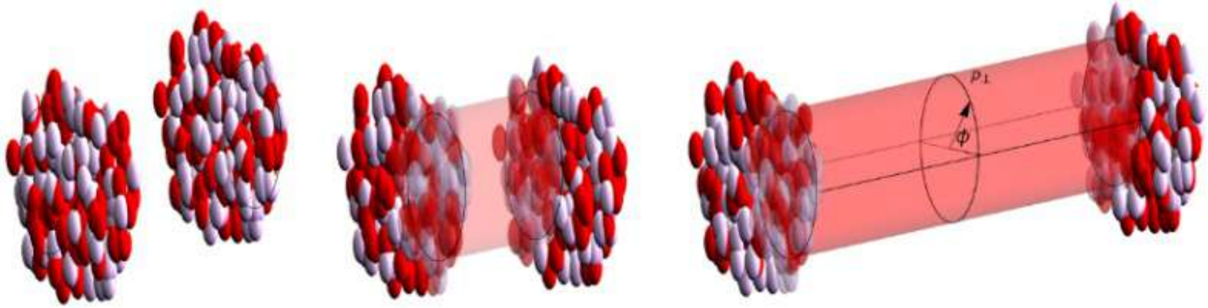
Flow and jet quenching in small systems

an inroad to the creation and properties of the densest form of matter



Urs Achim Wiedemann
Physics colloquium, Arizona State University
Online, 17 March 2021

Atomic diameter $\sim 1\mathring{A} = 10^{-10}\mathrm{m}$

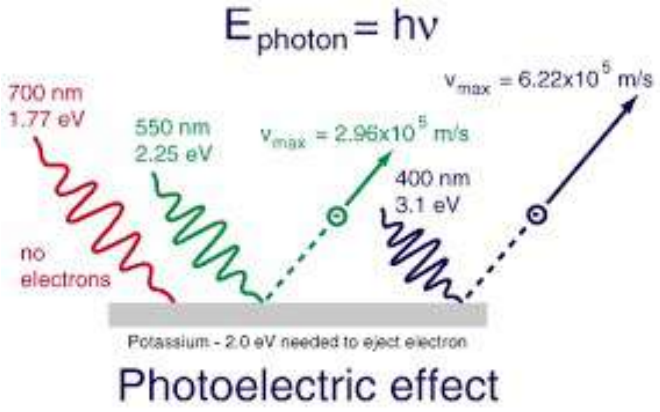
A brief history of matter

corpuscular composition of all forms of matter

1900 Planck

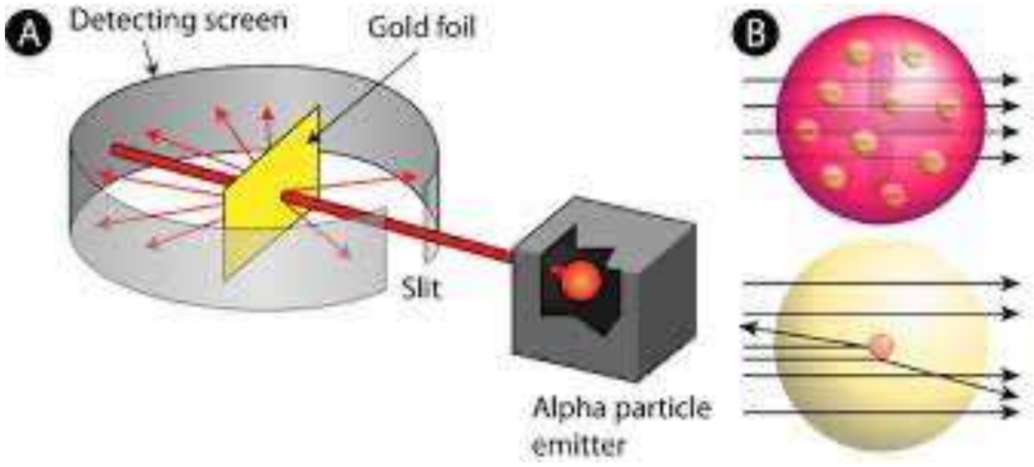
$$E = h\nu$$

1906 Einstein

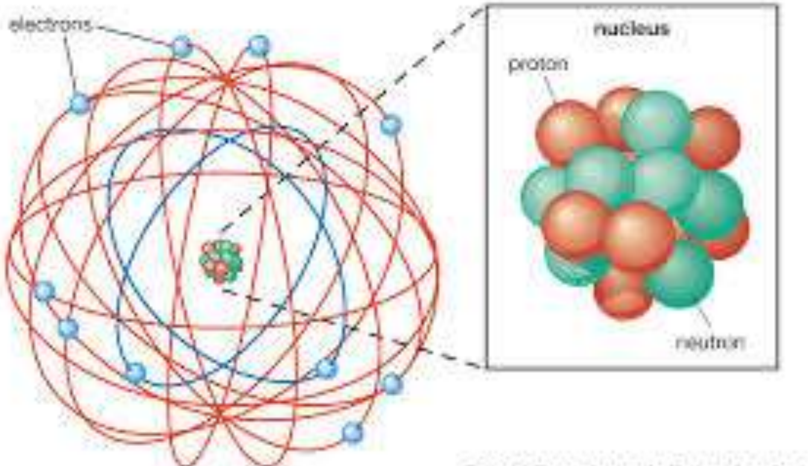


Photoelectric effect

1908-13 Rutherford



Electromagnetic interactions
explain atomic structure, chemistry, …



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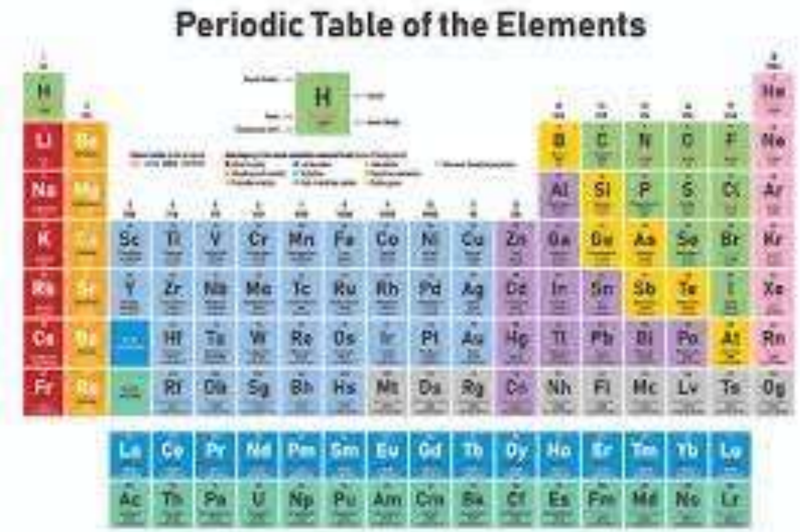


Periodic Table of the Elements

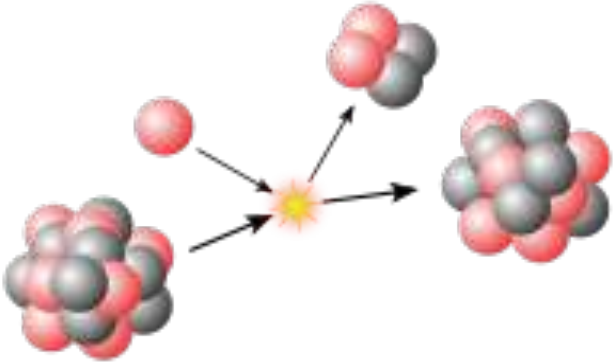
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

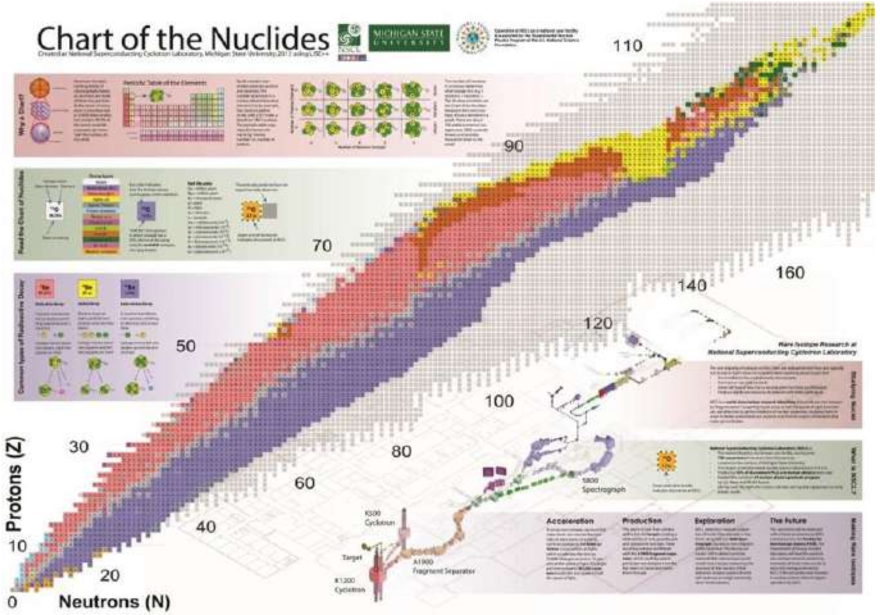
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Nuclear diameter $> 1\mathrm{fm} = 10^{-15}\mathrm{m}$

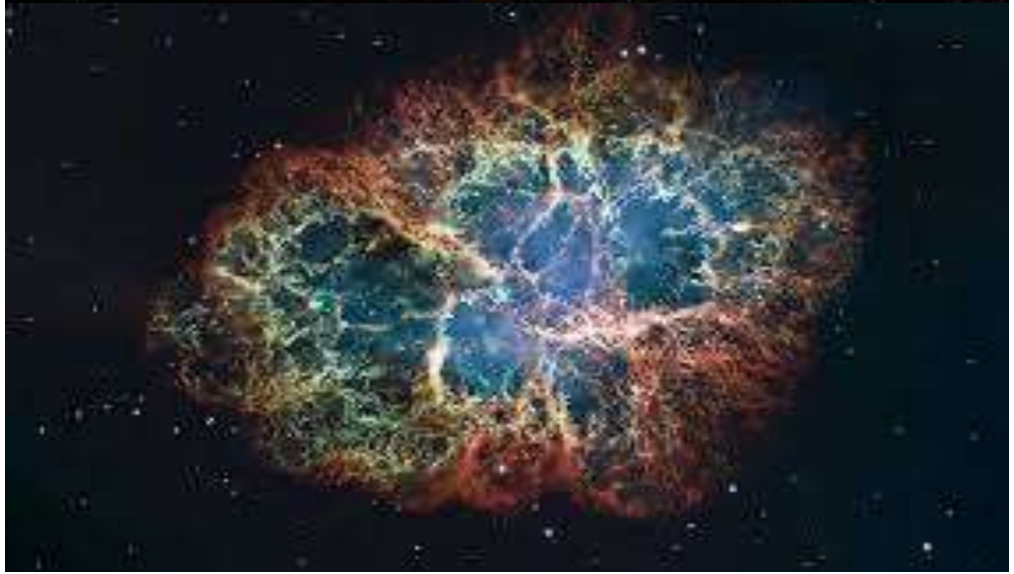
The world of nuclear structure

That’s what we test in the laboratory.





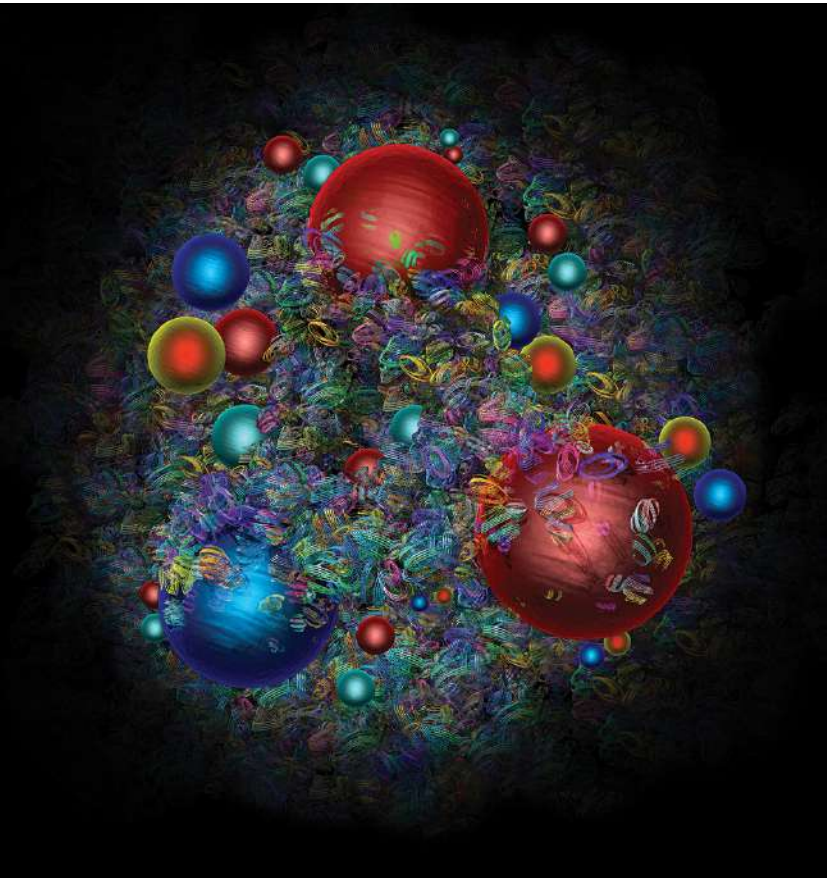
That’s where it occurs in nature.



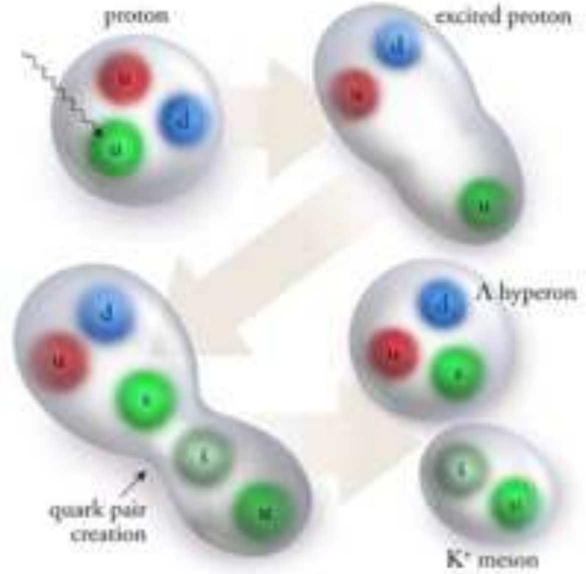
hadrons $\sim 1\,\mathrm{fm} = 10^{-15}$

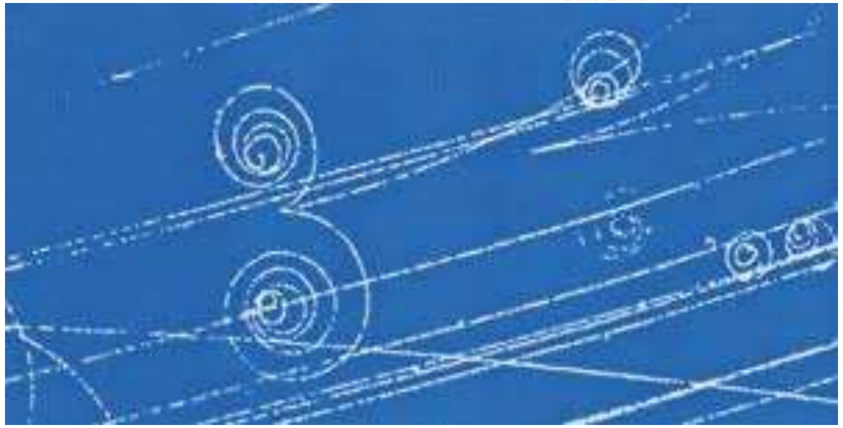
The hadronic world

What is a proton?



Its constituents cannot be isolated …

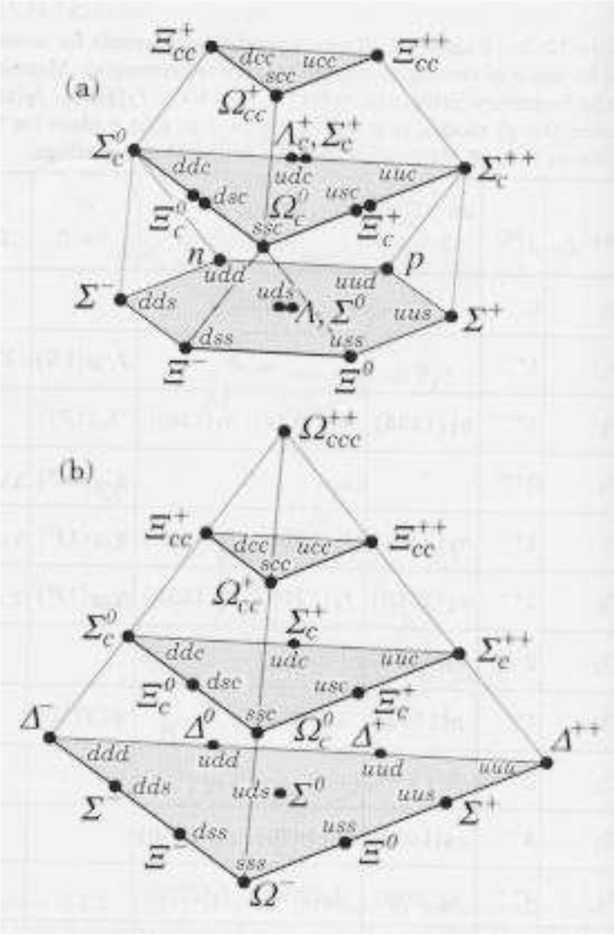




1950s / 1960s

… but they classify hadronic states

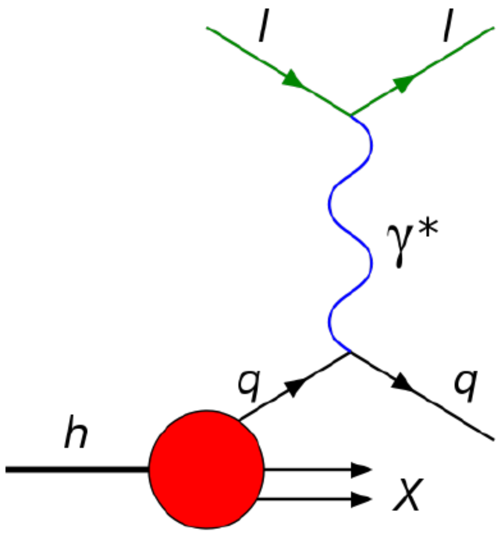
1964 M. Gell-Mann; G. Zweig



hadrons $< 1\mathrm{fm} = 10^{-15}\mathrm{m}$

Quarks and their glue

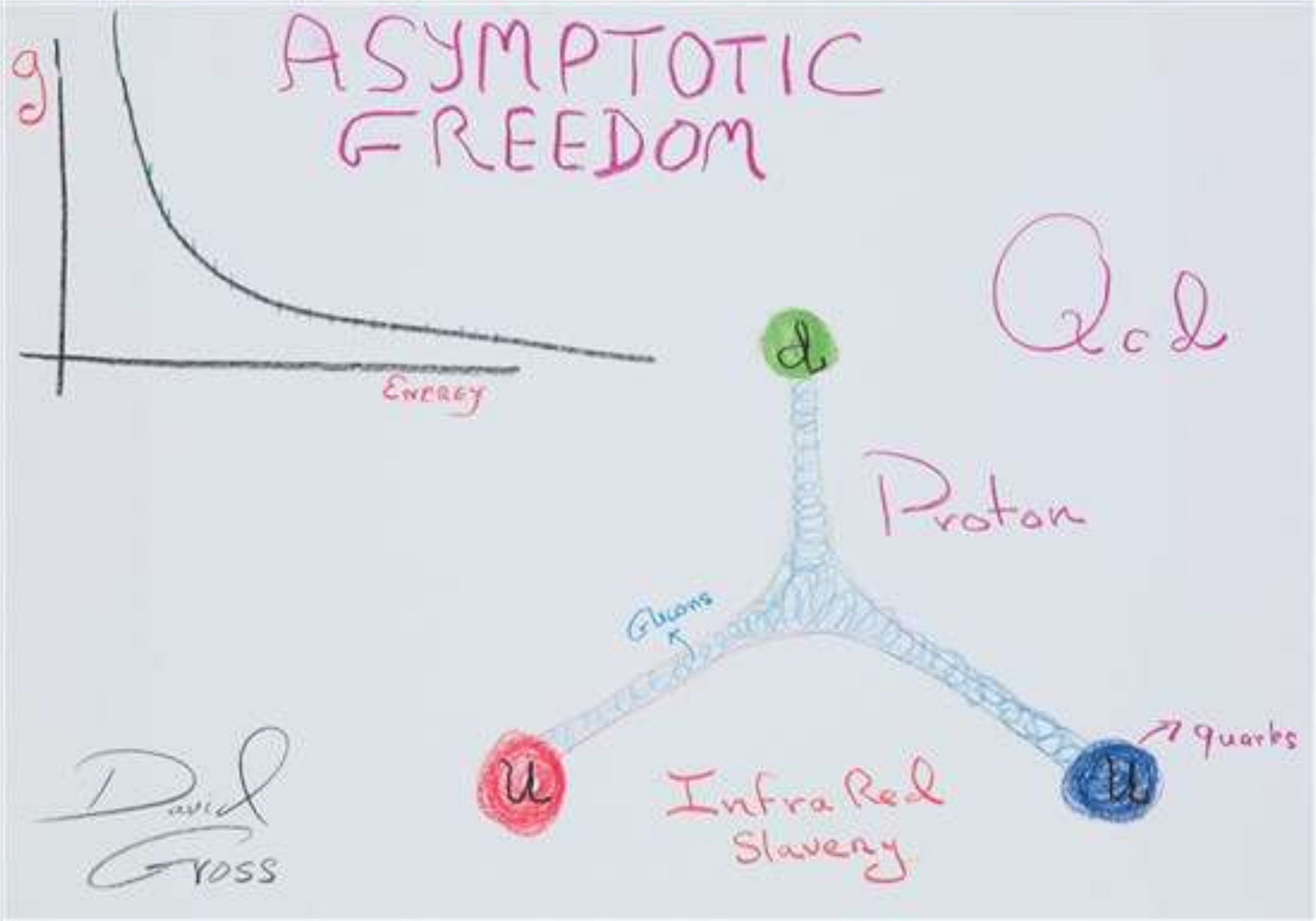
1968 SLAC deep inelastic scattering



1973 Gross, Wilczek; Politzer

Quantum **C**hromo **D**ynamics

First theory valid down to arbitrary small distances



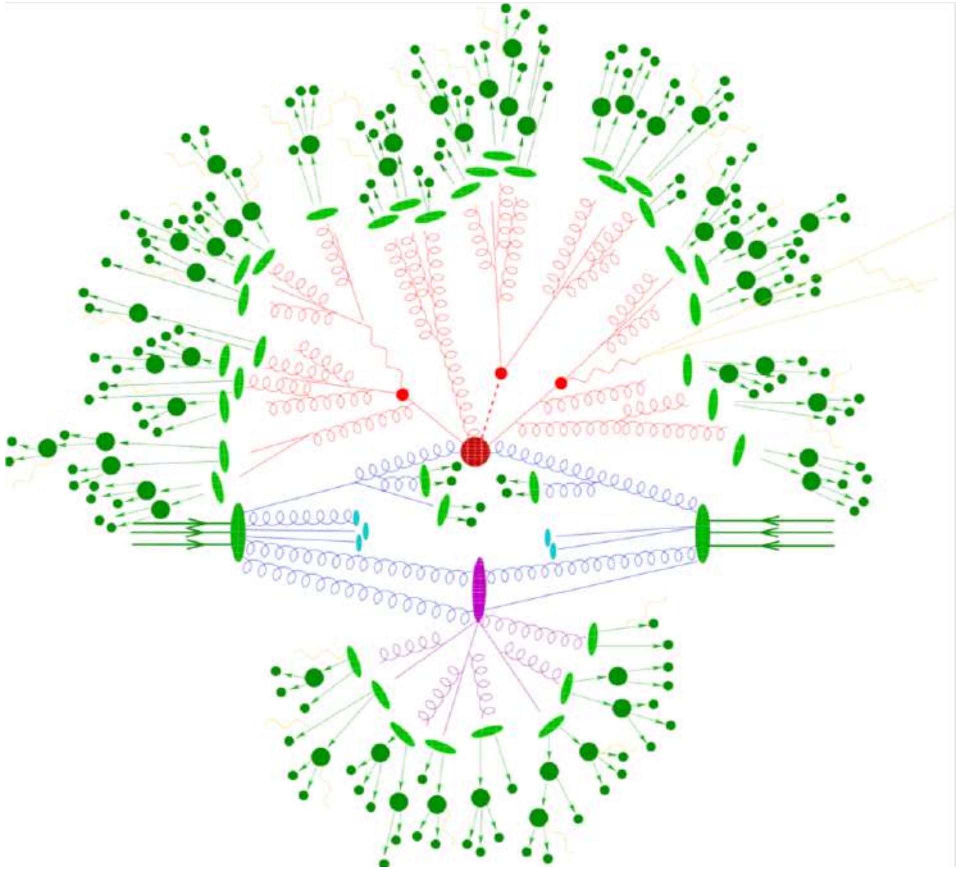
Two protons collide in the vacuum

Long distance: infrared slavery

Short distance: asymptotic freedom

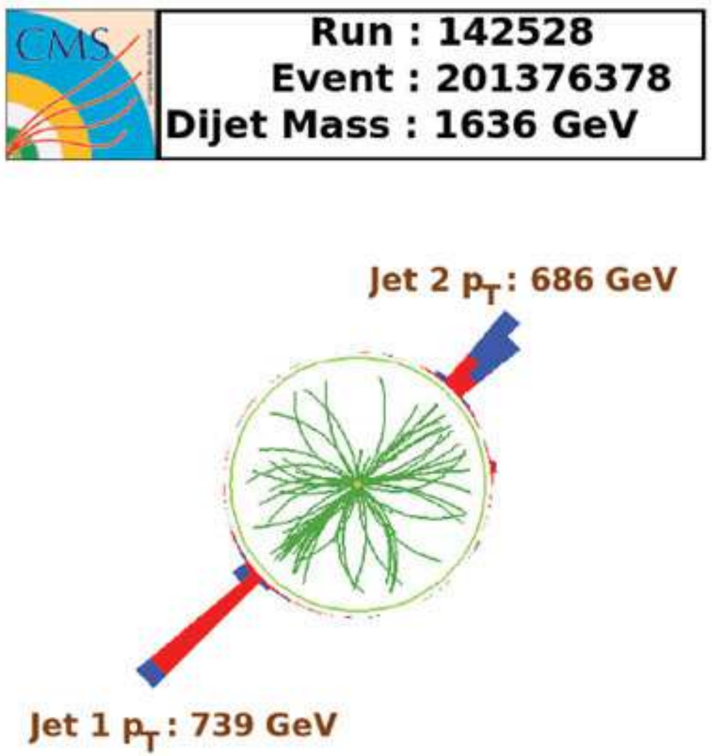
1977	Scale dependence Sterman-Weinberg Jets
1980s	Factorization theorems
1990s -	Monte-Carlo Simulations
2000s -	Precision frontier

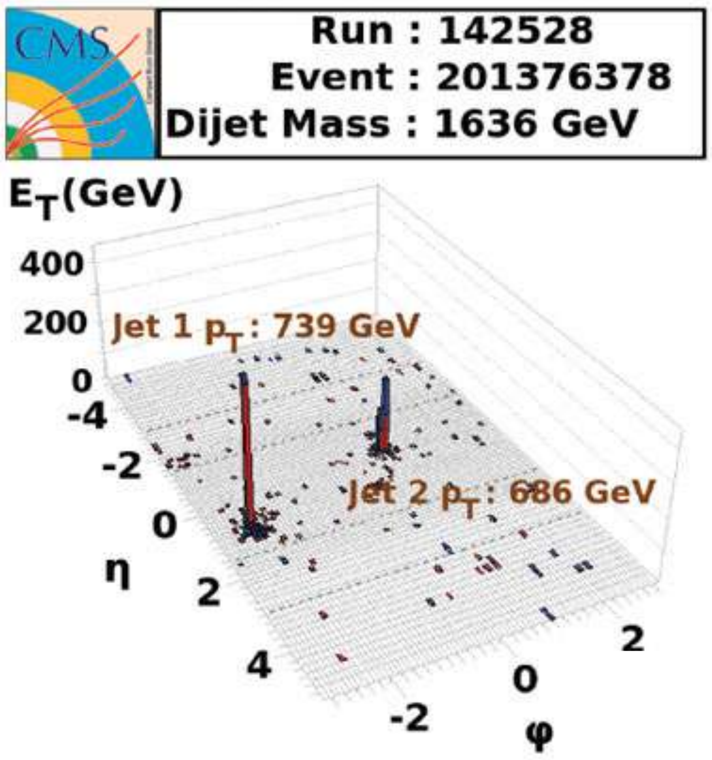
QCD provides quantitatively reliable description, based on free-streaming but fragmenting parton showers.



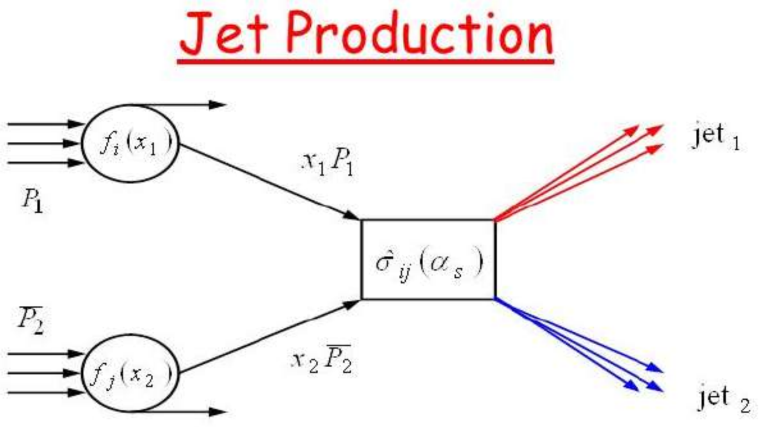
QCD Jets in the vacuum

What we measure





What we calculate



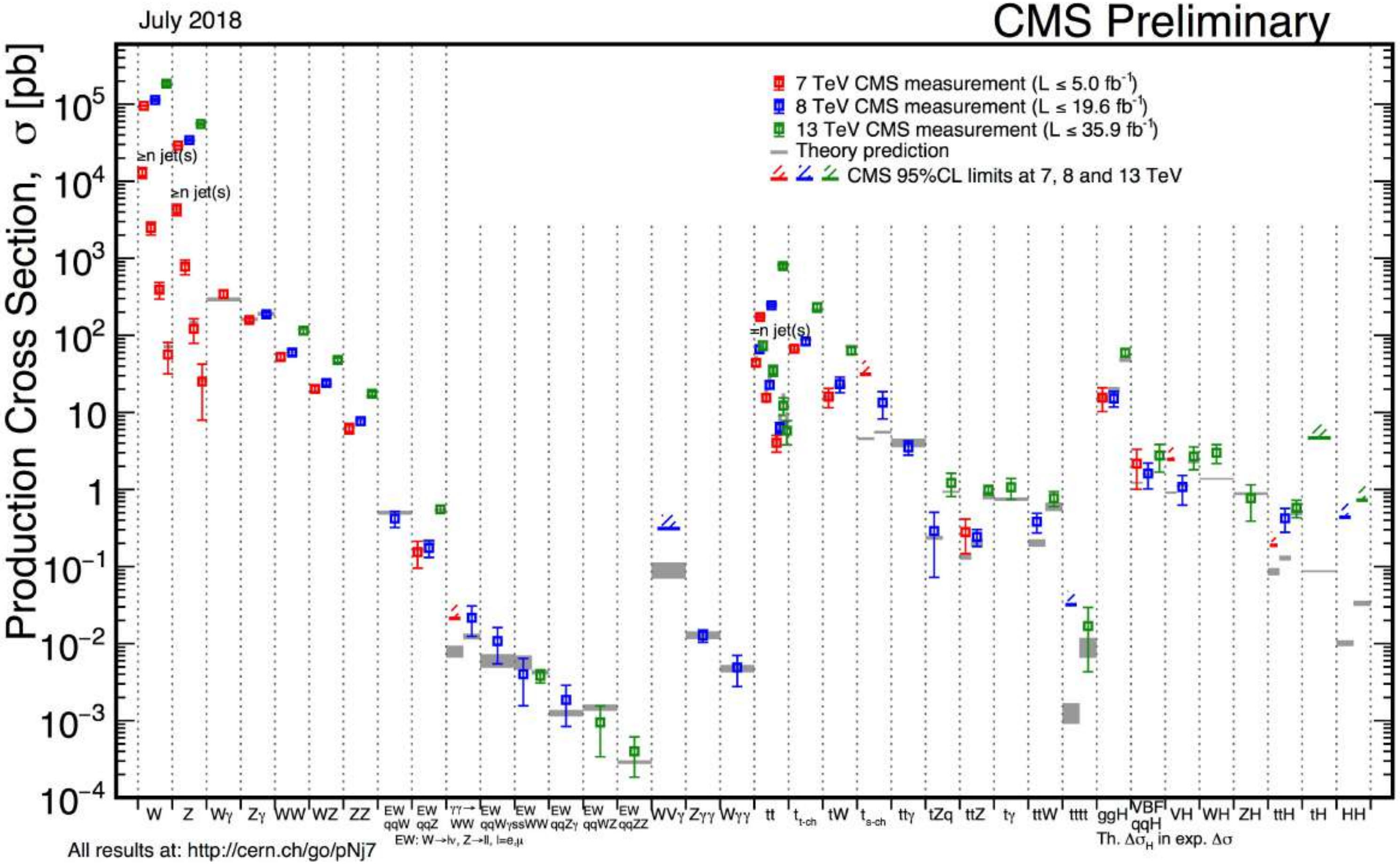
$$\sigma = \sum_{ij} \int dx_1 dx_2 \, f_i\left(x_1, \mu_F^2\right) f_j\left(x_2, \mu_F^2\right) \hat{\sigma}_{ij}\left(x_1P_1, x_2P_2, \alpha_s\left(\mu_R^2\right) \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

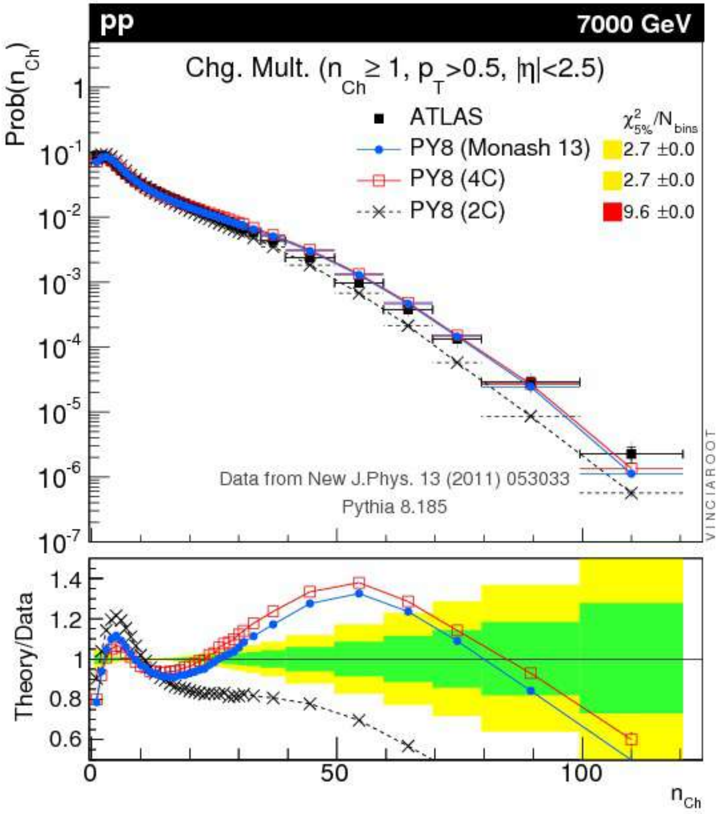
+ parton shower + hadronization
+ jet algorithm + jet substructure
+ …

QCD in vacuum – a success story

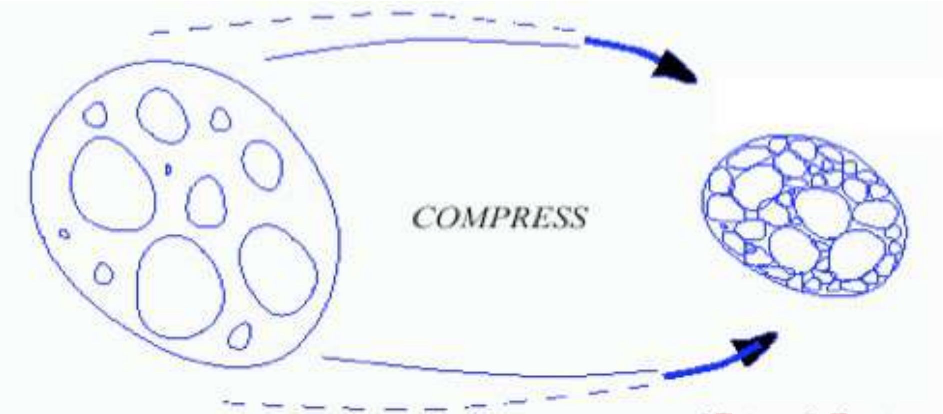
Reliable baseline in testing electroweak interactions and searching for new physics

Imperfect / good modeling at low momentum transfers

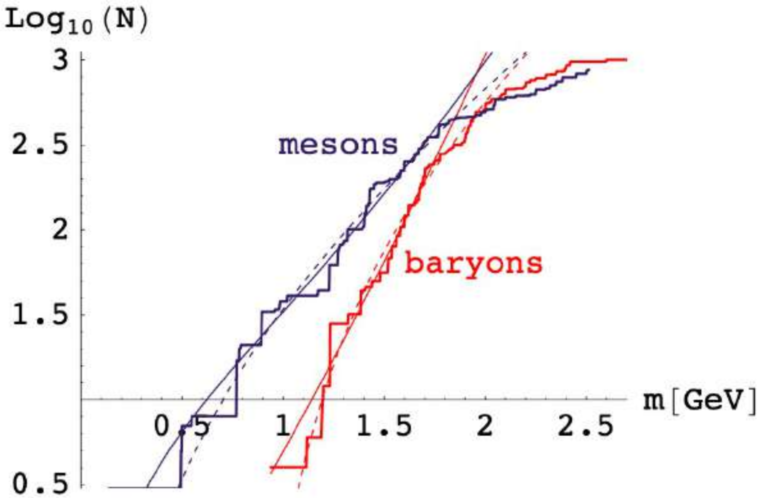




The compressed hadronic world



$$\rho(m, V_c) = \frac{\text{const}}{m^3} \exp\left[\frac{m}{T_H}\right]$$



1965 R. Hagedorn's Statistical Bootstrap

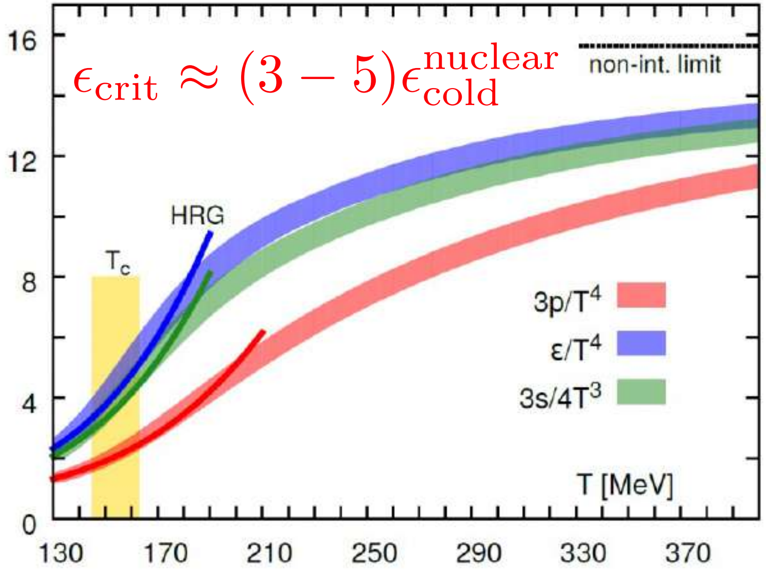
T_H - maximal temperature of hadron gas

1975 Cabbibo and Parisi:

T_H - temperature of phase transition

1990-2020 Lattice QCD*

quantitative understanding of the QCD phase transition



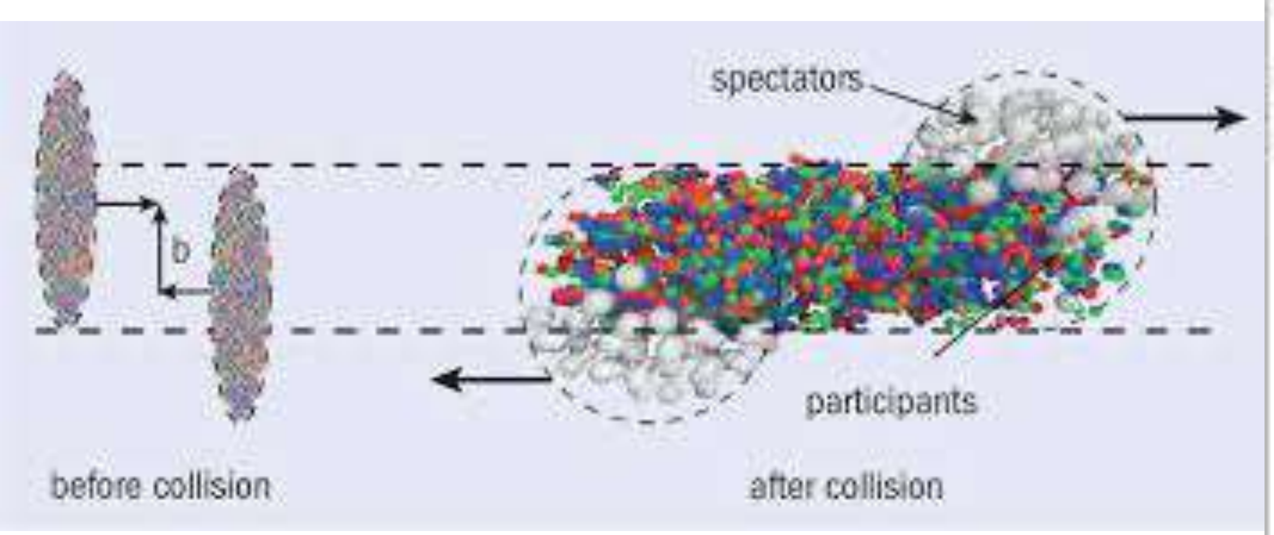
$$\epsilon_{\text{crit}} \approx (3-5)\epsilon_{\text{cold}}^{\text{nuclear}}$$

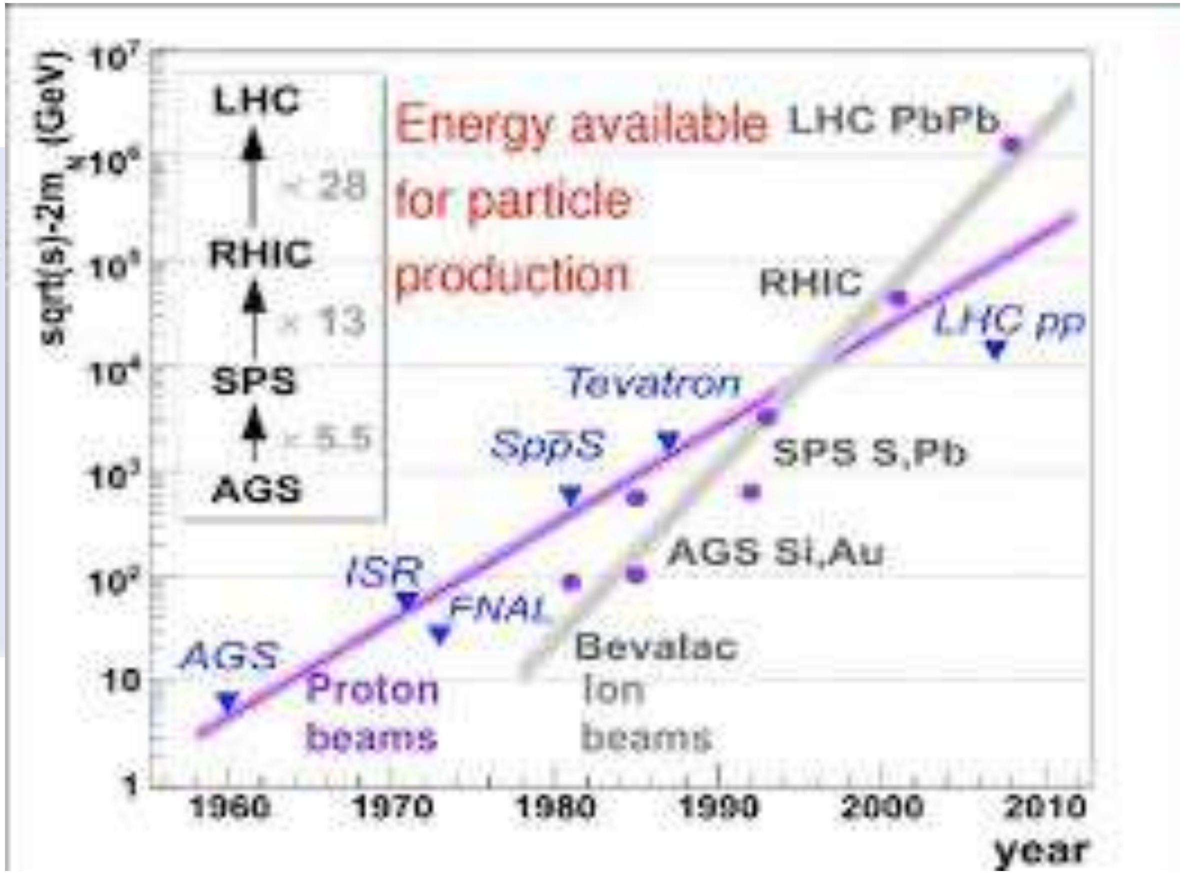
*D. Bazavov et al, The equation of state in (2+1)-flavor QCD, Phys. Rev. D90 (2014) 094503

S. Borsanyi et al, JHEP 09 (2010) 073

Ultra-relativistic heavy ion collisions

Compressing hadronic matter beyond $\epsilon_{\text{crit}} \approx (3-5)\epsilon^{\text{nuclear}}_{\text{cold}}$





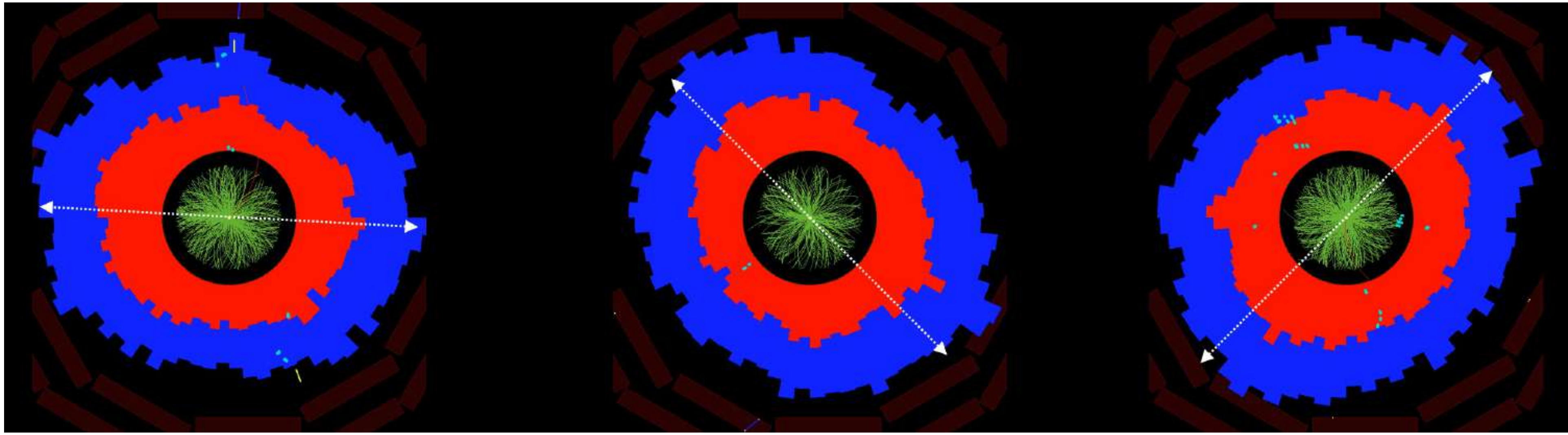
What do we see in PbPb @ LHC?

ALICE Run Control Center

Flow

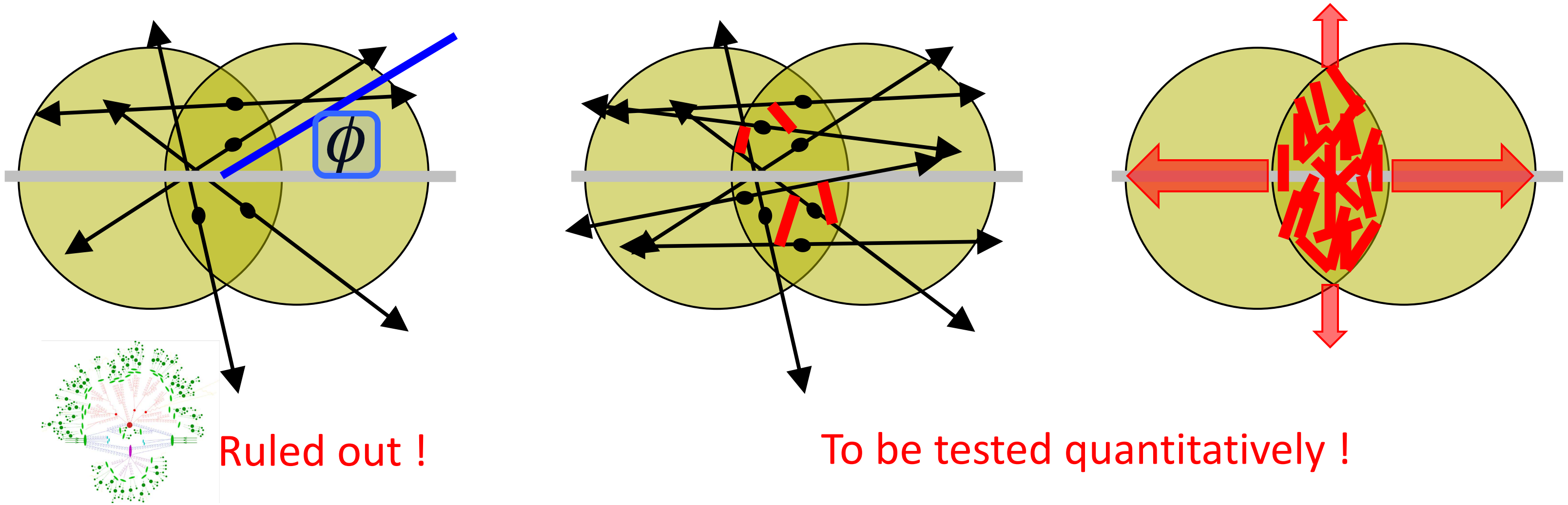
Collectivity
at soft p_T

Single event calorimeter distribution of O(10'000) particles in PbPb @ LHC, CMS Coll.



Which dynamics
is at play?

Free streaming → QCD transport theory → Dissipative fluid dynamics → Perfect fluid dynamics

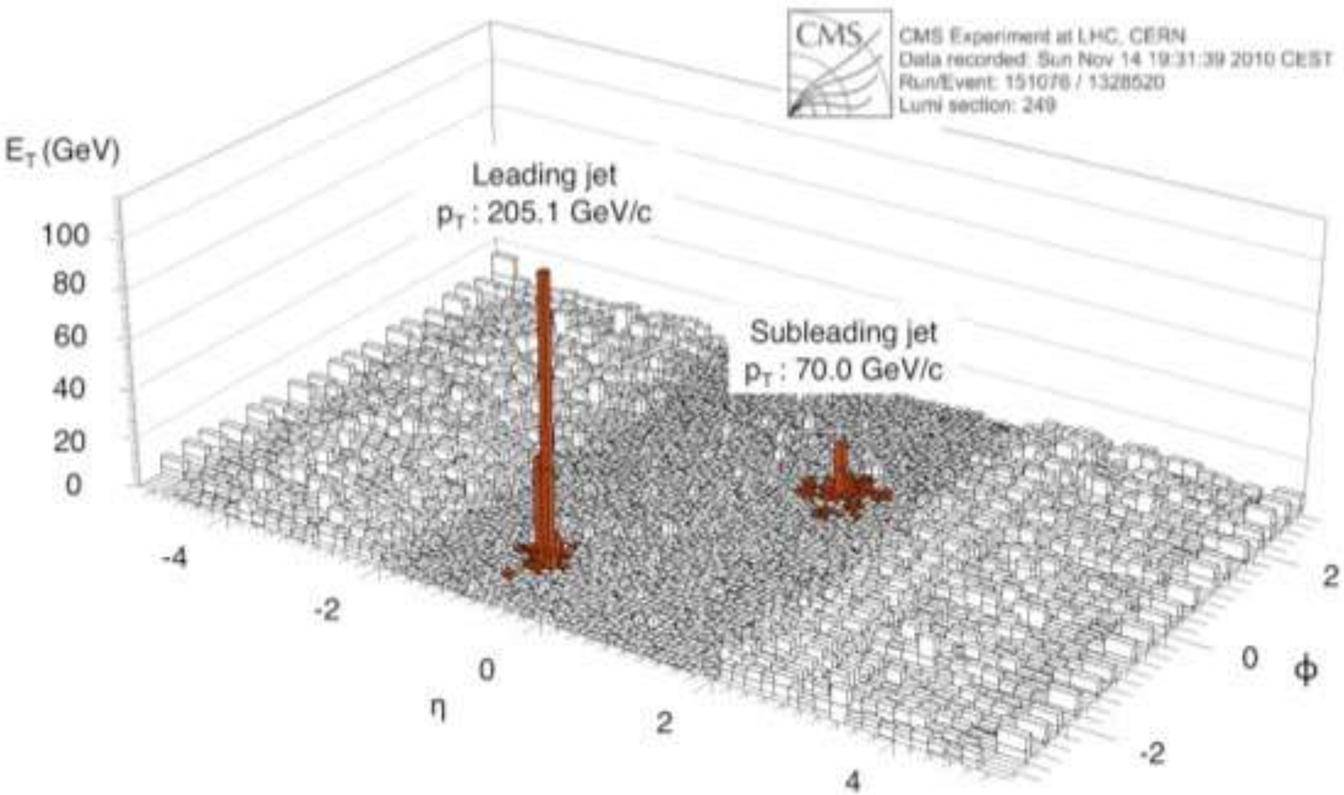


Ruled out !

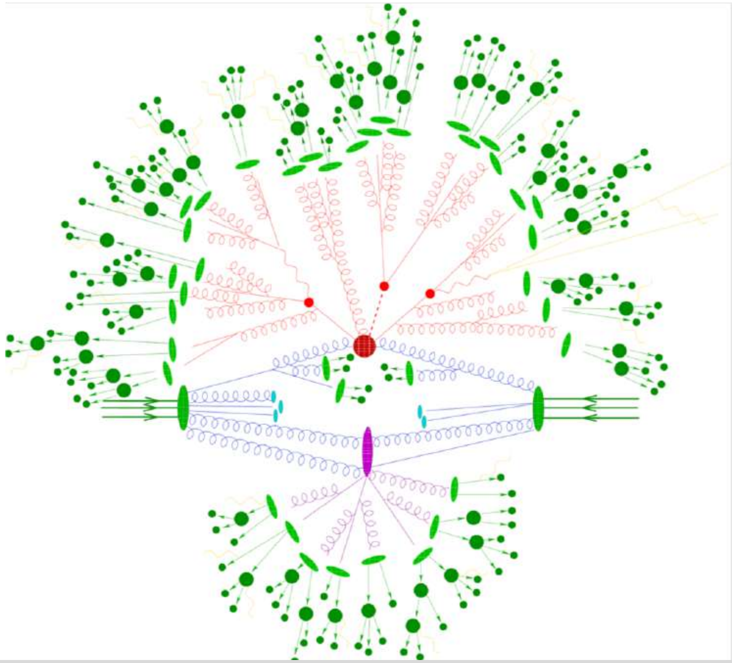
To be tested quantitatively !

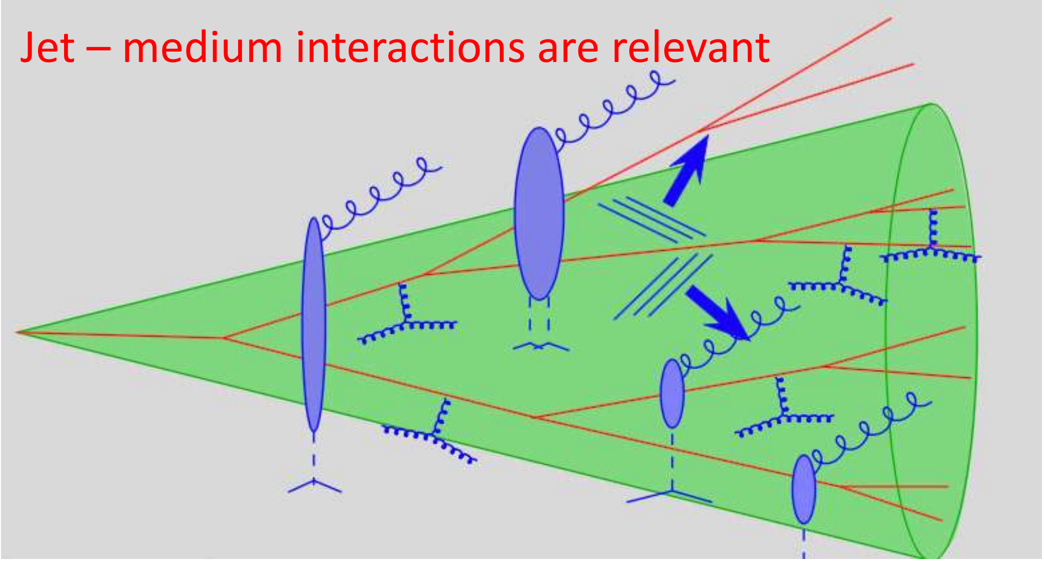
Jet quenching

Deviation form free-streaming & fragmentation at high p_T



This is not sufficient!





Jet – medium interactions are relevant

How do we test medium properties?

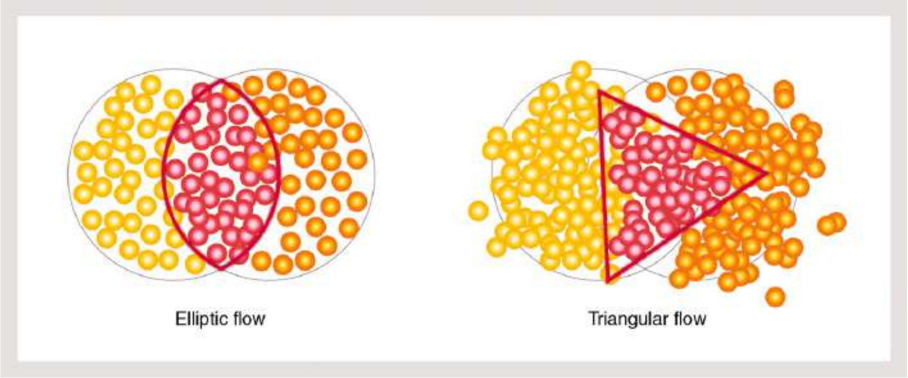
- **Excite medium**
- **Listen to response**
- Analyze

In theory:

$$G_{\mathrm{R}}^{\mu\nu,\alpha\beta} = \frac{\delta T^{\mu\nu}}{\delta h_{\alpha\beta}}$$

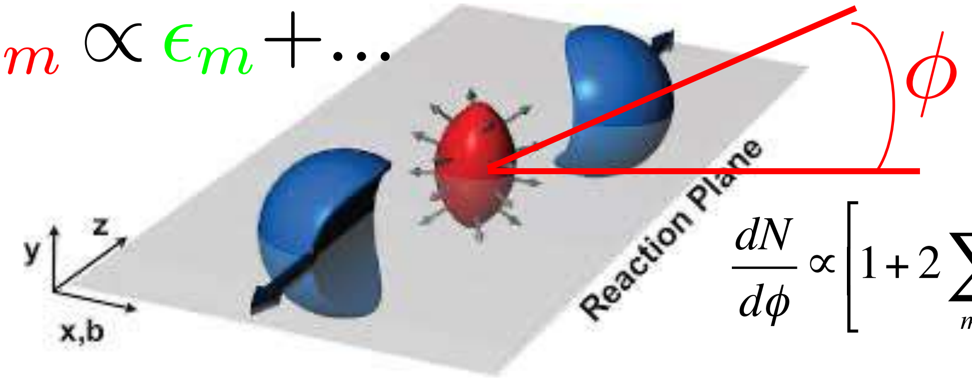
In experiment:

Prepare different **excitations** ϵ_m



measure their **response**

$$v_m \propto \epsilon_m + \ldots$$



$$\frac{dN}{d\phi} \propto \left[1 + 2\sum_m v_m \cos(m\phi)\right]$$

Analyzing medium response

$$G_R(t,k) = \int_{-\infty}^{\infty} d\omega \tilde{G}_R(\underbrace{\omega}_{\in\mathbb{C}}, k)e^{-i\omega t} = c_{\rm hyd}\exp\left[-\Gamma_s k^2 t\right] + c_{\rm non-hyd}\exp\left[-t/\tau_R\right]$$

- **Hydrodynamic excitations,** e.g.

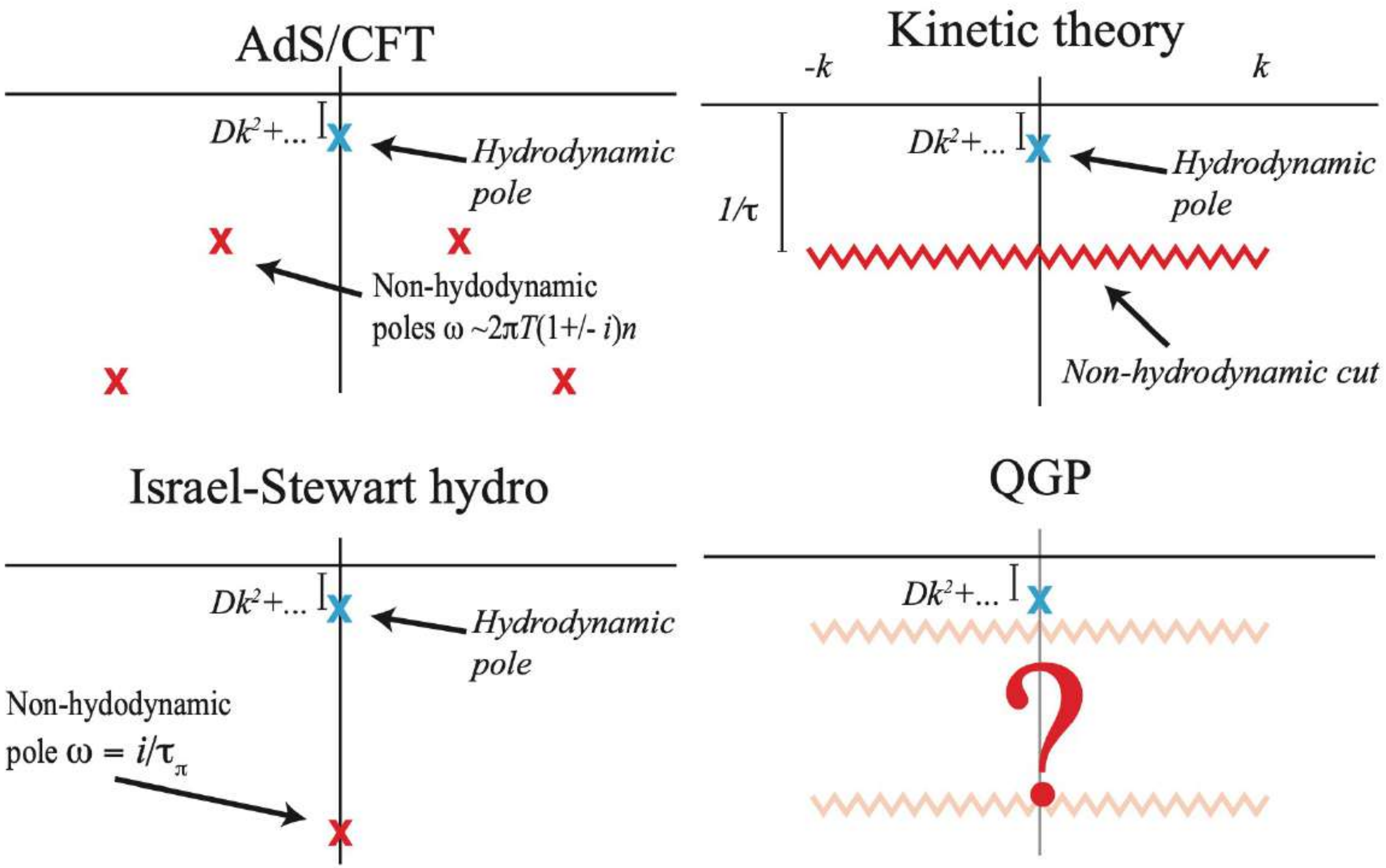
$$\omega^{\rm hyd}_{\rm pole}(k) = -i\underbrace{\frac{\eta}{sT}}_{\equiv\Gamma_s}k^2$$

  - Universal in QFTs
  - Consequence of conservation laws
  - Described by gradient expansion $k \leftrightarrow \nabla$

- **Non-hydro excitations,** e.g.

$$\omega^{\rm non-hyd}_{\rm pole}(k) = -i\frac{1}{\tau_\pi}$$

  - No QFTs without non-hydro modes
  - Consequence of causality
  - Not described by gradient expansion



What do we learn from hydro?

Testing the thermal sector of fundamental quantum fields.

- based *only* on: E-p conservation: $\partial_\mu T^{\mu\nu} = 0$

  2nd law of thermodynamics: $\partial_\mu S^\mu(x) \geq 0$

- sensitive *only* to properties of matter that are

calculable from first principles in quantum field theory

Lattice QCD =>

Finite Temp pQCD =>

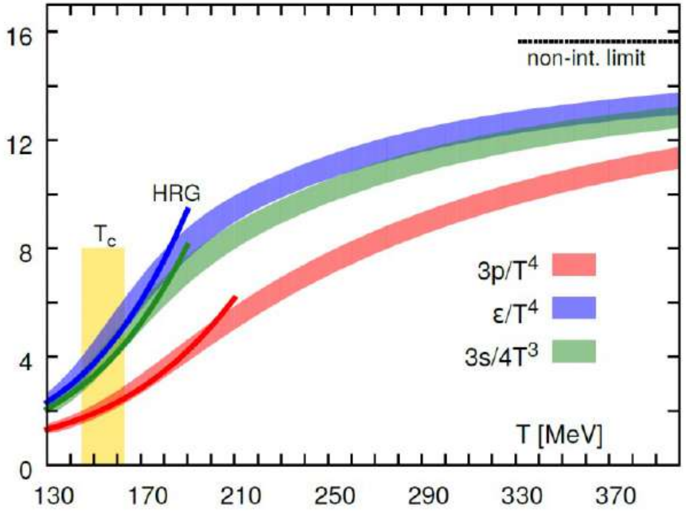
AdS/CFT =>

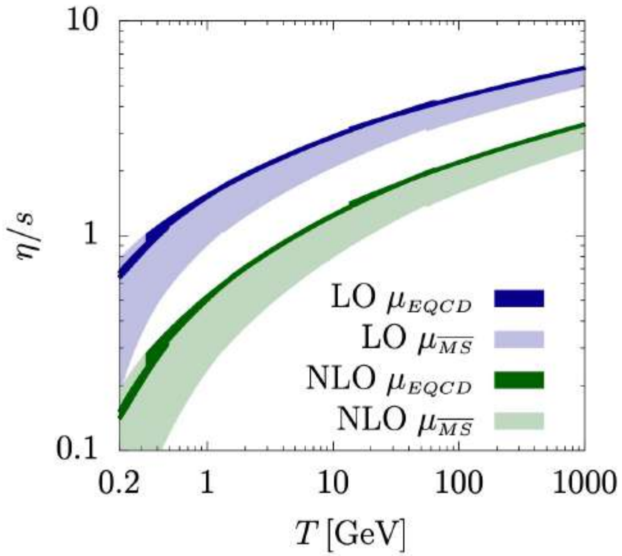
- **EOS**: $\varepsilon = \varepsilon(p,n)$ and **sound velocity** $c_s = \partial p / \partial \varepsilon$

- **transport coefficients**: shear η, bulk ξ viscosity, …

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, dx\, e^{i\omega t} \left\langle \left[T^{xy}(x,t), T^{xy}(0,0) \right] \right\rangle_{eq}$$

- **relaxation times**: τ_π, τ_Π, …

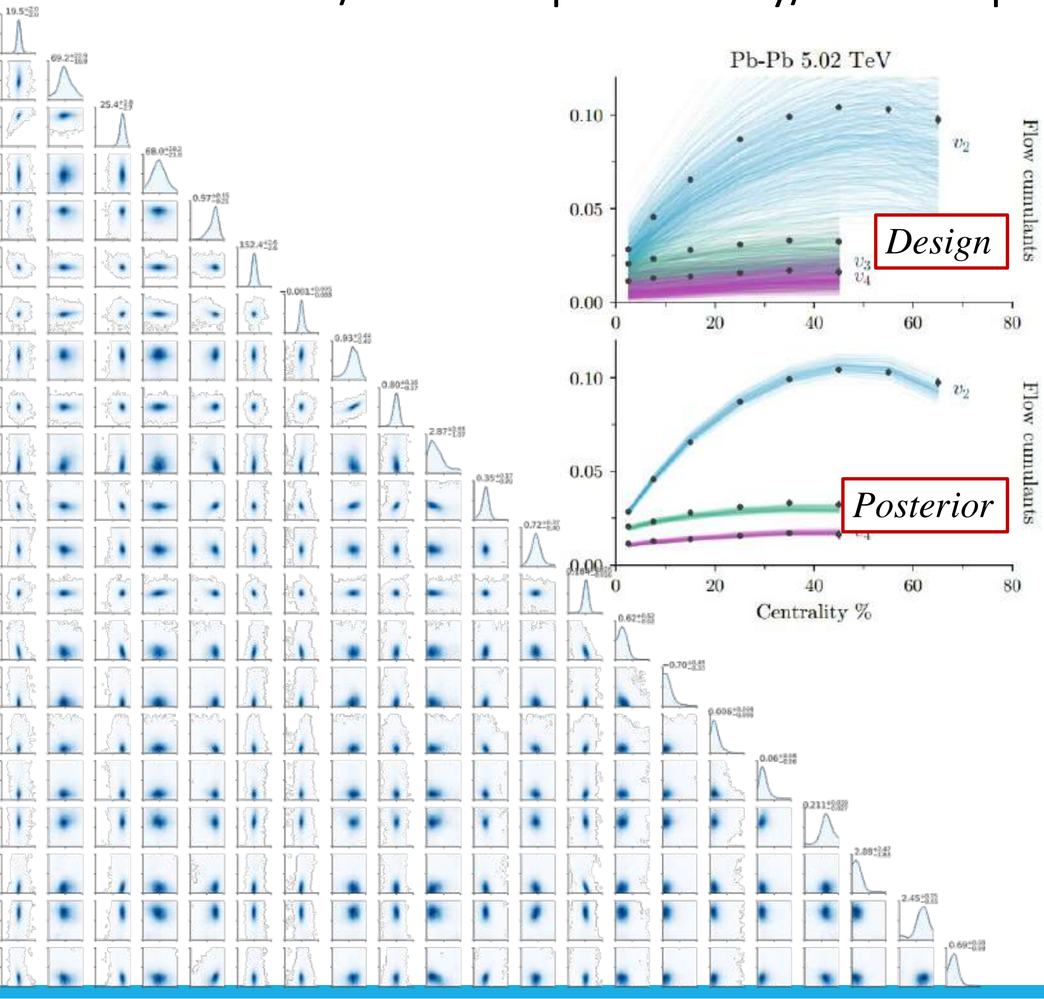




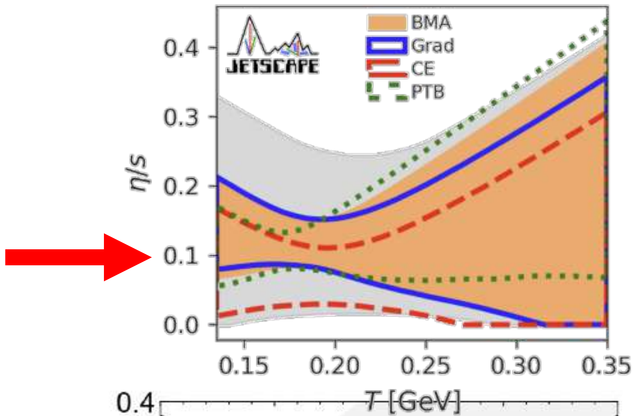
J. Ghiglieri, G. Moore, D. Teaney, QCD Shear Viscosity at (almost) NLO, JHEP 03 (2018) 179

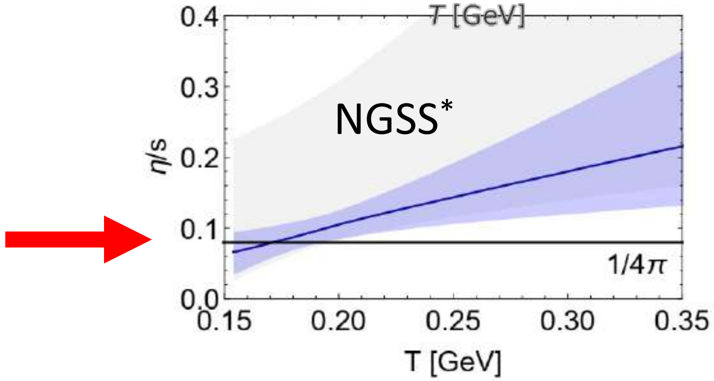
Bayesian Inference

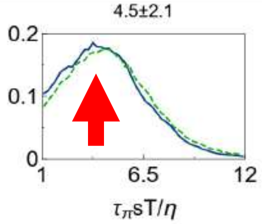
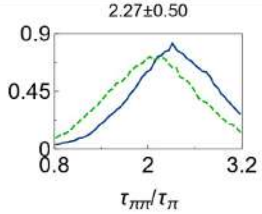
- More than fluid dynamics but constrains fluid dynamics
- Best/most complete theory/data comparison at soft p_T



State of the art: 514 data points,
20 parameters, unprecedented detail.





	NGSS*	AdS/CFT	kinetic theory
$\frac{\tau_\pi sT}{\eta}$		$4-\log(4)\approx 2.61$	5
$\frac{\tau_{\pi\pi}}{\tau_\pi}$		$\frac{88}{35(2-\log 2)}\approx 1.92$	$\frac{10}{7}\approx 1.43$

Steffen Bass, A data-driven approach to quantifying the shear viscosity of nature's most ideal liquid, https://www.youtube.com/watch?v=MGE8K8IY4cg

*G. Nijs, U. Gursoy, W. v.d. Schee, R. Snellings, arXiv:2010.15130, arXiv:2010.15134

How fluid is the fluid?

- N=4 SYM plasma has no internal structure
  “universal” lower bound $\frac{\eta}{s} = \frac{1}{4\pi}$ 2001 Policastro, Son, Starinets*
- 1-d Bjorken expansion is **isentropic** if $\frac{d(\tau s)}{d\tau} = \frac{\frac{4}{3}\eta}{\tau T} \ll s \Longrightarrow \frac{\eta}{s} \ll \underbrace{\tau T}_{>1}$ ✓
- Hydro-modes dominate if

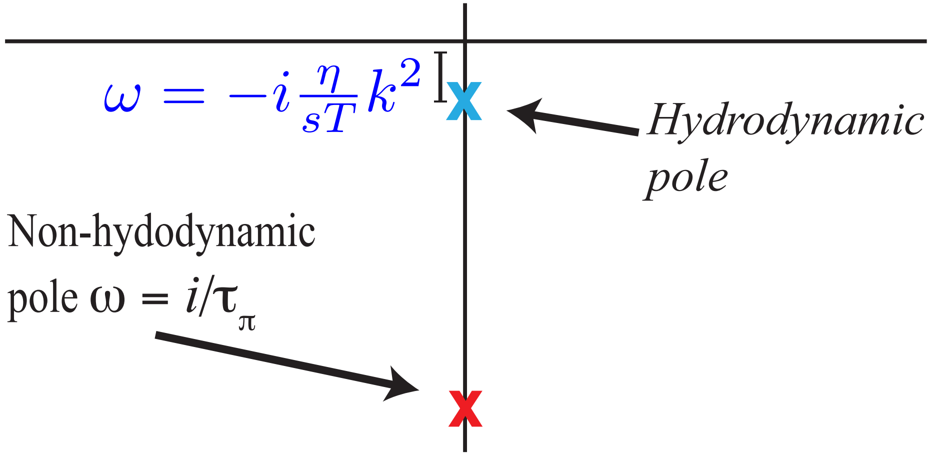
$$\frac{\eta}{sT}k^2 \ll \frac{1}{\tau_\pi} \approx \frac{1}{5}\frac{sT}{\eta}$$

- Hydro-dominated wavelengths satisfy

$$\lambda = \frac{2\pi}{k} \gg \underbrace{2\pi\sqrt{5}}_{10}\ \underbrace{\frac{\eta}{s}}_{0.1}\ \underbrace{\frac{1}{T}}_{1\ \mathrm{fm}}$$

Such wavelengths do not fit into a proton !
Experimental access of non-hydro modes seems feasible.

Israel-Stewart hydro


$\omega = -i\frac{\eta}{sT}k^2$

Hydrodynamic pole

Non-hydodynamic pole $\omega = i/\tau_\pi$

---

*G. Policastro, D.T. Son, A. Starinets, The Shear viscosity of strongly coupled N=4 supersymmetric Yang-Mills plasma, Phys.Rev.Lett. 87 (2001) 081601

How non-fluid is the fluid?

That depends on its size R:

- ☐ **Smallest wavenumber**

$$k \sim \frac{1}{R}$$

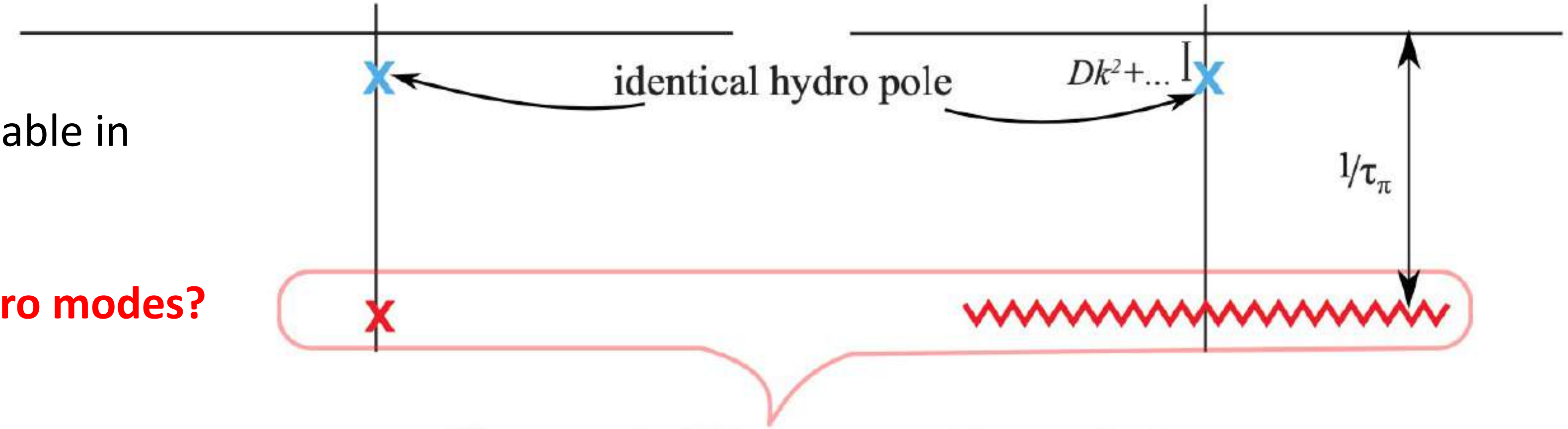
- ☐ **Longest propagation time**

$$t \sim R$$

$$G_R(t,k) = \underbrace{c_{\text{hyd}}\ \exp\left[-\Gamma_s k^2 t\right]}_{\text{reduced for smaller R}} + \underbrace{c_{\text{non-hyd}}\ \exp\left[-t/\tau_R\right]}_{\text{enhanced for smaller R}}$$

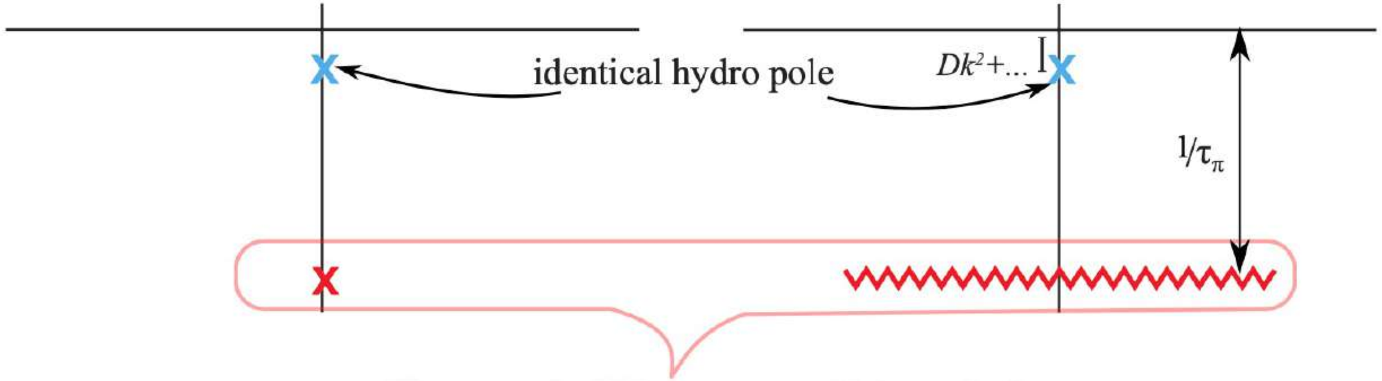
Non-hydro excitations become testable in systems of sufficiently small size R:

Can we test the nature of non-hydro modes?



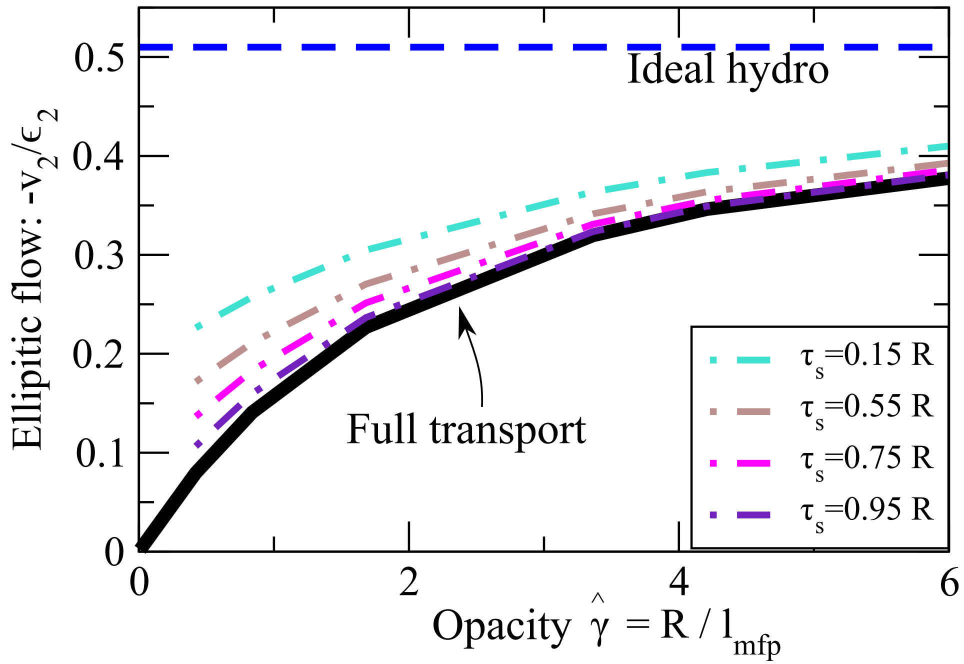
How much difference can this make?

A proof of principle (a toy model)



How much difference can this make?

Construct a theory with **identical hydro poles** but **different non-hydro excitations** of the same relaxation time τ_π



Switching from one theory to the other at time τ_s leads to differences in the response v_2/ϵ_2 though the hydrodynamics did not change.

The differences increase with decreasing R.

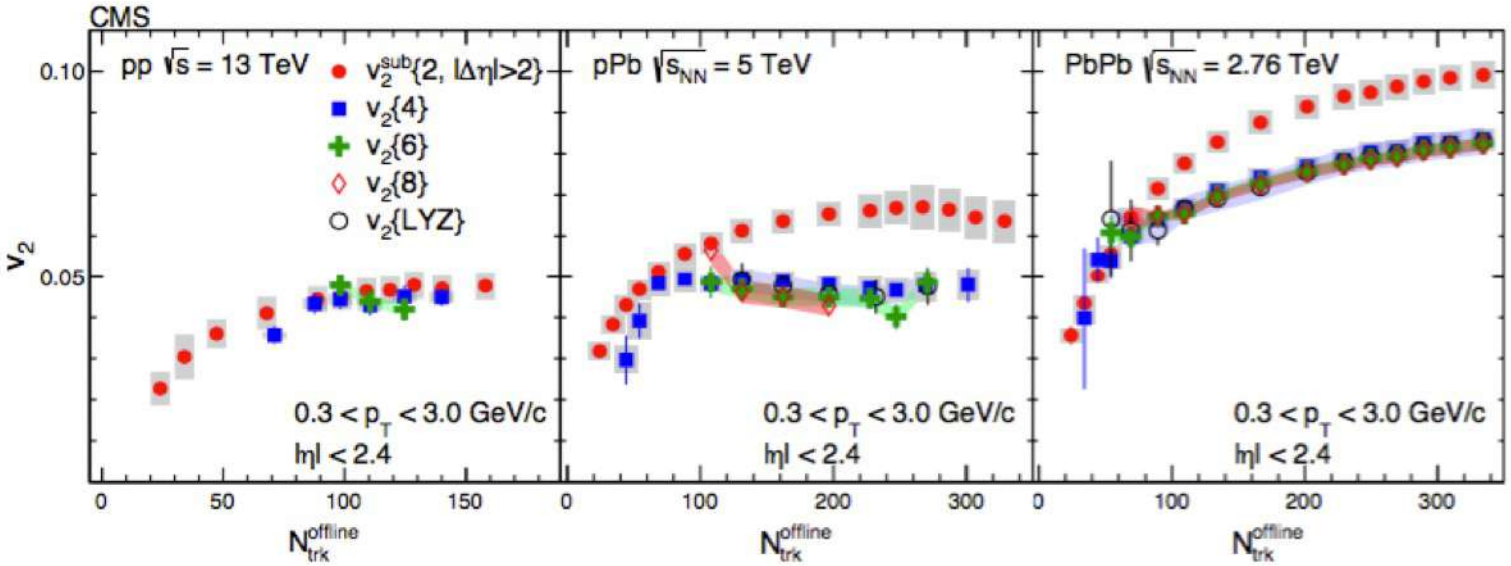
Elliptic flow is sensitive to non-hydro modes.

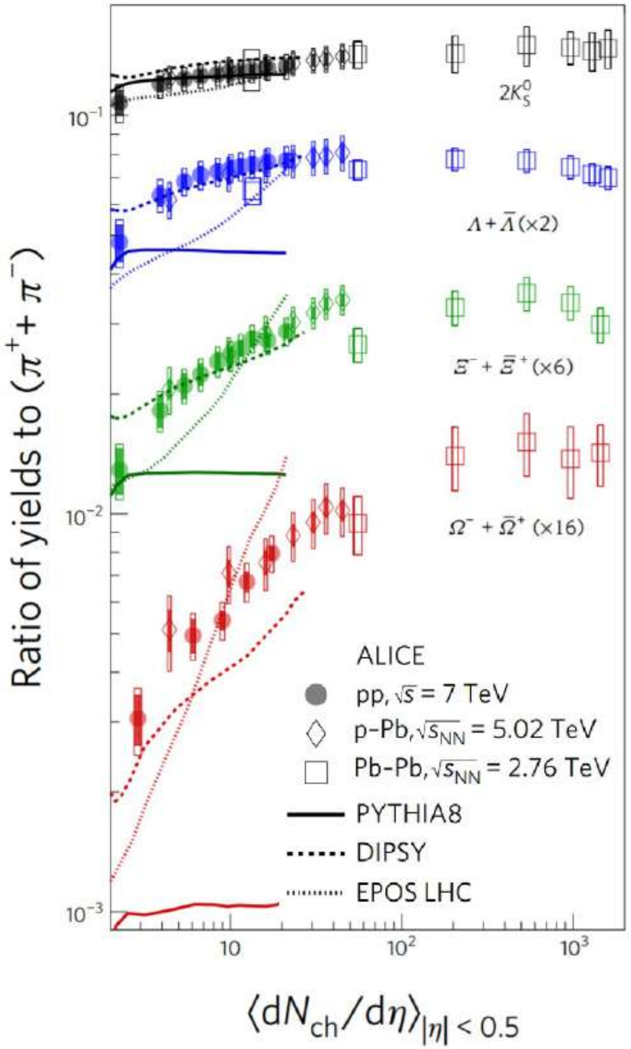
*A. Kurkela, U. Wiedemann, Bin Wu, Eur. Phys. J. C79 (2019) 9,. 759
UAW talk at Initial Stages, Rehovot, https://cds.cern.ch/record/2749317

Discovery of collectivity in pp and pPb @ LHC

Hypothesis (consistent with what we know)

If collectivity persists to the smallest systems, it is not mediated by hydro modes alone.





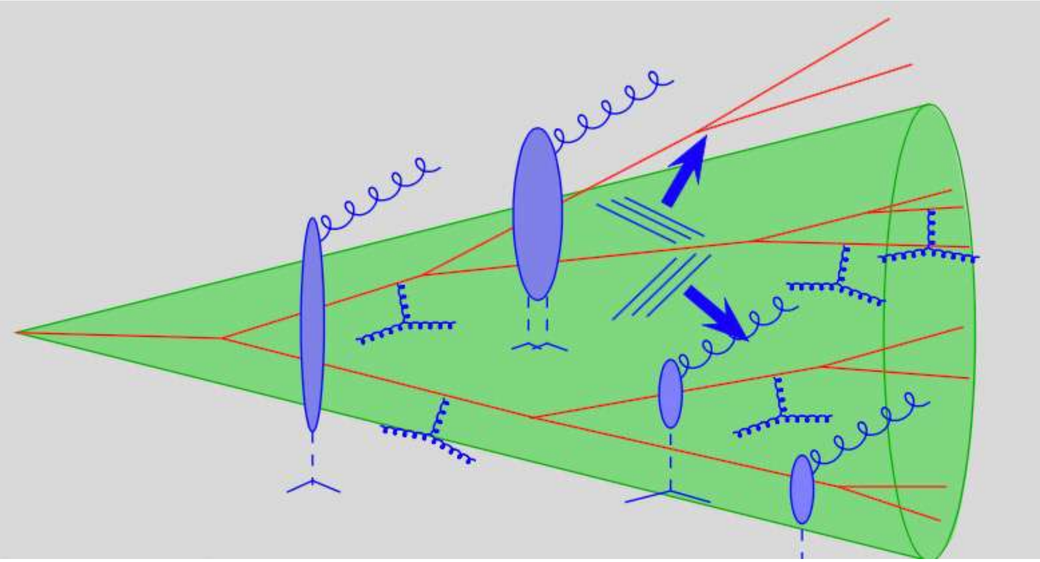
CMS, Phys. Lett. B765 (2017) 193

ALICE, Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions, Nature Physics 13 (2017) 535

Jet quenching – a *peculiar* kinetic transport

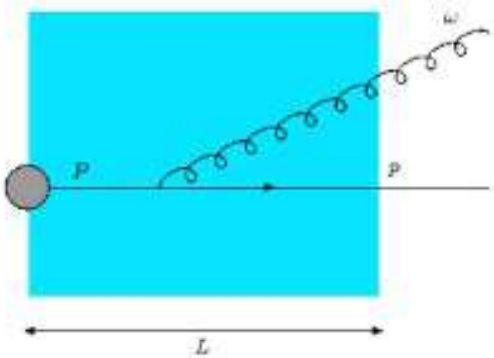
A generic quenching model implements

$$\boxed{\partial_t f_g(x,p) = -C_{2\to 2}[f] - C_{1\to 2}[f]}$$



- ☐ Hard partons p>> T
- ☐ Embedded in medium
- ☐ 1->2 LPM (and DGLAP)
- ☐ 2->2 elastic

What is peculiar? Soft emittees are emitted first.



☐ In vacuum

- ➢ Time $\tau_{\text{form}}^{\text{vac}} \simeq \frac{\omega}{k_\perp^2} = \frac{1}{\Theta^2\,\omega}$
- ➢ Hard gluons first
- ➢ Soft gluons late

medium never

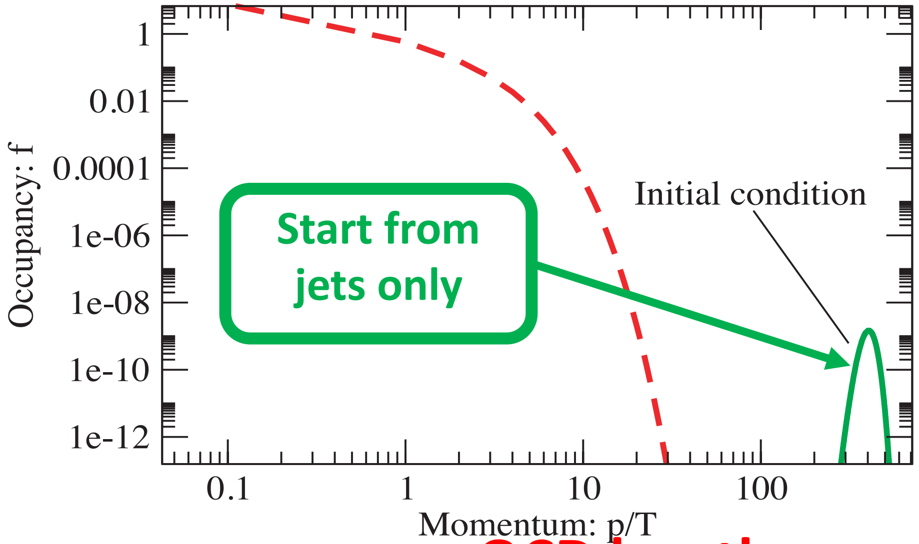
☐ In medium

- ➢ Time $\tau_{\text{form}}^{\text{med}} \simeq \frac{\omega}{k_\perp^2} = \sqrt{\frac{\omega}{\hat{q}}}$
- ➢ Soft gluons first
- ➢ medium forms fast (PTO)

Quenching models: Q-Pythia, Q-Herwig, JEWEL, LBT, MATTER, MARTINI … HYBRID is different

X.N. Wang, Jet tomography of hot and cold nuclear matter, https://www.youtube.com/watch?v=a69d22ZiiT8

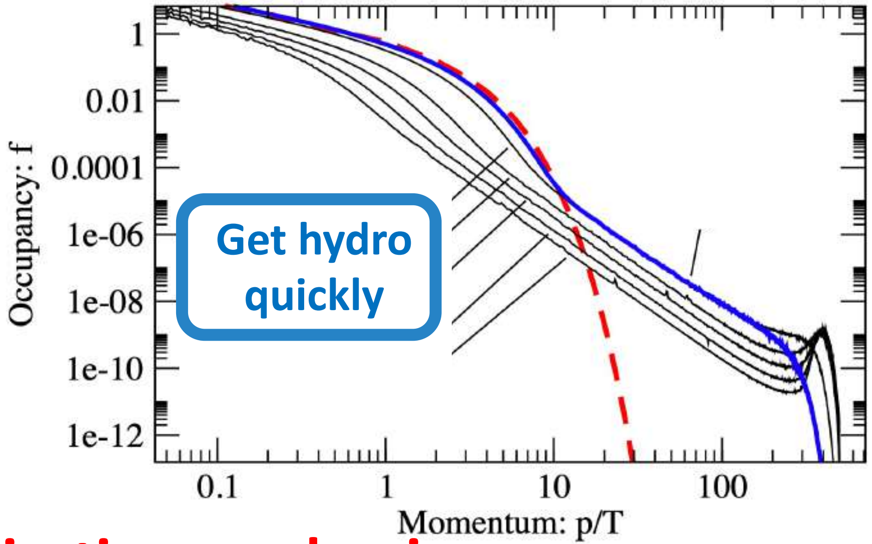
Jet quenching = fast perturbative hydrodynamization



Start from jets only

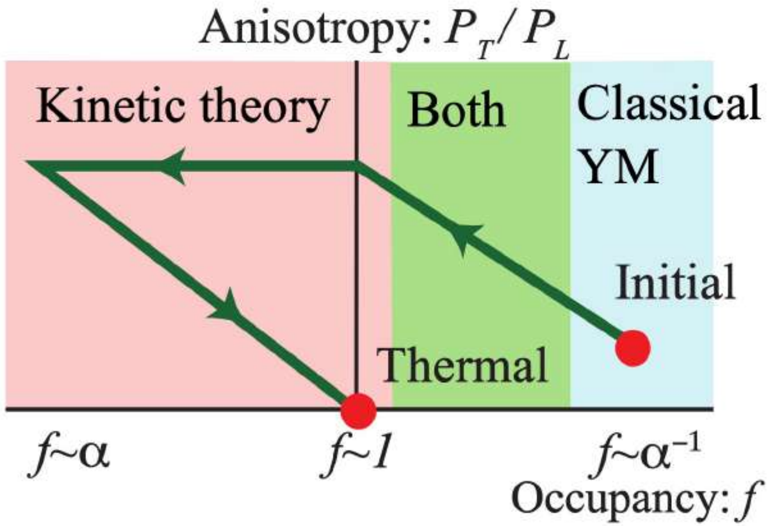
“Bottom-up”

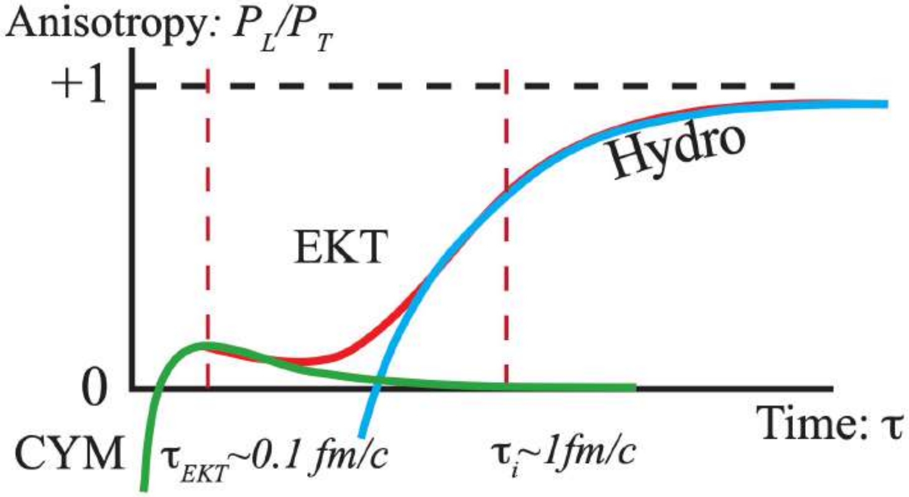
$$\partial_t f_g(x,p) = -C_{2\to2}[f] - C_{1\to2}[f]$$



Get hydro quickly

pQCD has the most remarkable thermalization mechanism

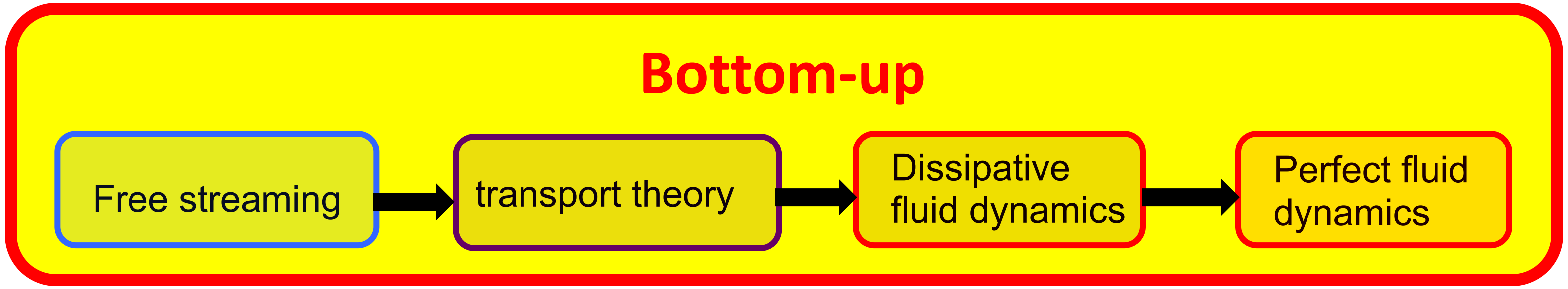




R. Baier, A.H. Mueller, D. Schiff, D.T. Son, ‘Bottom up’ thermalization in heavy ion collisions, Phys. Lett. B502 (2001) 51

A. Kurkela, E. Lu Phys.Rev.Lett. 113 (2014) 18; A. Kurkela, Y. Zhu Phys.Rev.Lett. 115 (2015) 18

Bottom-up is a more encompassing HI paradigm than the perfect fluid



Bottom-up

Free streaming → transport theory → Dissipative fluid dynamics → Perfect fluid dynamics

Bottom-up includes:

- pre-equilibrium dynamics*
  from $f \sim O(1/\alpha_s)$ to $f \sim 1$
- Close-to-perfect fluidity
  (with specific non-hydro modes)
- Jet quenching

Many open questions:

- Nature of non-hydro excitations?
- Onset of jet quenching
- Origin of hadrochemical equilibration
- Transport of heavy flavor
- …

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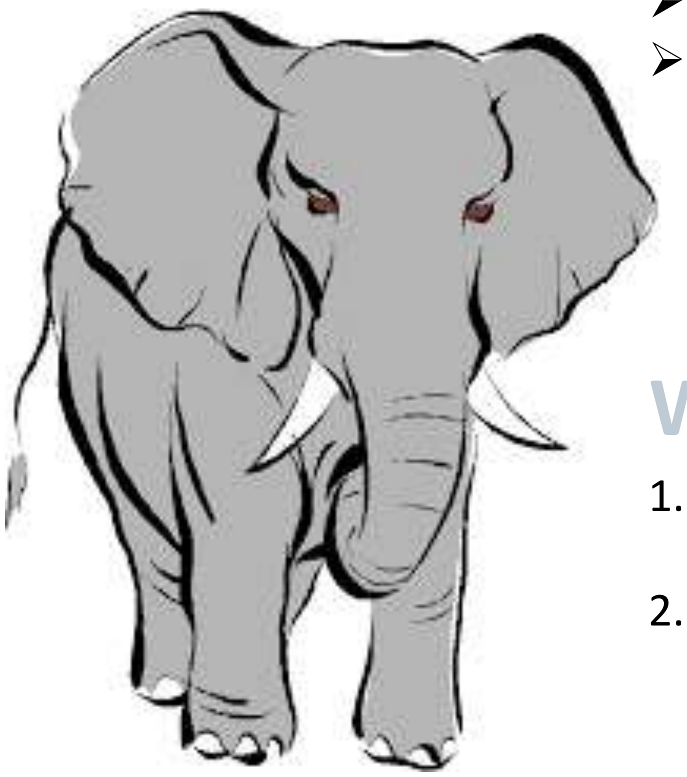
*A. Kurkela, A. Mazeliauskas, J.F. Paquet, S. Schlichting, D. Teaney, “KOMPOST”, Phys. Rev. Lett. 122 (2019) 12 and Phys. Rev. C99 (2019) 3

Jet quenching in small systems

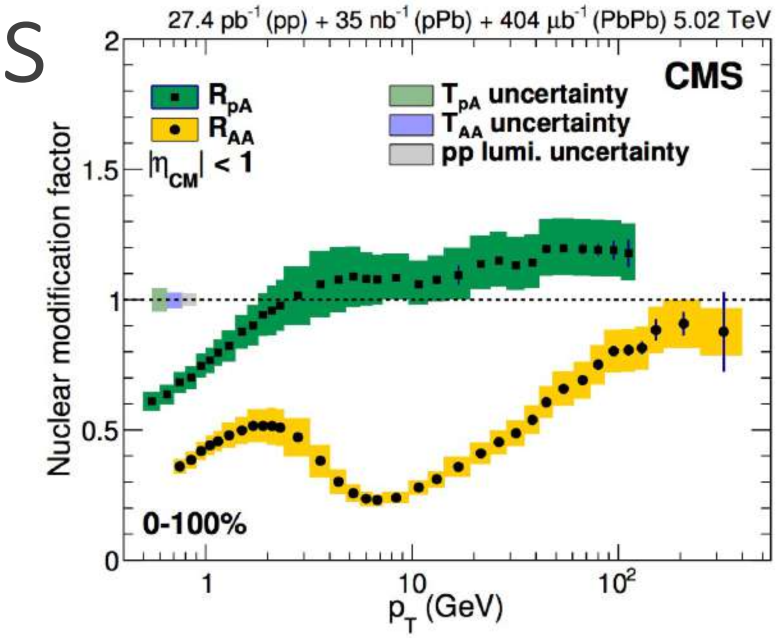


- Collectivity requires final state interaction
- Final state interactions imply jet quenching
- Jet quenching not seen in pPb or peripheral PbPb

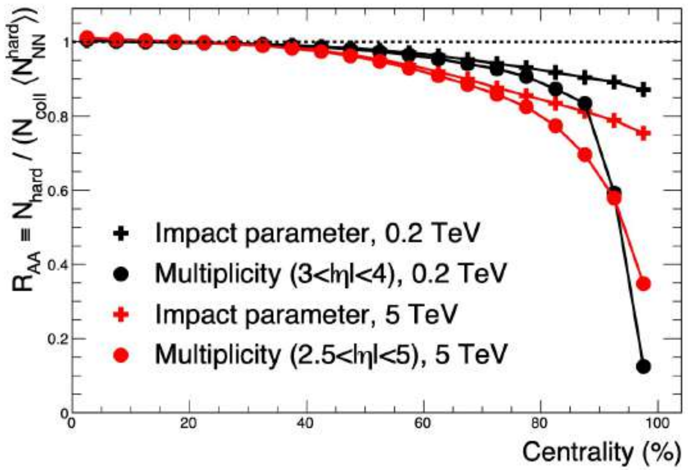
$$R_{AA} = \frac{Y_{AA}}{N_{\mathrm{coll}}\, Y_{pp}} = \frac{Y_{AA}}{T_{AA}\sigma_{pp}}$$

Why?

1. Because the effect is not there.
   Then, what I told you so far is wrong!
2. Because the effect is too small to be measured.
   How to improve accuracy of null-hypothesis on top of which an effect could be seen?



Soft physics modelling uncertainties increase in small systems*



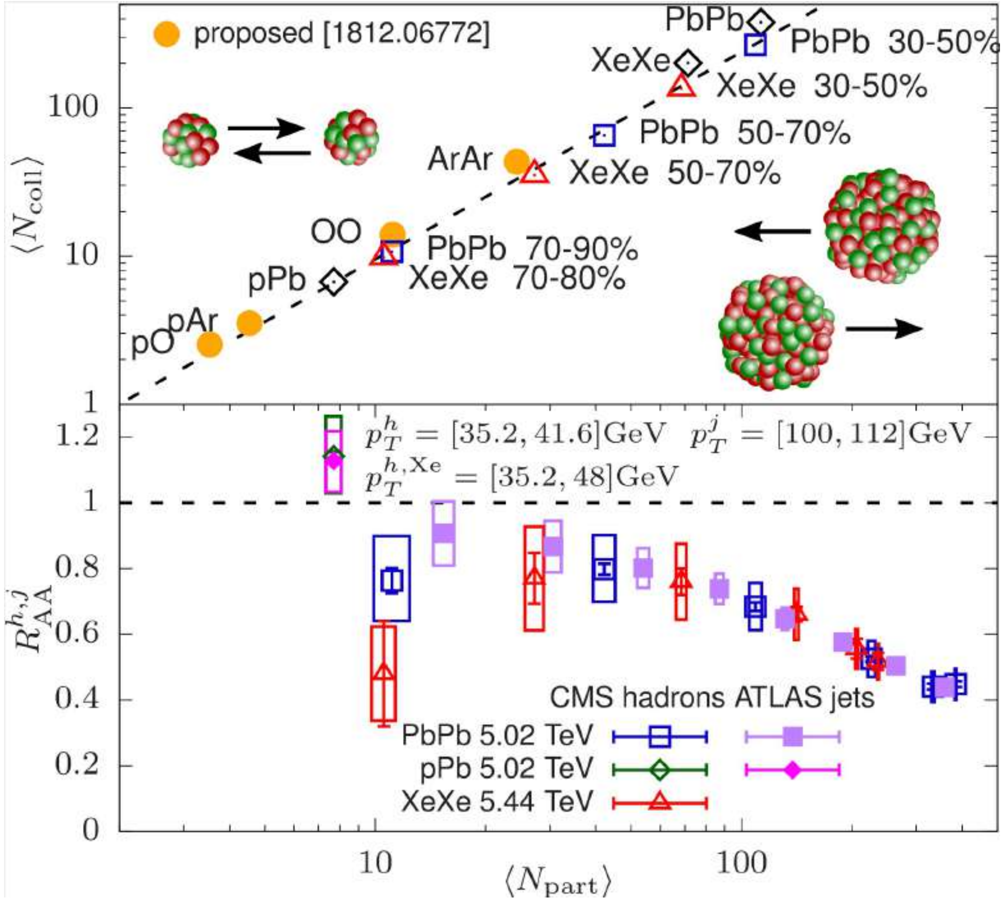
CMS, JHEP 04 (2017) 039

*C. Loizides, A. Morsch, Absence of jet quenching in peripheral nucleus-nucleus collisions, Phys. Lett. B773 (2017) 408

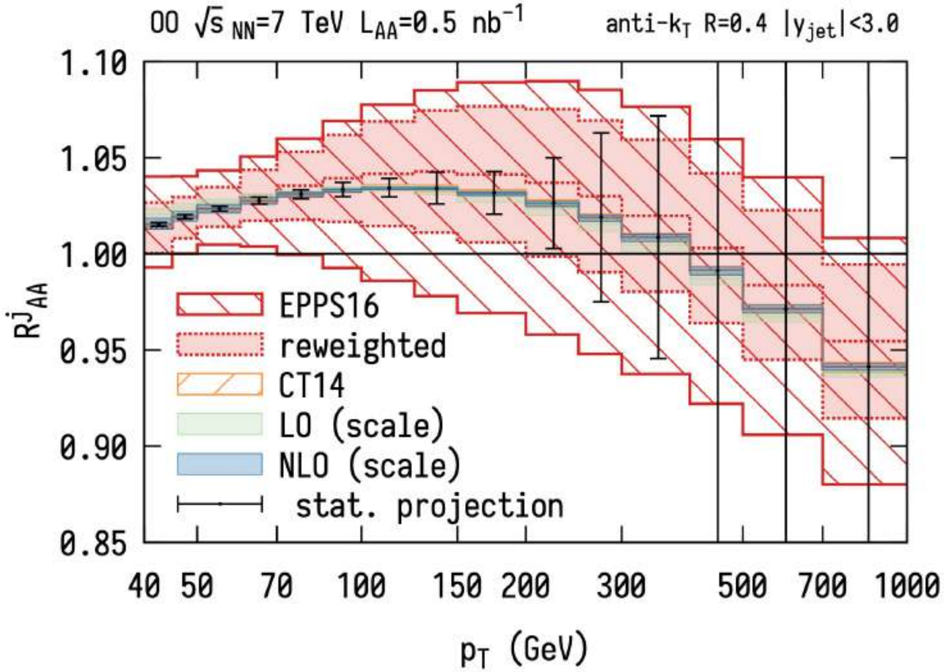
A small system: Oxygen-Oxygen @ LHC

- Inclusive OO ~ 70-90 % PbPb, perturbatively controlled baseline

$$R^{h,j}_{AA,\text{ minbias}} = \frac{1}{A^2}\frac{\frac{d\sigma_{AA}}{dp_T\,dy}}{\frac{d\sigma_{pp}}{dp_T\,dy}}$$



- **2-5 % theory precision** on no-quench baseline*
  systematically controlled pQCD standard



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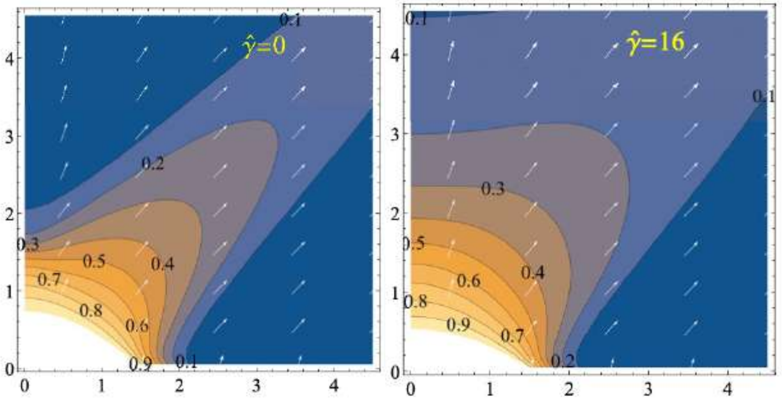
*A. Huss, A. Kurkela, A. Mazeliauskas, R. Paatelainen, W. v.d. Schee, UAW, Discovering partonic rescattering in light nucleus collisions, arXiv:2007.13754 and arXiv:2007.13758

How to estimate quenching signal in OO?

- **Vary freely what you don't know**

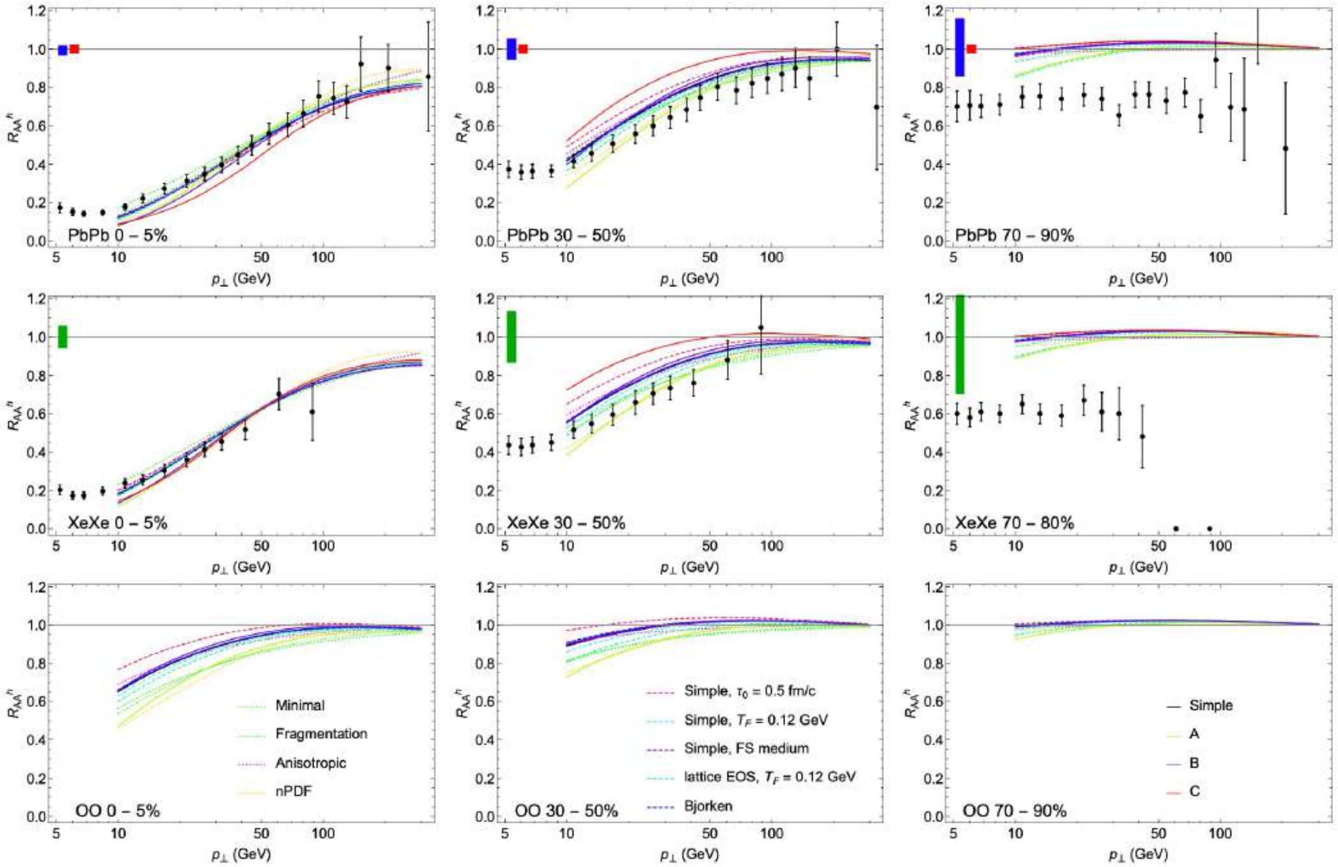
- Initial conditions
- collective expansion



- microscopic dynamics

model	nPDF	$\langle R\rangle$, $\langle N_{\rm part}\rangle$, $\langle N_{\rm coll}\rangle$	$\langle\epsilon_2\rangle$	T evolution	Energy loss	Fragmentation	$\hat{\bar{q}}/T^3$ or κ
Minimal	no	optical Glauber	no	kinetic	BDMPS-Z	no	0.90 ± 0.25
Anisotropic	no	TrENTo	yes	kinetic	BDMPS-Z	no	0.85 ± 0.24
nPDF	yes	optical Glauber	no	kinetic	BDMPS-Z	no	1.08 ± 0.27
Fragmentation	no	optical Glauber	no	kinetic	BDMPS-Z	yes	2.93 ± 0.87
Simple	yes	TrENTo	yes	kinetic	BDMPS-Z	yes	3.63 ± 0.91
Simple, $\tau_0 = 0.5{\rm fm}/c$	yes	TrENTo	yes	kinetic	BDMPS-Z	yes	6.78 ± 1.73
Simple, $T_{\rm F} = 0.12{\rm GeV}$	yes	TrENTo	yes	kinetic	BDMPS-Z	yes	3.15 ± 0.77
Free streaming	yes	TrENTo	no	free streaming	BDMPS-Z	yes	2.25 ± 0.57
Lattice EOS	yes	TrENTo	yes	kinetic	BDMPS-Z	yes	2.38 ± 0.57
Bjorken	yes	TrENTo	yes	$\propto \tau^{-1/3}$	BDMPS-Z	yes	3.01 ± 0.76
A	yes	TrENTo	yes	kinetic	$dE/dx \sim \tau^{0.4}T^{1.2}$	yes	2.83 ± 0.58
B	yes	TrENTo	yes	kinetic	$dE/dx \sim \tau T^3$	yes	2.70 ± 0.57
C	yes	TrENTo	yes	kinetic	Stopping	yes	2.41 ± 0.18

- **Anchor on what is measured and extrapolate**

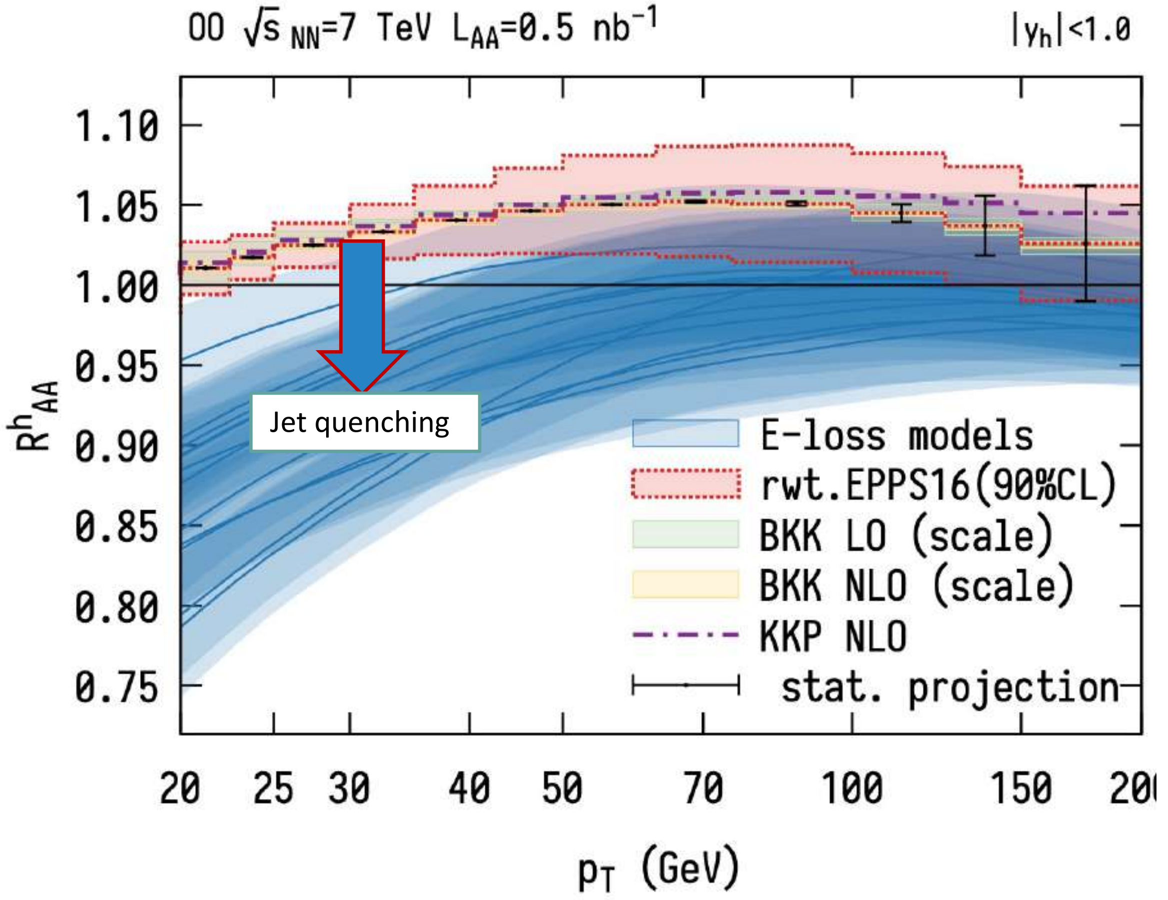


*A. Huss, A. Kurkela, A. Mazeliauskas, R. Paatelainen, W. v.d. Schee, UAW, Discovering partonic rescattering in light nucleus collisions, arXiv:2007.13754 and arXiv:2007.13758

Other recent R_{AA} comparisons: Chien et al. 1509.02936, Bianchi et al. 1702.00481, Andres et al 1606.04837, Noronha-Hostler et al. 1602.03788, Casalderrey et al. 1405.3864, Jetscape 2102.11337

Discovering jet quenching in OO & LHC

- should be possible since **extrapolated jet quenching effects** can be separated from **precisely known no-quench baseline**



*A. Huss, A. Kurkela, A. Mazeliauskas, R. Paatelainen, W. v.d. Schee, UAW, Discovering partonic rescattering in light nucleus collisions, arXiv:2007.13754 and arXiv:2007.13758

This is only one of many

J. Brewer, A. Mazeliauskas, W. v.d. Schee (org) , cern.ch/OppOatLHC

Write-up “Opportunities of OO and pO collisions at the LHC”, Jasmine Brewer and Aleksas Mazeliauskas, arXiv:2103.01939

Take-home message

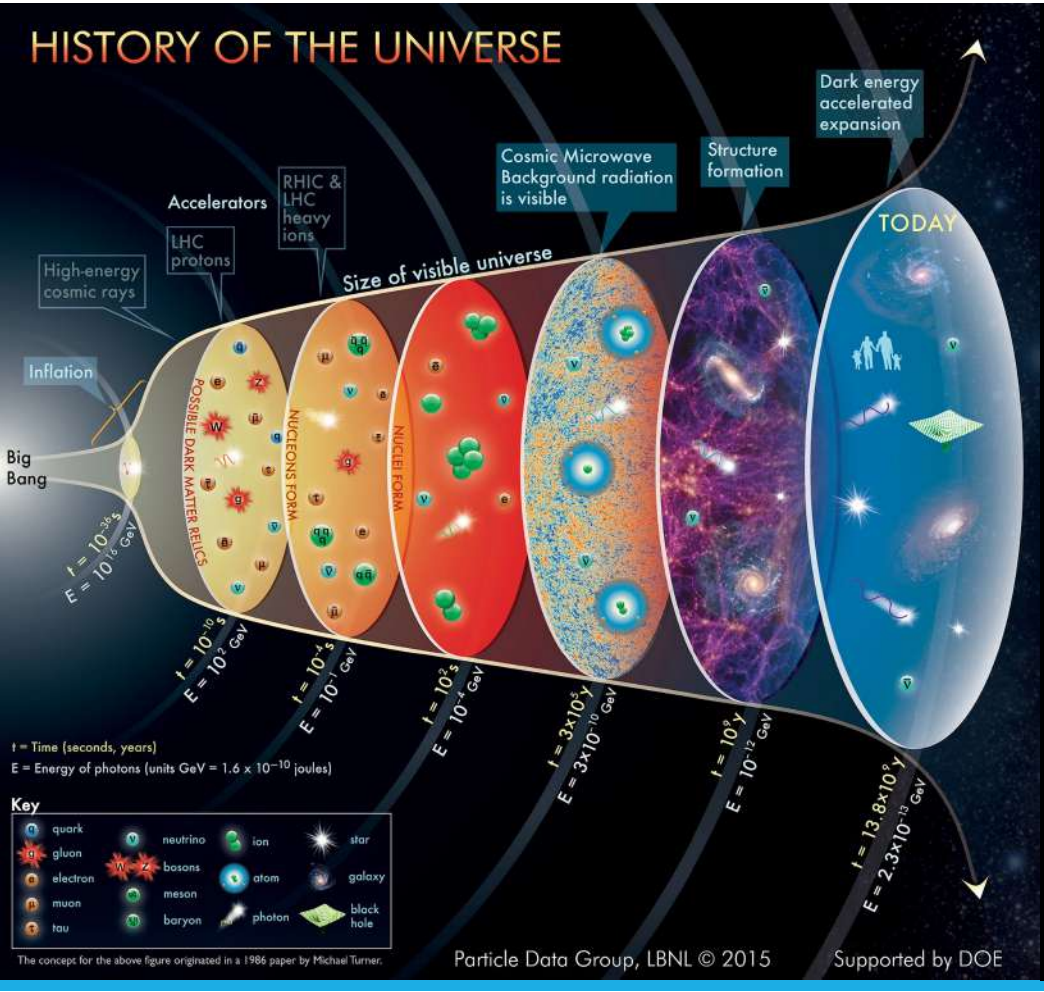
Heavy ion collisions

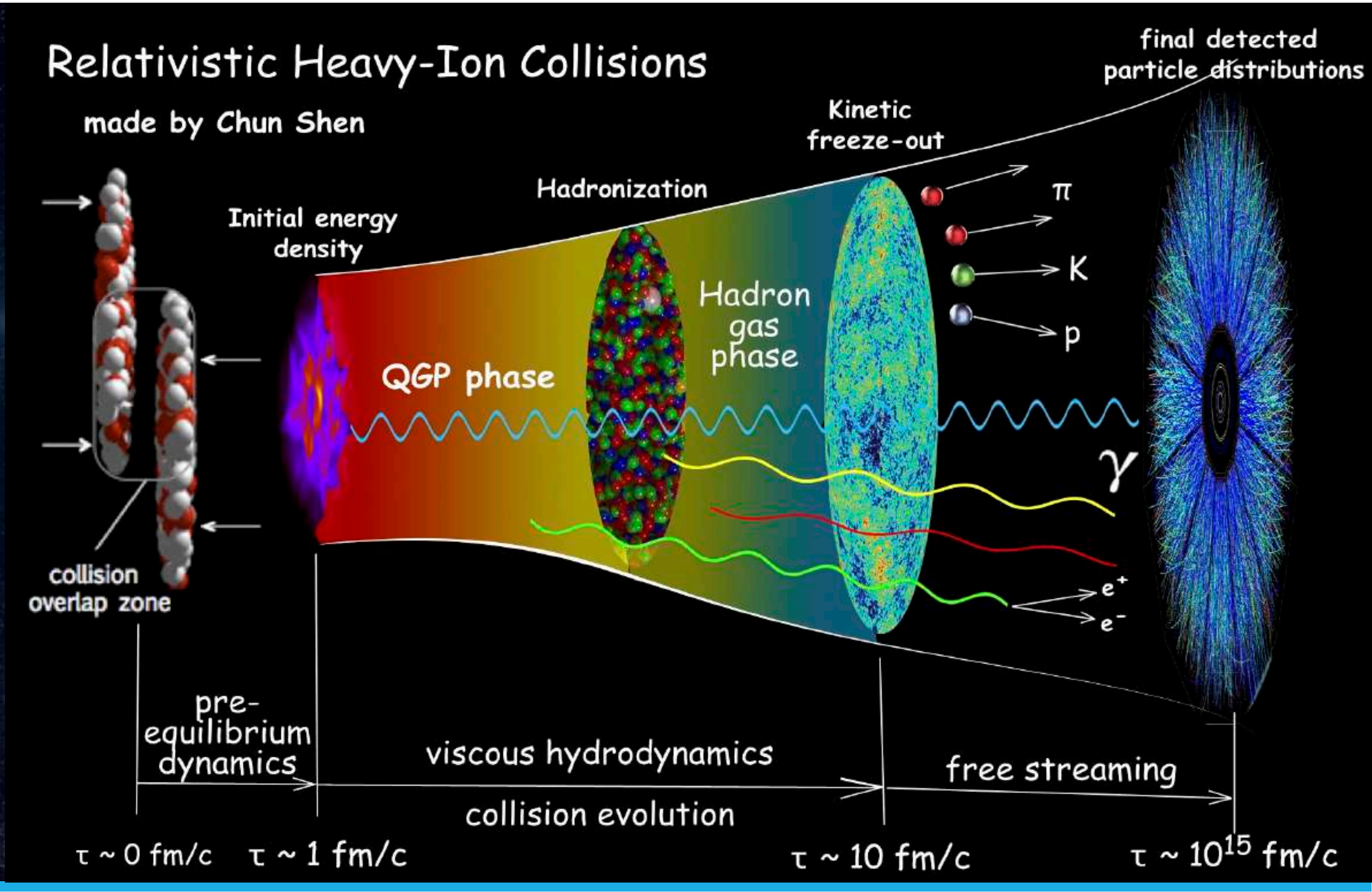
- provide unique tests of how collectivity and thermal properties arise in the fundamental non-abelian quantum field theory **QCD**.
- Understanding hydrodynamic properties of **QCD**-matter starts reaching maturity.
- We start being sensitive to non-hydrodynamic excitations of **QCD**-matter:
  - these excitations probe the **”inner workings of the QGP”**
  - testing bottom-up, a more encompassing HI paradigm?
- Many **O**pp**O**rtunities for interplay between theory and experiment in the coming decade*

Z. Citron et al., Report of Working Group 5: Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams, arXiv:1812.06772

D. Adamova et al, A next-generation LHC heavy-ion experiment, arXiv:1902.01211

Plasma


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3\times10^{5}$ y
$E = 3\times10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8\times10^{9}$ y
$E = 2.3\times10^{-13}$ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6×10^{-10} joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE


Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
QGP phase
Hadron gas phase
π
K
p
γ
e^+
e^-
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^{15} fm/c