The heavy-ion theory road map

Aleksi Kurkela, UiS
Spåtind 2023

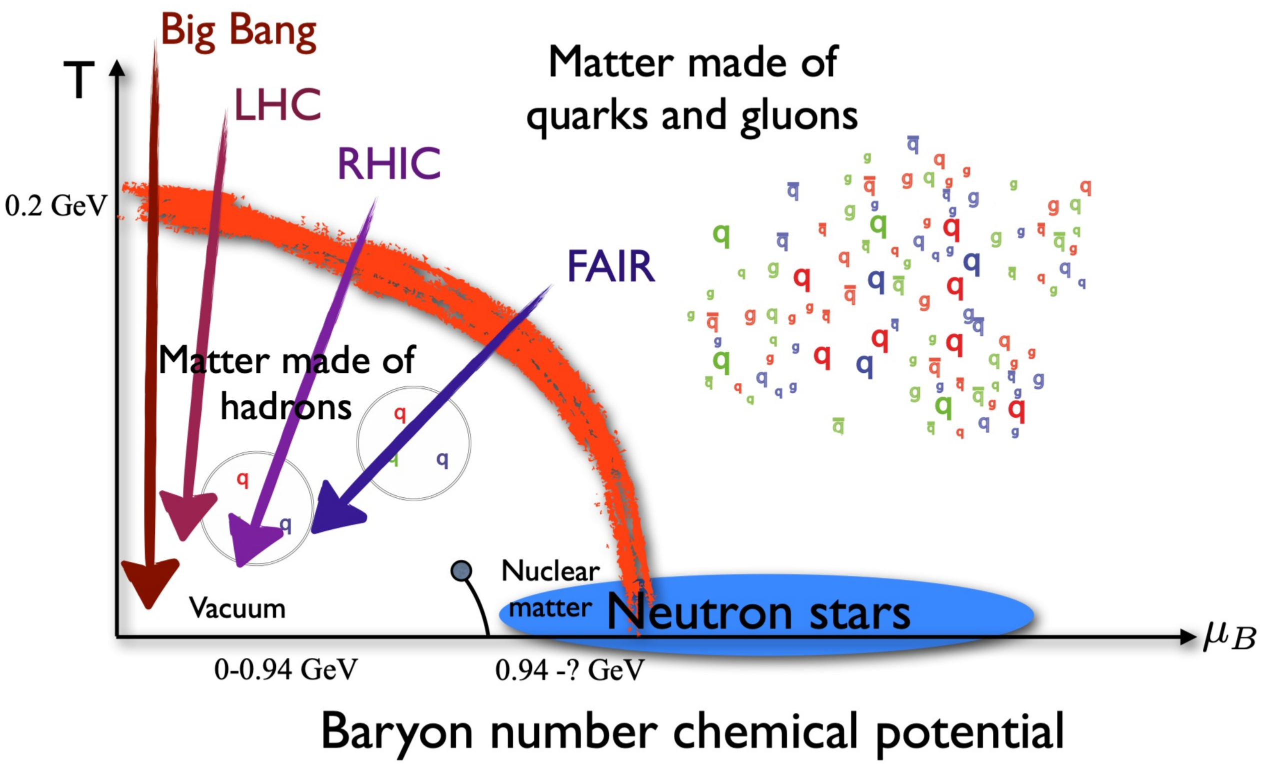
Universitetet i Stavanger

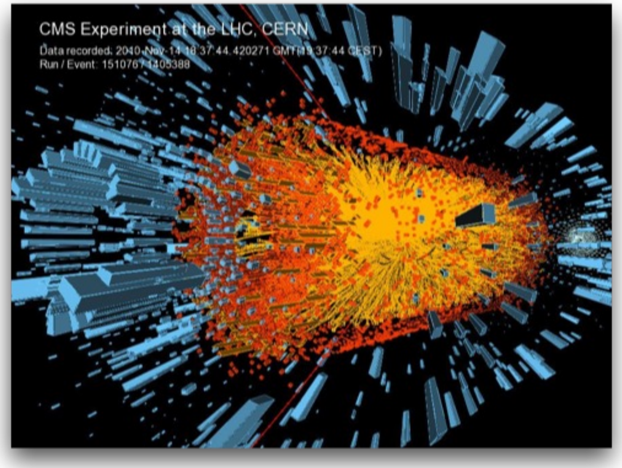
~~The~~ A heavy-ion theory road map

Aleksi Kurkela, UiS
Spåtind 2023

Universitetet i Stavanger

Elementary particle matter

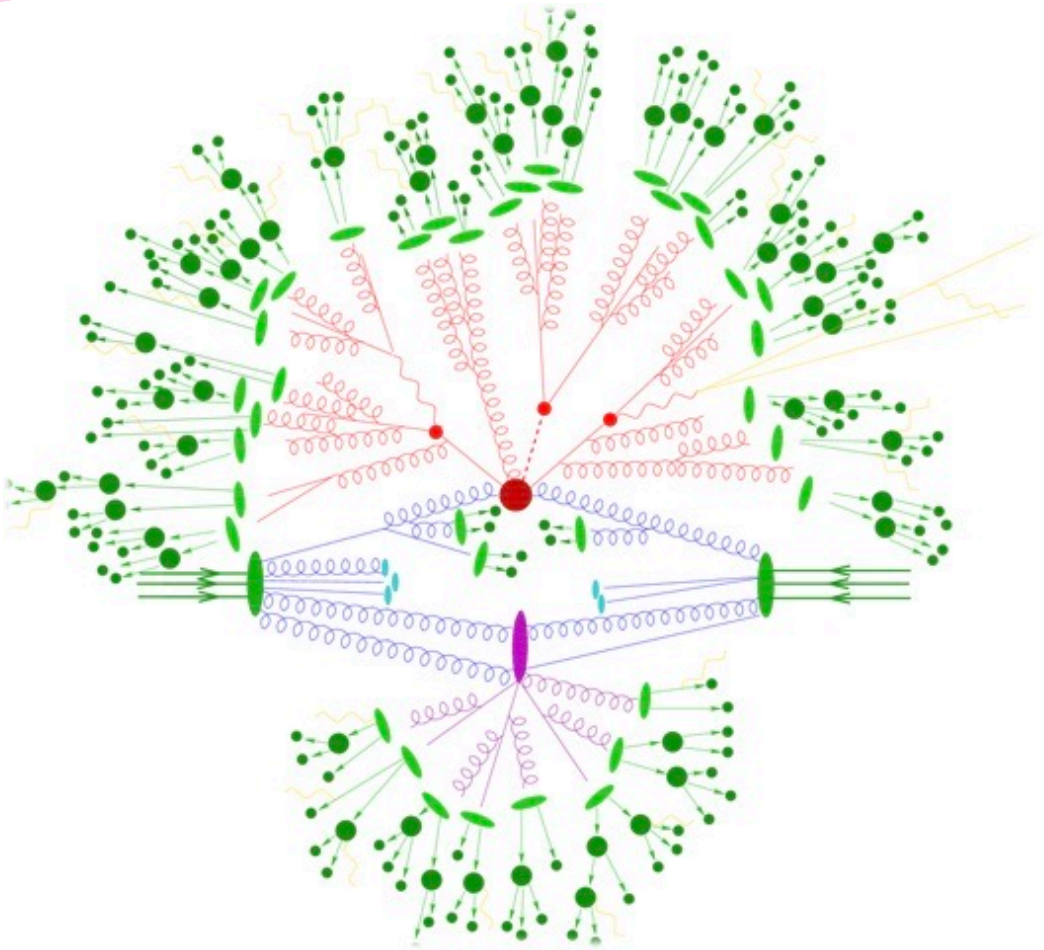




LHC, RHIC, FAIR, NICA,…

LIGO+Virgo+Kagra, NICER, eXTP,…

“Standard picture” in p-p collisions

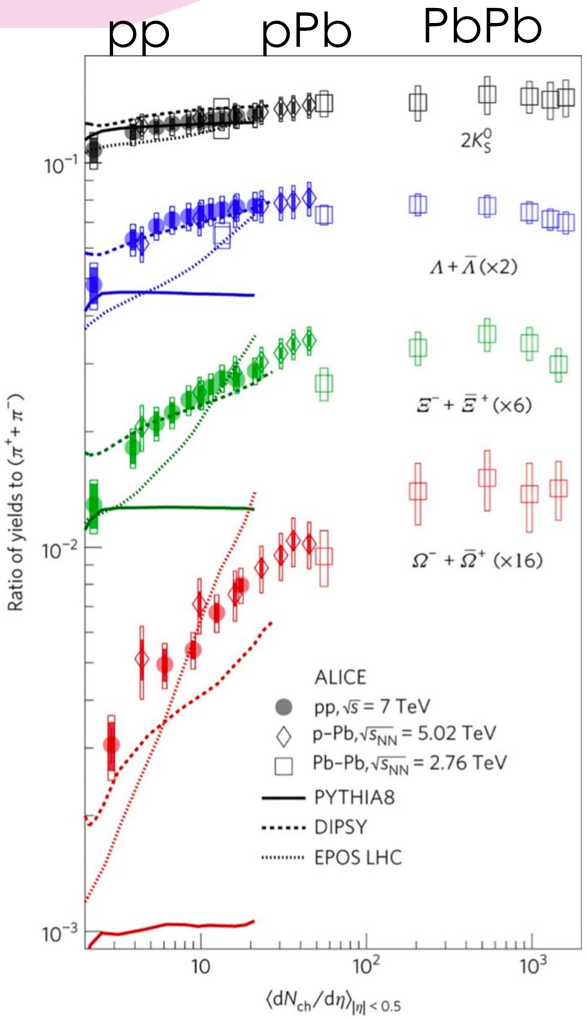


- Initial state radiation
- Hard processes
- Multi-parton interactions
- Fragmentation
- Hadronisation
- …

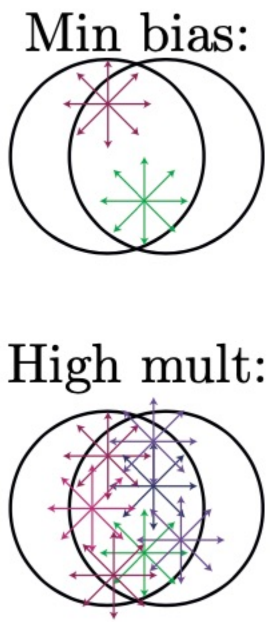
Pythia, Herwig,…

But *no final state interactions*

More is not more of the same



ALICE Nature Phys. 13 (2017) 535-539



The **kind** of particles changes with multiplicity

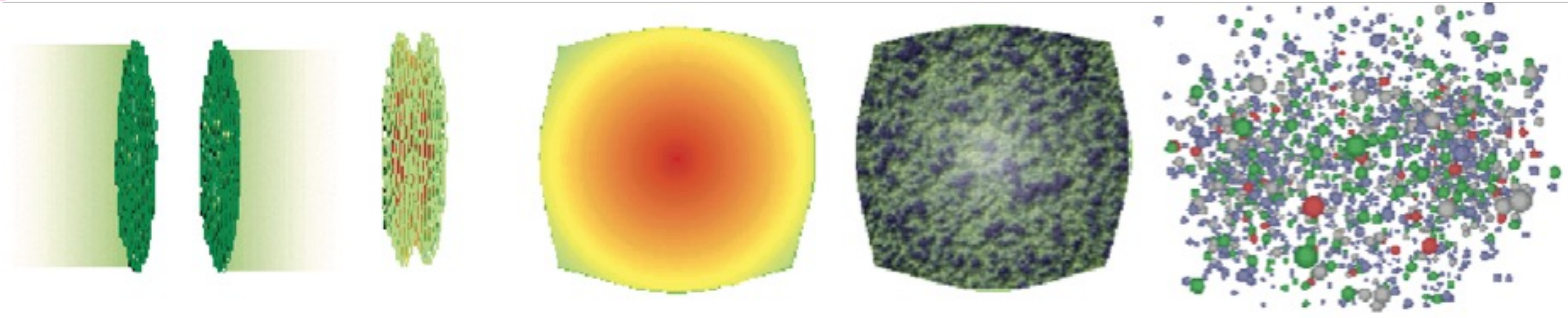
⇒ "Significant new physics required to reproduce the qualitative features"

Sjöstrand, Fischer JHEP 1701 (2017)
Bierlich et al. JHEP 10 (2018), Phys.Lett.B 835 (2022)

Smooth trend from $pp, pPb, PbPb$

Lund group

“Standard picture” in Heavy-ion collisions



Creation of a droplet of strongly coupled fluid: quark-gluon plasma

Relativistic fluid dynamics

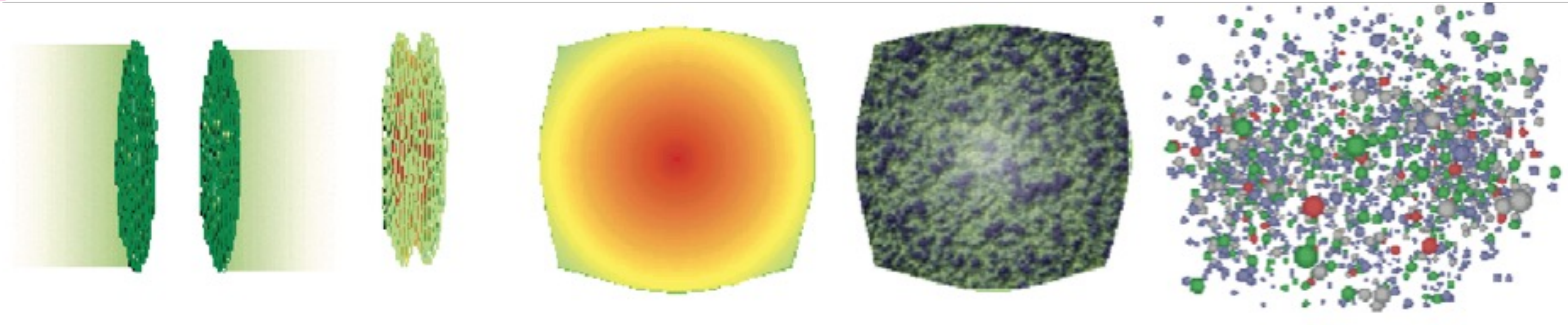
u_μ = flow field, rest frame of the medium

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

$$T^{\mu\nu} = T^{\mu\nu}_{eq.} + \eta(T)\nabla^{<\mu}u^{\mu>} - \zeta(T)\{g^{\mu\nu} + u^\mu u^\nu\}(\nabla \cdot u) + \ldots$$

$$T^{\mu\nu}_{eq.} = \mathrm{diag}(e(T), p(T), p(T), p(T))$$

“Standard picture” in Heavy-ion collisions



Creation of a droplet of strongly coupled fluid: quark-gluon plasma

Relativistic fluid dynamics

Expansion around local thermal equilibrium
⇒ **Infinite number of final state interactions**

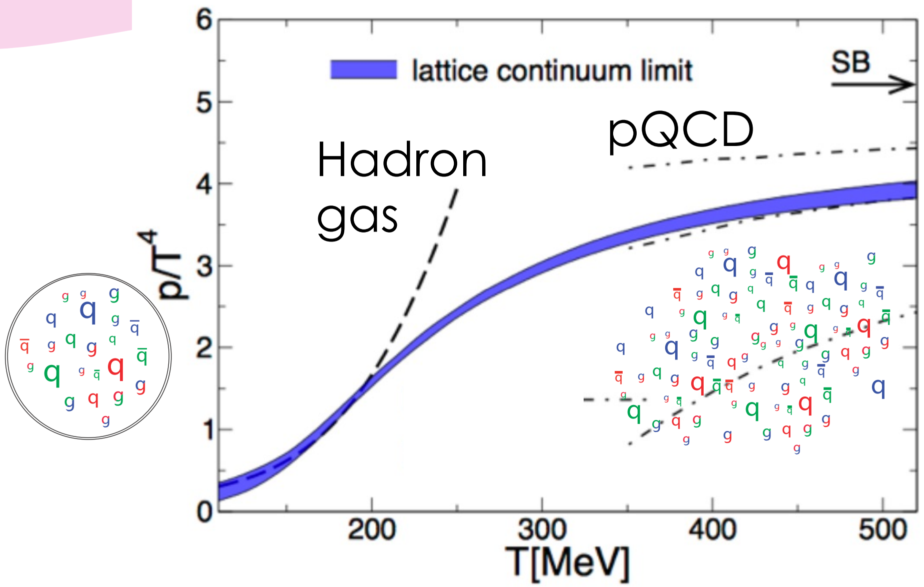
Standard picture in Heavy-ion collisions

Questions:

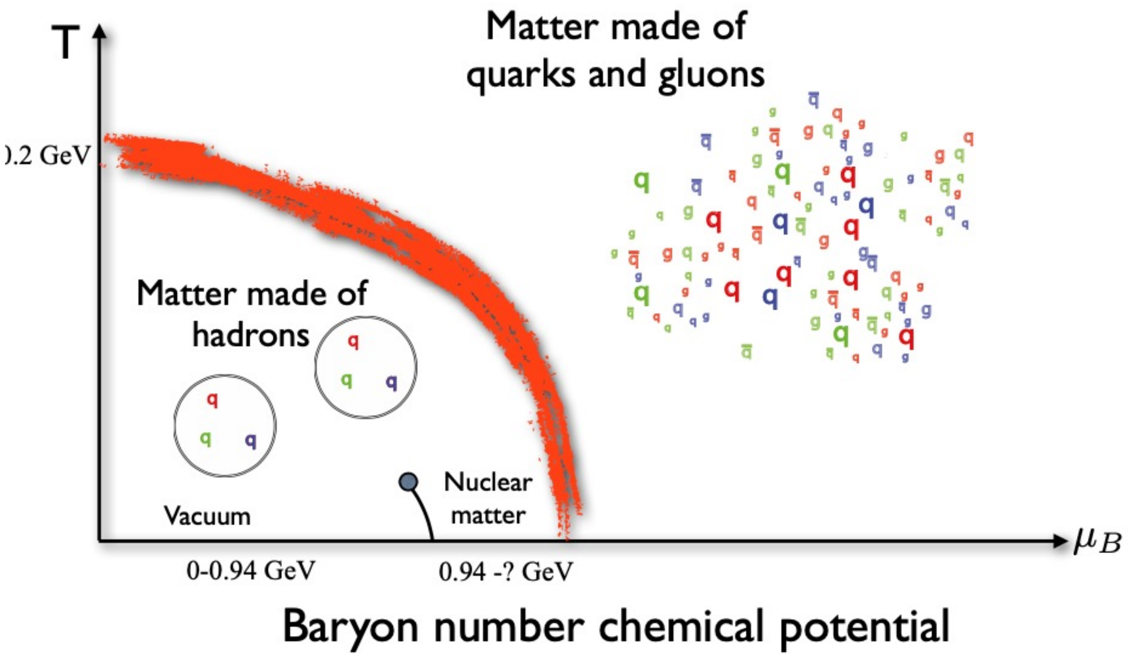
- What are material properties of QGP? $p(T), \eta(T), \zeta(T), \ldots$
- How does the fluid arise from the final state intercations? How are the two “cartoons” connected

Characterization of Quark-Gluon plasma

Equation of state:



Borsanyi et al. PLB 370 (2014)

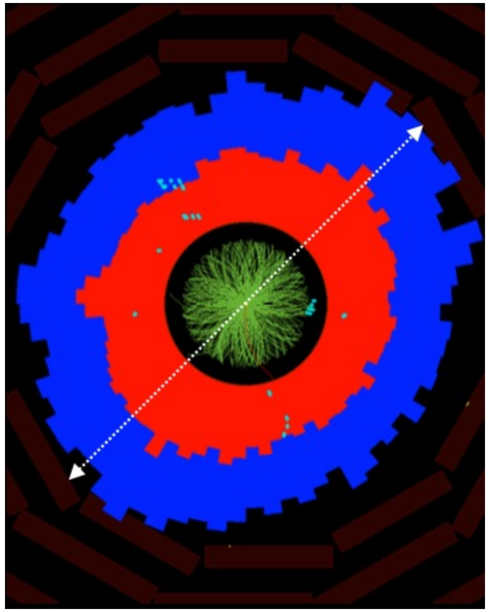


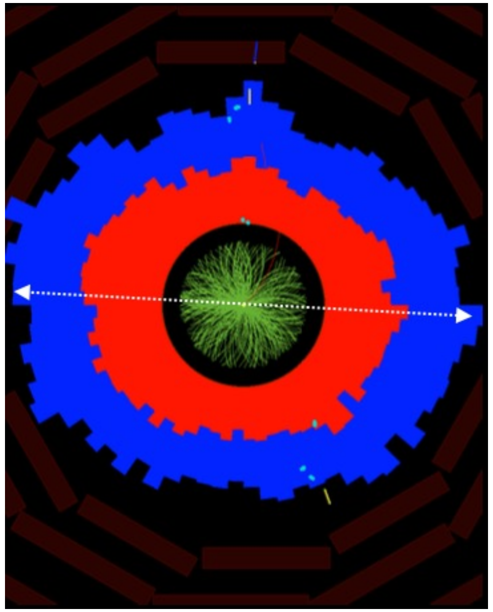
- Can be computed non-perturbaively using lattice (for $\mu_B = 0$)
- Rapid change reflects a **transition from hadronic matter to quark gluon plasma**

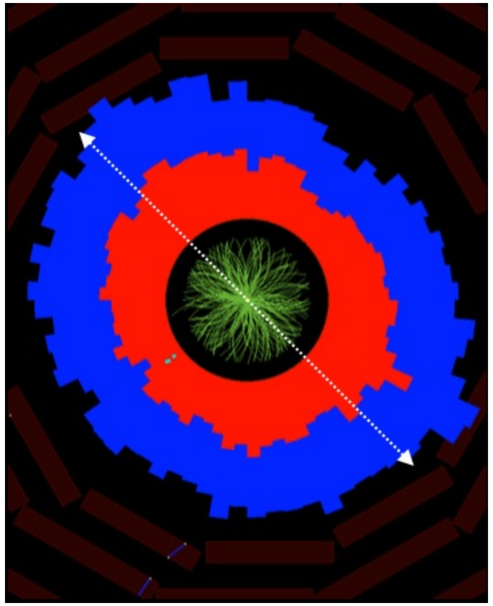
- Other transport properties can not be accessed from lattice due to **sign problem**
  ⇒ Model/limit calculations and empirical determination

Helsinki group

Azimuthal correlations:

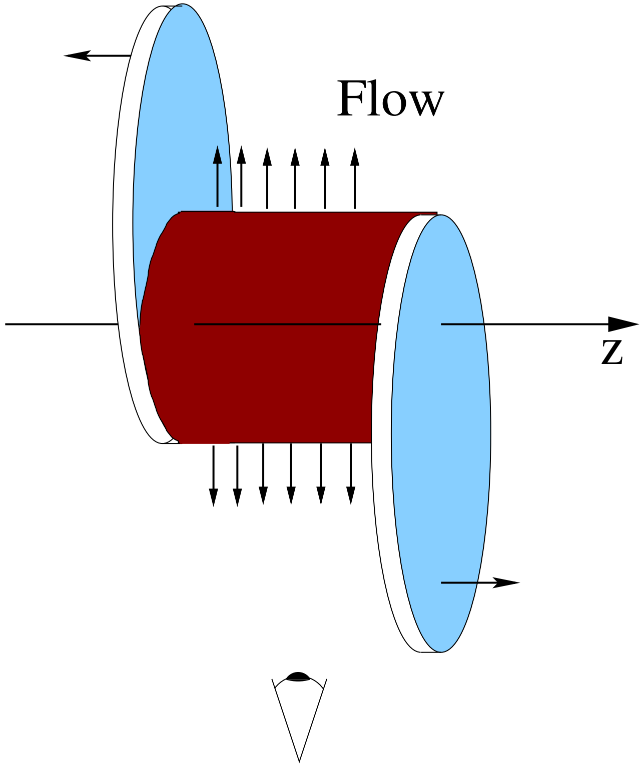


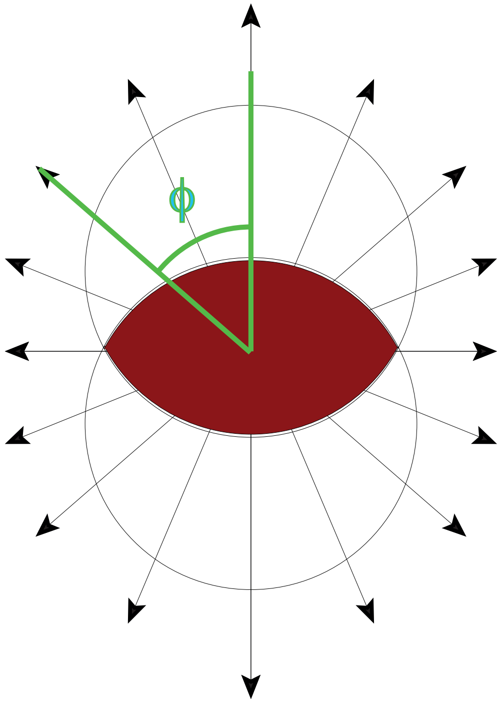




Single-event calorimetric distributions of ~10k charged particles, PbPb @ LHC

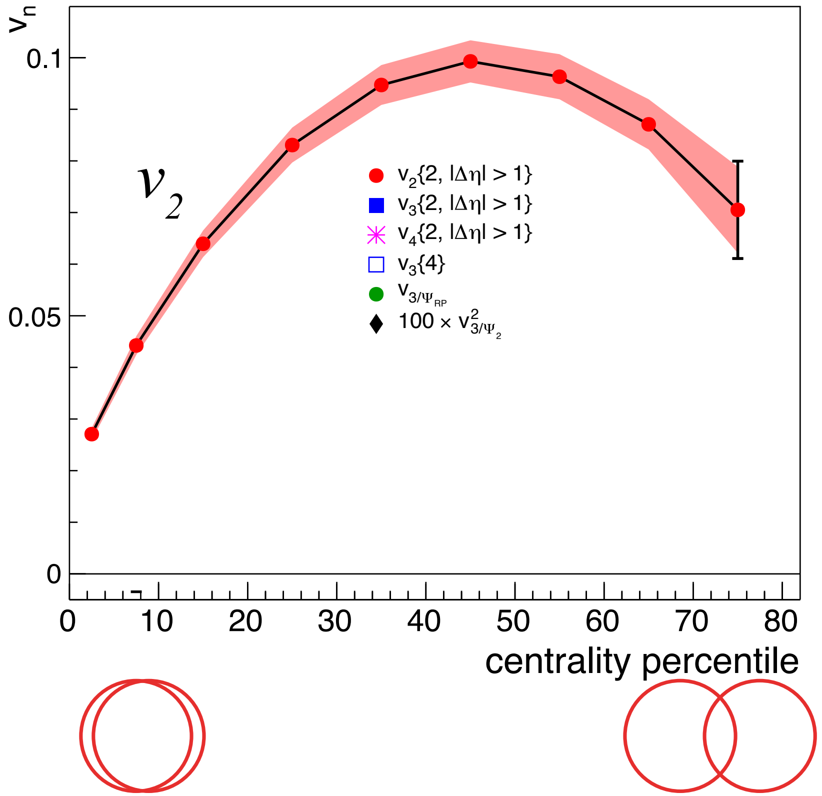
Azimuthal correlations:





$$\frac{dN}{d\phi} \propto \left[1 + 2 \sum_n v_n \cos(n\phi) \right]$$

Azimuthal correlations:

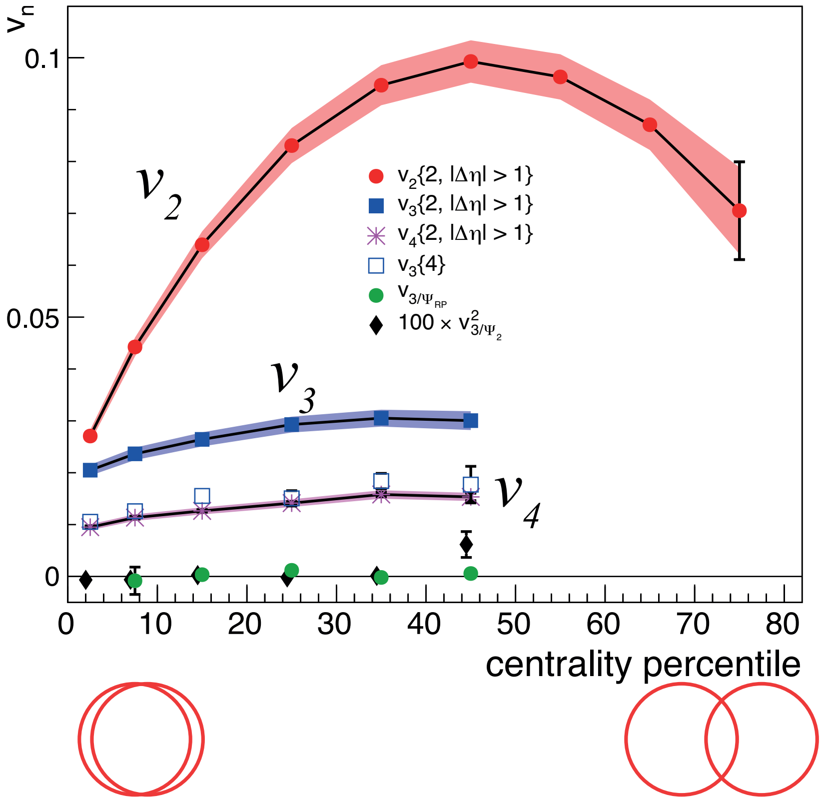


More viscous the fluid, less there is flow:

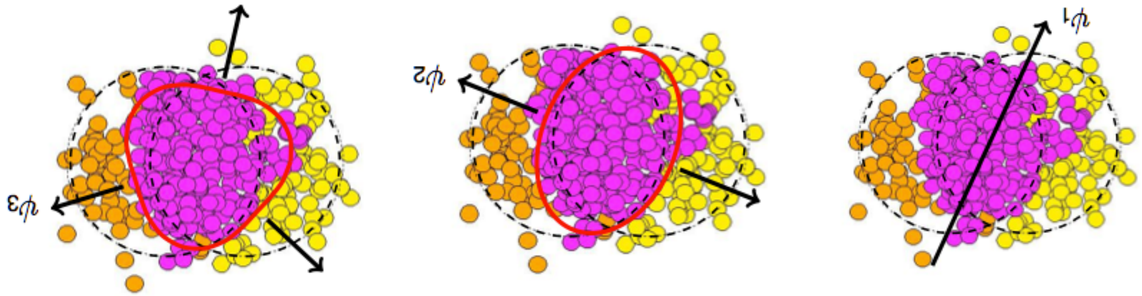
$$v_2 \approx v_2^{ideal} \frac{1}{1 + K/K_0}$$

$$K \sim \frac{l_{micro}}{l_{macro}} \sim \frac{\eta}{sT} \frac{1}{R}$$

Azimuthal correlations:

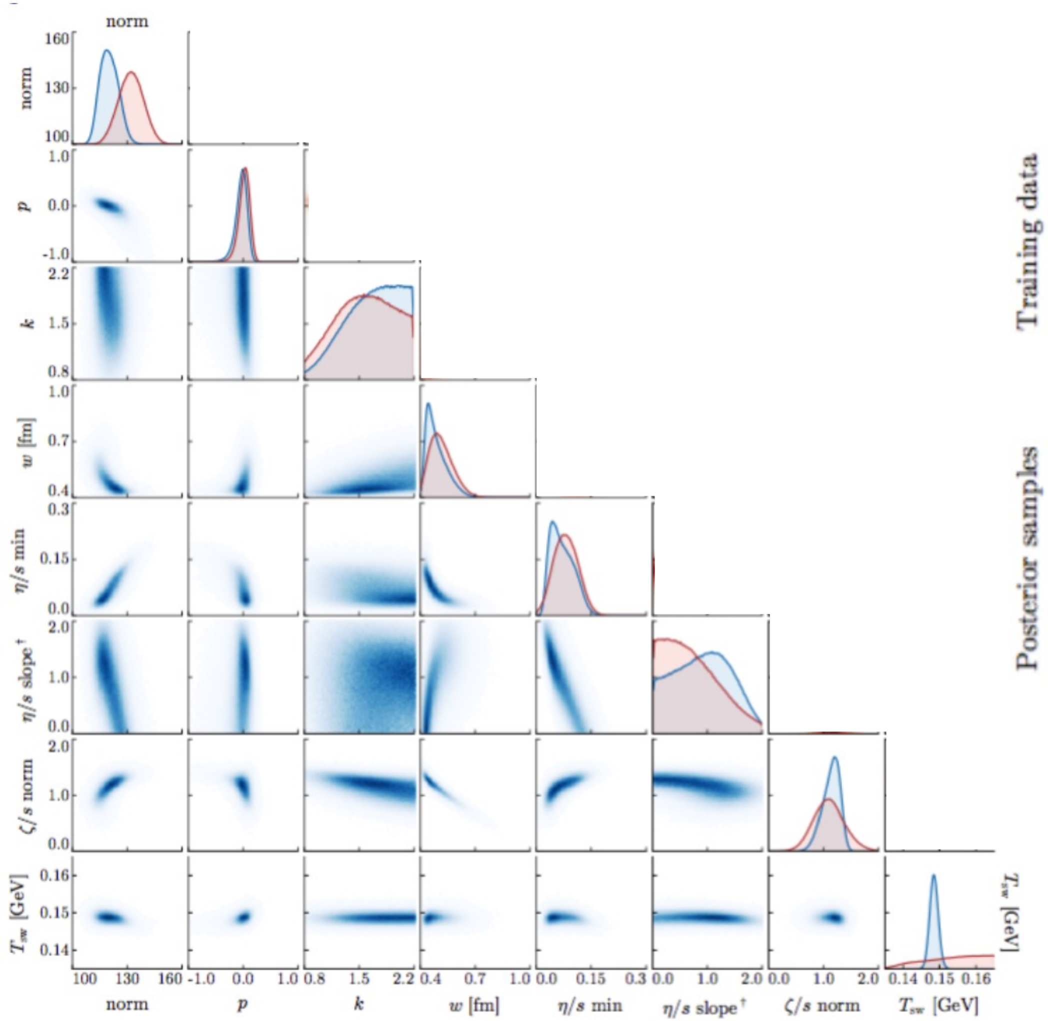


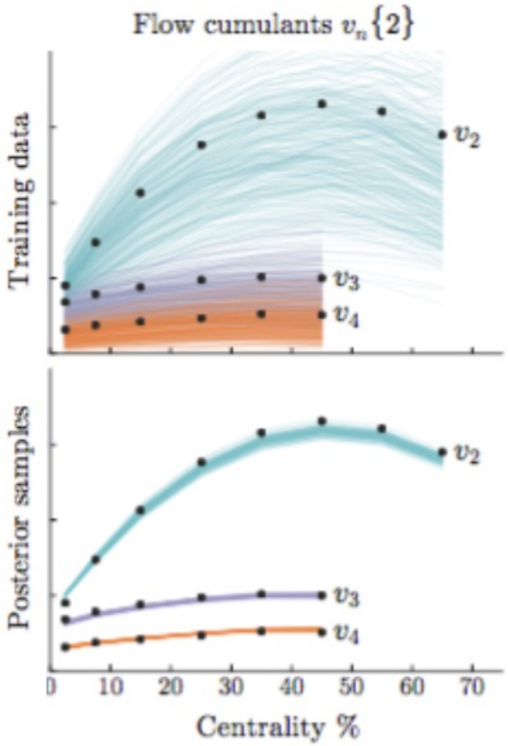
Suite of data:
Different harmonics, correlations between harmonics, event-by-event distributions, p_T-spectra etc..



Copenhagen group, You Zhou's talk
Alice Ohlsen's talk

Hydro models and Bayesian inference:





Models contain:

- Initial conditions
- **Fluid dynamics**
- Particlization
- …

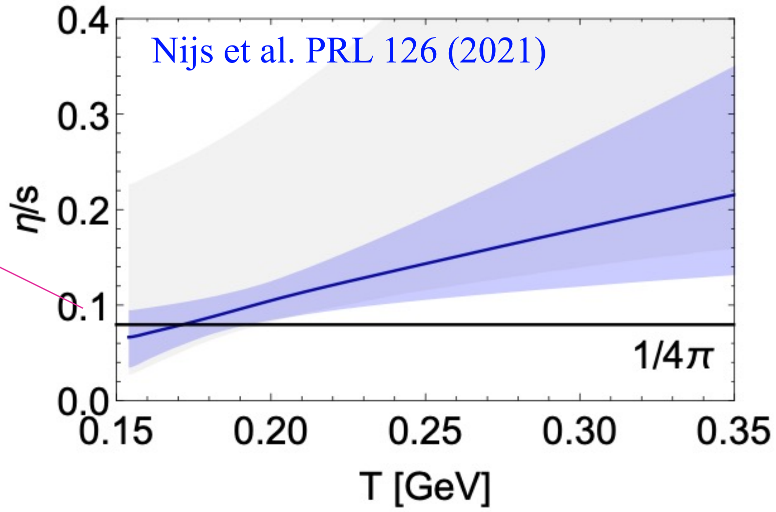
Several dedicated codes

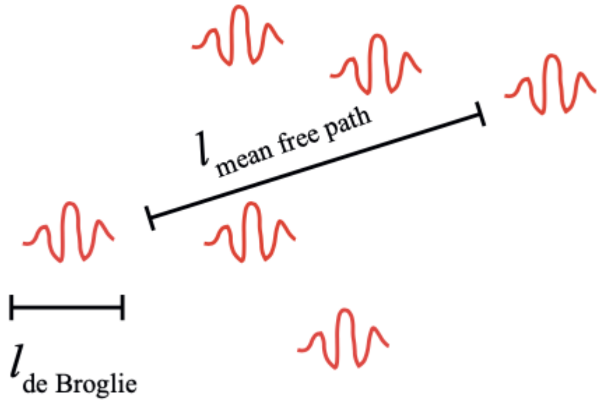
- Vishnu, SuperSonic, Music, Trajectum,…
- State-of-the-art: ~600 data point, 20 parameters

Jyväskylä group, Anna Onnerstad's and Maxim Virta's Talk
Emil Nielsen's talk

What does a small viscosity imply?

$\frac{\eta}{s} \sim 0.1$





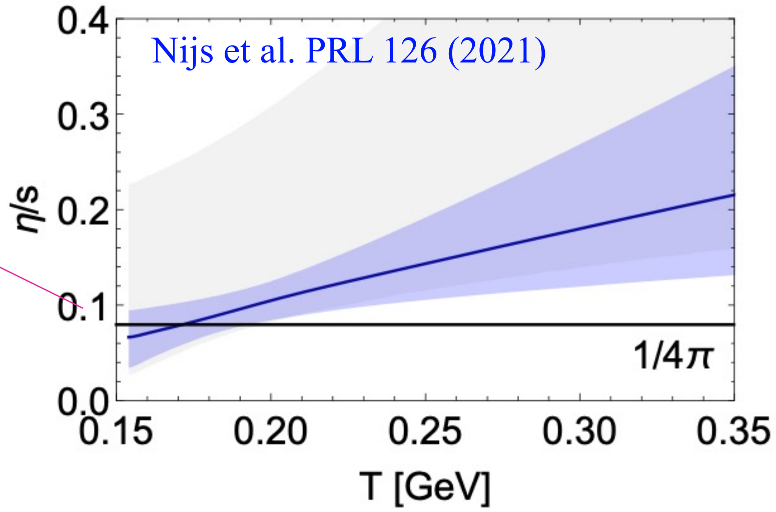
$$\eta/s \sim \langle p \rangle l_{\text{mean free path}} \sim \frac{l_{\text{mean free path}}}{l_{\text{de Broglie}}} \sim \frac{4.74T}{g^4 \log(g) T} \gtrsim 1$$

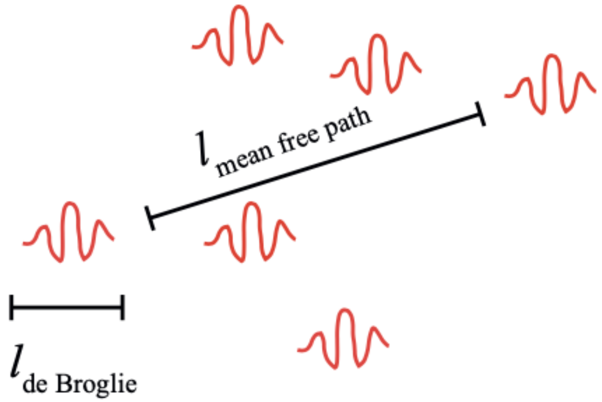
Arnold et al. JHEP 0305 (2003)

Wave-packages not clearly separted between interactions

What does a small viscosity imply?

$\frac{\eta}{s} \sim 0.1$





No non-perturbative calculation in QCD, but **strong-coupling limit** in QCD-like theory:

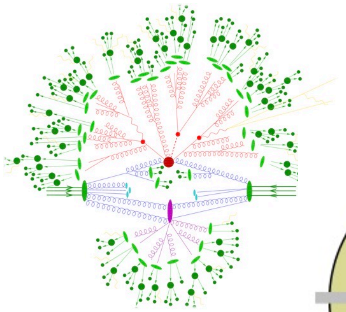
Super Yang-Mills $\mathcal{N} = 4$, $N_c \to \infty$, $\lambda N_c \to \infty$, Starinets, Son, PRL 87 (2001)

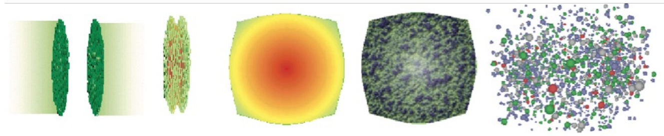
$$\eta/s = \frac{1}{4\pi} \approx 0.08$$

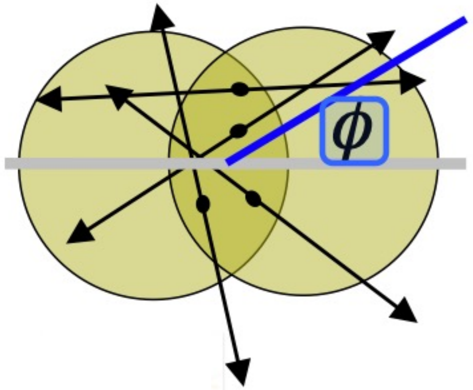
⇒ "Strongly coupled" fluid paradigm

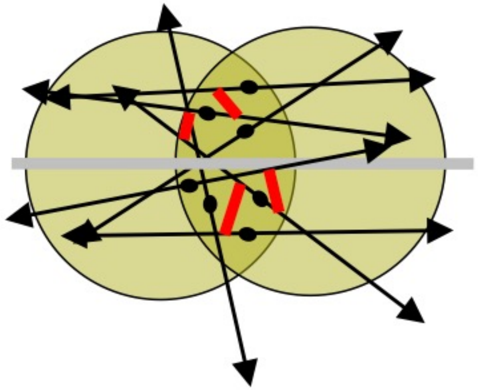
What physics is at play in different systems?

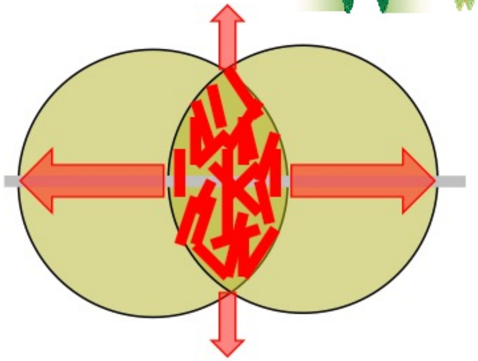
How does the strongly coupled fuild emerge from the final state interactions?
What is the microscopic structure of Quark-Gluon Plasma?











No final-state interactions,
Free streaming

?

Inifinite final-state interactions,
Ideal fluid dynamics

Microscopic structure of quark gluon plasma:

Microscopic structure becomes accessible when fluid-dynamical paradigm is strained, in systems that are **hydrodynamizing**:

- Jets in dense medium
  - hydrodynamization as a function of energy
- Early-time dynamics of Heavy-Ion collisions
  - Hydrodynamization as a function time
- Transition from pp, pA to AA
  - Hydrodynamization as a function of system size

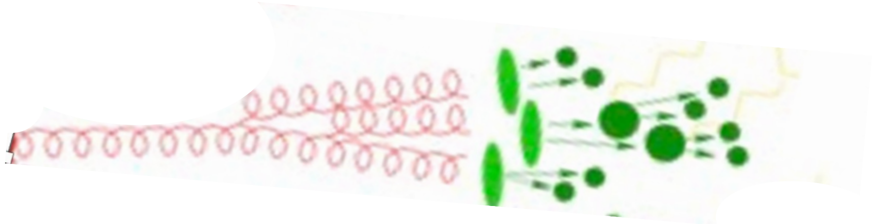
Microscopic structure of quark gluon plasma:

Microscopic structure becomes accessible when fluid-dynamical paradigm is strained, in systems that are **hydrodynamizing**:

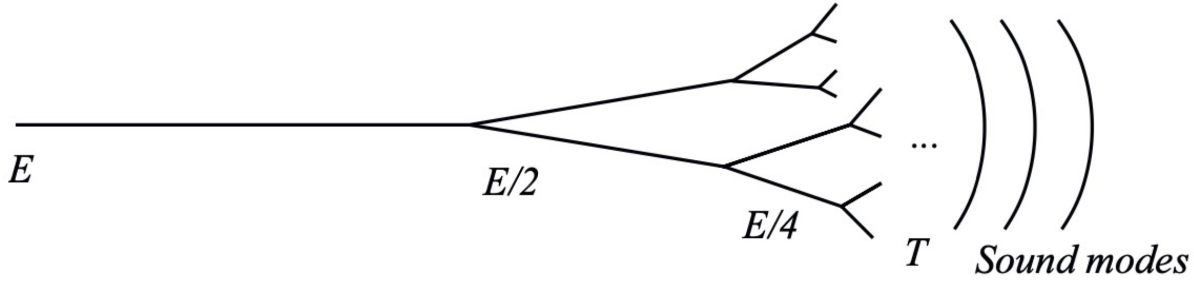
- Jets in dense medium
  - hydrodynamization as a function of energy
- Early-time dynamics of Heavy-Ion collisions
  - Hydrodynamization as a function time
- Transition from pp, pA to AA
  - Hydrodynamization as a function of system size

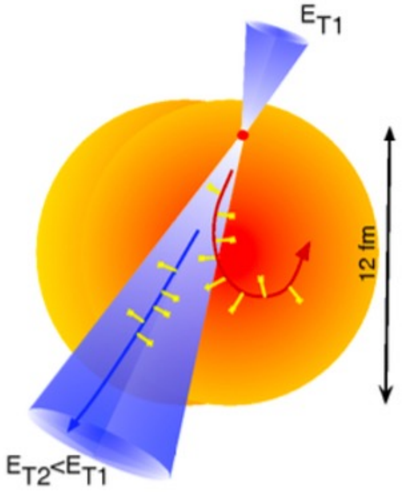
Jet thermalization:

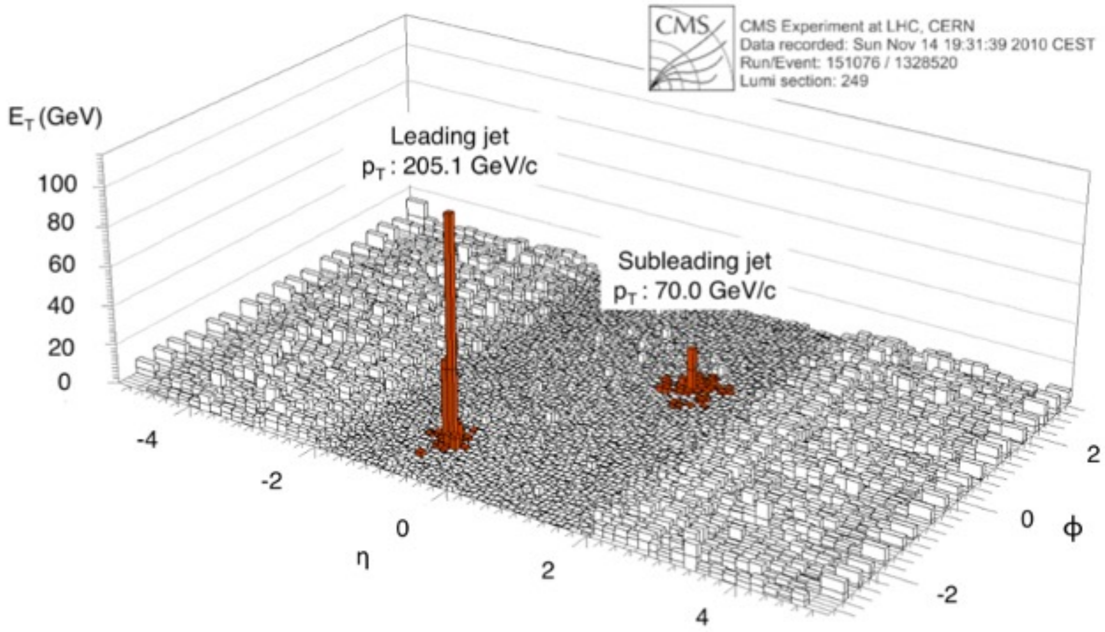
- In vacuum, jets **hadronize**:



- In medium, jets **thermalize**:





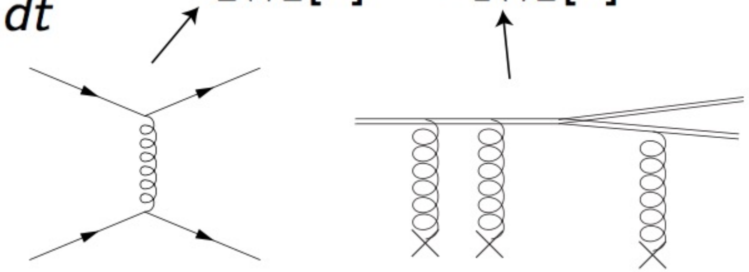


Jet thermalization:

- At weak coupling α_s, the evolution can be followed in effective transport theory:

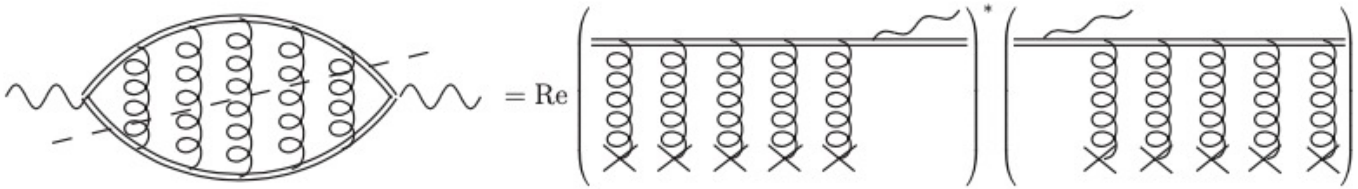
LO: Arnold, Moore, Yaffe, JHEP 0301 (2003) 030
NLO: Ghiglieri, Moore, Teaney, HEP 03 (2016) 095

$$\frac{df}{dt} = -C_{2\leftrightarrow 2}[f] - C_{1\leftrightarrow 2}[f]$$



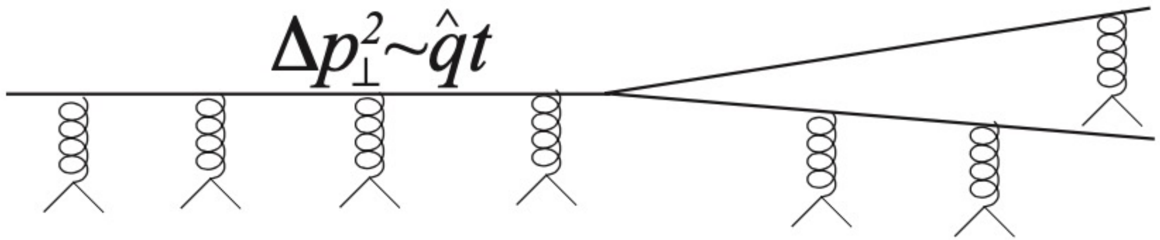
- Soft and collinear divergences lead to non-trivial in-medium matrix elements:

soft in-medium screening; collinear: LPM, BDMPS-Z



Bergen group, Johannes Isaksen's talk

Jet thermalization:



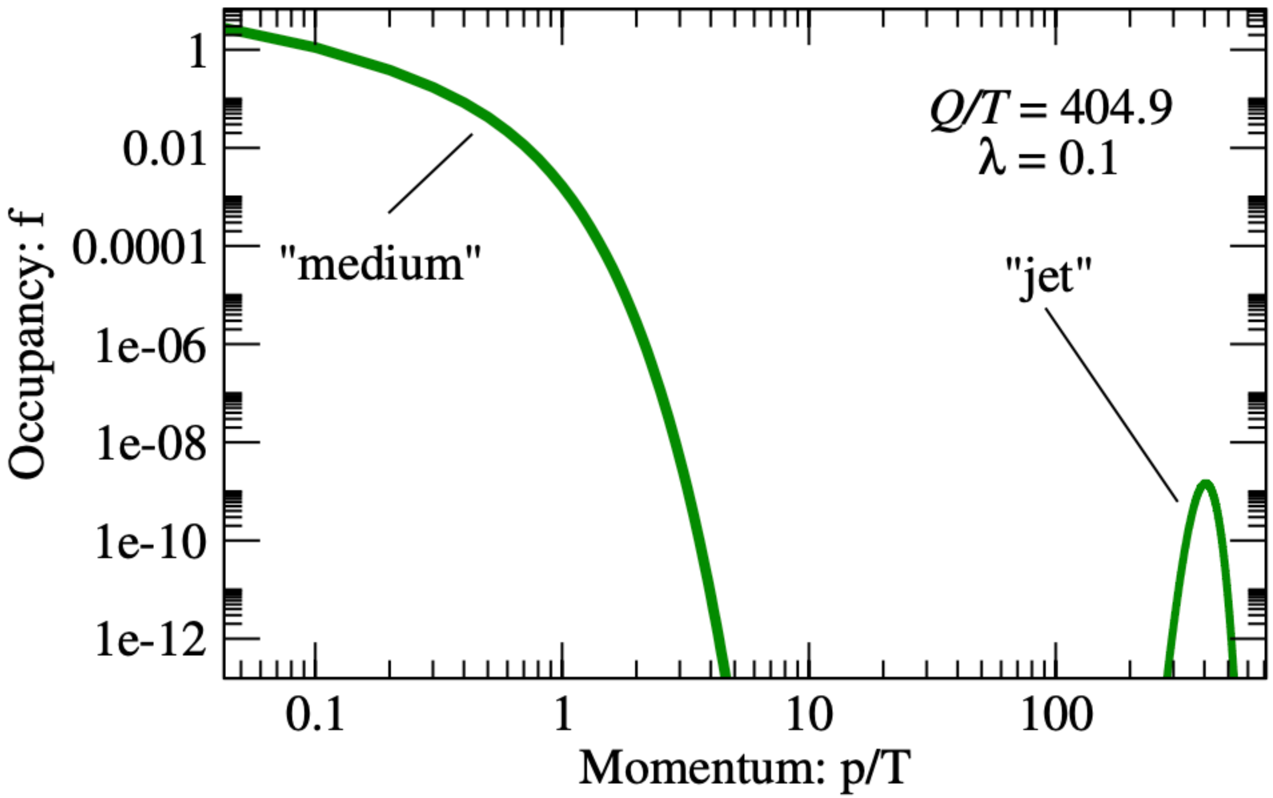
- In vacuum: DGALP $t_{\mathrm{DGLAP}} \sim \frac{E}{Q^2}$
- In medium:
  - frequent soft scatterings with medium, mom. diffusion: $\Delta p^2 \sim \hat{q}t$
  - Scatterings lead to virtuality: $Q^2 \sim \hat{q}t$
  - Now offshell particle may split collinearly: $t_f \sim E/Q^2 \sim \sqrt{E/\hat{q}}$
  - Splitting time $t_{\mathrm{split}}(E) \sim \frac{1}{\alpha_s} t_f \sim \frac{1}{\alpha_s}\sqrt{\frac{E}{\hat{q}}}$

QED: Landau, Pomeranchuk, Migdal 1953.
QCD: Baier Dokshitzer Mueller Peigne Schiff NPB483 (1997)

Bergen group, Johannes Isaksen's talk

Jet thermalization:

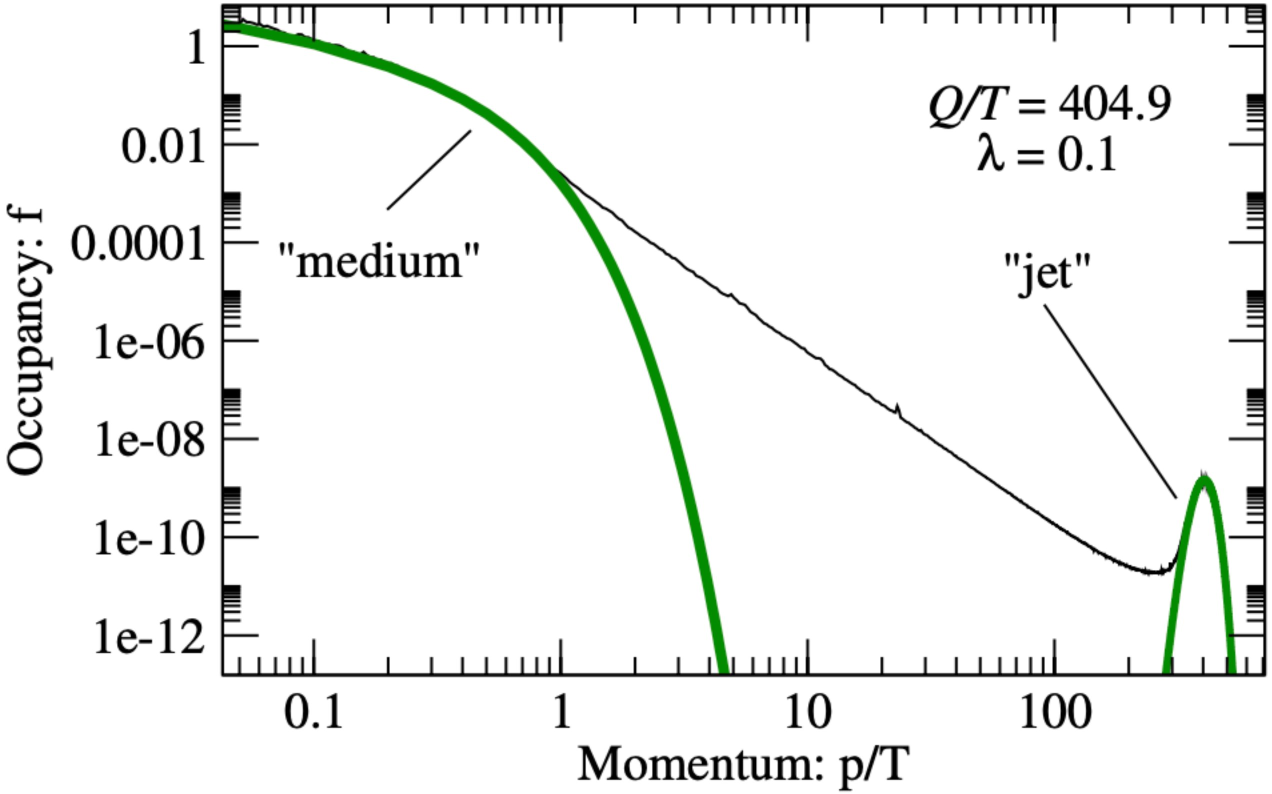
Simple numerical example: “Bottom-up thermalization”



AK, Lu, PRL 113 (2014) 18, 182301

Jet thermalization:

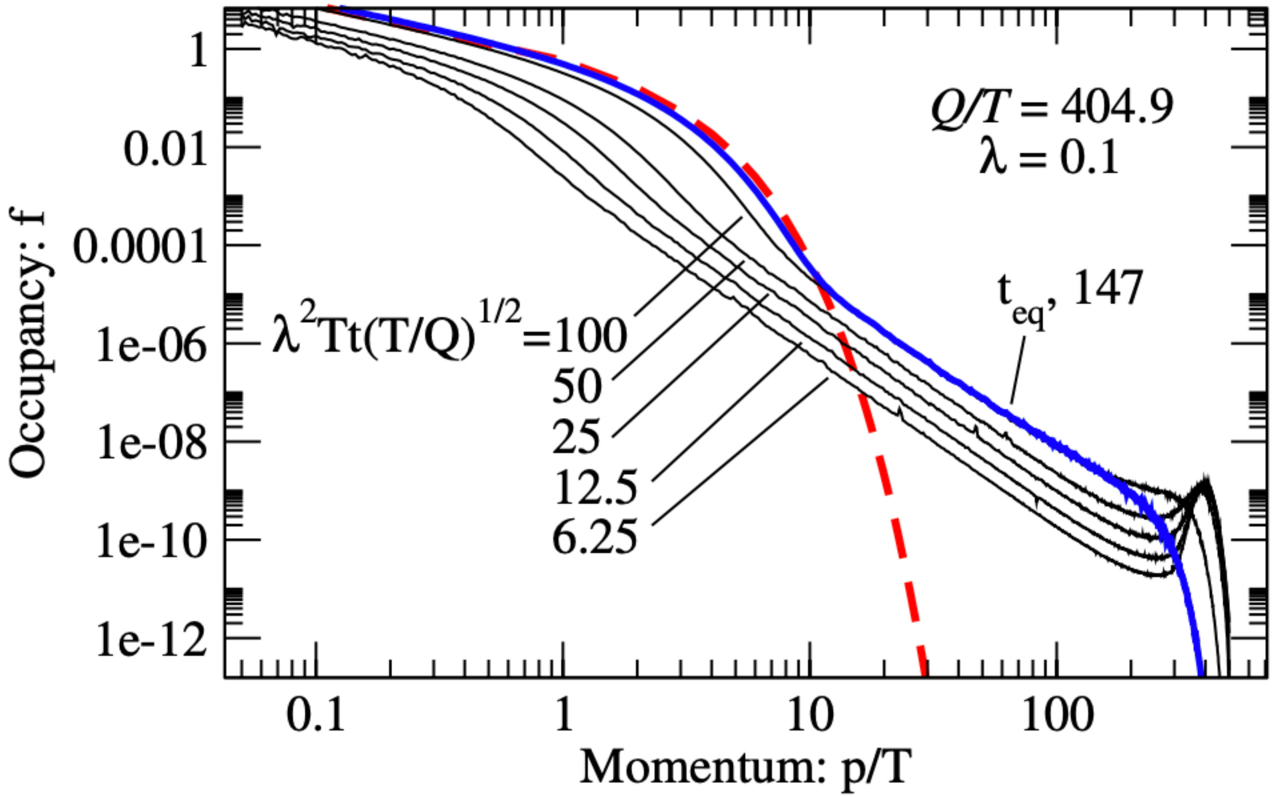
Simple numerical example: “Bottom-up thermalization”



AK, Lu, PRL 113 (2014) 18, 182301

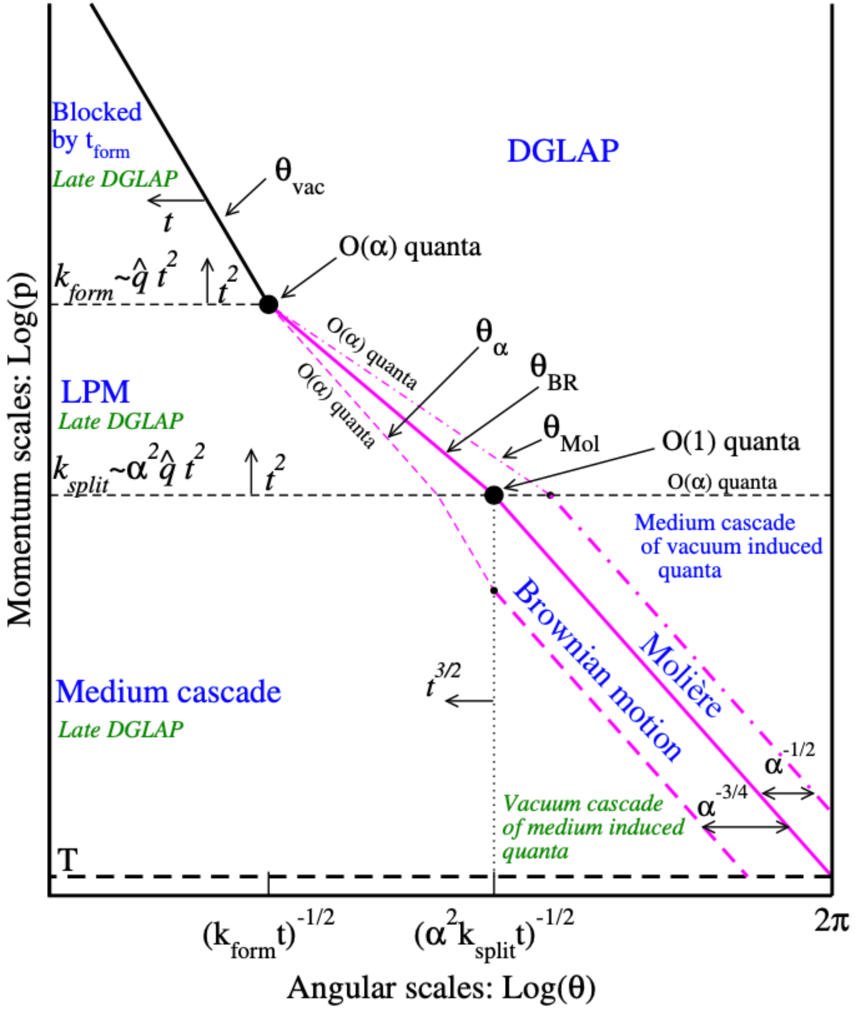
Jet thermalization:

Simple numerical example: “Bottom-up thermalization”



AK, Lu, PRL 113 (2014) 18, 182301

Jet thermalization:



AK, Wiedemann PLB740 (2015) 172-178

Structure of a physical jet much more complicated:

- Harder fragments more coolimated
- Softer particles more isotropic
- Large and small angle scattering
- Final state resacttering mixed with vacuum fragmentation
- Baground medium time-dependent
- …

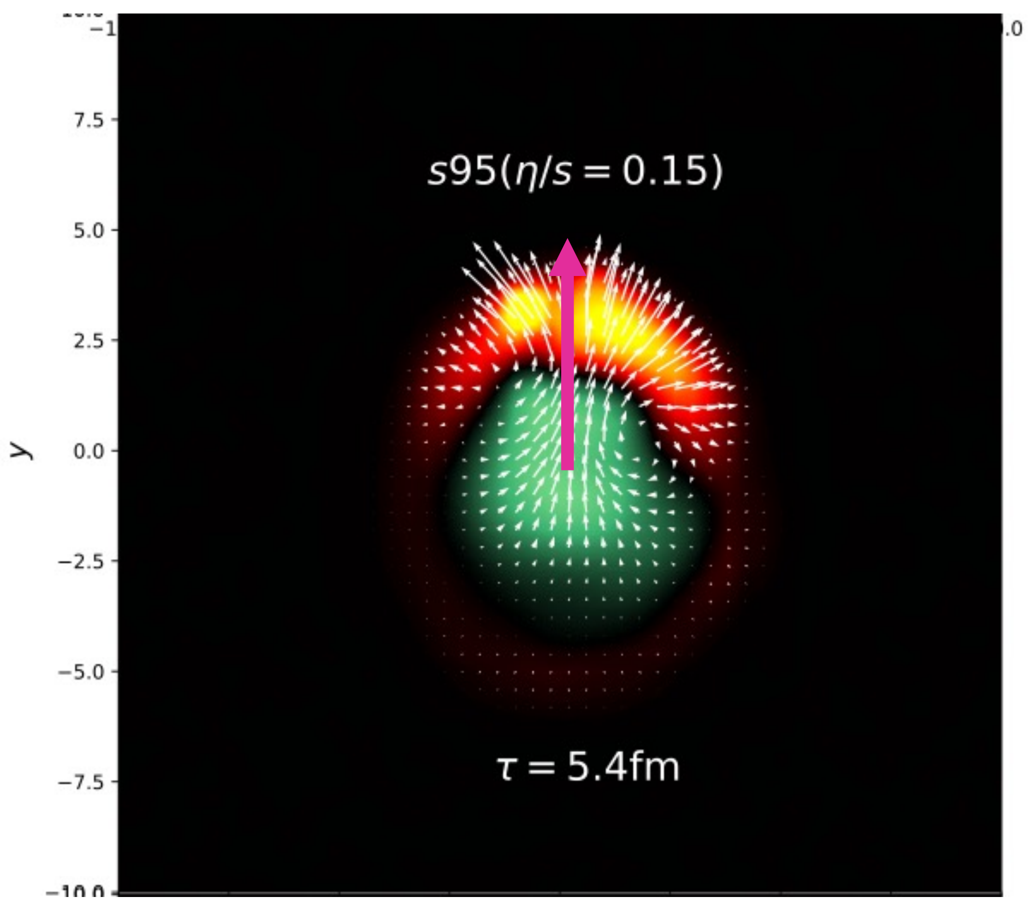
Qualitatively

Quantitatively: Several dedicated codes

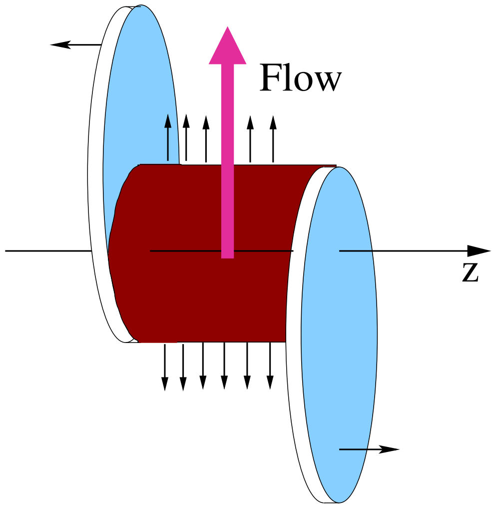
Martini, Sherpa, JetScape, HydJet, CoLBT, …

Oslo and Bergen groups

Jet thermalization



Zhon Yang et al.: 2203.03683



- **Jet-medium interactions** embedded in a complete phenomenological setups
- Connection of these ideas to observables challenging but significant progress

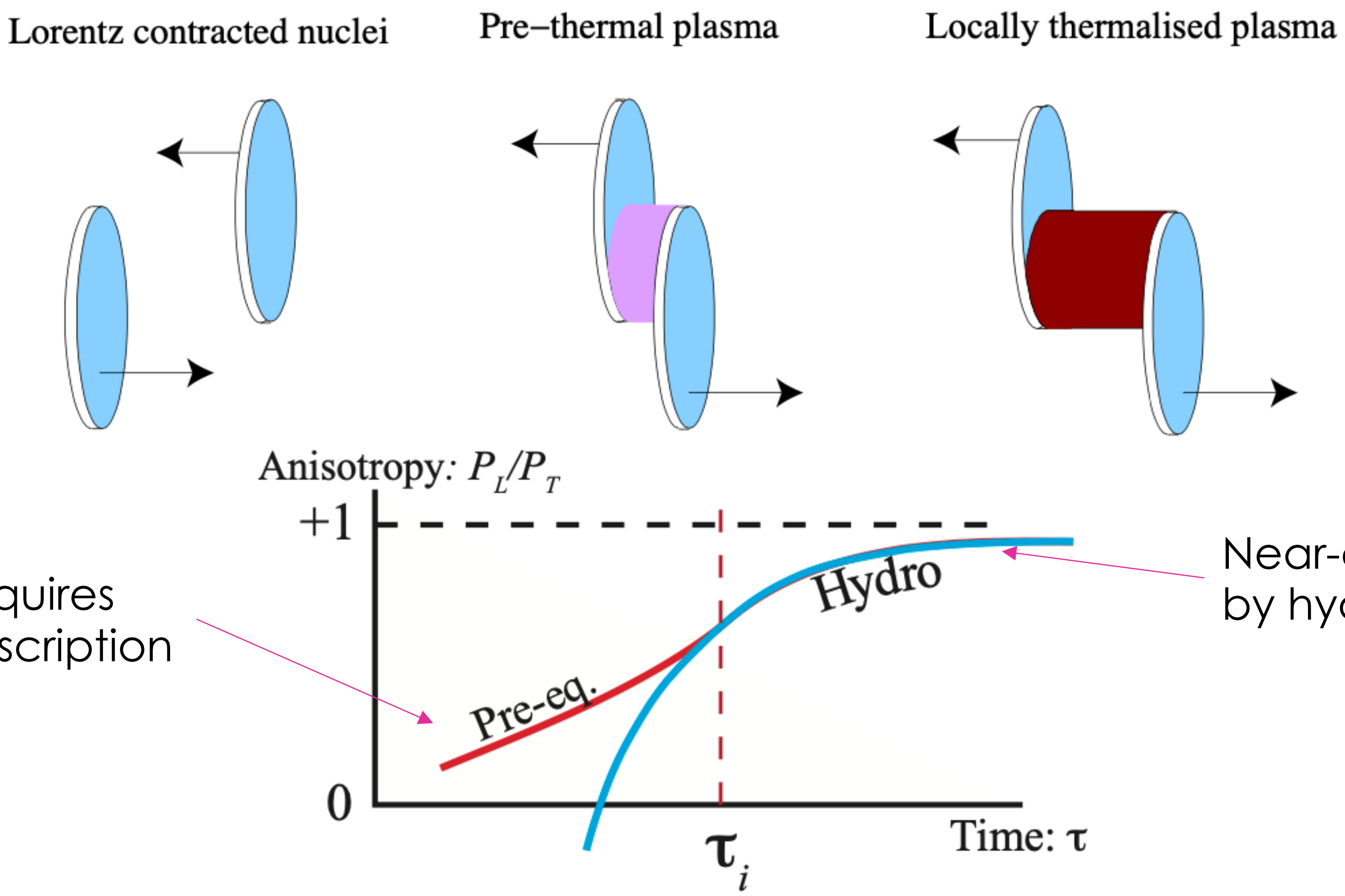
Oslo and Bergen groups

Microscopic structure of quark gluon plasma:

Microscopic structure becomes accessible when fluid-dynamical paradigm is strained, in systems that are **hydrodynamizing**:

- Jets in dense medium
  - hydrodynamization as a function of energy
- Early-time dynamics of Heavy-Ion collisions
  - Hydrodynamization as a function time
- Transition from e^+e^-, pp, pA to AA
  - Hydrodynamization as a function of system size

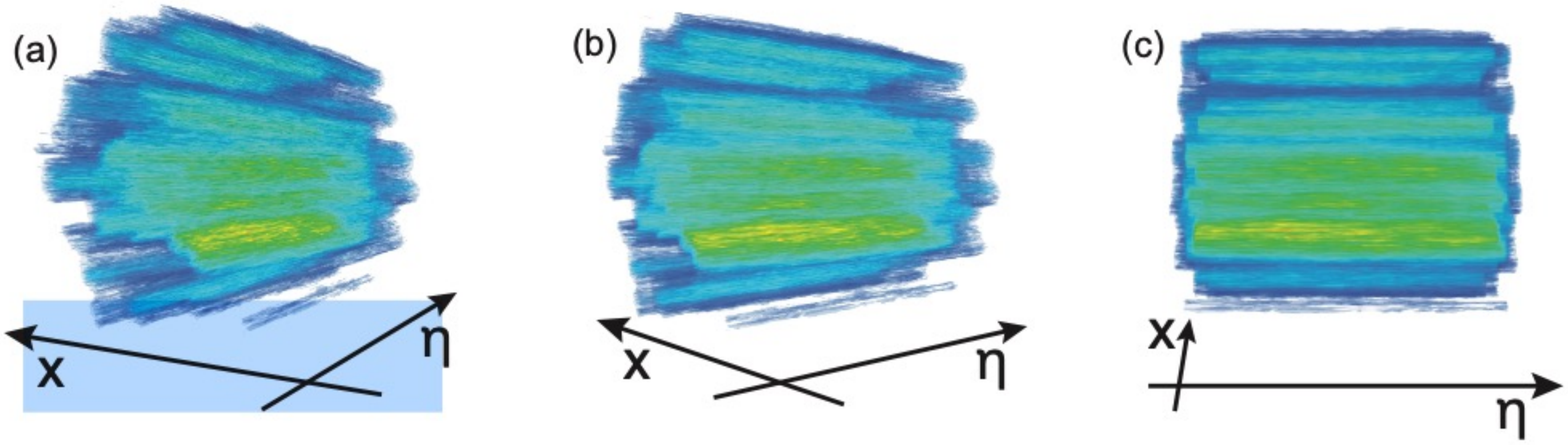
Early-time dynamics in HIC



Pre-equilibrium requires a microscopic description

Near-equilibrium described by hydrodynamics

Early-time dynamics in HIC



Schenke, Schlichting, PRC 94 (2016)

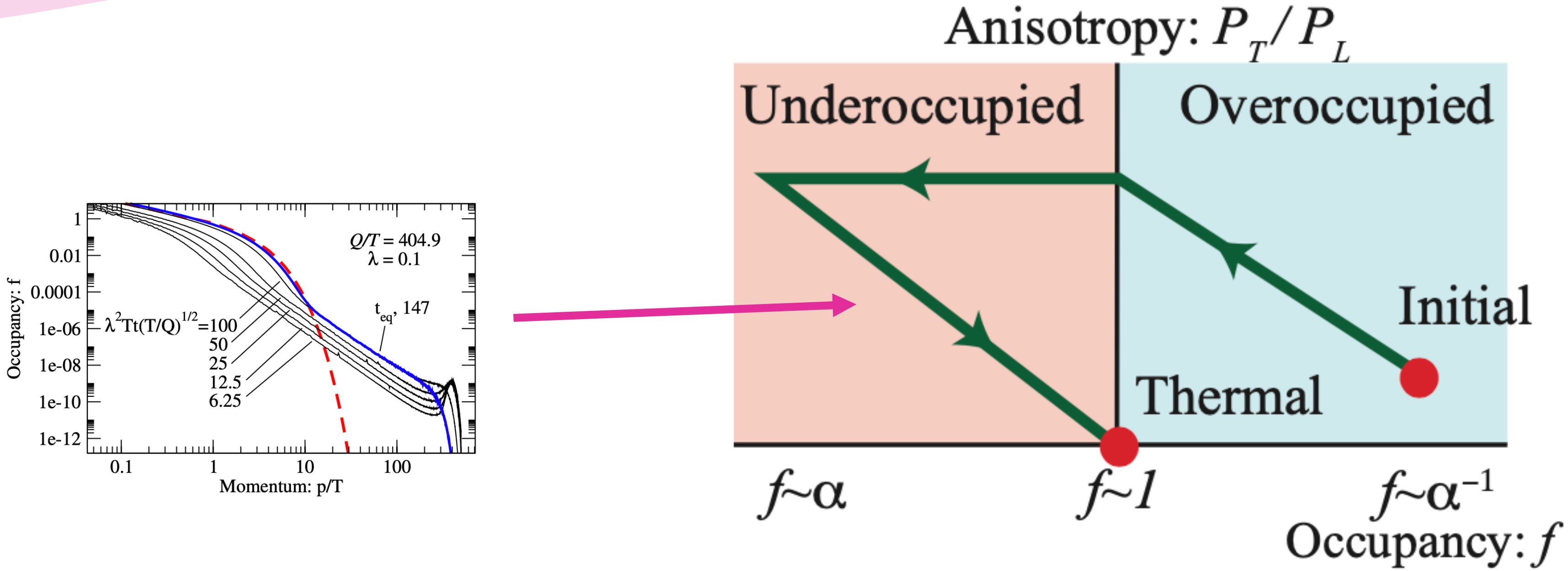
- At weak coupling α_s: **Initial condition** of HIC far from equilibrium, described by "color-glass-condensate" effective theory

McLerran, Venugopalan PRD49 (1994) 2233-2241 , PRD49 (1994) 3352-3355; Lappi, McLerran NPA 772 (2006); Gelis et. al Int.J.Mod.Phys. E16 (2007) 2595-2637 , Ann.Rev.Nucl.Part.Sci. 60 (2010) 463-489,

- Approach to equilibrium can be followed with the same transport-framework as jet thermalization

Jyväskylä group

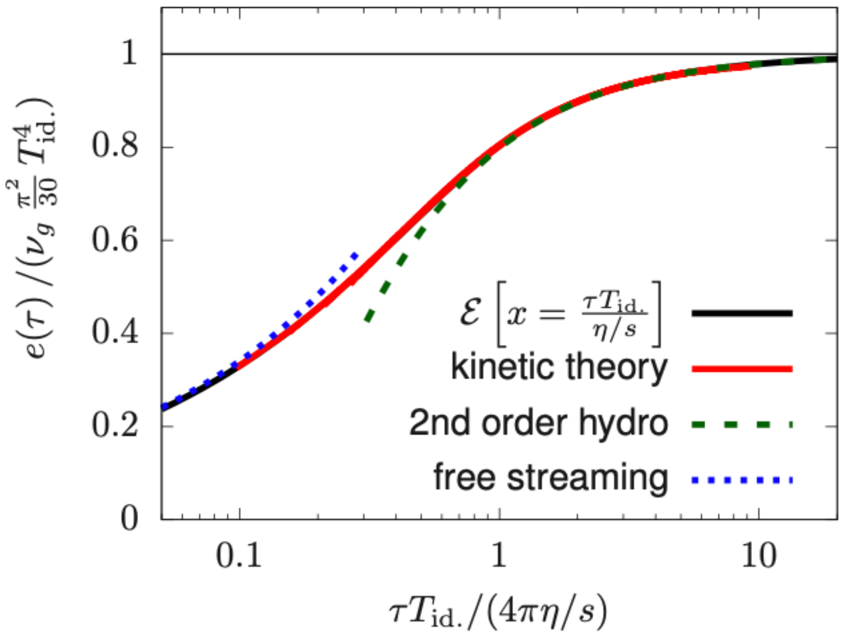
Early-time dynamics in HIC

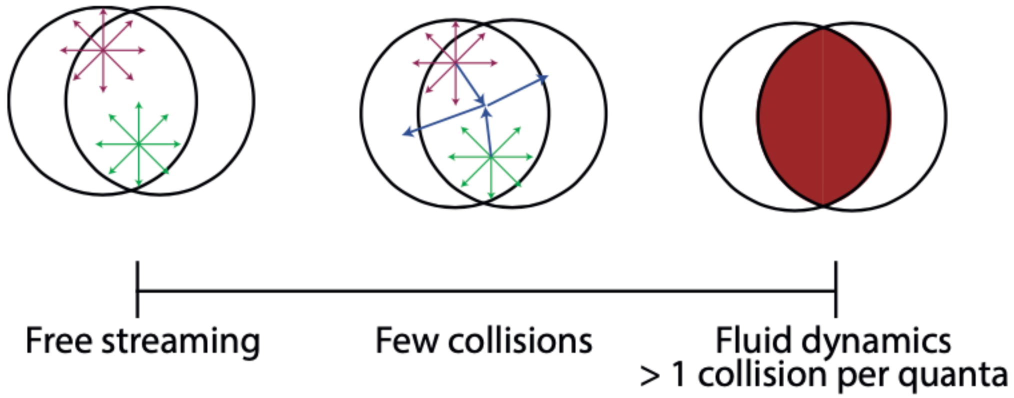


- "Bottom-up" thermalization:
  - Initial condition overoccupied and anisotropic
  - Expansion makes system **underoccupied** before thermalization
  - Initial partons undergo a **radiative cascade** to form a medium

Baier at al A, Phys. Lett. B502 (2001) 51

Early-time dynamics in HIC





- Hydrodynamics approached smoothly and automatically

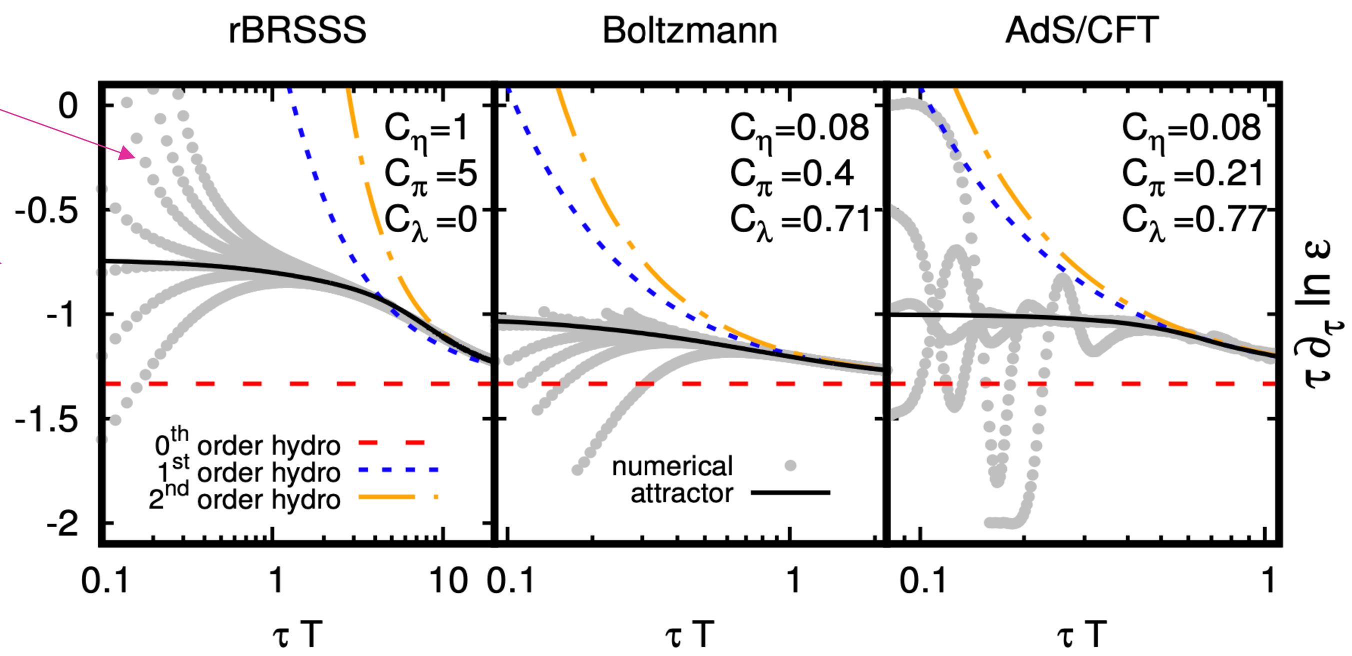
AK, Zhu, PRL 115 (2015) 18, 182301
AK et al. PRL 122 (2019)

$$\tau_i \approx 1.1\mathrm{fm/c}\left(\frac{4\pi(\eta/s)}{2}\right)^{3/2}\left(\frac{\langle\tau s\rangle}{4.1\mathrm{GeV}^2}\right)^{-1/2}$$

Early-time dynamics in HIC

Various initial coditions

Attractor



Romatchke 1704.08699;
Blaizot,Yan 1712.03856;
Strickland 1809.01200;
Almaalol et al 2004.05195;
Kamata et al. 2004.06751;
Du, Schlichting 2012.09079 ,
…

- Many initial conditions decay quickly to **non-equilibrium attractor** before *hydrodynamization*
  - Observed in wide variety of models with HIC geometry
  - Connection to resurgence and trans-series

Microscopic structure of quark gluon plasma:

Microscopic structure becomes accessible when fluid-dynamical paradigm is strained, in systems that are *hydrodynamizing*:

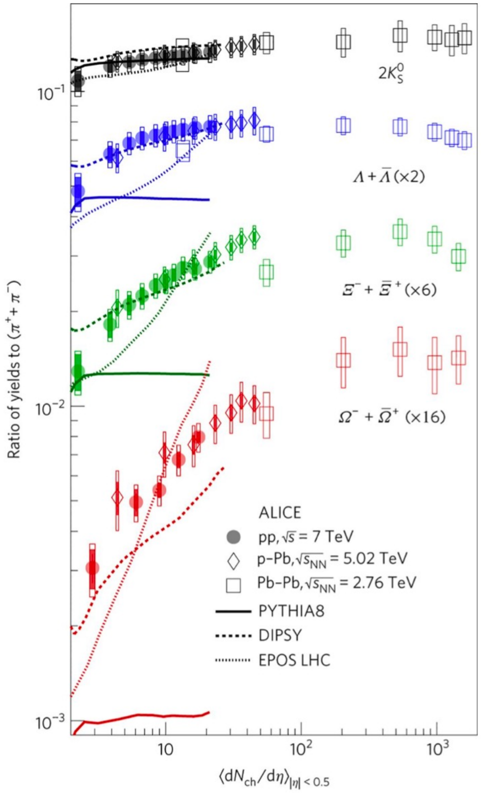
- Jets in dense medium
  - hydrodynamization as a function of energy
- Early-time dynamics of Heavy-Ion collisions
  - Hydrodynamization as a function time
- Transition from e^+e^-, pp, pA to AA
  - Hydrodynamization as a function of system size

Transition from small to large systems:

"*Collectivity*" arisies gradually as a function of system size:

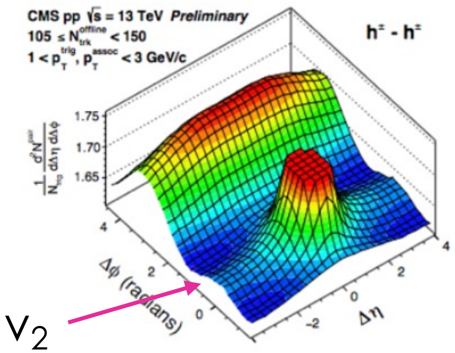
Azimuthal anisotropies:

Strangeness enhancement:

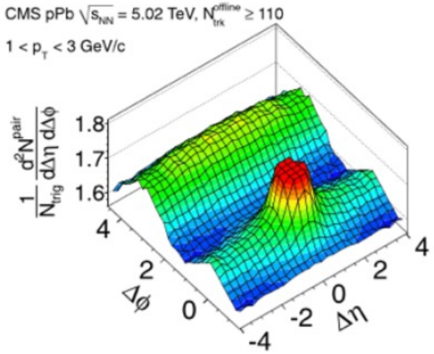


ALICE Nature Phys. 13 (2017) 535-539

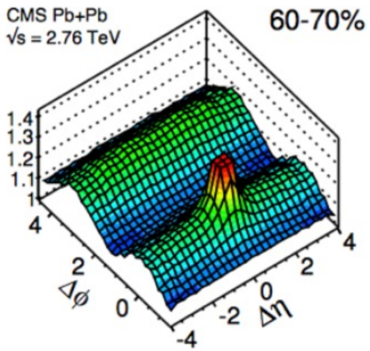
pp:



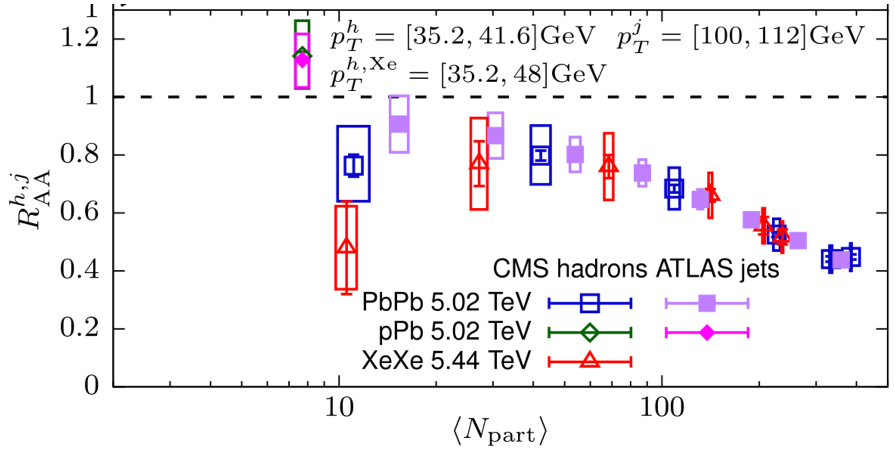
pA:



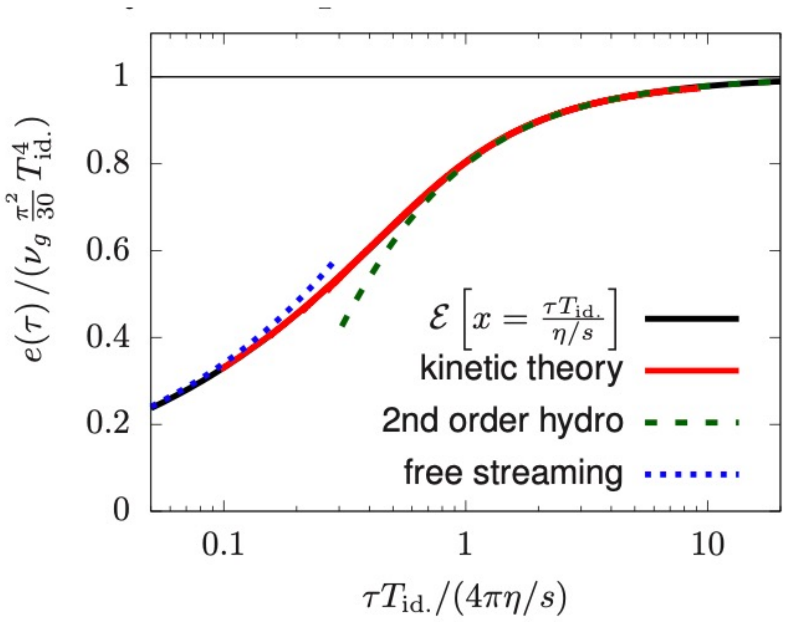
AA:

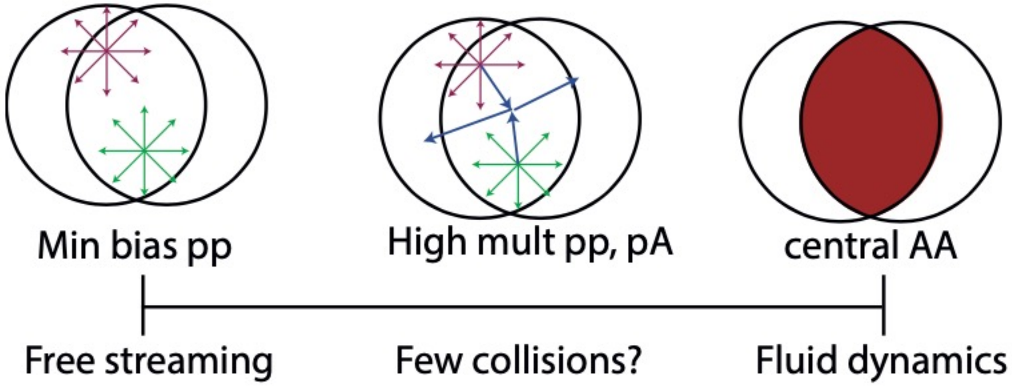


Jet energy-loss:

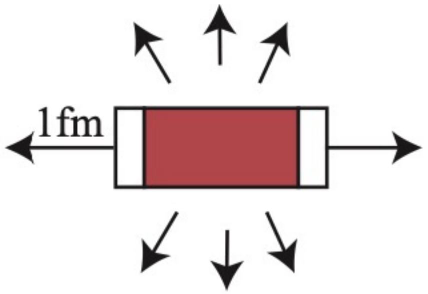


Transition from small to large systems:





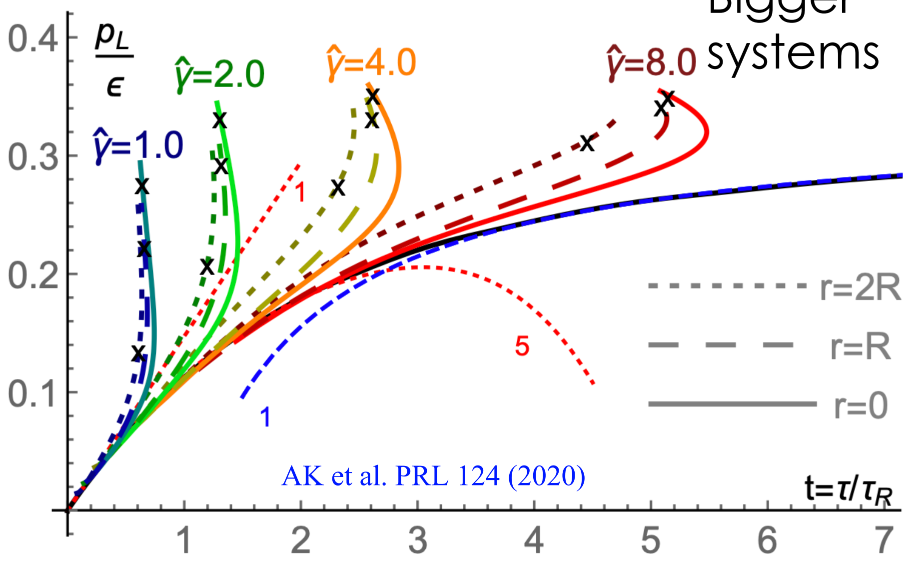
Once $\tau \sim R$, the system explodes in 3D and the evolution terminates:

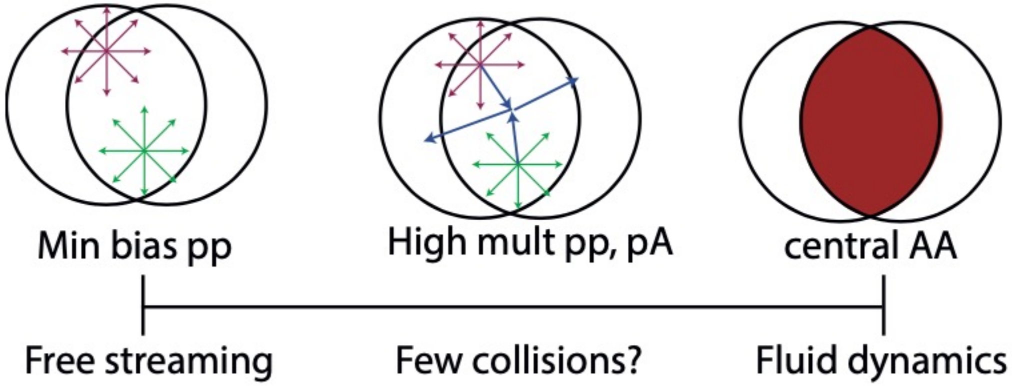


Transition from small to large systems:

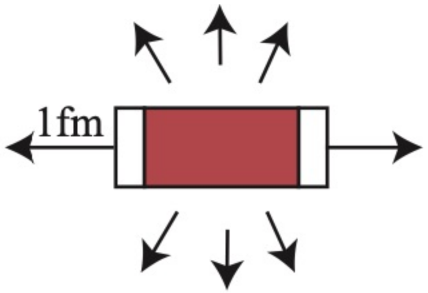
Bigger systems

Smaller systems

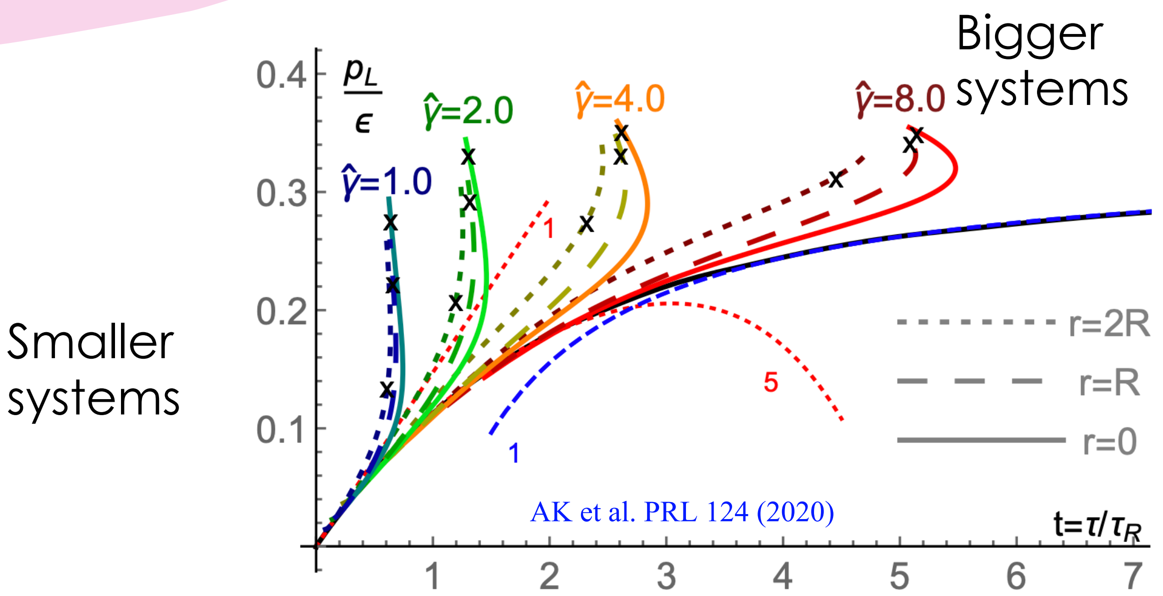


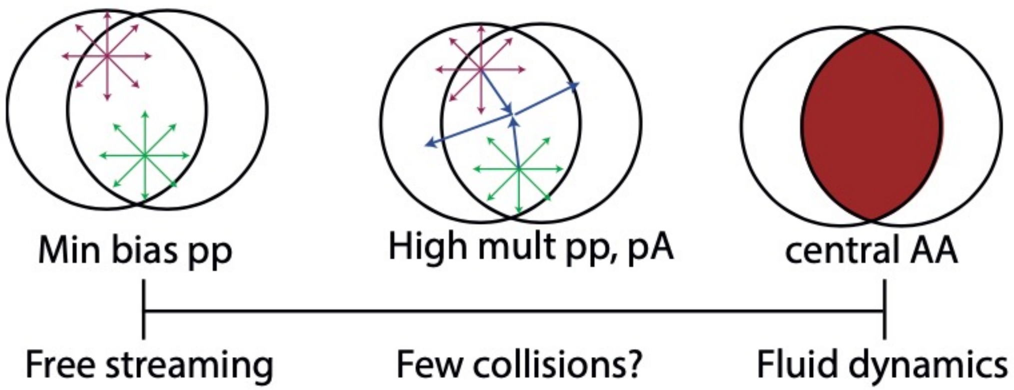


Once $\tau \sim R$, the system explodes in 3D and the evolution terminates:

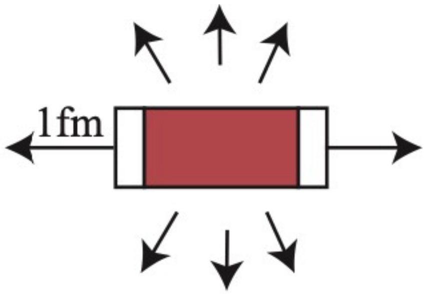


Transition from small to large systems:





Once $\tau \sim R$, the system explodes in 3D and the evolution terminates:



Important complementary developments of final-state interactions from Monte-Carlo side

Lund group

Conclusions

Wenya Wu's talk

- I could have talked about many other things

Theoretical development in relatvistic fluid dynamics, magnetohydrodynamics, using HIC to study nuclear strucutre, anomalies and chiral magnetic effect, vorticity, spin-polarization and Λ-polarization, phase diagram and critical point, quarkonium suppression, nuclear PDFs, connection to neutron stars, …

Debojit Sarkar's talk

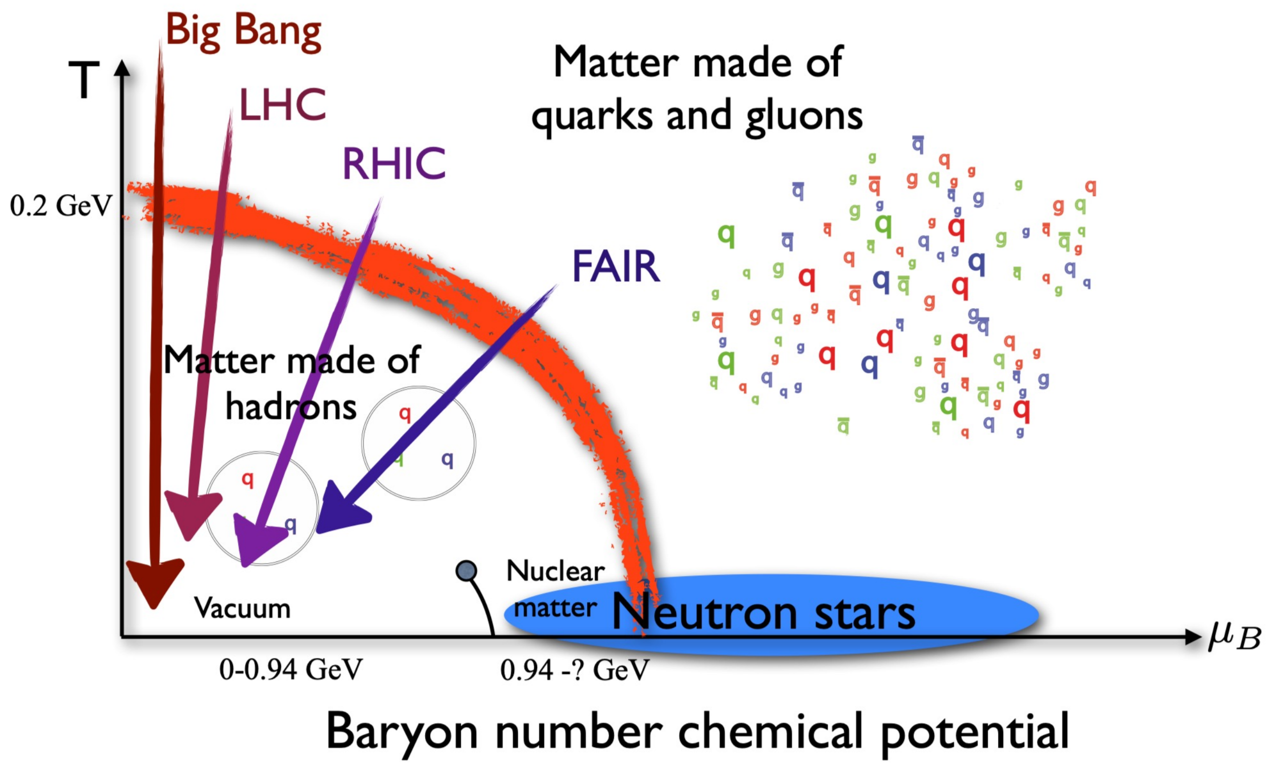
- Heavy-ion (and light-ion) collisions allow a diverse and interesting inroad to physics of QCD extreme conditions

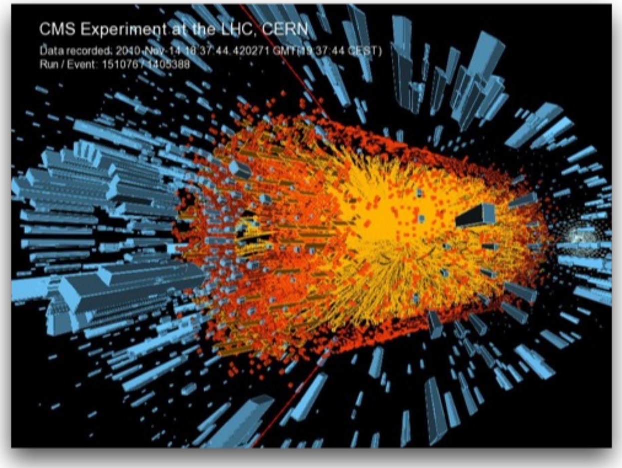
- HIC started as the study of QCD in finite temperature
  - Hydrodynamical modelling and material properites of Quark-Gluon-Plasma at precision level

- The question has evolved to include how the collective behaviour emerges from the fundamental QCD inderactions
  - How does the system go from free-streaming to strongly coupled fluid?

Extra slides:
Heavy-ion collisions and neutron stars

Elementary particle matter

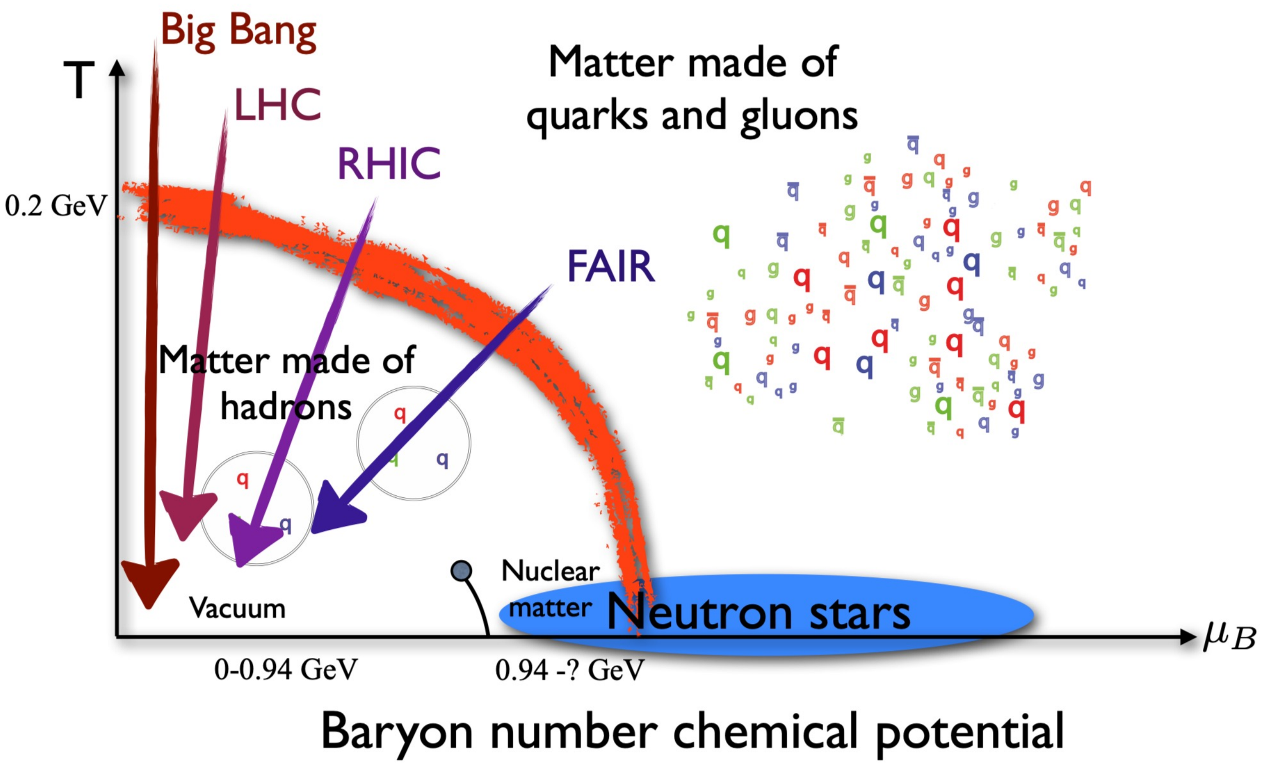


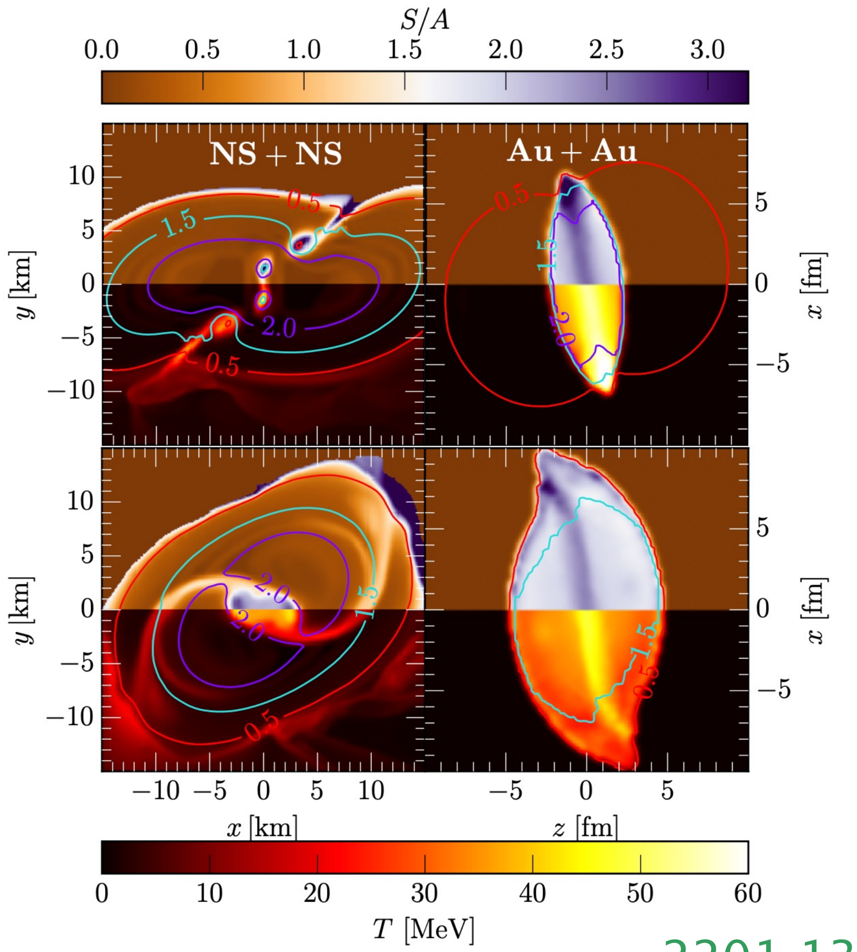


LHC, RHIC, FAIR, NICA,…

LIGO+Virgo+Kagra, NICER, eXTP,…

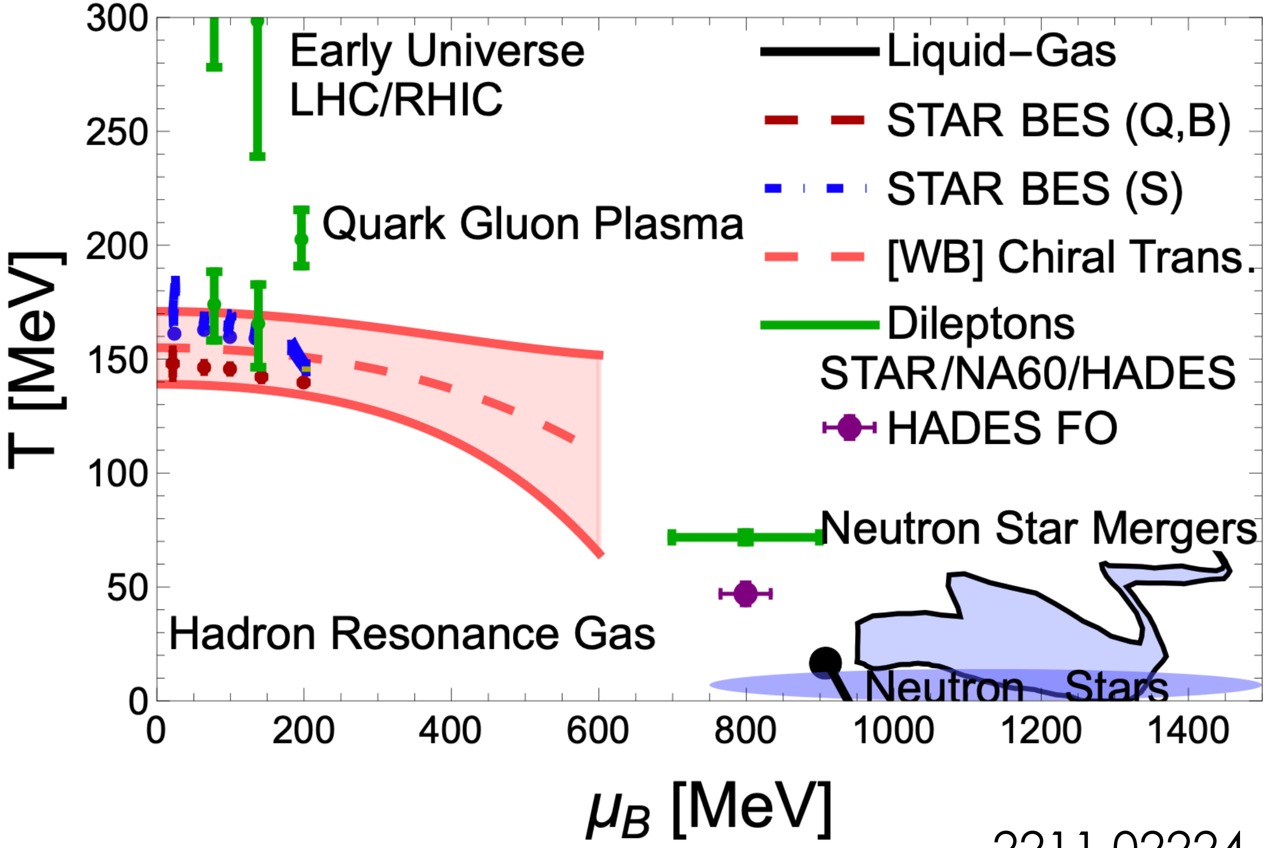
Elementary particle matter:



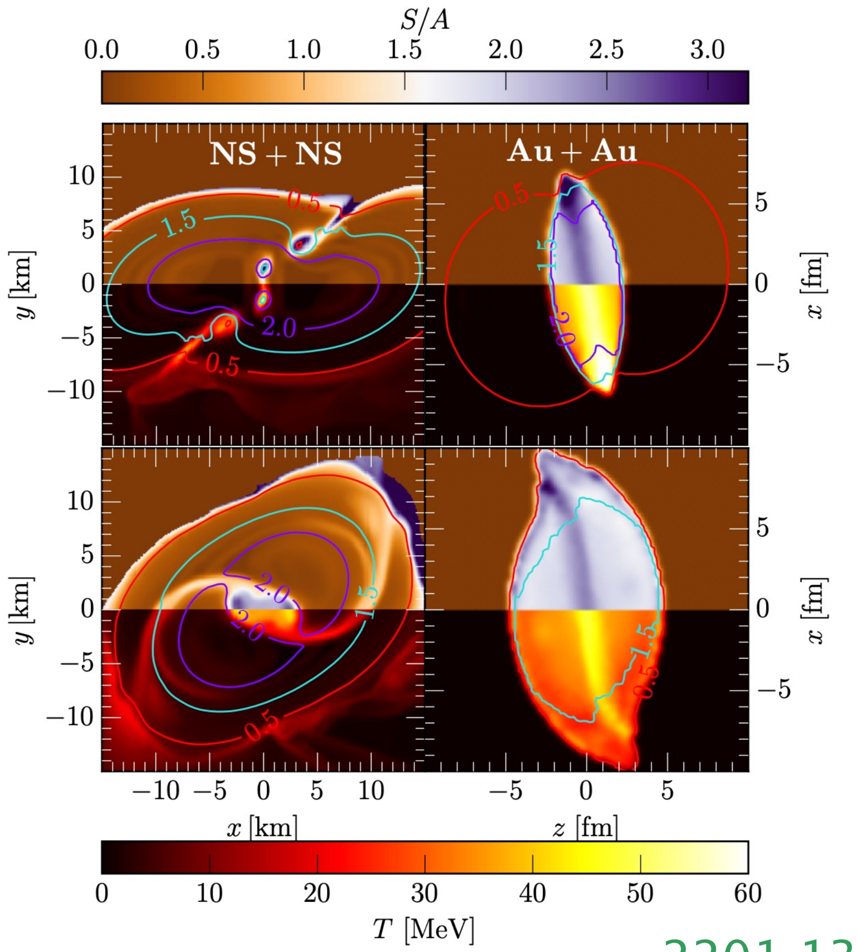


2201.13150

Elementary particle matter:

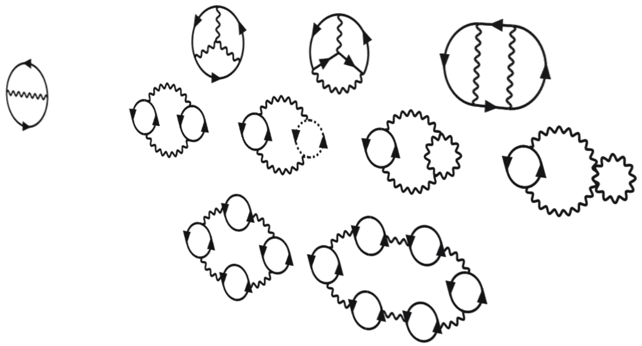


2211.02224

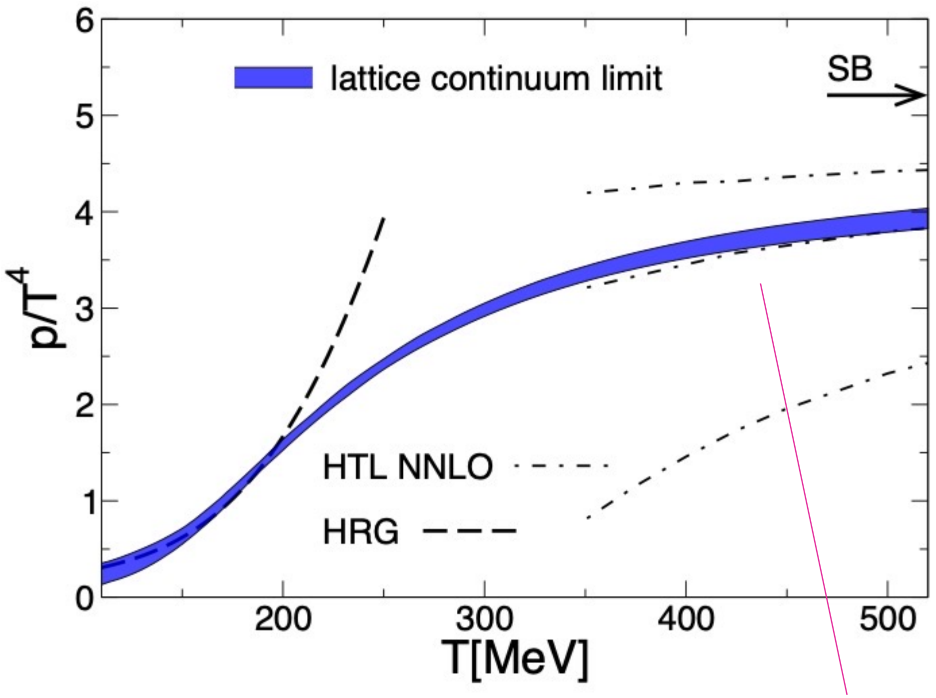


2201.13150

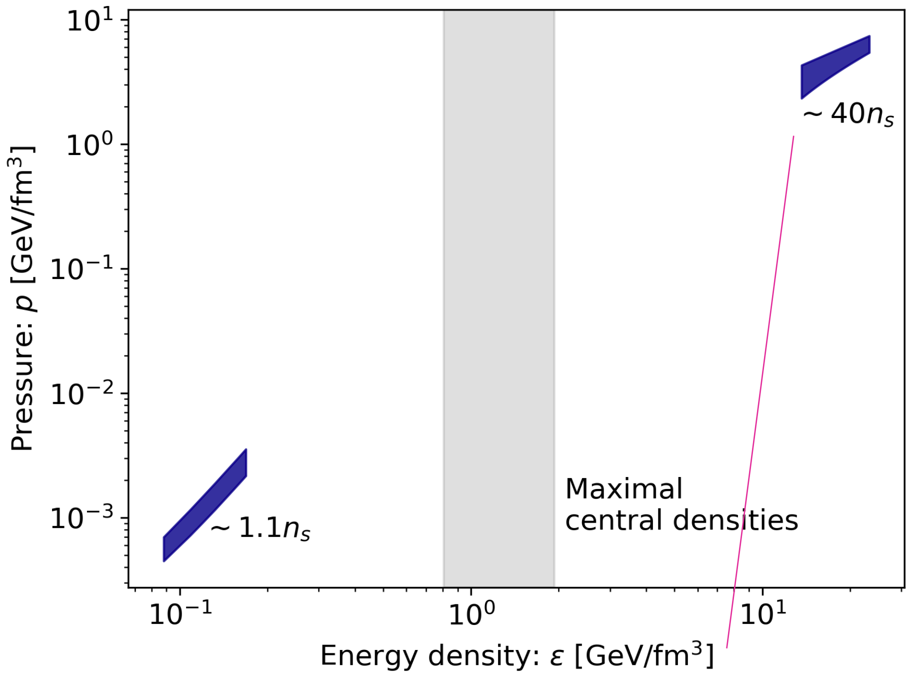
Theoretical tools from HIC to NS



EoS at high-T, LHC



EoS at high density, Neutron stars



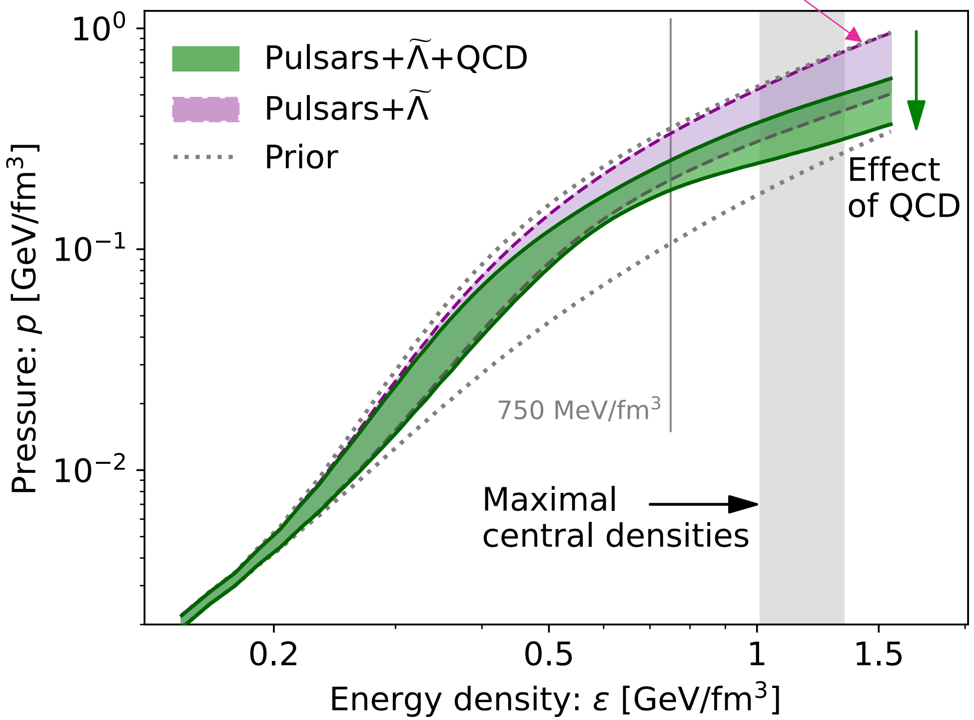
Pertrubative QCD

Pertrubative QCD

Resummed (Hard-thermal-loop) perturbation theory

Theoretical tools from HIC to NS

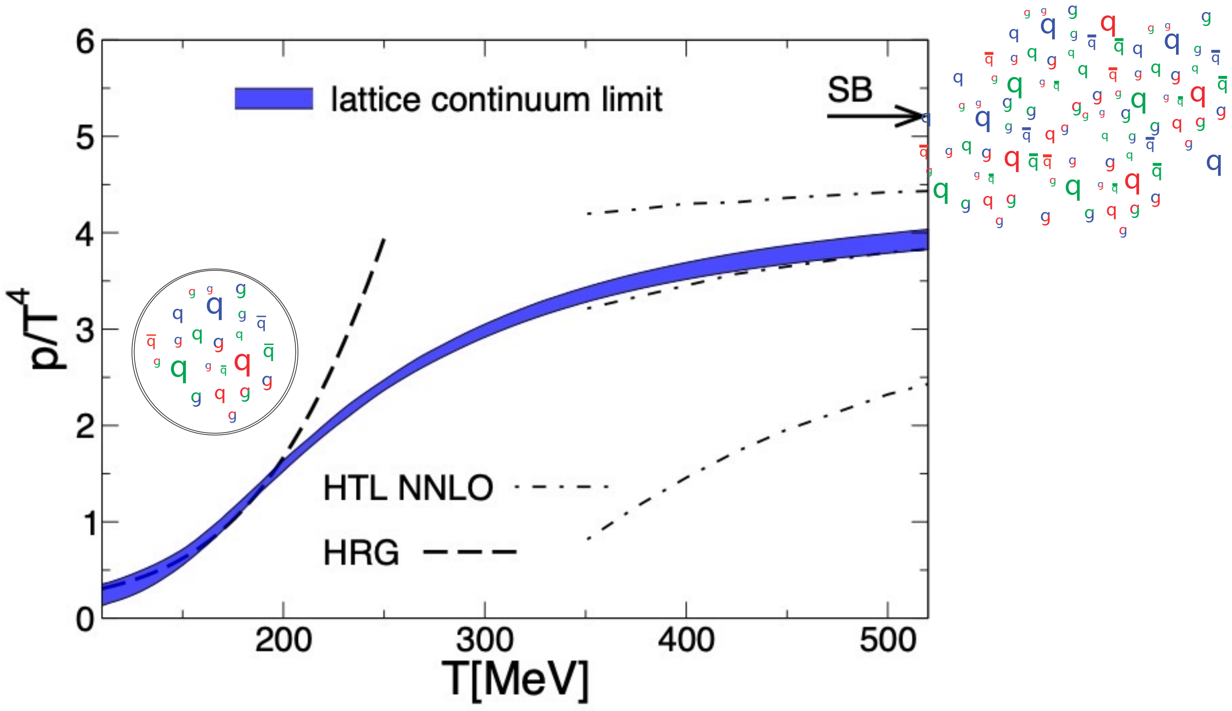
EoS Inferred from NS observvtions

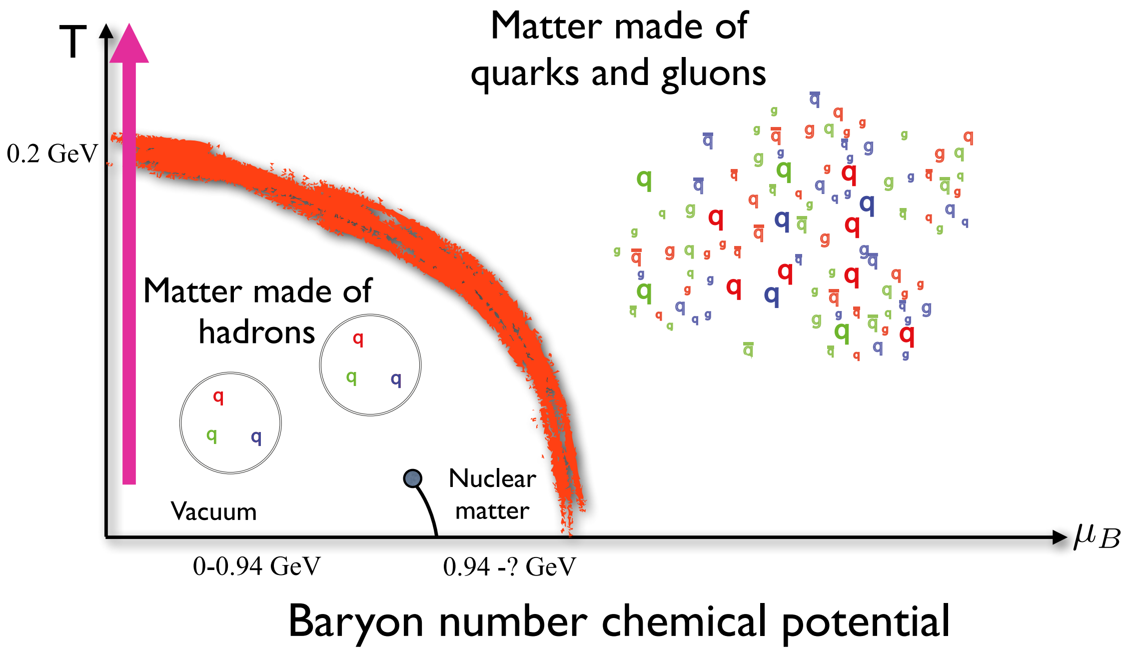


pQCD calculations, developed for HIC, significantly affect the EoS inference in Neutron Stars

Gorda, Komoltsev & Kurkela 2204.11877
Also: Annala et al. PRX 12 (2022), Altiparmak, Ecker, Rezzolla 2203.14974, Han, Huang, Tang & Yi-Zhong Fan 2207.13613, Marczenko, McLerran, Redlich & Sasaki 2207.13059, …

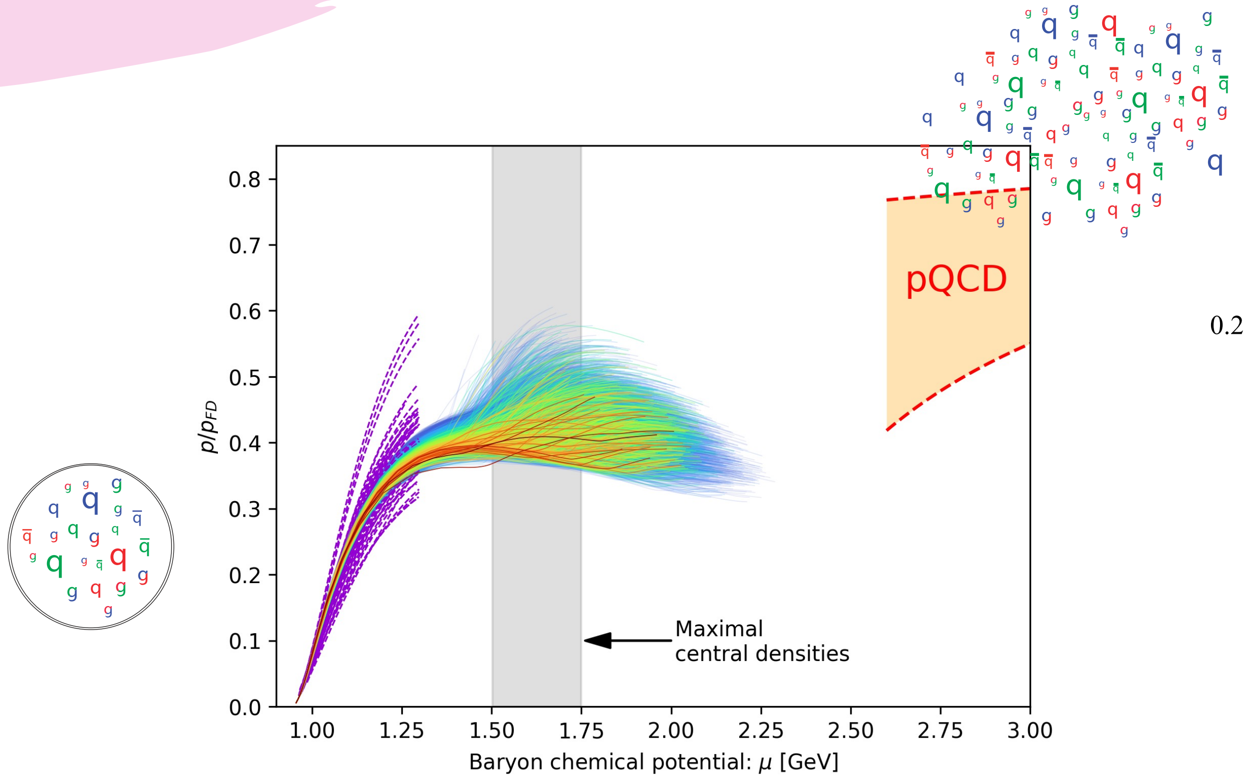
Theoretical arguments from HIC to NS

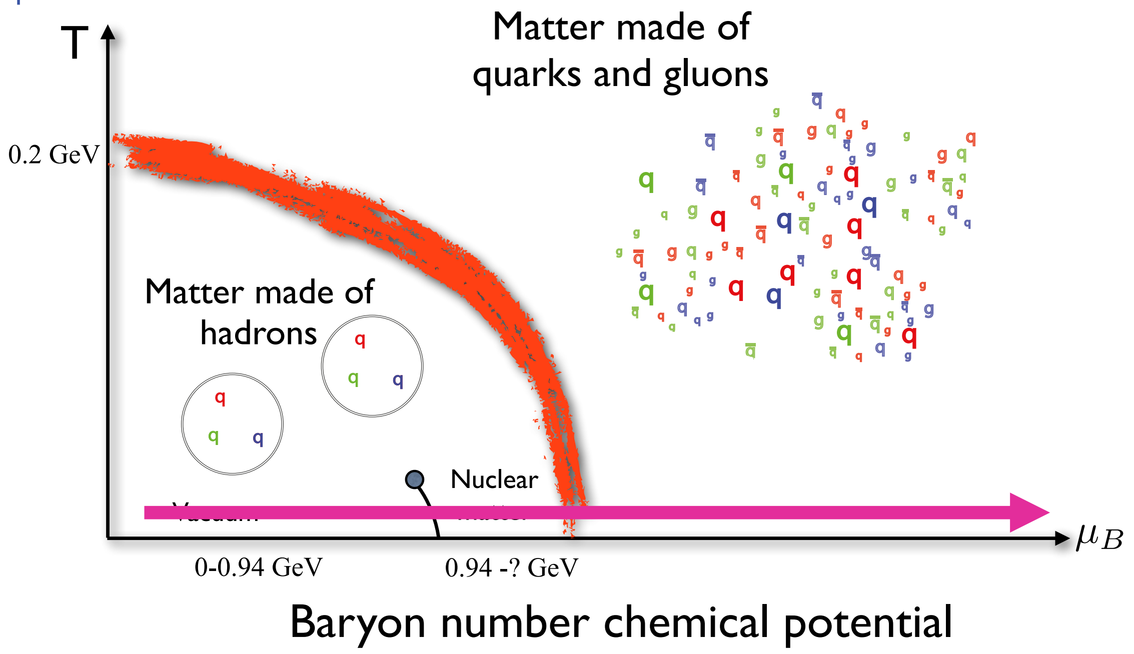




From hadronic matter to quark gluon plasma
in heavy-ion collisions

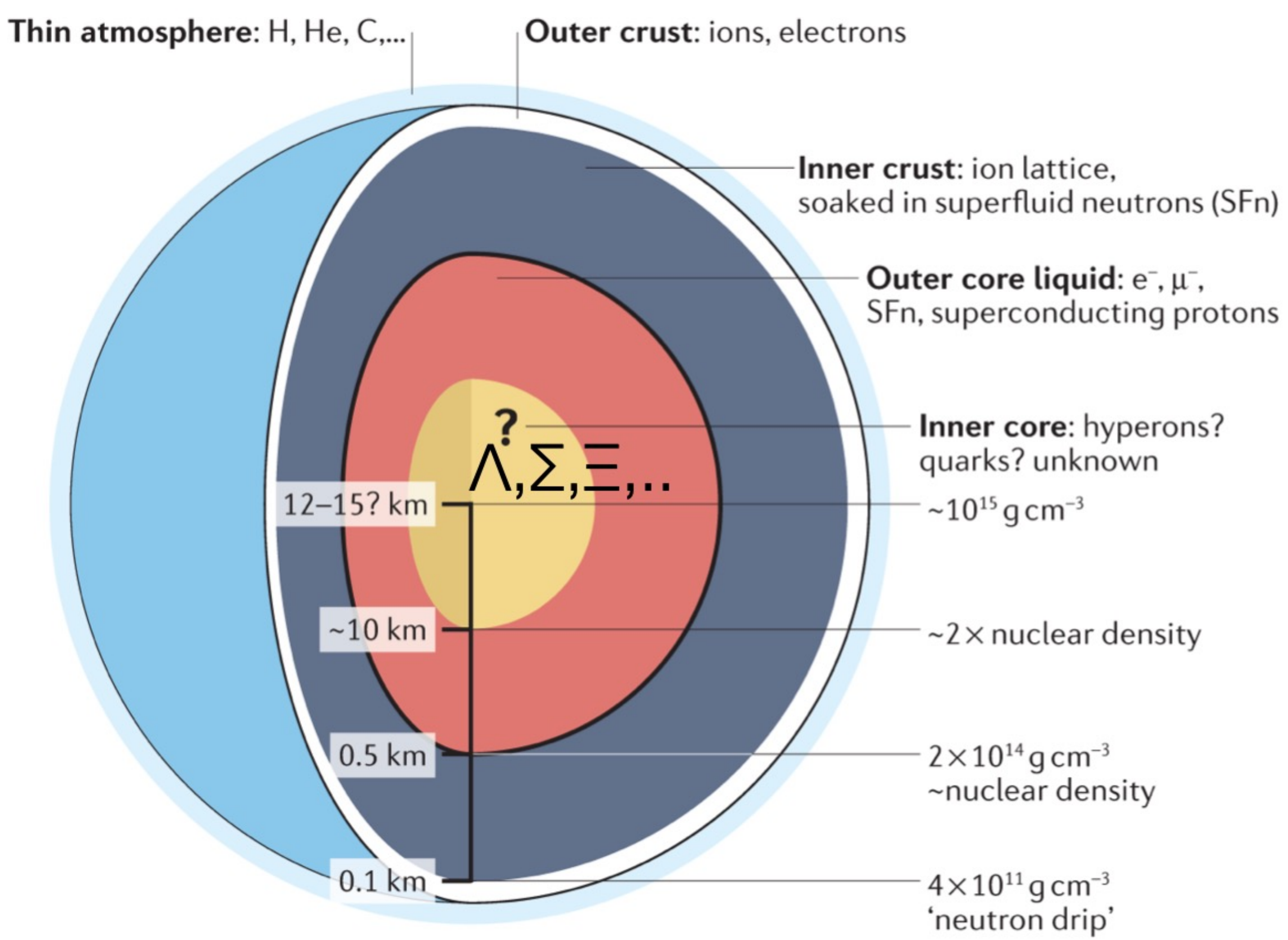
Theoretical arguments from HIC to NS





Annala, Gorda, Kurkela, Nätttilä, Vuorinen Nature Physics 16 (2020) 9
Gorda, Komoltsev & Kurkela 2204.11877
Also: Fujimoto, Fukushima, McLerran, Praszalowicz 2207.06753,
Kojo PRD 104, …

Λ's in NS and the LHC

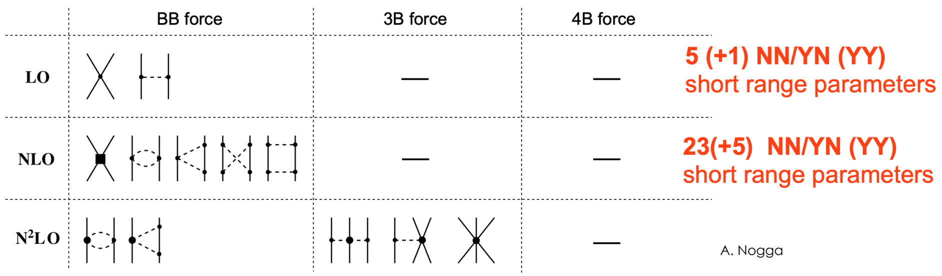


Cores of neutron stars may contain Hyperons (Lambda's in particular)

Hyperon puzzle: models suggest that the precense of hyperons make the star unstable

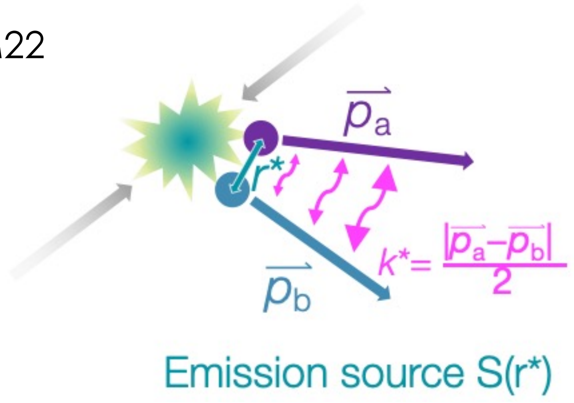
ΛΛ and Λn interactions poorly known (hypernuclei), but needed in modelling

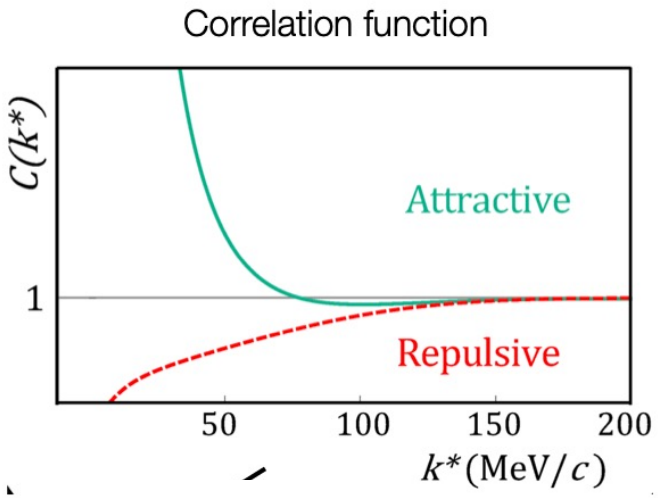
Chrial effective field theory with Λ :



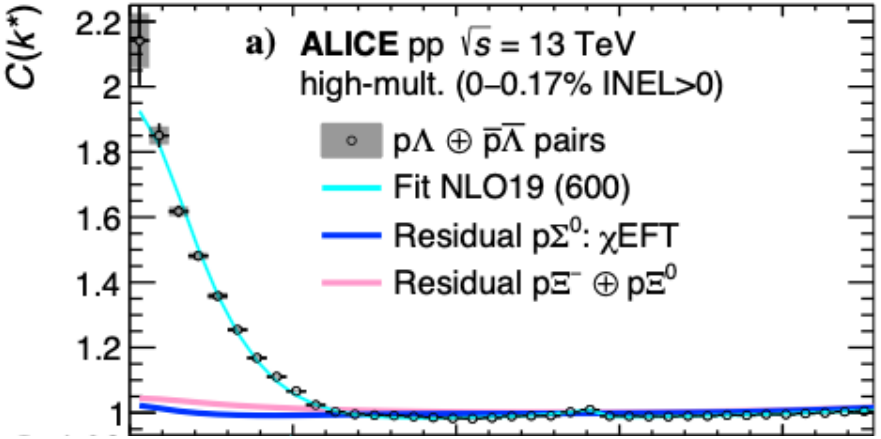
Λ′s in NS and the LHC

Sarti, QM22





pΛ



ΛΛ