Chemical Equilibrium in Low Density Nuclear Matter

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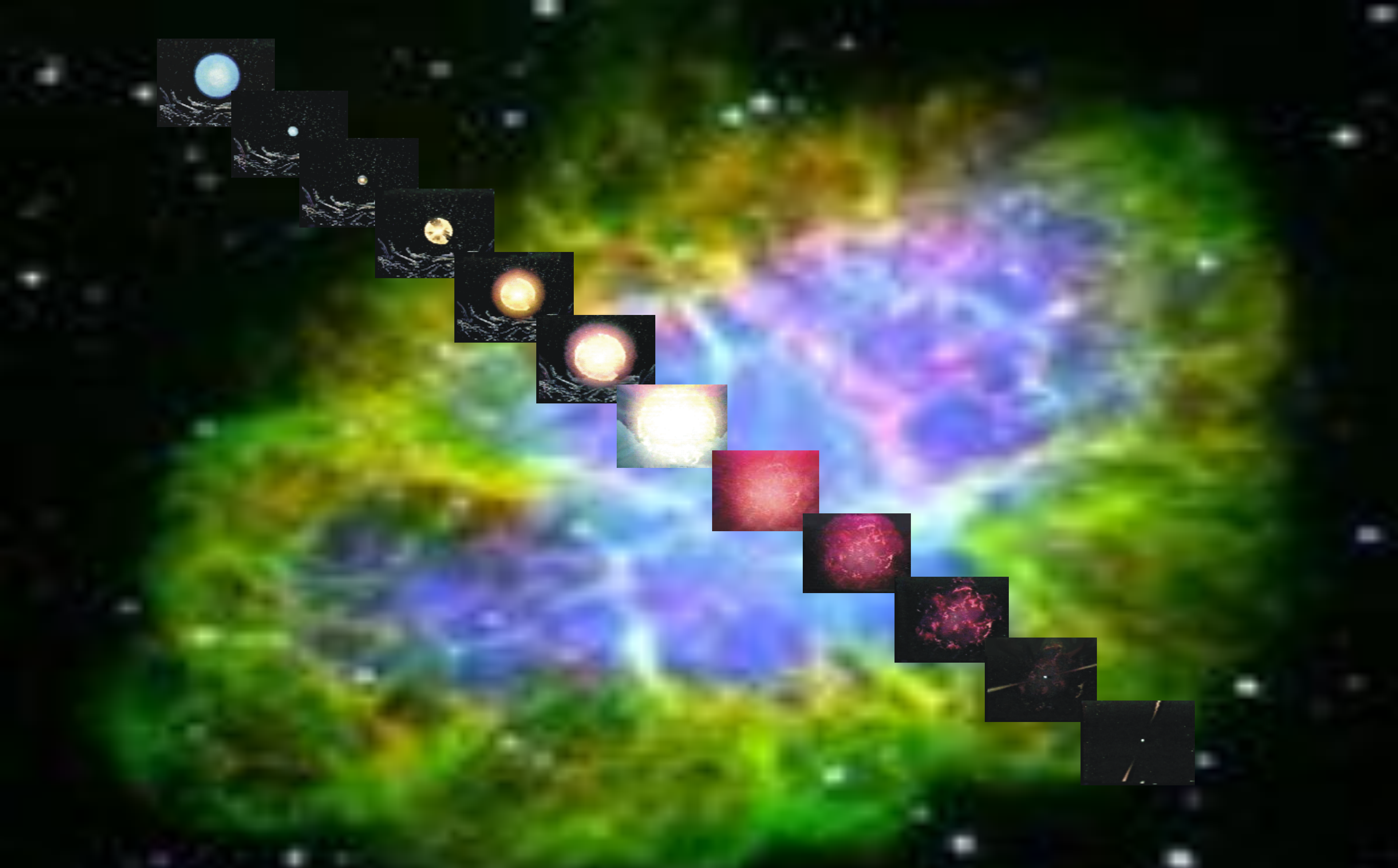
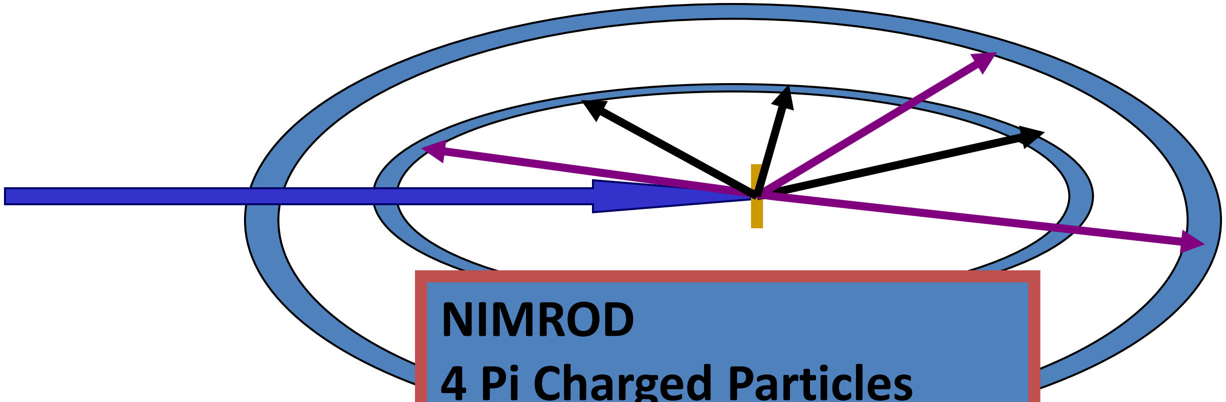
NUSYM15
KRAKOW
28 June 2015

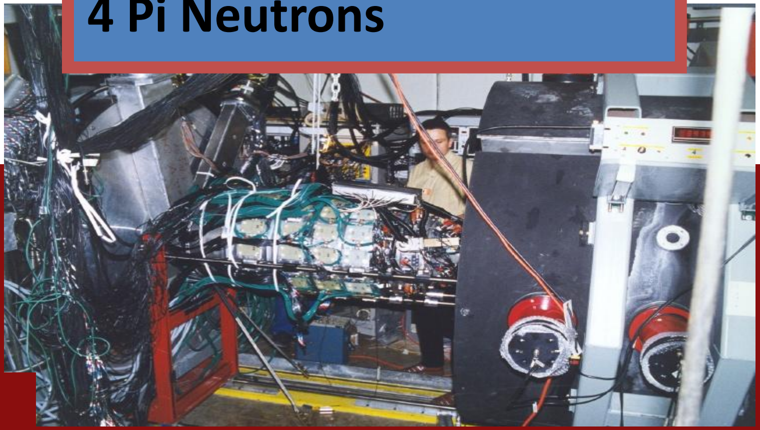


Nuclear and Astrophysical Equations of State - Relevance to Properties of The Neutrino Surface in Supernovae, Binary Mergers--Nucleosynthesis in Neutrino Winds

Light Charged Particle Emission Studies



NIMROD
4 Pi Charged Particles
4 Pi Neutrons



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Reaction System List

4He + 112Sn and 124Sn
10B + 112Sn and 124Sn

- ***20Ne + 112Sn and 124Sn***
- ***40Ar + 112Sn and 124Sn***
- ***64Zn+ 112Sn and 124Sn***

- ***Projectile Energy - 47A MeV***

Thesis – L. Qin
TAMU- 2008

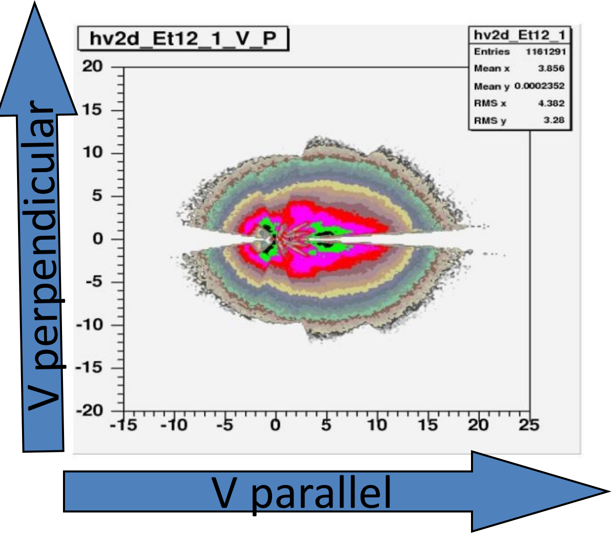
Velocity Plots

Light Charged Particles- Most Violent Collisions

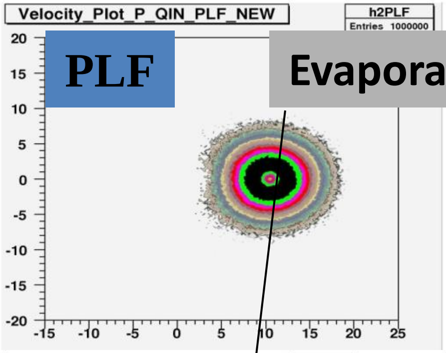
Velocity Plot Protons

^{40}Ar+^{124}Sn

Experiment

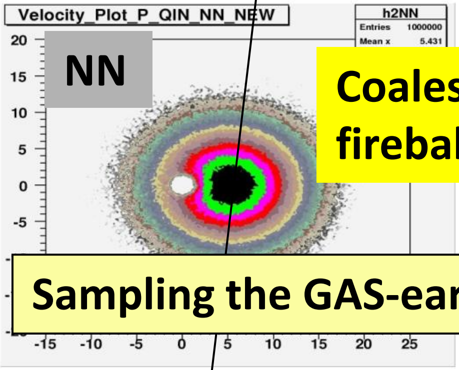


From Fitting



PLF

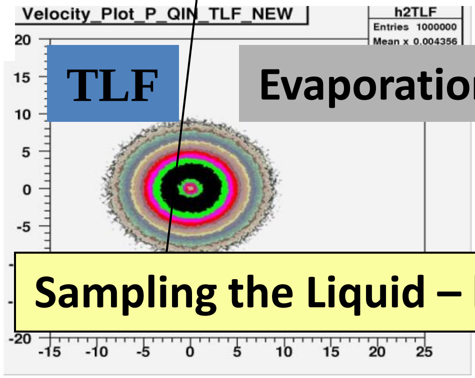
Evaporation-like



NN

Coalescence-like fireball

Sampling the GAS-early emission

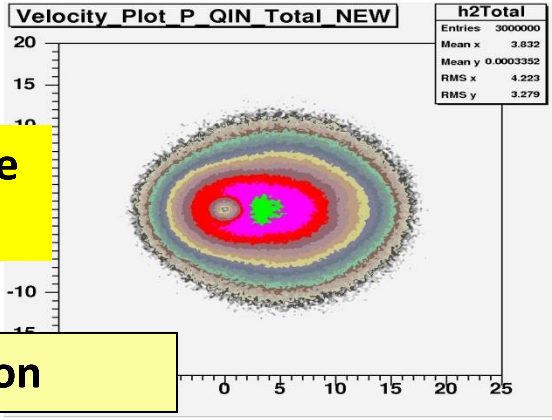


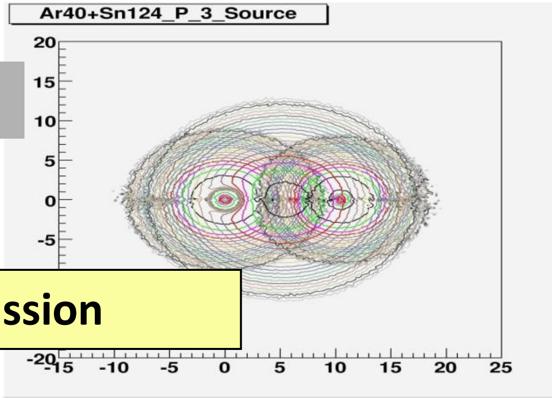
TLF

Evaporation-like

Sampling the Liquid – late emission

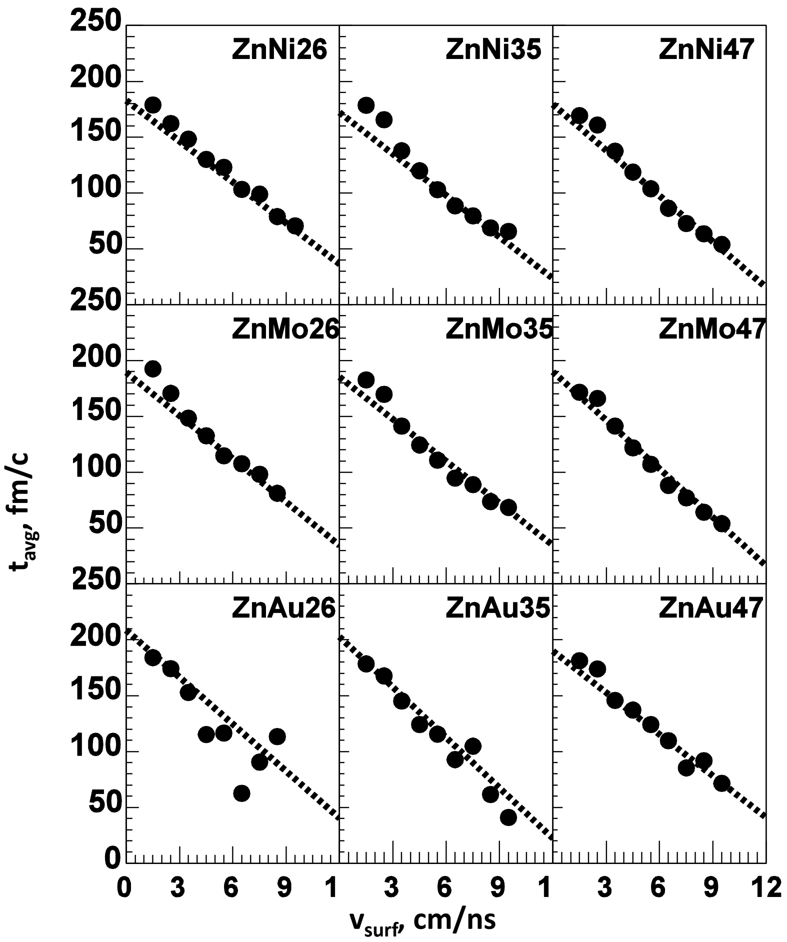
Sum of Source Fits





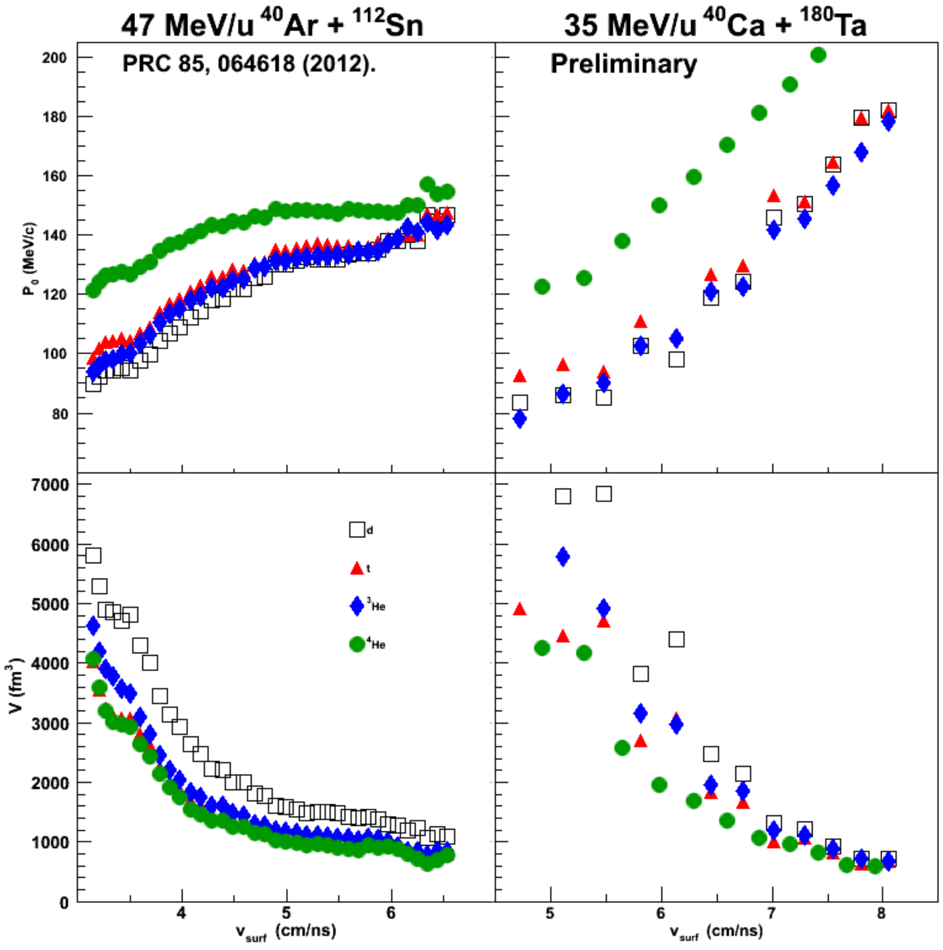
Experiment Analysis

- 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

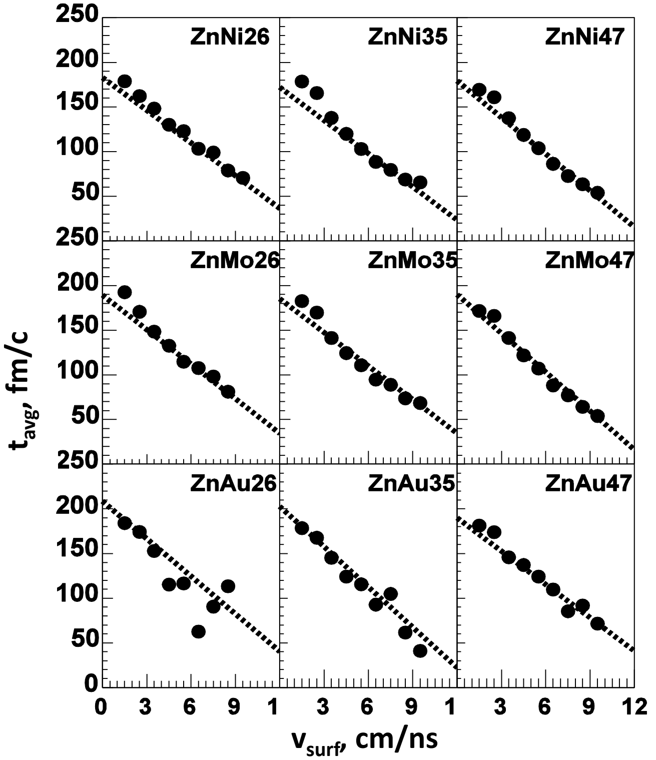


47 MeV/u ^{40}Ar + ^{112}Sn

PRC 85, 064618 (2012).

35 MeV/u ^{40}Ca + ^{180}Ta

Preliminary



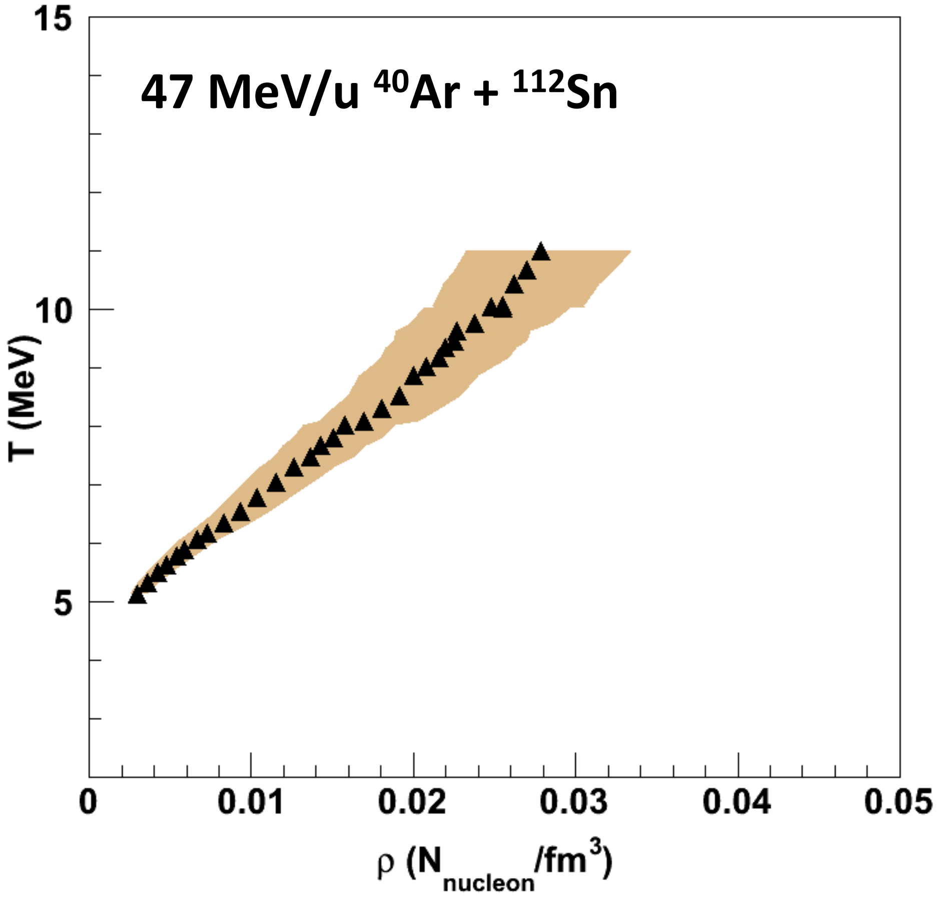
A. Mekjian PRC **72** (2005) 024603

Thermally and Chemically Equilibrated Fireball

Temperatures and Densities

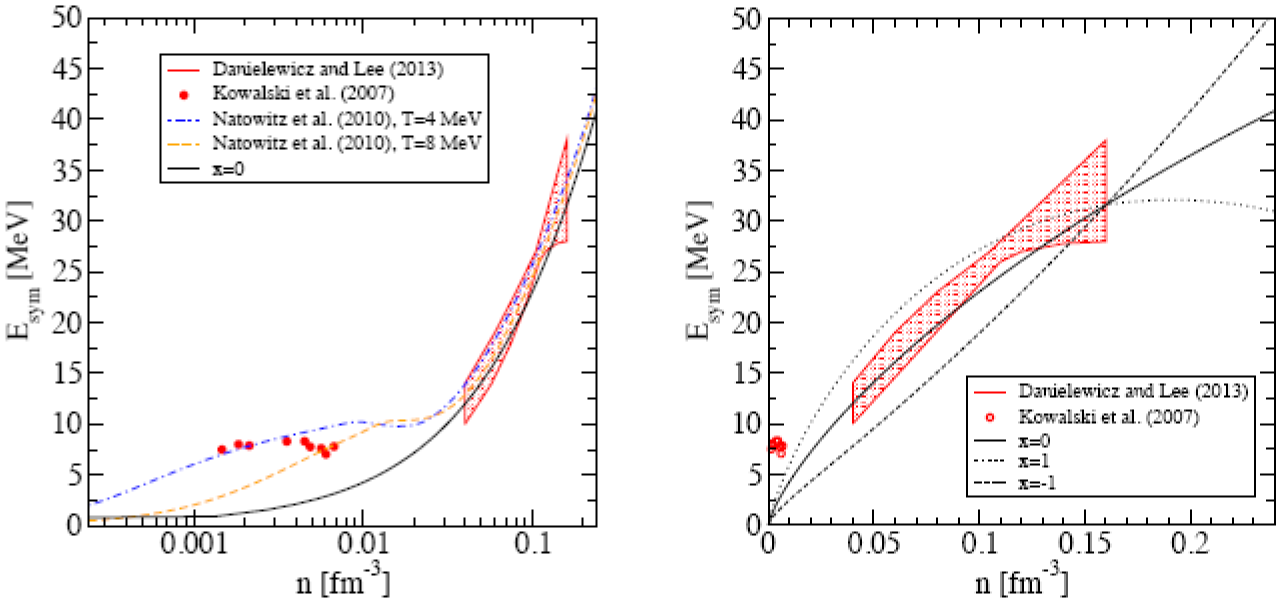
- Recall v_{surf} vs time calculation
- System starts hot
- As it cools, it expands

T_{HHe} Albergo



SYMMETRY ENERGY LOW DENSITY LIMIT

At Low Density The Symmetry Energy is Determined by Cluster Formation. Analysis of Cluster Yield Ratios For Different N/Z Systems (ISOSCALING) Allows Determination of The Symmetry Free Energy. Employment of Entropies Calculated with the QSM Model of Roepke, Typel et al (shown to be appropriate by other measured quantities) Allows Extraction of The LOW Density Symmetry Energy $F_{sym} + T \cdot S_{sym} = E_{sym}$



The equation of state and symmetry energy of low density nuclear matter

K. Hagel, G. Roepke and J. Natowitz , EPJA, **50**, 39 (2014)

See also **S. Typel *et al*., Phys. Rev. C 81, 015803 (2010).**

J.B. Natowitz et al., Phys.Rev.Lett.104:202501 (2010).

NOTE CHEMICAL EQUILIBRIUM ASSUMPTIONS FOR FIREBALL

Light Fragment Emission: ^{136,124}Xe+^{124,112}Sn, E = 32,.,150 AMeV ,

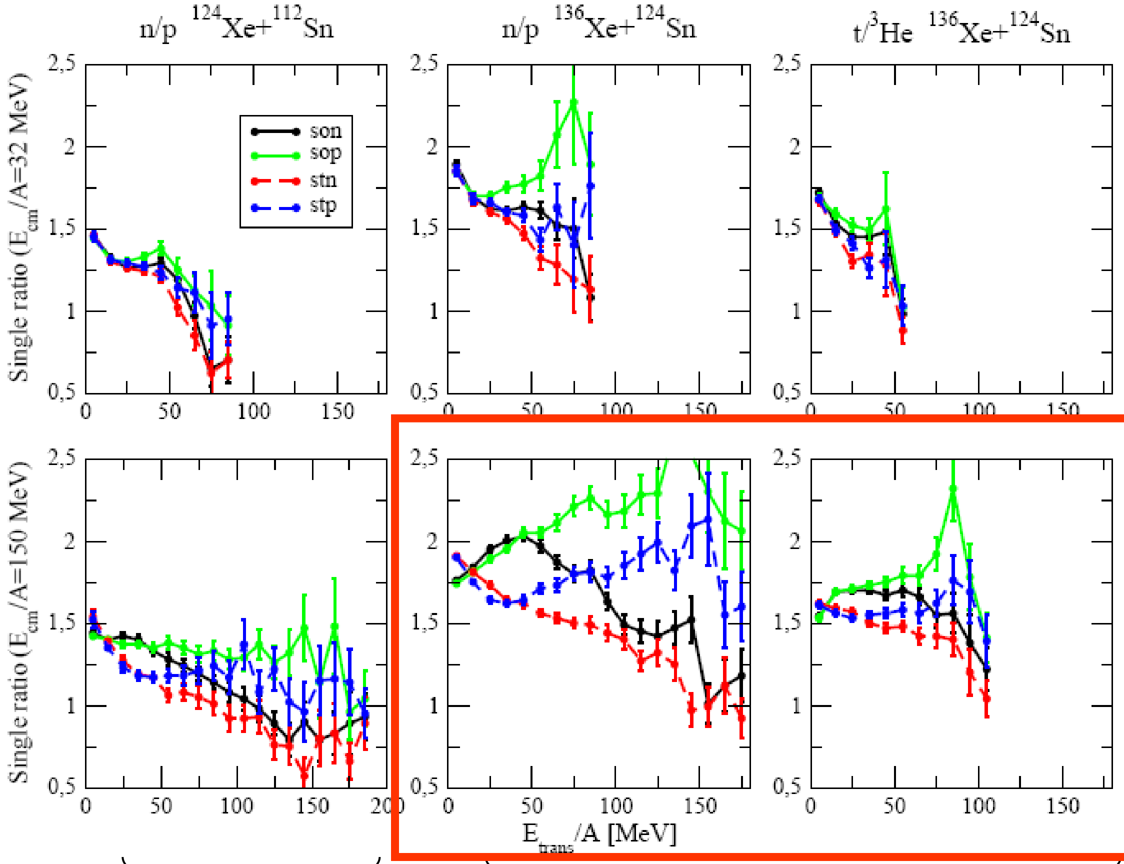
Single ratios

NUSYM13 Z.Chajecki et al.

Variation
of density dep. and
effective mass splitting
with isoscalar potential
held fixed
(Bombaci-Gale-Bertsch-
DasGupta type)

n/p

t/3He



E=32 AMeV

E=150 AMeV

son: asysoft, $m_n^*>m_p^*$
stn: asystiff, $m_n^*>m_p^*$
sop: asysoft, $m_n^*<m_p^*$
stp: asystiff, $m_n^*<m_p^*$

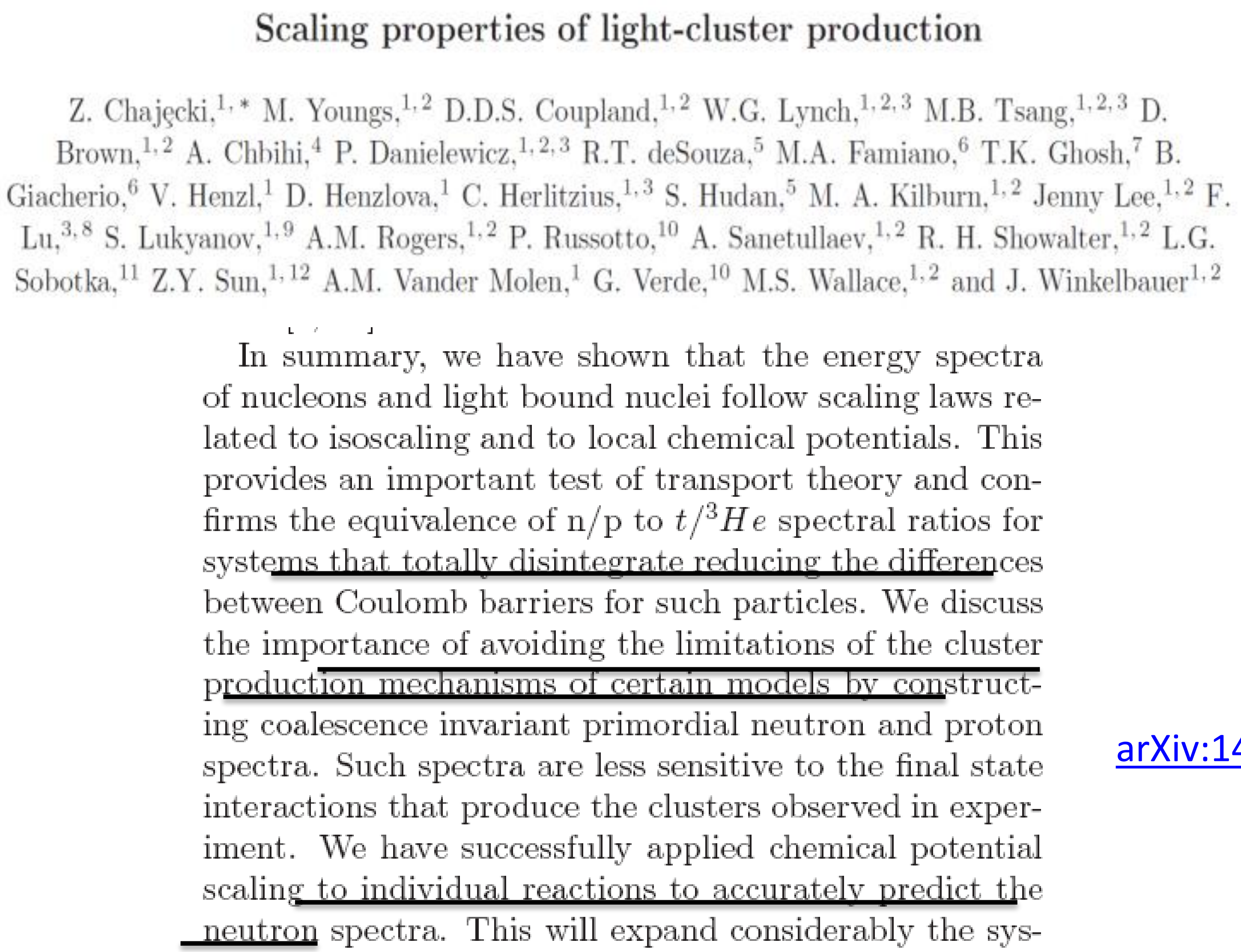
look in more detail

neutron poor
^{124}Xe+^{112}Sn

neutron rich
^{136}Xe+^{124}Sn

effects larger for higher energy and neutron rich system

H.H. Wolter, et al.,
EPJ Web of Conf. &&, 03097 (2014)



Scaling properties of light-cluster production

Z. Chajęcki,[1,*] M. Youngs,[1,2] D.D.S. Coupland,[1,2] W.G. Lynch,[1,2,3] M.B. Tsang,[1,2,3] D. Brown,[1,2] A. Chbihi,[4] P. Danielewicz,[1,2,3] R.T. deSouza,[5] M.A. Famiano,[6] T.K. Ghosh,[7] B. Giacherio,[6] V. Henzl,[1] D. Henzlova,[1] C. Herlitzius,[1,3] S. Hudan,[5] M. A. Kilburn,[1,2] Jenny Lee,[1,2] F. Lu,[3,8] S. Lukyanov,[1,9] A.M. Rogers,[1,2] P. Russotto,[10] A. Sanetullaev,[1,2] R. H. Showalter,[1,2] L.G. Sobotka,[11] Z.Y. Sun,[1,12] A.M. Vander Molen,[1] G. Verde,[10] M.S. Wallace,[1,2] and J. Winkelbauer[1,2]

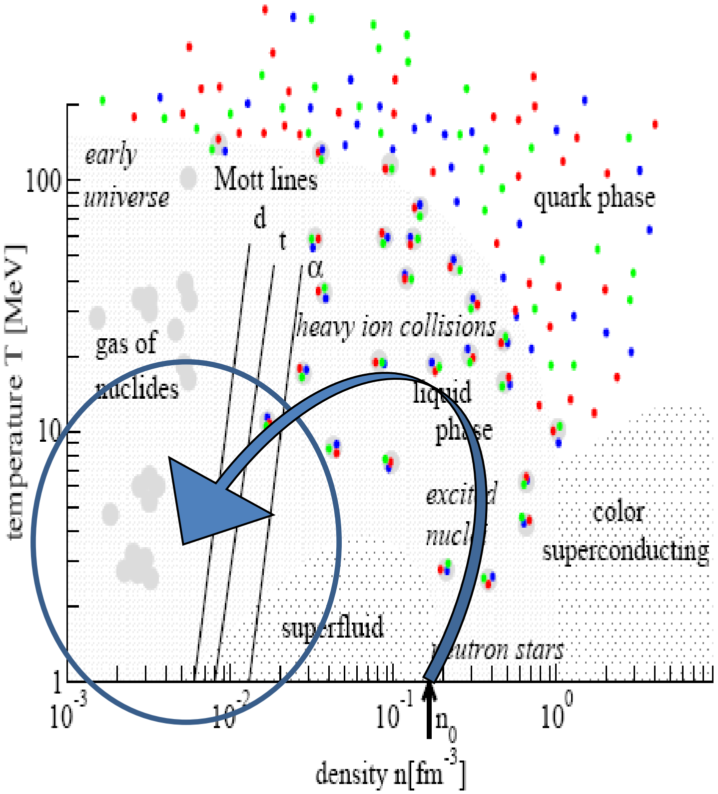
In summary, we have shown that the energy spectra of nucleons and light bound nuclei follow scaling laws related to isoscaling and to local chemical potentials. This provides an important test of transport theory and confirms the equivalence of n/p to $t/^3He$ spectral ratios for systems that totally disintegrate reducing the differences between Coulomb barriers for such particles. We discuss the importance of avoiding the limitations of the cluster production mechanisms of certain models by constructing coalescence invariant primordial neutron and proton spectra. Such spectra are less sensitive to the final state interactions that produce the clusters observed in experiment. We have successfully applied chemical potential scaling to individual reactions to accurately predict the neutron spectra. This will expand considerably the sys-

arXiv:1402.5216

CHEMICAL EQUILIBRIUM FOR LIGHT CLUSTER PRODUCTION

Transport models need work

CLUSTER FORMATION Modifies Nuclear EOS



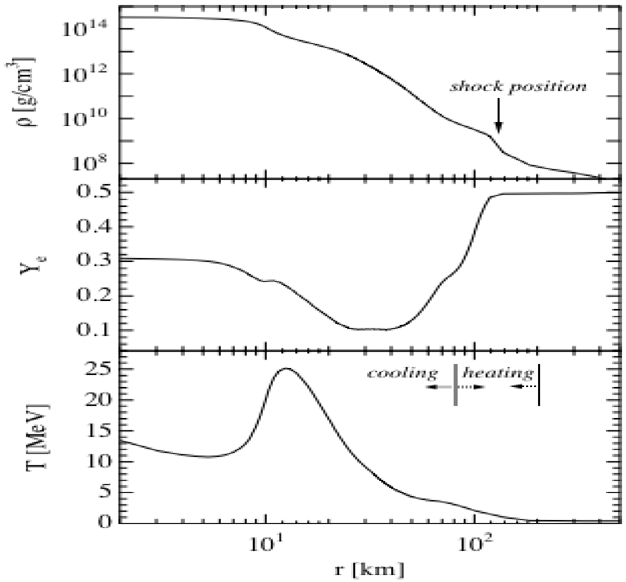
M. Beyer et al.,
Phys.Lett. B488, 247-253 (2000)

S. Typel, et al., ArXiv 0908.2344v1
August 2009

Astrophysical Implications, e.g., Core-collapse Supernovae

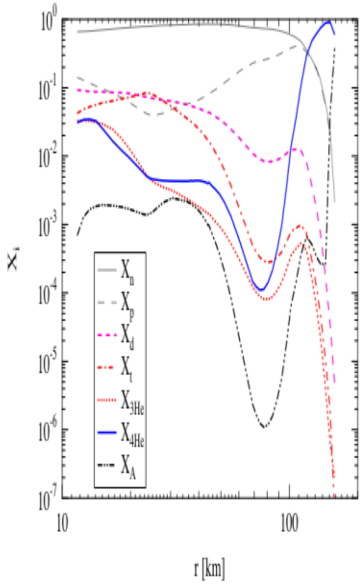
K.Sumiyoshi et al.,
Astrophys.J. **629**,
922 (2005)

Density. electron fraction, and temperature profileof a 15 solar mass supernova at 150 ms after core bounce --as function of the radius.



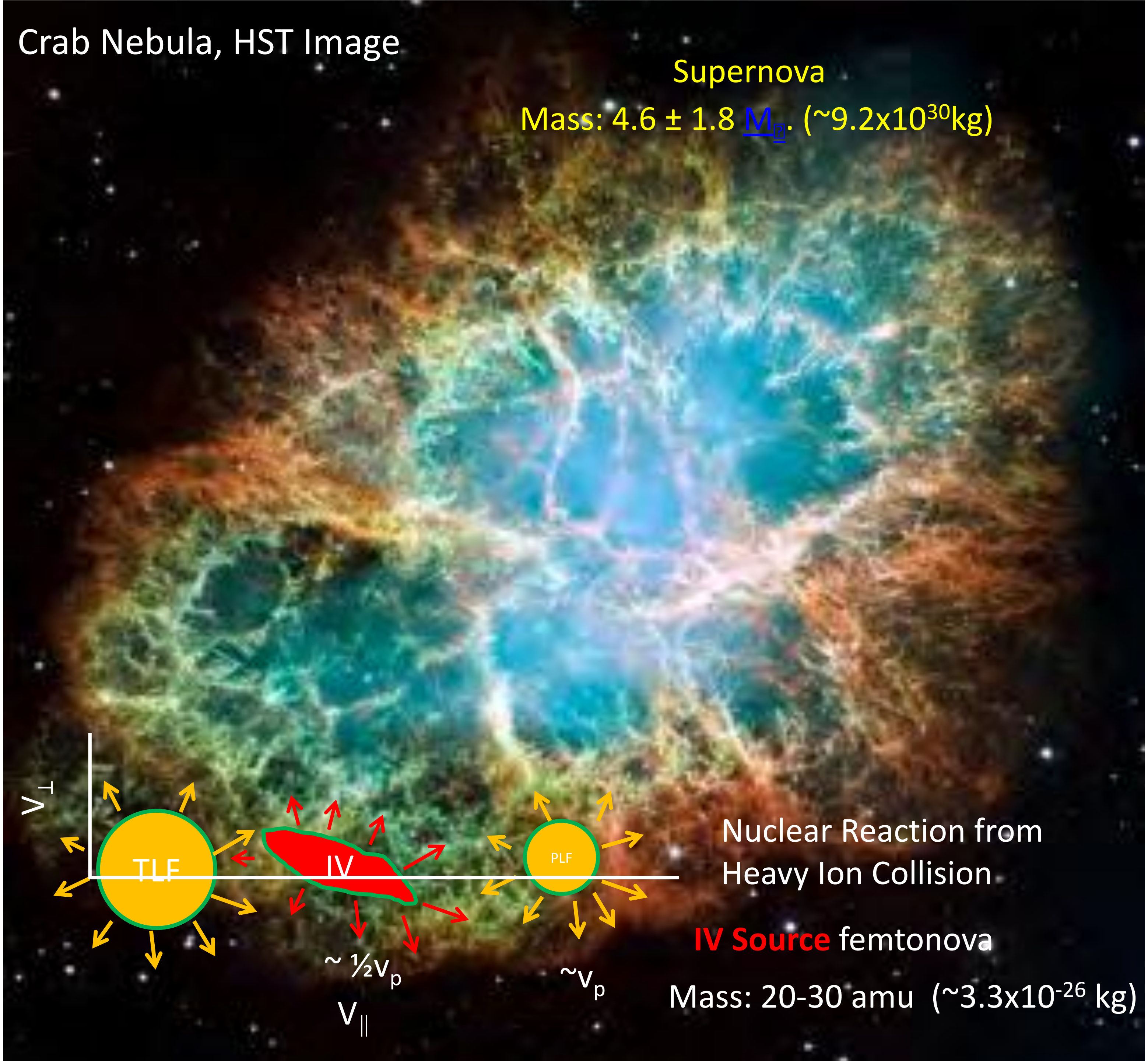
K.Sumiyoshi, G. Roepke
PRC 77, 055804
(2008)

cluster formation Influences neutrino flux



INSTITUTE
Texas A&M University

- 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: ~10^{12} g/cm^3 (~$6x10^{-4}$ 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



Crab Nebula, HST Image

Supernova

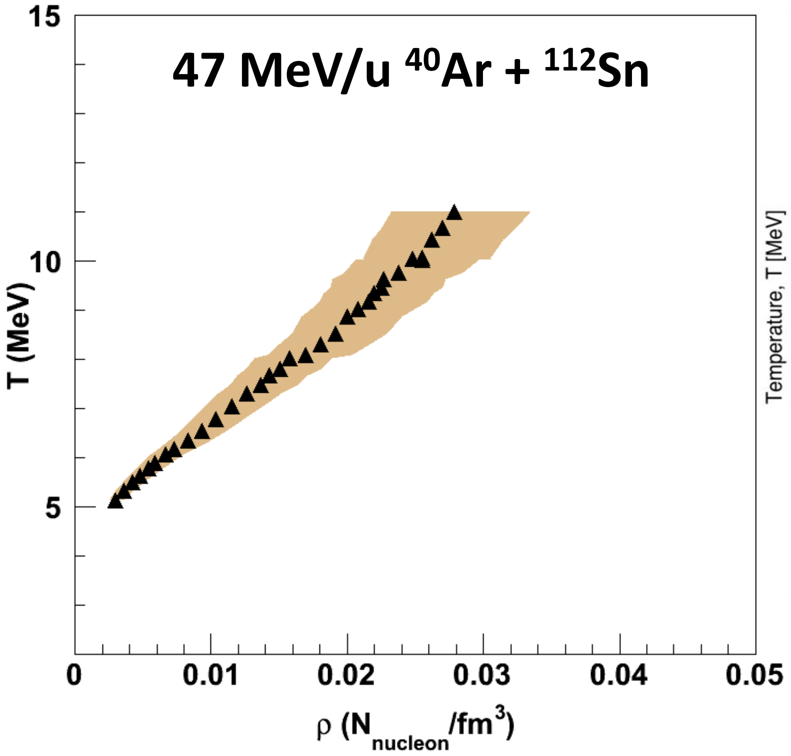
Mass: 4.6 ± 1.8 $M_{\odot}$. (~9.2×10^{30}kg)

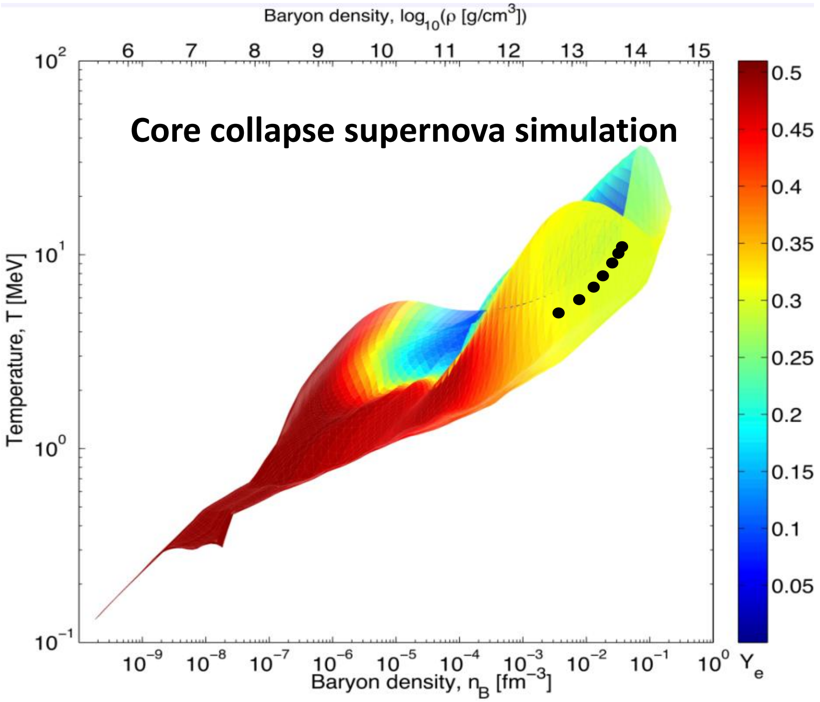
Nuclear Reaction from
Heavy Ion Collision

IV Source femtonova

Mass: 20-30 amu (~3.3×10^{-26} kg)

Temperatures and Densities





- SN are "infinite", but HIC are finite

- The "infinite" matter in SN is charge neutral, but HIC has a net charge
- Proton fraction, Y_p can differ
- Composition of nuclear matter in calculations
  - Different calculations include different species

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

Effects of the microphysical Equation of State in the mergers of magnetized Neutron Stars With Neutrino Cooling

Carlos Palenzuela,[1] Steven L. Liebling,[2] David Neilsen,[3] Luis Lehner,[4] O. L. Caballero,[5] Evan O'Connor,[6] and Matthew Anderson[7]

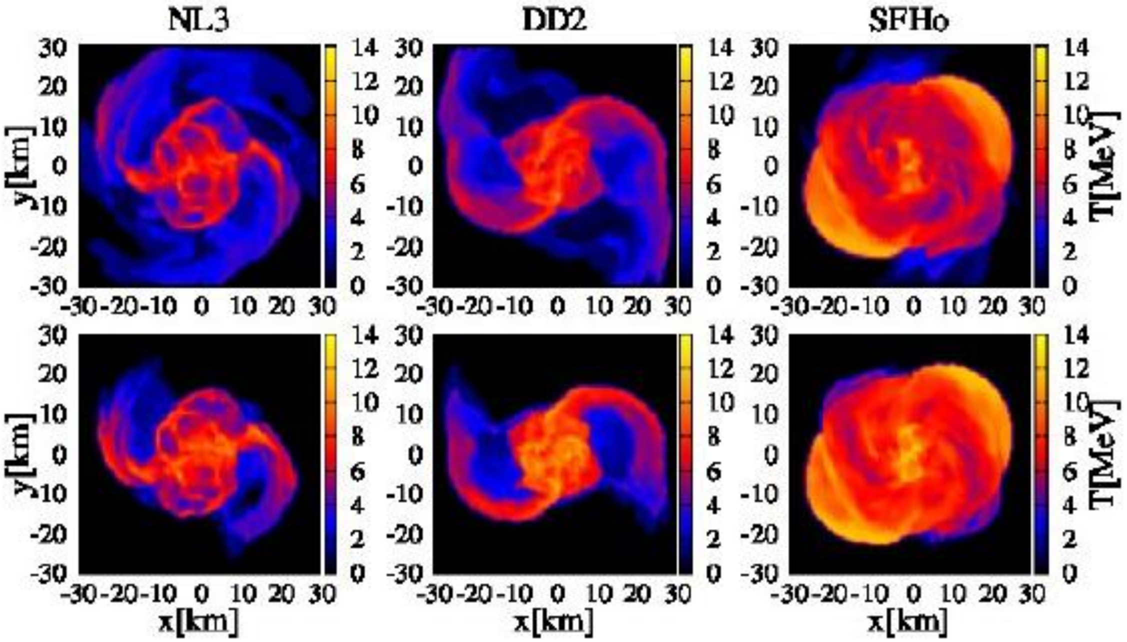


FIG. 15: Color map of the temperature at the scattering neutrinospheres at ∼ 2.5–3 ms after merger for the NL3 EoS (left), DD2 EoS (center) and SFHo EoS (right). The top panels show the electron neutrinosphere, and the bottom panels show the electron antineutrinosphere.

arXiv:1505.01607v1 [gr-qc] 7 May 2015

Draft version June 17, 2015
Preprint typeset using LaTeX style emulateapj v. 5/2/11

NUCLEOSYNTHESIS IN NEUTRINO-DRIVEN WINDS AFTER NEUTRON STAR MERGERS

D. Martin, A. Perego, and A. Arcones
Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstr. 2, Darmstadt D-64289, Germany
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(Dated: today)
Draft version June 17, 2015

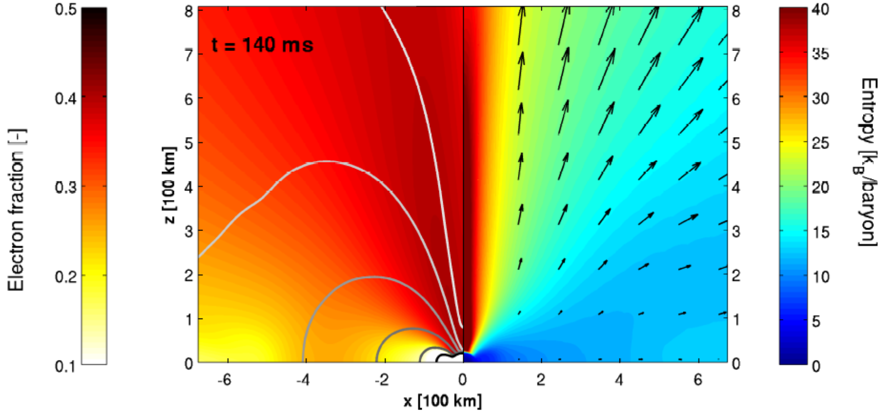


Fig. 1.— $x - z$ plane at 140 ms after the beginning of the simulation. The left panel shows the electron fraction with a superimposed contour plot of the density. A color gradient from white to black indicates the regions with densities of $\rho = 10^6$ g/cm^3 to $\rho = 10^{11}$ g/cm^3. Entropy profile and the projected velocity are presented in the right panel. The length of the arrows characterizes the magnitude of the velocity.

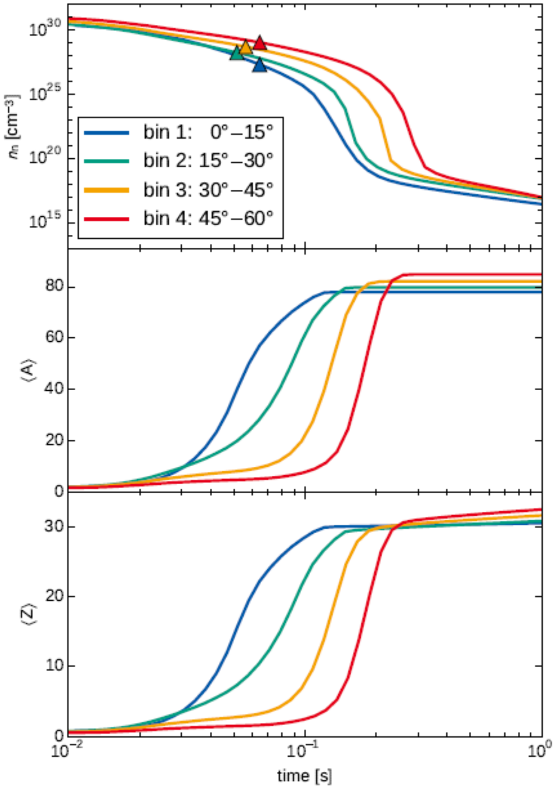


Fig. 10.— Evolution of the neutron density n_n (top), average mass number $\langle A \rangle$ (middle) and average proton number $\langle Z \rangle$ (bottom). The solid lines follow the mean values of the four angular bins (see also Fig. 9). Triangles indicate times, when the temperature reaches $T = 3$ GK, i.e. the onset of the r-process.

Neutrinos and gravitational attraction from Black Hole accretion disks

- O. L. Caballero *et al*.

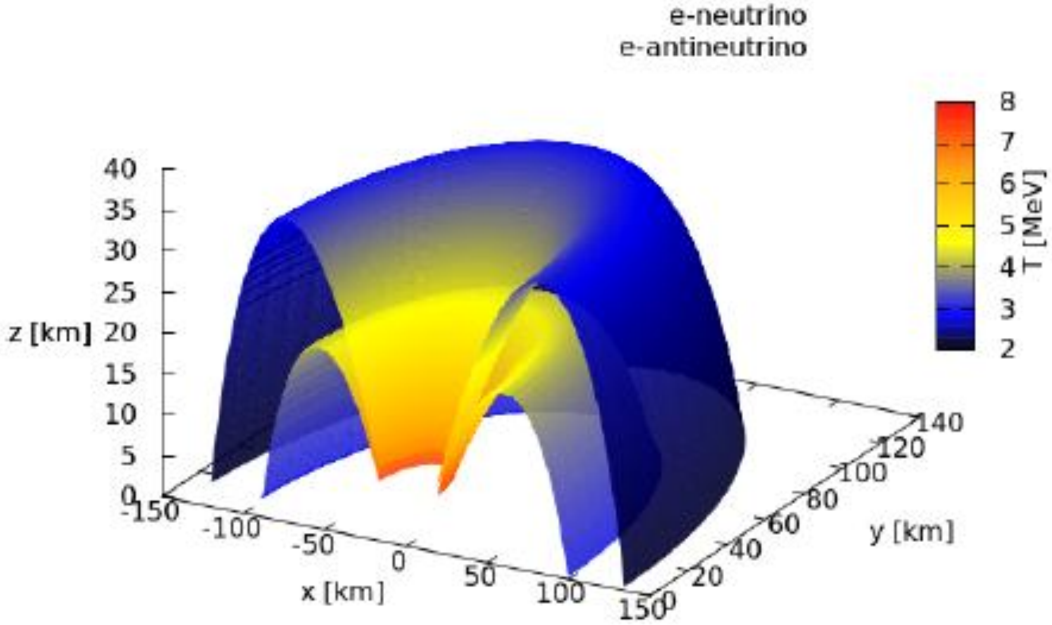
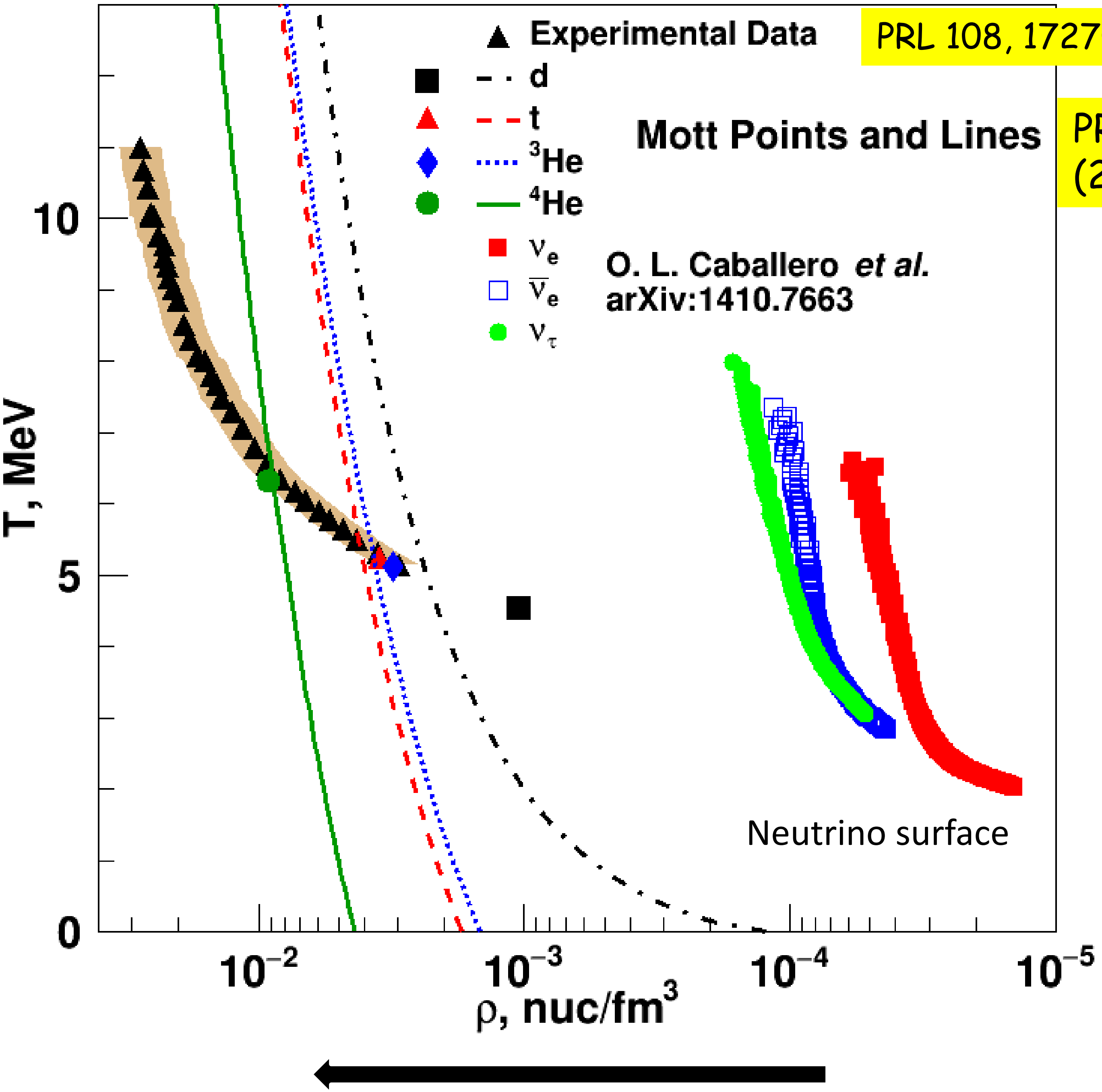


Figure 1. Electron neutrino (outter) and antineutrino (inner) surfaces corresponding to a snapshop at t=20 ms, of a hydrodynamical simulation of a torus around a 3 solar mass black hole.

PRL 108, 172701 (2012).

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



Mott Points and Lines

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

Neutrino surface

- Clusters appear in shock heated nuclear matter
- Critical region is near last neutrino scattering surface
  - Clusters Role on the dynamics is not yet fully understood
- Relevance of heavy ion collisions to core collapse supernovae
  - Allow to probe the lower densities in the lab
  - Valid treatment of the correlations and clusterization in low density matter is a vital ingredient of astrophysical models
  - Comparisons of heavy ion data to supernovae calculations may help discriminate between different models.

From Wikipedia, the free encyclopedia

The **equilibrium constant** of a chemical reaction

$$\alpha A + \beta B ... \rightleftharpoons \rho R + \sigma S ...$$

is the value of the reaction quotient when the reaction has reached equilibrium.

For a general chemical equilibriumthe thermodynamic equilibrium constant can be defined such that, at equilibrium,[1][2]

$$K^\ominus = \frac{\{R\}^\rho \{S\}^\sigma ...}{\{A\}^\alpha \{B\}^\beta ...}$$

where curly brackets denote the thermodynamic activities** of the chemical species. The right-hand side of this equation corresponds to the reaction quotient Q for arbitrary values of the activities. The reaction coefficient becomes the equilibrium constant as shown when the reaction reaches equilibrium.

An equilibrium constant value is independent of the analytical concentrations of the reactant and product species in a mixture, but depends on temperature and on ionic strength. Known equilibrium constant values can be used to determine the composition of a system at equilibrium.

The equilibrium constant is related to the standard Gibbs free energy change for the reaction.

$$\Delta G^\ominus = -RT \ln K^\ominus$$

If deviations from ideal behavior are neglected, the activities of solutes may be replaced by concentrations, [*A*], and the activity quotient becomes a concentration quotient, K_c.

$$K_c = \frac{[R]^\rho [S]^\sigma ...}{[A]^\alpha [B]^\beta ...}$$

K_c is defined in an equivalent way to the thermodynamic equilibrium constant but with concentrations of reactants and products instead of activities. (K_c appears here to have units of concentration raised to some power while K is dimensionless; however the concentration factors in K_c are properly divided by a standard concentration so that K_c is dimensionless also.

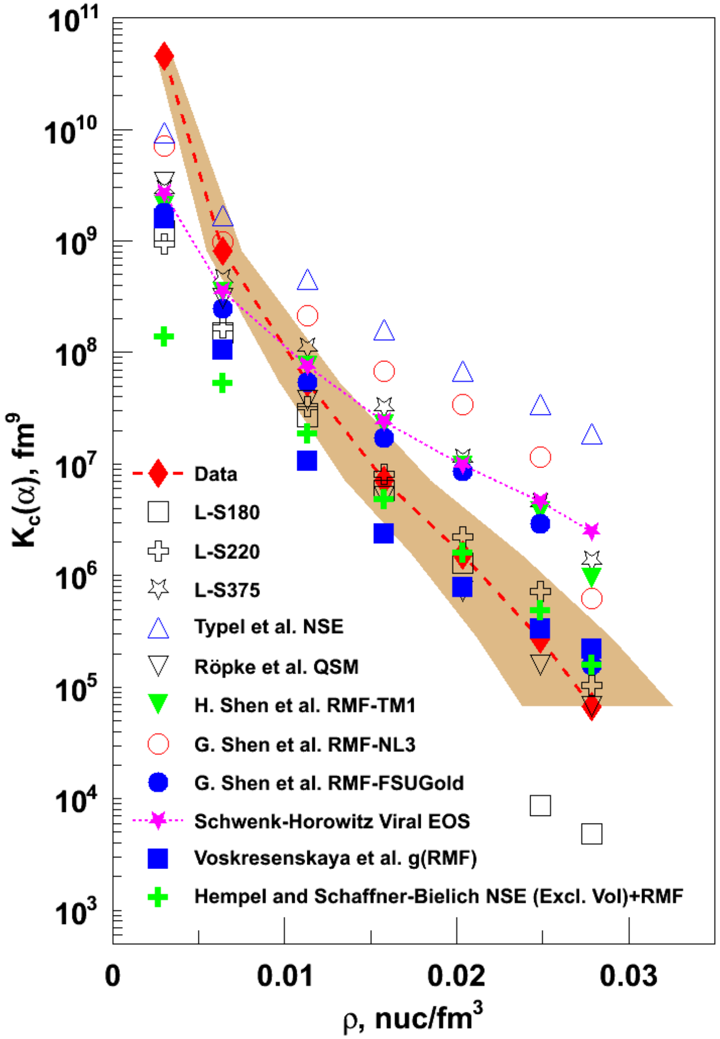
Assuming ideal behavior, the activity of a solvent may be replaced by its mole fraction, (approximately by 1 in dilute solution). The activity of a pure liquid or solid phase is exactly 1. The activity of a species in an ideal gas phase may be replaced by its partial pressure.

** In chemical thermodynamics, **activity**) is a measure of the "effective concentration" of a species in a mixture. The species' chemical potential depends on the activity Activity depends on temperature, pressure and composition of the mixture, among other things. The difference between activity and other measures of composition arises because molecules in non-ideal gases or solutions interact with each other, either to attract or to repel each other.

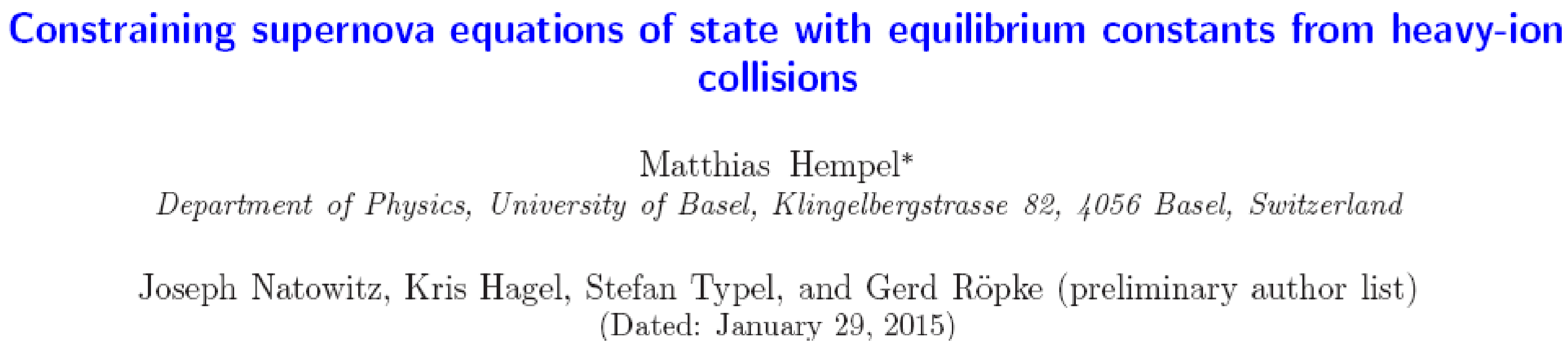
Equilibrium constants from α-particles model predictions

( )

- 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



PRL **108** (2012) 172701.



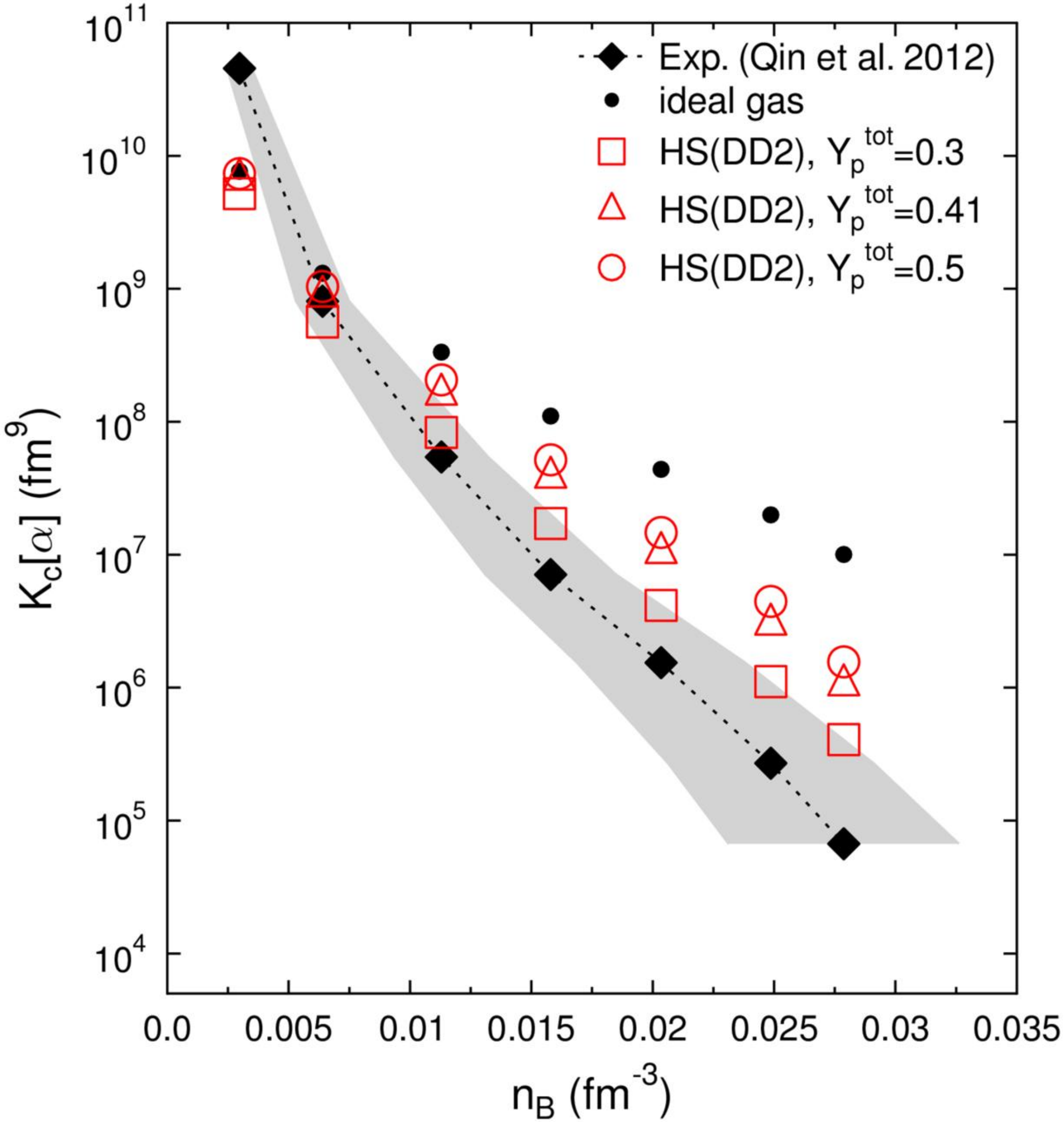
Constraining supernova equations of state with equilibrium constants from heavy-ion collisions

Matthias Hempel*
Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland

Joseph Natowitz, Kris Hagel, Stefan Typel, and Gerd Röpke (preliminary author list)
(Dated: January 29, 2015)

- **Phys. Rev. C 91, 045805 (2015).**
- 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



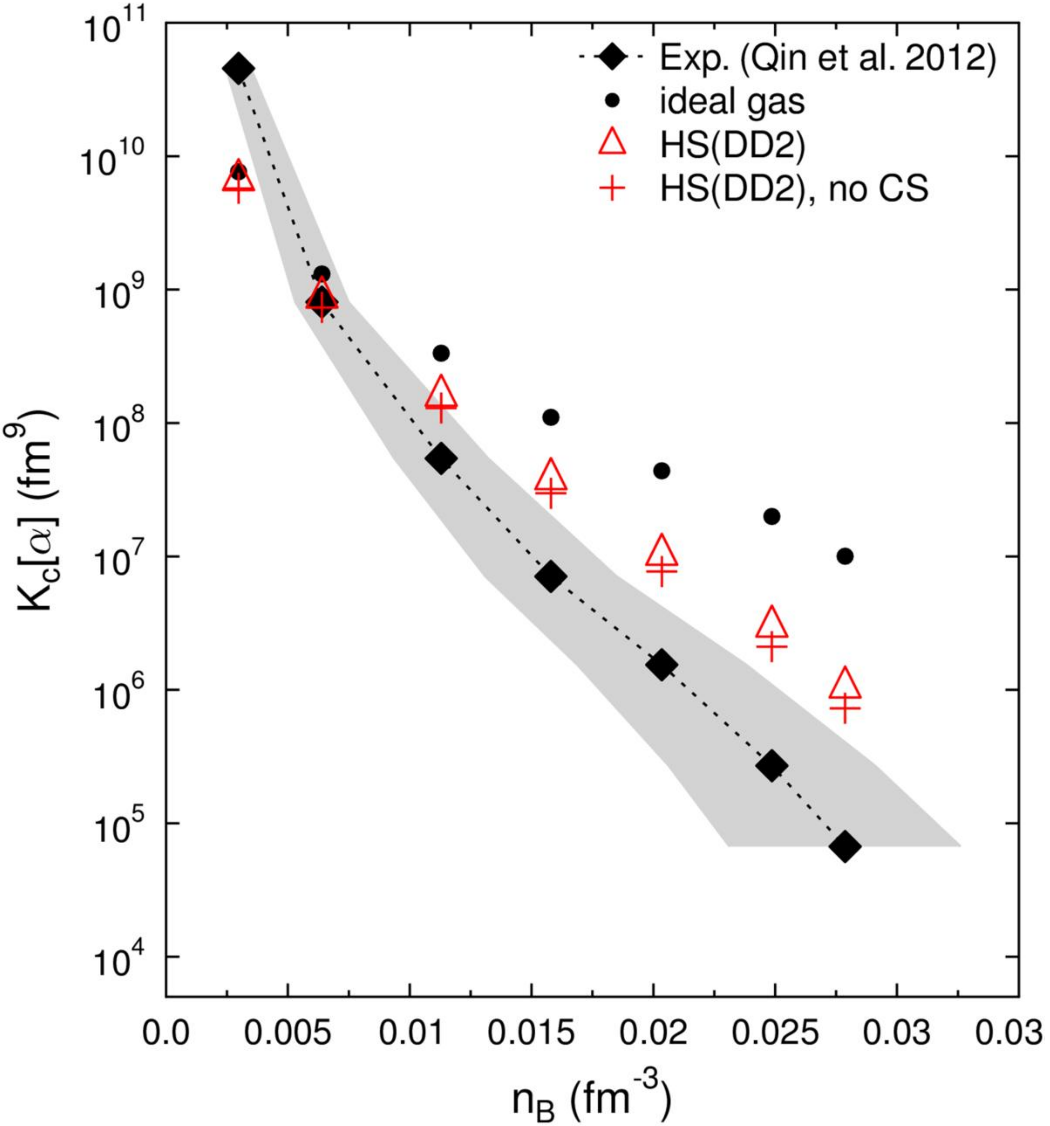
- Ideal gas
  - Equilibrium constant is Function only of temperature no ρ or Y_p dependence.

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.

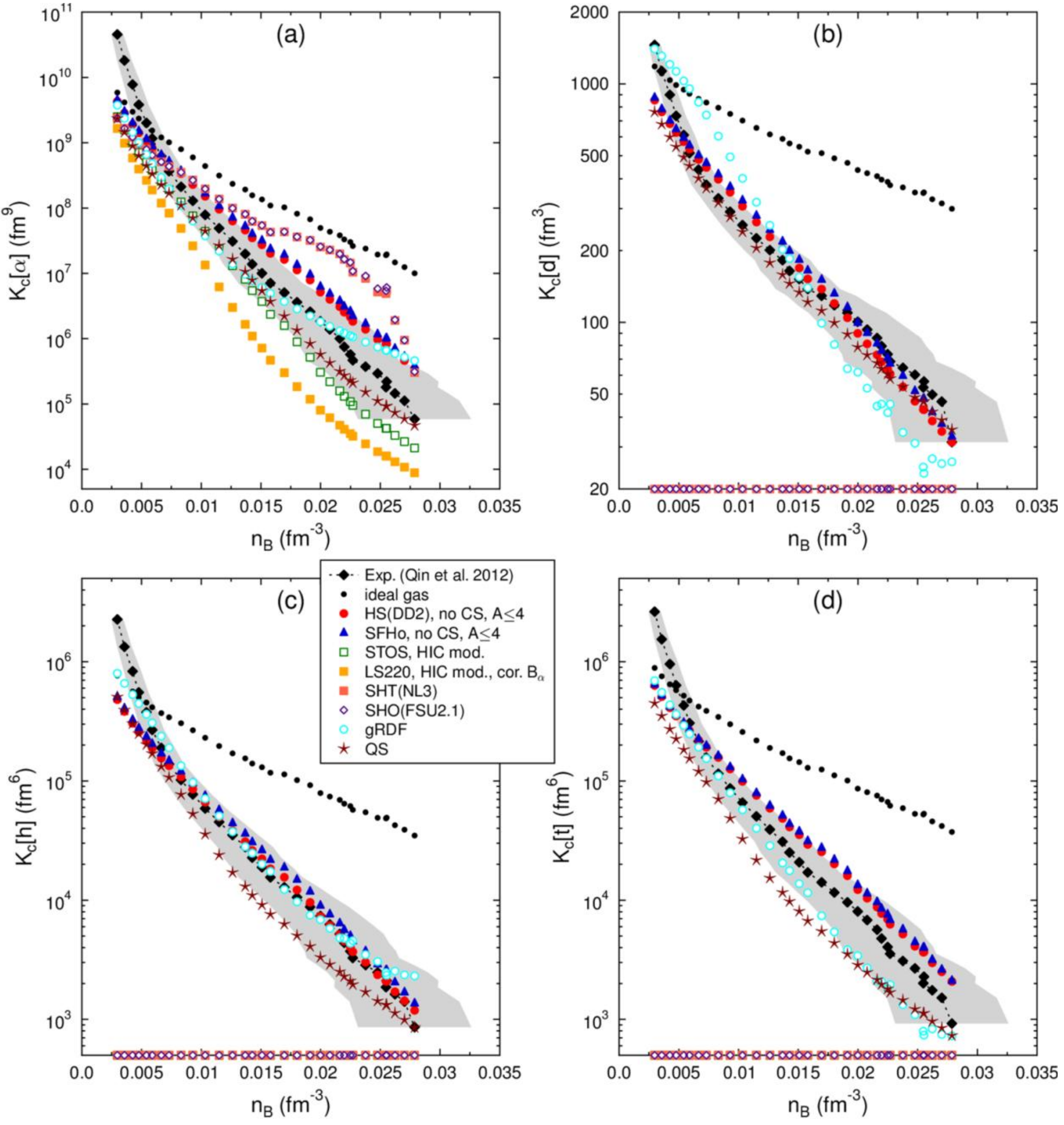
Use Y_p = 0.41 in remainder of calculations since that is what was extracted from experiment.

Coulomb effects



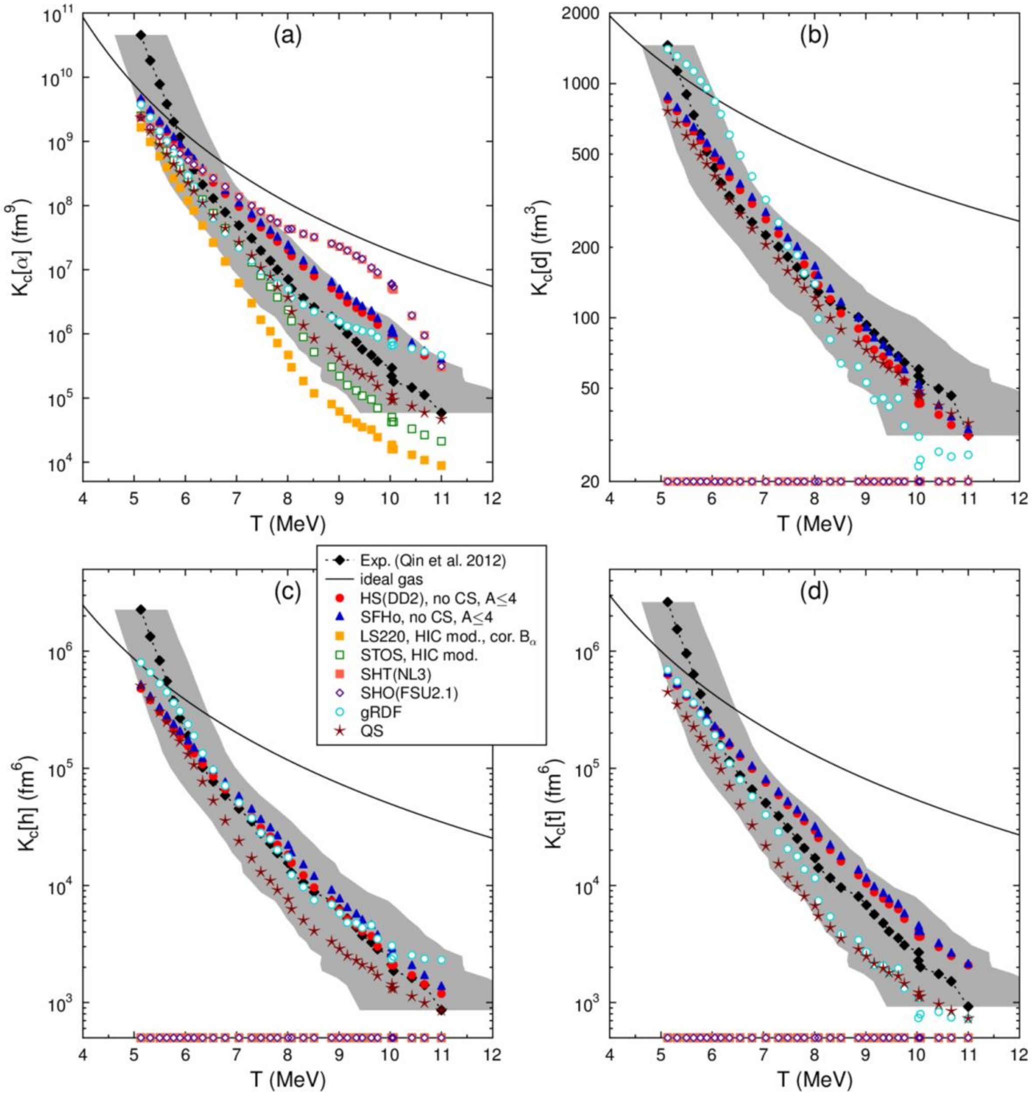
- In SN matter, coulomb interactions screened by surrounding electrons in contrast to matter in heavy ion collisions
- Small effect in calculations when screening is turned off.

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

$K_{eq}(T)$



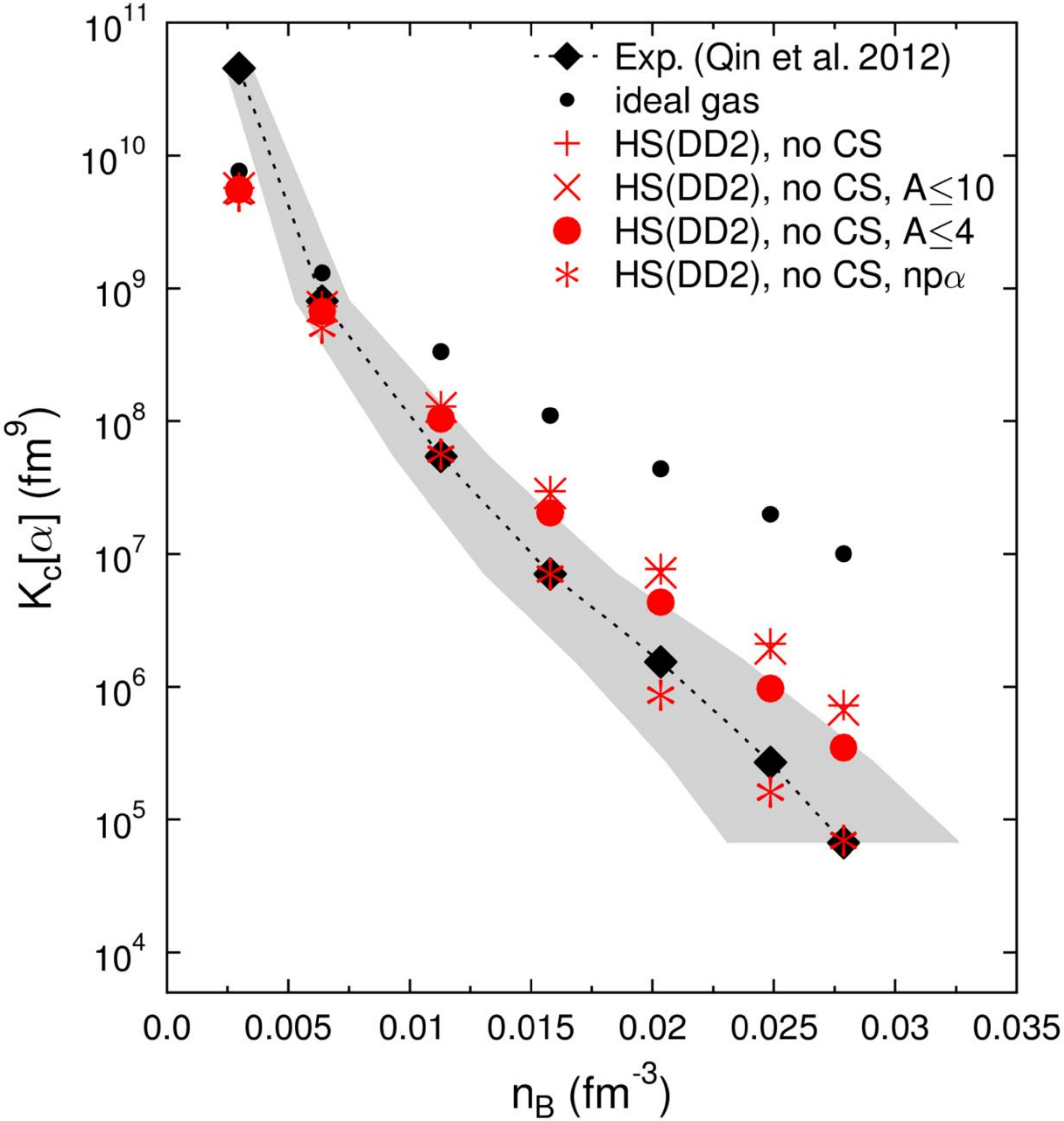
- Keq(T)
- Uncertainity in temperature measurement including at low density
- Ideal gas Keq is function of T only.
- Some models ignore light clusters other than alphas.
- Keq(T) for models **that treat all particles** are generally within experimental error bars. Others require particular parameterization
- Can we reduce experimental uncertainties?

THANK YOU

Collaborators

M. Hempel, K. Hagel, S. Kowalski, R. Wada, L. Qin,J. B. Natowitz, G. Röpke, S. Typel, M. Barbui, K. Schmidt, S. Wuenschel, E. J. Kim, G. Giuliani, S. Shlomo, A. Bonasera, Z. Chen, M. Huang, J. Wang, H. Zheng, M. R. D. Rodrigues, 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

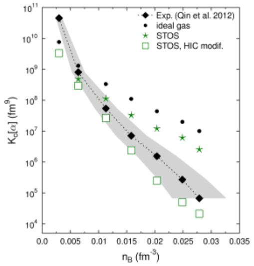
Particle Degrees of Freedom



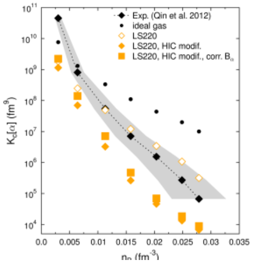
- Almost no dependence when constraining to A ≤ 10.
- Larger dependence when constraining to A ≤ 4
  - Production of A>4 very small in experiment
- Best agreement when only n,p,a included
  - Coincidence
  - Not realistic since significant d, t, ^{3}He observed in experiment.
  - Indicates importance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

Constraining the EOS

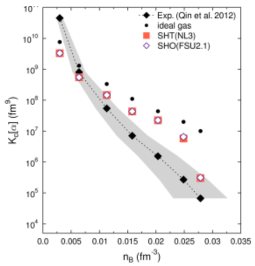
- STOS
  - Treats only n, p, α
  - Fits $K_{eq}(\alpha)$ with heavy nuclei suppression, but cannot fit d, t, ^{3}He



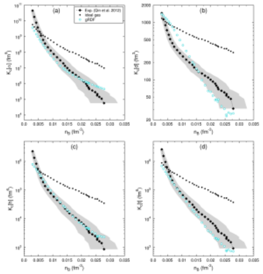
- LS
  - Treats n, p, α and heavy nuclei
  - Fits $K_{eq}(\alpha)$ in unmodified form, but not when heavy nuclei suppressed



- 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.