heavy ion physics [in two lectures]

Guilherme Milhano [LIP & IST, Lisbon]
gmilhano@lip.pt

TÉCNICO LISBOA
FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA
erc European Research Council
Established by the European Commission

ESHEP2024, Peebles – UK, 4-5 Oct 2024

OUTLINE

- lecture I [today]
  - general introduction
  - what is Quark Gluon Plasma
  - the stages of a Heavy Collision

- lecture II [tomorrow]
  - how do we know what we know about Quark Gluon Plasma
  - how do we get to know more

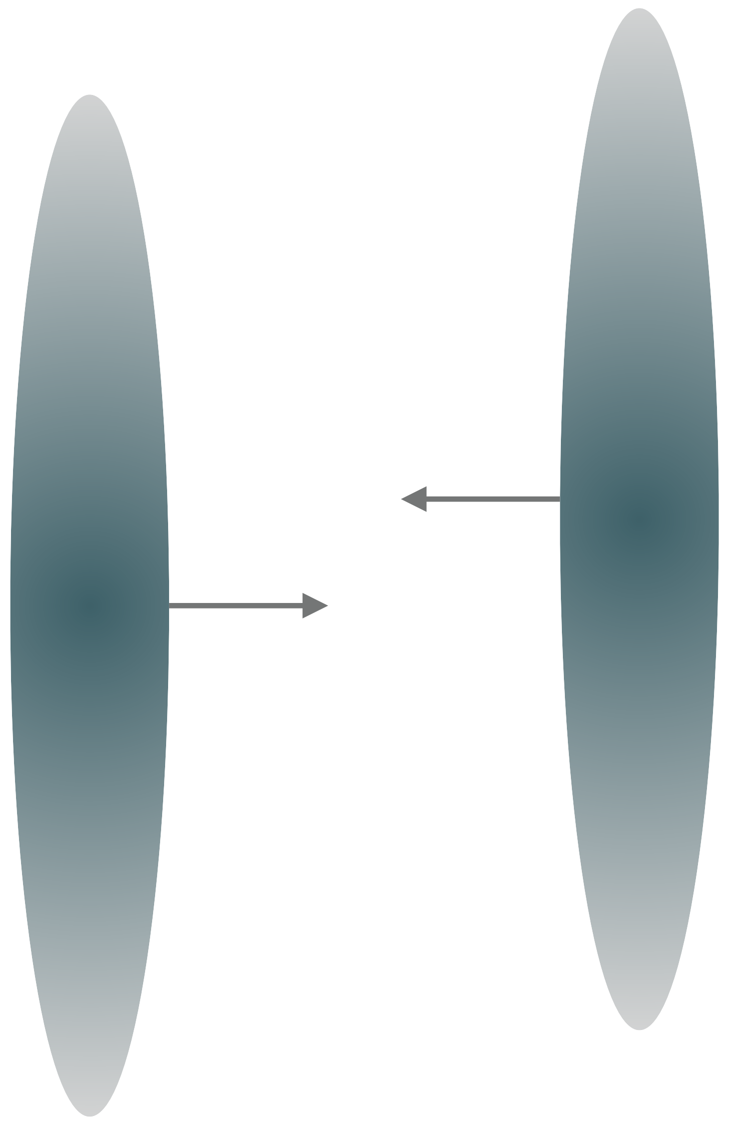
OUTLINE

- **lecture I [today]**
  - **general introduction**
  - **what is Quark Gluon Plasma**
  - **the stages of a Heavy Collision**
- lecture II [tomorrow]
  - how do we know what we know about Quark Gluon Plasma
  - how do we get to know more

heavy ion physics [lecture I]

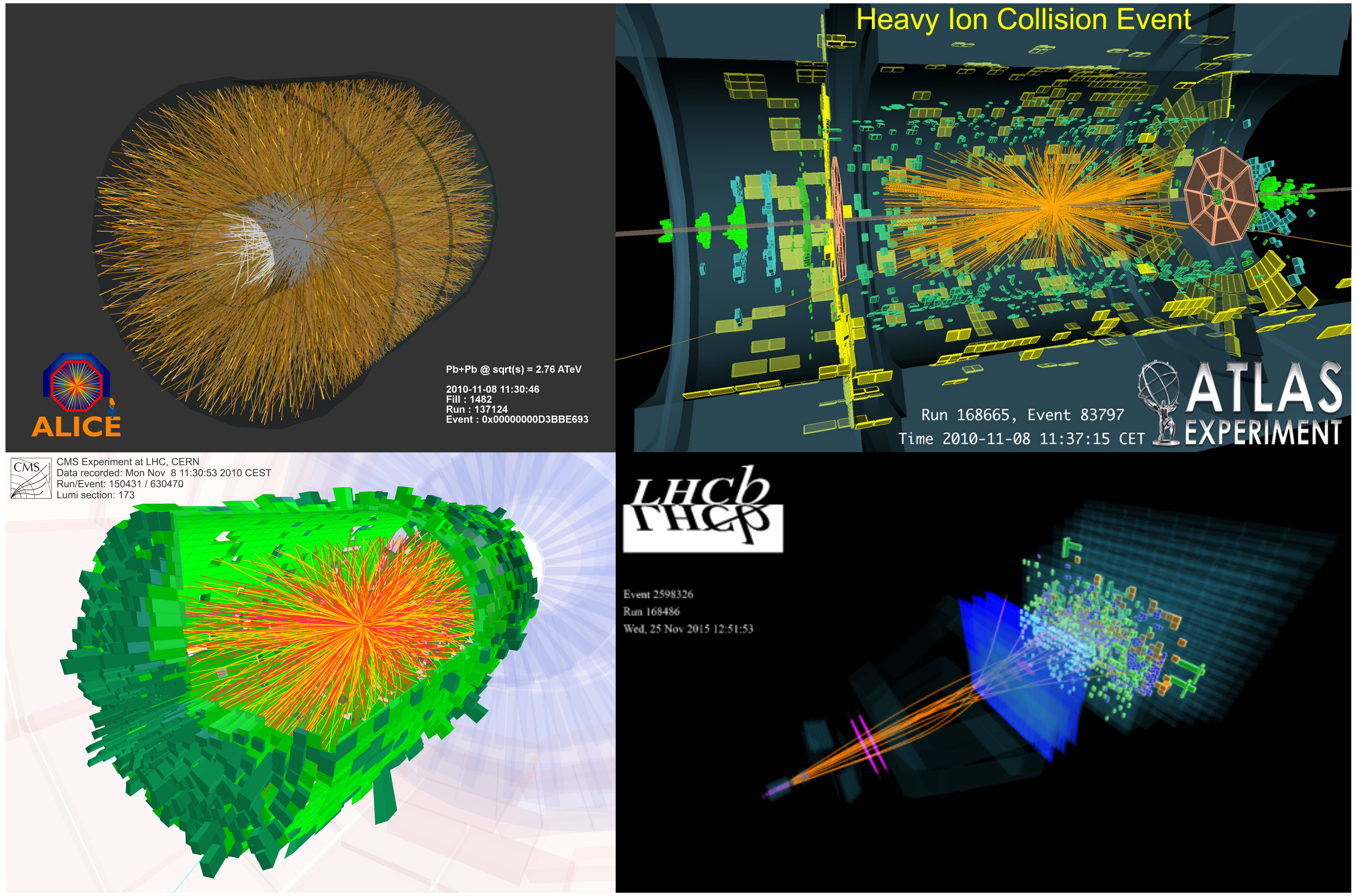
Guilherme Milhano [LIP & IST, Lisbon]
gmilhano@lip.pt

HEAVY ION PHYSICS



:: the physics of ultra-relativistic collisions of heavy nuclei

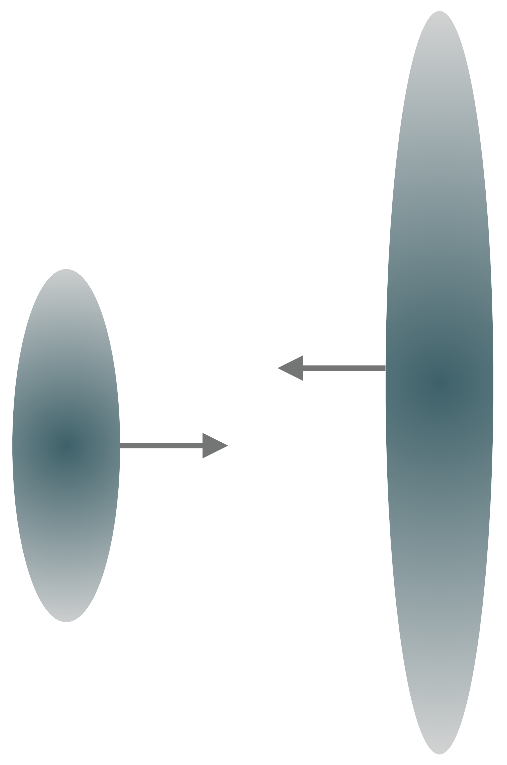
{PbPb,XeXe}@LHC, {AuAu,CuCu,$^{96}\mathrm{Zr}^{40+}$Zr,$^{96}\mathrm{Ru}^{44+}$Ru,UU}@RHIC, {PbPb,InIn,...}@SPS[fixed target], ...



the main focus of these lectures

HEAVY ION PHYSICS

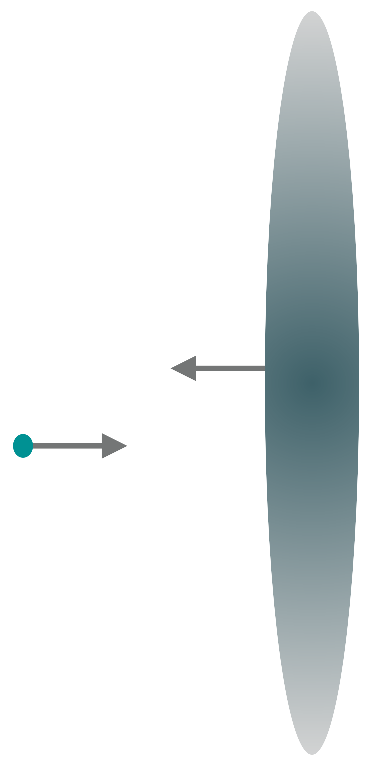
:: but also



:: light[er]-heavy ion collisions

{CuAu, dAu}@RHIC, {PbNe}@LHC [LHCb fixed target]

:: which [obviously] includes



:: proton-nucleus collisions

pPb@LHC, pAl@RHIC

the lightest of all ions

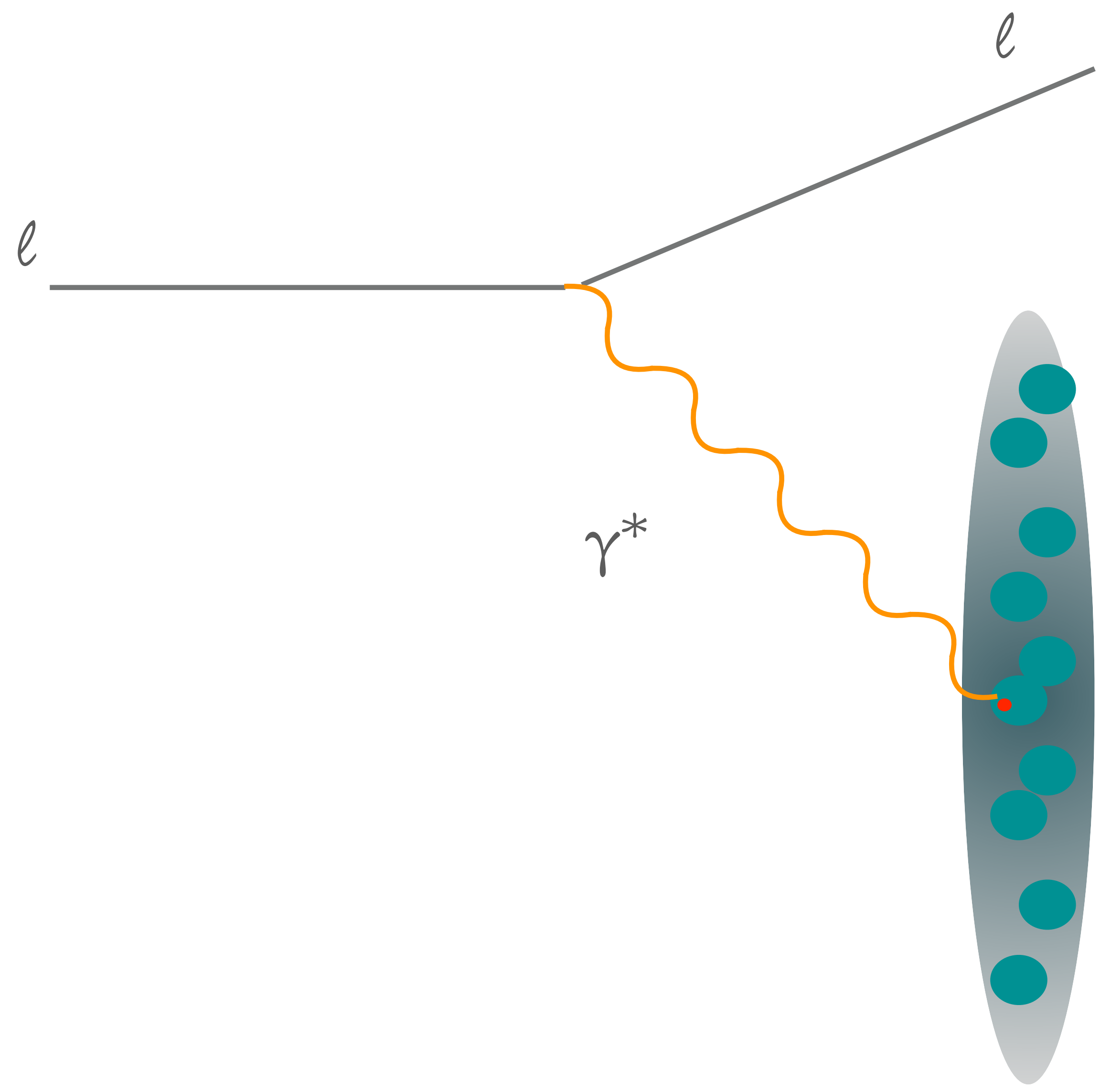
:: and [less obviously]

:: whenever 'heavy-ion-like' behaviour is involved

HEAVY ION PHYSICS

:: and deep-inelastic scattering off nuclei

EIC@BNL, LHeC (?), FCC-eA (?)

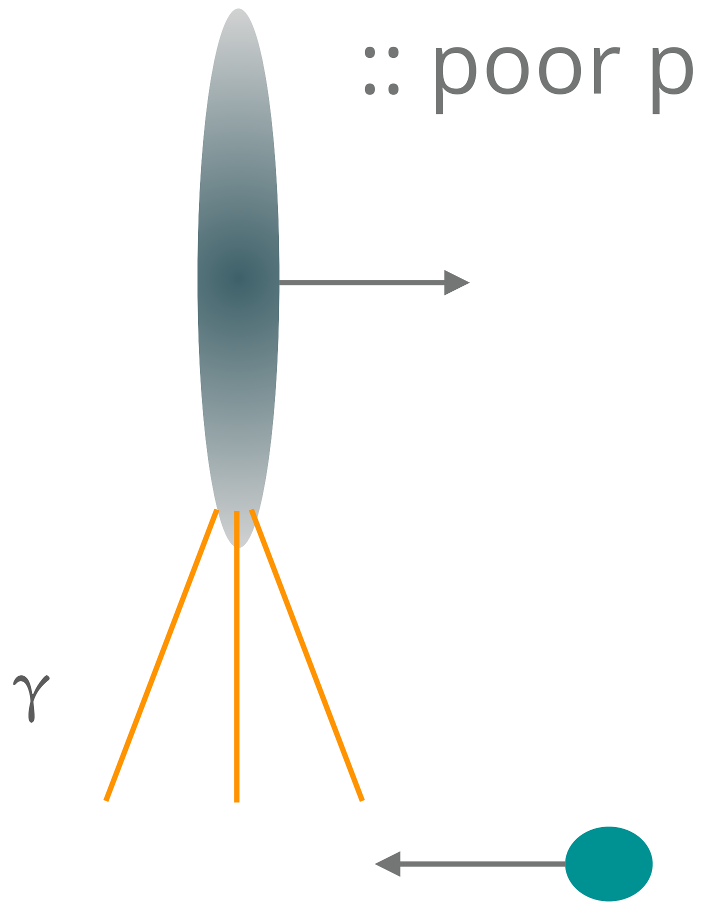


which is essential to know the initial conditions of a heavy-ion collision

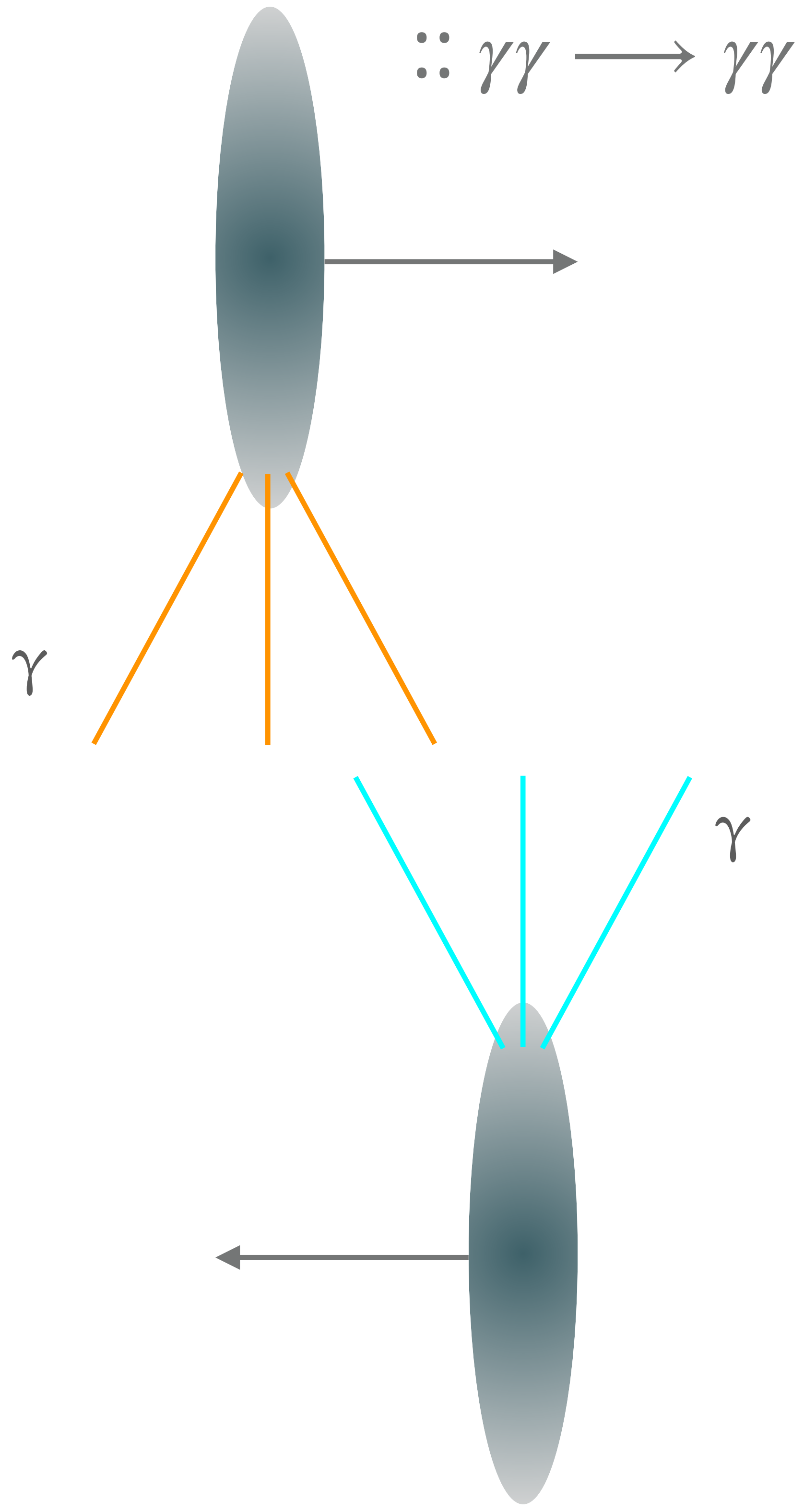
:: the structure of the colliding nuclei at all relevant scales [nuclear PDFs]

HEAVY ION PHYSICS

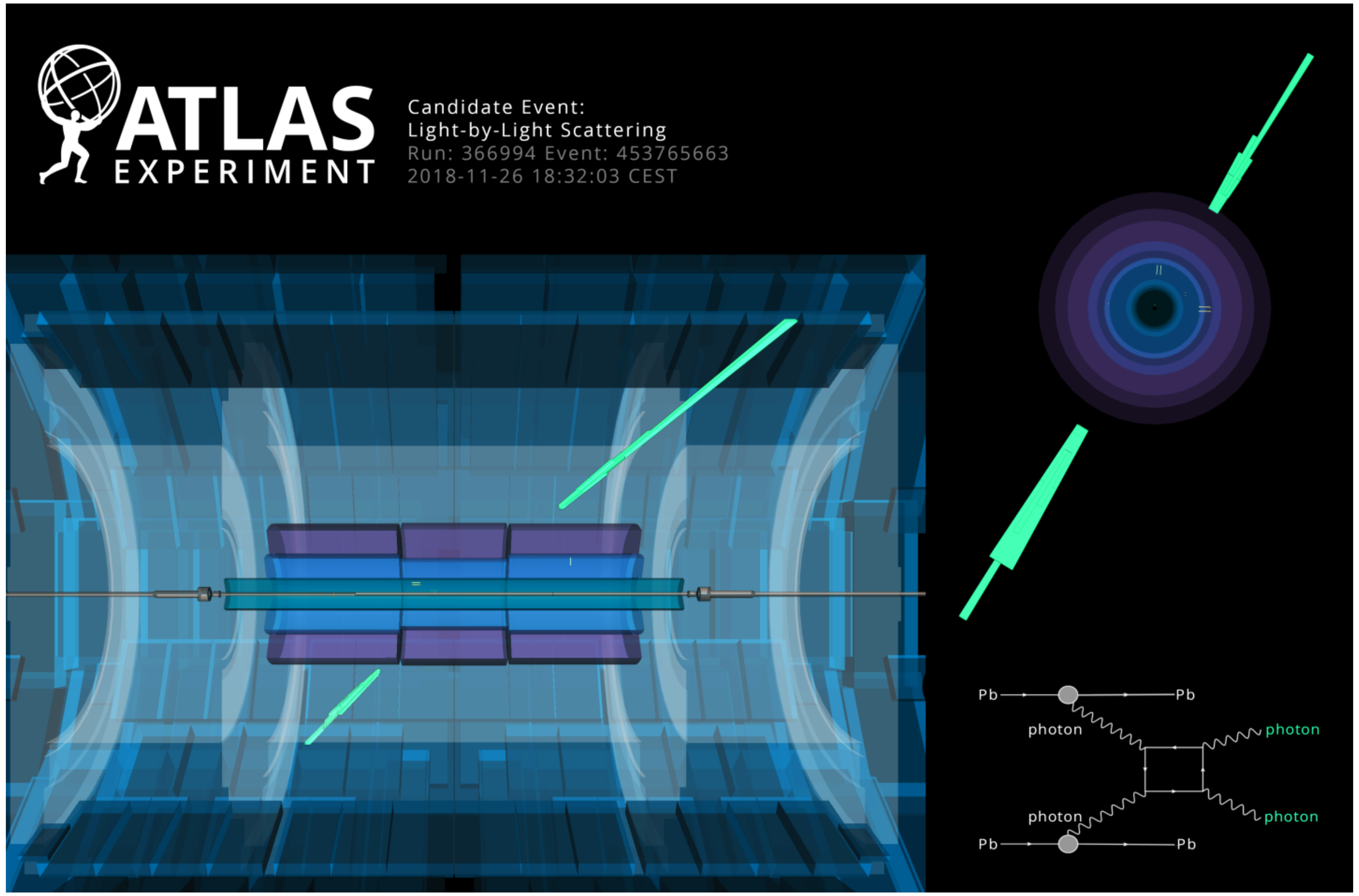
:: and, even less obviously, nuclei as EM field sources [ultra -peripheral collisions]



:: poor person's DIS



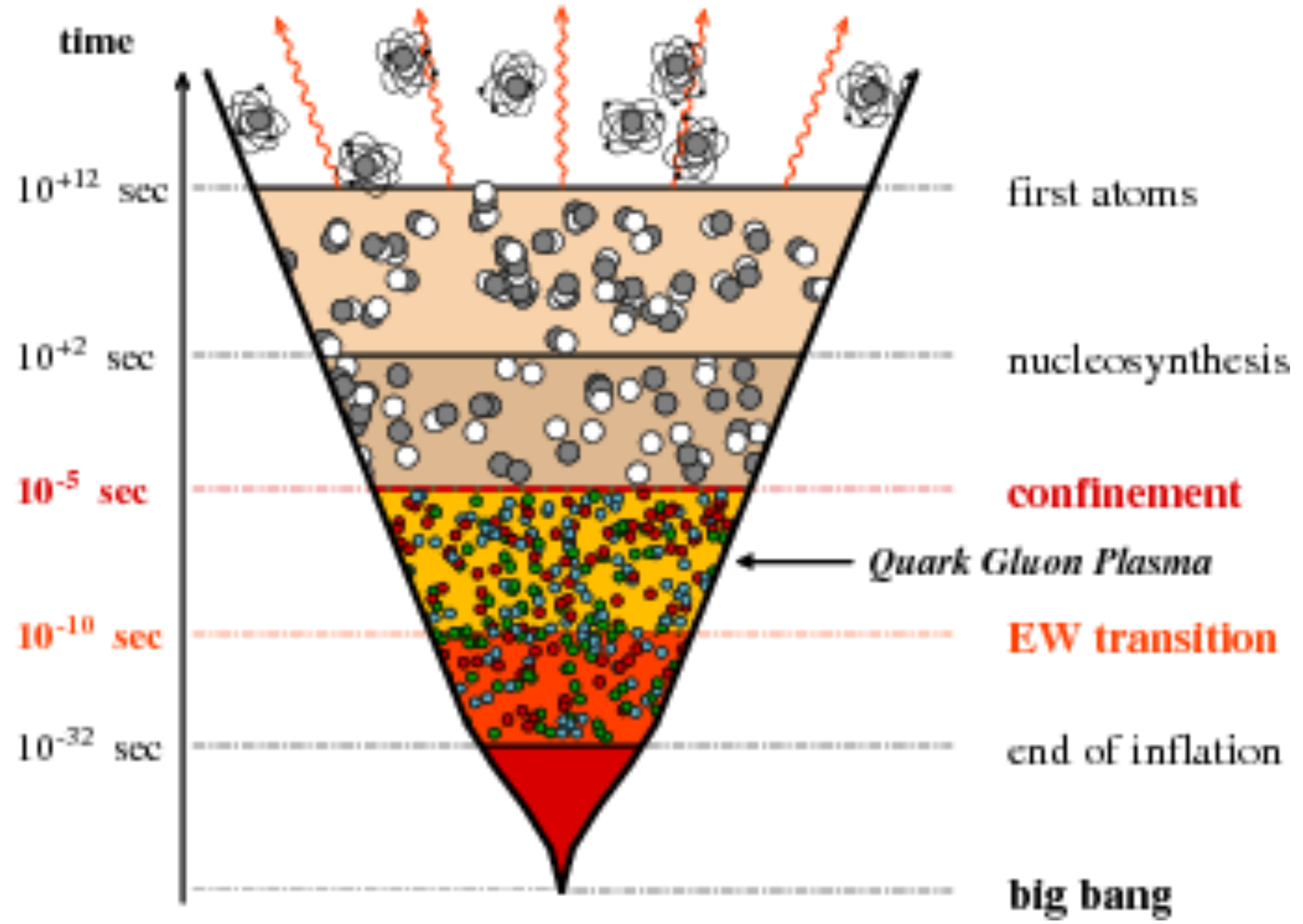
:: $\gamma\gamma \longrightarrow \gamma\gamma$ scattering [classically forbidden process]



ATLAS :: Nature Physics 13 (2017) no.9, 852 ;1702.01625 [hep-ex]

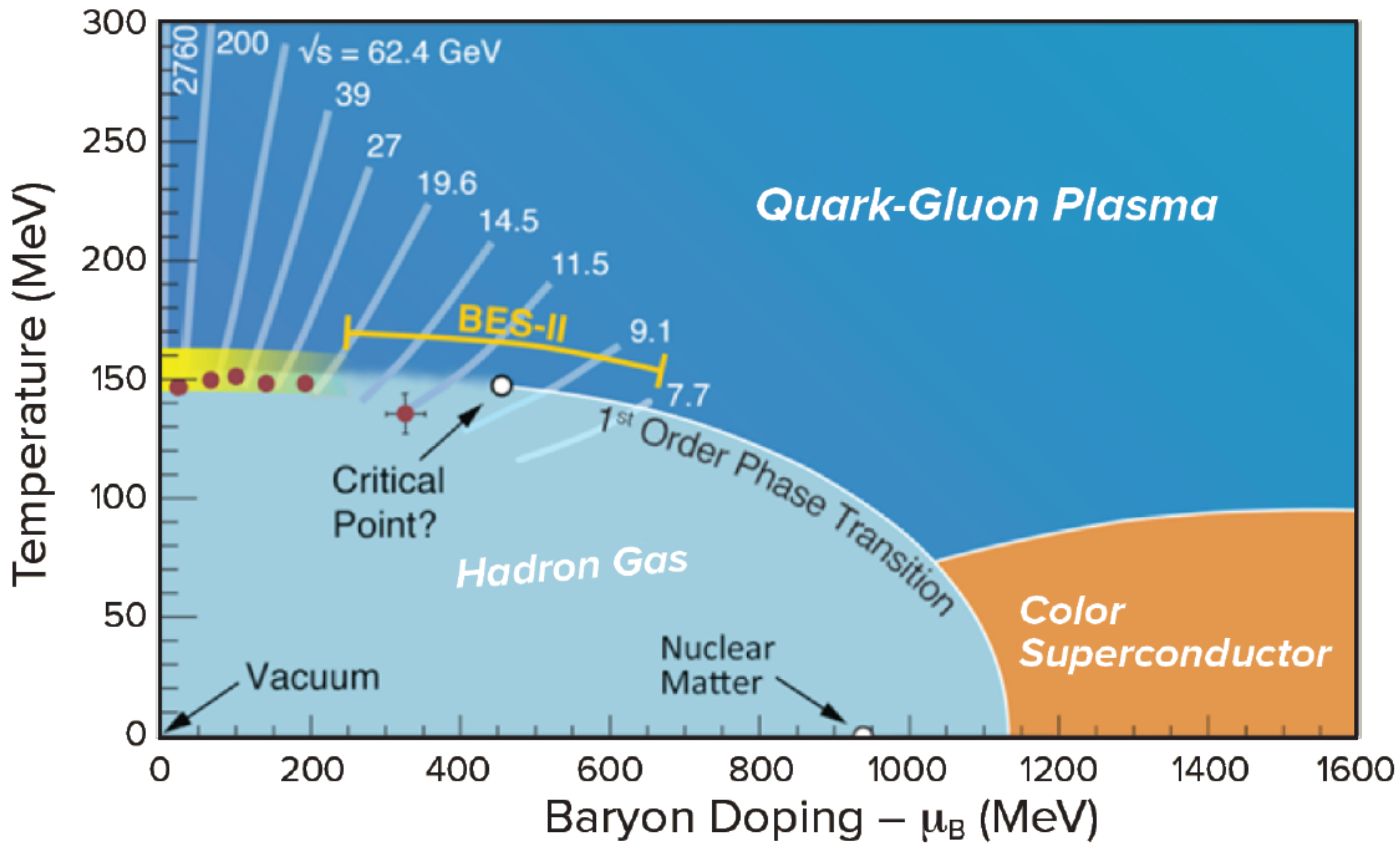
HEAVY ION PHYSICS [PURPOSE]

- explore and understand fundamental properties of matter at the most extreme temperature [~10^5 higher than the Sun's core] and density achievable in a laboratory
    - make droplets of early Universe [∼10^{-6} seconds after the Big Bang]



HEAVY ION PHYSICS [PURPOSE]

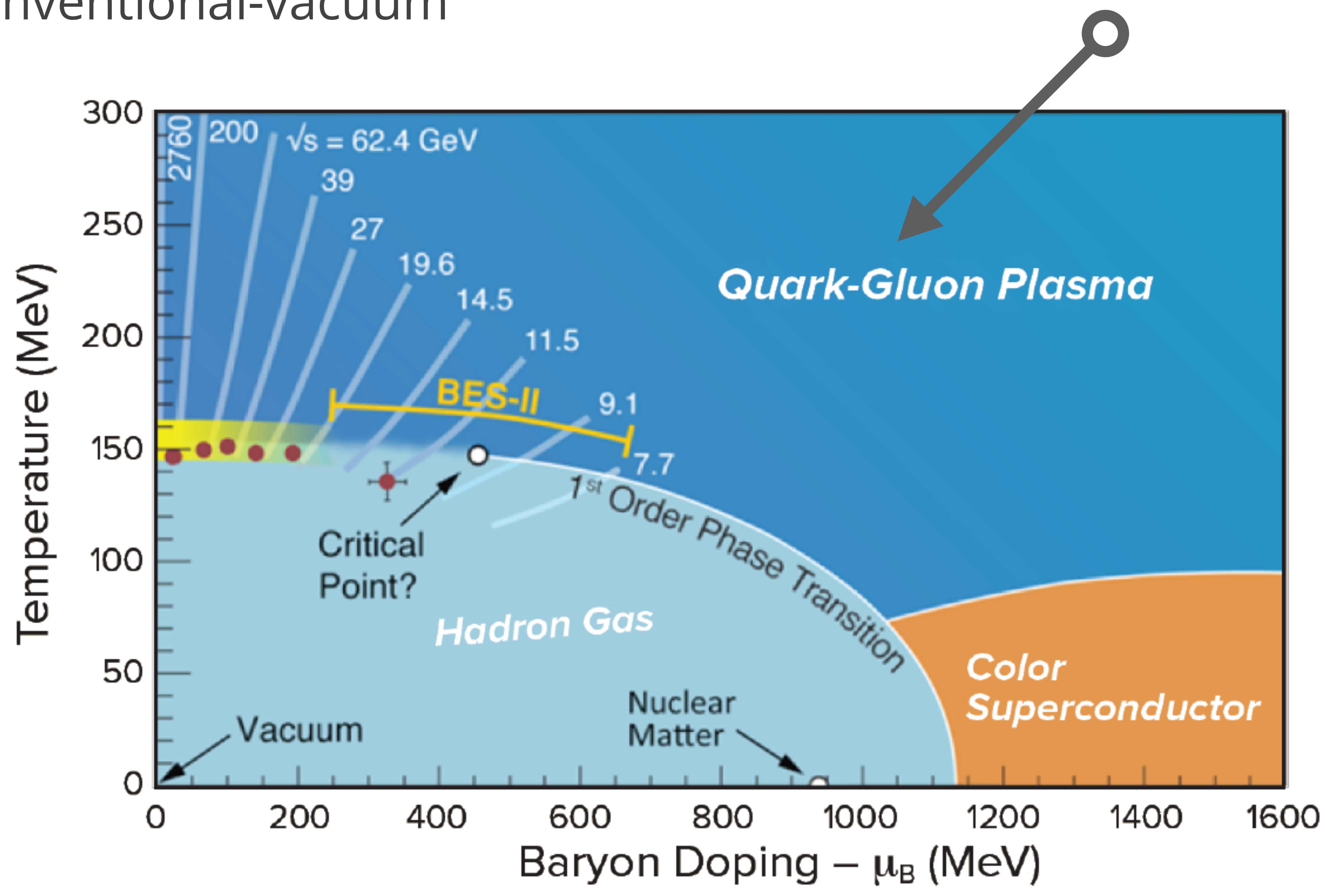
- explore and understand fundamental properties of matter at the most extreme temperature [~10^5 higher than the Sun's core] and density achievable in a laboratory
- understand QCD beyond 'few-particles' and 'conventional-vacuum'
    - explore the QCD phase diagram



Reaching for the horizon: The 2015 long range plan for nuclear science

HEAVY ION PHYSICS [PURPOSE]

- explore and understand fundamental properties of matter at the most extreme temperature [~10^5 higher than the Sun's core] and density achievable in a laboratory
- understand QCD beyond 'few-particles' and 'conventional-vacuum'
- understand the Quark Gluon Plasma [QGP]



Reaching for the horizon: The 2015 long range plan for nuclear science

HEAVY ION PHYSICS [PURPOSE]

- explore and understand fundamental properties of matter at the most extreme temperature [~10^5 higher than the Sun's core] and density achievable in a laboratory
- understand QCD beyond 'few-particles' and 'conventional-vacuum'
- understand the Quark Gluon Plasma [QGP]
  - the simplest form of complex quantum matter
    - only strongly coupled system of SM fundamental dof
    - how does complexity/complexity emerge from simple fundamental laws ?

these remain open questions?

WHAT IS QGP

- a system of very high energy density [Bjorken's estimate]

$$\epsilon_0(\tau_0 = 1\,\text{GeV/fm}) = \frac{1}{\pi R^2 \tau_0} \frac{dE_\perp}{d\eta}\bigg|_{\eta=0} \simeq 20\,\text{GeV/fm}^3$$

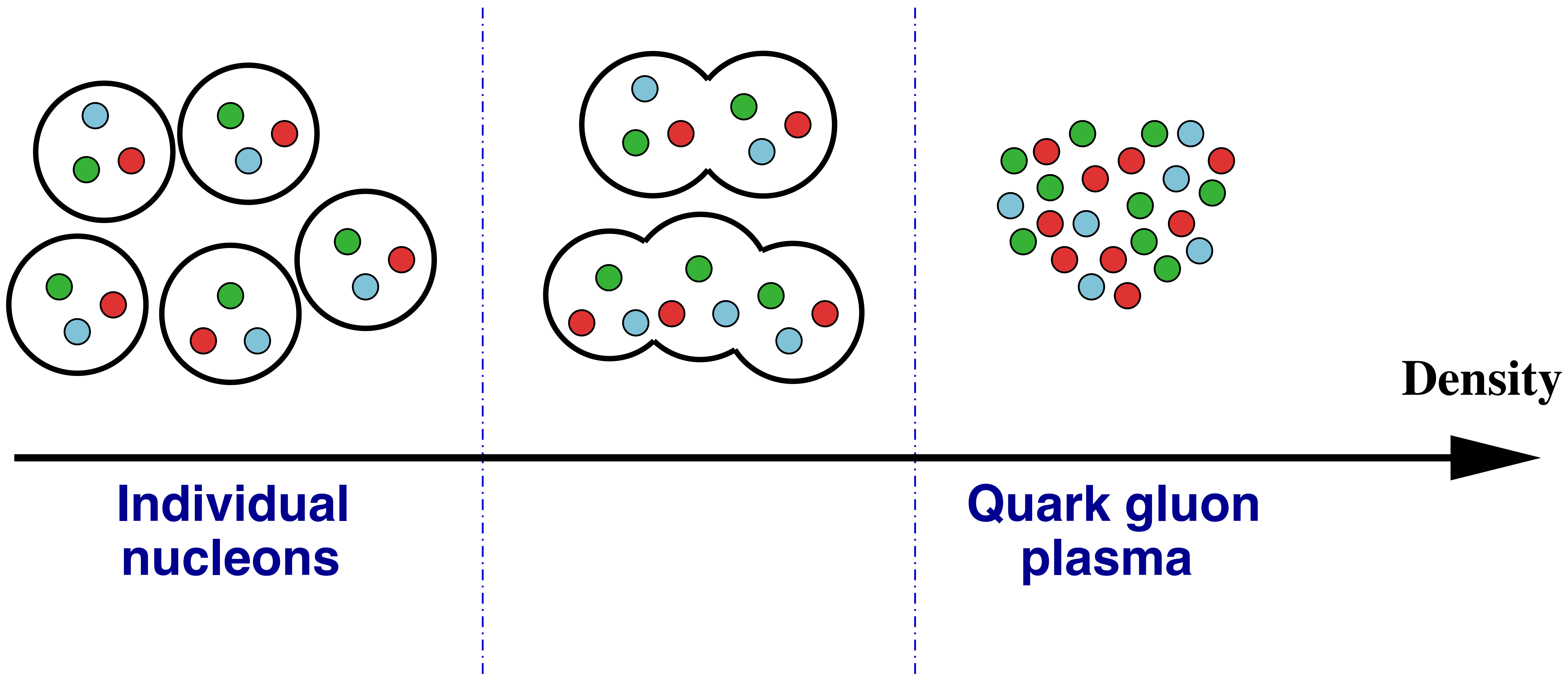
Bjorken, Phys. Rev. D27 (1983) 140
ALICE, Phys. Rev. D27 (1983) 140

[$\epsilon_0 = 0.16\,\text{Gev/fm}^3$ for a nucleon at rest]

- re-scattering in the final state is unavoidable and should drive system towards thermal equilibrium

WHAT IS QGP

- temperature/energy density acts as scale to free (anti-)quarks and gluons beyond nucleon radius



S. Floerchinger, ESHEP2015

- QGP is a system of deconfined (anti-)quarks and gluons with chiral symmetry restored

WHAT IS QGP

- if QGP were a non-interacting gas of N_B massless bosons and N_F massless fermions, its pressure would be [Stefan–Boltzmann]

$$p(T) = \frac{\pi^2}{90}\left(N_b + \frac{7}{8}N_F\right)T^4$$

$$N_B = [\text{\#polarizations}] \times [\text{\#colours}] = 2 \times 8$$

$$N_F = [\text{\#spins}] \times [\text{particle/anti} - \text{particle}] \times [\text{\#colours} \times [\text{\#flavours}] = 2 \times 2 \times 3 \times 3$$

- at low temperatures $M_\pi < T < M_\rho$ [non-interacting hadron gas]

$$N_B = [\text{\#pions}] = 3$$
$$N_F = 0$$

$\longrightarrow$ **should expect a significant pressure increase at boundary between phases**

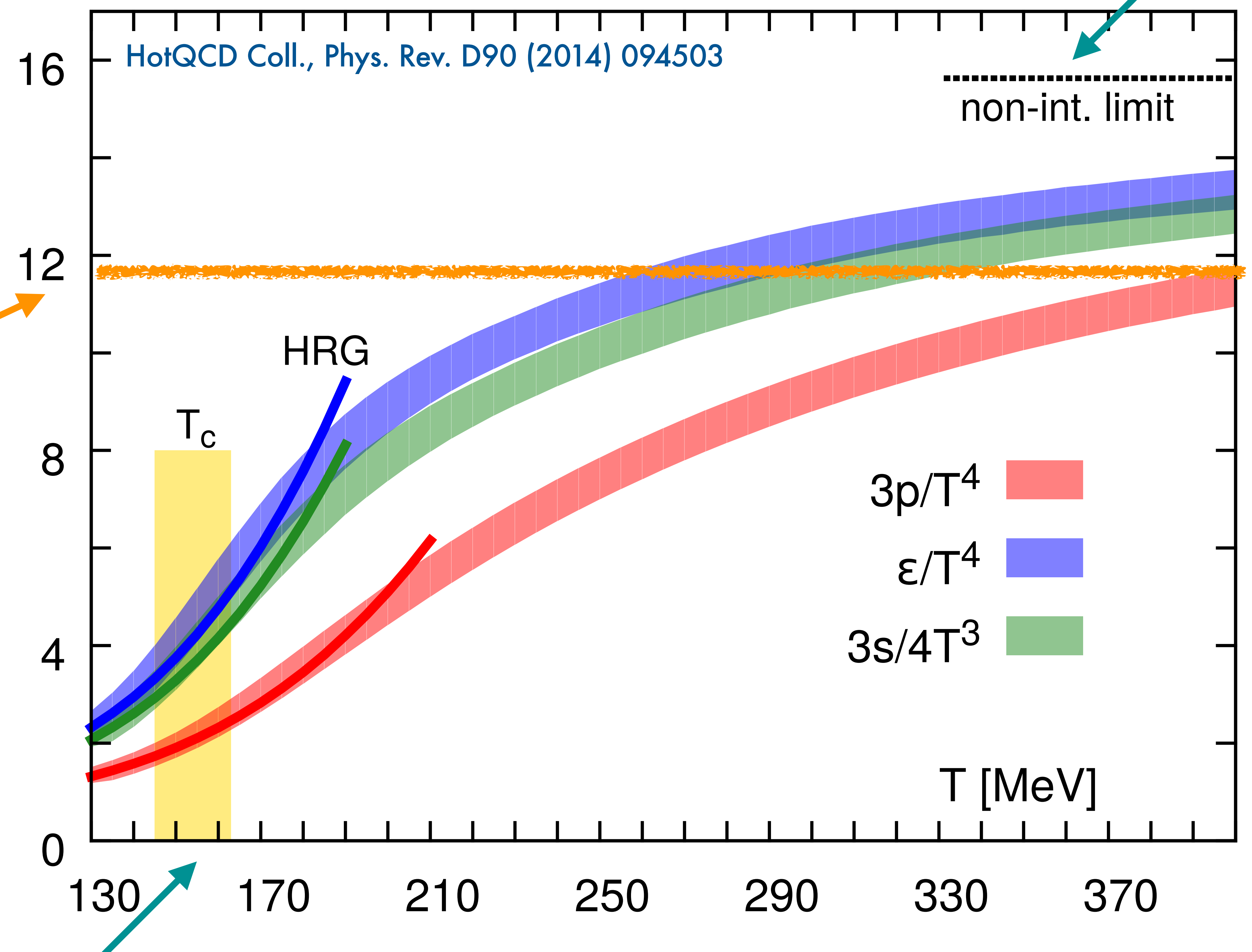
WHAT IS QGP

- from first principles [lattice QCD :: solve QCD numerically on space-time lattice]

- at high-T it may appear that asymptotic freedom is approached
  - however, equation of state for non-interacting gas is not satisfied $\left(\epsilon \neq 3p \neq \frac{3sT}{4}\right)$
  - for field theories with a gravity dual ($\mathcal{N}=4$ SYM, not QCD) where both the strong [$\lambda=\infty$] and weak [$\lambda=0$] limits are calculable

$$\frac{s_{\lambda=\infty}}{s_{\lambda=0}} = \frac{\epsilon_{\lambda=\infty}}{\epsilon_{\lambda=0}} = \frac{p_{\lambda=\infty}}{p_{\lambda=0}} = \frac{3}{4}$$

for non-interacting gas: $\epsilon = 3p = \frac{3sT}{4}$

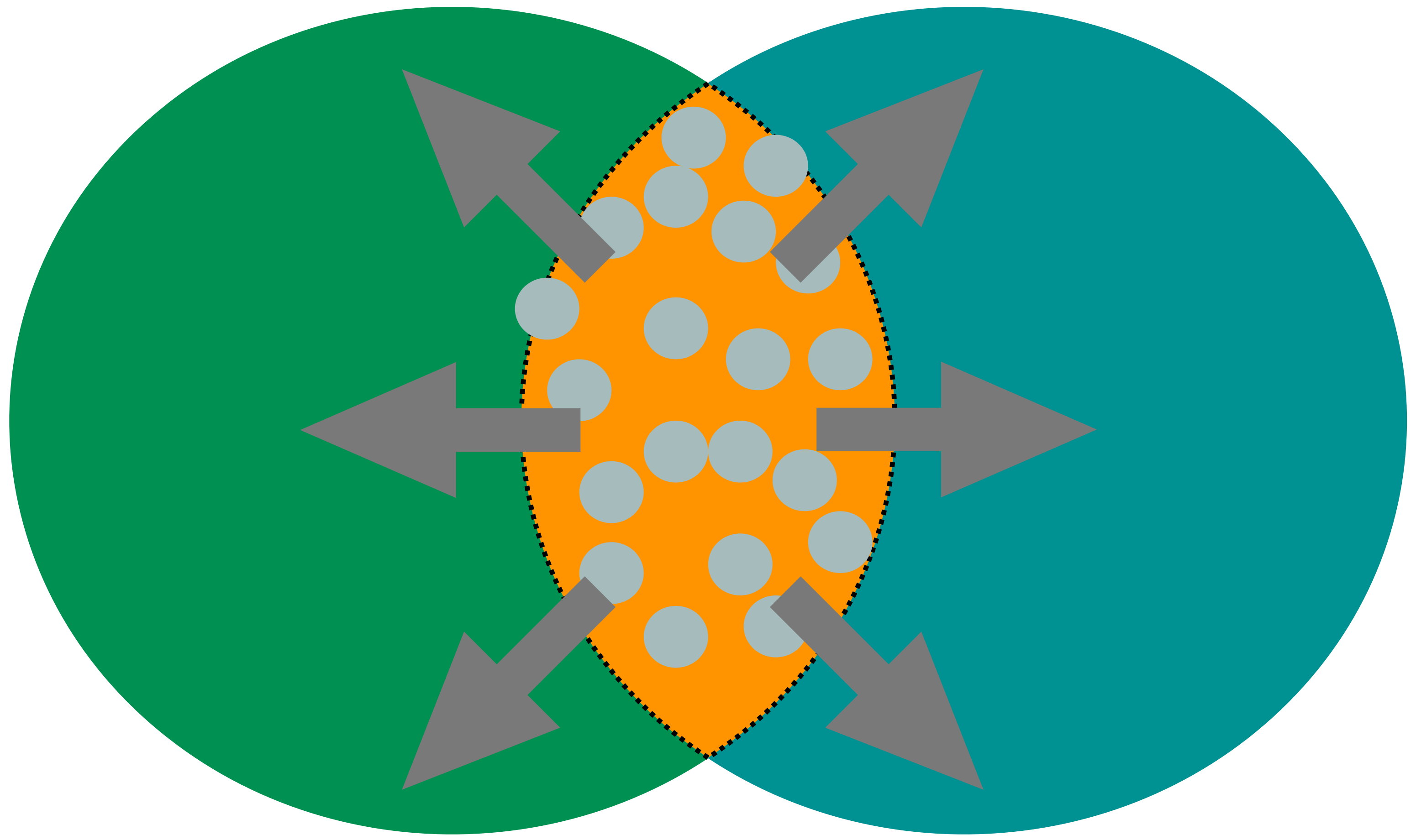


cross-over at $T_c = (154 \pm 9)\text{MeV} \approx 1.7 \cdot 10^{12} K$

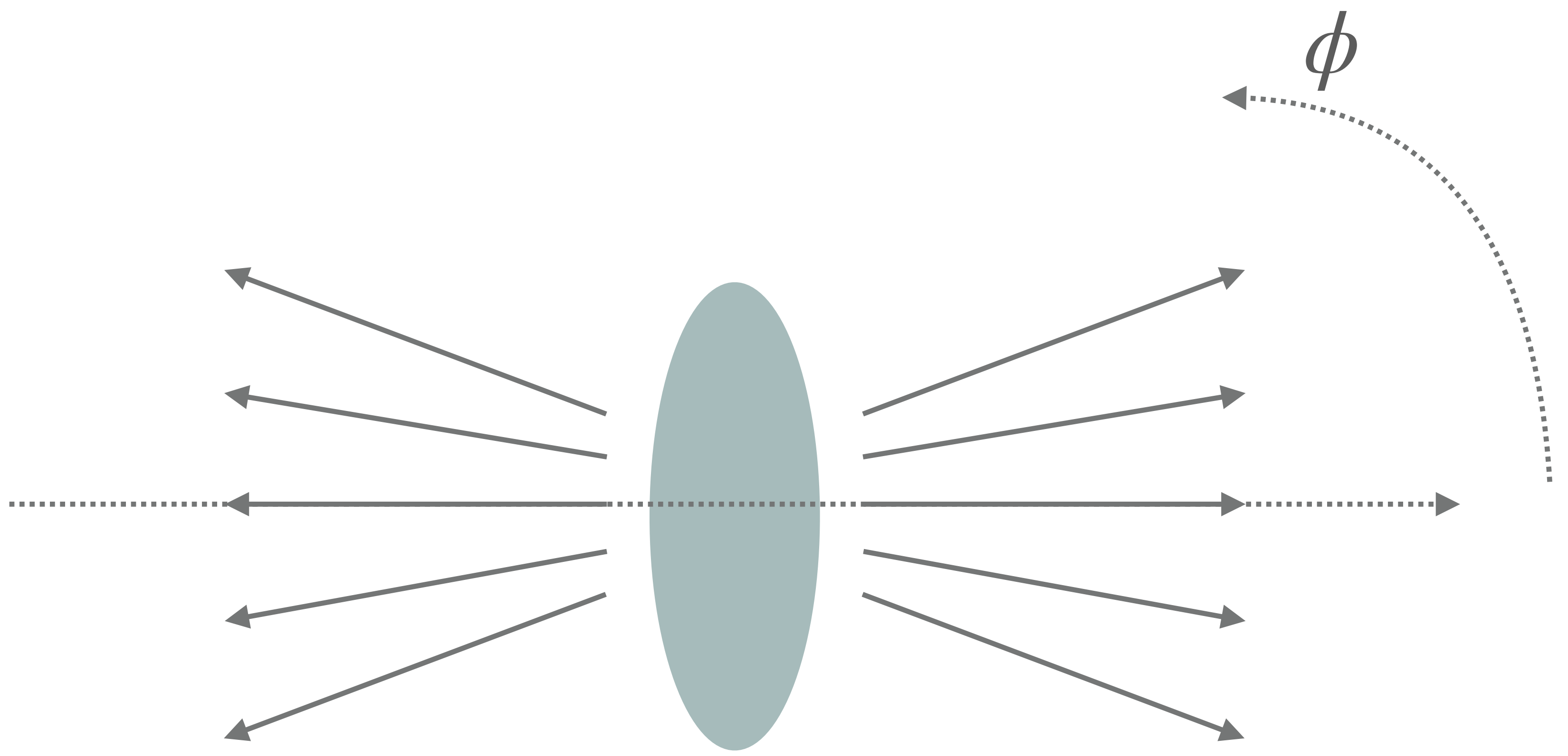
QGP is strongly coupled ?

A REMARKABLE PROPERTY OF QGP

Ollitrault, Phys. Rev. D46 (1992) 229-245



[beam axis view of collision]



final state soft particles preferably aligned along the collision plane

initial *spatial* anisotropy → pressure gradients → final state *momentum* anisotropy

a natural consequence of hydrodynamics

QGP manifests collectivity. It flows like a nearly perfect liquid. QGP is strongly coupled

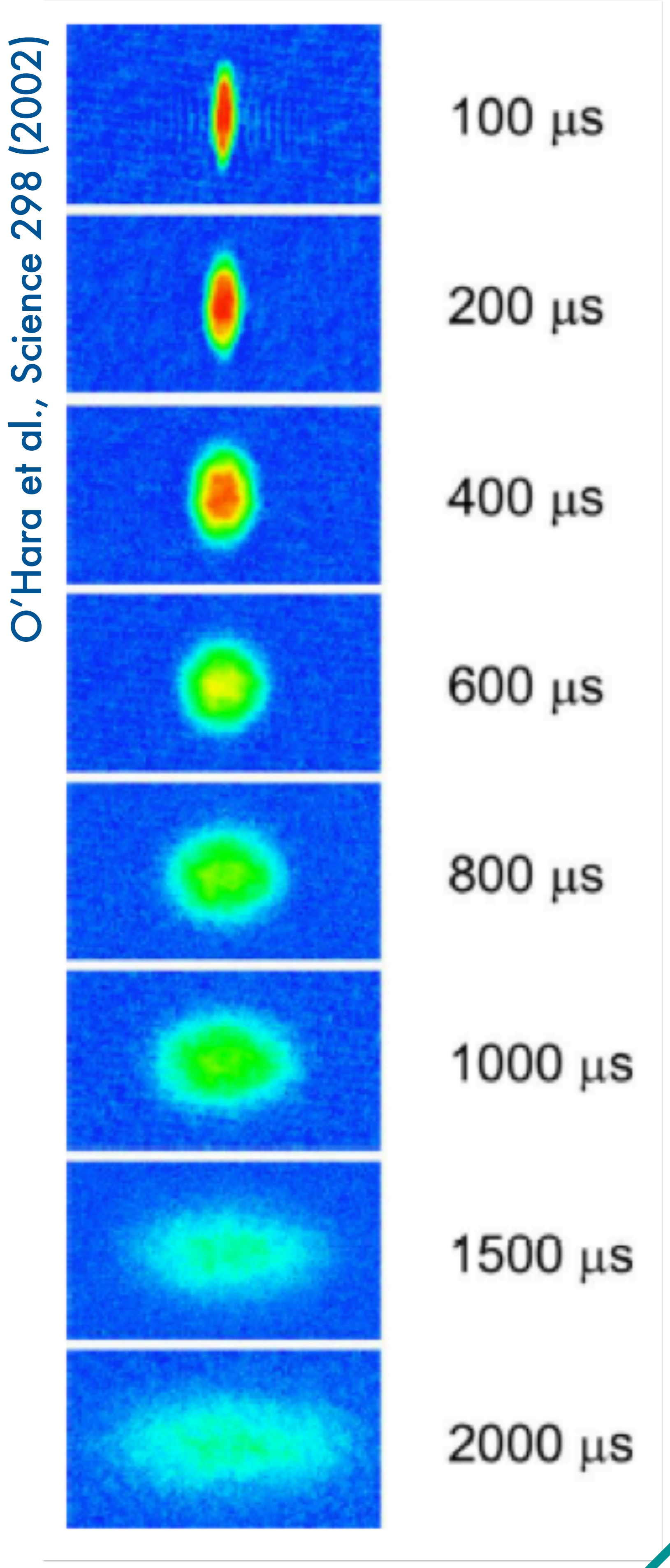
FLOW AND STRONG COUPLING

- strongly coupled systems flow
  - both systems are nearly perfect liquids with viscosity to entropy ratio close the ‘universal’ lower bound for theories with a gravity dual

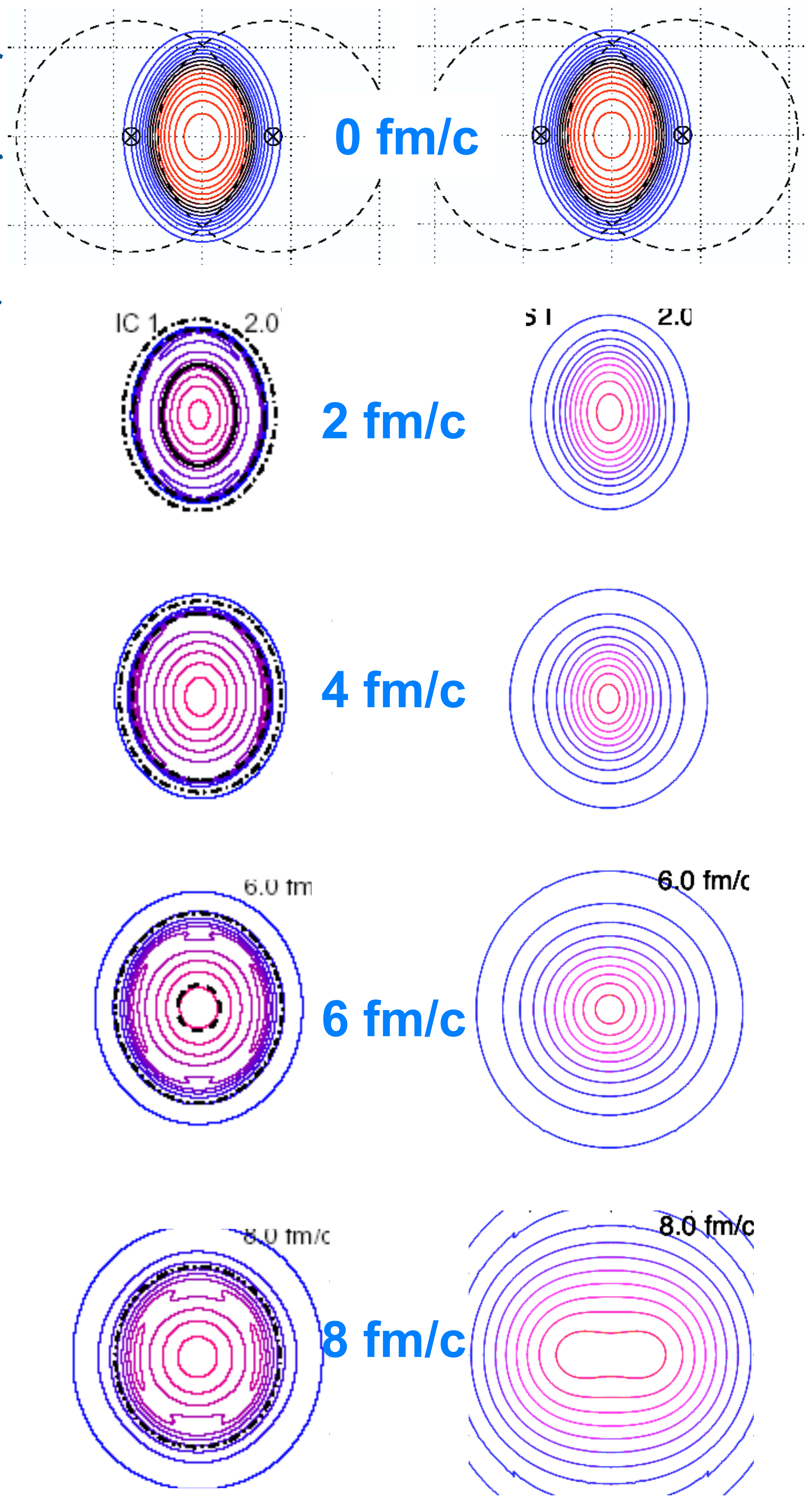
$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

Policastro, Son, Starinets, PRL 87, 081601 (2001)
Buchel, Liu,, PRL 93, 090602 (2004)

O’Hara et al., Science 298 (2002)



Kolb and Heinz, QGP3 (2003)



degenerate Fermi gas of ultracold Li atoms released from anisotropic trap [exp. data]

QGP [hydrodynamic simulation]

Lisa et al., New J.Phys 13 (2011)

FLOW AND STRONG COUPLING

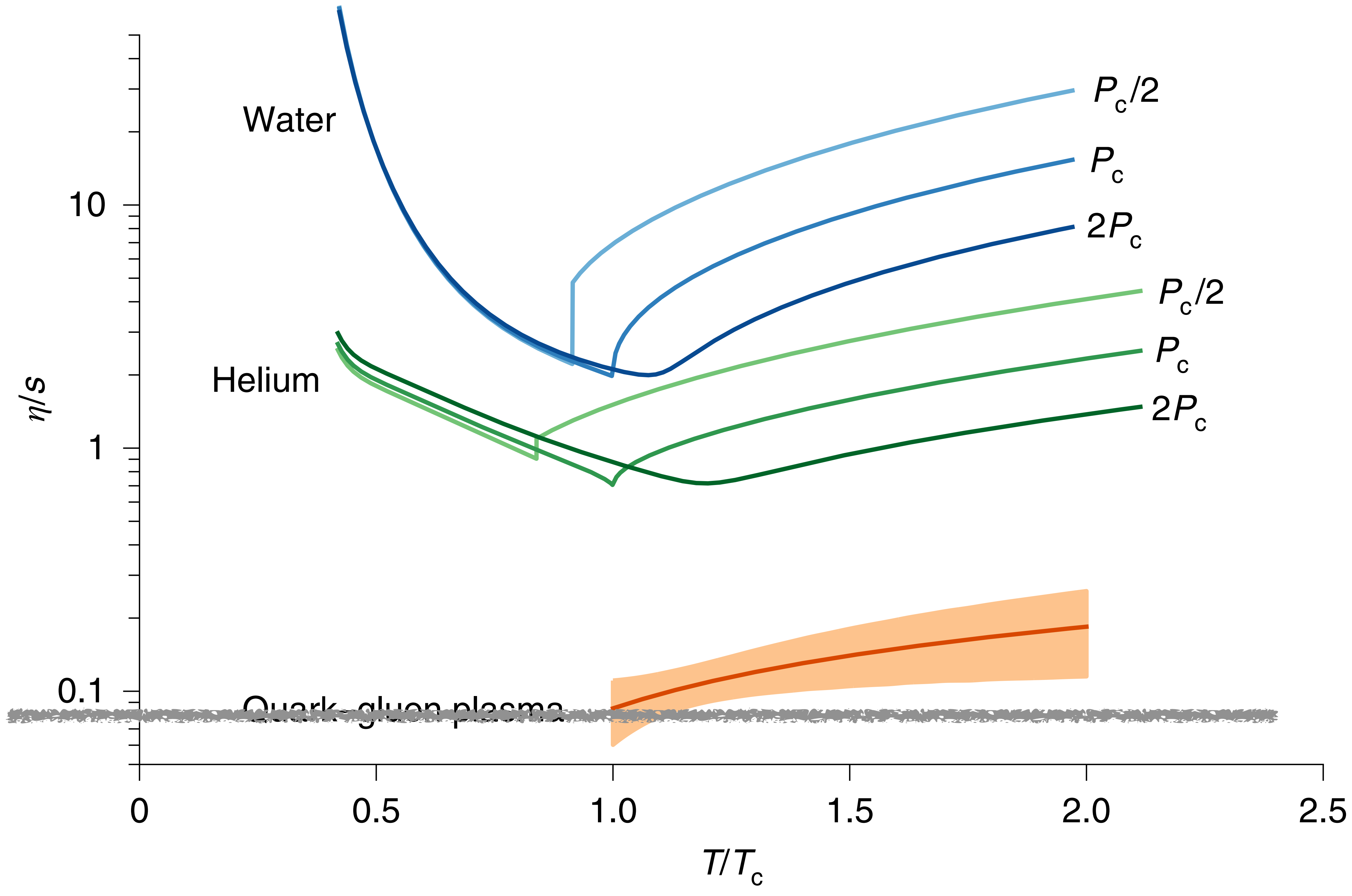
- strongly coupled systems flow
  - both are nearly perfect liquids with viscosity to entropy ratio close the 'universal' lower bound for theories with a gravity dual

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

Policastro, Son, Starinets, PRL 87, 081601 (2001)

Buchel, Liu,, PRL 93, 090602 (2004)

- Bayesian extraction from LHC data confirms extremely low η/s

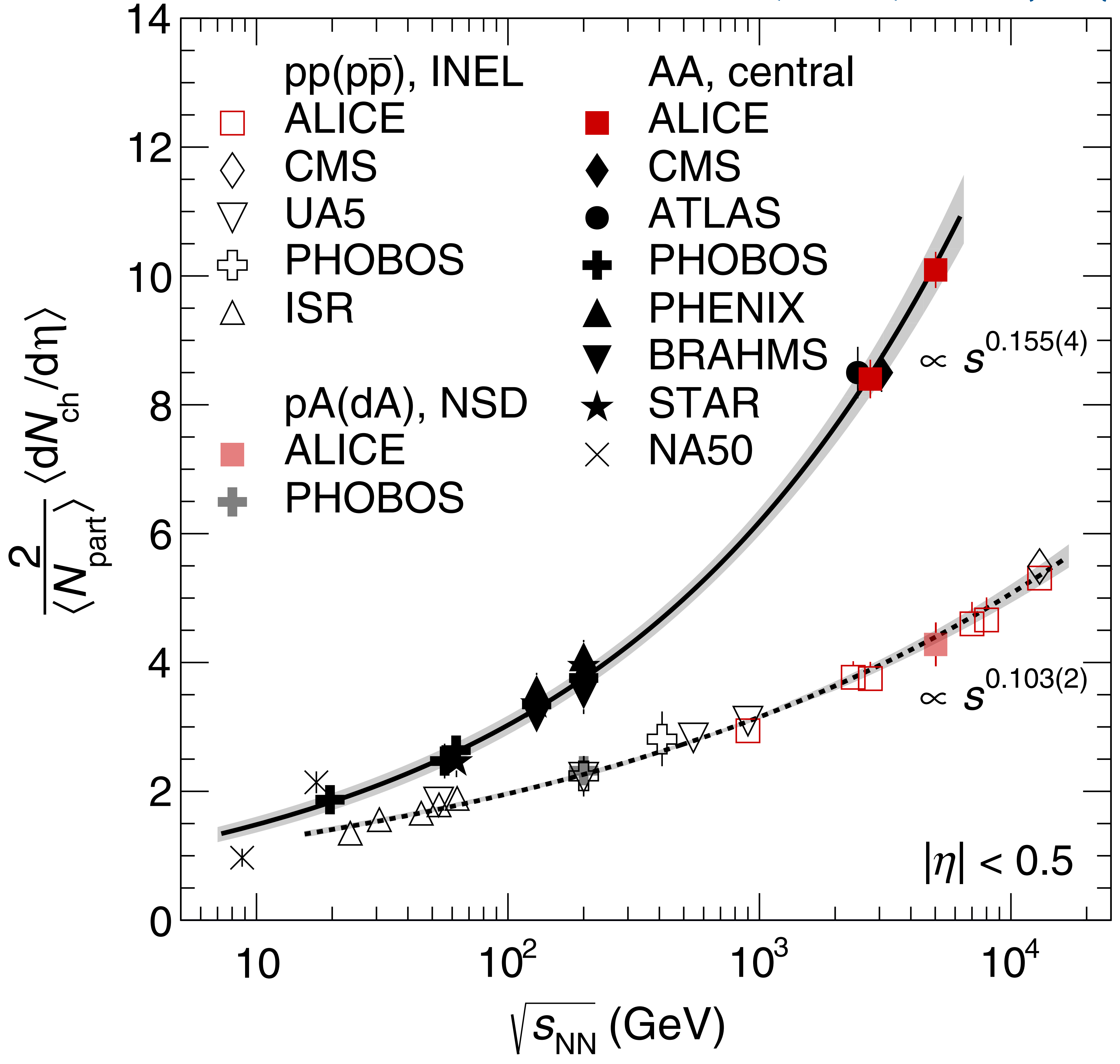


Bernhard, Moreland, Bass, Nature Physics 15, 1113-1117 (2019)

HEAVY ION COLLISIONS

	SPS	RHIC	LHC	FCC
$\sqrt{s_{NN}}$ [TeV]	0.017	0.2	2.76 (5.5)	39
volume at freezout [fm³]	1200	2300	5000 (6200)	11000
ε(τ=1fm/c) [GeV/fm³]	3-4	4-7	12-13 (16-17)	35-40
lifetime [fm/c]	4	7	10 (11)	13

ALICE, PRL 116, 222302 (2016)

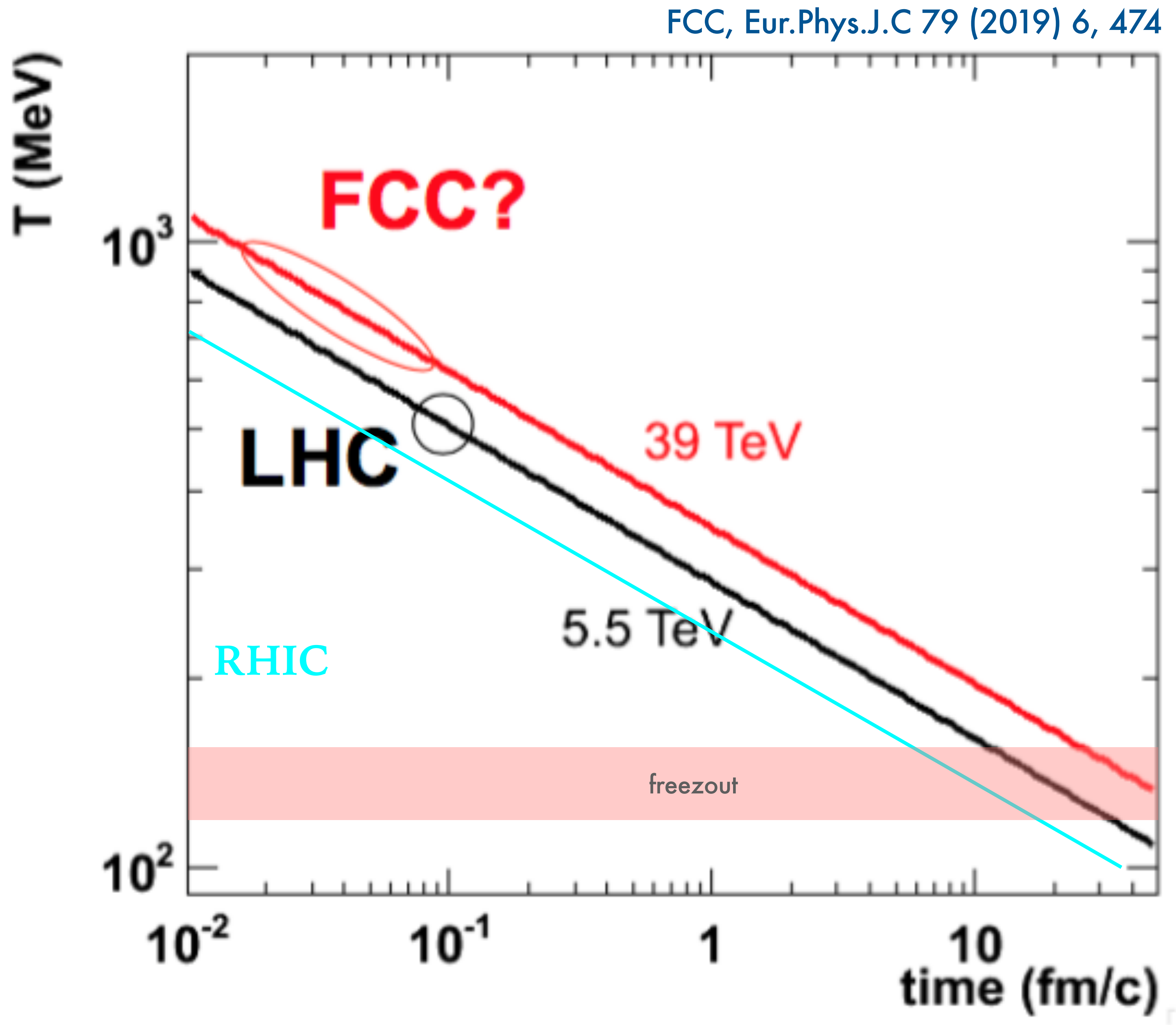


all this can be estimated from the number of particles produced at mid-rapidity

HEAVY ION COLLISIONS

	SPS	RHIC	LHC	FCC
√sNN [TeV]	0.017	0.2	2.76 (5.5)	39
volume at freezout [fm³]	1200	2300	5000 (6200)	11000
ε(τ=1fm/c) [GeV/fm³]	3-4	4-7	12-13 (16-17)	35-40
lifetime [fm/c]	4	7	10 (11)	13

QGP is short-lived

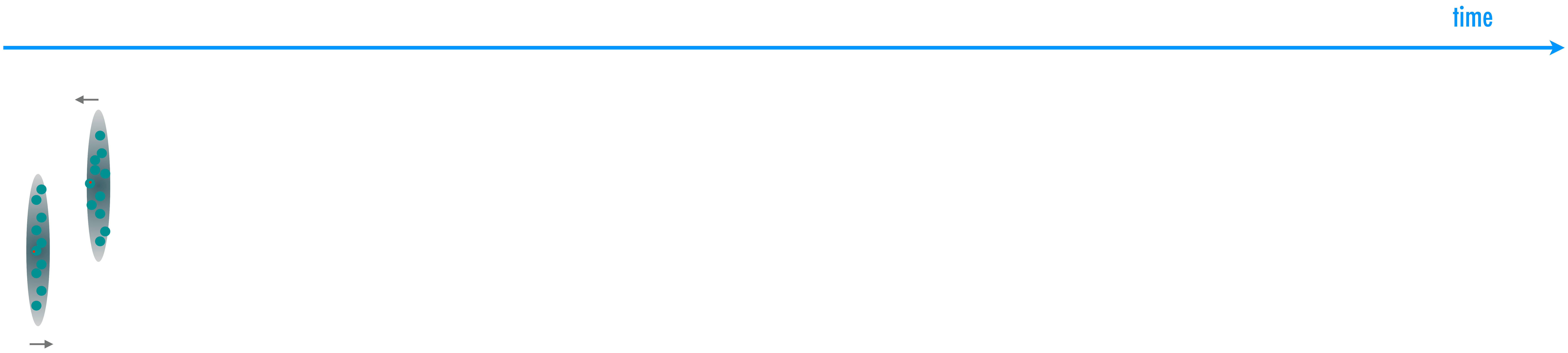


in heavy ions √s given per nucleon pair

$$\sqrt{s_{NN}} = \frac{Z}{A}\sqrt{s_{pp}}$$

:: for PbPb [LHC 14TeV] :: 82/208 x 14 = 5.5 TeV

TIMELINE OF A HEAVY ION COLLISION



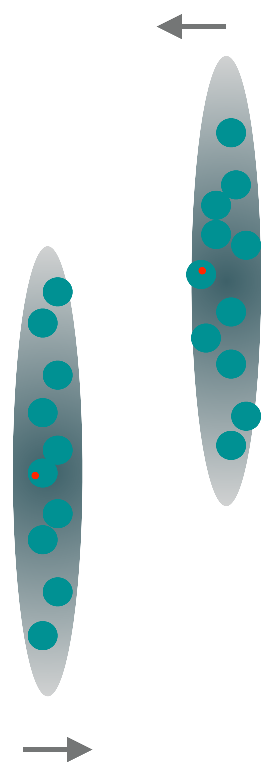
colliding nuclei

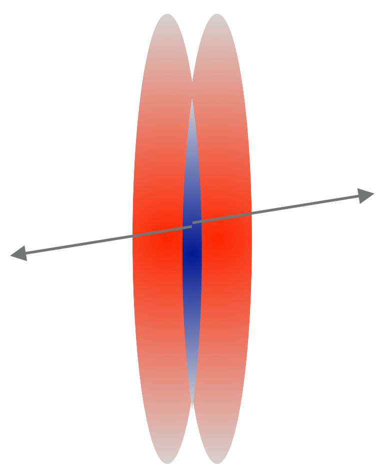
- need to how likely it is to find (anti-)quarks and gluons of given energy fraction [n(uclear)PDFs]
  - can be constrained in electron-nucleus EIC/LHeC/FCC-eA
  - also [to a lesser extent] in proton-nucleus LHC/RHIC
- geometry of collision [how head-on] is **very** important

TIMELINE OF A HEAVY ION COLLISION

~ 0.1 fm/c
[~10^{-25} s]

time





collision [out-of-equilibrium process]

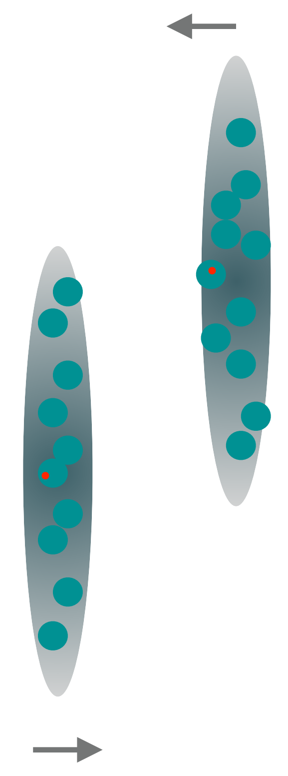
- many soft [small momentum exchange] collisions
  - responsible for bulk low-momentum particle production
  - will quickly hydrodynamize
- very few hard [large momentum exchange] collisons
  - off-spring will slowly relax toward hydrodynamization, yet remain out-of-equilibrium while traversing hot soup

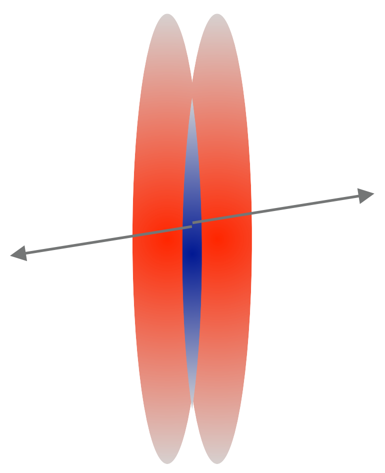
TIMELINE OF A HEAVY ION COLLISION

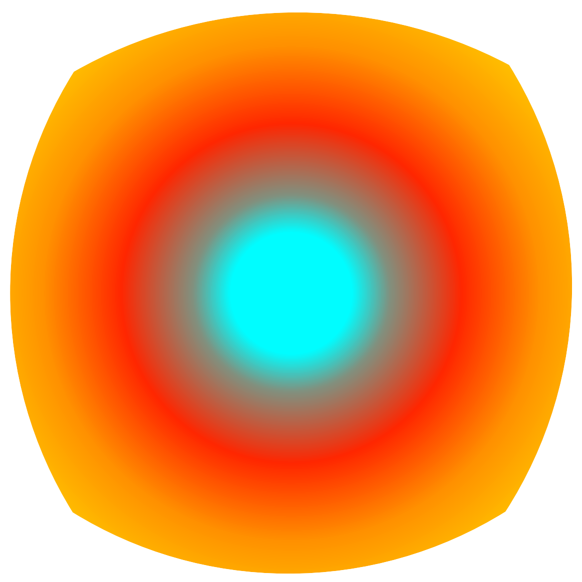
~ 0.1 fm/c [~10^{-25} s]

~1 fm/c [~10^{-24} s]

time



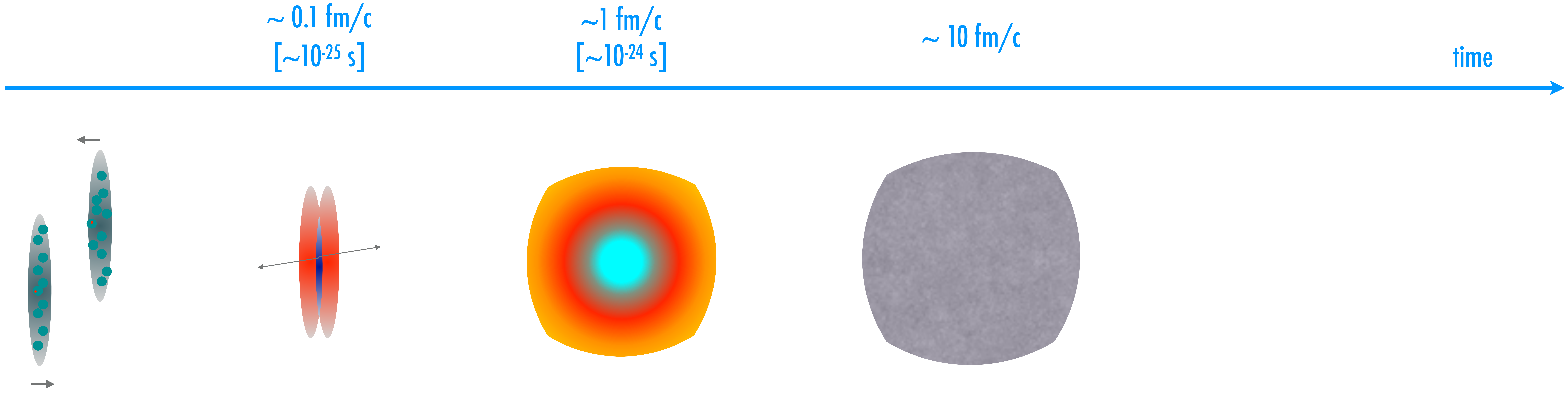




QGP

- hot, dense, and coloured matter
- quarks and gluons are the relevant dof

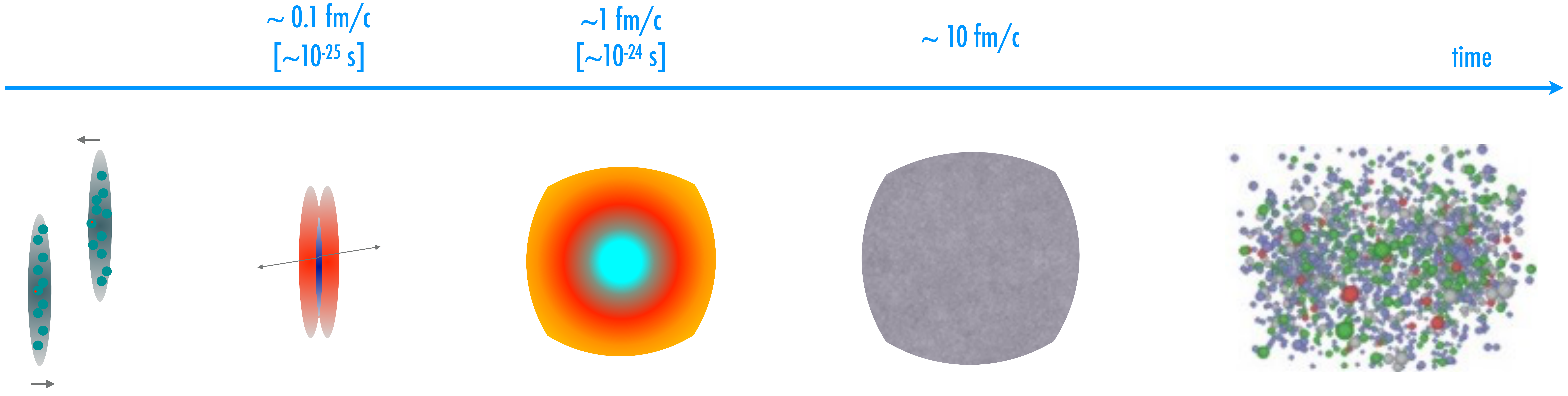
TIMELINE OF A HEAVY ION COLLISION



hadronization

- QGP expands and thus cools down
- once T~150 MeV back to hadronic matter

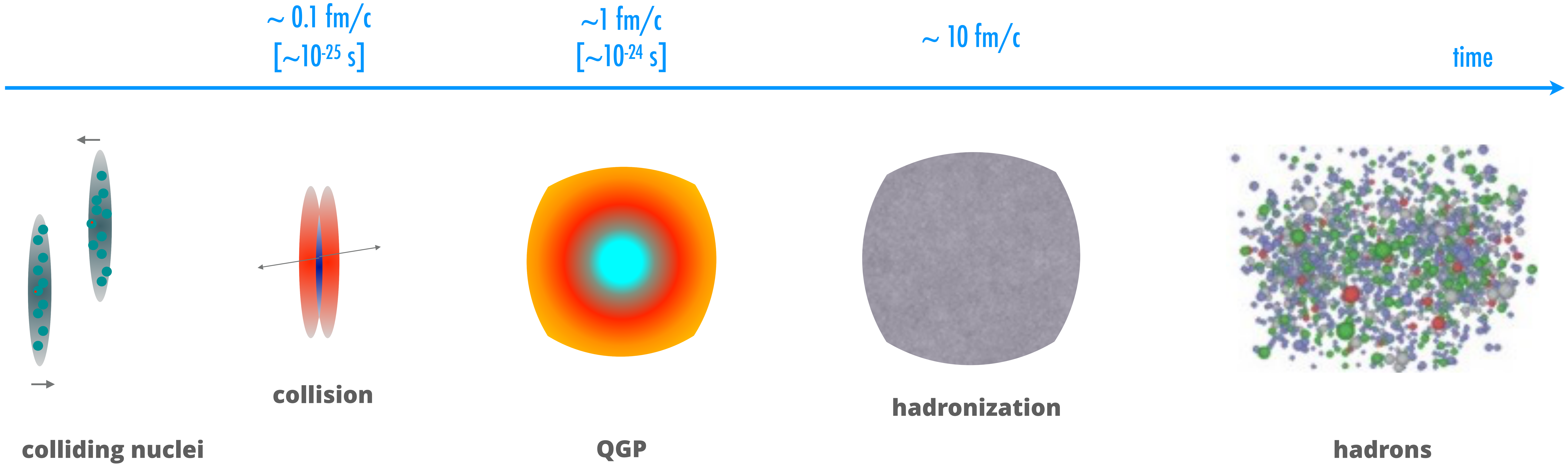
TIMELINE OF A HEAVY ION COLLISION



hadrons

- rescattering folllowed by free-streaming to detector

TIMELINE OF A HEAVY ION COLLISION

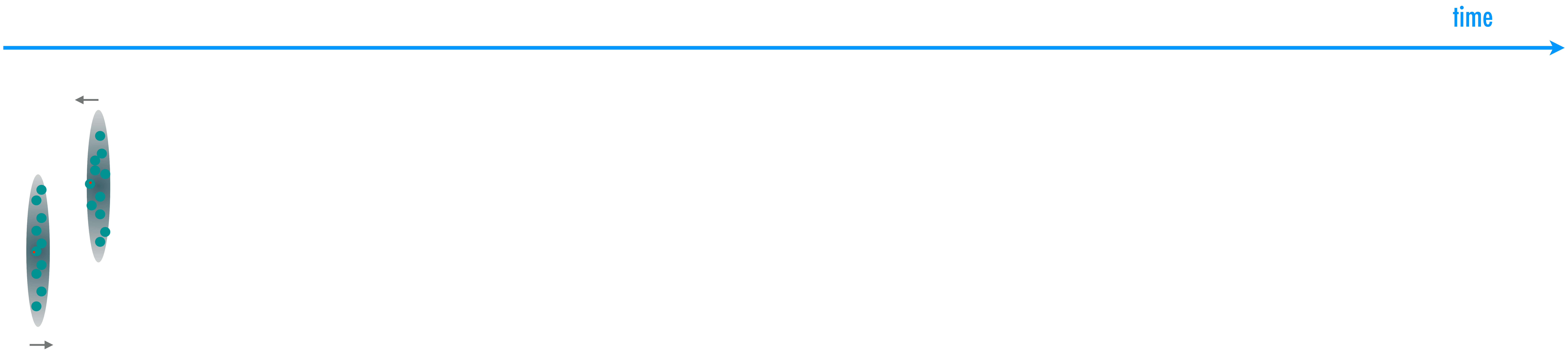


what we constrain elsewhere

what we want to understand
- how we get here?
- what it is?
- how it stops being?

all we have

INITIAL CONDITIONS

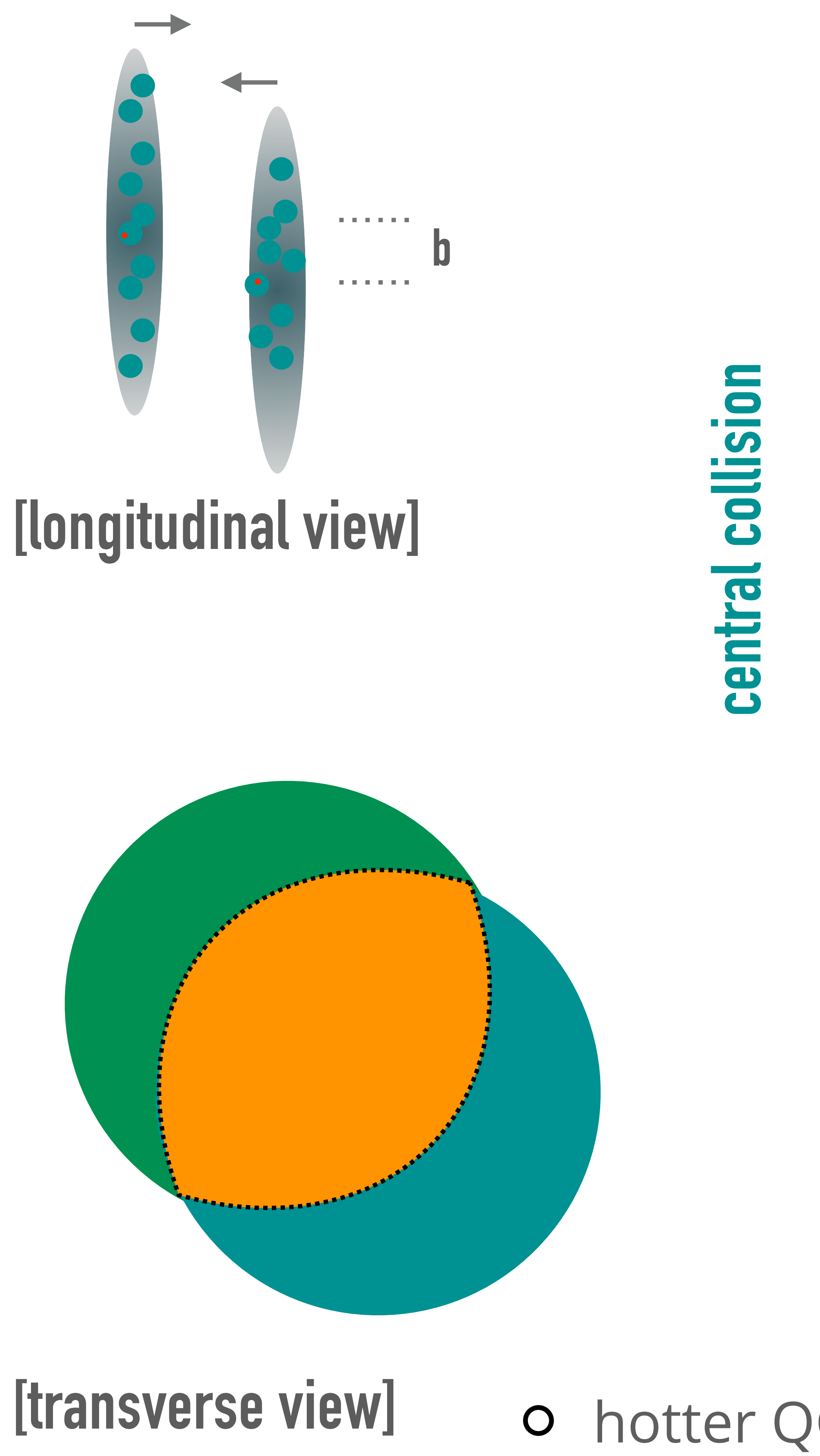


colliding nuclei

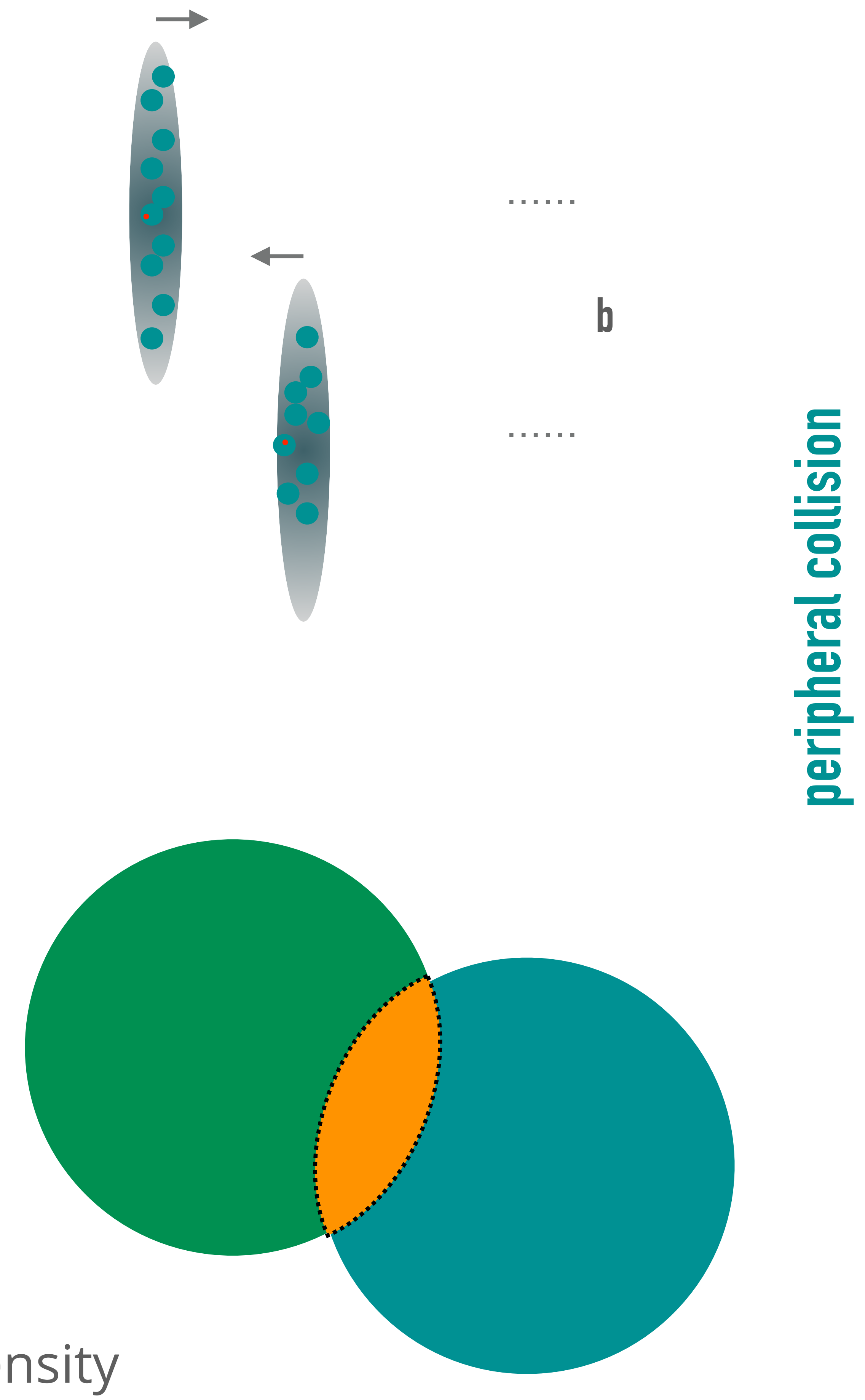
- need to how likely it is to find (anti-)quarks and gluons of given energy fraction [n(uclear)PDFs]
  - can be constrained in electron-nucleus EIC/LHeC/FCC-eA
  - also [to a lesser extent] in proton-nucleus LHC/RHIC
- geometry of collision [how head-on] is **very** important

Collision geometry

- impact parameter of collision defines initial geometry [size and shape of overlap]



- hotter QGP
- higher energy density
- more particle production

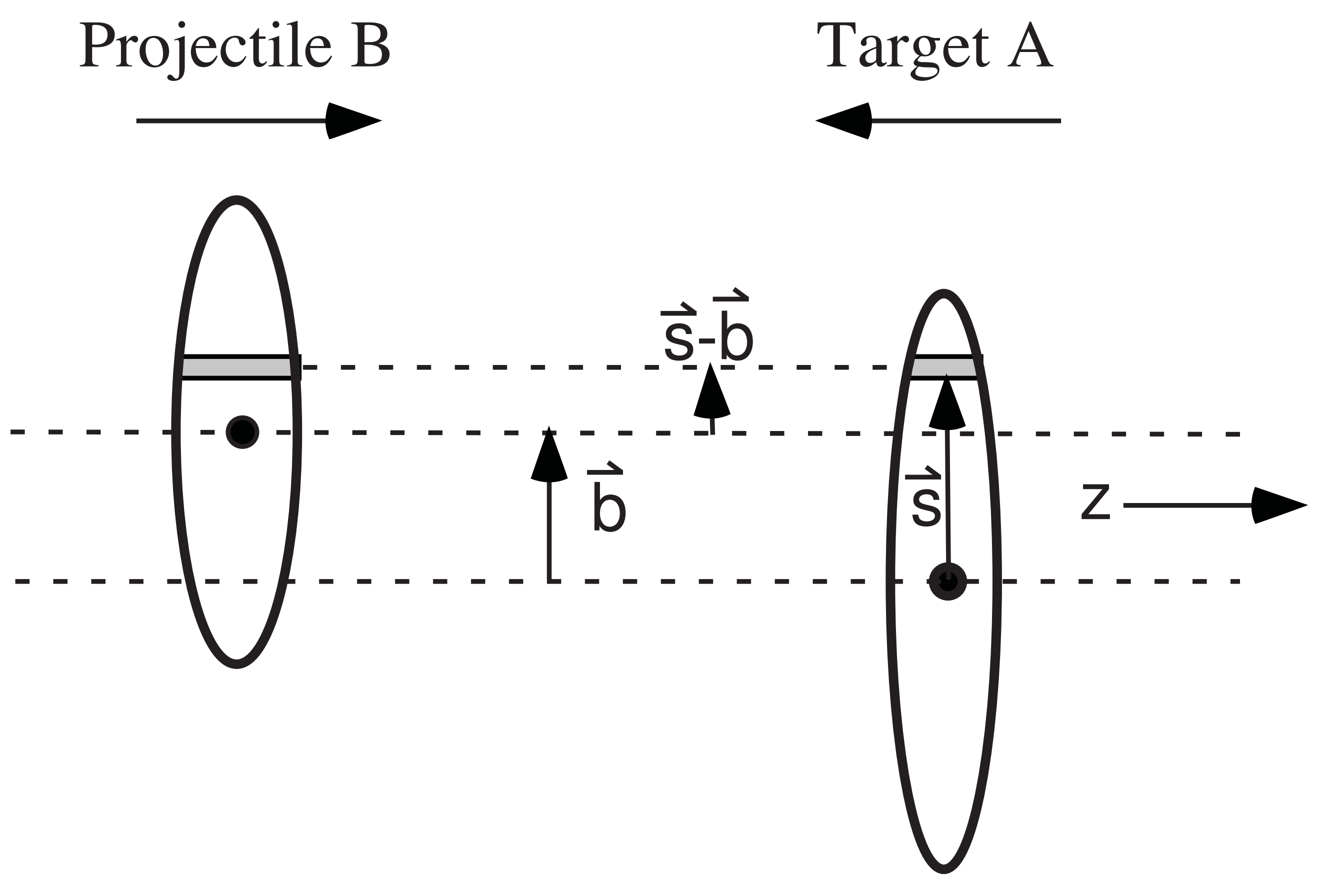


- cooler QGP
- lower energy density
- less particle production

Collision geometry [Glauber model]

Ann.Rev.Nucl.Part.Sci.57:205-243,2007

- impact parameter cannot be measured, it has to be related to observables through modelling
- optical [analytical] Glauber model allows for the computation of the [average] number of participants and collisions for a given impact parameter



* nuclear density [e.g Woods-Saxon potential]

$$\rho_A(r) = \frac{\rho_0}{1 + e^{\frac{r-R}{a}}}$$

ρ_0 :: density at the centre
R :: nuclear radius
a :: skin depth

* nucleon-nucleon inelastic cross-section

$$\sigma_{\text{inel}}^{NN}(\sqrt{s})$$

* integrate over beam direction [nuclei are squeezed by Lorentz boost]

$$T_A(\mathbf{s}) = \int_{-\infty}^{+\infty} dz\, \rho_A\left(\sqrt{\mathbf{s}^2 + z^2}\right)$$

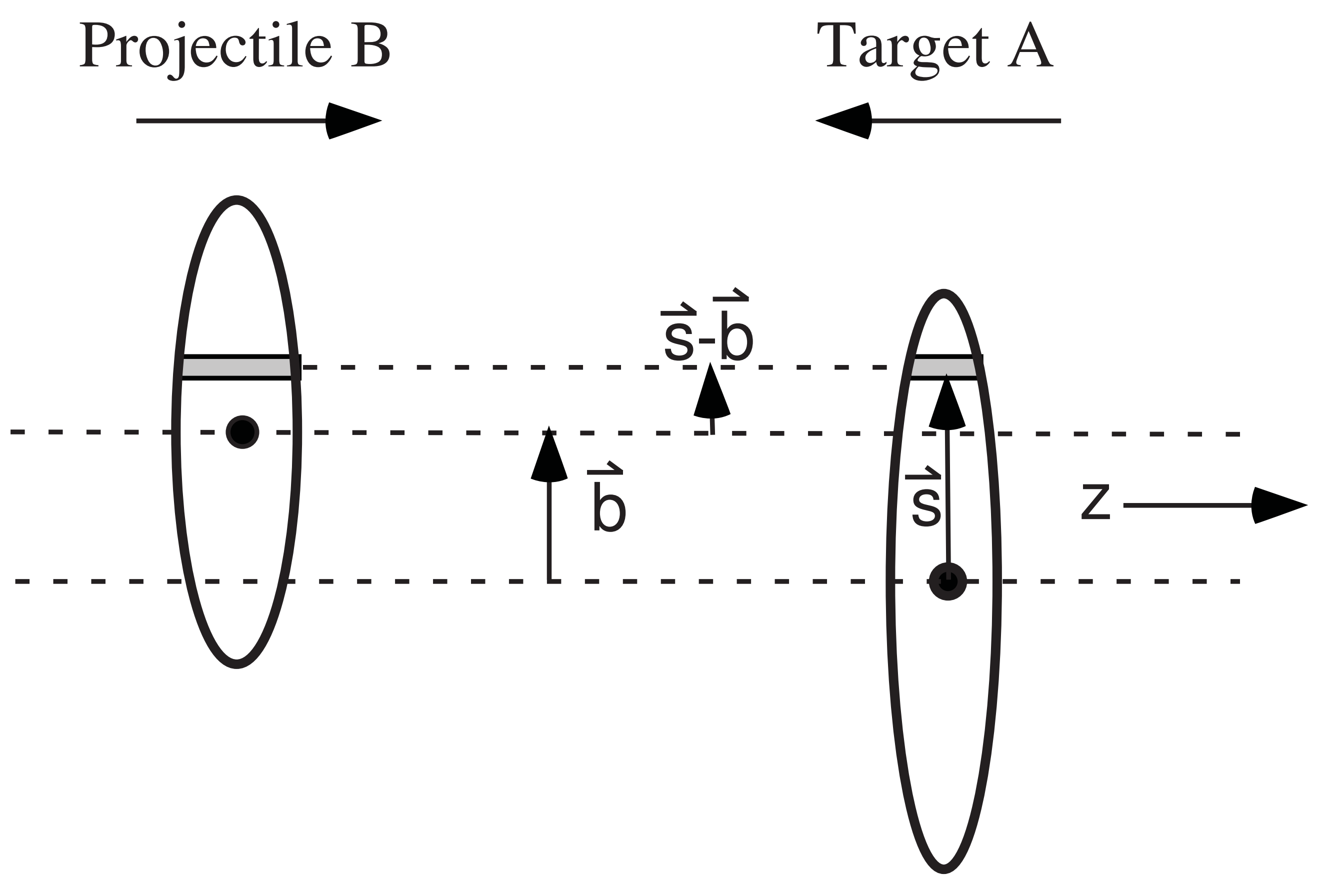
*overlap the two nuclei

$$T_{AB}(\mathbf{b}) = \int d^2\mathbf{s}\, T_A(\mathbf{s})\, T_B(\mathbf{s} - \mathbf{b})$$

Collision geometry [Glauber model]

Ann.Rev.Nucl.Part.Sci.57:205-243,2007

- impact parameter cannot be measured, it has to be related to observables through modelling
- optical [analytical] Glauber model allows for the computation of the [average] number of participants and collisions for a given impact parameter



*nuclear overlap

$$T_{AB}(\mathbf{b}) = \int d^2\mathbf{s}\, T_A(\mathbf{s})\, T_B(\mathbf{s}-\mathbf{b})$$

*probability for n interactions

$$P(n,\mathbf{b}) = \binom{AB}{n} \left[T_{AB}(\mathbf{b})\,\sigma_{\text{inel}}^{NN}\right]^n \left[1 - \left[T_{AB}(\mathbf{b})\,\sigma_{\text{inel}}^{NN}\right]\right]^{AB-n}$$

*number of binary nucleon-nucleon collisions

$$N_{\text{coll}}(\mathbf{b}) = \sum_{n=1}^{AB} n\,P(n,\mathbf{b}) = AB\,T_{AB}(\mathbf{b})\,\sigma_{\text{inel}}^{NN}$$

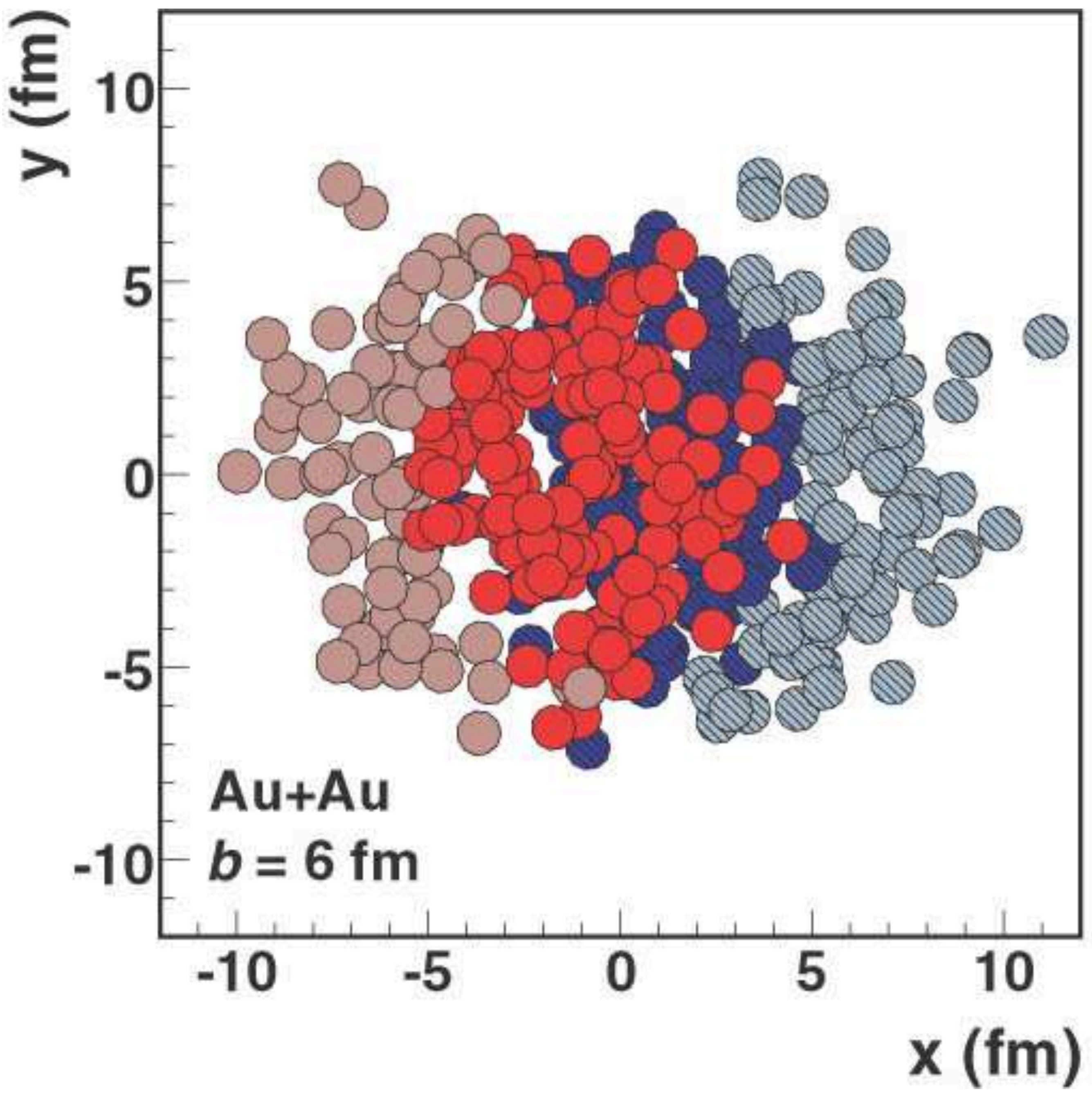
*number of participant nucleons

$$N_{\text{part}}(\mathbf{b}) = A\int d^2\mathbf{s}\, T_A(\mathbf{s})\left\{1 - \left[1 - T_B(\mathbf{s}-\mathbf{b})\,\sigma_{\text{inel}}^{NN}\right]^B\right\} + B\int d^2\mathbf{s}\, T_B(\mathbf{s}-\mathbf{b})\left\{1 - \left[1 - T_A(\mathbf{s})\,\sigma_{\text{inel}}^{NN}\right]^A\right\}$$

COLLISION GEOMETRY [GLAUBER MC]

https://tglaubermc.hepforge.org/

- to account for fluctuations, a 'Glauber MC' is used



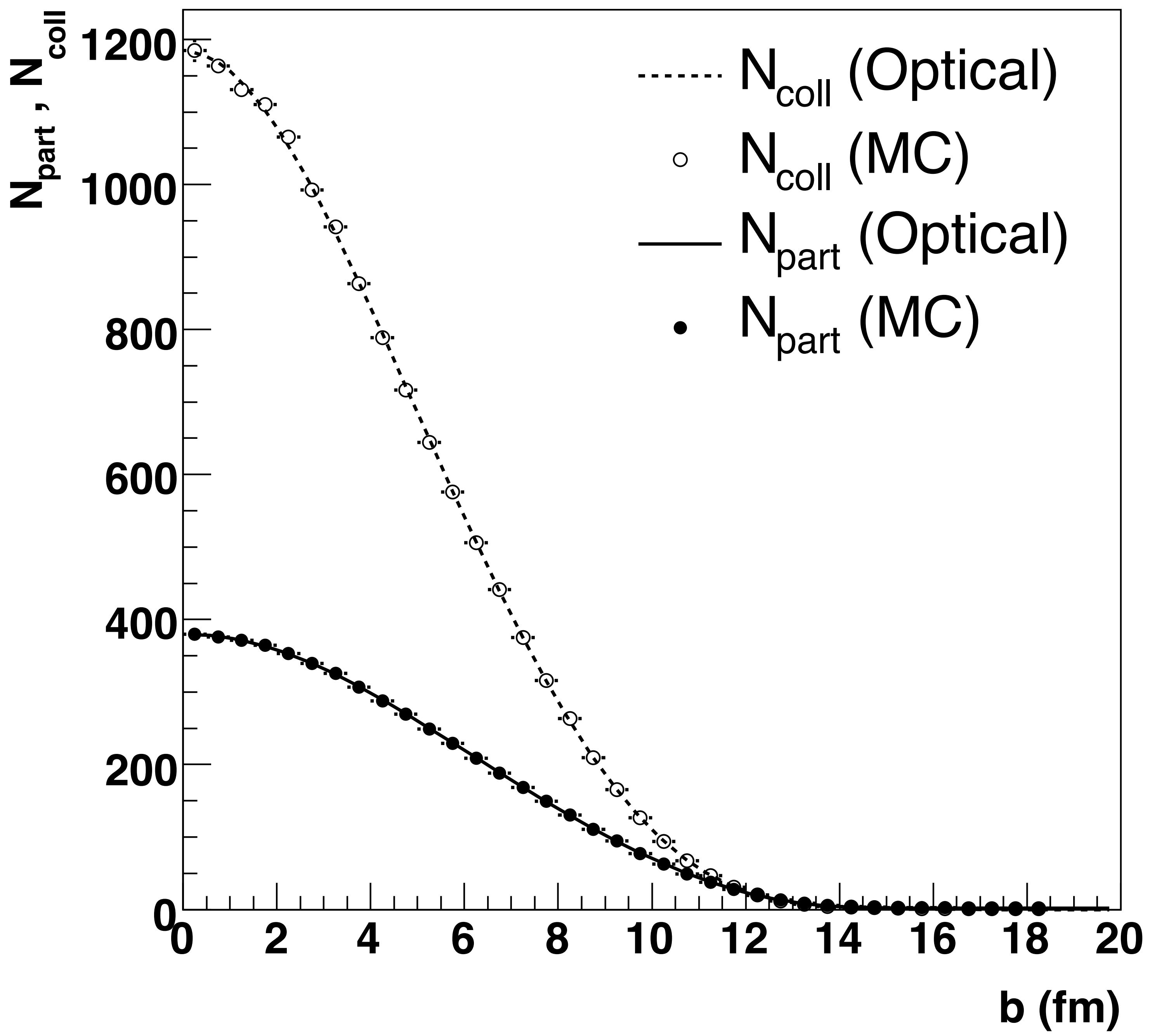
+ take nucleon-nucleon cross-section from pp measurents
+ distribute nucleons in nuclei by sampling Wood-Saxons distribution

$$\rho(r) = \rho_0 \frac{1}{1+\exp\left(\frac{r-R}{a}\right)}$$

Nuclear radius R

Skin depth a

Density in the center



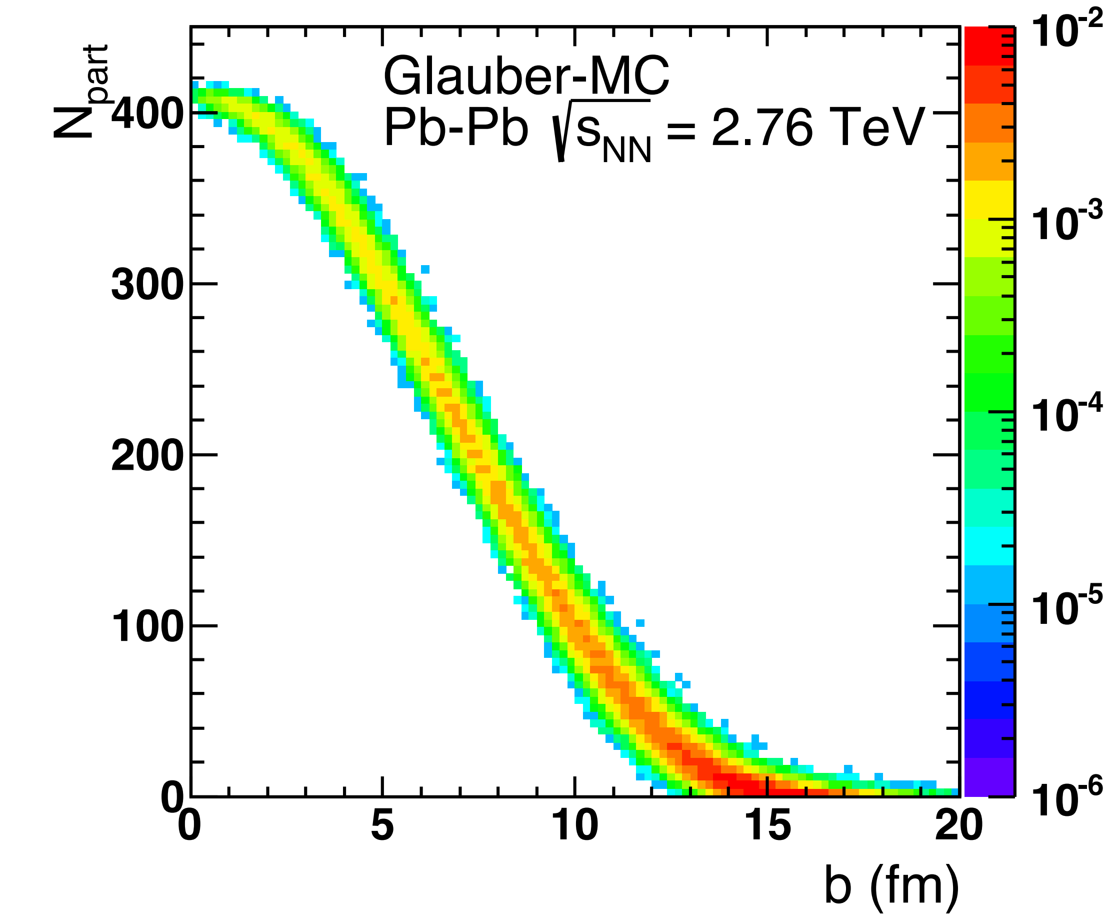
✓ N_{part} ~ number of nucleons

✓ N_{coll} ~ (number of nucleons) ^ (4/3)

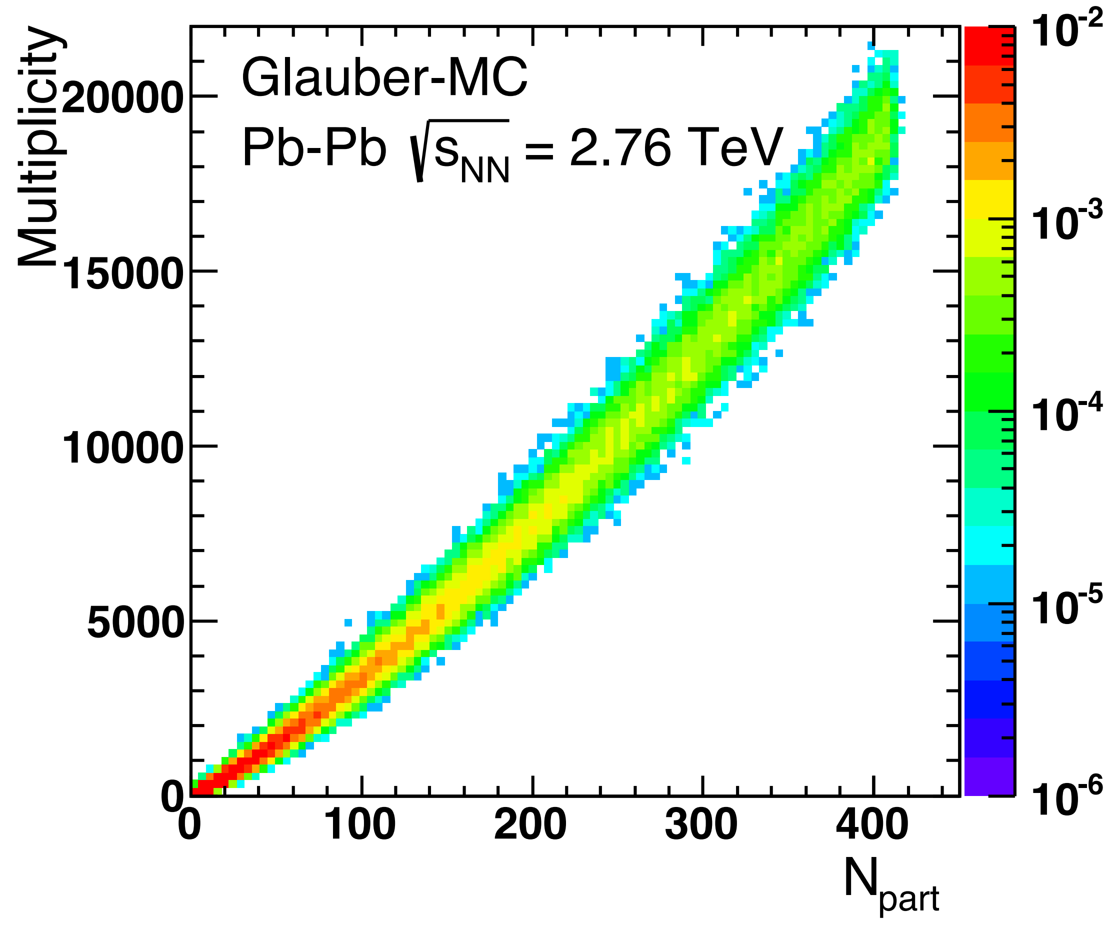
✓ soft [low p_t] observables ~ N_{part}

✓ hard [high p_t] observables ~ N_{coll}

Collision geometry [measurement]



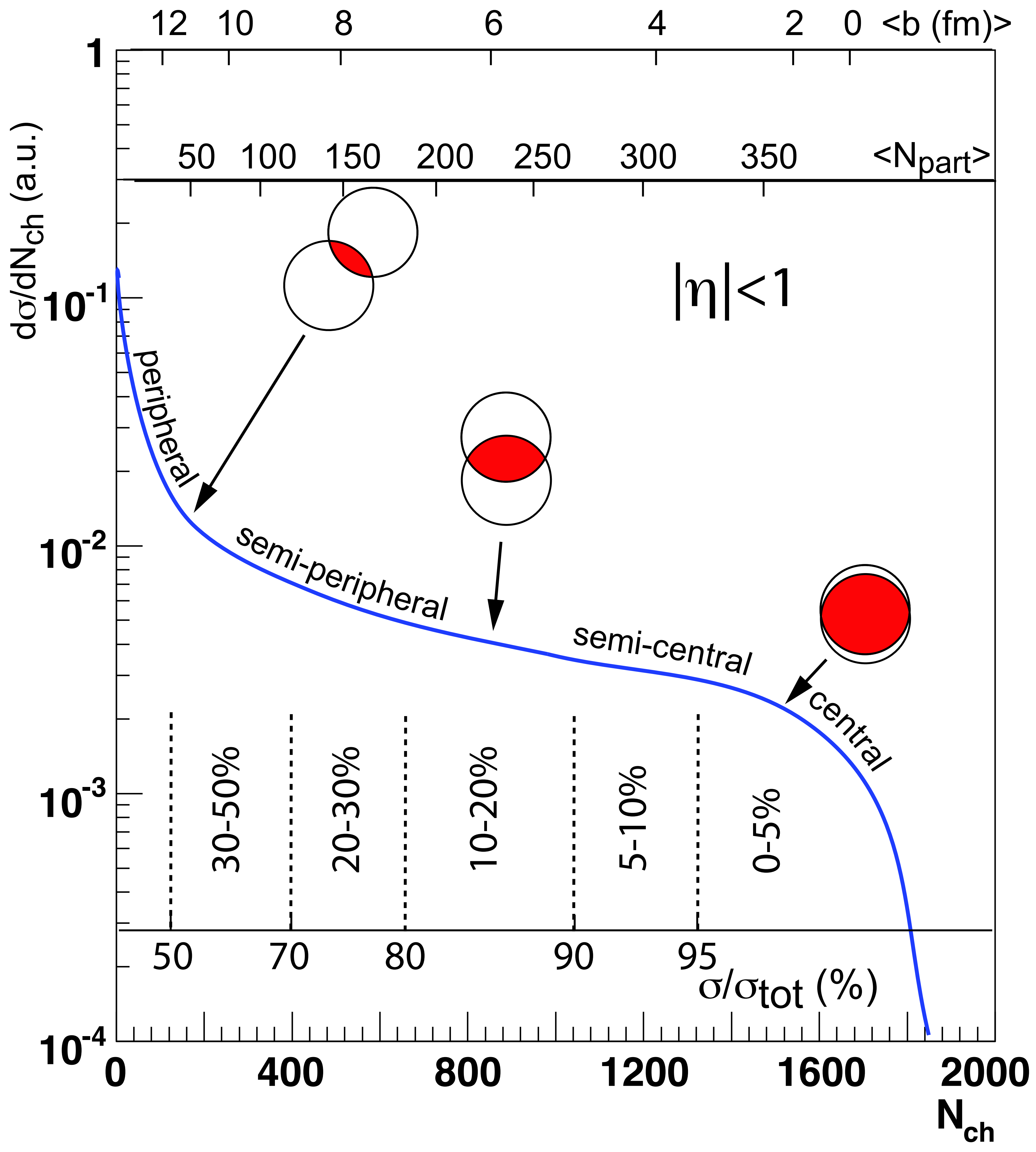
N_{part} [also N_{coll}] tightly correlated with impact parameter



activity [multiplicity or calorimetric energy] computed from model[s] for particle production tightly correlated with N_{part}

:: centrality can be inferred from activity or, alternatively, from spectators [not so simple in proton-nucleus where large fluctuations fuzz the correlations]

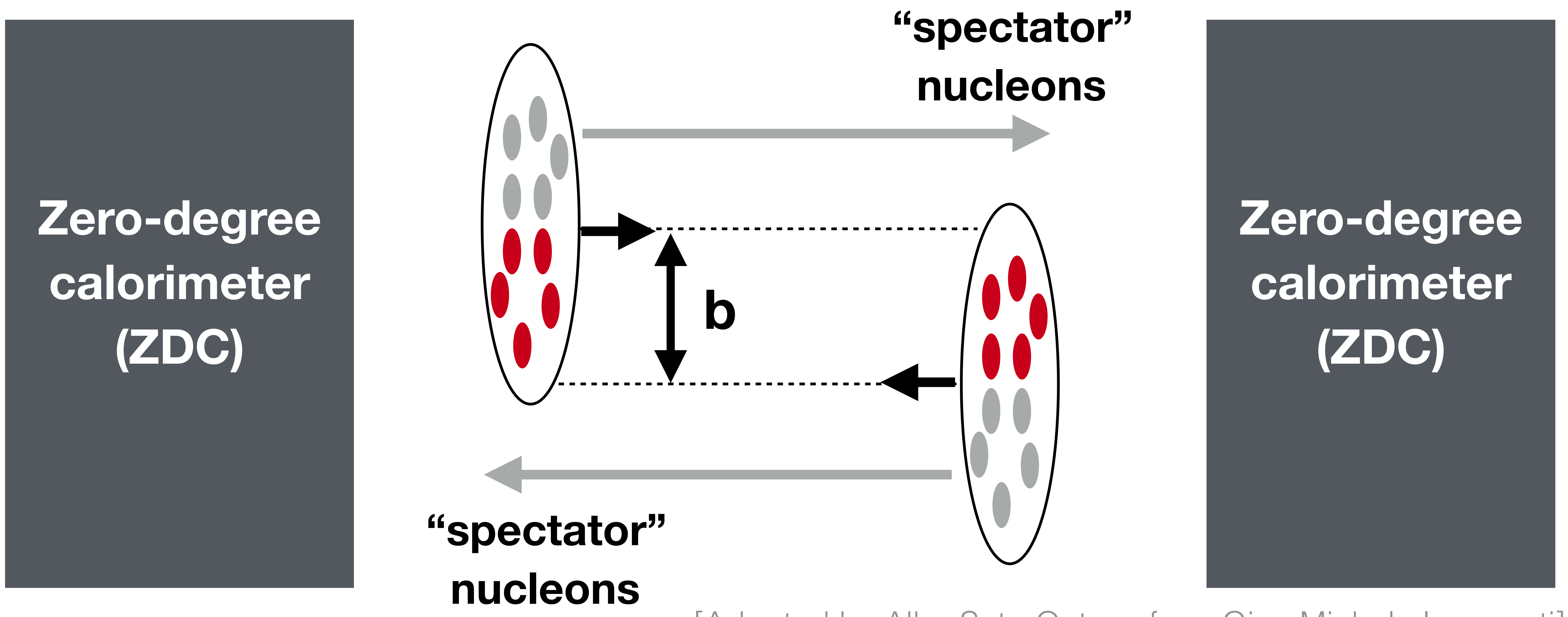
Collision geometry [measurement]



- Glauber model determines $N_{\text{coll}}(\mathbf{b})$
- further modelling for particle production relates N_{ch} to N_{coll} and thus to $\mathbf{b}$
- centrality is then usually defined as percentile ranges of minimum-bias cross section

Collision geometry [measurement]

- alternatively, measure directly energy deposited by spectators in ZDCs

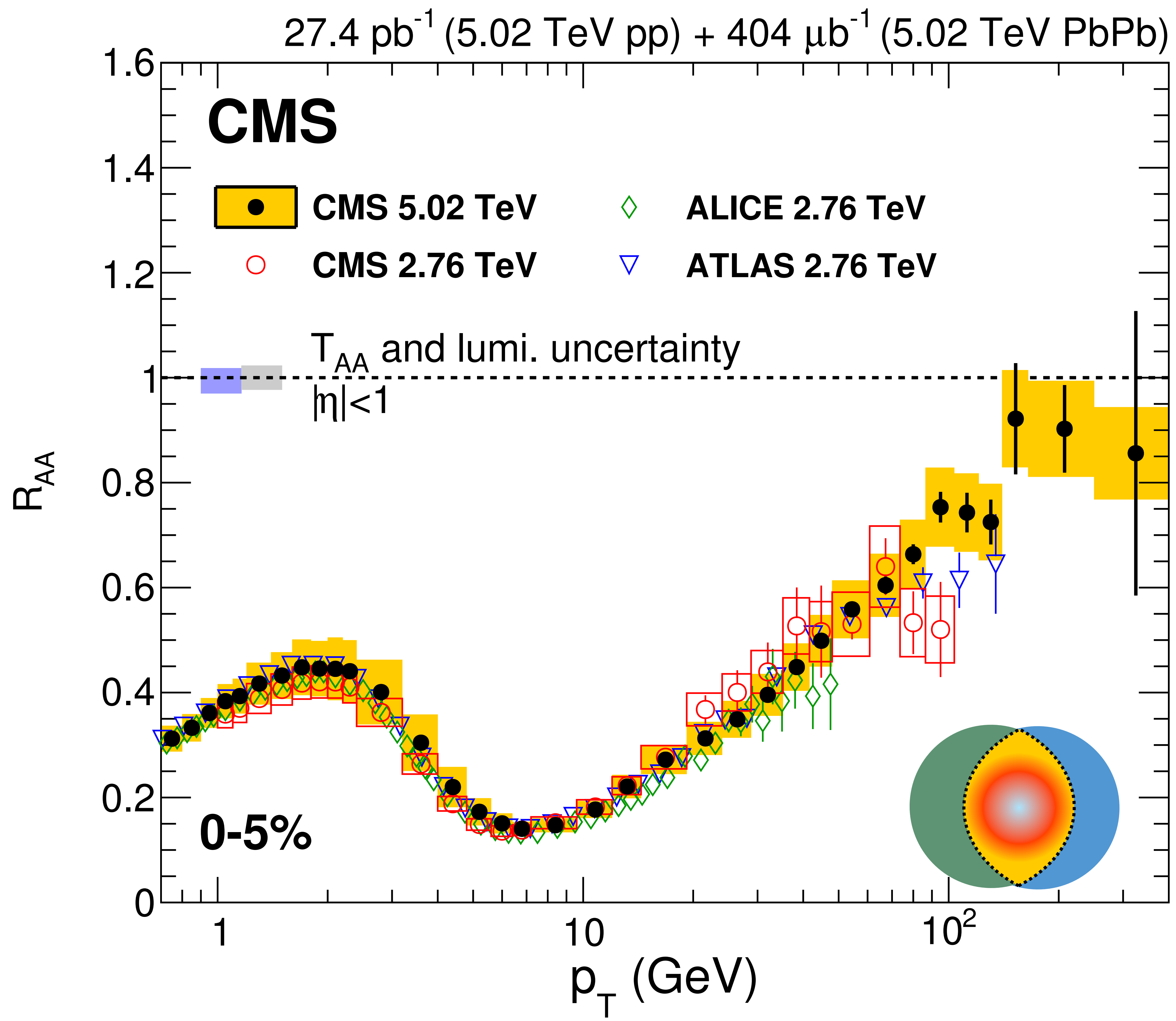


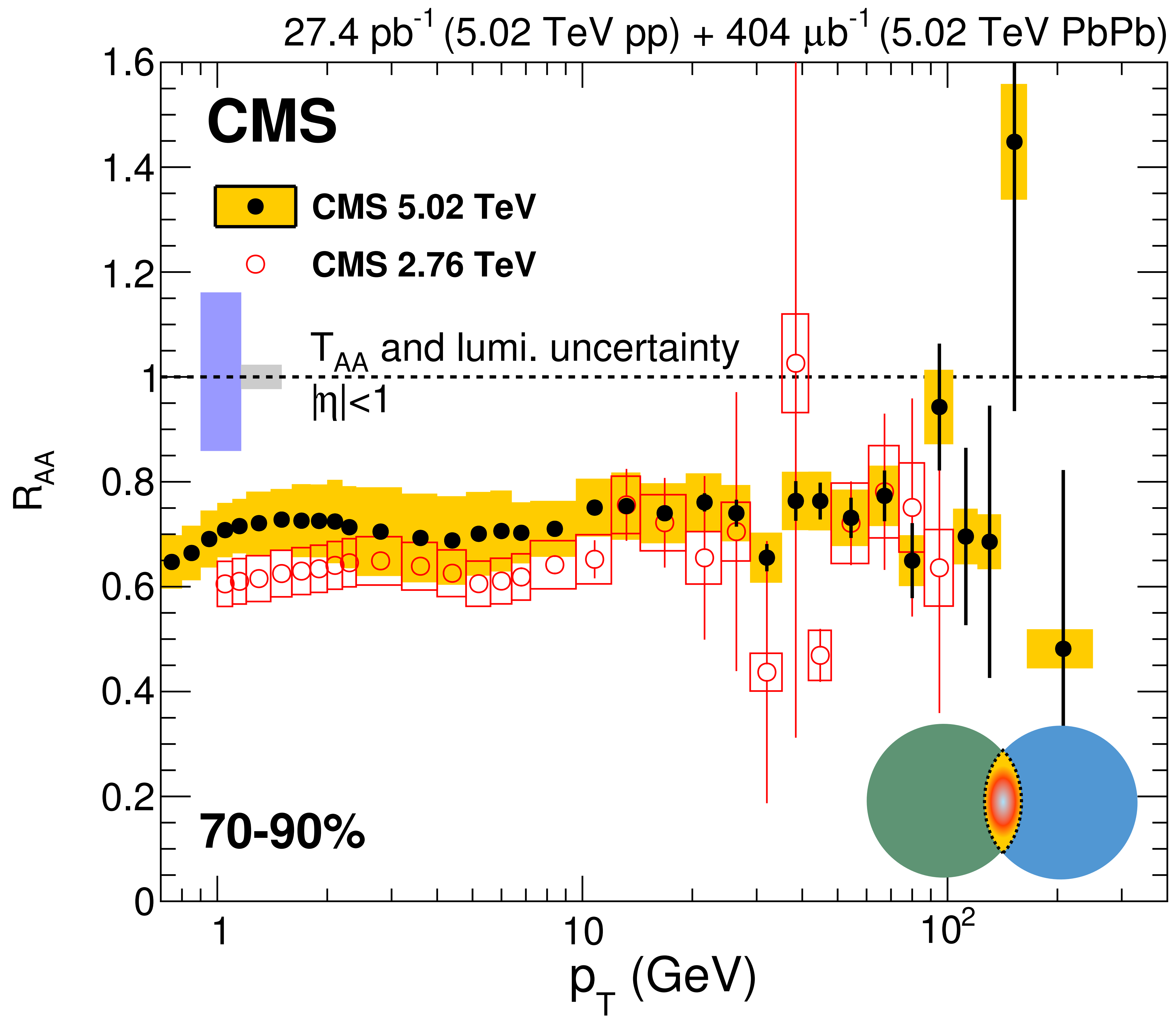
[Adapted by Alba Soto-Ontoso from Gian Michele Innocenti]

:: Monotonic relation between E^{ZDC} and impact parameter b breaks down in peripheral collisions

Centrality dependence of observables

- high-p_T particle suppression [wrt to pp] smaller for peripheral collisions [smaller and cooler QGP]
  - $R_{AA} = 1$ if PbPb is just incoherent superposition of pp collisions

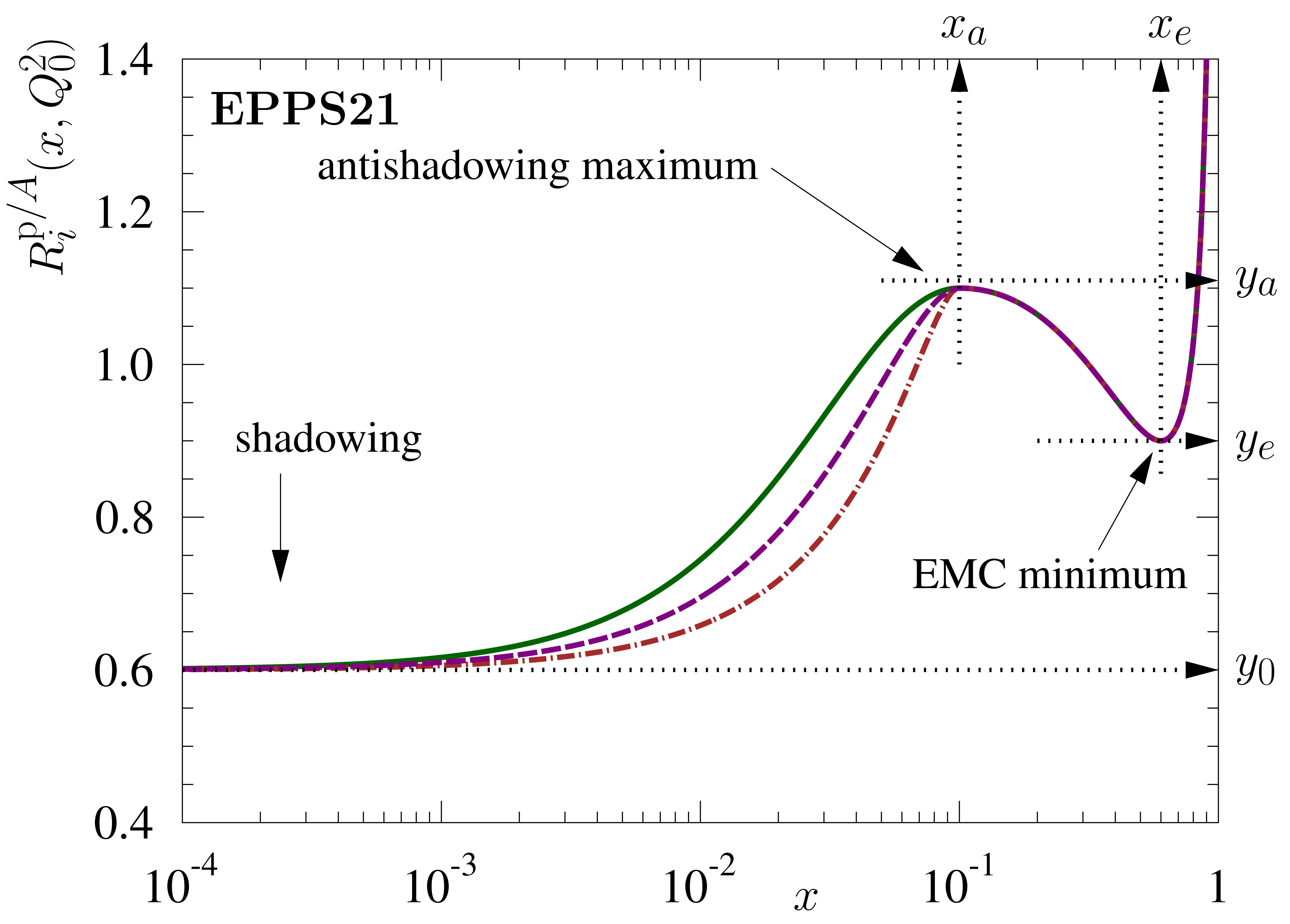




NUCLEAR PARTON DISTRIBUTION FUNCTIONS [nPDF]

Eur.Phys.J.C 82 (2022) 5, 413

- nuclei are not a simple superposition of nucleons
  - parton distributions in a bound nucleon are different than those of a free proton/neutron



*PDF of a bound proton [neutron obtained by isospin symmetry]

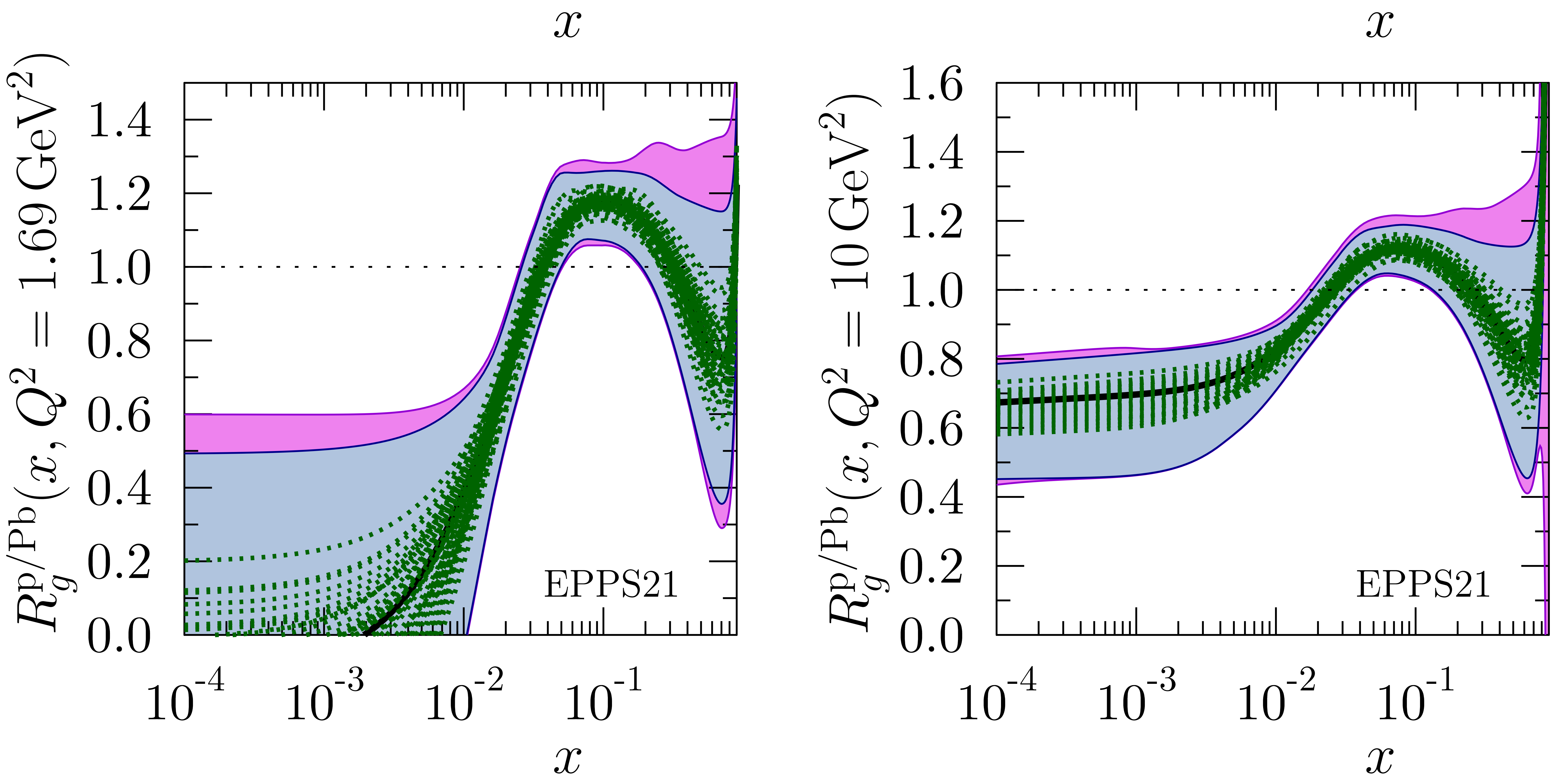
$$f_i^{p/A}(x, Q^2) = R_i^{p/A}(x, Q^2) f_i^{p}(x, Q^2)$$

  - several independent sets available: nCTEQ, nDS/DSSZ, nTuJu, EKS/EPS/EPPS, HKM/HKN, KA/KSASG, nNNPDF

NUCLEAR PARTON DISTRIBUTION FUNCTIONS [nPDF]

Eur.Phys.J.C 82 (2022) 5, 413

- modifications less important at higher momentum scales [more important for soft processes that for hard]

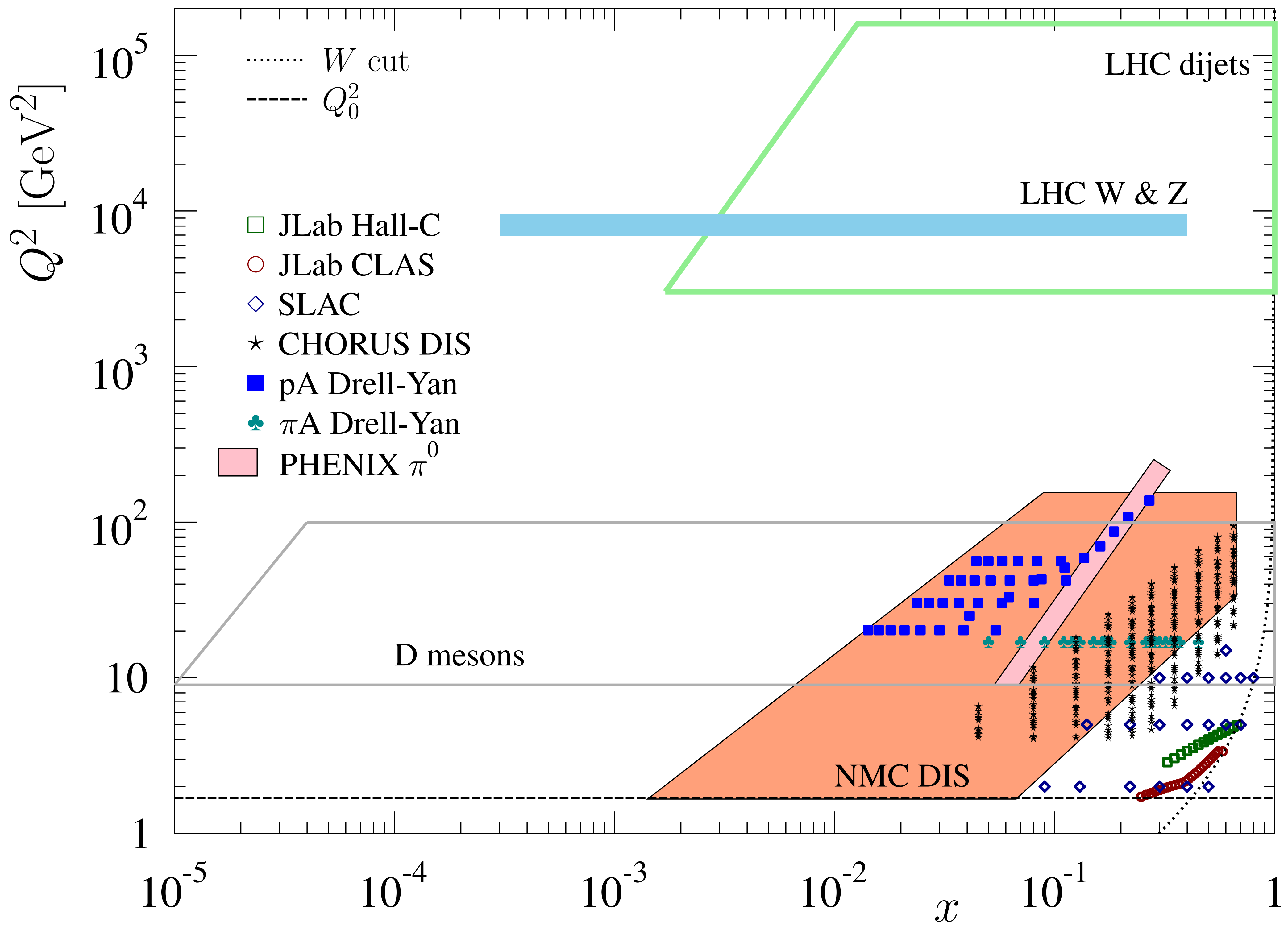


- uncertainties very large at low and high Bjorken-x

NUCLEAR PARTON DISTRIBUTION FUNCTIONS [nPDF]

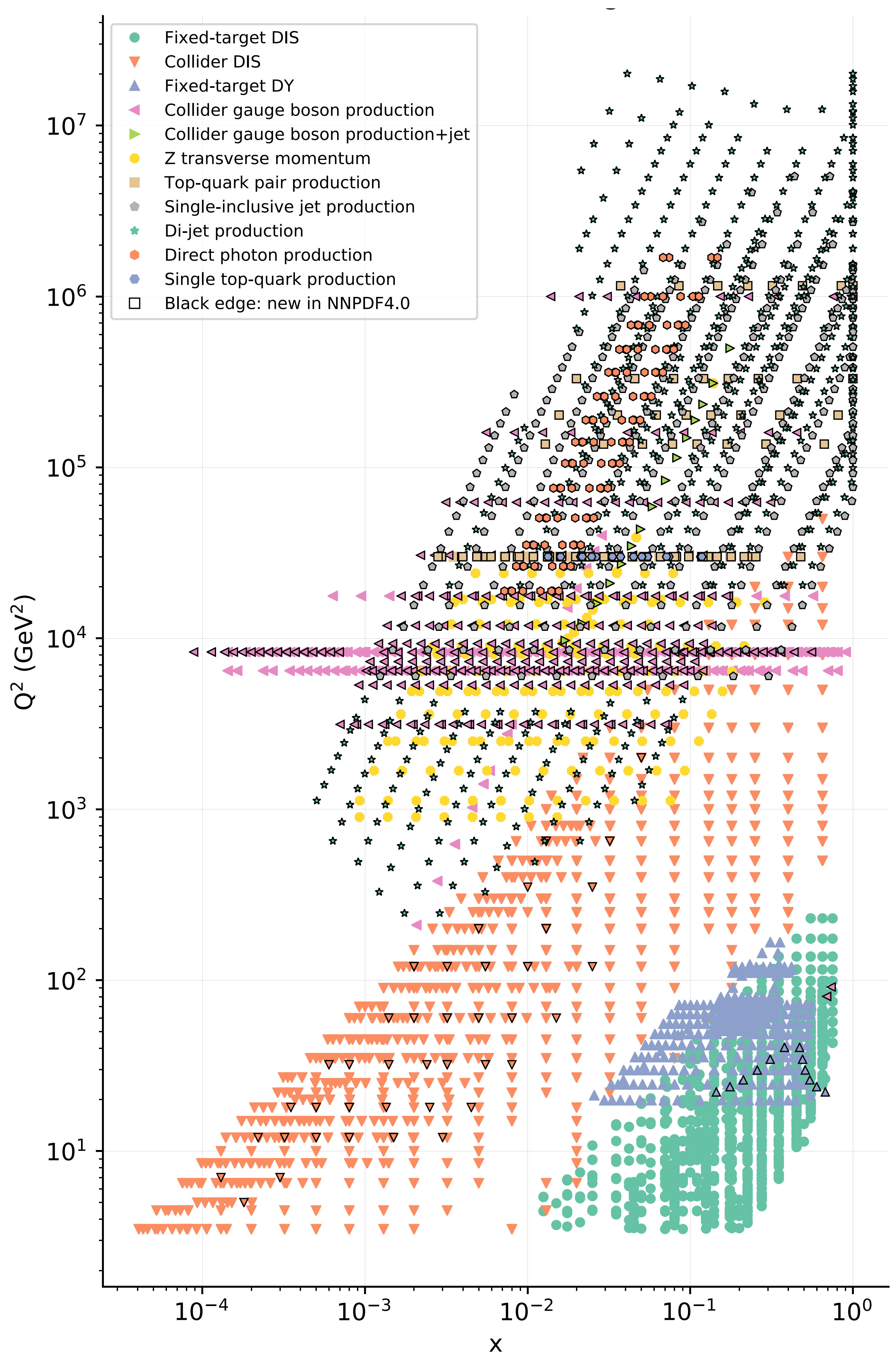
Eur.Phys.J.C 82 (2022) 5, 413

- constraining data is sparse



data used in EPPS21 nPDF fit

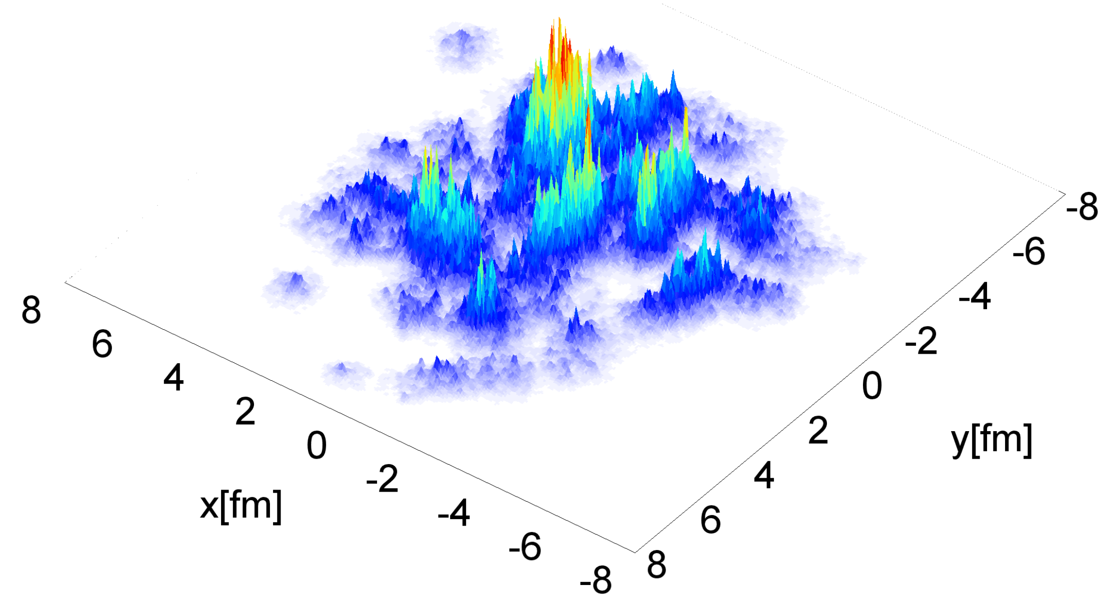
data used in NNPDF4.0 PDF fit



Initial conditions

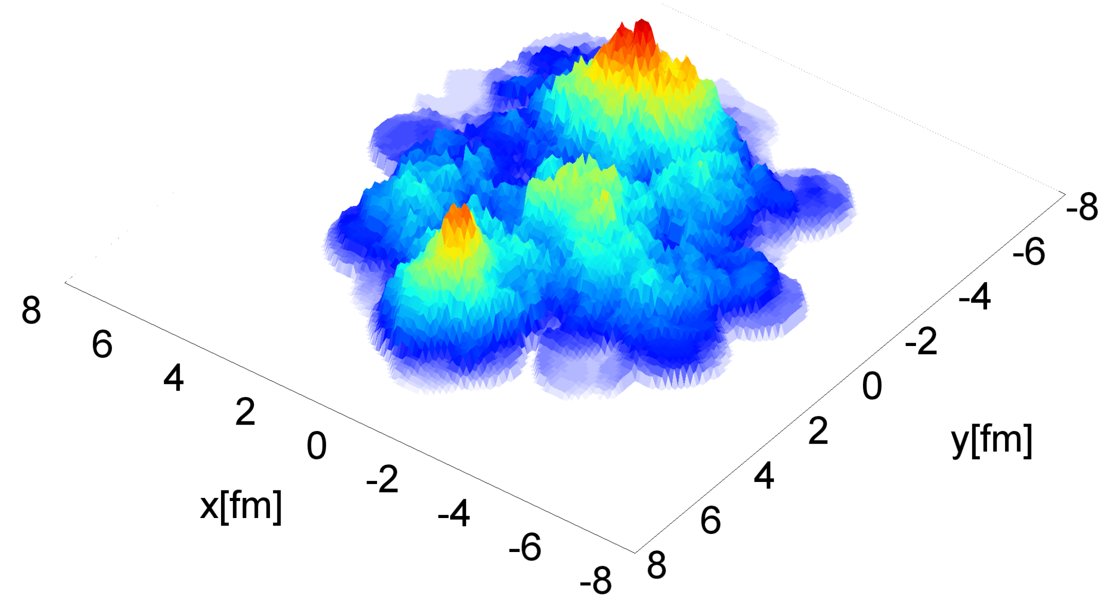
Phys.Rev.Lett. 108 (2012) 252301

- full initial conditions for the collisions require further modelling [distribution of energy density]



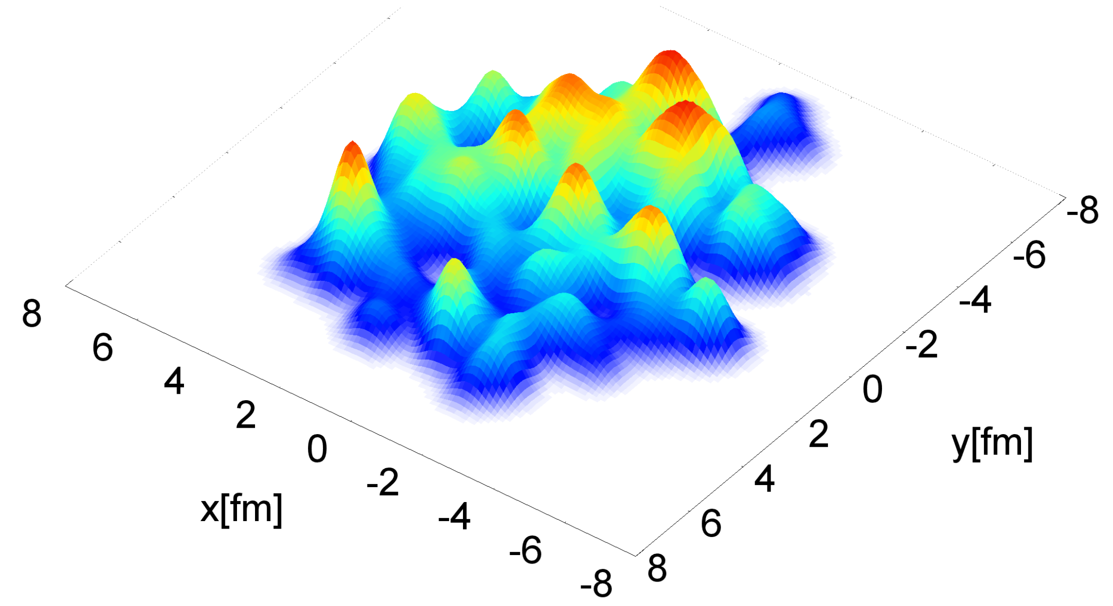
IP-Glasma

- encodes the physics of gluon saturation and long-range correlations [over a scale $1/Q_s$, where the saturation scale Q_s is such that states with momenta below it are fully occupied]
- computed directly from classic YM equations [CGC-Glasma]
- includes event-by-event fluctuations for position of nucleons



MC-KLM

- encodes the physics of gluon saturation [over a scale $1/Q_s$, where the saturation scale Q_s is such that states with momenta below it are fully occupied] through an approximate model
- includes event-by-event fluctuations for position of nucleons



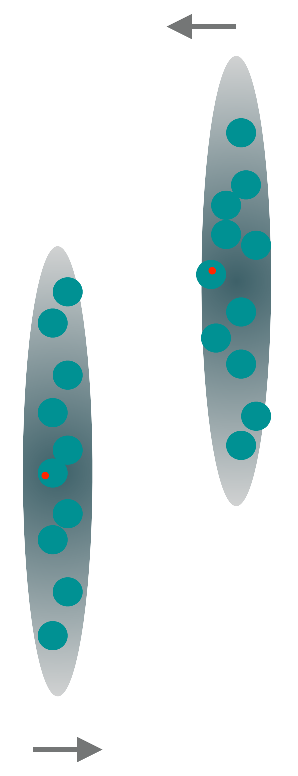
MC-Glauber

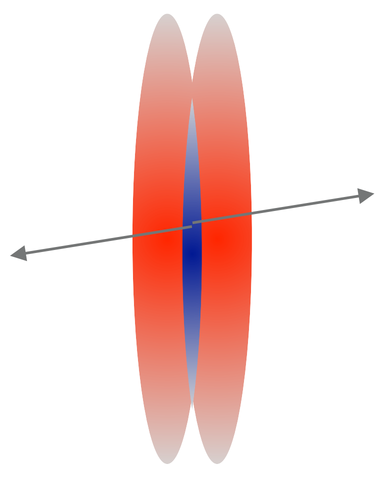
- includes event-by-event fluctuations for position of nucleons
- nucleons with gaussian shape
- calculation of energy density requires additional assumptions and fit to data

TIMELINE OF A HEAVY ION COLLISION

~ 0.1 fm/c
[~10^{-25} s]

time





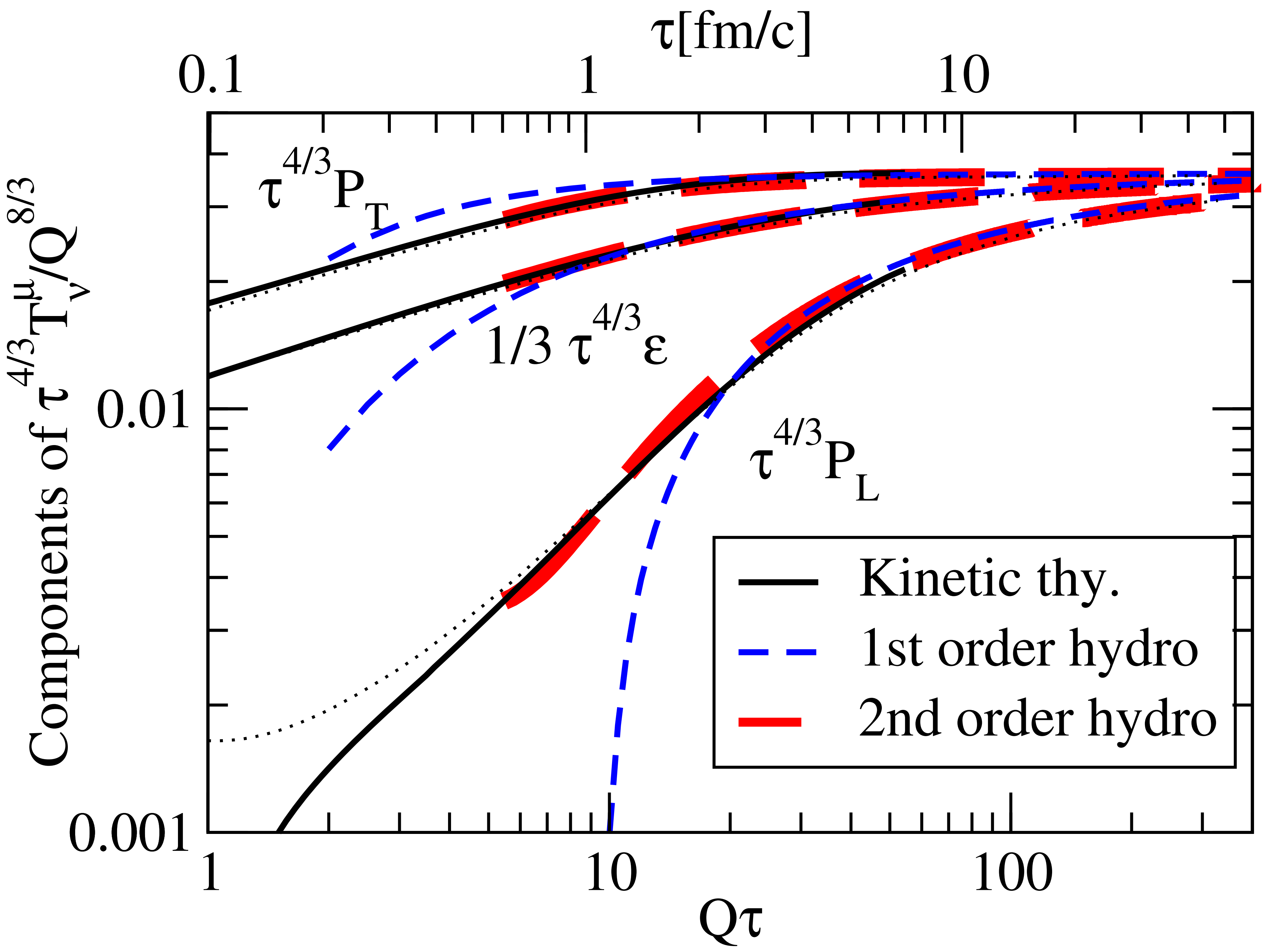
collision [out-of-equilibrium process]

- many soft [small momentum exchange] collisions
  - responsible for bulk low-momentum particle production
  - will quickly hydrodynamize
- very few hard [large momentum exchange] collisons
  - off-spring will slowly relax toward hydrodynamization, yet remain out-of-equilibrium while traversing hot soup

TOWARDS EQUILIBRATION

Phys. Rev. Lett. 115, 182301

- kinetic theory provides a bridge between the very far from equilibrium initial stages and a system that can be described by hydrodynamics [hydrodynamization]



- solve Boltzmann equation

$$-(\partial_t + \mathrm{v}\cdot\nabla_x)f(\mathrm{x},\mathrm{p},t) = \mathcal{C}_{\text{“}1\leftrightarrow 2\text{”}}[f] + \mathcal{C}_{2\leftrightarrow 2}[f]$$

splitting/merging rate in the presence of multiple scattering

elastic scattering rate

- system becomes hydrodynamical on a time scale $\tau \lesssim 1$ fm/c, well before it is isotropic ($P_L \neq P_T$)

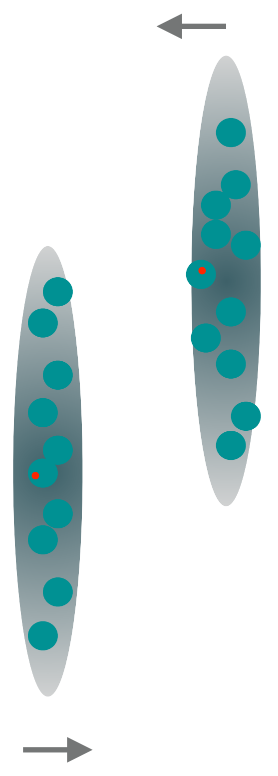
- in theories with a gravity dual (e.g, $\mathcal{N}=4$ SYM), hydrodynamic behaviour is reached very fast ($\tau \sim 1/T$)

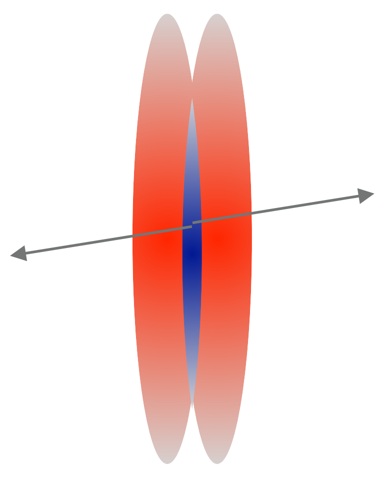
TIMELINE OF A HEAVY ION COLLISION

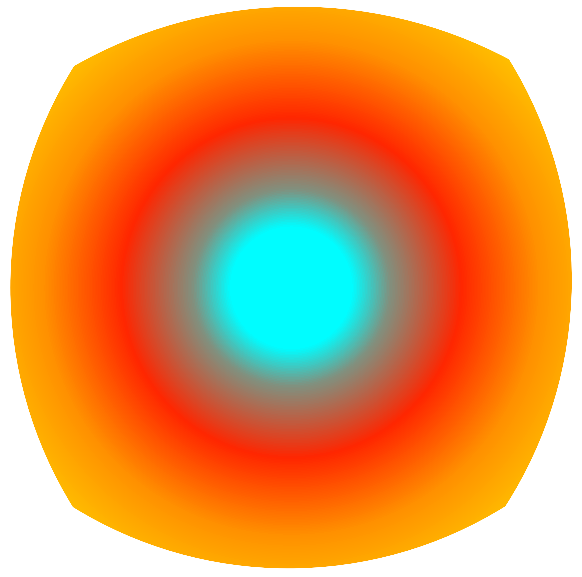
~ 0.1 fm/c [~10^{-25} s]

~1 fm/c [~10^{-24} s]

time







QGP

- hot, dense, and coloured matter
- quarks and gluons are the relevant dof

HYDRODYNAMICS

- effective theory description of long-distance [low momentum], long-time, strongly coupled dynamics in terms of macroscopic quantities
  - behaviour of averaged macroscopic properties of system – applicable to very generic set of theories
  - microscopic details of theory course-grained into
    - equation of state
    - transport coefficients
    - relaxation times
  - valid for distances large compared with mean free path and times long compared to inverse scattering rate, and for sufficiently smooth systems
- incredibly successful in heavy-ion collisions

IDEAL RELATIVISTIC HYDRODYNAMICS

:: energy momentum tensor for fluid in global thermal equilibrium

$$T^{\mu\nu} = \epsilon\, u^\mu u^\nu + p\,(g^{\mu\nu} + u^\mu u^\nu)$$

velocity field   metric

:: thermodynamical equation of state

$$p = p(\epsilon)$$

pressure   energy density

:: ideal fluid → local thermal equilibrium

$$u^\mu = u^\mu(x) \qquad \epsilon = \epsilon(x)$$

:: energy-momentum conservation → hydrodynamical evolution equations

$$\nabla_\mu T^{\mu\nu} = 0 \implies \quad u^\mu \partial_\mu \epsilon + (\epsilon + p)\nabla_\mu u^\mu = 0$$

$$(\epsilon + p) u^\mu \nabla_\mu u^\nu + (g^{\nu\mu} + u^\nu u^\mu)\partial_\mu p = 0$$

VISCOUS RELATIVISTIC HYDRODYNAMICS

:: more general energy momentum tensor

$$T^{\mu\nu} = \epsilon\, u^\mu u^\nu + (p + \pi_{\text{bulk}})(g^{\mu\nu} + u^\mu u^\nu) + \pi^{\mu\nu}$$

bulk viscous pressure

shear stress [transverse and traceless]

deviations from ideal hydro

:: can be organized as a derivative [gradient] expansion

$$\Delta^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu$$

$$\pi_{\text{bulk}} = -\,\zeta \nabla_\mu u^\mu + \ldots,$$

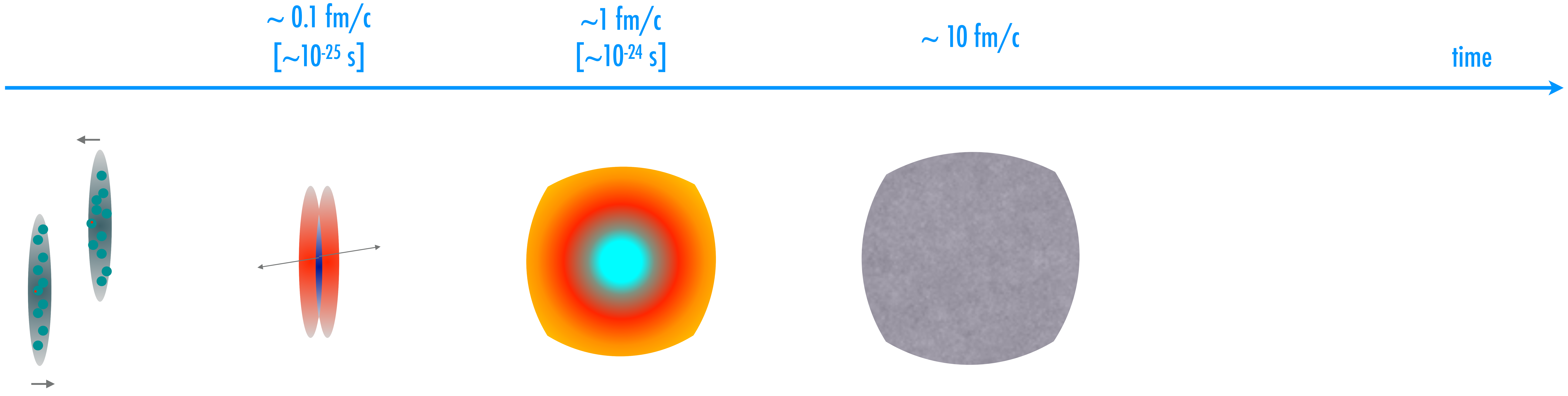
$$\pi^{\mu\nu} = -\,2\eta \left(\tfrac{1}{2}\Delta^{\mu\alpha}\Delta^{\nu\beta} + \tfrac{1}{2}\Delta^{\mu\beta}\Delta^{\nu\alpha} - \tfrac{1}{3}\Delta^{\mu\nu}\Delta^{\alpha\beta} \right) \nabla_\alpha u_\beta + \ldots$$

:: at first order, dependence on bulk viscosity [ζ =ζ(ε)] and shear viscosity [η=η(ε)]

:: at higher orders, further coefficients…

:: increasingly complicated evolution equations [to be solved numerically]

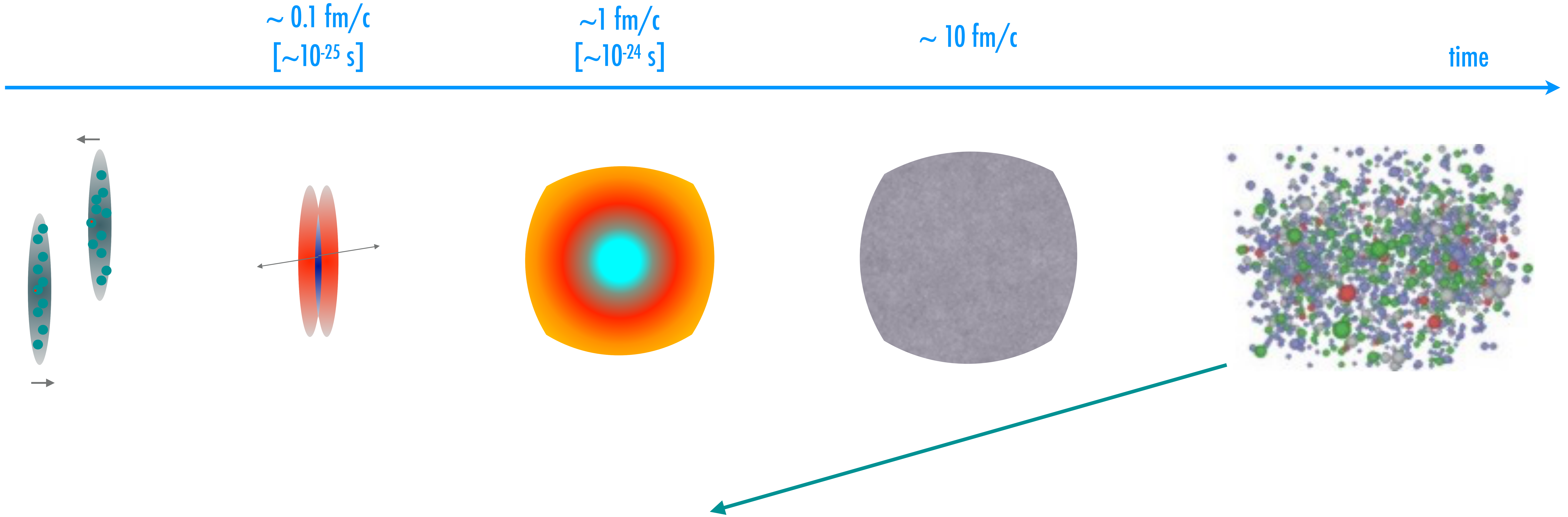
TIMELINE OF A HEAVY ION COLLISION



hadronization

- convert fluid into particles
  - run hydrodynamics until interactions stop
  - particle spectra computed from integral over surface of last scattering [Cooper-Frye prescription]
  - alternatively, compute quark and anti-quark distributions and form hadrons by coalescence
  - several other proposals
- out-of-equilibrium [eg, jets] components to hadronize in the usual way [Lund strings, Colour clusters, …]

TIMELINE OF A HEAVY ION COLLISION



hadrons

- hadron rescattering in hydro
  - need to supplement hydro with hadronic phase
- Boltzmann transport after-burner
  - requires a lot of additional input [cross-sections and ressonances]