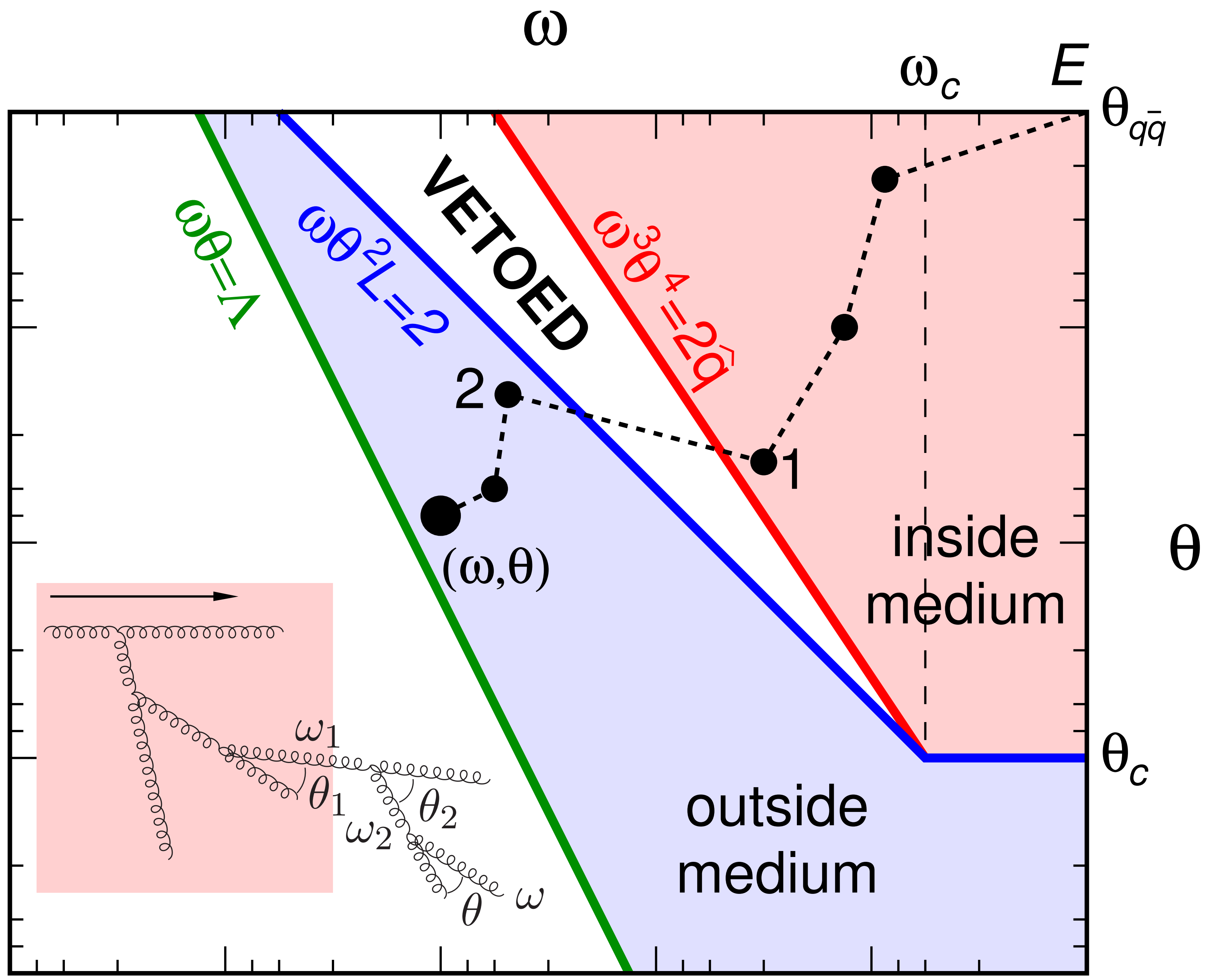
[Balizot, Dominguez, Iancu, Mehtar-Tani 2013; Jeon, Moore 2005]

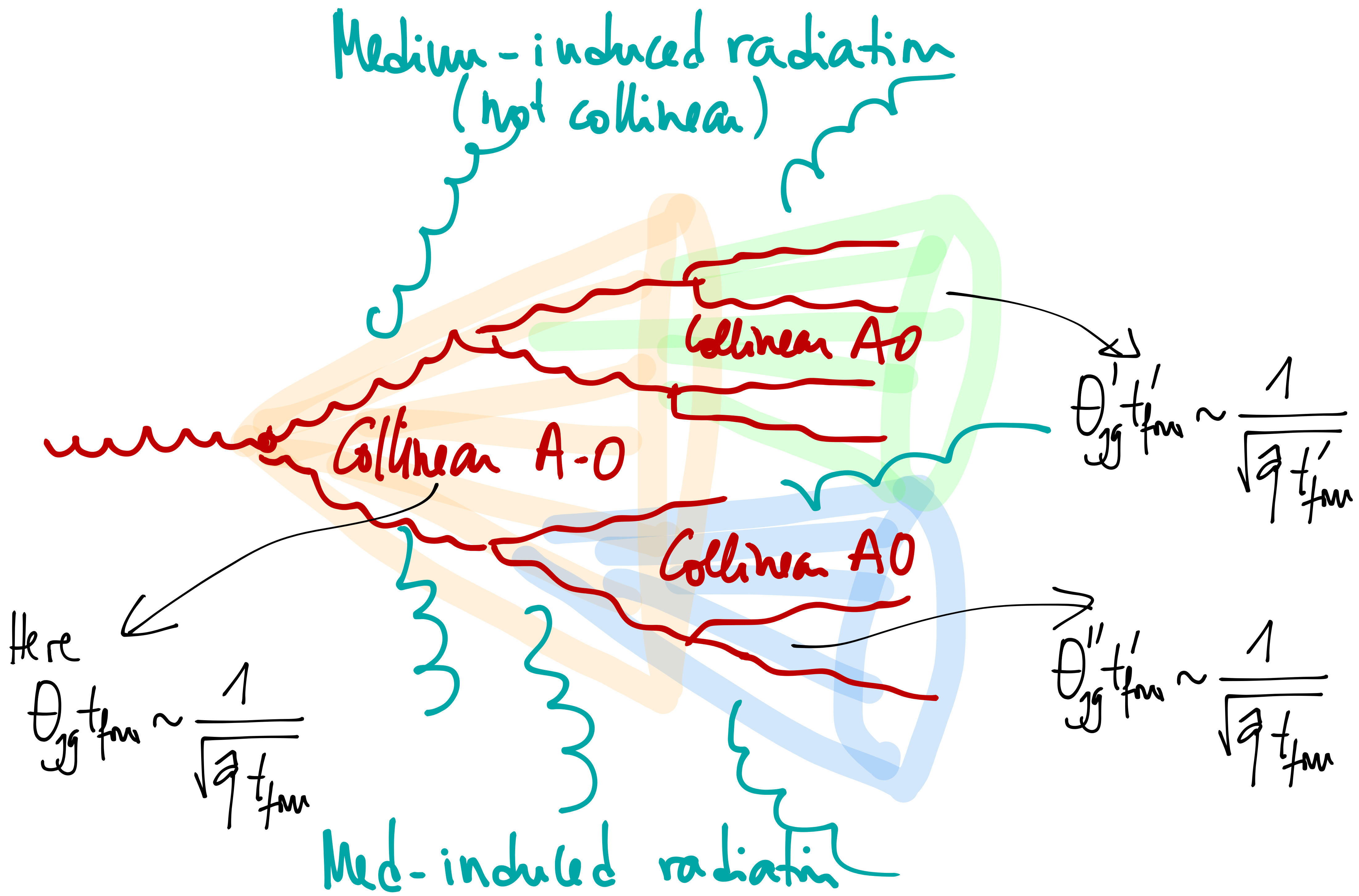
Vacuum-like emissions

Hard splittings with small formation time 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]





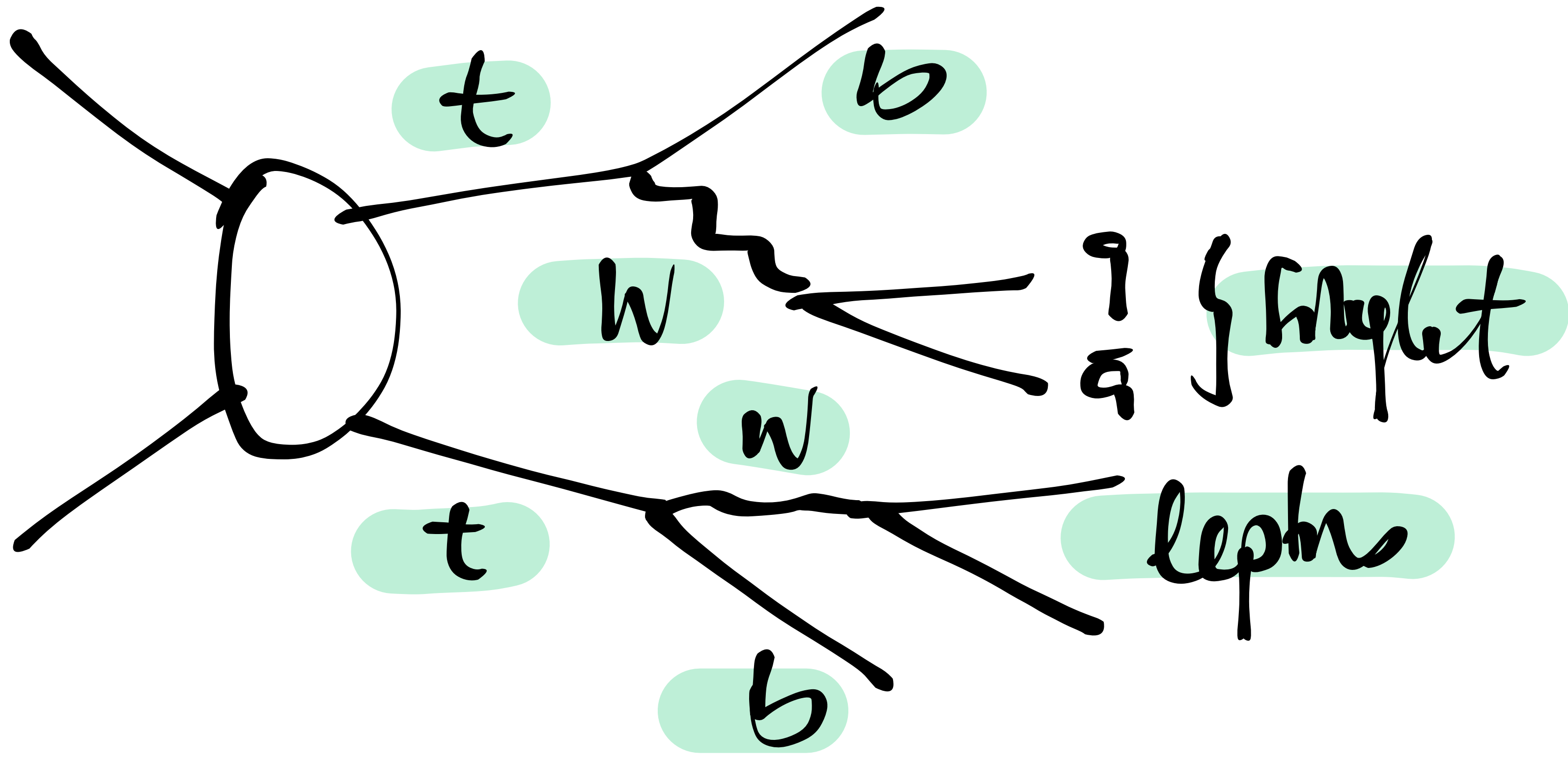
[Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk 2012]

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

A yoctosecond chronometer

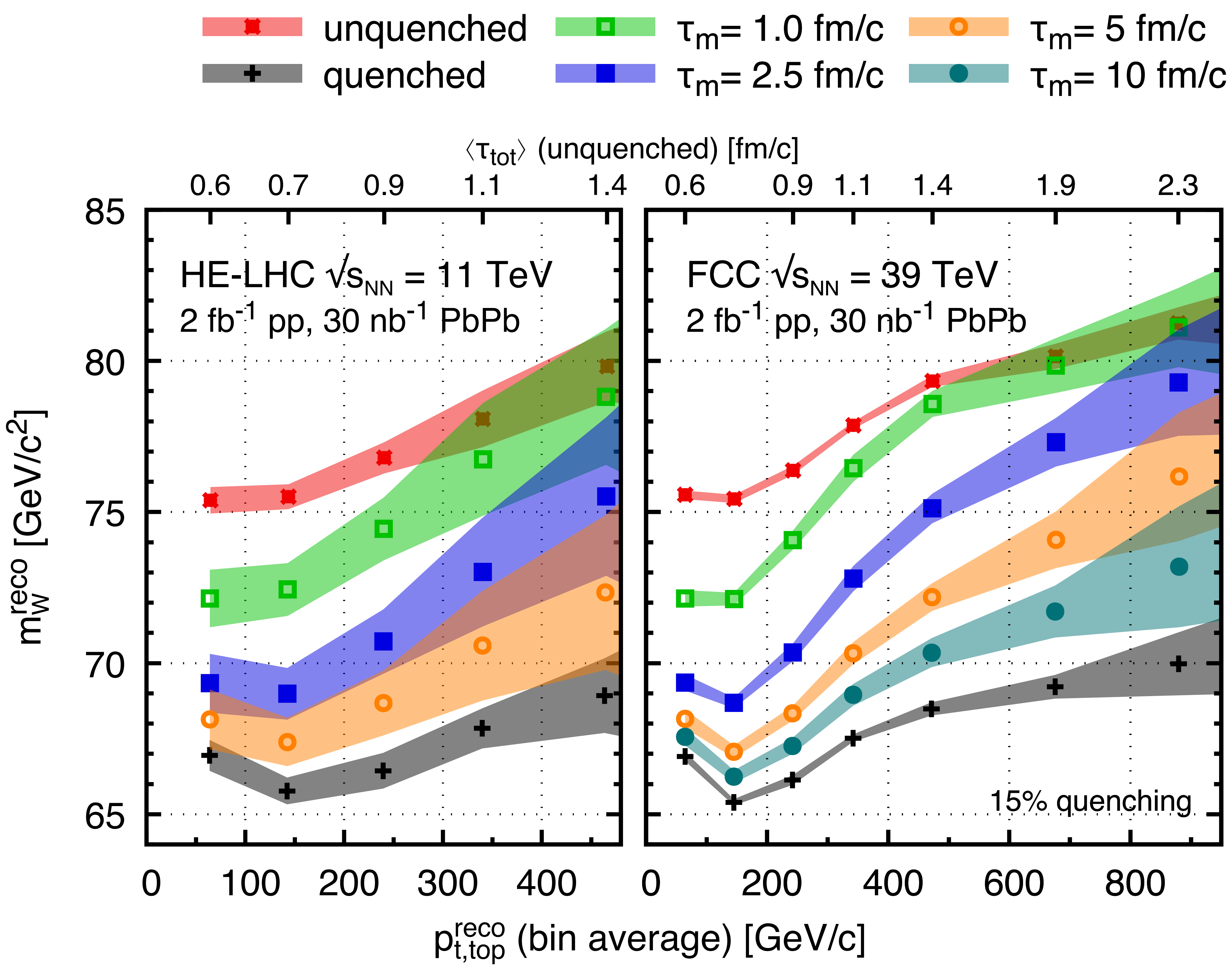
[late times]

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



Boosted tops
(difficult with present LHC PbPb luminosity)

See also talk by L. Apolinario for studies with formation time clustering and jet splitting function



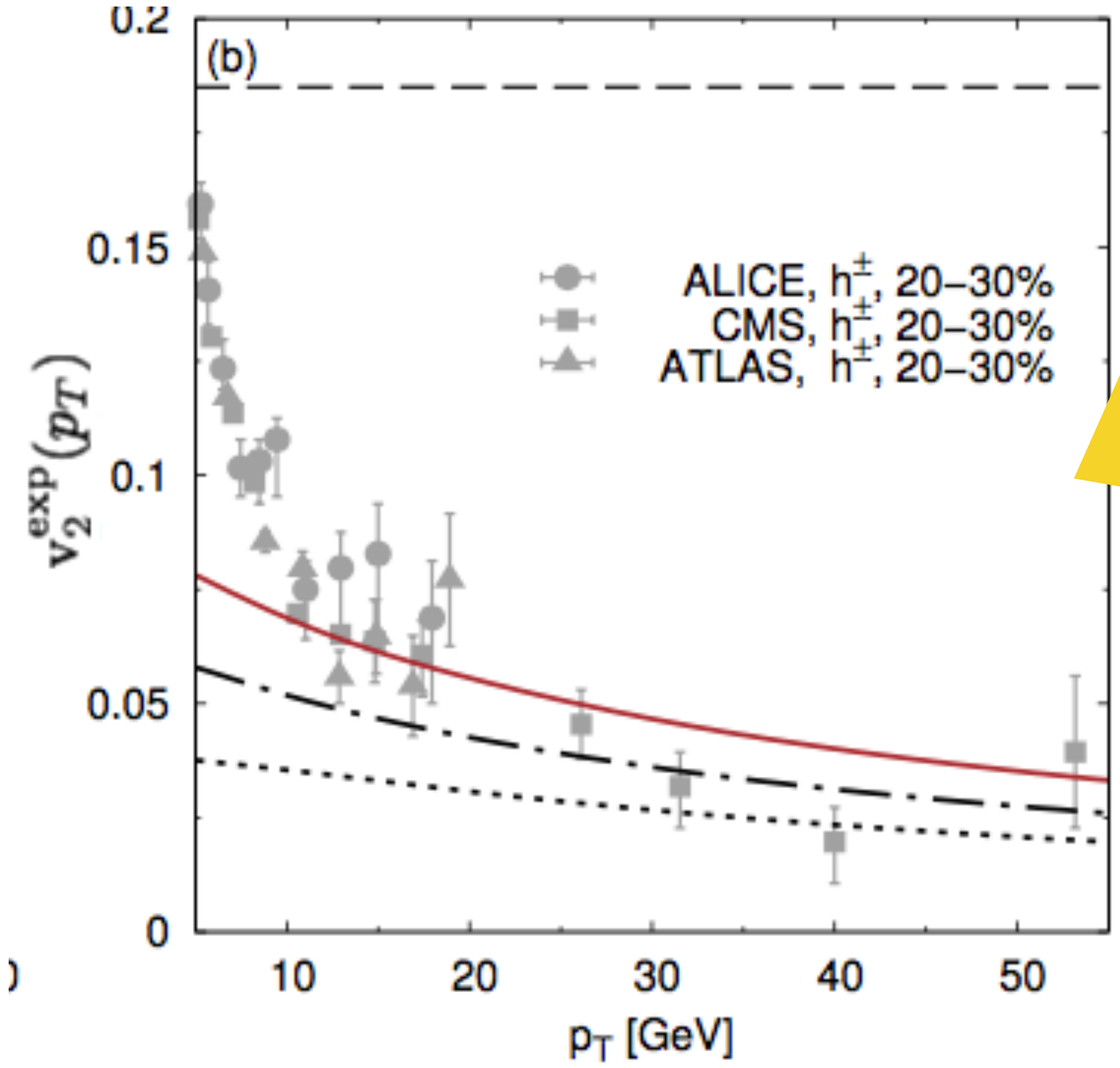
[Apolinario et al 2019]

A yoctosecond chronometer

[early times]

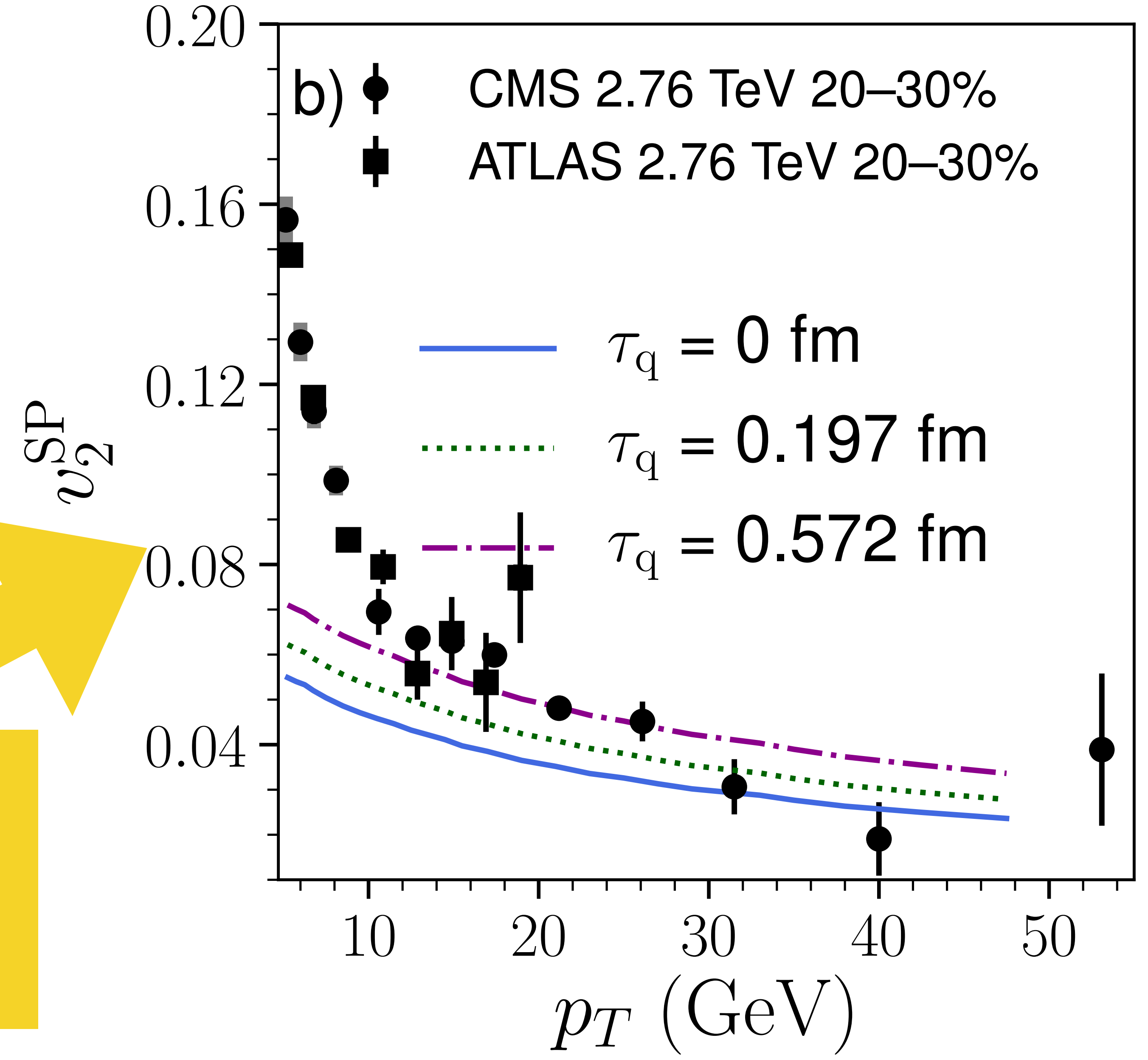
Inclusive high-pT particle suppression well reproduced by energy loss models — but traditionally problem to reproduce harmonics

[Noronha-Hostler et al 2016]



Improvements in phenomenology

Study of the relevance of the initial stages — delay time needed

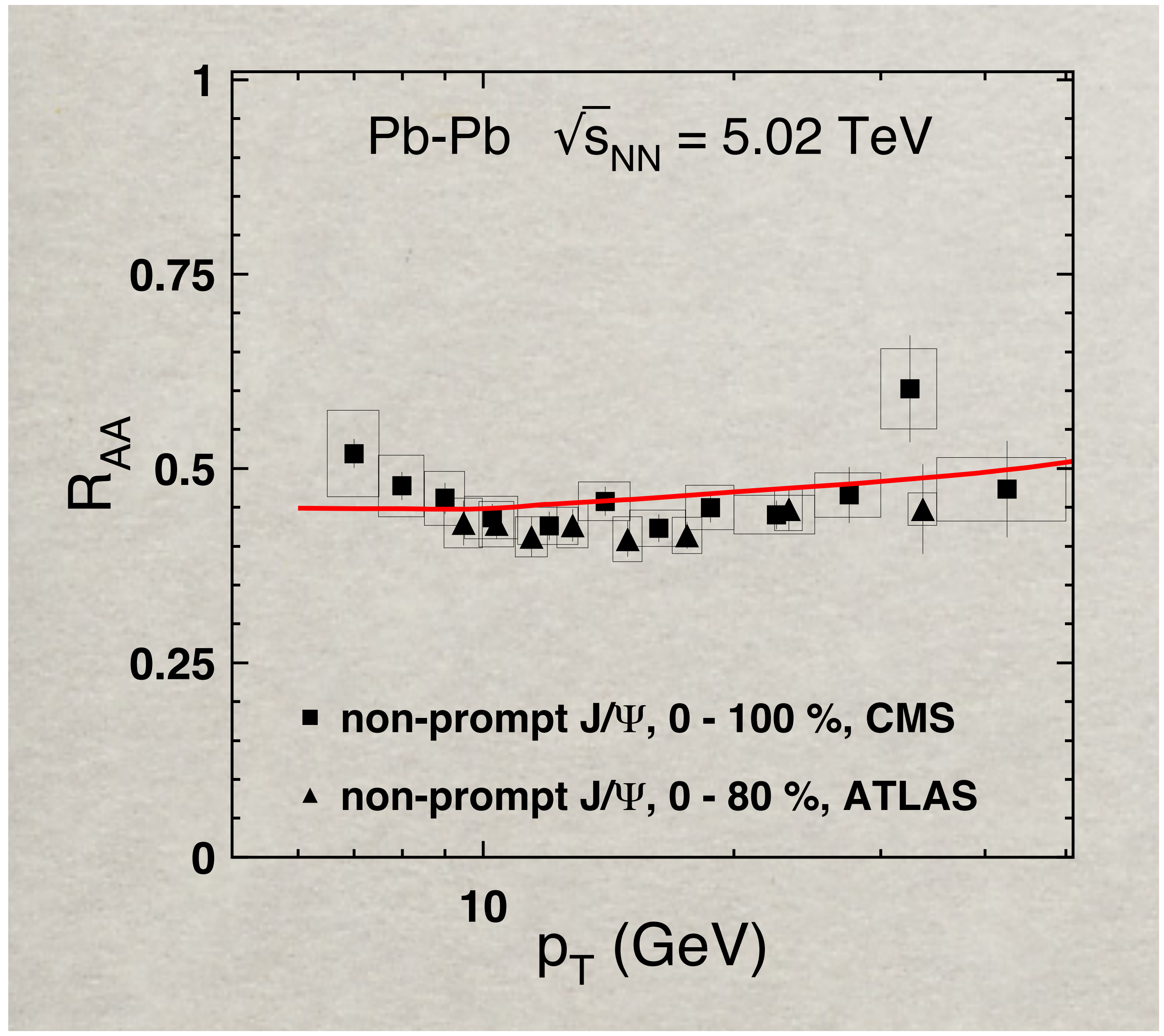


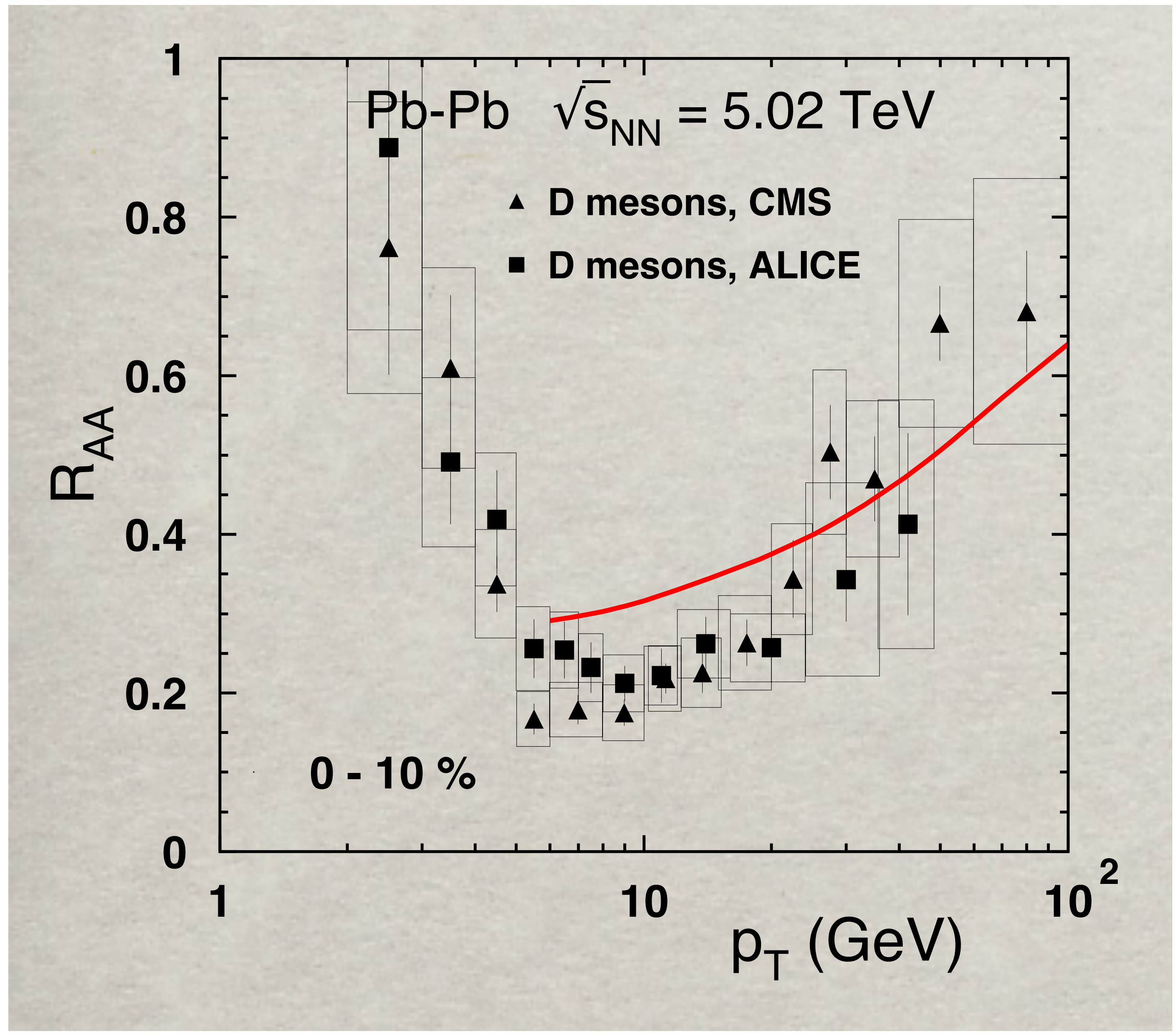
[Andres et al 2019]

Jets sensitive to the initial stages of the collision — a new tool to study equilibration

Heavy quark suppression

Heavy-quark suppression provides additional information about the jet quenching mechanism

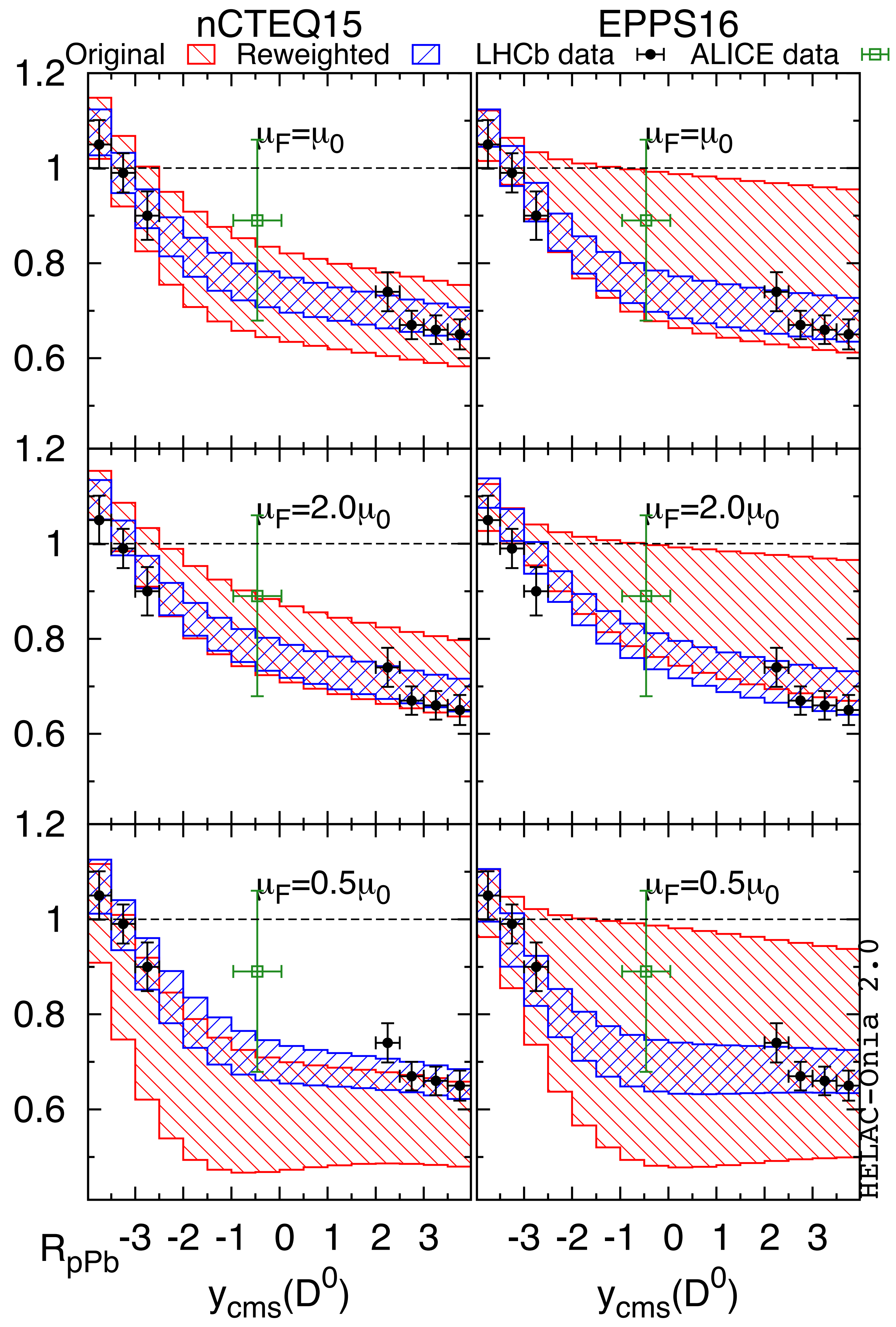




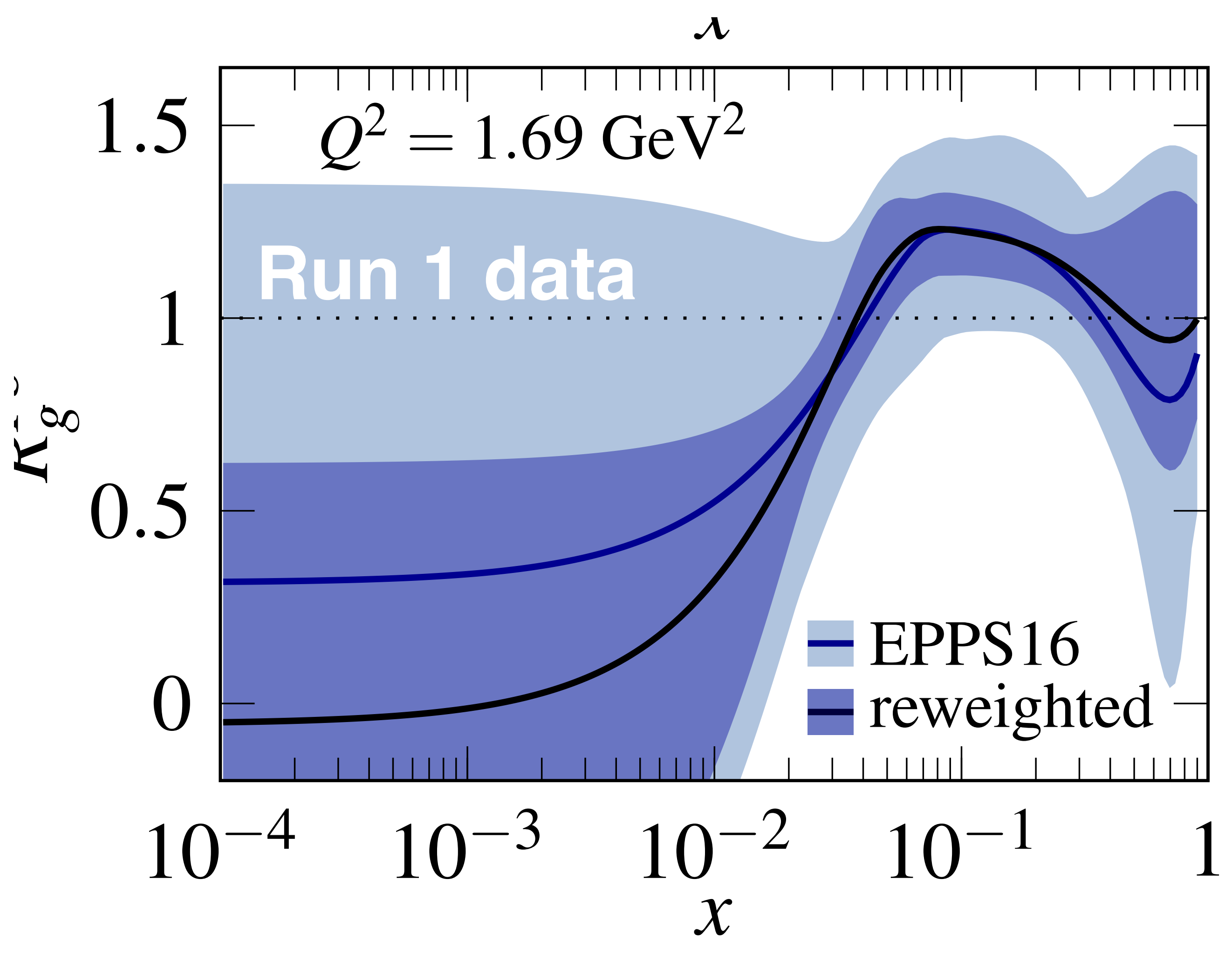
[Boris Kopeliovich parallel talk]

In-medium dead-cone effect makes energy loss smaller for heavy quarks

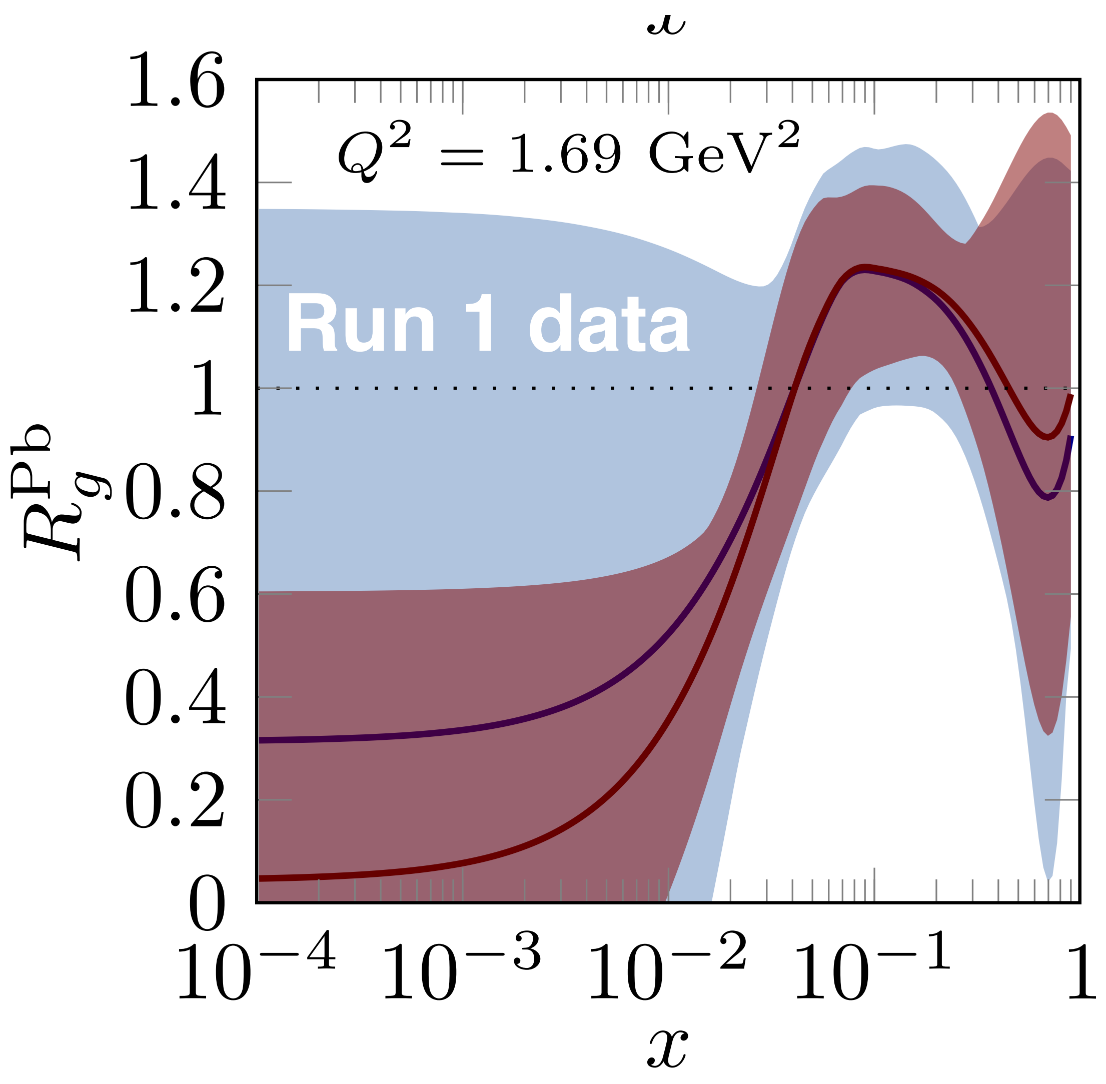
nPDFs — reweighting



[Lansberg parallel talk]



+ CMS dijets



+ pPb charm

[Eskola, Paakkinen, Paukkunen 2019]

Nuclear PDF analyses have remarkably improved with LHC proton-lead data

[See also Michael Klasen Parallel talk and Anna Stasto for future opportunities with nuclear DIS at LHeC/FCC-eh]

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 where equilibration, role of quantum entanglement, etc… are very active lines

Study of the QCD equation of state both for cold and hot dense matter with very different experimental tools

- **GW observations showing the potential to pin-down the structure of neutron stars**
- **Heavy-ion collisions fundamental tool for Earth experiments**

New data from LHC and RHIC

- Continuous progress on the characterization of the QGP
- **Completely new opportunities — initial stages / small systems — directly access time evolution**
- New facilities (FCC, HE-LHC, EIC, LHeC…) and future of LHC key for a rigurous determination of this region (+theoretical developments) and access to unchartered properties of the QGP