Integrated HydroKinetic Model at Relativistic Heavy Ion Collider Energies

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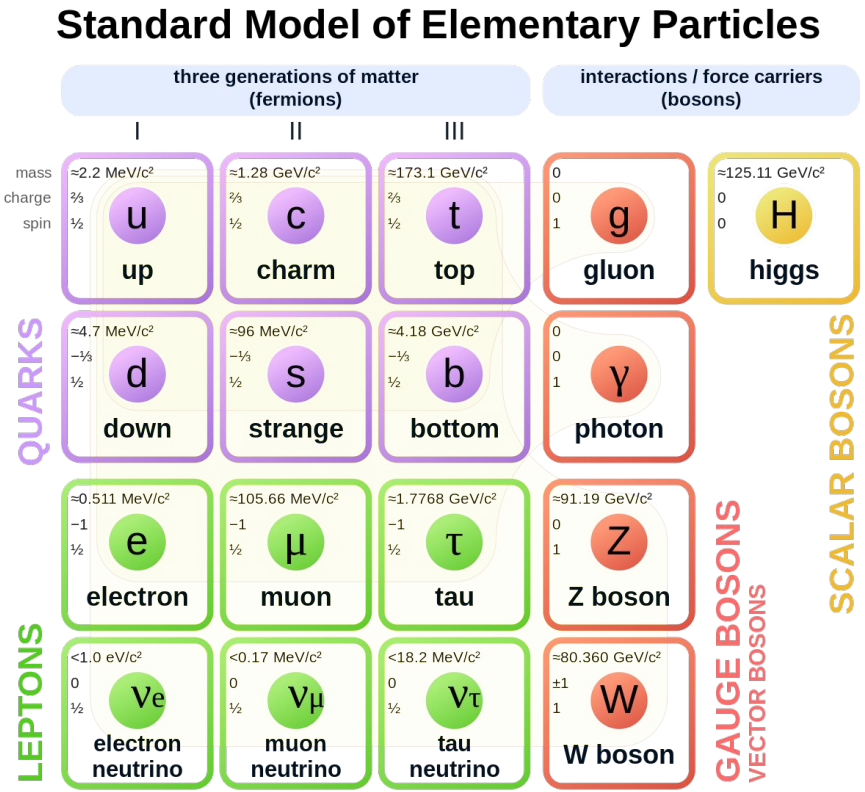
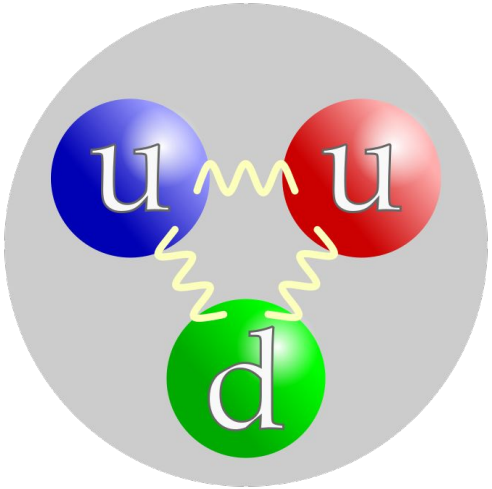
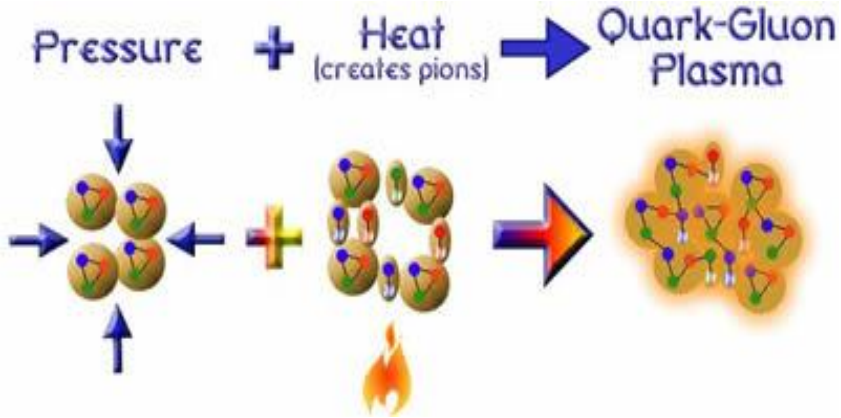
Strong Force in the Standard Model



Quarks and gluons can only exist in a confined (colorless) state within hadrons



New forms of matter

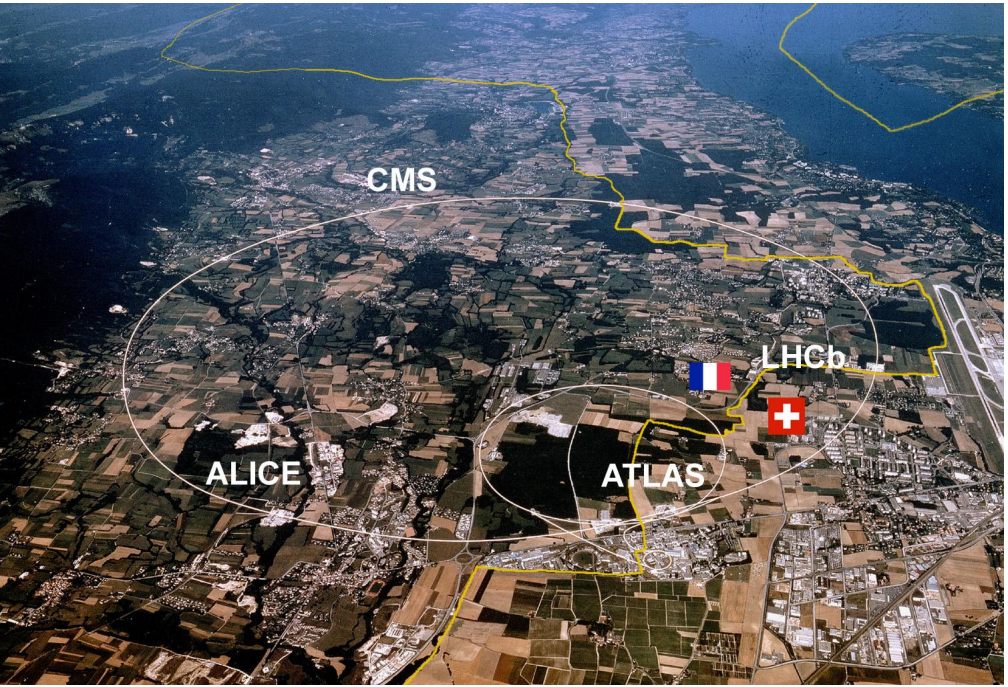


Take nuclear matter squeeze it heat up
Deconfined quarks and gluons in thermal equilibrium can form quark-gluon plasma

How to reach it in laboratory?

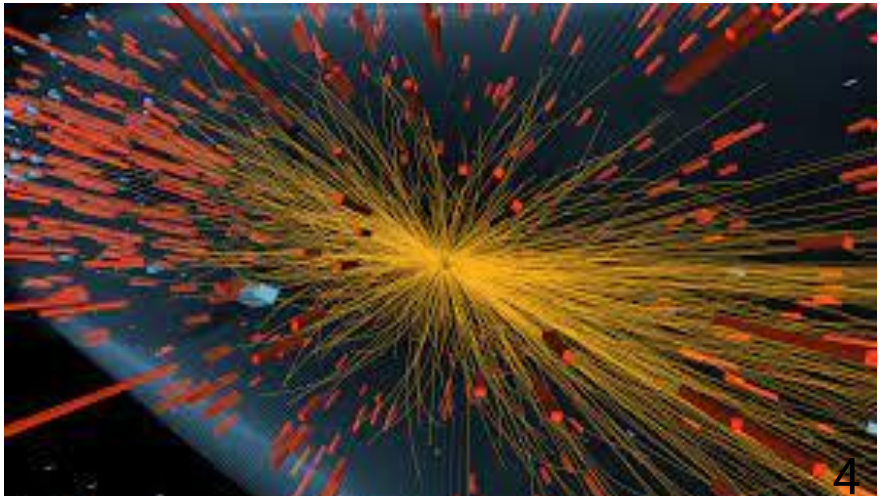
Collider experiments!

Collider experiments



The Large Hadron Collider

Thousands of new hadrons are created as a result of the collision of two nuclei



Standard Model of Heavy-Ion Collisions

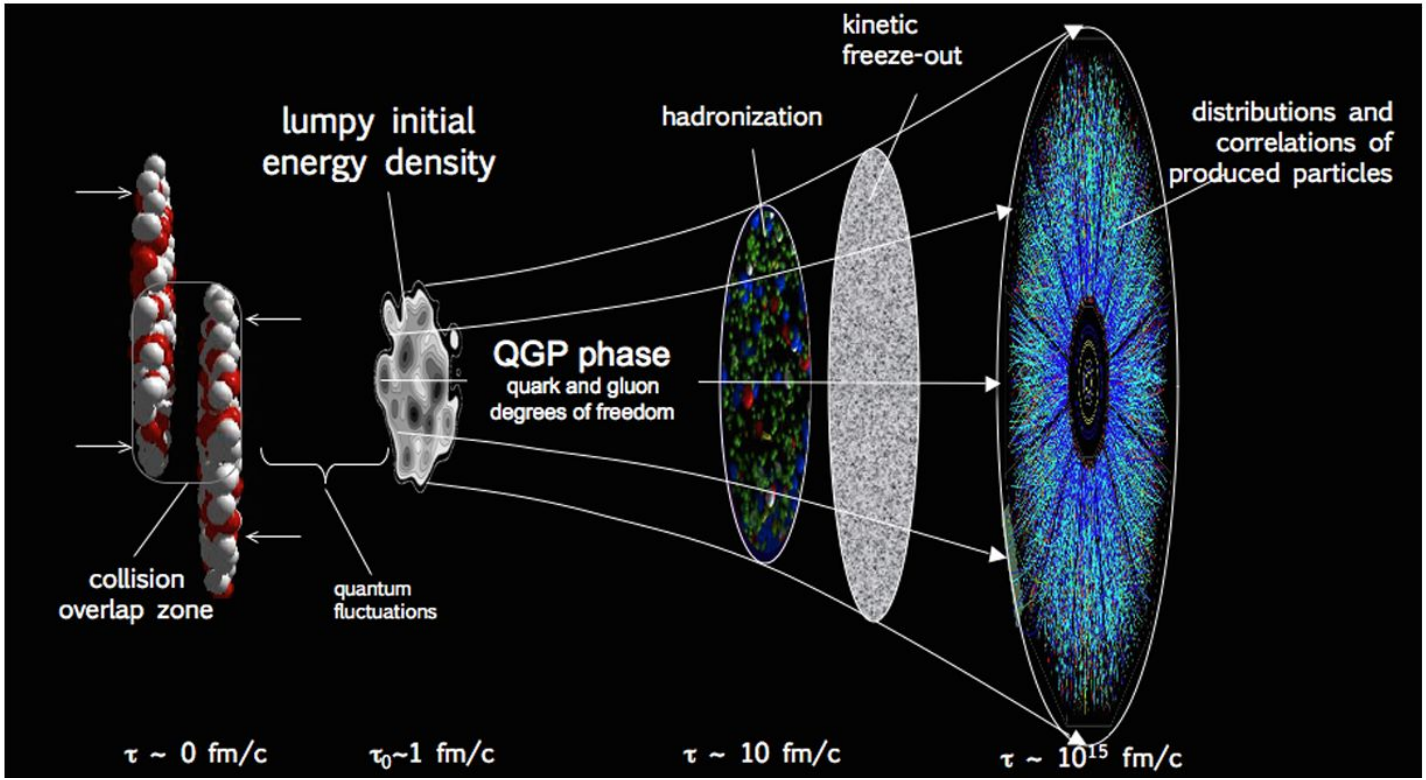
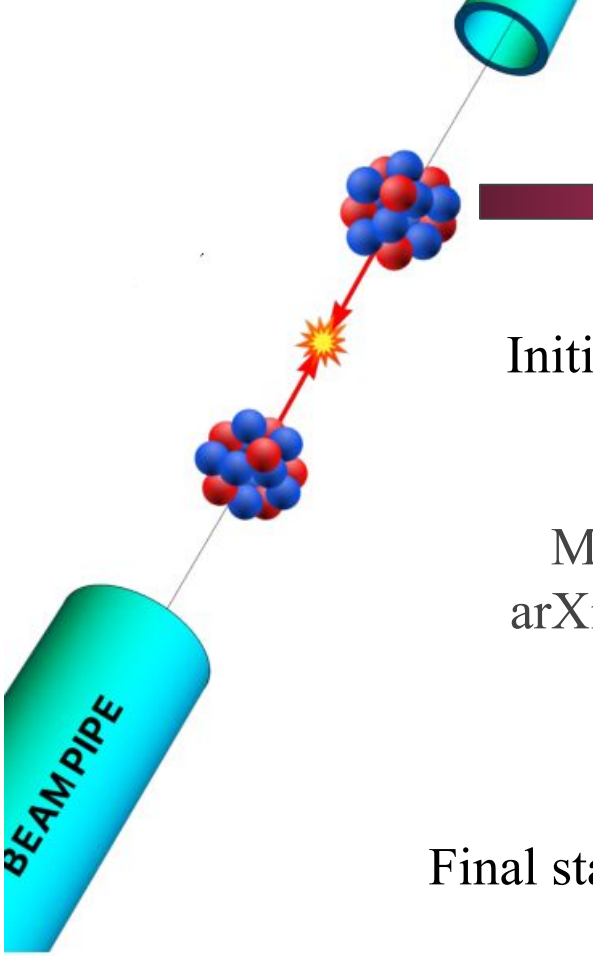


Image from Stefan Floerchinger

Short QGP stage or **no thermalization** at **low-energy** collisions (several GeV)

Integrated Hydro-Kinetic model (iHKM)



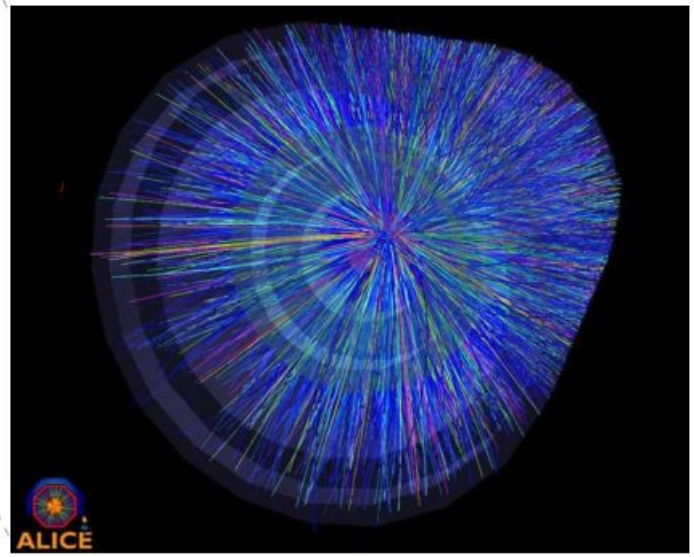
Initial condition: two nuclei

M.A. and Yu. Sinyukov
arXiv:2412.00458 [hep-ph]
iHKM

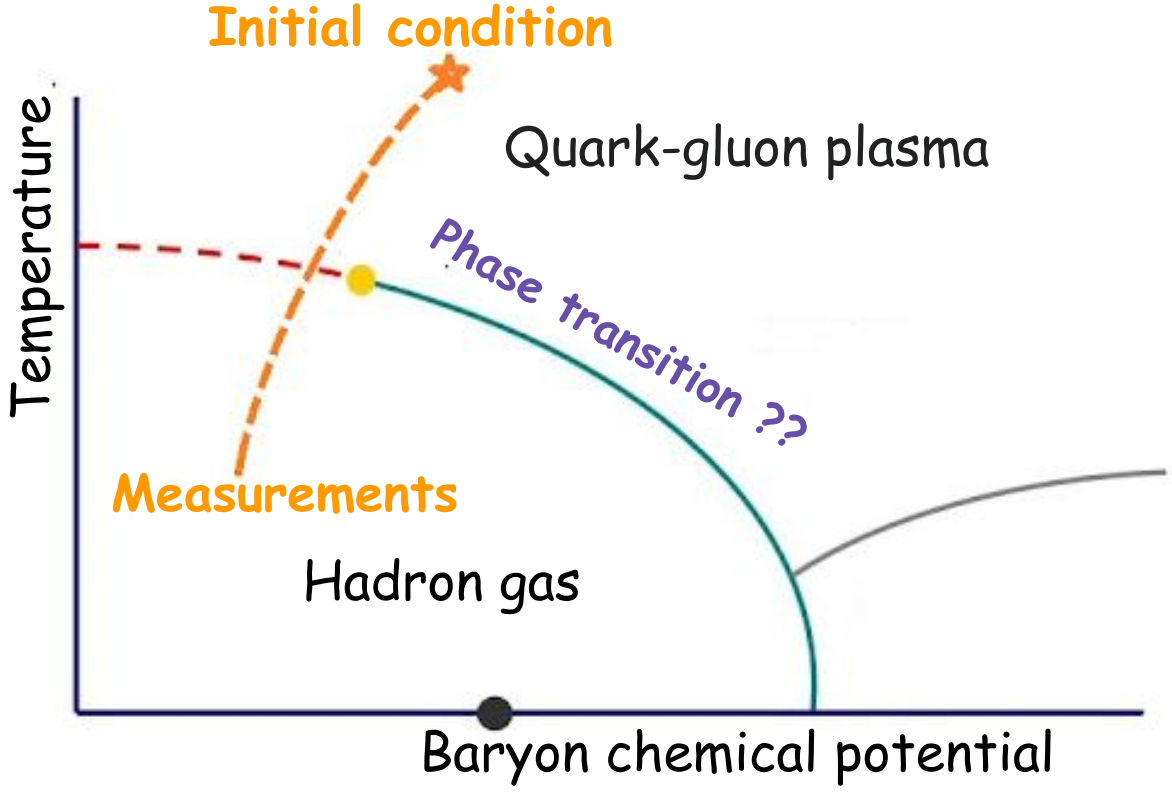
Final state: Free streaming hadrons

For GeV range: RHIC, FAIR

Image modified from Bally, Benjamin et al
arXiv:2209.11042

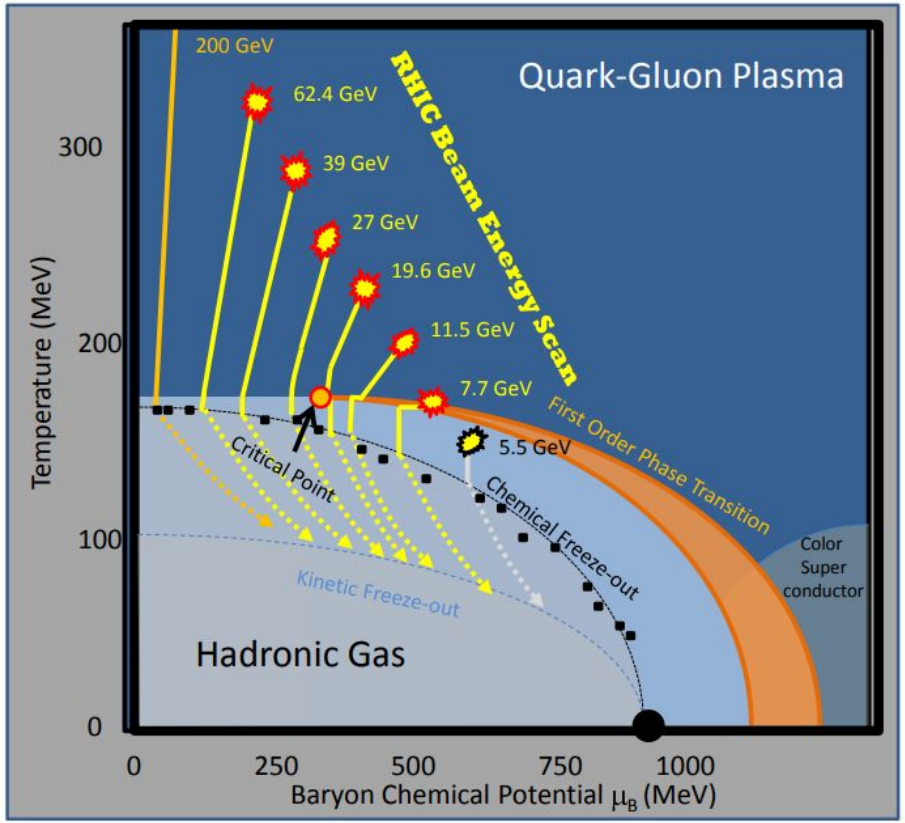


Usage showcase: Phase diagram scanning



Measurements always happen in hadron gas phase

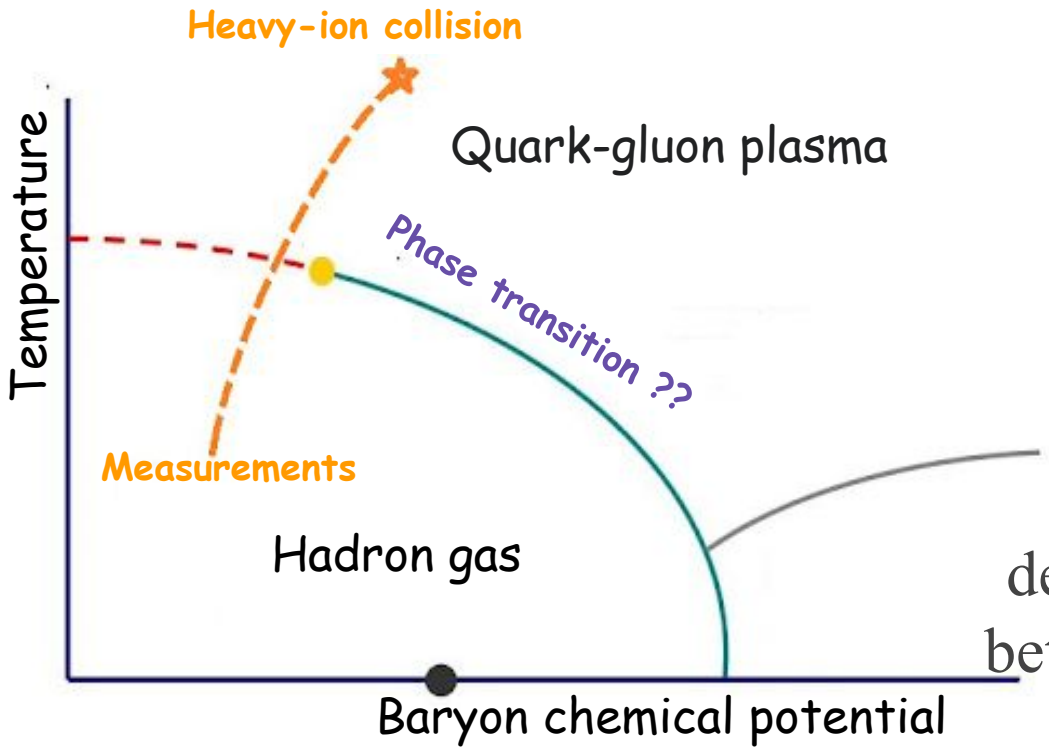
RHIC Beam Energy Scan and FAIR CBM



Experimental programs **scan phase diagram** by varying the energy

Expect to see signals of critical point in the final observables

Phase diagram



Equation of state

$$p = p(T, \mu)$$

or

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

defines how the system evolves between the moment of collision and measurements

Relativistic hydrodynamics

Relativistic (ideal) hydrodynamics with one conserving charge

$$\begin{cases} T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - p g^{\mu\nu}, \\ J^\mu = n u^\mu. \end{cases}$$

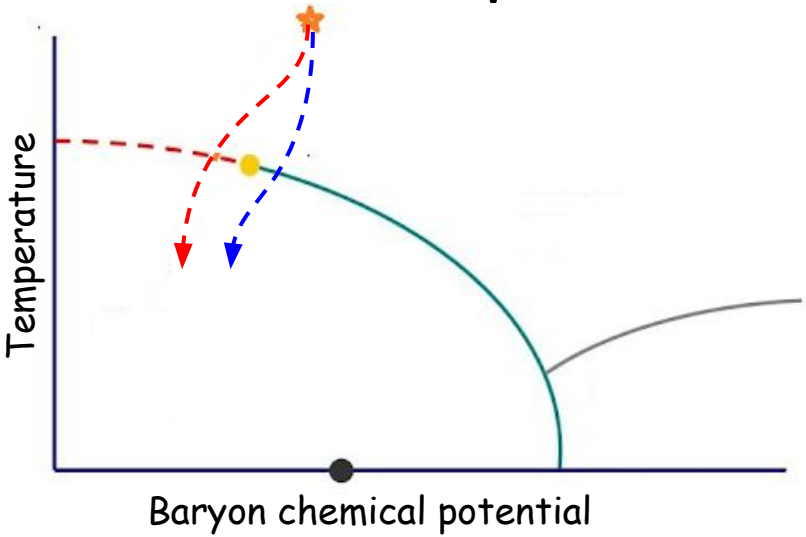
There are **1** + **1** + **1** + **3** = **6** fields

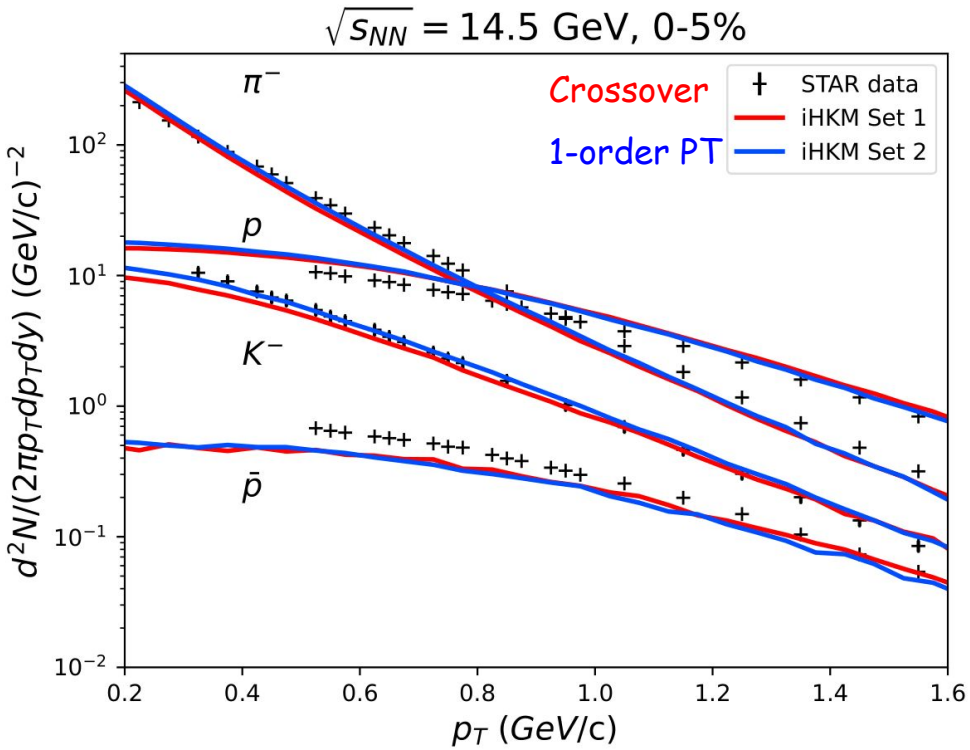
$$\begin{cases} \partial_\mu T^{\mu\nu} = 0, \\ \partial_\mu J^\mu = 0, \\ p = p(\epsilon, n) \end{cases}$$

Only **5** PDEs (4 for stress-energy tensor and 1 for the baryon current)

Need one more — equation of state !!

Observables: Transverse spectra

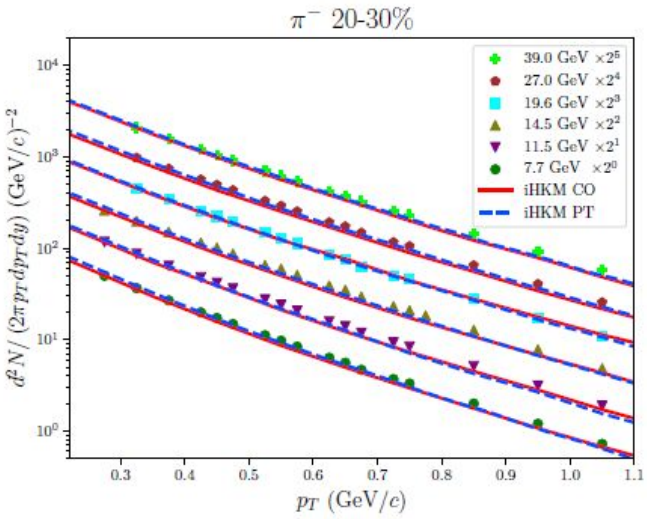


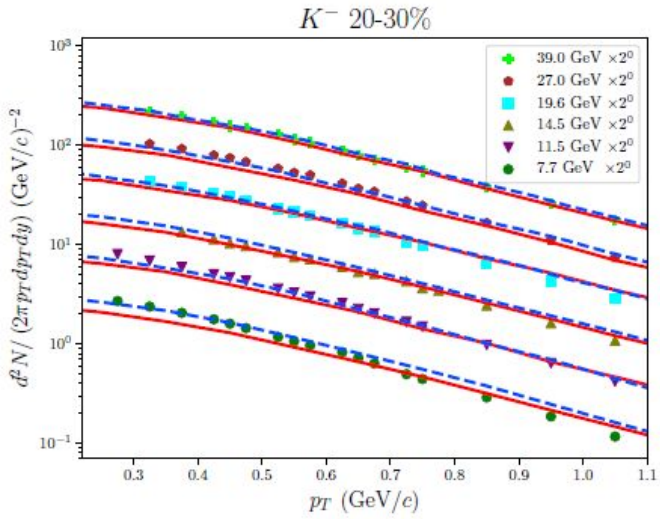


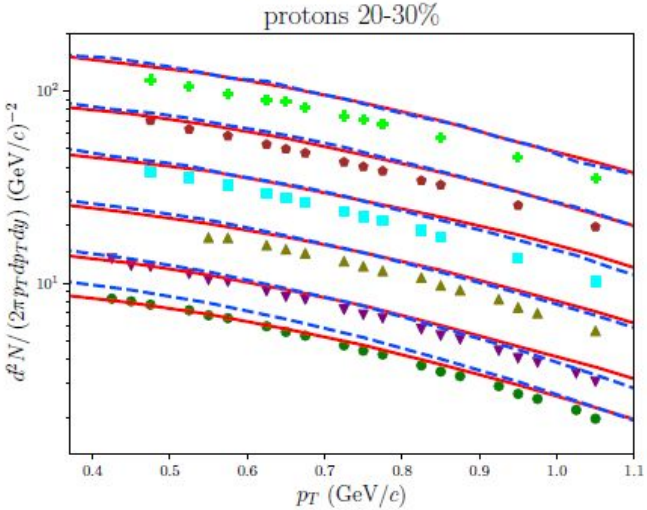
Title	EoS	$R_\perp$	R_η	τ_0	τ_{th}	τ_{rel}	η/s	ϵ_{sw}
Set 1	chiral	0.5 fm	0.5 fm	1.2 fm/c	2.6 fm/c	1.4 fm/c	0.08	0.50 GeV/fm^3
Set 2	AZHYDRO	0.5 fm	0.5 fm	1.4 fm/c	1.8 fm/c	0.4 fm/c	0.08	0.35 GeV/fm^3

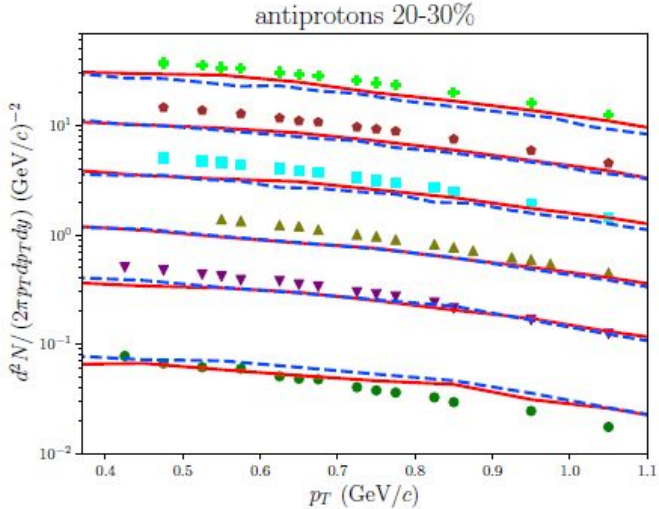
Spectra for RHIC BES program 7.7 – 39 GeV

Spectra for pion, kaon, protons and antiprotons look similar for both equations of state









Elliptic flow

Sensitive to EoS and viscosity!

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3\mathbf{p}} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\mathrm{t}\mathrm{d}p_\mathrm{t}\mathrm{d}y}\left(1+2\sum_{n=1}^{\infty}v_n\cos[n(\varphi-\Psi_\mathrm{RP})]\right)$$

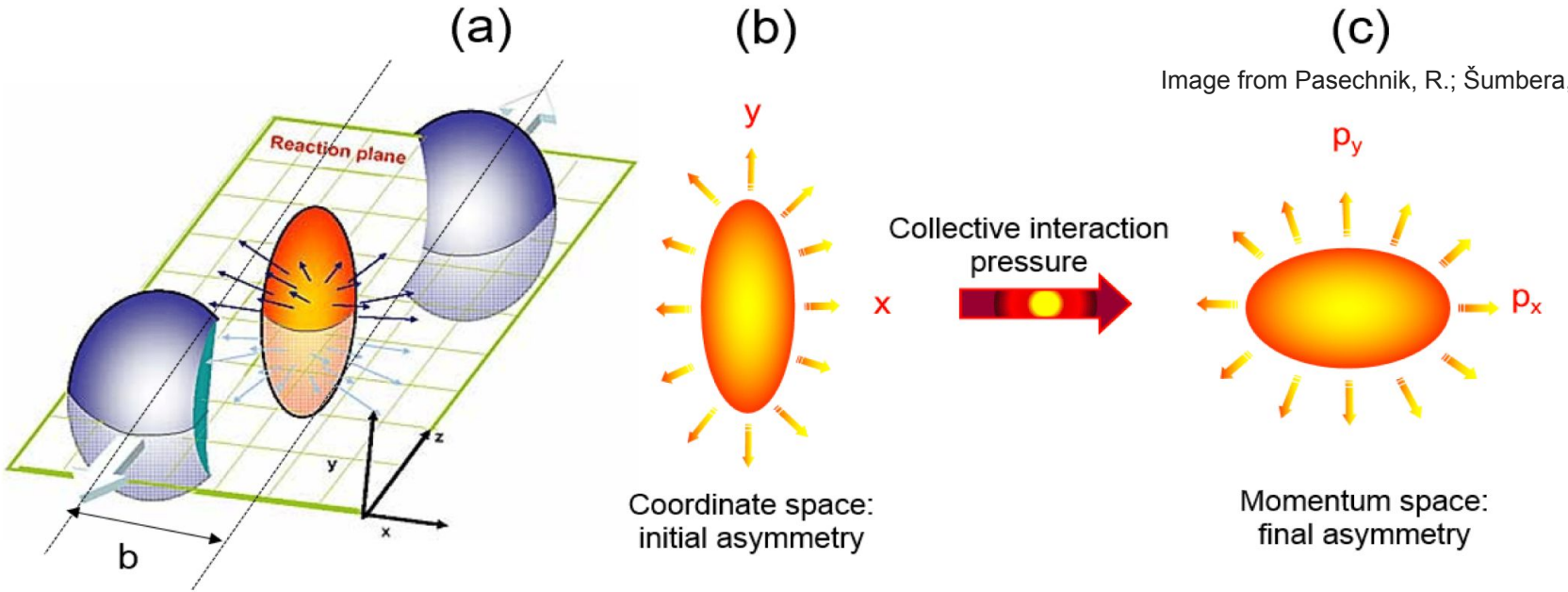
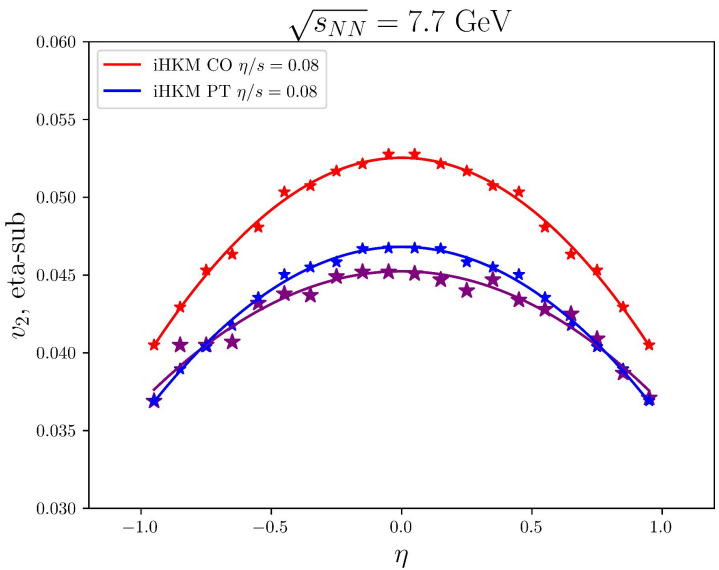
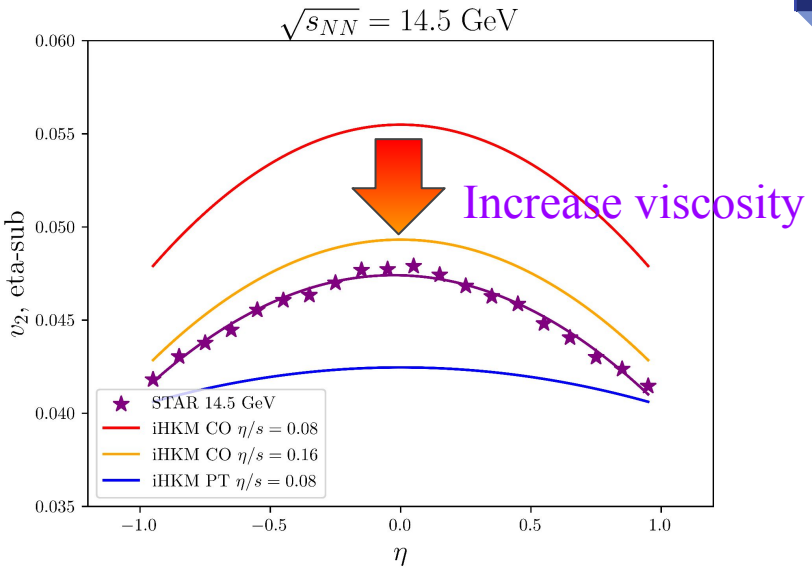


Image from Pasechnik, R.; Šumbera, M. *Universe* **2017**

Signal of phase transition?





At 7.7GeV The model prefers equation of state with phase transition. At higher — crossover.
Possible position of critical point around 7.7 GeV?

Need new data below 7.7 GeV!
Must come from future CMB of RHIC BES Fixed target

Conclusions for RHIC BES program

1. Crossover and minimal viscosity at 27 GeV and higher

2. 11.5 GeV to 19.6 GeV – Crossover but with higher viscosity

3. 7.7 GeV – Phase transition?

4. Need a) to scan lower energies (CBM experiment)
   b) include other observables (higher flow harmonics, HBT, fluctuations etc.)
   c) sensitive and robust analysis (e.g. machine learning)

Thank you!

Plans: research methodology