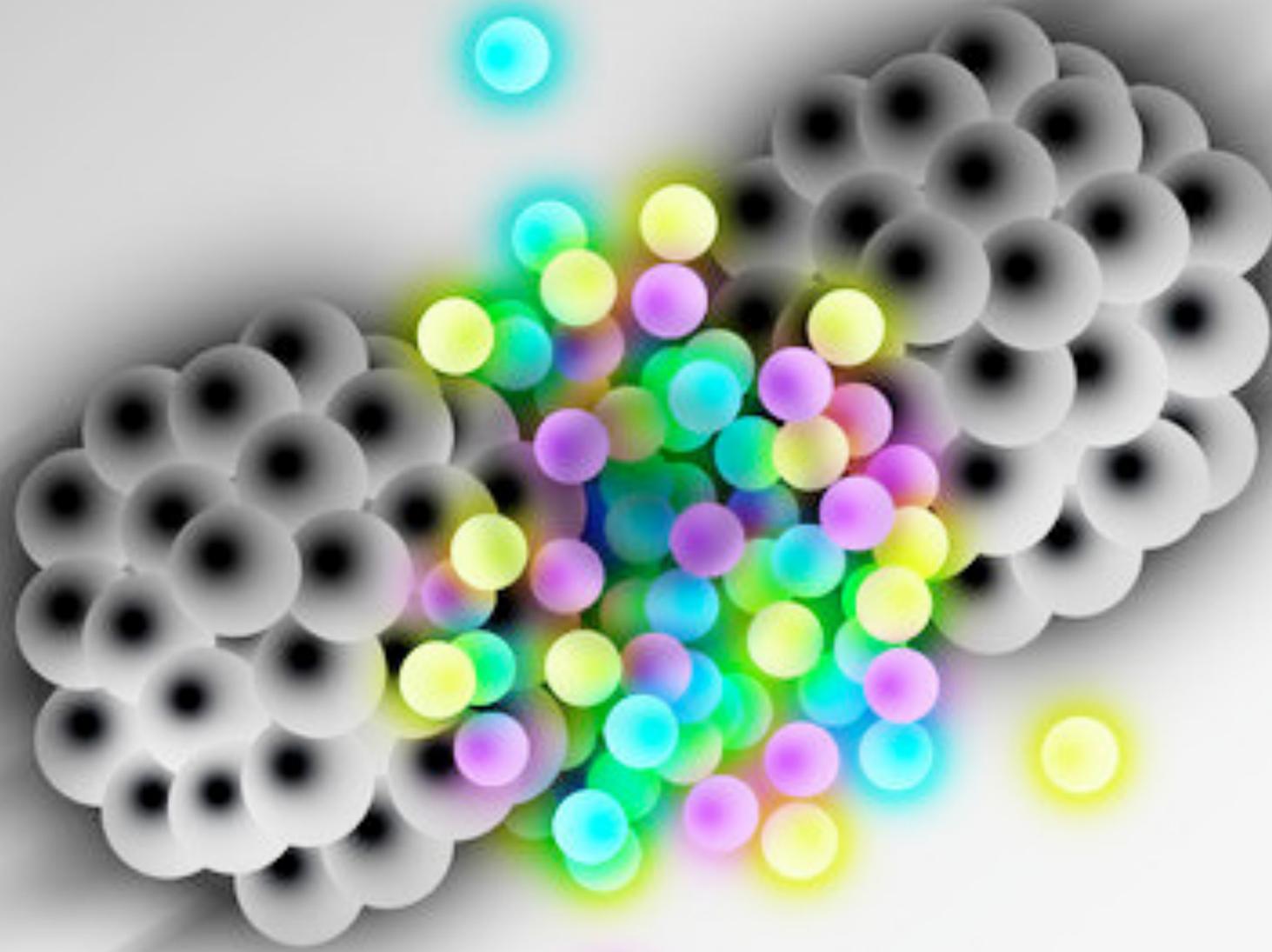


Heavy Ions: theory overview

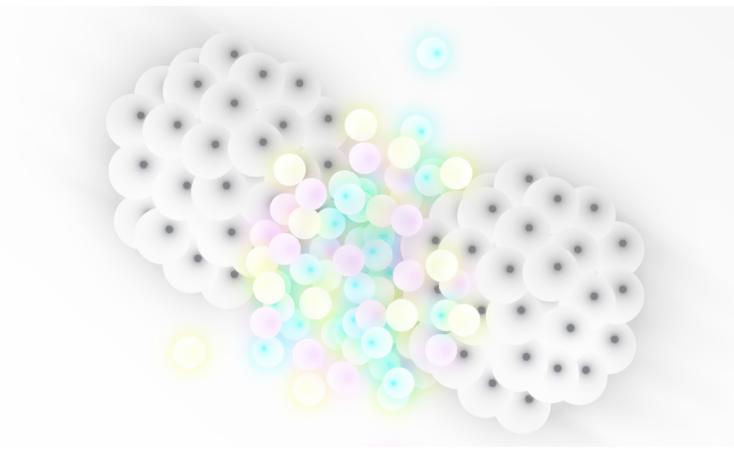


Liliana Apolinário



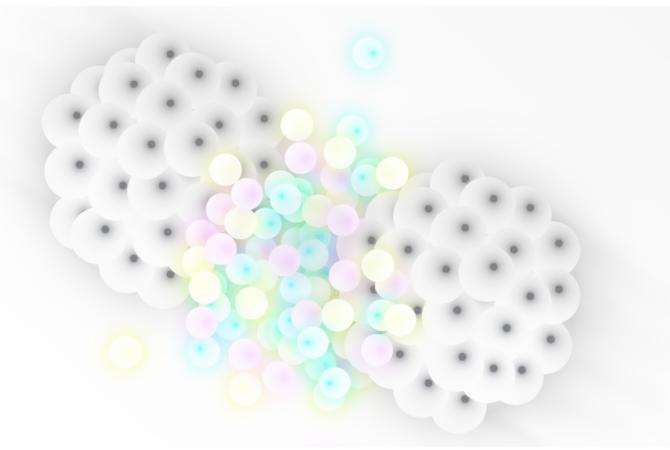
TÉCNICO
LISBOA

Outline



- Part I:
 - Heavy-Ion collisions:
 - What? Why?
 - Quark-Gluon Plasma:
 - What? Why?
 - Hydrodynamics & Flow
 - Initial state
 - Small Systems

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- Part II:
 - Probes of QGP short wave-length behaviour:
 - High-momentum particles
 - Jets & Jet substructure
 - See Gian Michele's lectures for quarkonia and heavy-quarks
 - Quark-Gluon Plasma properties:
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 - Timescale evolution

Outline

Today's lecture:

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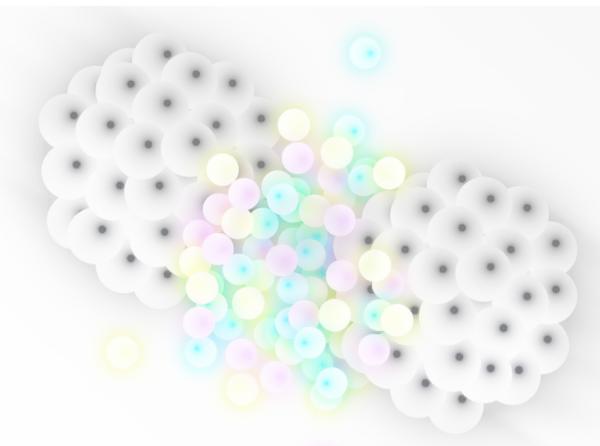
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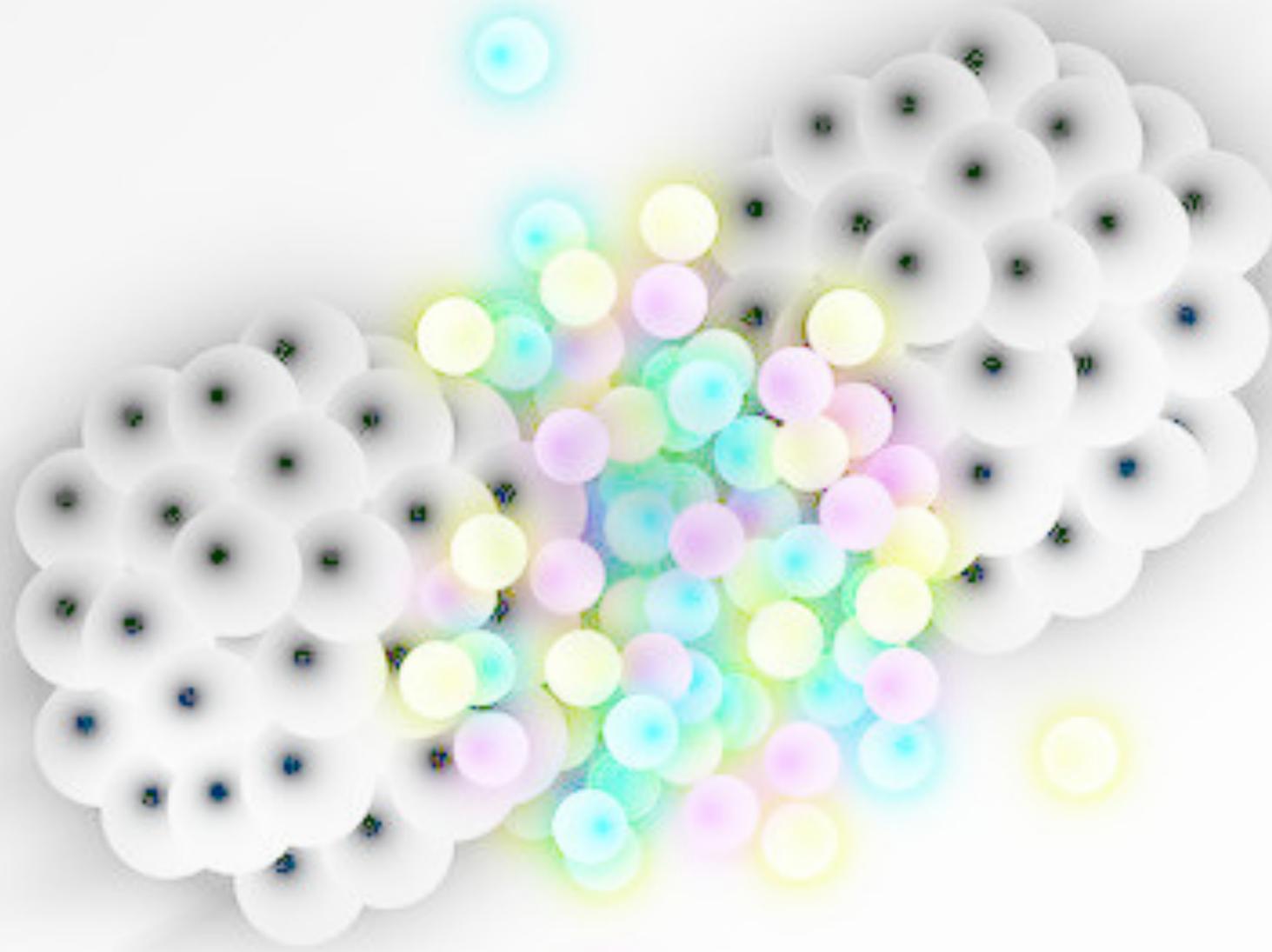
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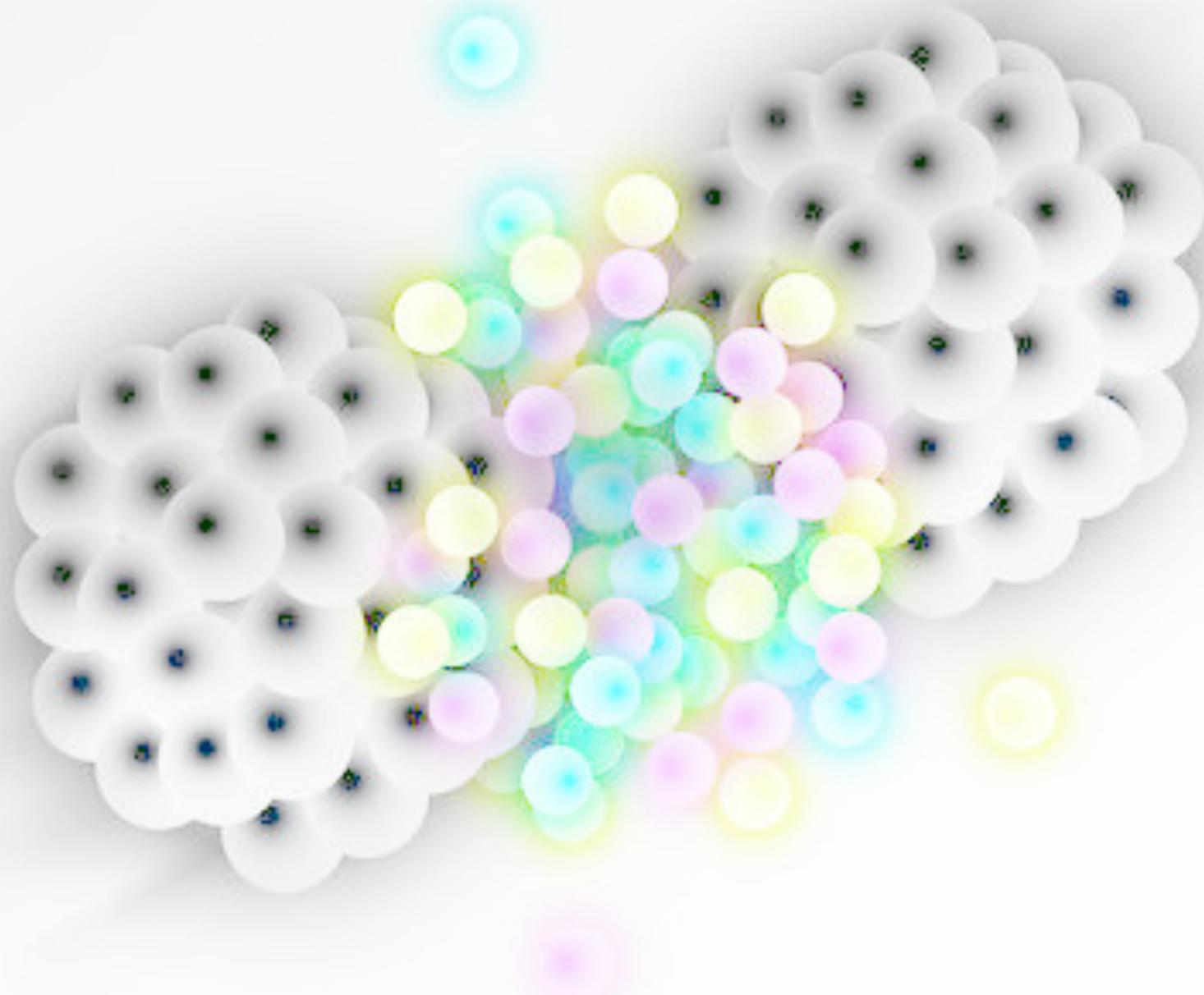


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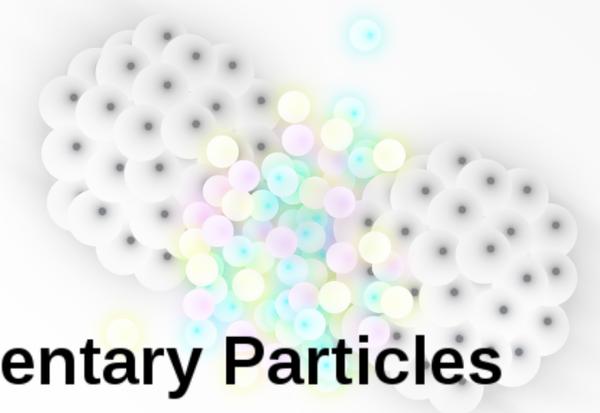
Part I

Introduction

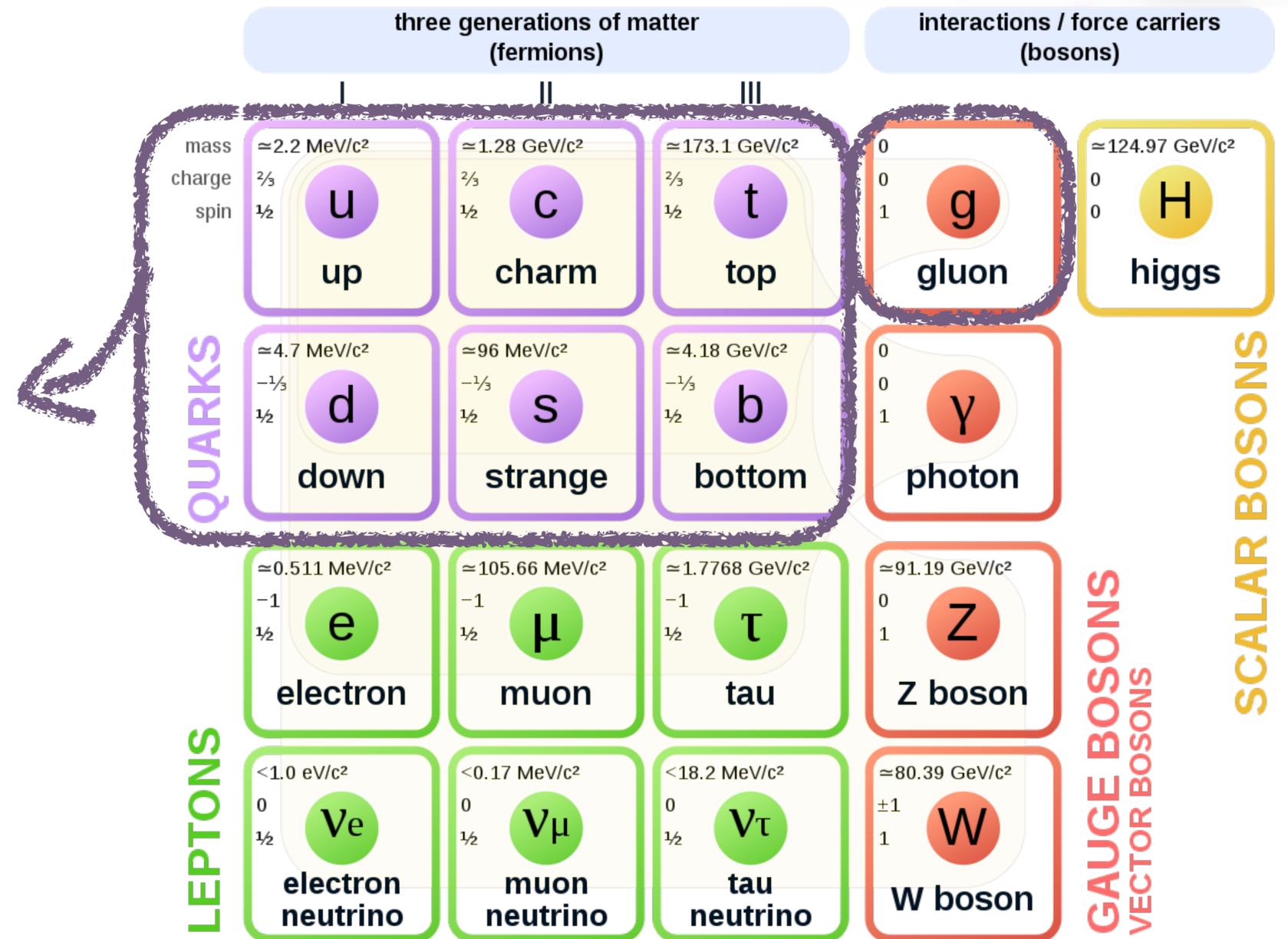


SM & QCD

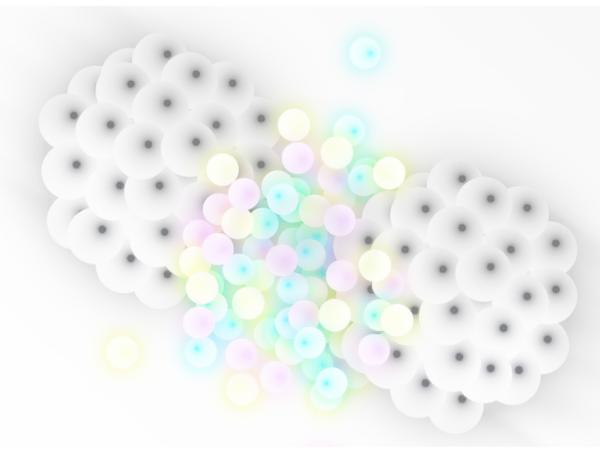
- Standard Model (SM);
 - Strong and Electro-weak interactions
- Color sector of SM:
 - Described by **Quantum Chromodynamics (QCD)**



Standard Model of Elementary Particles



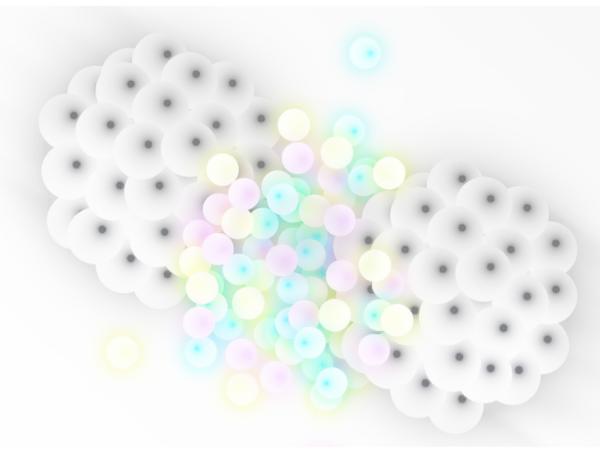
Quantum Chromodynamics (QCD)



- Lagrangian structure fixed by requiring SU(3) gauge invariance:
 - All (anti-)quark flavours exist in 3 (anti-)colours: R(ed), G(reen), B(lue)

$$\psi_a = \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix}$$

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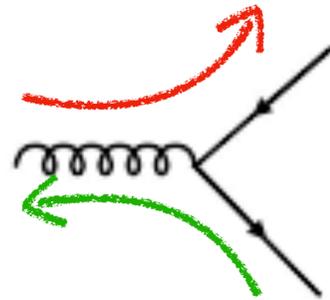
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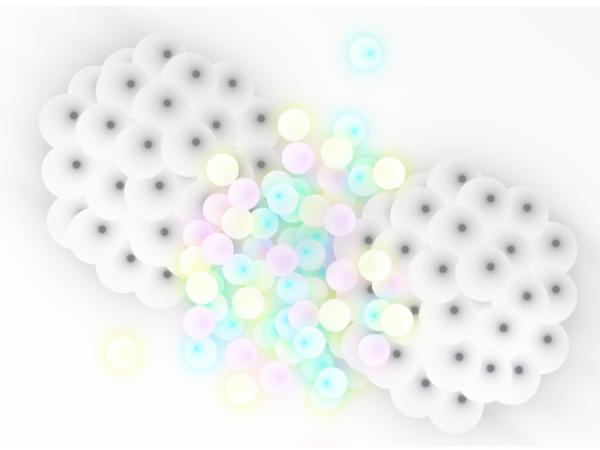
$$\mathcal{L}_{QCD} = \sum_{flavours} (\mathcal{L}_q + \mathcal{L}_g)$$

$$\mathcal{L}_q = \bar{\psi}_a (i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t_{ab}^C A_\mu^C - m) \psi_b$$

Quark propagator + interaction term



Quantum Chromodynamics (QCD)



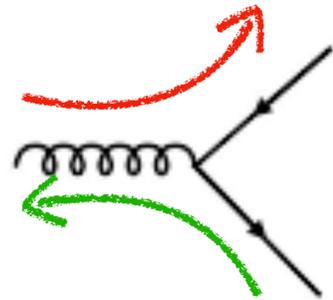
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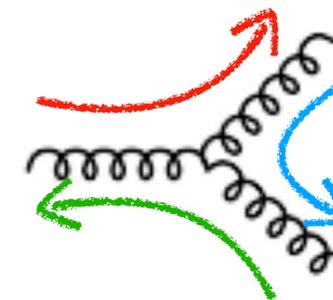
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$$\mathcal{L}_g = -\frac{1}{4} F_A^{\mu\nu} F^{A\mu\nu}$$

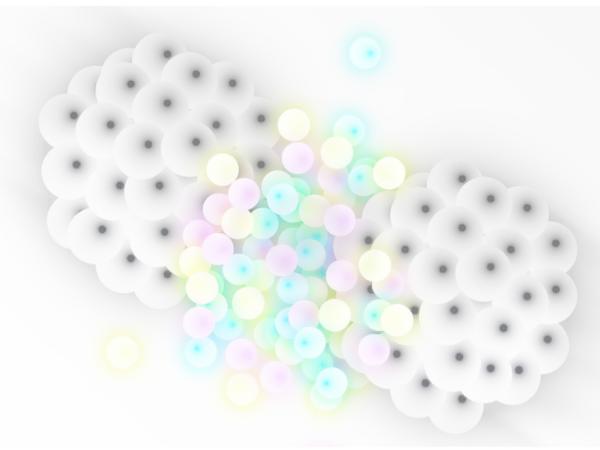
Gluon propagator + gluon self-interaction terms



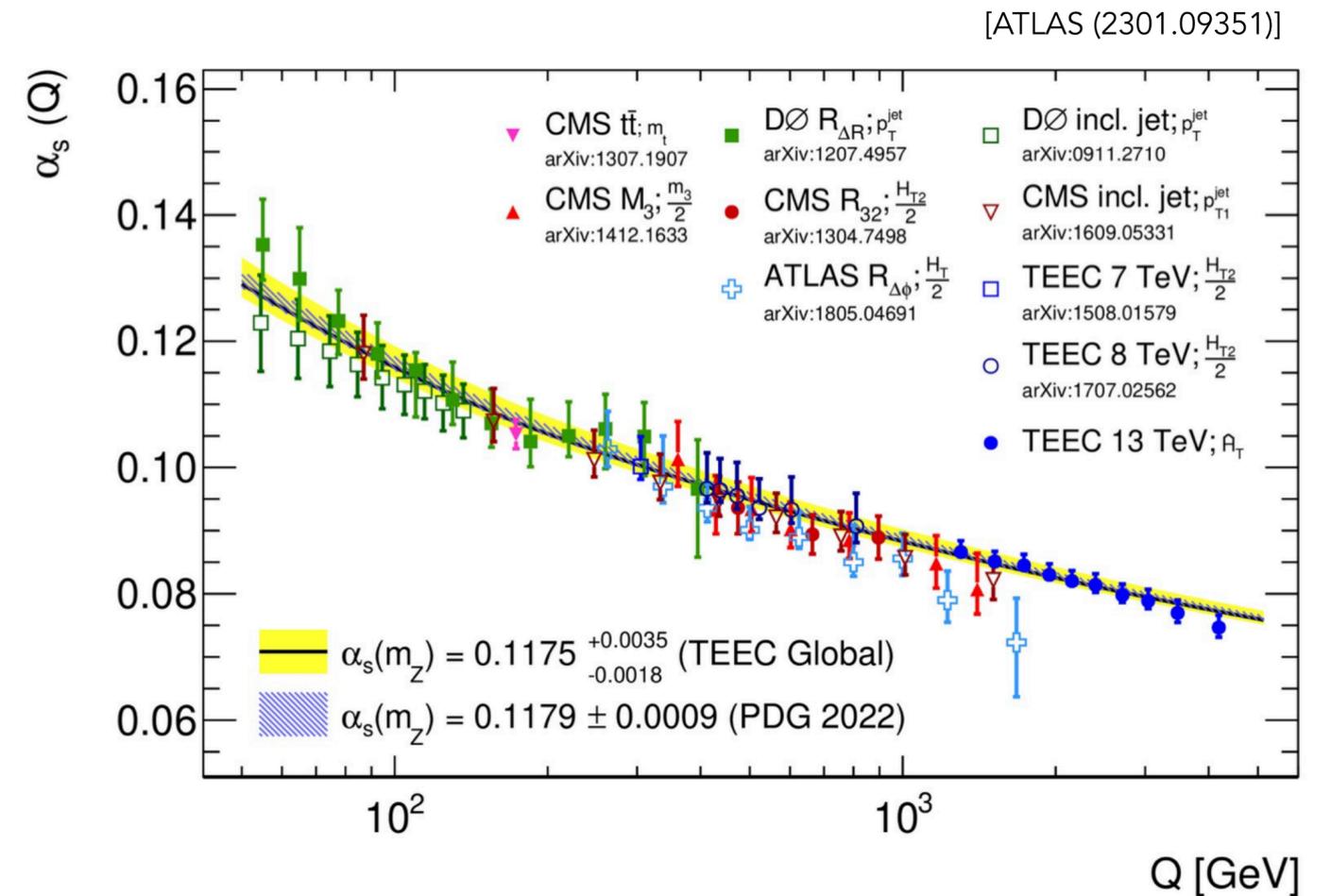
$$F_{\mu\nu}^A = \partial_\mu A_\nu^A - \partial_\nu A_\mu^A - g_s f_{ABC} A_\mu^B A_\nu^C$$

$$[t^A, t^B] = if_{ABC} t^C$$

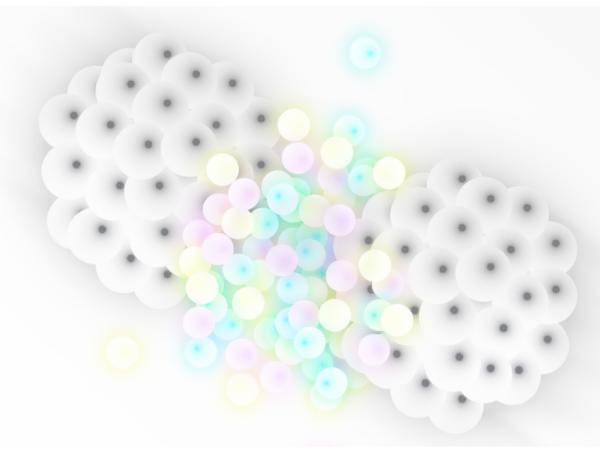
Quantum Chromodynamics



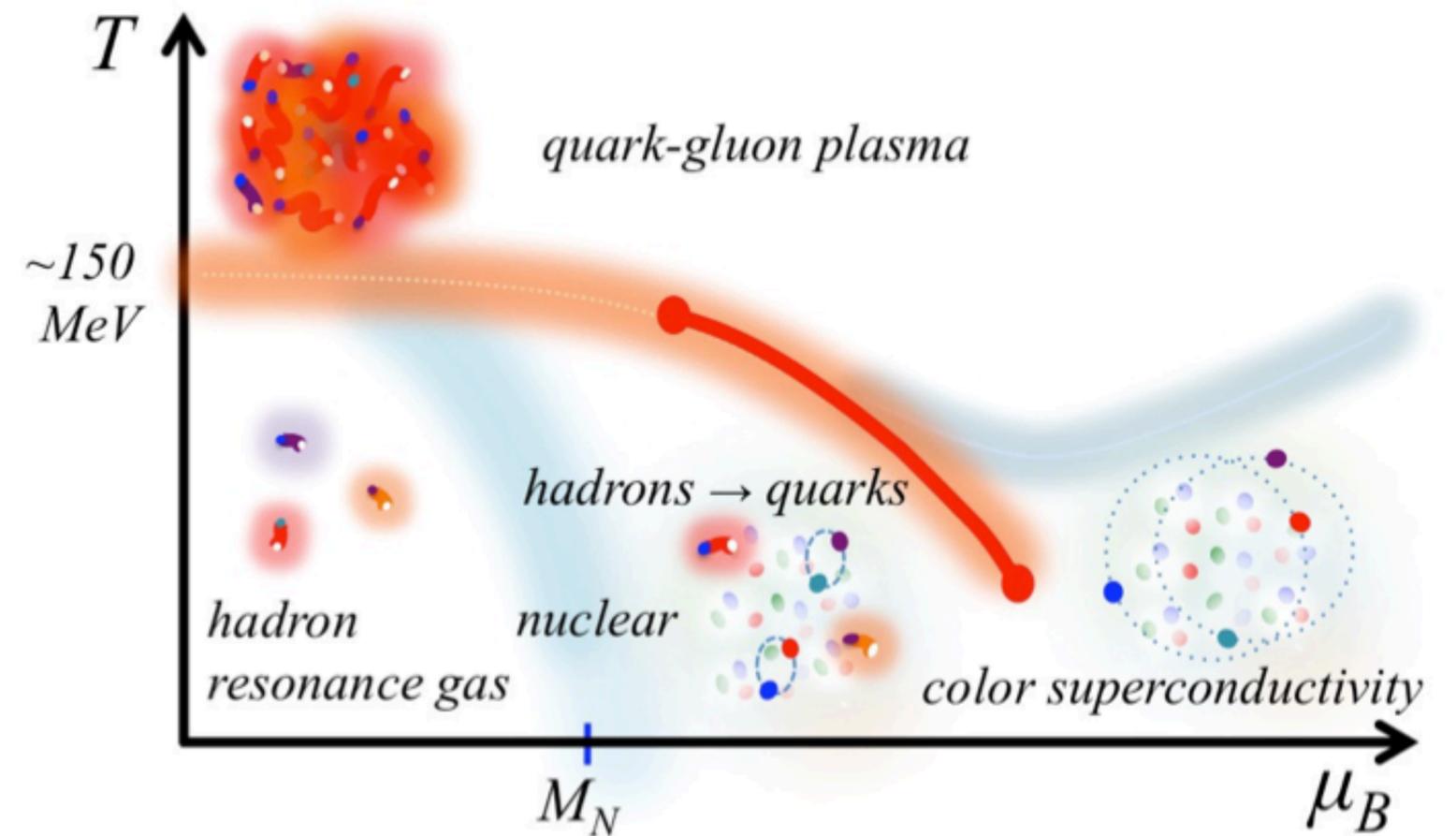
- Coupling is scale dependent (renormalisation)
- Self-interacting gauge fields lead to asymptotic freedom
- Quarks and gluons as degrees of freedom only at short distances (high momentum scales)



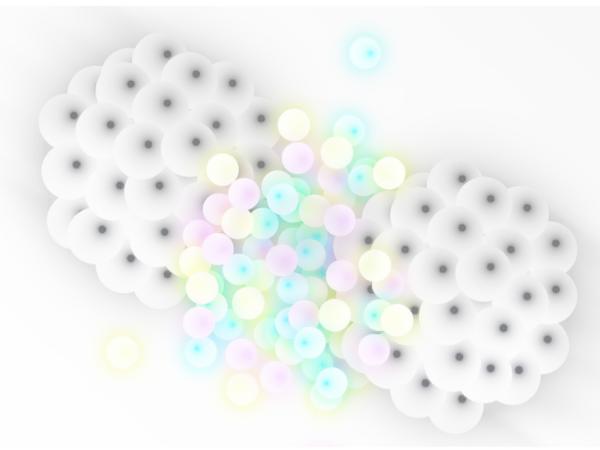
From dilute QCD to dense QCD



- QCD is not limited to a collection of small particles...
- QCD matter has a rich and vast phase diagram



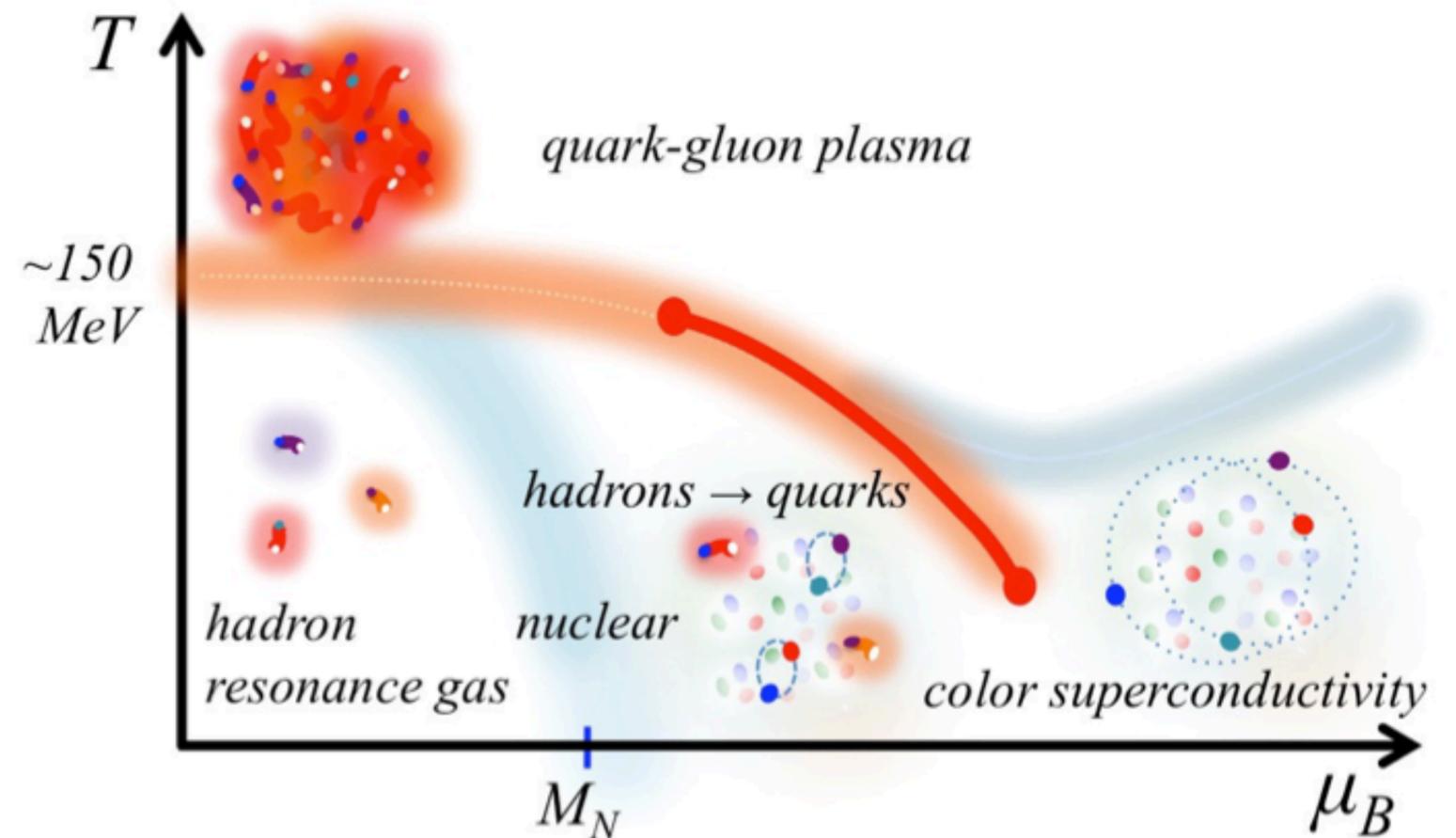
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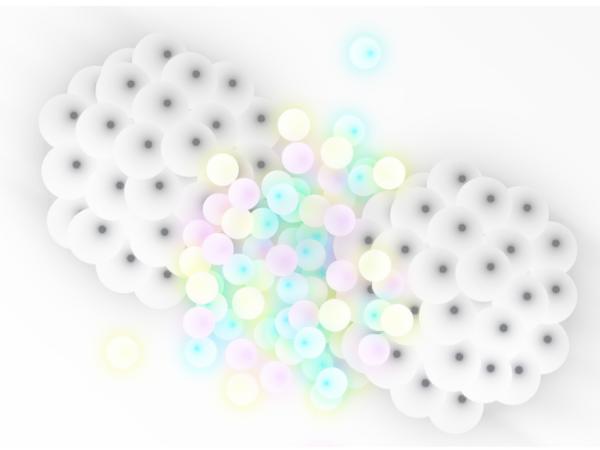
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QCD theory (1973)
SU(3) Color symmetry; confinement; asymptotic freedom, ...

QGP initial idea (1975)
“Weakly coupling quark soup”
State of matter where quarks and gluons are asymptotically free



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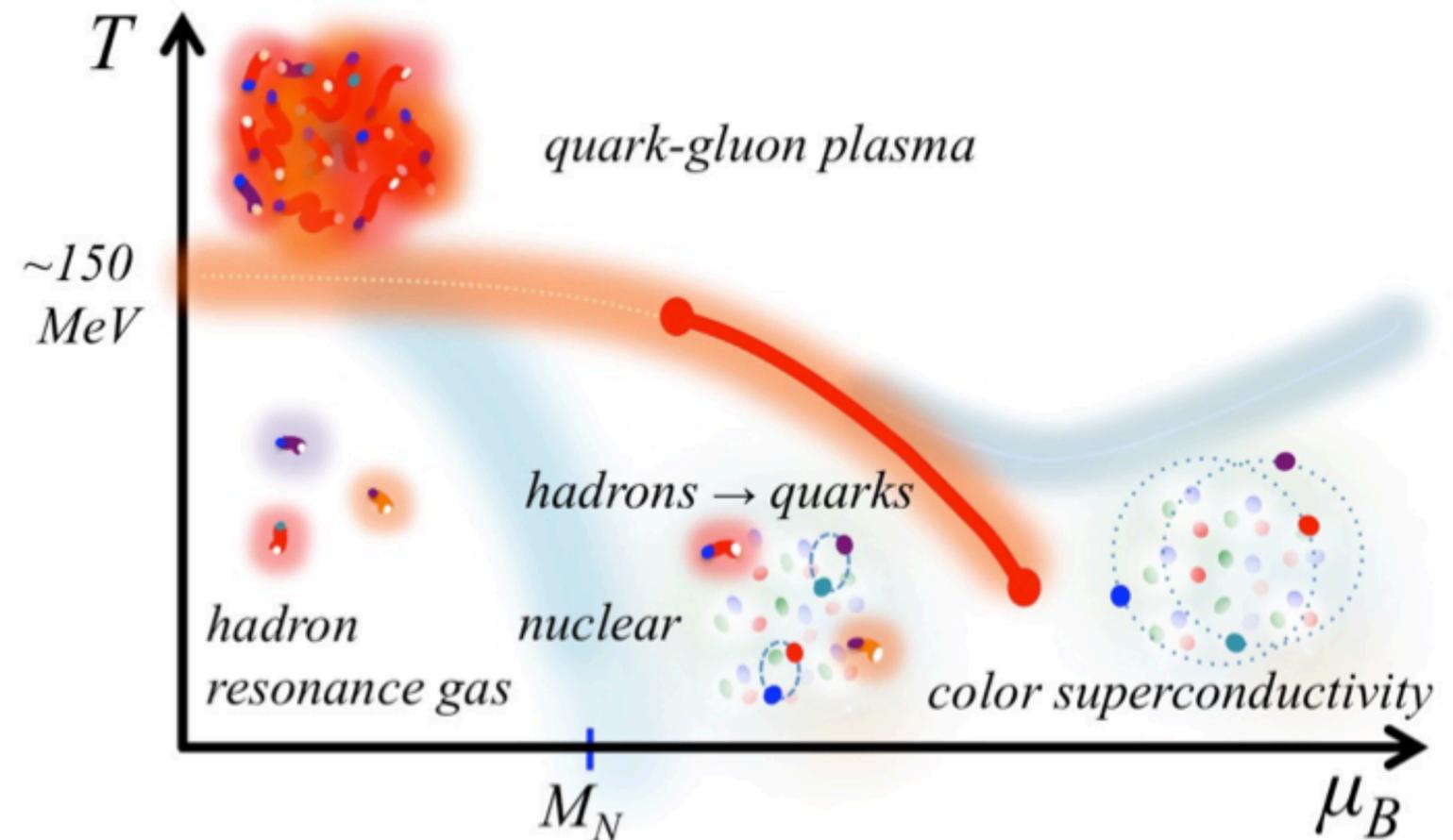
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Fundamental question: How collectivity emerge from elementary particles interaction?

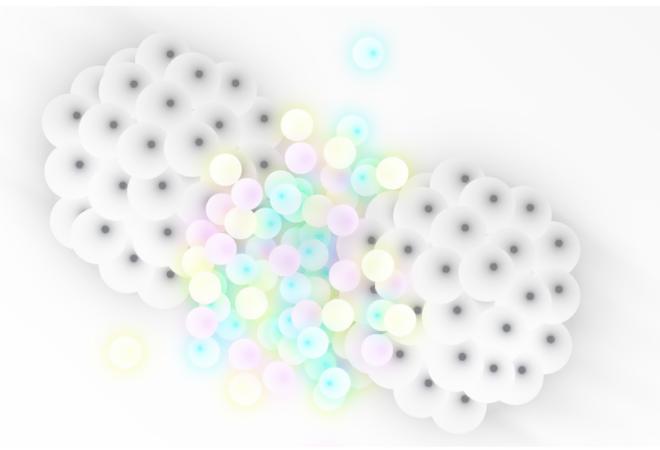
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“Weakly coupling quark soup”
State of matter where quarks and gluons are asymptotically free

QGP at present
“Strongly coupled fluid”



QCD Phase transition



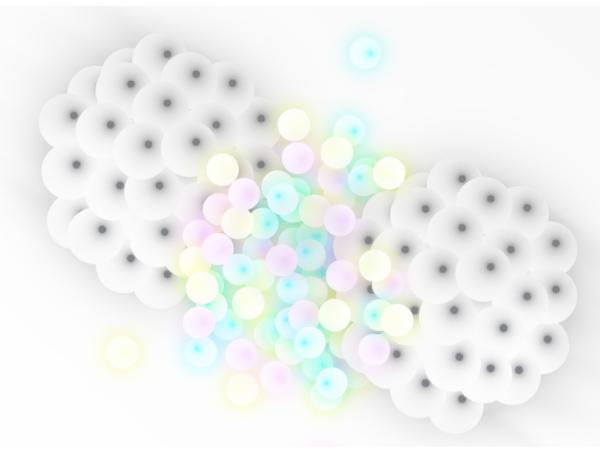
- If quarks and gluons effectively become free \rightarrow new d.o.f
- Stefan-Boltzmann (SB) ideal quark-gluon gas:

$$\epsilon(T) = n_{d.o.f} \frac{\pi^2}{30} T^4 \quad n_{d.o.f} = N_B + \frac{7}{8} N_F$$

$$N_B = 2 \times 8, \quad N_F = 2 \times 2 \times 3 \times 3$$

spin color spin particle/antiparticle color flavor: u/d/s

QCD Phase transition



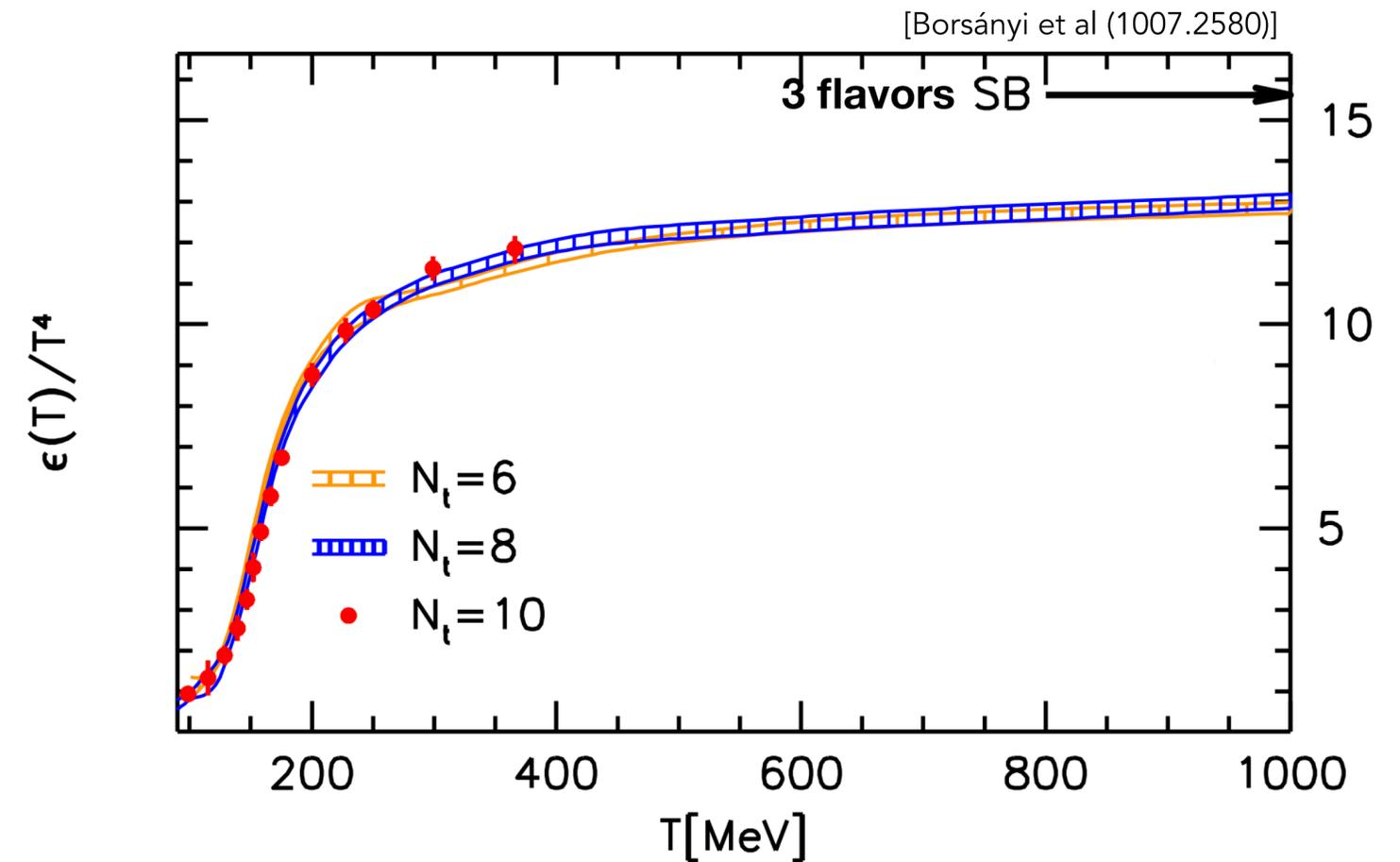
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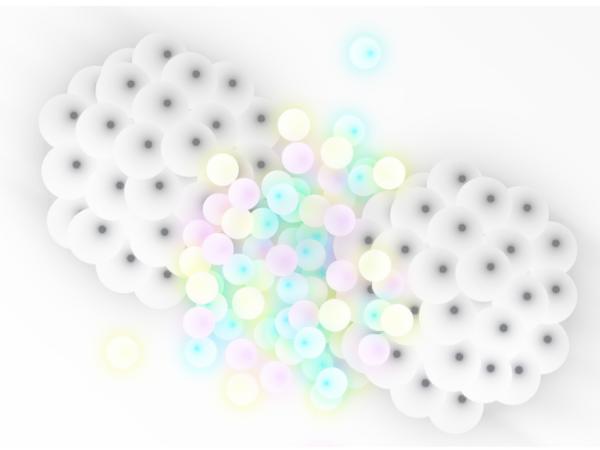
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- Lattice QCD results (first principles calculations)
 - QGP far from SB limit due to non-perturbative effects



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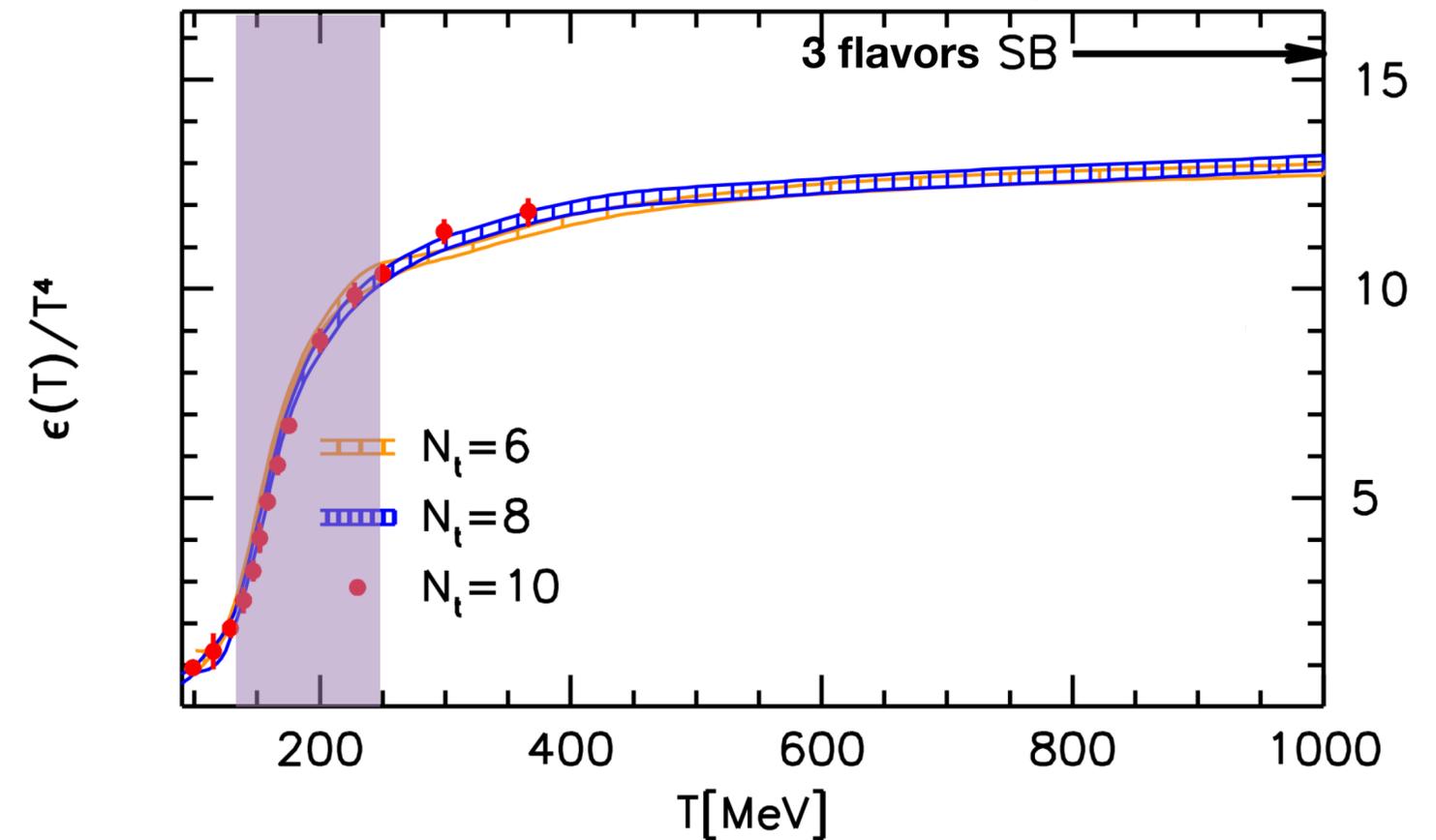
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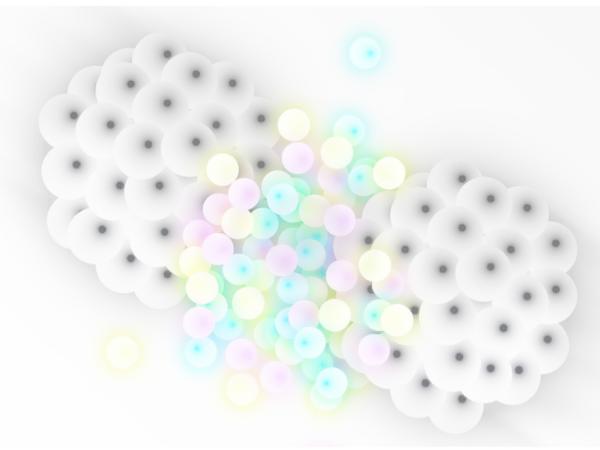
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QGP Phase transition

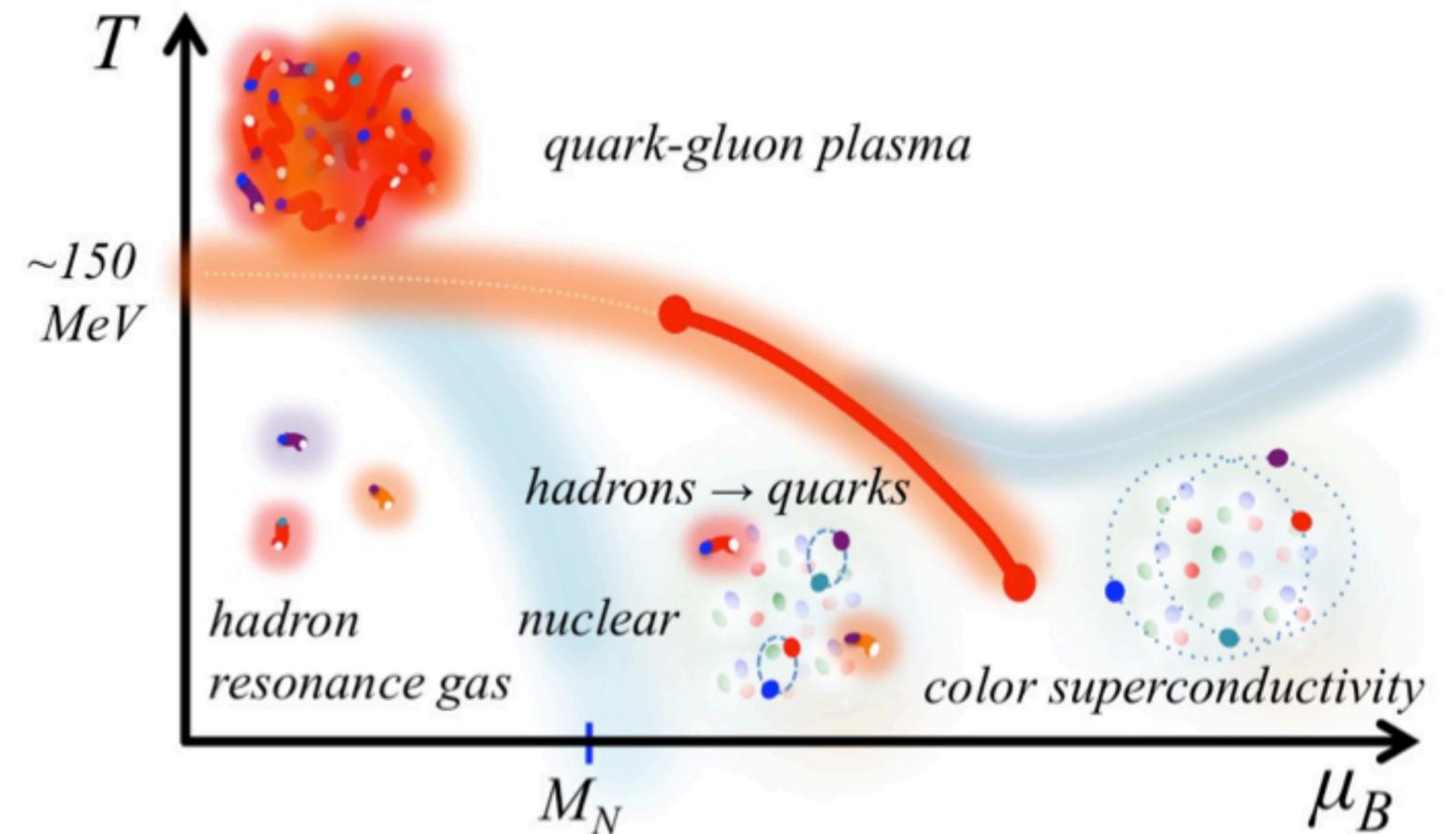
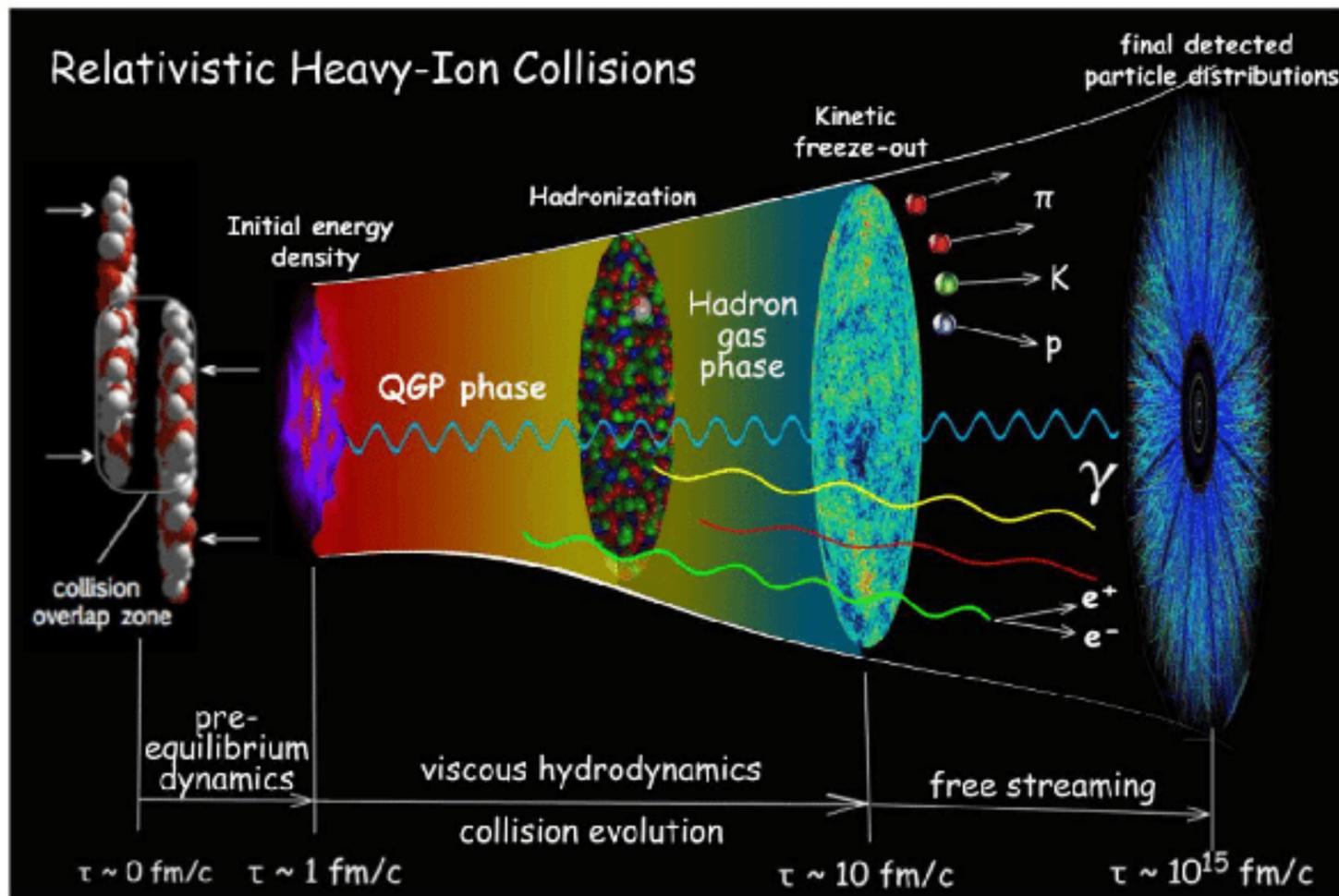
[Borsányi et al (1007.2580)]



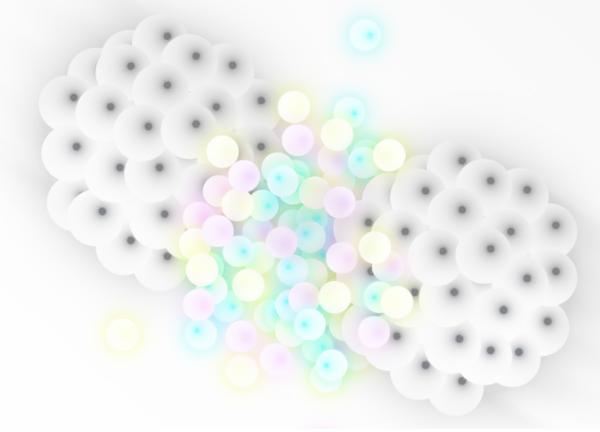
Discovering QCD phase diagram



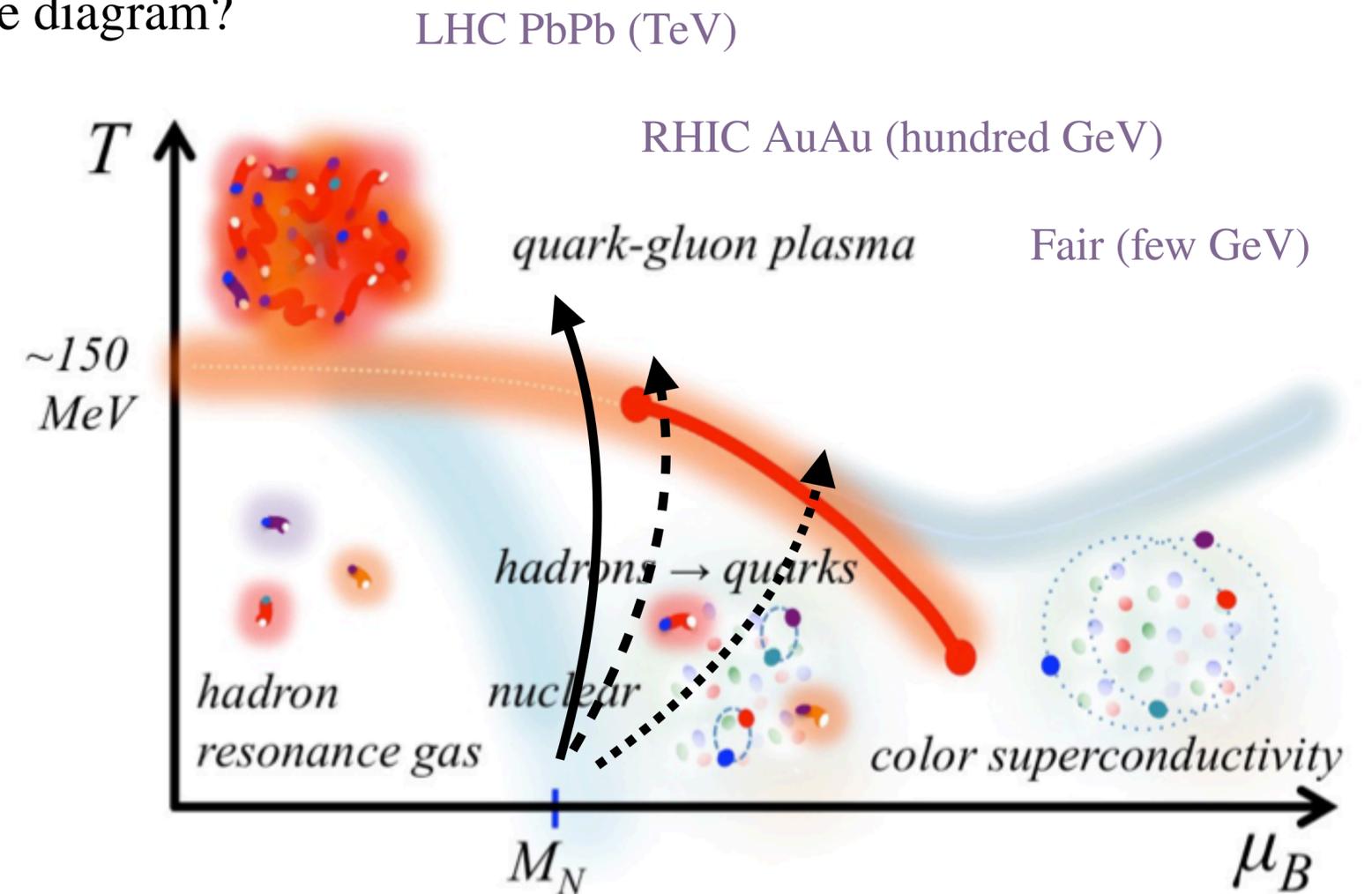
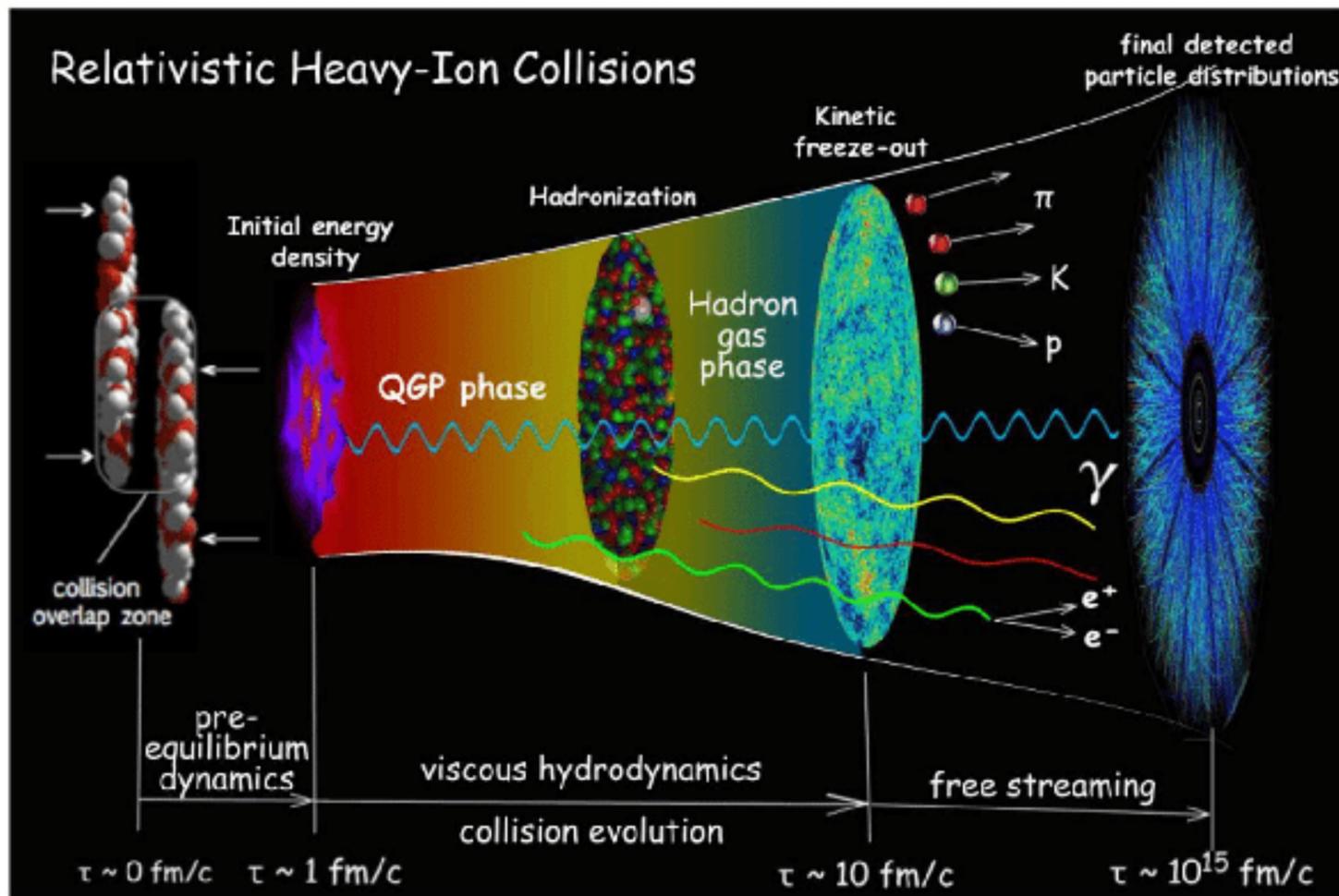
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- Through heavy-ion collisions:



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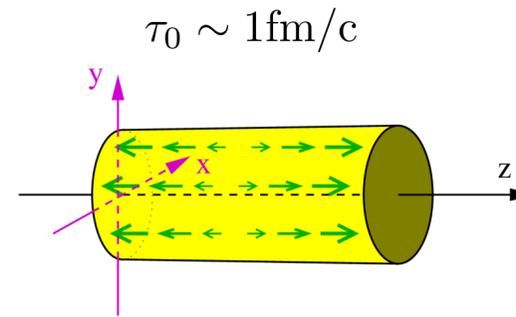
Heavy-ion address this question in the regime of highest temperature and densities accessed in laboratories

QGP @ Colliders

- Macroscopic quantities estimated from the number of particles produced at mid-rapidity:

$$\left. \frac{dN_{\text{ch}}}{d\eta} \right|_{\eta=0} \propto (\sqrt{s_{\text{NN}}})^{0.3}$$

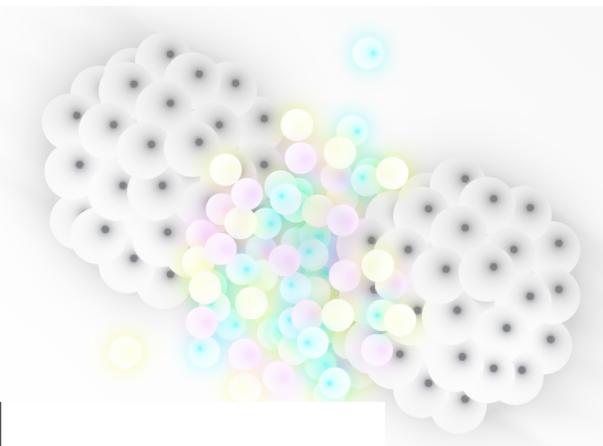
- Energy density computed with Bjorken estimate:



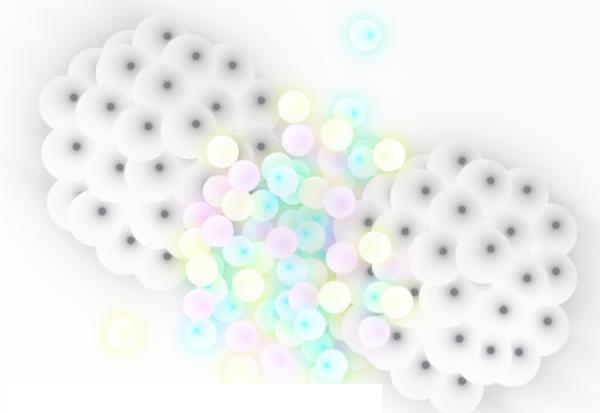
$$\epsilon = \frac{dE_T}{d\eta} \frac{1}{\tau_0 \pi r^2}$$

$$r \sim A^{1/3}$$

[A. Dainese et al. (1605.01389)]

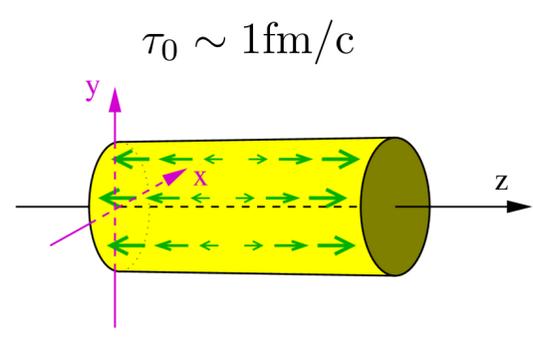


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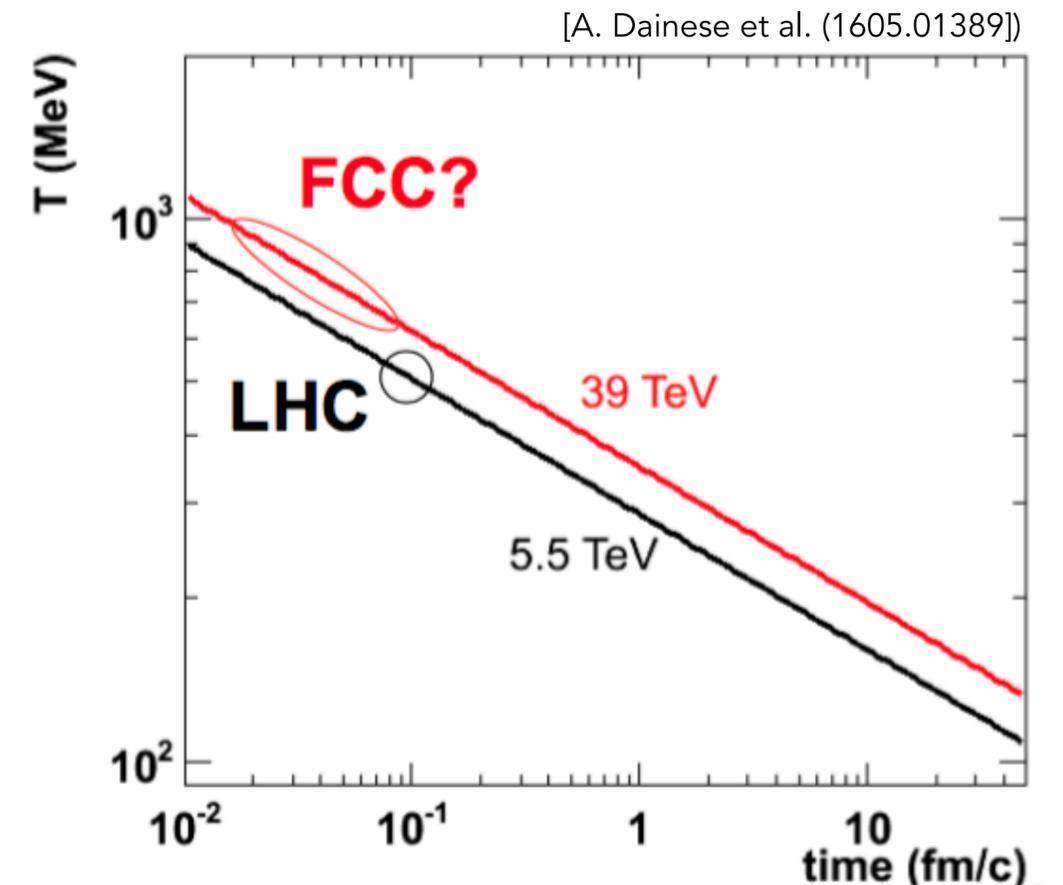
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Quantity	SPS	RHIC	LHC	FCC
$\sqrt{s_{NN}}$ [TeV]	0.017	2	5.5	39
Homogeneity volume [fm ³]	1200	2300	6200	11000
$\epsilon(\tau = 1 \text{ fm}/c)$ [GeV/fm ³]	3-4	4-7	16-17	35-40
Decoupling time [fm/c]	4	7	11	13

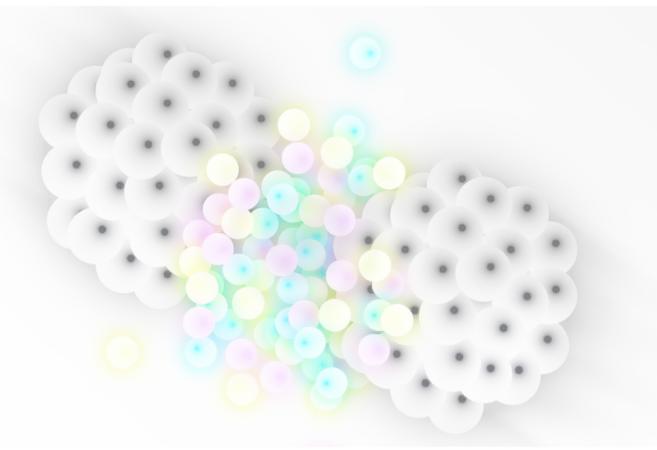
Denser medium \Rightarrow longer expansion and larger volume

Higher initial energy \Rightarrow larger temperature and smaller thermalisation time



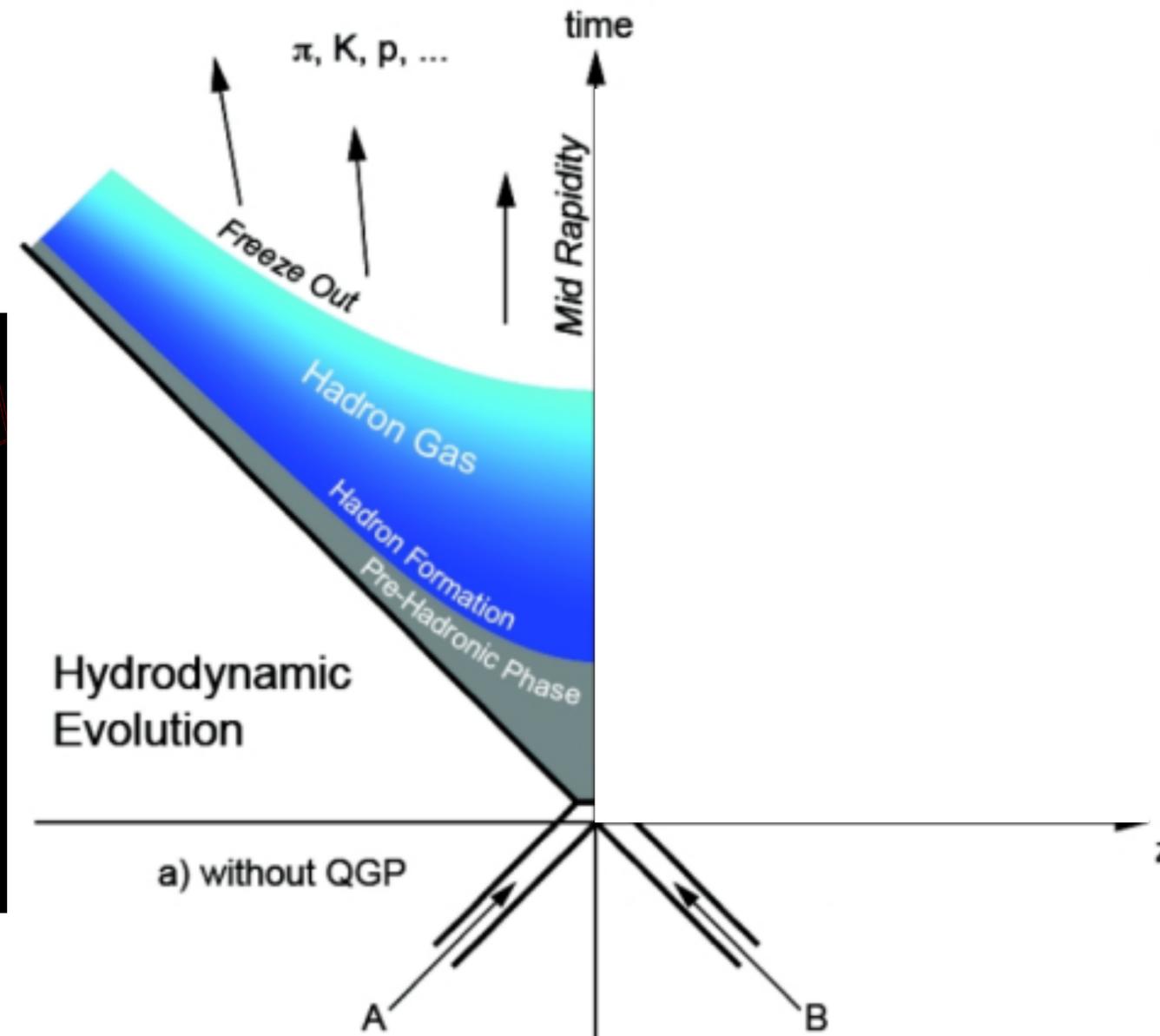
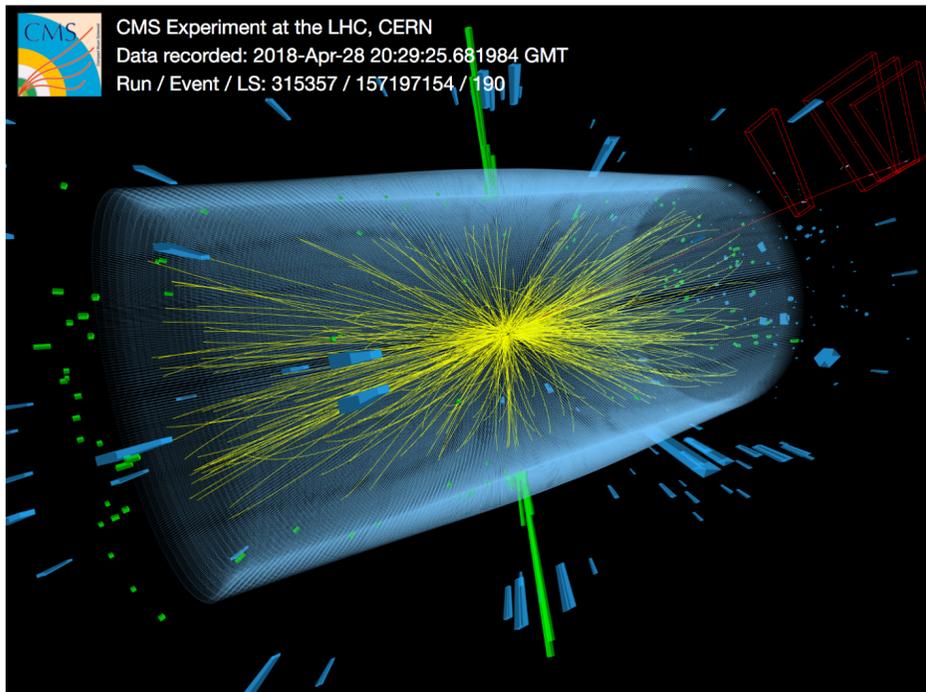
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Proton-proton vs heavy-ions

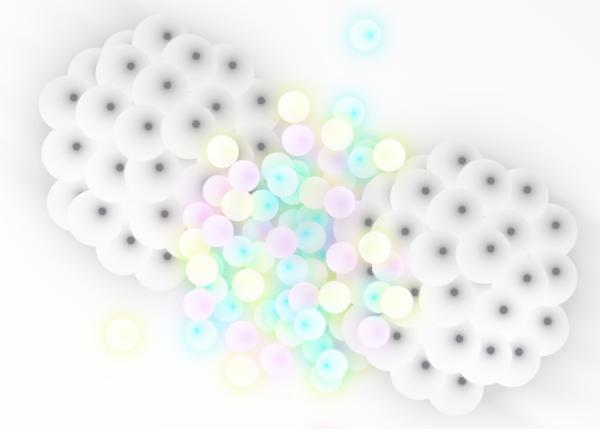


- Proton-proton vs heavy-ion collisions:

Proton-proton collisions
Low multiplicity event



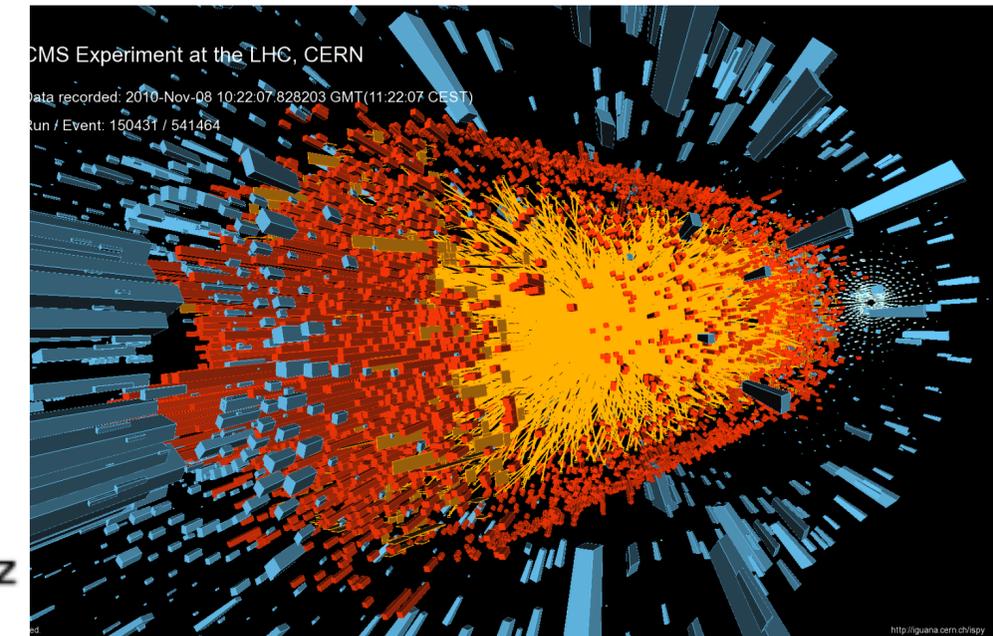
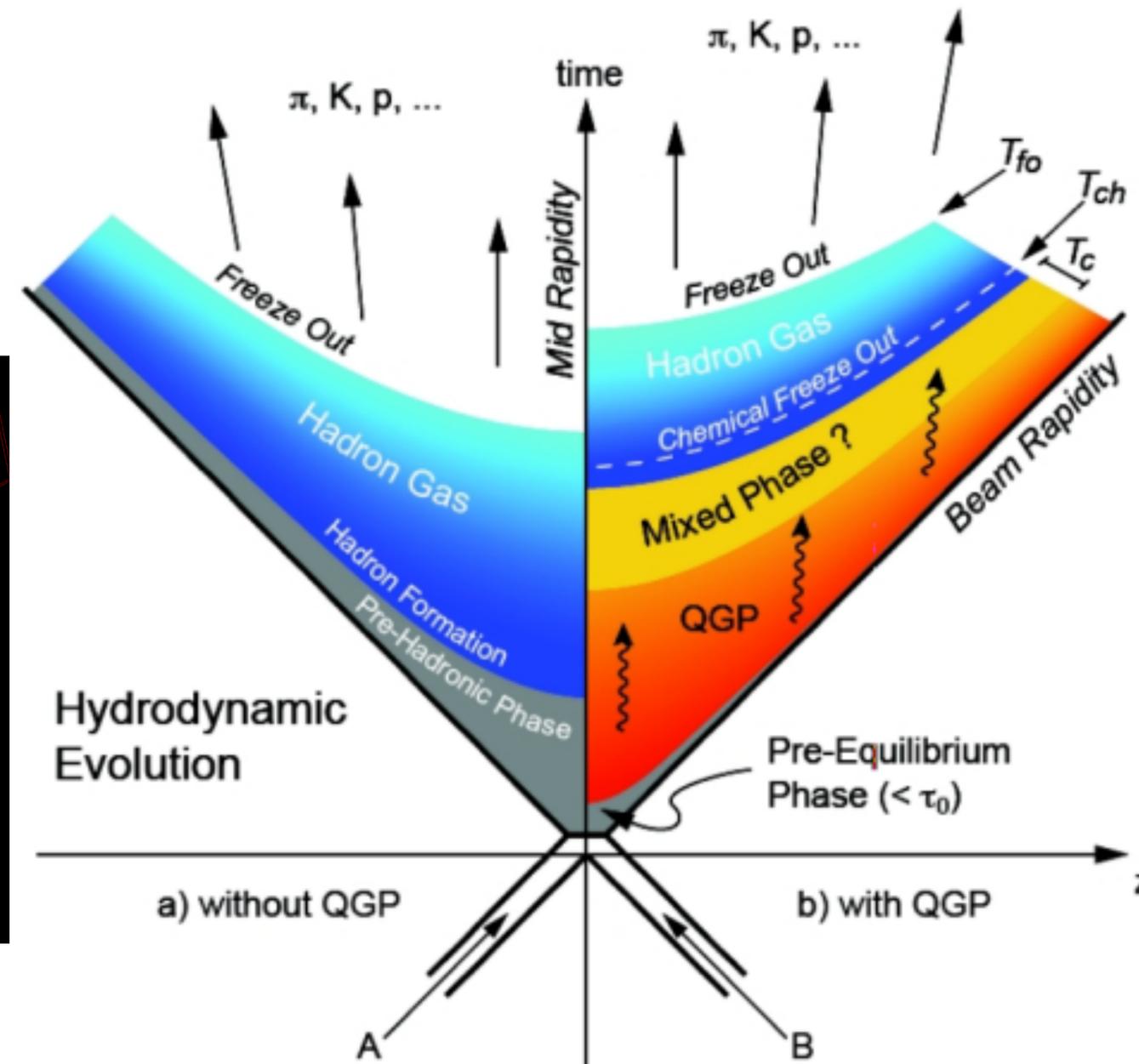
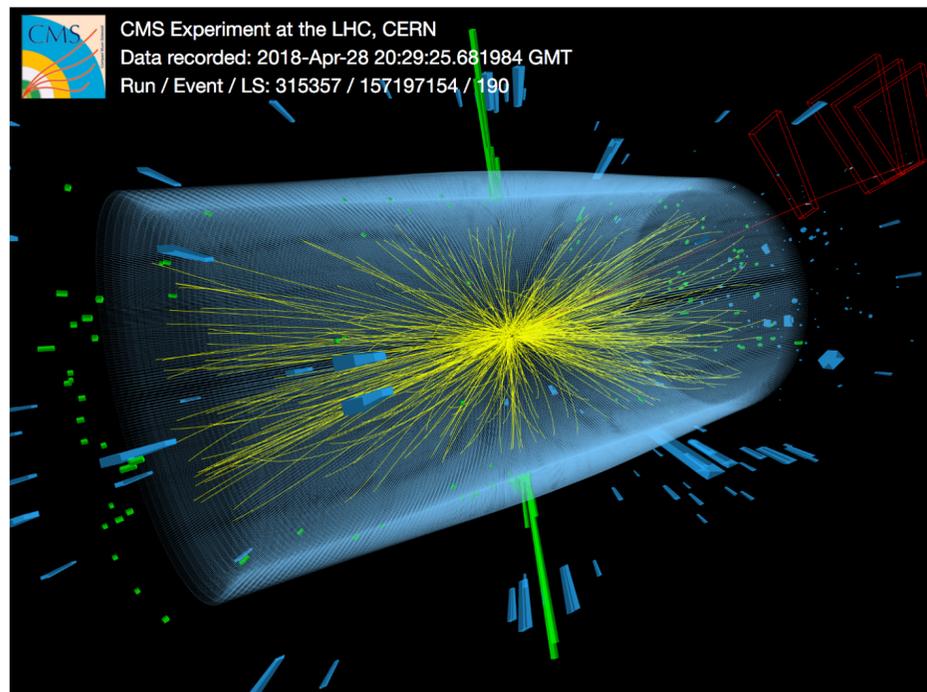
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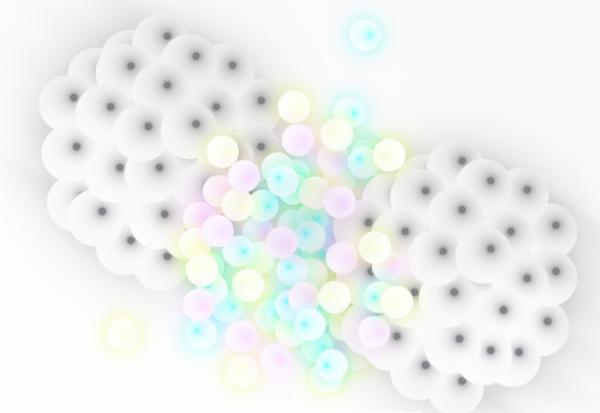
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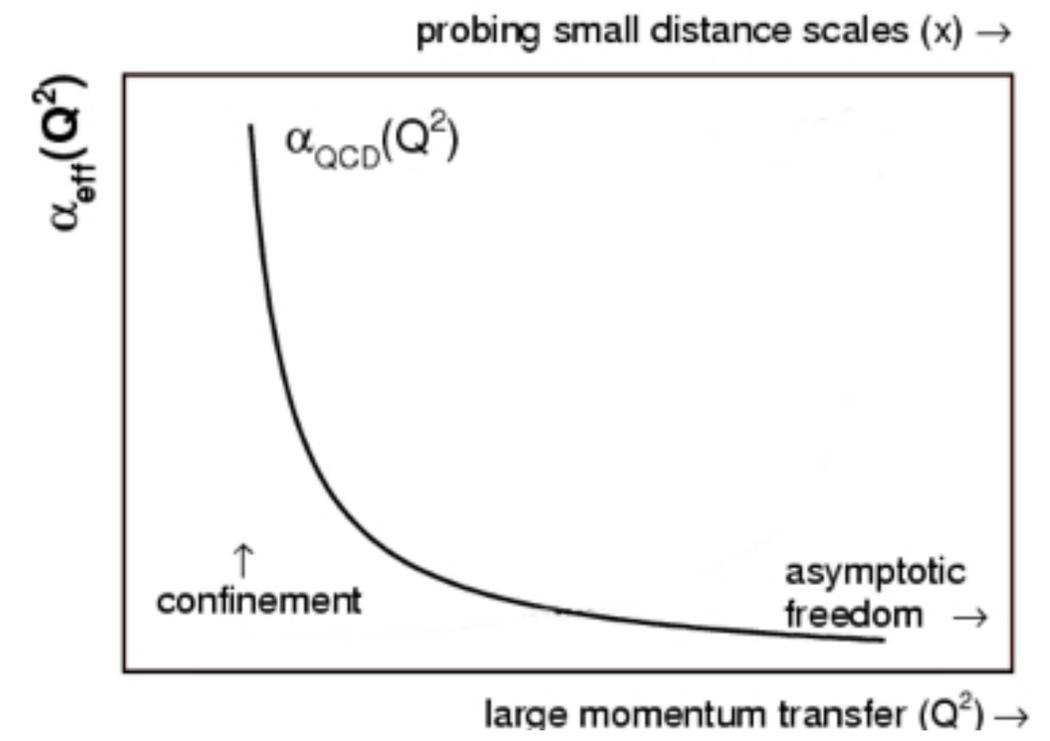
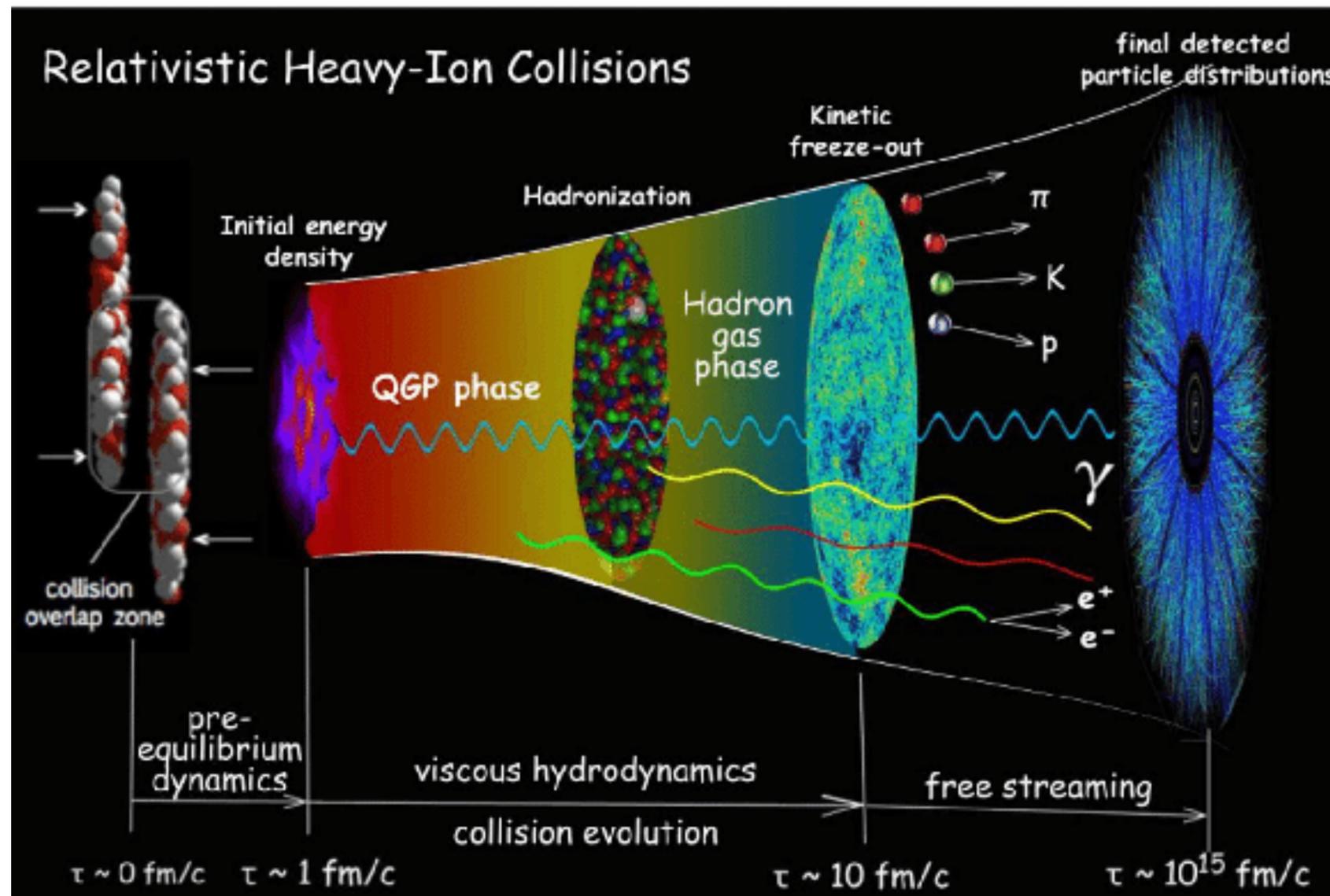
Lead-Lead collisions
High multiplicity event
(result of QGP formation)



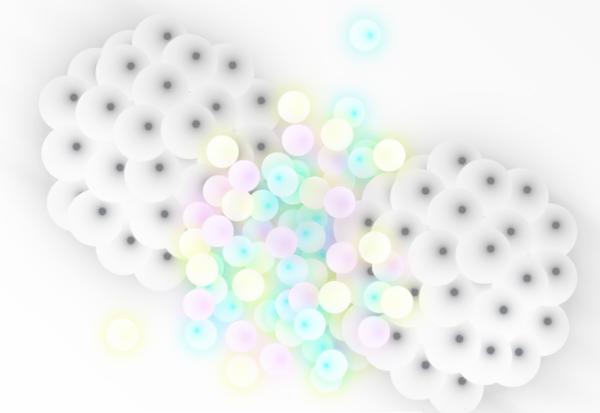
Quark-Gluon Plasma (QGP)



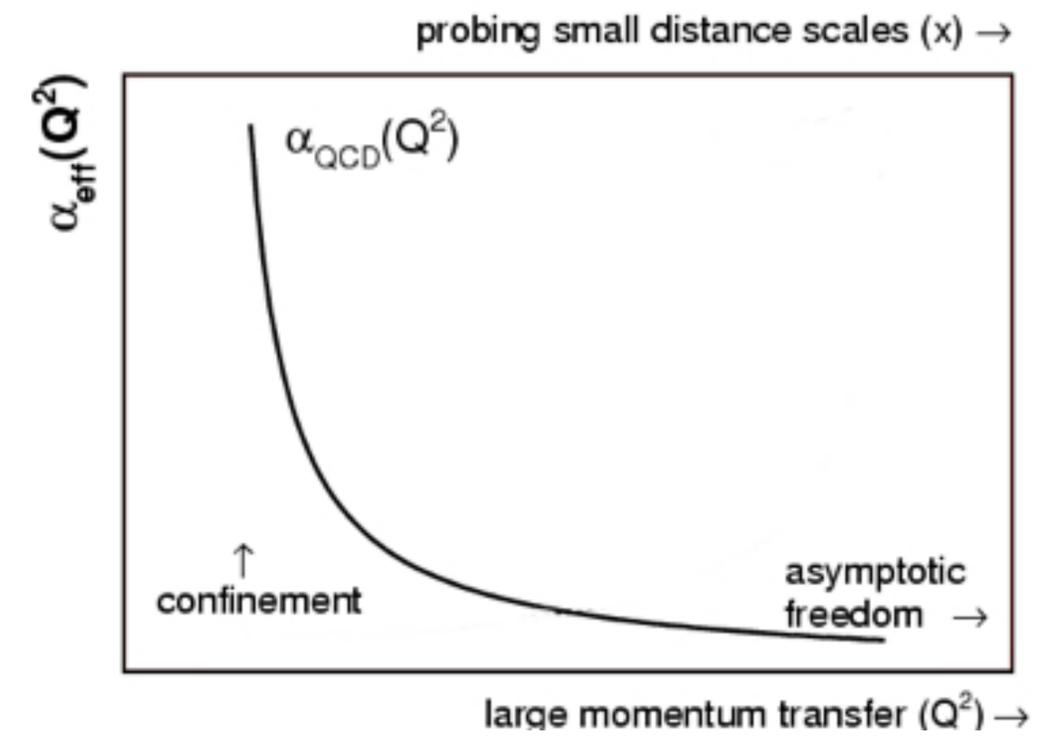
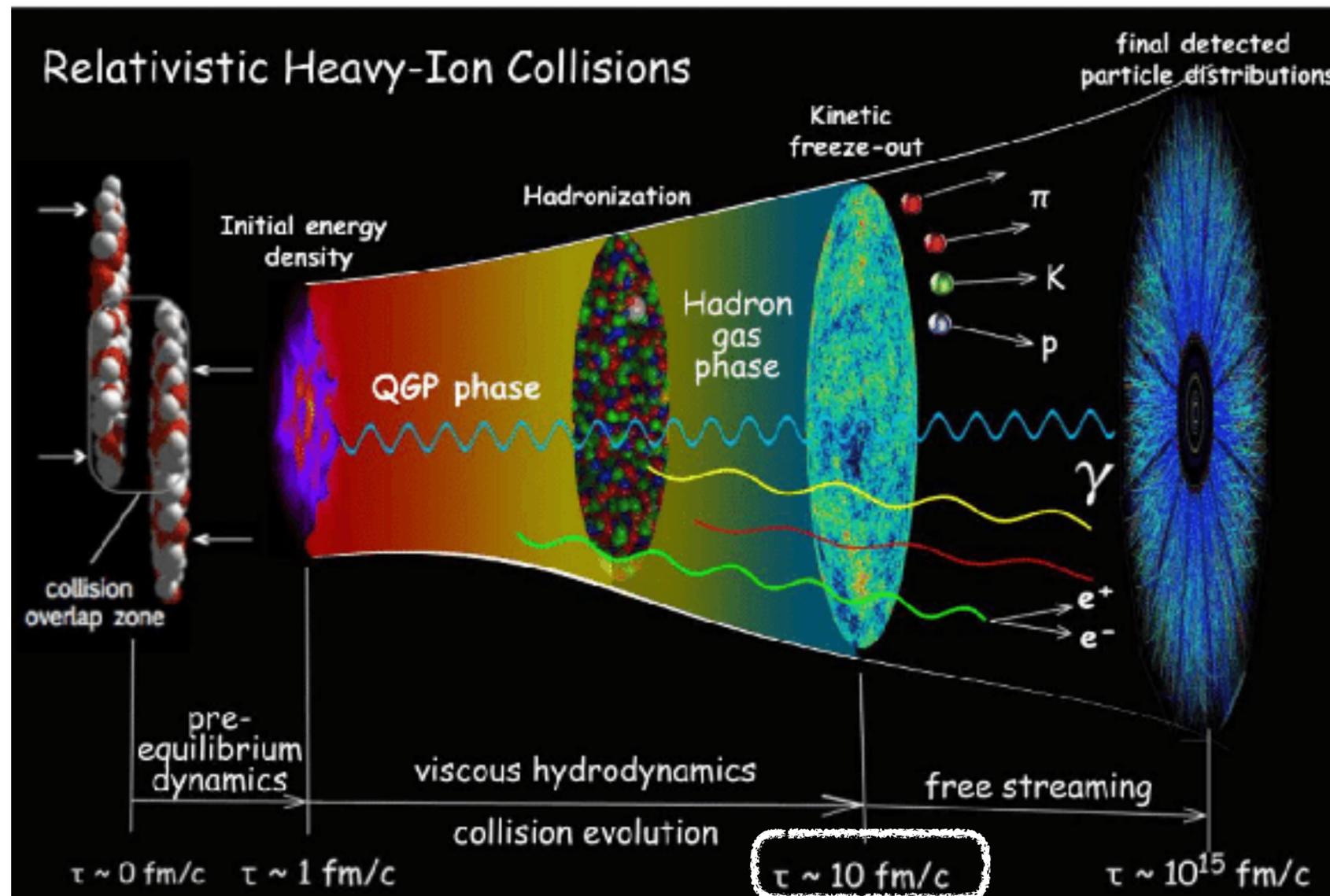
- We can create it in the lab. But how to study it?



Quark-Gluon Plasma (QGP)

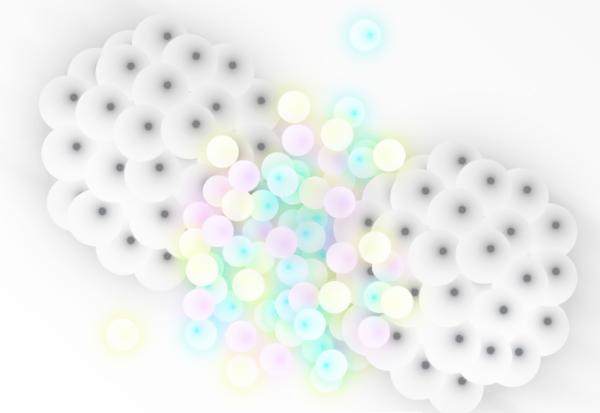


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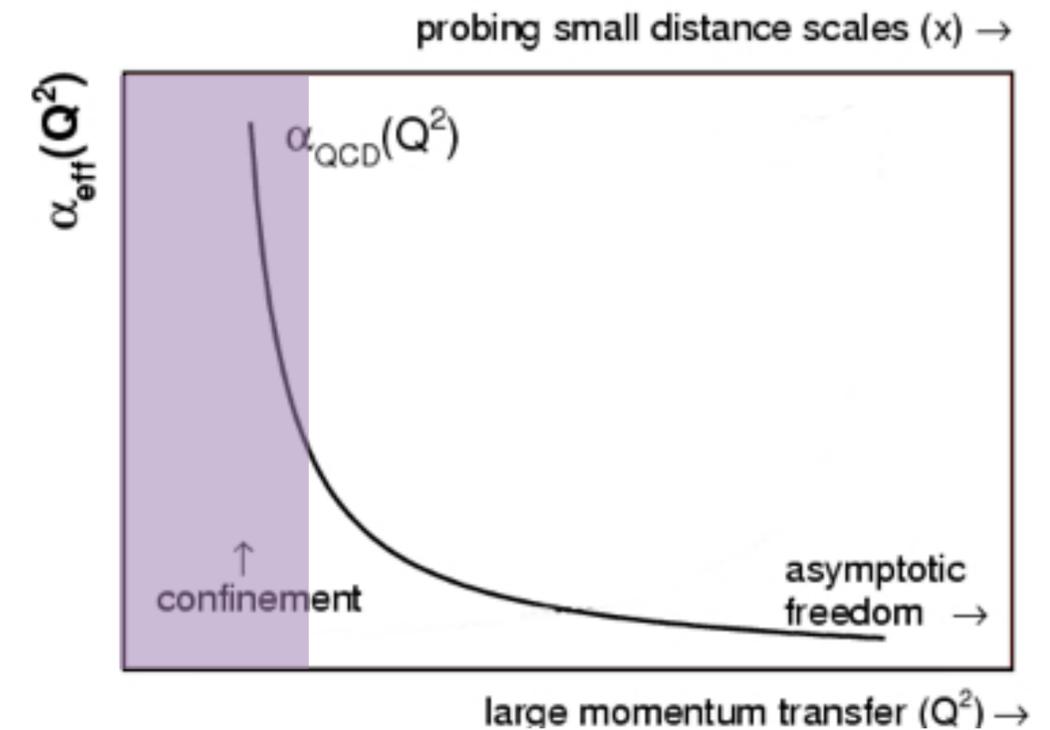
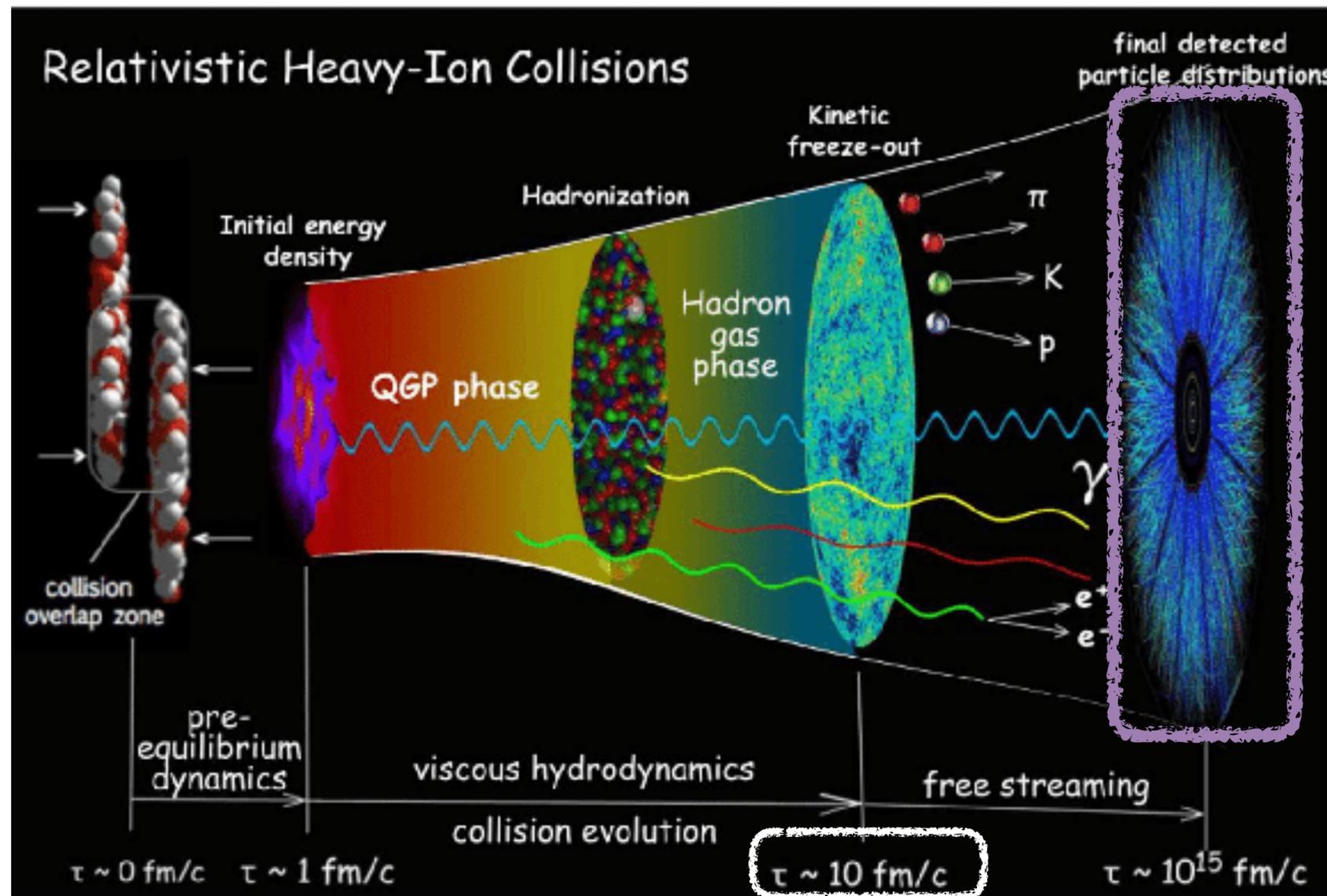


Caveat: need to rely on self-generated probes

Quark-Gluon Plasma (QGP)



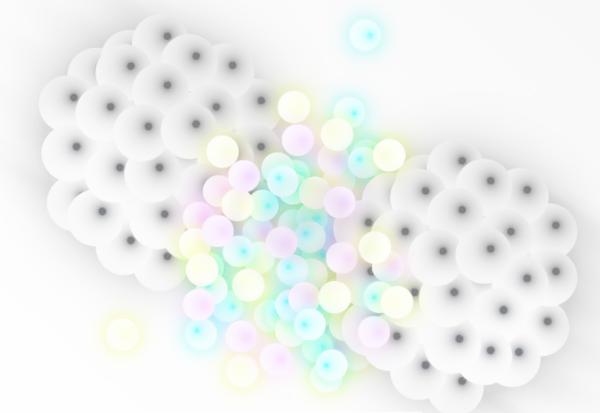
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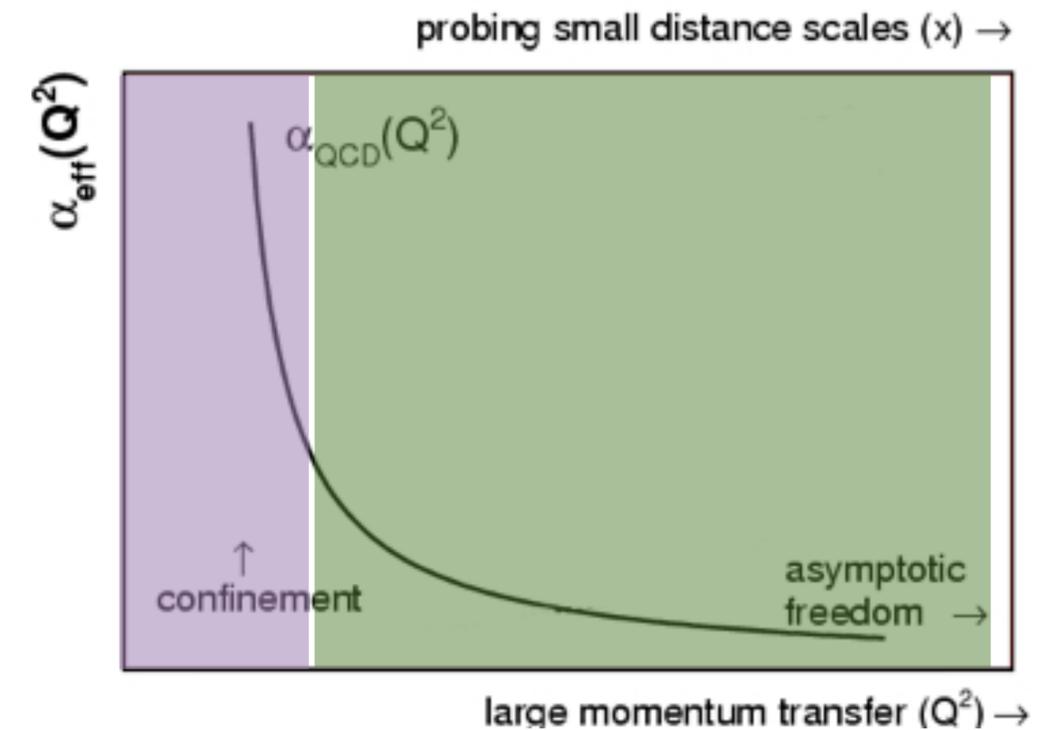
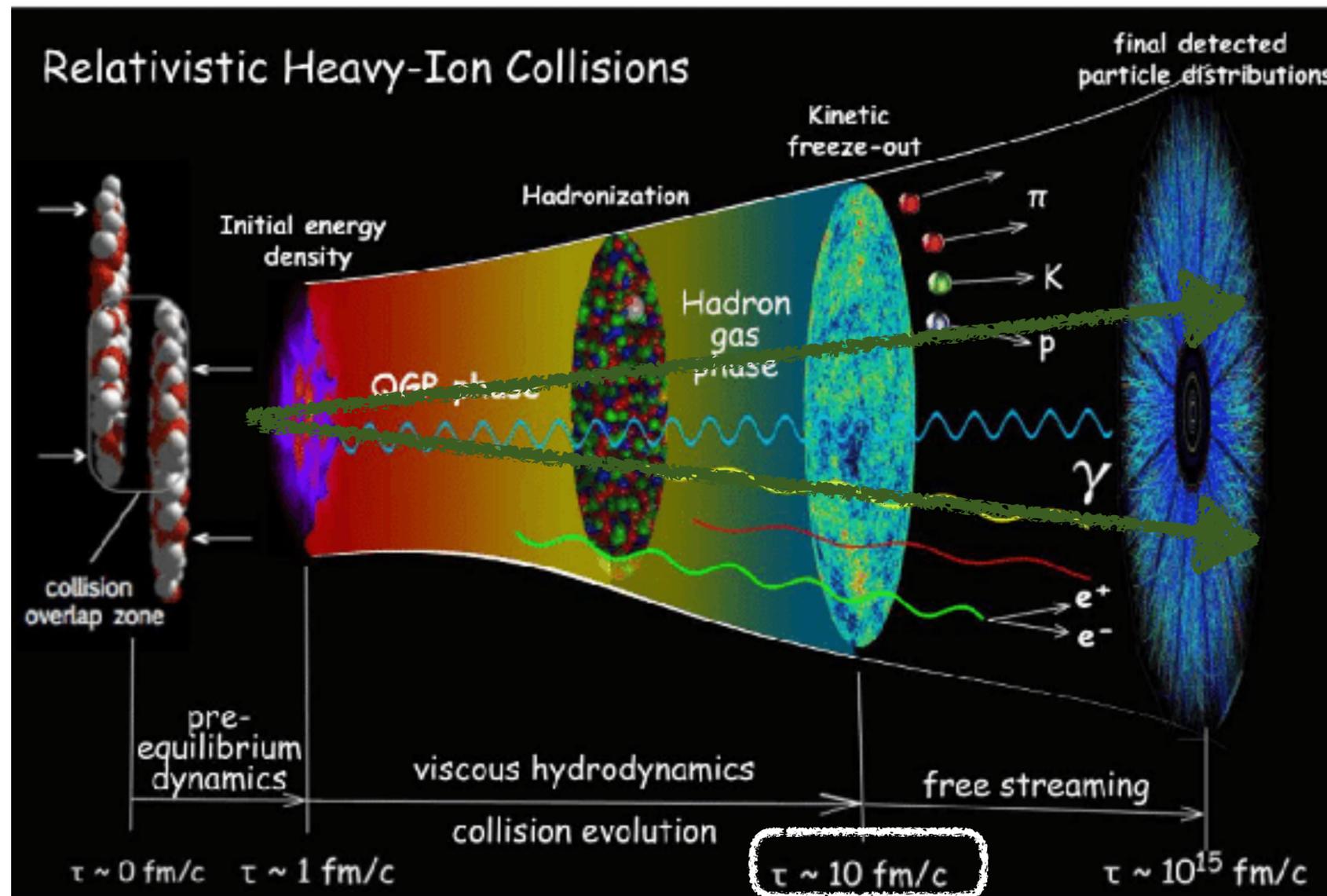
Soft probes
non-pQCD

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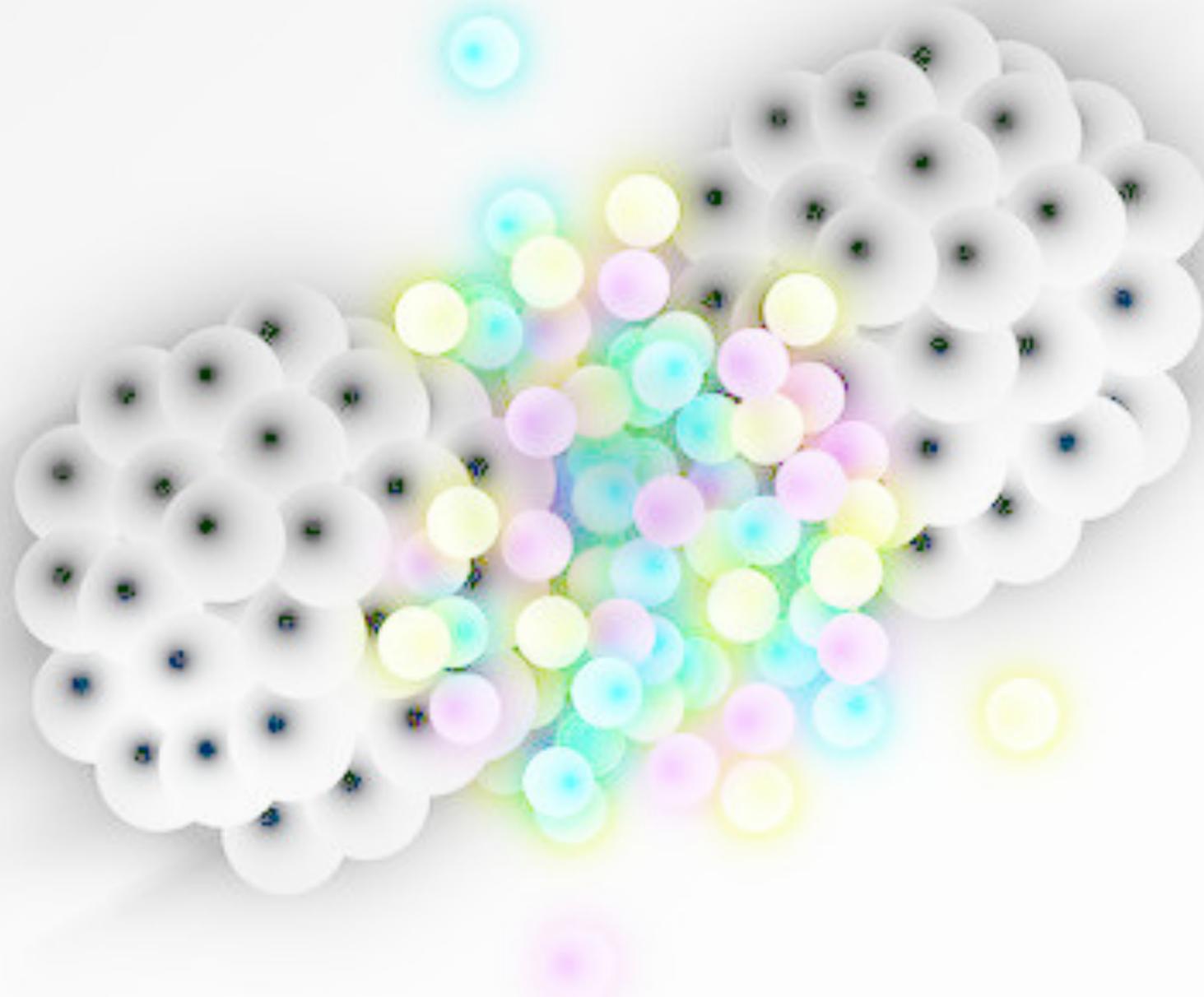


Soft probes
non-pQCD

Hard probes
pQCD

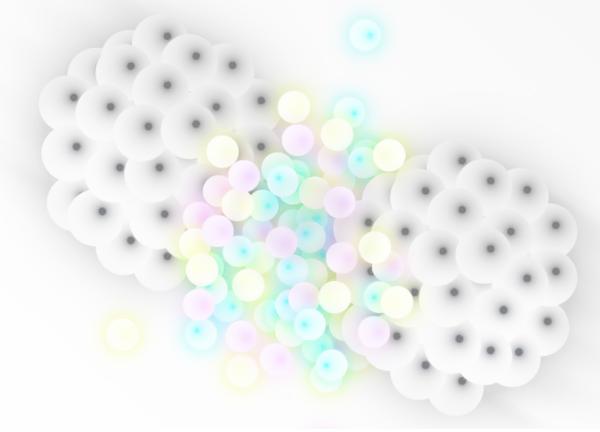
Caveat: need to rely on self-generated probes

Setting the collision system...

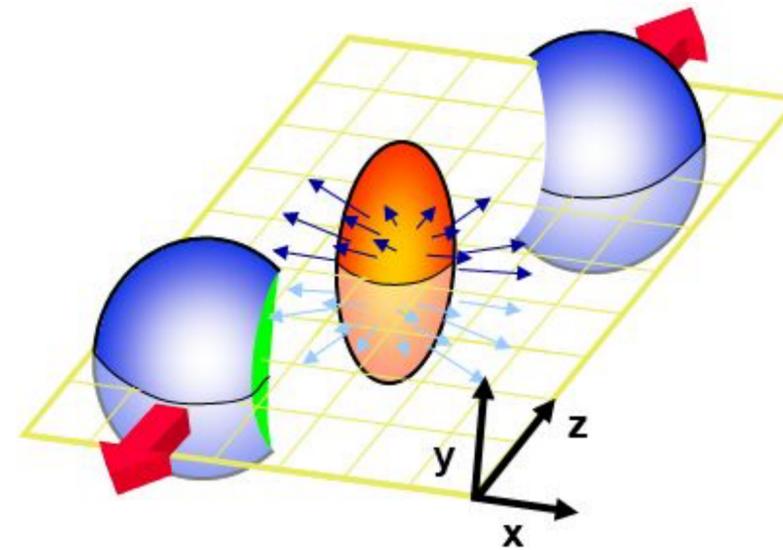


Collision Geometry

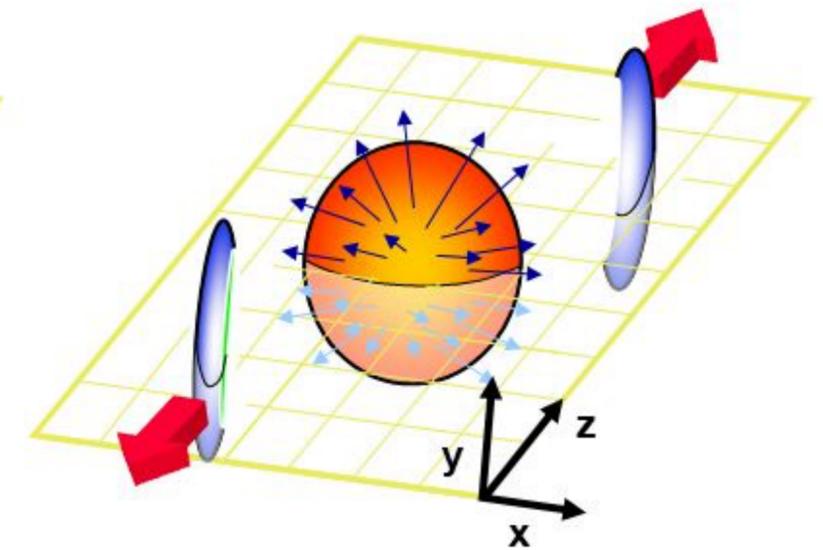
- Colliding Nuclei ~ collection of nucleons
- Collision system ~ nucleons that participate in the collision



Peripheral Collision

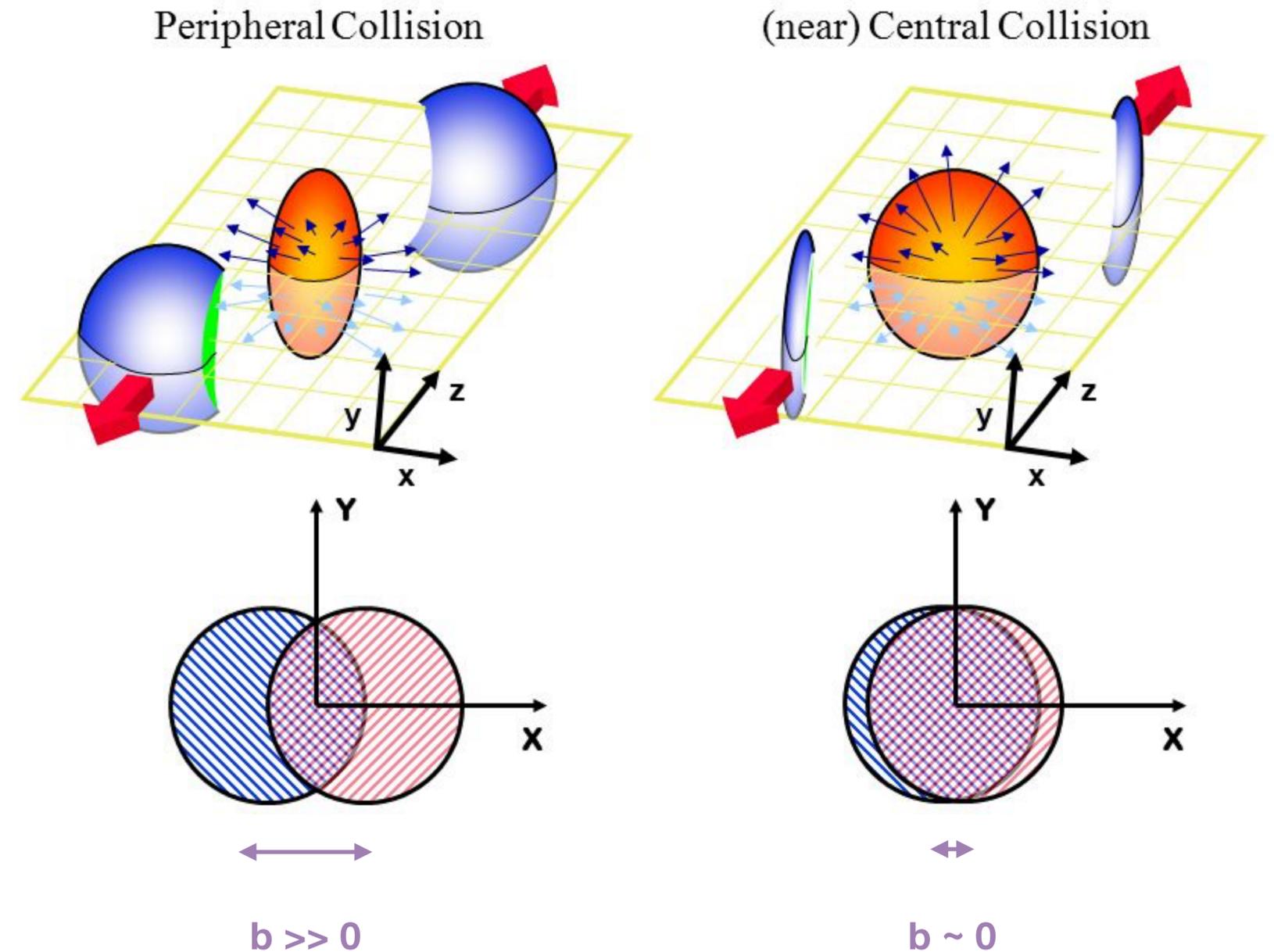


(near) Central Collision

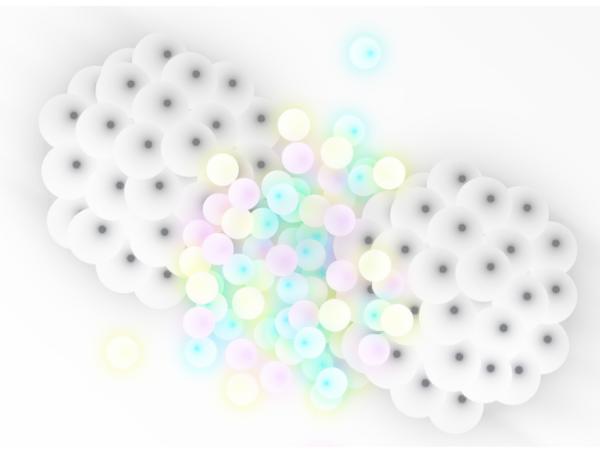


Collision Geometry

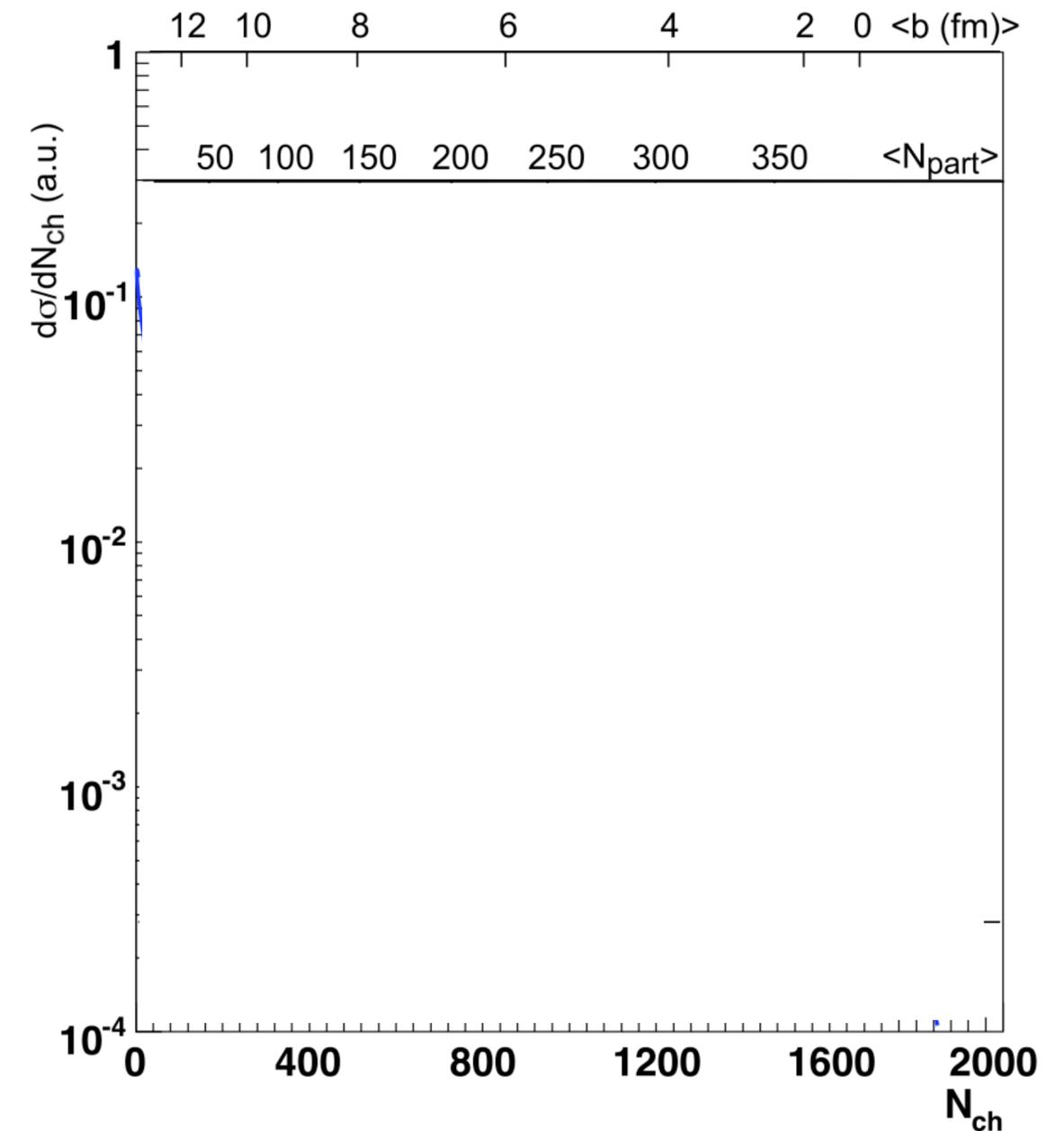
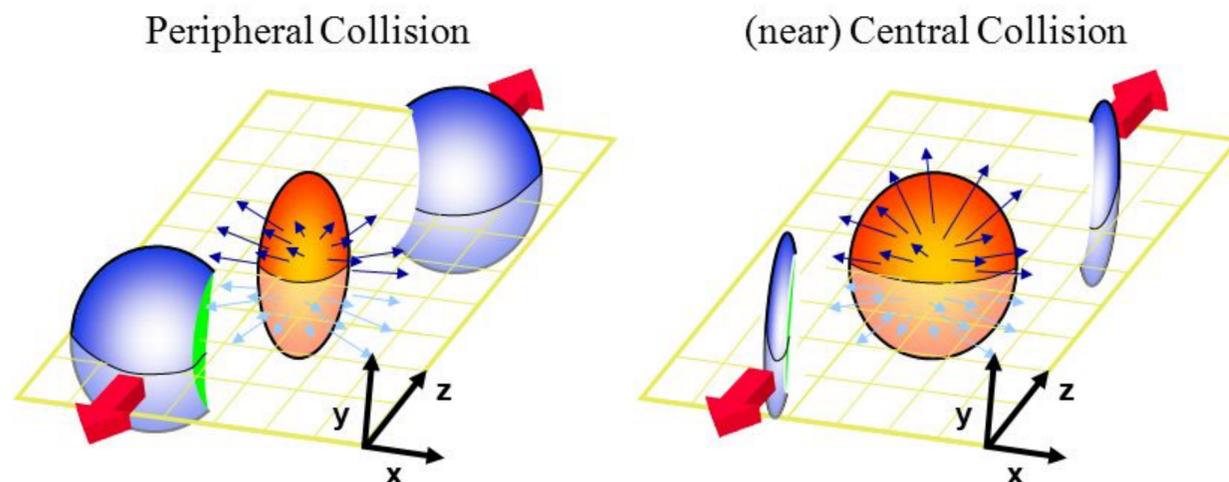
- Colliding Nuclei ~ collection of nucleons
- Collision system ~ nucleons that participate in the collision
- To define collision geometry:
 - Impact parameter (b): the transverse distance between the center of masses of the two nuclei
 - It will control the extent of the medium that is created



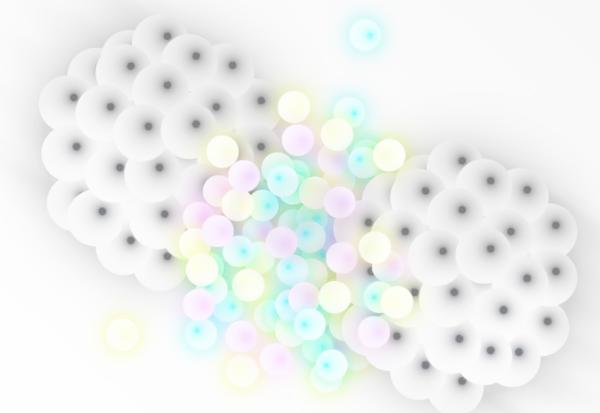
Centrality Classes



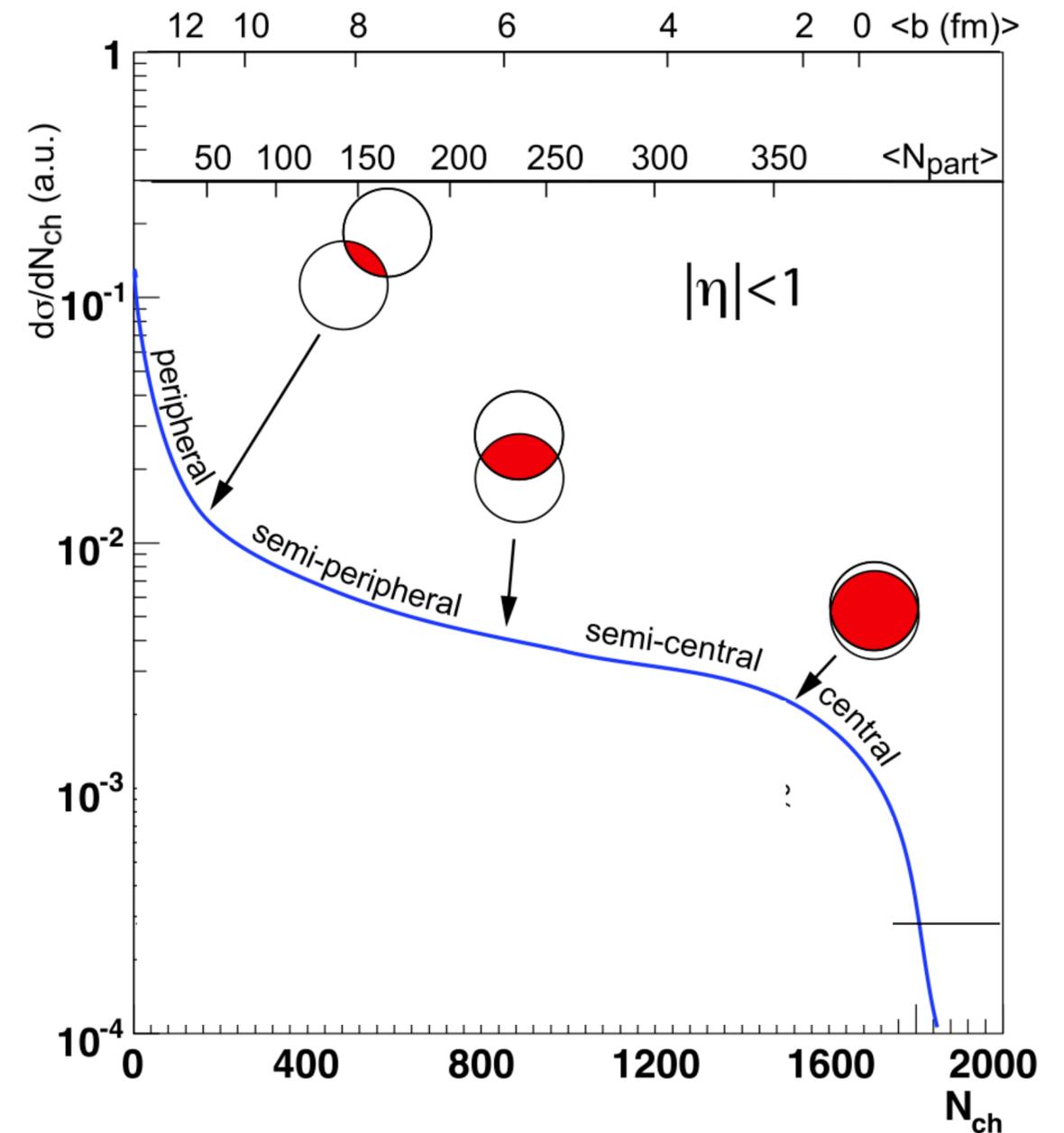
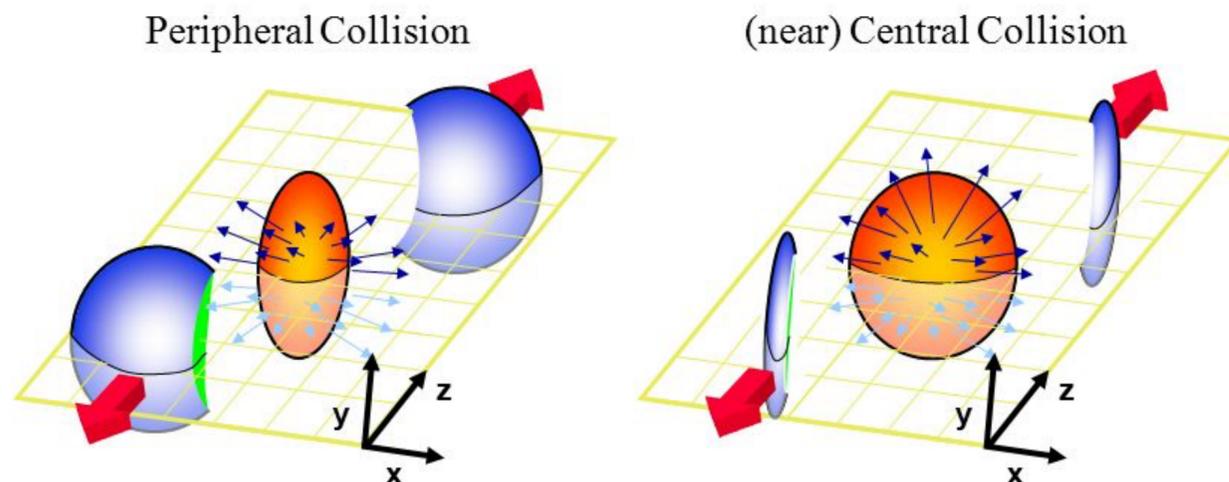
- Using a geometrical model (Glauber), one can relate impact parameter to average
 - Number of participants in the collision



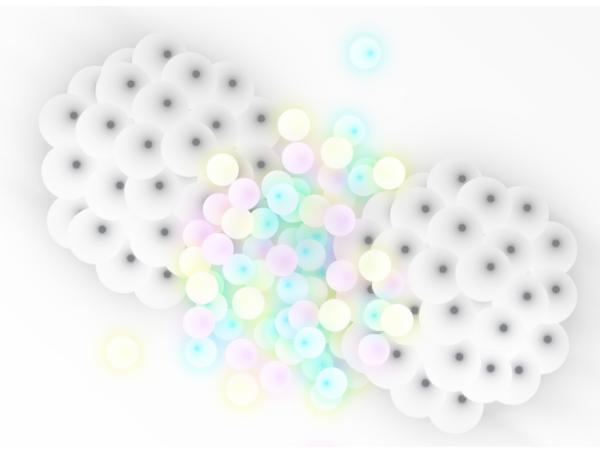
Centrality Classes



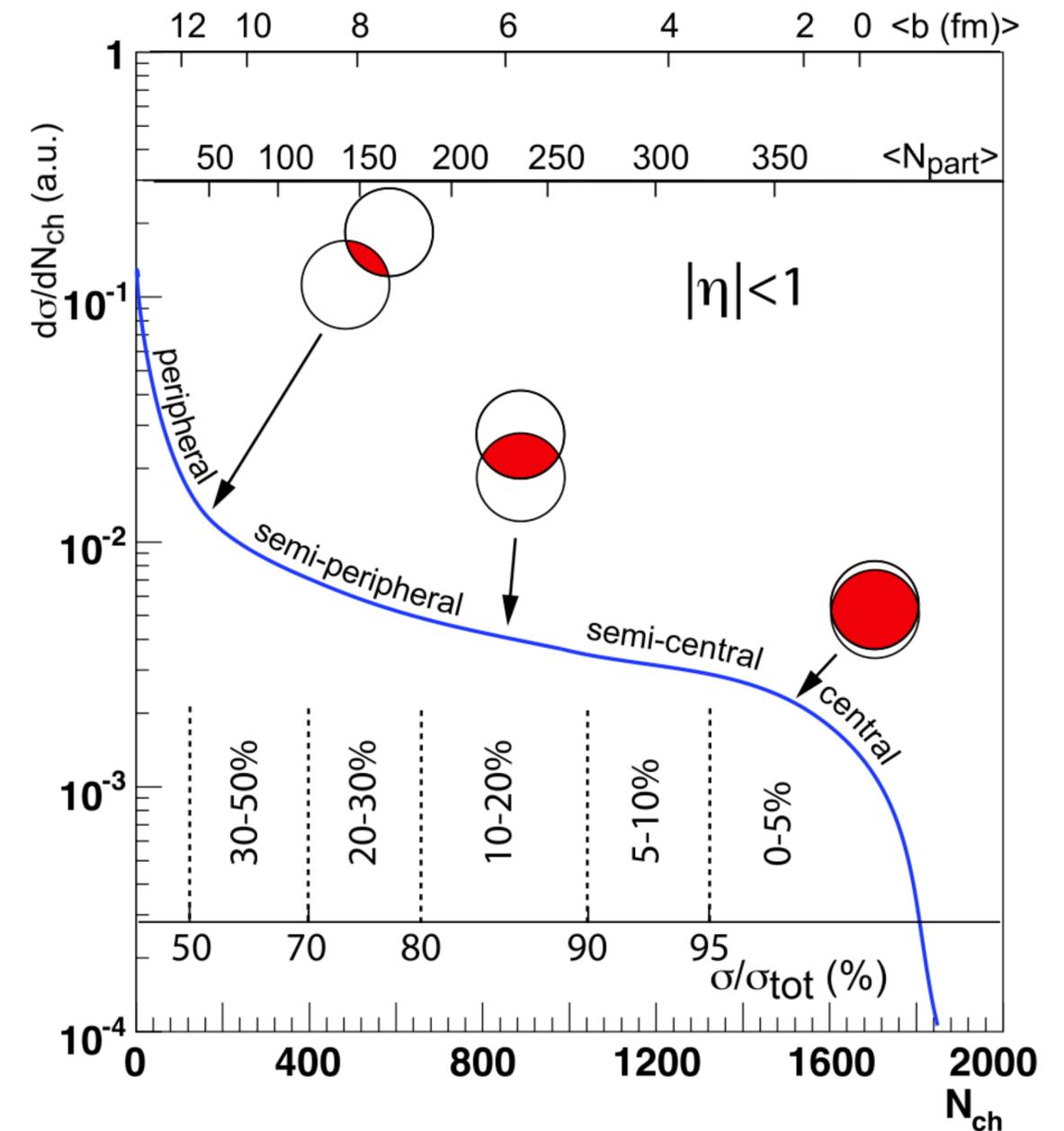
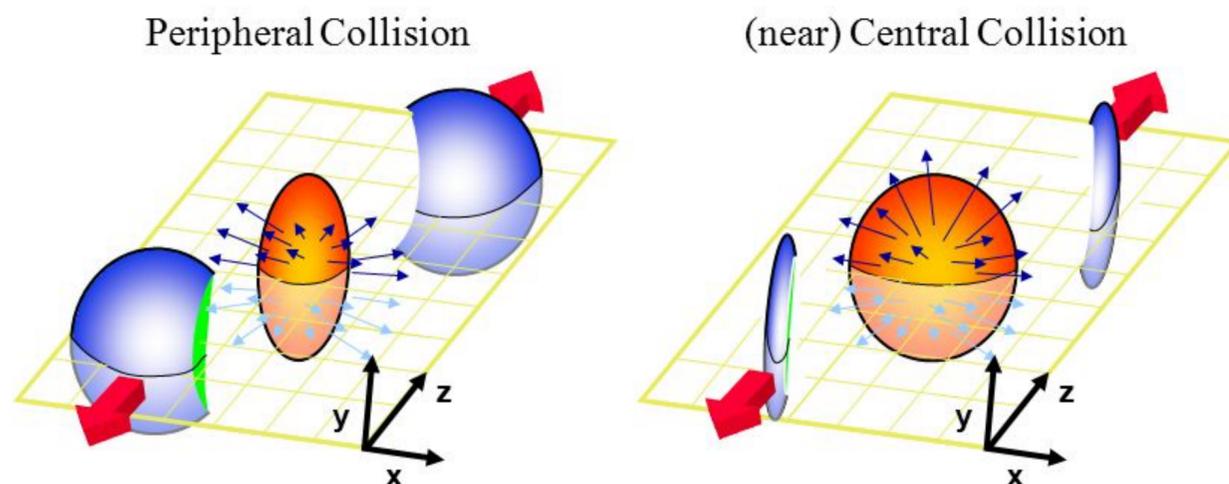
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 - Number of produced particles



Centrality Classes



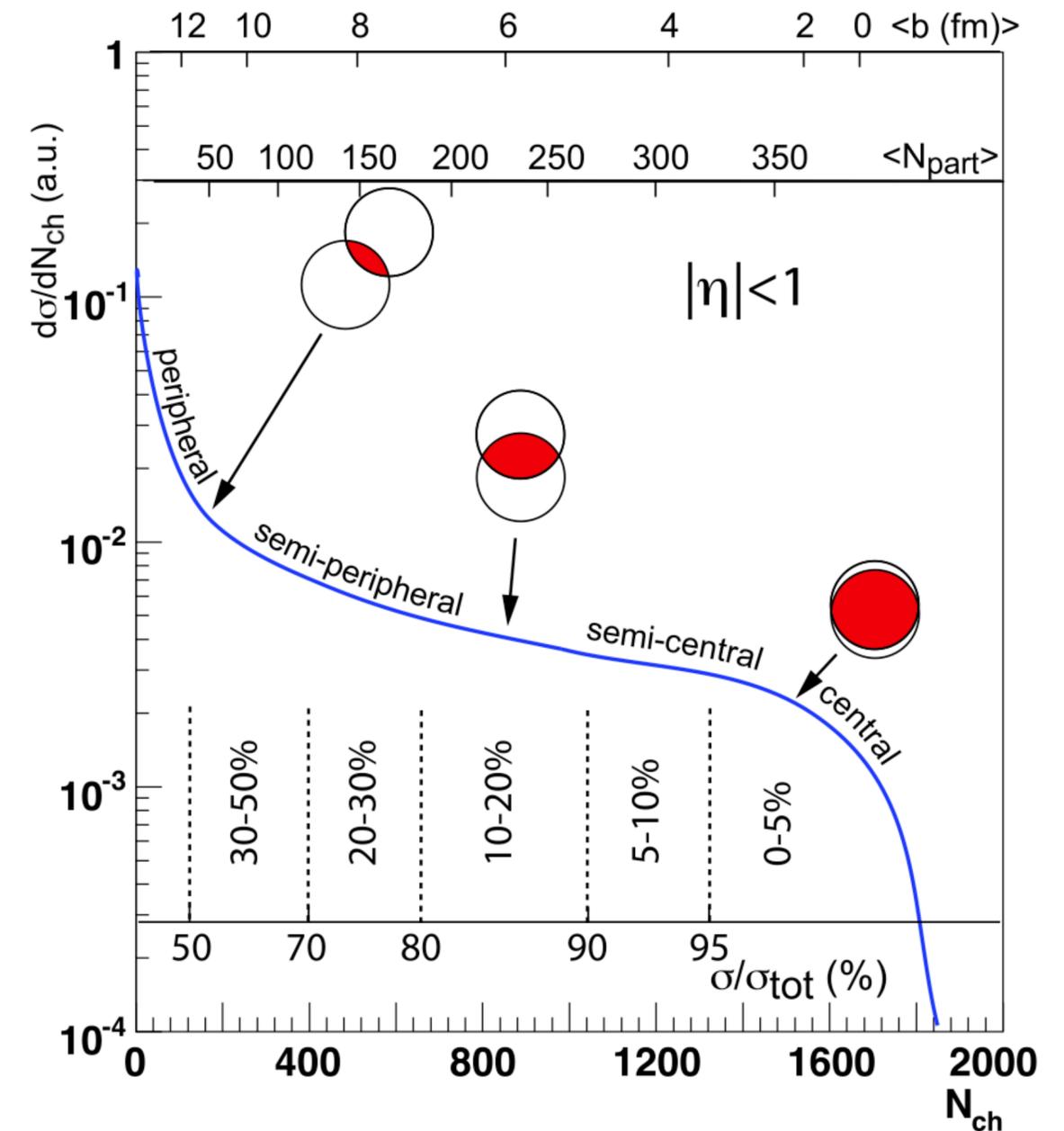
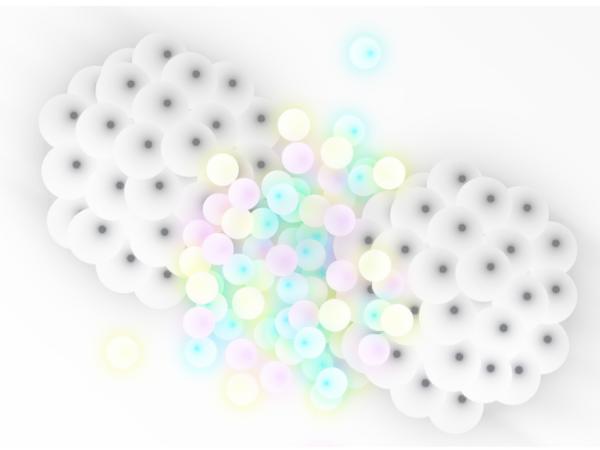
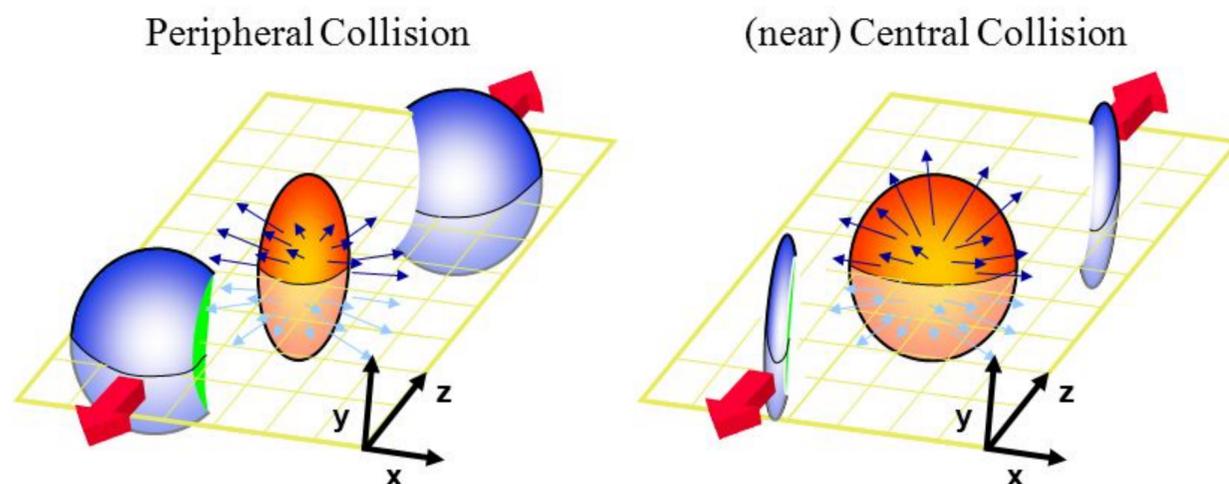
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 - Centrality class defined as percentile ranges of minimum-bias cross section



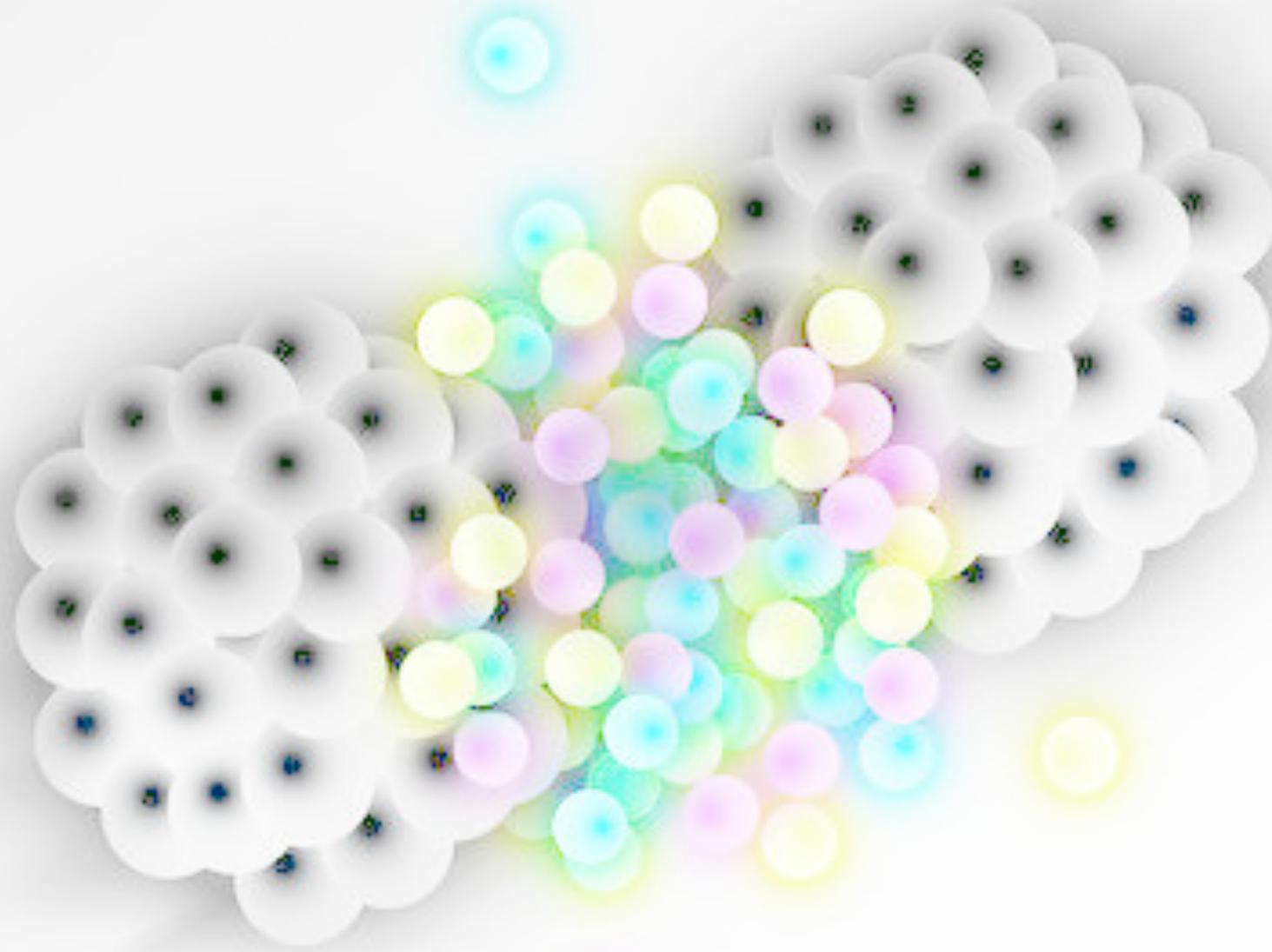
Centrality Classes

See Gian Michele's lectures

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 - Number of produced particles
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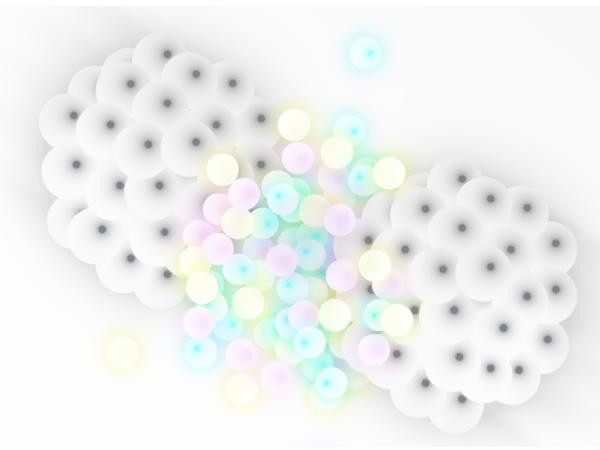
Macroscopic view:



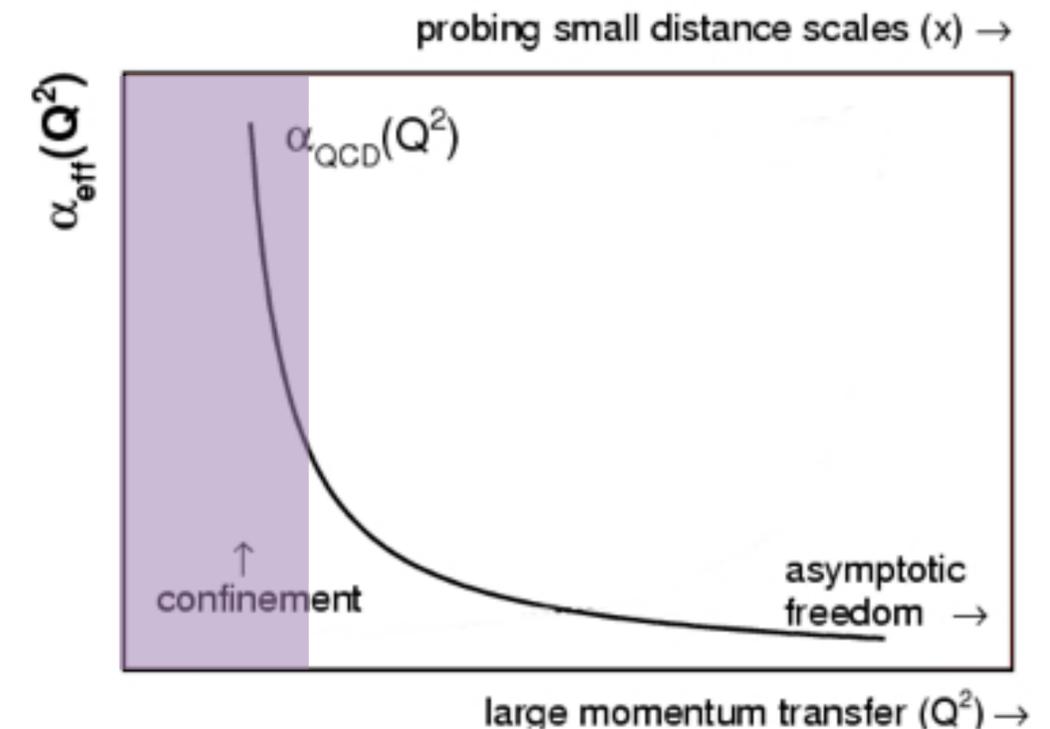
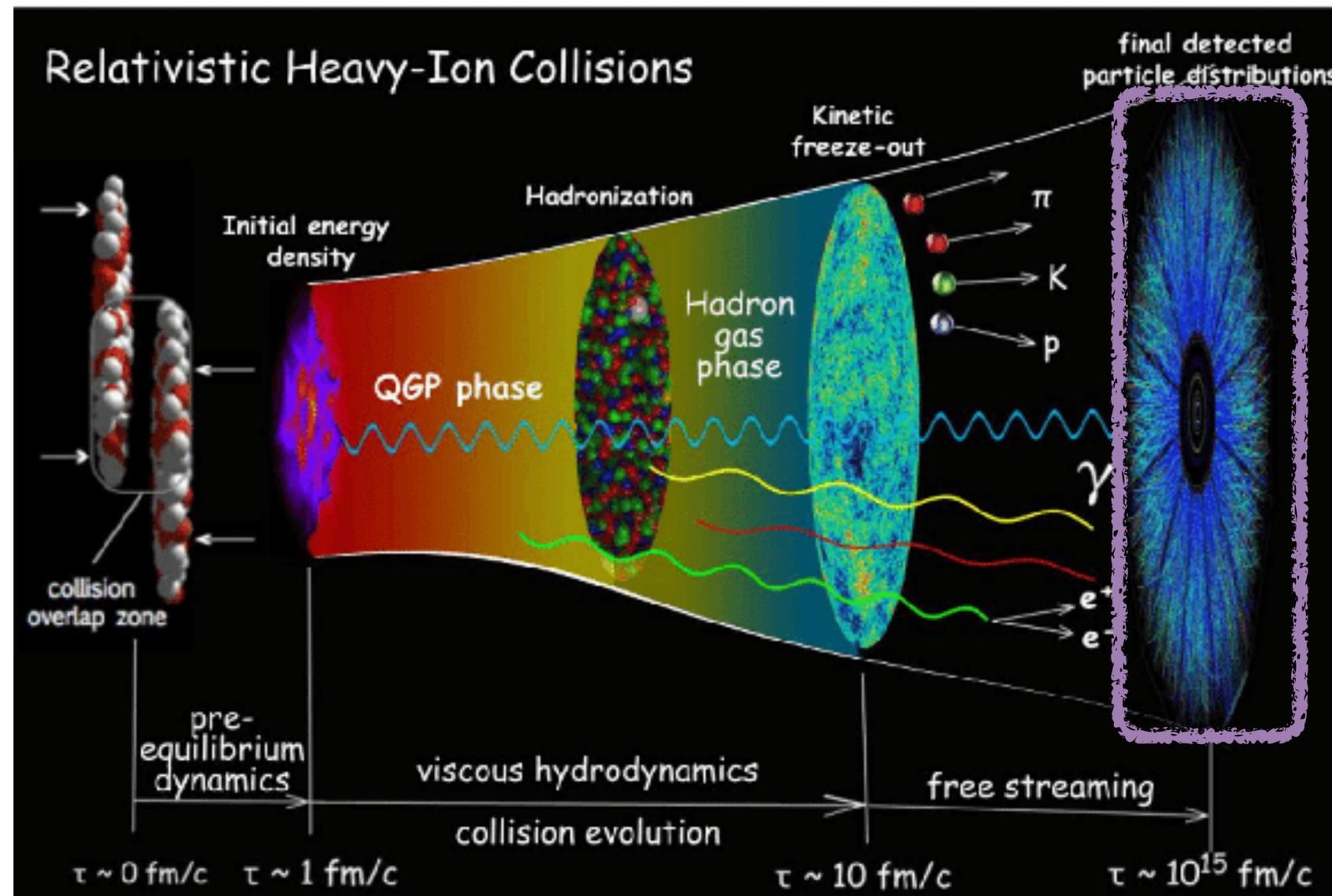
Soft Probes



Heavy-Ion Collision bulk



- Collection of final-state particles that are the result of the QGP evolution



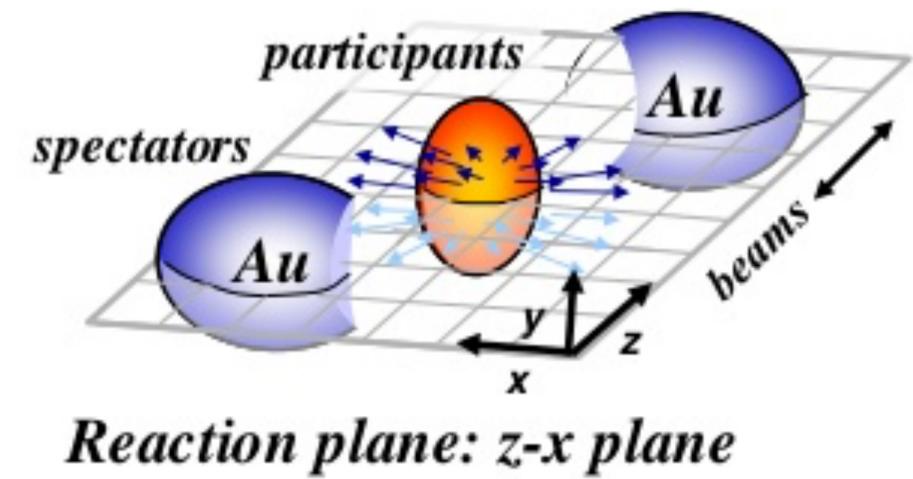
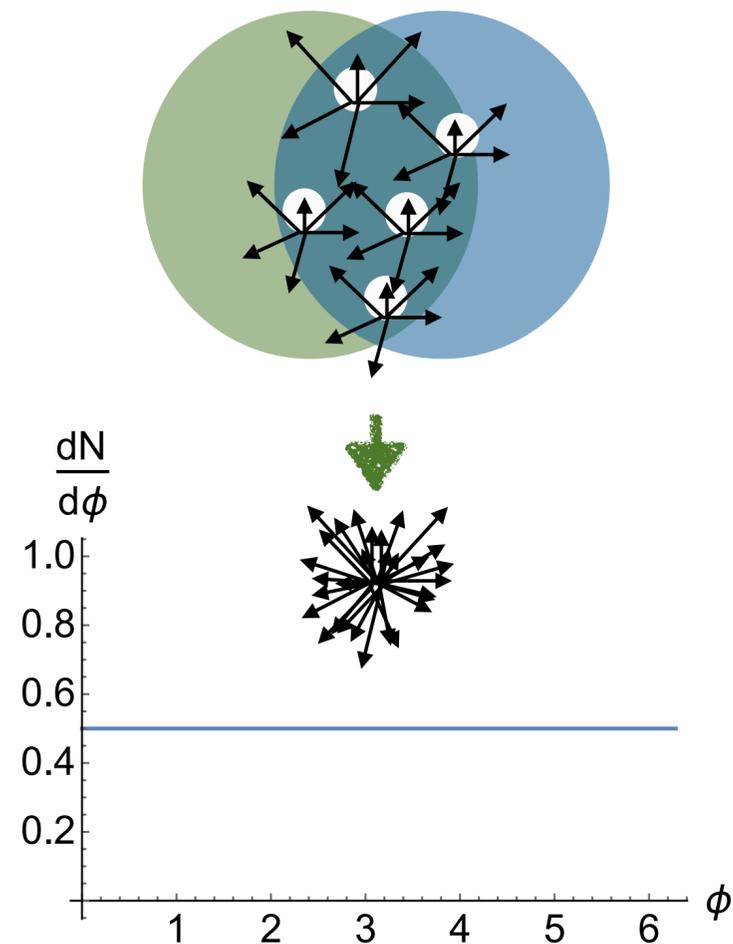
Soft probes
non-pQCD

Sensitive to global
properties of the QGP

From central to peripheral

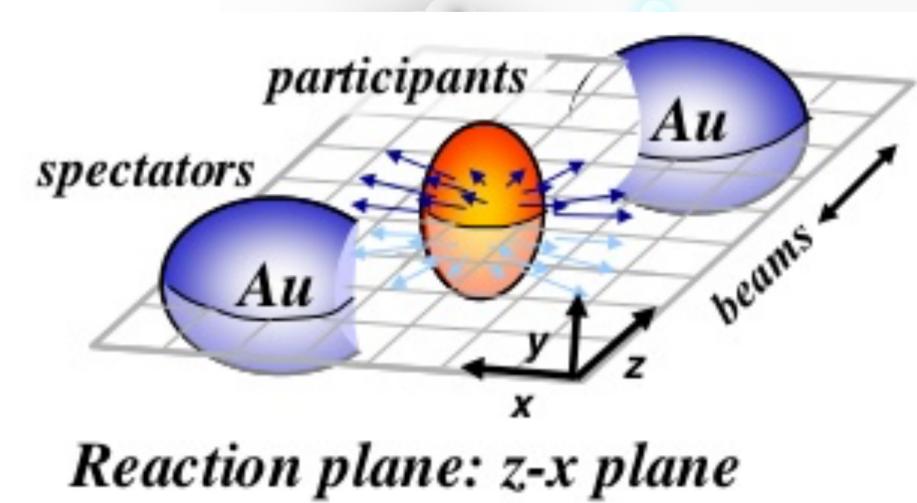
- Try different centralities and check response of the system to initial spatial anisotropy:

Superposition of multiple pp collisions

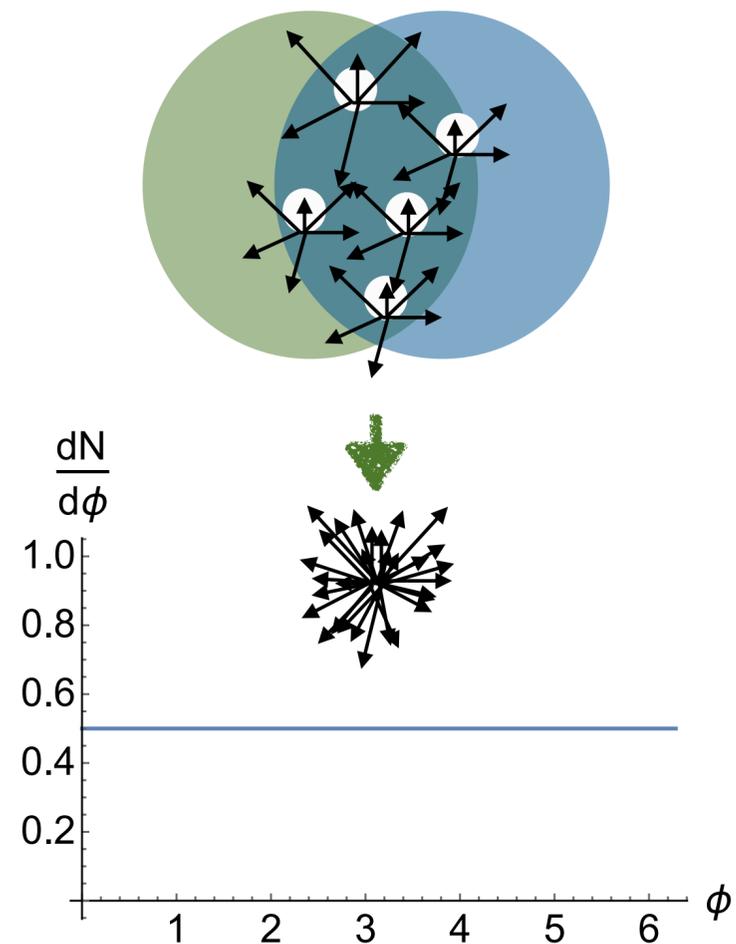


From central to peripheral

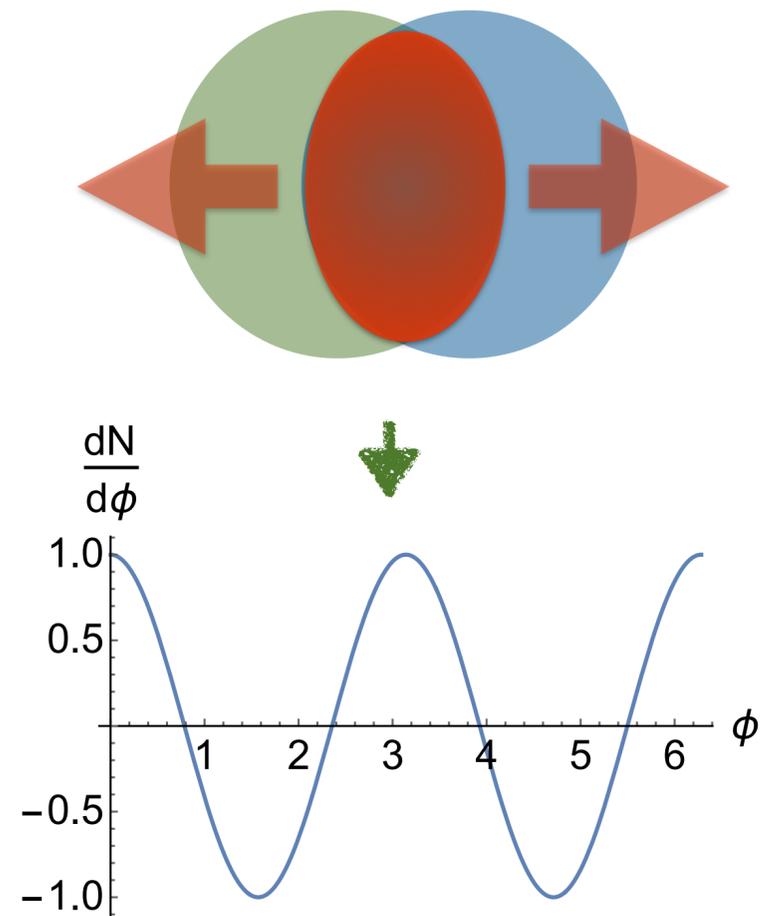
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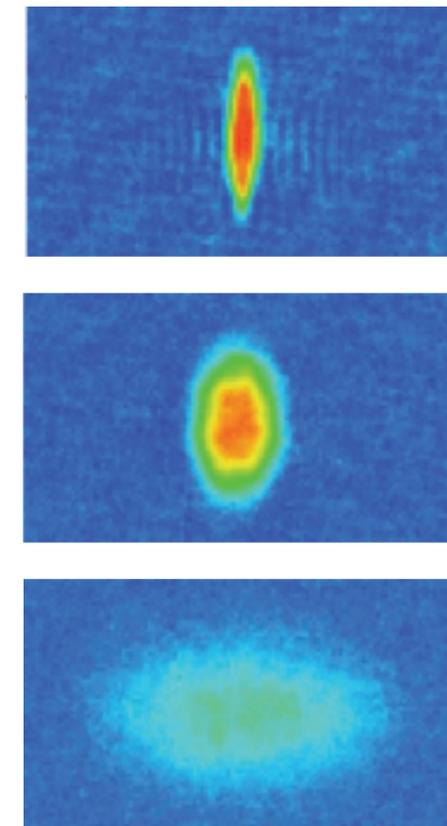
Superposition of multiple pp collisions



Collective bulk behaviour

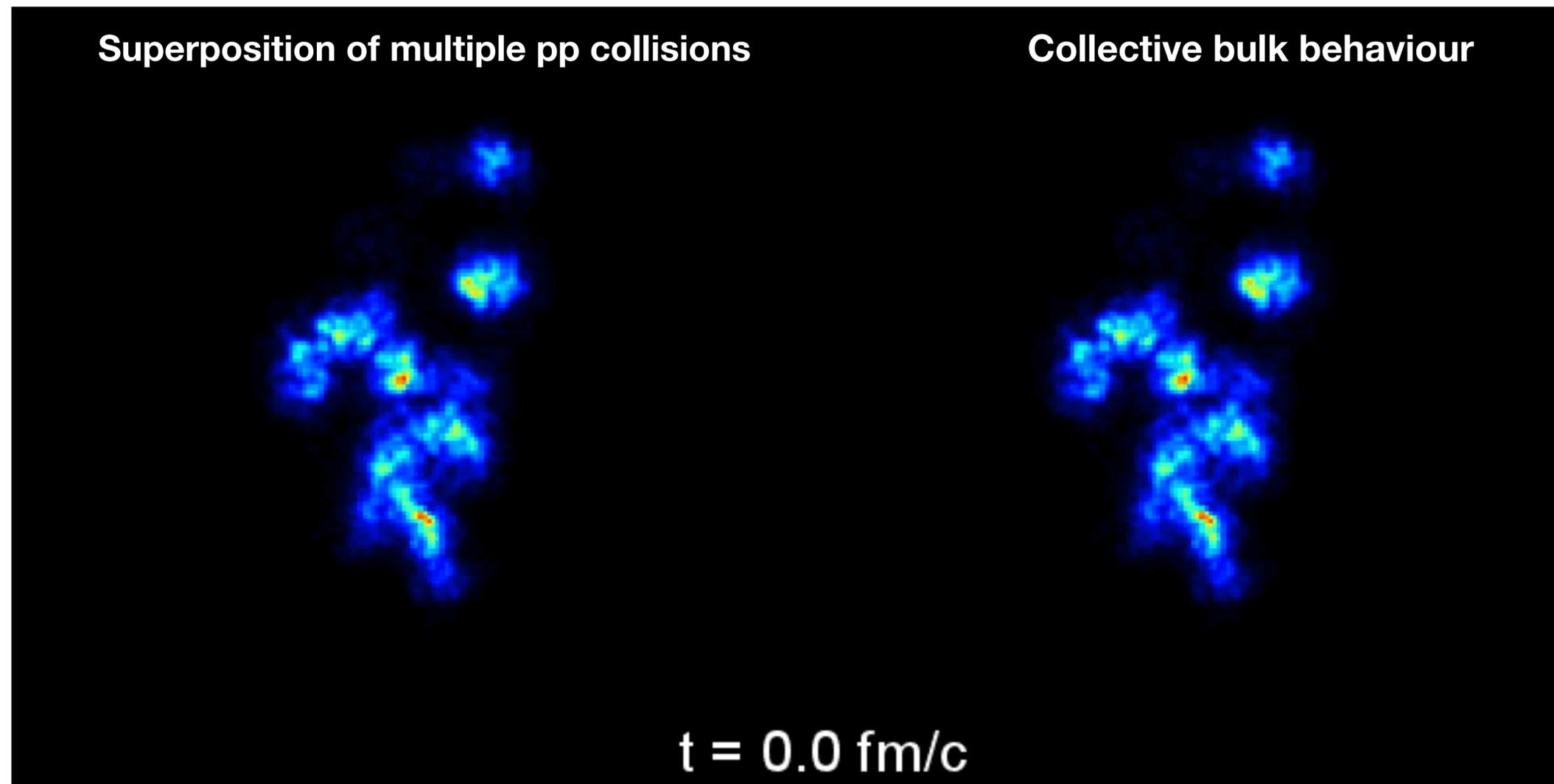
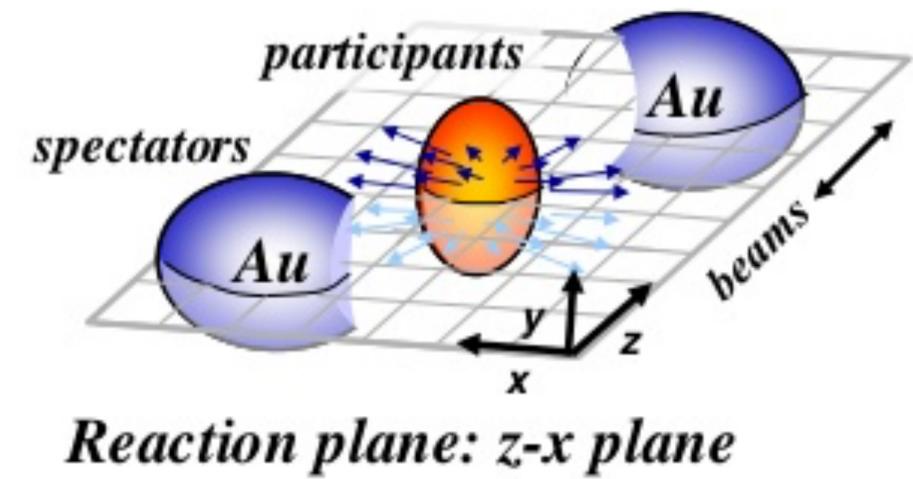


Pressure driven expansion:



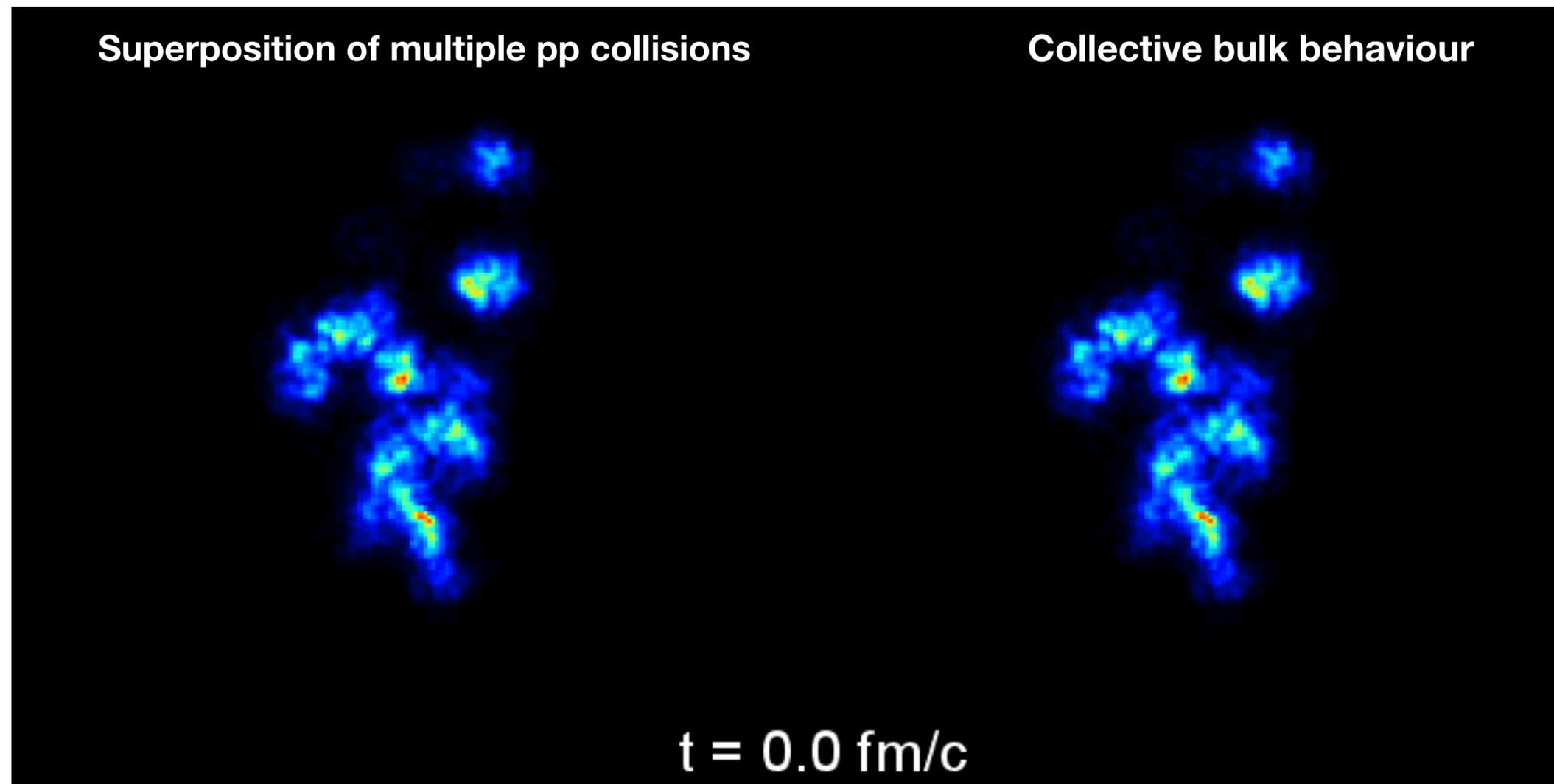
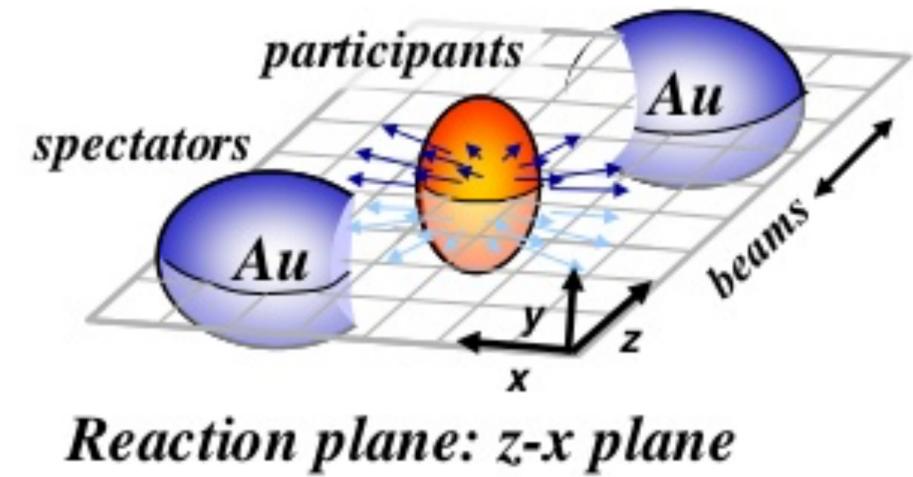
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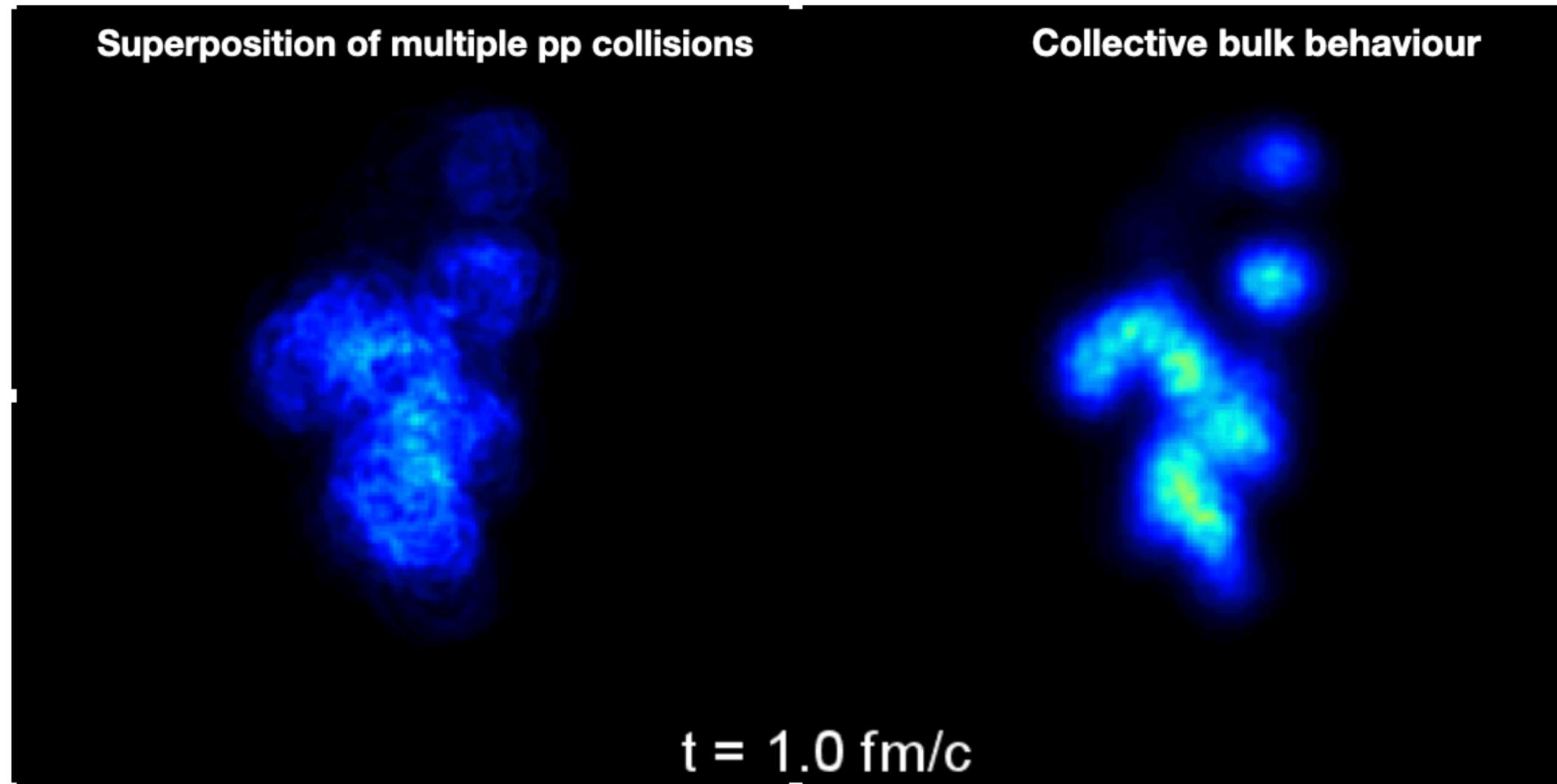
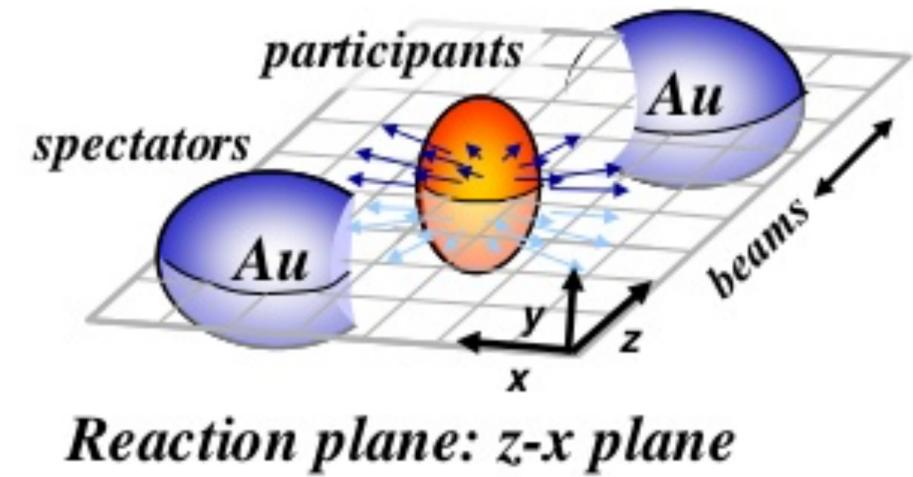
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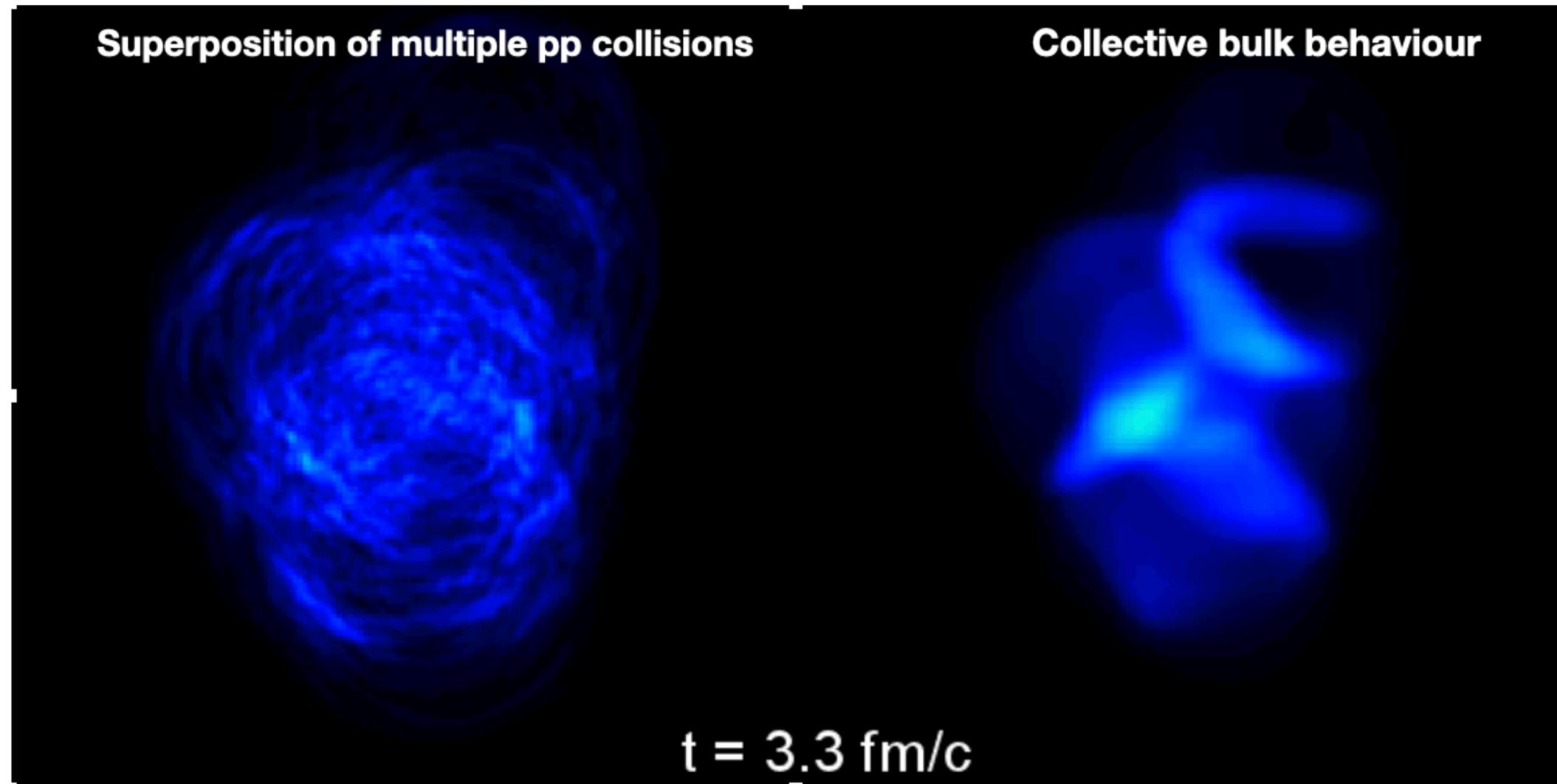
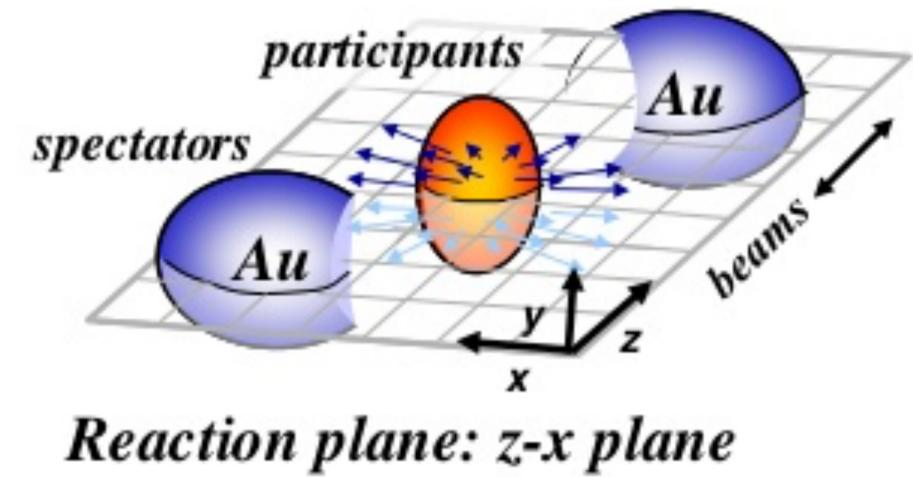
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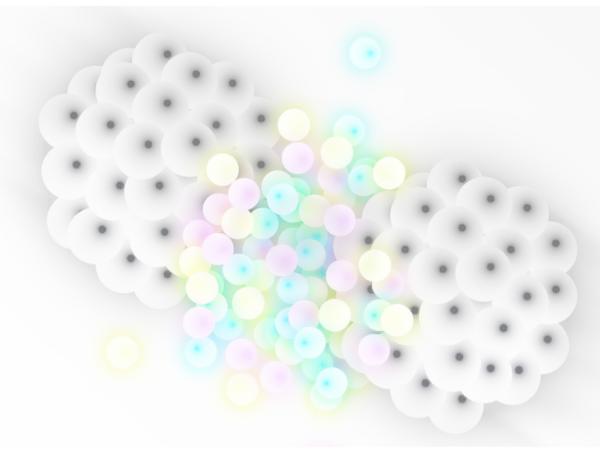


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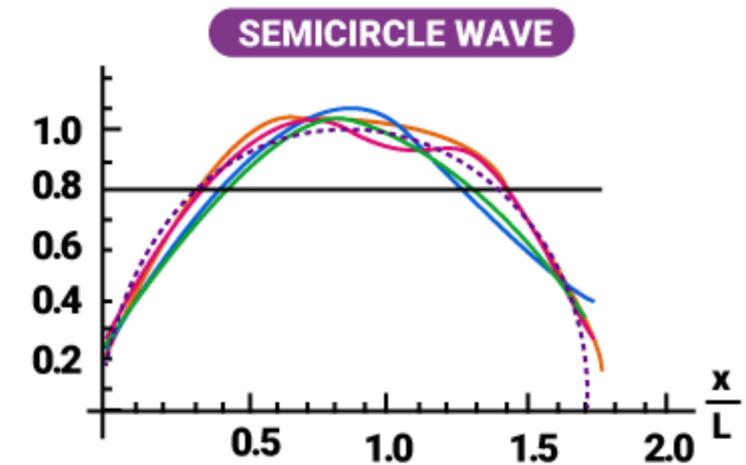
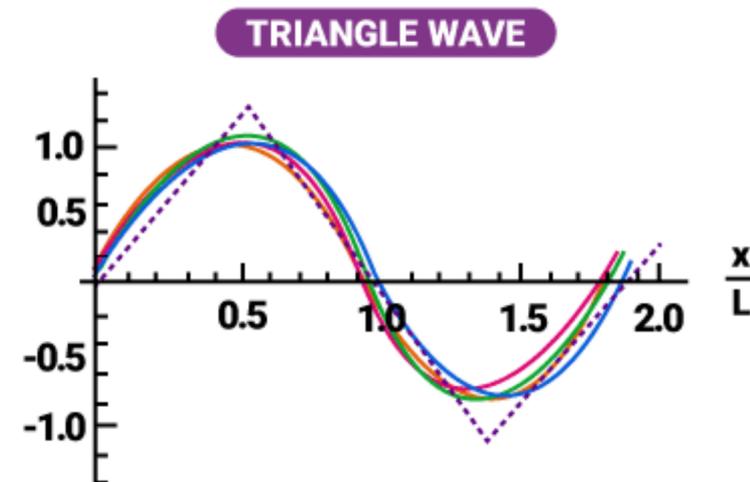
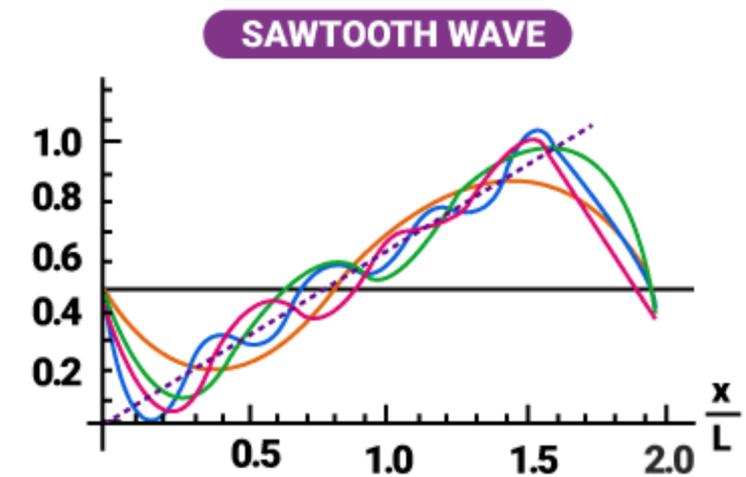
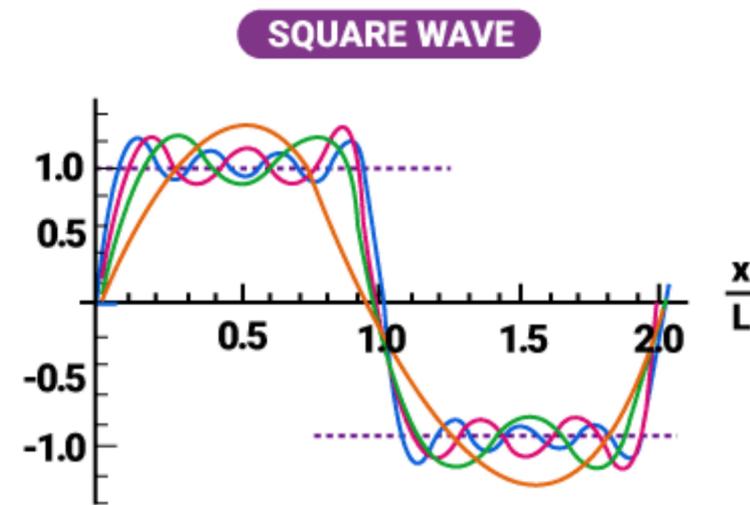
Spatial anisotropies



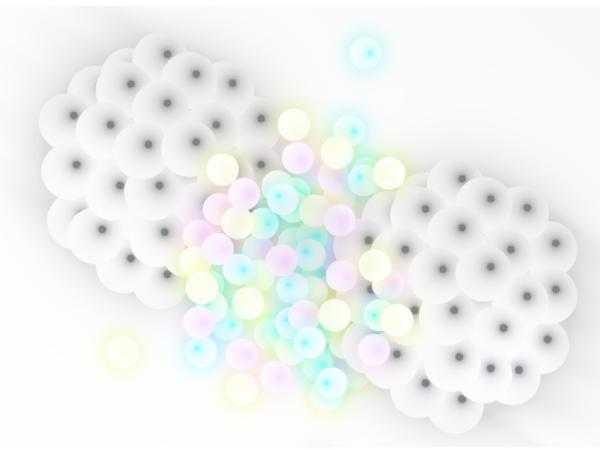
- Quantification through Fourier transformation of the particles angular distribution:

$$\frac{dN}{d\phi} = \frac{N}{2\pi} \left(1 + 2 \sum_{n=1}^{\infty} \nu_n \cos(n(\phi - \Psi_n)) \right)$$

Fourier parameterisations:



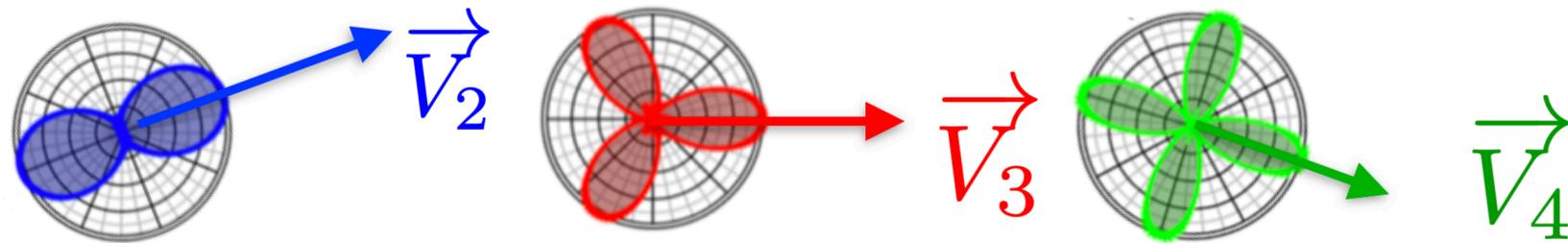
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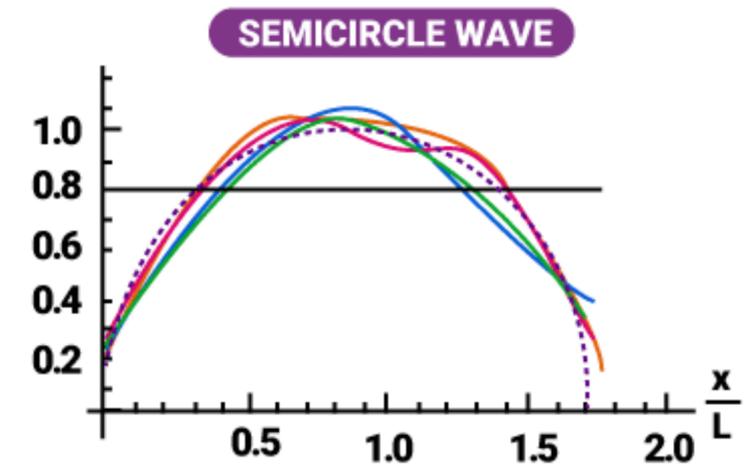
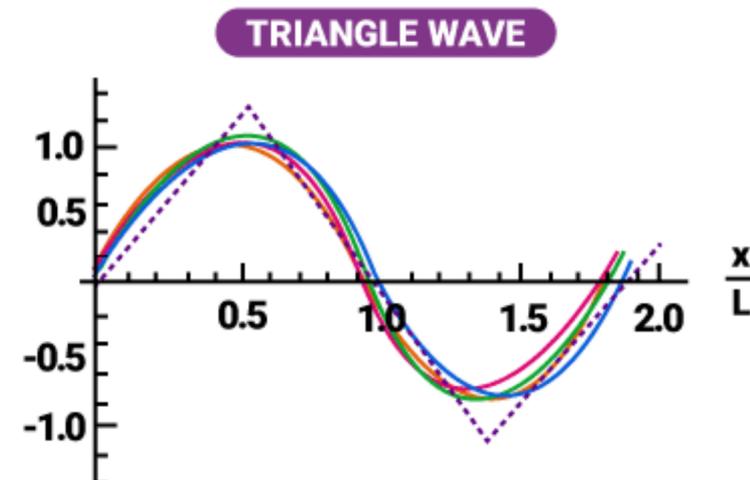
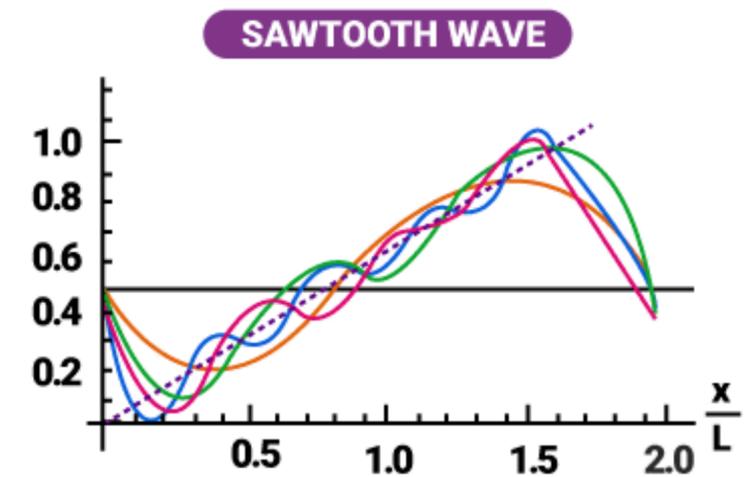
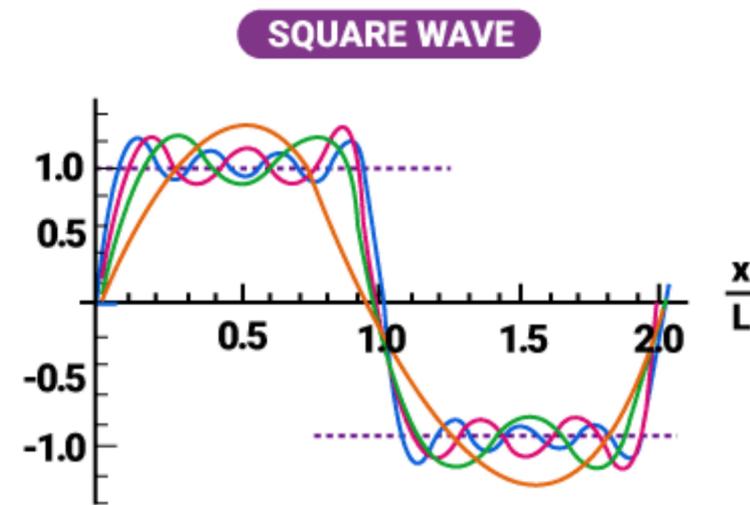
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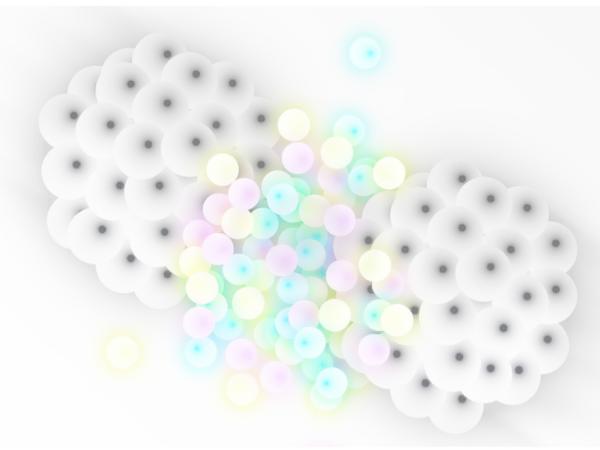
Reaction plane angle
(where the n th harmonic component has its maximum multiplicity)



Fourier parameterisations:



Spatial anisotropies

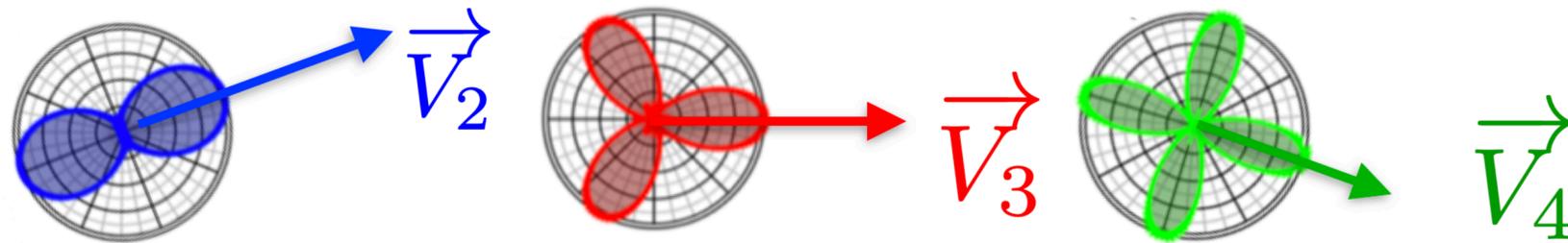


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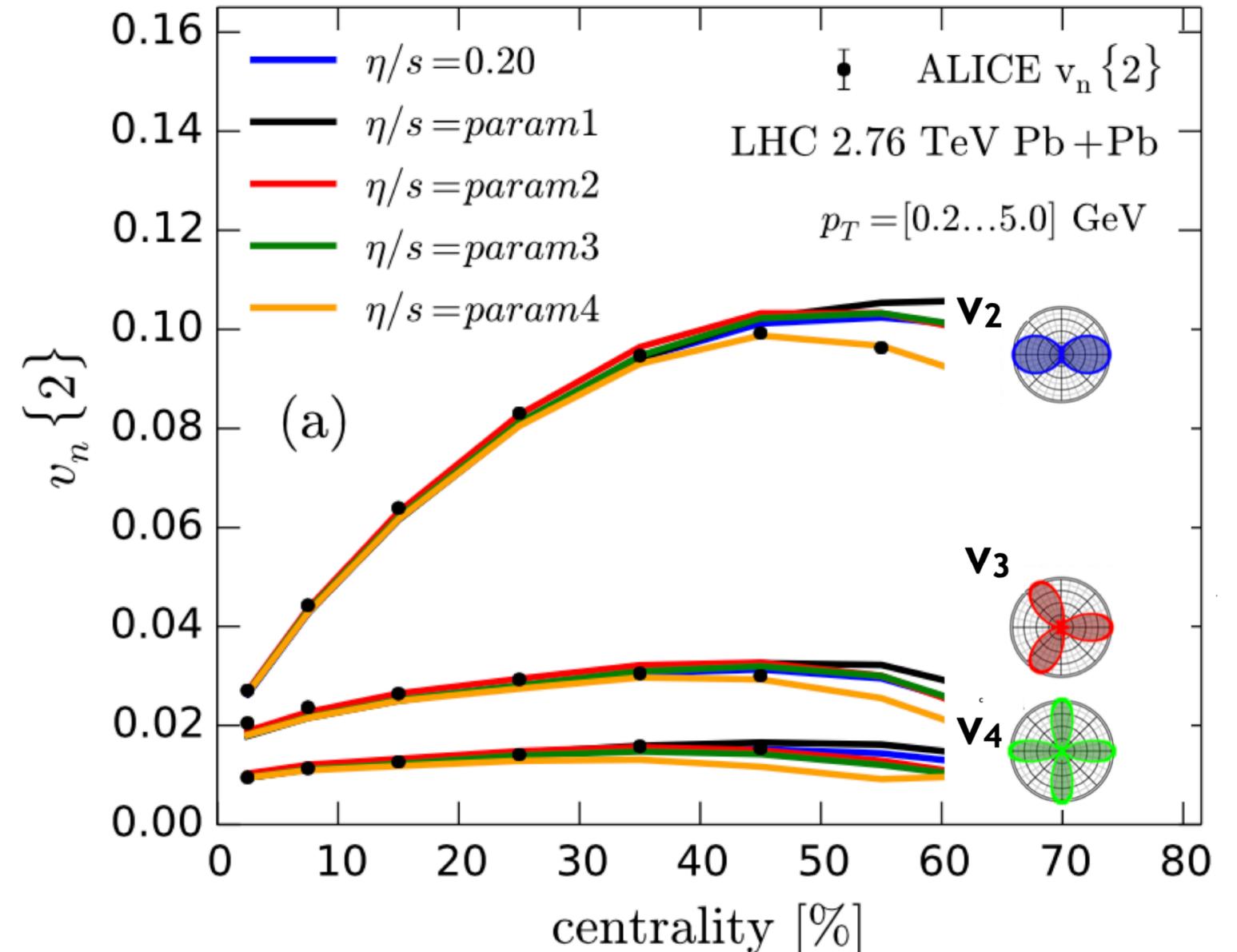


From charged multiplicity, extract elliptic (v_2), triangular (v_3),... flow coefficients

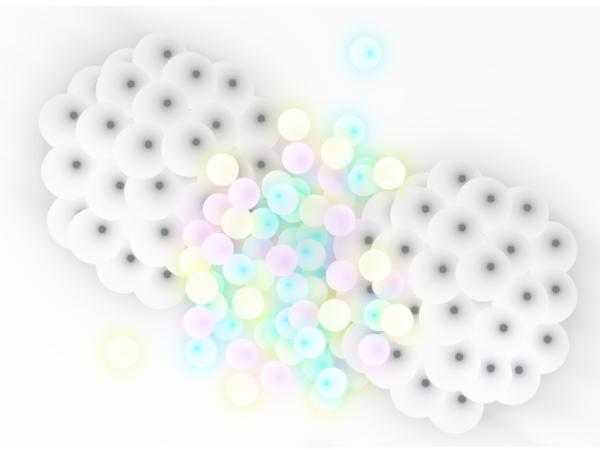
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...

[Busza et al (1802.04801)]



Spatial anisotropies

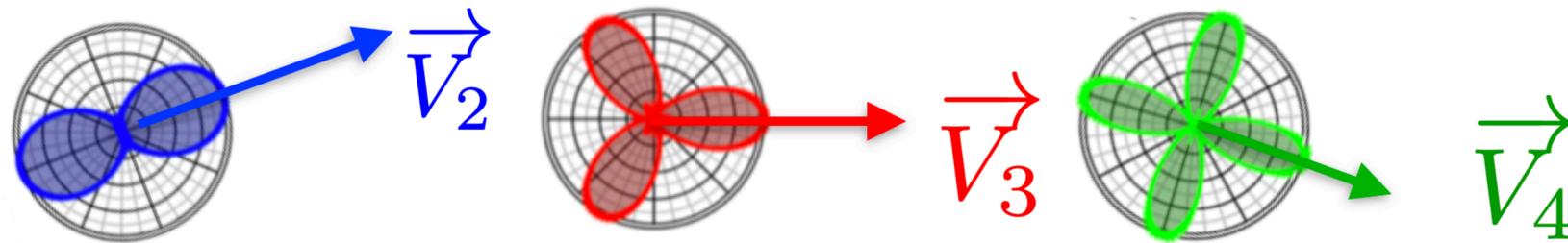


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Reaction plane angle

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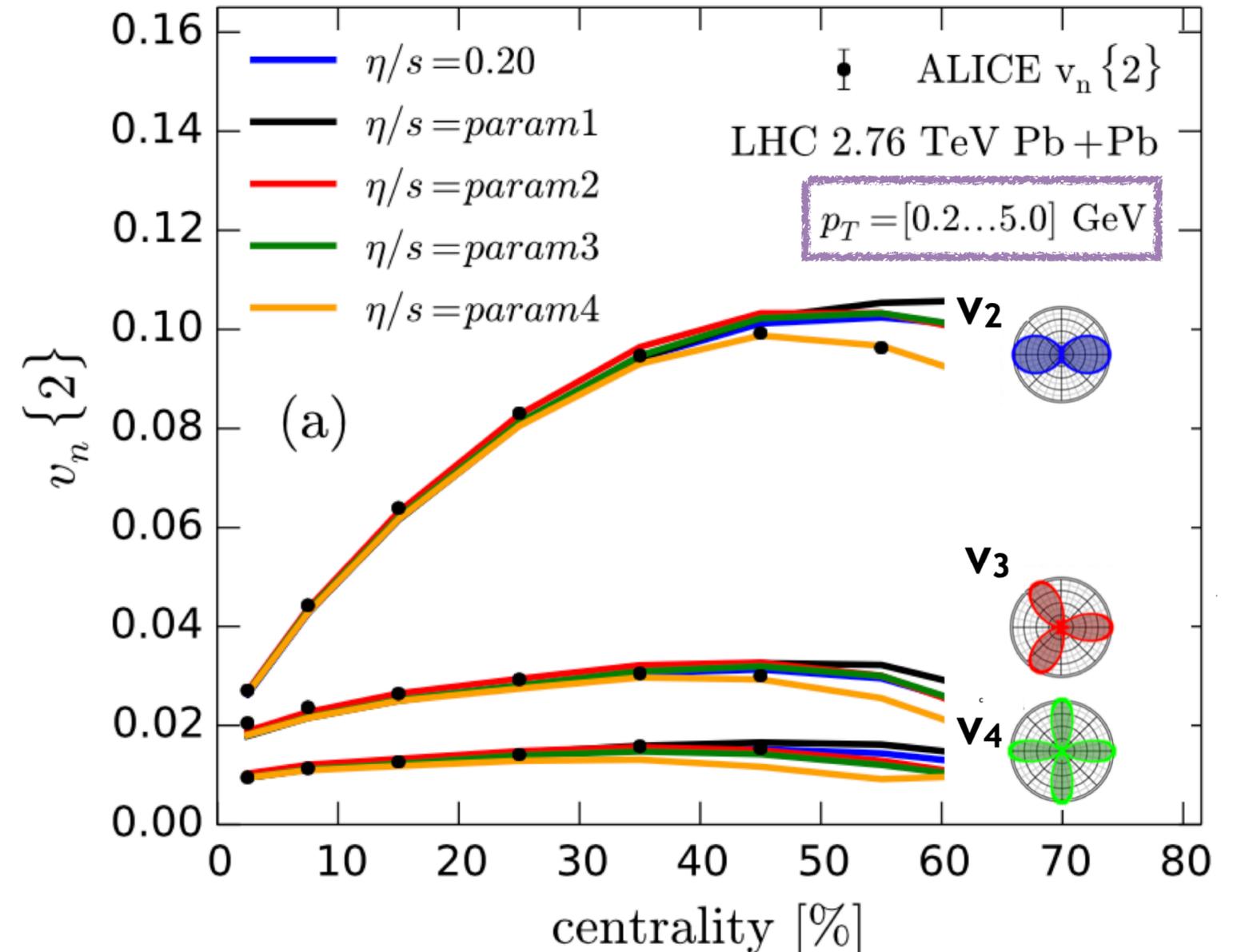


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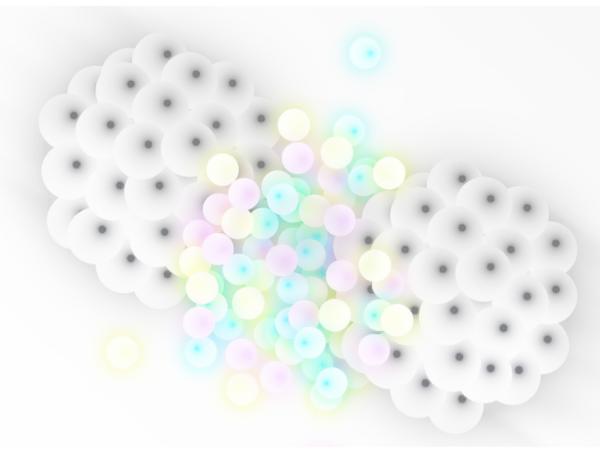
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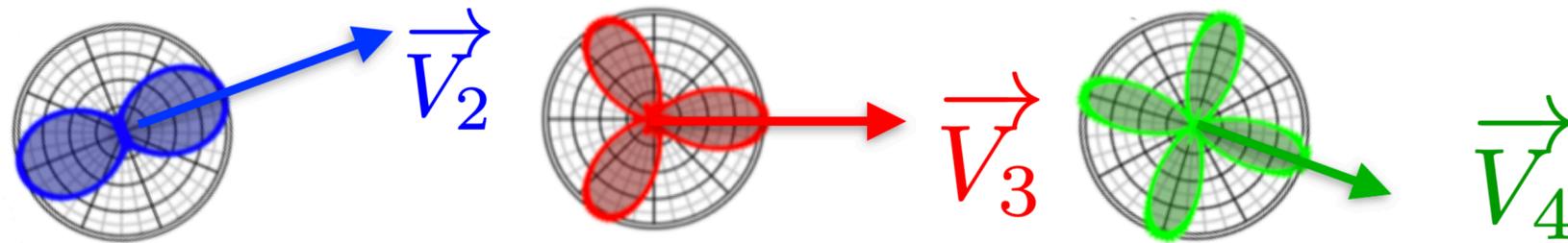


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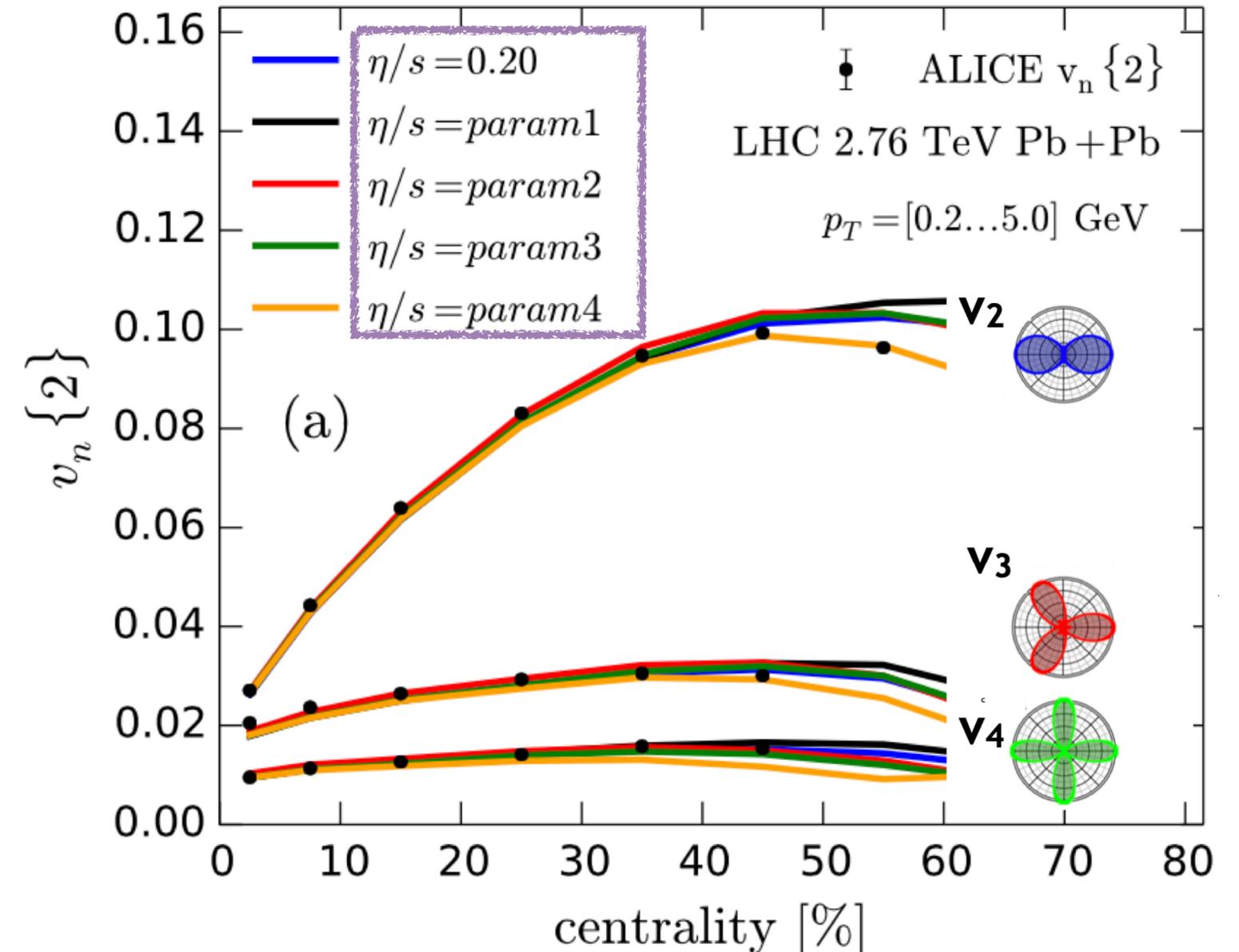


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Hydrodynamics

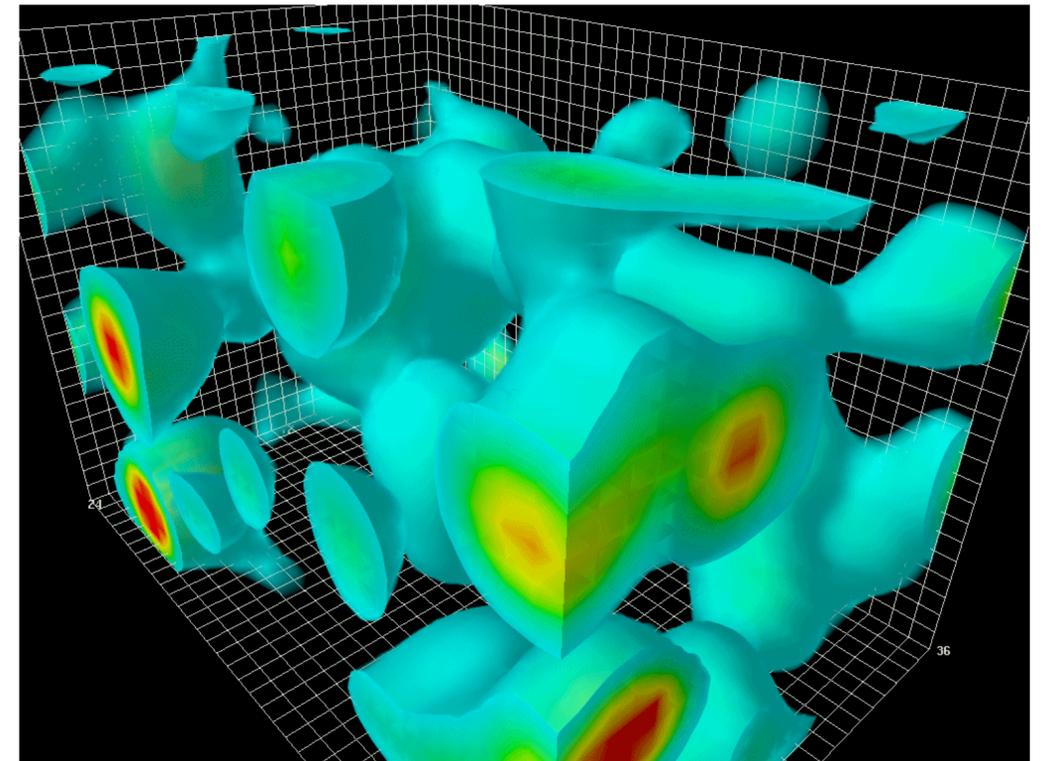
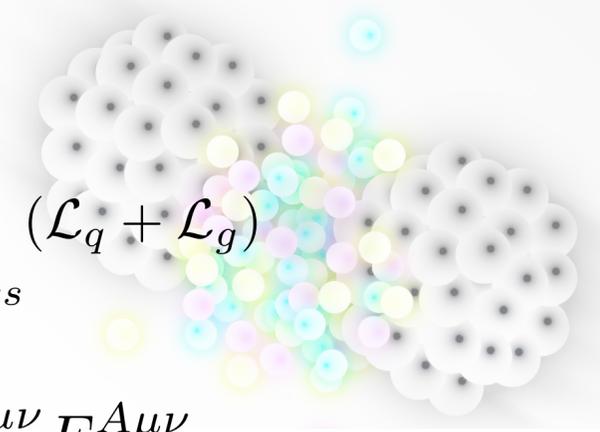
- Why hydrodynamics?

- Complicated to withdraw information from QCD Lagrangian...

$$\mathcal{L}_{QCD} = \sum_{flavours} (\mathcal{L}_q + \mathcal{L}_g)$$

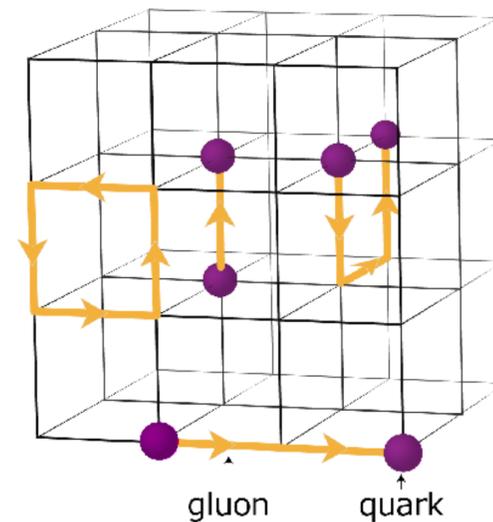
$$\mathcal{L}_g = -\frac{1}{4} F_A^{\mu\nu} F_A^{\mu\nu}$$

$$\mathcal{L}_q = \bar{\psi}_a (i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t_{ab}^C A_\mu^C - m) \psi_b$$



Hydrodynamics

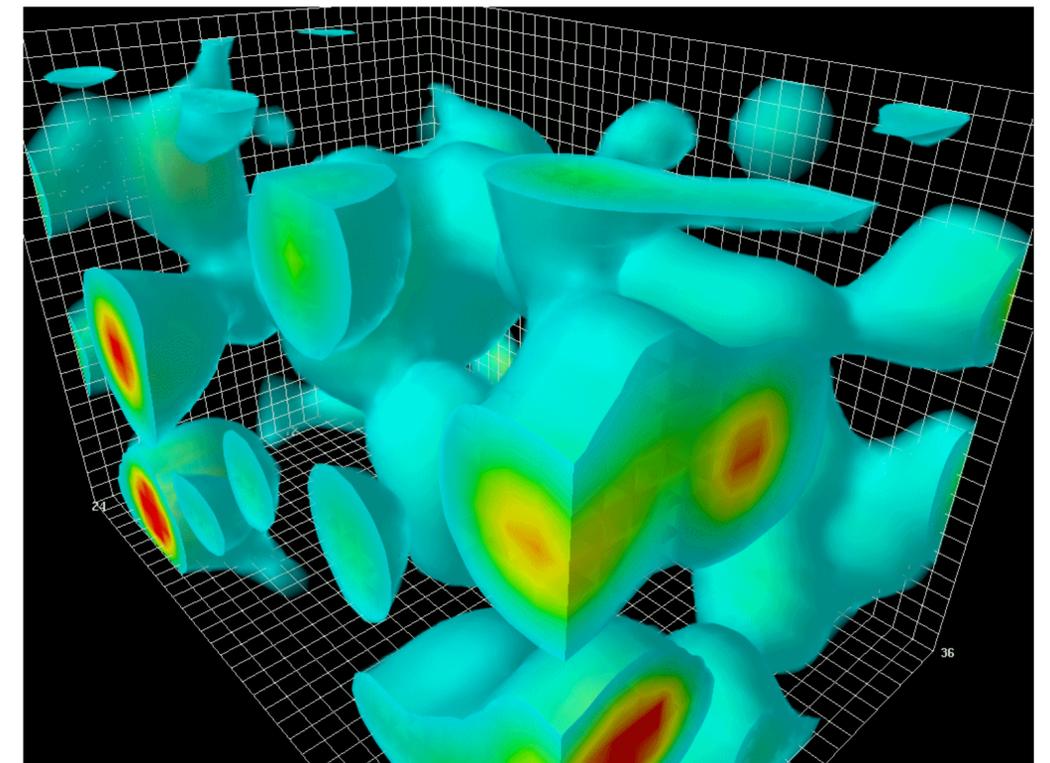
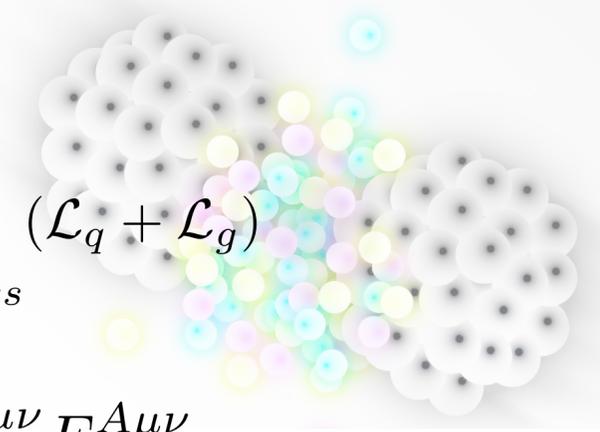
- Why hydrodynamics?
 - Complicated to withdraw information from QCD Lagrangian...
 - Lattice QCD:
 - Discretise space-time and evaluate numerically the Lagrangian
 - Use Monte Carlo sampling to obtain the relative likelihood of all possible configurations
 - Excellent tool to calculate static properties but it is computational demanding for high-energy processes



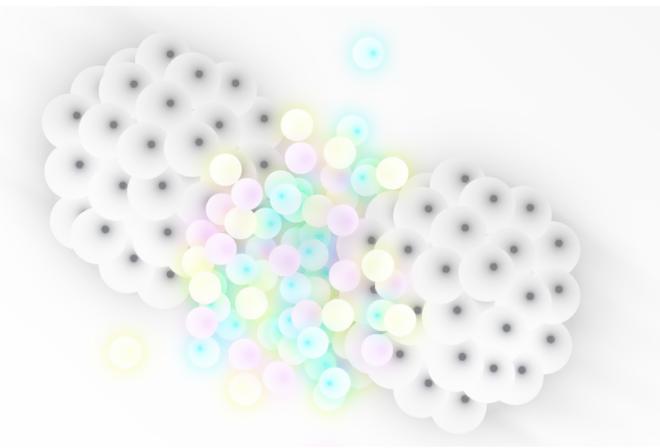
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Hydrodynamics



- Why hydrodynamics?
 - Effective theory that describes extremely well QGP phenomena
 - Input includes the Equation-of-State (EoS)

Energy-momentum tensor (ideal hydro):

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

Velocity

EoS (ideal hydro):

$$p = p(\epsilon)$$

Pressure

Energy density

Energy-momentum conservation:

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

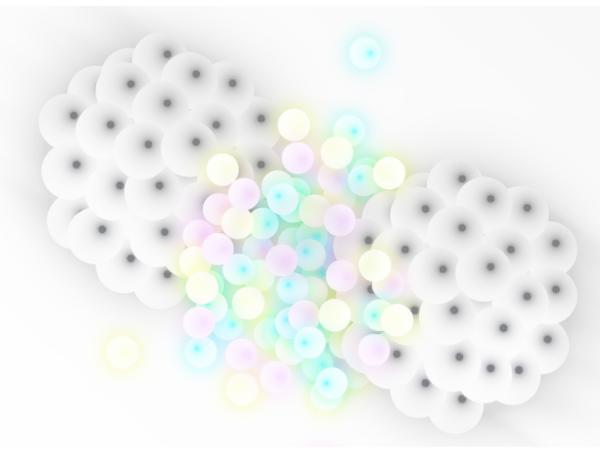
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Hydrodynamic evolution equations

Hydrodynamics



- Why hydrodynamics?
 - Effective theory that describes extremely well QGP phenomena
 - Input includes the Equation-of-State (EoS)
 - Provided by, e.g: Lattice QCD

Energy-momentum tensor:

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

EoS:

$$p = p(\epsilon, n)$$

Bulk viscous pressure

Shear viscous tensor

Charge density

Energy-momentum conservation:

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Current conservation:

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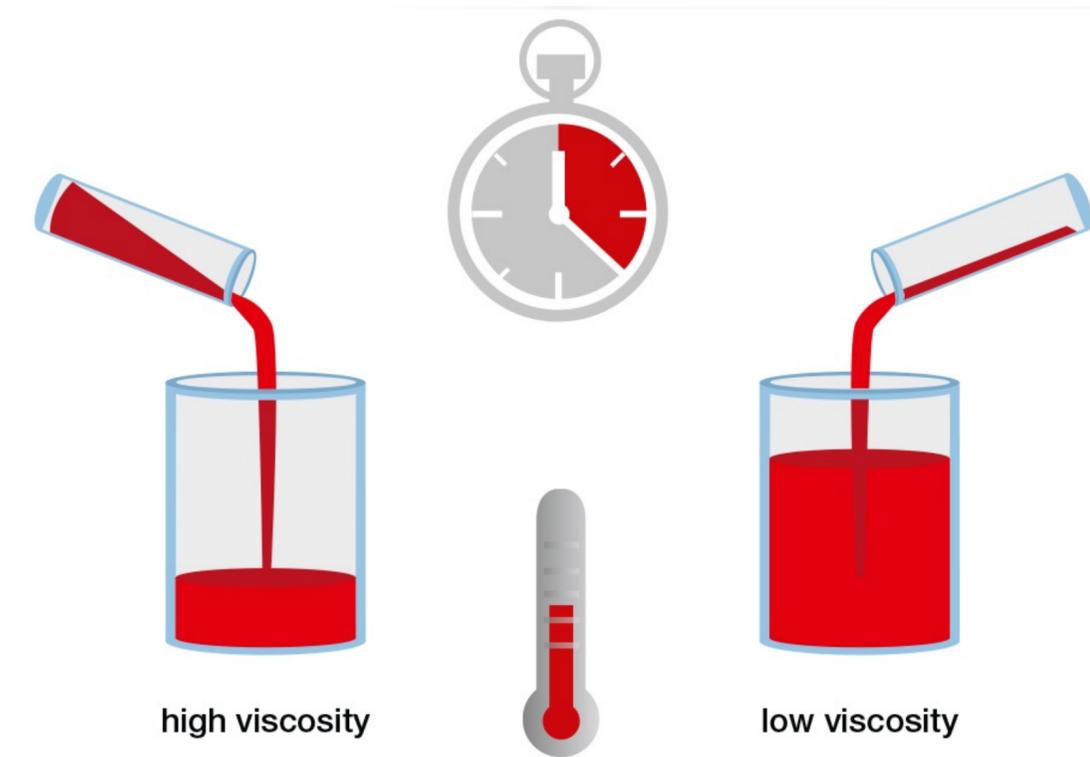
(More involving) 3+1 Hydrodynamic evolution equations

Deviations from ideal hydro (viscous hydro) include additional coefficients:

Shear viscosity η , bulk viscosity ζ , ...

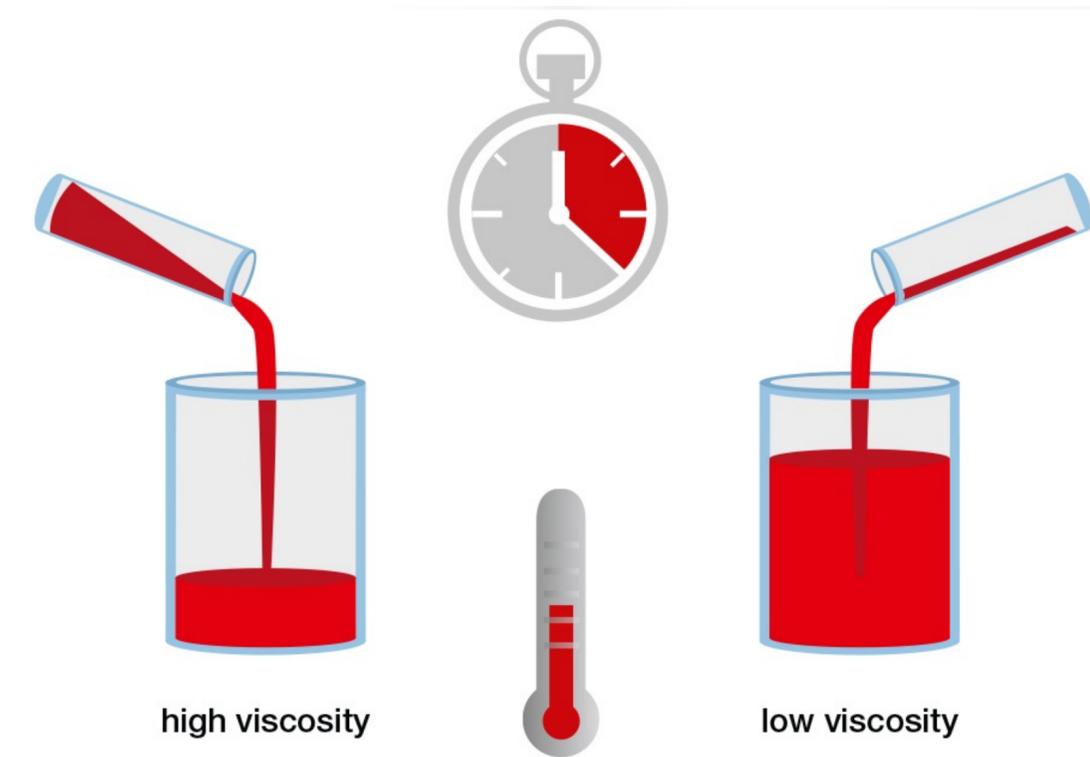
Specific Shear Viscosity η/s

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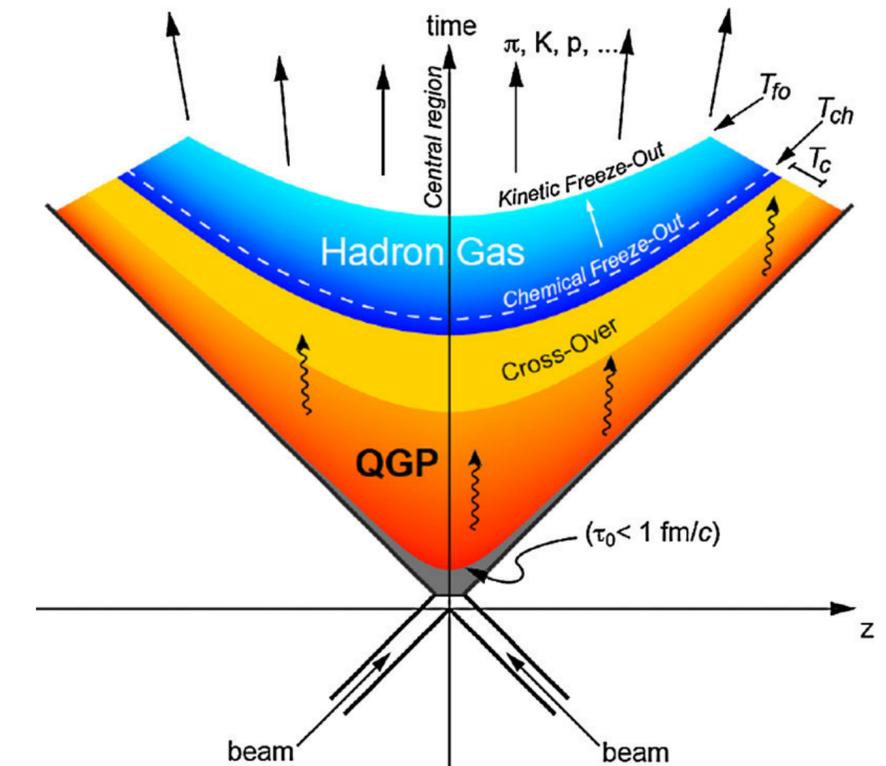
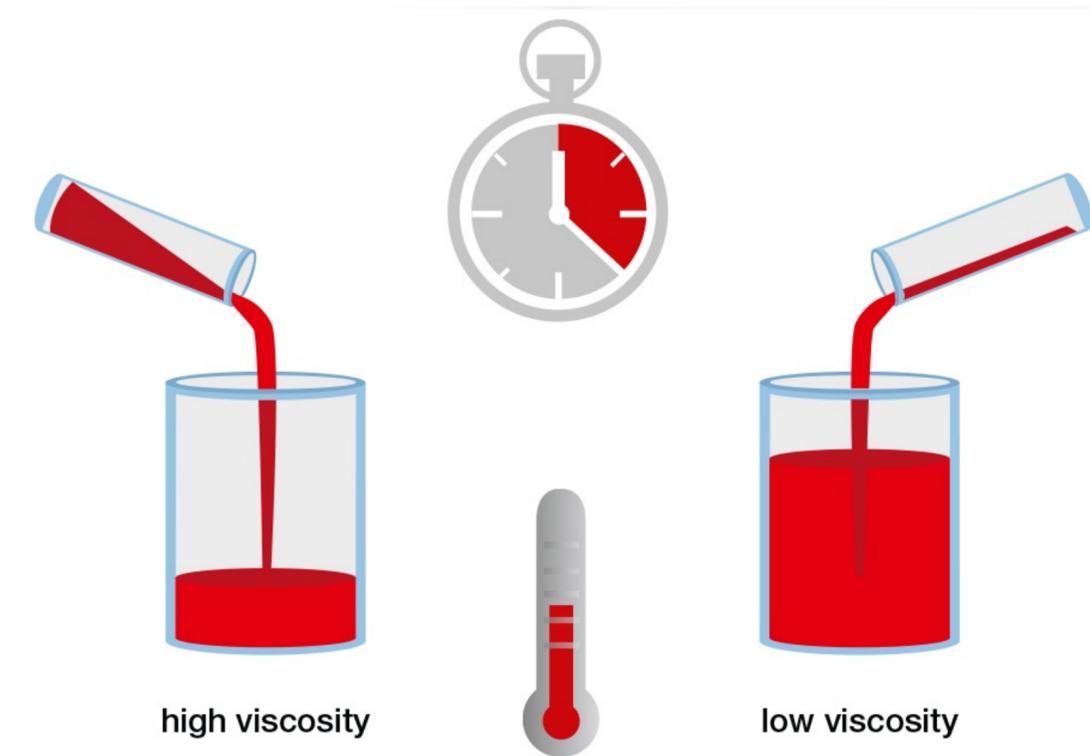
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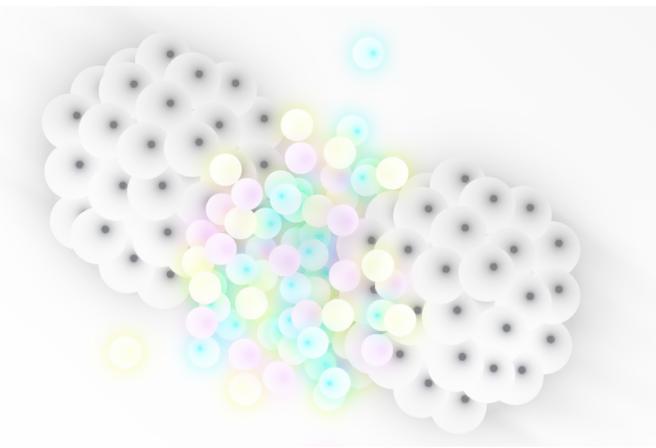
η/s + EoS + temperature dependence

⇒ Hydrodynamic calculation data comparison

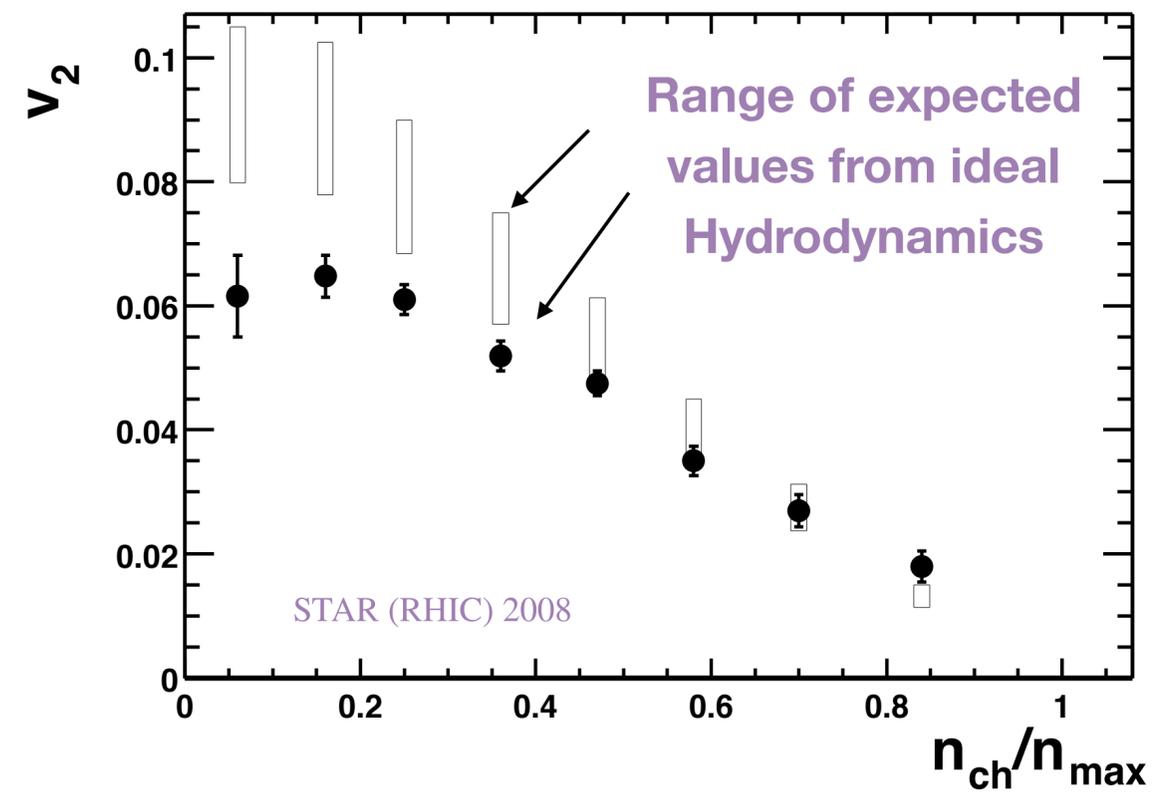
(With hadronic re-scattering after QGP)



QGP Fluidity



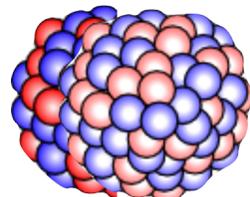
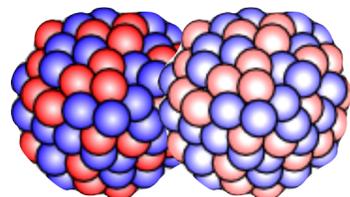
- QGP is an (almost) ideal fluid:



Peripheral

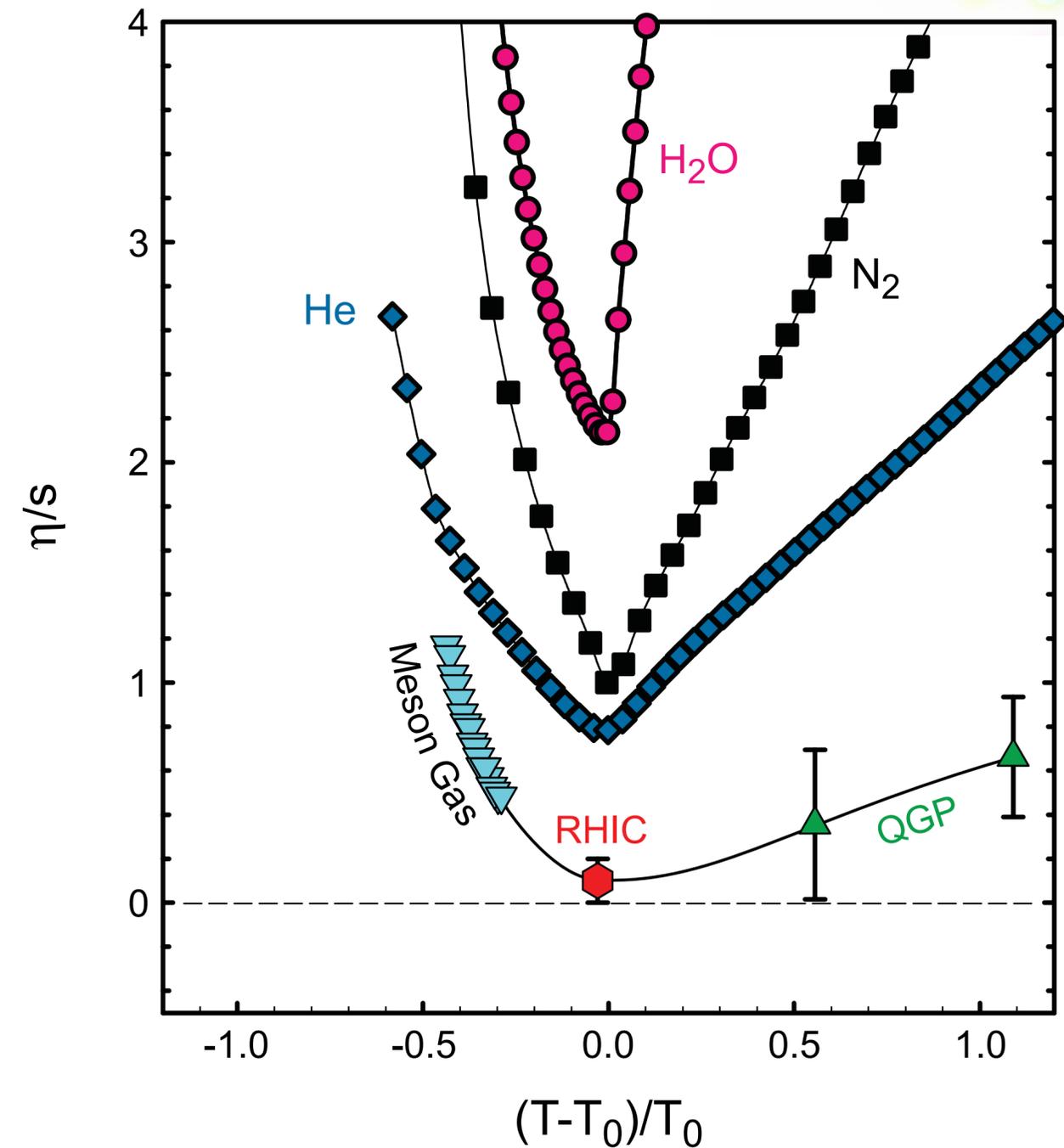
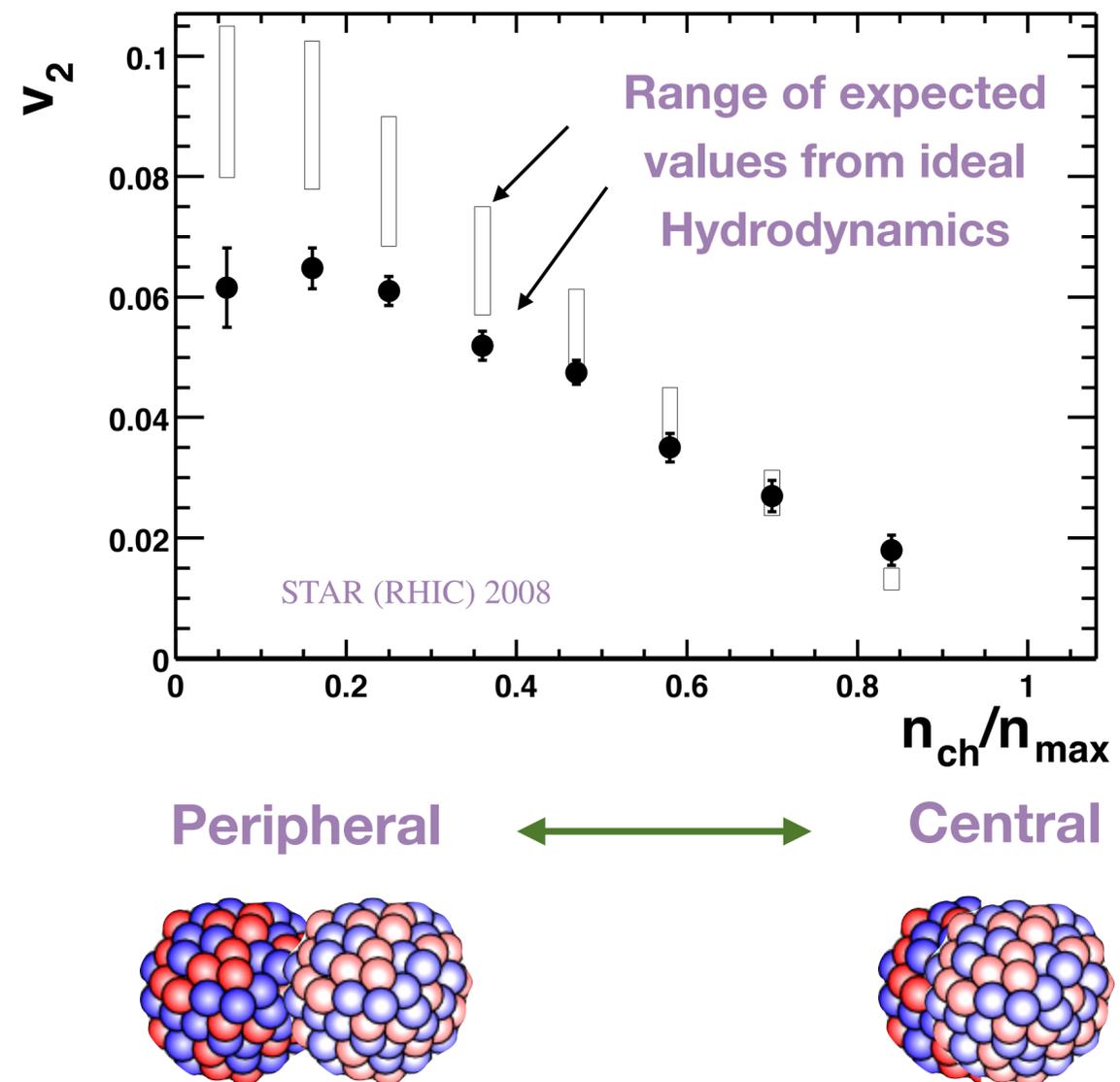


Central

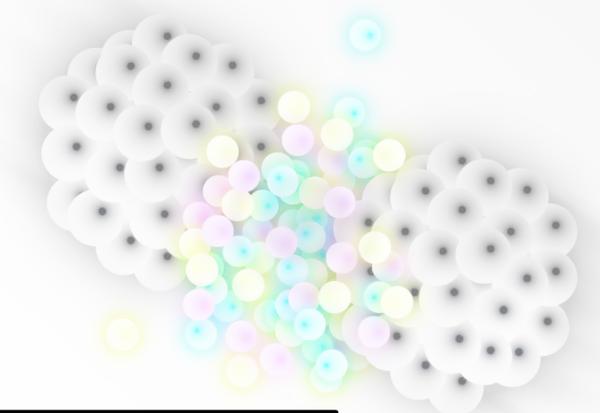


QGP Fluidity

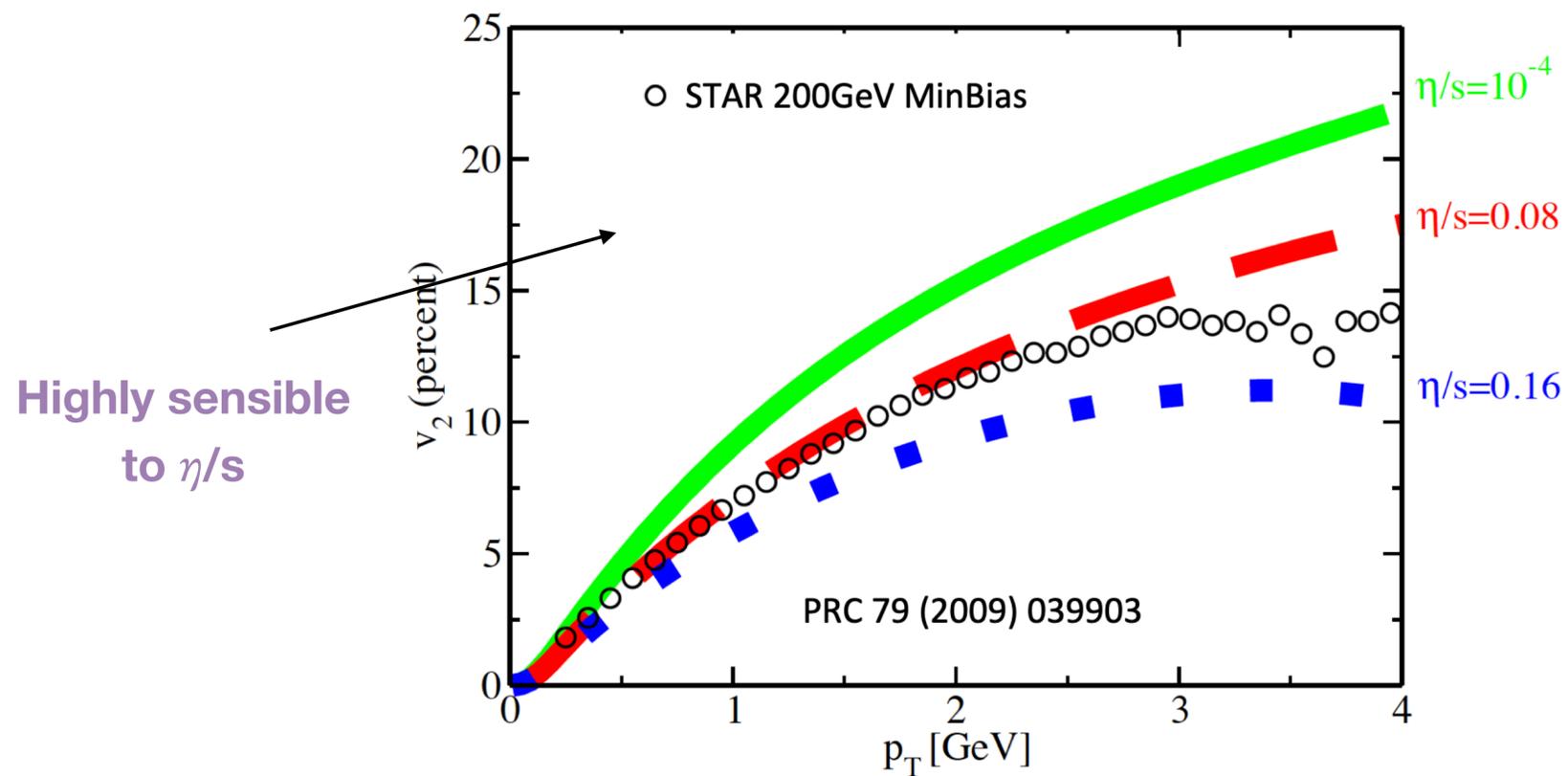
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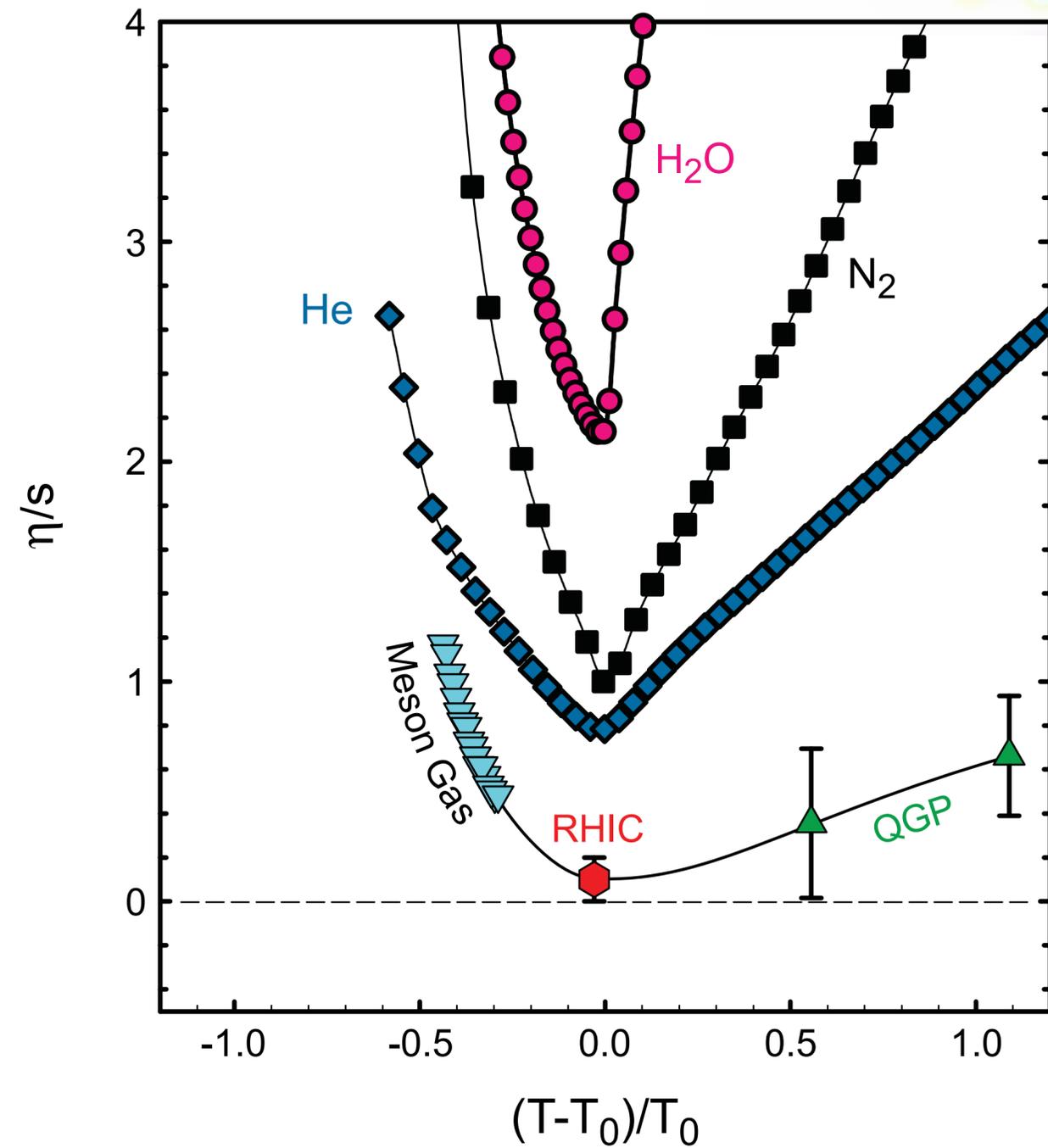
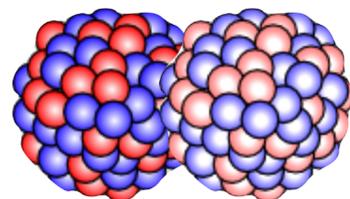
QGP Fluidity



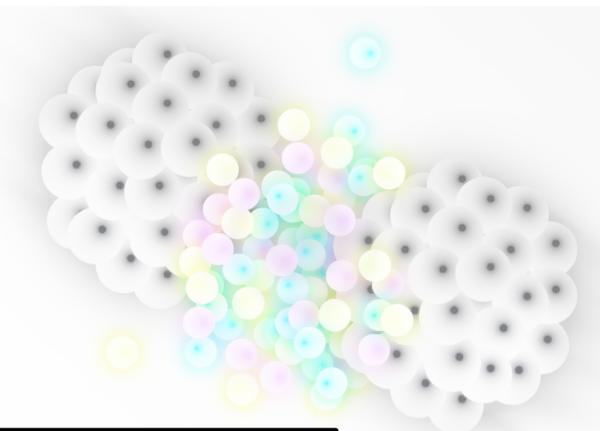
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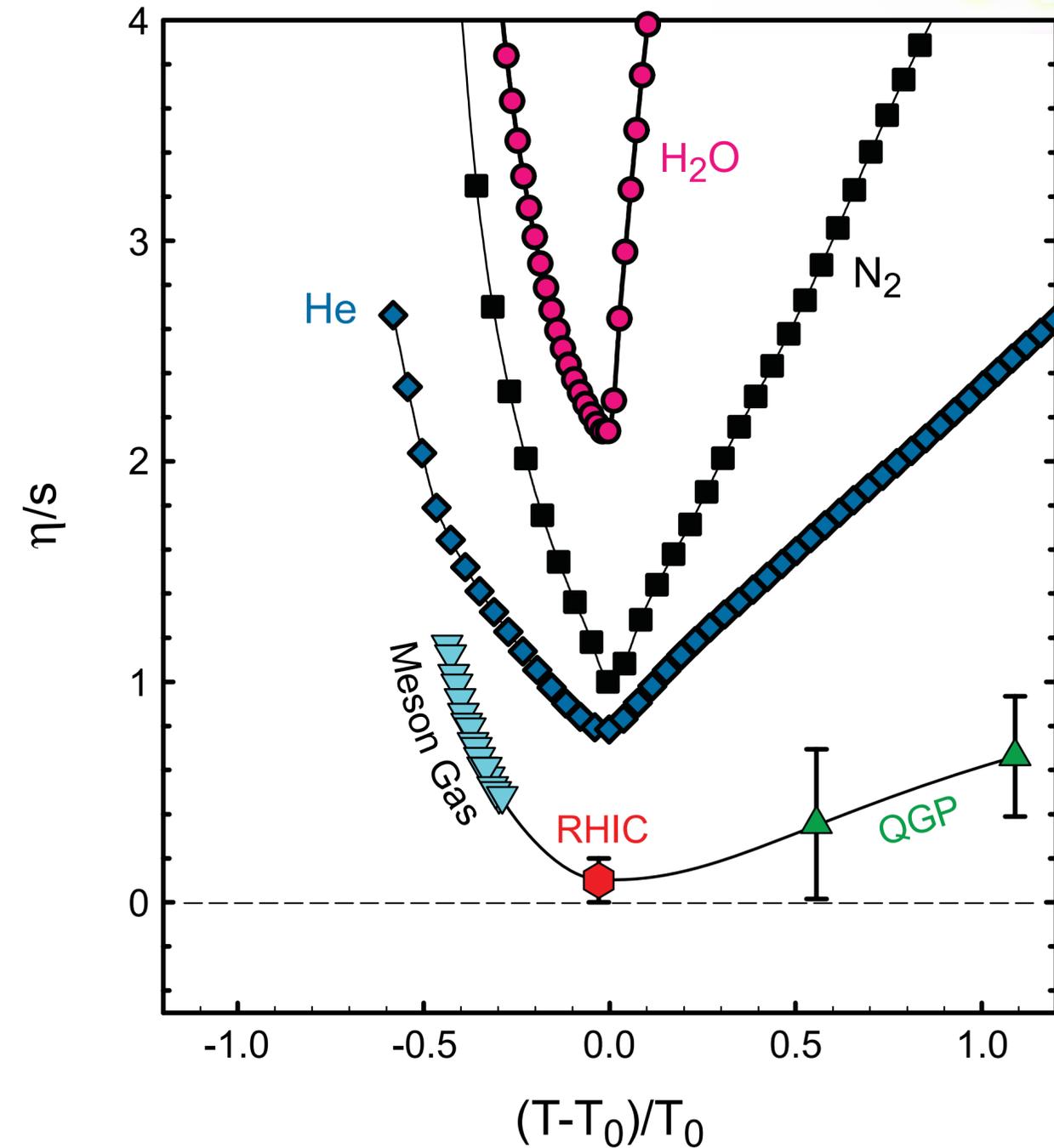
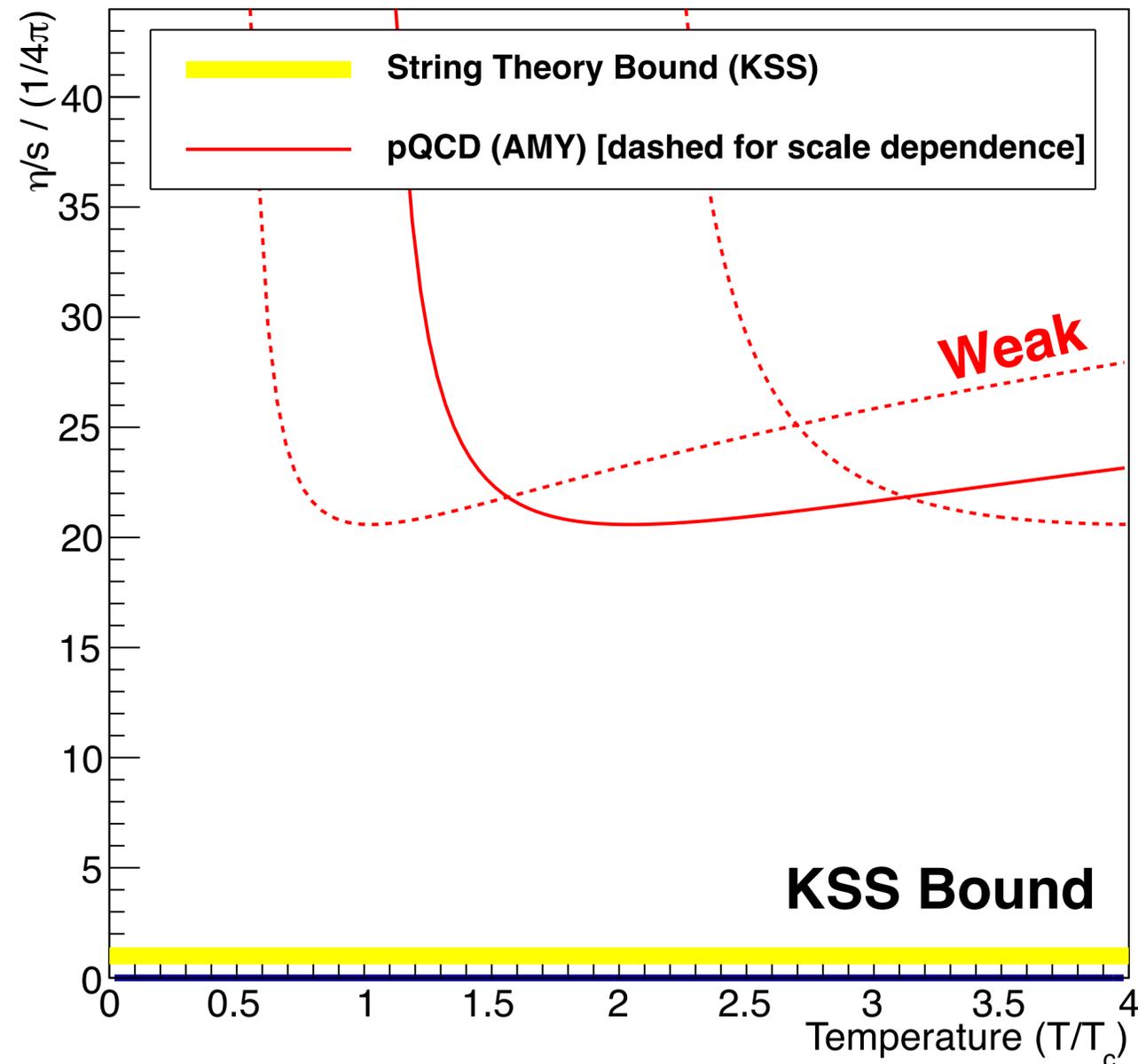
Peripheral



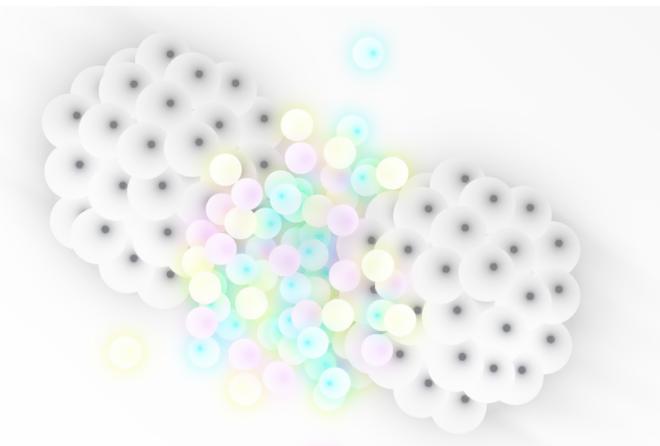
QGP Fluidity



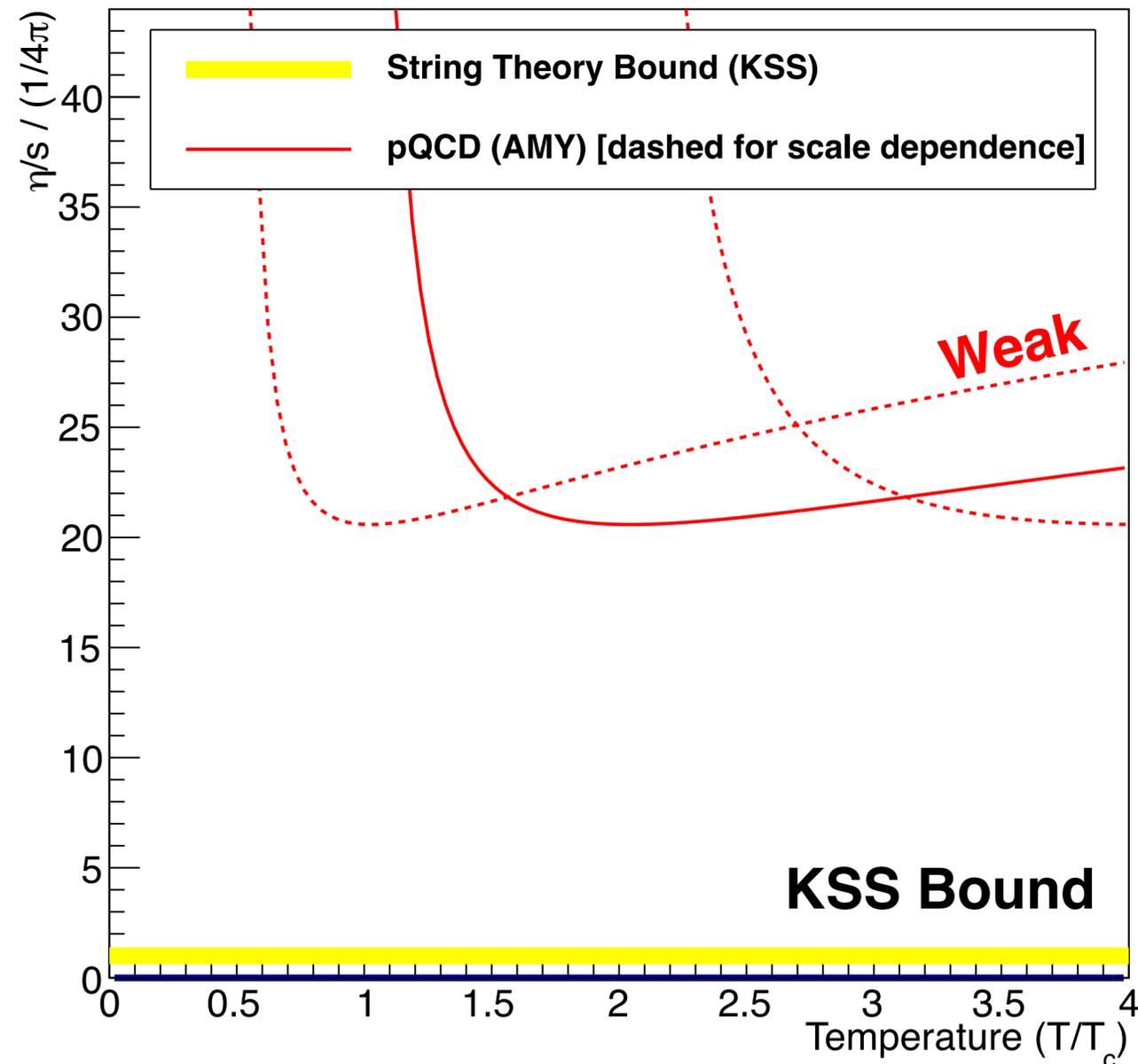
- QGP is an (almost) ideal **strongly-coupled** fluid:



QGP Fluidity

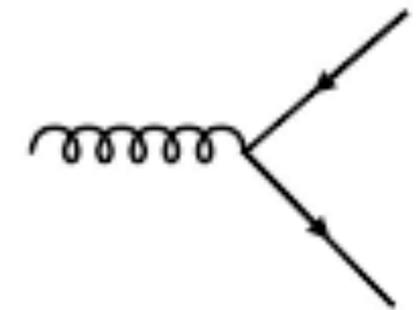


- QGP is an (almost) ideal **strongly-coupled** fluid:



Weak coupling

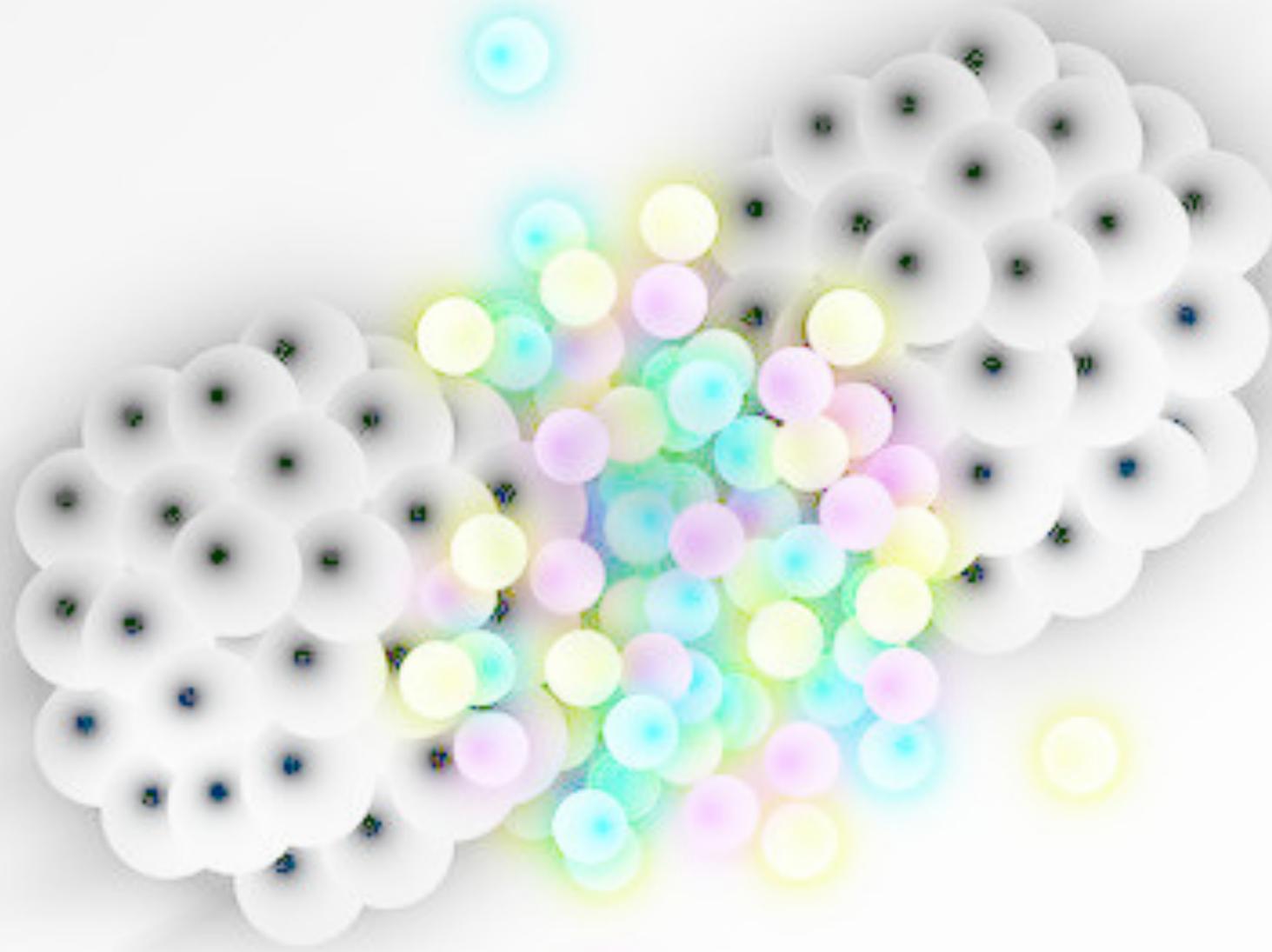
$$\alpha_s = \frac{g_s^2}{4\pi} \ll 1$$



Strong coupling

$$\alpha_s \simeq 1$$

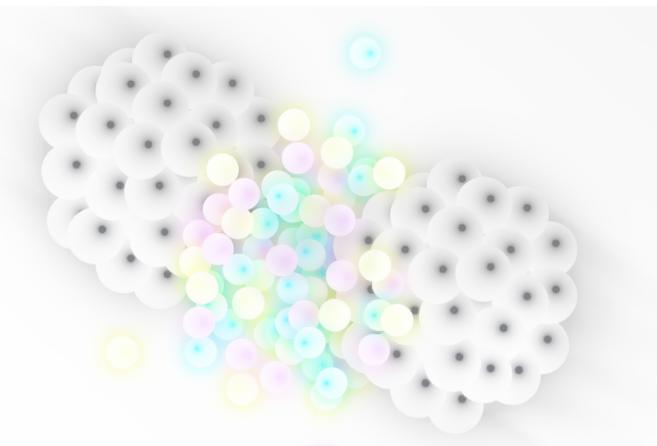
Initial State



**From nuclei to
QGP**

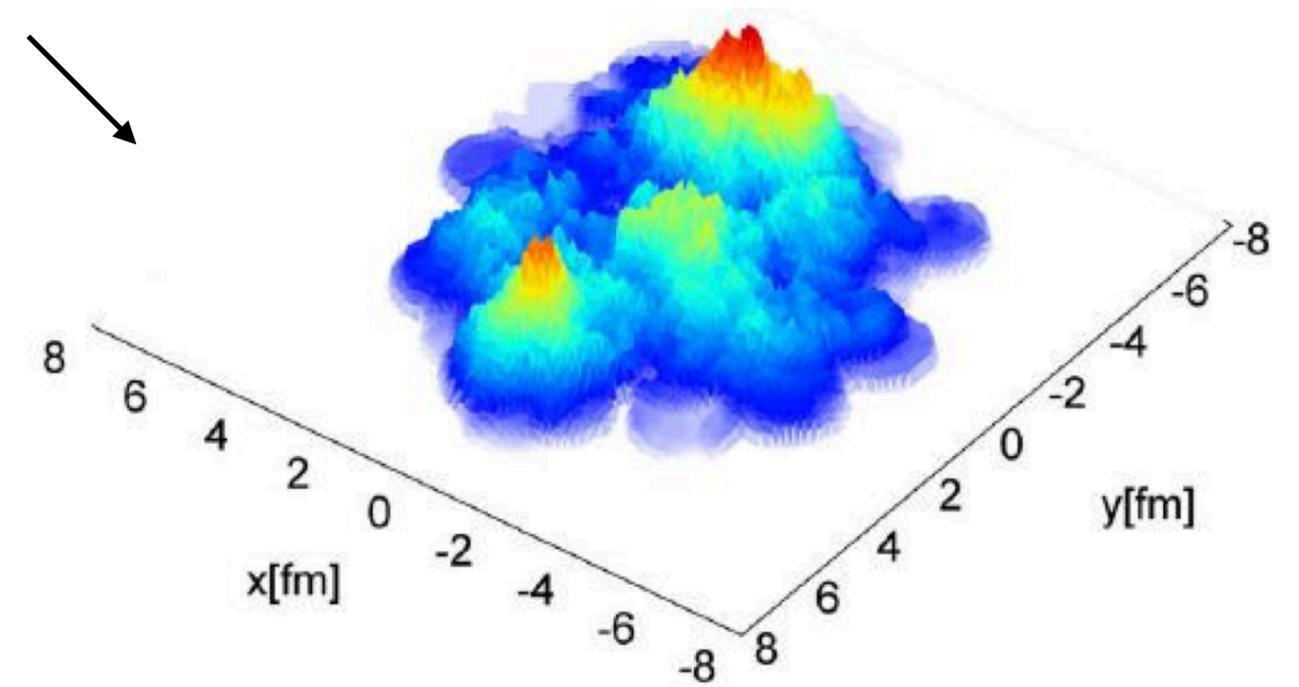
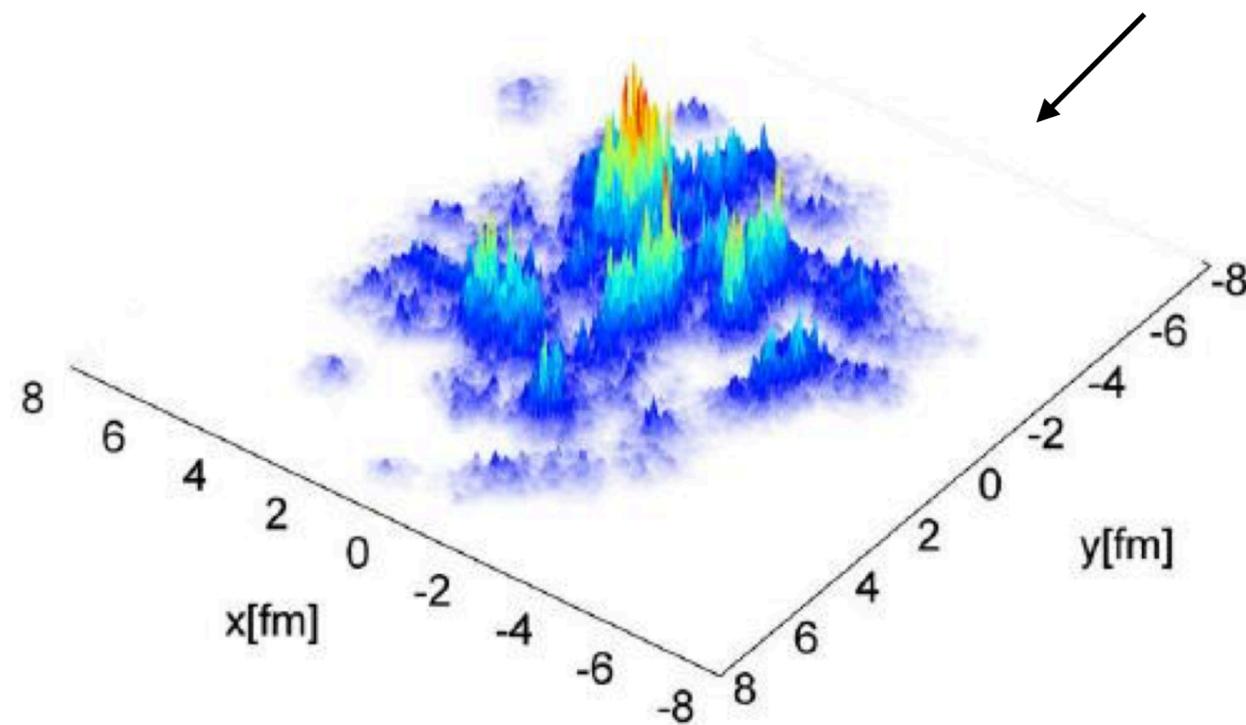


Initial state

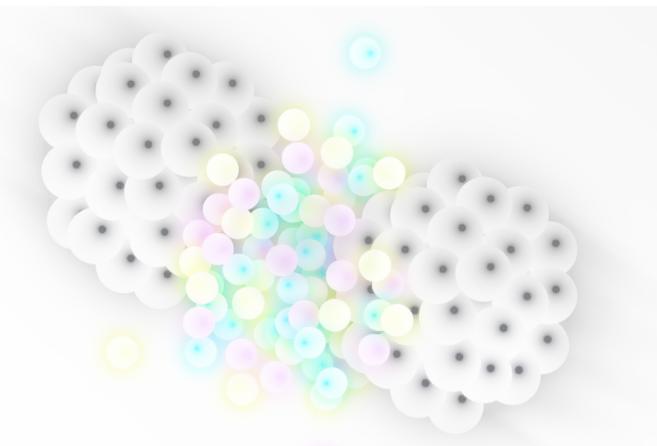


- Will the final result depend on the initial conditions?

What were the QGP initial conditions?

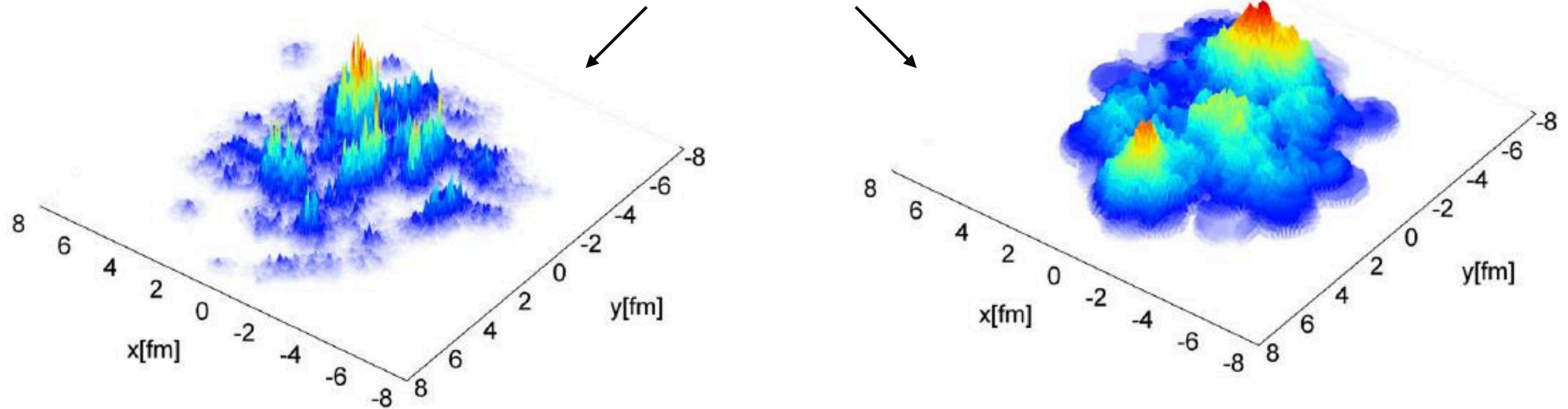


Initial state



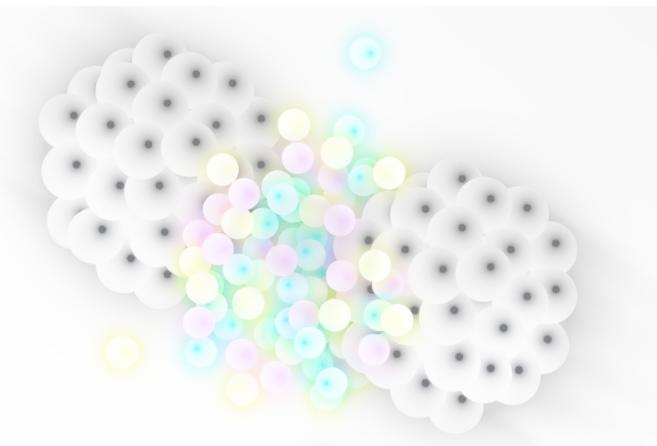
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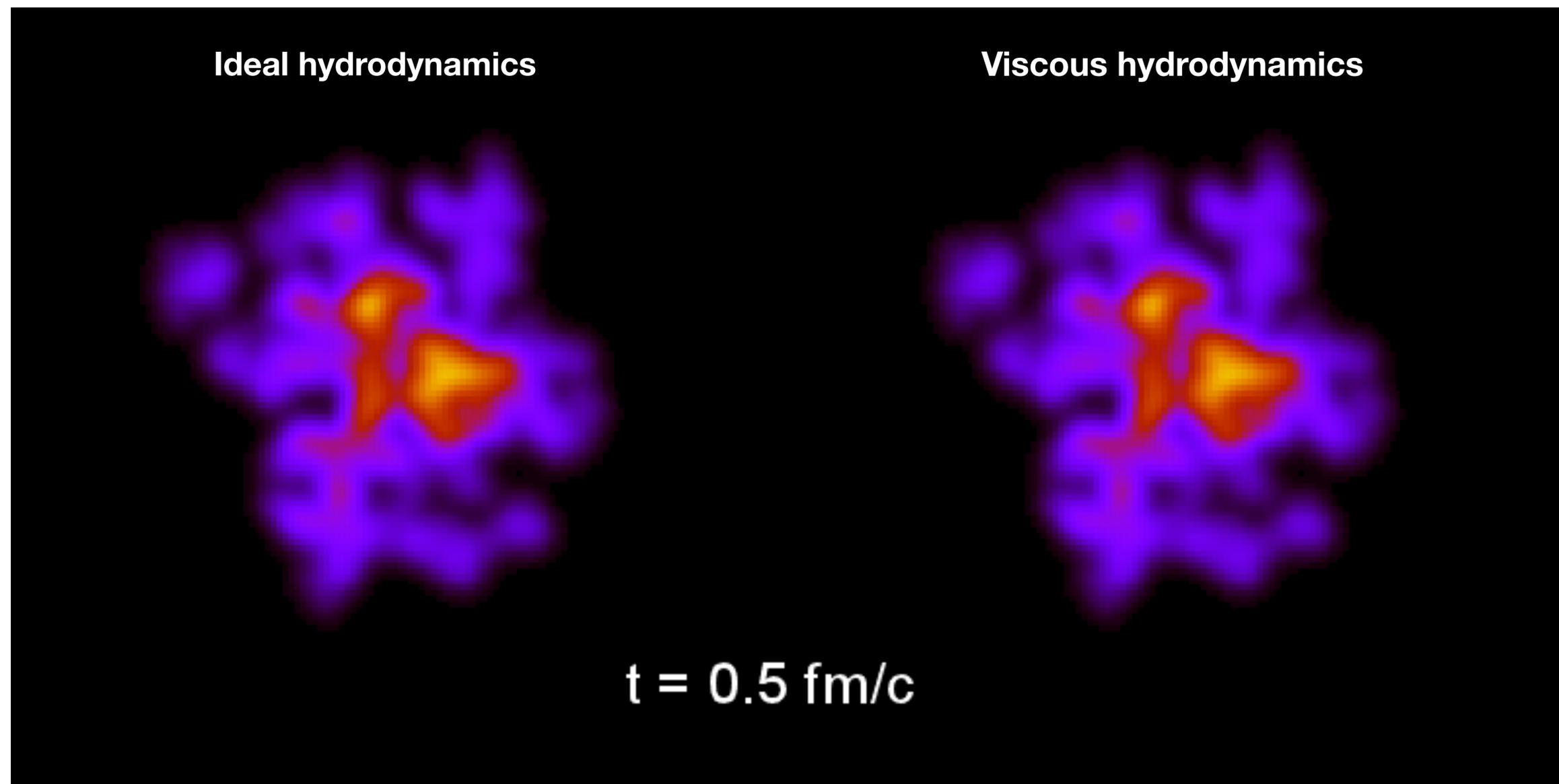


Are the fluctuations of the initial energy density distribution able to survive the hydrodynamic evolution?

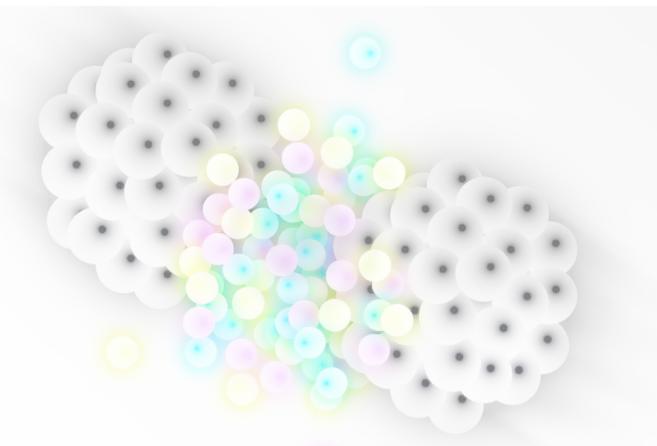
Initial state



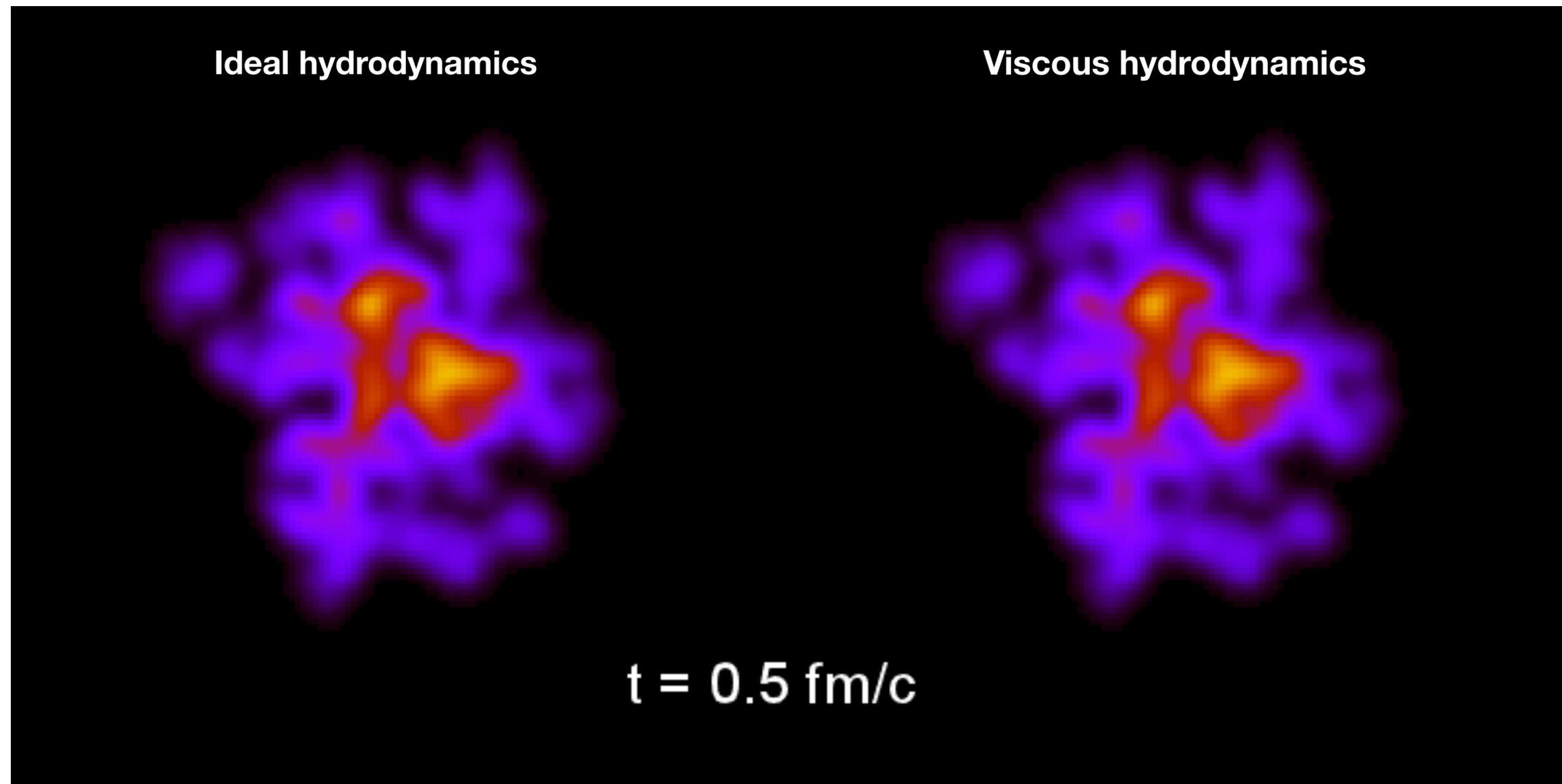
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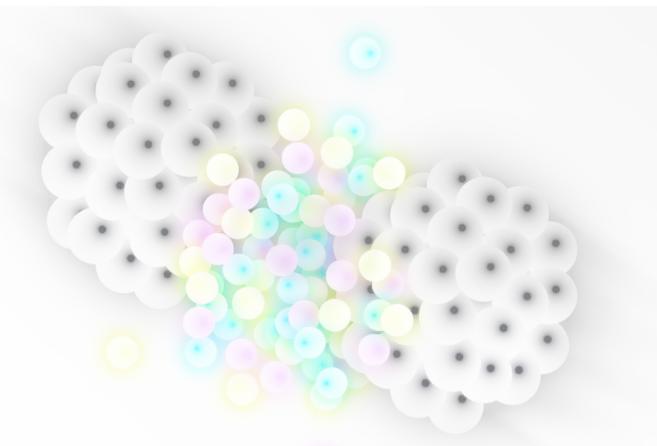
Initial state



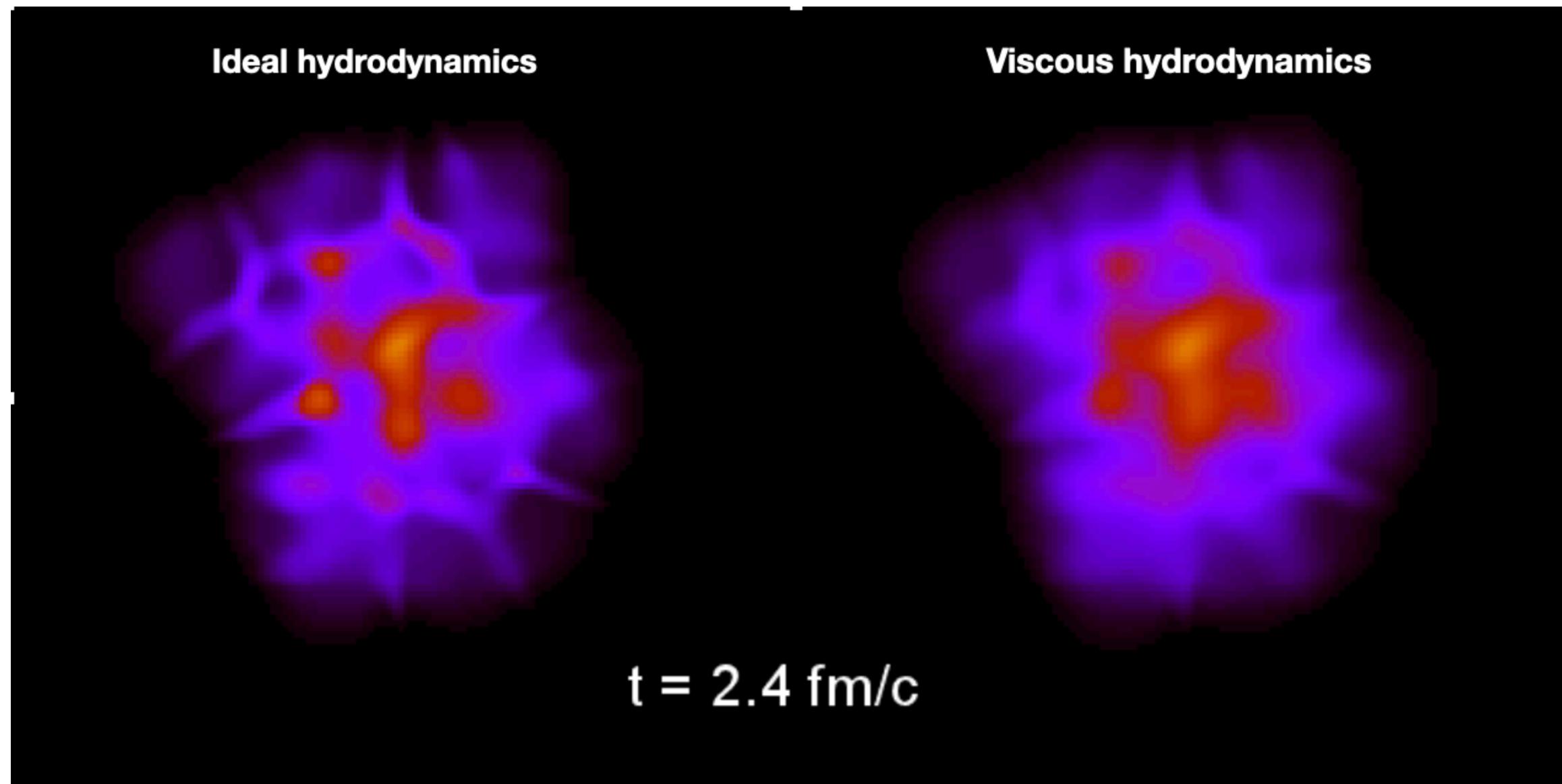
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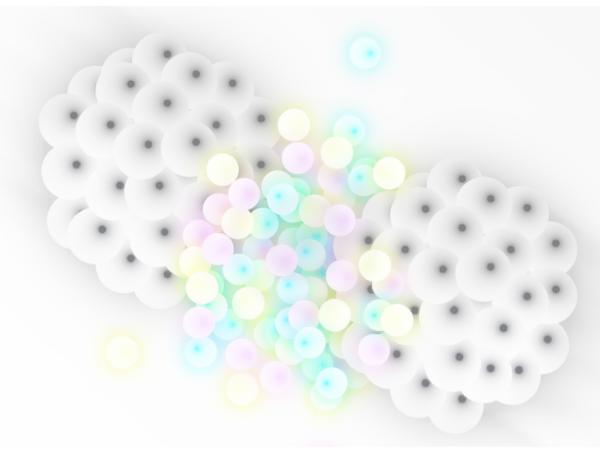
Initial state



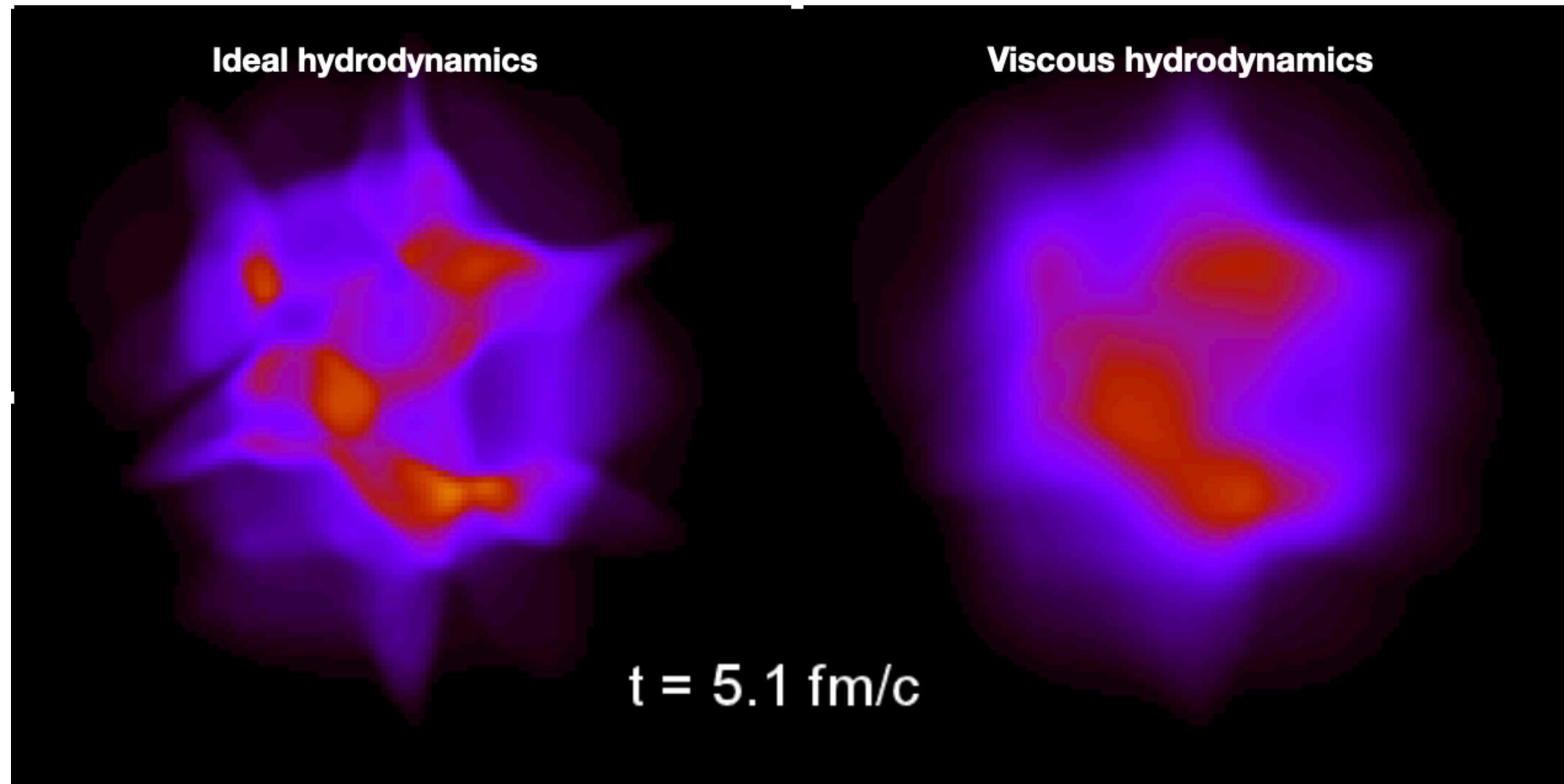
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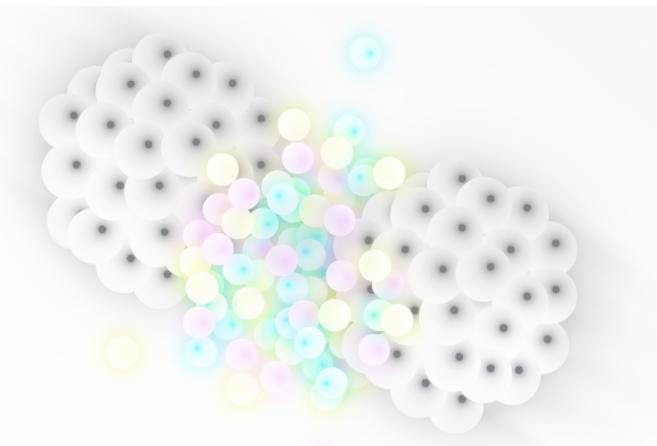
Initial state



- Will the final result depend on the initial conditions?



Nuclear Parton Distribution functions



- In collinear factorisation:

$$\sigma_O(s, Q^2) = \sum_{n=0}^{\infty} \alpha_S^n(\mu_R^2) \cdot \sum_{i,j} \int dx_1 dx_2 f_{i/h1}(x_i, \mu_F^2) f_{j/h2}(x_j, \mu_F^2) \times \hat{\sigma}_{i,j \rightarrow O+X}(Q(x_i, x_j, s), \mu_R^2, \mu_F^2),$$

- Nuclear PDF (nPDF):

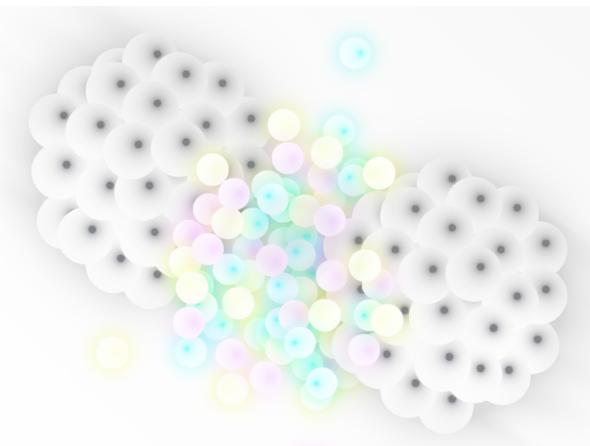
$$f_{i,(A,Z)}(x, \mu_F) = \frac{Z}{A} f_{i,p(A,Z)}(x, \mu_F) + \frac{A-Z}{A} f_{i,n(A,Z)}(x, \mu_F)$$

Average proton and neutrons PDFs

Modifications less important for higher energies, but it will affect softer processes

⇒ Extraction of QGP properties highly dependent on initial conditions

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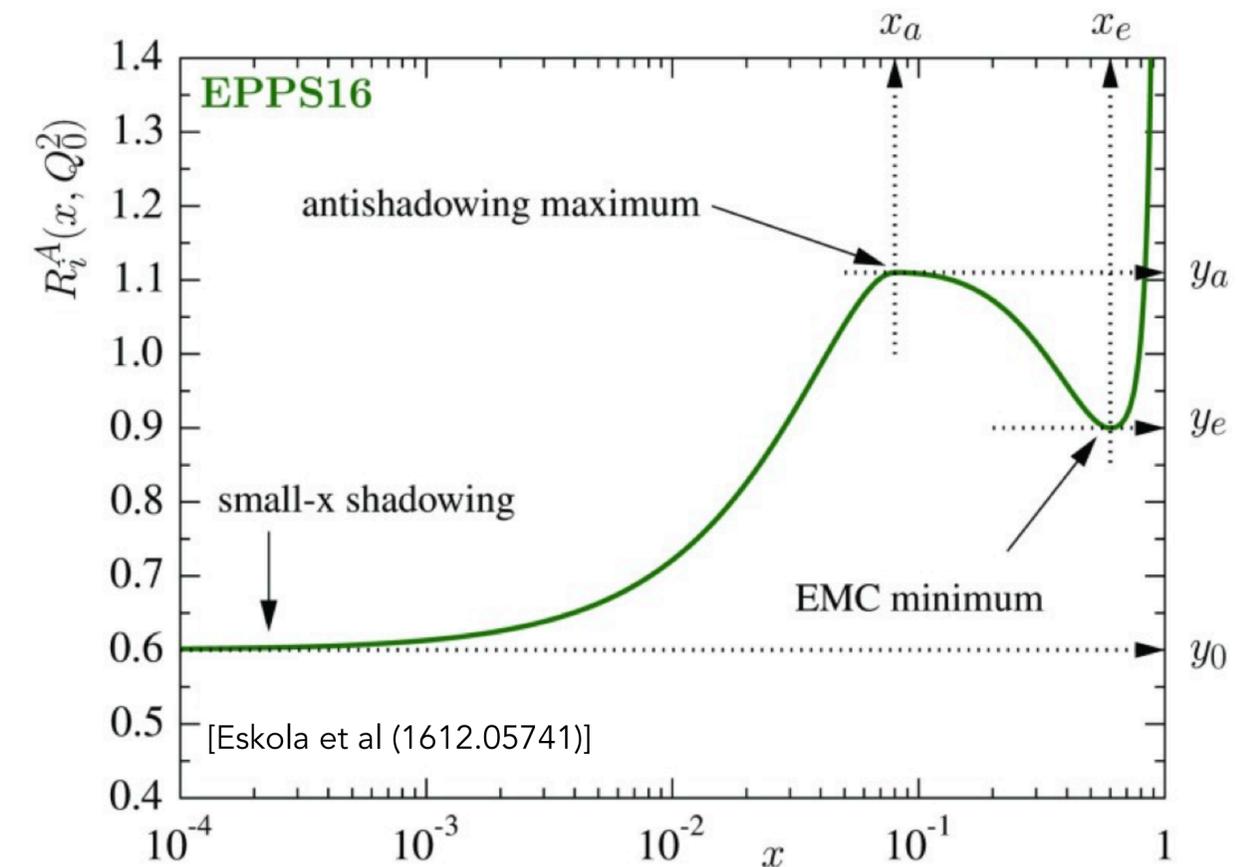
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Average proton and neutrons PDFs

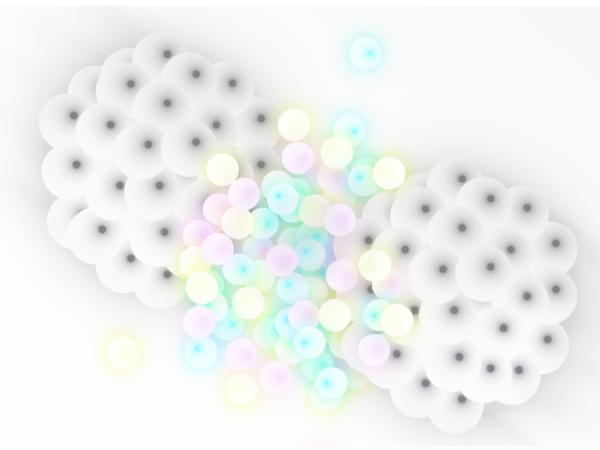
Modifications less important for higher energies, but it will affect softer processes

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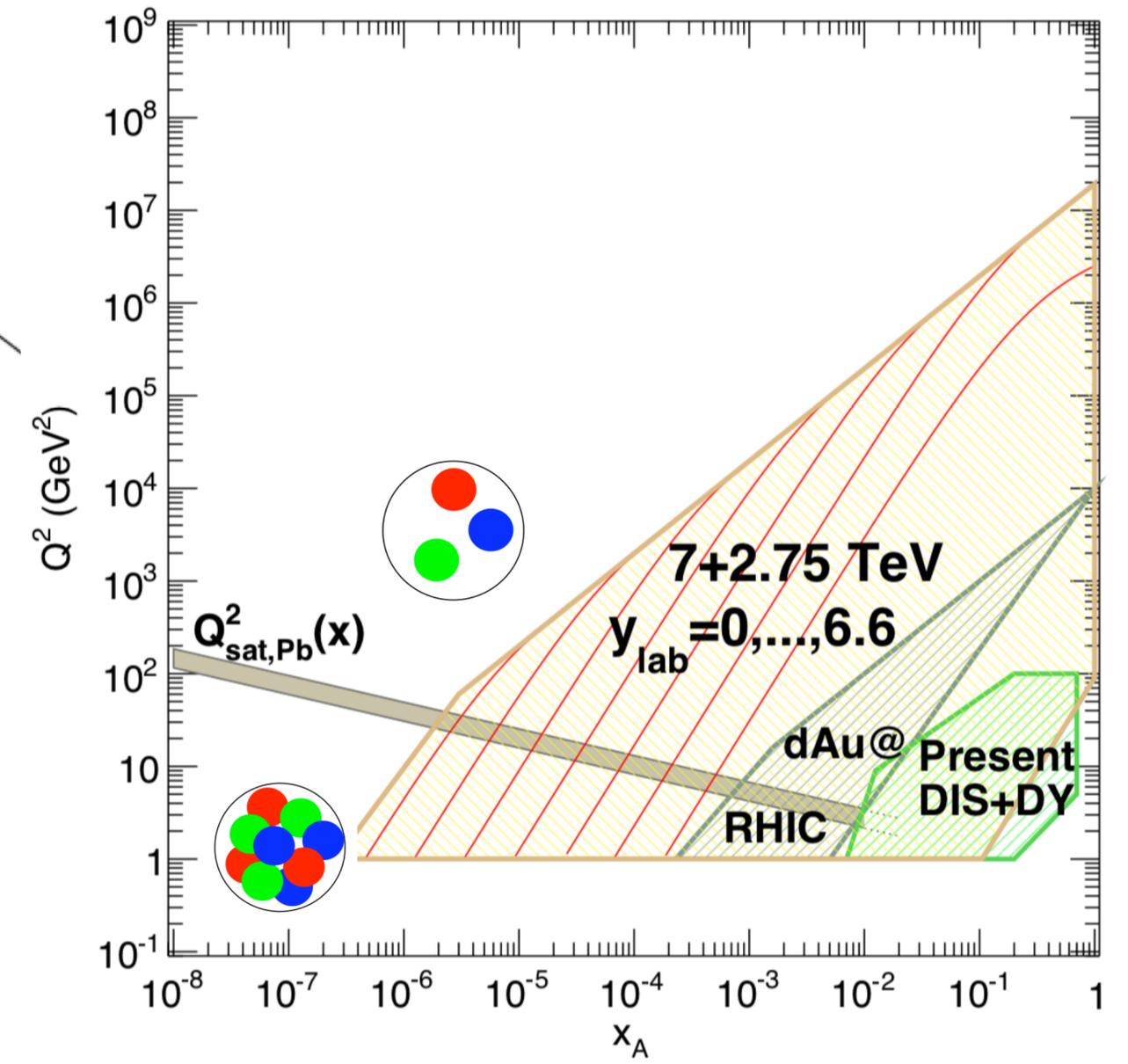
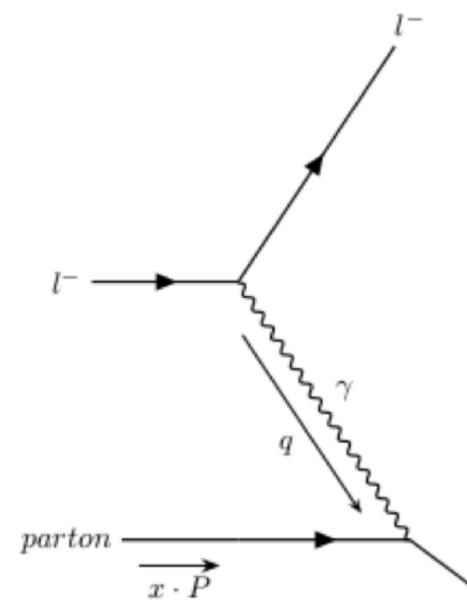
Typical form of PDF modifications in a nucleus.



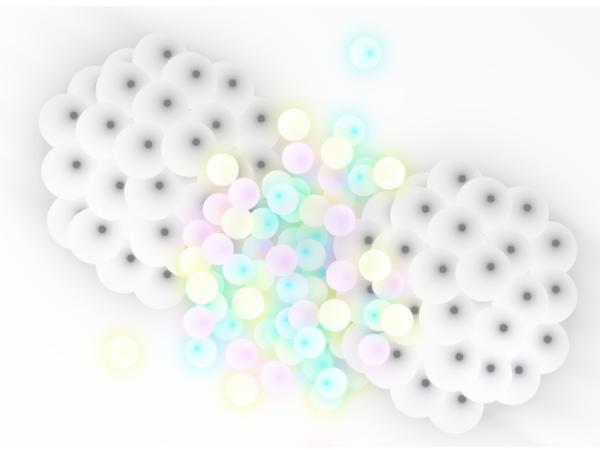
Nuclear Parton Distribution functions



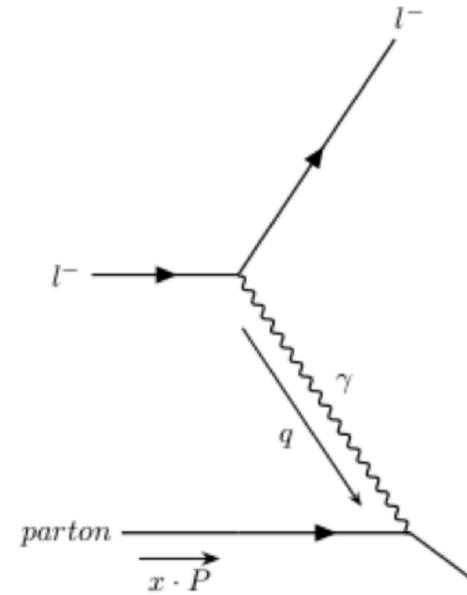
- Able to probe nucleus through DIS:
- Kinematic coverage still limited...



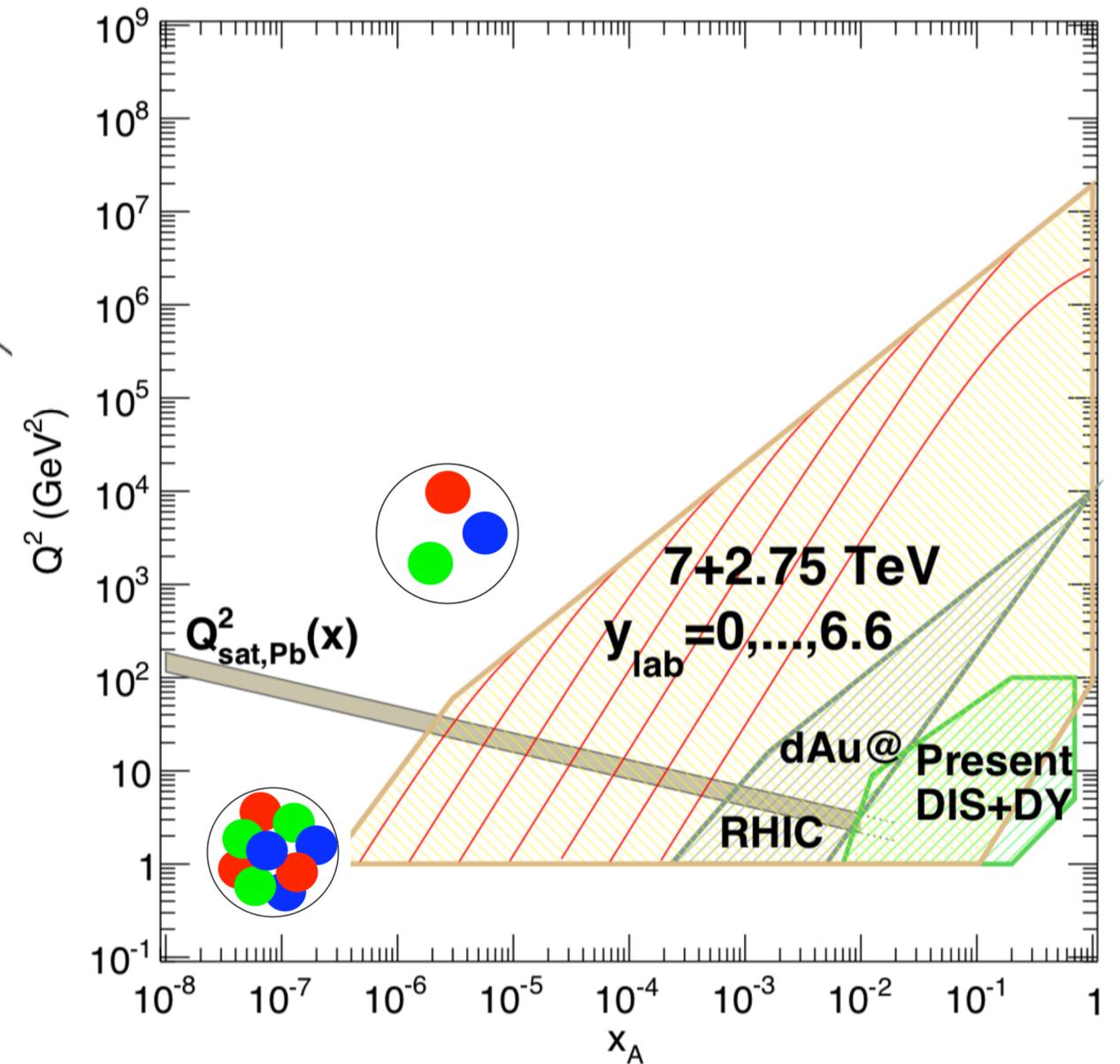
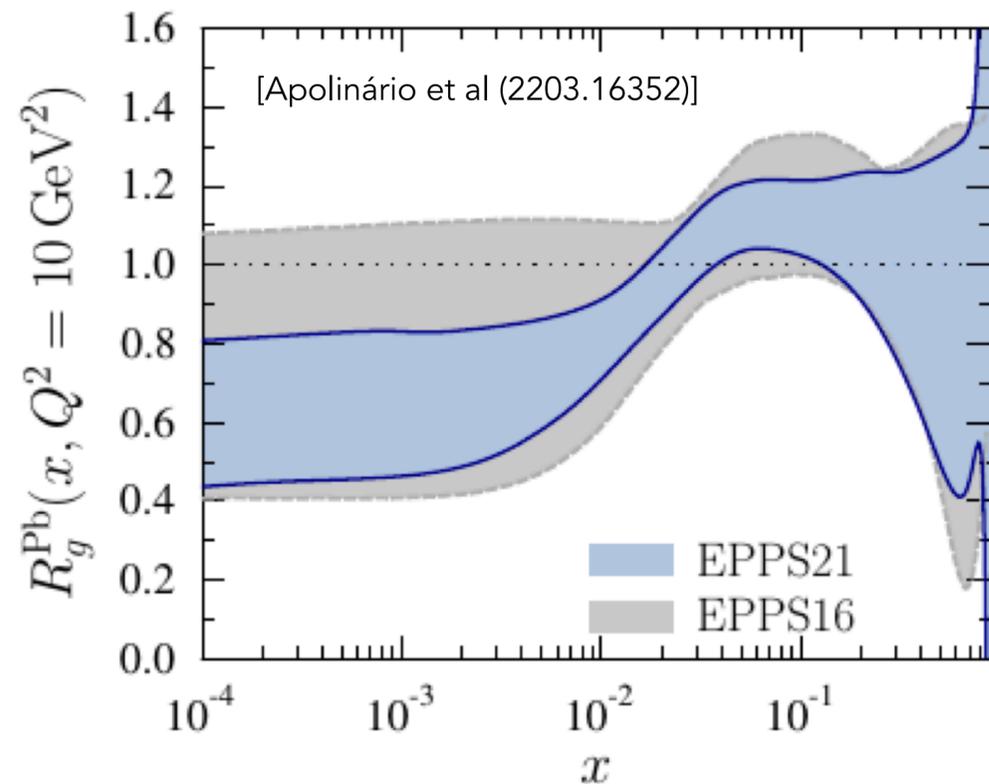
Nuclear Parton Distribution functions



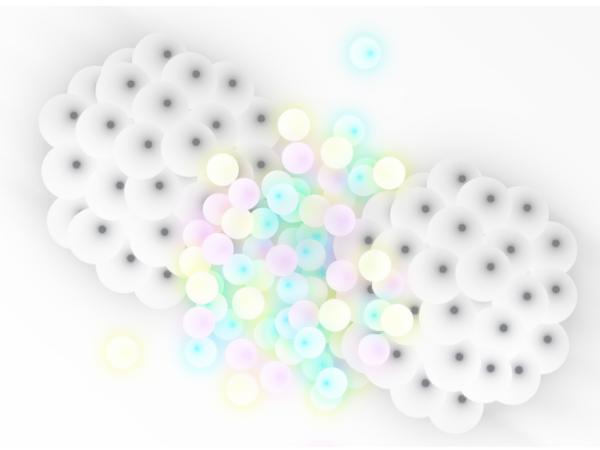
- Able to probe nucleus through DIS:
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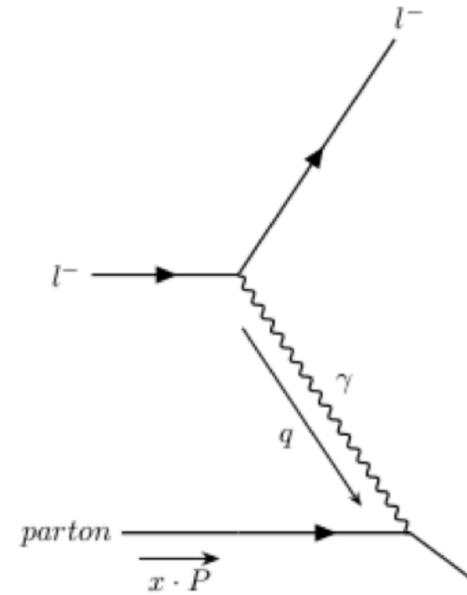
Effect of including additional data (D-mesons and dijets) on gluon PDF:



Nuclear Parton Distribution functions



- Able to probe nucleus through DIS:
 - Kinematic coverage still limited...
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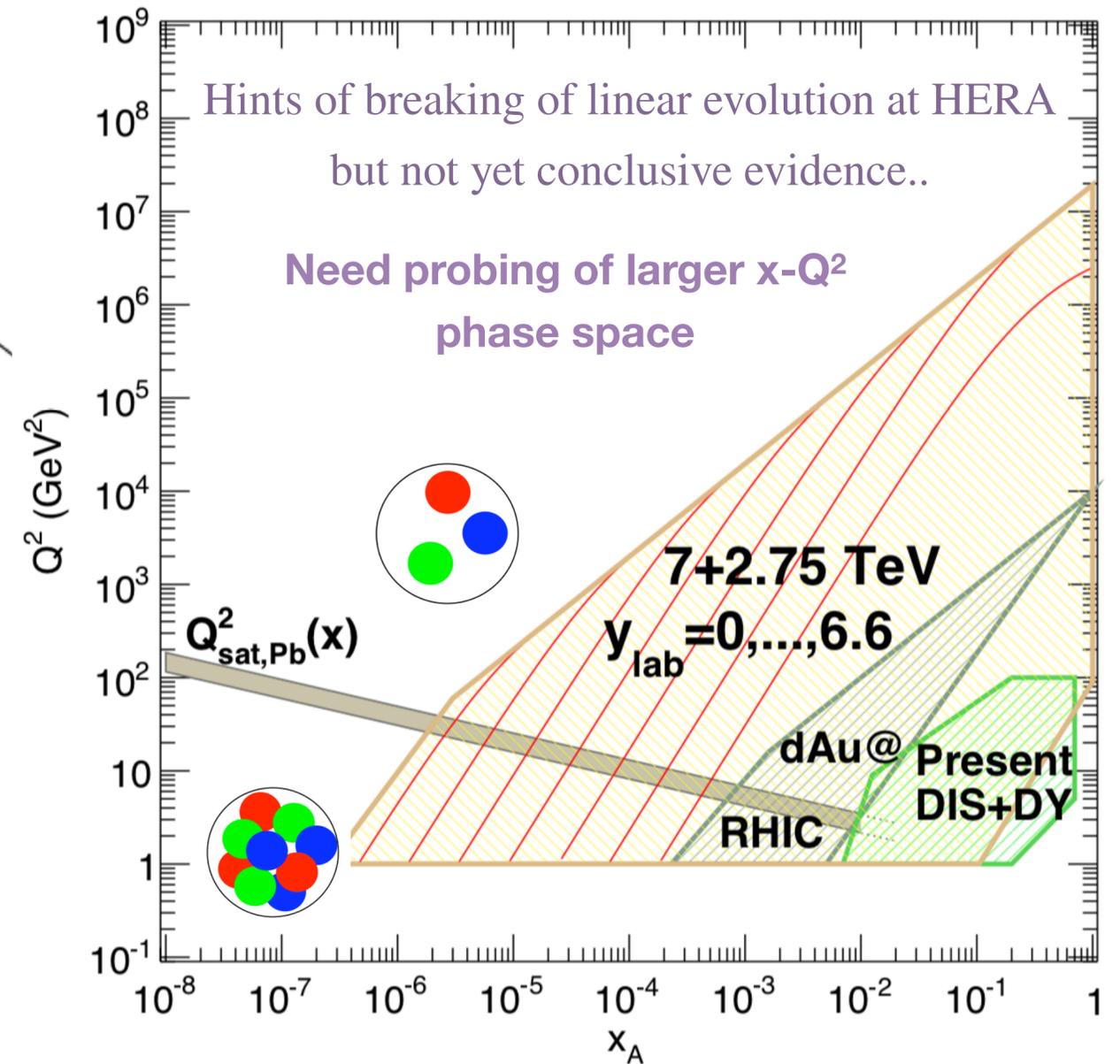
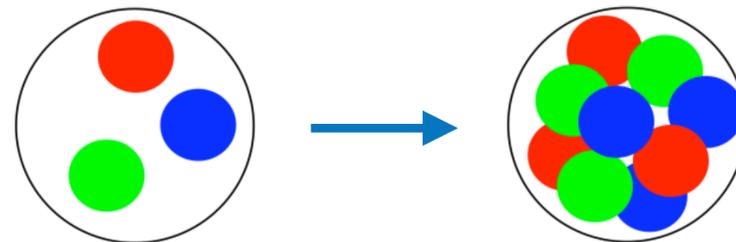
- Onset of saturation:

Transverse area

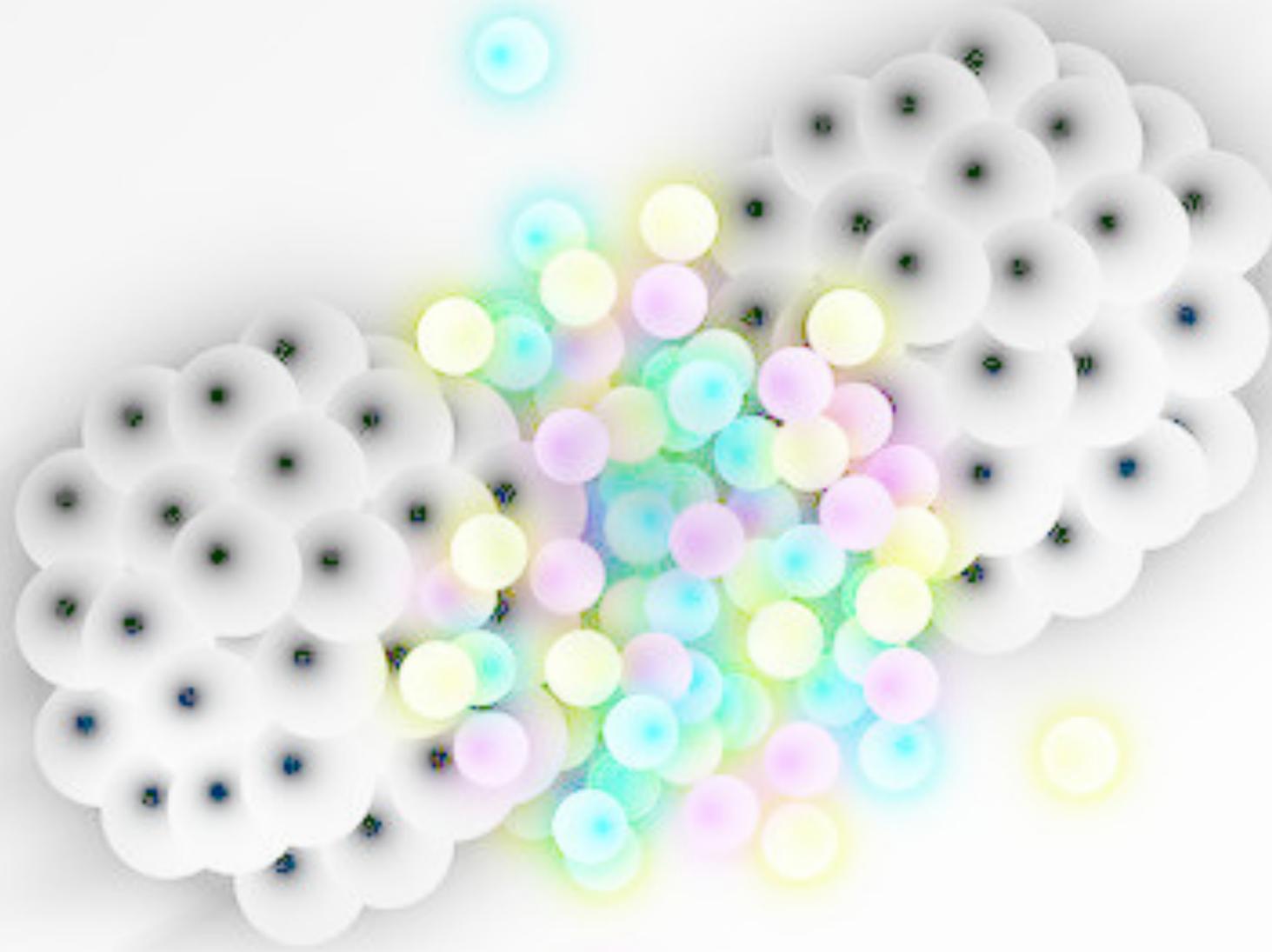
Number of gluons

$$\pi R_A^2 \sim \frac{Axg(x, Q_s^2)}{Q_s^2} \Rightarrow Q_s^2 \sim A^{1/3} (\sqrt{s_{NN}})^{0.3} e^{0.3y}$$

gluon size $\sim 1/Q_s^2$



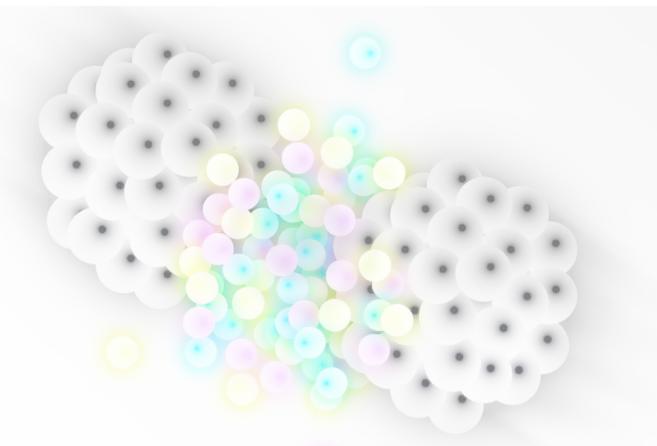
Small systems



**Conditions for
QGP formation?**

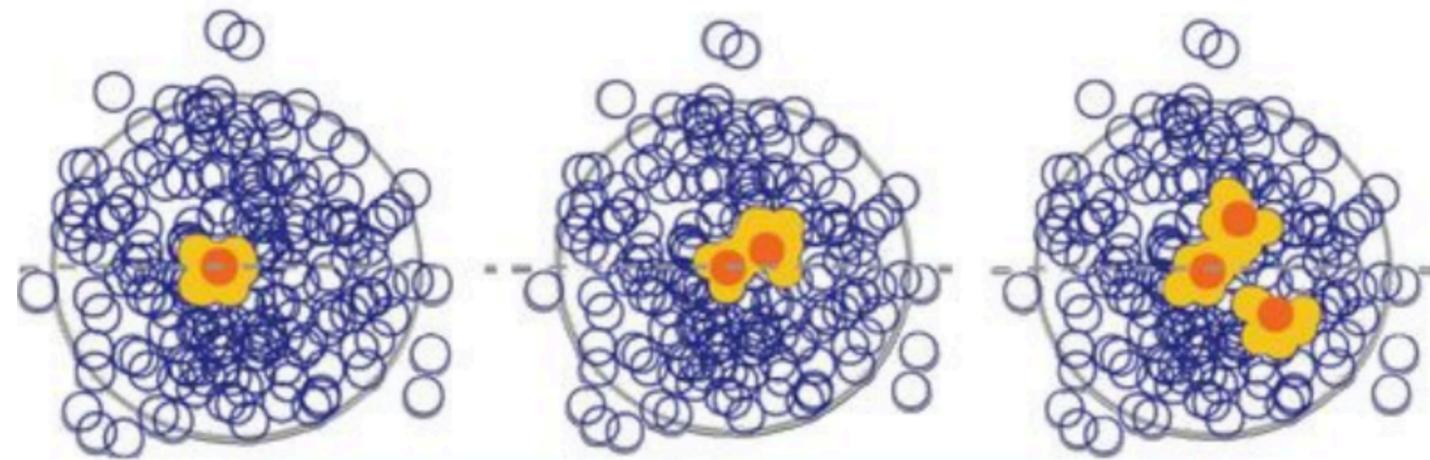


From AA to pA



- Going to a “simpler” system to understand the initial conditions:

AA collisions
(Large systems)

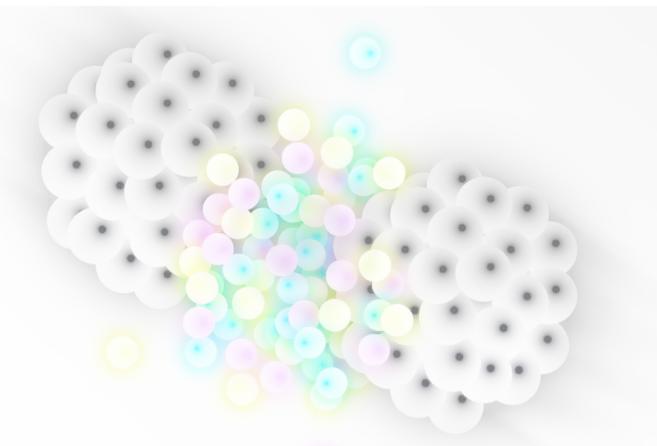


pA collisions
(Small systems)

Learn about created medium (QGP)

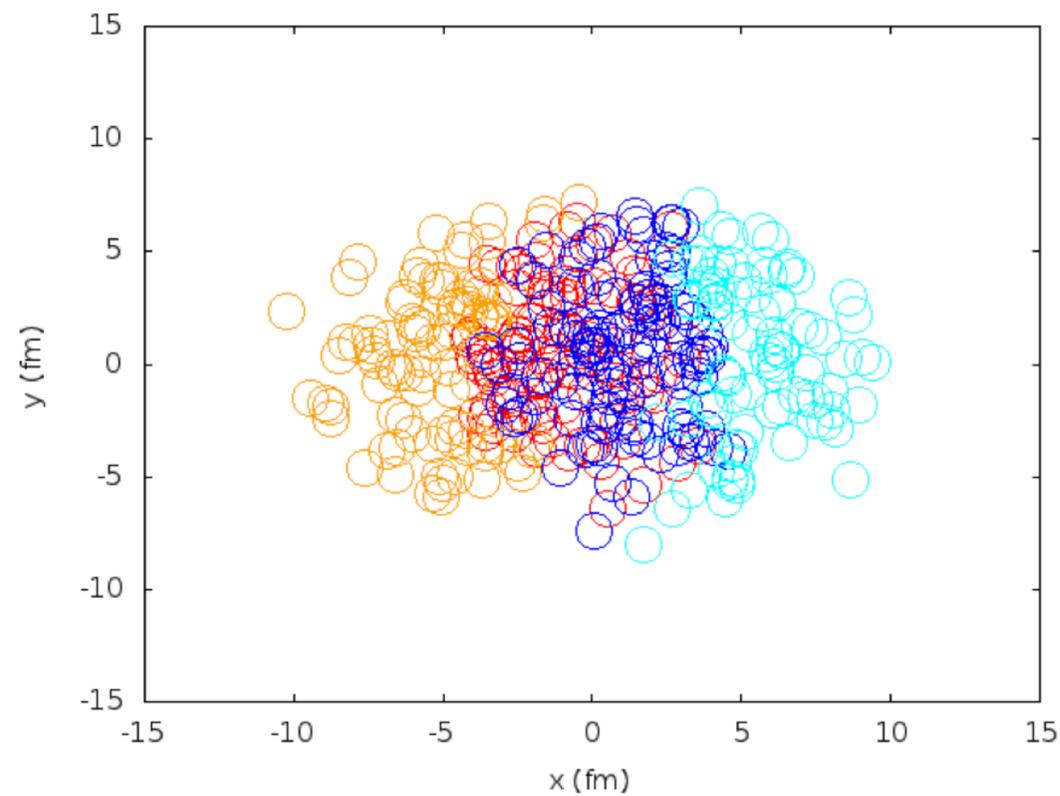
Learn about incoming nuclei (Pb/Au)

From AA to pA



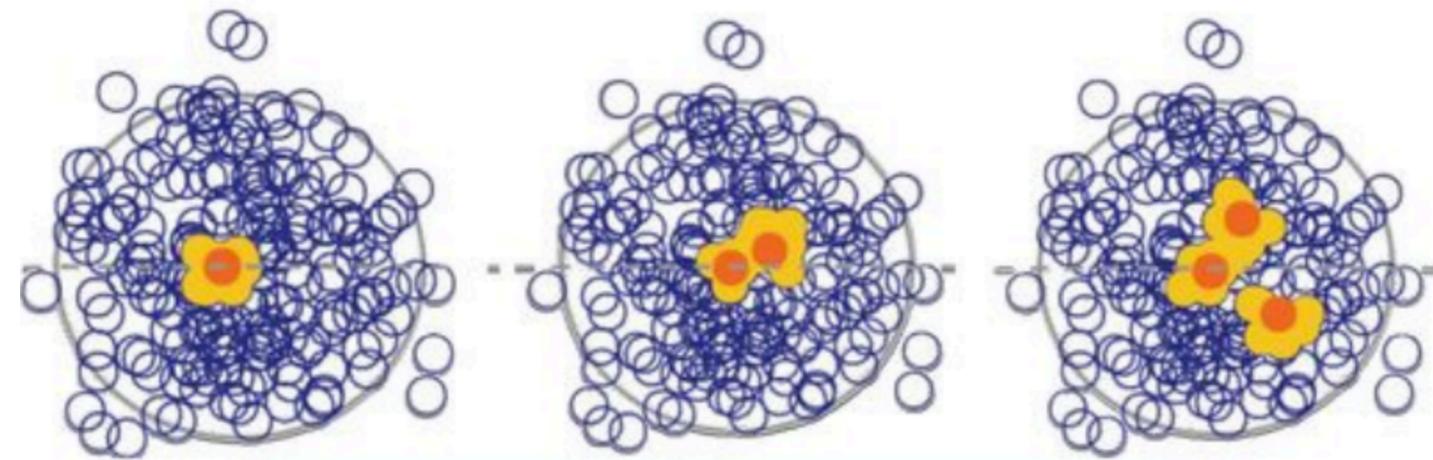
- Going to a “simpler” system to understand the initial conditions:

**AA collisions
(Large systems)**



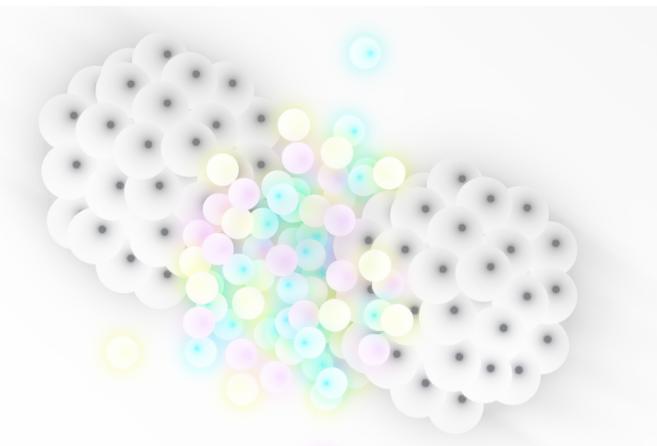
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**pA collisions
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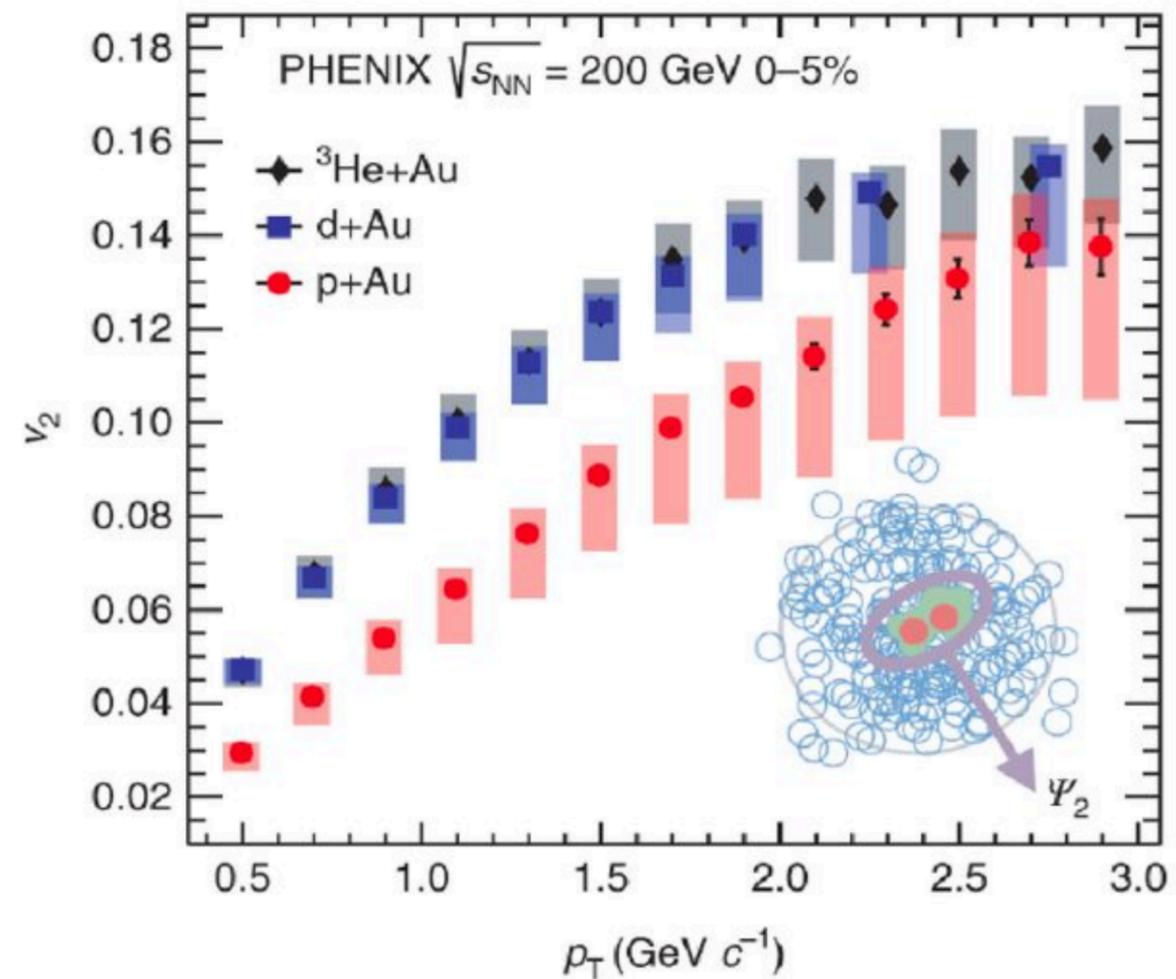
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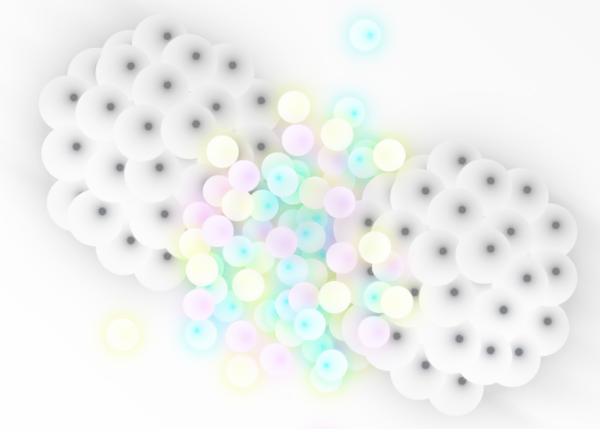
Soft probes

Collectivity signs? → QGP?



(Compatible with hydrodynamics expectations)

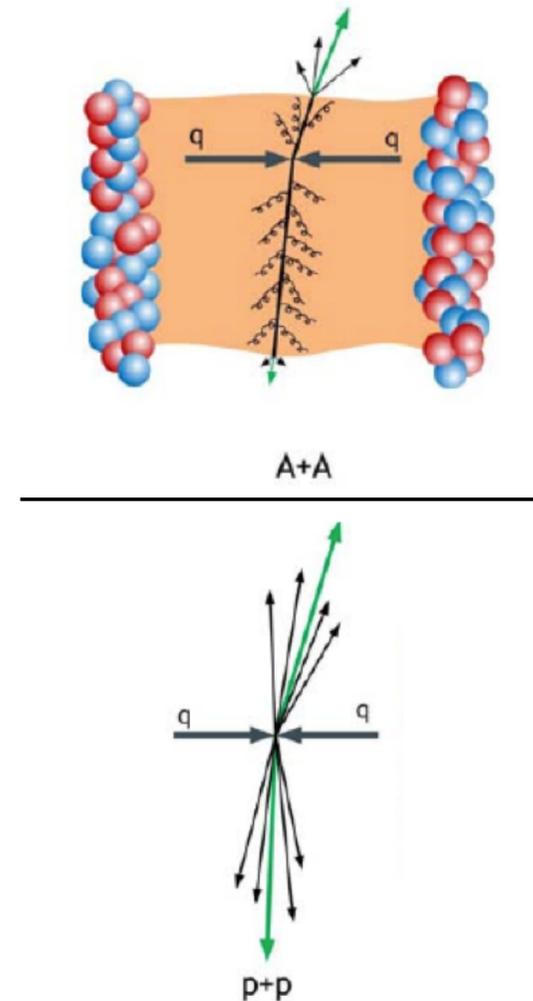
From AA to pA



- Going to a “simpler” system to understand the initial conditions:

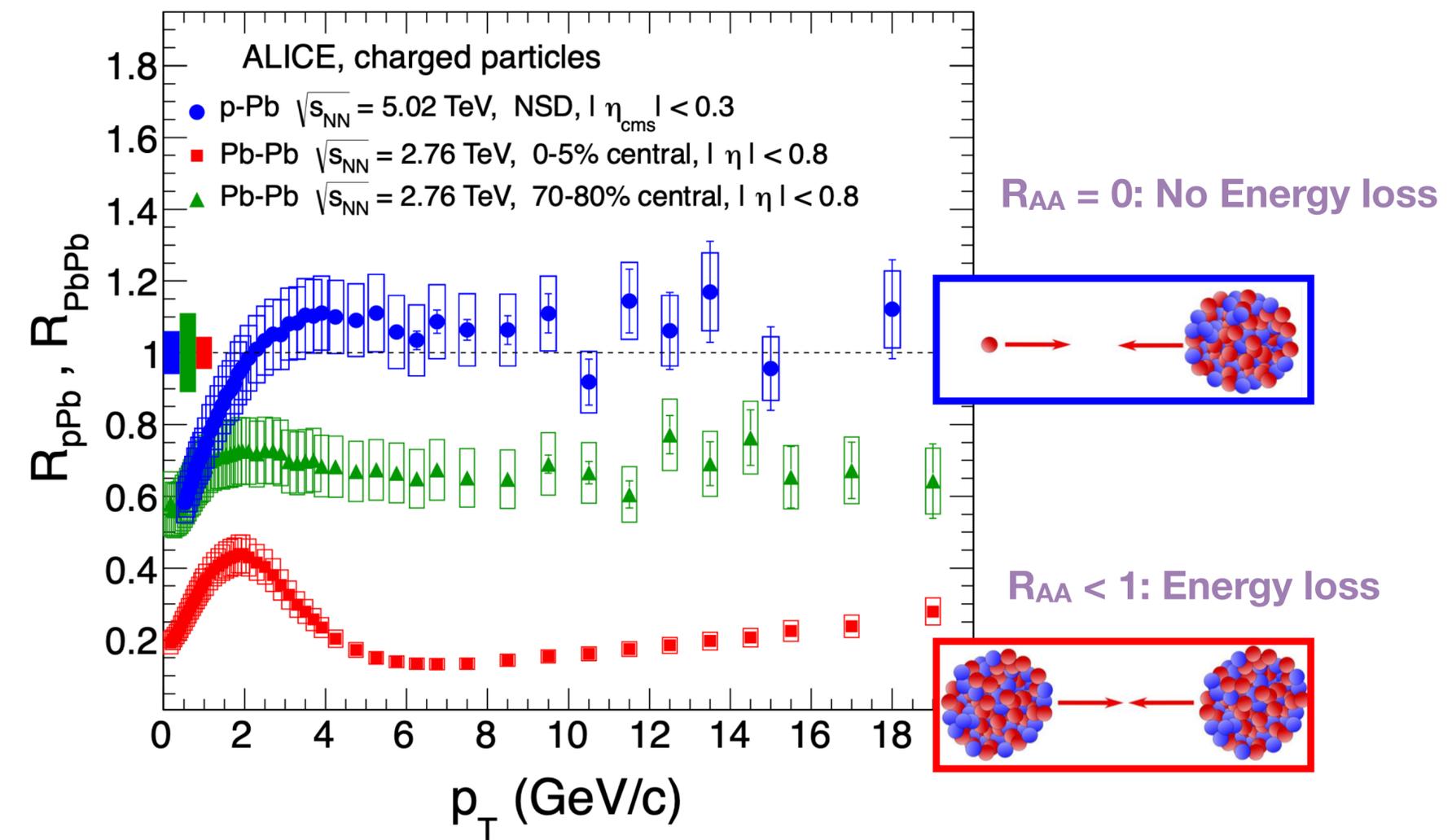
Normalised ratio of yields
between AA and pp

$$R_{AA} = \frac{Y_{AA}^X}{\langle T_{AA} \rangle \cdot \sigma_{pp}^X} =$$

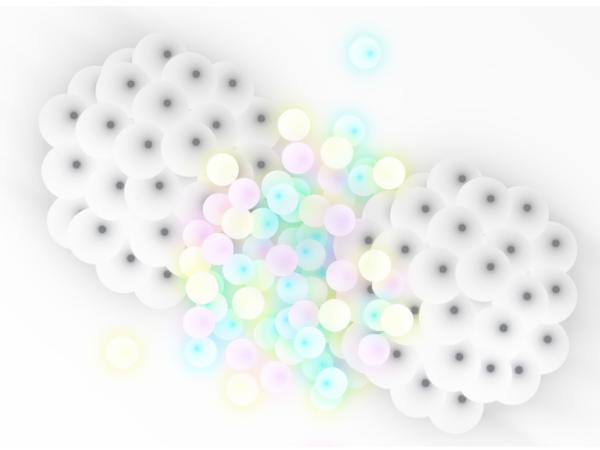


Hard sector

No jet quenching → no QGP



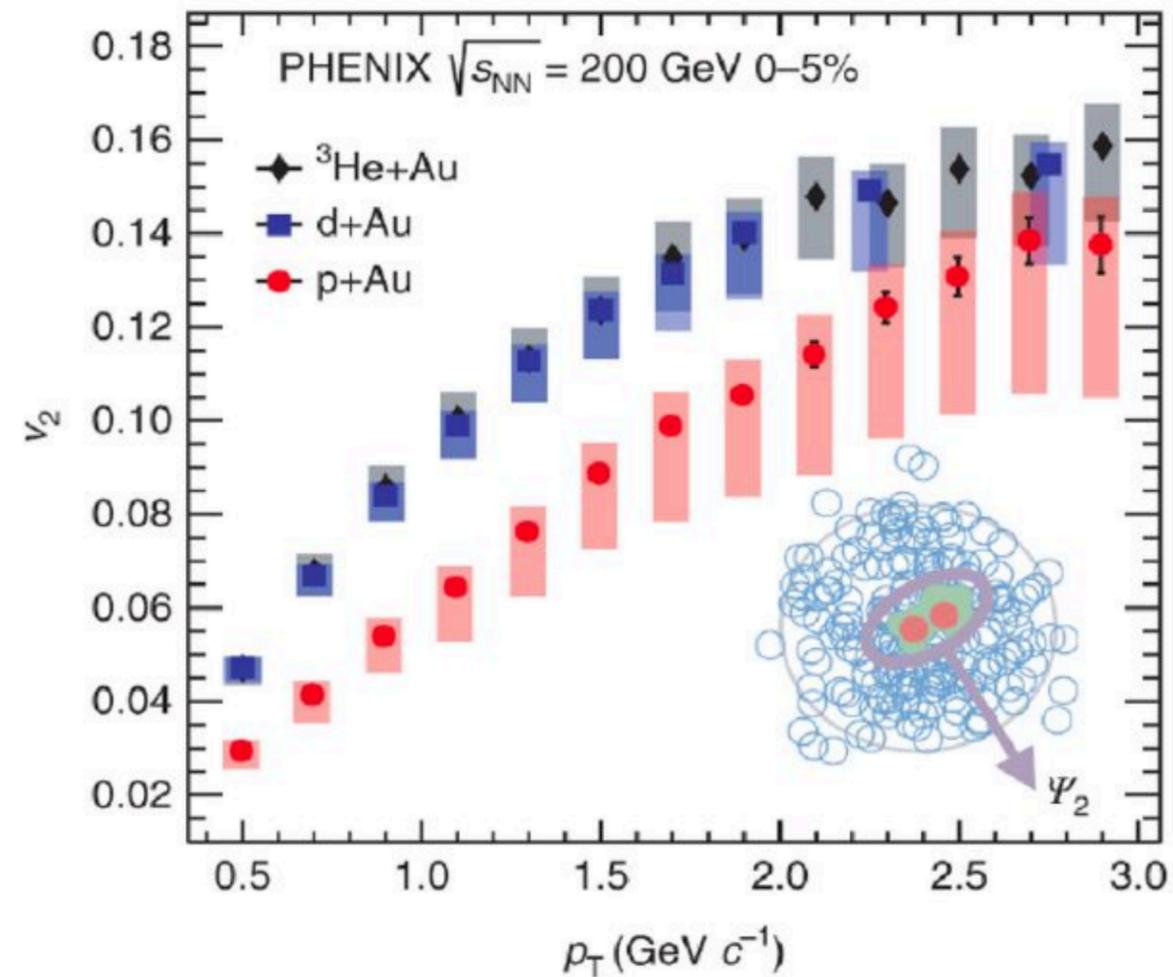
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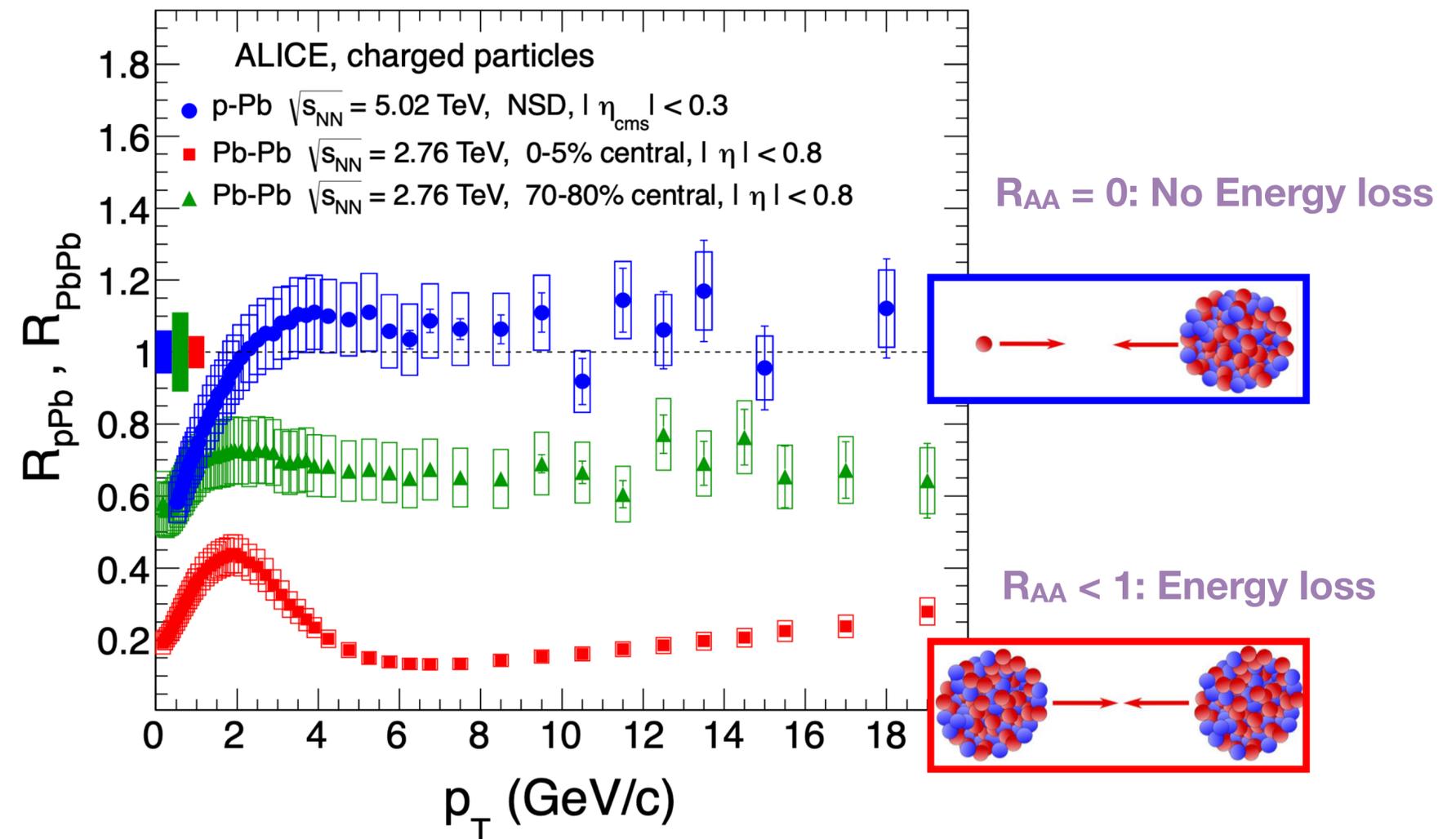
Collectivity signs? → QGP?



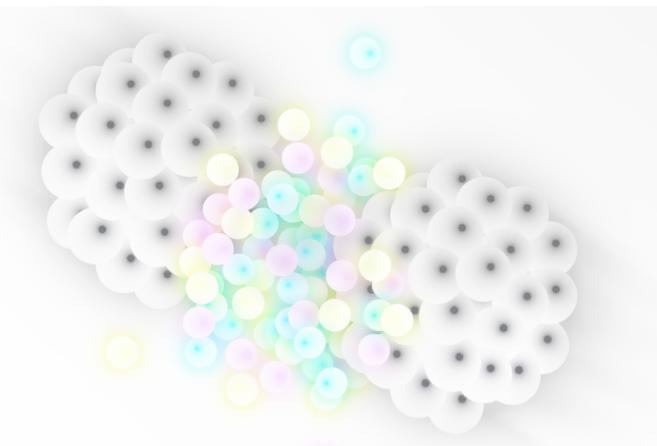
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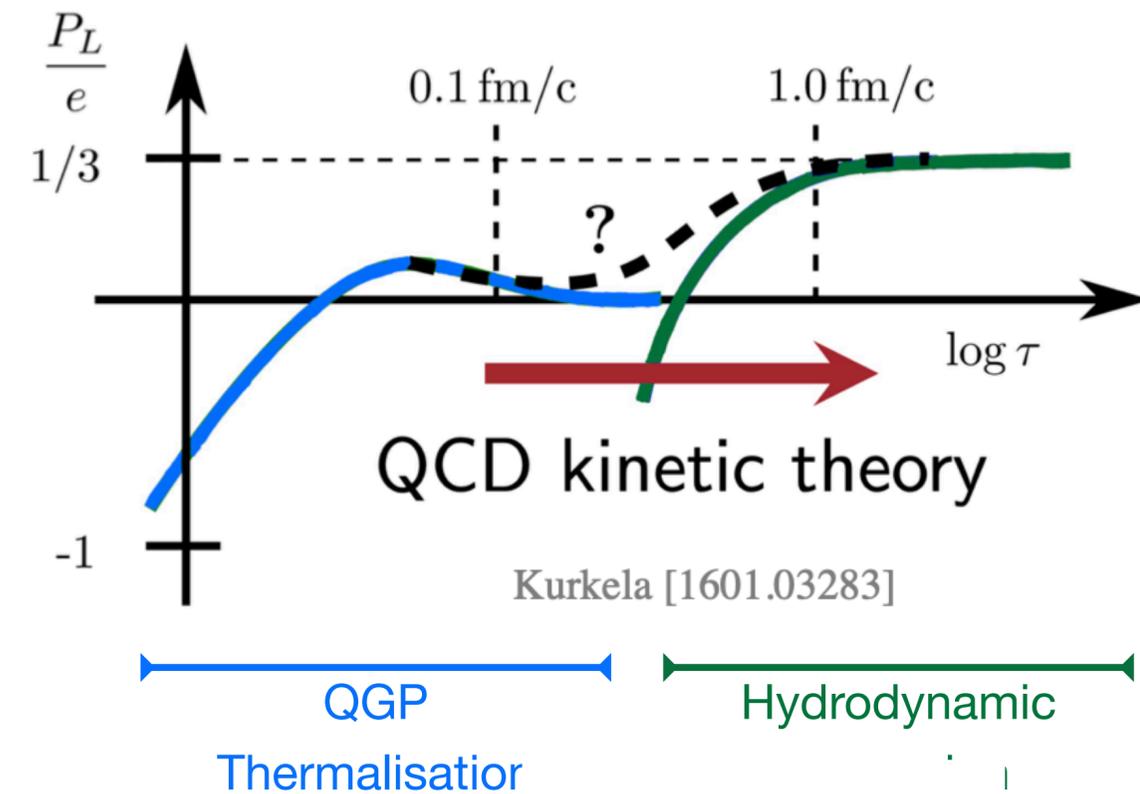
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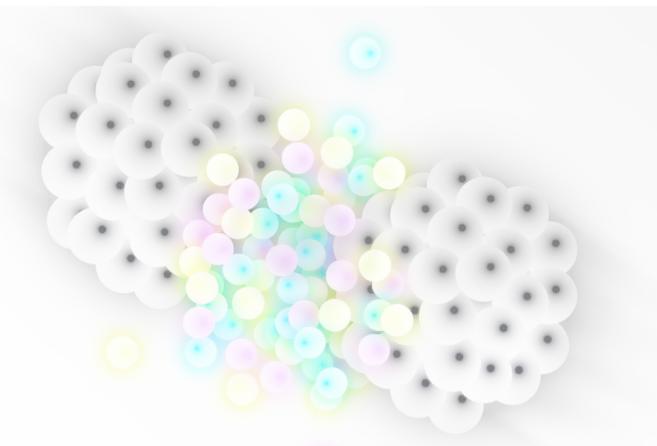
QGP onset conditions



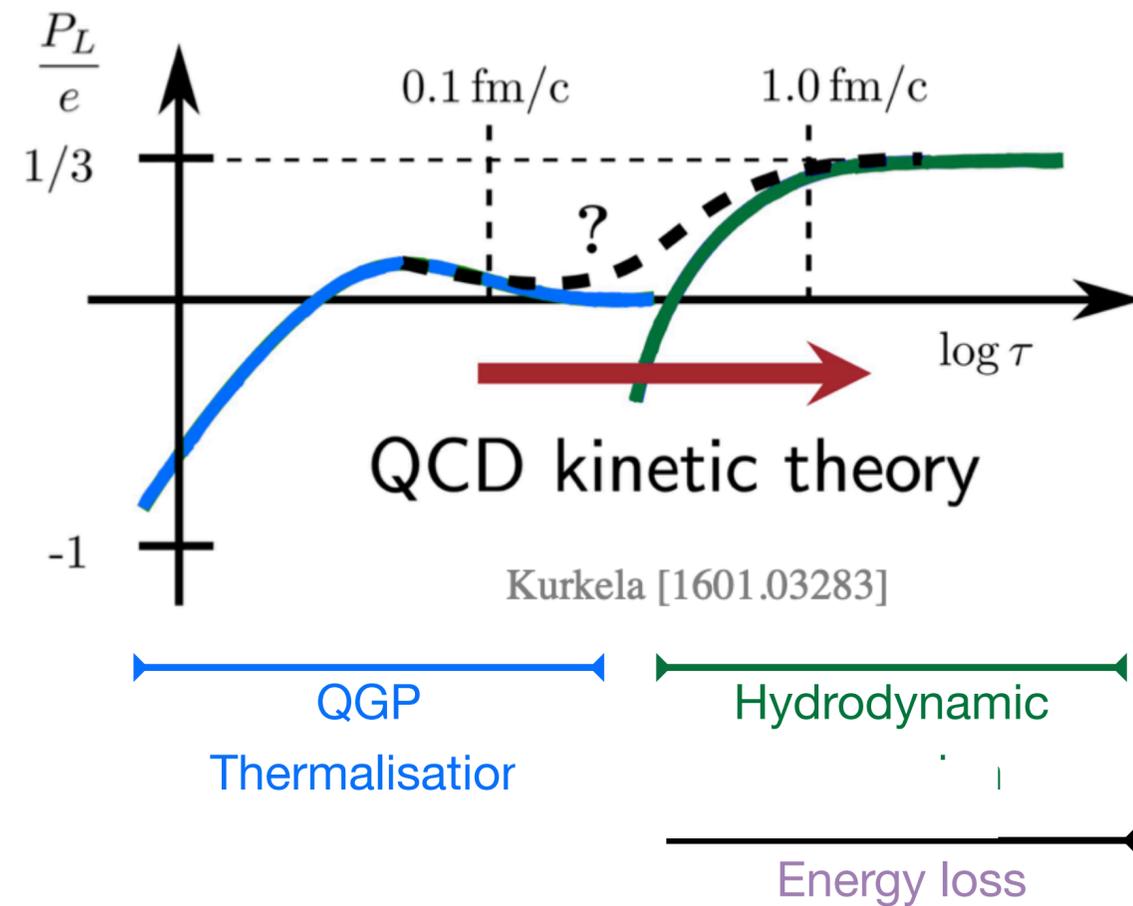
- Extrapolation from dense to light needs further understanding...



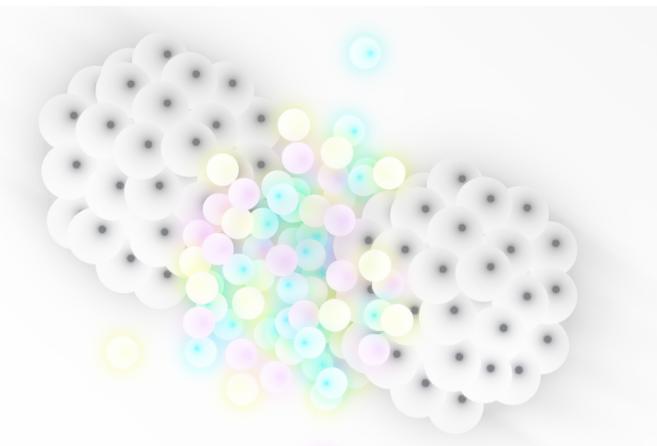
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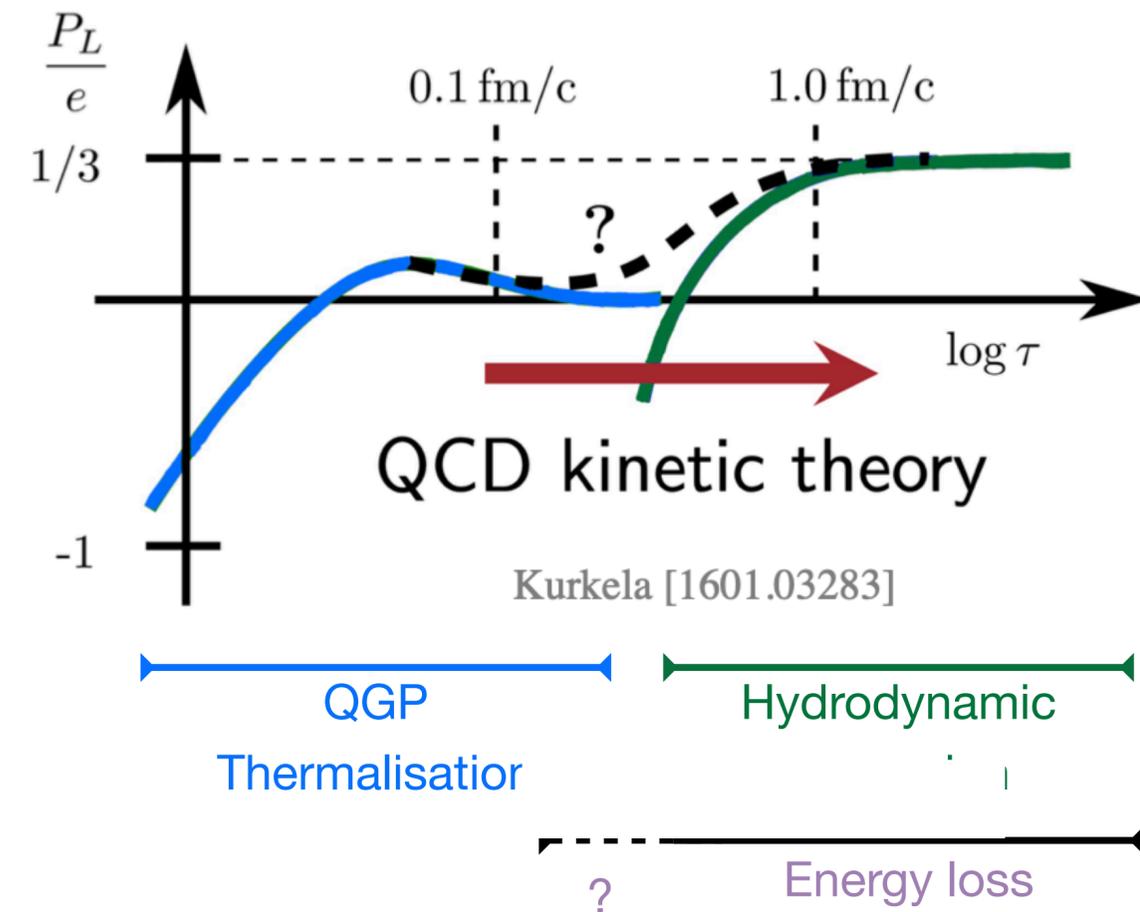
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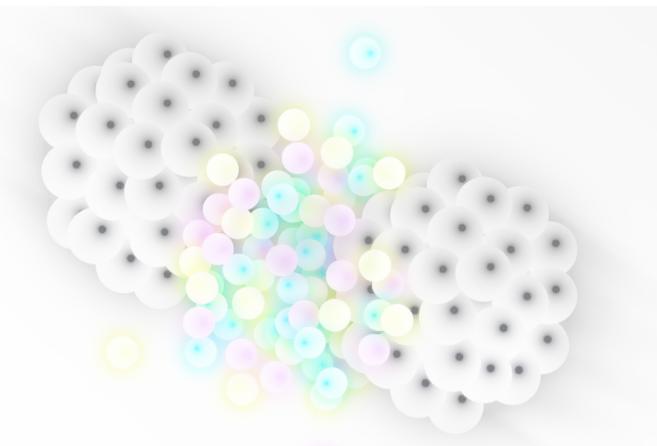
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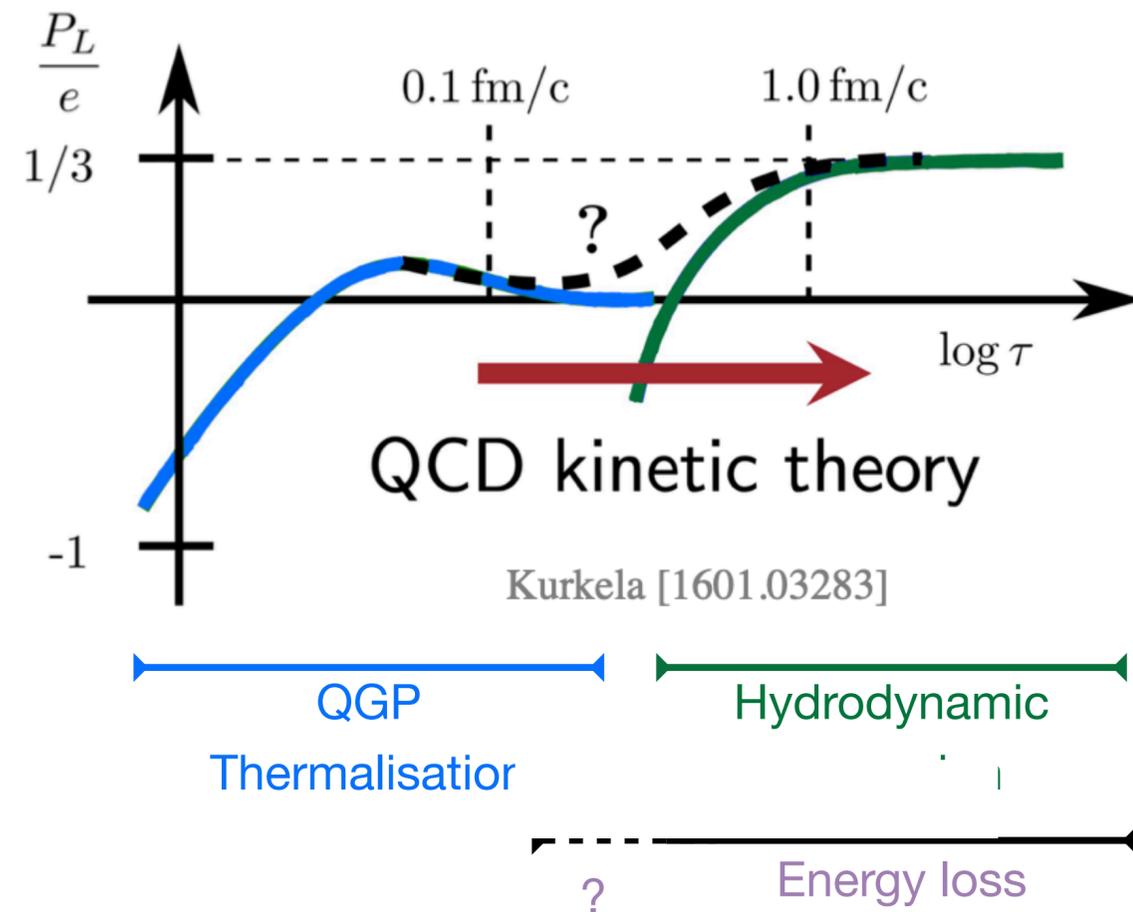
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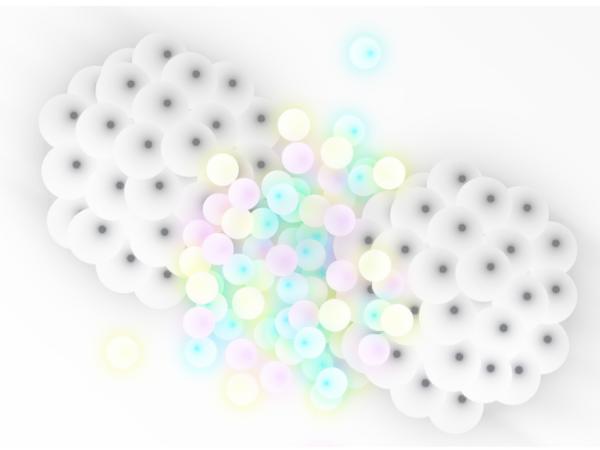
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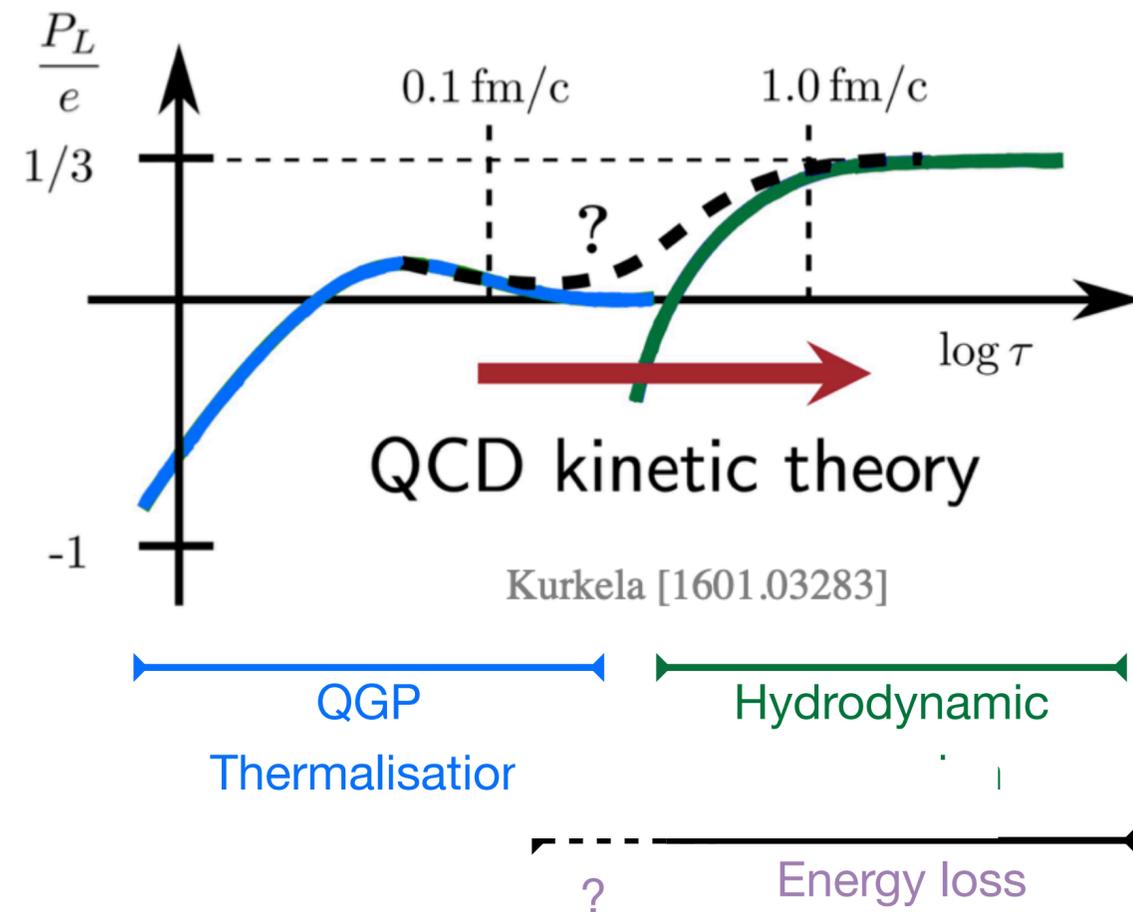
Effective kinetic theory can bridge the dynamics from out-of-equilibrium initial conditions to hydrodynamic description

Weak coupling \leftrightarrow **Strong coupling**

QGP onset conditions



- Extrapolation from dense to light needs further understanding...

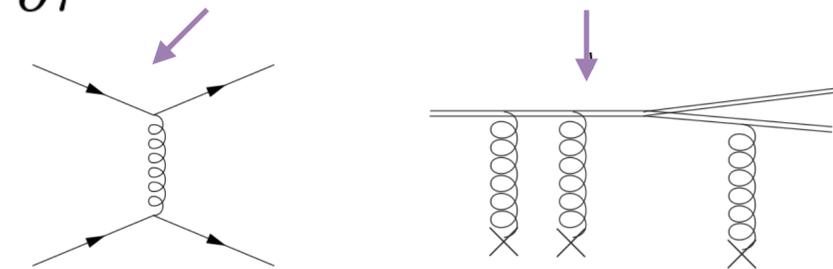


Effective kinetic theory can bridge the dynamics from out-of-equilibrium initial conditions to hydrodynamic description

Weak coupling ↔ Strong coupling

Description based on quasiparticle distribution functions $f_{\mathbf{p}}$
 Evolution follow Boltzmann equation with elastic and radiative collision rates:

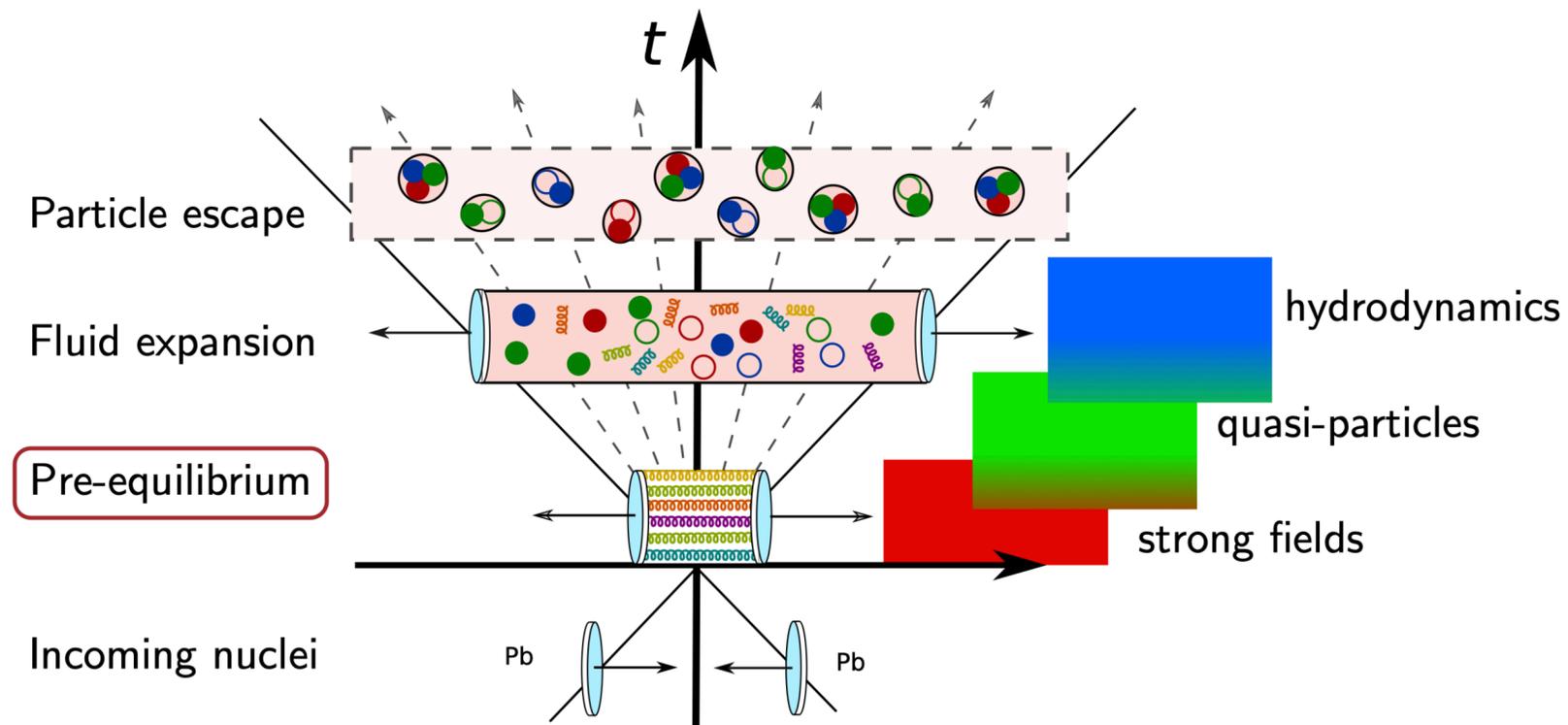
$$-\frac{\partial f_{\mathbf{p}}}{\partial \tau} = \mathcal{C}^{1 \leftrightarrow 2}[f_{\mathbf{p}}] + \mathcal{C}^{2 \leftrightarrow 2}[f_{\mathbf{p}}]$$



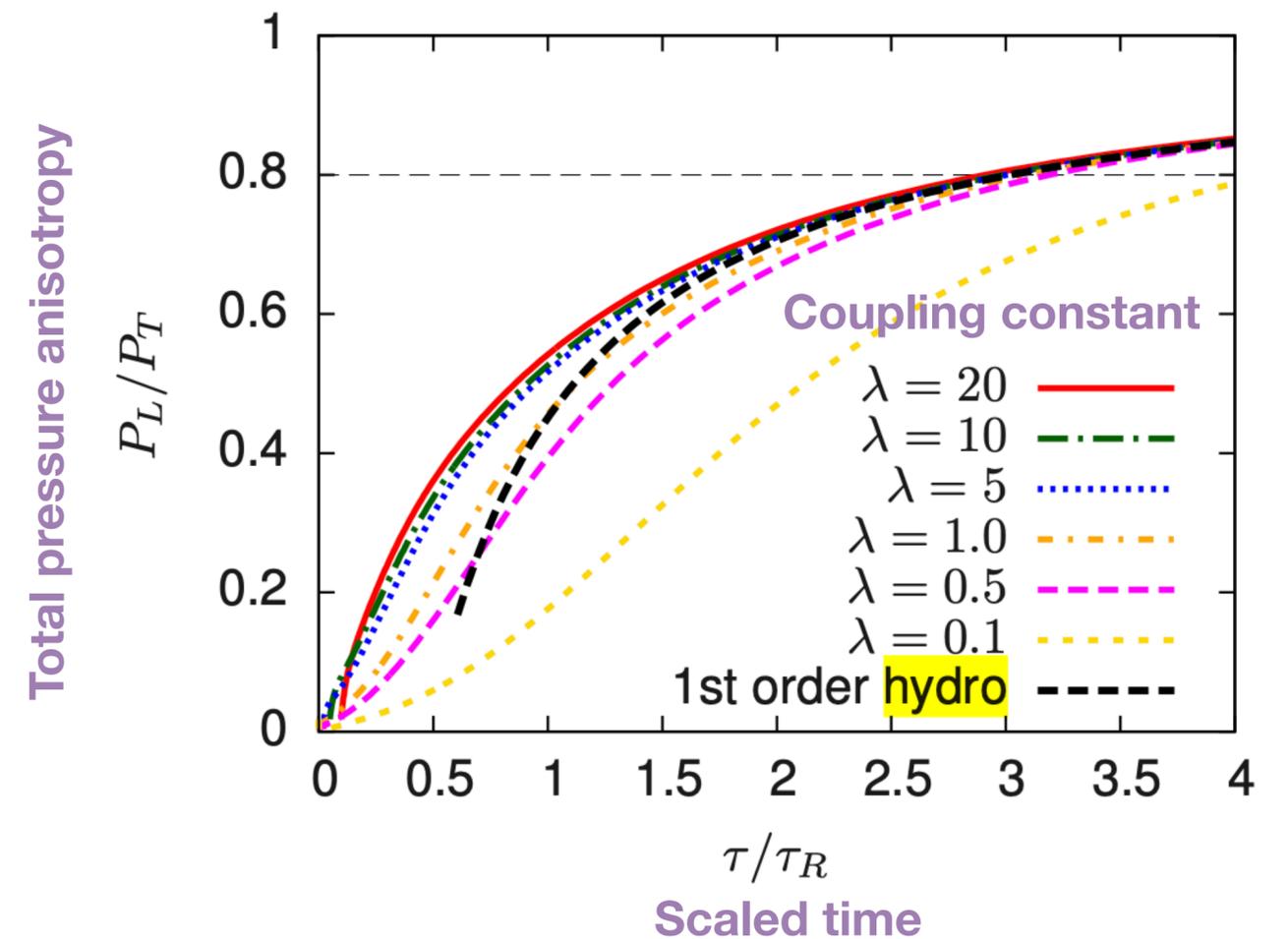
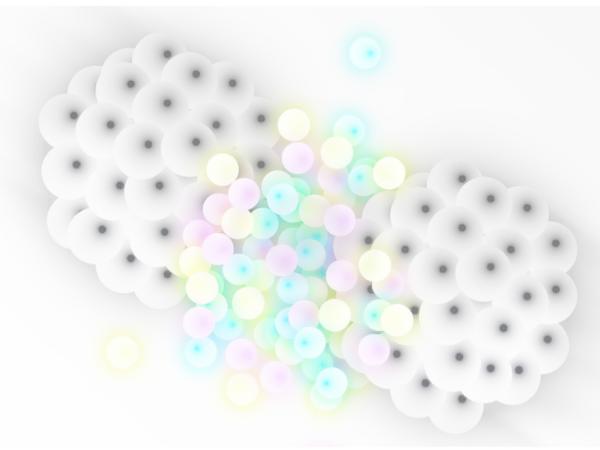
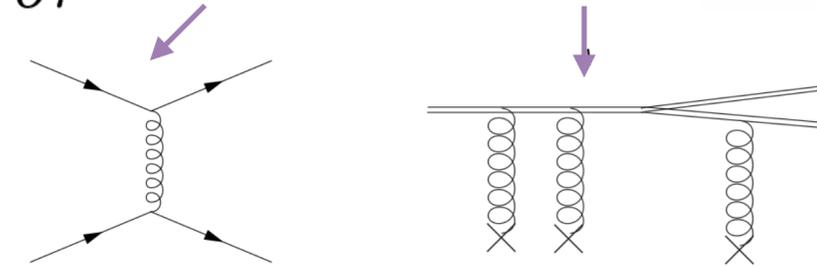
Effective Kinetic Theory

- Pre-equilibrium studies using effective kinetic theory:

How does the thermalisation time arise?



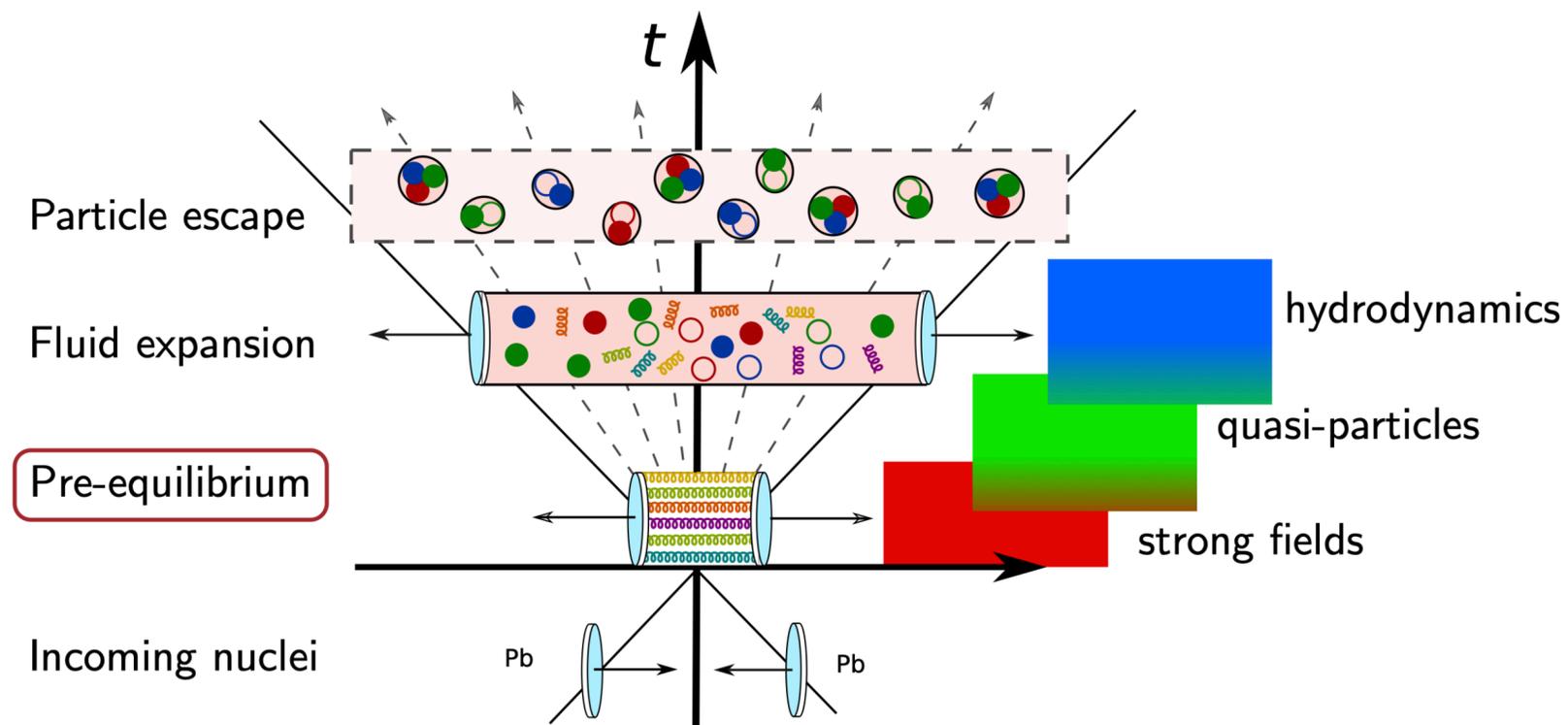
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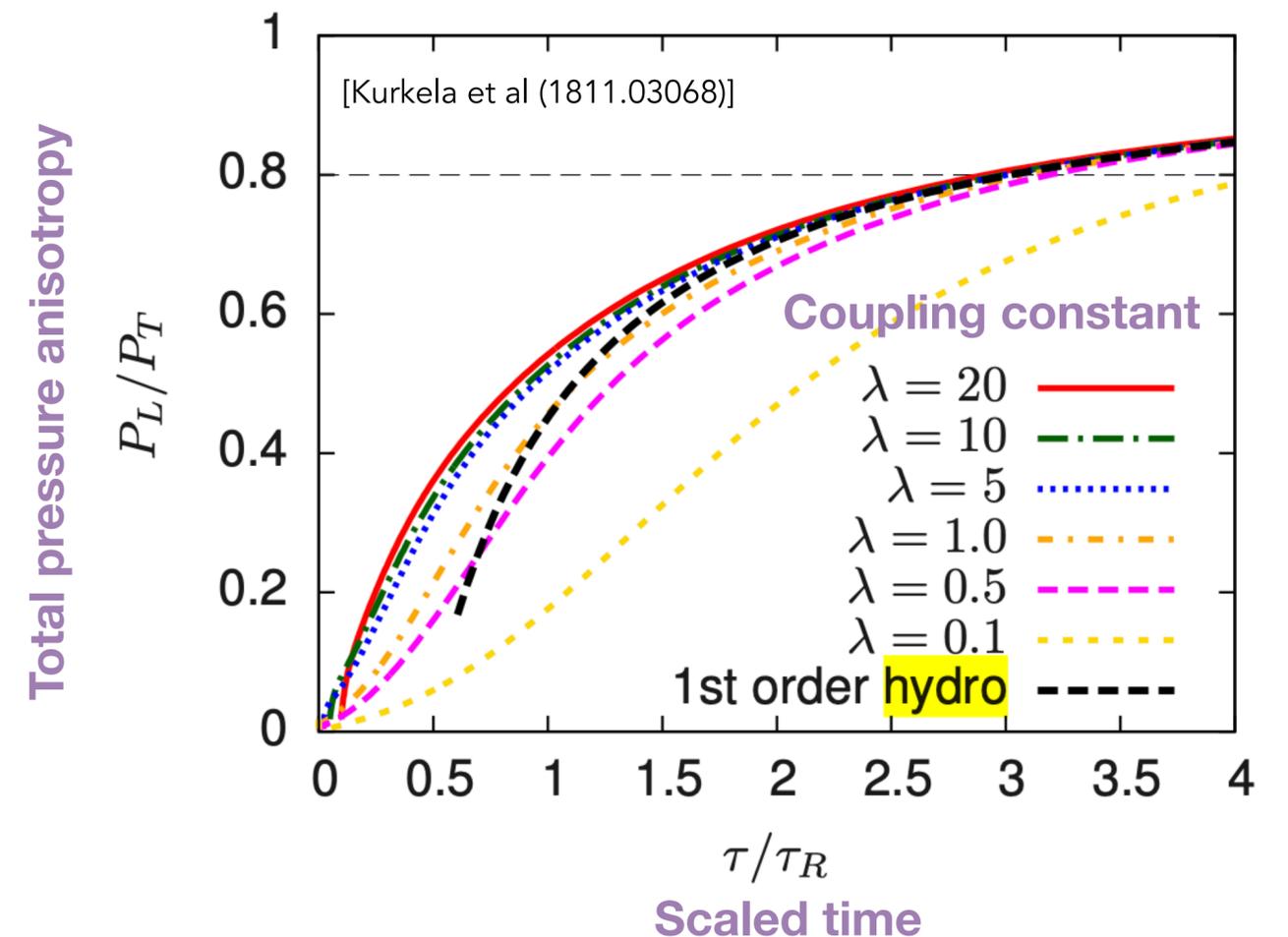
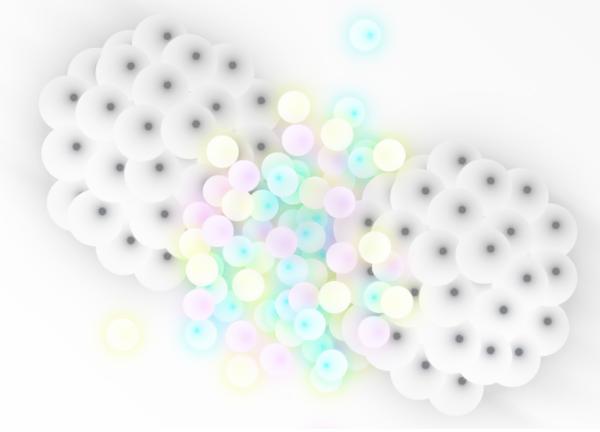
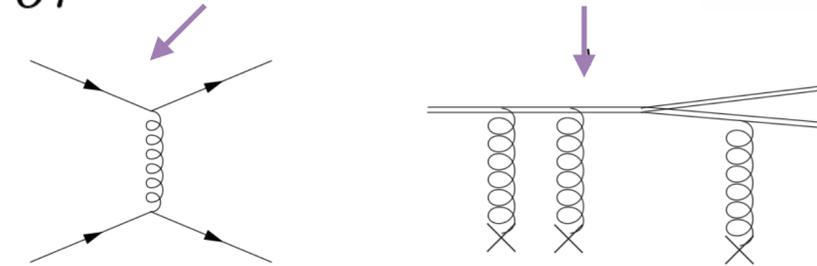
Effective Kinetic Theory

- Pre-equilibrium studies using effective kinetic theory:

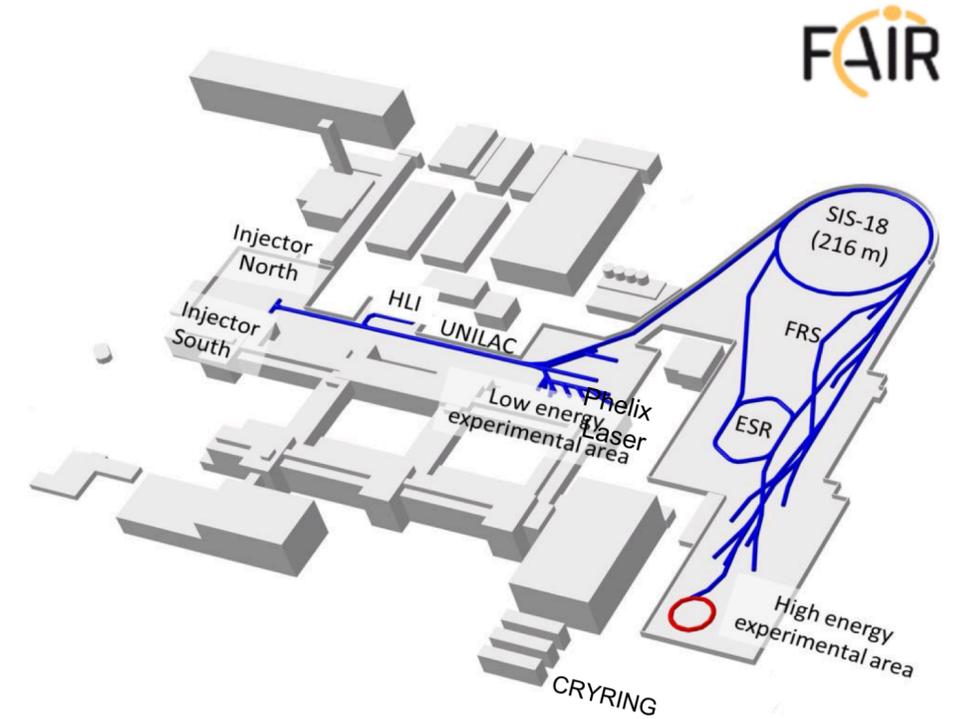
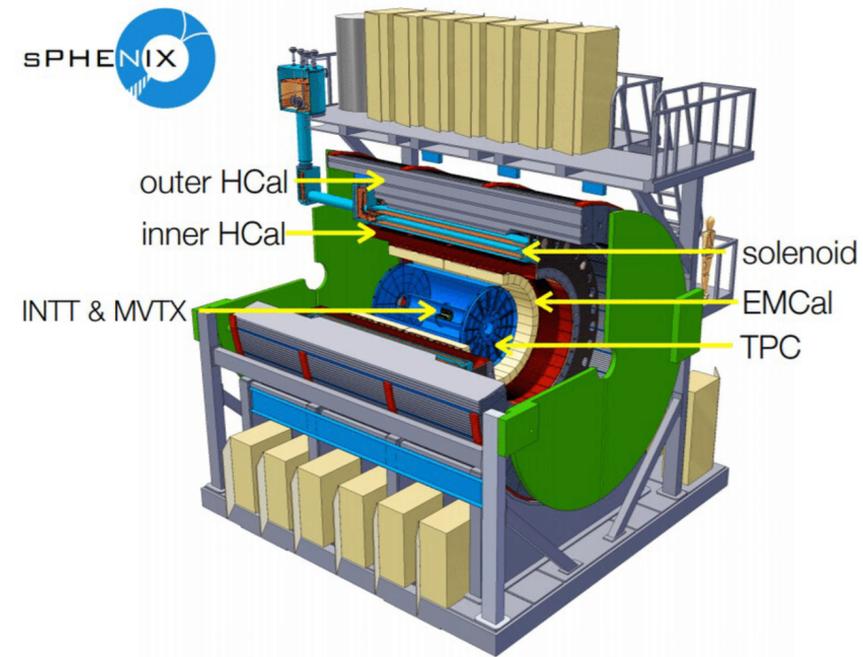
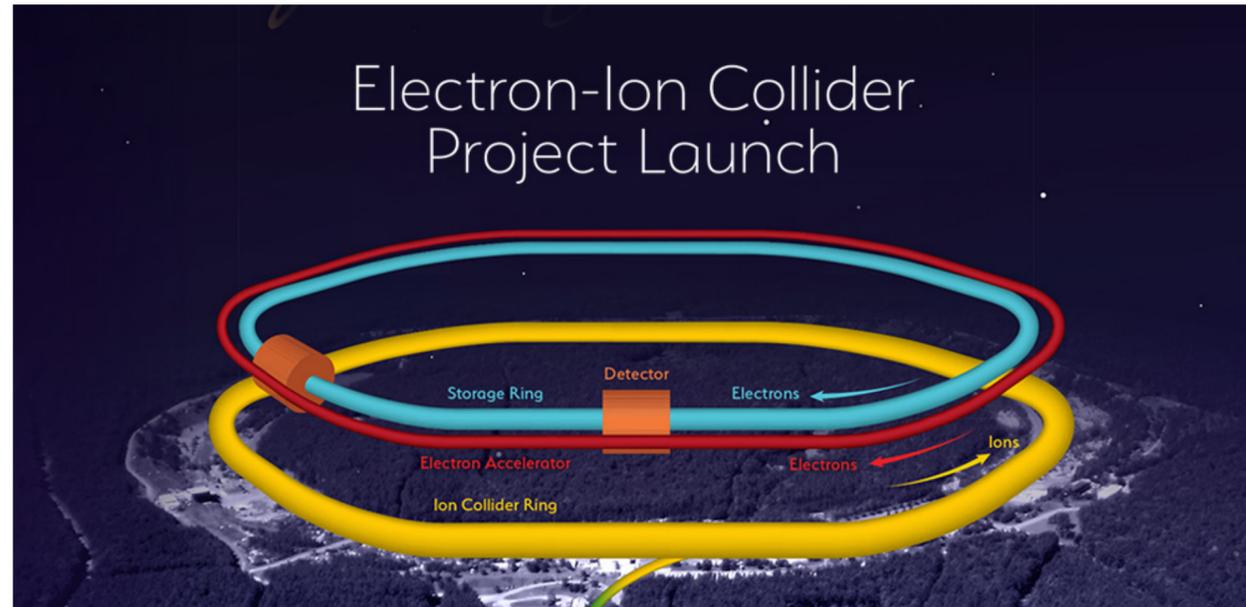
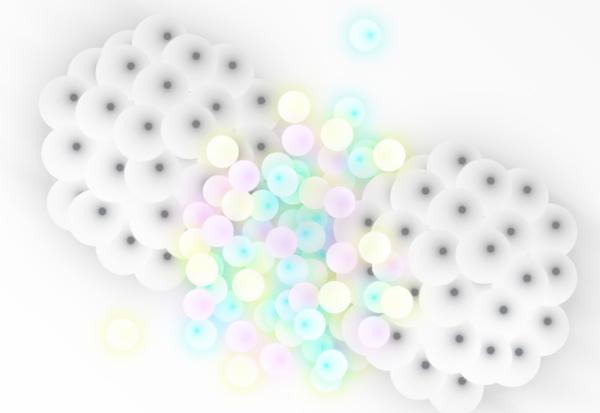
How does the thermalisation time arise?



$$-\frac{\partial f_{\mathbf{p}}}{\partial \tau} = c^{1 \leftrightarrow 2}[f_{\mathbf{p}}] + c^{2 \leftrightarrow 2}[f_{\mathbf{p}}]$$



Future Experiments

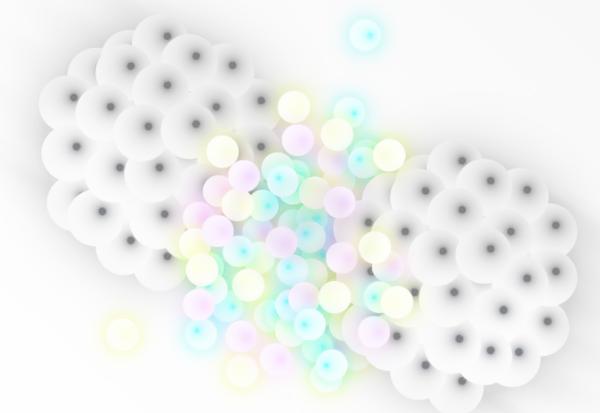


Electron Ion Collider (EIC)
 Nucleon/Nuclei Structure affect the initial state
 (important for small systems)
 > 2025

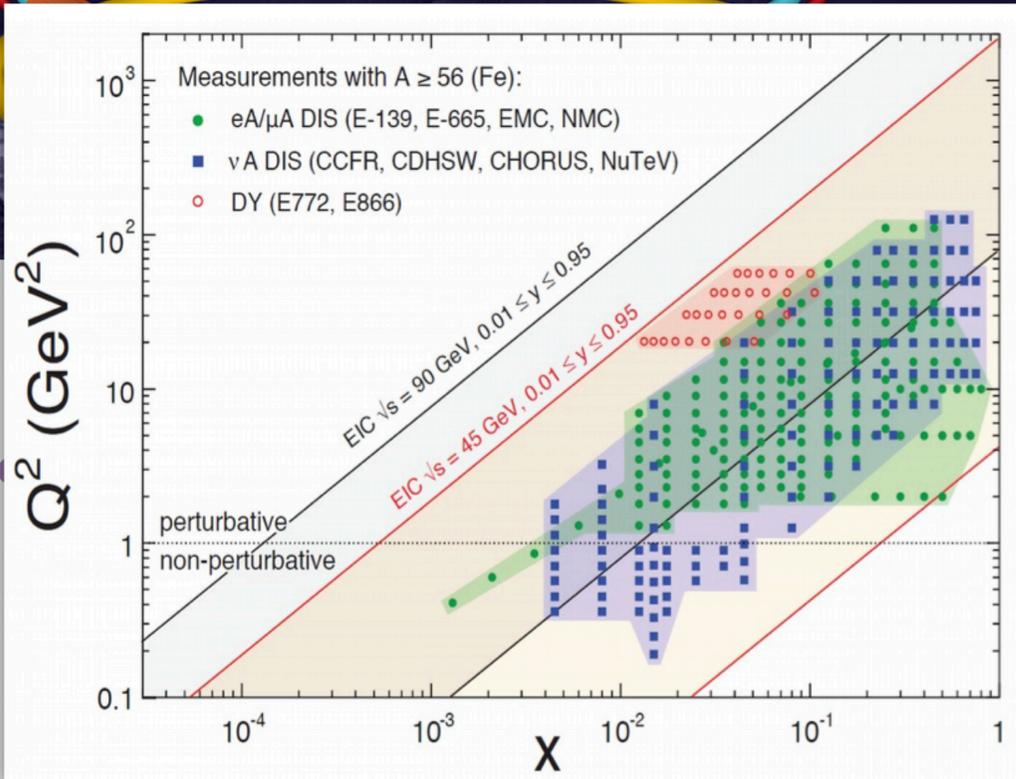
RHIC/LHC Upgrades
 +
 OO run (LHC)
 2018-2025

Beam Energy Scan (RHIC)/ FAIR
 - High baryon densities, hadron
 gas phase
 2018-2020, > 2024

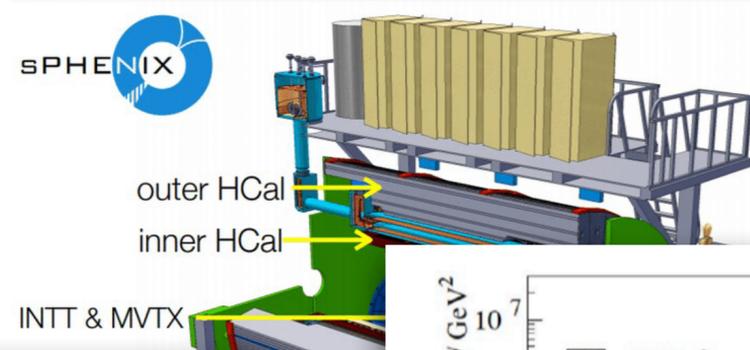
Future Experiments



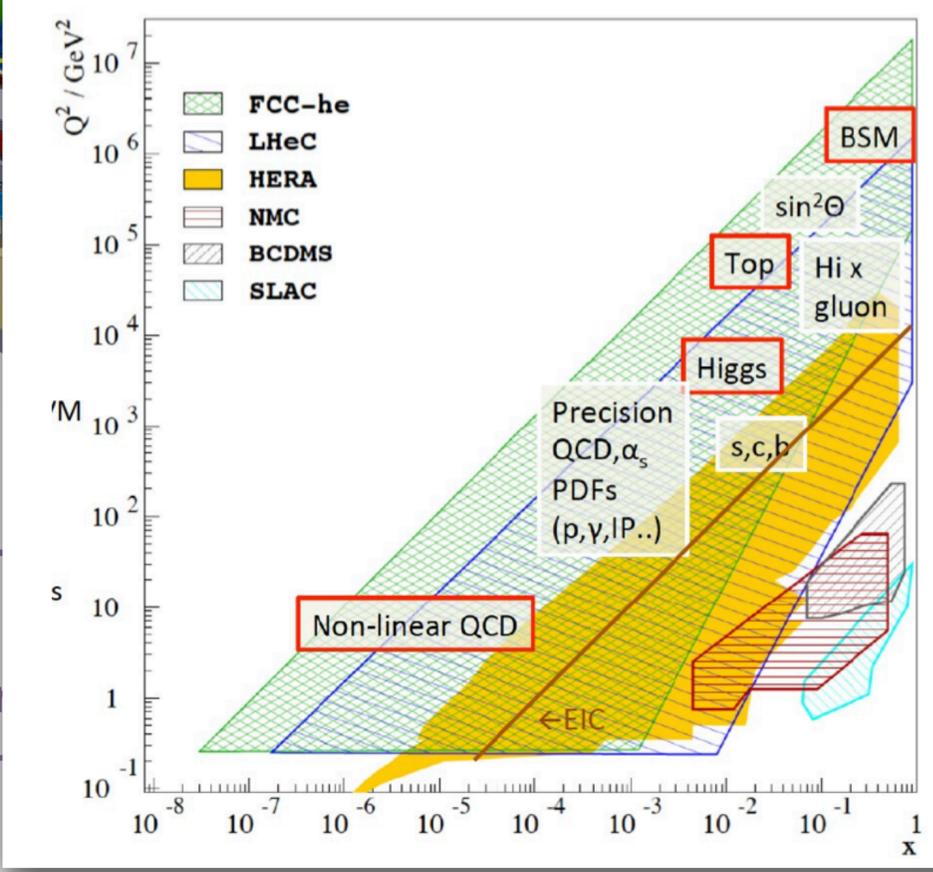
Electron-Ion Collider
Project Launch



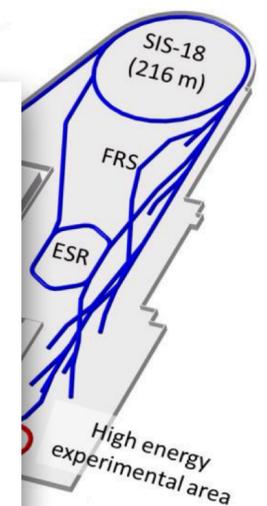
EIC



FAIR

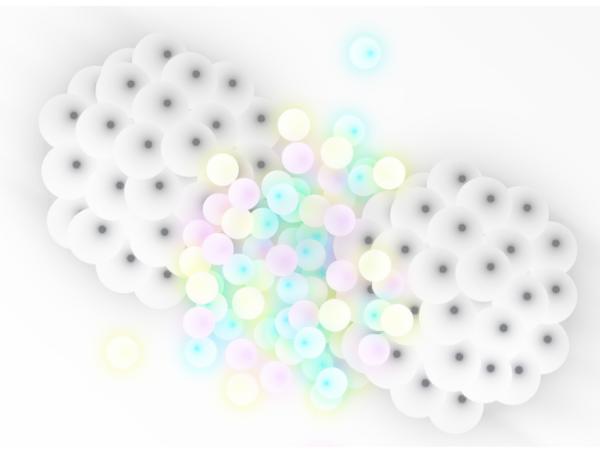


LHeC



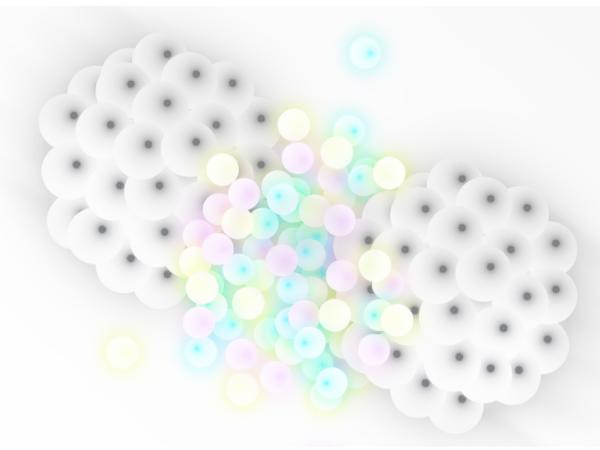
FAIR
hadron

Take-home messages



- Heavy-Ion collisions are a **rich laboratory** to study QCD
 - **QGP Phase transition** at high temperature/density
 - Application of first principle QCD (pQCD, Lattice QCD) and effective models (Hydrodynamics,...)
- **Soft probes** (non-pQCD sector) are a powerful tool to identify **QGP macroscopic properties**
 - Quark-Gluon Plasma is a **strongly coupled fluid**:
 - Present in proton-nucleus (small systems)?
 - Conditions to form a QGP? Saturation effects?

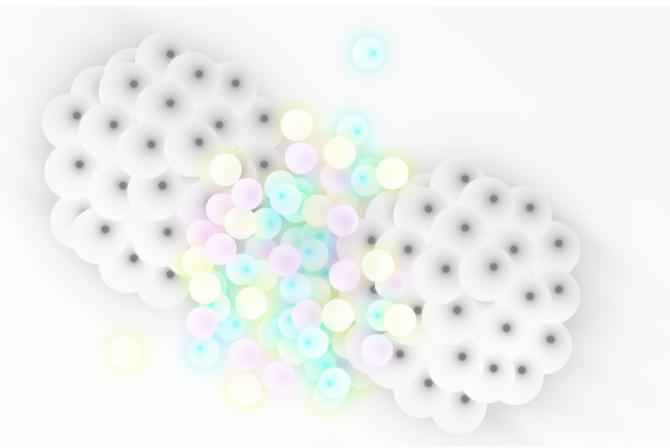
Take-home messages



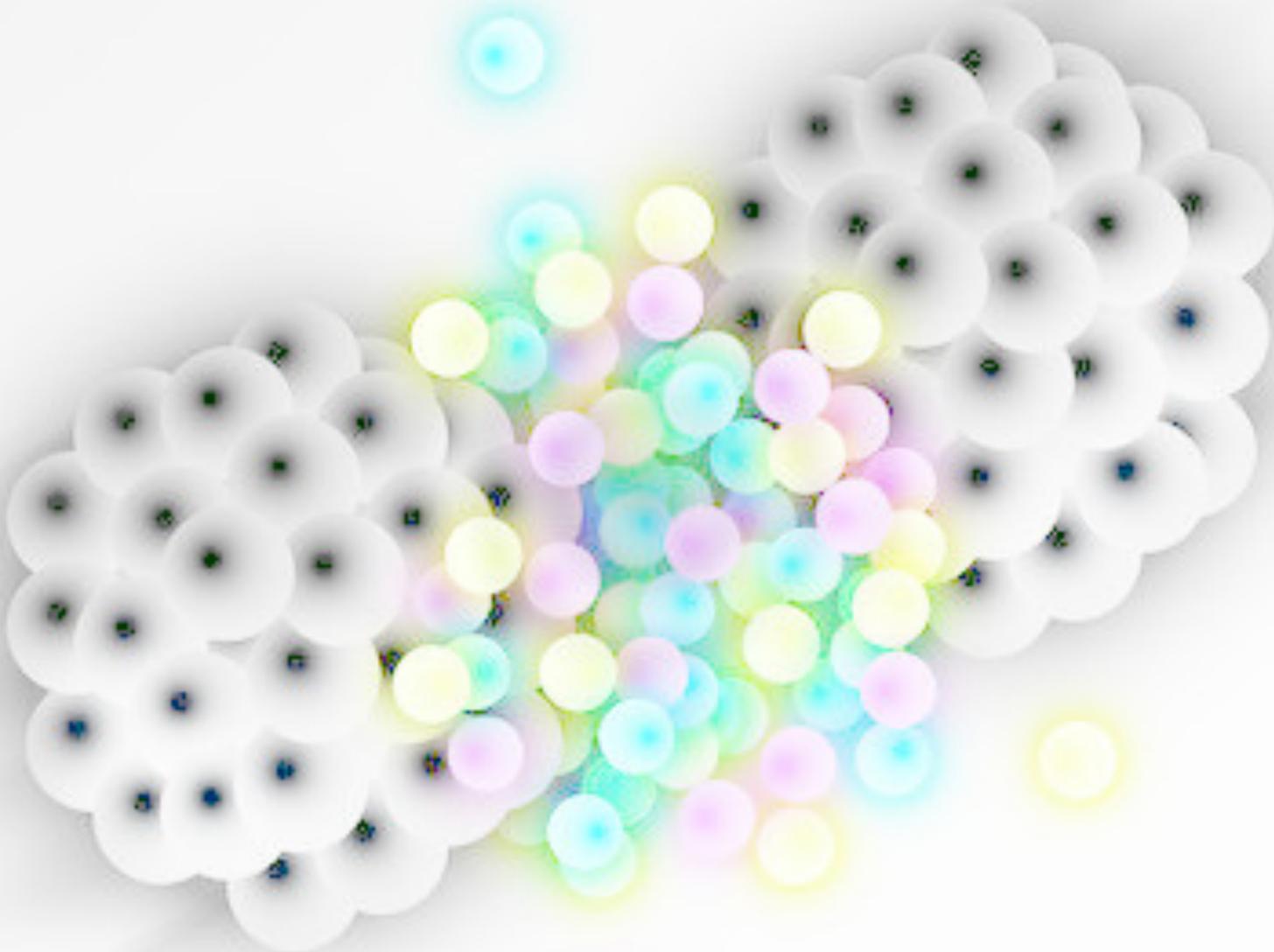
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Thank you!

Acknowledgments

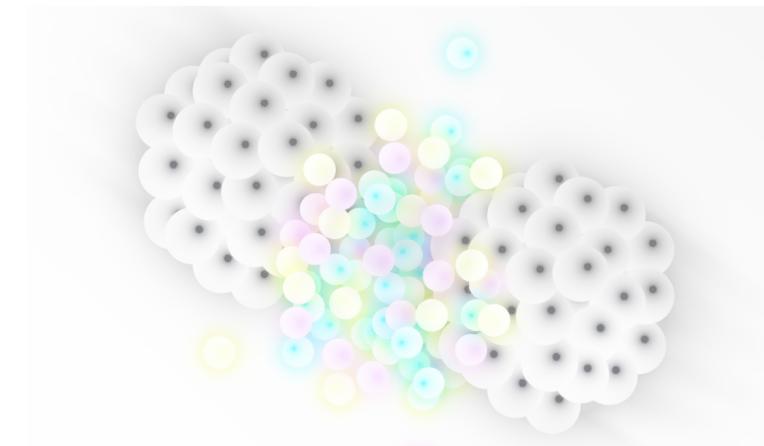


Backup Slides



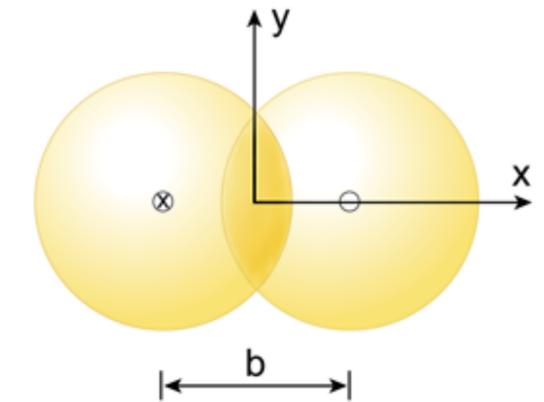
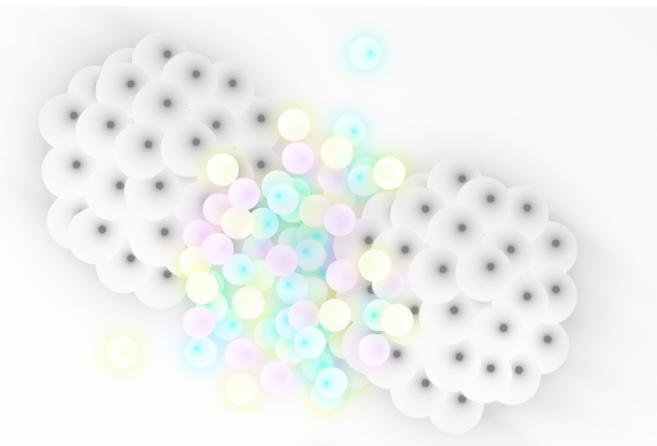
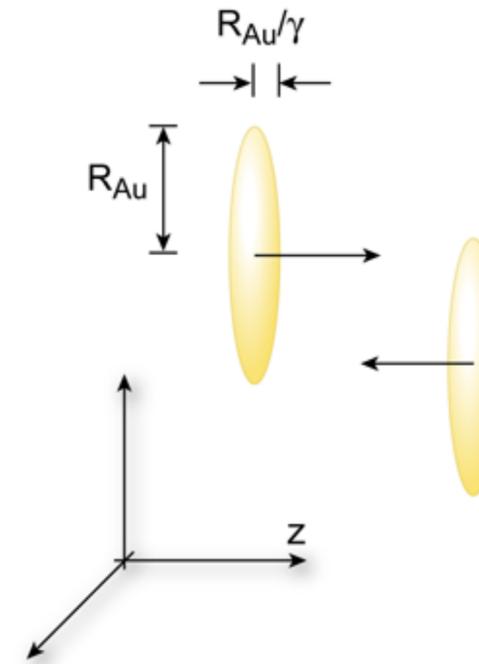
Collision Geometry

- Colliding Nuclei ~ collection of nucleons
- Collision system ~ nucleons that participate in the collision



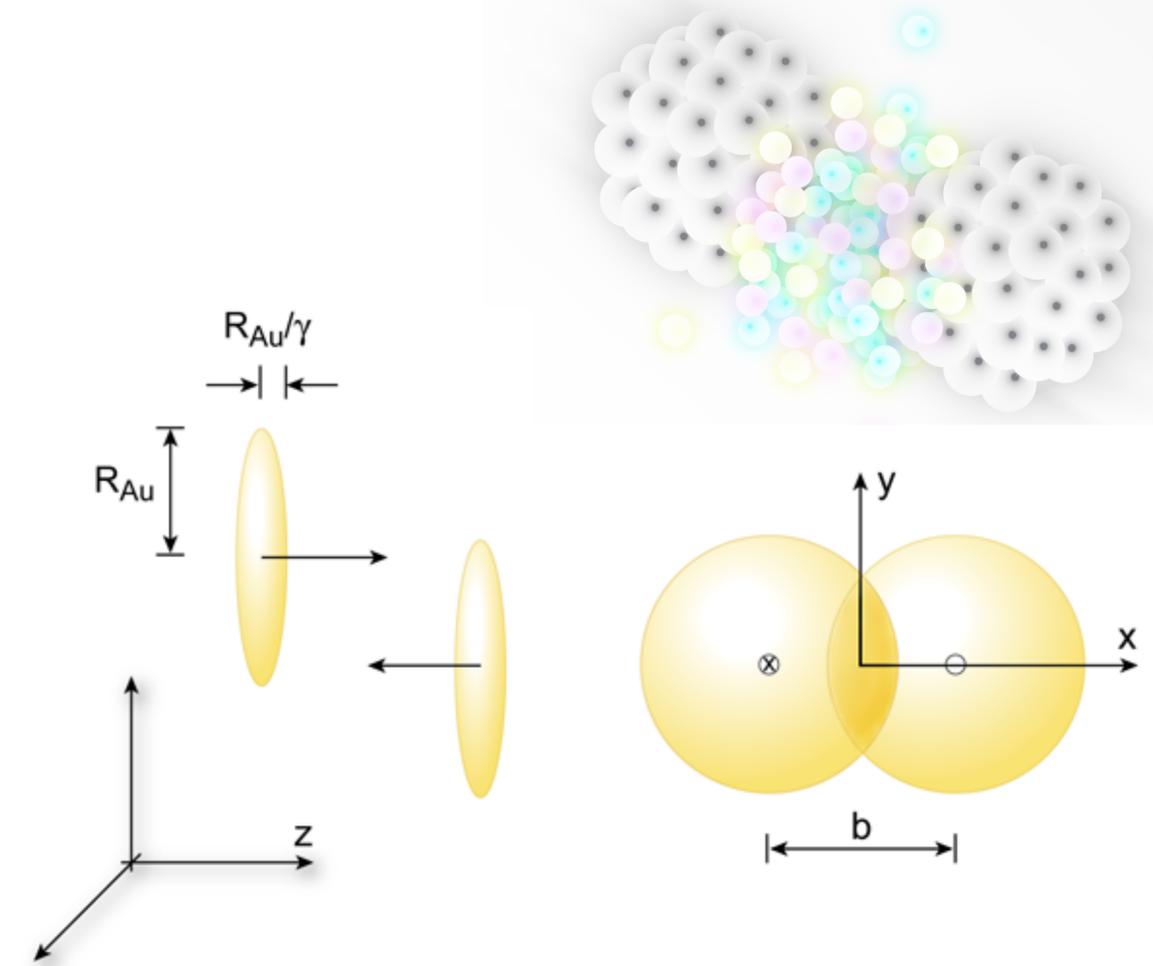
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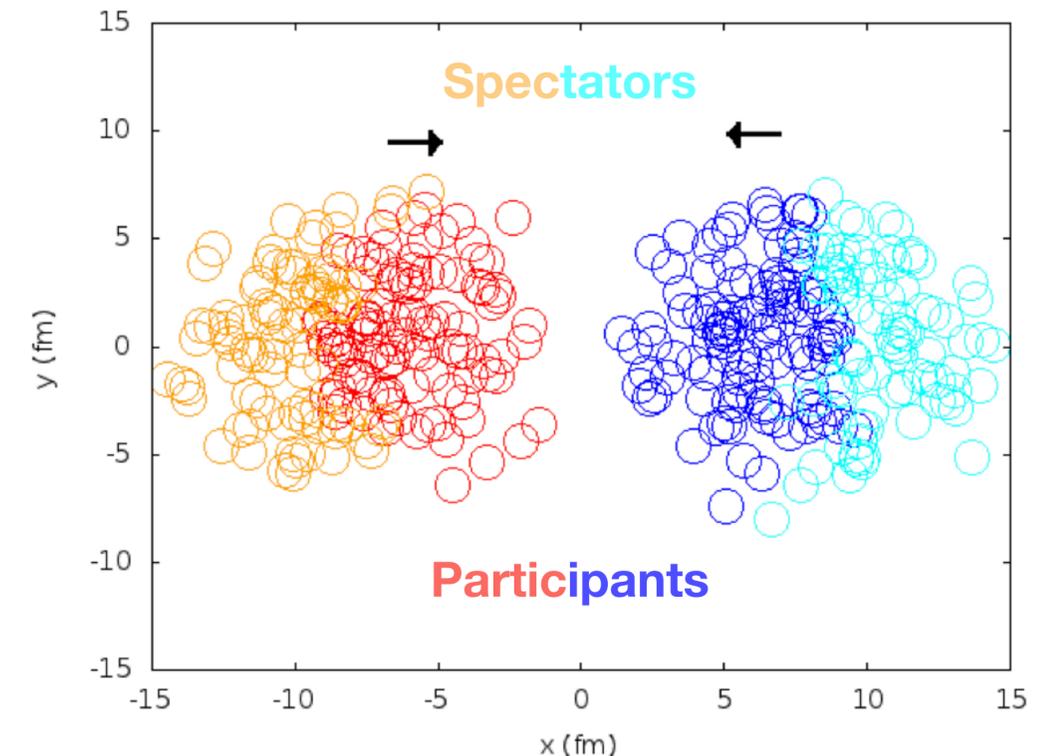
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[Borsányi et al (1007.2580)]

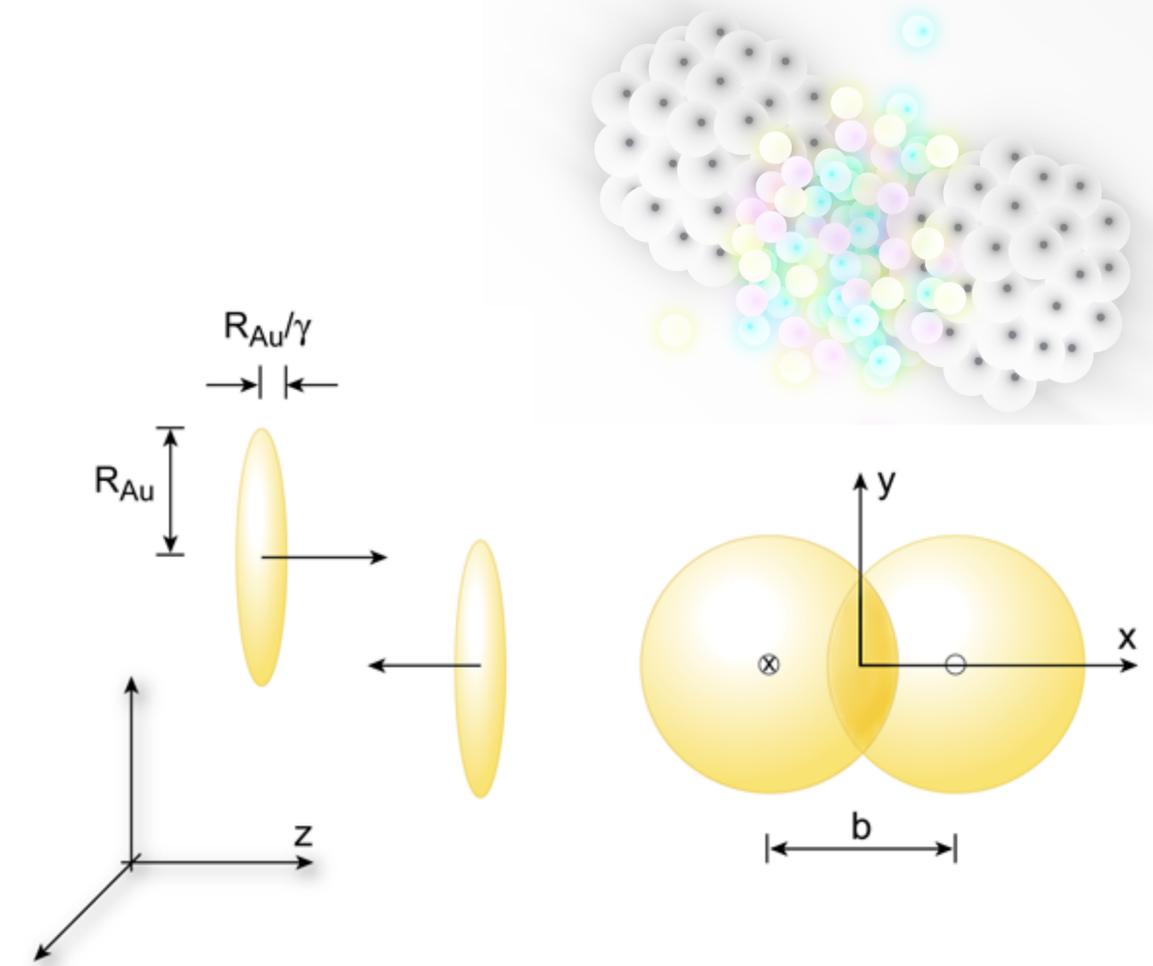
Monte Carlo Simulation for
RHIC AuAu 200 GeV



CERN-Fermilab HCP Summer School

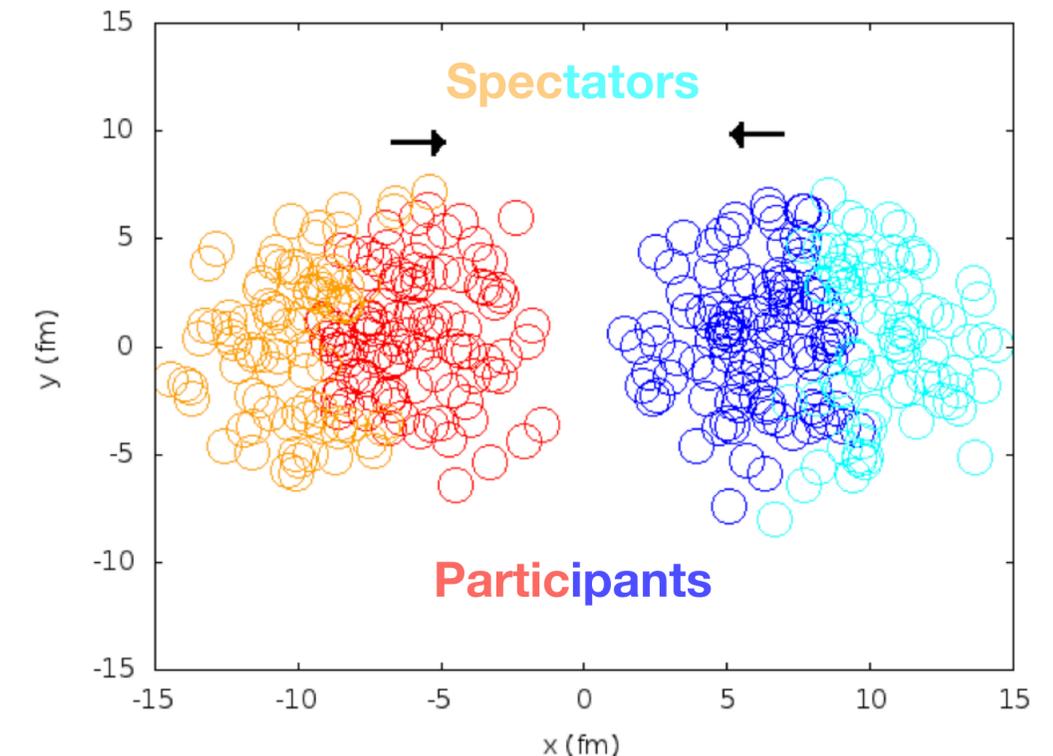
Collision Geometry

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- Collision system ~ nucleons that participate in the collision
 - To define collision geometry:
 - Impact parameter: the transverse distance between the center of masses of the two nuclei
 - Location and motion of the nucleons in the nuclei
- $N_{\text{Spec}} + N_{\text{Part}} = A_L + A_R$
 - N_{spec} will continue travelling along beam pipe
(but cannot be measurable experimentally)
 - N_{part} will collide with at least other nucleon
(what we want to know)



[Borsányi et al (1007.2580)]

Monte Carlo Simulation for
RHIC AuAu 200 GeV

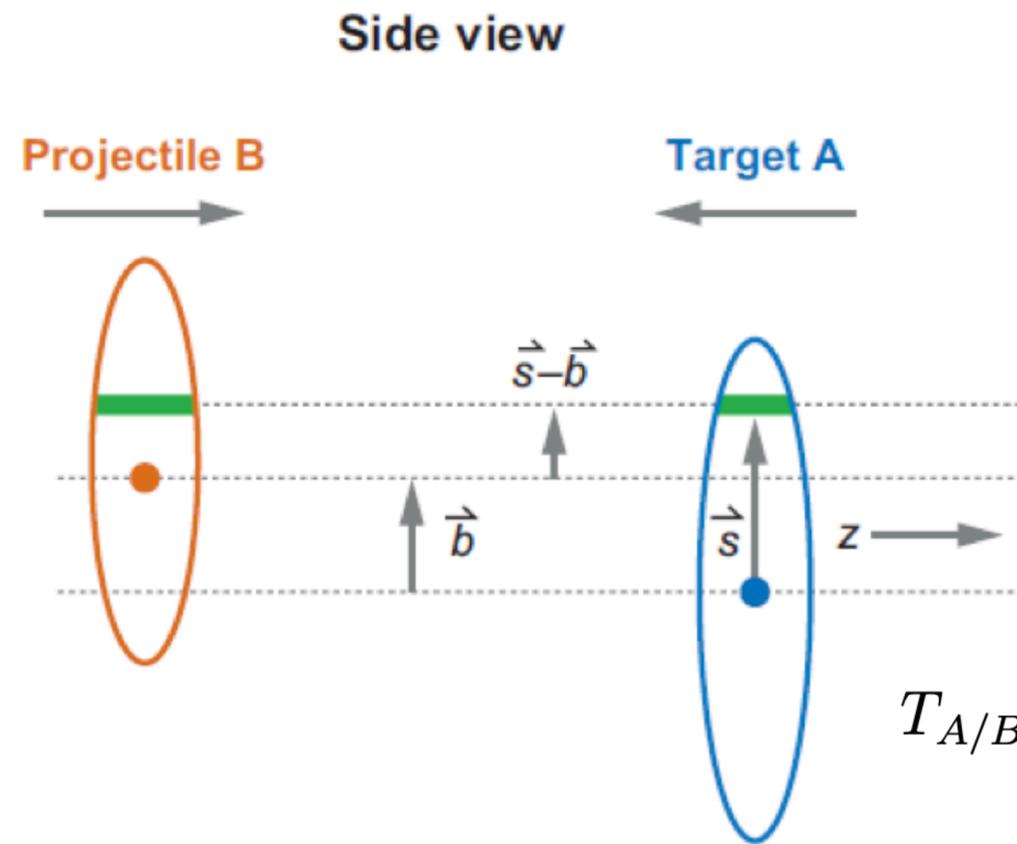
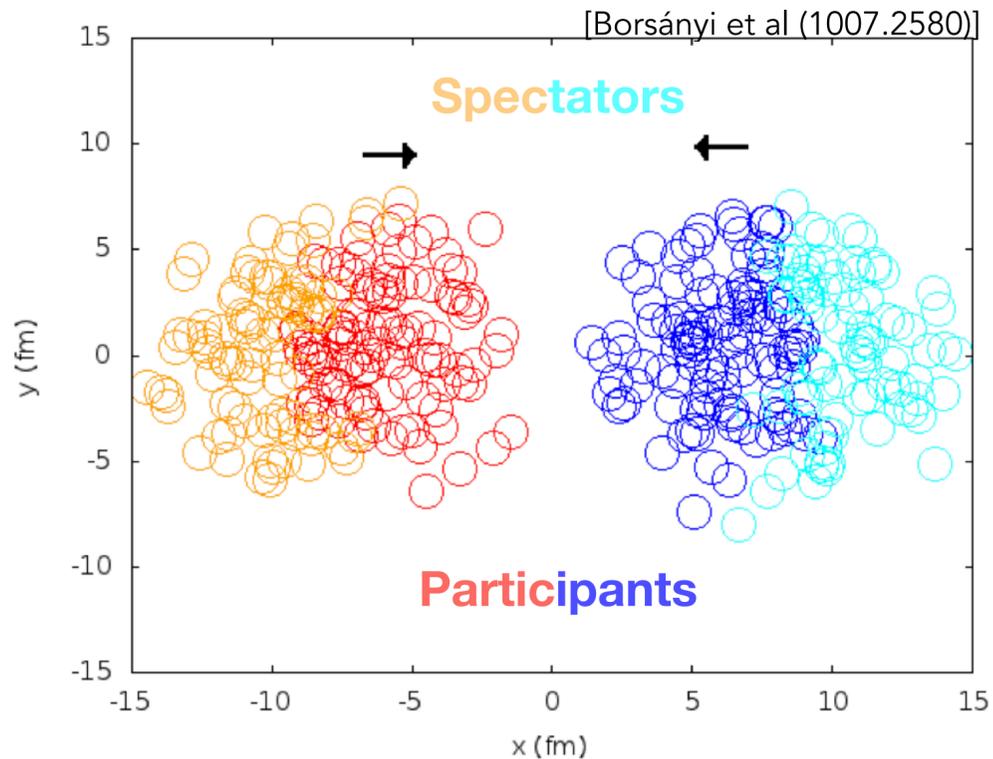


CERN-Fermilab HCP Summer School

Glauber Model

- Geometric model to calculate:
 - N_{part} : number of participants
 - N_{coll} : number of total collisions

Monte Carlo Simulation for RHIC AuAu 200 GeV



Nuclear thickness function :

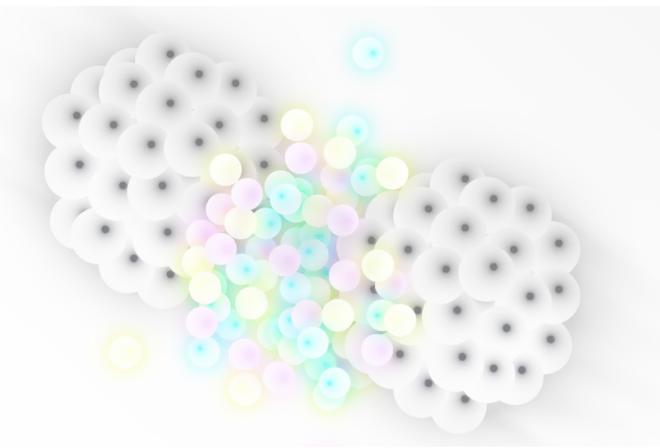
$$T_{A/B}(\mathbf{b}) = \int \rho_{A/B}(\mathbf{b}, z_{A/B}) dz_{A/B}$$

Probability of finding a nucleon at a point (\mathbf{b}, z) per unit volume

Thickness function from overlap region:

$$T_{AB}(\mathbf{b}) = \int T_A(\mathbf{s}) T_B(\mathbf{s} - \mathbf{b}) d^2s \quad \int T_{AB}(\mathbf{b}) d\mathbf{b} = A \cdot B$$

Glauber Model



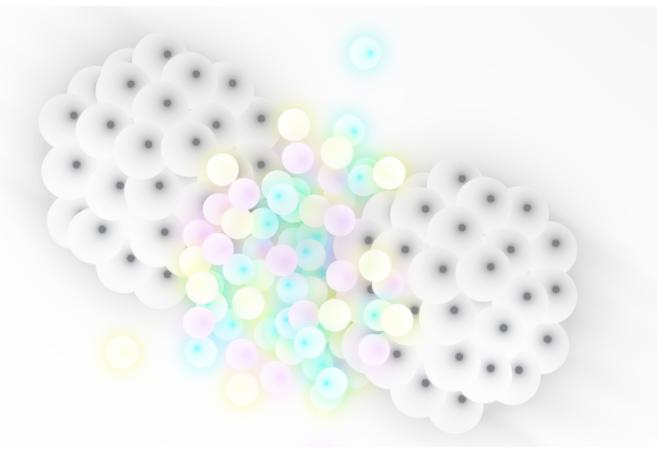
- Geometric model to calculate N_{part} and N_{coll}

$$N_{\text{coll}}(\mathbf{b}) = \sigma_{\text{inel}}^{NN} T_{AB}(\mathbf{b})$$

$$N_{\text{part}}(\mathbf{b}) = \int T_A(\mathbf{s}) (1 - \exp[-\sigma_{\text{inel}}^{NN} T_B(\mathbf{b} - \mathbf{s})]) d\mathbf{s} \\ + \int T_B(\mathbf{b} - \mathbf{s}) (1 - \exp[-\sigma_{\text{inel}}^{NN} T_A(\mathbf{b})]) d\mathbf{s}$$

Geometry (Optical Glauber model) allows to calculate average N_{part} and N_{coll}

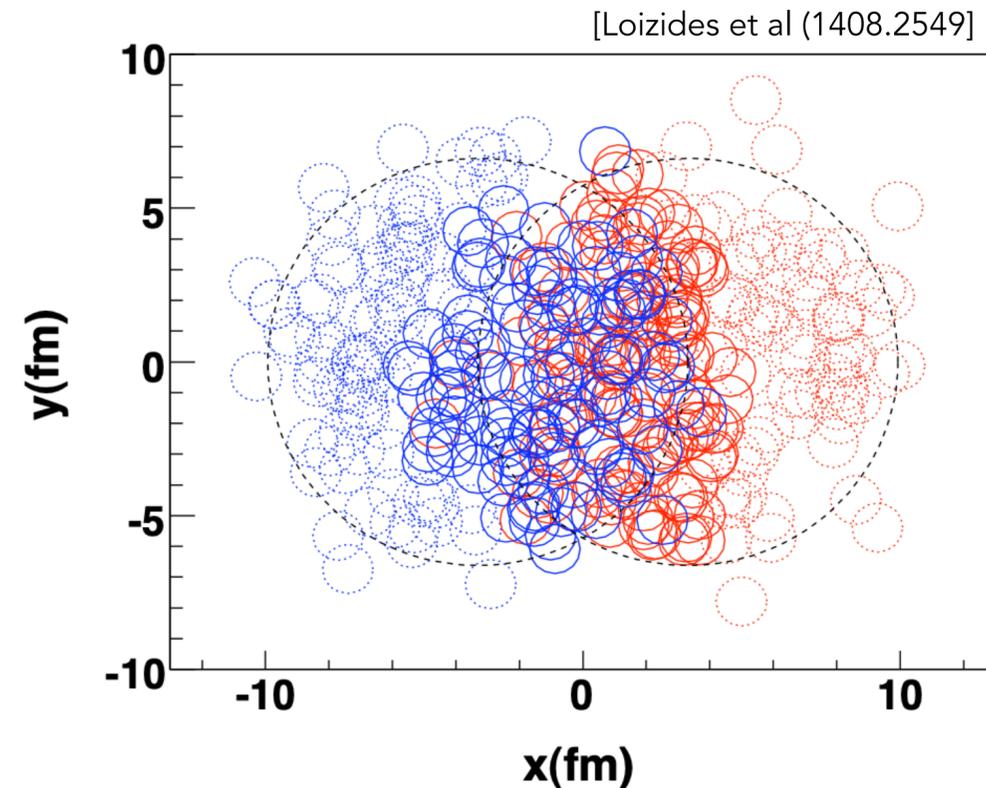
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Geometry (Optical Glauber model) allows to calculate average N_{part} and N_{coll}

How about fluctuations?

Individual nucleons are stochastically distributed event-by-event in nuclei following Wood-Saxon distribution

$$\rho(r) = \rho_0 \frac{1 + w(r/R)^2}{1 + \exp(\frac{r-R}{a})}$$

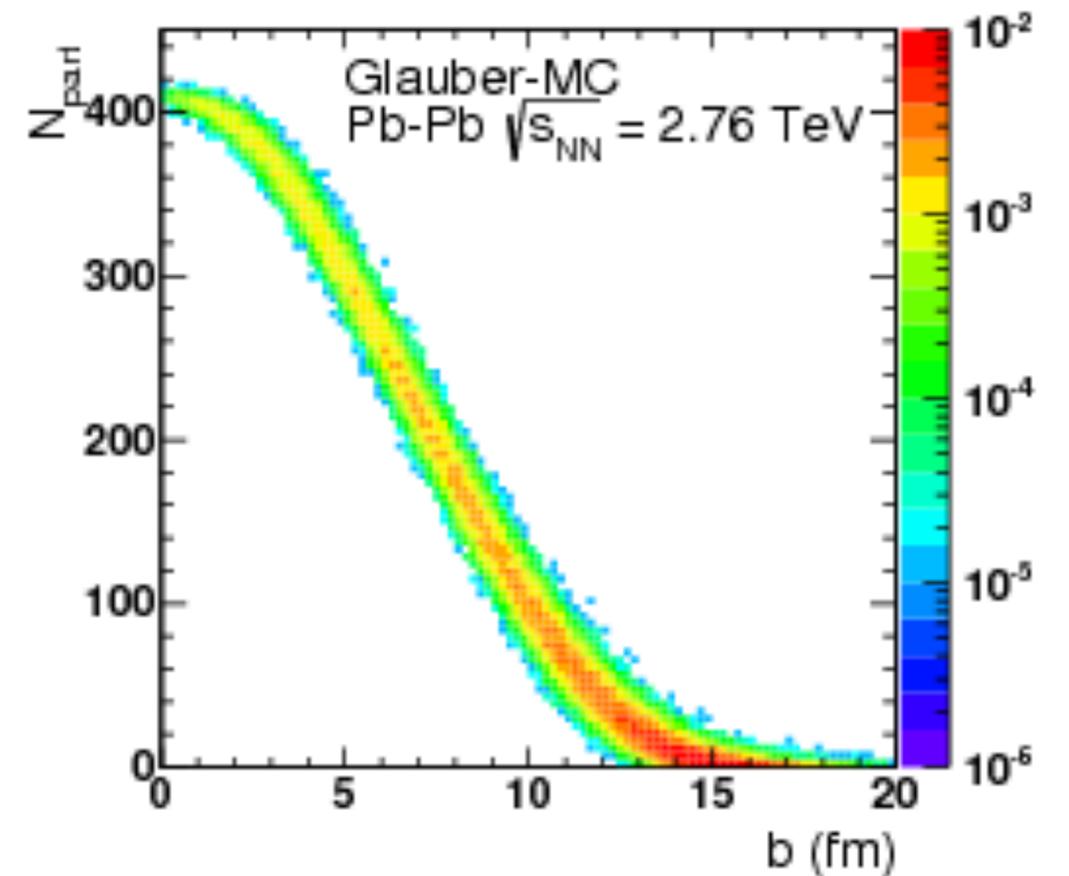
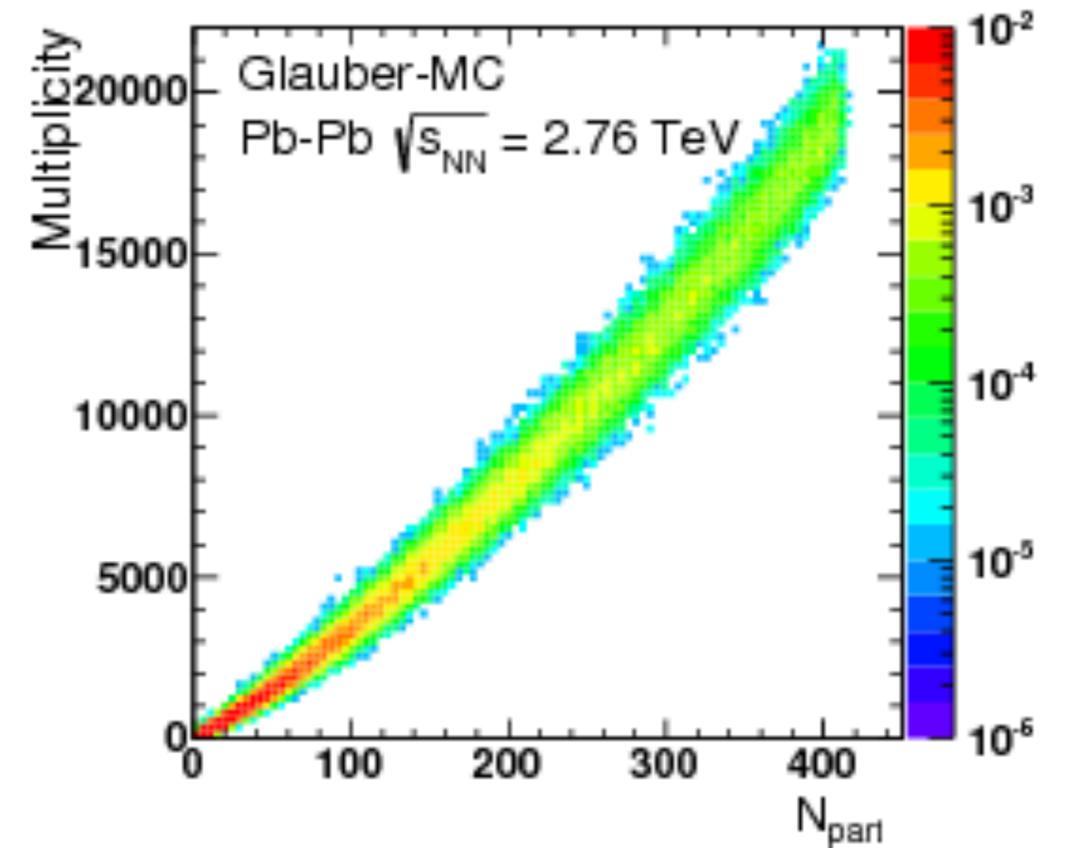
Glauber Model

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Geometry (Glauber model) relates multiplicity to N_{part} and impact parameter (b)



Glauber Model

- Geometric model to calculate N_{part} and N_{coll}

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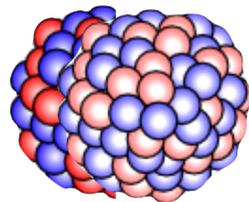
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Geometry (Glauber model) relates multiplicity to N_{part} and impact parameter (b)

Can now define centrality classes

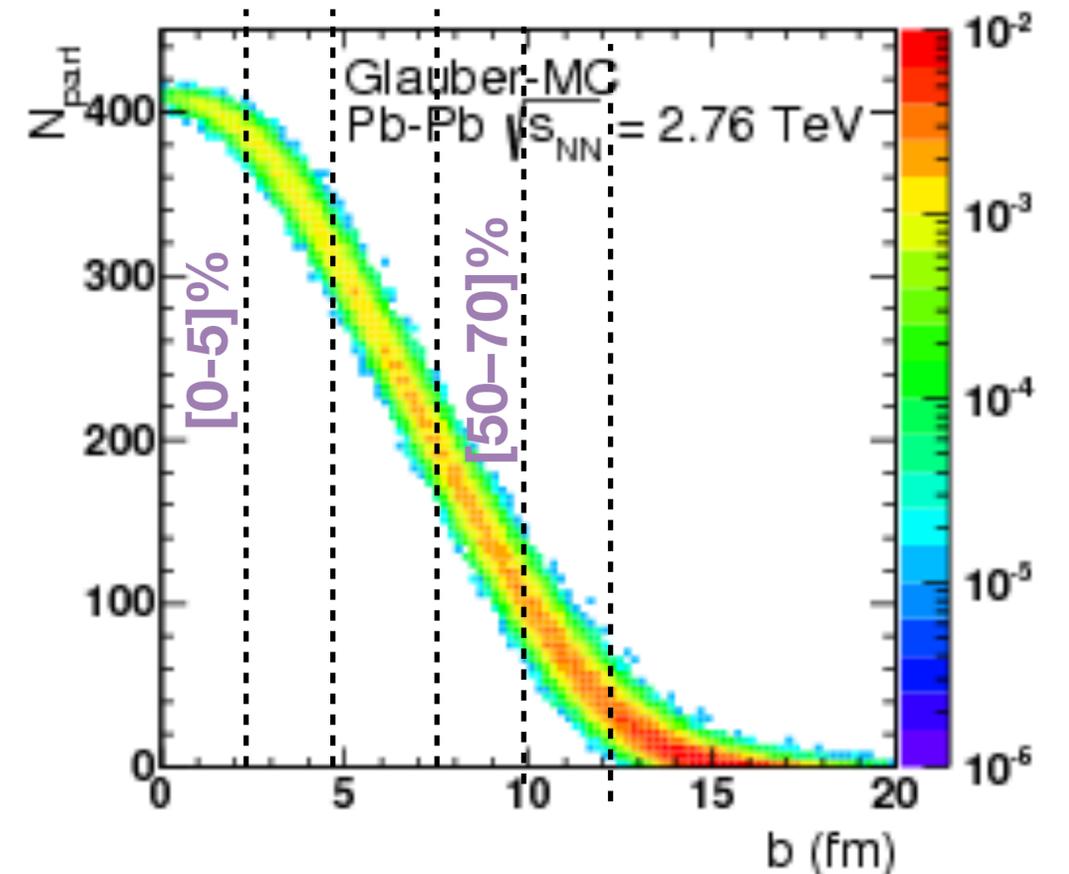
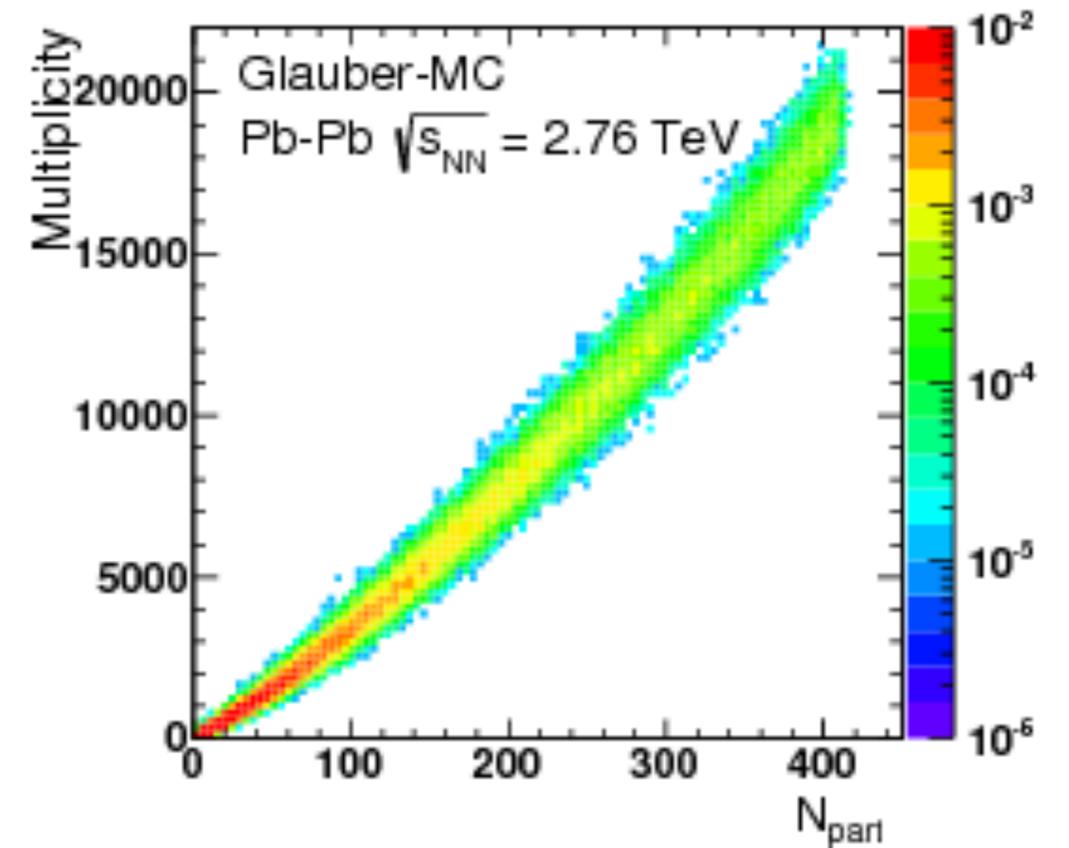
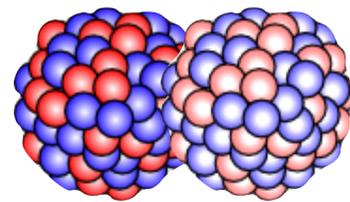
[0-5]%

Central collisions



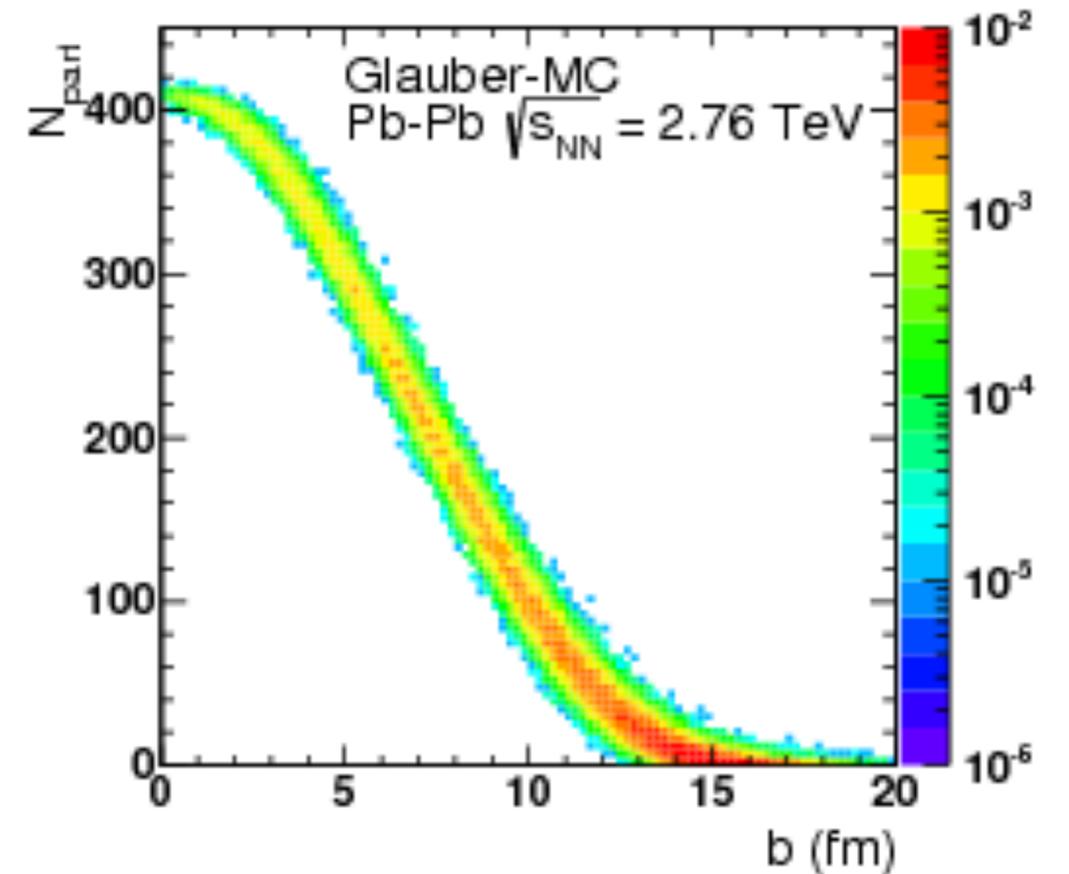
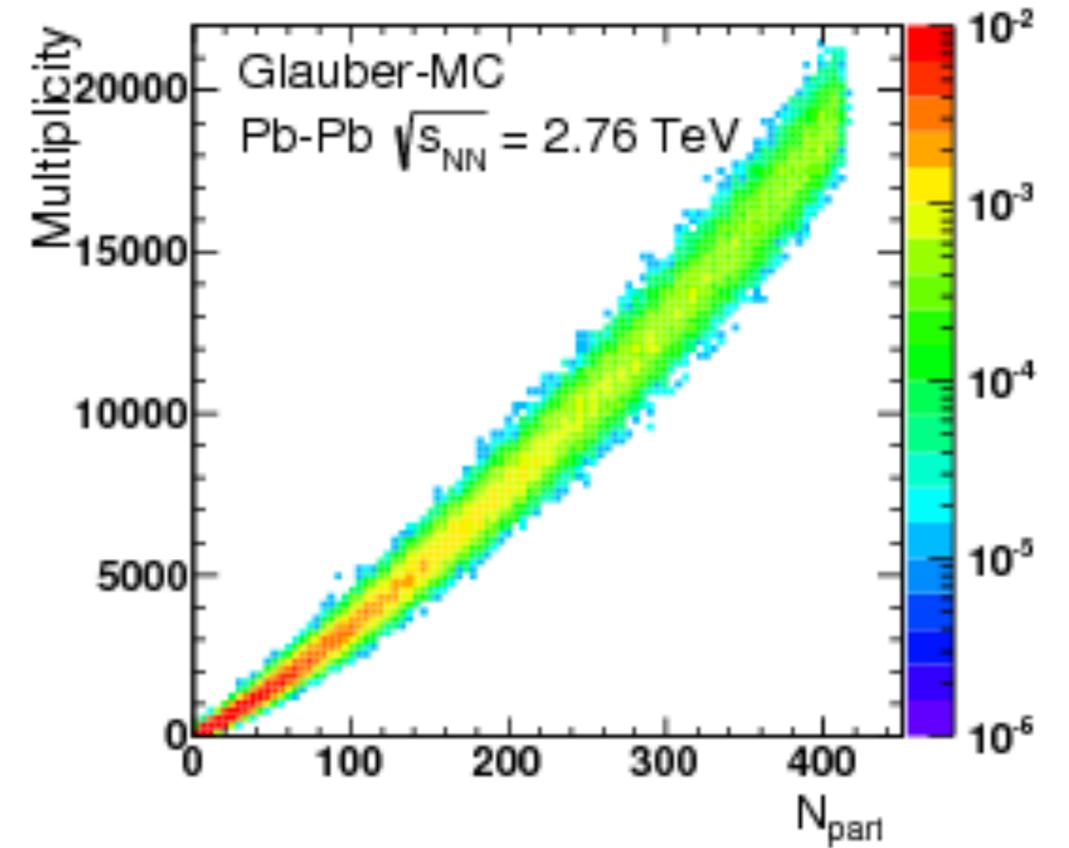
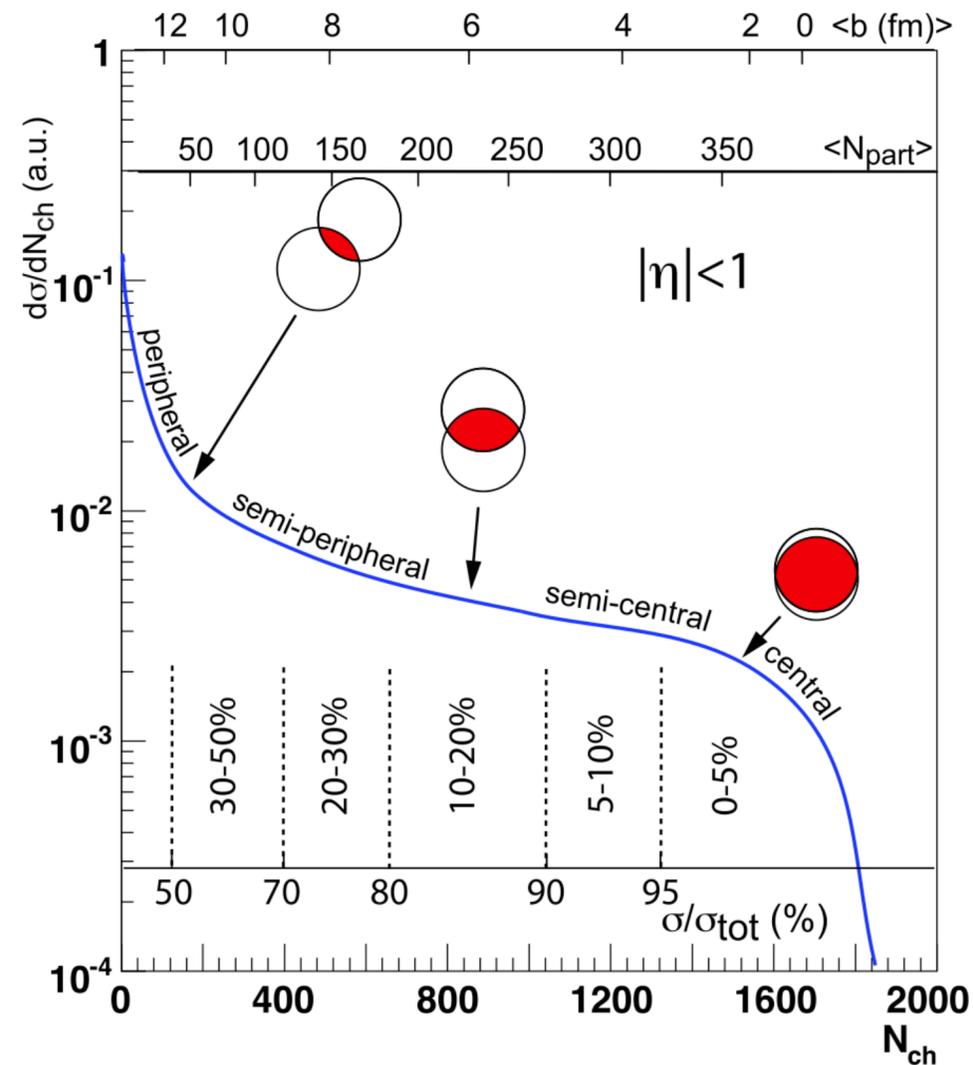
[50-70]%

Peripheral collisions

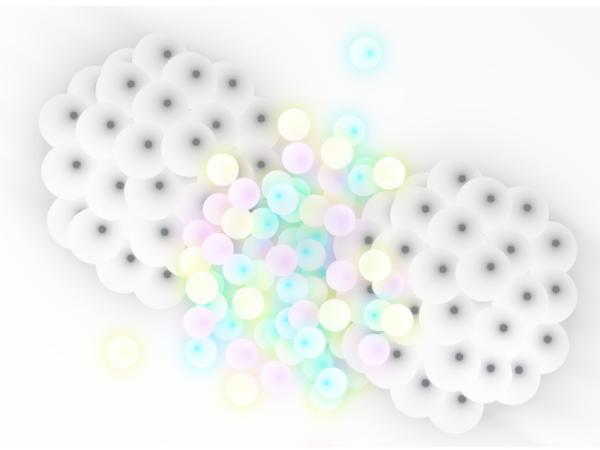


Centrality Classes

- Centrality class defined as percentile ranges of minimum-bias cross section:

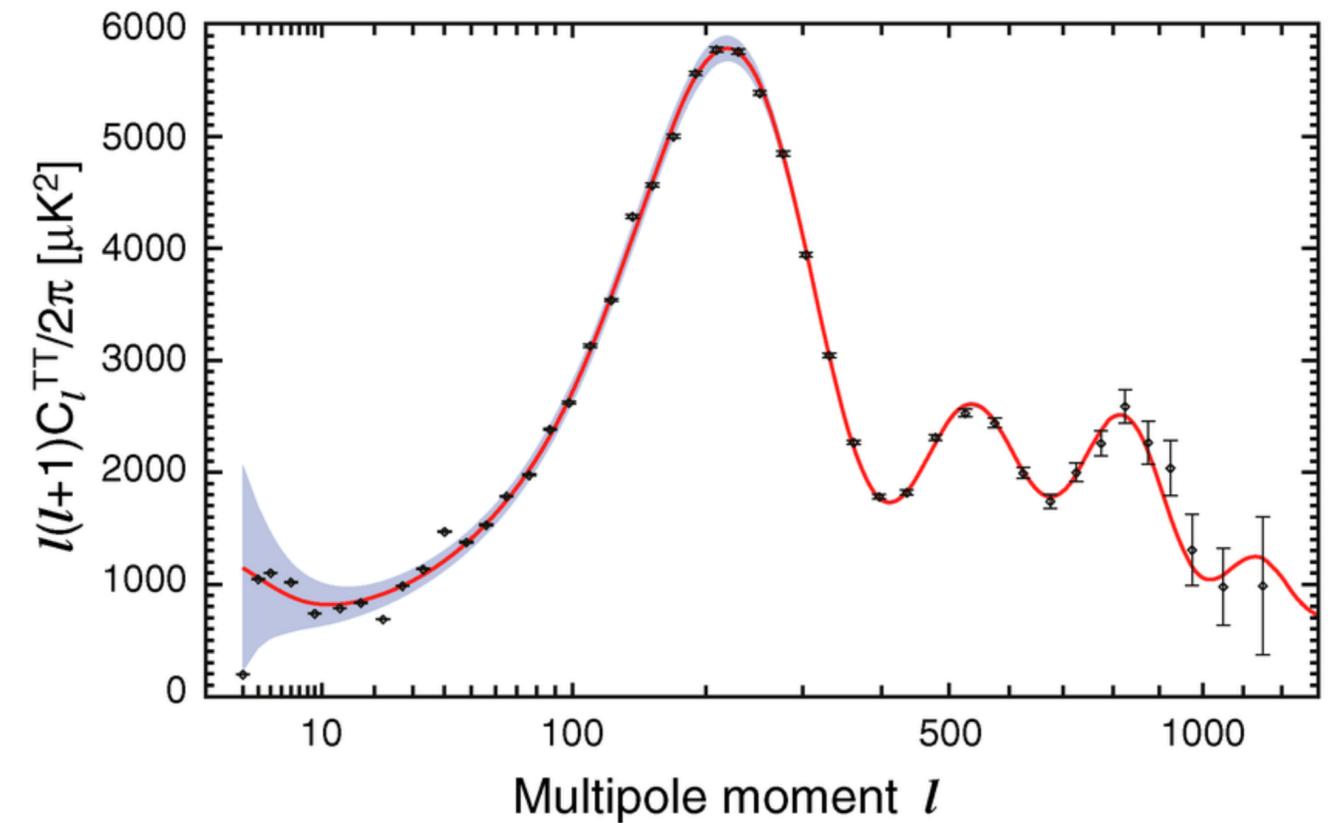
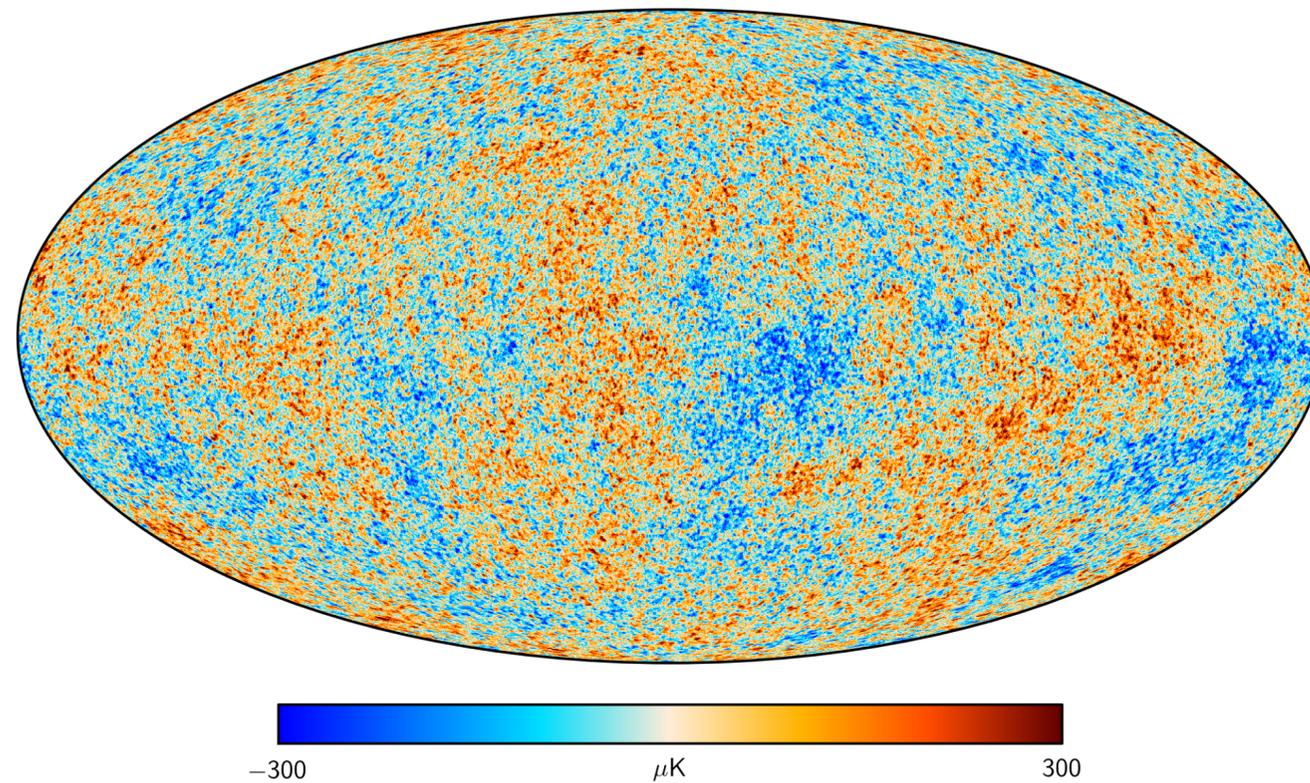


Big-Bang vs “Little-Bang”



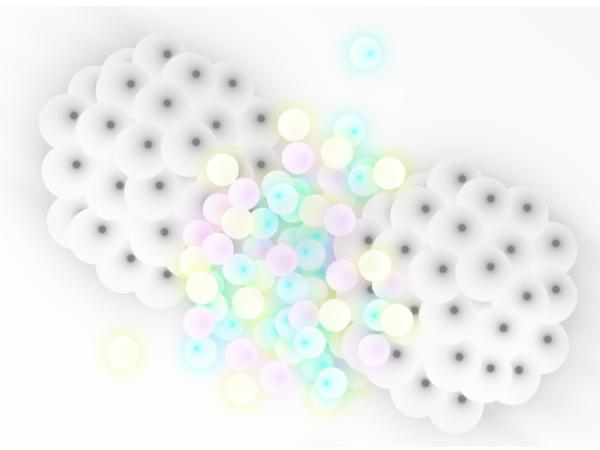
- Harmonics also applied to CMB analysis

Cosmic Microwave Background



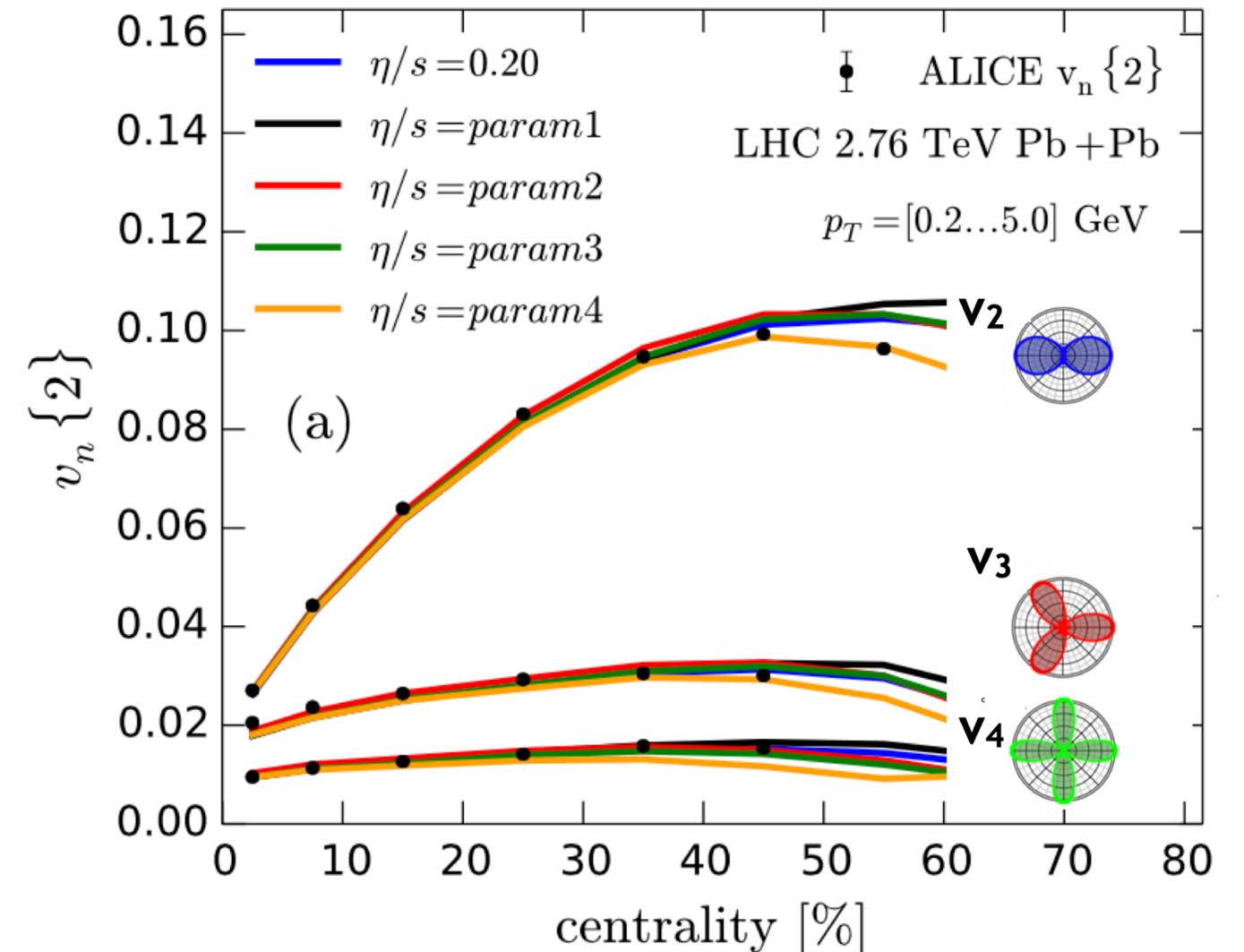
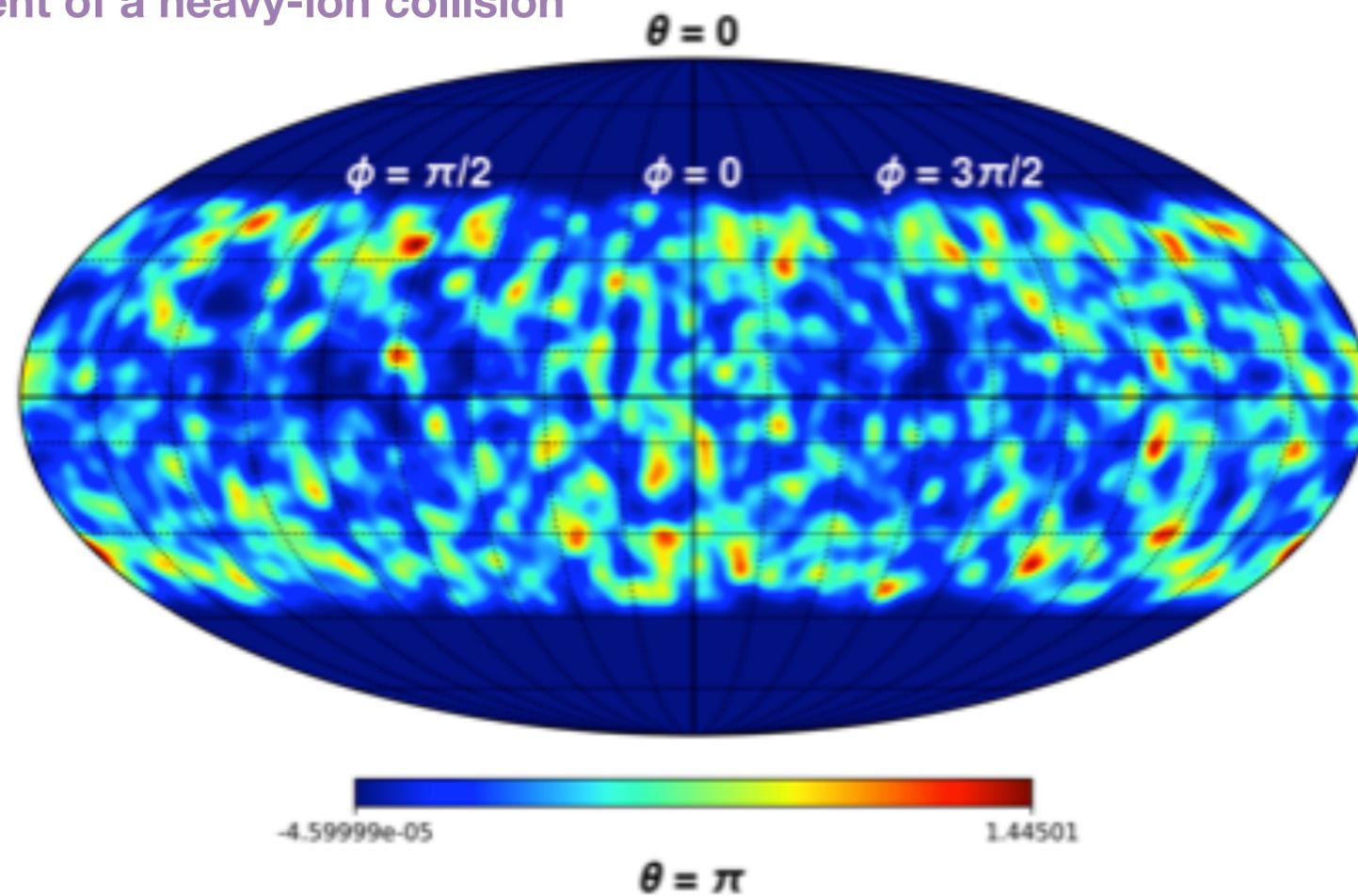
CMB anisotropies reveal information about recombination epoch (when photons decoupled)

Big-Bang vs “Little-Bang”



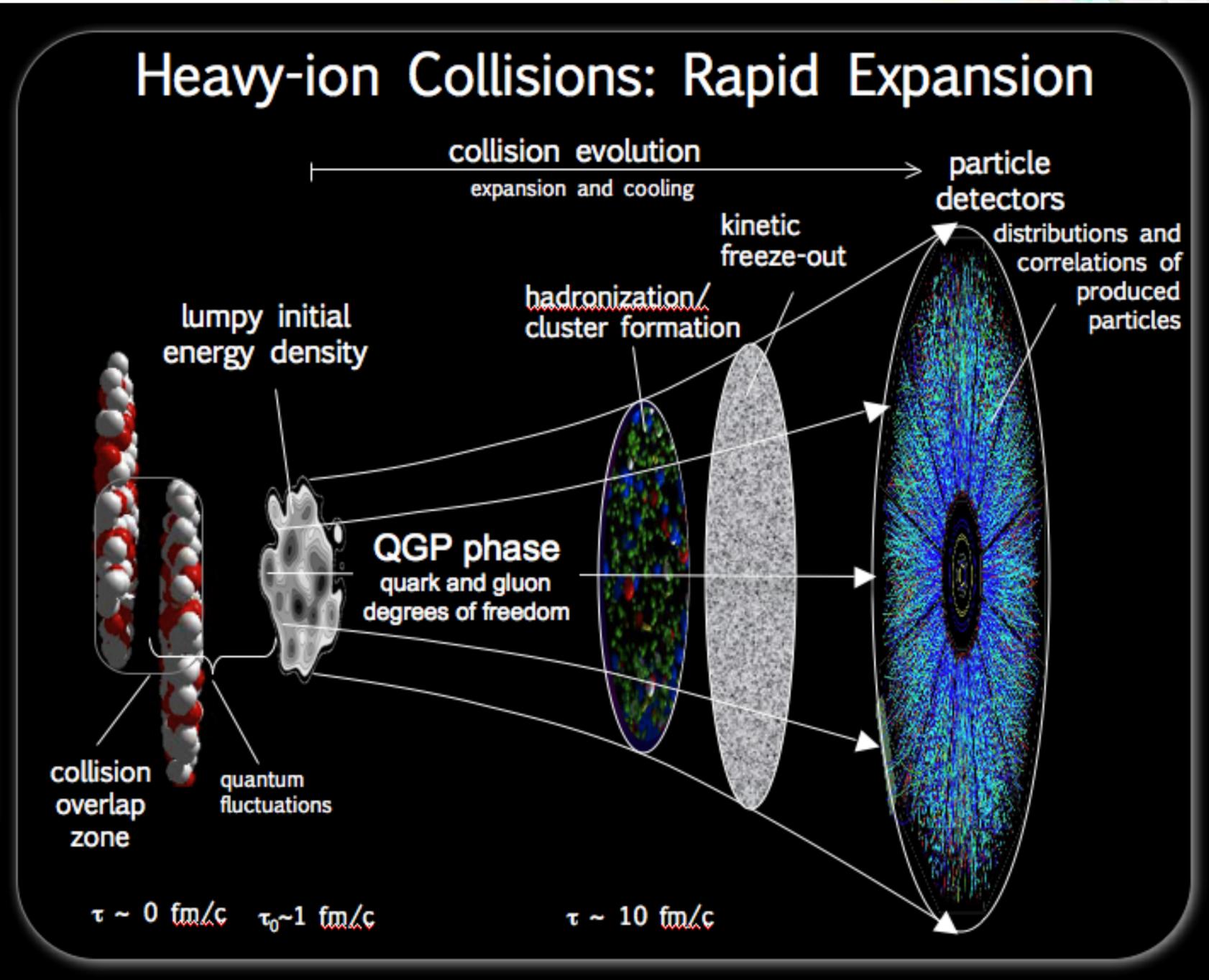
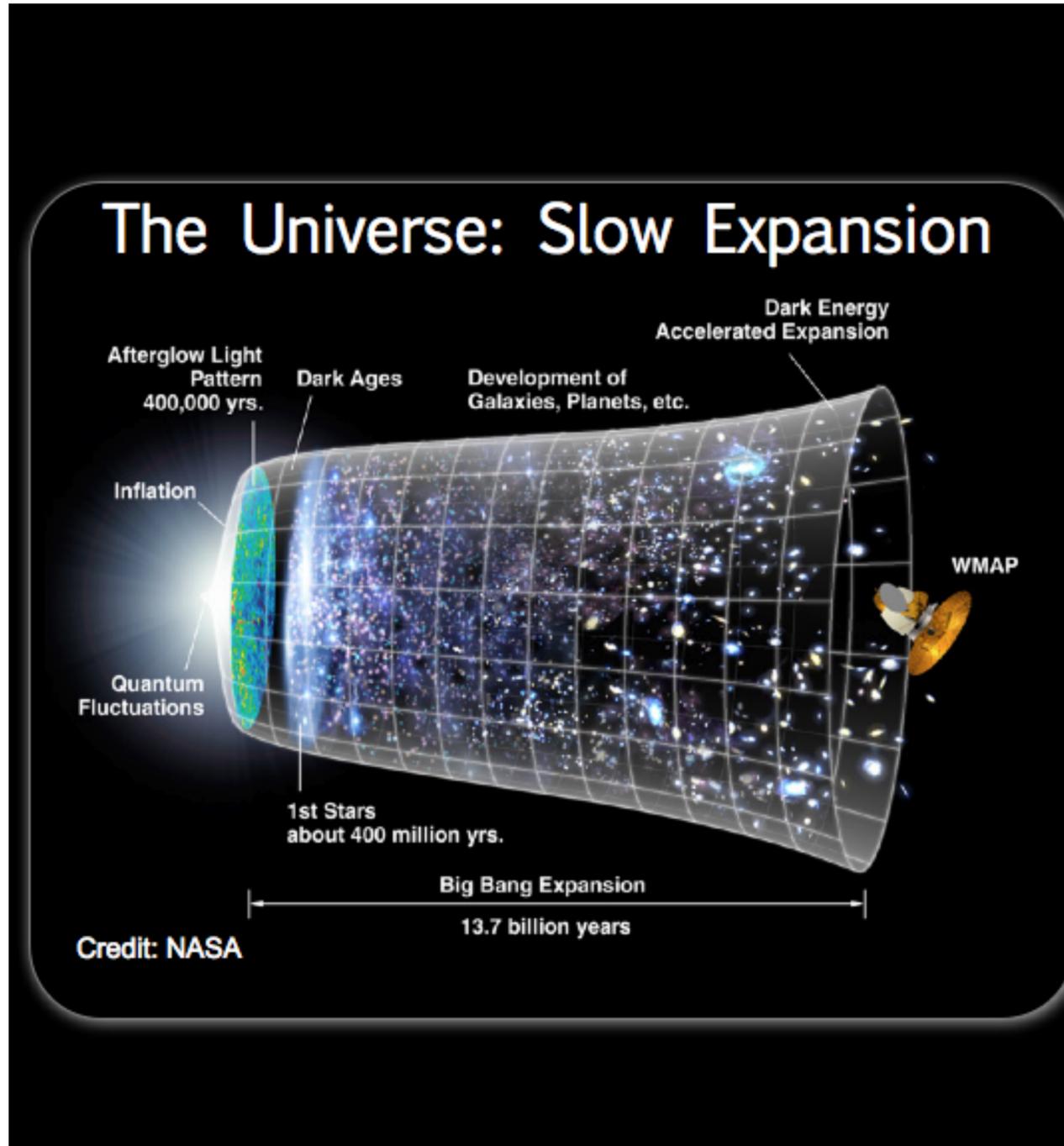
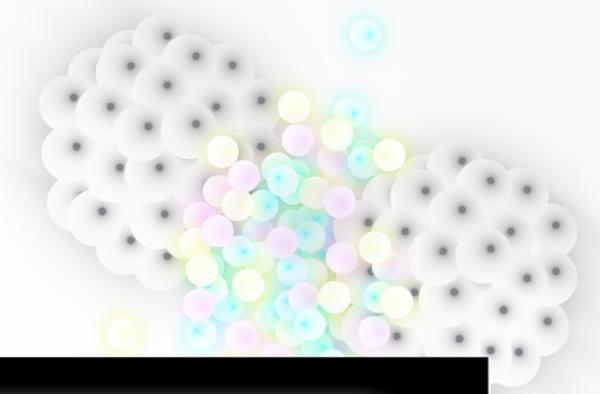
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1 event of a heavy-ion collision

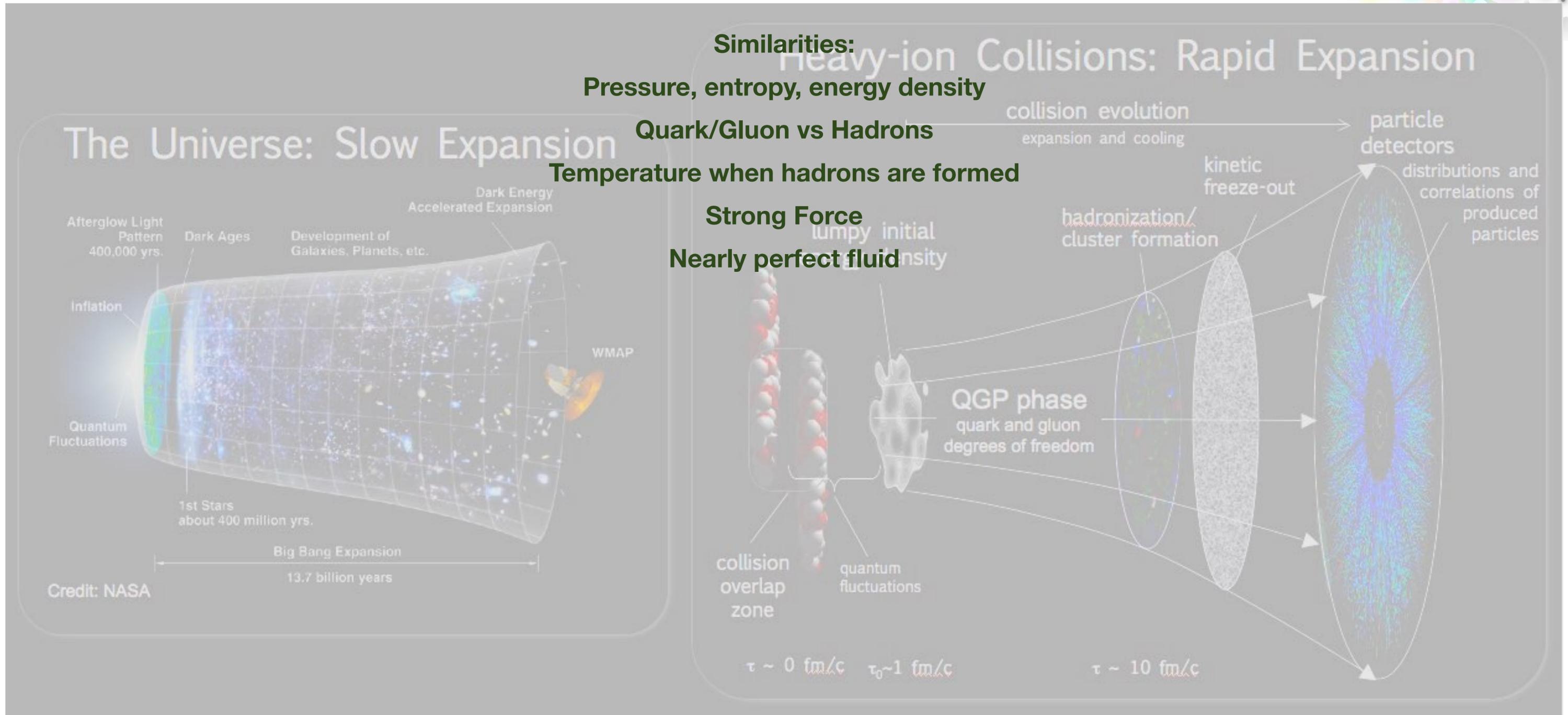
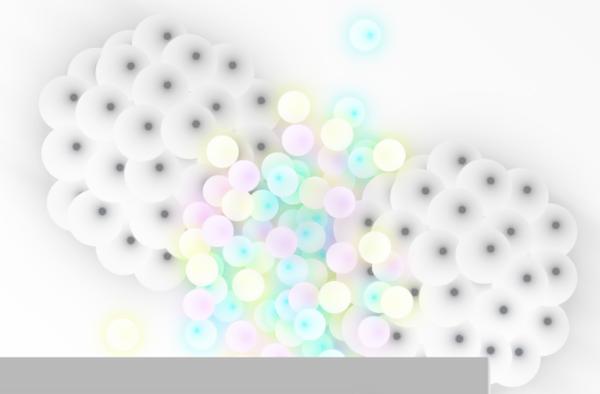


In heavy-ion collisions, they yield the anisotropic coefficients

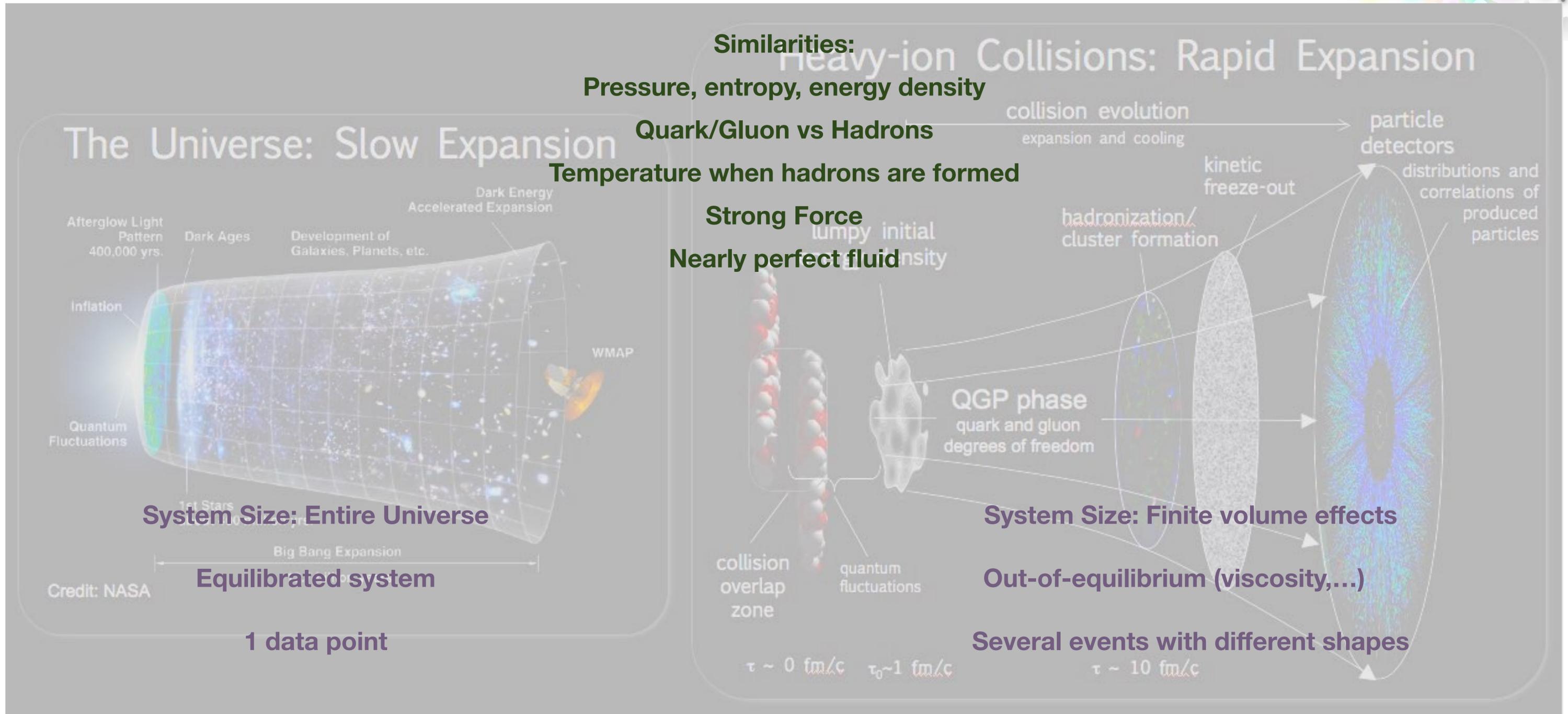
Big-Bang vs “Little-Bang”



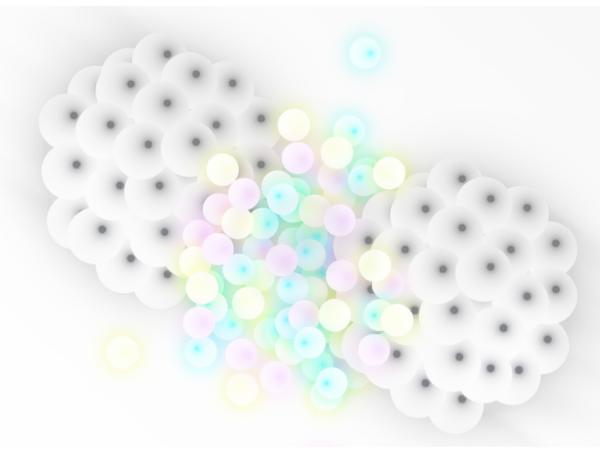
Big-Bang vs “Little-Bang”



Big-Bang vs “Little-Bang”



From dense to light systems

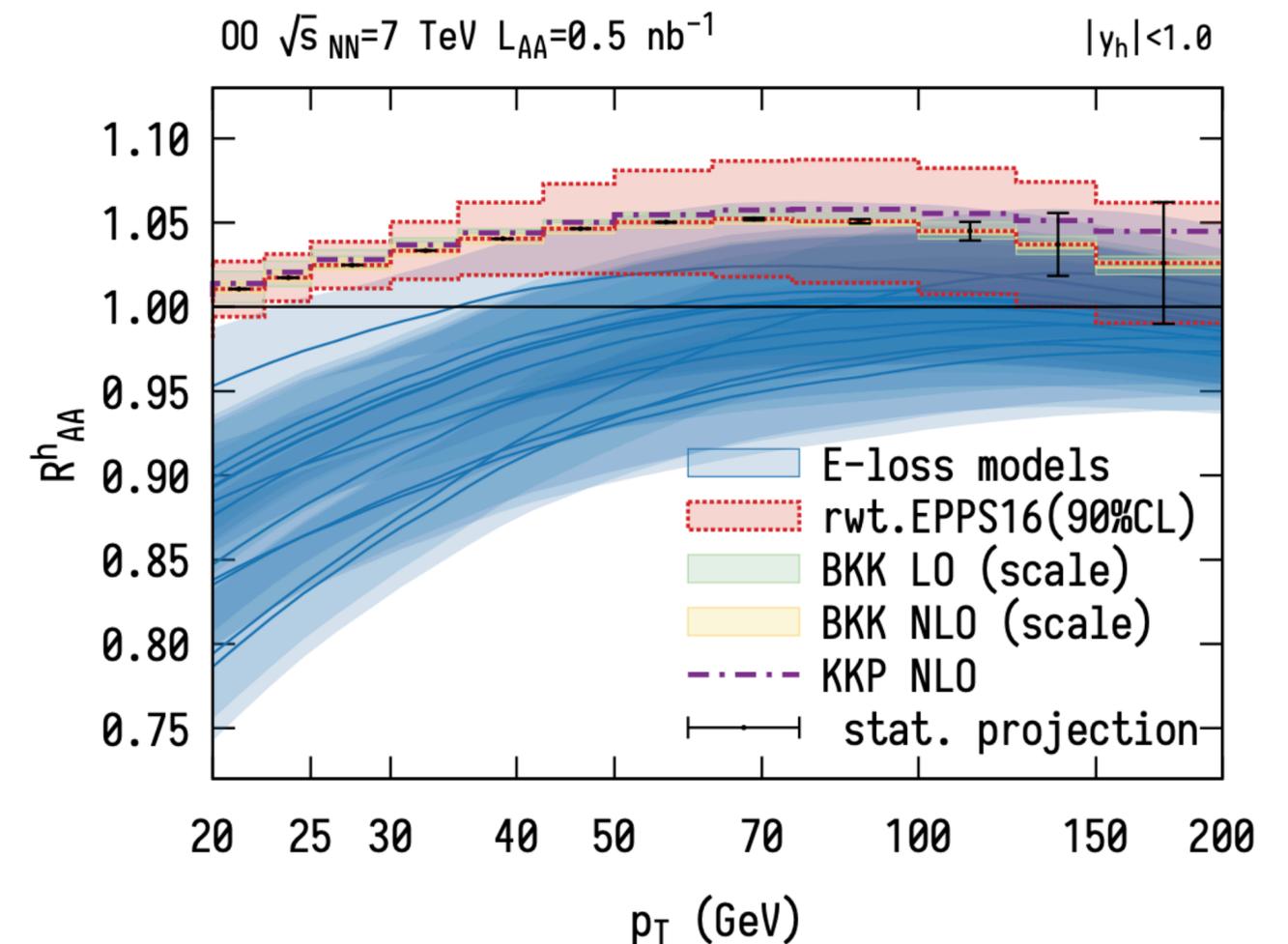


- Extrapolation from dense to light needs further understanding...
- Future oxygen runs can help us to determine the smallest amount of energy loss, provided that we control the initial state

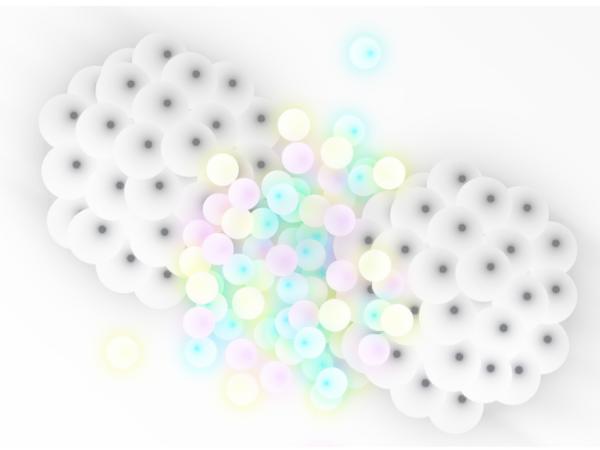
Future OO run similar to PbPb peripheral
(better suited to system-size dependence)

Future pO run crucial do reduce nPDF
uncertainties

[Huss, et al (2007.13754)]



From dense to light systems



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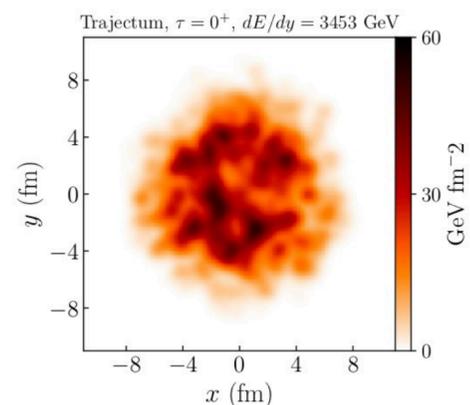
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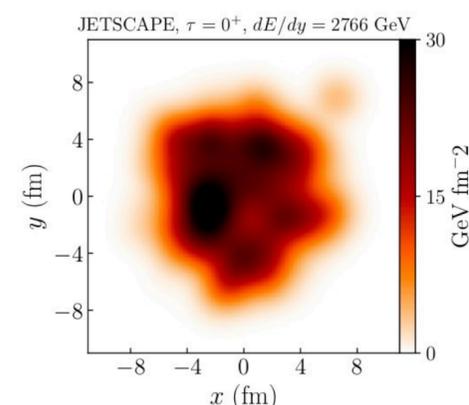
Future pO run crucial to reduce nPDF
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Cold or Hot nuclear matter effects?

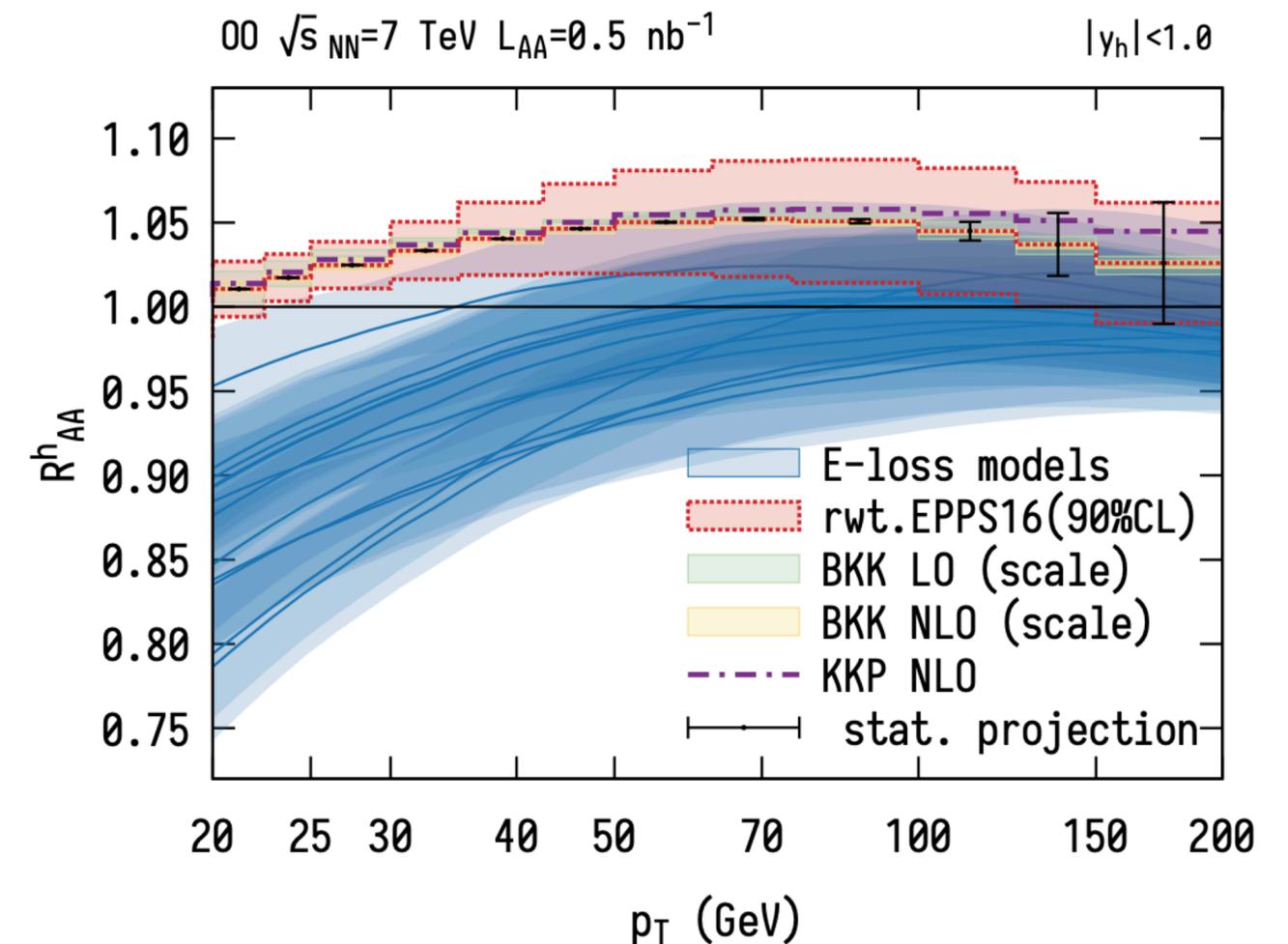
Nucleon structure at high
energy:



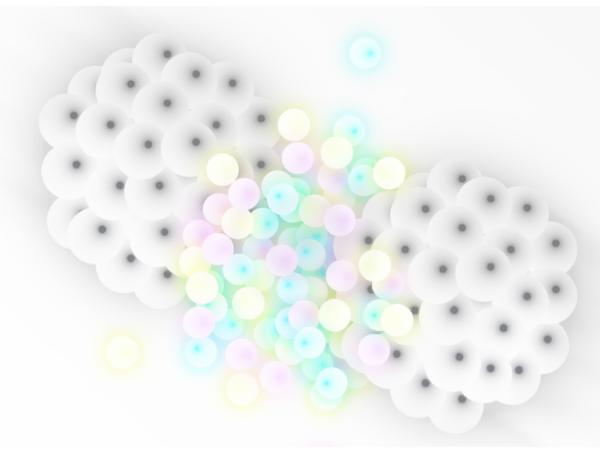
or



?

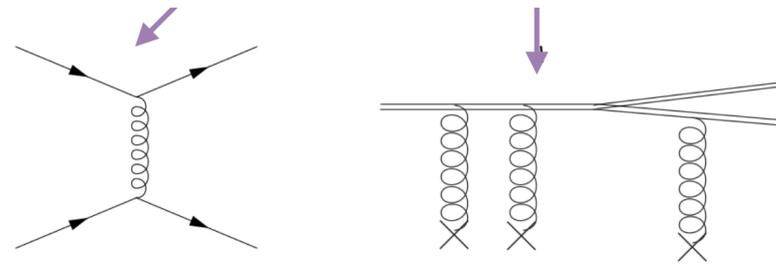


Effective Kinetic Theory



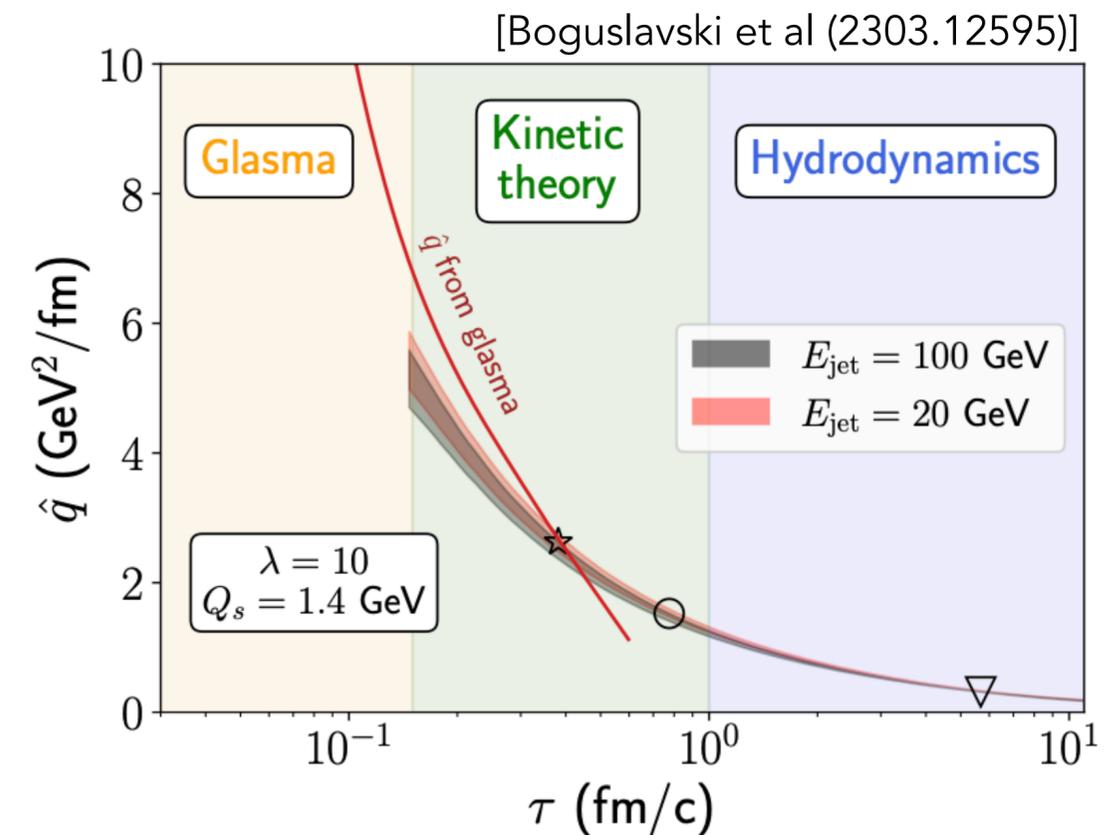
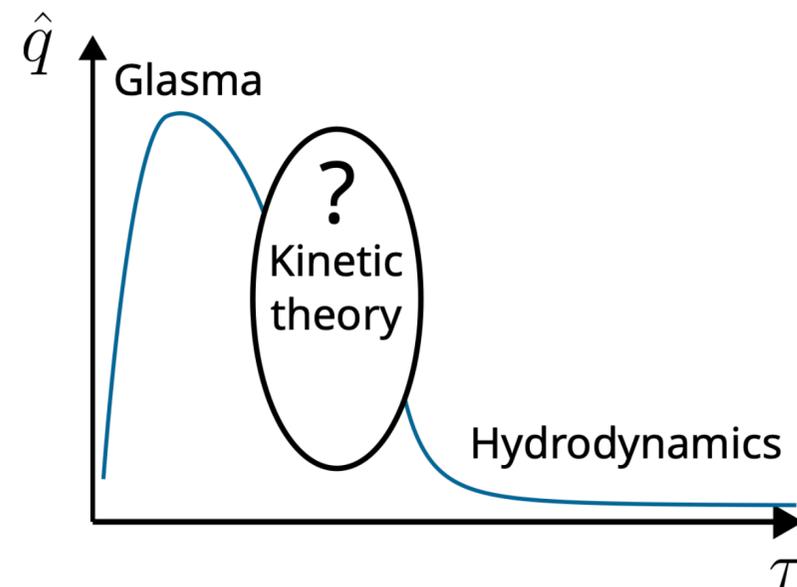
- Pre-equilibrium studies using effective kinetic theory also on jets (next lecture)

$$-\frac{\partial f_{\mathbf{p}}}{\partial \tau} = \mathcal{C}^{1 \leftrightarrow 2}[f_{\mathbf{p}}] + \mathcal{C}^{2 \leftrightarrow 2}[f_{\mathbf{p}}] + \mathcal{C}^{\text{exp}}[f_{\mathbf{p}}]$$

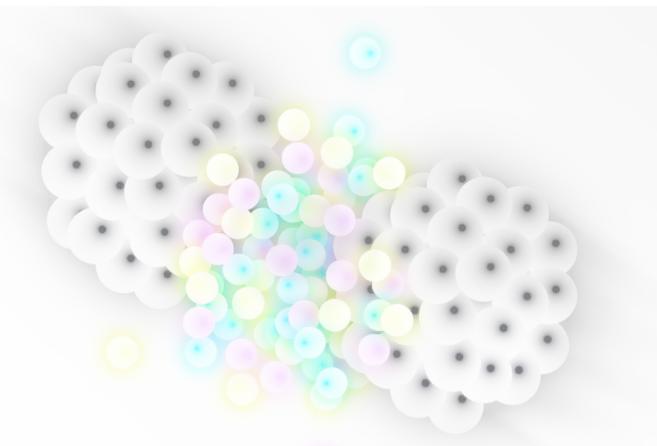


Longitudinal expansion

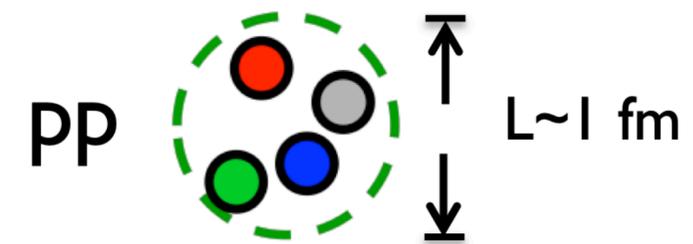
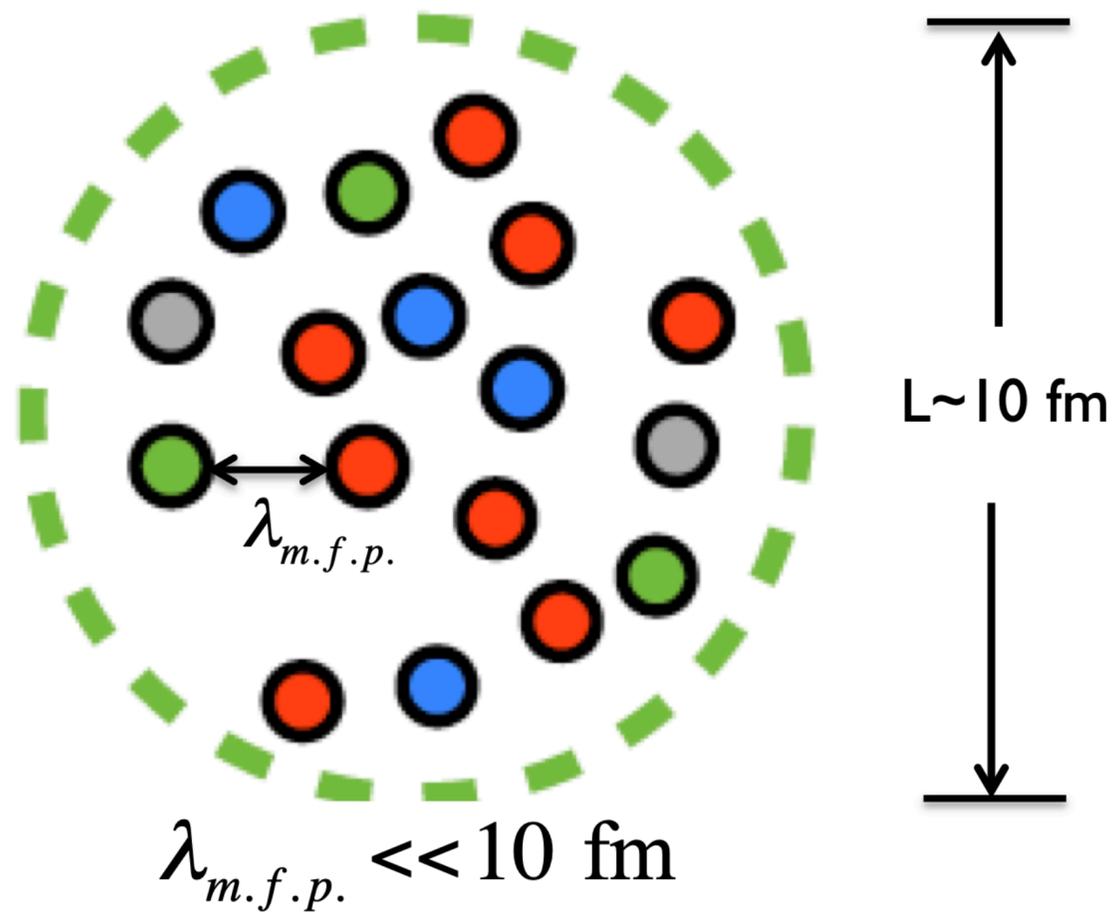
How does the thermalisation time arise?



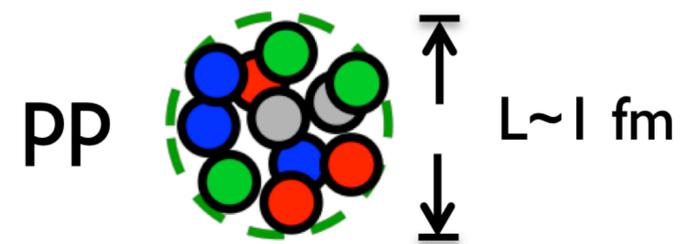
QGP onset?



- Hydrodynamic applies when system is in local equilibrium



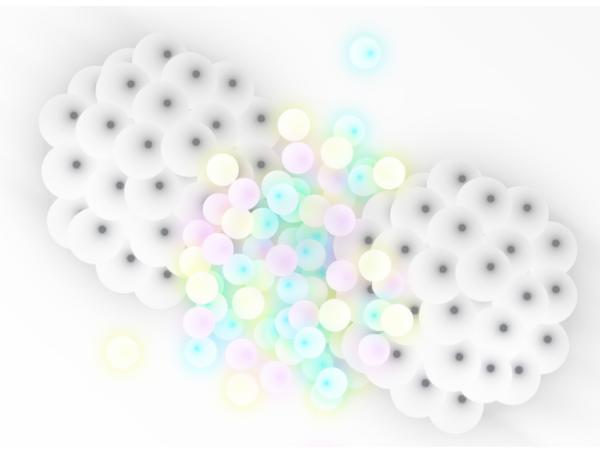
Light and dilute?



Or small but dense?

Need to collider smaller/different systems to identify QGP onset conditions

From dense to light systems

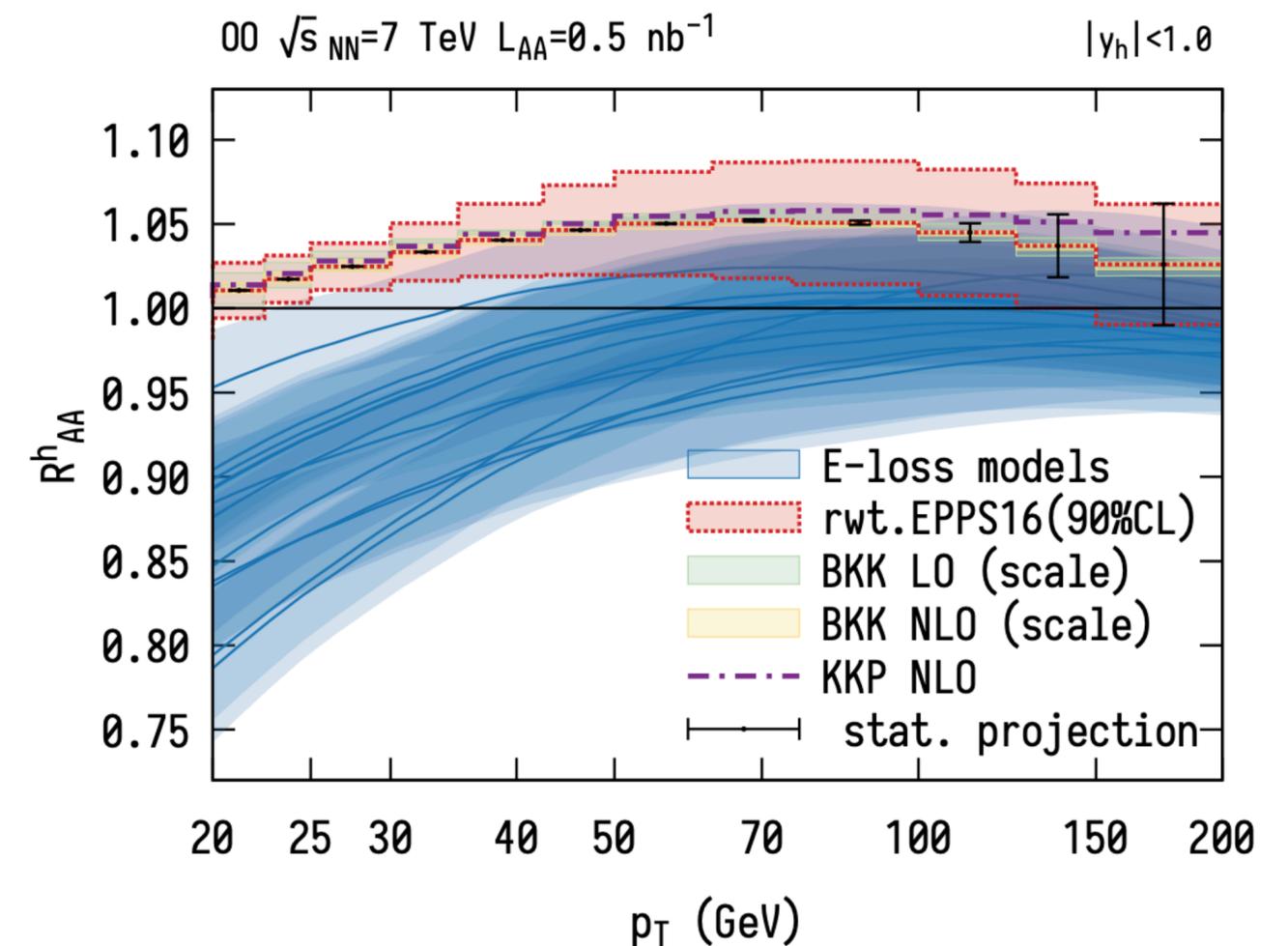


- Future oxygen runs can help us to determine the smallest amount of energy loss, provided that we control the initial state

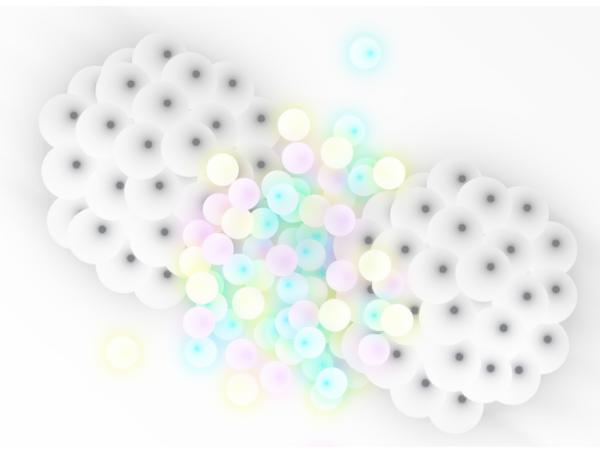
Future OO run similar to PbPb peripheral
(better suited to system-size dependence)

Future pO run crucial to reduce nPDF
uncertainties

[Huss, et al (2007.13754)]



From dense to light systems



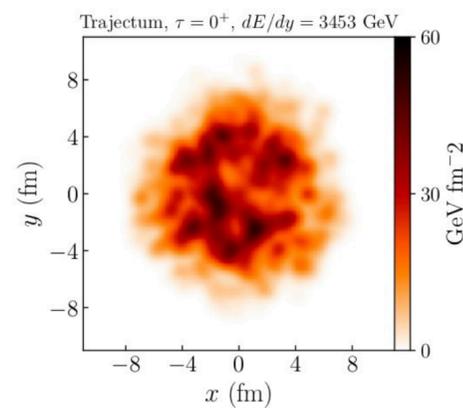
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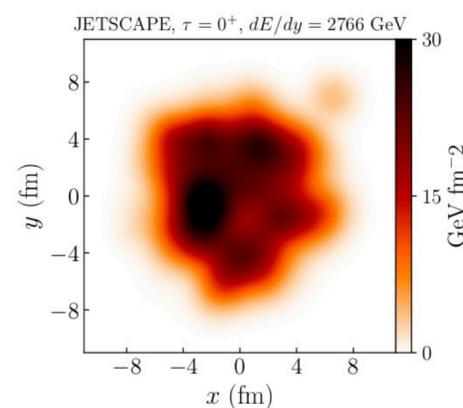
Future pO run crucial to reduce nPDF
uncertainties

Cold or Hot nuclear matter effects?

Nucleon structure at high
energy:



or



?

[Huss, et al (2007.13754)]

