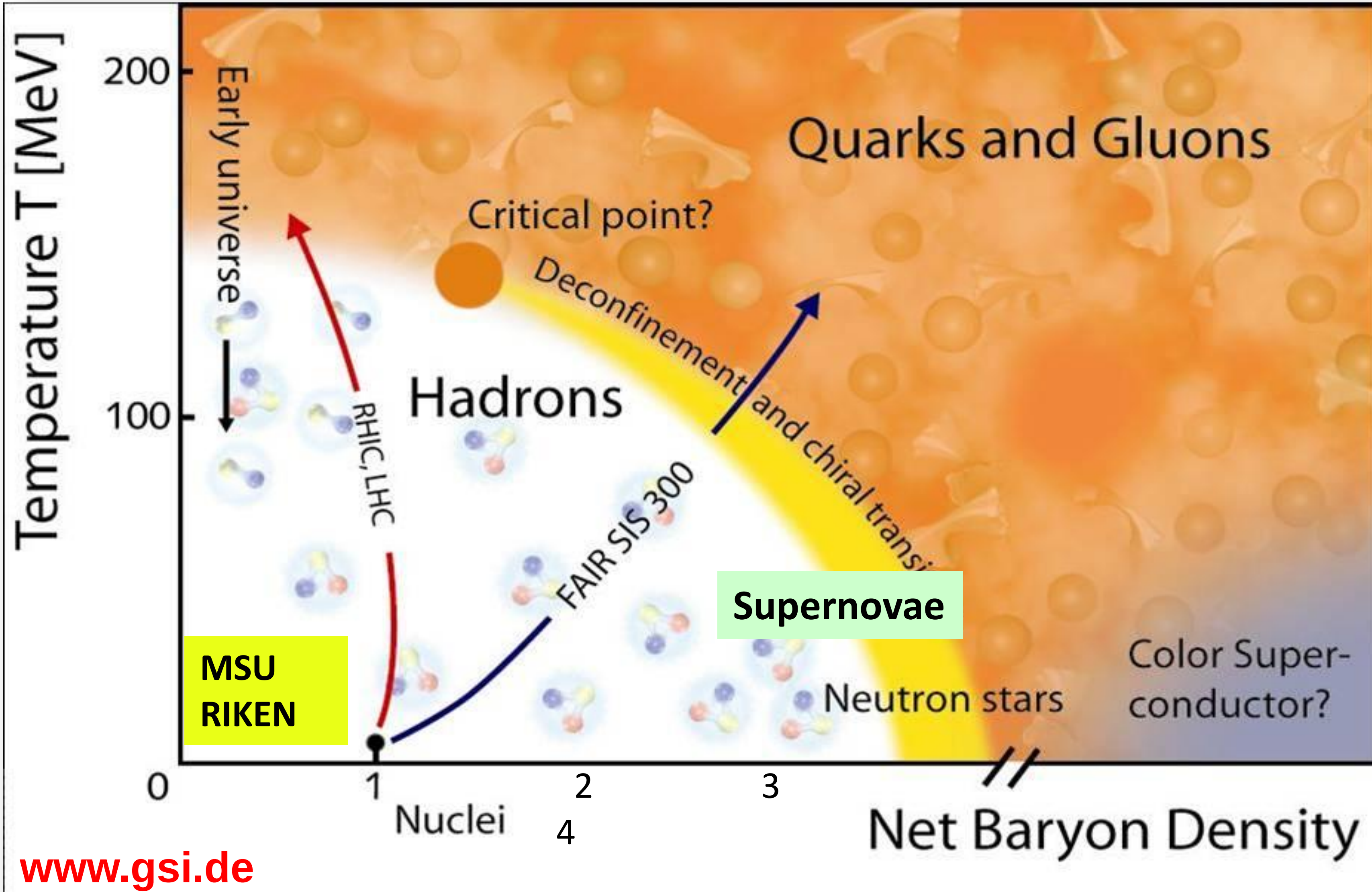
High-Density Matter: Current Status and Future Challenges

J. R. Stone

University of Oxford/Tennessee/Maryland

QCD phase diagram



Outline:

1. The Equation of State

2. Nuclear physics input

3. Observational constraints: neutron stars
proto-neutron stars
core-collapse supernovae

4.Terrestrial experiments: heavy ion collisions

5. Quark-meson coupling model

6. Summary and outlook

The Equation of State (EoS)

Relation between pressure P, energy density ε, particle number density ρ at temperature T

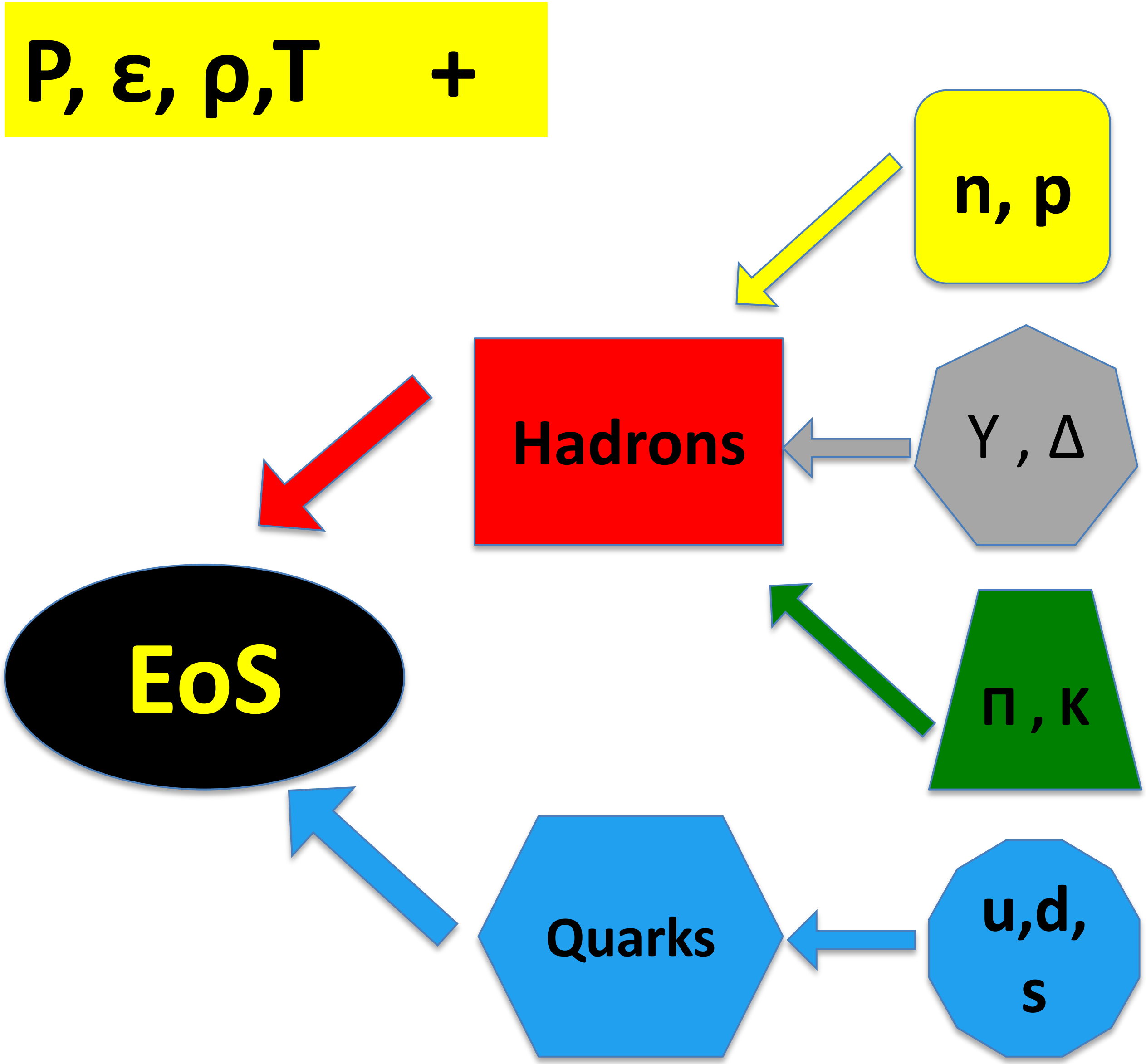
$$P = r^2 \left(\frac{\partial (e / r)}{\partial r} \right)_{s/r} \qquad\qquad e(r, T) = \sum_f e_f (r, T)$$

summation over f includes all hadronic (baryons, mesons), leptonic and quark (if applicable) components present in the system at density ρ and temperature T

Two key points:

The EoS is dependent on composition
CONSTITUENTS + INTERACTIONS

ε_f and ITS DENSITY AND TEMPERATURE DEPENDENCE
must be determined by nuclear and/or particle models.



Symmetric
Asymmetric
Pure neutron
Beta-equilibrium
Superfluidity
Superconductivity

Strangeness

Boson Condensates

Color superconductivity
CFL phase, Quarkonium

Hybrids, phase transitions, threshold conditions

The “Universal” EoS of high density matter with all the physically allowed components is not observed in nature in its entirety.

We are sensitive only to projections to particular sectors (sets of degrees of freedom) which can be constrained by observation and/or measurements.

Long term aim:

All sectors are described consistently within a unified model.

At present – a large variety of models are in use:

HADRONIC MATTER:

Many variants of microscopic and phenomenological models at a different level of complexity:

Mean-field (non)relativistic models, Chiral effective field theory,
“Ab initio” models with 2- and 3-body forces

QUARK MATTER:

MIT bag, Nambu-Jona-Lasinio (NJL)
Polyakov – NJL (PNJL), Polyakov - Quark Meson (PQM)
Chromo-dielectric (CDM), Dyson-Schwinger (DS)

Forces (interactions) between the constituents are not known.
Each model HAS FREE PARAMETERS which has to fitted to data.

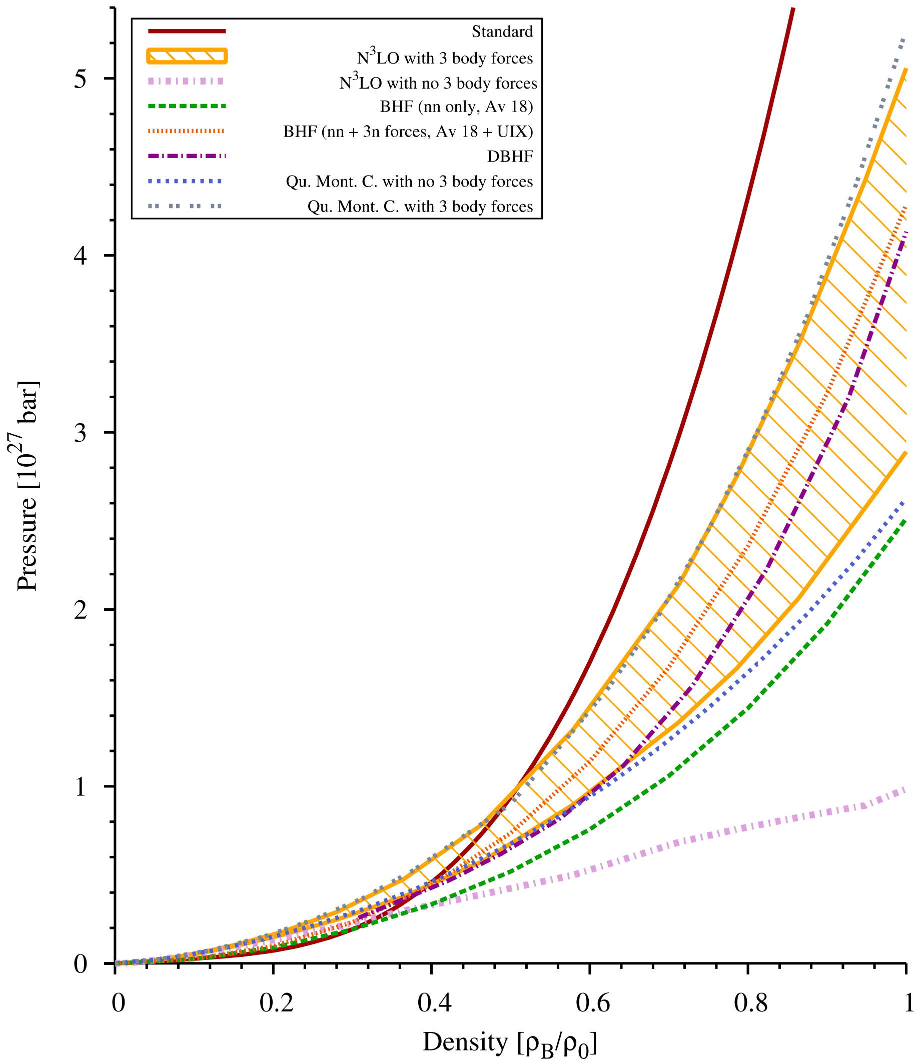
NUCLEAR MATTER PROPERTIES FROM MEAN FIELD MODELS WITH DENSITY DEPENDENT EFFECTIVE INTERACTION:

1. **240 non-relativistic models based on the Skyrme interaction - density dependent effective nucleon-nucleon force dependent on up to 15 adjustable parameters were recently tested against the most up-to-date constraints on properties of nuclear matter:**

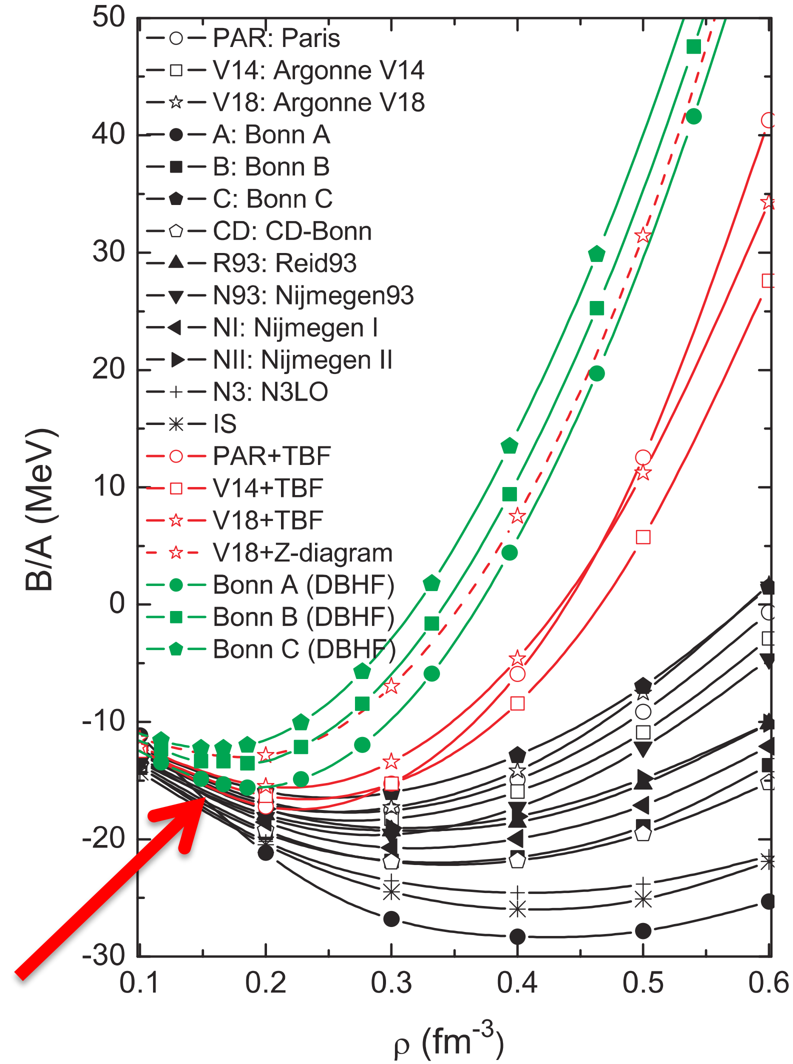
SET 1: 5 satisfied all the constraints Dutra et al., PRC 85, 035201

2. **263 relativistic mean field models were tested against 3 slightly different sets of constraints and the number of models that satisfied the constraints**

SET 1 : 2 models
SET 2a: 4 models (30)
SET 2b: 3 models (35) Dutra et al., arXiv:1405.3633 [nucl-th]



Pressure in pure neutron matter at sub-saturation density

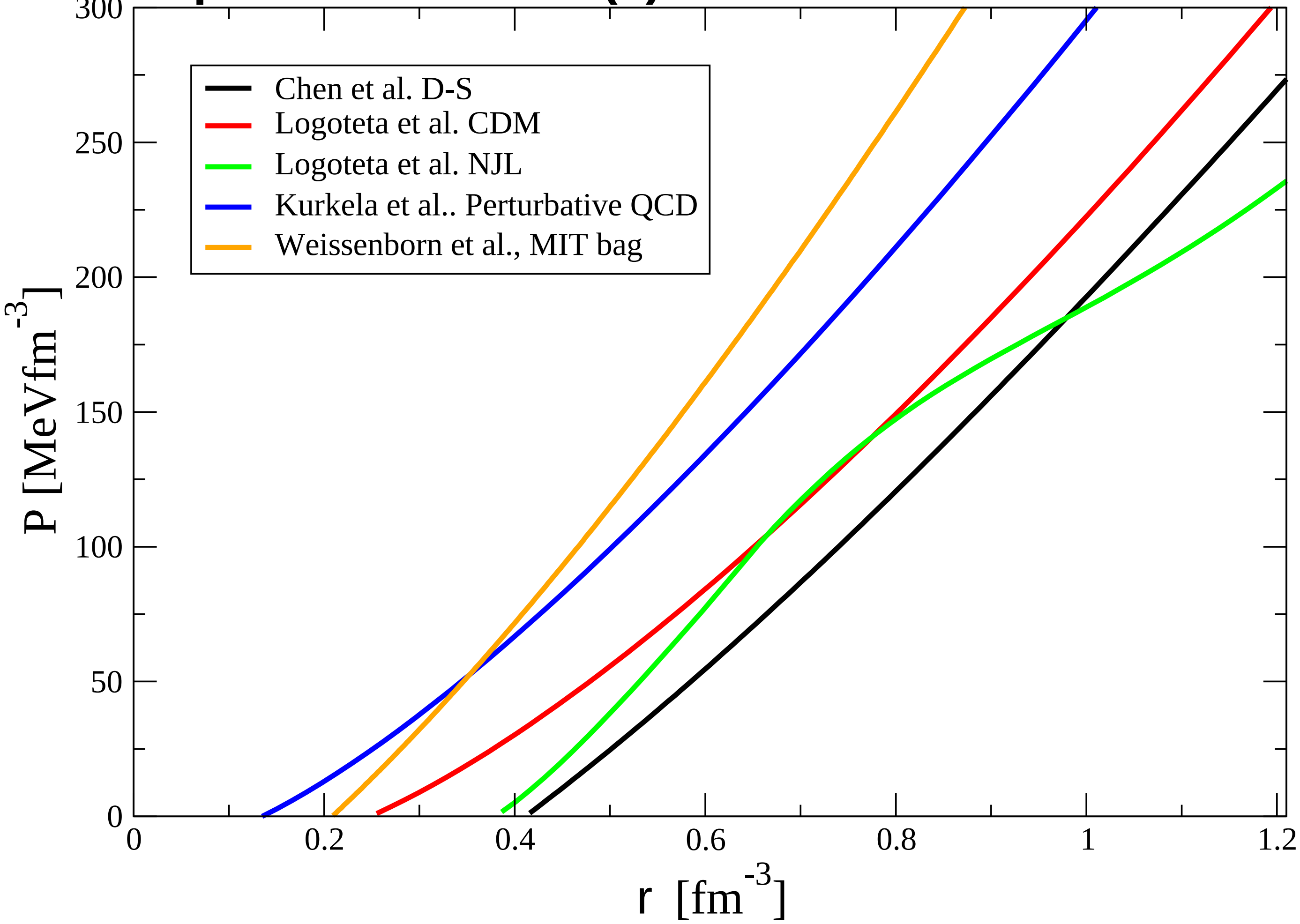


Binding energy per particle
In symmetric nuclear matter

Whittenbury et al, 2013

Li et al., PRC74, 047304 (2006)

Examples of EoS of ud(s) matter in different models

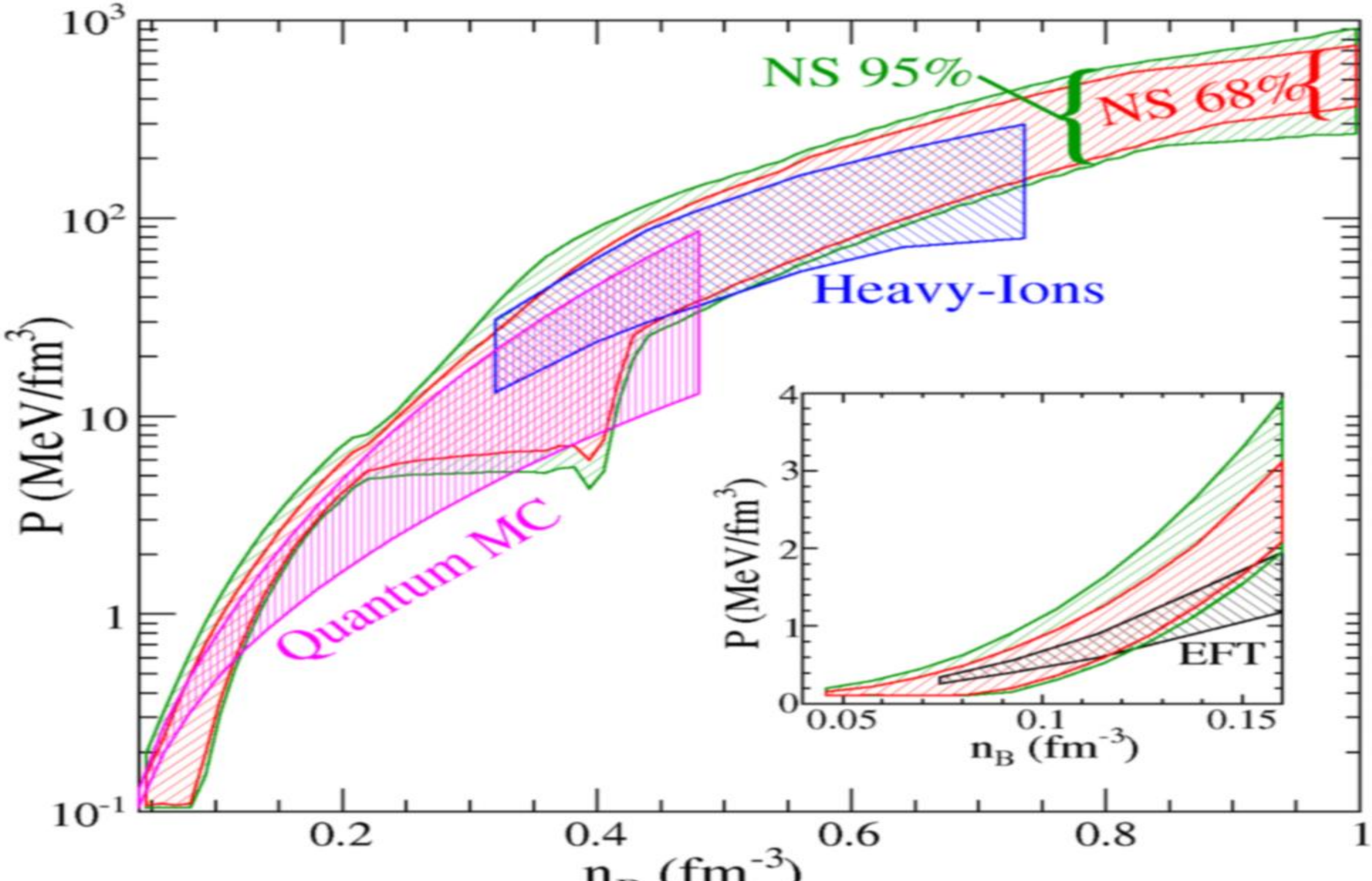


Logoteta et al., PRD85, 023003 (2012) Kurkela et al., PRD81, 105021(2010)

Chen et al., PRD86, 045006 (2012) Weissenborn et sl., 2011

Empirical approach:

Assumptions: **The "universal EoS" can be approximated by a combination of models and observation data**



Steiner et al., ApJ Letters 765, L5 (2013)

Questions:

Physical content?

Predictive power?

How sensitive is observation to microphysics?

Do we have enough data to fix our theories?

Astronomical Observation:

NEUTRON STARS
Proto-neutron stars
Supernovae

Terrestrial experiments:

HEAVY ION COLLISIONS
Hypernuclei

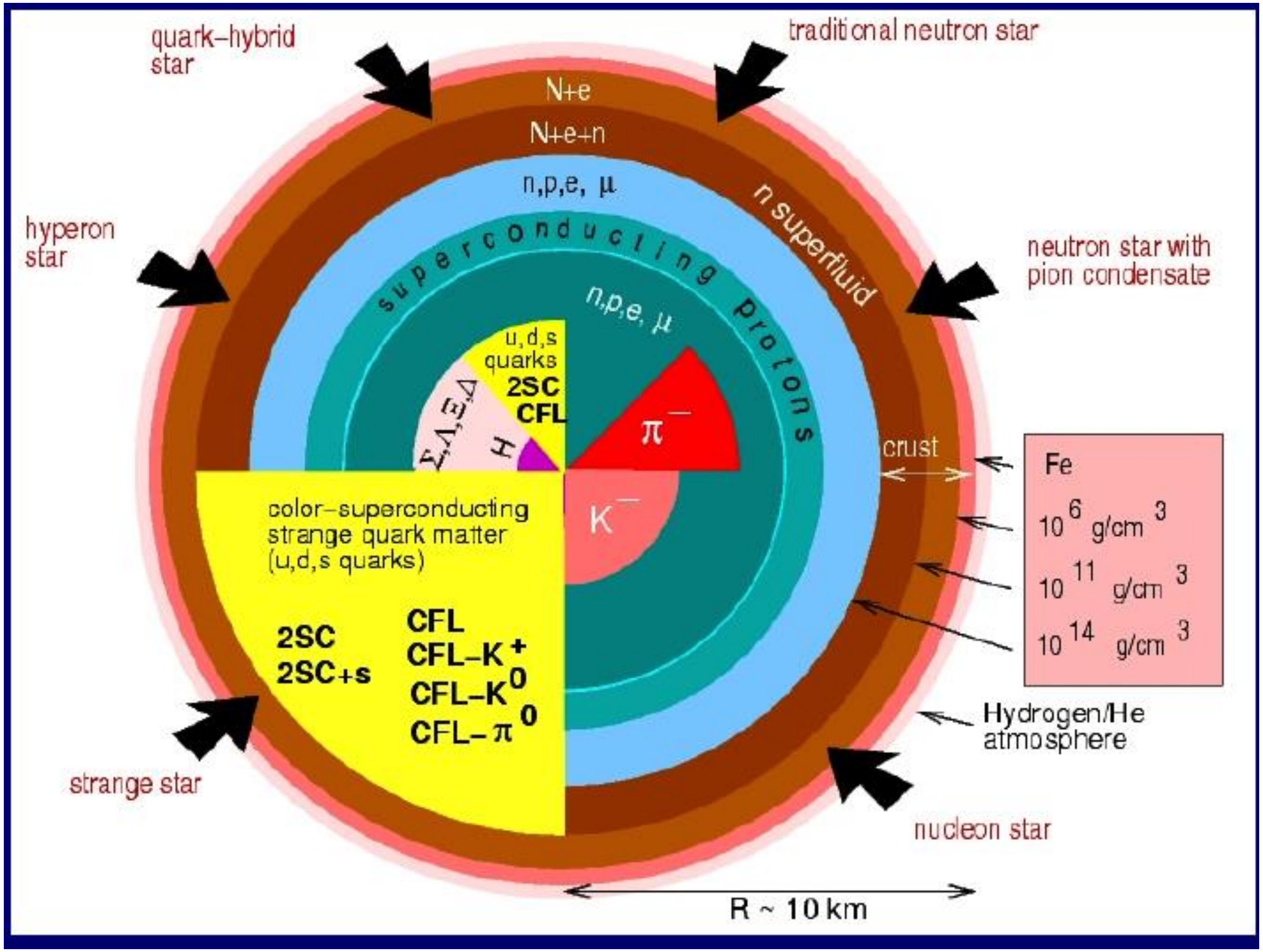
Lattice QCD Thermodynamics:

Calculation currently available only for zero baryo-chemical potential.
Extrapolation to finite potential is provided by models - convergence problem.
The (T,μ) coordinates of the critical point is particularly Interesting.

W. Weise / Progress in Particle and Nuclear Physics 67, 299–311 (2012)

Neutron Stars

Extreme conditions in neutron stars allow wide speculations about their internal structure: WHICH ARE REALLY THERE?



F. Weber Prog.Part.Nucl.Phys. 54, 193 (2005)

Basic model of (non-rotating) neutron star properties:

Tolman-Oppenheimer-Volkoff (TOV) equations for hydrostatic equilibrium of a spherical object with isotropic mass distribution in general relativity:

- **Input:** The Equation of State P(ε) – pressure as a function of energy density
- **Output: Mass as a function of Radius M(R)**

$$\frac{dP}{dr} = -\frac{GM(r)\varepsilon}{r^2}\frac{(1+P/\varepsilon c^2)(1+4\pi r^3 P/M(r)c^2)}{1-2GM(r)/rc^2}$$

$$M(r) = \int_0^r 4\pi r'^2 \varepsilon(r')dr'$$

I. Precise determination of a neutron star mass alone is not sufficient to compare models with observation.

II. Strong dependence on the equation of state

A selection of five most accurately measured neutron star masses:

PSR J0737-3039 the first double pulsar (A,B)
$M = 1.249 +/- 0.001\ M_\odot$ (Lyne et al., Science 303, 1153 (2004))
P = 2.77s (B)

PSR B1913+16 NS binary (Hulse-Taylor)
$M = 1.4414 \pm 0.0002\ M_\odot$: (Hulse and Taylor, ApJ 195, 1975)
P = 59 ms

PSR J1903+0327 NS on an eccentric orbit around MS star
$M = 1.667 \pm 0.021\ M_\odot$: (Freire, P. C. C. et al., MNRAS, 412, 2763 (2011))
P = 2.5 ms

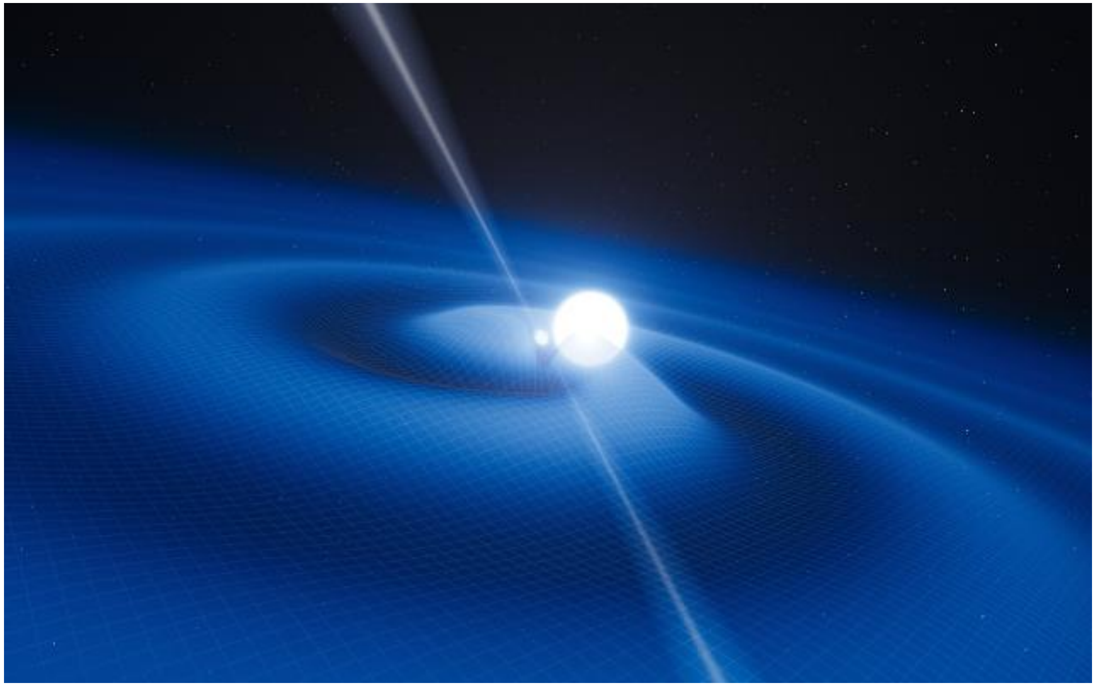
PSR J1614-2230 NS+WD
$M_g = 1.97 +/- 0.04\ M_\odot$ (Demorest at al., Nature 467, 1081 (2010))
P = 3.15 ms

PSR J0348+0432 NS+WD
$M_g = 2.03 +/- 0.03\ M_\odot$ (Antoniades et al., Science 340, 448 (2013)
P = 39 ms

NS mass can be measured only in binary systems.

BUT

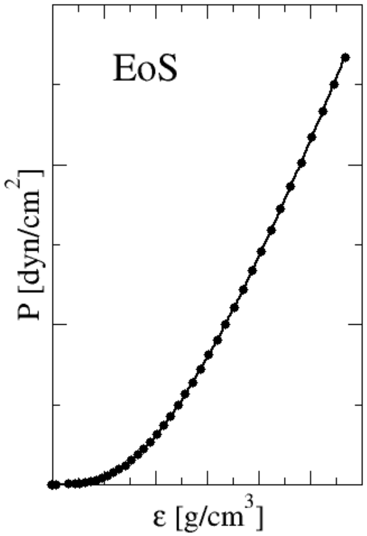
Only 5-10% of known pulsars are in binaries

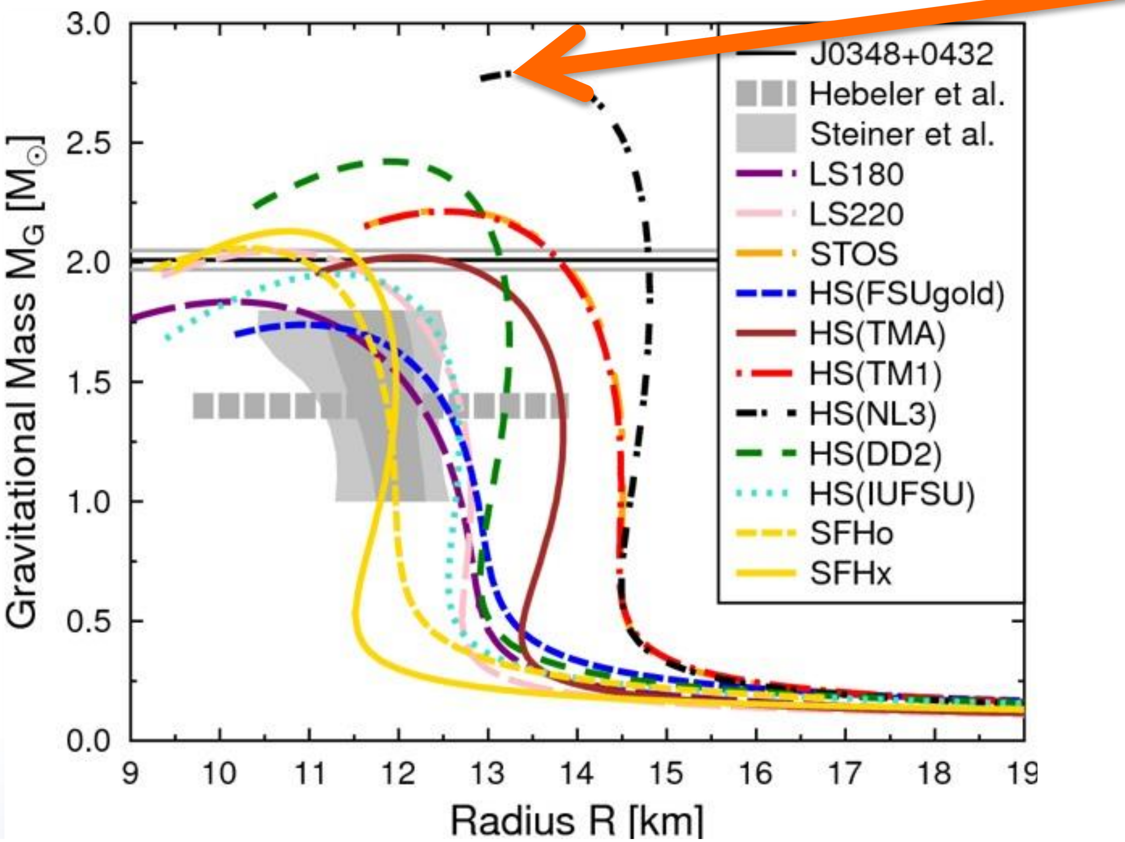


Artist's impression of a binary system containing a pulsar (smaller object with jets of light) and a white dwarf. The result of their mutual orbit generates gravitational waves, shown as the ripples in space-time.

Examples of TOV solutions for different EoS P = f(ε)

Each point on the "goose neck–like" curve represents a maximum mass of a neutron star model with a particular central energy density ε





Models:

Stable: right from maximum

Unstable: left from maximum

Fischer and Hempel, Eur. Phys. J. A50, 46 (2014)

MAIN INTEREST: MAXIMUM (M,R) PROVIDES CONSTRAINT ON THE EOS

Simultaneous determination of mass and radius Low-mass X-ray binaries inside globular clusters (bursting and transiently accreting)

Problems:

Distance, atmosphere, redshift, EoS.....

Latest:

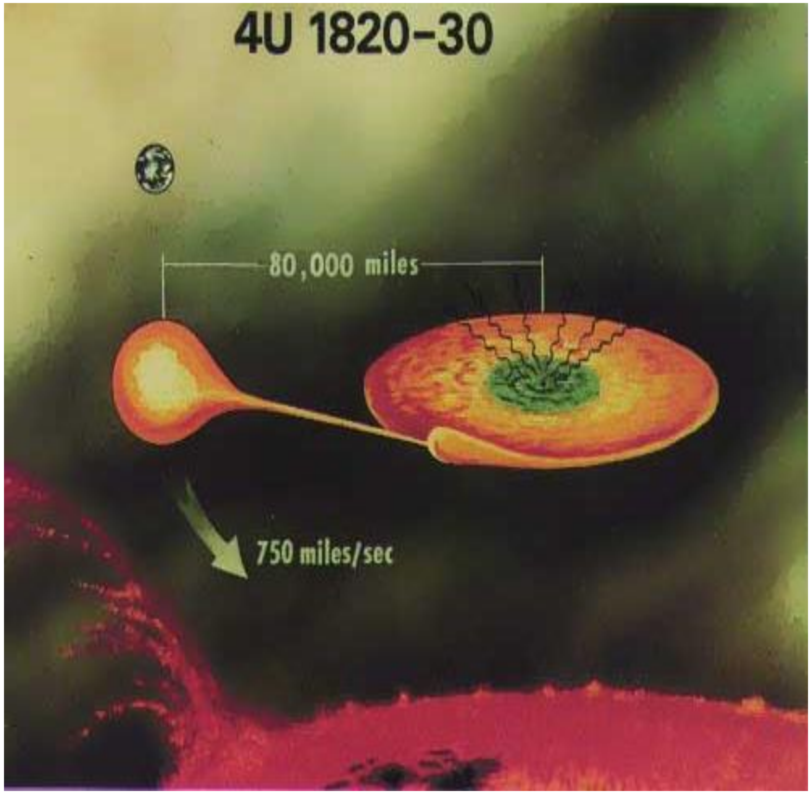
Lattimer +Steiner ApJ, 784:123 (2014)

1.4 M_{sol} 11.15 < R < 12.66 km

Guillot at al. ApJ 772:7 (2013)

All masses   7.6 < R < 10.4 km

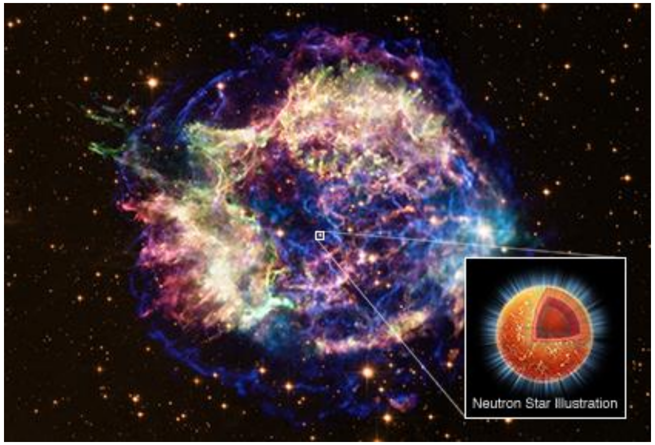
Main difference: H or He atmosphere



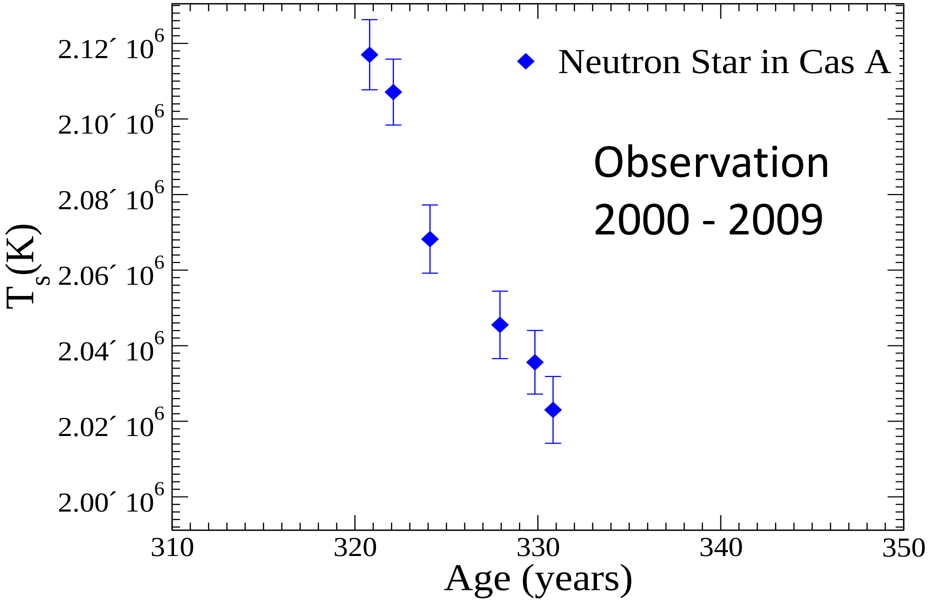
Ignition T of H and He in the accreting material from the companion is reached at the surface of the star

Cassiopeia A (Cas A)

Remnant of the historical 1680 SN explosion discovered in 1999 with Chandra X-ray Observatory



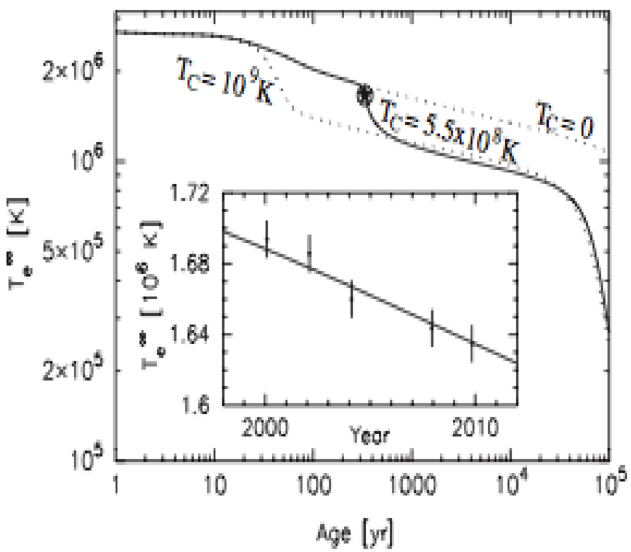
Isolated young neutron star with a carbon atmosphere and low magnetic field provided precise data on unexpected rapid cooling

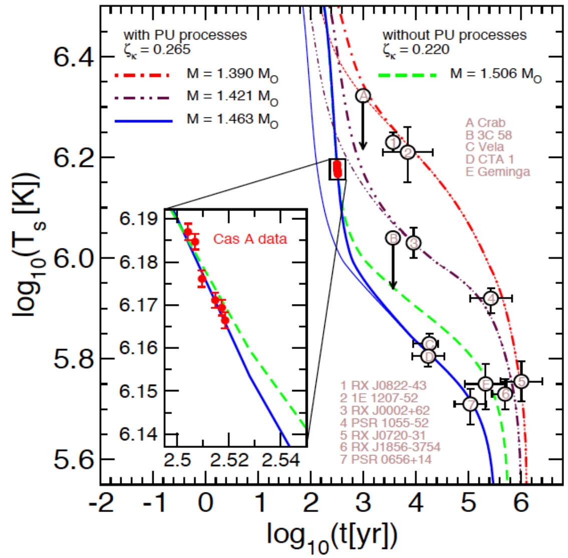


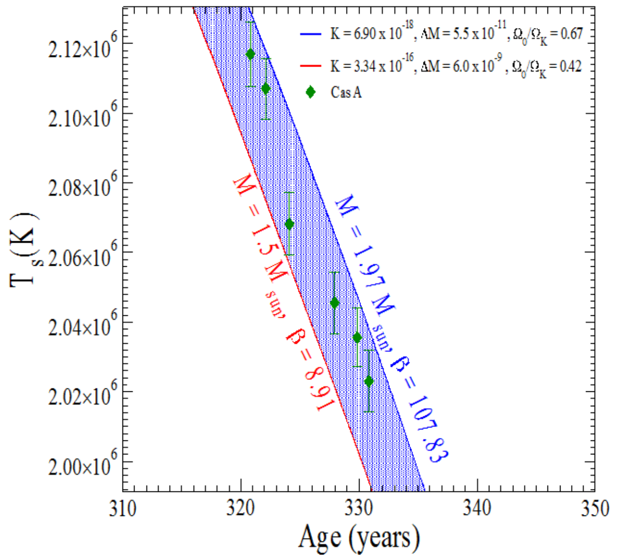
C. O. Heinke & W. C. G. Ho, ApJ Letters 719 (2010) L167

K. G. Elshamouty et al, ApJ 777,22 (2013)

(Added 2012 point)







Rapid cooling is triggered by neutron superfluidity in dense matter enhanced by neutrino emission from the recent onset of the breaking and formation of neutron Cooper pairs in the $^3P_2$ channel in the star's core. Large proton superconductivity need to be present in the core.

Page et al., PRL 106,081101 (2011)

The cooling rates account for medium-modified one-pion exchange in dense matter and polarization effects in the pair-breaking formations of superfluid neutrons and protons.

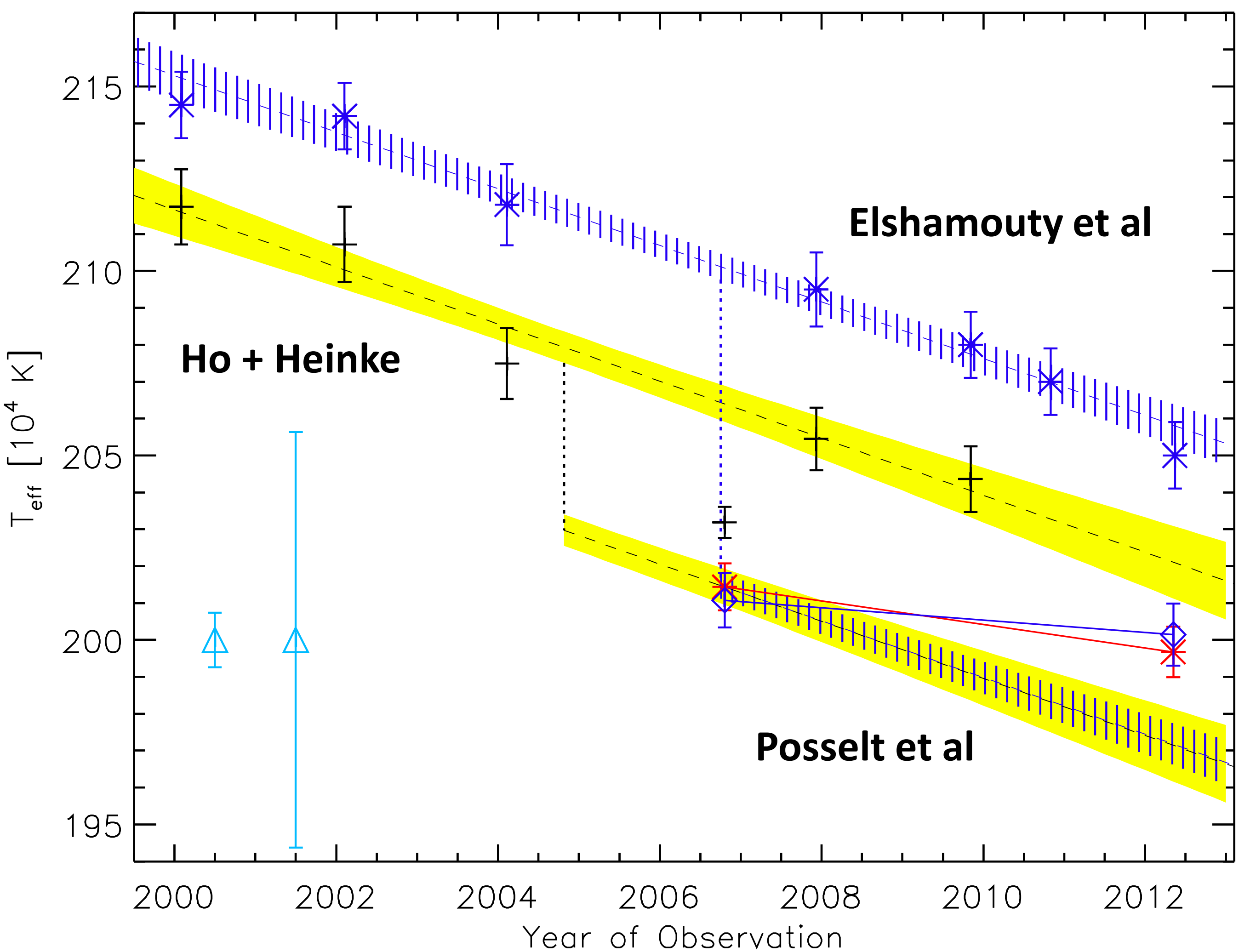
Blaschke et al., PRC 85, 022802(R) 2012

Relativistic model of a 2D rotating neutron star combined with relativistic thermal energy transport: Frequency dependent composition and temperature distribution

Weber, Compstar Tahiti 2012
Negreiros et al., PRD 85, 014019 (2012)

Posselt et al., ApJ 779:186 (2013)

Re-analysis and a new 2012 point



Different N_H (blue)

Same N_H (red)

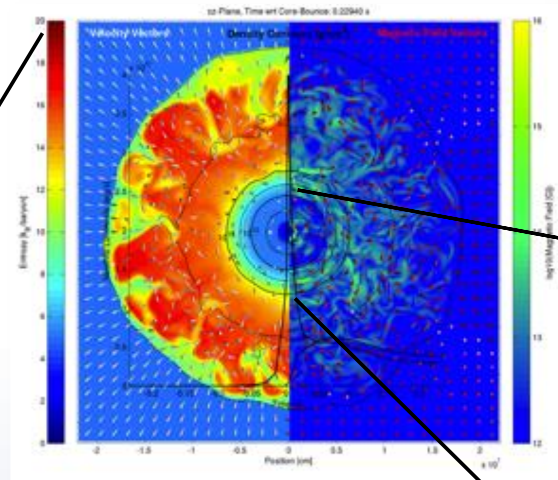
Light blue triangles: Typical 1 σ errors in T for two different normalisations

Core collapse supernovae
Proto-neutron stars
and their evolution

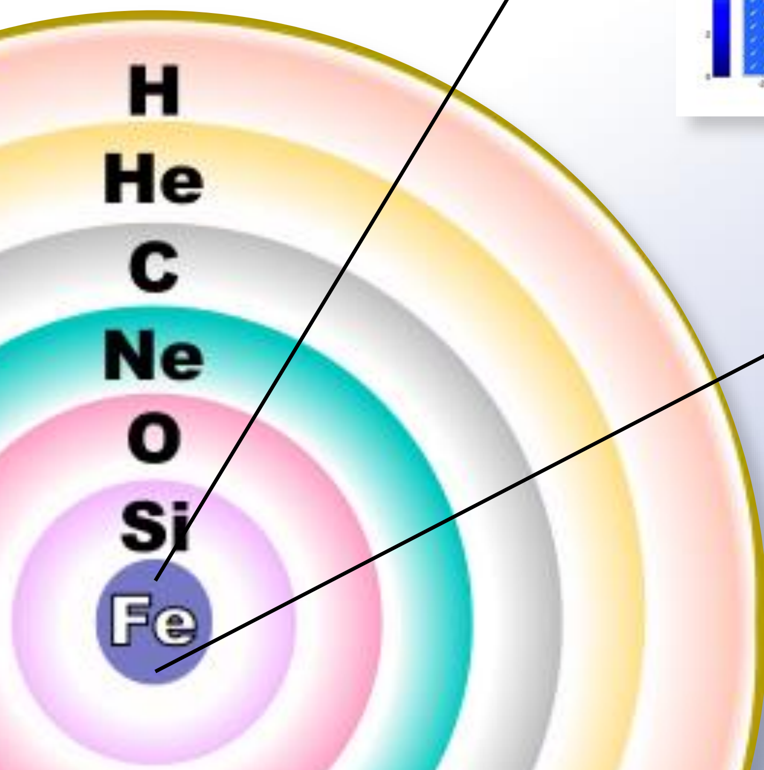
Data on sensitivity of CCS simulation to EoS limited (Lattimer-Swesty or Shen) or non-existent

From progenitor stars via CCSNe to neutron stars

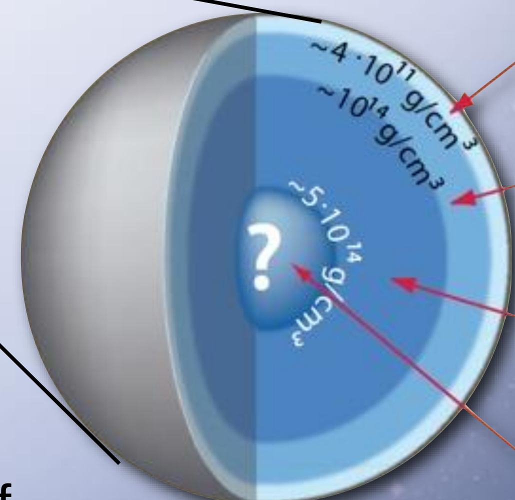
core-collapse
supernova explosion



progenitor star at
onset of collapse



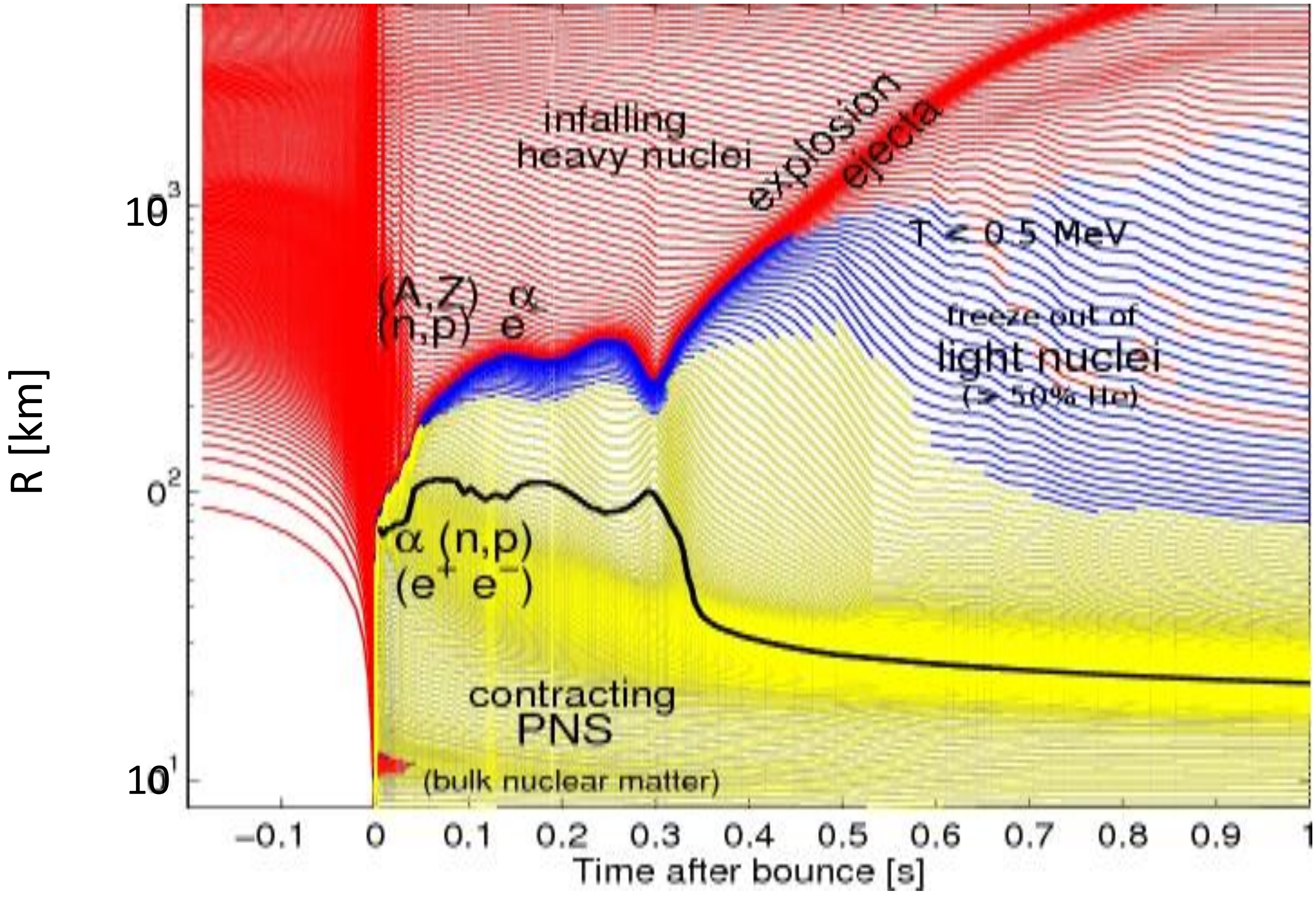
cold neutron star



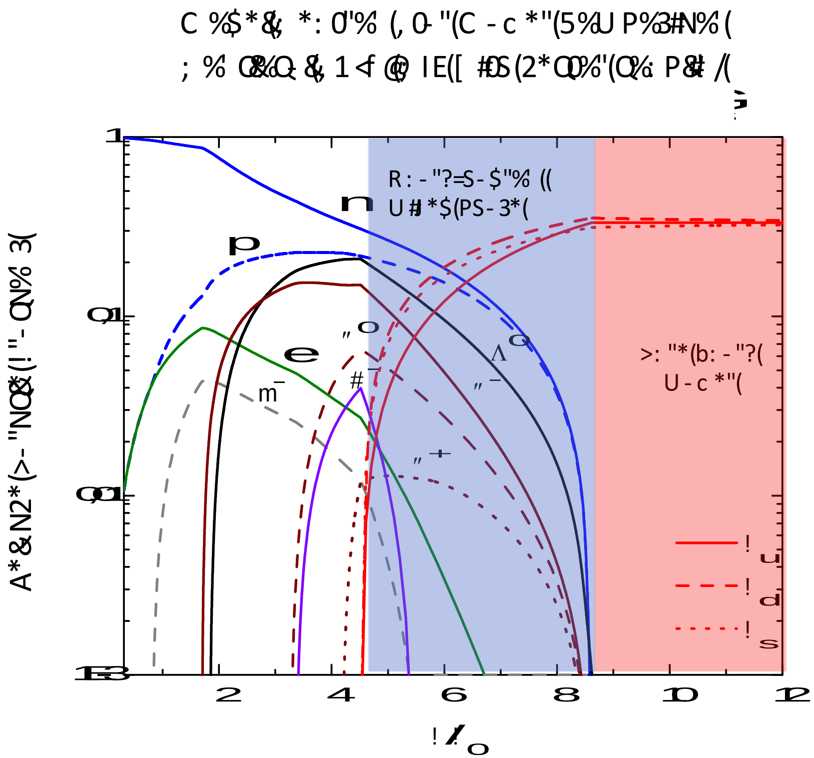
- what is the state of matter during all these stages?

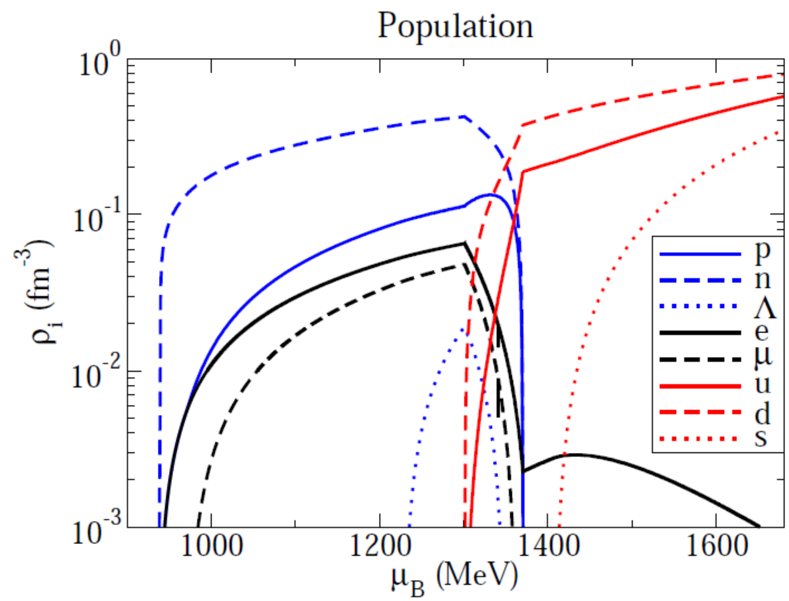
Slide from M.Hempel, Russbach, 2014

What energy density is available during the formation of the PNS? (essential time up to 60 sec after bounce)



T. Fischer, talk at CSQCD II, May 2009





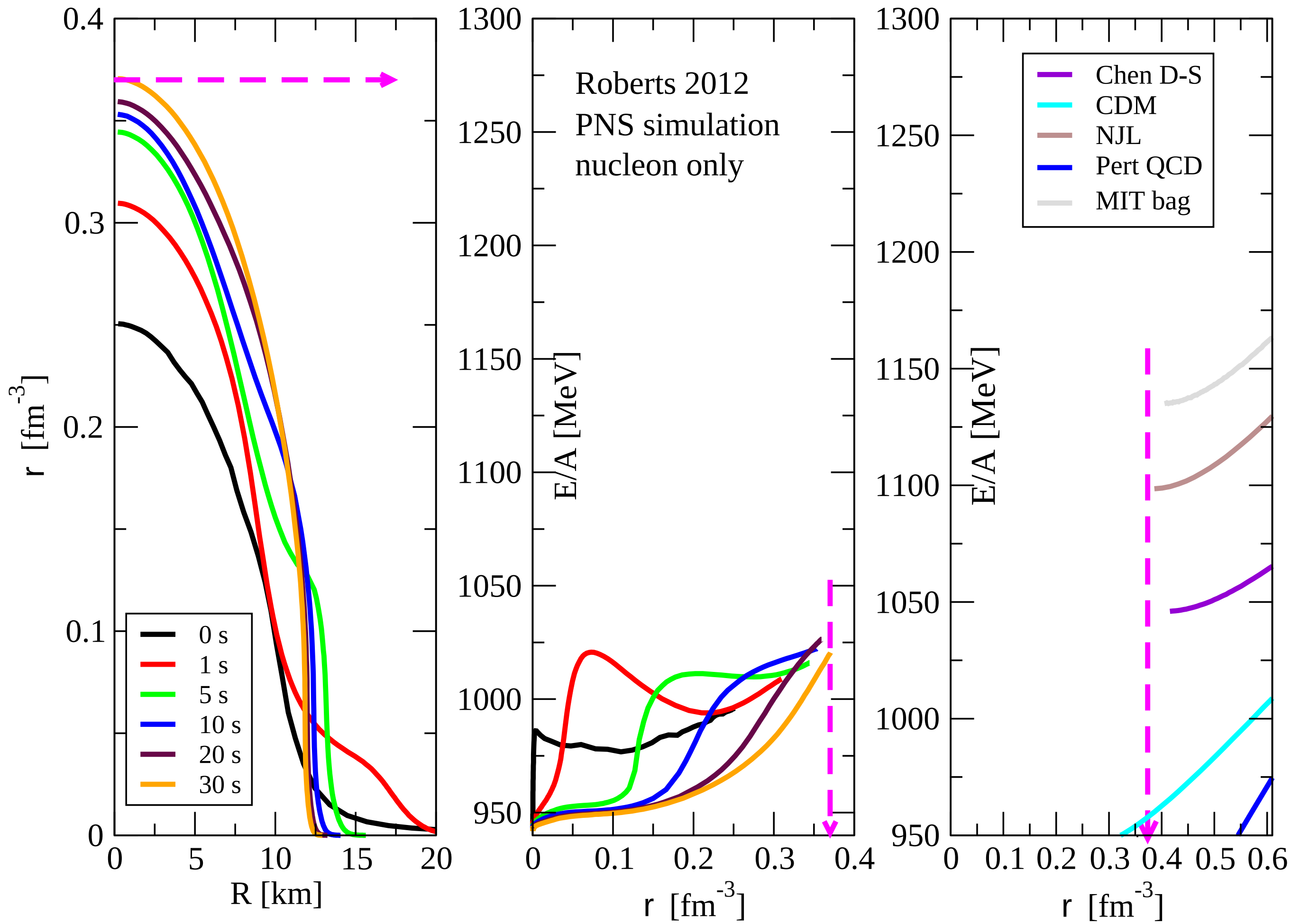
Dexheimer and Schramm, PRC81 045201 (2010)

Physical conditions for appearance: hyperons,

π and K meson condensates

u d s matter +

THRESHOLD DENSITIES UNKNOWN – STRONGLY MODEL DEPENDENT



Can quark matter be created in NS cores?

Heavy Ion Collisions

Heavy Ion collisions:

GSI, MSU, Texas A&M, RHIC, LHC existing
FAIR (GSI), NICA (Dubna, Russia) planned

Measurement: Beam energy 35 A MeV – 5.5 A TeV
Collisions (Au,Au), (Sn,Sn) , (Cu,Cu)
but also (p,p) for a comparison
Transverse and Elliptical particle flow

Calculation: Transport models -- empirical mean field potentials
Fit to data → energy density → P (ε) → the EoS
(extrapolation to equilibrium, zero temperature, infinite matter) (e.g Danielewicz et al., Science 298, 2002, Bao-An Li et al., Phys.Rep. 464, 2008)

Quantum Molecular Dynamics
(e.g. Yingxun Zhang, Zhuxia Li, Akira Ono)

Matter in HIC and compact objects have different EoS:

Central A-A collision:

Strongly beam energy dependent
Beam energy < 1GeV/ A:

Temperature: < 50 MeV
Energy density: ~ 1 -2 GeV/fm^3
Baryon density < ρ_0
Time scale to cool-down: 10^{-22-24} s
No neutrinos

Strong Interaction: (S, B and L conserved)
Time scale 10^{-24} s

NEARLY SYMMETRIC MATTER

Inelastic NN scatterings,
N,N*, Δ's
LOTS of PIONS
strangeness
less important (kaons)

? (Local)EQUILIBRIUM?

Proto-neutron star:

(progenitor mass dependent)
~ 8 – 20 solar mass

Temperature: < 50 MeV
Energy density: ~ 1 GeV/fm3
Baryon density ~ 2-3 ρ_s
Time scale to cool-down: 1 -10 s
Neutrino rich matter

Strong +Weak Interaction: (B and L con)
Time scale 10^{-10} s

HIGHLY ASYMMETRIC MATTER

Higher T: strangeness produced in
in weak processes
Lower T: freeze-out
N, strange baryons and mesons,
NO PIONS, leptons

EQUILIBRIUM

SUMMARY SO FAR

I. Current models have limited predictive power – they have too many parameters and it is impossible to constrain them unambiguously

II. Models are often adjusted to fit only a selected class of data well, but they failure elsewhere is neglected . Such models cannot be right. Even "minimal" models are of a limited use in a broader context.

POSSIBLE SOLUTION?

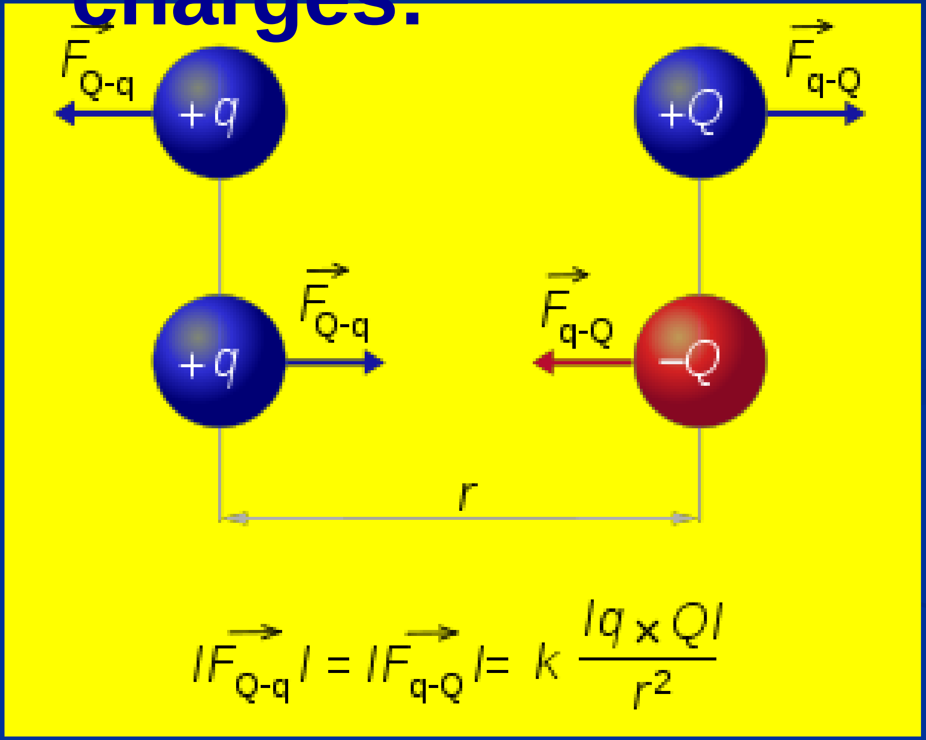
I. Understand behaviour of hadrons in medium

II. Evaluate basic assumptions of each models and regions of applicability. Focus on models with INDIVIDUAL parameters constrained by physics. Microphysics is important!

DATA LIMITED BY AVAILABLE TECHNIQUE – PHYSICS SHOULD BE ADOPTED AS A CONSTRAINT

Coulomb force:

2 electrical charges:



Many electrical charges:

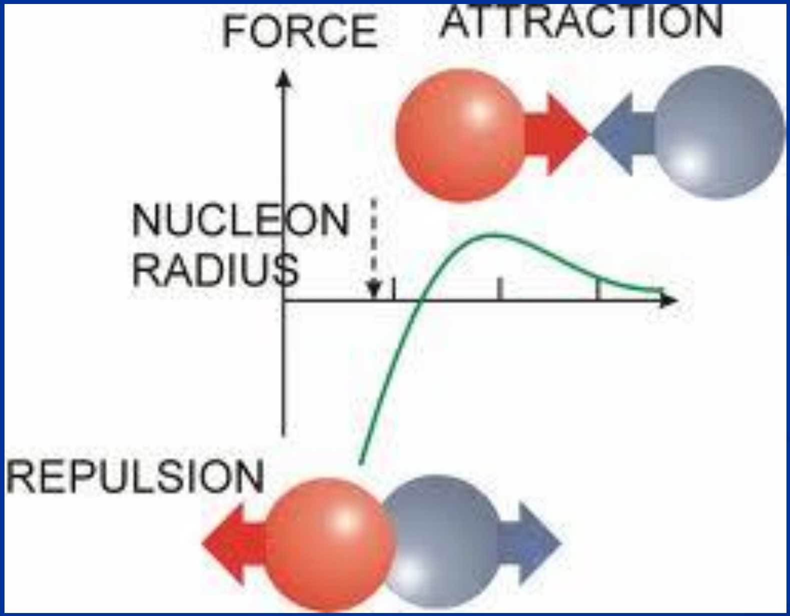
principle of superposition

Force acting on a charge q at position r due to N discrete charges:

$$F(r) = \frac{q}{4\pi\varepsilon_0} \sum_{i=1}^{N} \frac{q_i (r - r_i)}{|r - r_i|^3}$$

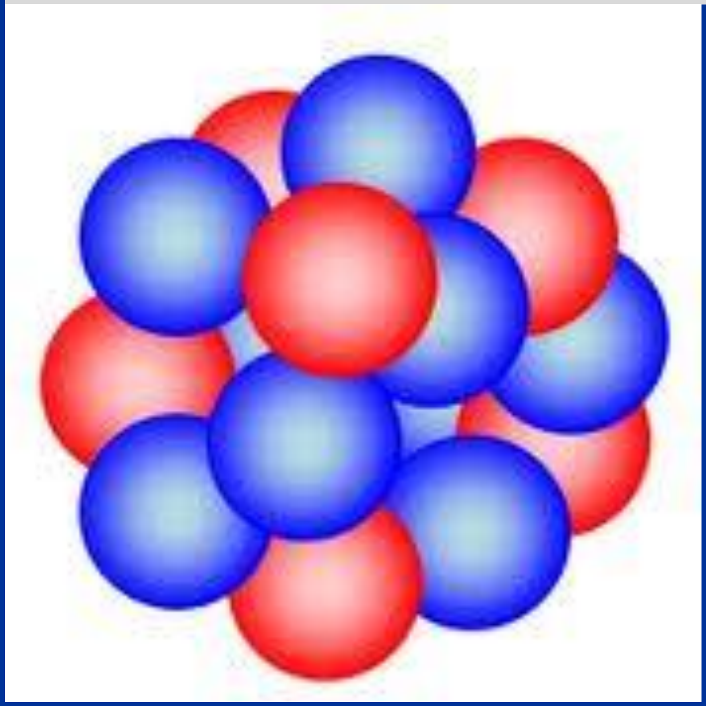
Nuclear force

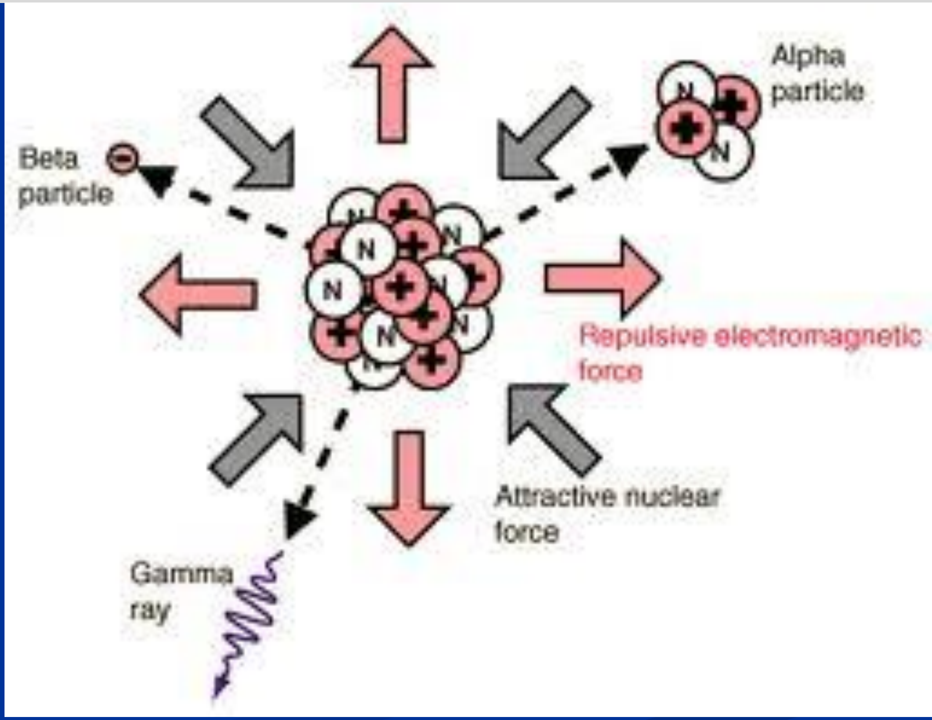
2 nucleons:
nucleon-nucleon scattering
tractable with many parameters
no unique model



Many nucleons:

force depends on medium (density) and momentum
strong, weak and elmg interactions play role
– intractable?





Quark-Meson-Coupling Model

History:

Original: Pierre Guichon (Saclay), Tony Thomas (Adelaide) 1980'

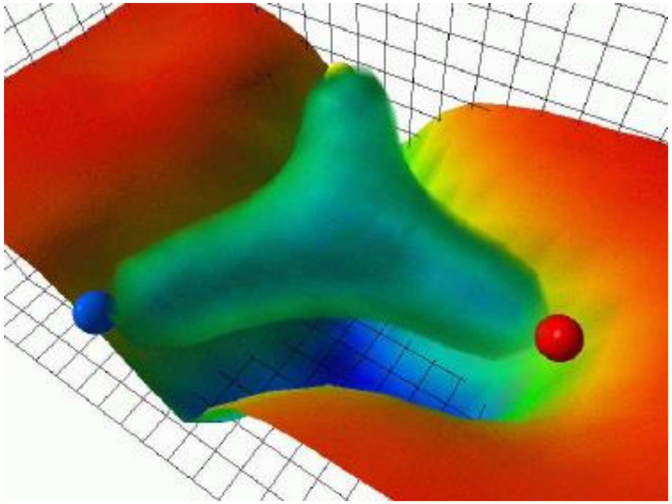
Several variants developed in Japan, Europe, Brazil, Korea, China

Latest: Whittenbury et al. arXiv:1307.4166v1, July 2013

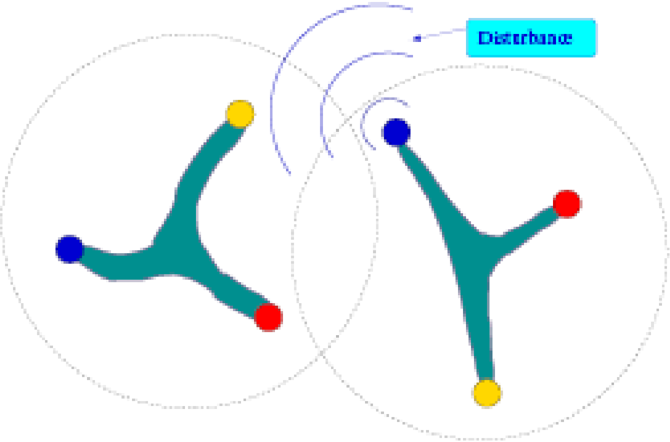
Main idea:

Effective model of the MEDIUM EFFECT on baryon structure and interactions

Quark level – coupling between u and d quarks of non-overlapping baryons by meson exchange - significantly simplifies as compared to nucleonic level.



http://www.physics.adelaide.edu.au/cssm/lattice/)



Schematic ***(Guichon)***

WHAT WE DO:

For technical details see Whittenbury et al. PRC 89, 065801 (2014)

1. **Take a baryon in medium as an MIT bag (with one qluon exchange) immersed in a mean scalar field (NJL in progress)**

2. **Solve the bag equations in the scalar field to obtain a dynamical effective mass**

$$M_N^* = M_N - g_{\sigma N}\bar{\sigma} + \frac{d}{2}\left(g_{\sigma N}\bar{\sigma}\right)^2$$

the last term represents the response of the nucleon to the scalar field $d = 0.22\ R_B$ and the coupling constants for a free nucleon are calculated.

3 **Construct QMC Lagrangian on a hadronic level in the same way as in RMF but using the effective baryon mass M^*_N. and proceed to calculate standard observables.**

4. **Technically: Full Fock term is included (vector and tensor), and σωρπ mesons**

Parameters (very little maneuvering space) :

3 meson-quark coupling constants:

$$g_\sigma^q,\ g_\omega^q,\ \text{and}\ g_\rho^q\ \text{for}\ q = u, d\ (g_\alpha^s = 0\ \text{for all mesons}\ \alpha).$$

Fixed to saturation density 0.16 fm^{-3}, binding energy of SNM -16 MeV and the symmetry energy 32.5 MeV

Meson masses: ω, ρ, π keep their physical values
σ = 700 MeV

Cut-off parameter Λ (in form-factors in the exchange terms)
constrained between 0.9 and 1.3 GeV

Free nucleon radius: 1 fm (limited sensitivity within change +/- 20%)

All other parameters either calculated or fixed by symmetry.

Results: Nuclear Matter and Cold Neutron Stars (Full Baryon Octet included)

Model	$g_{\sigma N}$	$g_{\omega N}$	g_ρ	K_0 (MeV)	L (MeV)	R (km)	$M_{\max}$ ($M_\odot$)	$\rho_c^{\max}$ (ρ_0)
Standard	10.42	11.02	4.55	298	101	12.27	1.93	5.52
$\Lambda = 1.0$	10.74	11.66	4.68	305	106	12.45	2.00	5.32
$\Lambda = 1.1$	11.10	12.33	4.84	312	111	12.64	2.07	5.12
$\Lambda = 1.2$	11.49	13.06	5.03	319	117	12.83	2.14	4.92
$\Lambda = 1.3$	11.93	13.85	5.24	329	124	13.02	2.23	4.74
$R = 0.8$	11.20	12.01	4.52	300	110	12.41	1.98	5.38

Stone, Stone and Moszkowski: PRC 89, 044316, 2014 : $250 < K_0 < 315$ MeV

NEW DEVELOPMENT:

FINITE NUCLEI:

QMC implemented into a 2D Hartree-Fock + BCS model

Preliminary results: Ground state binding energy and charge radii within 1% or less for:
C12, O16, Ca20 -50, Ni 56 – 78, Sn100 – 134, Gd146, Pb 198 – 208, Fm248-256, No254-256, Rf256,258, Hs264,266, Sg260,262, Ds270

Deformation of superheavy nuclei

Satisfactory spin-orbit splitting and charge density distribution

Near future projects:

Extention to 3D – β-γ potential energy surfaces.

Matrix elements in harmonic oscillator basis – shell model

Table 2
Single-particle energies (in MeV) for $^{17}_{Y}$O, $^{41}_{Y}$Ca and $^{49}_{Y}$Ca hypernuclei. The experimental data are taken from Ref. [5, Table 11] for ^{16}O and from Ref. [33] for ^{40}Ca.

	$^{16}_{\Lambda}$O (Expt.)	$^{17}_{\Lambda}$O	$^{17}_{\Xi^0}$O	$^{40}_{\Lambda}$Ca (Expt.)	$^{41}_{\Lambda}$Ca	$^{41}_{\Xi^0}$Ca	$^{49}_{\Lambda}$Ca	$^{49}_{\Xi^0}$Ca
$1s_{1/2}$	$-12.42 \pm 0.05 \pm 0.36$	-16.2	-5.3	-18.7 ± 1.1	-20.6	-5.5	-21.9	-9.4

Same as Table 2 but for $^{91}_{Y}$Zr and $^{208}_{Y}$Pb hypernuclei. The experimental data are taken from Ref. [5, Table 13].

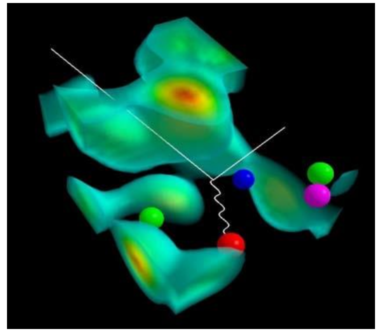
	$^{89}_{\Lambda}$Yb (Expt.)	$^{91}_{\Lambda}$Zr	$^{91}_{\Xi^0}$Zr	$^{208}_{\Lambda}$Pb (Expt.)	$^{209}_{\Lambda}$Pb	$^{209}_{\Xi^0}$Pb
$1s_{1/2}$	-23.1 ± 0.5	-24.0	-9.9	-26.3 ± 0.8	-26.9	-15.0

Application to hypernuclei: Guichon et al., Nucl.Phys. A814, 66 (2008)

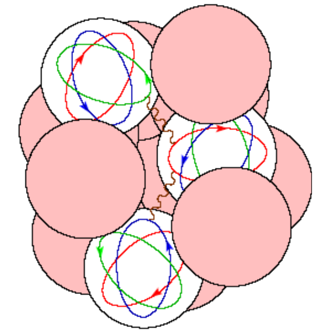
Good agreement with experiment

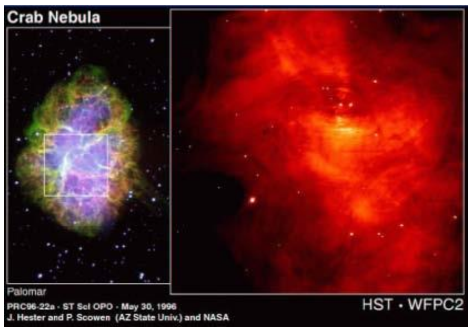
Predicts bound cascade hypernuclei – experiment at JPARC - pending

N, Λ, Ξ, ω, D, J/Ψ in nuclear matter



QCD & hadron structure

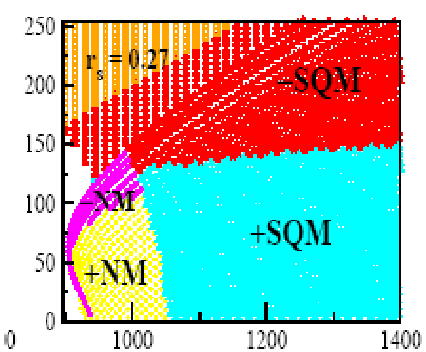




n star

∞ nuclear matter

Density dependent effective NN (and N Λ, N Ξ) forces



quark matter

Structure of finite nuclei & hypernuclei

THE UNIVERSITY of ADELAIDE

Courtesy Anthony Thomas University of Adelaide

Low energy nuclear physics is essential for understanding of many phenomena in the Universe

We should seek NEW PHYSICS beyond the "nuclear standard model" approaches

The field is open and there is always light at the end of the tunnel.......