Heavy Ion Collisions

Jorge Casalderrey-Solana

Plan of the Lectures

- Lecture 1
  - Part 1: A new phase of matter: the QGP
  - Part 2: Generating the QGP in the lab:
    basics of heavy ion collisions
- Lecture 2
  - Part 3: The most perfect fluid
  - Part 4: A holographic connection
- Extra
  - Physics of probes

Lecture 1

Part I

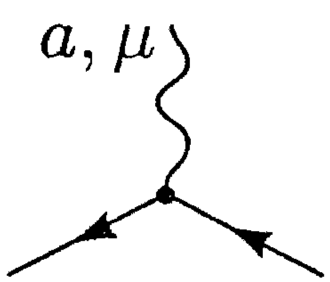
QCD

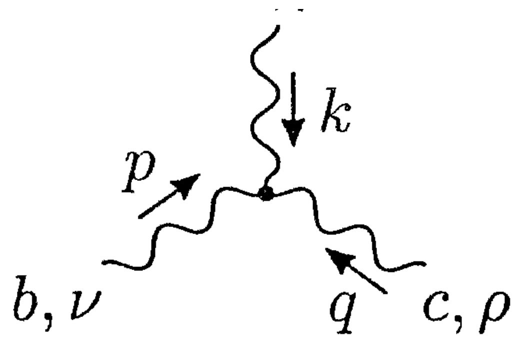
- A simple Lagrangian:

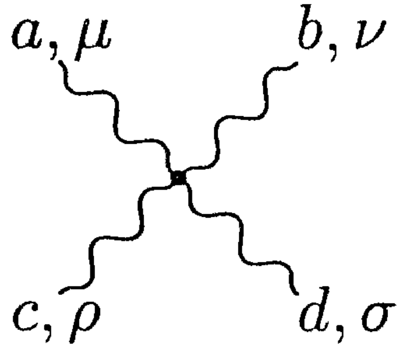
$$\mathcal{L}_{\text{QCD}} = -\frac{1}{2}\text{Tr}_{\text{c}}\left[F_{\mu\nu}F^{\mu\nu}\right] + \sum_f \overline{\psi}_f \left[\gamma_\mu (i\partial^\mu + gA^\mu) - m_f\right]\psi_f$$

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu - ig\left[A^\mu, A^\nu\right]$$

- Formulated in terms of quarks and gluons and their interactions







- But we know that what we observe are mesons and baryons

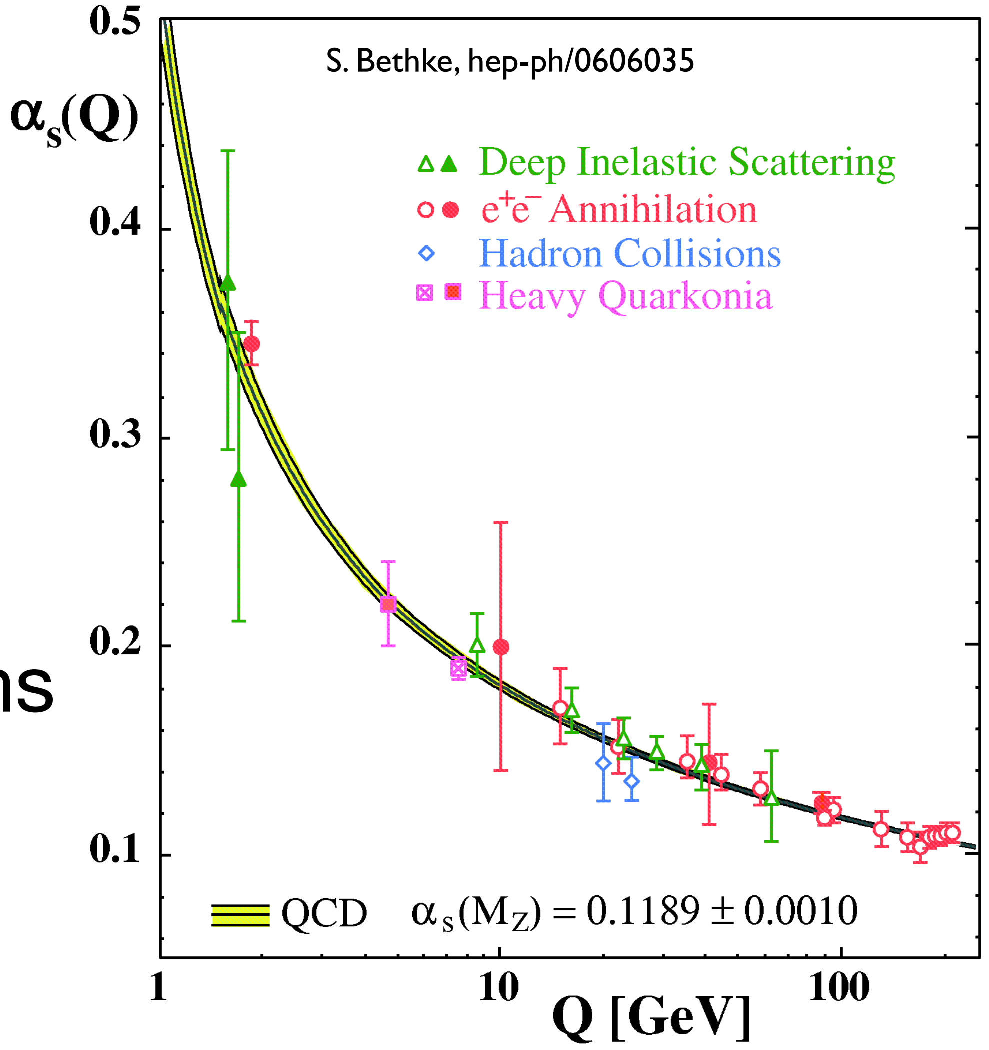
Asymptotic Freedom

- Strength of the charge depends on the scale!

- At asymptotic:

  short distances
  high energies
  high temperatures

  } quark and gluons are almost free



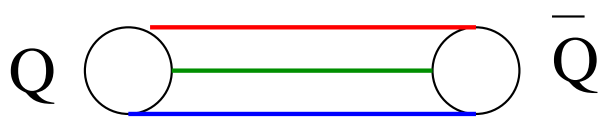
- At lower scales the coupling constant becomes large

  Quark and Gluons stay confined into hadrons

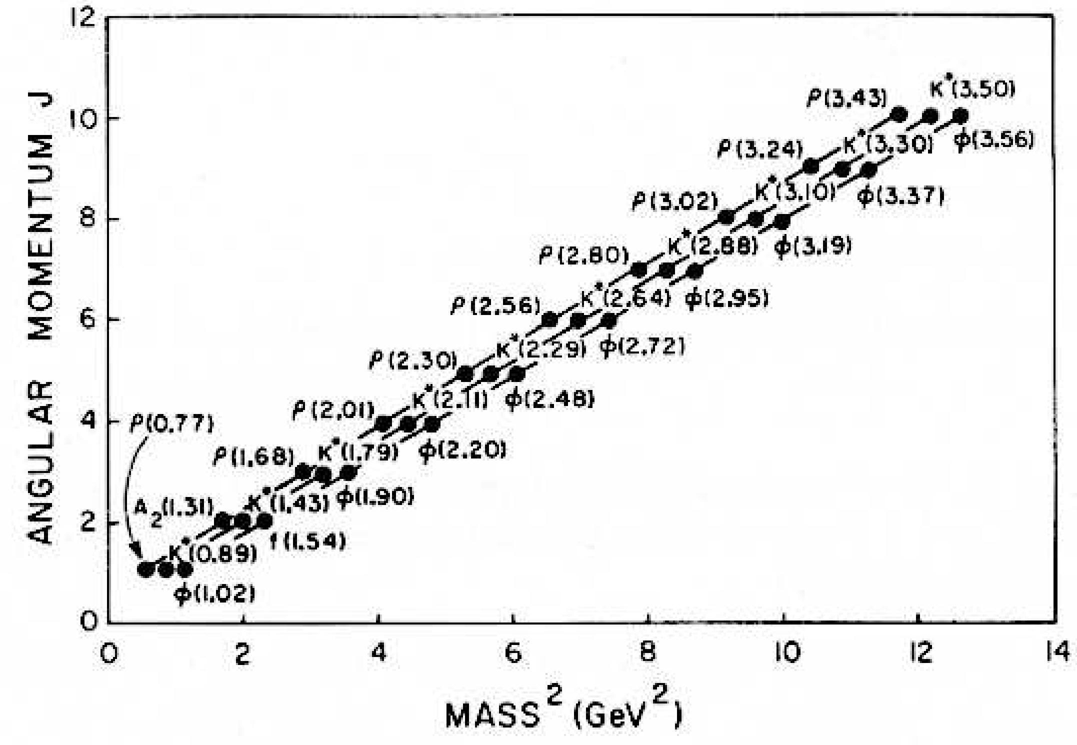
  Solving QCD dynamics becomes very hard

QCD Strings

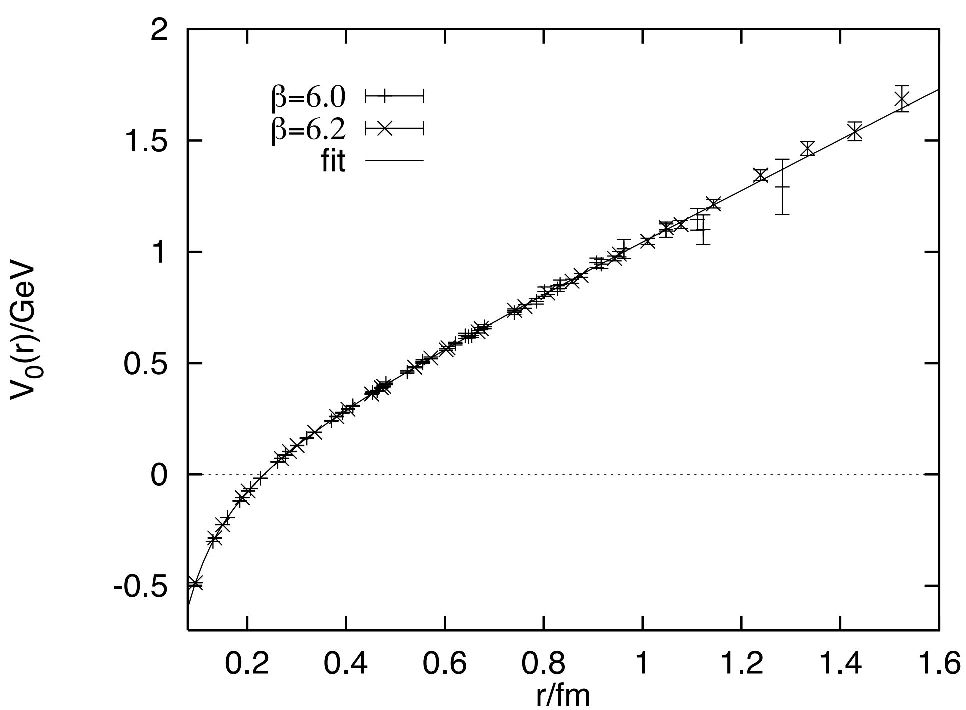
- A simple model: quarks joined by strings



$$E = \kappa \, r$$



  - Explains relation between J and M
  - Isolated quarks have infinite energy



- Heavy Quark potential
  - Determined via non perturbative methods
  - Simple fit

$$V_0(r) = -\frac{e}{r} + \sigma r + \frac{f}{r^2}$$

short distance: perturbative

long distance: confinement

- Is there a phase of matter in which quark and gluons are dominant?

- If there is... is there a phase transition?

Chiral Symmetry

- The QCD lagrangian enjoys an (approximate) global flavour symmetry

$$\Psi = \begin{pmatrix} \psi_u \\ \psi_d \\ \psi_s \end{pmatrix} \qquad \Psi' = e^{i\gamma_5 \phi_f T^f}\Psi$$

$SU(3)_{flavor}$ generator

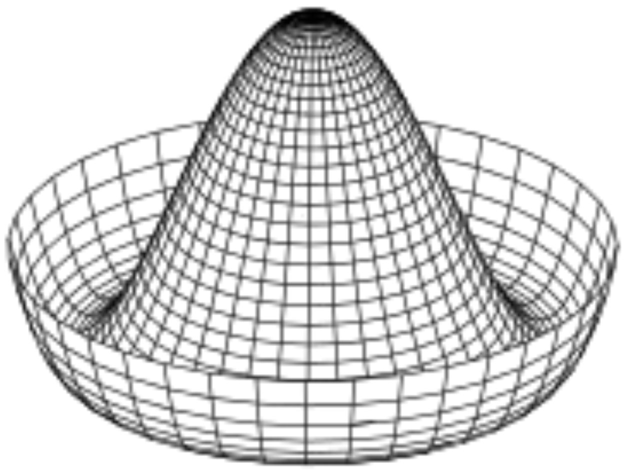
- Symmetry not observed! (chiral partners have different masses)

- Spontaneously broken in the vacuum

    - A vacuum condensate:

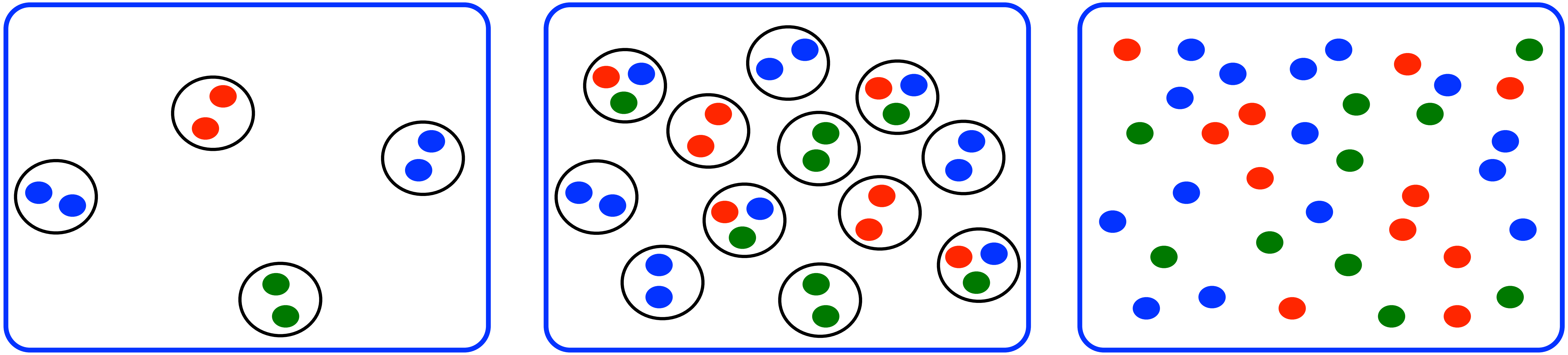
$$\langle 0|\, \bar{\Psi}\Psi \,|0\rangle \neq 0$$

    - (almost) goldstone boson



- At finite temperature the condensate can melt and lead to a transition!

The Intuitive Idea



- At low $T<m_N$: dilute gas of mesons (pions)
- At higher T hadrons are activated: density increases
- If thermal density is larger than nuclear density: quark and gluon liberation
- At very very high T: violent collisions

  small coupling constant

Thermodynamics from Fields

- Helmholtz Free Energy $F = -T \log Z$ $p = -\frac{dF}{dV}$

- In statistical mechanics:

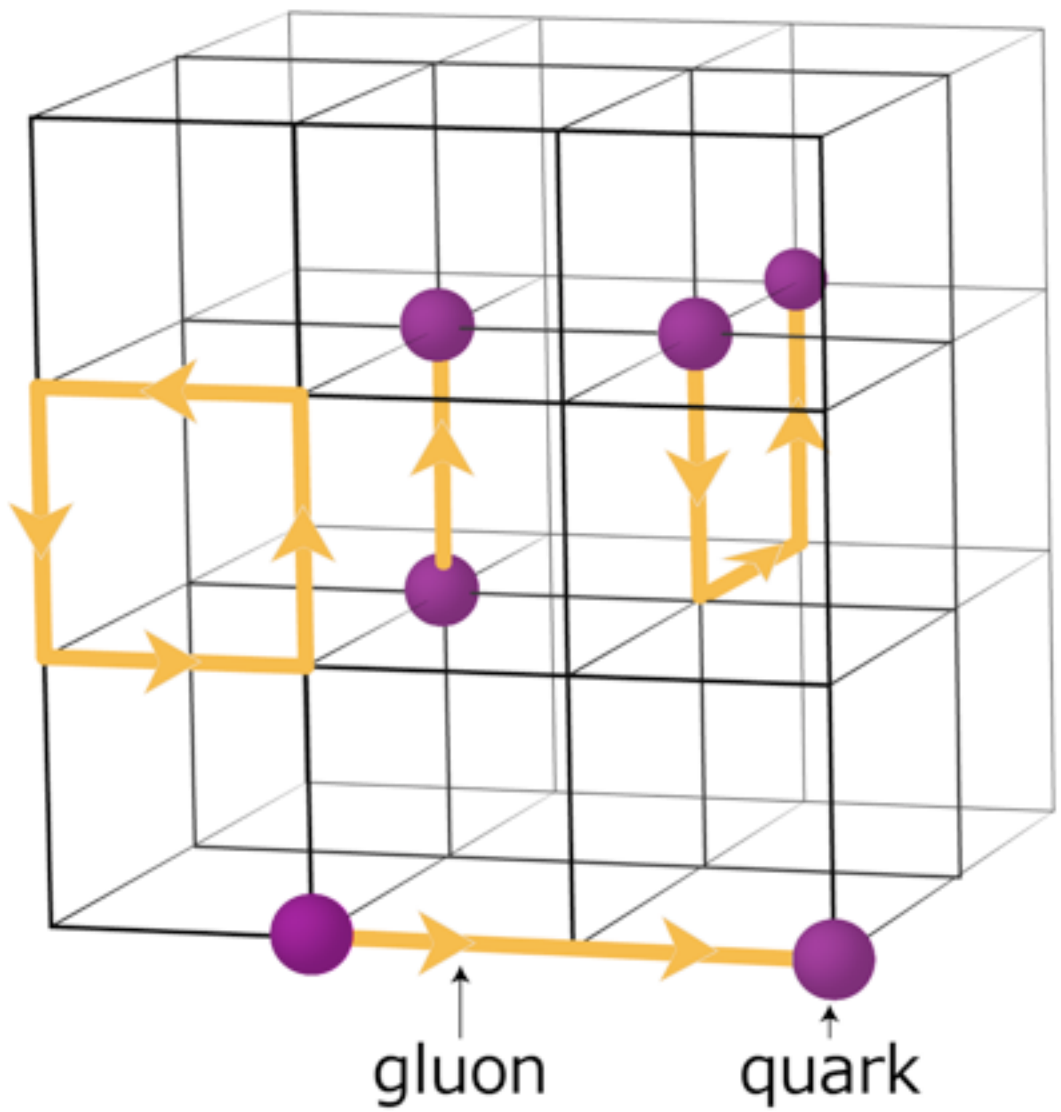
$$Z = \sum_i e^{-E_i/T} \qquad Z(T) = \mathrm{Tr}\left[e^{-H_{QCD}/T}\right]$$

- Formally very similar to

$$Z = \langle 0 | \, e^{-iHt} \, | 0 \rangle$$ (path integral)

- Analogy: thermal partition function has a path integral rep
  - Imaginary time (just a trick).
  - Tr ⇒(anti) periodicity of (fermionic) bosonic fields

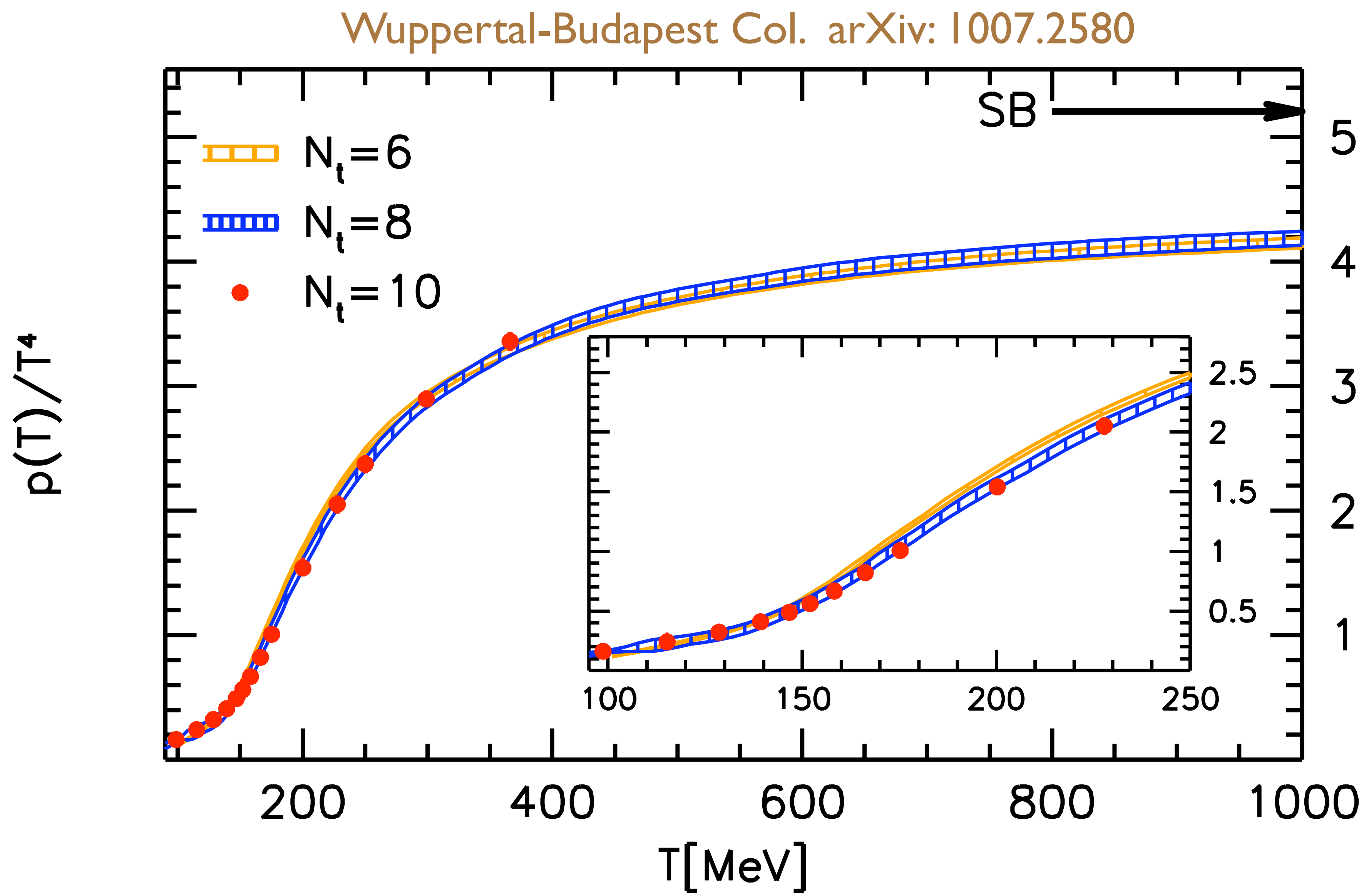
Lattice QCD



http://www.jicfus.jp/en/wp-content/uploads/2012/12/LatticeQCD.png

- Computer simulations in discretized space
- Access to non-perturbative dynamics
- Euclidean space ⇒ static properties

Equation of State

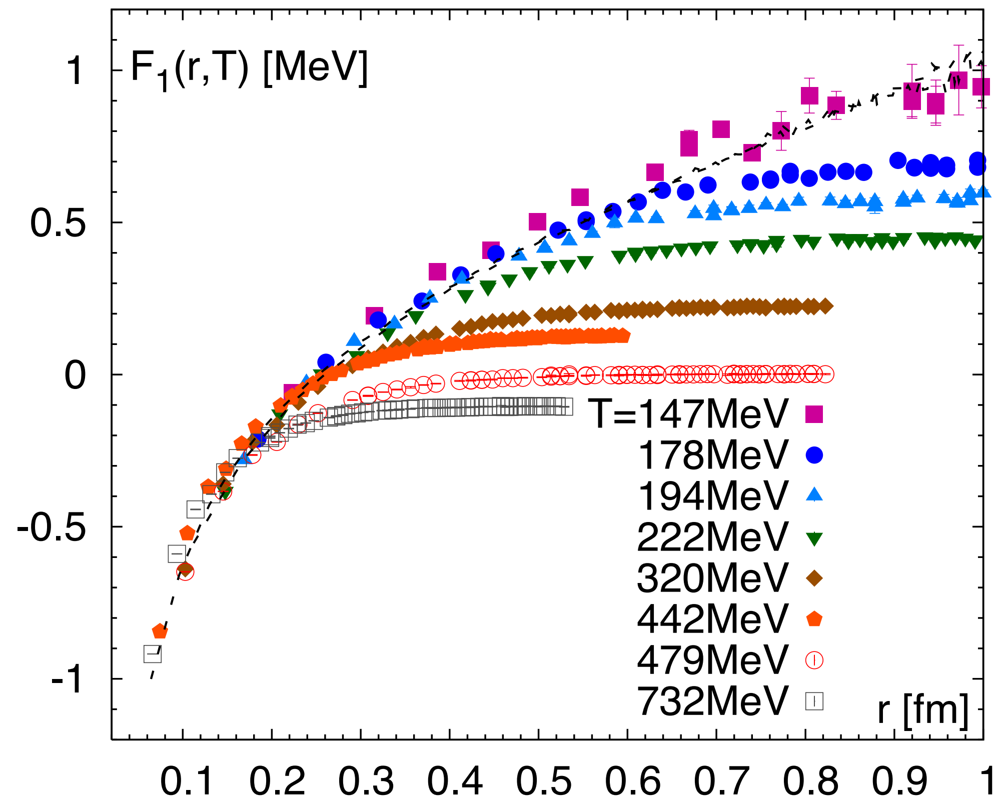


Rapid cross over transition:

- Deconfined matter: Quark Gluon Plasma

Is it Deconfined?

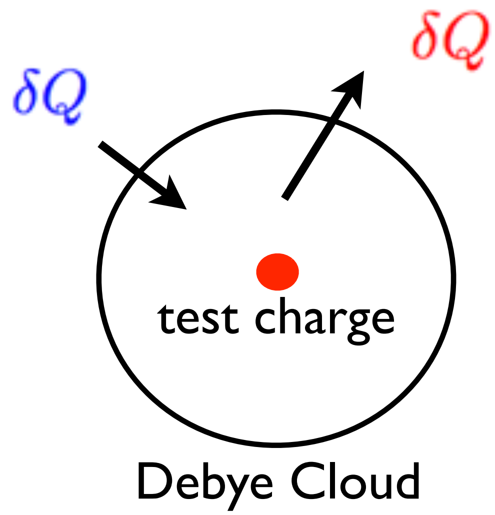
- Free energy associated to a QQ pair



- It becomes finite at finite long distances
- The asymptotic value depends on T⇒ quarks get dressed
- At high T the perturbative part of the potential is modified.

Screening

- In E&M free charges screen the charge of a test particle



- Same charge medium particles are pushed away
- Opposite charge medium particles are attracted
- Test particle is dressed by a Debye Cloud

$$\nabla^2 V = -q\delta^3(r) - qn_+(r) + qn_-(r)$$

$$n(r)_\pm = \int \frac{d^3k}{(2\pi)^3} \exp\left\{-\frac{\sqrt{m^2+k^2} \pm qV(r)}{T}\right\}$$

$$\approx n_0(T)\left(1 \mp \frac{qV(r)}{T}\right)$$

$$\nabla^2 V - m_D^2 V = -q\delta^3(r)$$

$$V(r) = \frac{qe^{-m_D r}}{r} \qquad m_D^2 = 2q^2 \frac{n_0(T)}{T}$$

- Charge is screened for $r>1/m_D$

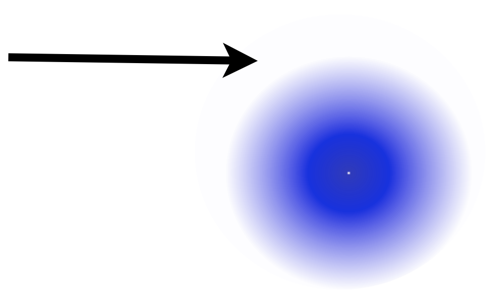
- The phenomenon is identical in QCD

High T Phase of Hadronic Matter

- At T>Tc: free colour charges: plasma-like state

Quark Gluon Plasma

- At T>>Tc: pQCD allows to understand its basic properties



Plasma Density

$$n \sim T^3$$

Cross section

$$\sigma \sim \frac{\alpha^2}{m_D^2} \sim \frac{g^2}{T^2}$$

Mean free path

$$\lambda = \frac{1}{n\sigma} \sim \frac{1}{g^2 T}$$

Mass of particles

$$m_{th} \sim m_D \sim gT$$

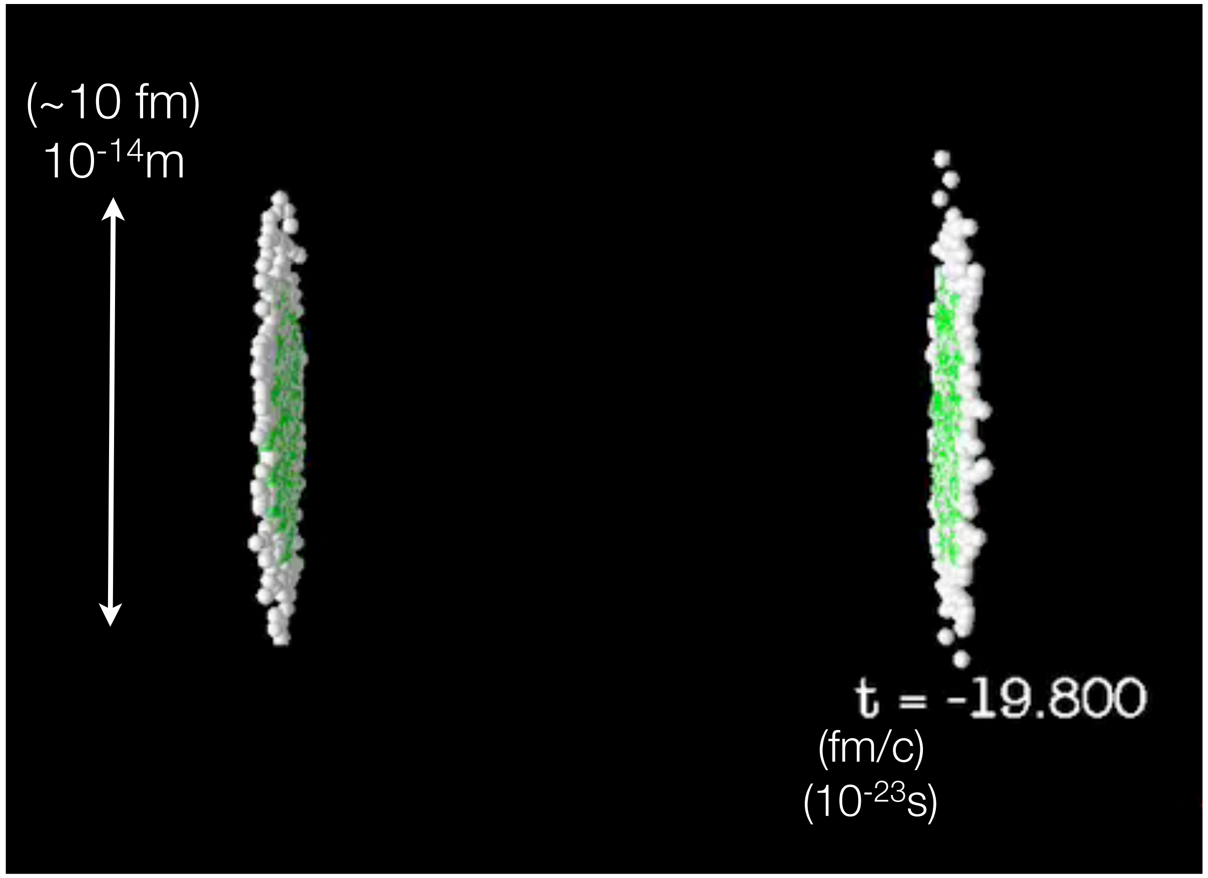
- If g≪1, quarks and gluons travel long distances without interactions

dressed long lived excitations ≡ quasiparticles

Part II

Heavy Ion Colisions

- Large ions are contracted into thin disks: L=2 R/γ

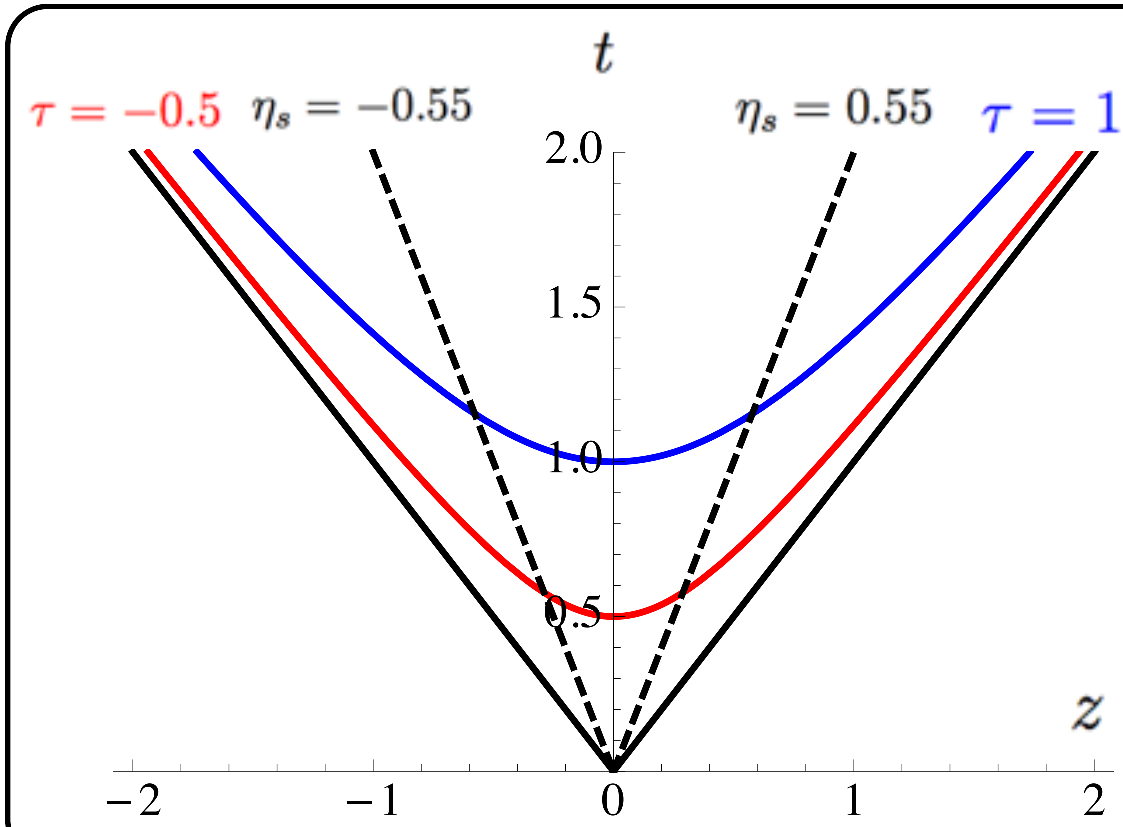


- RHIC: Au-Au@√s= A 200 GeV =39.4 TeV ⇒ L~0.06 fm
- LHC: Pb-Pb @ √s= A 5.02 TeV = 1039 TeV ⇒ L~0.002 fm

Huge amount of energy in very small volumes!

(but not all goes into forming matter)

Kinematics



- A set of space-time coordinates

$$t = \tau \cosh \eta_s \qquad z = \tau \sinh \eta_s$$

  - Under boosts

$$\eta_s \to \eta_s + \eta_{boost} \qquad \tau \to \tau$$

$$ds^2 = d\tau^2 - \tau^2 d\eta_s^2 - dx_\perp^2$$

- Momentum rapidity

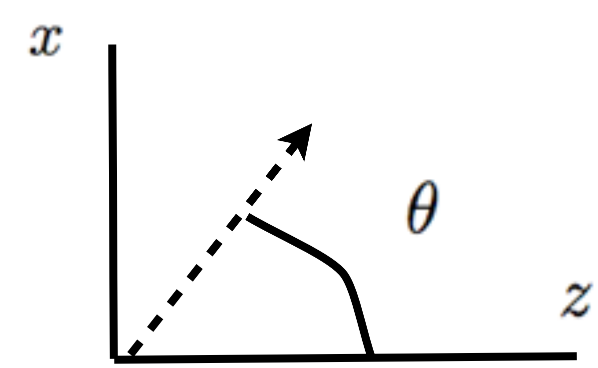
$$E = m_T \cosh y \qquad p_z = m_T \sinh y$$

$$m_T = \sqrt{m^2 + p_T^2}$$

- Fixed y particles follow fixed η_s trajectories

- Pseudo rapidity

$$\eta = \tanh^{-1}(\sin\theta)$$

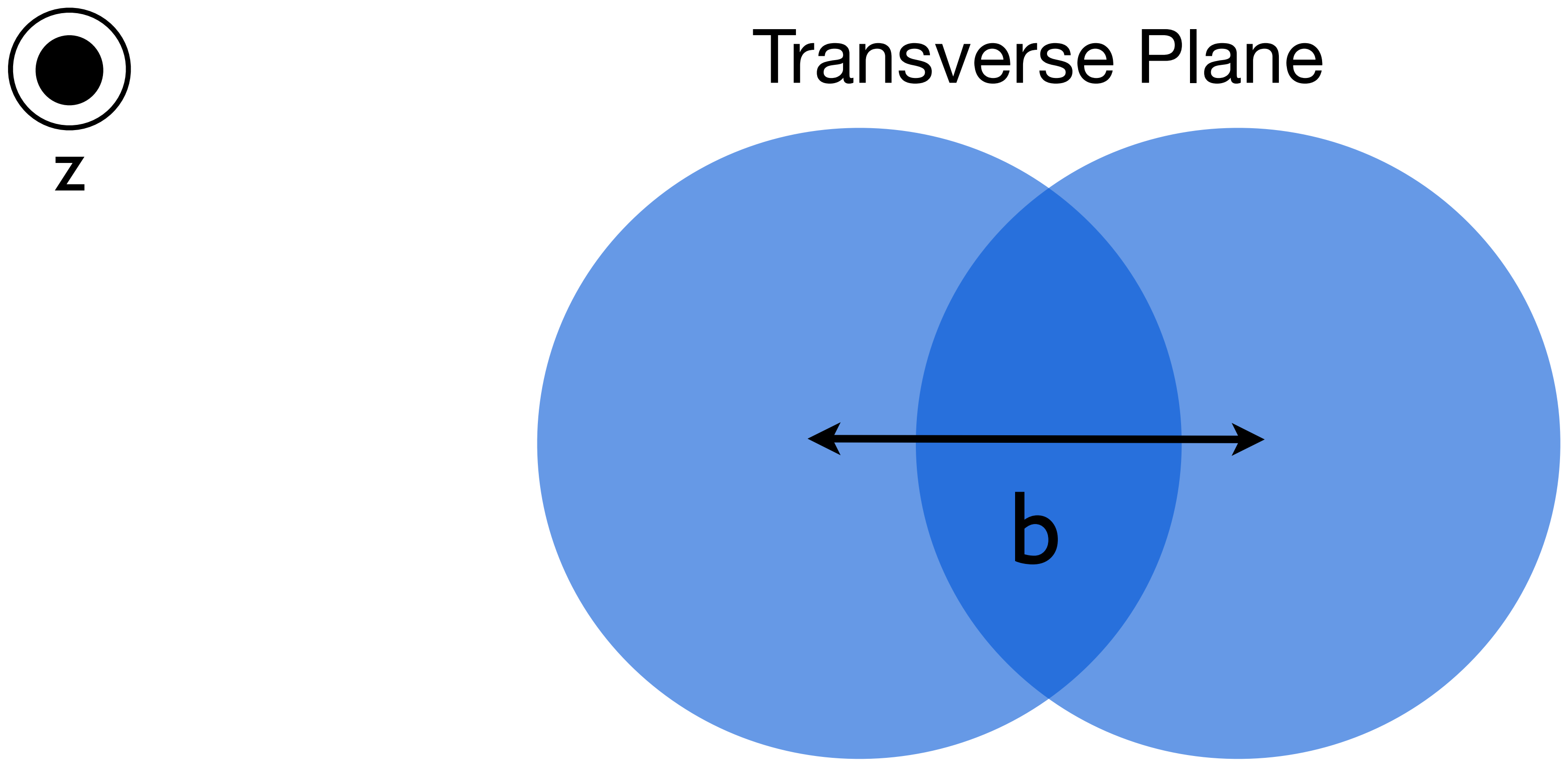


- For massless particles (only)

$$\eta = y$$

Centrality

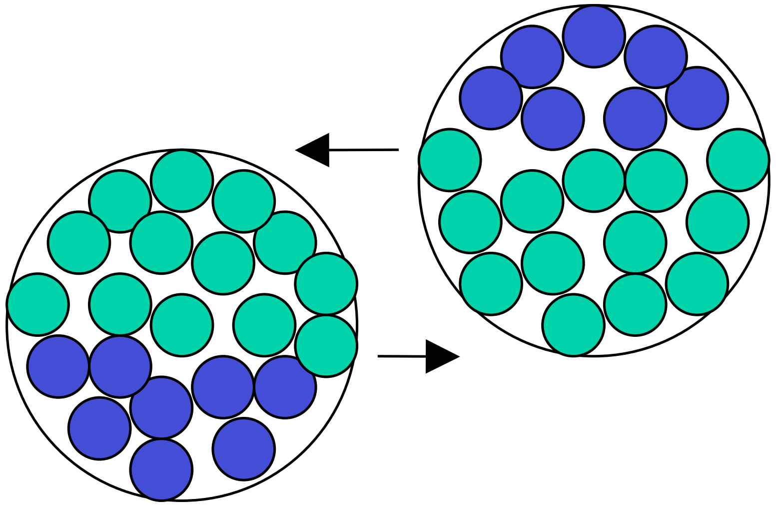
- Nuclei are extended objects ⇒ impact parameter b



- Centrality ⇔b
  - More central collisions ⇒ smaller b ⇒ larger multiplicity
  - Less central collisions ⇒ larger b ⇒ smaller multiplicity

Nuclear Geometry

- Multiplicity can be understood from nucleon-nucleon interactions:
  - N_{coll}: binary n-n collision
  - N_{part}: nucleons that interact at least once



- Computed from the nuclear density profile ρ
  - T_A: thickness function $T_A(b) = \int_{-\infty}^{\infty} dz\ \rho(b,z)$ $\quad \int dz\, db\, \rho(b,z) = 1$

$$N_{\rm coll}^{AB} = AB \int d^2x_\perp T_A(\mathbf{x}_\perp) T_B(\mathbf{b} - \mathbf{x}_\perp)\sigma_{NN}$$

$$N_{\rm part}^{A} = \int d^2x_\perp B T_B(\mathbf{x}_\perp) \left[1 - \exp\{ - A T_A(\mathbf{b} - \mathbf{x}_\perp)\sigma_{NN} \}\right]$$

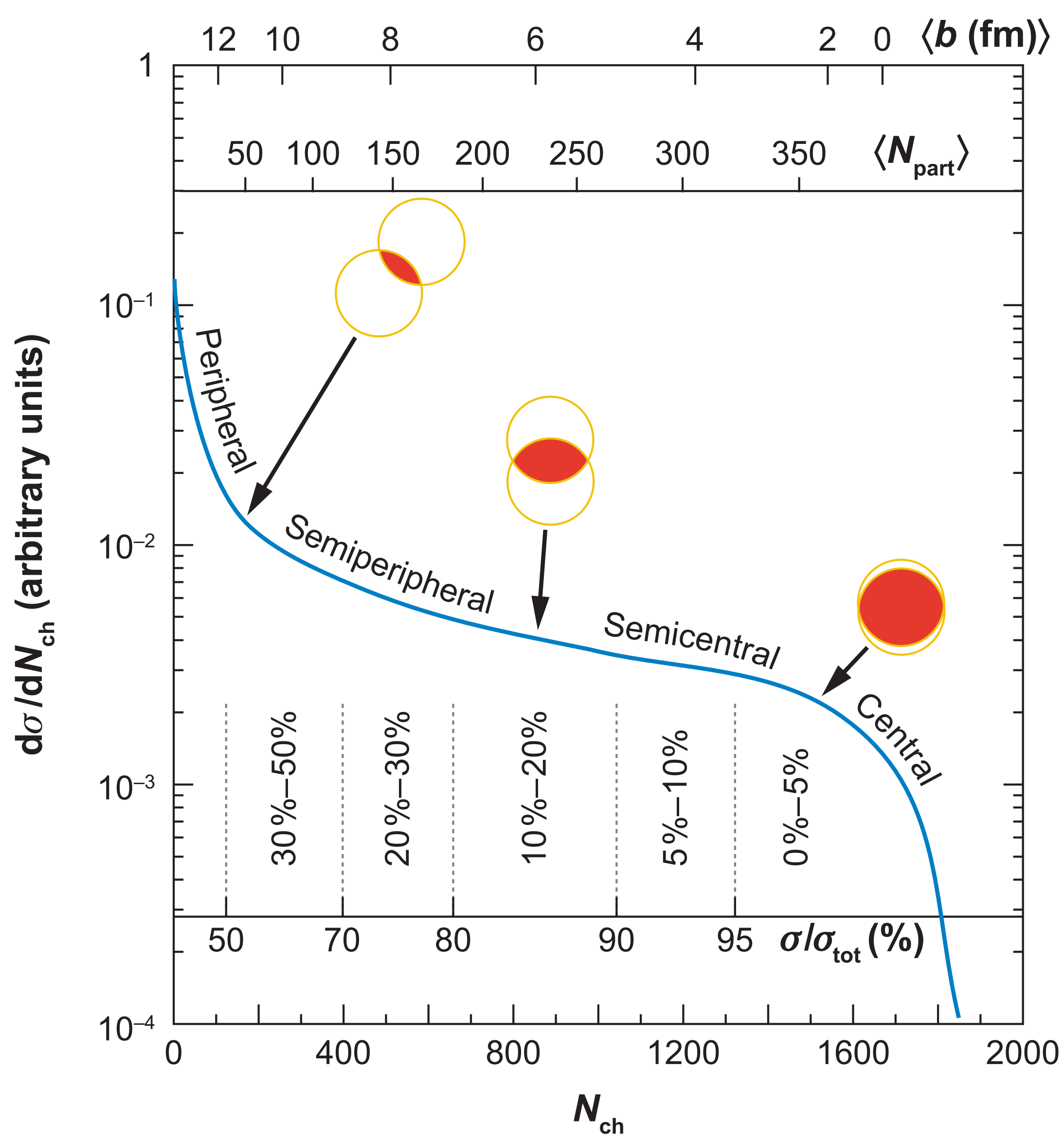
$$N_{\rm part}(\boldsymbol{b}) = N_{\rm part}^{A}(\boldsymbol{b}) + N_{\rm part}^{B}(\boldsymbol{b})$$

nucleon nucleon cross section

probability of no interaction

Multiplicity Distribution

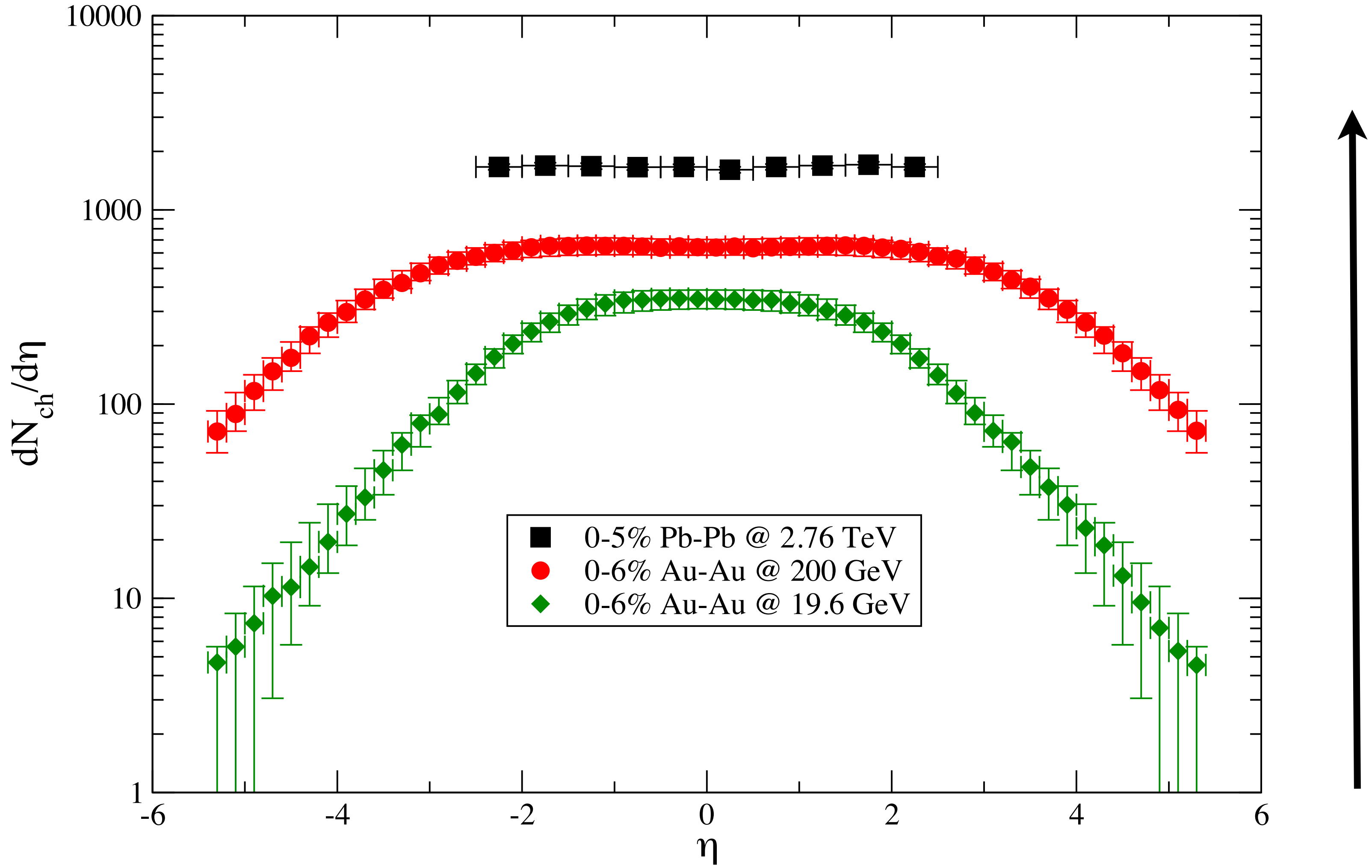
- Simple model: $$\bar{n}_{AB}(b) = \left(\frac{1-x}{2}\bar{N}^{AB}_{part}(b) + x\,\bar{N}^{AB}_{coll}(b)\right)\bar{n}_{NN}$$



- Geometry plays a crucial role in the collision

Longitudinal distribution

- Very wide rapidity distribution

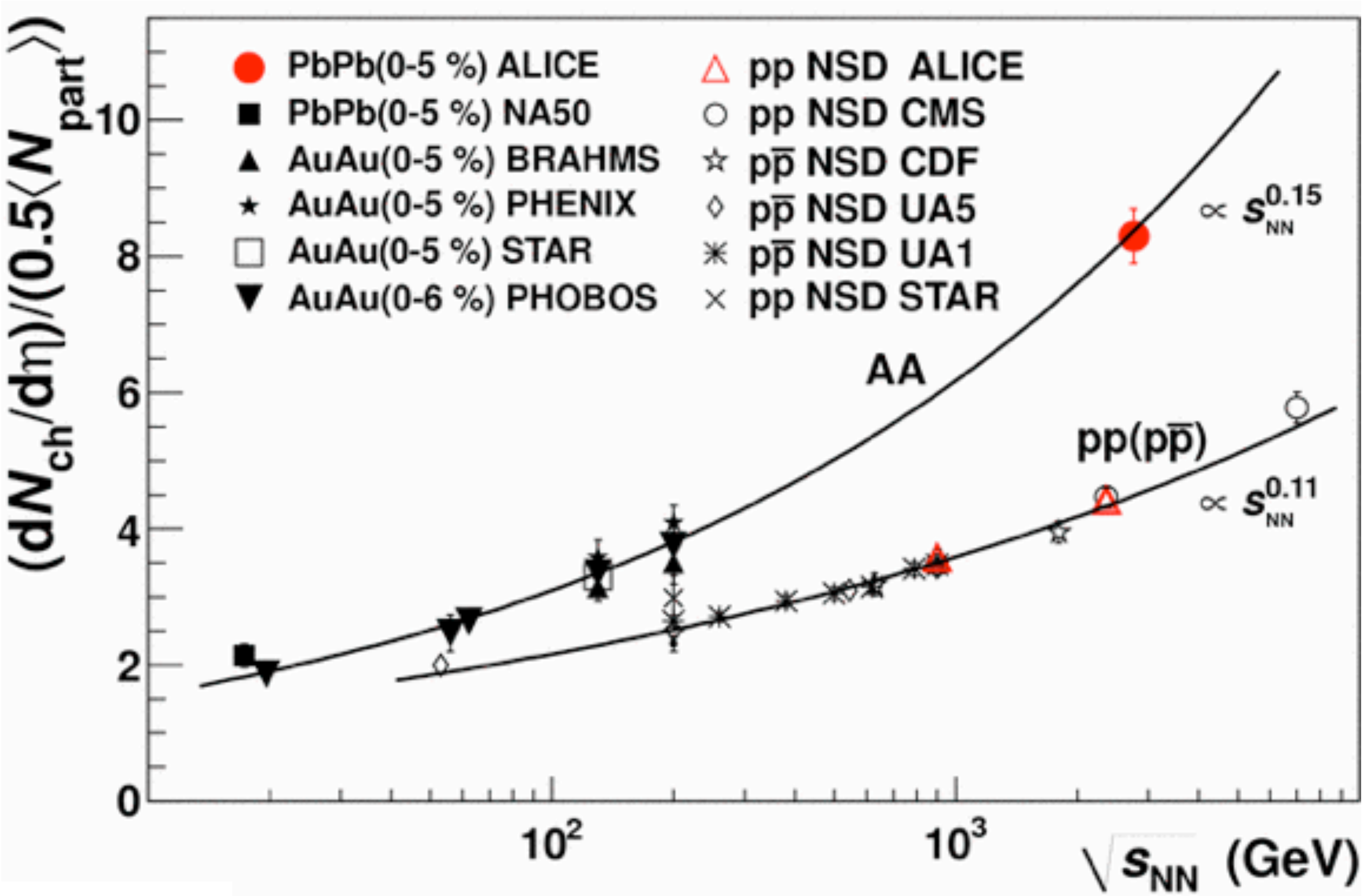


Increasing plateau

- Approximately (pseudo) rapidity independent
    - Approximately boost invariant!

Multiplicity

- At higher energies, the number of particles grows

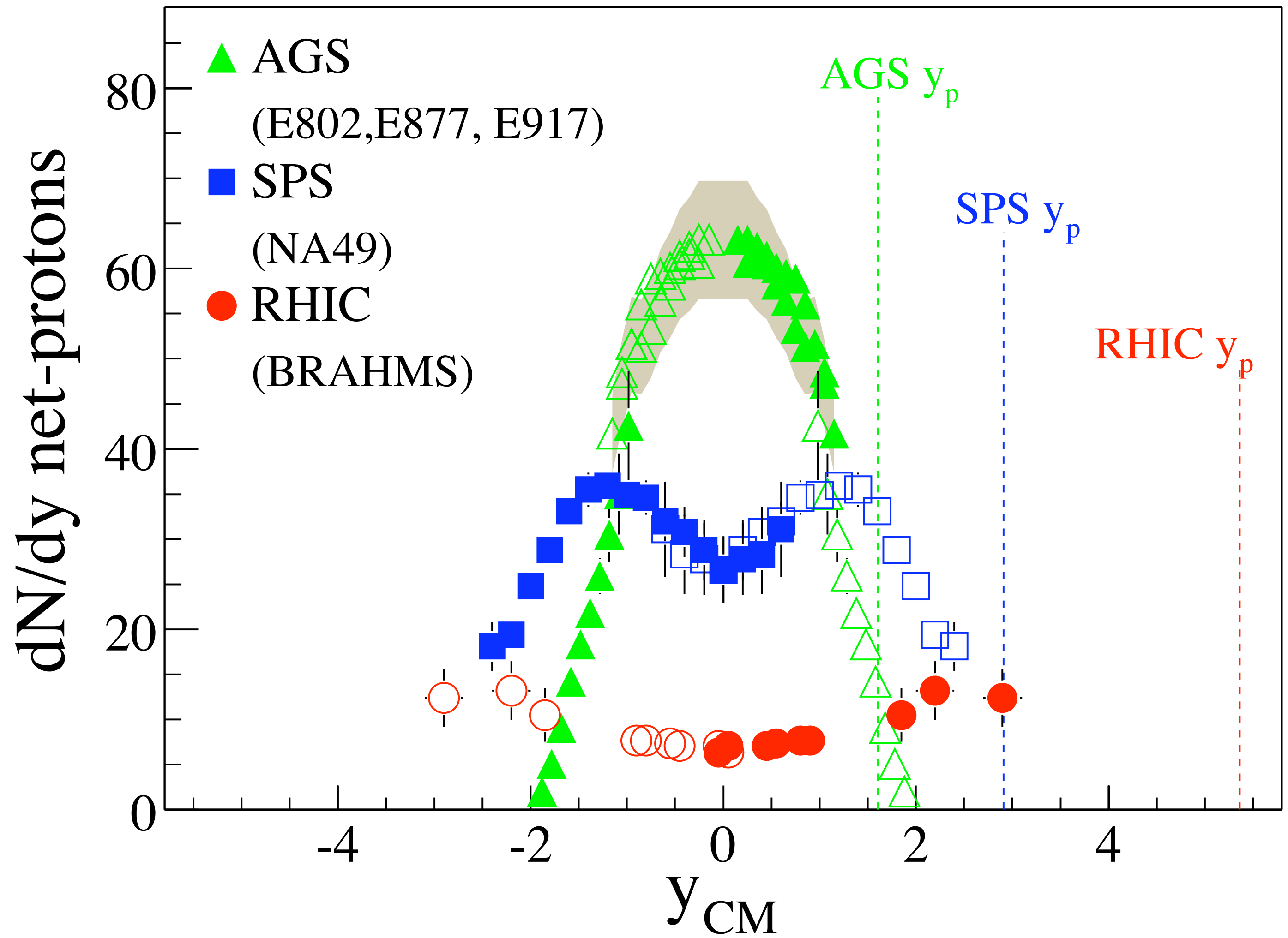


- At the LHC:

$$\frac{dN_{ch}}{d\eta} \sim 1600$$

Charge Distribution

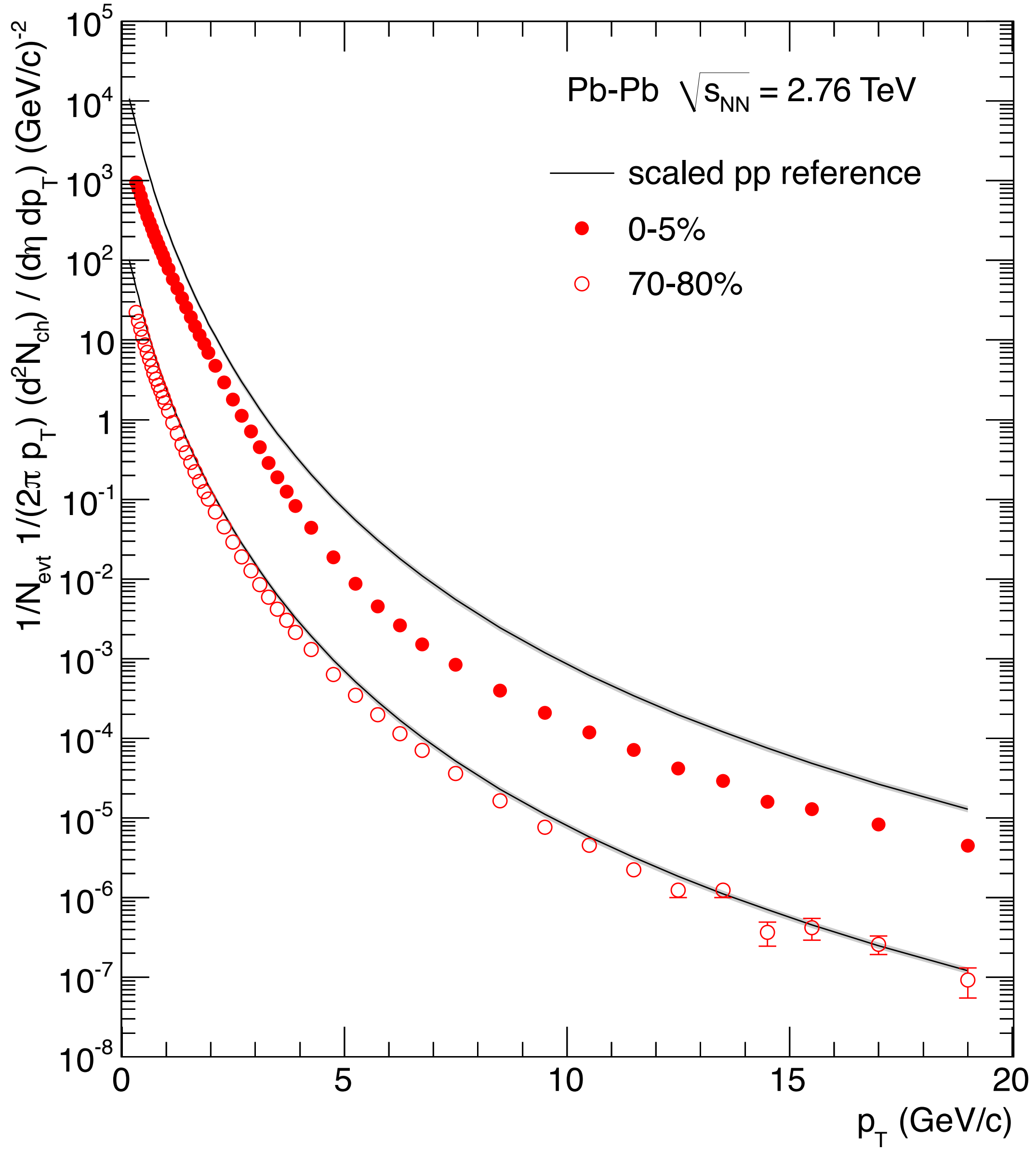
- Valence charges at high energy are stopped very little



- The midd rapidity matter is mostly baryon neutral

Transverse Momentum Distribution

- Most particles are soft



- LHC

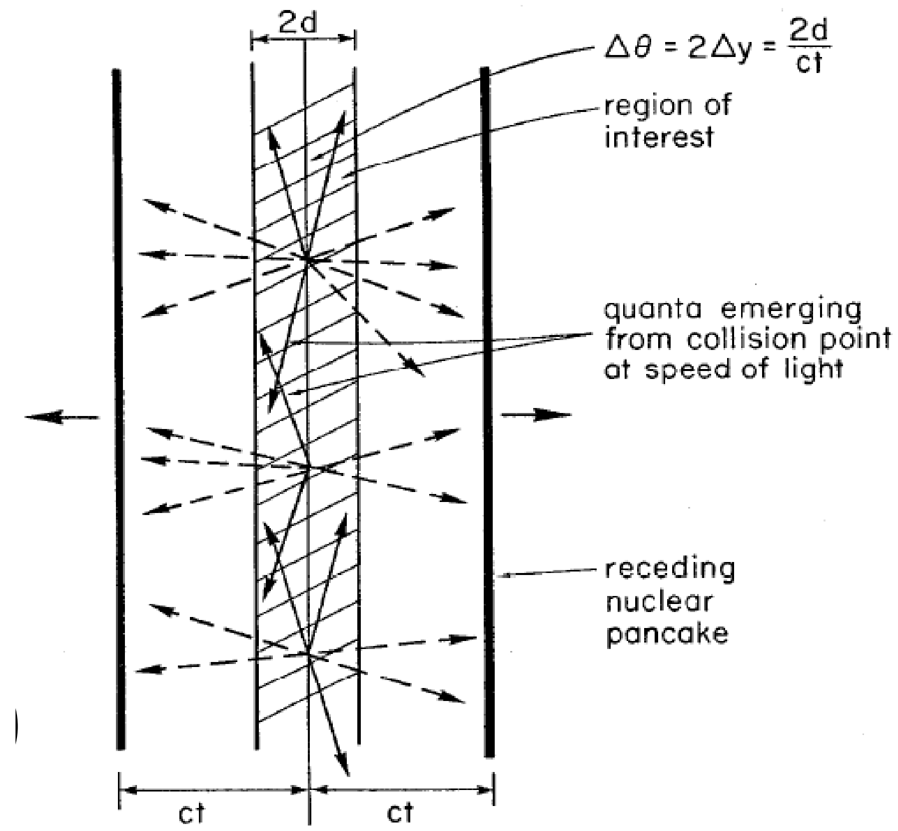
$$\left.\frac{dE_T}{d\eta}\right|_{\eta=0} \sim 1700\,\mathrm{GeV} \sim 1\,\mathrm{GeV}\,\frac{dN_{ch}}{d\eta}$$

- Rare energetic particles can be used as probes (end of second lenctures)

Estimating Initial Energy Density

- Bjorken's estimate
  - At a given time t, energy within d=2t

$$E > 2\left.\frac{dE_T}{d\eta}\right|_{\eta=0} \qquad \epsilon > \left.\frac{dE_T}{d\eta}\right|_{\eta=0}\frac{1}{\pi R^2 t}$$



  - At at typical time of t= 1fm (R= 7 fm)

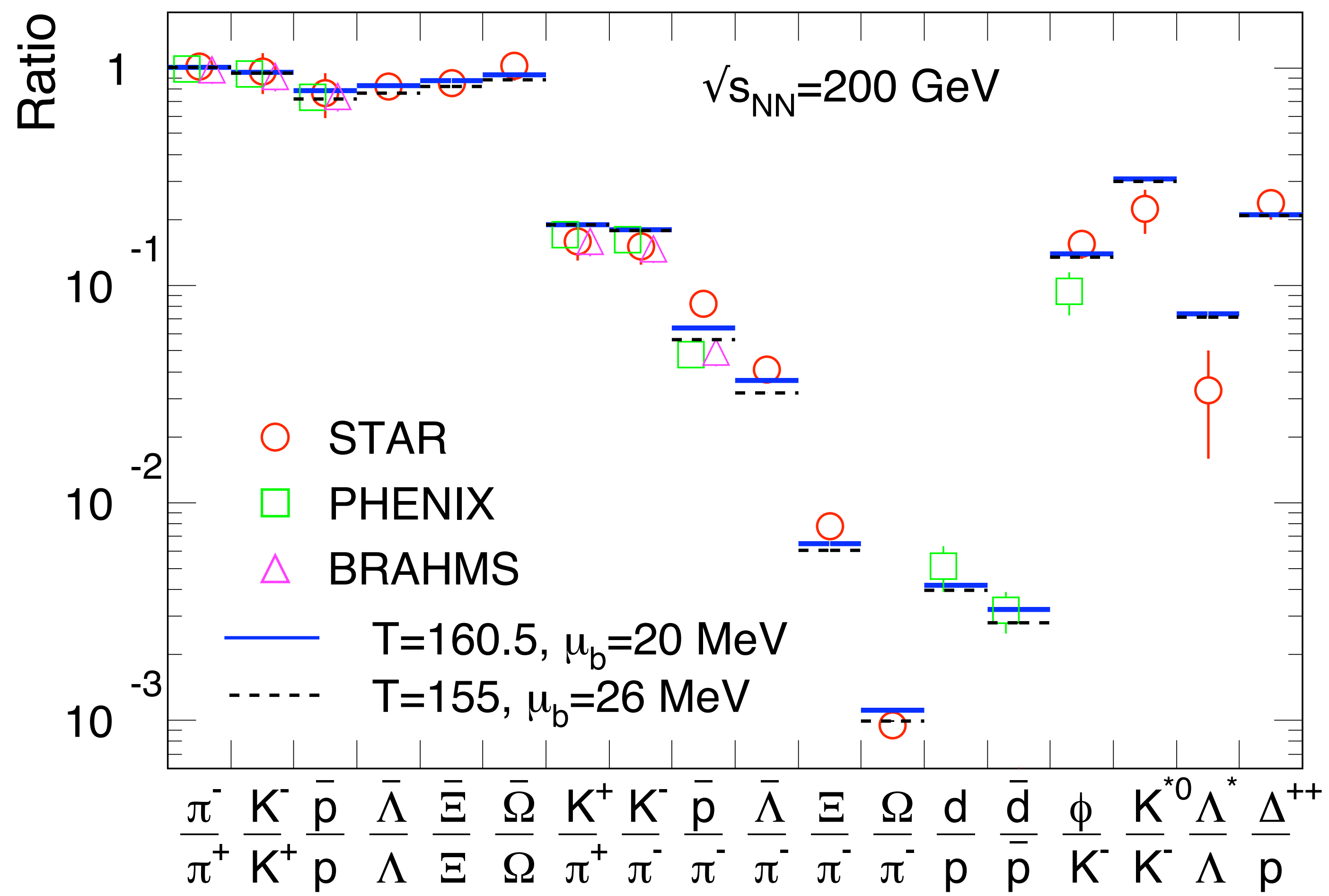
$$\epsilon_{RHIC} > 5\mathrm{GeV}/\mathrm{fm}^3 \qquad \epsilon_{LHC} > 14\,\mathrm{GeV}/\mathrm{fm}^3$$

  - Well above critical energy density (lattice) $\epsilon_c \sim 1\,\mathrm{GeV}/\mathrm{fm}^3$

- If this energy thermalizes we produce the QGP!

Apparent Thermalization

- Simple thermal fit: 2 paremeters, fit 18 species

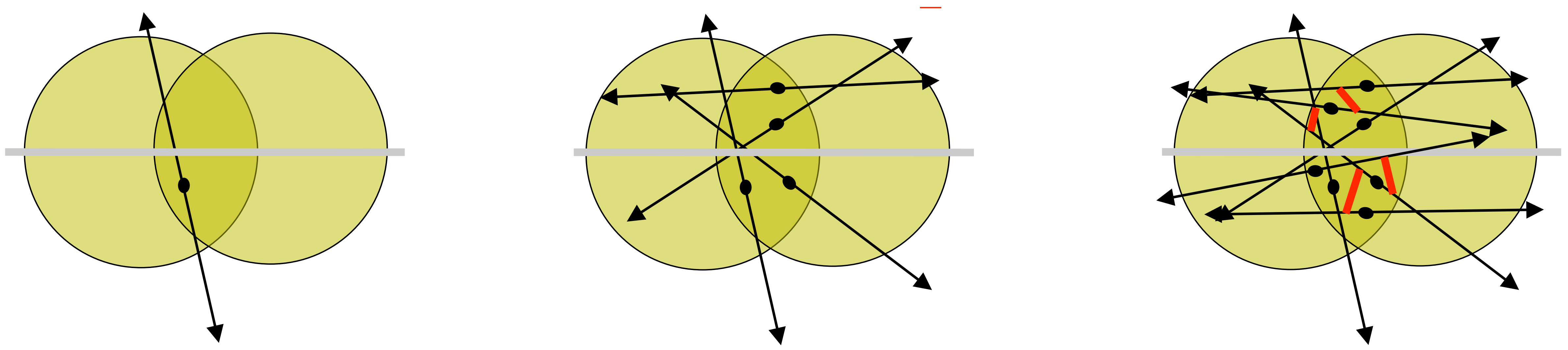


- Indication of strong interactions among produced particles

Part 3

Is matter behaving collectively?

Interaction and Collectivity



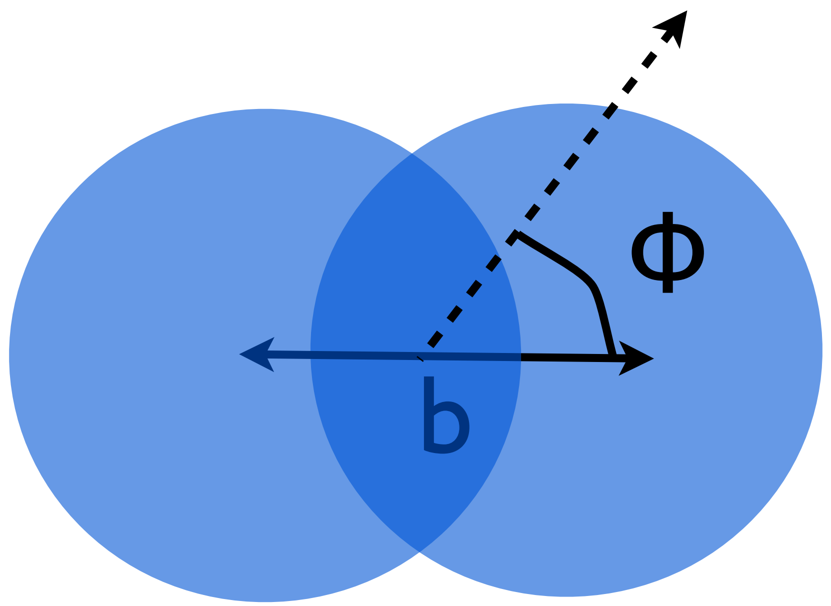
- Single 2 -> 2 process produces particles independent of the impact parameter (to first approximation)
- Large multiplicities ⇒ multiple independent production
- Interactions between particles correlate emission direction and geometry

Correlation of ***all*** particles with the reaction plane

Azimuthal Anisotropy

- Non-central collisions
  - • asymmetry in transverse plane

    ⇒ asymmetry in momentum distribution



$$E\frac{dN}{d^3p} = \frac{1}{2\pi}\frac{dN}{p_T dp_T d\eta}\left[1 + 2v_2(p_T)\cos\left(2(\phi - \psi_{reaction\ plane})\right)\right]$$

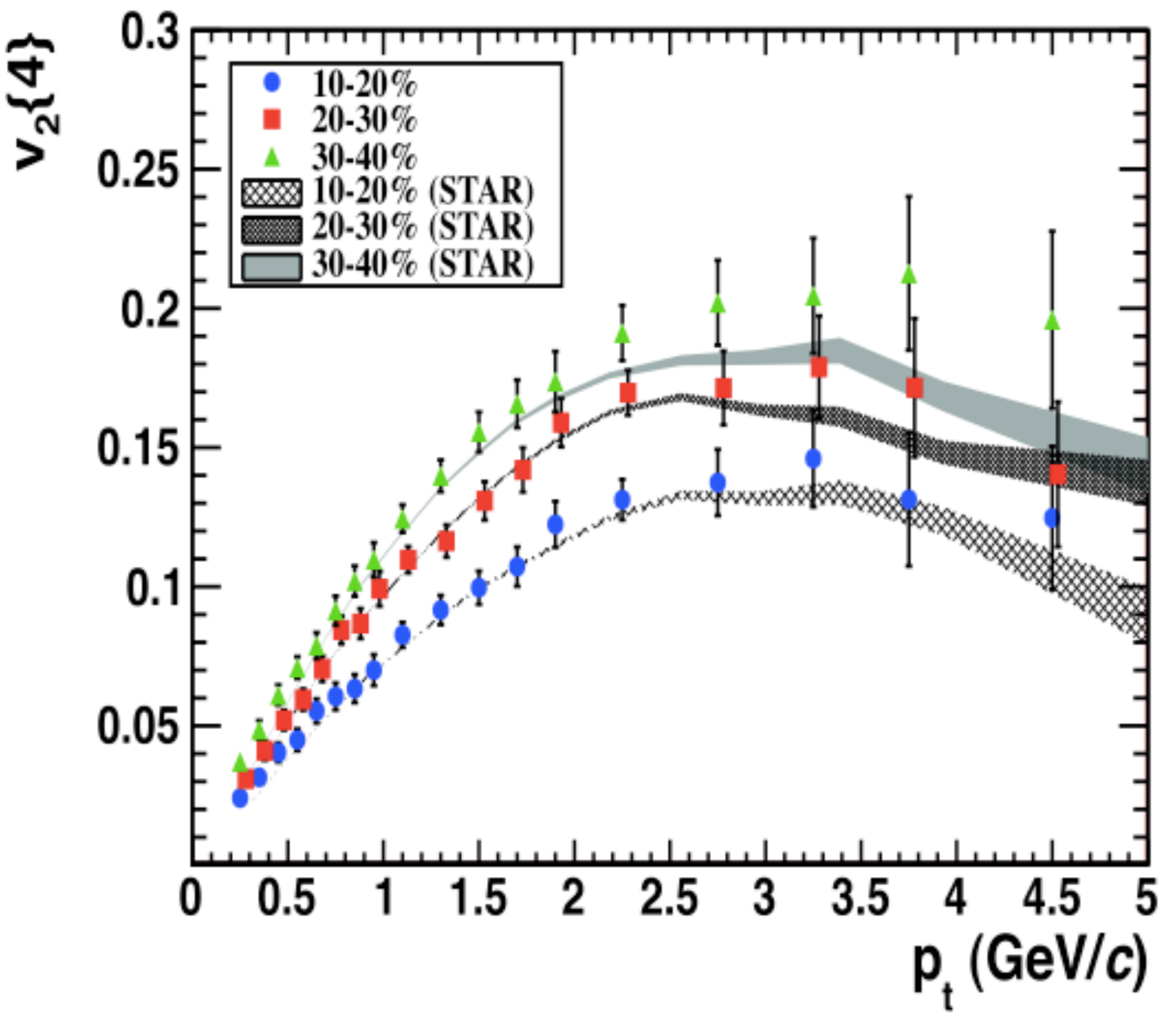
- Reaction plane is hard to determine
  - • Azimuthal correlation of particles

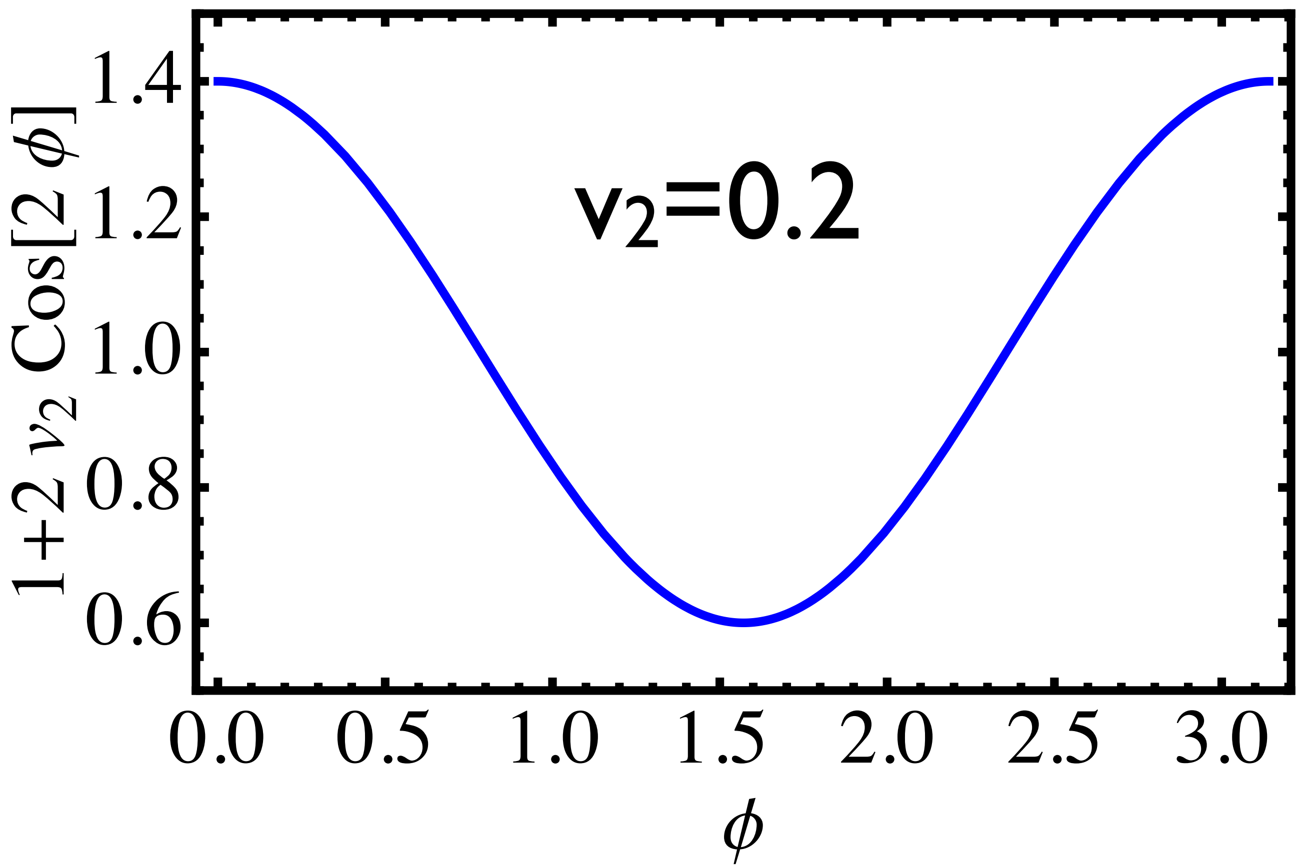
$$\left\langle e^{in(\phi_1-\phi_2)}\right\rangle = v_n^2 + \mathcal{O}\left(\frac{1}{N}\right)$$

→ "non-flow effects"
(correlations involving few particles)

  - • Correlations among more particles reduce further sensitivity to non-flow Borghini, Dinh and Ollitrault 01

Measured Anisotropy



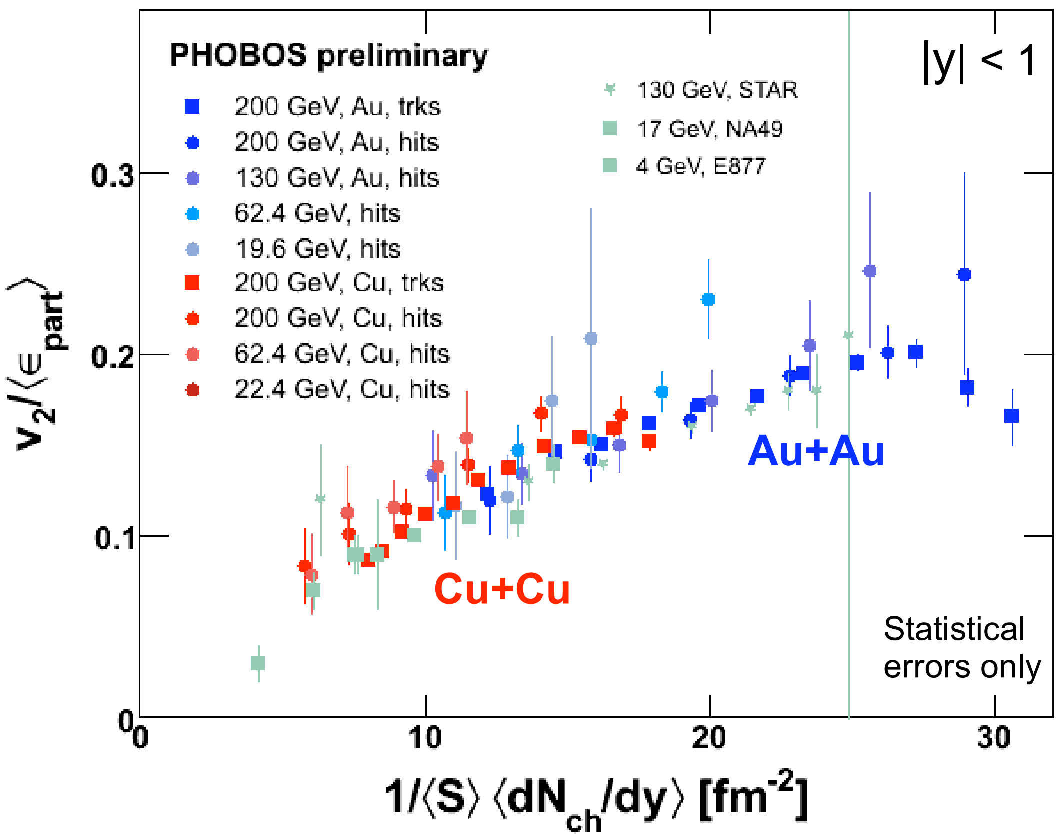


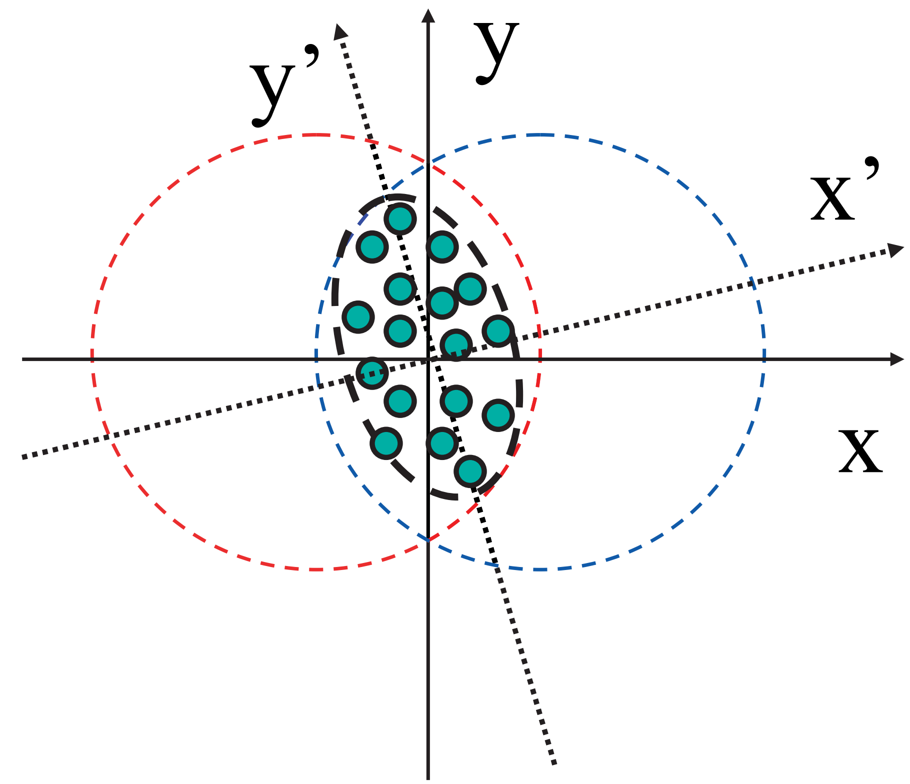
- A very large effect

A Geometric Property

- Relation of flow in different systems
    - Take into account event by event

$$\epsilon = \frac{\langle y'^2 \rangle - \langle x'^2 \rangle}{\langle y'^2 \rangle + \langle x'^2 \rangle}$$





- v_2 scales with eccentricity (geometrical property)
- v_2 is a function of transverse density (density ⇔ interactions)

- Scaling over a large variety of systems and collision energies.

Microscopic Modeling

- If we understand the microsocpic d.o.f and their interactions:

Boltzmann eq: $$p^\mu \partial_\mu f_i = \sum_{porcesses} \mathcal{C}_{process}[f]$$ ← Collision rates

computed via underlying theory

- Can be derived at very high temperatures in QCD (g(T)≪ 1)
- In experiments, applicability is questionable (T<0.6 GeV)
- Leading order (2-2) computations underpredicts flow effects

- Can we have a model independent description?

- Yes, provided we assume interactions are extremely frequent

microscopic scale ← $$\lambda_{m.f.p} \ll R$$ → variation rate of density (size)

Hydrodynamics

Relativistic Hydrodynamics

- The stress tensor of any (homogeneous, isotropic..) theory after all process settle

$$T^{\mu\nu} = \begin{pmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & p(\varepsilon) & 0 & 0 \\ 0 & 0 & p(\varepsilon) & 0 \\ 0 & 0 & 0 & p(\varepsilon) \end{pmatrix} \xrightarrow{\text{boosting to another frame}} T^{\mu\nu}_{ideal} = (e+p)u^\mu u^\nu - p g^{\mu\nu}$$

u^μ velocity of the frame

e.o.s

- Hydro approximation: assume all variation of stress tensor are very small compared to microscopic scales ⇔ gradient expansion
  - At the scale of the variation all micro-process are local
- Ideal approximation: even in dynamical situation

$$T^{\mu\nu} \approx T^{\mu\nu}_{ideal} \qquad \text{with} \quad \epsilon(x) \quad u^\mu(x)$$ (5) dynamical fields

- And 5 equations

$$\nabla_\mu T^{\mu\nu} = 0$$ Enough to solve dynamics

Viscosity

- Hydrodynamics: systematic approach ⇒gradient expansion
  - Expand to leading order in gradients

$$T^{\mu\nu} = T^{\mu\nu}_{ideal} + \eta\Pi^{\mu\nu} + \zeta\Theta^{\mu\nu}$$

η: shear viscosity; ζ: bulk viscosity

Two different symmetric structure → easier in fluid rest frame

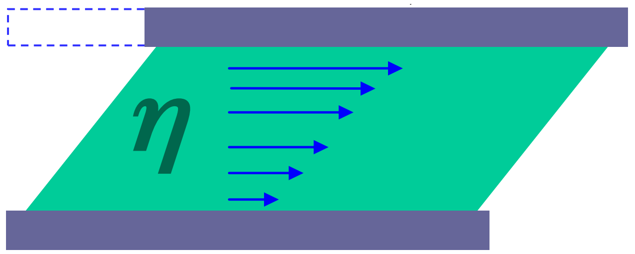
$$\Pi_{ij} = \partial_i v_j + \partial_j v_i - \frac{2}{3}\partial_k v^k \delta_{ij}$$

$$\Theta_{ij} = \frac{2}{3}\partial_k v^k \delta_{ij}$$

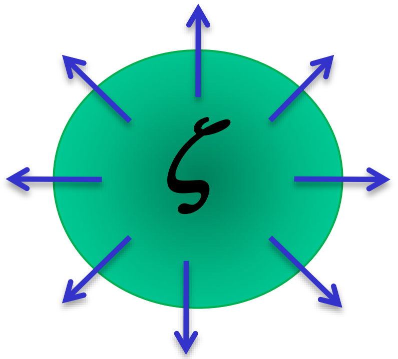
  - These are transport coefficients: Intrinsic properties of the theory

- Same interpretation as in non-relativistic fluid

Shear viscosity



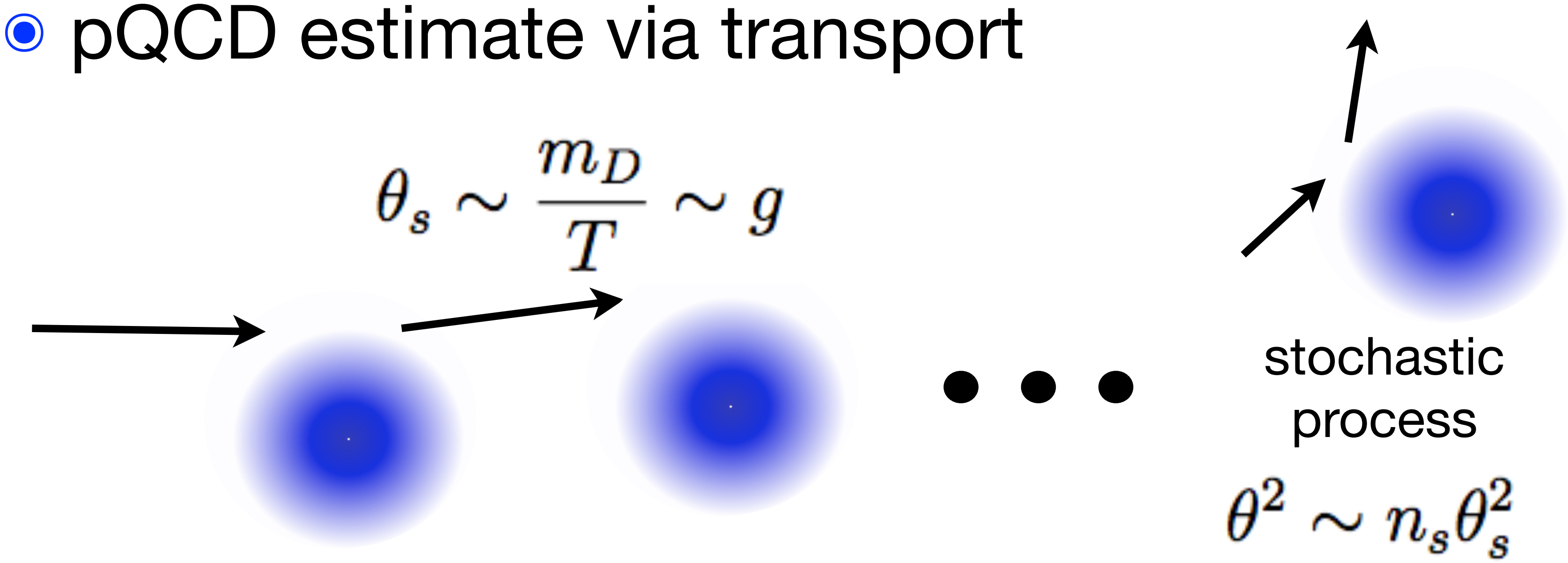
Bulk viscosity



Computations of Viscosity

- pQCD estimate via transport

$$\theta_s \sim \frac{m_D}{T} \sim g$$



$$\theta^2 \sim n_s \theta_s^2$$

Momentum transfer

$$\theta \sim \mathcal{O}(1)$$

$$\lambda_{\rm transport} \sim n_s \lambda \sim \frac{1}{g^4 T}$$

- Shear viscosity

$$\eta \sim \frac{P}{A} \sim \frac{T}{\lambda_{\rm transport}} s$$

- Bulk viscosity

$$\zeta \approx 0$$

(QCD is approximately conformal)

- Kinematic viscosity:

$$\frac{\eta}{s} \sim \frac{1}{g^4}$$

- Large for weakly interacting plasma
- Small for strongly interacting plasma

Field Theory Extractions

- Transport coefficients can be computed via correlation functions

  Kubo Relation

$$\eta = -\lim_{\omega\to 0}\lim_{k\to 0}\frac{1}{\omega}\mathrm{Im}\int d^4x\, e^{iwt-kz}\, \underbrace{i\theta(t)\,\langle[T^{xy}(x),T^{xy}(0)]\rangle}_{G_R}$$

  - Derived via linear response:

$$\langle T(x)\rangle = \int dy G_R(x-y)\delta g(y)$$

  ⟷ equate to hydro response

  δg ↳ metric perturbation (source)

- General expression but... hard to use in QCD
  - small ω problematic in thermal perturbation theory (IR problems)
  - Real time dynamics: hard for lattice computations

- Can we extract this from data?

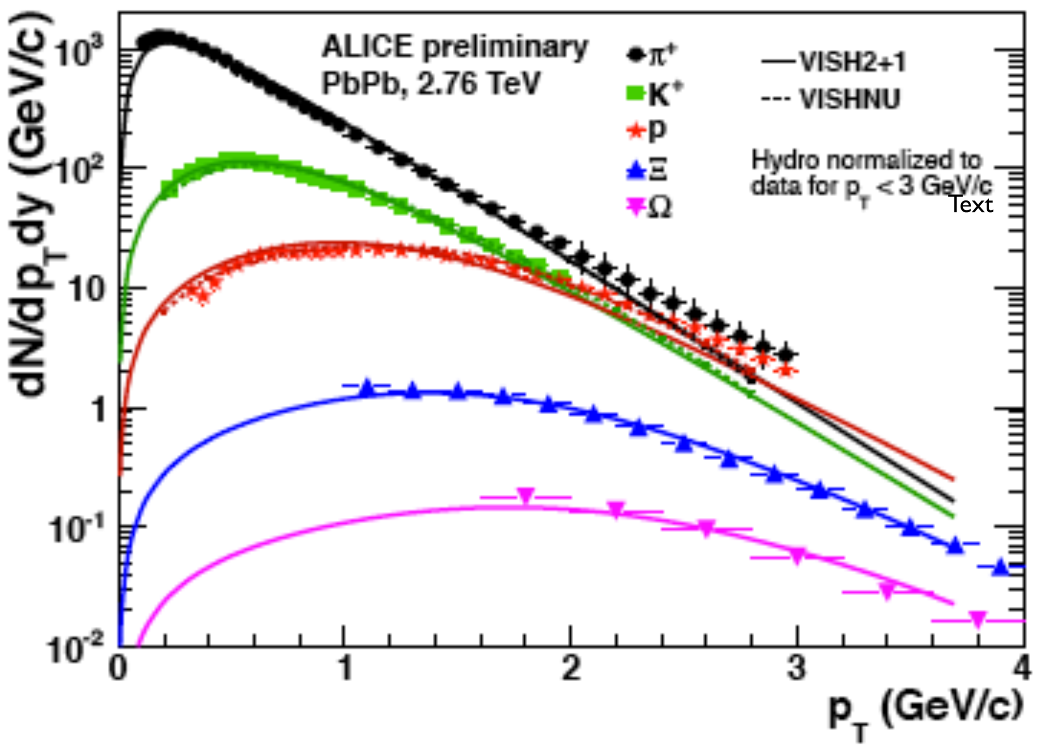
Hydrodynamic Modeling

- Initial value of fields
  - Initiate hydrodynamics at some time after collision (model parameter)
  - Most simulations assume boost invariant distributions
  - Initial energy density from dynamical model or empirical

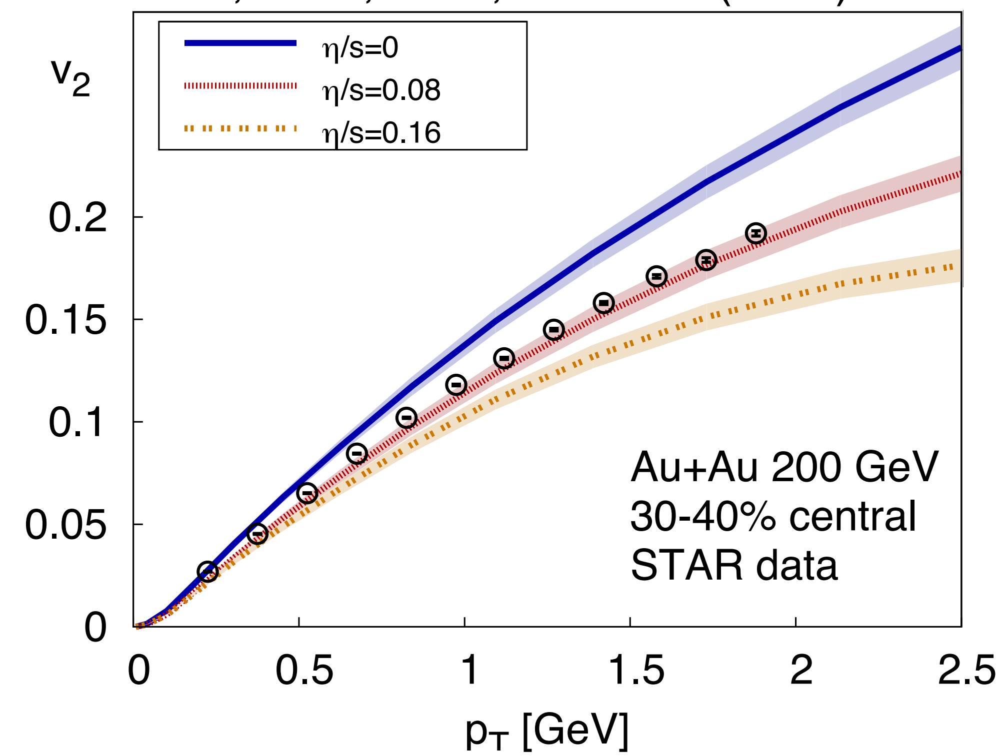
$$\frac{ds}{dx_\perp^2} \propto \left[(1-x)N_{\rm part}(x_\perp) + xN_{\rm coll}(x_\perp)\right]$$

- Hydro solver
  - Needs e.o.s (usually taken from lattice computations)
- Decoupling
  - At Tc~165 MeV hadrons decoupled quickly ⇒thermal abundance
  - Evolved with Boltzmann equation + known cross sections

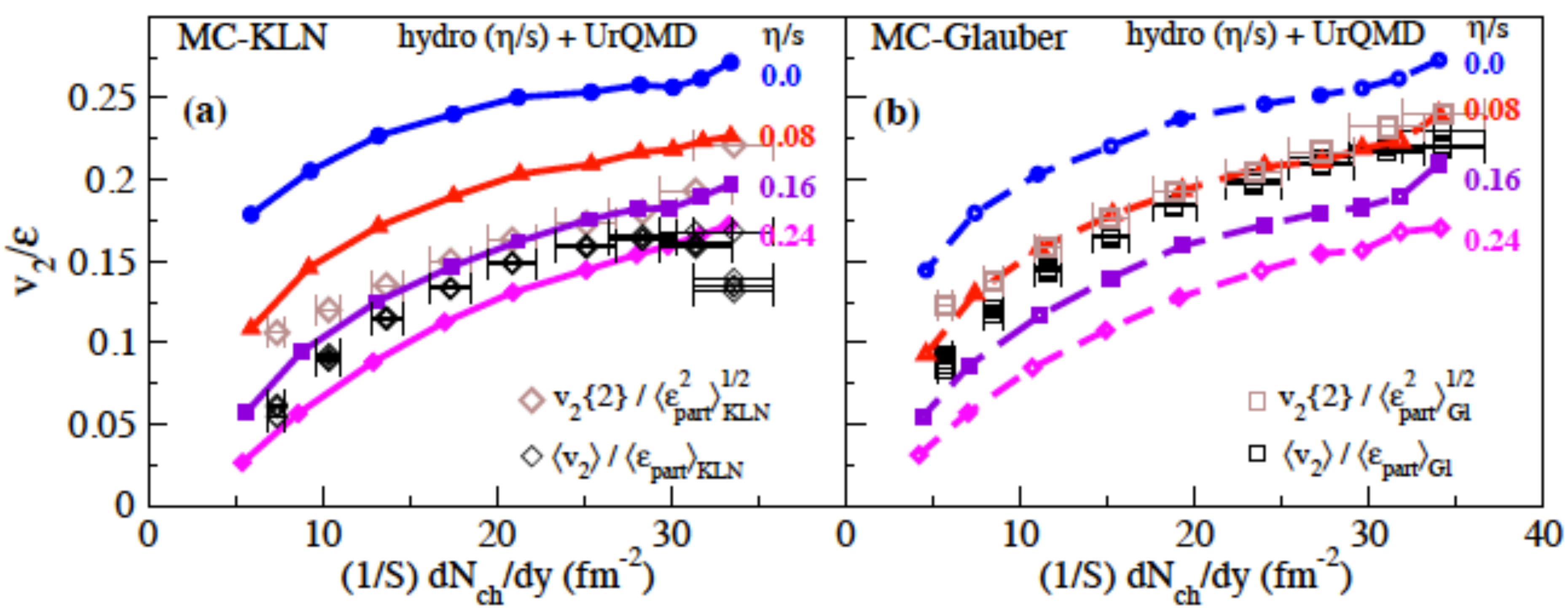
Success of Hydro



Schenke, Jeon, Gale, PRL 106 (2011) 042301



Song, Bass, Heinz, Hirano, Shen, PRL 106 (2011) 192301



Hydro from Early Times

- Hydro works but... from when

  - Typical simulations at the LHC have

$$\tau_0 T = \frac{0.5 \times 0.5\,\mathrm{GeVfm}}{0.2\mathrm{GeVfm}} \sim 1.25$$

size of the medium (τ_0) — micro scale (T)

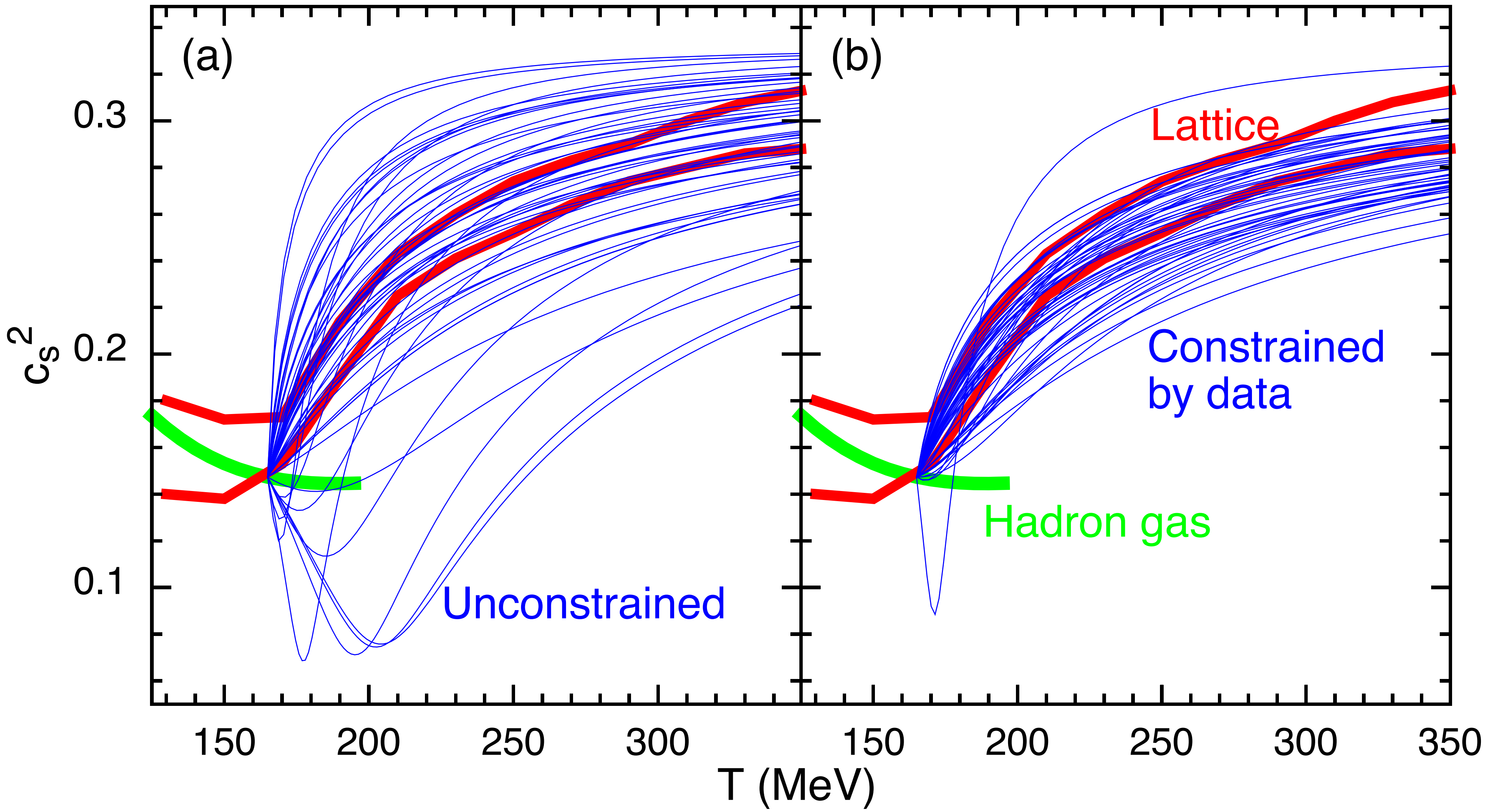
  - It does not seem as if hydro should work...

  - yet...

Extracting QCD properties from Data

- Example: is data sensitive to known QCD propertie?

Pratt, Sangaline, Sorensen and Wang 15



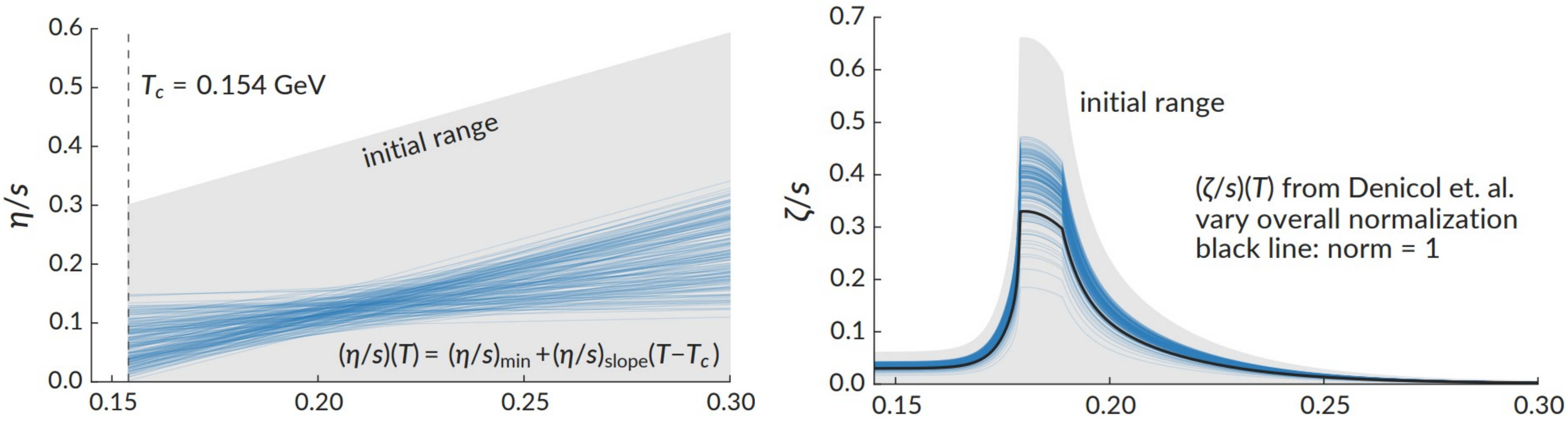
$$c_s^2 = \frac{dp}{d\epsilon}$$

- Combined hydro fits of collision data of different species and energies constraint the equation of state

Extracting Viscosities

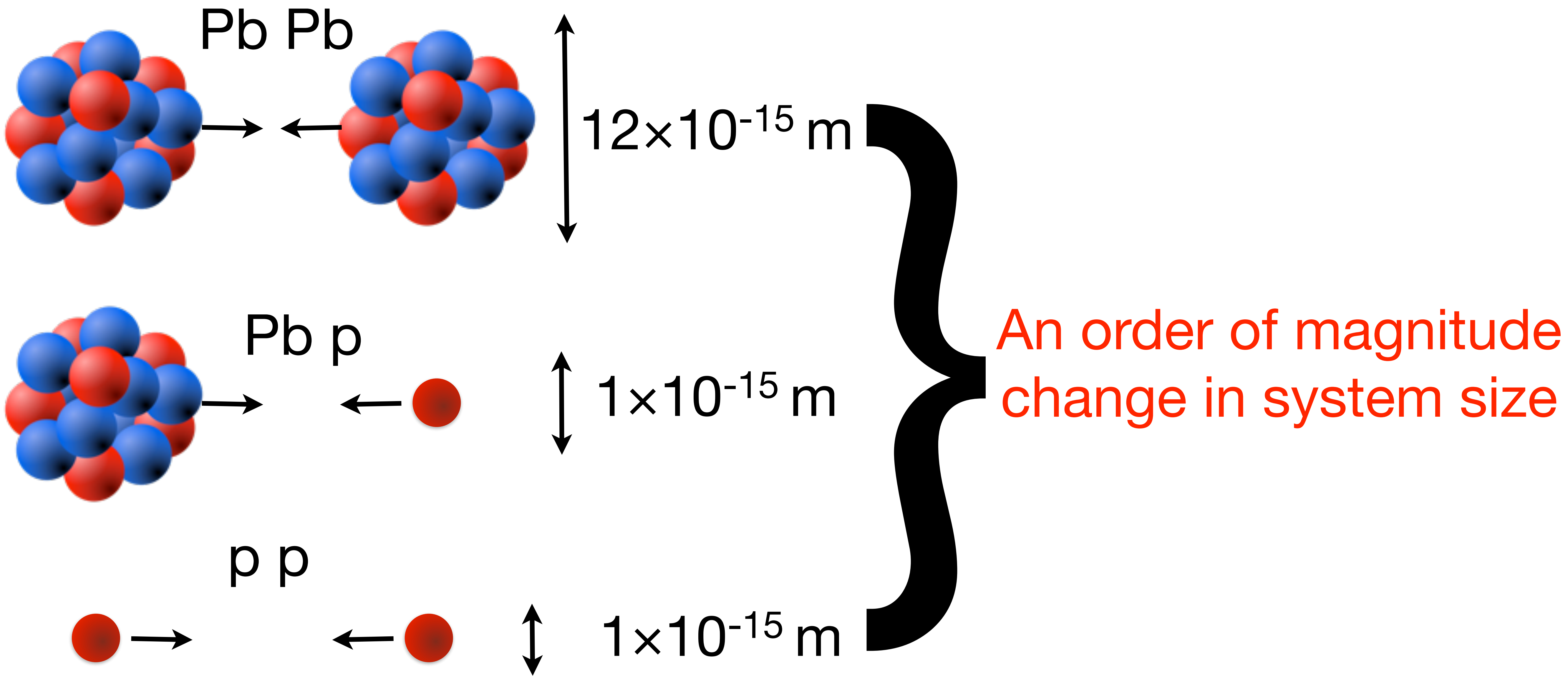
Global fit to several sets of data

J. Bernhard, J.S. Moreland, S. Bass, J. Liu, U. Heinz arXiv:1605.03954



$$\left(\frac{\eta}{s}\right)_{\mathrm{T_c}} = 0.08 \pm 0.05$$

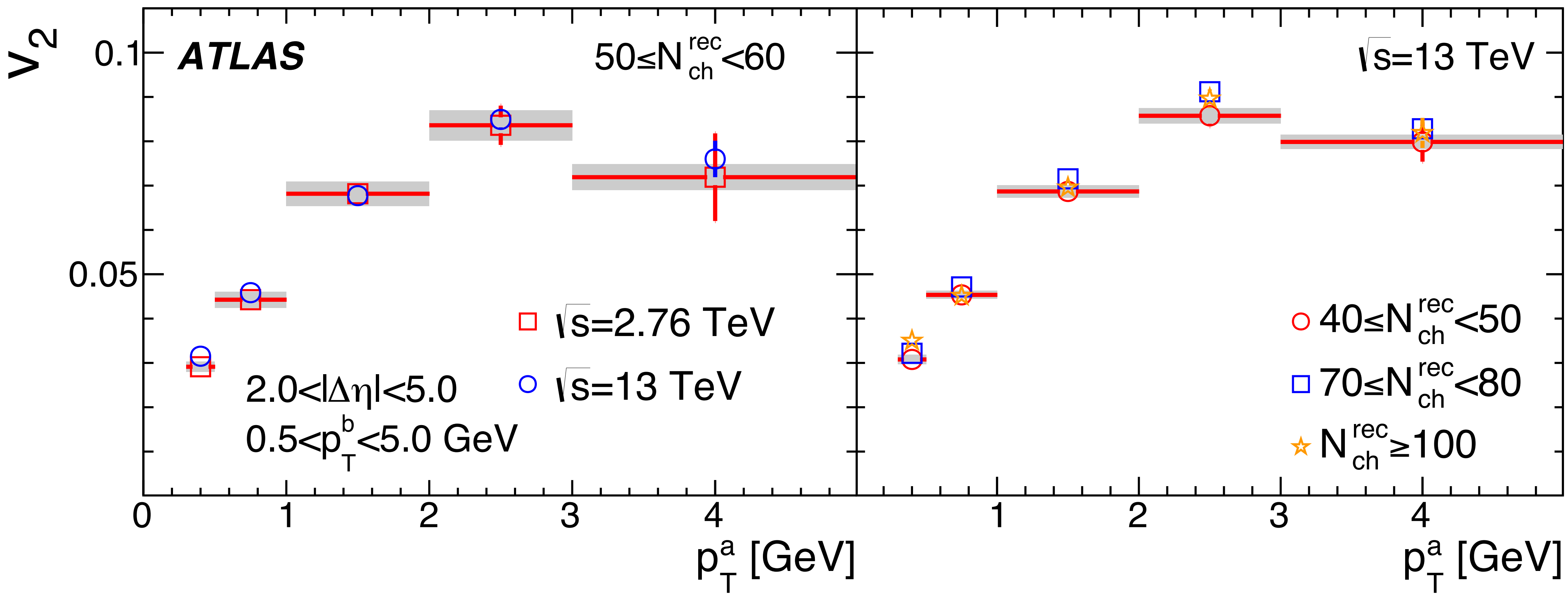
Changing the Collision System



- Collision at extremely high energy ⟺ extremely high densities

Hydrodynamics in Small Systems

- Flow in p-p! (and in p-Pb)



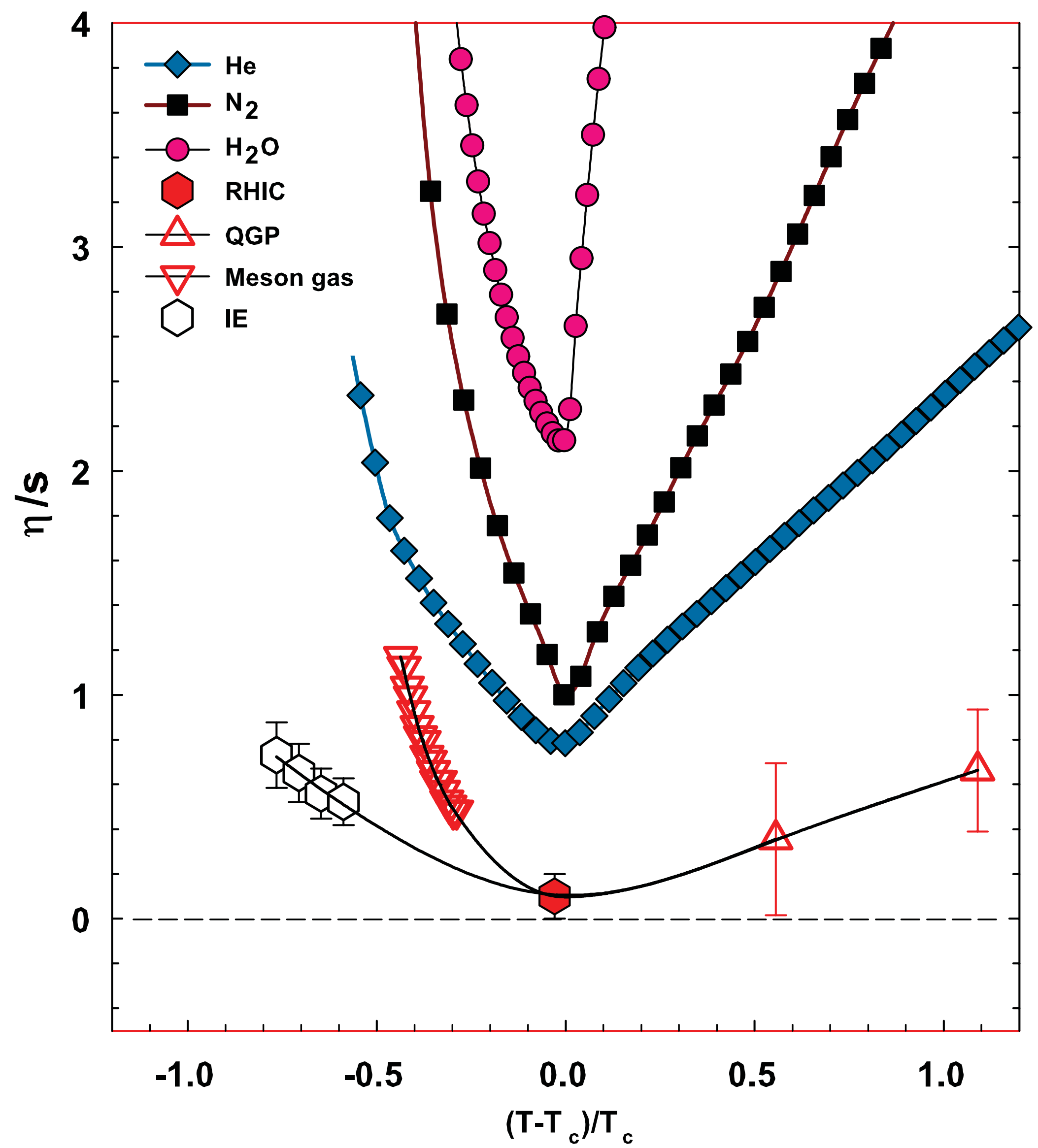
- Hydrodynamic explosions describe the observed distributions

Bozek (12, 15), Nagle et al. (13), Schenke & Venugopalan (14), Kozlov et al. (14), Romatschke(15)

Implication of η/s Value

- It is the smallest value ever measured in any substance.

  The Quark Gluon Plasma is the most perfect fluid!



Lacey et al 07

Implication of η/s Value

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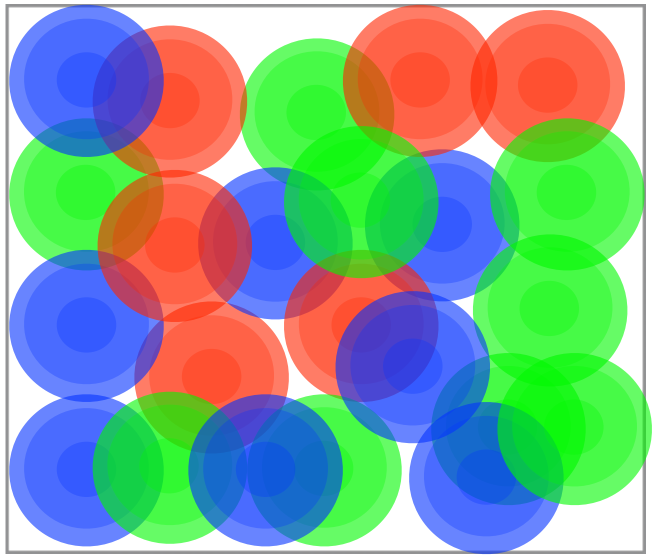
- It is incompatible with quasiparticles

Boltzmann equation $\Rightarrow$ $\tau_{qp} \sim 5\,\frac{\eta}{s}\,\frac{1}{T} \sim \frac{1}{T}$



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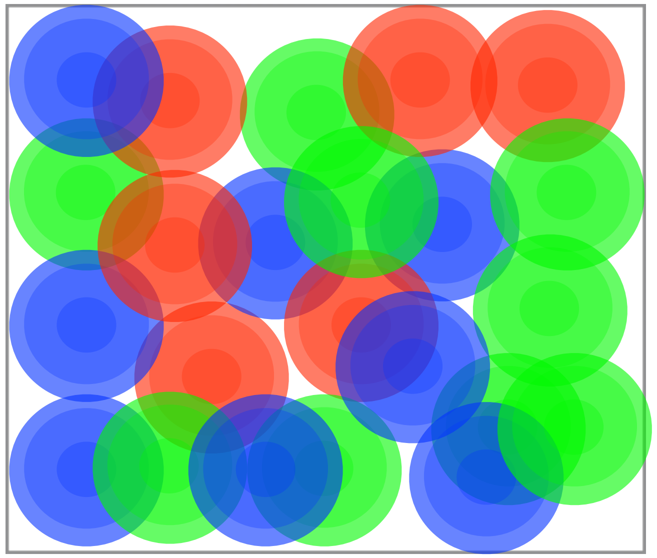

- It was predicted in 2001 (Policastro, Son, Starients)

$$\frac{\eta}{s} = \frac{1}{4\pi} = 0.08$$

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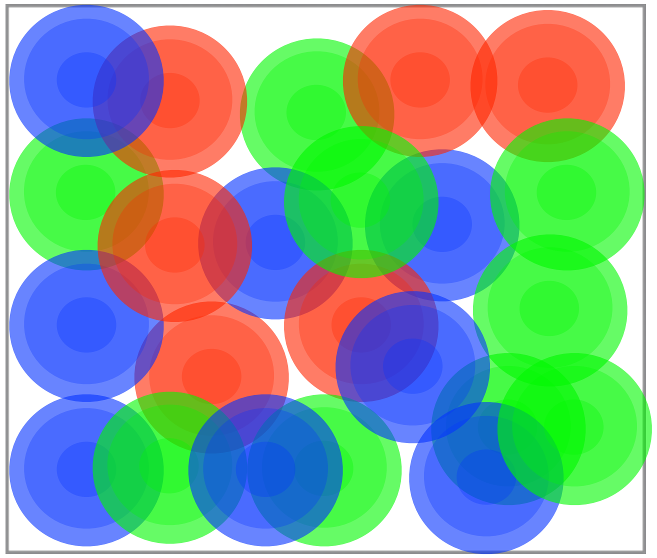

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$$\frac{\eta}{s} = \frac{1}{4\pi} = 0.08$$

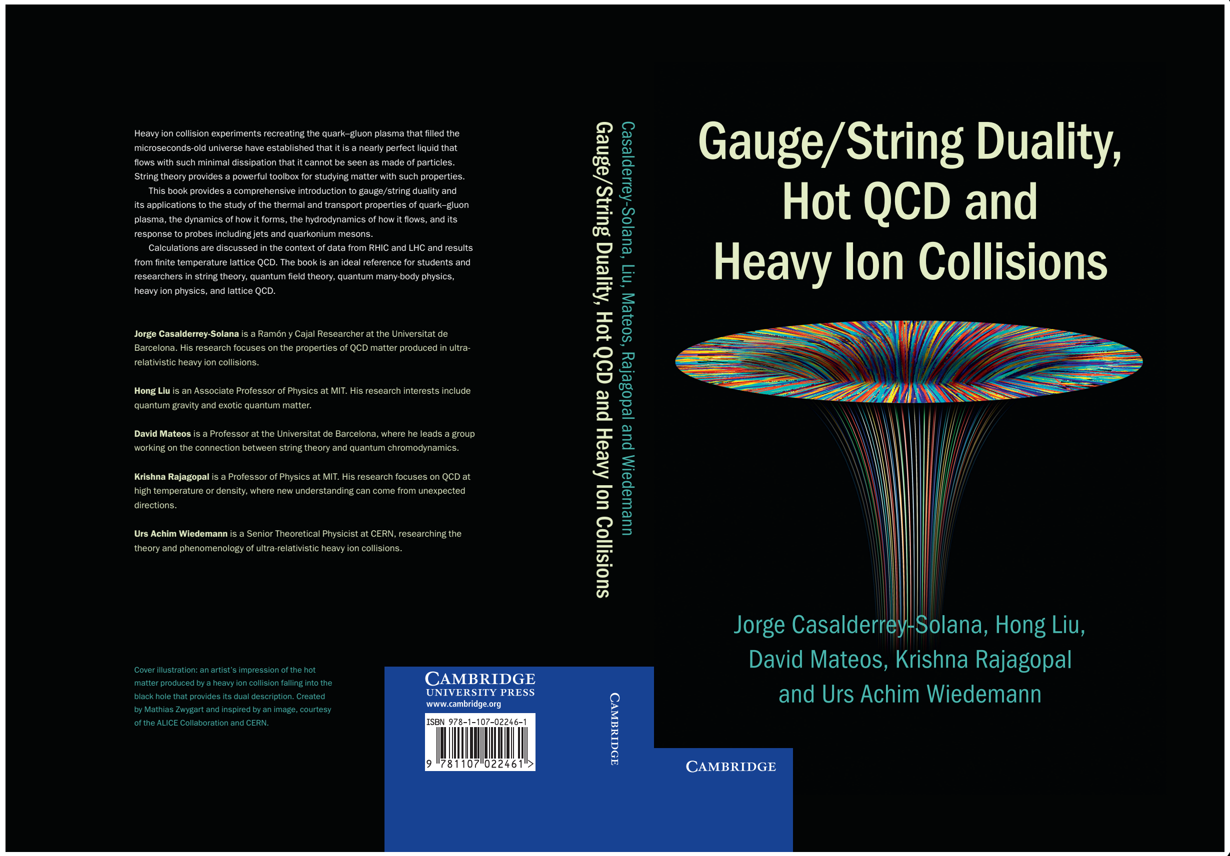
... but for a large class of non-abelian gauge theories at infinite coupling via holography

Part IV

Holography

- Gauge Theories in the limit

$$\lambda = 4\pi\alpha_s N_c \to \infty$$



Holography

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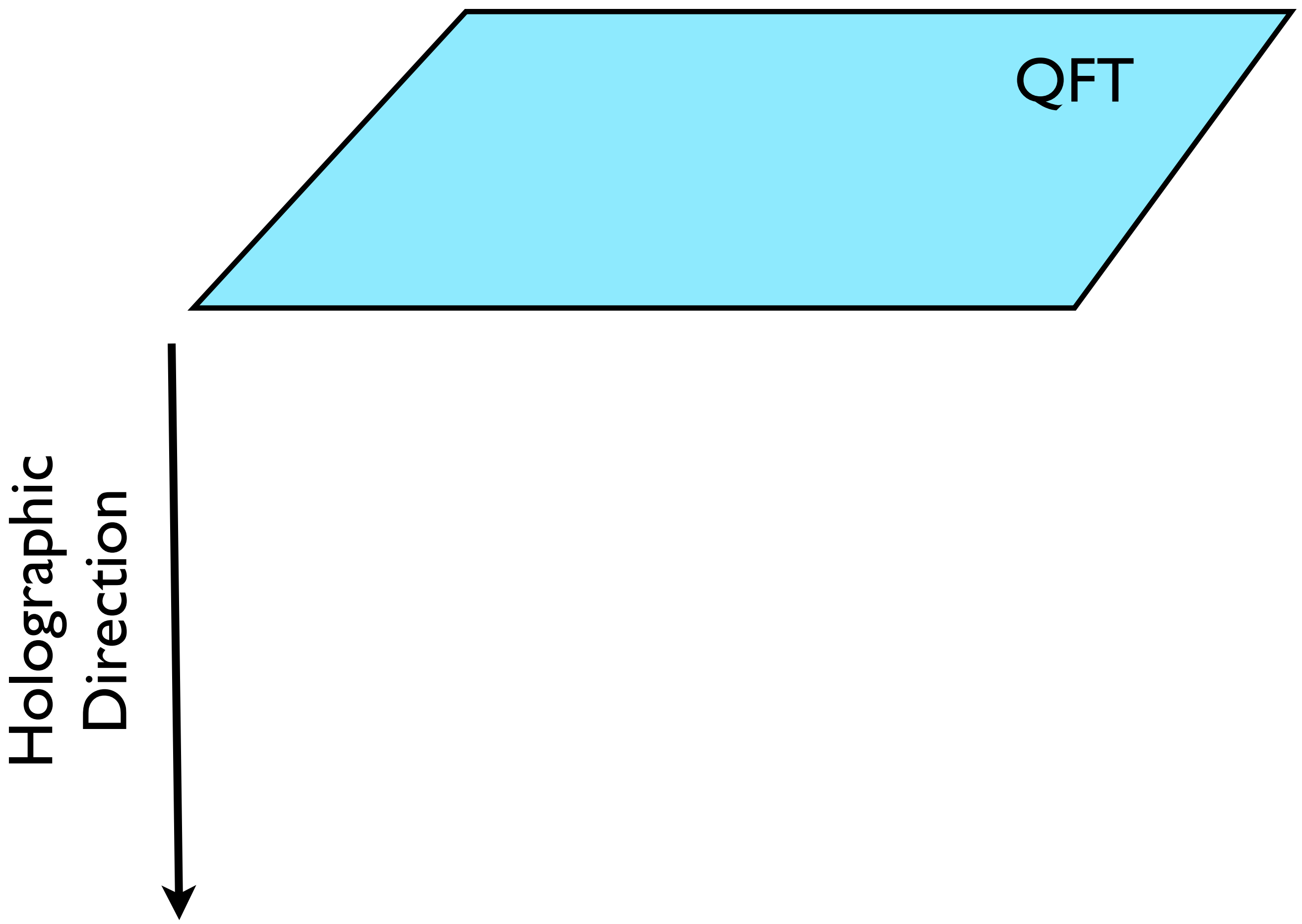

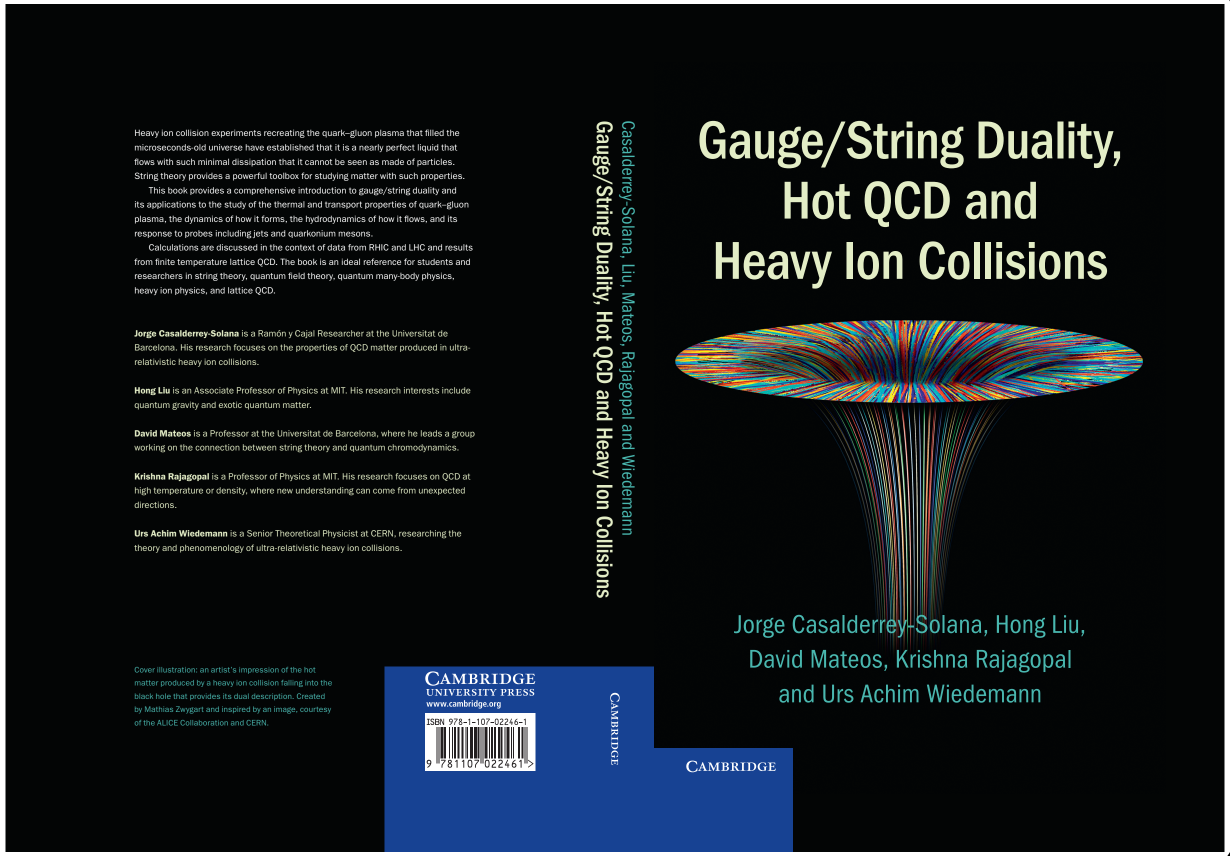

J. M. Maldacena, *Adv. Theor. Math. Phys* 2, 231 *(1998)*

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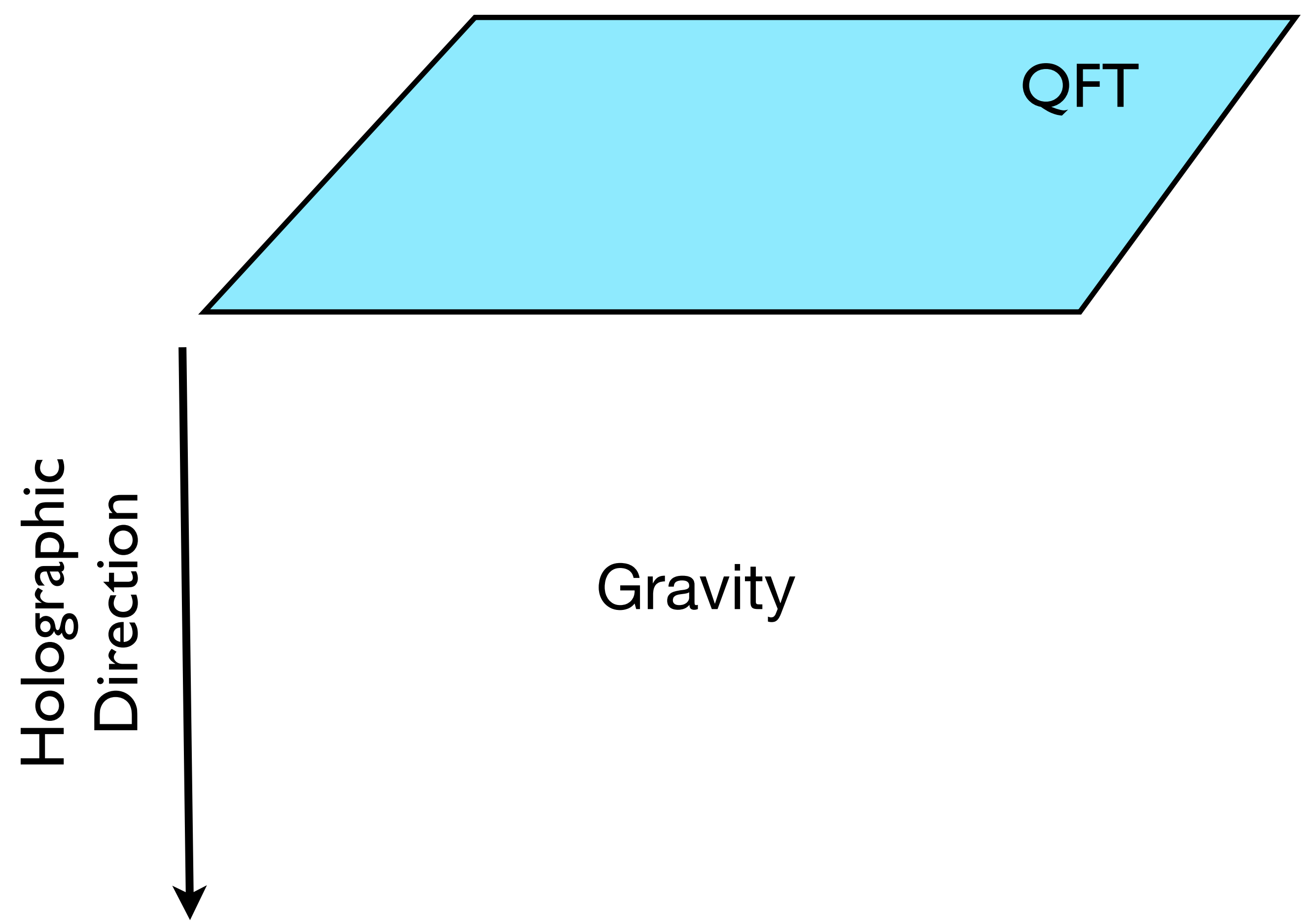

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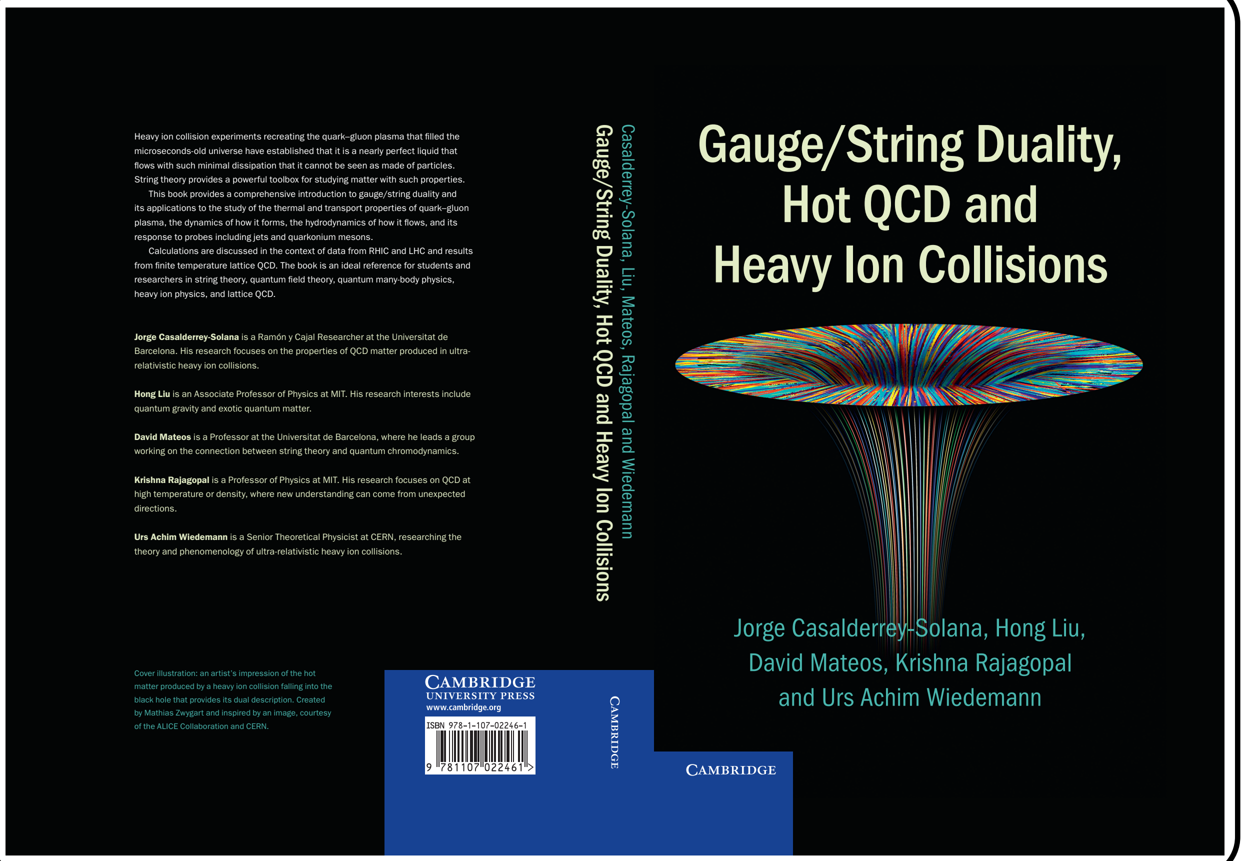

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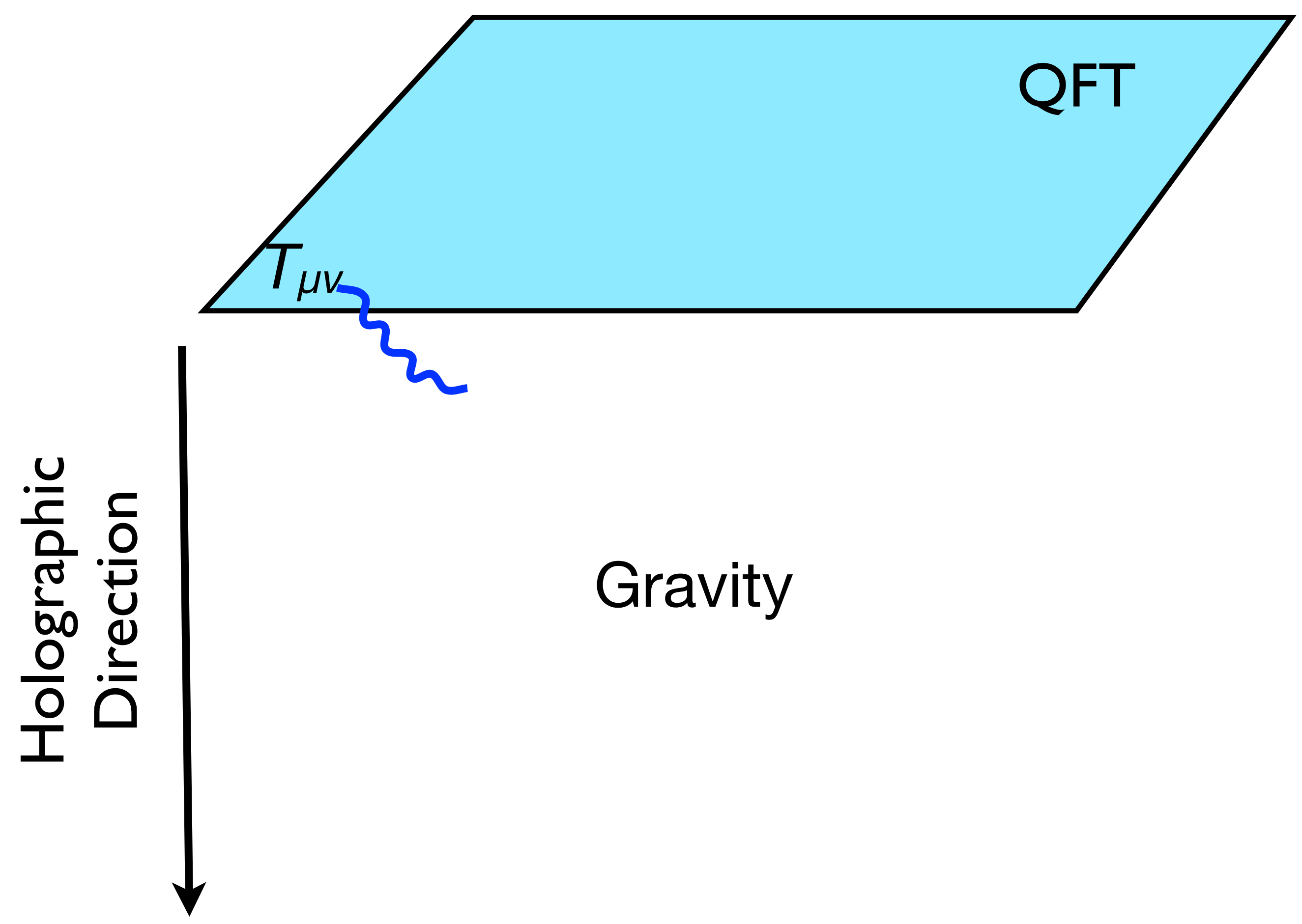

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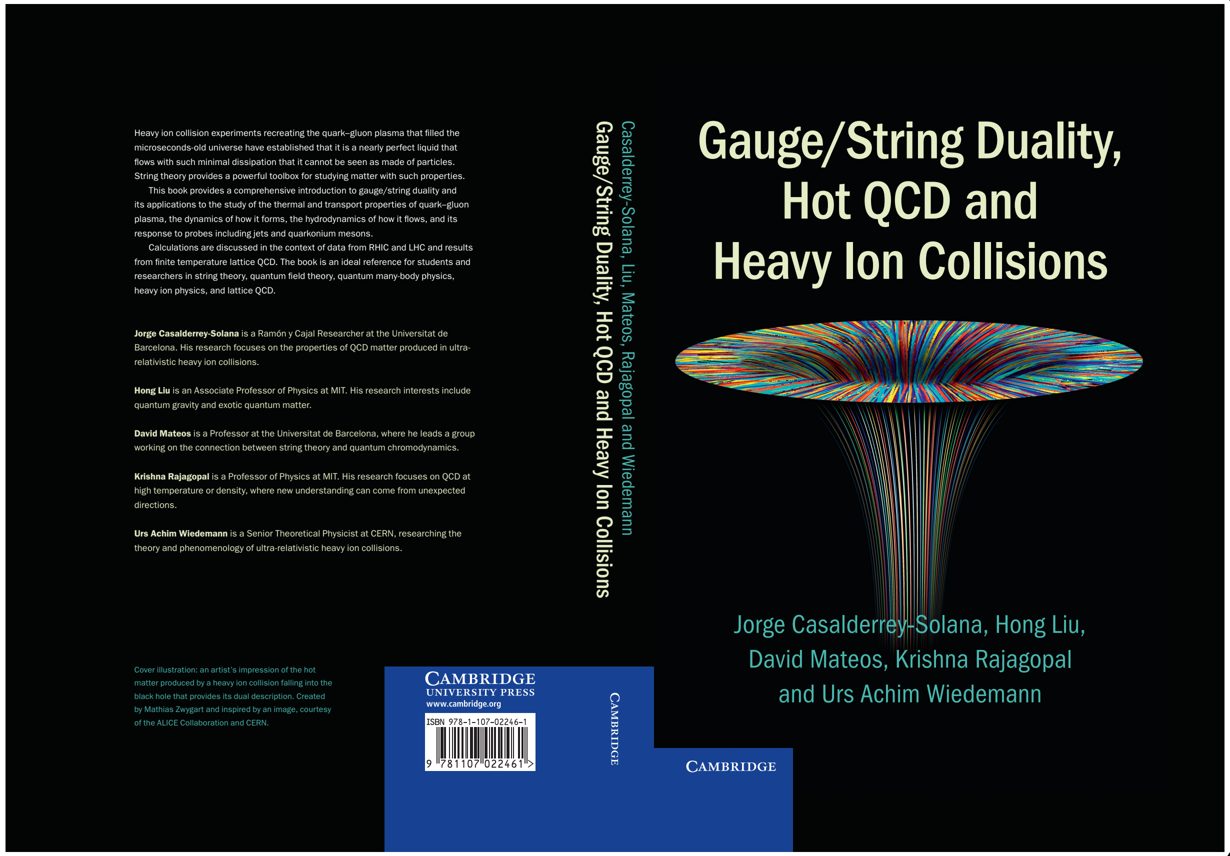

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$$T_{\mu\nu} \leftrightarrow g_{\mu\nu}$$

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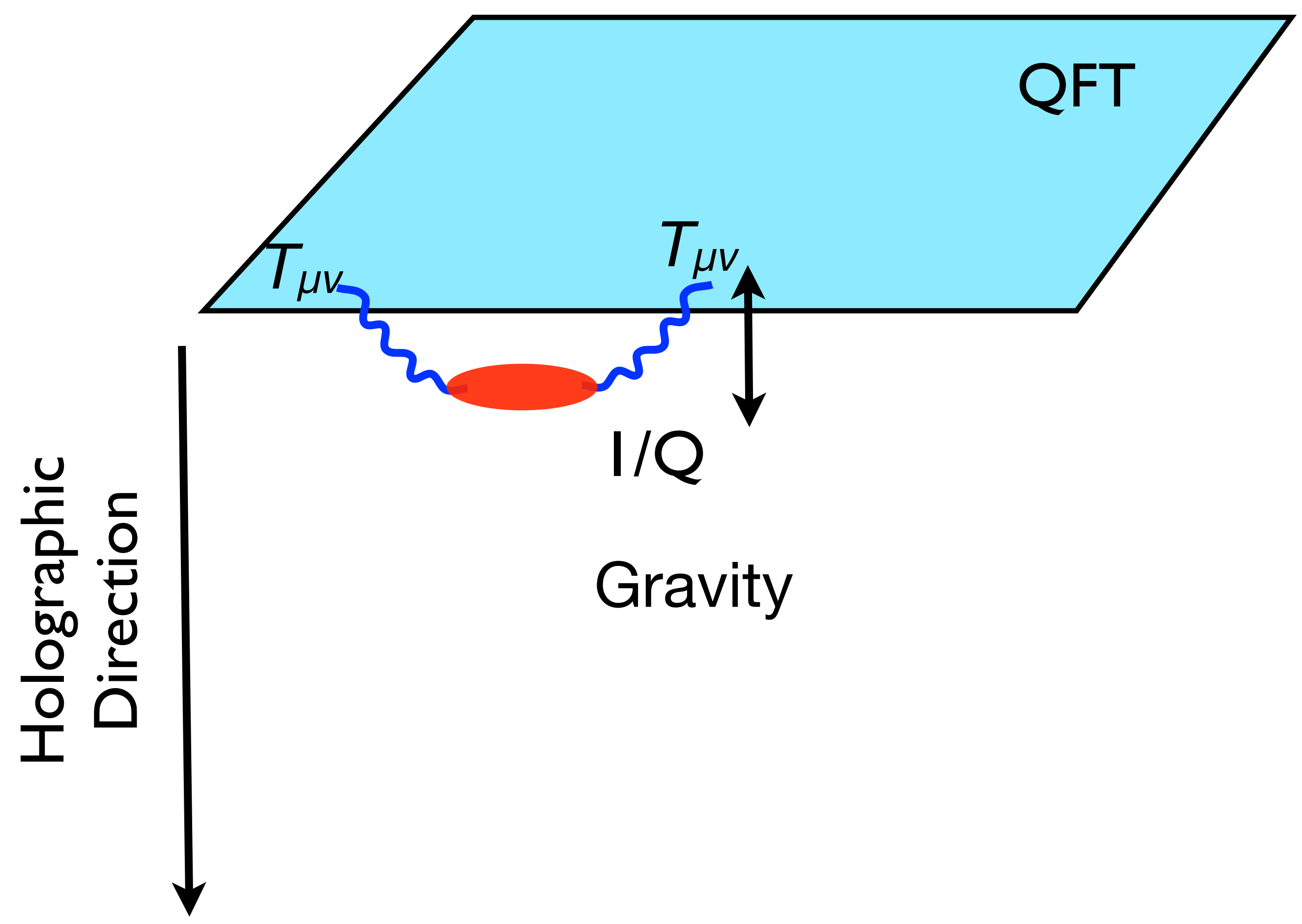

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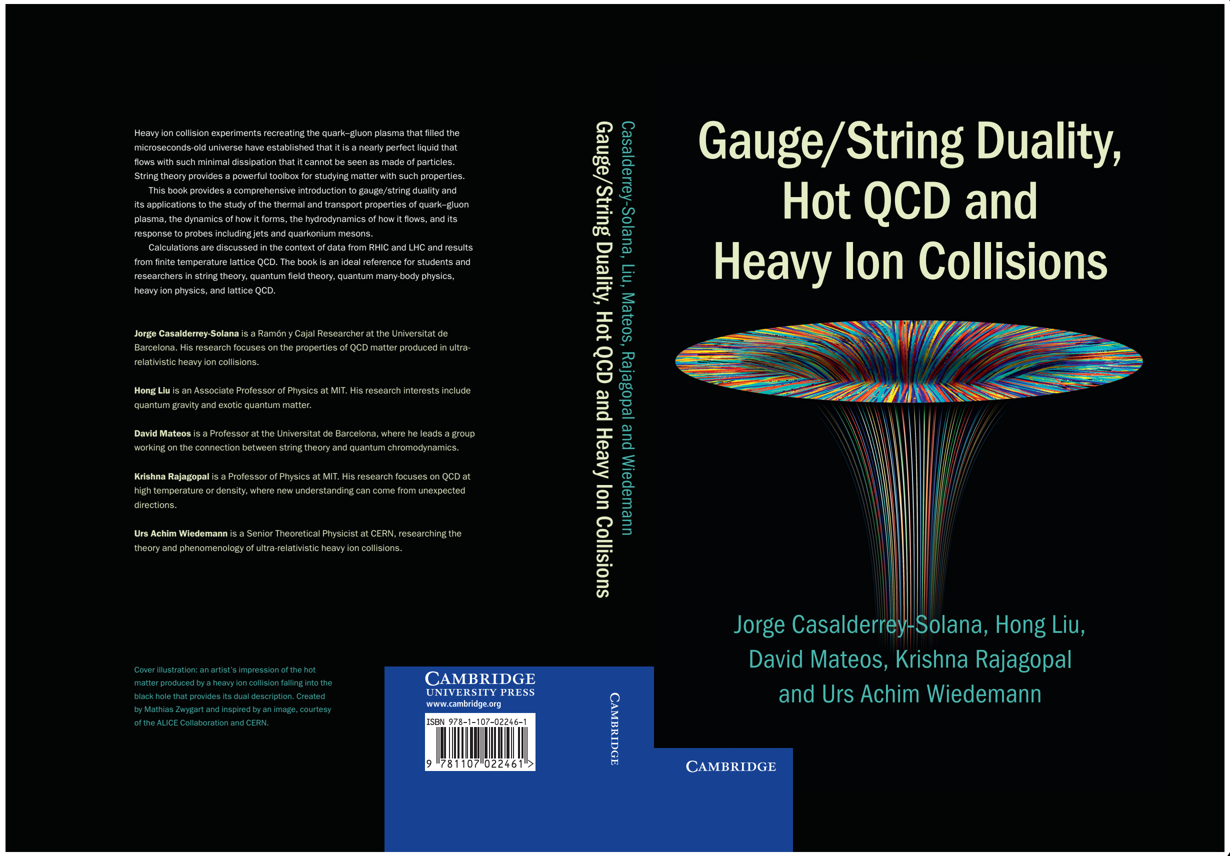

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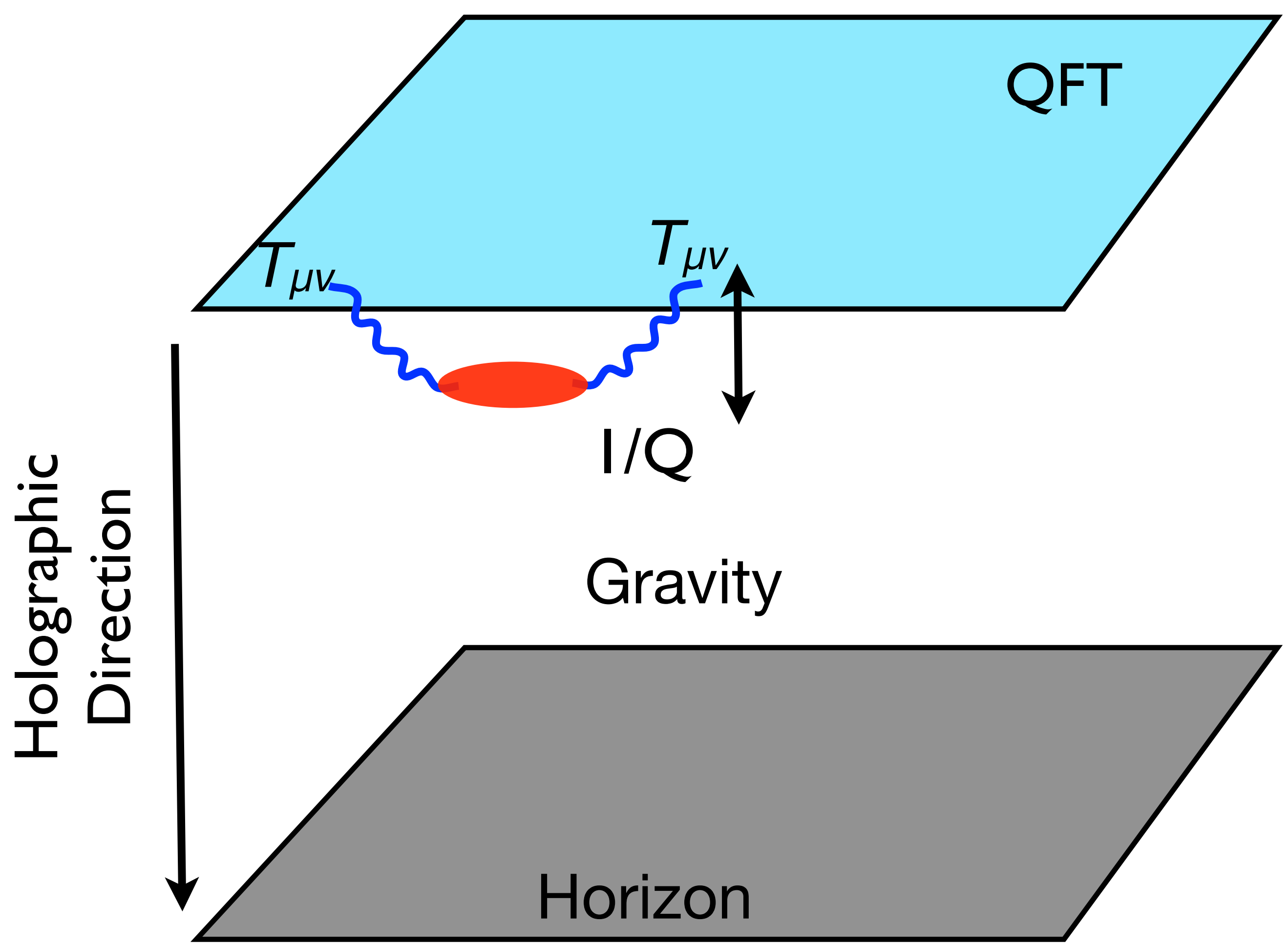

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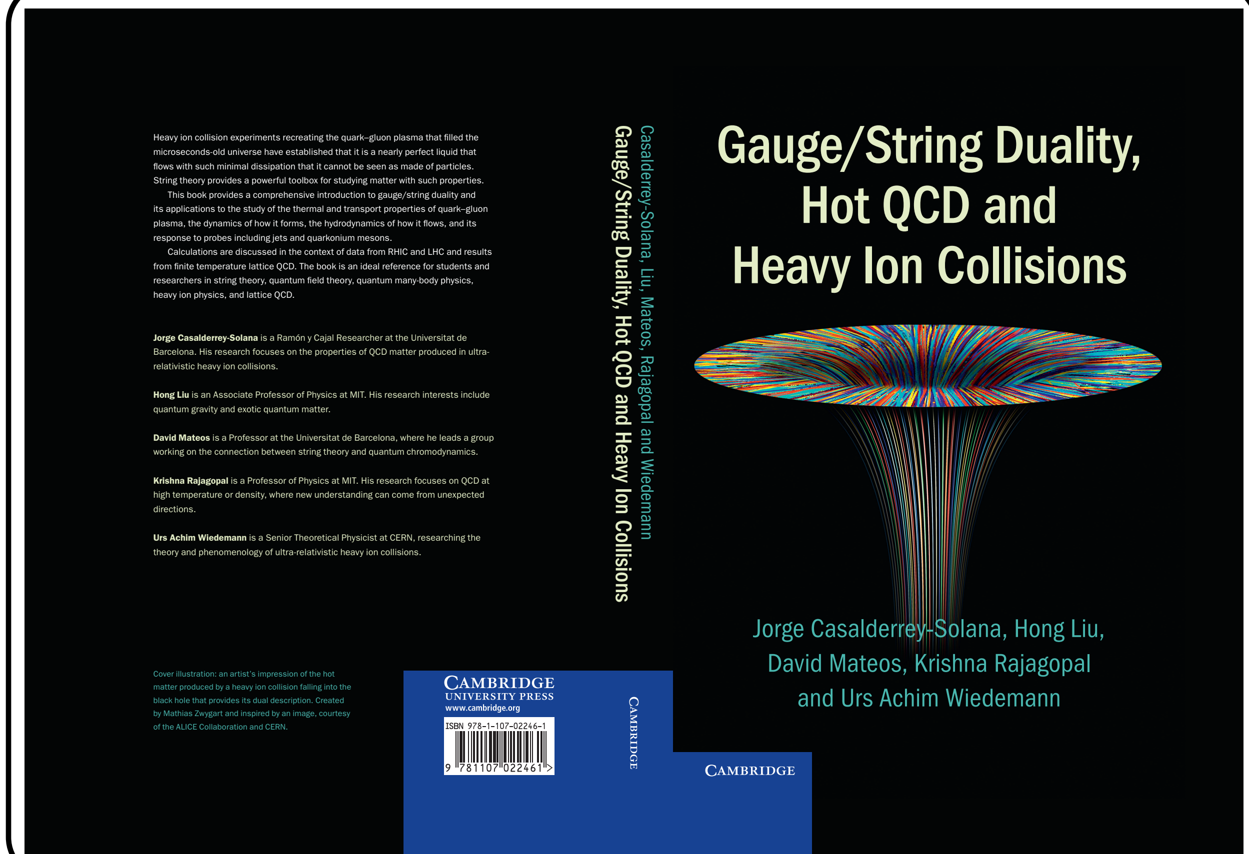

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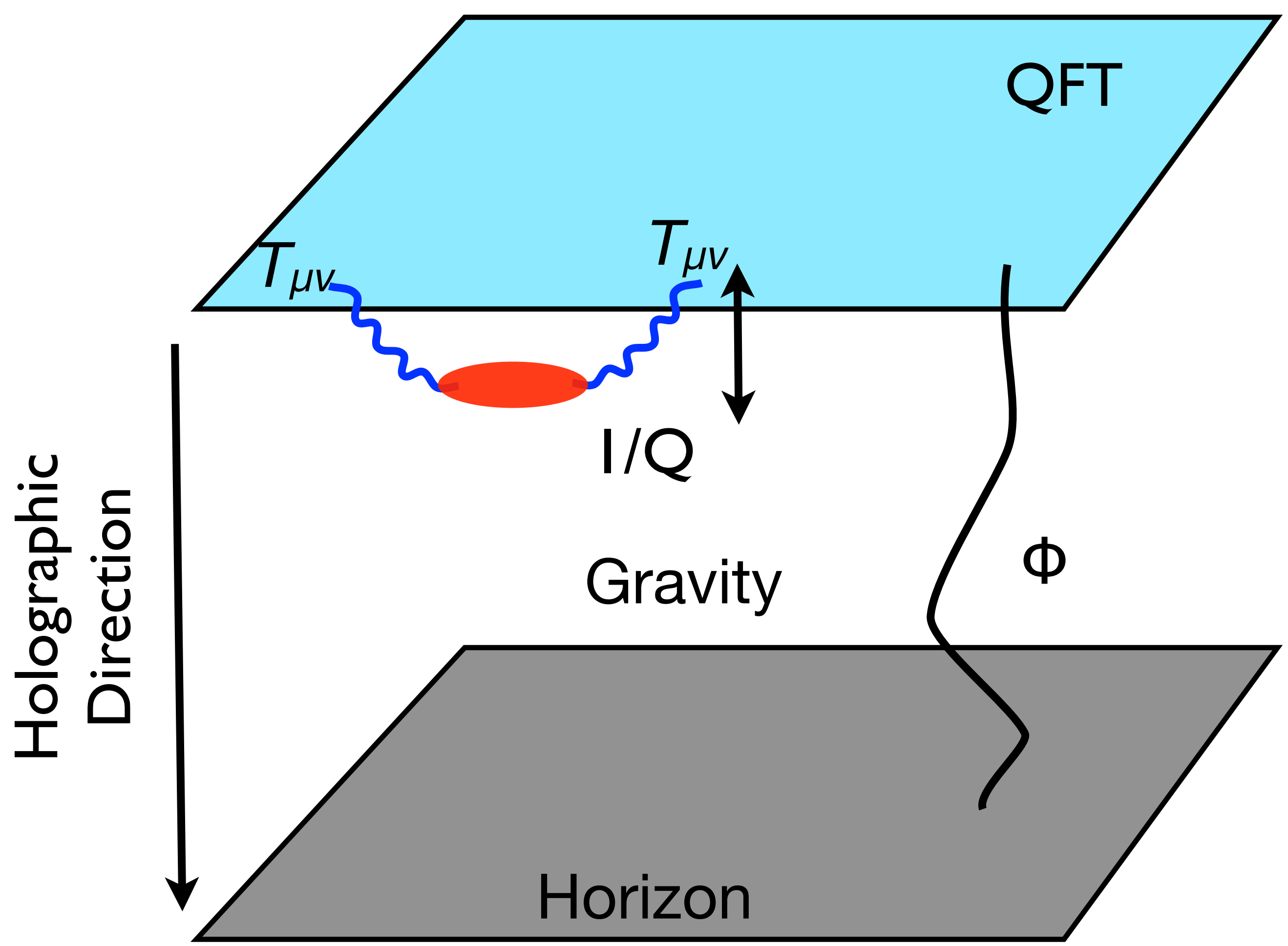

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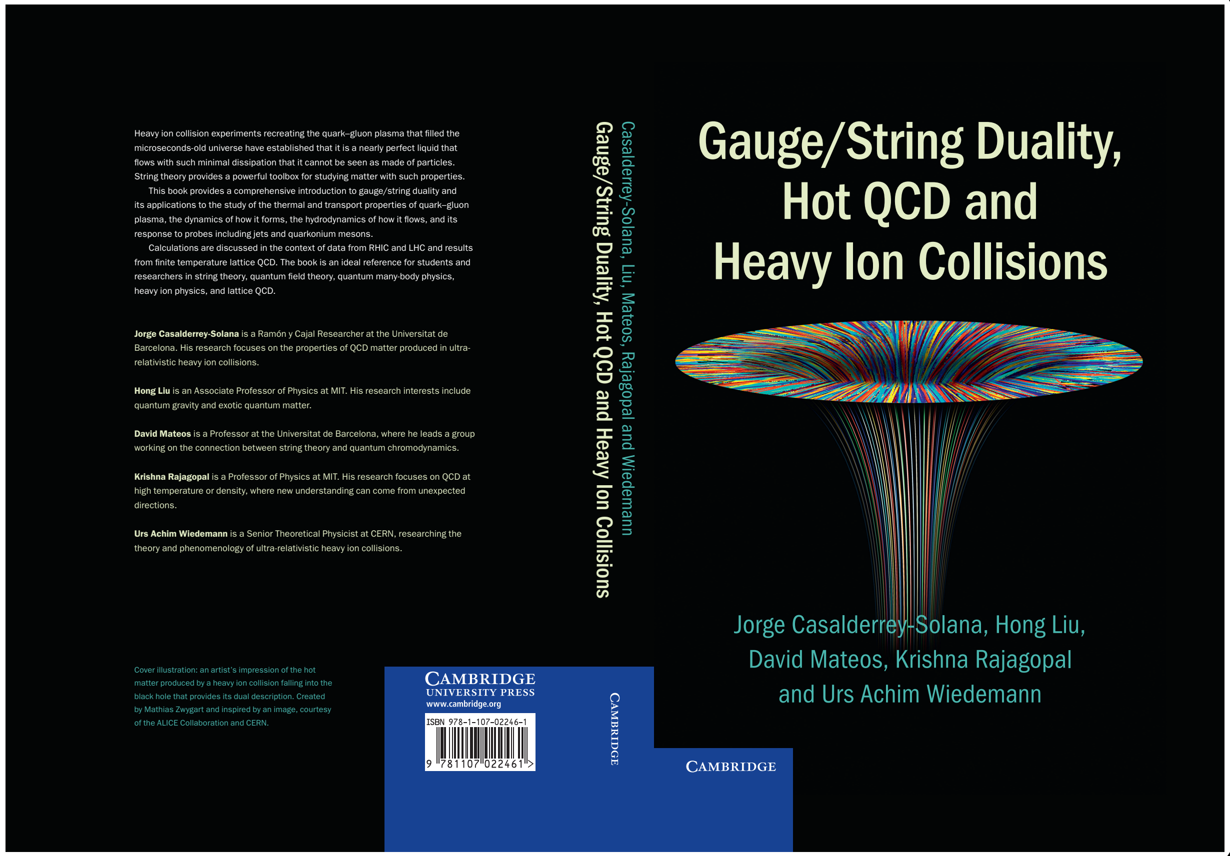


Dictionary

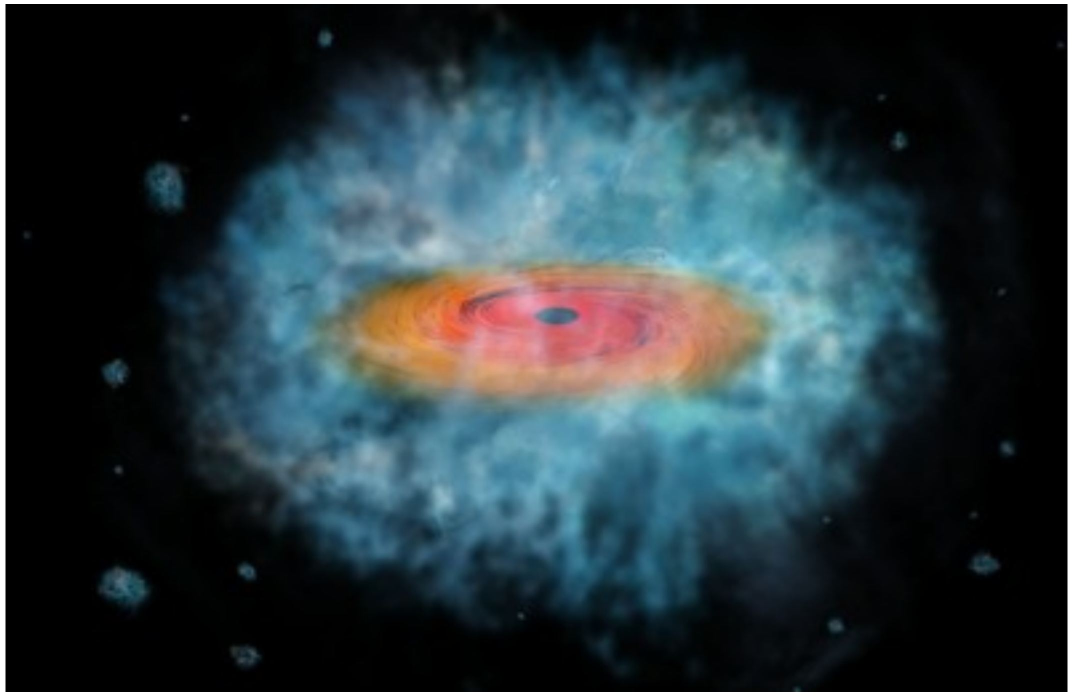
$$T_{\mu\nu} \leftrightarrow g_{\mu\nu}$$

$$T \leftrightarrow \textit{black hole}$$

operator ↔ classical field

Entropy and Black Branes

- Black holes (or branes) have entropy



- Hawking Bekenstein entropy

$$S_{HB} = \frac{1}{4}\frac{c^3 k}{G\hbar}A$$

- From the duality
  - *A*: property of the metric
  - *G*: related to N_c of dual theory

- Putting numbers

$$s_{\lambda=\infty} = \frac{\pi^2}{2}N_c^2 T^3 \qquad s_{\lambda=0} = \left(8 + 8\times\frac{7}{8}\right)\frac{2\pi^2}{45}(N_c^2-1)T^3 \simeq \frac{2\pi^2}{3}N_c^2 T^3$$

- Thermodynamics are very poor estimator of coupling strength!

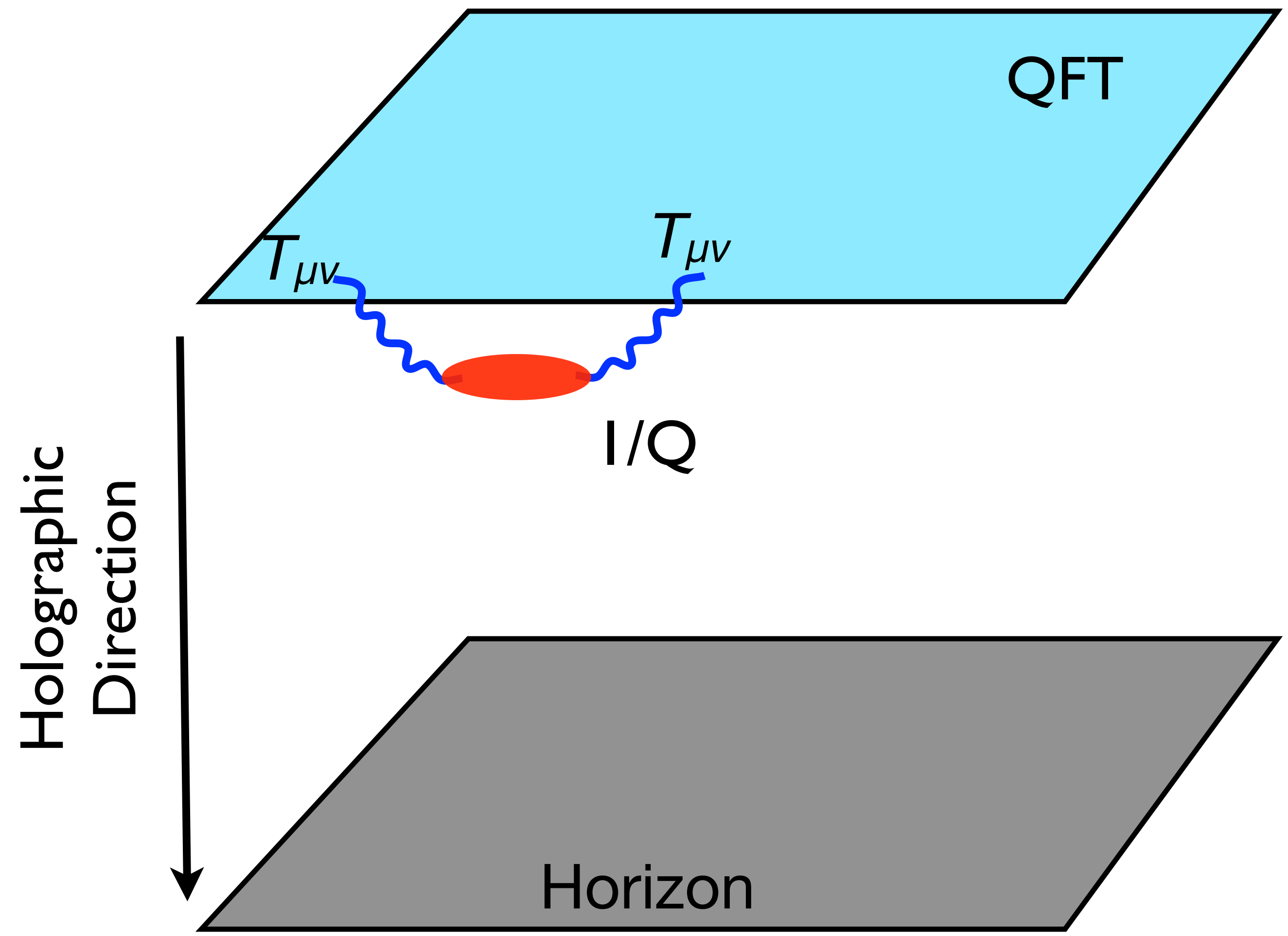
$$\frac{s_{\lambda=\infty}}{s_{\lambda=0}} = \frac{P_{\lambda=\infty}}{P_{\lambda=0}} = \frac{\varepsilon_{\lambda=\infty}}{\varepsilon_{\lambda=0}} = \frac{3}{4}$$

Gubser et al98

η/s

- Shear viscosity computed via Kubo formula

$$\eta = -\lim_{\omega\to 0}\lim_{k\to 0}\frac{1}{\omega}\mathrm{Im}\int d^4x\, e^{iwt-kz}\, i\theta(t)\,\langle[T^{xy}(x),T^{xy}(0)]\rangle$$



- Im part ⇔ absorption of gravitons

$$\eta \propto \sigma_{\mathrm{absoption}} = A$$

(universal in ω→0)

$$s \propto A$$ (universal)

- Putting everything together

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

- A universal value for all strongly coupled theories with a gravity dual.

Kovtun, Son, Starinets 05

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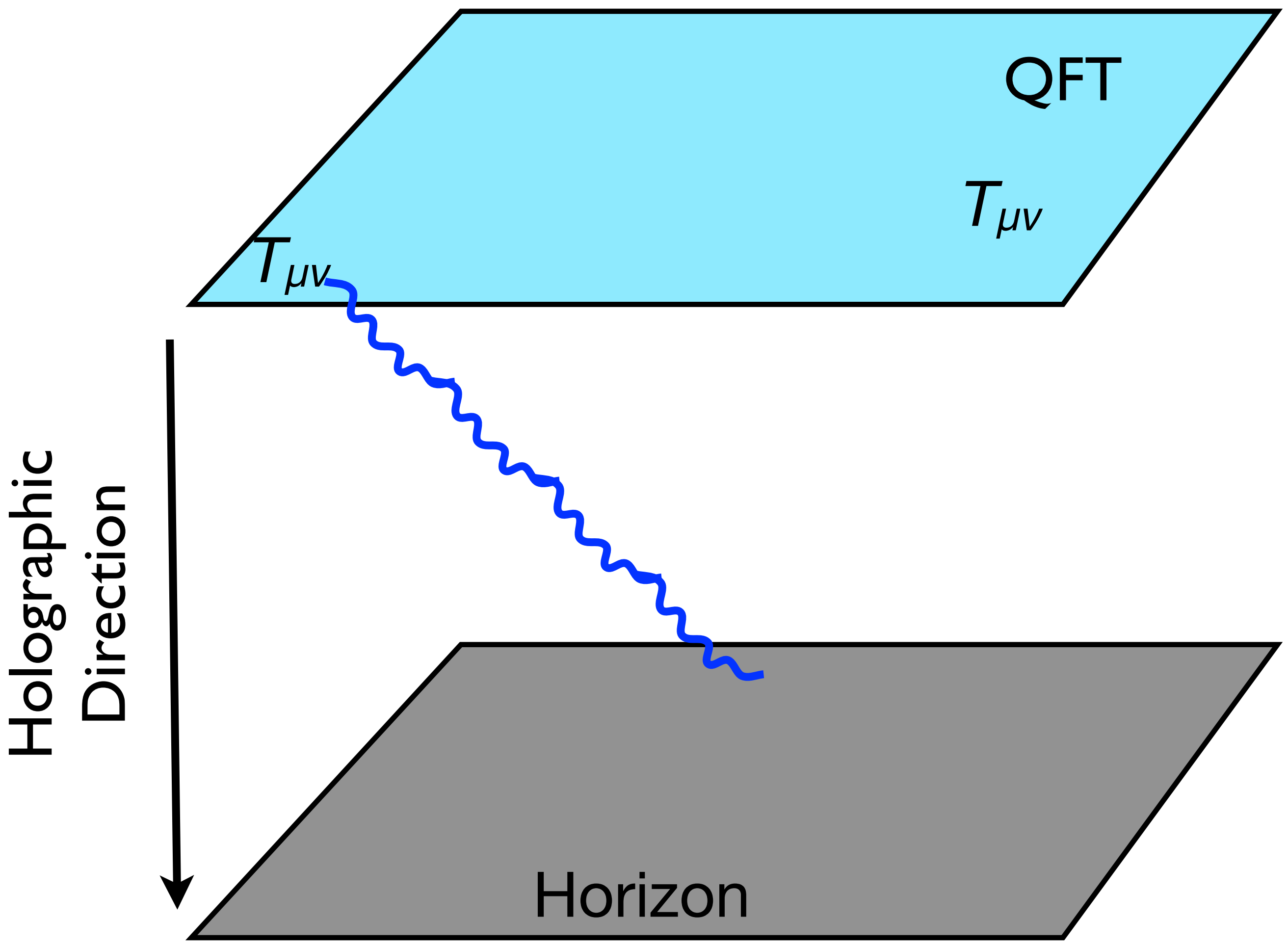

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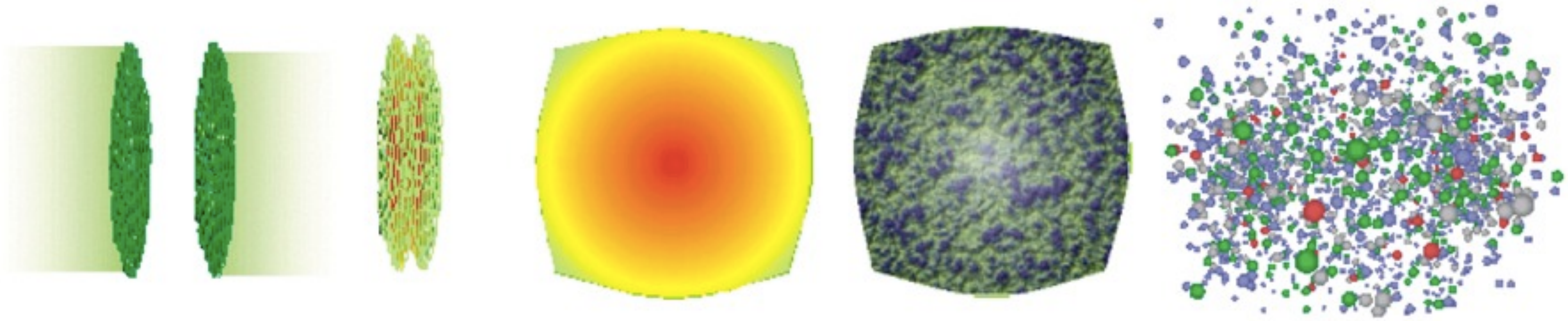
Kovtun, Son, Starinets 05

Warnings

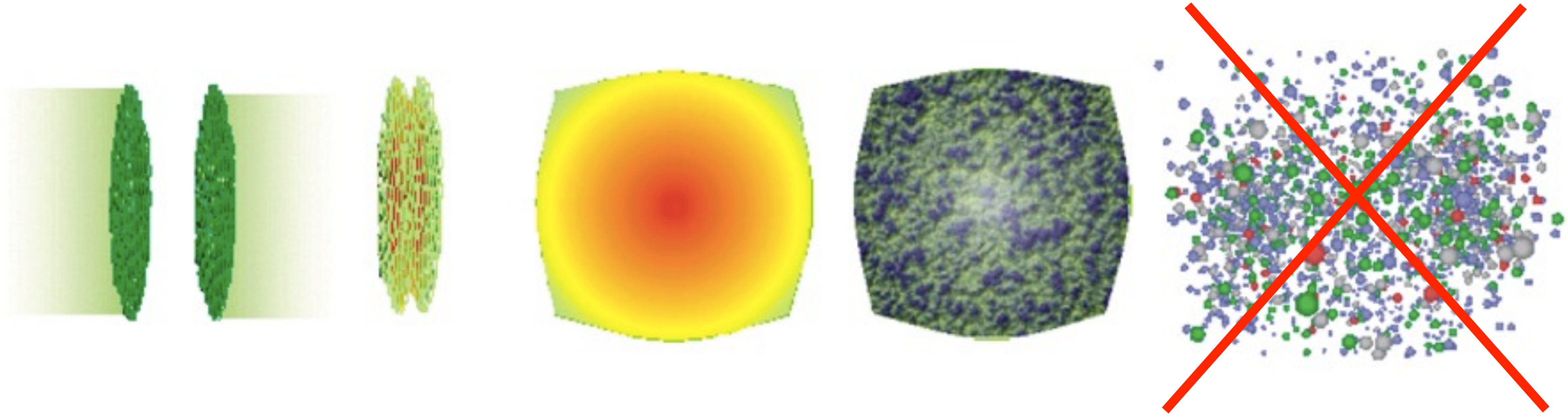
- The theories with known gravity duals are not QCD
  - They have different symmetries, different matter content...
- Some properties are common to all those theories
  - Independent of different symmetries, different matter content...
- One of the few methods to study gauge theory plasmas with no quasiparticles
- It provides answers to complicated dynamical problems
  - They correct misconceptions
  - They give qualitative understanding
  - But one should be careful with quantitative statments

From Initial to Final State in Holography



- Can we describes all these stages in a single framework?

From Initial to Final State in Holography



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  - Holography says: yes! (up to the last one)

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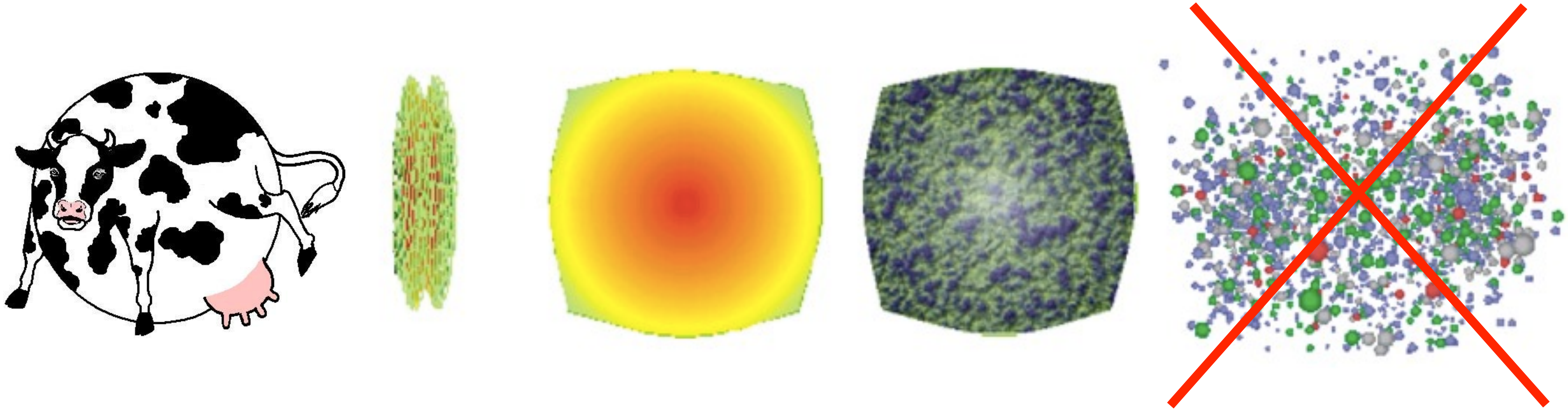

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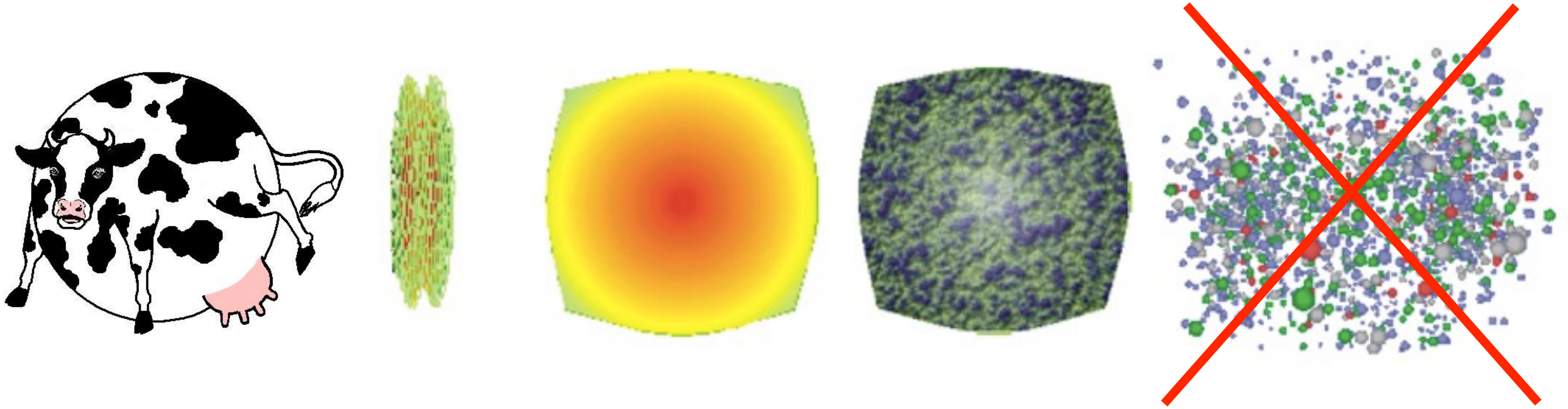
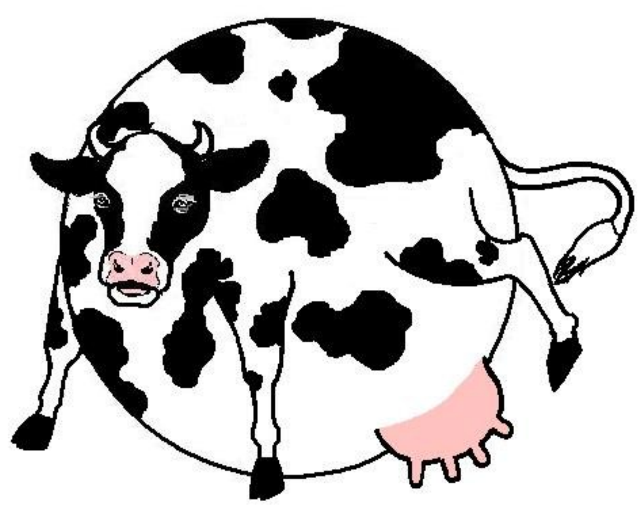


- Can we describes all these stages in a single framework?
  - Holography says: yes! (up to the last one)
  - As long as we are happy with an oversimplified "nucleus"

  - As long as we are happy with other strongly coupled theory



Einstein Equation

- Numerically solve in 5D

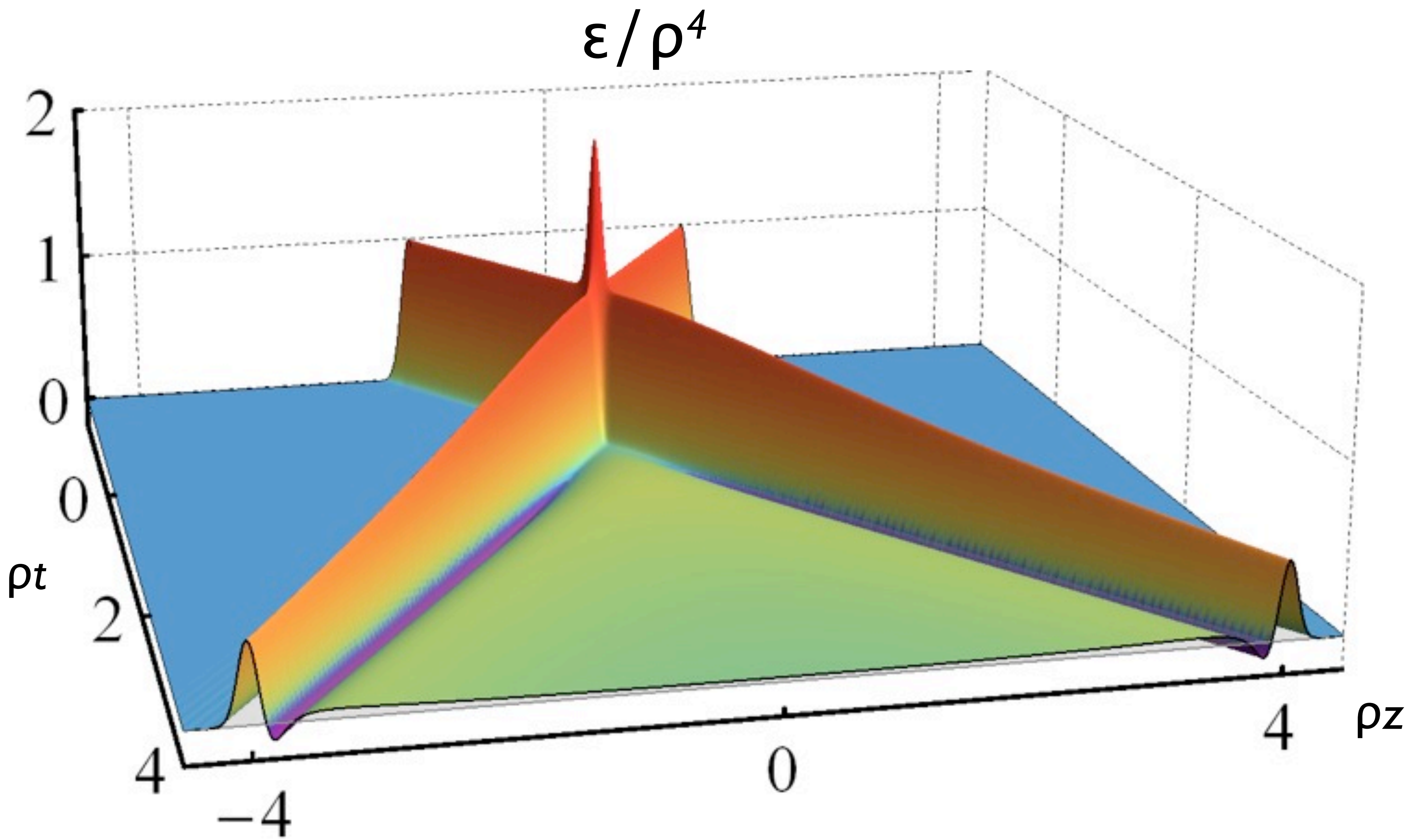
$$R_{MN} - \frac{1}{2} R\, G_{MN} + \Lambda\, G_{MN} = 0$$

- Specify initial data: shock wave solutions

- Read off the dual stress tensor using the dictionary:

$$ds^2 = \frac{1}{z^2}\left\{dz^2 + \left(g_{\mu\nu} + z^4 T_{\mu\nu} + \ldots.\right) dx^\mu dx^\nu\right\}$$

Shock Wave Collisions

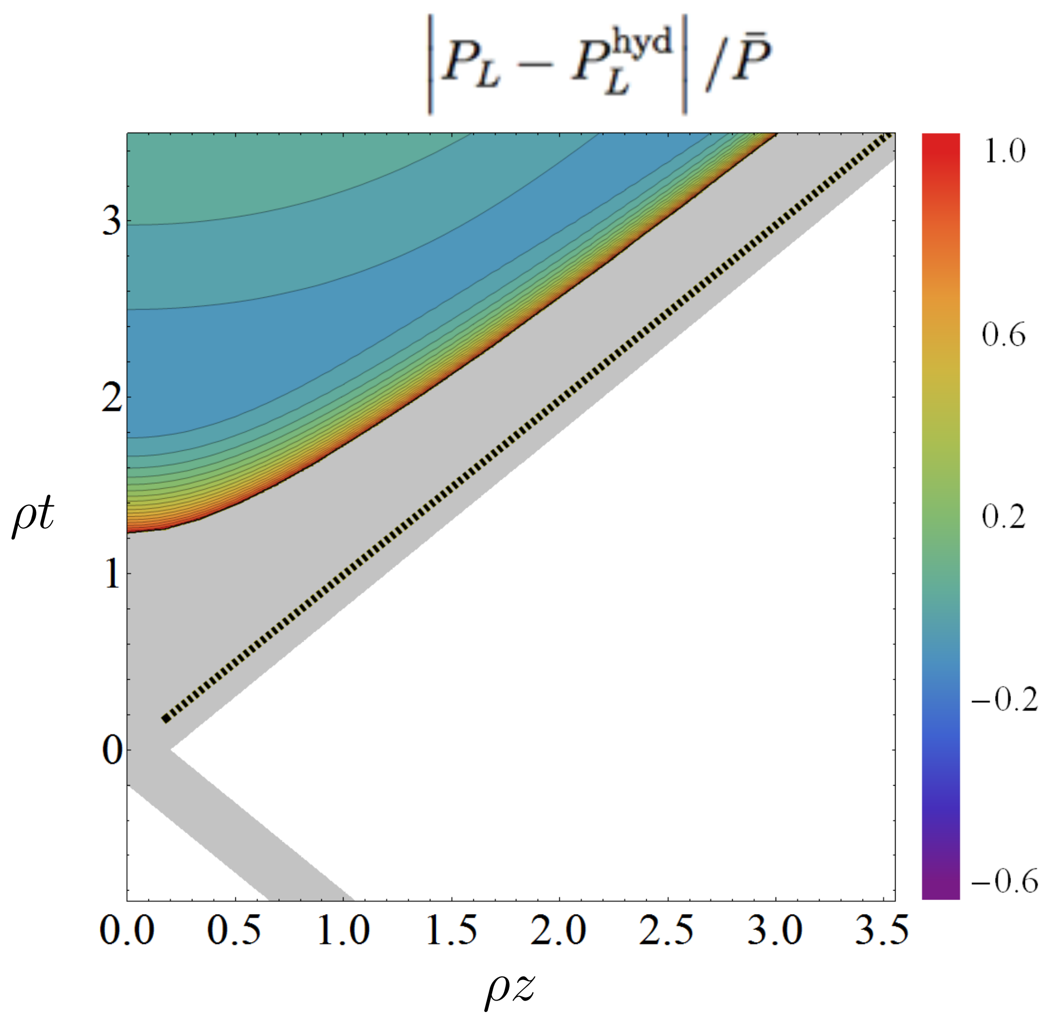


JCS, Heller, Mateos, van der Schee, 2013

Chesler & Yaffe 2011

How well does Hydro Work?

- Compare full simulations to hydro predictions



- Define an energy density and velocity

$$u^\mu T^\nu_\mu \equiv \varepsilon_{\rm local} u^\nu$$

- Compute viscous stress tensor

$$T^{\mu\nu}_{hydro} = T^{\mu\nu}_{ideal} + \eta \Pi^{\mu\nu} + \zeta \Theta^{\mu\nu}$$

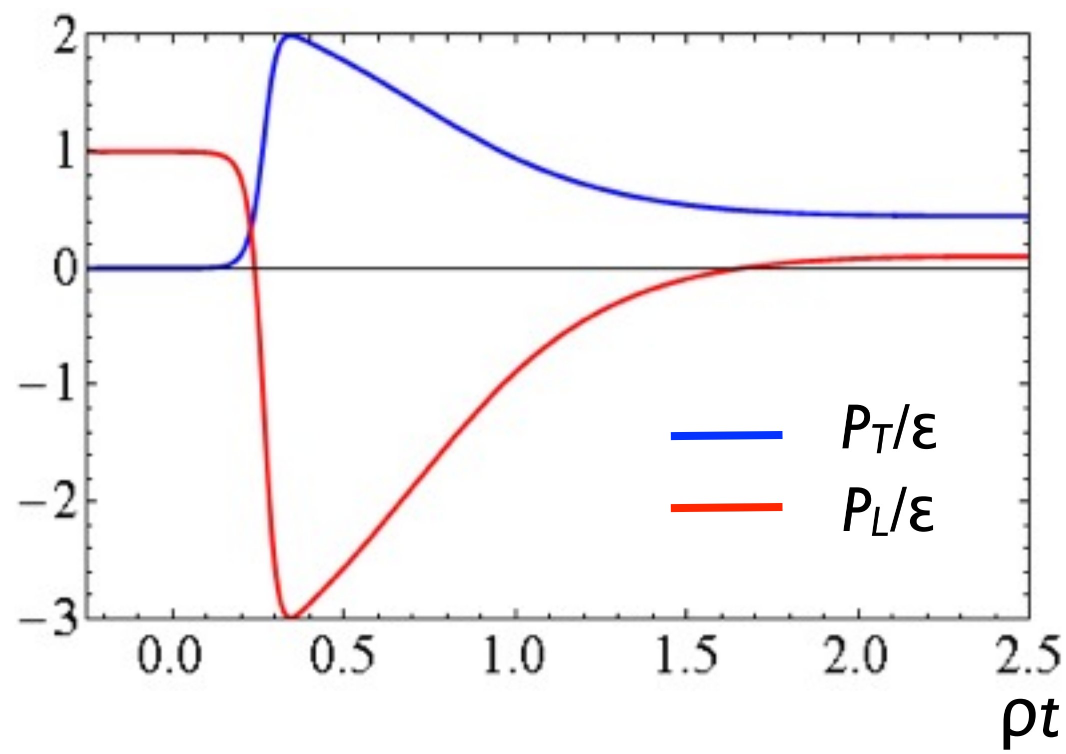
- Compare the hydro and numerics

- Hydro works within 10% from very early times

$$t_{hyd} T_{hyd} \sim 0.5$$

time smaller than micro scale!

Hydro with Large Gradients

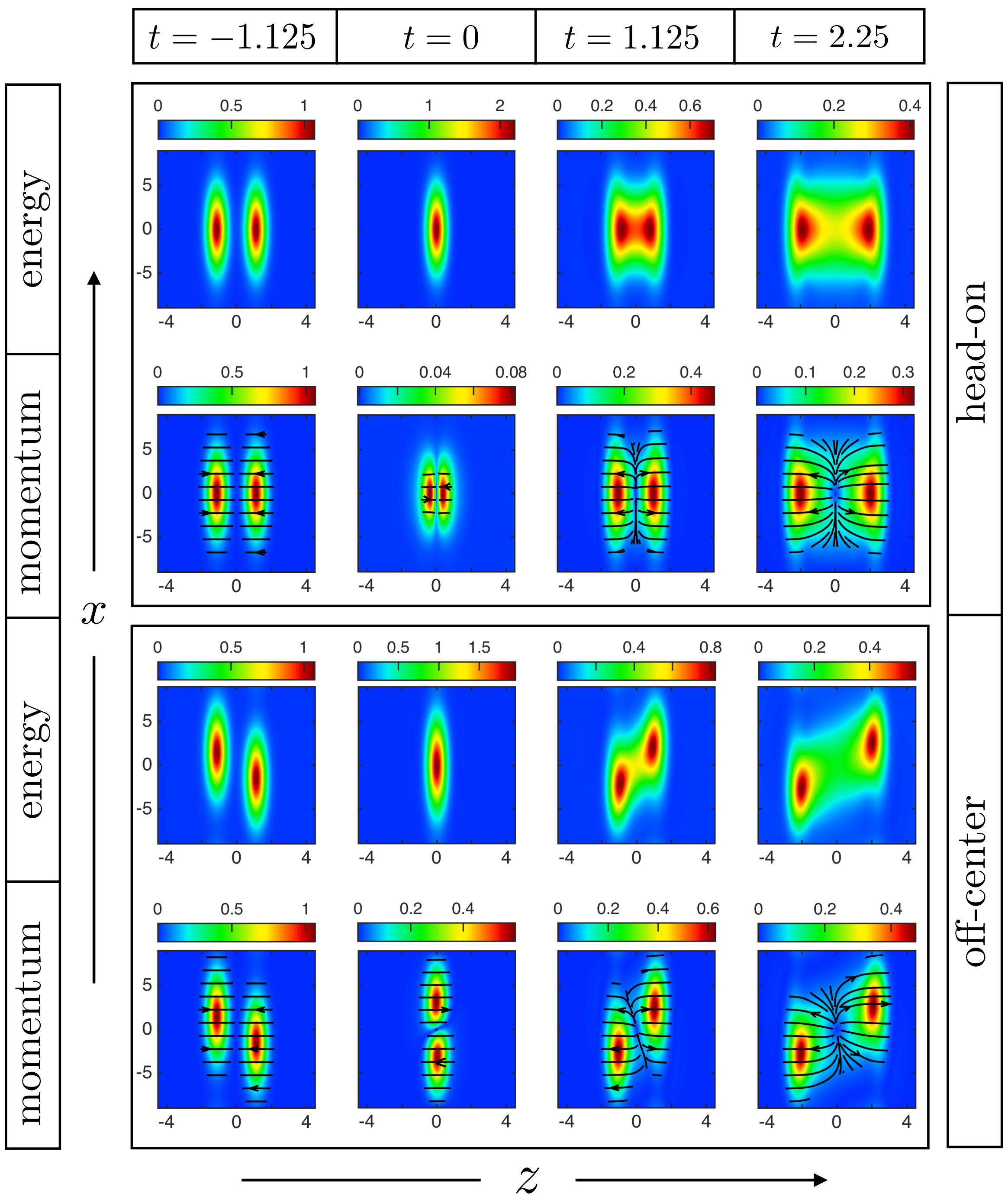


- Hydrodynamics works even where it should not work
  - Good description even when gradient corrections are large!
  - Hydrodynamization without isotropization

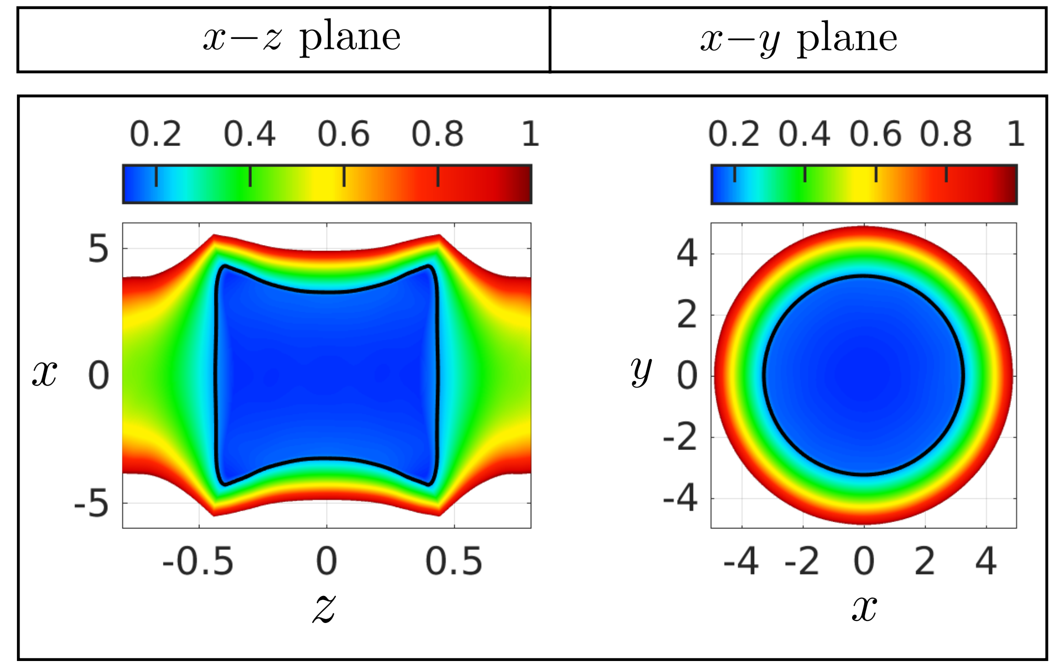
Chesler & Yaffe, Wu & Romatschke, Heller, Janik & Witaszczyk, Heller, Mateos, van der Schee, Trancanelli

Smallest size of liquids?

P. Chesler 2016



Hydro residual



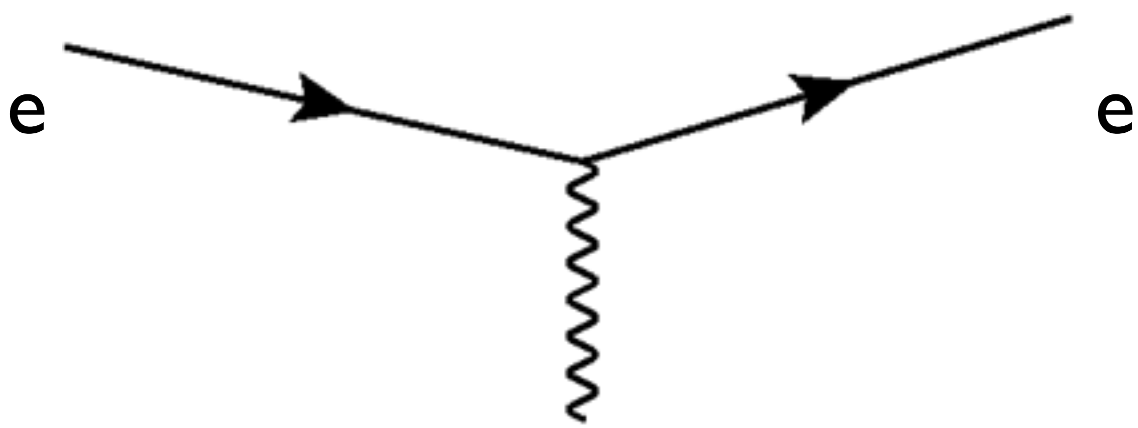
- Hydro works for small systems!

$$R T_{\text{eff}} \sim 1$$

Extra

Microscopic Structure of Plasma

- Can we probe the system?



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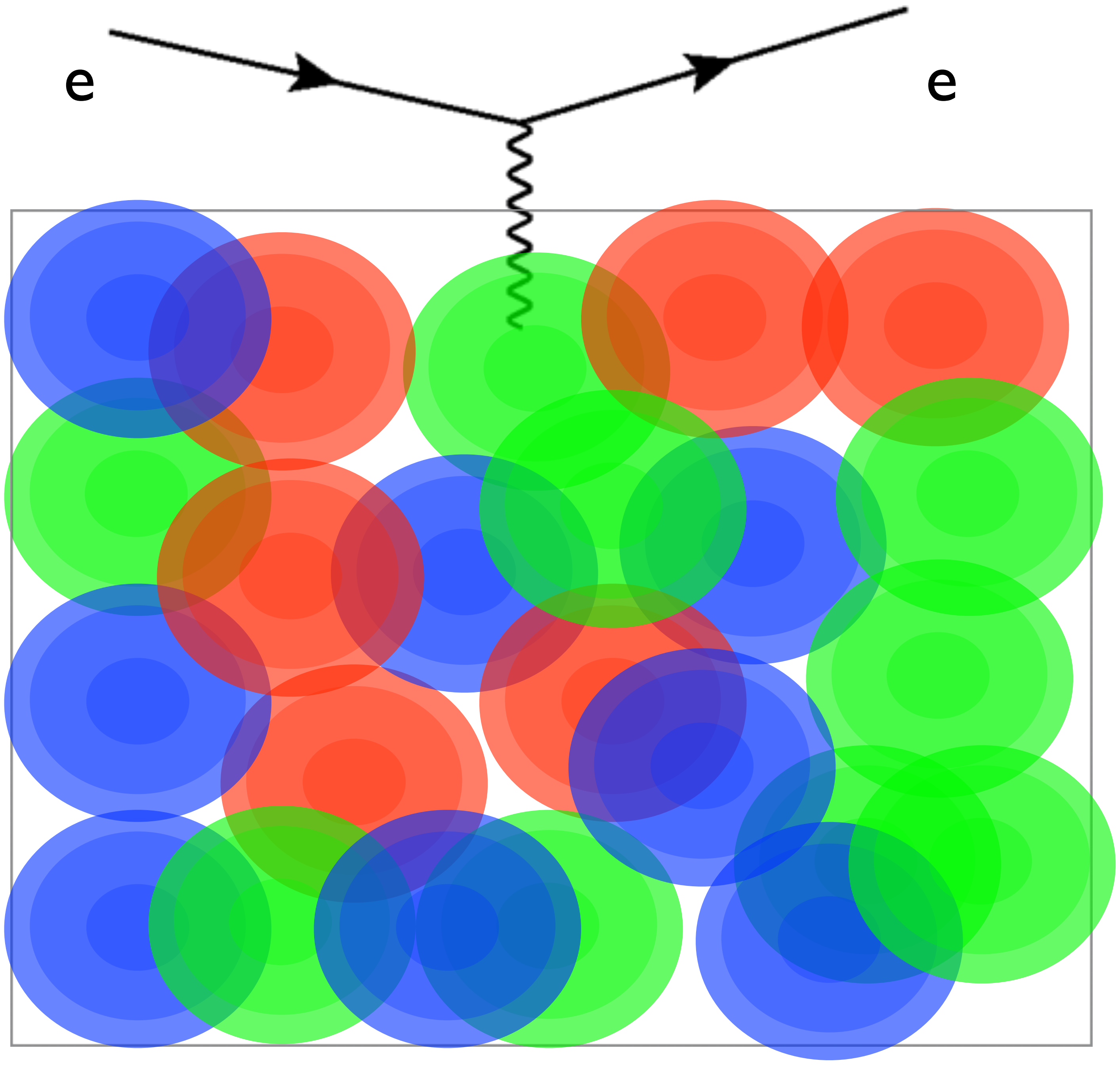
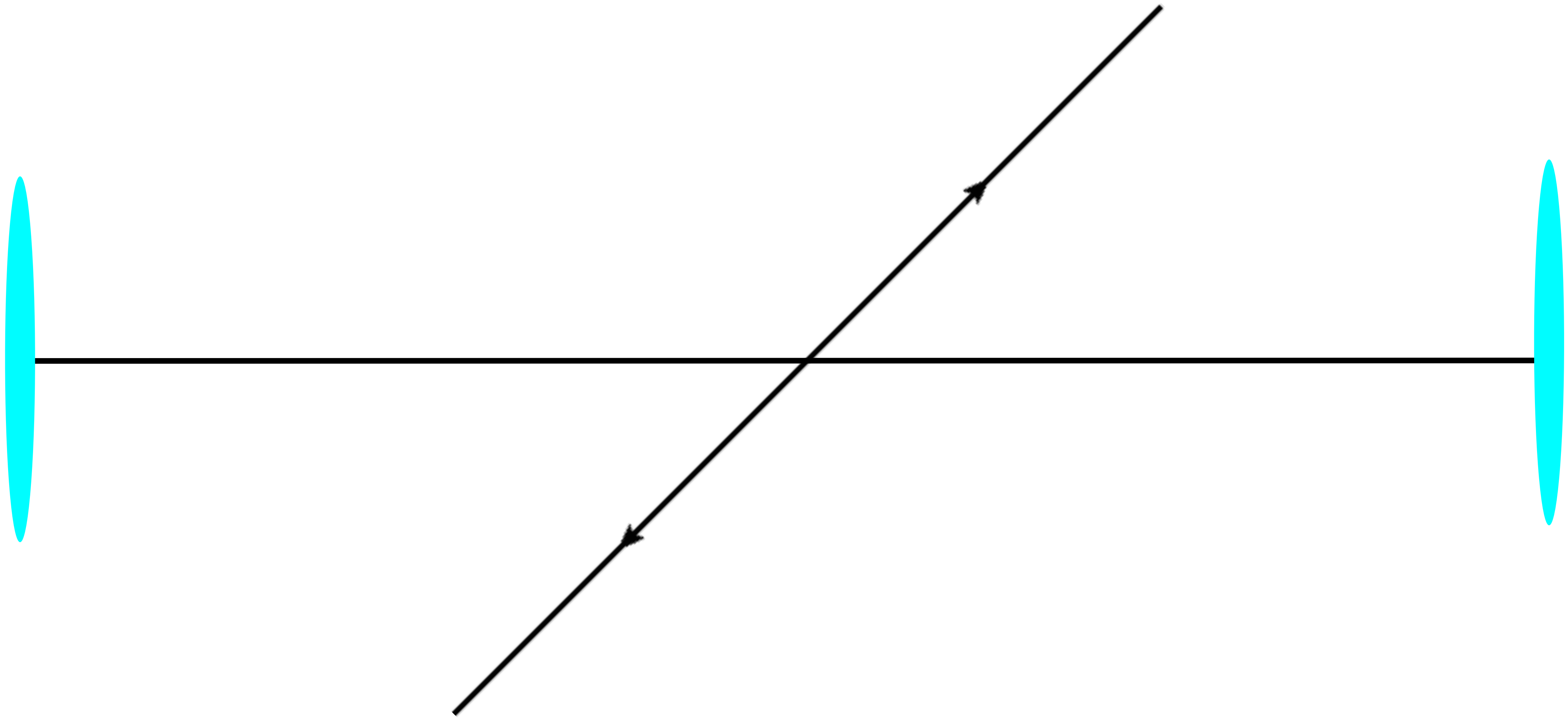


Jets

- Energetic Quarks are produced in pairs



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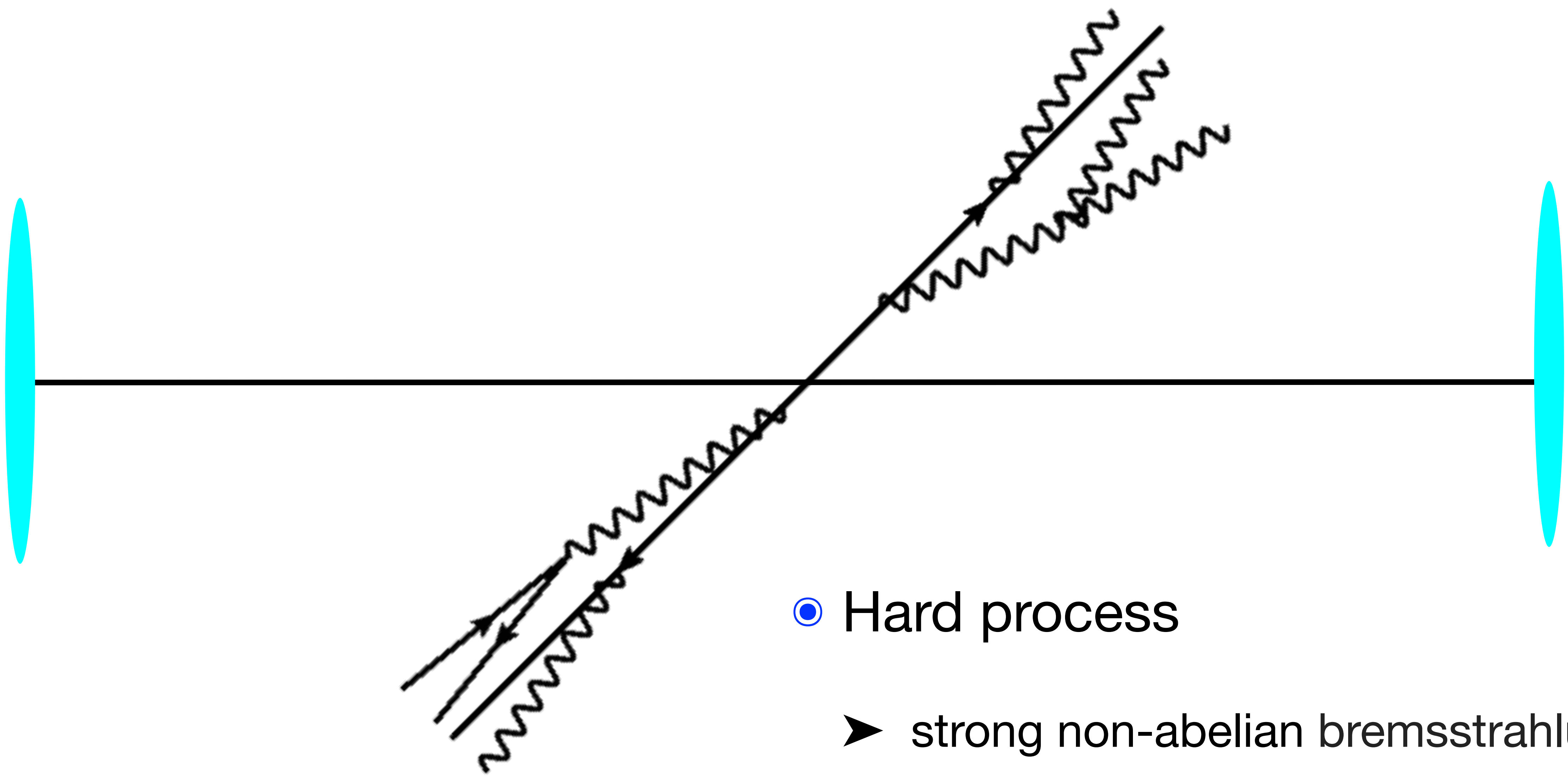

- Hard process
  - ➤ strong non-abelian bremsstrahlung

Jets

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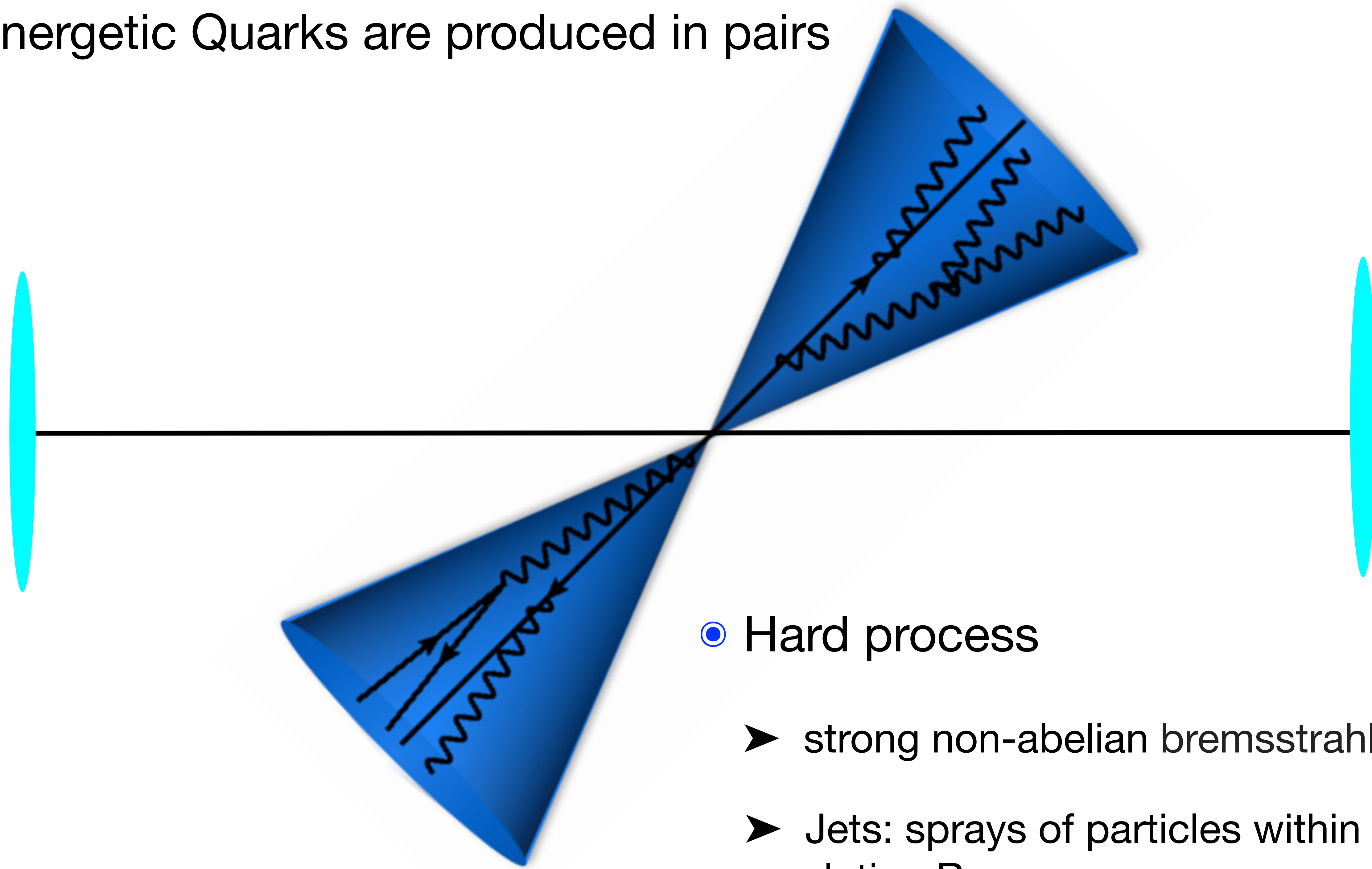
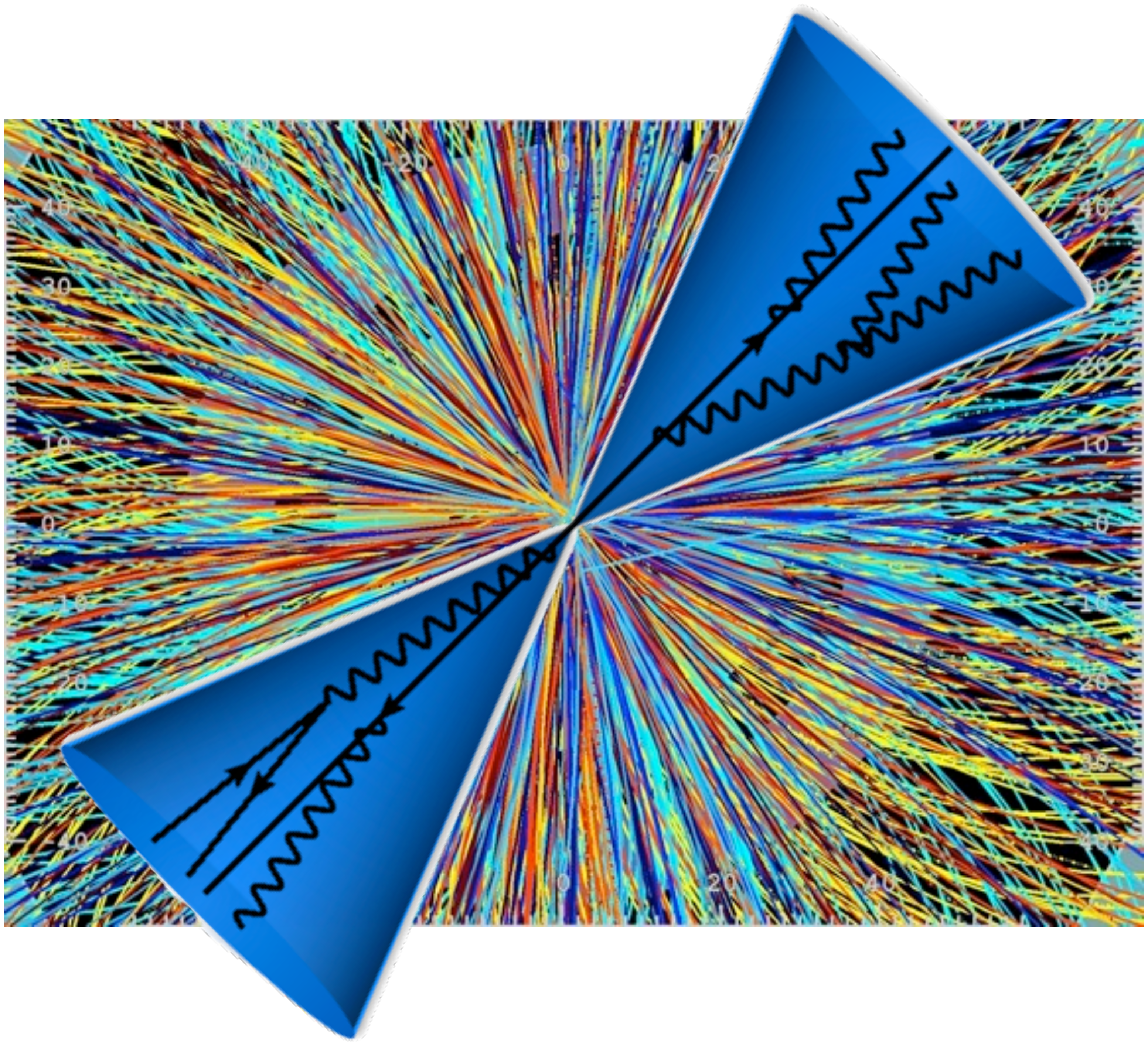
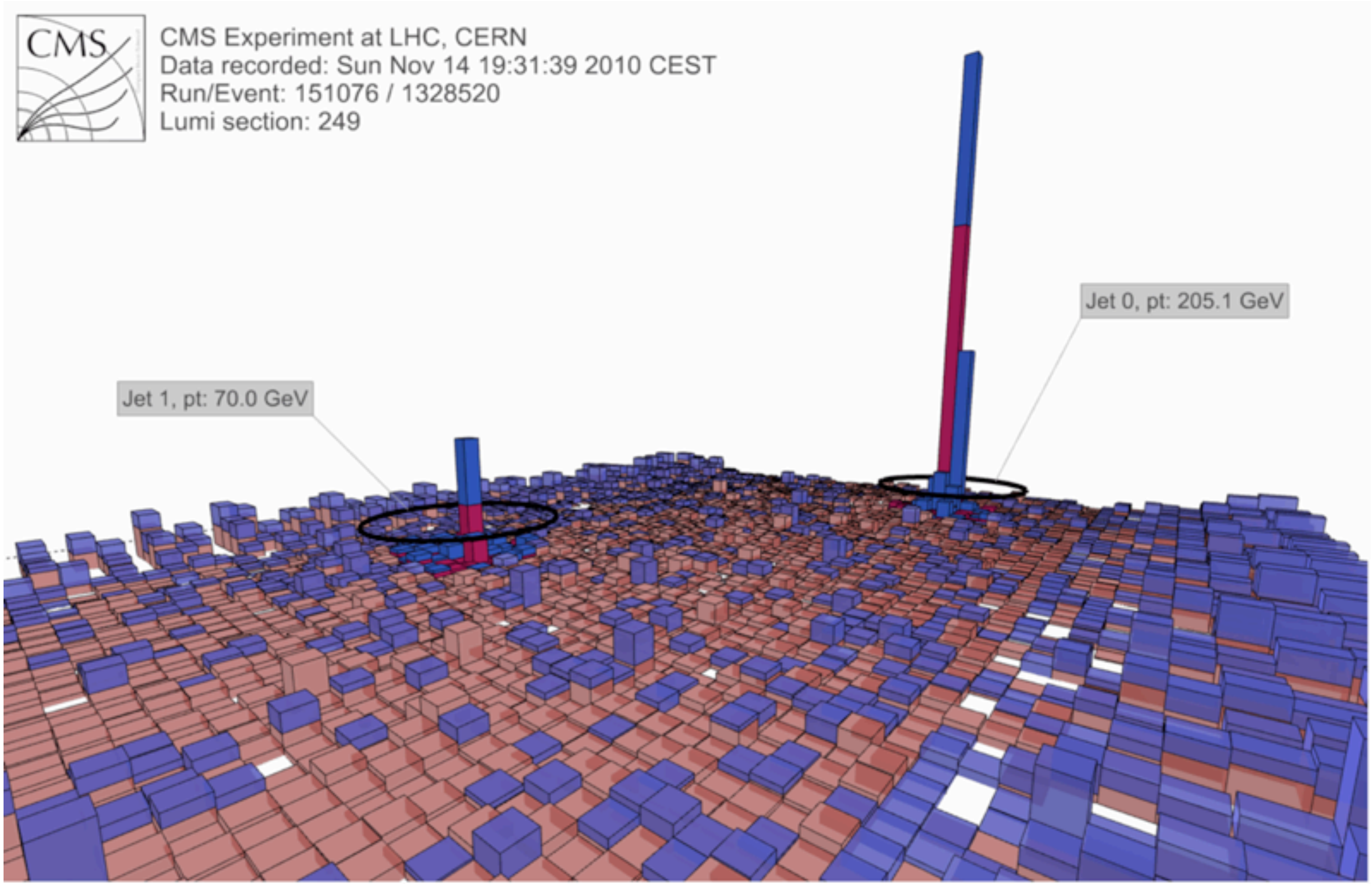


- Hard process
  - ➤ strong non-abelian bremsstrahlung
  - ➤ Jets: sprays of particles within a fixed resolution R

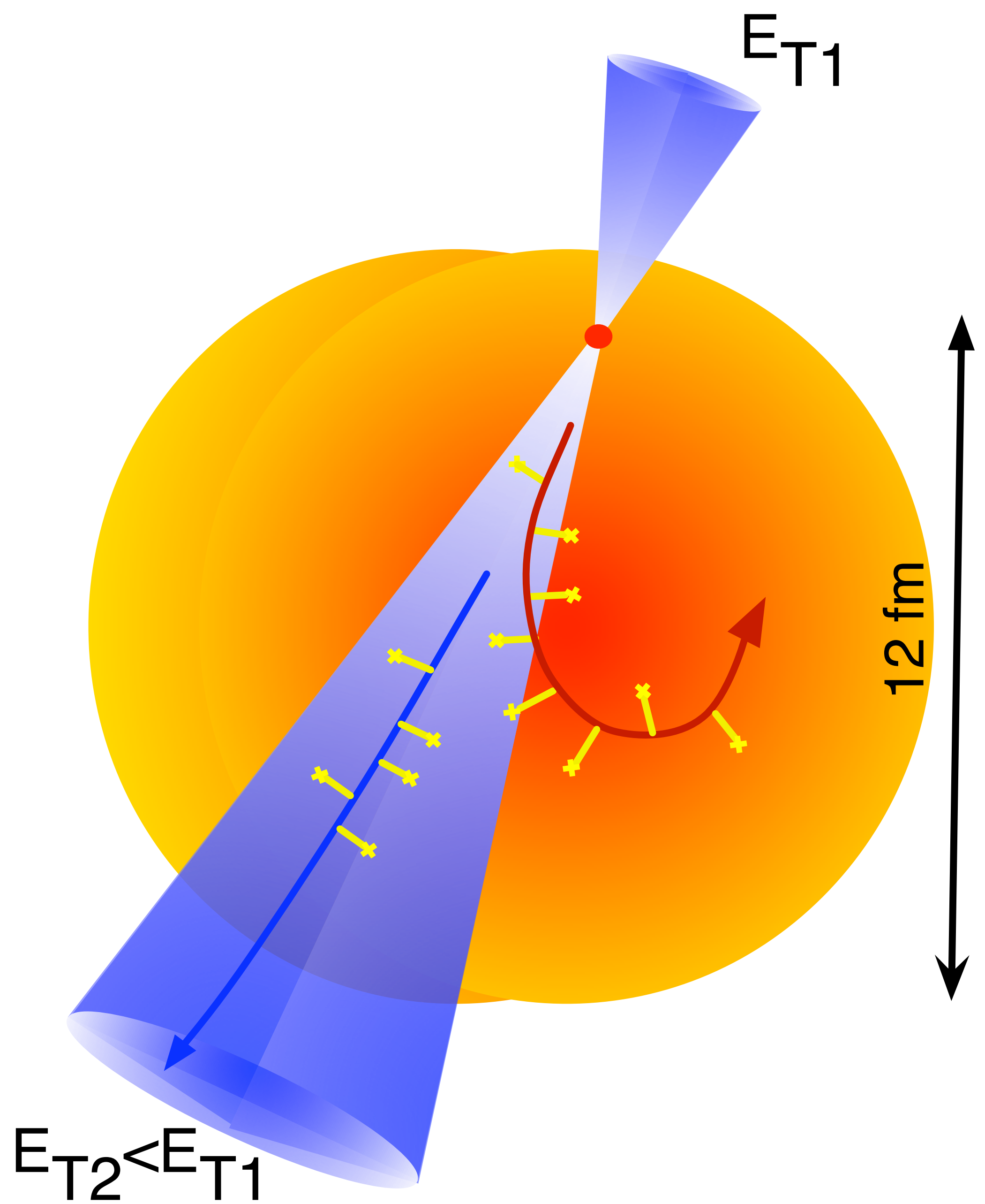
Jets as Probes



Jet Quenching



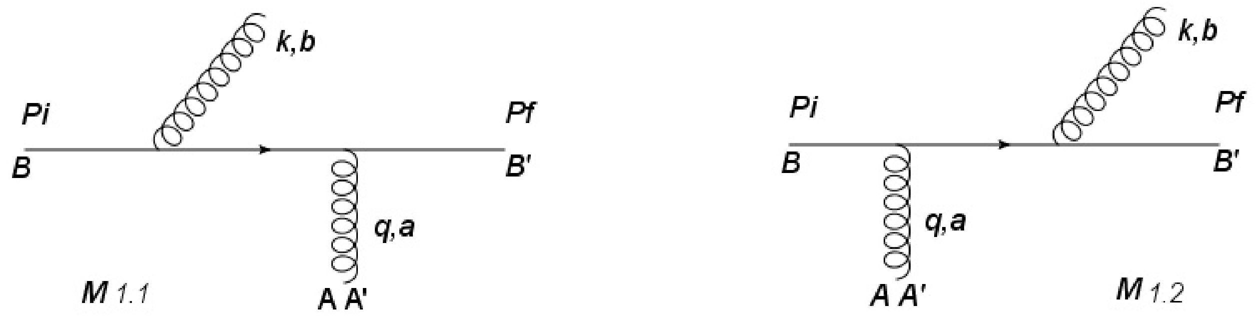
Soft Fragment Decorrelation



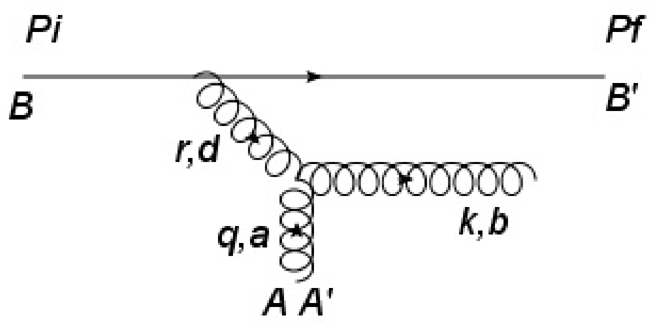
JCS, Milhano, Wiedemann 10

Stimulated Emission

- Exchanges with the medium



(QED-like diagrams)



(QCD diagram)

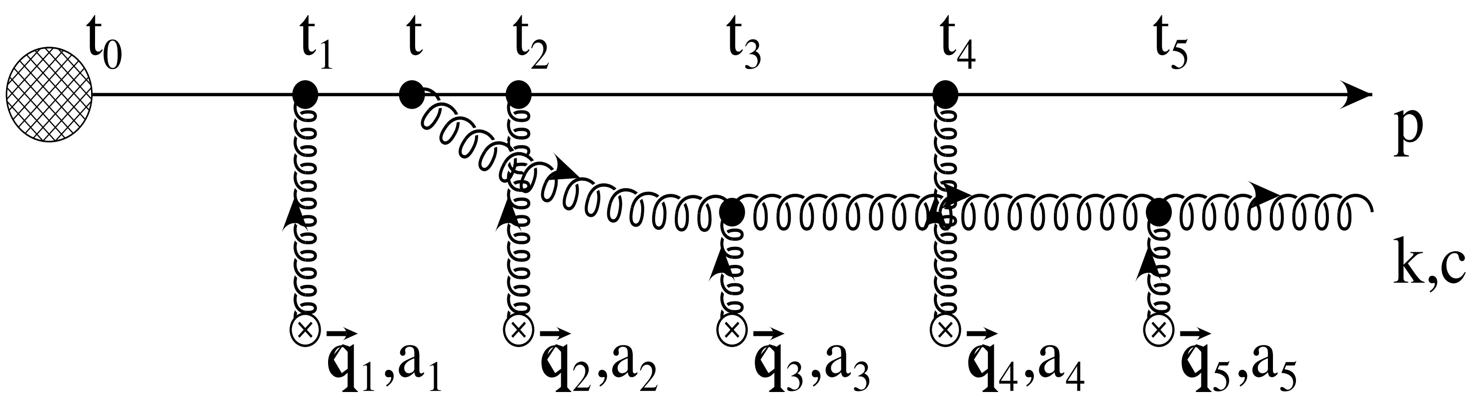
- Finite rate for large energy quarks (unlike QED)
  - Rate controlled by gluon kinematics
- Induce rate:

$$dI \propto \frac{\mu^2}{k_\perp^2\left(k_\perp^2+\mu^2\right)}$$

Interference

- Multiple scattering: interference between scattering centers

  (LPM effect)



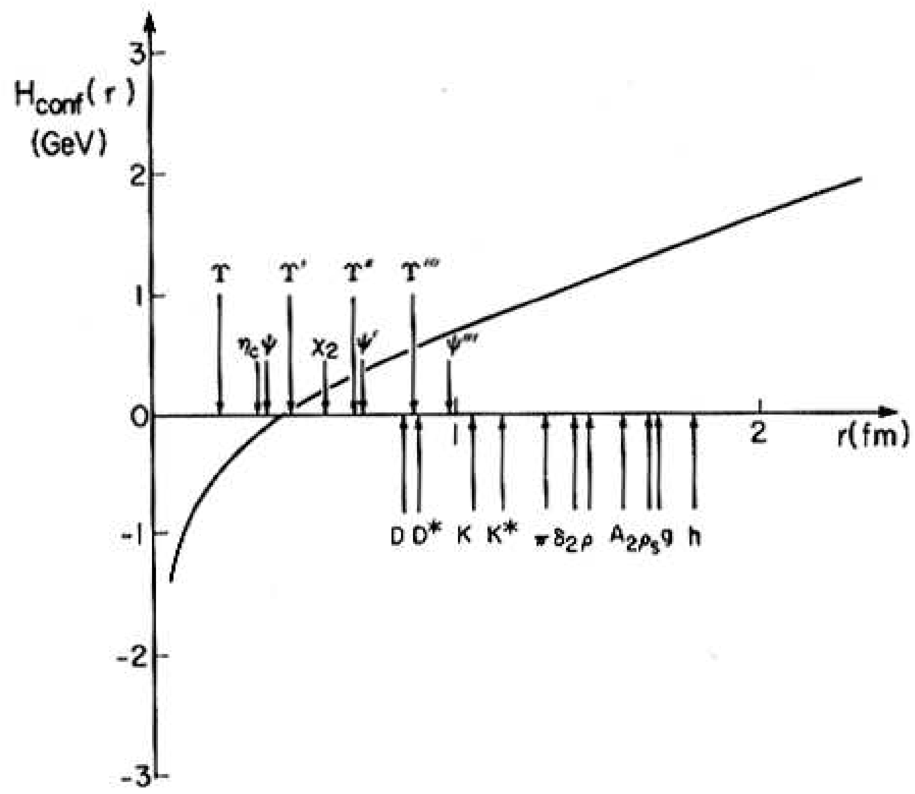
BDMPS-Z 96

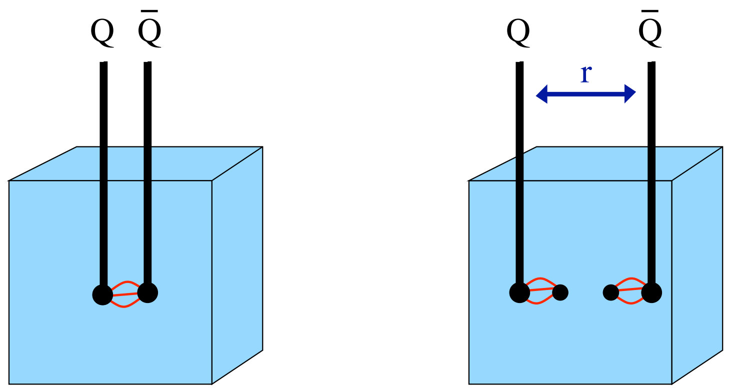
(GLV, ASW, AMY, HT ...)

(Review: JCS & C. Salgado arXiv:0712.3443)

- Emission takes a formation time $\tau_{\rm form} \sim \frac{2\omega}{k_\perp^2}$
- Frustration of radiation if $\lambda \sim \tau_{\rm form}$
- Equivalent scattering with momentum exchange $\mu^2_{\rm transfer} \sim \hat{q}\tau_{\rm form}$
- A medium parameter: $\hat{q} = \frac{(\text{mean transferred momentum})^2}{\text{length}} \sim \frac{m_D^2}{\lambda_{\rm m.\,f.\,p}}$

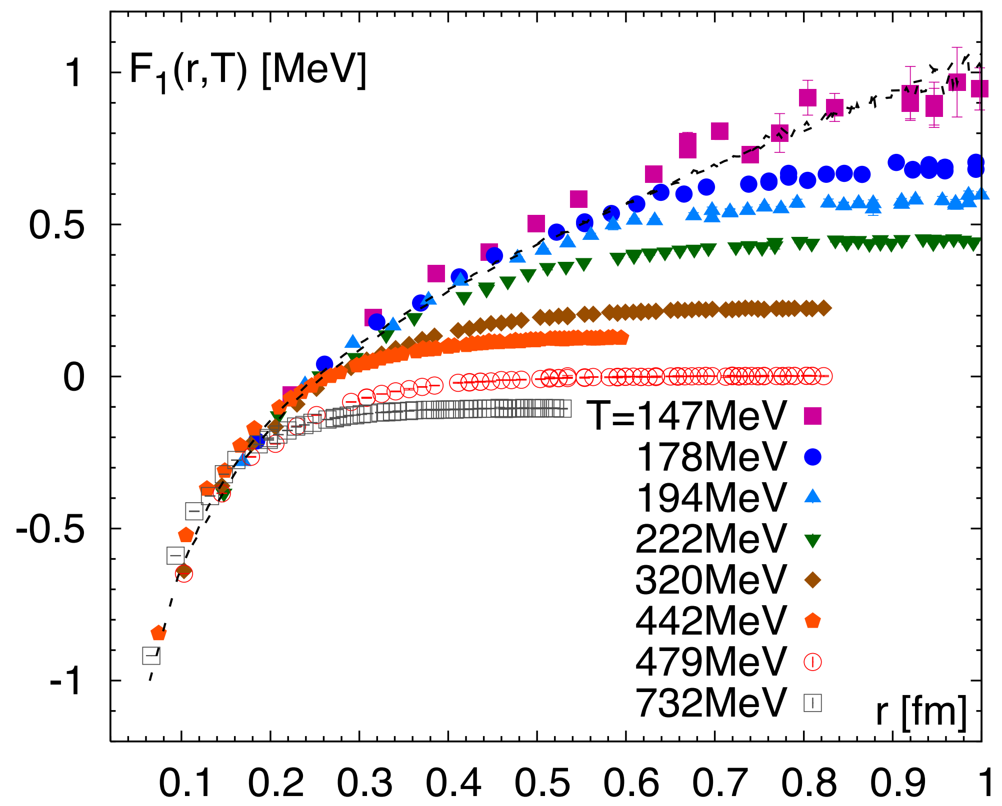
Quarkonia Suppression

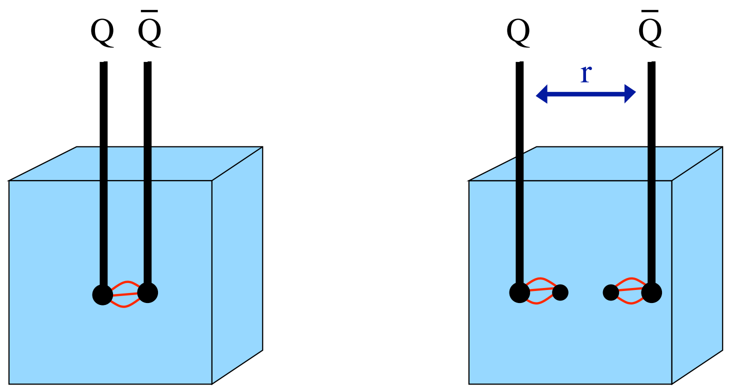




- Different quarkonia states prove different distances
- Medium effects alter long distance behavior of the HQ potential
  - Screening
  - Potential develops an imaginary part
- Quarkonia melting probes the plasma at different distances

Quarkonia Suppression





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Upsilon Melting