

Astrophysical objects meet constraints of high and low energy nuclear physics

Constraints on
the EoS

IST EoS

Effect of the
IST

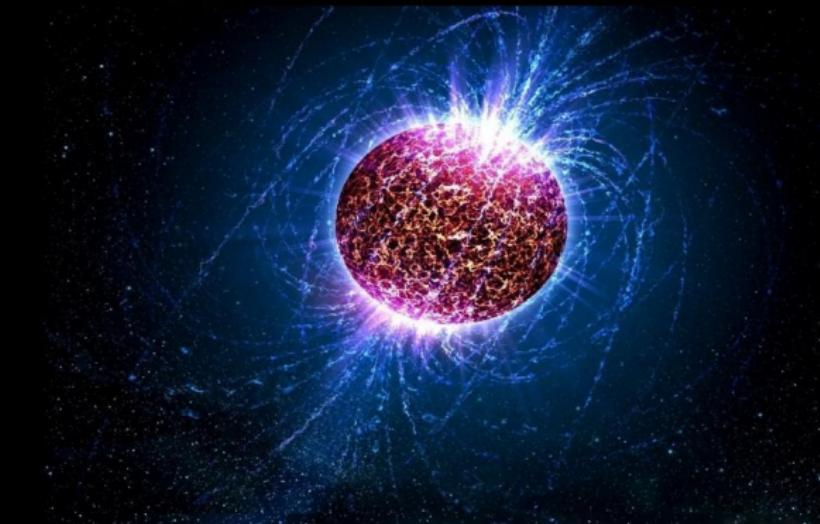
Application to
the NS

Conclusions

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1 Constraints on the EoS

2 IST EoS



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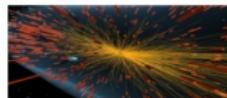
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HEP

- proton flow
- hadron multiplicities



Astro

- $2.01(4) M_{\text{sun}}$
- observations of pulsars



M-R relation



Nucl. Phys.

- nuclear matter ground state



Grav. Phys.

- NS+NS collisions
- NS+BH



IN THE NEAREST FUTURE !

General Requirements

- causality
- thermodynamic consistency

HEP Constraints

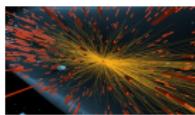
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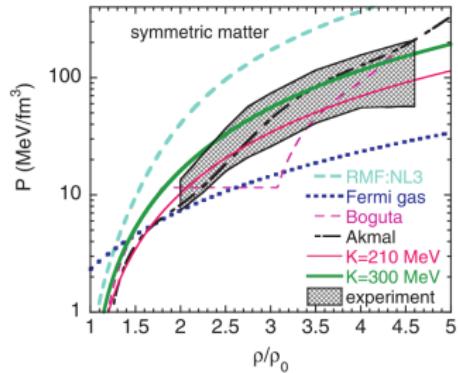
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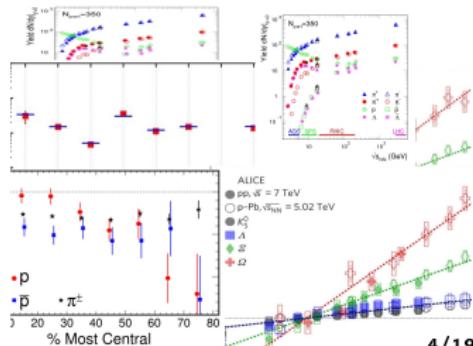
■ Constraint from collective flow on EoS

P. Danieliewicz, R. Lacey and W. G. Lynch, Science 298, 1593
(2002)



■ Description of particle yields created in different A+A collision experiments e.g. AGS, SPS, RHIC and LHC

In the nearest future: FAIR and NICA



Astro Constraints

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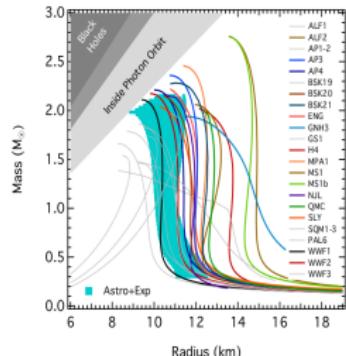
- Highest observed NS masses:

$$1.97(4)M_{\odot}$$

Demorest, P. B., et al., Nature, 467, 1081 (2010)

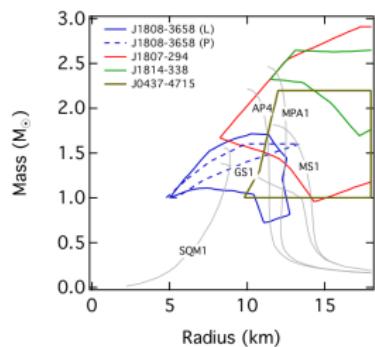
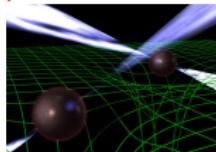
$$2.01(4)M_{\odot}$$

Antoniadis, J., et al., Science, 340, 448 (2013)



- Observations of the double systems with pulsar(s) give constraints on the M and R of NS

Özel, F., & Freire, P., A&A, 54, 401 (2006)



Nuclear Physics Constraints

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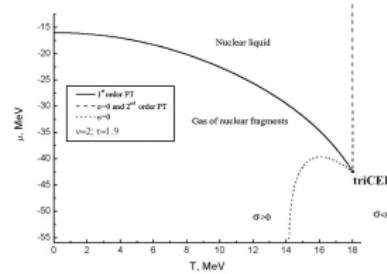


- Ground state properties of the nuclear matter at $T = 0$, baryonic density $n_B = n_0 = 0.16 \text{ fm}^{-3}$ and pressure $p = 0$ the binding energy per nucleon $W(n) = -16 \text{ MeV}$

- Nuclear matter critical temperature is 15.5-18 MeV

- The incompressibility constant is $K_0 = 9 \frac{\partial p}{\partial n} \Big|_{T=0, n=n_0} = 230 \pm 30 \text{ MeV}$

Dutra, M., et al., PRC, 85, 035201 (2012)



Constraints from Gravitation Physics

- Gravitational-wave data from the binary coalescence put a strong constraints on the softness or stiffness of the NS EoS
We are particularly interesting in NS+NS, BH+NS mergers

Constraints on
the EoS

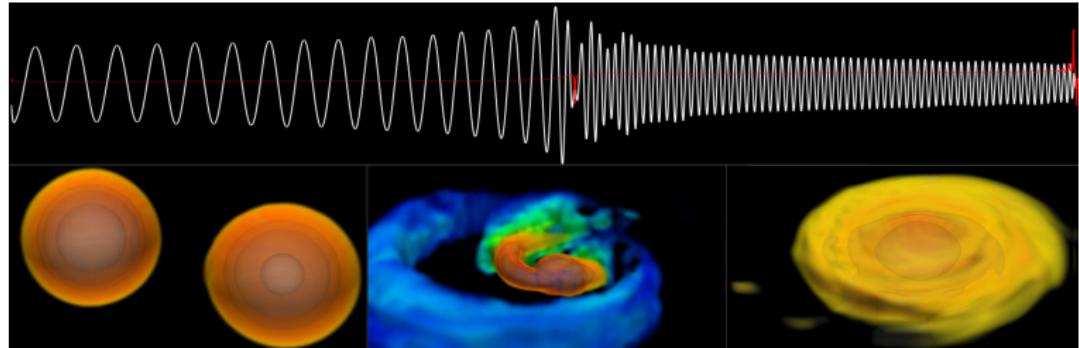
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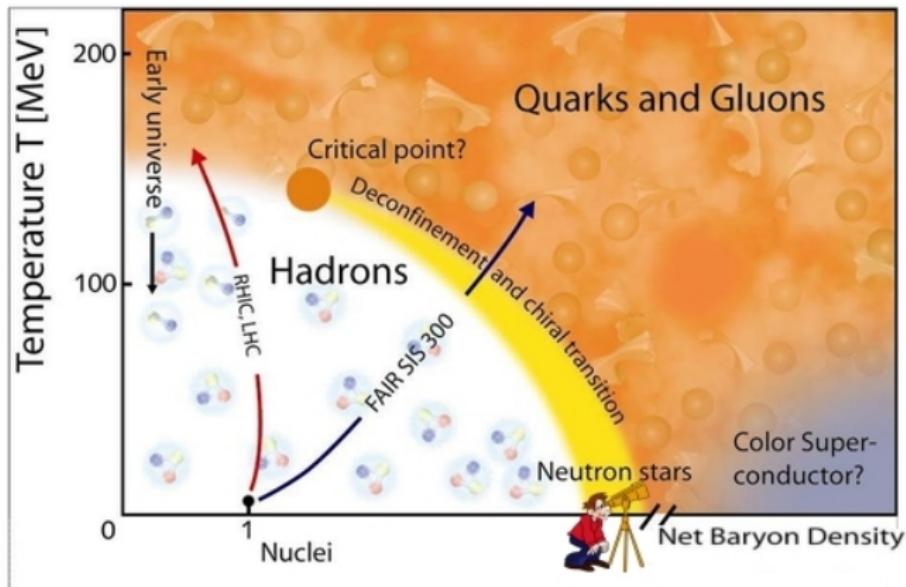
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First detection of binary neutron star coalescence on August 17, 2017!
[LIGO collaboration, et al., ApJL, 848, L12 \(2017\)](#)



Strongly Interacting Matter Phase Diagram

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The Induced Surface Tension (IST) EoS

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$$\left\{ \begin{array}{l} p = \sum_i^{\text{all particles}} [p_{id}(T, \mu_i - pV_i - \Sigma S_i + U(n_{id})) - p_{int}(n_{id})] \\ \Sigma = \sum_i^{\text{all particles}} p_{id}(T, \mu_i - pV_i - \alpha \Sigma S_i + U_0) R_i \end{array} \right.$$

p_{id} – pressure of the ideal gas for quantum statistics

Σ – induced surface tension

U_0, α – model parameters

$$\text{Thermodynamic consistency of the model : } \frac{\partial p_{int}}{\partial n_{id}} = n_{id} \frac{\partial U(n_{id})}{\partial n_{id}}$$

$$\text{Parametrization of the mean field potential : } U(n_{id}) = -C_d^2 n_{id}^\kappa$$

V.V. Sagun, et al., Nucl. Phys. A, 924, 24 (2014)

A.I. Ivanytskyi, et al., arXiv: 1710.08218 (2017)

Main ingredients of the IST EoS

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- **Multicomponent EoS** \Rightarrow Grand Canonical Ensemble (GCE) is natural choice

- **Higher order virial coefficients:**

Second virial coefficient – reproduced for any α

Third virial coefficient – reproduced for $\alpha = 1.245$ within 16%

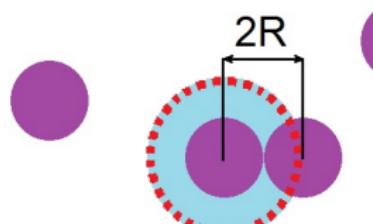
Fourth virial coefficient – reproduced for $\alpha = 1.245$

- **Thermodynamic consistency** $\Rightarrow n = \frac{\partial p}{\partial \mu}$

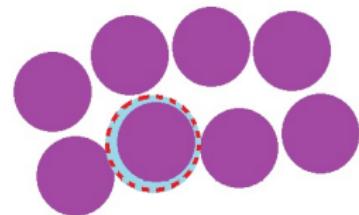
L. van Hove, Physica 15, 951 (1949) and Physica 16, 137 (1950)

- **Switching between excluded and eigen volumes (per particle)**

Low densities



High densities



$$V_{excl} \simeq 4V_{eigen}$$

high order virial coefficients are needed

- **Causality:** $c_{sound} \leq c_{light} = 1$, where $c_{sound}^2 = \frac{dp}{d\epsilon}|_{s/n=const}$

ST EoS is causal up to $\simeq 7$ normal nuclear densities where quark matter is expected

Physical Origin of the Induced Surface Tension

Constraints on
the EoS

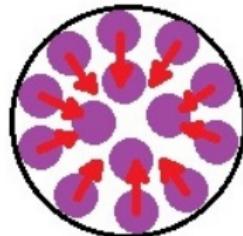
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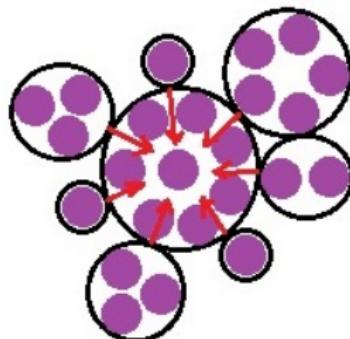
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Vacuum

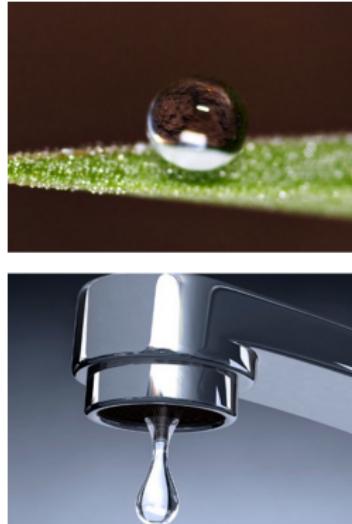


attraction of constituents
 \Rightarrow eigen surface tension

Medium



repulsion of clusters
 \Rightarrow induced surface tension



- Hard core repulsion only in part is accounted by eigen volume
- The rest corresponds to surface tension and curvature tension
Curvature tension can be accounted explicitly or implicitly
- Physical clusters tend to have spherical (in average) shape

Effect of the IST

Constraints on
the EoS

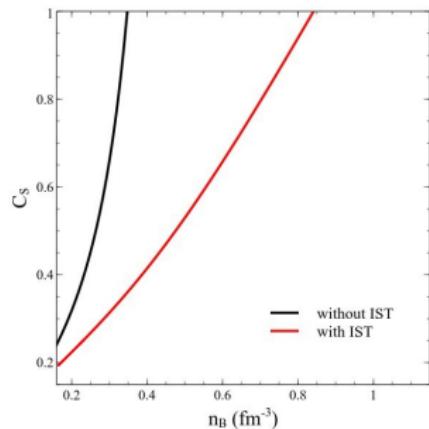
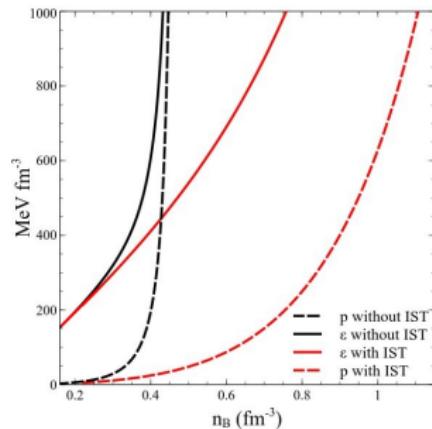
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Thermodynamic parameters with and without IST



Hadron Resonance Gas Model

Constraints on
the EoS

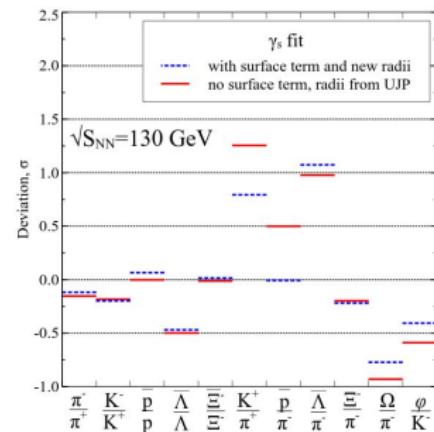
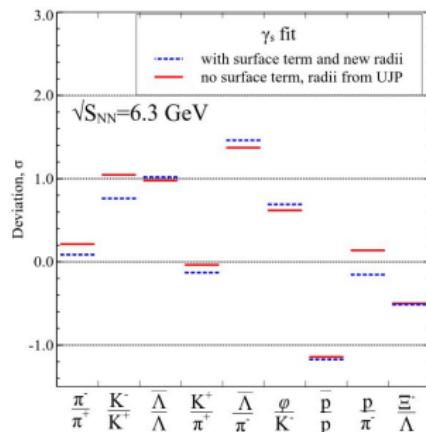
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- Hadrons with masses ≤ 2.5 GeV (widths, strong decays, zero strangeness)
- 111 independent particle ratios measured at 14 energies (from 2.7 GeV to 200 GeV)
- 14×4 local parameters ($T, \mu_B, \mu_{I3}, \gamma_s$) + 5 global parameters (hard core radii)



$$R_b = 0.365 \text{ fm}, R_m = 0.42 \text{ fm}, R_\pi = 0.15 \text{ fm}, R_K = 0.395 \text{ fm}, R_\Lambda = 0.085 \text{ fm}$$

Overall $\chi^2/\text{dof} \simeq 1.038$

K.A. Bugaev, et al., NPA 970, p. 133-155, (2018)
V.V. Sagun, Ukr. J. Phys. 59, 755 (2014)

Hadron Resonance Gas at ALICE Energies

- 11 independent particle yields, 6 parameters (temperature + 5 hard core radii)
- Overall $\chi^2/dof \simeq 0.89$
- Freeze out temperature $T_{FO} = 148 \pm 7$ MeV

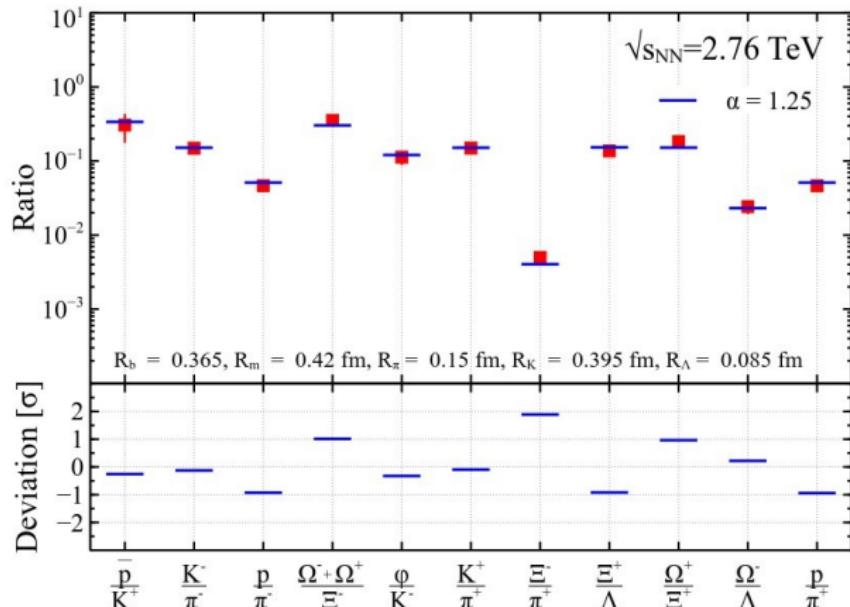
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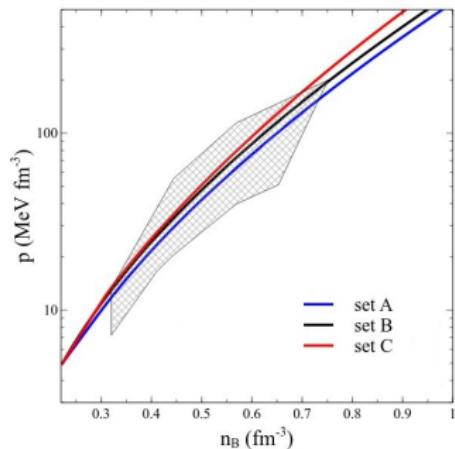
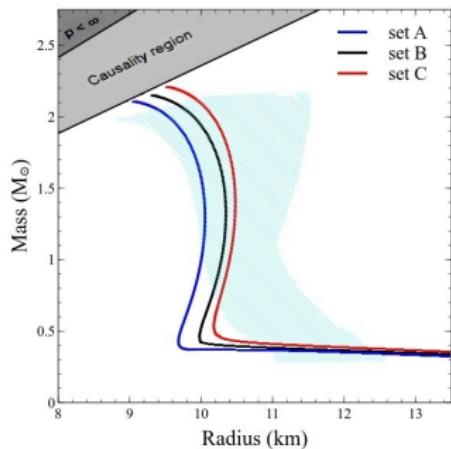
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Mass-Radius Relation and Flow Constraint

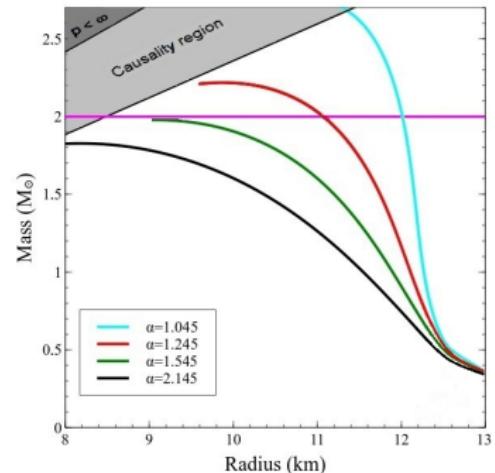
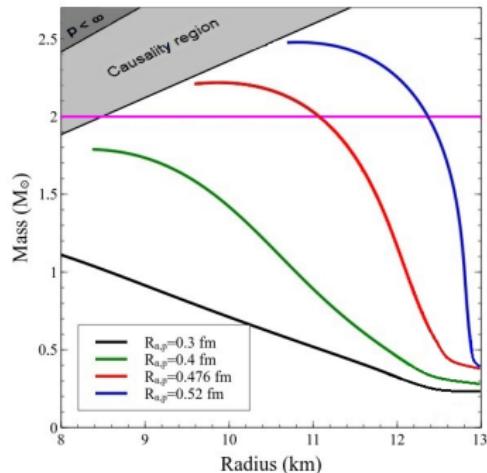
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Sets	$R_{n,p}$ fm	α —	κ —	C_d^2 MeV · $f_m^{3\kappa}$	U_0 MeV	M_{NS} M_\odot
A	0.476	1.17	0.375	112.9088	58.8765	2.115
B	0.5	1.25	0.375	113.8456	58.9183	2.157
C	0.495	1.17	0.372	114.4686	61.7951	2.217

The Effect of Hard-Core Radii and α Parameters

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V.V. Sagun, & I. Lopes, ApJ, 850, 75 (2017)

Summary

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- Using a novel a thermodynamically self-consistent IST EoS the properties of the NS at zero-temperature limit were calculated.
- It was shown that the present EoS can be successfully applied to the description of the hadron multiplicities measured in A+A collisions, to studies of the nuclear matter phase diagram and to modelling of the NS interiors.
- IST EoS satisfies all astrophysical constraints, correctly reproduce properties of normal nuclear density, proton flow data, hadron multiplicities measured in A+A collisions and nuclear matter properties near the (3)CEP.
- The description of the compact stars with the IST provides with a strong constraint on the attraction contribution in EoS at zero temperature.
- The IST EoS gives a possibility to describe the strongly interacting matter phase diagram in a wide range of its thermodynamic parameters which helps to create a solid bridge between the astrophysical data, high-energy nuclear physics and gravitation physics.



Constraints on
the EoS

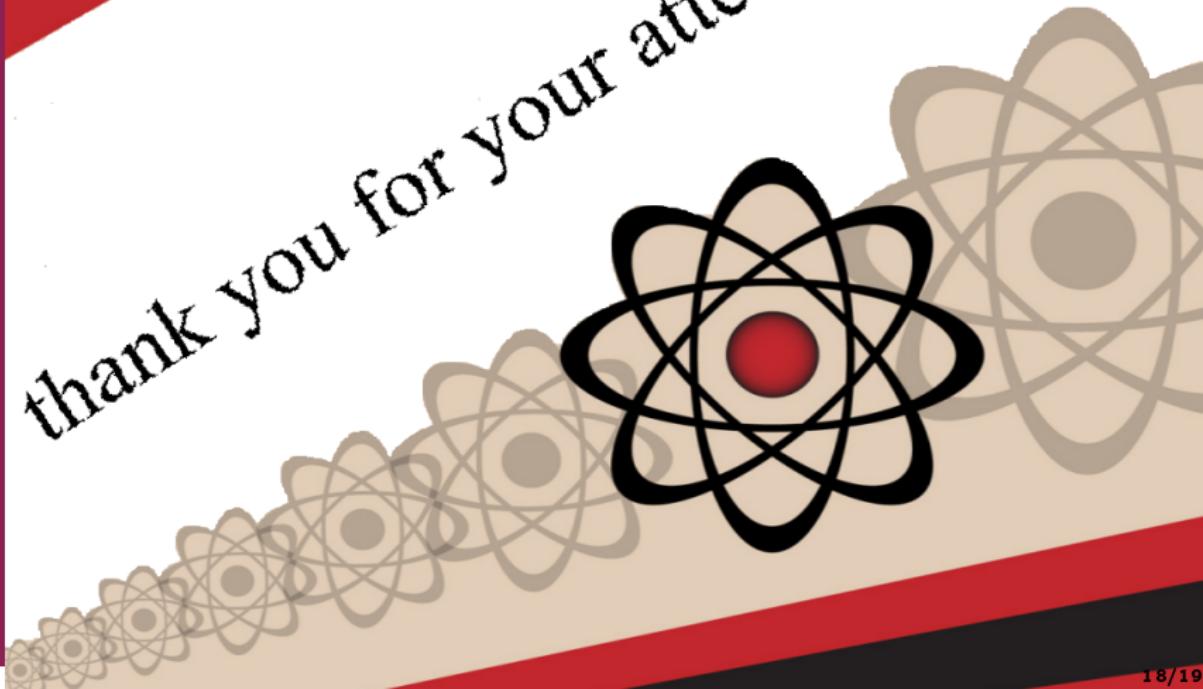
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thank you for your attention!



The Induced Surface Tension (IST) EoS

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- System of equations for pressure p and induced surface tension Σ :

$$\frac{p}{T} = \sum_i \phi_i \exp\left(\frac{\mu_i - pV_i - \Sigma S_i}{T}\right)$$

$$\frac{\Sigma}{T} = \sum_i R_i \phi_i \exp\left(\frac{\mu_i - pV_i - \Sigma S_i}{T}\right) \cdot \underbrace{\exp\left(\frac{(1-\alpha)S_i\Sigma}{T}\right)}_{\text{extrapolation to high densities}}, \quad \alpha = \text{const}$$

- Meaning of $\alpha > 1$: one component case

$$\Sigma = pR \exp\left(\frac{(1-\alpha)S\Sigma}{T}\right)$$

$$p = T\phi \exp\left(\frac{\mu - pV_{\text{eff}}}{T}\right)$$

$$V_{\text{eff}} = V \left[1 + 3 \exp\left(\frac{(1-\alpha)S\Sigma}{T}\right) \right]$$

low densities ($\Sigma \rightarrow 0$) : $V_{\text{eff}} = 4V$
high densities ($\Sigma \rightarrow \infty$) : $V_{\text{eff}} = V$

α switches excluded and eigen volume regimes
high order virial coefficients?

- Higher virial coefficients of hard spheres

- Second virial coefficient – reproduced
- Third virial coefficient – reproduced
- Fourth virial coefficient – reproduced for $\alpha = 1.245$

- IST EoS is causal up to $\simeq 7$ normal nuclear densities where quark matter is expected

