Transport Theory
for Energetic Nuclear Reactions

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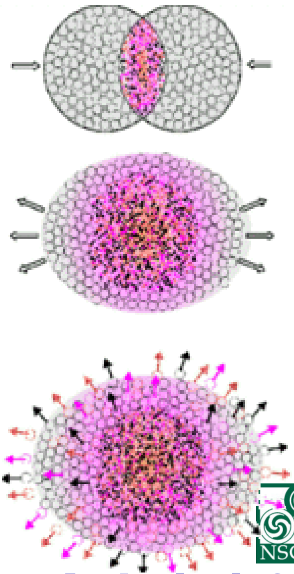
Outline

Need for Transport

Many repeated elementary interactions

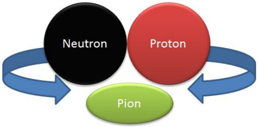
- Central Nuclear Collisions
- Isotope Production
- Energetic Hadron-Nucleus Collision
- ν Detection
- Technological Applications
- ...



Degrees of Freedom

Choice depends on energy and application

- Nucleons
- Clusters
- Pions, Baryon Resonances
- Kaons, Strange Baryons
- Photons
- ...



Dominant degrees of freedom must be included; other may be treated perturbatively.

Phase-space distribution (in configuration space and momentum) $\Leftrightarrow$ Wigner function

$$f(\mathbf{p};\mathbf{R},T) = \int d\mathbf{r}\, \mathrm{e}^{-i\mathbf{p}\mathbf{r}}\, \langle \hat{\psi}_H^\dagger(\mathbf{R}-\mathbf{r}/2,T)\, \hat{\psi}_H(\mathbf{R}+\mathbf{r}/2,T) \rangle$$

Statistical Description

Phase-space distribution

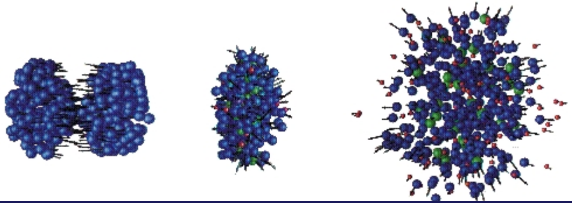
$$f(\mathbf{p};\mathbf{R},T)=\int d\mathbf{r}\,\mathrm{e}^{-i\mathbf{pr}}\,\langle\hat{\psi}_H^{\dagger}(\mathbf{R}-\mathbf{r}/2,T)\,\hat{\psi}_H(\mathbf{R}+\mathbf{r}/2,T)\rangle$$

Dynamics: Particles move through noisy medium: stochastic + deterministic impact of the medium on the particle - collisions + mean field

Descriptions invoke Boltzmann equation:

$$\frac{\partial f}{\partial t}+\frac{\partial \epsilon}{\partial \mathbf{p}}\frac{\partial f}{\partial \mathbf{r}}-\frac{\partial \epsilon}{\partial \mathbf{r}}\frac{\partial f}{\partial \mathbf{p}}=\mathcal{K}^{<}\,(1\mp f)-\mathcal{K}^{>}\,f$$

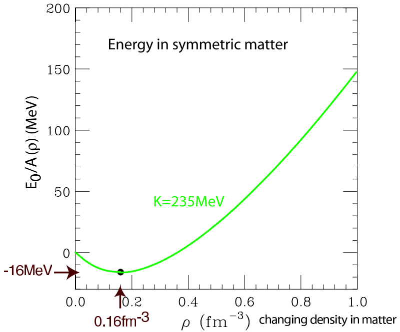
Left-hand deterministic impact   Right-hand stochastic

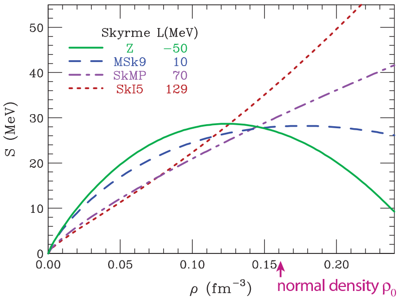


Means of Learning on EOS at $\rho > \rho_0$

$$\frac{E}{A}(\rho_n, \rho_p) = \frac{E_0}{A}(\rho) + S(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + \mathcal{O}(\ldots^4)$$

symmetric matter (a)symmetry energy $\rho = \rho_n + \rho_p$





$$\frac{E_0}{A}(\rho) = -B + \frac{K}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 + \ldots \qquad S(\rho) = S_0 + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0} + \ldots$$

Known: $B \approx 16$ MeV $K \sim 235$ MeV Unknown: S_0 ? L ?

- Boltzmann Equation Type
  - Examples: GIBUU, IBUU, pBUU, RVUU
  - Pros: Well-defined equation, derivable from microscopic theory, solved; easy Pauli principle & mean-field
  - Cons: No fluctuations
- Molecular Dynamics
  - Examples: IQMD, CoMD, TuQMD, UrQMD
  - Pros: Good fluctuations late in reactions
  - Cons: Wrong fluctuations initially, troubles with Pauli & mean-field, too much phenomenology?
- Antisymmetrized Molecular Dynamics (AMD)
  - Pros: Excellent initial states, good mean field & Pauli
  - Cons: Troubles with final states, dose of phenomenology

EOS in Central Reactions

Reaction plane: plane in which the centers of initial nuclei lie

Spectators: nucleons in the reaction periphery, little disturbed by the reaction

Participants: nucleons that dive into compressed excited matter

Nuclear EOS deduced from the features of collective flow in reactions of heavy nuclei

Collective flow: motion characterized by significant space-momentum correlations, deduced from momentum distributions of particles emitted in the reactions

Euler eq. in $\vec{v} = 0$ frame:

$$m_N \, \rho \, \frac{\partial}{\partial t} \, \vec{v} = -\vec{\nabla} p$$

EOS and Flow Anisotropies

EOS assessed through reaction plane anisotropies characterizing particle collective motion

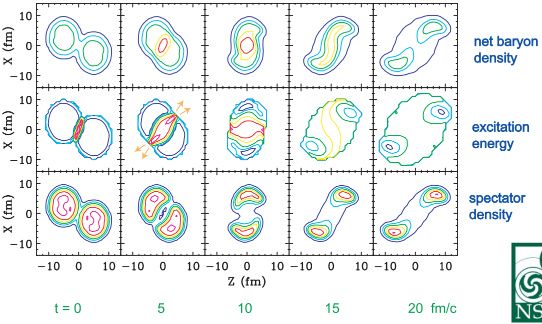
Hydro? Euler eq. in $\vec{v} = 0$ frame: $\boxed{m_N \, \rho \, \frac{\partial}{\partial t} \, \vec{v} = -\vec{\nabla} p}$

where p - pressure. From features of v, knowing Δt, we may learn about p in relation to ρ. Δt fixed by spectator motion

For high p, expansion rapid and much affected by spectators

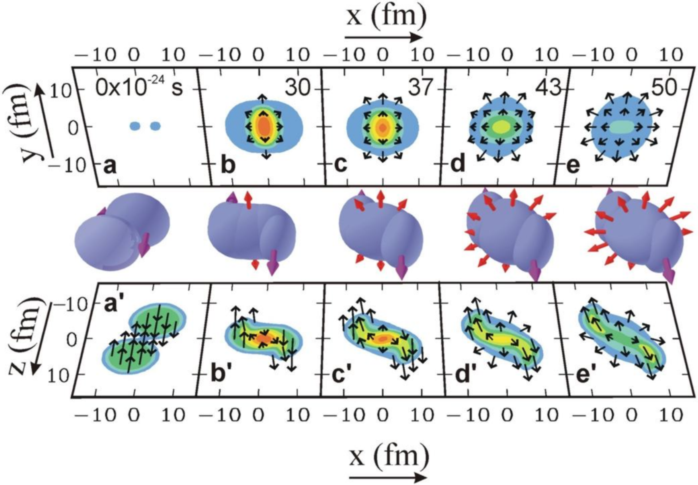
For low p, expansion sluggish and completes after spectators gone

Simulation by Shi (pBUU)



Medium-Energy Collisions of Heavy Nuclei

Thermalized matter at high baryon density! 2 GeV/u Au+Au



Top panels: pressure $\perp$ to beam axis (up to 90 MeV/fm^3) + flow

Bottom panels: density (up to $3\rho_0$) in reaction plane + flow

Sideward Flow Systematics

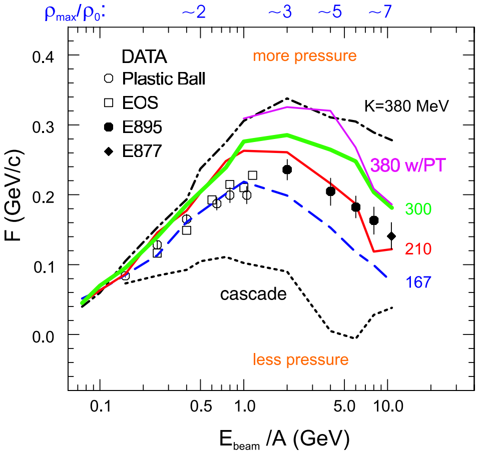
Deflection of forwards and backwards moving particles away from the beam axis, within the reaction plane

Au + Au Flow
Excitation Function

Note: *K* used as a label

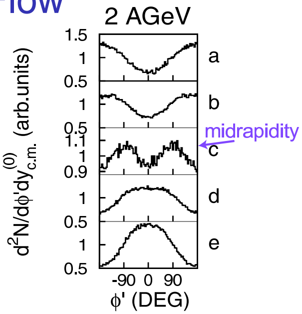
PD, Lacey & Lynch (pBUU)

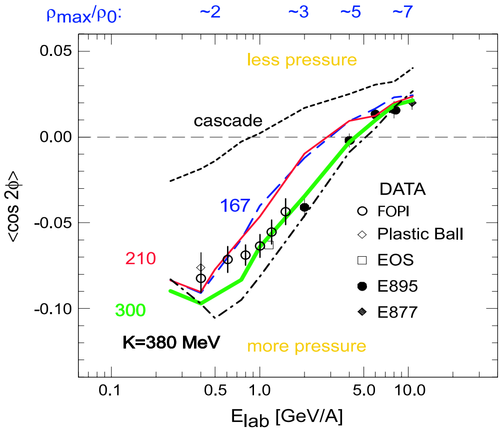
The sideward-flow observable results from dynamics that spans a ρ-range varying with the incident energy



2^{nd}-Order or Elliptic Flow

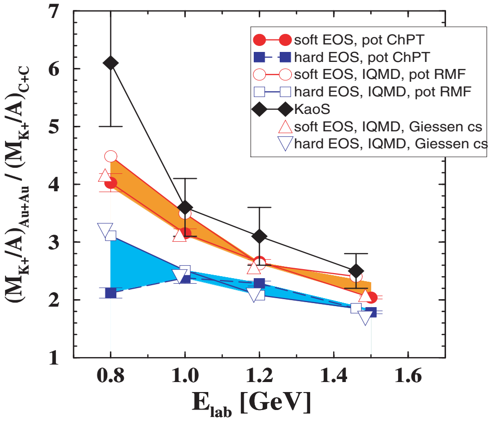
Another anisotropy, studied at midrapidity: $v_2 = \langle \cos 2\phi \rangle$, where ϕ is azimuthal angle relative to reaction plane





Au+Au v_2
Excitation Function

Subthreshold Meson (K/π) Production



Ratio of kaons per participant nucleon in Au+Au collisions to kaons in C+C collisions vs beam energy

filled diamonds: KaoS data

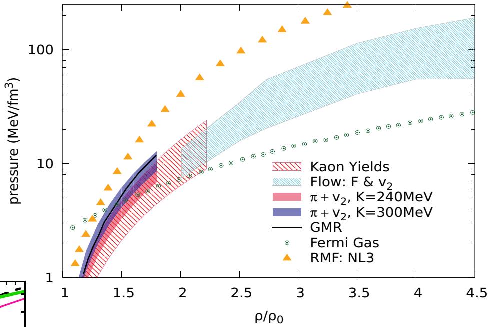
open symbols: theory Fuchs *et al*

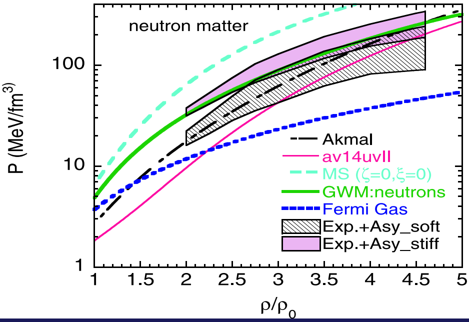
Kaon yield sensitive to EOS because multiple interactions needed for production, testing density

The data suggest a relatively soft EOS

Constraints from Flow on EOS

Au+Au flow anisotropies:
$\rho \simeq (2-4.6)\rho_0$.
No one EOS yields both flows right. Discrepancies: inaccuracy of theory
Most extreme models for EOS can be eliminated





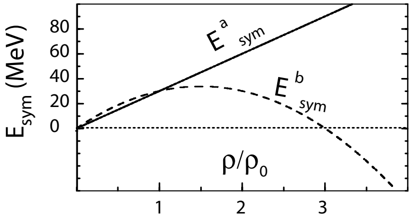
PD, Lacey & Lynch
+ Fuchs + Hong + others

Neutron Matter:

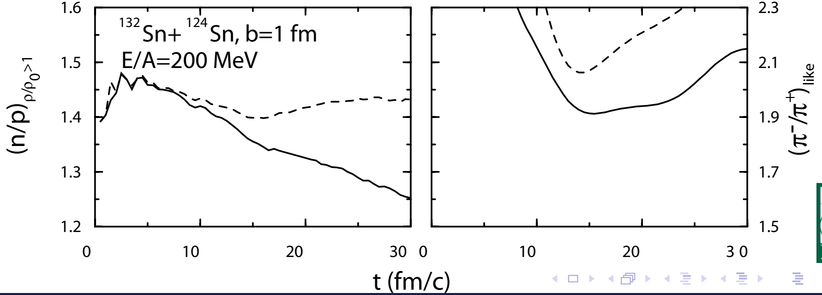
Uncertainty in symmetry energy

Pions as Probe of High-ρ Symmetry Energy

B-A Li PRL88(02)192701: $S(\rho > \rho_0) \Rightarrow n/p_{\rho>\rho_0} \Rightarrow \pi^-/\pi^+$



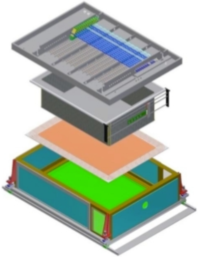
Pions originate from high ρ



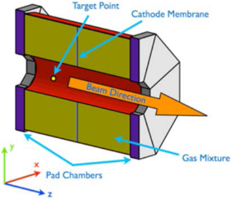
Dedicated Experimental Efforts

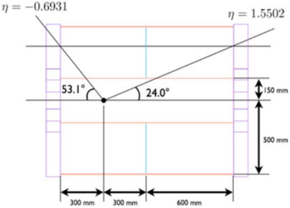
SAMURAI-TPC Collaboration (data taken; 8 countries and 43 researchers): comparisons of near-threshold π^- and π^+ and also *n*-*p* spectra and flows at RIKEN, Japan.

NSCL/MSU, Texas A&M U
Western Michigan U, U of Notre Dame
GSI, Daresbury Lab, INFN/LNS
U of Budapest, SUBATECH, GANIL
China IAE, Brazil, RIKEN, Rikkyo U
Tohoku U, Kyoto U



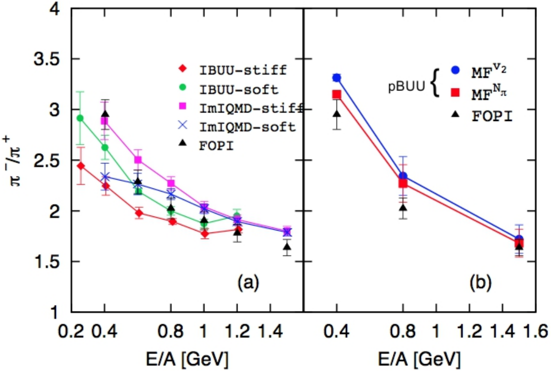
LAMPS TPC at RAON (S Korea): triple GEM, 3π sr





FOPI Au+Au π^-/π^+ Data?

Reisdorf *et al.* (FOPI) NPA781(07)459



data: black symbols

theory: colored symbols

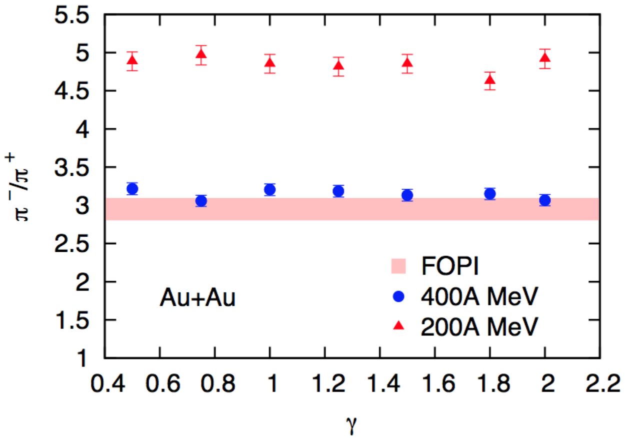
Opposing claims on $S(\rho)$ needed to explain data!


PRL **102,** 062502 (2009) PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2009

Circumstantial Evidence for a Soft Nuclear Symmetry Energy at Suprasaturation Densities

FOPI π^-/π^+ Reproduced by pBUU

...irrespectively of $S_{\text{int}}(\rho) = S_0\,(\rho/\rho_0)^\gamma$:



Jun Hong & PD PRC90(14)024605

...Other probes possible, but general problem of model ambiguity remains!

Code Comparison Project

BUU type	Code correspondents	Energy range	QMD type	Code correspondents	Energy range
BLOB	P. Napolitani, M. Colonna	0.01 0.5	AMD	A. Ono	0.01 0.3
GIBUU-RMF	J. Weil	0.05 40	IQMD-BNU	J. Su, F. S. Zhang	0.05 2
GIBUU-Skyrme	J. Weil	0.05 40	IQMD	C. Hartnack, J. Aichelin	0.05 2
IBL	W. J. Xie, F. S. Zhang	0.05 2	CoMD	M. Papa	0.01 0.3
IBUU	J. Xu, L. W. Chen, B. A. Li	0.05 2	ImQMD-CIAE	Y. X. Zhang, Z. X. Li	0.02 0.4
pBUU	P. Danielewicz	0.01 12	IQMD-IMP	Z. Q. Feng	0.01 10
RBUU	K. Kim, Y. Kim, T. Gaitanos	0.05 2	IQMD-SINAP	G. Q. Zhang	0.05 2
RVUU	T. Song, G. Q. Li, C. M. Ko	0.05 2	TuQMD	D. Cozma	0.1 2
SMF	M. Colonna, P. Napolitani	0.01 0.5	UrQMD	Y. J. Wang, Q. F. Li	0.05 200

Leaders in the effort:
Jorg Aichelin, Evgeni Kolomeitsev, Betty Tsang + others

Jun Xu *et al.* PRC93(16)044609, Yingxun Zhang *et al.* arXiv:1711.05950

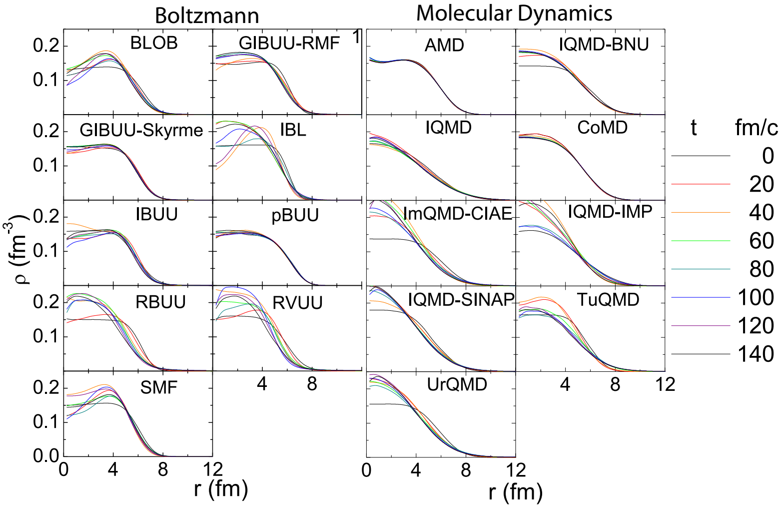
Premise

– Specify the same physics inputs for different transport codes
– Compare outputs

- elastic collisions only
- constant isotropic cross section $\sigma = 40\,\mathrm{mb}$
- soft EOS + momentum-independent mean-field

– Full-run comparisons
– Controlled simplified conditions
  * collisions in a box $\leftarrow$ approach to equilibrium
  * mean field in a box
  * Next: $\Delta + \pi$ production in a box...

Full Runs: Stability of Initial Density

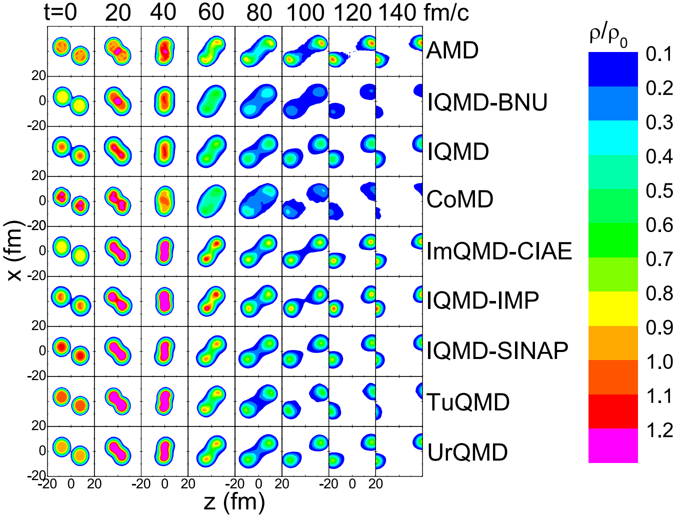


Jun Xu *et al.* PRC93(16)044609 Isolated Au nucleus

⇒ Initial state must be constructed consistently with dynamics

Density Evolutions for Molecular Dynamics

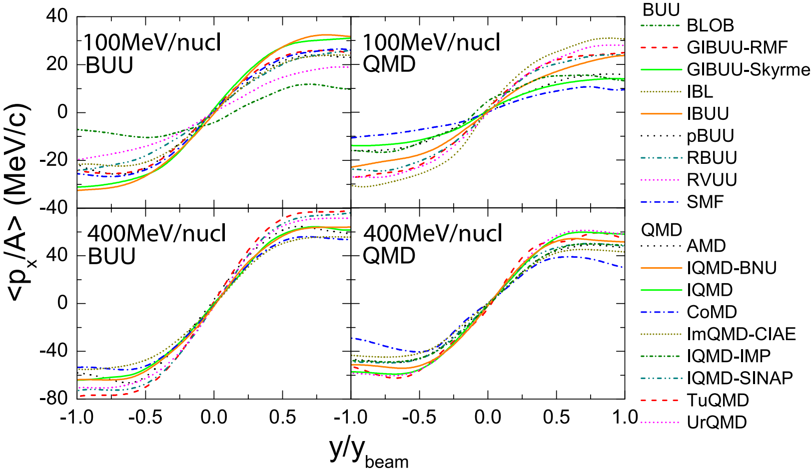
100 MeV/nucleon Au + Au at $b = 7$ fm



General characteristics the same but differences in details

From Differences in Dynamics to Observables

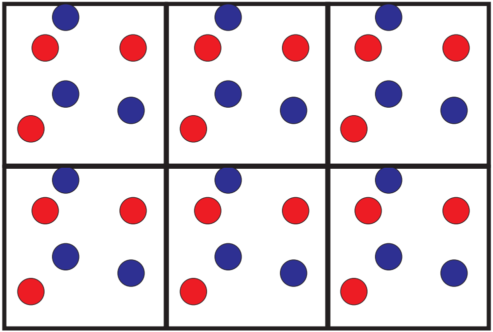
Au + Au at $b = 7$ fm



Less dispersion at high than low energy. But who is right??

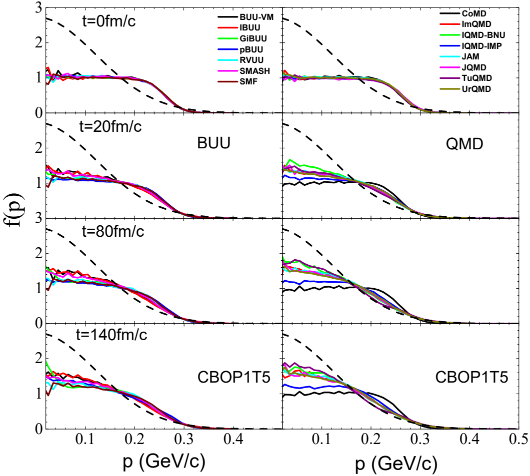
Periodic Box Comparions

1. Elastic Collisions Only
2. Mean-Field Only
3. Delta Production & Absorption…



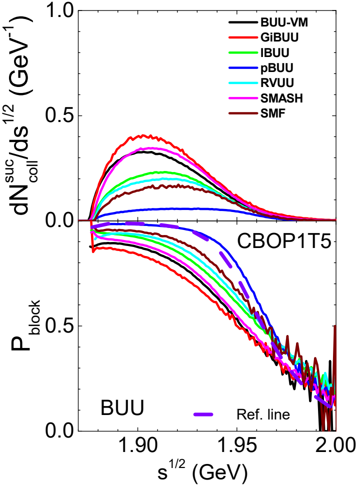
Collisions w/Pauli: Stability of Fermi-Dirac

Systems initialized with Fermi-Dirac at ρ_0 and $T = 5\,\mathrm{MeV}$



Molecular codes progress towards Boltzmann distribution (dashed line). Blocking of collisions? Zhang *et al.* arXiv:1711.05950

Box: Collision Frequency



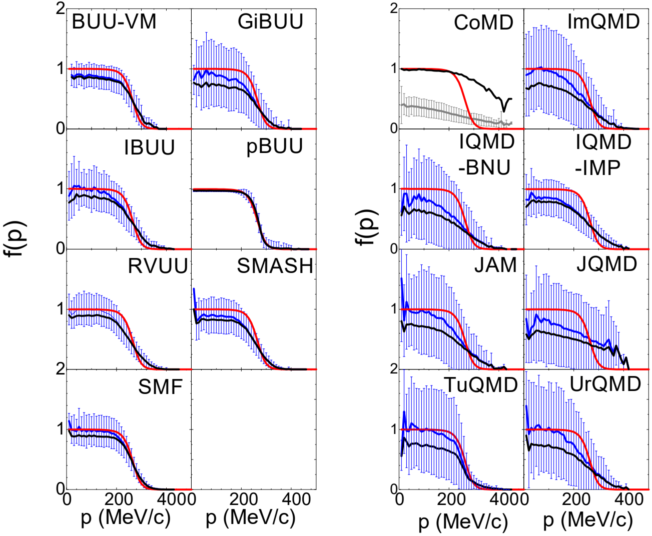
collision rate vs $\sqrt{s}$

blocking fraction

dashed line – reference

Far too many collisions allowed at low excitations ($T = 5\,$MeV)!

Box: Occupation Probabilities in Blocking Factors



red – exact

Large fluctuations in estimated probabilities!

Way Forward

Different codes perform differently in different tests

Some do well

After each sweep procedures are identified that lead to satisfactory performance and are recommended for all codes, e.g. initialization

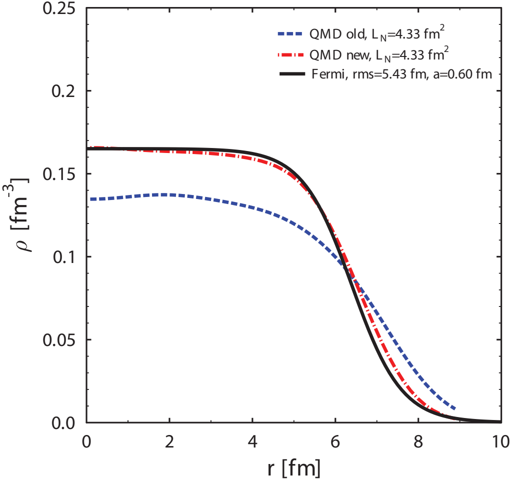
In consequence of the code comparisons, the codes are rebuilt

E.g. TuQMD

Example: Rebuilt TuQMD

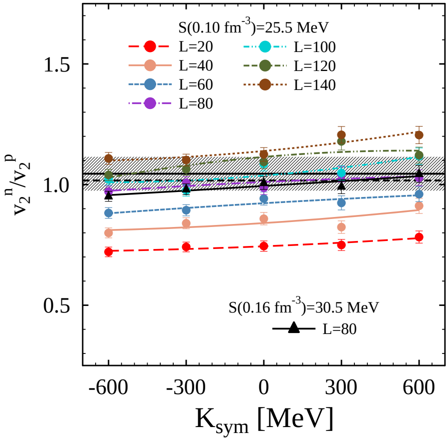
Dan Cozma arXiv: 1706.01300

Rebuilt density initializations and Pauli principle



FOPI-LAND & ASYEOS Elliptic-Flow Data

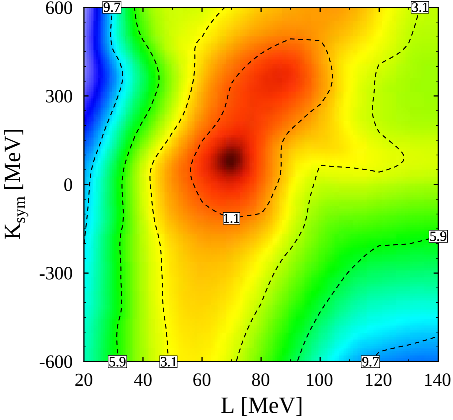
Data Cozma PRC88(13)044912



400 MeV/mucl Au + Au data above + other, particularly more differential

Constraints on Symmetry Energy Parameters

Dan Cozma arXiv: 1706.01300



Linear slope parameter L & curvature K_{sym} vs density

Conclusions

- Transport theory is indispensible in many situations
- $\Rightarrow$ It is means to learn on nuclear properties at supranormal densities
- It has been used to extract constraints on nuclear pressure at supranormal densities from flow data!
- The ability to learn from finer details in data, especially at lower energies, calls for stringent quality control of the theory
- The community effort produces quality standards, helps to sort out the best procedures and prune out mistakes
- This helps to elevate the level of validity of conclusions reached using transport, e.g. TuQMD

Thanks to the authors participating in the code comparisons!!

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