Constraining supernova EOS with equilibrium constants from heavy-ion collisions

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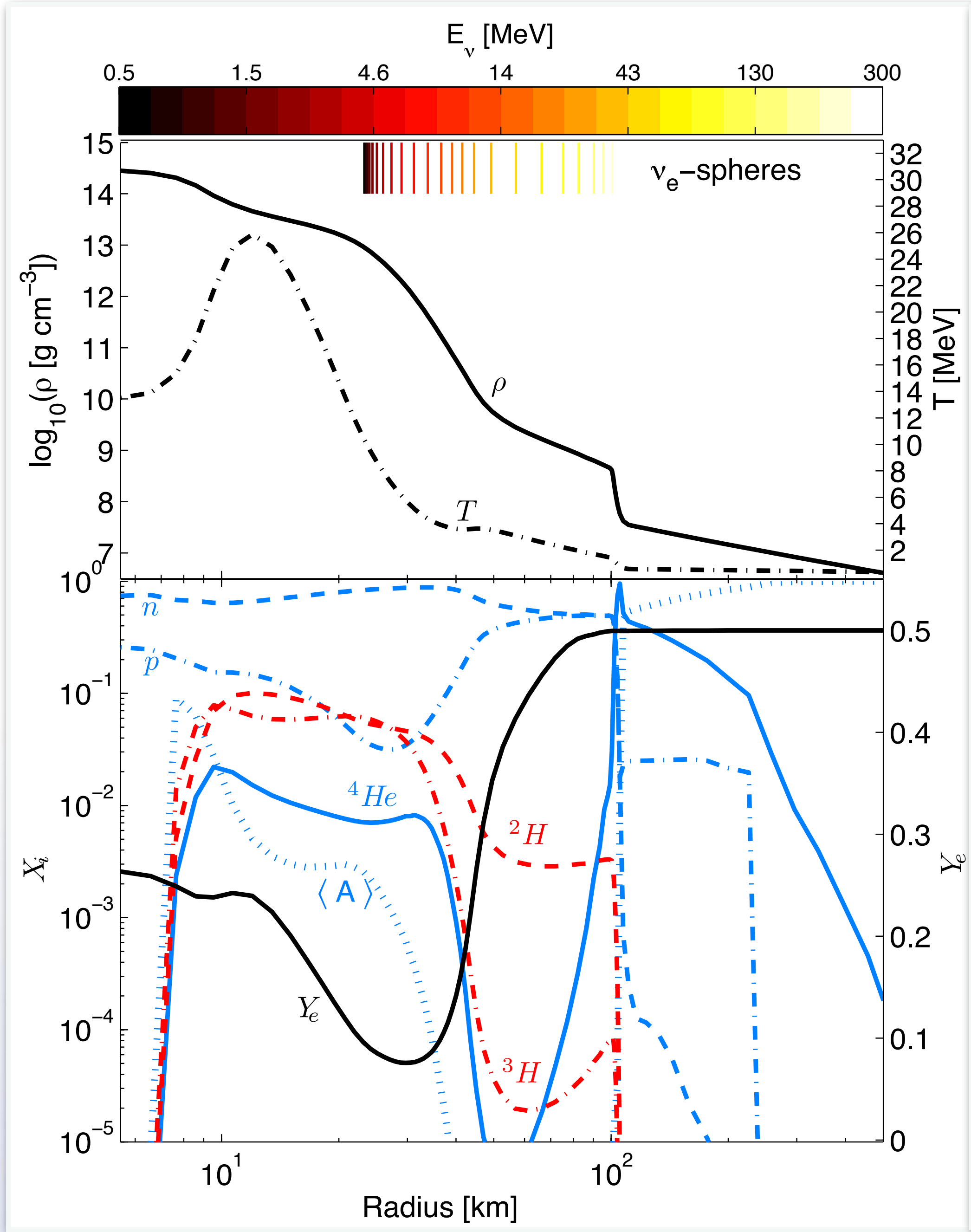
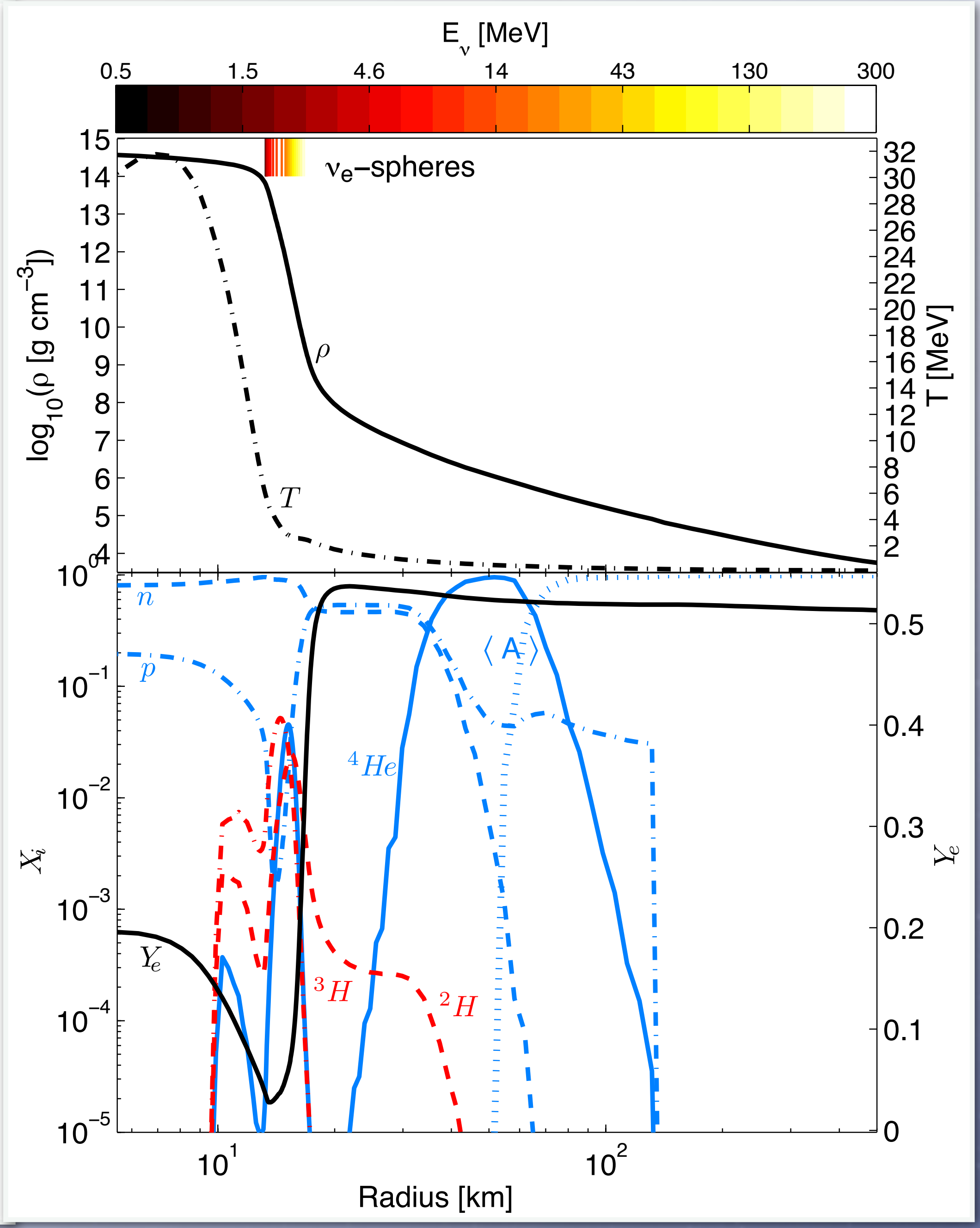
Light cluster in supernova matter

- cluster formation is an essential aspect of warm and dense matter
- light clusters can be more abundant than protons (cf. Sumiyoshi & Röpke 2008)

250 ms post-bounce



5 s post-bounce



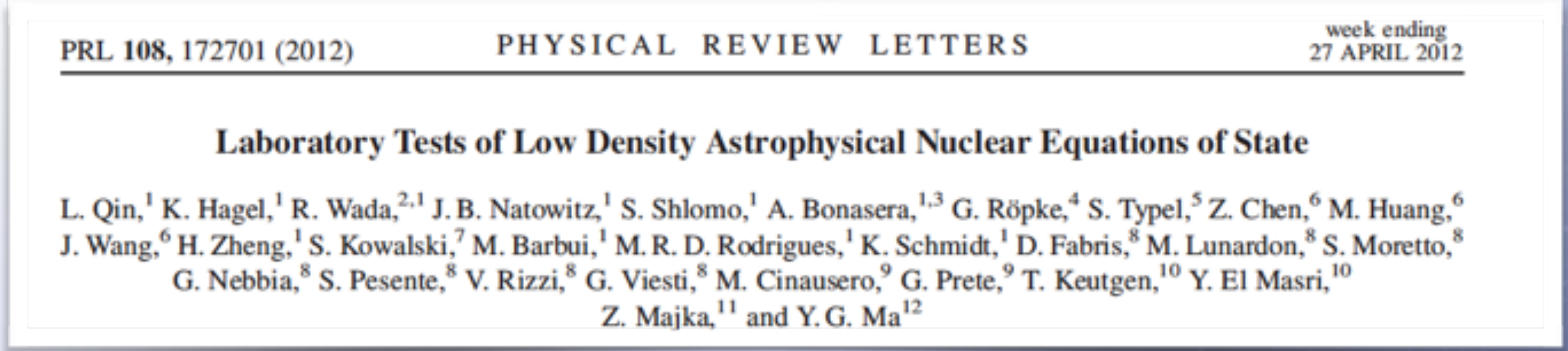
[Fischer et al. EPJA 2014]

Light cluster in supernova matter

- modify cooling of proto-neutron star
- relevant for nucleosynthesis in neutrino-driven winds (Arcones et al. 2008)
- supernova dynamics (?)
- see: O'Connor et al. 2007, Sumiyoshi and Röpke 2008, Arcones et al. 2008, Hempel et al. 2012, Furusawa et a. 2013, …

- EOS: various different theoretical approaches

cluster formation can be probed in the lab, „femtonova“



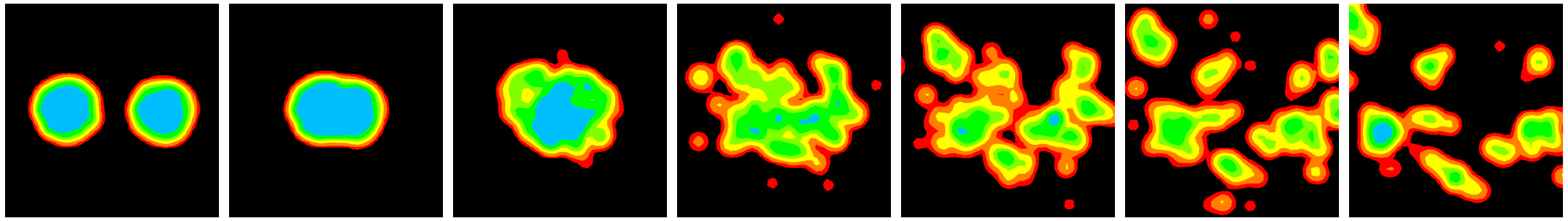
PRL **108,** 172701 (2012) PHYSICAL REVIEW LETTERS week ending 27 APRIL 2012

Laboratory Tests of Low Density Astrophysical Nuclear Equations of State

L. Qin,[1] K. Hagel,[1] R. Wada,[2,1] J. B. Natowitz,[1] S. Shlomo,[1] A. Bonasera,[1,3] G. Röpke,[4] S. Typel,[5] Z. Chen,[6] M. Huang,[6] J. Wang,[6] H. Zheng,[1] S. Kowalski,[7] M. Barbui,[1] M. R. D. Rodrigues,[1] K. Schmidt,[1] D. Fabris,[8] M. Lunardon,[8] S. Moretto,[8] G. Nebbia,[8] S. Pesente,[8] V. Rizzi,[8] G. Viesti,[8] M. Cinausero,[9] G. Prete,[9] T. Keutgen,[10] Y. El Masri,[10] Z. Majka,[11] and Y. G. Ma[12]

Original work of Qin et al.

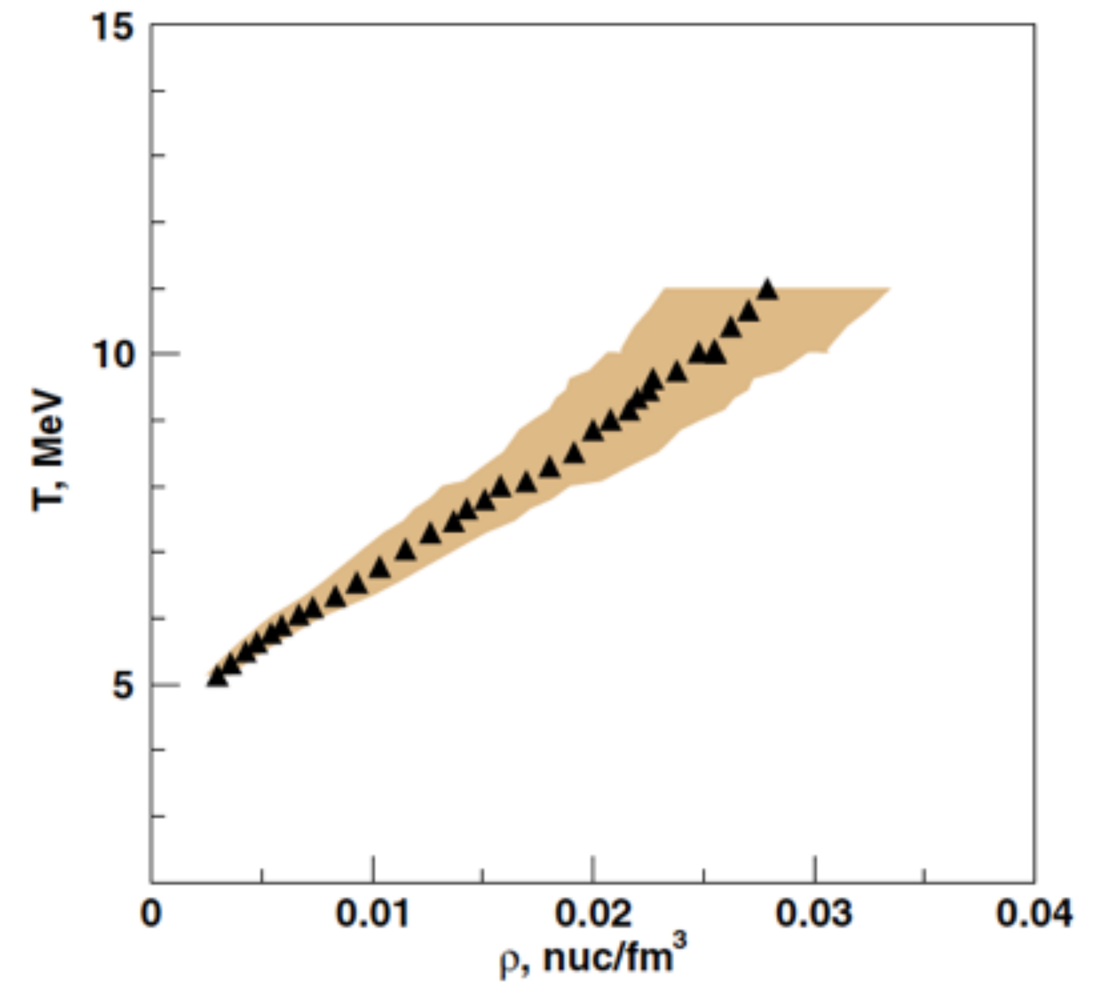
- Qin et al. PRL108 (2012): measured charged particle yields at Texas A&M with low-energy heavy ion collisions



Akira Ono An event of central collision of Xe + Sn at 50 MeV/nucleon (AMD calculation)

- density extraction: thermal coalescence model of Mekjian
- temperature: double isotope yield ratios

- conditions similar as in core-collapse supernovae



Basic aspects of equilibrium constants

- primary observable used by Qin et al.: equilibrium constant
- defined by particle yields or number densities

$$K_c[i] = \frac{n_i}{n_n^{N_i} n_p^{Z_i}}$$

- ideal gas:

$$n_i^{\mathrm{id}}(T, \mu_i) = g_i \left(\frac{M_i T}{2\pi}\right)^{3/2} \exp\left(\frac{1}{T}(\mu_i - M_i)\right)$$

- using nuclear statistical equilibrium

$$\mu_i = N_i \mu_n + Z_i \mu_p$$

- K_c^{id} only a function of temperature, e.g.:

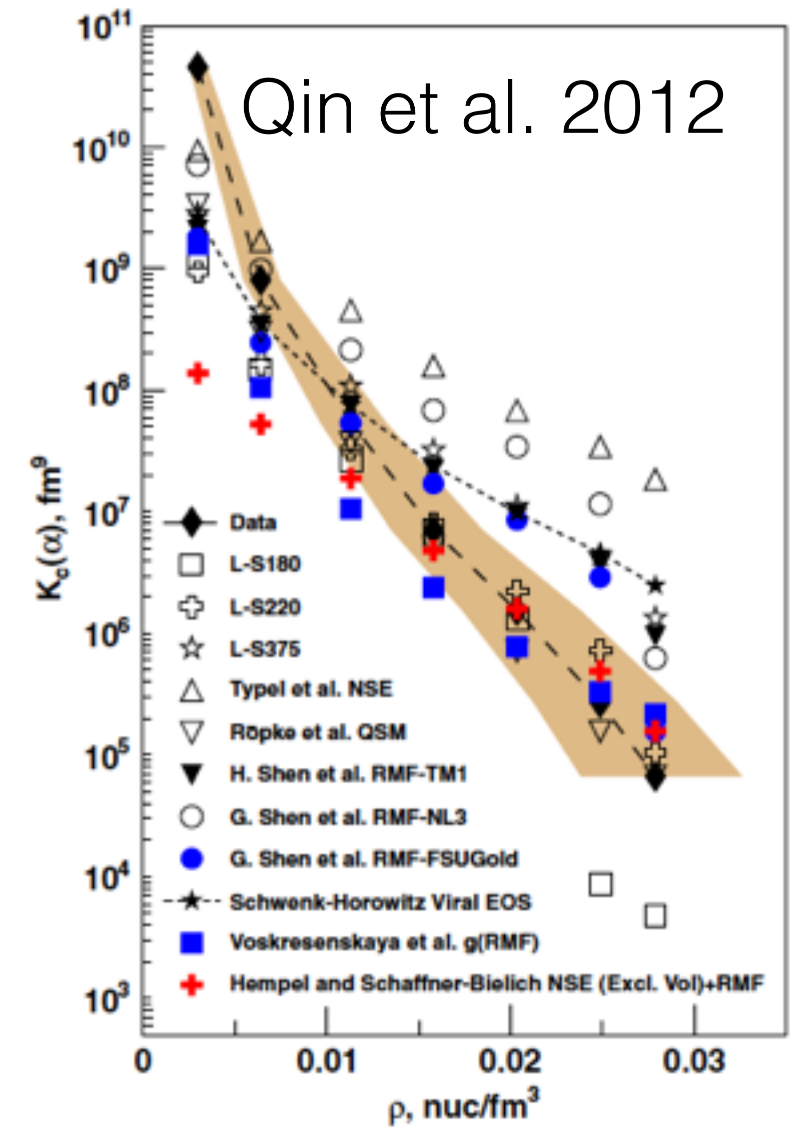
$$K_c^{\mathrm{id}}[\alpha] = \frac{1}{2}\left(\frac{2\pi}{mT}\right)^{9/2} \exp\left(\frac{B_\alpha}{T}\right)$$

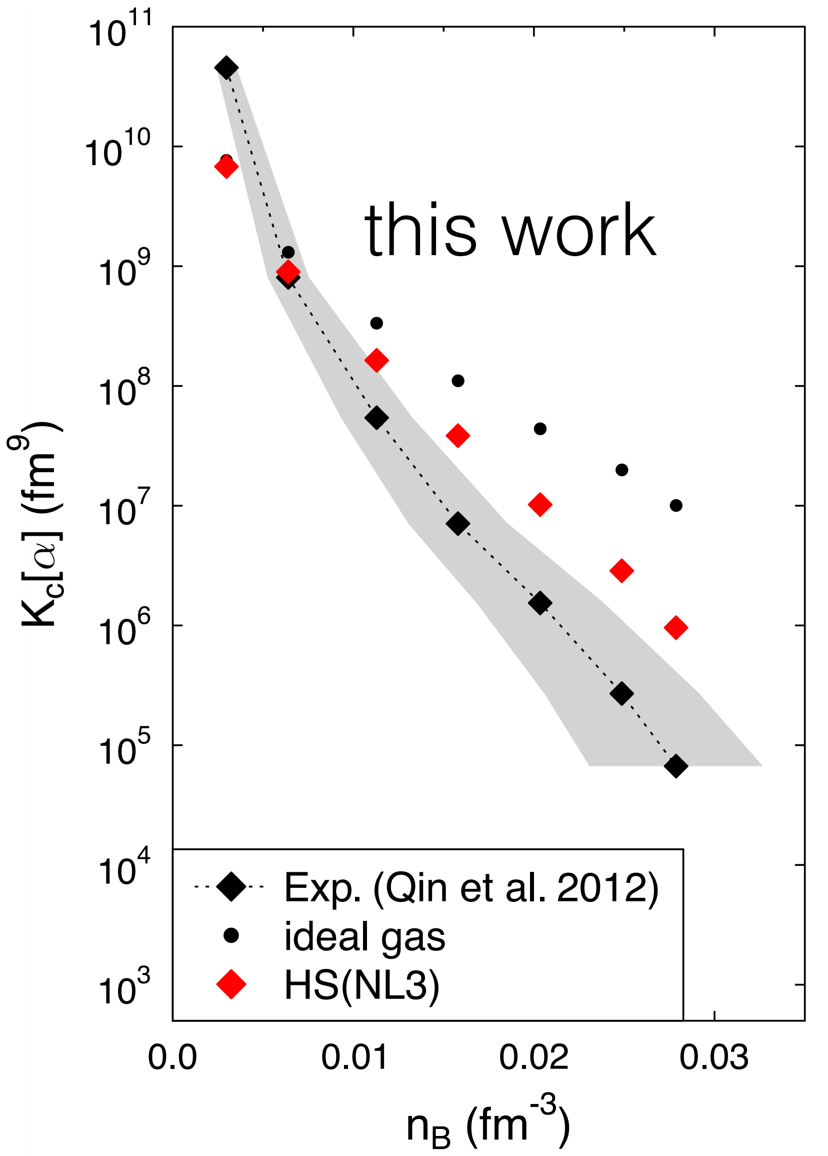
- thus also „composition independent“ (Qin et al. 2012)
- not true for an non-ideal (i.e. interacting) system

Qin et al. 2012 – measurement of equilibrium constants

- big spread at low densities (!?)

- different results for HS EOS
- HS: *[MH, J. Schaffner-Bielich; NPA 837 (2010)]*
- origin not clear: table interpolation? misunderstanding of definitions?





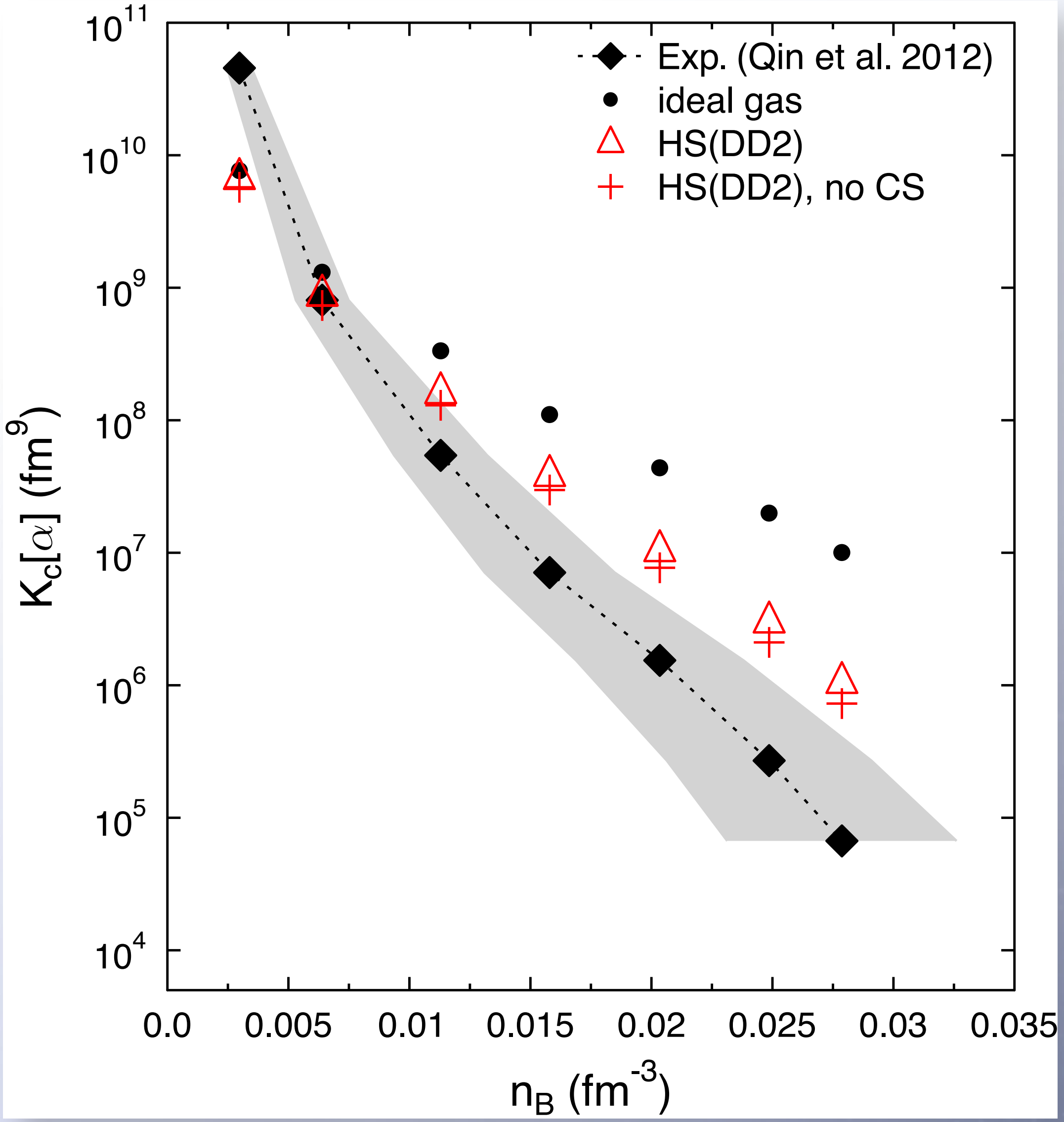
also: systematic differences between matter in heavy-ion collisions and supernovae

- isospin asymmetry; in the experiment: Y_C~0.41
- Coulomb interactions
- limited number of participating nucleons

Dependencies of equilibrium constants using the HS EOS

HS EOS – Coulomb screening

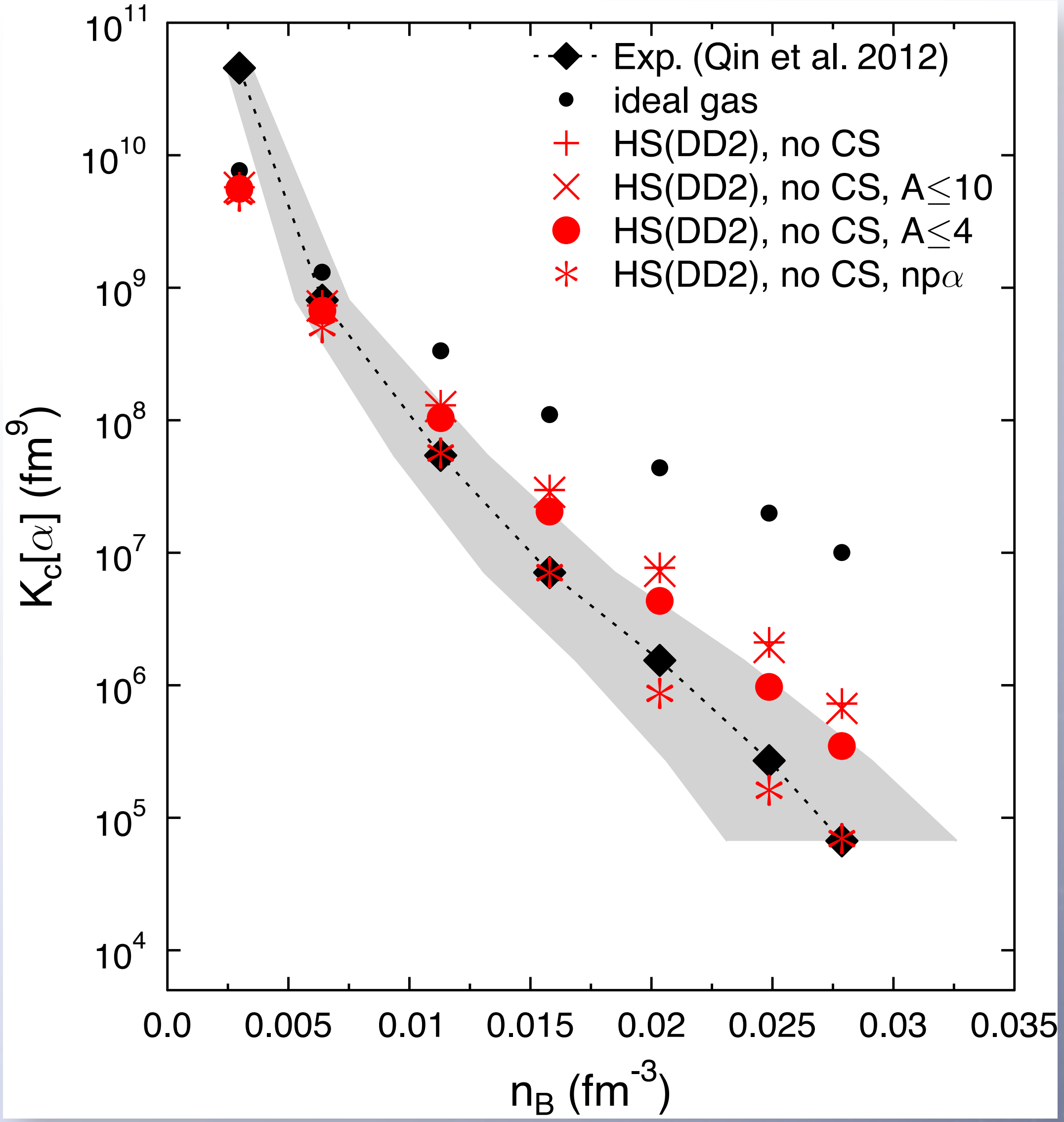
- supernova matter: electron background screens Coulomb interactions of nuclei
- absent in heavy-ion collisions
- marginally better agreement without Coulomb screening (CS)
- in the following: CS removed where possible



HS EOS – effects of particle degrees of freedom

- which nuclei can be produced in the experiment?
  - $A_{max}<2A$(colliding nuclei)?
  - $A_{max} \leq 4$?
  - experiment suggests $Z \leq 2$

- similar results for $A \leq 300$, $A \leq 10$, and $A \leq 4$
- different for npα
- better agreement of npα: coincidence



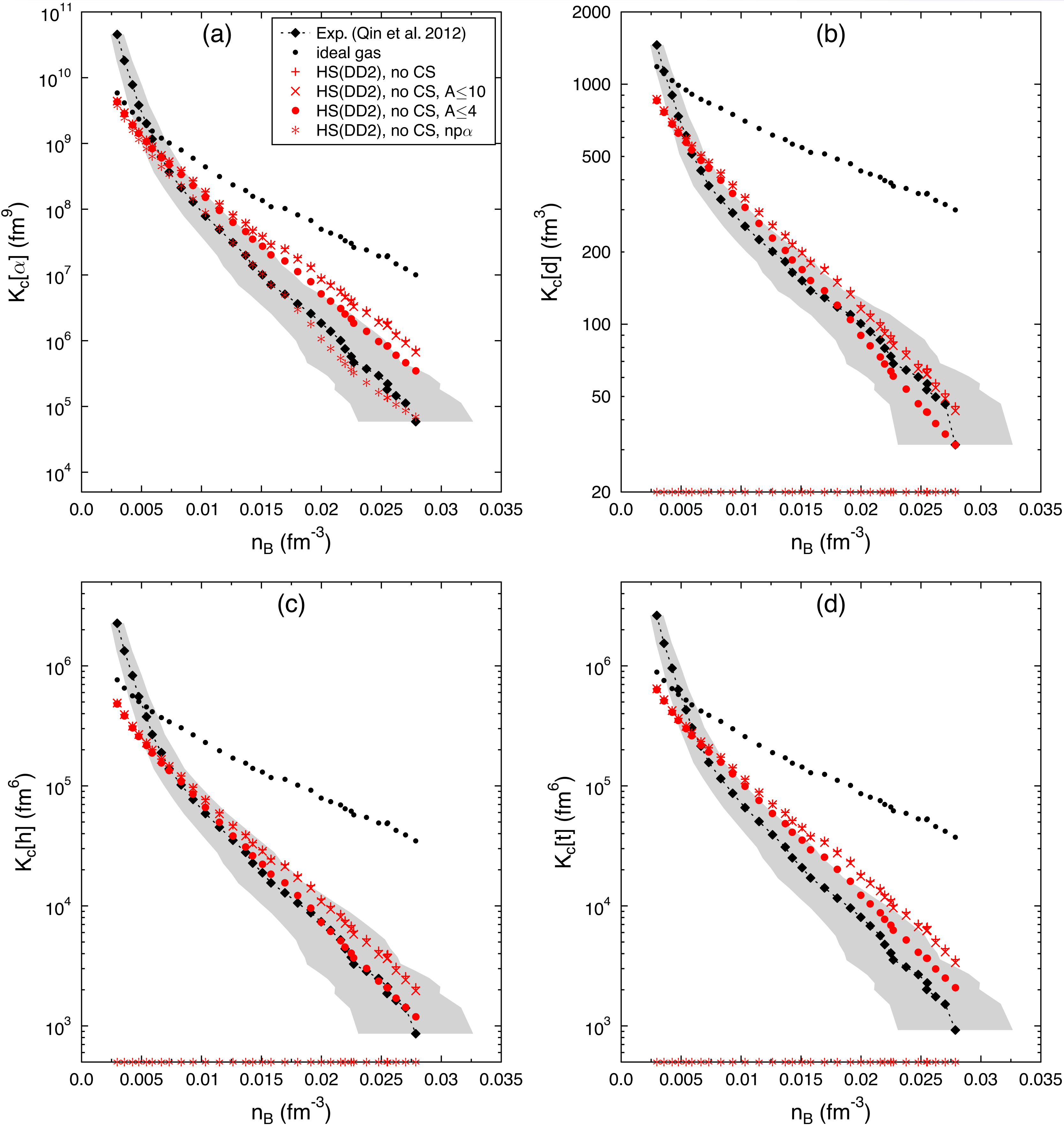
Matthias Hempel
Budapest, 15.6.2015

HS EOS – the full picture: K_α, K_d, K_t, K_h

- d, t, and h also well identified in experiment
- npα cannot explain them by construction
- in the following: A≤4, i.e. n, p, d, t, α, h as the most realistic composition of the fireball in the heavy-ion collision

HS, no CS, A≤4 EOS:

- n, p, d, t, α, h
- relativistic mean-field interactions of nucleons (DD2)
- excluded volume effects
- internal partition function

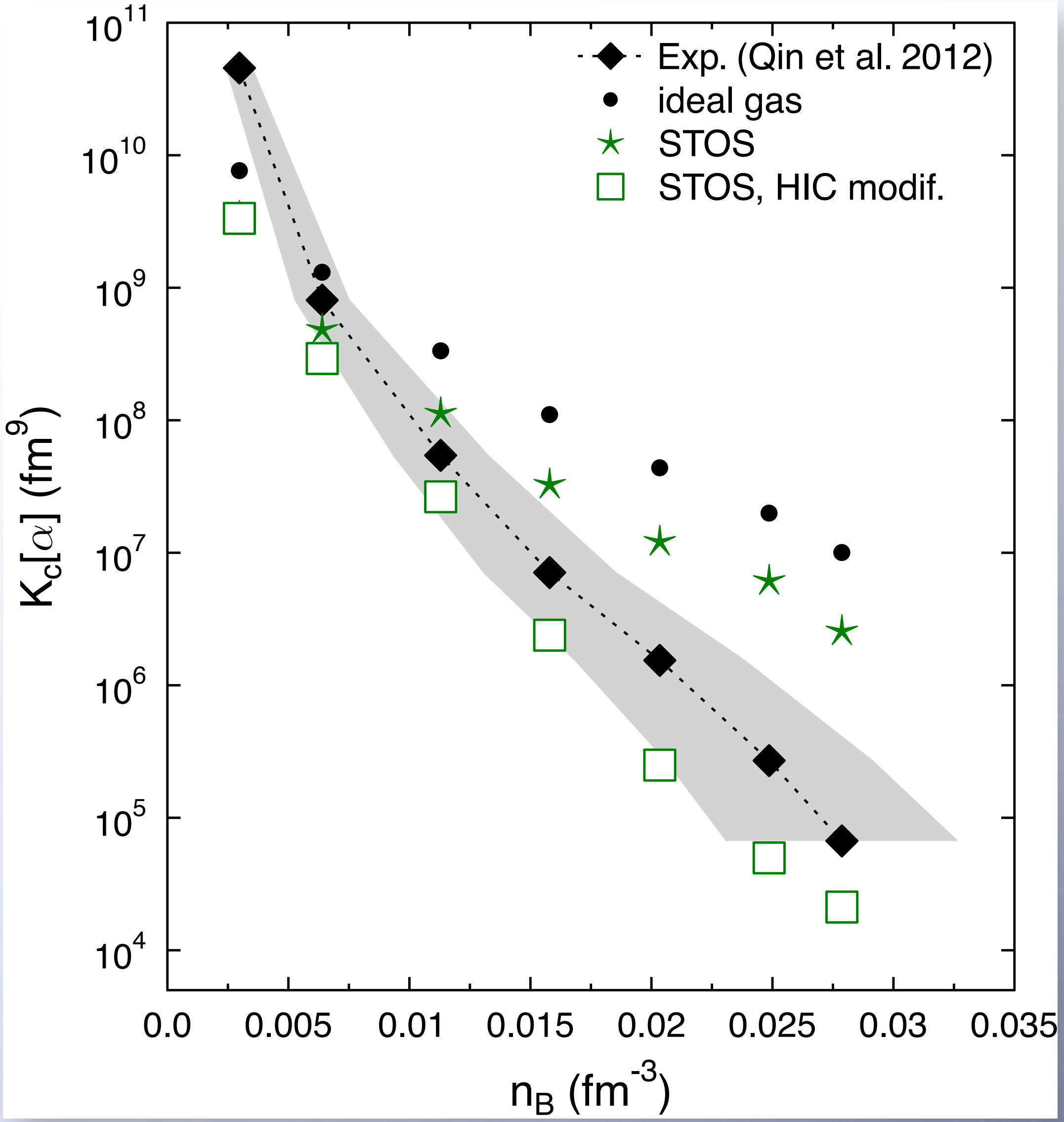


Other EOS

STOS – modifications for HIC

H. Shen et al. 1998

- up to 70% of nuclei with A~100
- new calculation for the STOS model without heavy nuclei → npα, called „HIC modif."



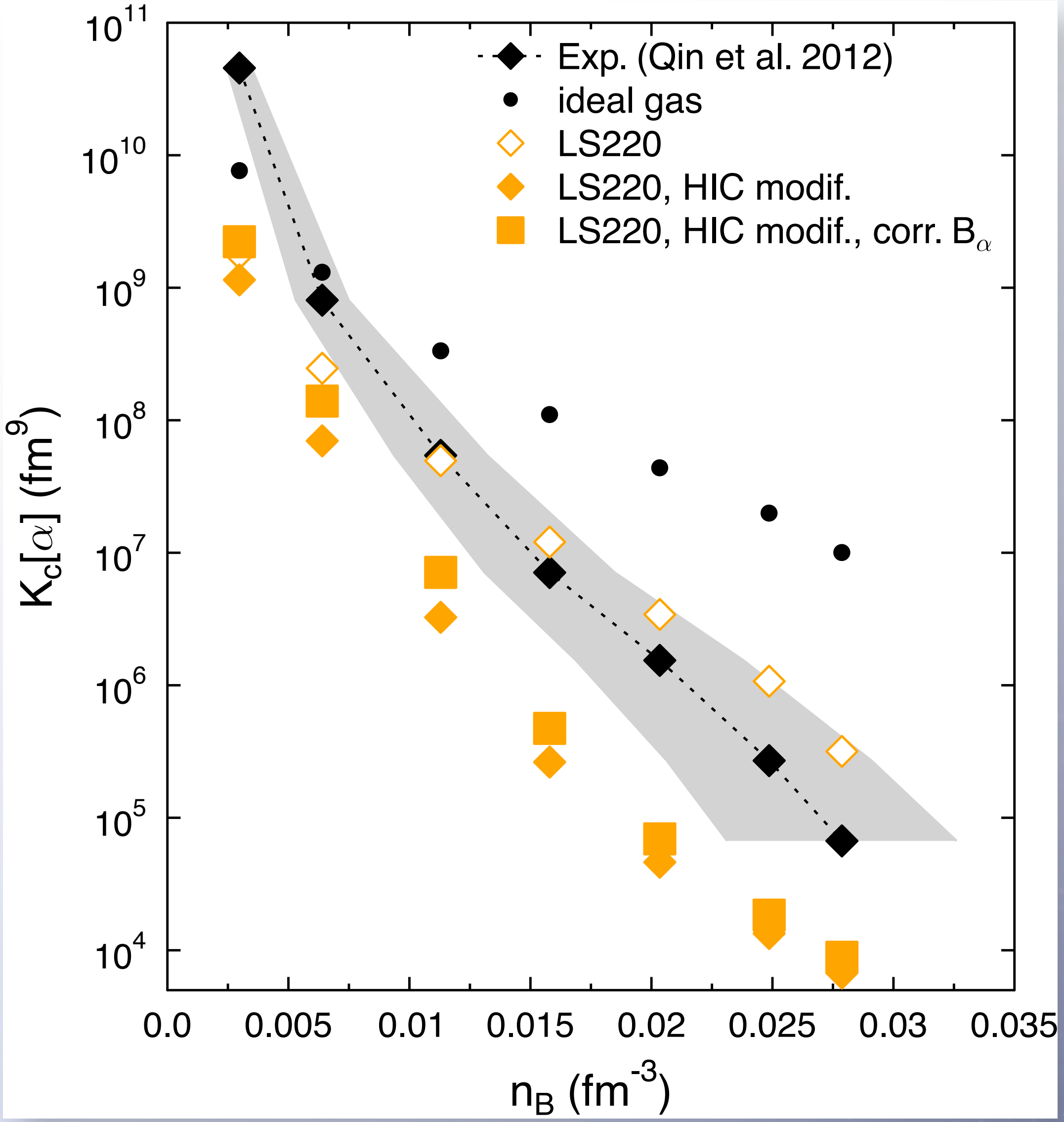
STOS, HIC modif. EOS:

- npα
- relativistic mean-field interactions of nucleons (TM1)
- excluded volume effects

LS – modifications for HIC

Lattimer & Swesty 1991

- up to 70% of nuclei with A~80
- new calculation for the LS model without heavy nuclei → npα, called „HIC modif.“
- known bug in alpha-particle binding energy: neutron-proton-rest mass difference not treated correctly



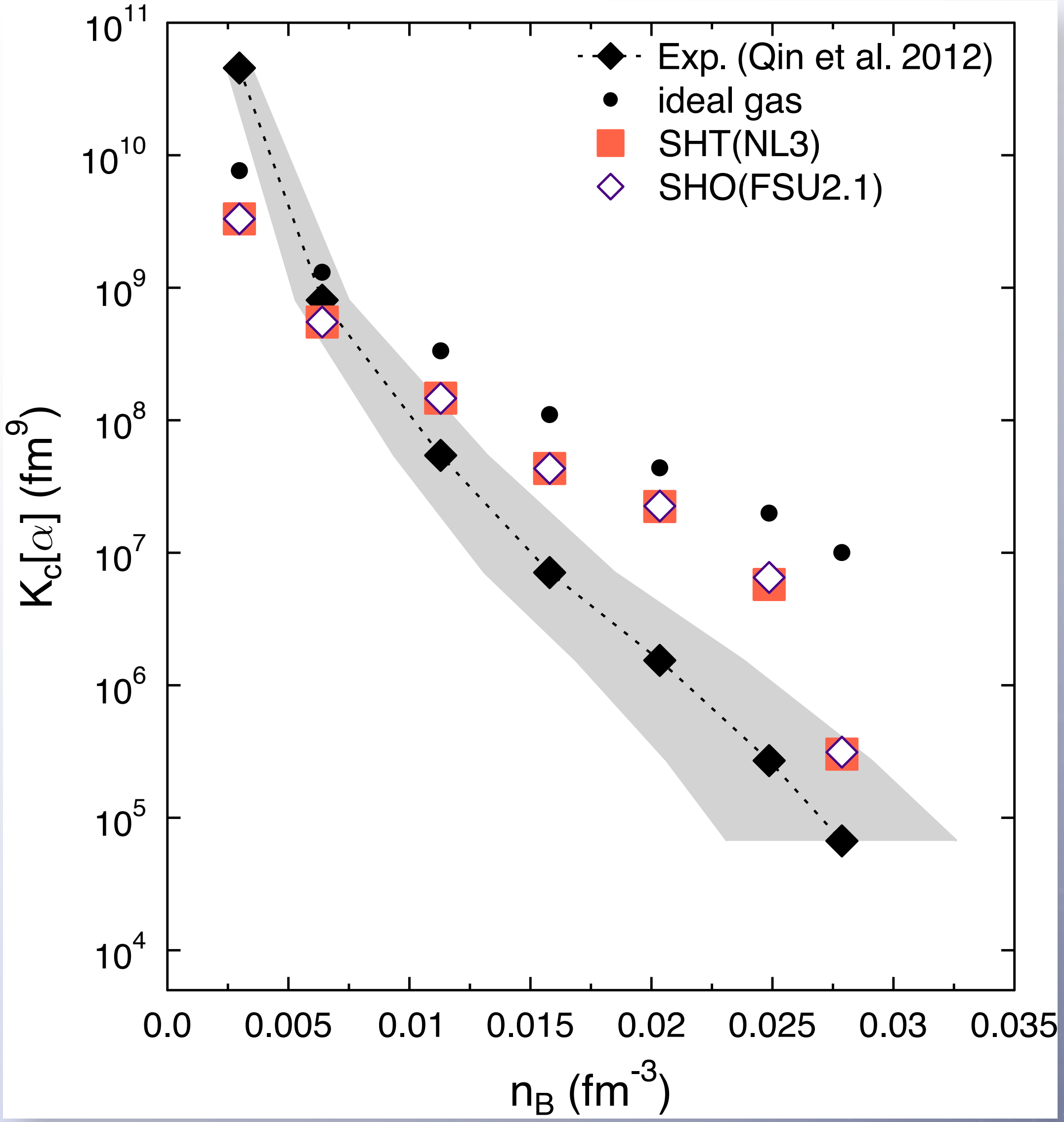
LS220, HIC modif., corr B_α EOS:

- npα
- Skyrme-like interactions of nucleons (LS220)
- excluded volume effects
- corrected binding energy B_α

G. Shen EOS

G. Shen et al. 2012/13

- less than 15% of heavy nuclei with A~20
- here: unmodified results (i.e. including A>4)



SHT(NL3) & SHO(FSU2.1) EOS:
- npα, ideal gas of nuclei with A≥12
- 2nd order virial corrections

Dedicated EOS for light clusters; npdthα composition

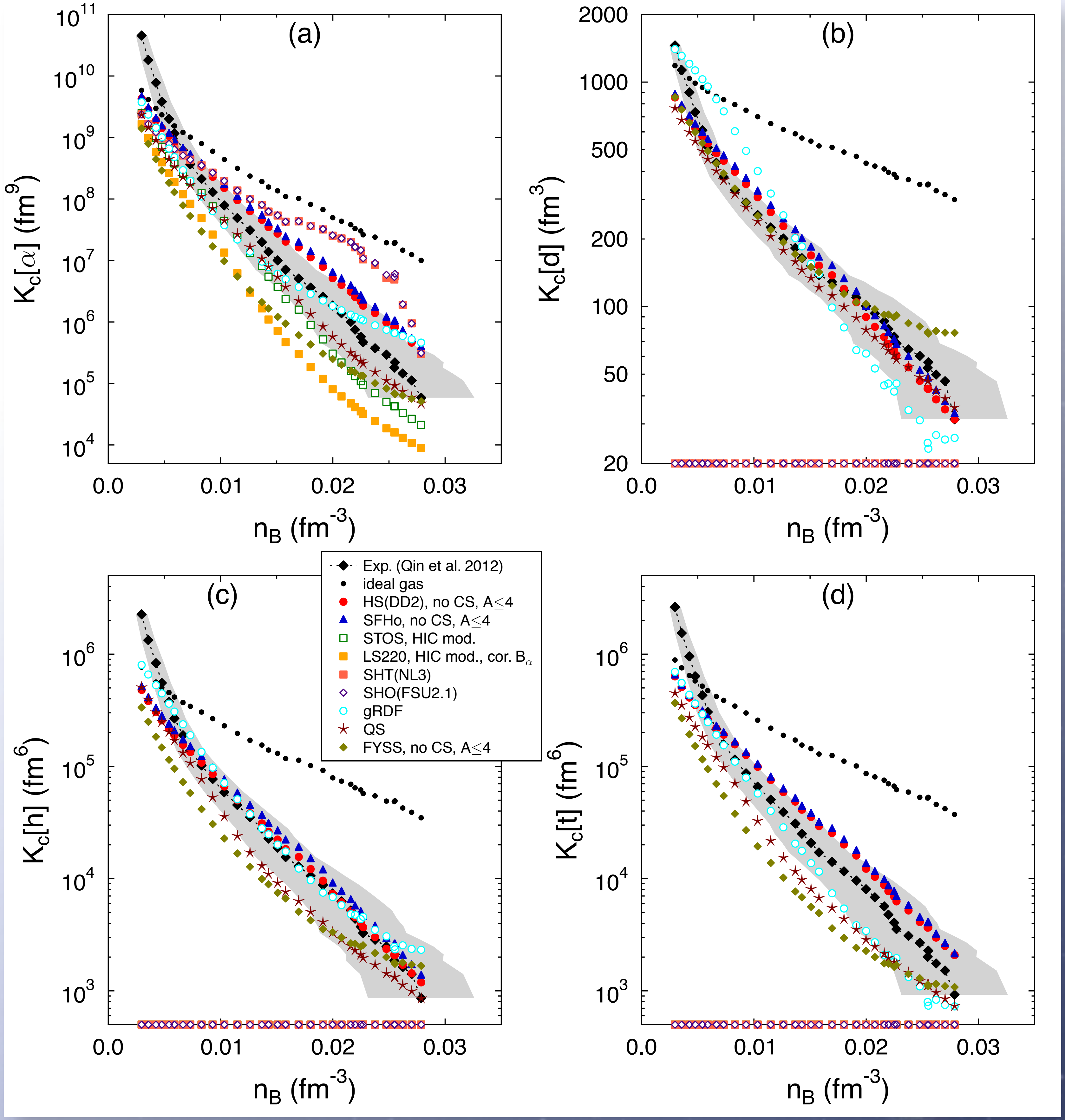
- Quantum statistical (QS) approach by G. Röpke:
  - the only „ab-initio“ model for clustered nuclear matter
  - effective NN-interaction
  - Green-function approach for medium modifications → Pauli-blocking and self-energy
  - continuum states
- generalized relativistic density functional (gRDF) by S. Typel et al. 2010:
  - mean-field interactions of all particles (DD2)
  - parameterized Pauli-blocking
  - continuum states
- FYSS model by Furusawa et al. 2013
  - mean-field interactions of all particles (TM1)
  - parameterized Pauli-blocking
  - excluded volume effects
  - available as EOS table for SN simulations

Comparison of all models

Comparison of all models I

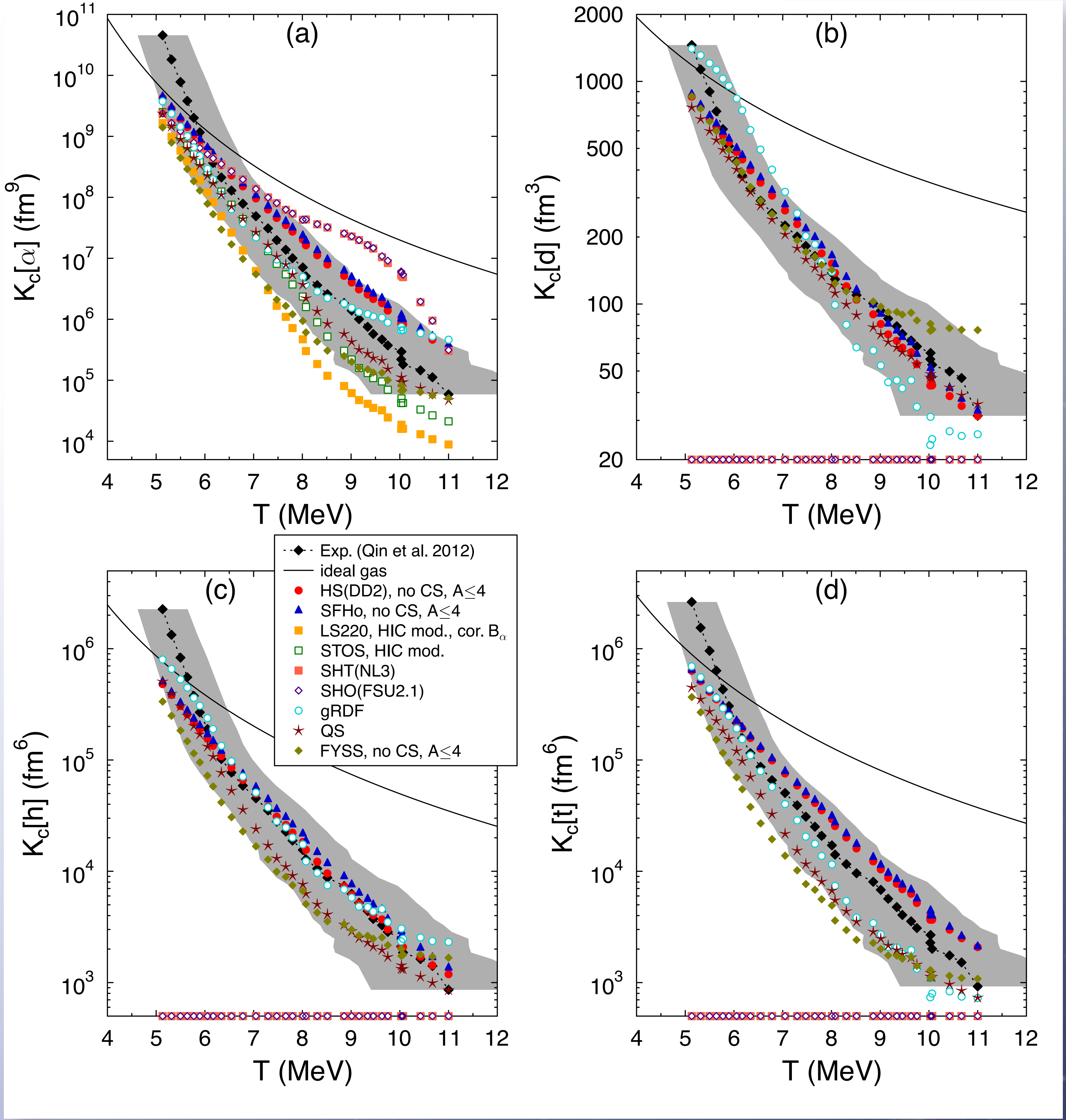
- K_α: QS, gRDF, HS(DD2), SFHO, STOS in agreement
- K_d, K_t, K_h: cannot be explained by LS, STOS, SHT, SHO

- QS, gRDF, HS(DD2), SFHO, FYSS compatible with experimental data
- still deviations between ideal gas and experiment at low n_B



Comparison of all models II

- $K^{id=}K^{id}(T)$
- same results but as a function of temperature
- more significant error bars
- more consistent at low T



Conclusions

- systematic differences of matter in heavy-ion collisions and supernovae are important

- three components seem to be necessary to explain the experimental data
  - inclusion of all relevant particle degrees of freedom
  - mean-field interactions of nucleons
  - suppression mechanism of nuclei at high densities

- experimental data not accurate enough to discriminate details, e.g., Pauli-blocking vs. excluded volume