Heavy Ion Collisions and the Supernova Equation of State

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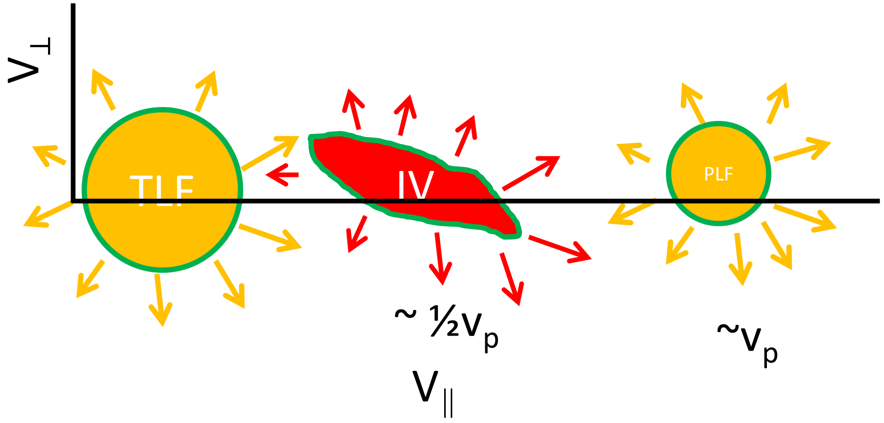
Outline

- Motivation
  - Heavy Ion Collision studies and their implications on the description of core collapse supernovae.
  - Challenges in comparison
- Experiment
  - Coalescence analysis
  - Results
- Systematic comparison to Astrophysical models
- Calculations of neutrinos from Black Hole accretion disks
- Aspects of clustering

- Core-collapse supernovae (SN)
  - Explosions of massive stars that radiate 99% of their energy in neutrinos
  - Birth places of neutron stars
  - Wide range of densities range from much lower than normal nuclear density to much higher
- Neutrinosphere
  - Last scattering site of neutrinos in proto-neutron star: $\sim 10^{12}$ g/cm^3 ($\sim 6 \times 10^{-4}$ fm^{-3}), T~5 MeV
  - A thermal surface from which around 10^{53} ergs (10^{37} MeV) are emitted in all neutrino species during the explosion
- Core Collapse Supernovae dynamics and the neutrino signals can be sensitive to the details of neutrino interactions with nucleonic matter.
  - Neutrino properties determine the nucleosynthesis conditions in the so-called neutrino-driven wind
  - Detailed information on the composition and other thermodynamic properties of nucleonic matter are important to evaluate role of neutrino scattering.
  - Details of neutrino heating depend both on matter properties of low density nuclear matter and the conditions at the neutrinosphere

- Relevance of heavy ion collisions to core collapse supernovae
  - Allow to probe the lower densities in the lab
  - Comparisons of heavy ion data to supernovae calculations may help discriminate between different models.
- Clusters appear in shock heated nuclear matter
  - Clusters Role on the explosion dynamics and the subsequent cooling and compression of the proto-neutron star is not yet fully understood
  - Valid treatment of the correlations and clusterization in low density matter is a vital ingredient of astrophysical models
- Equation of state (EOS)
  - Many fundamental connections between the equation of state and neutrino interactions
  - Crucial input for understanding proto-neutron star evolution



Nuclear Reaction from Heavy Ion Collision

IV Source femtonova

Mass: 20-30 amu (~3.3×10^{-26} kg)

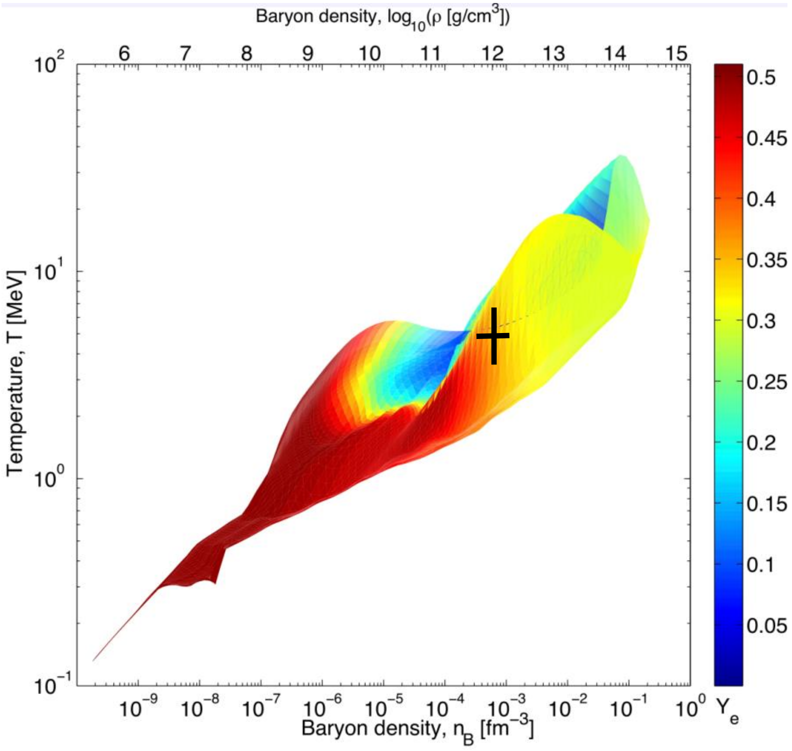

Crab Nebula, HST Image

Supernova

Mass: 4.6 ± 1.8 $M_\odot$. (~9.2×10^{30}kg)

Core collapse supernova simulation

T. Fischer et al., ApJS 194, 39 (2011)



	Supernova	Heavy Ion Nuclear reaction
Density (nuc/fm^3)	$10^{-10} < \rho < 2$	$2\times10^{-3} < \rho < 3\times10^{-2}$
Temperature (MeV)	$\sim 0 < T < 100$	$5 < T < 11$
Electron fraction	$0 < Y_p < 0.6$	$Y_p \sim 0.41$

Challenges in comparisons

- Lower proton fraction, Y_p
- SN are “infinite”, but HIC are finite
- The “infinite” matter in SN is charge neutral, but HIC has a net charge
- Composition of nuclear matter in calculations
  - Different calculations include different species which are probably different from the SN

Supernovae Simulations

List of wants:

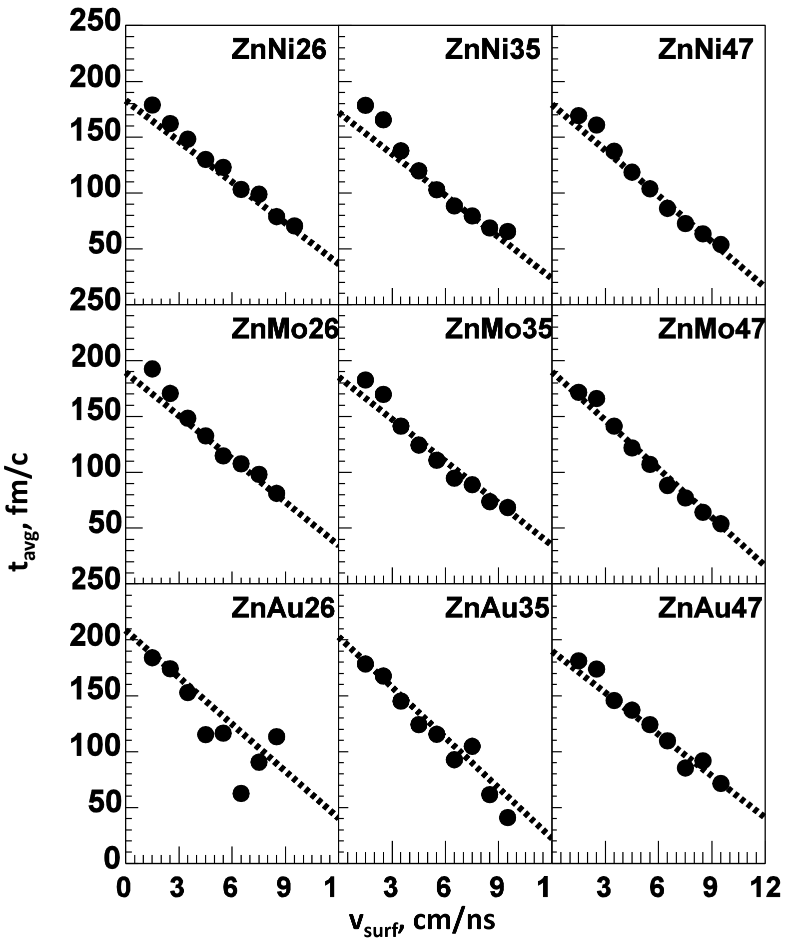
- Multidimensional (3D) (magneto-)hydrodynamics
- Enough resolution to resolve instabilities
- General relativistic treatment of gravity
- Consistent (and correct) equation of state (nuclear, and multispecies)
- Self-consistent and accurate neutrino transport (7D problem!)
- Consistent (correct, and complete) set of neutrino interactions
- Multidimensional progenitor models

What we have

- 3D simulations, but very computationally expensive (O(100) MSU) or simplified
- General relativistic treatment of gravity, some still use Newtonian
- Consistent equation of state (nuclear, and multispecies)
- Some approximation to full neutrino transport
- Neutrino interactions
- Only spherical progenitor models

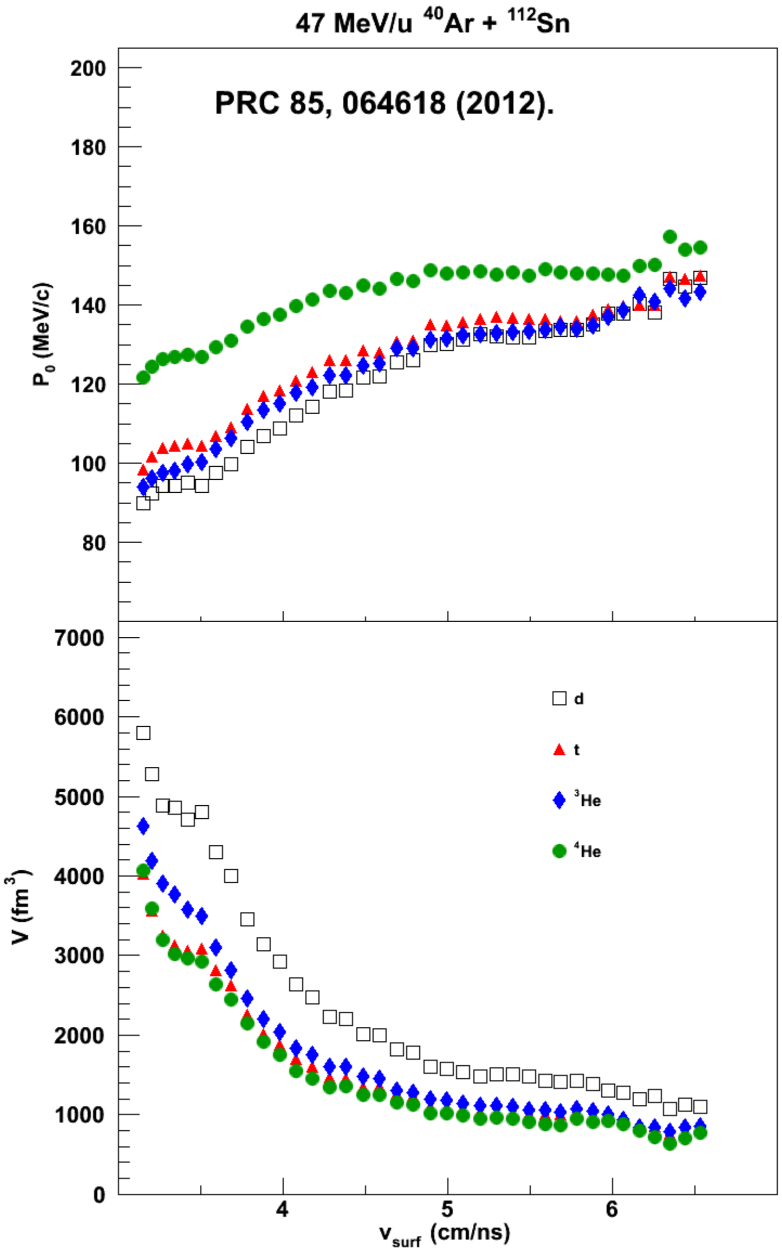
Experiment Analysis

- 47 MeV/u Ar + ^{112,124}Sn
- Select the most violent collisions
- Identify the femtonova
  - Intermediate velocity source
    - nucleon-nucleon collisions early in the reaction
  - Choose light particles at 45 deg because moving source fits suggest that most products at that angle result from that source.
- Density from Coalescense analysis
- Temperature from Albergo model
- Time scale from velocity of products from intermediate velocity source



PRC **72** (2005) 024603

Coalescence Parameters


47 MeV/u ^{40}Ar + ^{112}Sn

PRC 85, 064618 (2012).

Awes *et al.*, PRC 24, 89 (1981).

$$\frac{d^3N(Z,N)}{dp^3} \propto R_{np}^N f(P_0) \left[\frac{d^3N(1,0)}{dp^3}\right]^A$$

$$\frac{d^3N(Z,N,E_A)}{dE_A d\Omega} = R_{np}^N \frac{A^{-1}}{N!\,Z!} \left\{\frac{\frac{4\pi}{3}P_0^3}{[2m^3(E-E_c)]^{1/2}}\right\}^{A-1} \left[\frac{d^3N(1,0,E)}{dE\,d\Omega}\right]^A$$

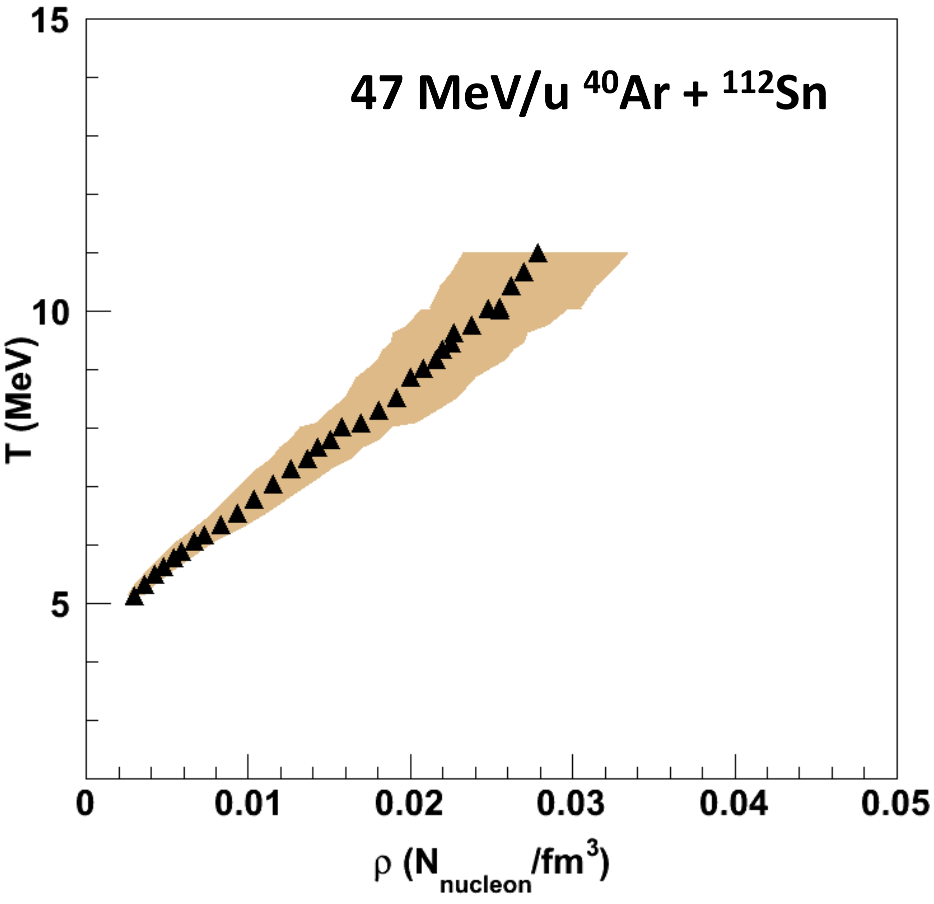
Mekjian *et al.*, PRC 17, 1051 (1978).

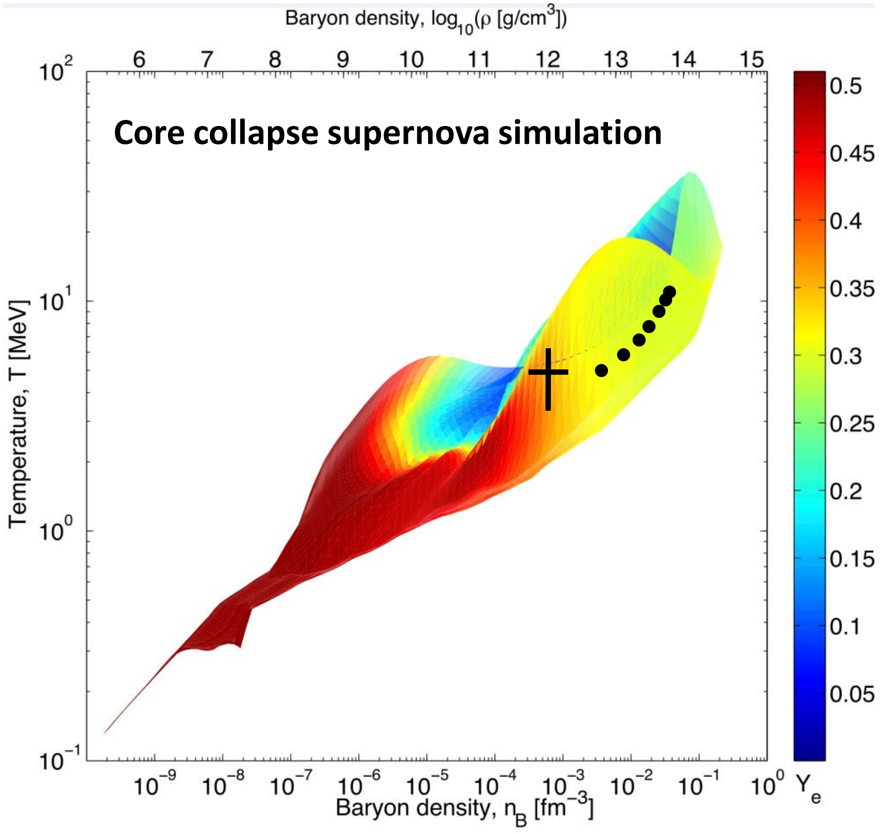
$$\frac{d^3N(Z,N)}{dp^3} = R_{np}^N \frac{A^3(2s+1)e^{(E_0/T)}}{2^A}\left(\frac{h^3}{V}\right)^{A-1}\left[\frac{d^3N(1,0)}{dp^3}\right]^A$$

$$V = \left[\left(\frac{Z!\,N!\,A^3}{2^A}\right)(2s+1)e^{(E_0/T)}\right]^{\frac{1}{A-1}} \frac{3h^3}{4\pi P_0^3}$$

Temperatures and Densities

- Recall v_{surf} vs time calculation
- System starts hot and expands as it cools

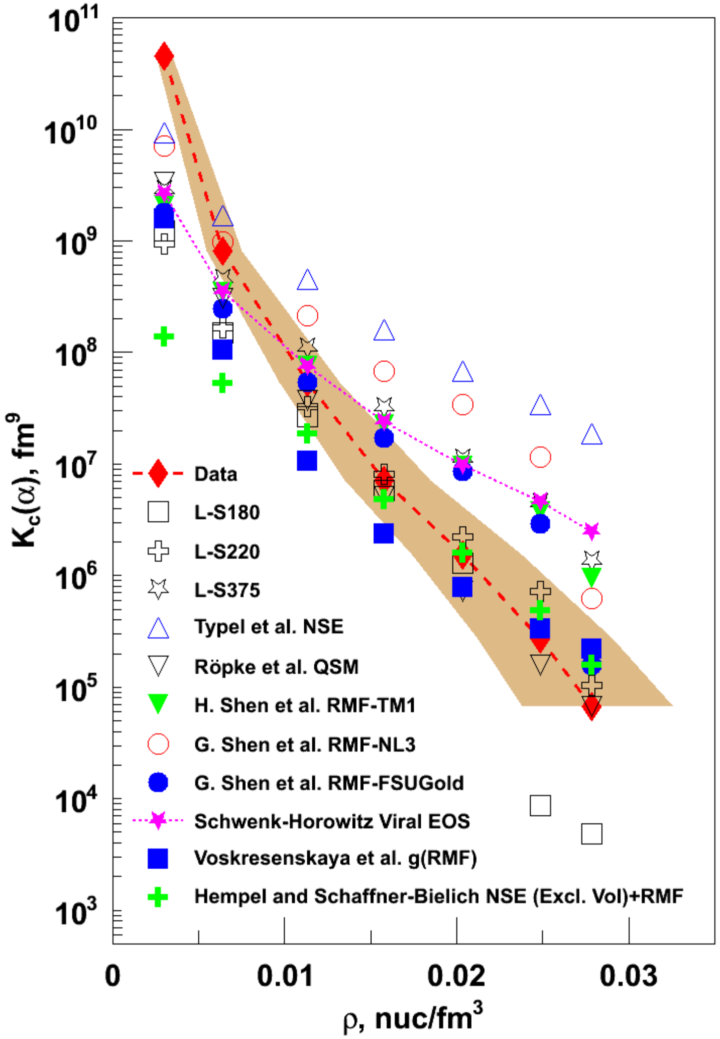




Equilibrium constants from α-particles model predictions

$$K_c(A,Z) = \frac{\rho(A,Z)}{\rho_p^Z \rho_n^{(A-Z)}}$$

- Many tests of EOS are done using mass fractions and various calculations include various different competing species.
- If any relevant species are not included, mass fractions are not accurate.
- Equilibrium constants should be more robust with respect to the choice of competing species assumed in a particular model if interactions are the same
- Differences in the equilibrium constants may offer the possibility to study the interactions
- Models converge at lowest densities, but are significantly below data

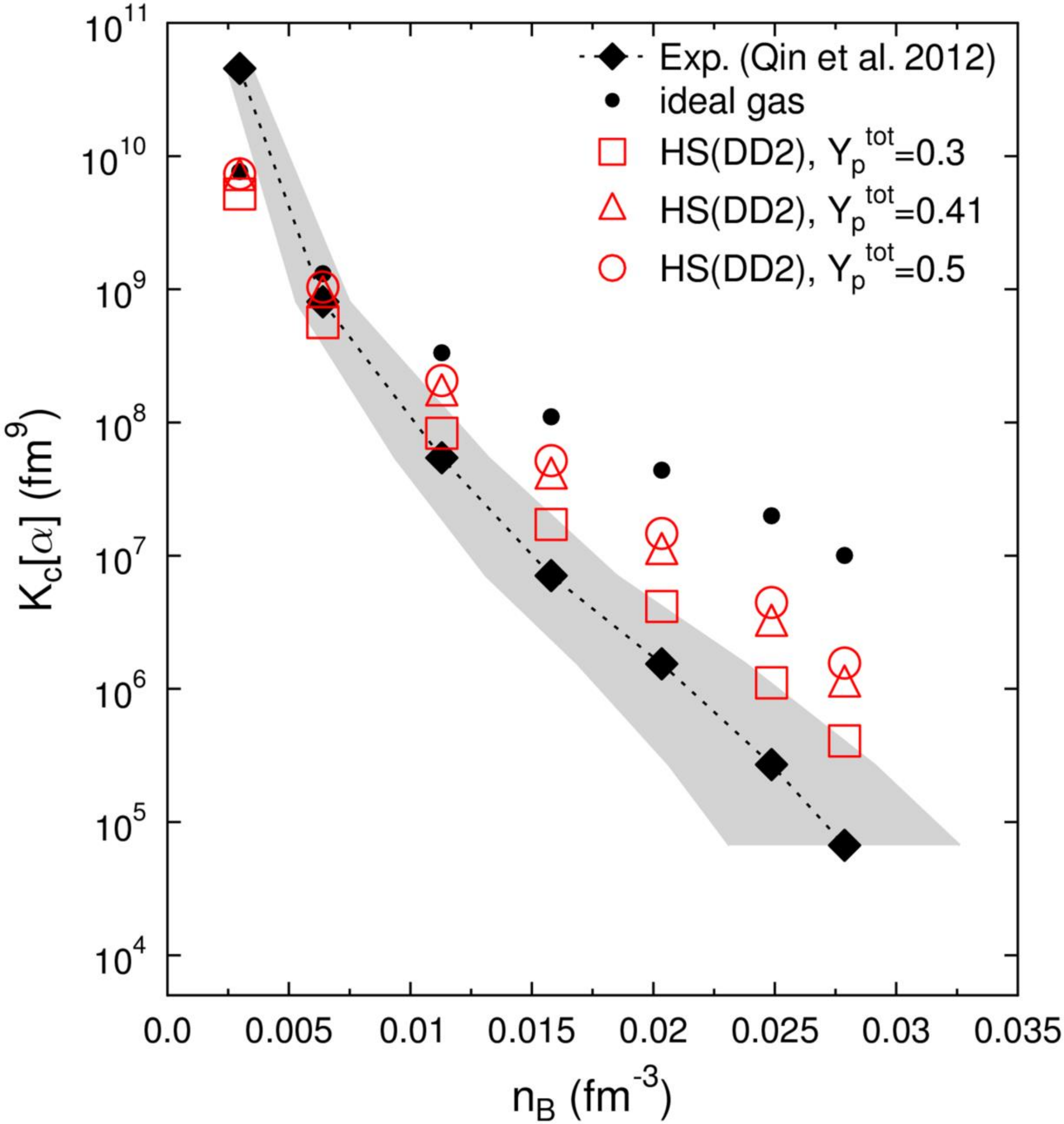


PRL **108** (2012) 172701.

Further Study

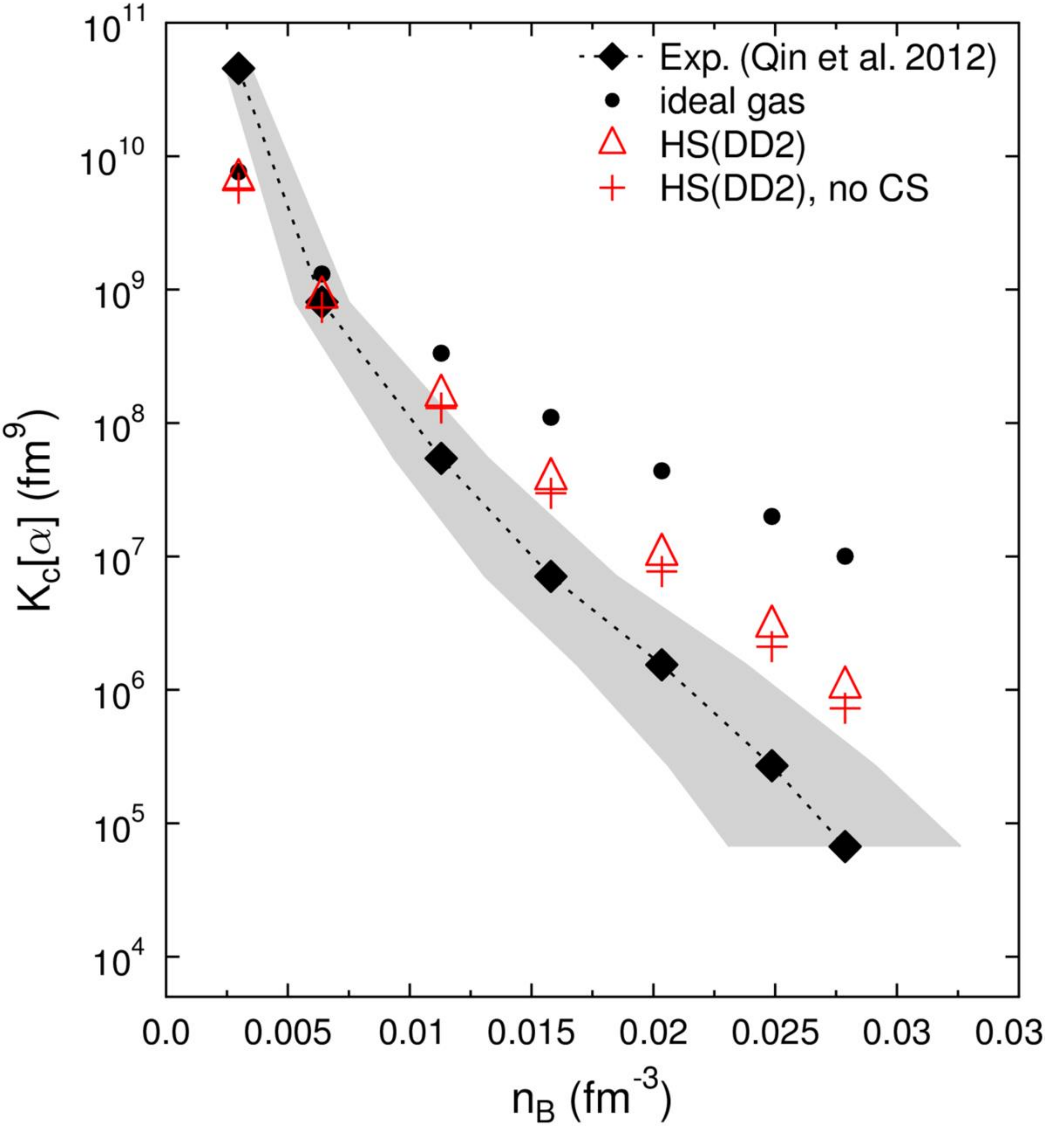
- M. Hempel et al.
  - arXiv:1503:00518
  - Submitted for publication to PRC
- Dependence of Equilibrium constants on various quantities
  - Asymmetry of system
  - Coulomb effects
  - Particle degrees of freedom
- Include comparison where possible to other particle types observed in experiment (d, t, ^{3}He)
- Other EOS models

Composition



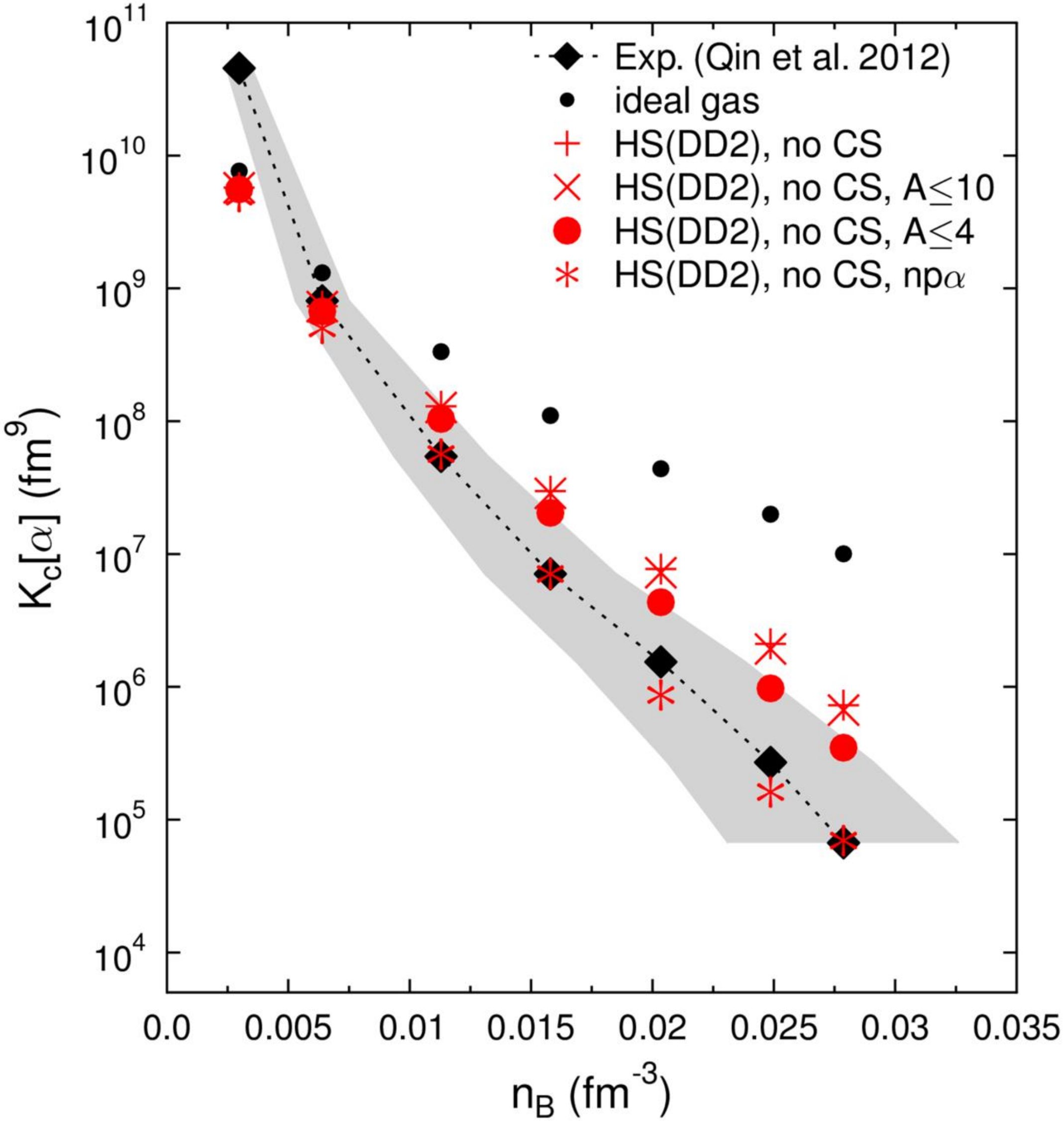
- Ideal gas
  - Chemical potentials cancel in the case of equilibrium
  - Function of temperature only.
  - no ρ or Y_p dependence.
- When interaction is present
  - Composition dependent
  - Values converge to ideal gas at low densities
  - Increase in K_{eq} with increasing Y_p at as density increases.
- Use Y_p = 0.41 in remainder of calculations since that is what was extracted from experiment.

Coulomb effects

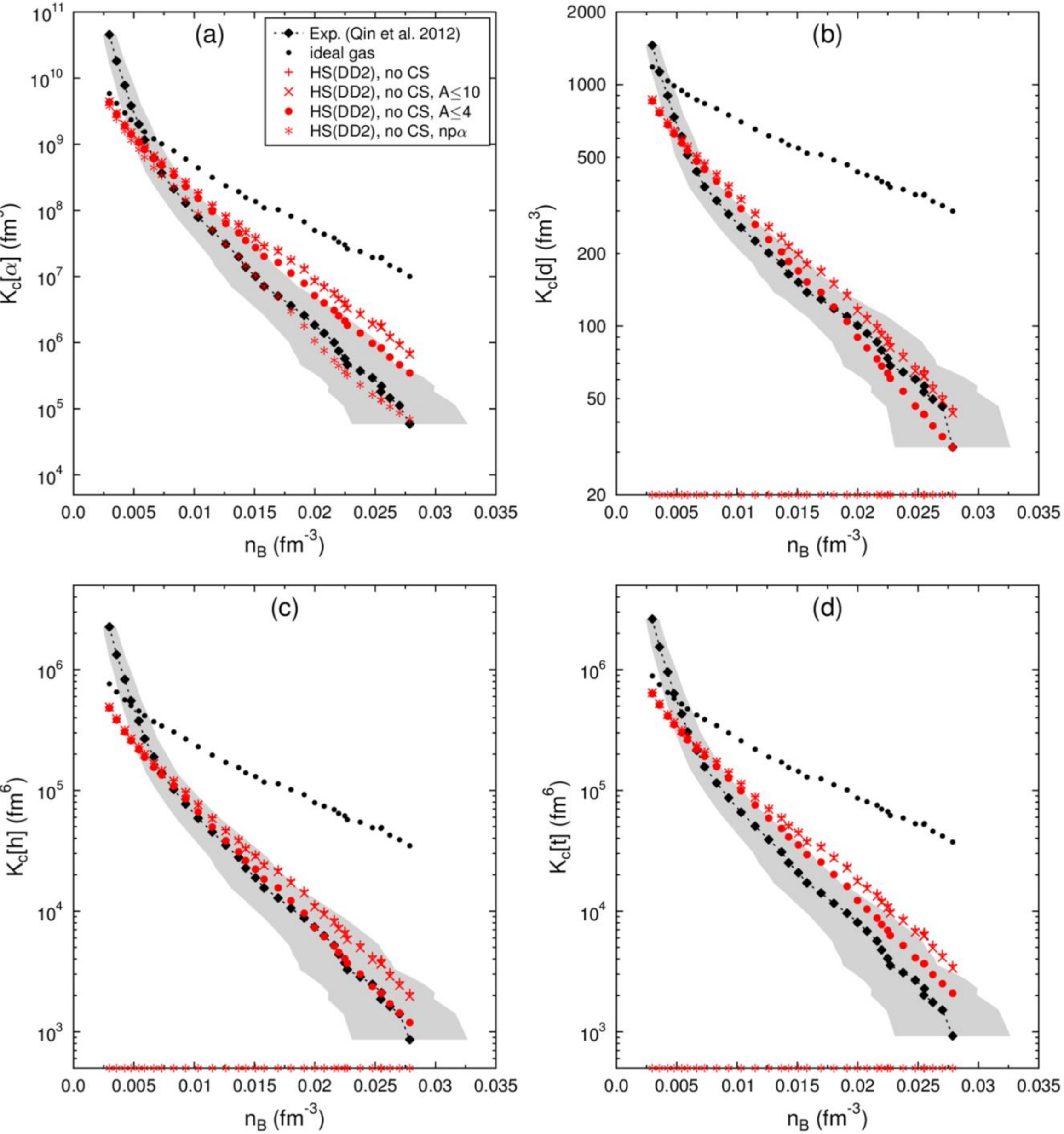


- In SN matter, coulomb interactions screened by surrounding electrons in contrast to matter in heavy ion collisions
- Small effect in calculations when screening is turned off.

Particle Degrees of Freedom



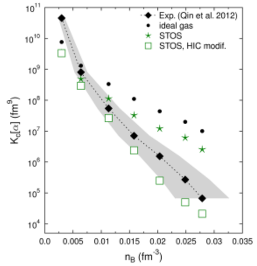
- Almost no dependence when constraining to A ≤ 10.
- Larger dependence when constraining to A ≤ 4
  - Production of A>4 very small in experiment
- Best agreement when only n,p,α included
  - Coincidence
  - Not realistic since significant d, t, ^{3}He observed in experiment.
  - Indicates importance of considering all experimental data



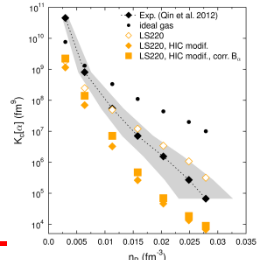
- All reaction products considered
- Species not included have K_{eq} = 0 which does not match data
- Including all reaction products and constraining to $A \leq 4$ yields good agreement with data within error bars.

Constraining the EOS

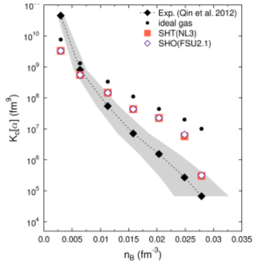
- STOS
  - Treats only n, p, α
  - Fits $K_{eq}(\alpha)$ with heavy nuclei suppression, but cannot fit d, t, ^{3}He



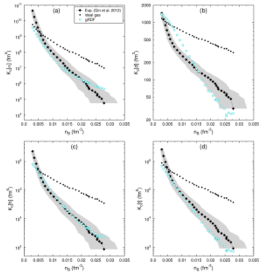
- LS
  - Treats n, p, α and heavy nuclei
  - Fits $K_{eq}(\alpha)$ in unmodified form, but not when heavy nuclei suppressed



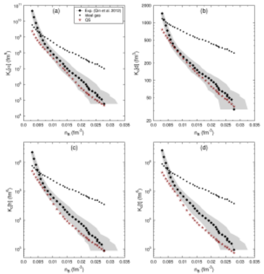
- NL3, FSUgold
  - Uses different assumptions in different density regimes
    - Large rho: uniform nuclear matter of nucleons
    - Intermediate rho: RMF with Hartree calculations leading to nucleons and heavy nuclei
    - Small rho: viral EOS to second order



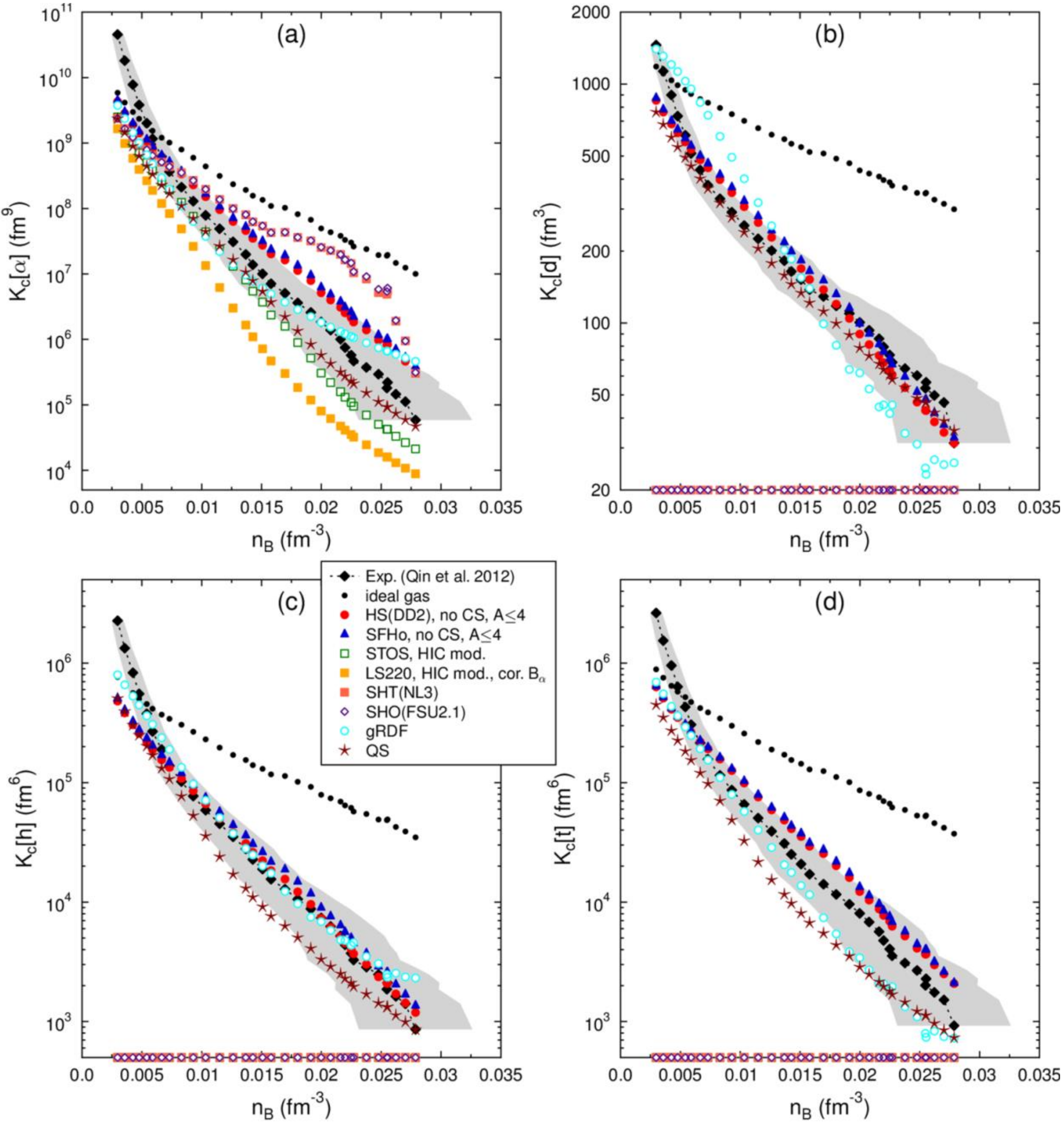
- gRDF
  - Treats nucleons, light and heavy nuclei
  - Interaction is meson-exchange based relativistic mean field approach.



- QS
  - Microscopic treatment with systematic quantum statistical approach
  - Effects of medium on cluster are taken into account.

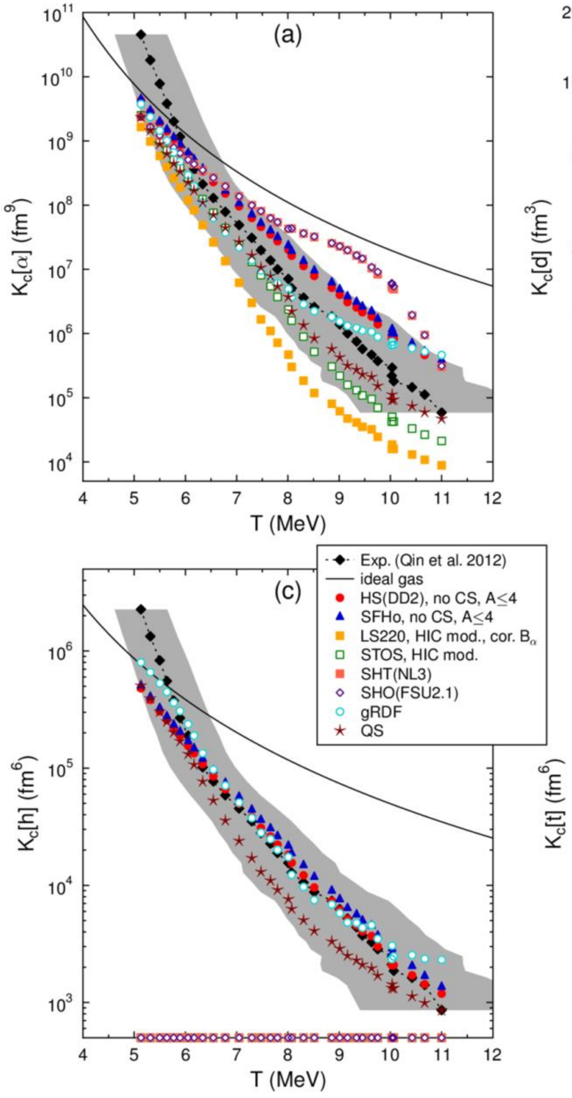


Comparison of all models together



- Two groups of calculations
  - n, p, α calculations which predict $K_{eq}(\alpha)$, but cannot predict other species.
  - Models with n, p, d, t, ^{3}He, α
- Low densities
  - All $K_{eq}(\alpha)$ converge to ideal gas
  - But are below experimental data which result from the very late stages of the reaction
- Models that treat all light particles are generally within error bars

$K_{eq}(T)$



- Keq(T)
- Uncertainity in temperature measurement including at low density
- Ideal gas Keq is function of T only.
- Keq(T) for models that treat all particles are within experimental error bars.

Neutrinos and gravitational attraction from Black Hole accretion disks

- O. L. Caballero *et al*.

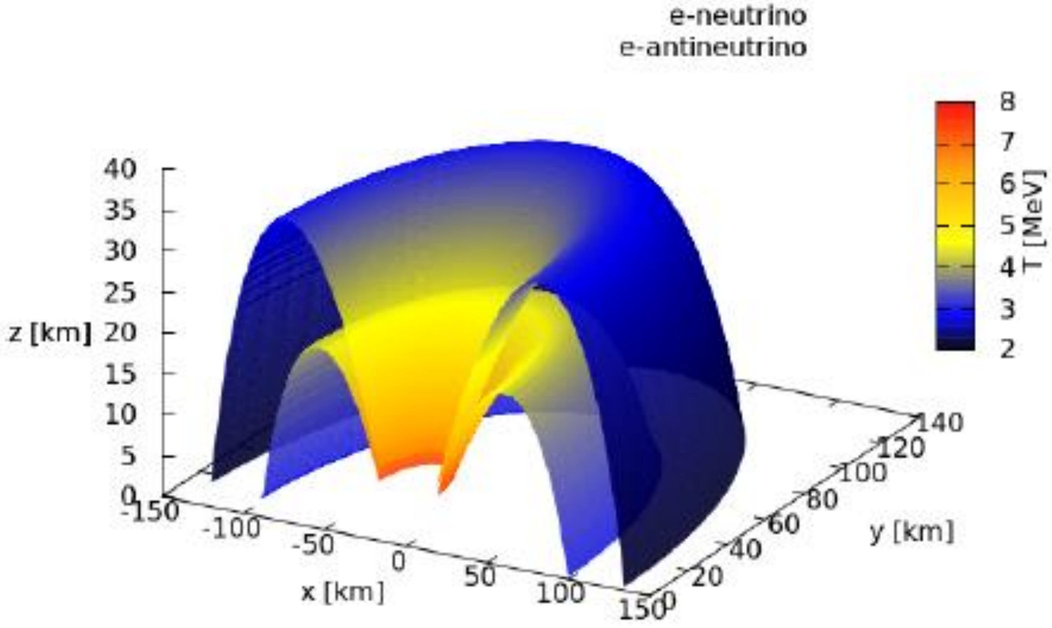
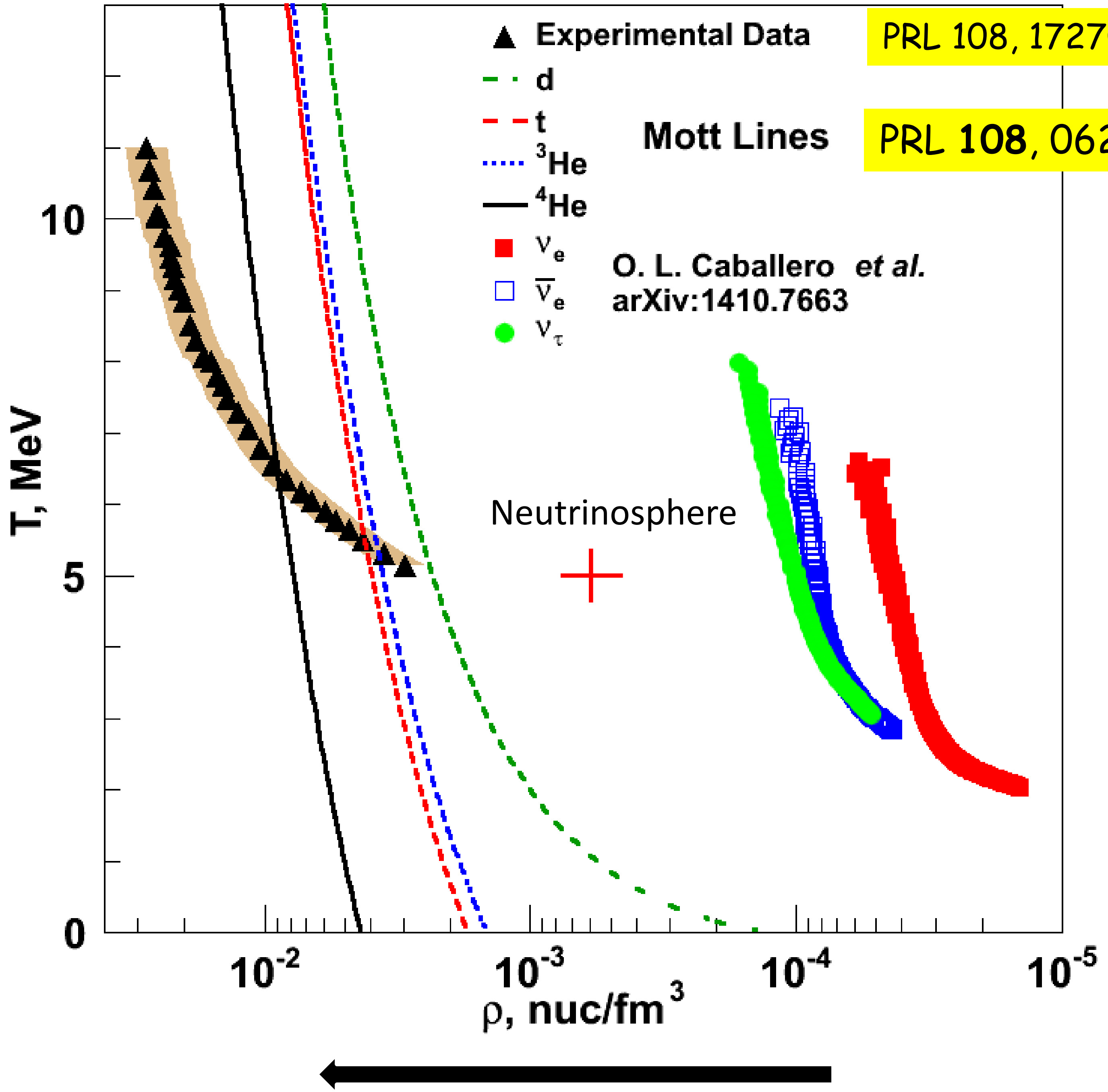


Figure 1. Electron neutrino (outter) and antineutrino (inner) surfaces corresponding to a snapshop at t=20 ms, of a hydrodynamical simulation of a torus around a 3 solar mass black hole.



PRL 108, 172701 (2012).

Mott Lines

PRL **108**, 062702 (2012).

O. L. Caballero ***et al.***
arXiv:1410.7663

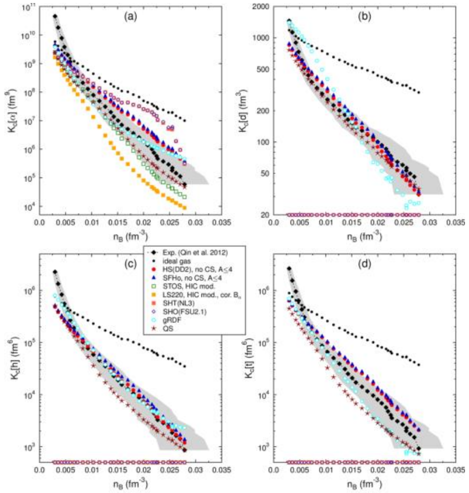
Neutrinosphere

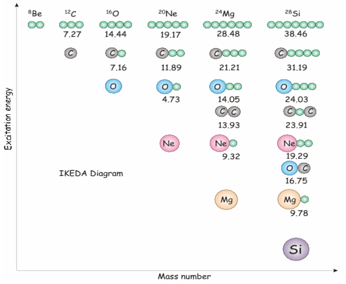
Summary

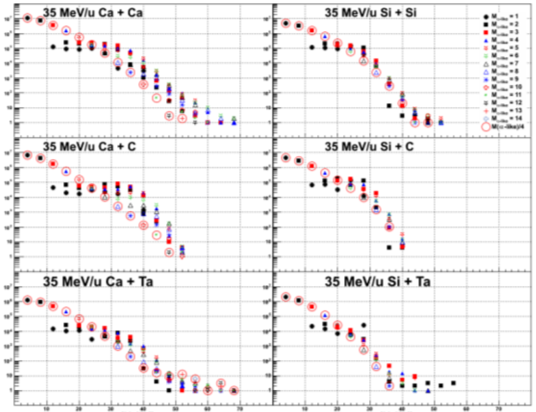
- Comparisons of objects that are different by 56 orders of magnitude in mass.
  - Femtonova and supernova
- Can use heavy ion collisions to create femtoscale objects having similar temperatures and densities of very large mass objects.
- Density and temperatures achieved in the range of those of the neutrinosphere
- Further study of properties and behavior of equilibrium constants
- Importance of including “important” ingredients in model calculations
- Importance of taking into account all available experimental data.

Clustering aspects in heavy ion collisions

- Coalescence analysis (shown in this talk)
  - Density and temperature
  - Low density and clustering
- Studies of reactions with alpha conjugate nuclei
  - Have ^{40}Ca and ^{28}Si projectiles with ^{40}Ca, ^{28}Si, ^{12}C, ^{181}Ta at 35, 25 and 10 MeV/u
  - 35 MeV/u analyzed so far
  - Various reactions with Ca and Si projectiles at 35 MeV/u have a large probability of breaking into alpha-like fragments
  - Further analysis into non-statistical behavior of these systems







Collaborators

M. Hempel, **J. B. Natowitz**, G. Röpke, S. Typel, K. Hagel, R. Wada, S. Wuenschel, M. Barbui, L. Qin, S. Shlomo, A. Bonasera, Z. Chen, M. Huang, J. Wang, H. Zheng, S. Kowalski, M. R. D. Rodrigues, K. Schmidt, G. Giuliani, D. Fabris, M. Lunardon, S. Moretto, G. Nebbia, S. Pesente, V. Rizzi, G. Viesti, M. Cinausero, G. Prete, T. Keutgen, Y. El Masri, Z. Majka, and Y. G. Ma,