Dynamics and Symmetry Energy at Intermediate Energies

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XIII Workshop on
Particle Correlations and Femtoscopy

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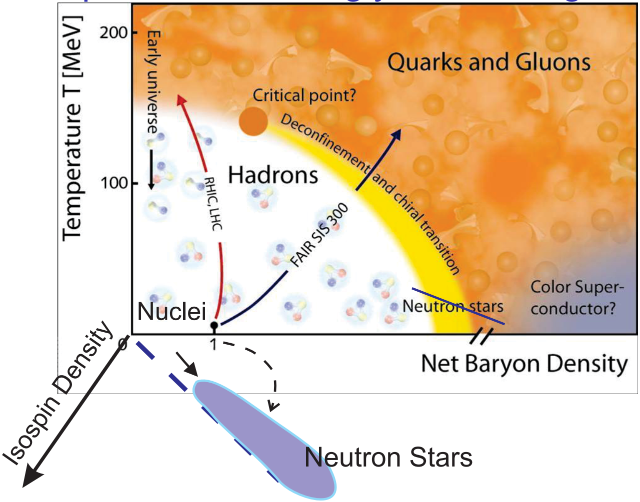
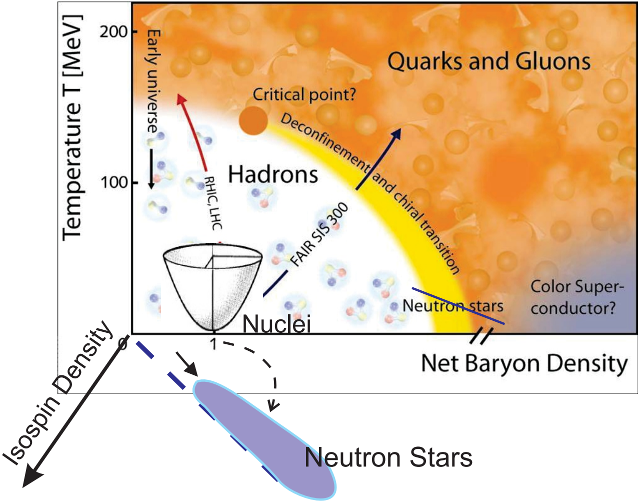
Outline

Bulk Properties of Strongly-Interacting Matter



Equation of State

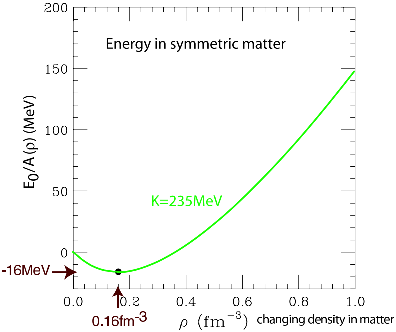


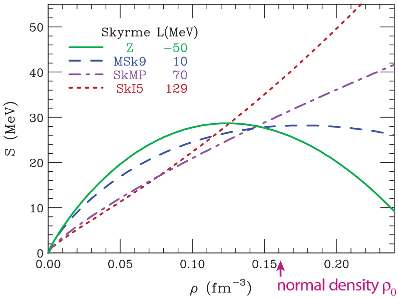
Reactions - coarse, but all ρ. Structure - $\rho < \rho_0$ only

Energy in Uniform Matter

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

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

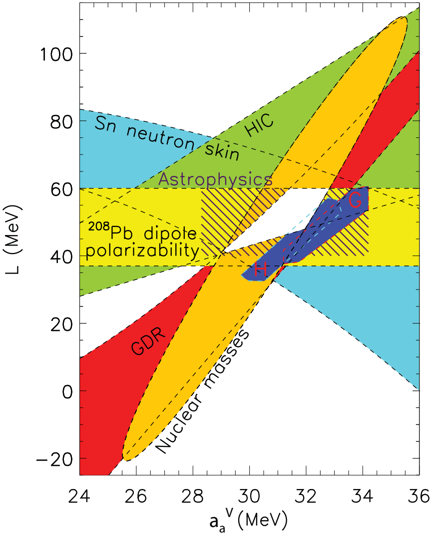




$$\frac{E_0}{A}(\rho) = -a_V + \frac{K}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 + \ldots \qquad S(\rho) = a_a^V + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0} + \ldots$$

Known: $a_a \approx 16\,\text{MeV}$ $K \sim 235\,\text{MeV}$ Unknown: a_a^V ? L ?

Importance of Slope



Lattimer&Lim ApJ771(2013)51

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

$$S \simeq a_a^V + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0}$$

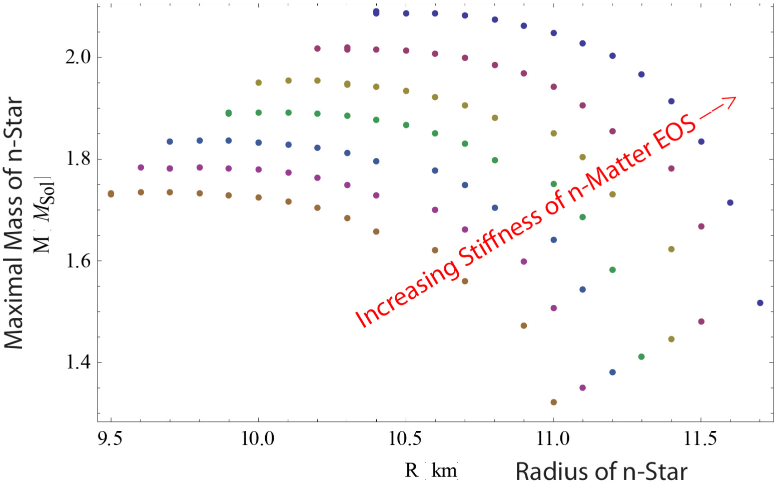
In neutron matter:
$\rho_p \approx 0$ & $\rho_n \approx \rho$.

Then, $\frac{E}{A}(\rho) \approx \frac{E_0}{A}(\rho) + S(\rho)$

Pressure:

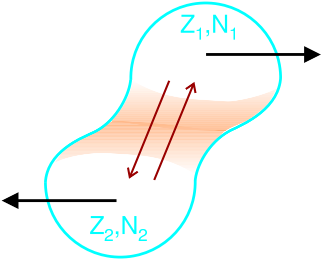
$$P = \rho^2 \frac{\mathrm{d}}{\mathrm{d}\rho}\frac{E}{A} \simeq \rho^2 \frac{\mathrm{d}S}{\mathrm{d}\rho} \simeq \frac{L}{3\rho_0}\rho^2$$

Both Radius & Max Mass Increase w/Stiffness



Schematic Calculation by Stephen Portillo (Harvard U)

n-p Asymmetry Diffusion



Different projectile-target combinations out of ${}^{112}_{50}$Sn and ${}^{124}_{50}$Sn at 50 MeV/nucl

Tsang *et al*

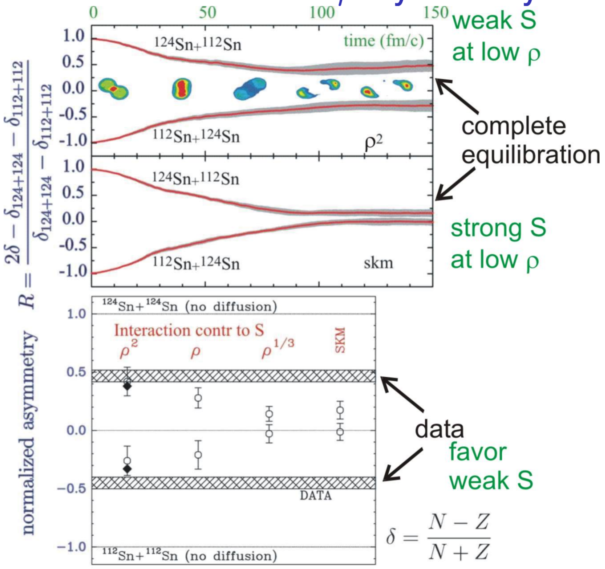
$$\delta_1 = \frac{N_1 - Z}{A_1} = 0.11$$
$$\delta_2 = \frac{N_2 - Z}{A_2} = 0.19$$

Irreversible flux of n-p asymmetry, according to Fick's law:

$$\vec{j}_{\rm np} = \vec{j}_{\rm n} - \vec{j}_{\rm p} = -\nu\,\vec{\nabla}\,[\mu_n - \mu_p] \simeq -4\nu\vec{\nabla}\left[S\,\frac{\rho_n - \rho_p}{\rho}\right]$$

where $\nu > 0$, independent of the symmetry energy S.
Analog of the electric conductivity eq: $\vec{j} = \sigma\,\vec{E} = -\sigma\,\vec{\nabla}\Phi$.
Shi&PD

Low-ρ Symmetry Energy



$$\delta = \frac{N-Z}{N+Z}$$

Linear theory:

$$\vec{j}_{np} \simeq -4\nu\vec{\nabla}\,[S\,\delta]$$

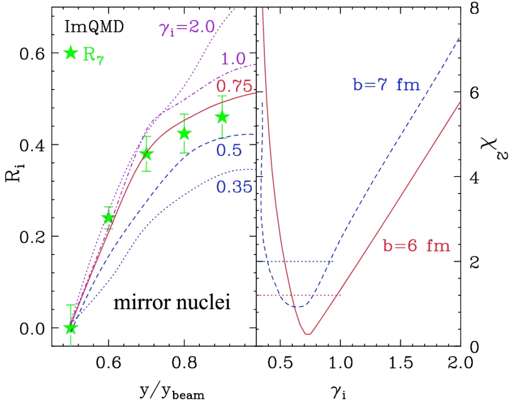
Transport simulations on n-p asymmetry equilibration at velocities close to a Sn projectile, by Shi (Tsang *et al*)

$\Rightarrow$ slow change of S with ρ eliminated

Impact-Parameter Filtered Isospin-Equilibration

Tsang, Zhang *et al*

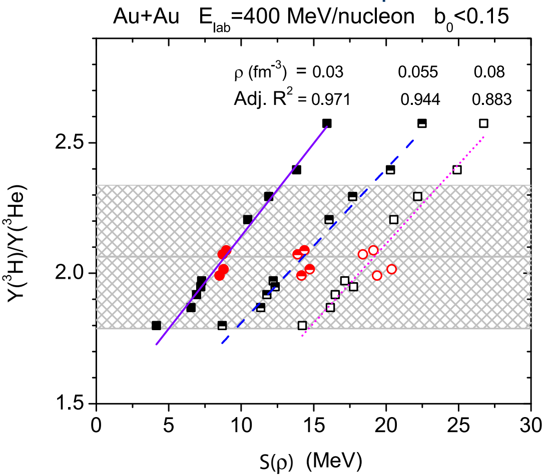
Equilibration ratio R from measured yields of $A = 7$ mirror nuclei, compared to ImQMD



$$S(\rho) = 12.3\,\mathrm{MeV}\,(\rho/\rho_0)^{2/3} + 17.6\,\mathrm{MeV}\,(\rho/\rho_0)^{\gamma_i}$$

^{3}H/^{3}He Yield Ratio

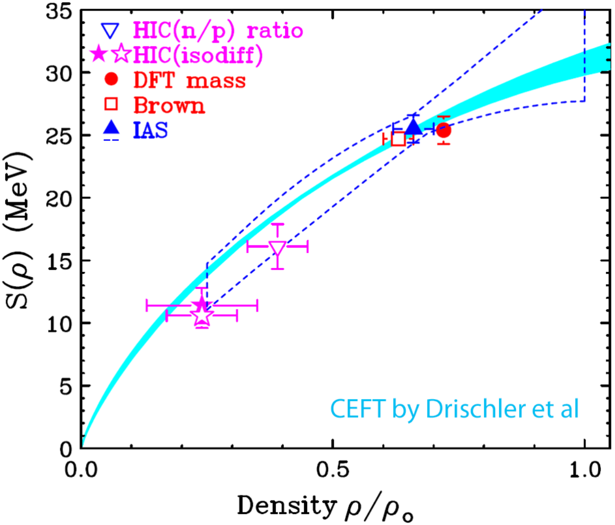
Clusters form at moderate ρ. Stiffness of $S(\rho)$ decides how *n-p* imbalance gets partitioned across densities & what yield ratios of clusters with different isospin become



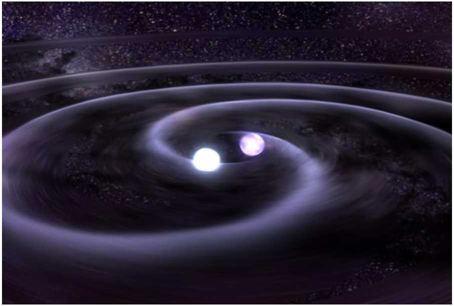
UrQMD + phase-space coalescence results by Yongjia Wang, Qingfeng Li *et al* for different Skyrme ints, plotted vs symmetry-energy values at different ρ, vs FOPI results from Au+Au collisions

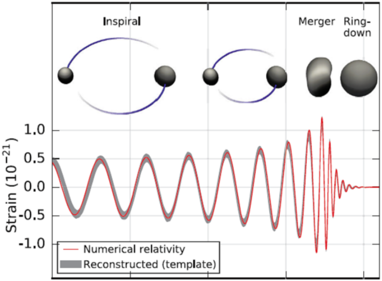
Low-ρ Summary of Symmetry Energy

from work of Tsang & Lynch



Neutron Star Merger Event

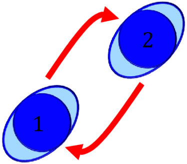




LIGO signal amenable to perturbative analysis - t-resolution insufficient for late stage.

First-order point masses, radiated power $P \propto Q^2$, where Q - quadrupole moment.

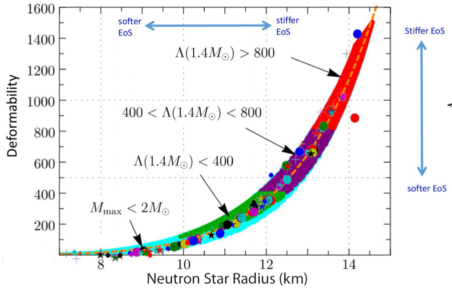
Next order distortion of extended masses matters, $Q_{ij} = \Lambda \, \partial^2 V / \partial r_i \, \partial r_j$, where Λ - tidal deformability

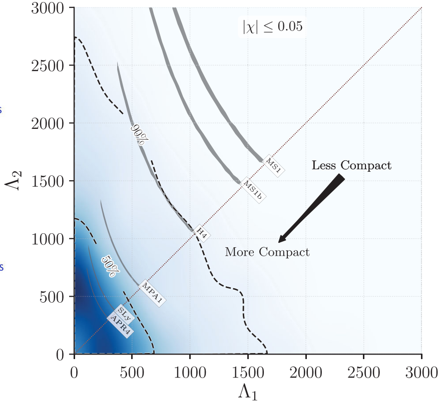


$\Rightarrow$ No significant additional contribution seen!

Implications for Stars & EOS

Large $\Lambda \Leftrightarrow$ large star

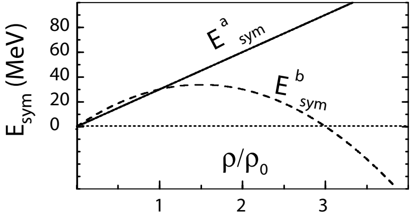




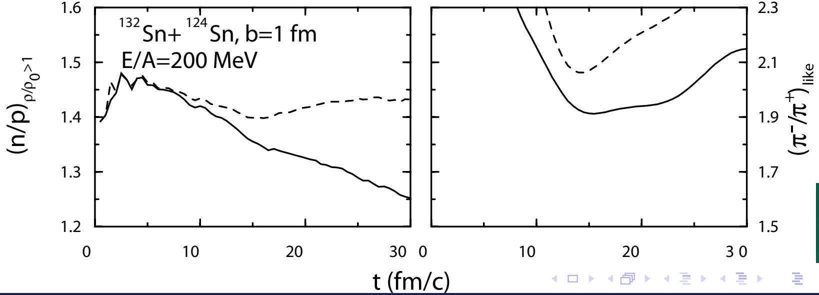
$\Rightarrow$ Largest deformabilities/largest stars/stiffest EOS excluded by merger event!

Pions as Probe of High-ρ Symmetry Energy

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



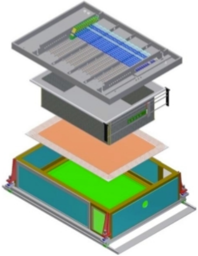
Pions originate from high ρ



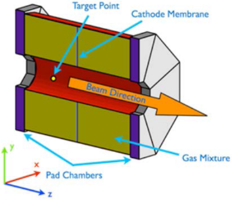
Dedicated Experimental Efforts

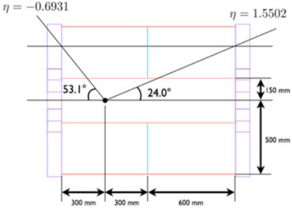
SAMURAI-TPC Collaboration (data taken; 8 countries and 43 researchers): comparisons of near-threshold π^- and π^+ and also *n*-*p* spectra and flows at RIKEN, Japan.

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



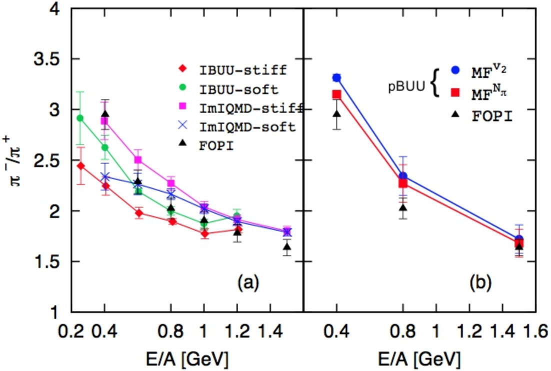
LAMPS TPC at RAON (S Korea): triple GEM, 3π sr





FOPI Au+Au π^-/π^+ Data?

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



data: black symbols

theory: colored symbols

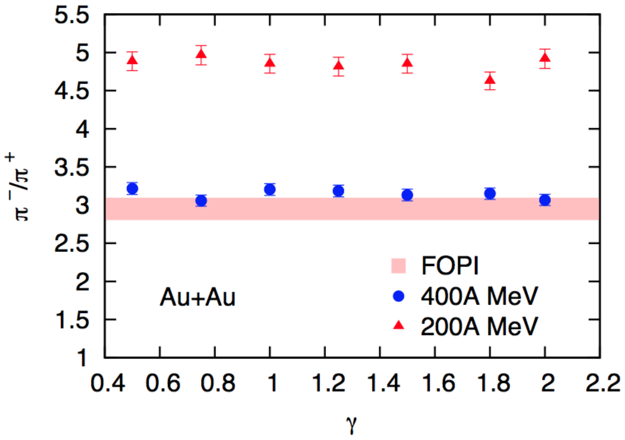
Opposing claims on $S(\rho)$ needed to explain data!

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 $S_{\rm int}(\rho) = S_0\,(\rho/\rho_0)^\gamma$:



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.* PRC97(18)034625

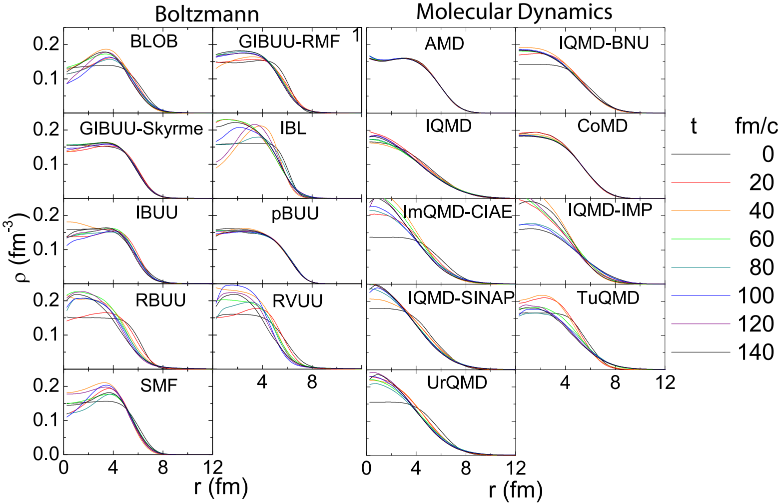
Premise

- 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



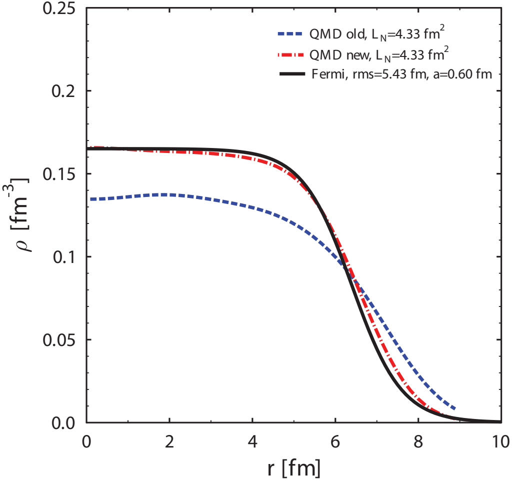
Jun Xu *et al.* PRC93(16)044609 Isolated Au nucleus

⇒ Initial state must be constructed consistently with dynamics

Example: Rebuilt TuQMD

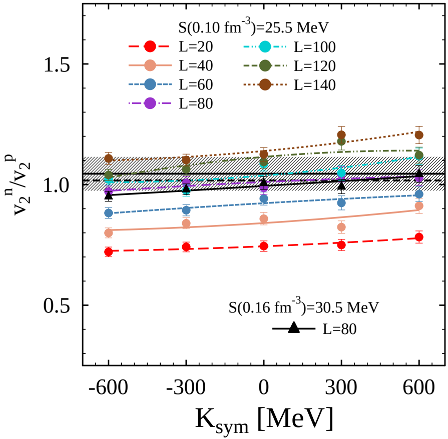
Dan Cozma arXiv: 1706.01300

Rebuilt density initializations and Pauli principle



FOPI-LAND & ASYEOS Elliptic-Flow Data

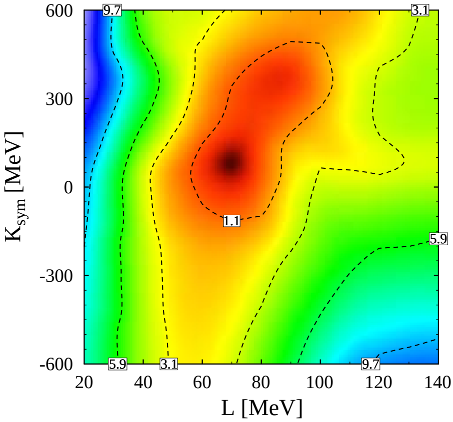
Data Cozma PRC88(13)044912



400 MeV/nucl 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

- Convergence on symmetry-energy conclusions at $\rho \lesssim \rho_0$. Slope parameter L at ρ_0 still elusive.
- Neutron-star merger constrains stiffness of EOS from above.
- Code comparison project aims at improving firmness of conclusions drawn from comparing data to transport. First benefits begin to emerge.