Symmetry Energy, Neutron Stars and Supernovae

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MITP Scientific Program "'Neutron Skins of Nuclei'"

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PROJEKTTRÄGER FÜR DAS Bundesministerium für Bildung und Forschung

comp star

HIC for FAIR Helmholtz International Center

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

Soft Nuclear EoS from Heavy-Ion Data and Implications for Compact Stars

Irina Sagert, Laura Tolos, Debarati Chatterjee, JSB and Christian Sturm

PRC 86 (2012) 045802

Symmetry Energy Impact in Simulations of Core-Collapse Supernovae

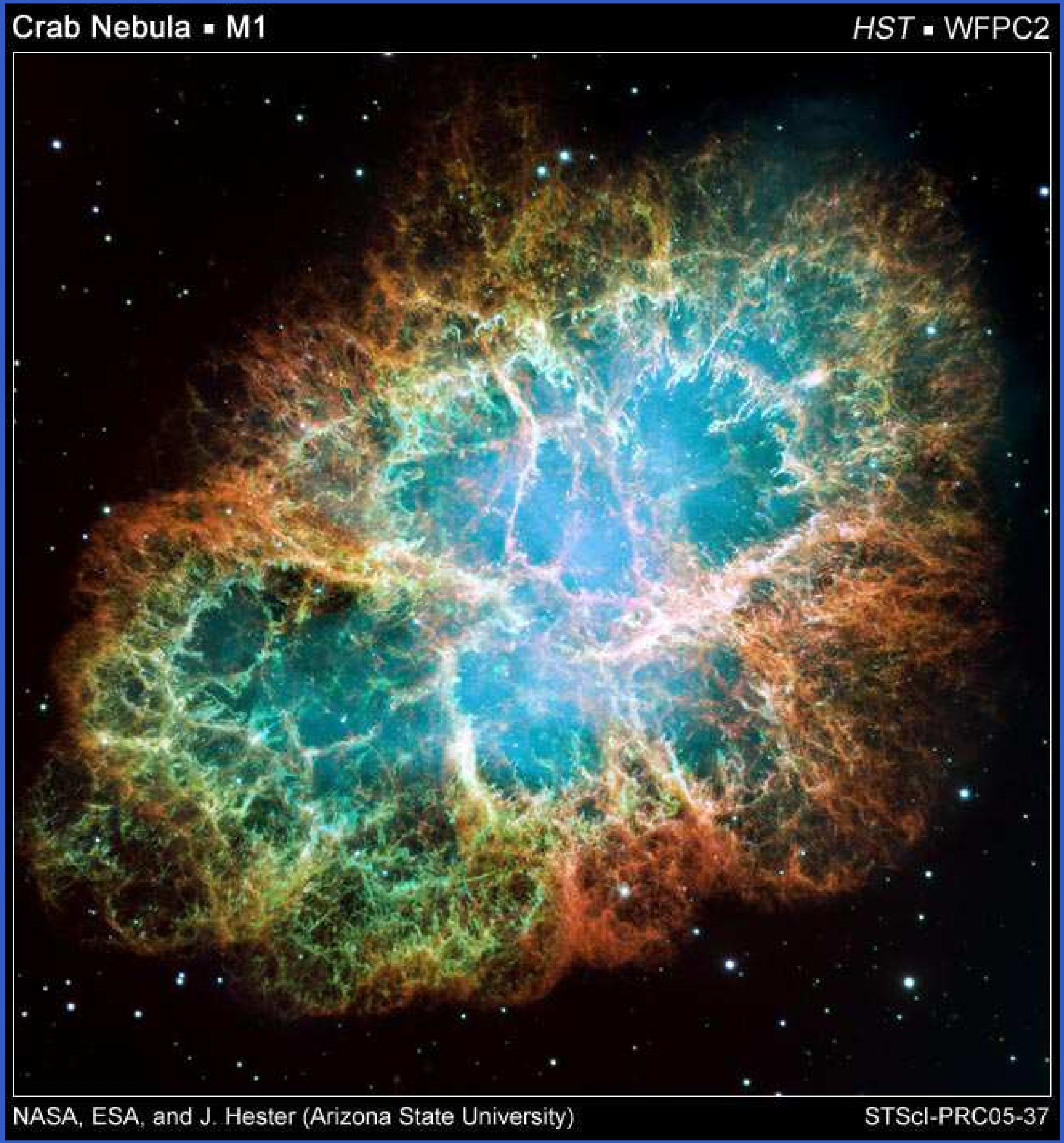
Tobias Fischer, Matthias Hempel, Irina Sagert, Yudai Suwa, JSB

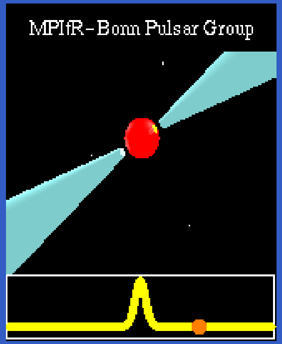
EPJA 50 (2014) 46

Outline

- Introduction: Neutron stars
- Nuclear EoS from kaon production in heavy-ion collisions
- Implications for neutron stars:
  - Neutron star radii for light neutron stars
  - Maximum possible neutron star mass
- Symmetry energy impact on core-collapse supernovae
- Summary

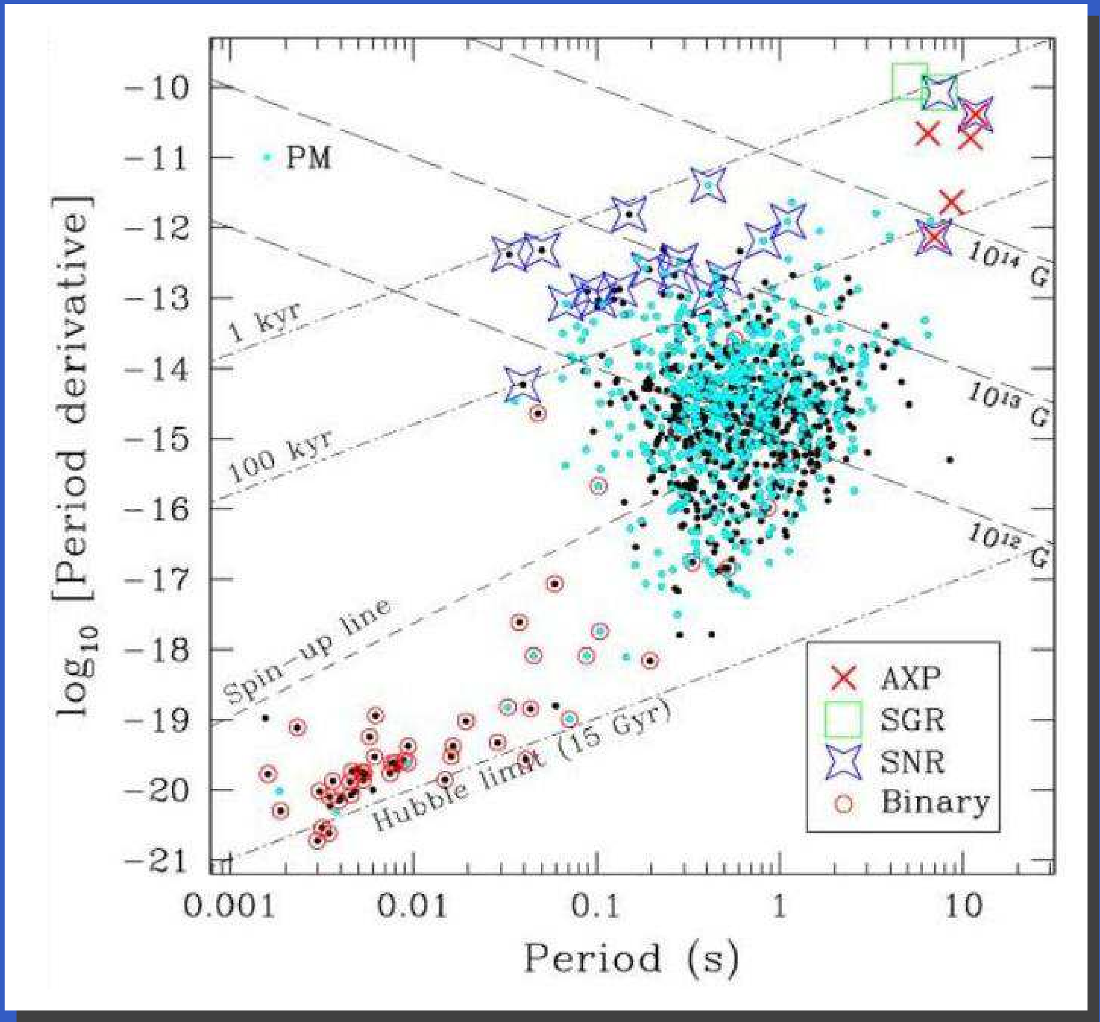
Neutron Stars





- produced in core collapse supernova explosions
- compact, massive objects: radius ≈ 10 km, mass $1 - 2 M_\odot$
- extreme densities, several times nuclear density: $n \gg n_0 = 3 \cdot 10^{14}$ g/cm^3
- in the middle of the crab nebula: a pulsar, a rotating neutron star!

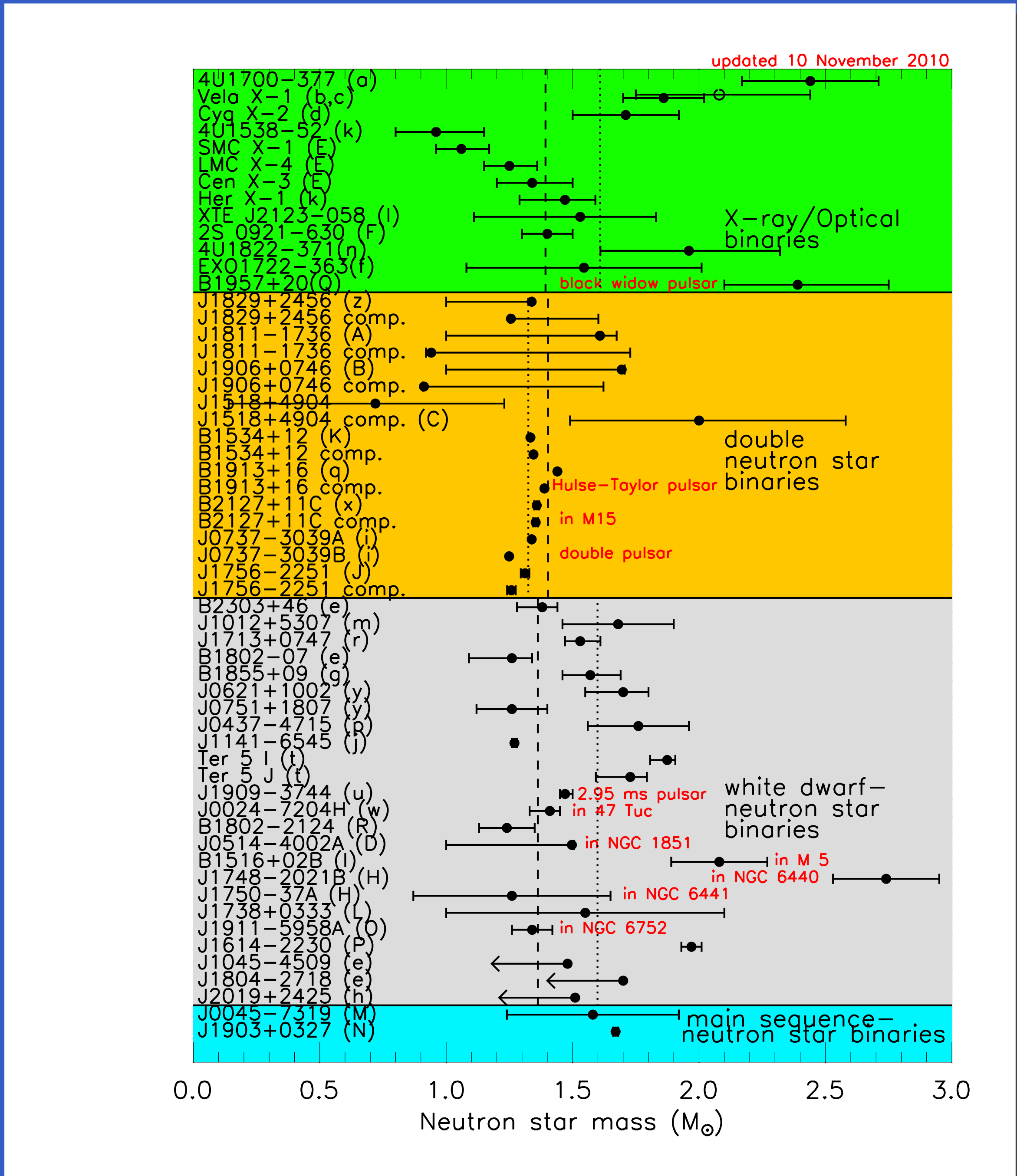
The Pulsar Diagram



(ATNF pulsar catalog)

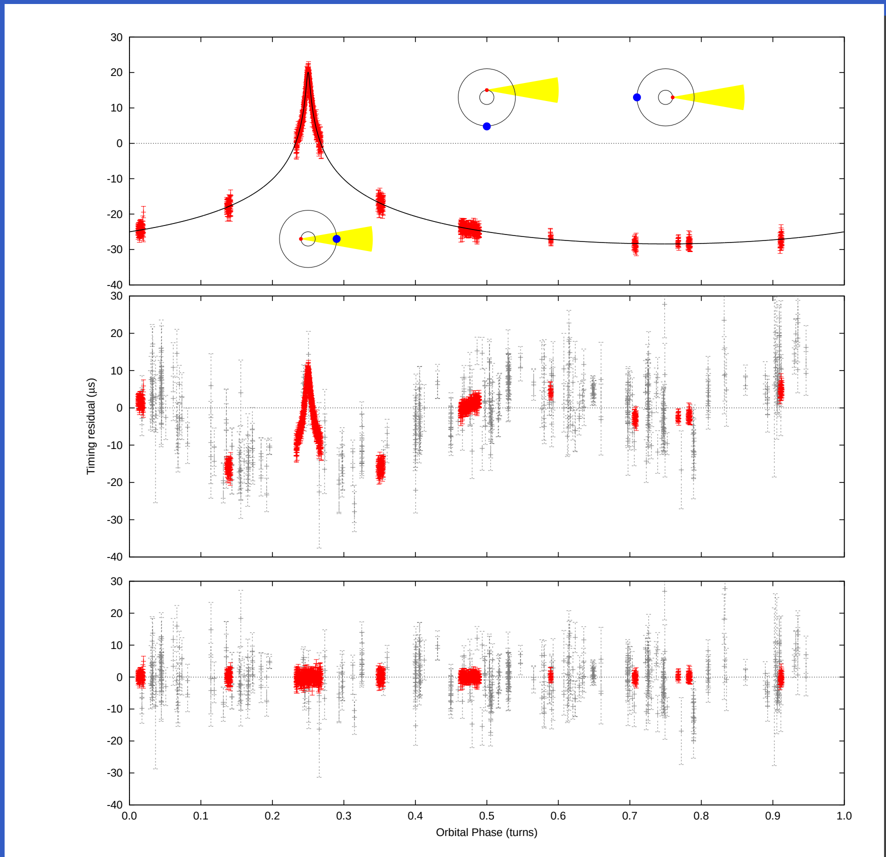
- the diagram for pulsars: period versus period change (P-$\dot{P}$)
- dipole model for pulsars: characteristic age: $\tau = P/(2\dot{P})$ and magnetic field $B = 2 \cdot 10^{19} (P \cdot \dot{P})^{1/2}$ Gauss
- anomalous x-ray pulsars: AXP, soft-gamma ray repeaters: SGR, young pulsars in supernova remnants: SNR
- rapidly rotating pulsars (millisecond pulsars): mostly in binary systems (old recycled pulsars!)

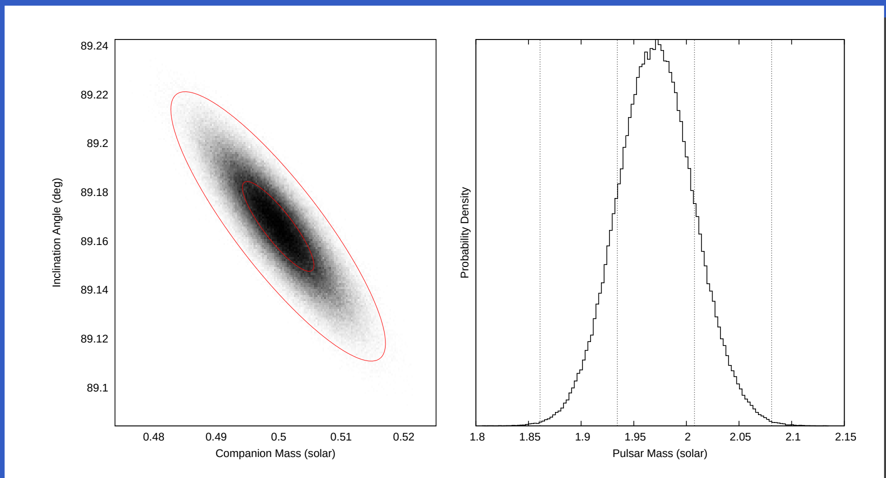
Masses of Pulsars (Lattimer and Prakash 2011)



- nearly 2000 pulsars known with 140 binary pulsars
- best determined mass: $M = (1.4414 \pm 0.0002) M_\odot$ Hulse-Taylor pulsar (Weisberg and Taylor, 2004)
- very high mass of $M = (2.74 \pm 0.21) M_\odot$ for PSR 1748-2021B (statistical analysis in inclination angle) (Freire et al. 2007)

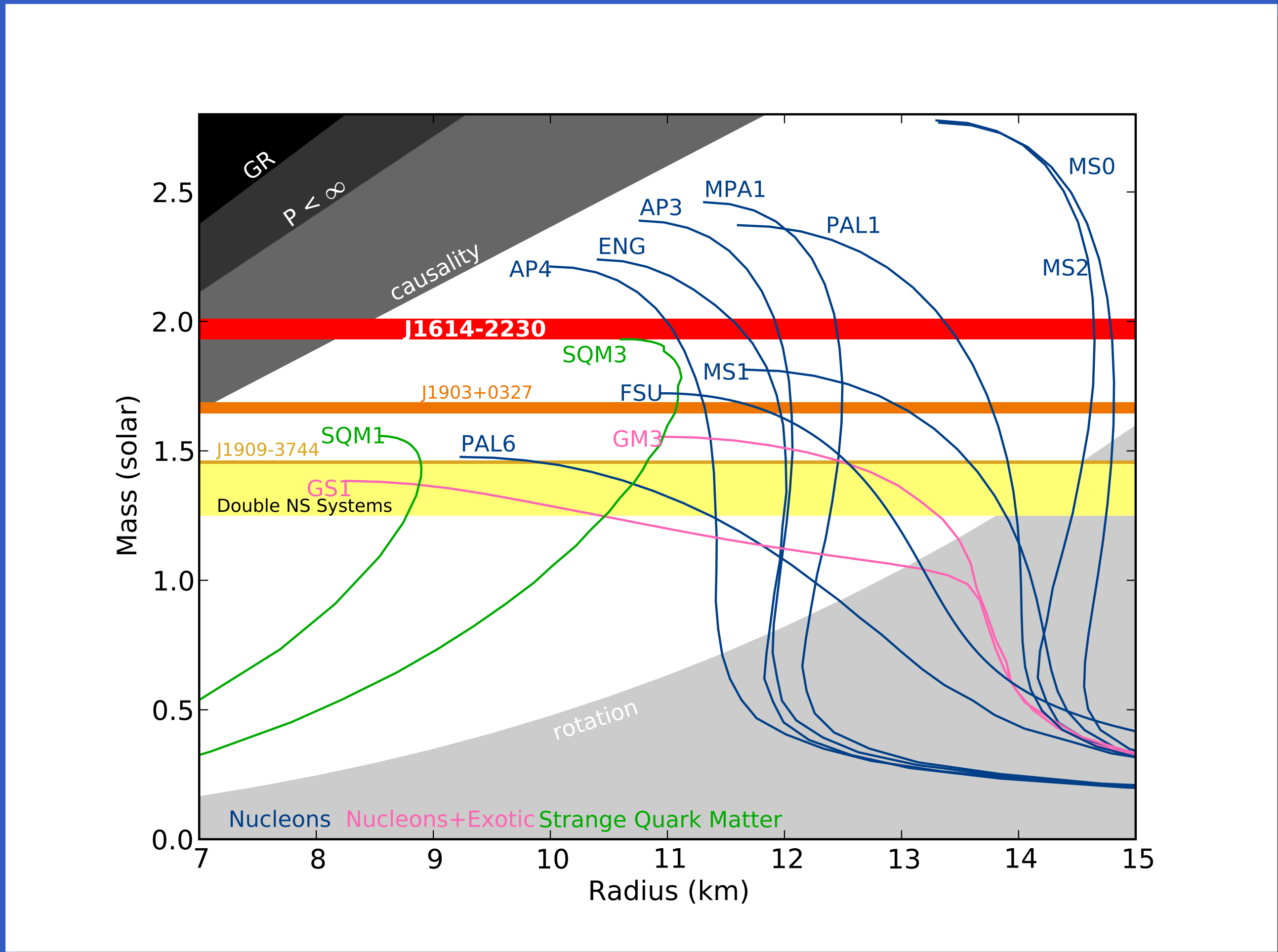
Mass measurement of pulsar PSR J1614-2230 (Demorest et al. 2010)





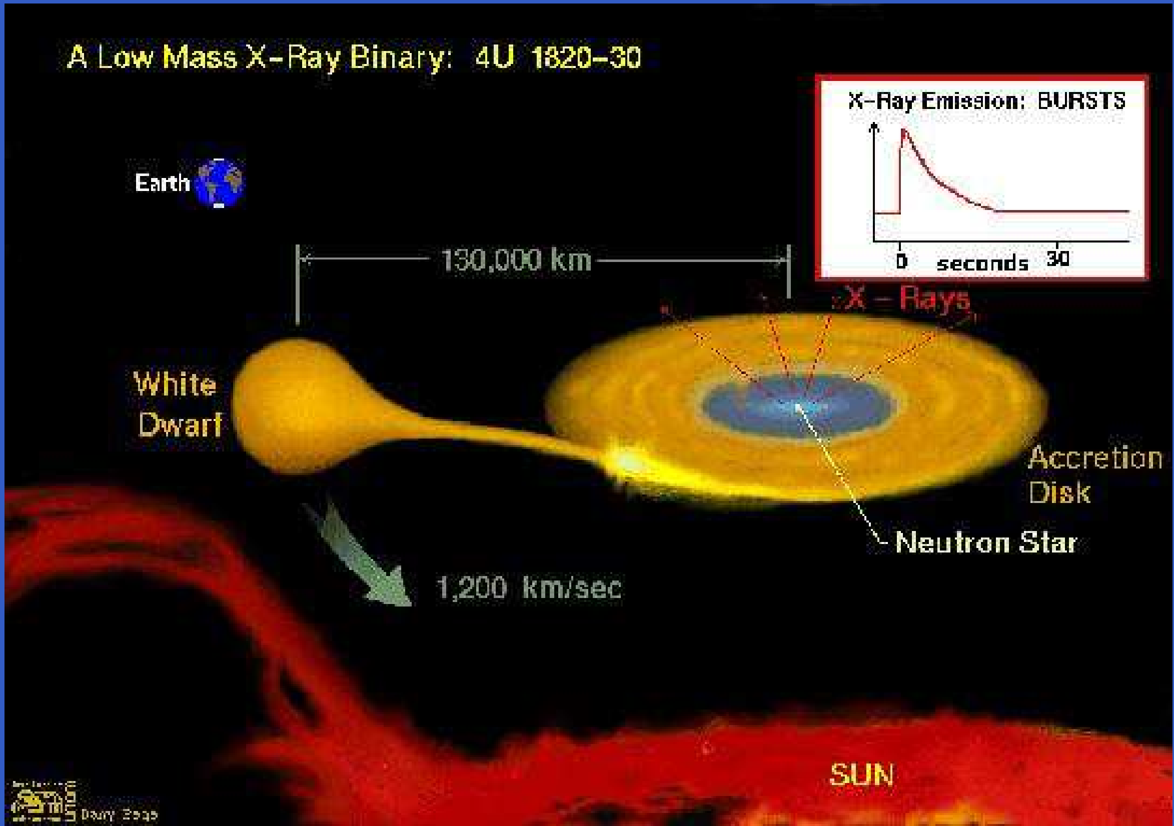
- extremely strong signal for Shapiro delay
- Shapiro delay parameters r and s alone give $M = (1.97 \pm 0.04) M_\odot$ - new record!
- by far the highest precisely measured pulsar mass!
- considerable constraints on neutron star matter properties!

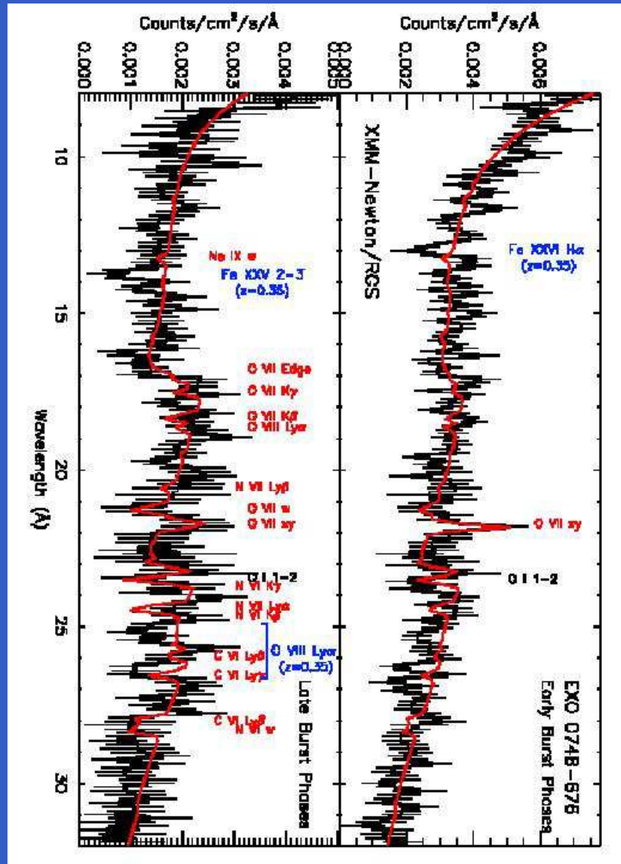
Constraints on the Mass–Radius Relation (Lattimer and Prakash 2004)



- spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4 M_\odot$
- Schwarzschild limit (GR): $R > 2GM = R_s$
- causality limit for EoS: $R > 3GM$
- mass limit from PSR J1614-2230 (red band): $M = (1.97 \pm 0.04) M_\odot$

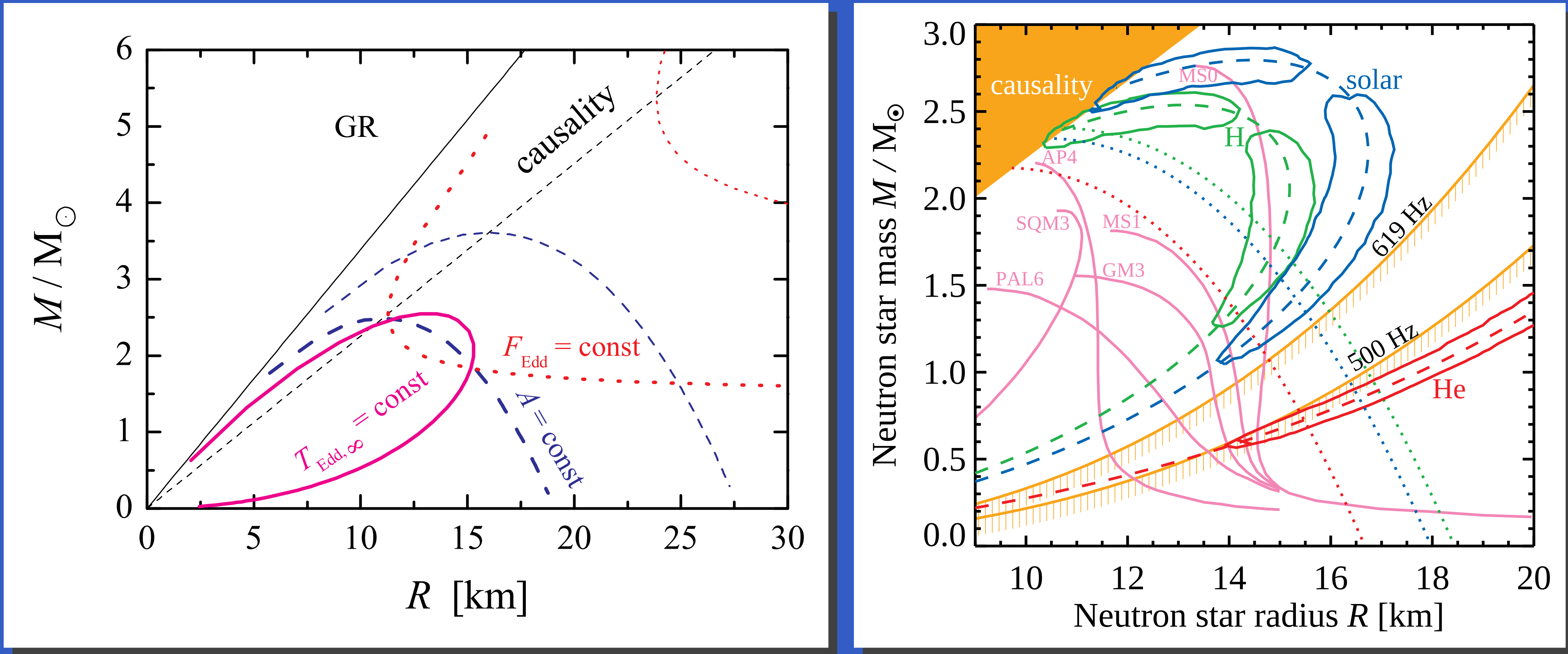
X-Ray burster





- binary systems of a neutron star with an ordinary star
- accreting material on the neutron star ignites nuclear burning
- red shifted spectral lines measured!
  ($z = 0.35 \rightarrow M/M_\odot = 1.5$ (R/10 km)) (Cottam, Paerels, Mendez (2002))
- Cottam et al. (2008): not confirmed with burst data from 2003

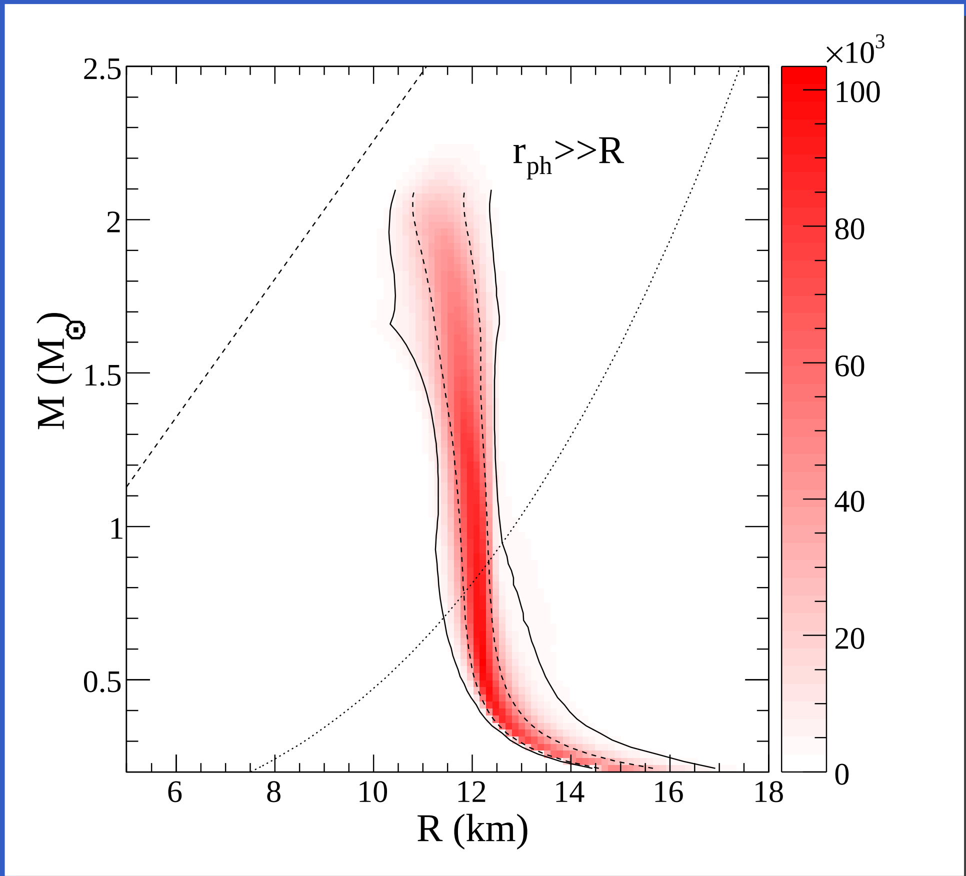
Fits to X-Ray Burster Spectra

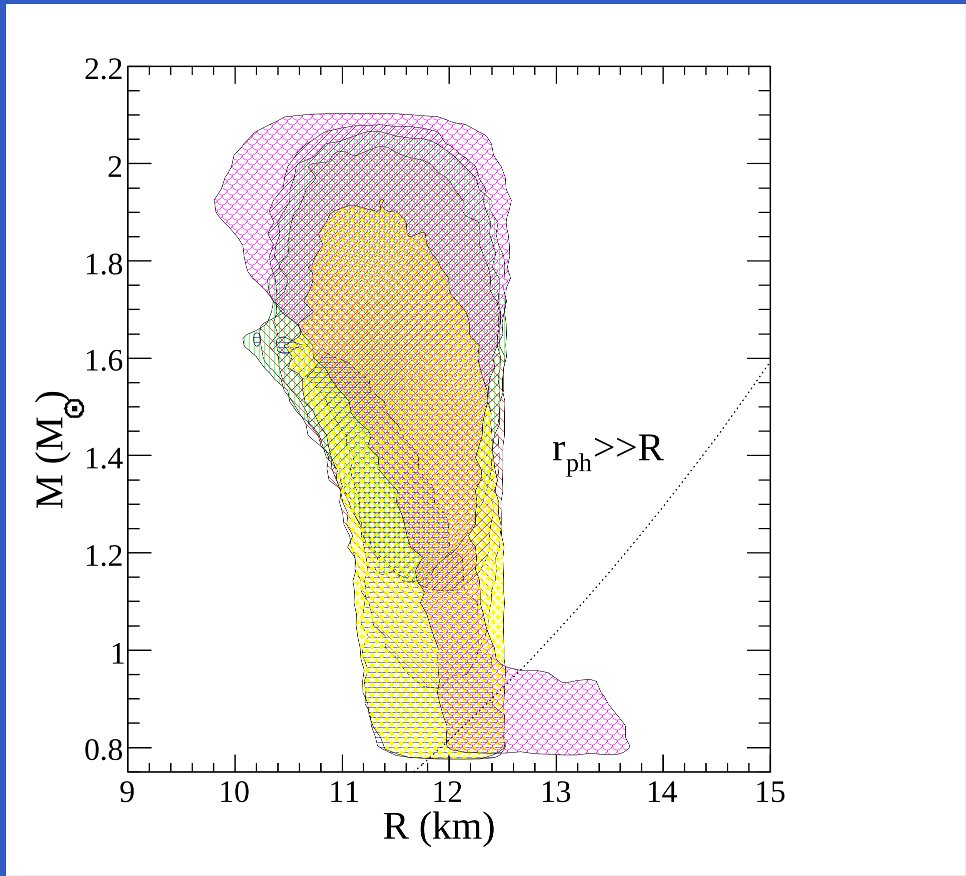


(Suleimanov, Poutanen, Revnivtsev, Werner 2011)

- x-ray burster with photospheric radius expansion
- assume (color-corrected) black-body emission and Eddington flux at 'touch-down' (Ozel 2006): simple model fit fails above a certain distance!
- large correction from model atmosphere composition

Mass-Radius Constraints from X-Ray Burster and Binaries



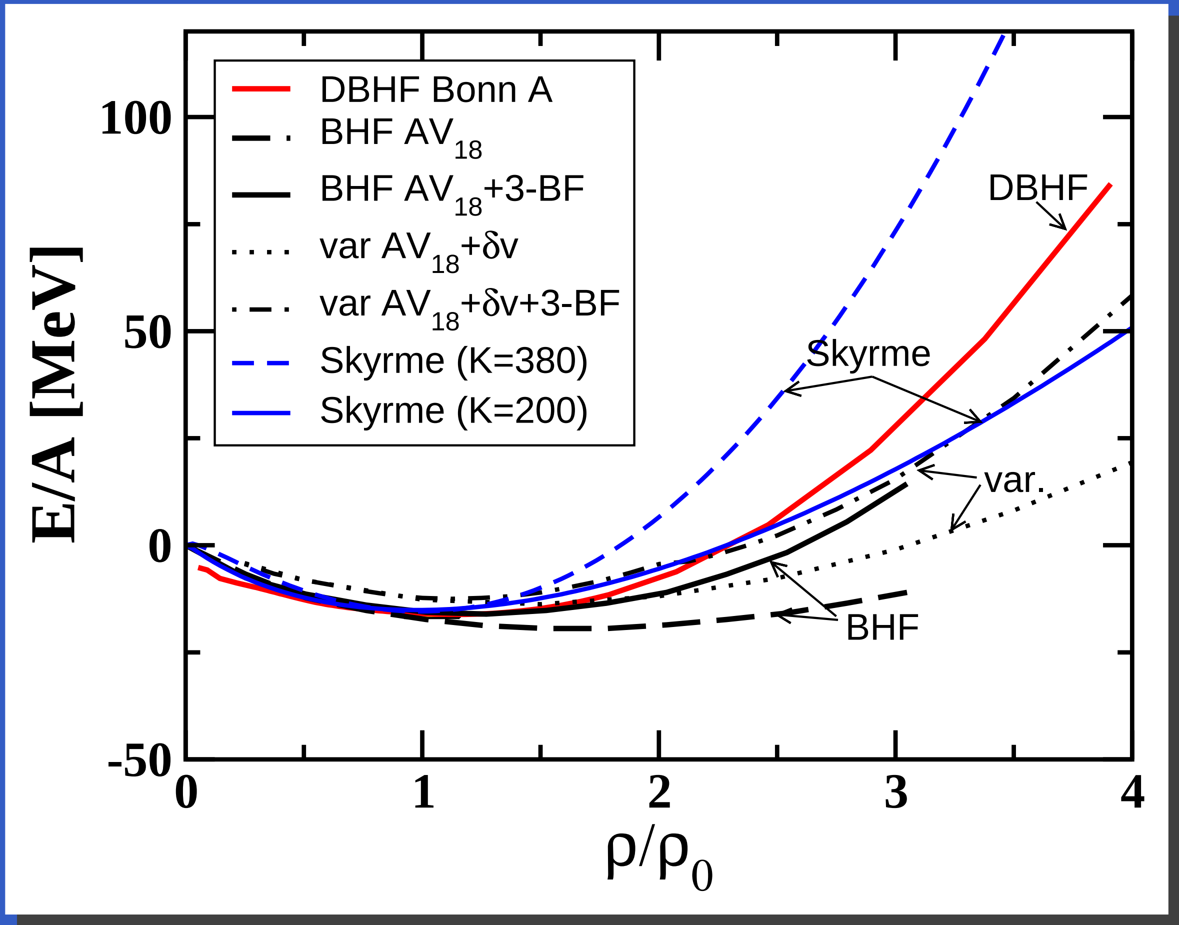


(Steiner, Lattimer, Brown 2011)

- fit to three x-ray burster data with photospheric radius expansion and three quiescent x-ray binaries (from previous analysis)
- relax constraint at 'touch-down' to be on the surface ($r_{ph} \gg R$)
- strong constraint on radius relation (left: combined fit, right: separate fits)

Kaon Subthreshold Production in Heavy-Ion Collisions

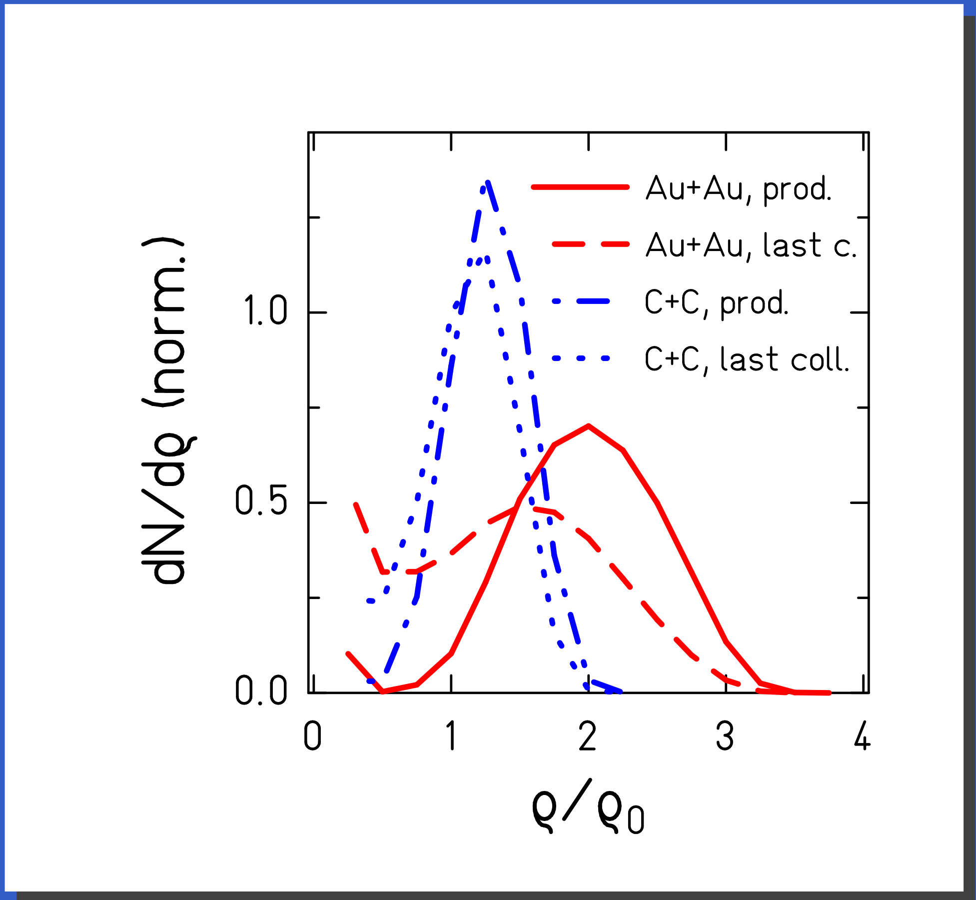
Input to transport models: the nucleon potential



(Fuchs 2006)

- crucial input to control the amount of compression: the nucleon potential
- study two extreme cases using the Skyrme model
- hard EoS: stiffness parameter $K = 380$ MeV, soft EoS: $K = 200$ MeV

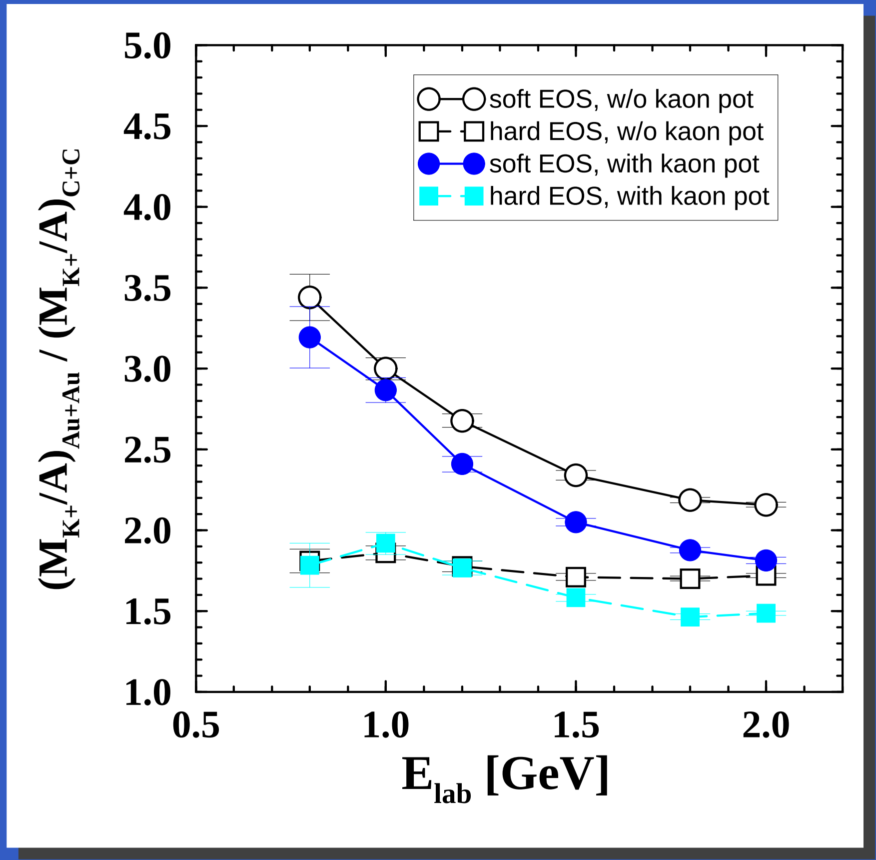
Heavy-ion collisions: density range probed with kaons



(Hartnack, Oeschler, Leifels, Bratkovskaya, Aichelin 2012)

- kaon production by associated production: NN$\rightarrow$ NΛK, NN$\rightarrow$NNK$\overline{\mathrm{K}}$
- produced in a baryon-rich medium at densities of $2n_0$ up to $3n_0$
- long mean-free path of kaons: escape from the high-density region

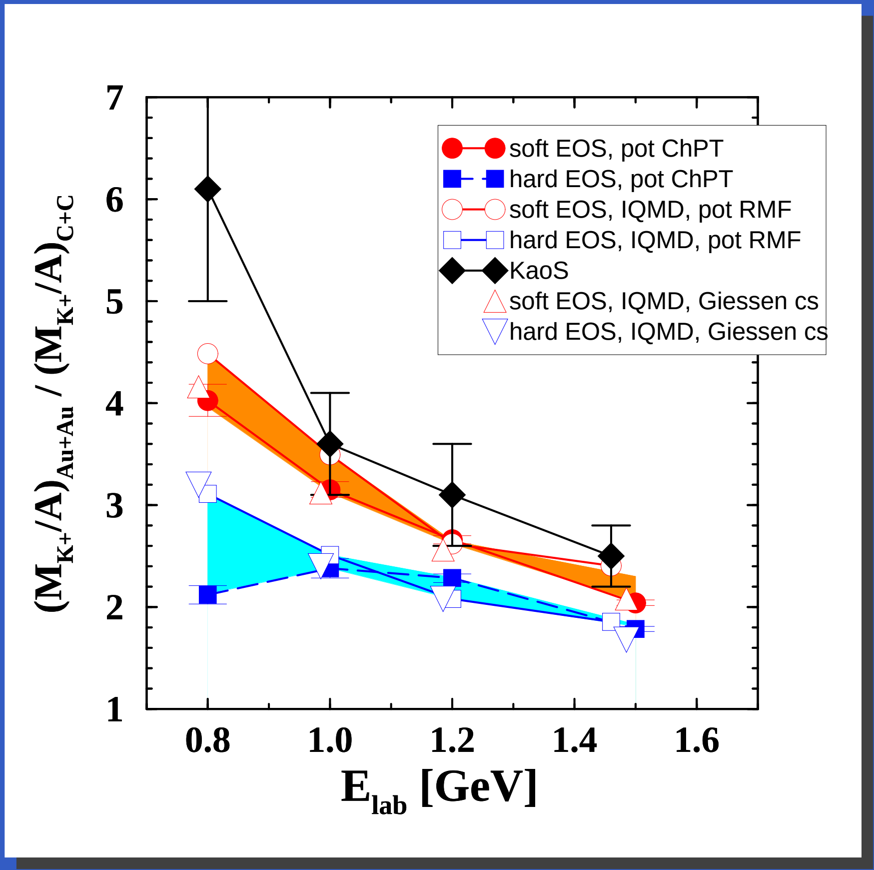
Effect of kaon potentials on double ratio



(Fuchs, Faessler, Zabrodin, Zheng 2001)

- study double ratio: compare kaon multiplicity in C+C with Au+Au collisions
- kaon potential is repulsive in dense matter
- effect is (nearly) linear in density → cancels in double ratio

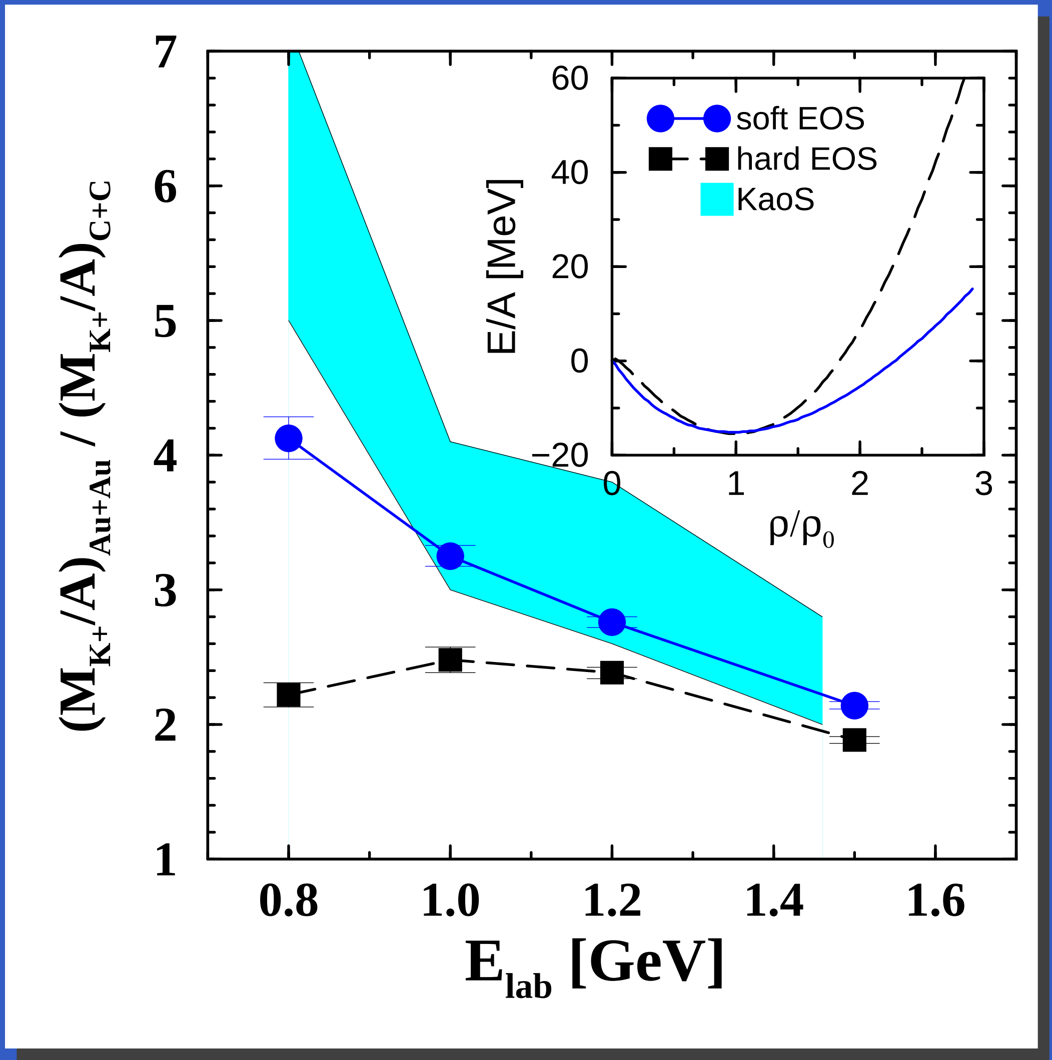
Kaon Production: Sensitivity to Different Models



(Fuchs 2006)

- study different transport models and cross sections
- excitation function for kaon production ratio rather insensitive
- main difference originates from the underlying EoS!

Kaon production in heavy-ion collisions

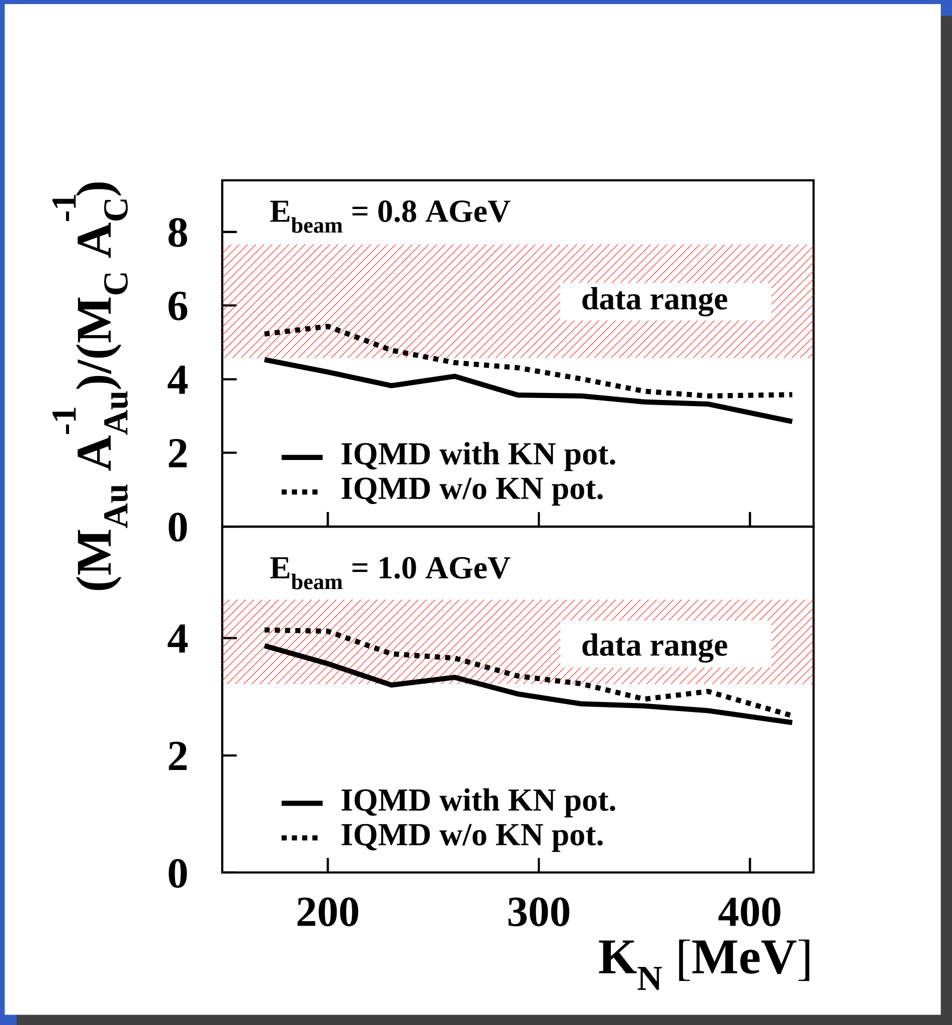


Sturm et al. (KaoS collaboration), PRL 2001

Fuchs, Faessler, Zabrodin, Zheng, PRL 2001

- nuclear matter is compressed up to $2 - 3n_0$!
- long mean-free path of kaons: kaons can escape high density matter
- clear trend indicating high compression $\rightarrow$ a soft EoS

Confirmed KaoS data analysis: the nuclear EoS is soft!



Forster et al. (KaoS collaboration) 2007

Hartnack, Oeschler, Aichelin, 2006

- kaon production (K^+) far below threshold
- double ratio: multiplicity per mass number for C+C collisions and Au+Au collisions at 0.8 AGeV and 1.0 AGeV
- only calculations with a compression modulus of $K_N \approx 200$ MeV and smaller can describe the data

$\Longrightarrow$ the nuclear equation of state is SOFT!

Implication I: Neutron Star Radii and the Asymmetry Potential

Probing the EoS: Empirical Nucleon-Nucleon Interaction

Ansatz for the energy per particle with $u = n/n_0$ (Prakash et al. 1988):

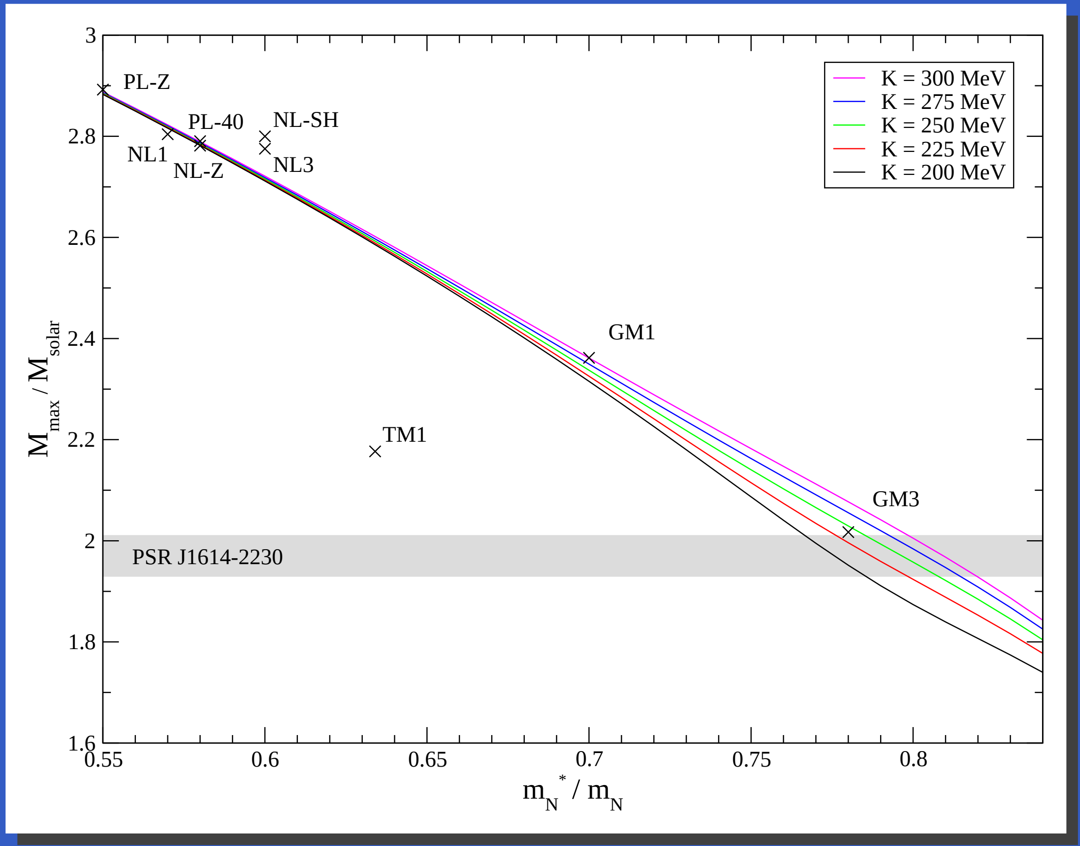
$$\epsilon/n = m_N + E_0^{kin} + \frac{A}{2} \cdot u + \frac{B}{\sigma + 1} u^\sigma + S_0 \cdot u^\gamma \cdot \left(\frac{n_n - n_p}{n} \right)^2$$

corresponds to the nucleon Skyrme potential used in transport codes

- parameters A, B, σ fixed by nuclear matter properties n_0, E/A, and compression modulus K_0
- asymmetry energy S_0 fixed at n_0, density dependence γ can vary between 0.5 and 1.1
- pressure determined by the thermodynamic relation

$$P = n^2 \frac{d}{dn} \left(\frac{\epsilon}{n} \right)$$

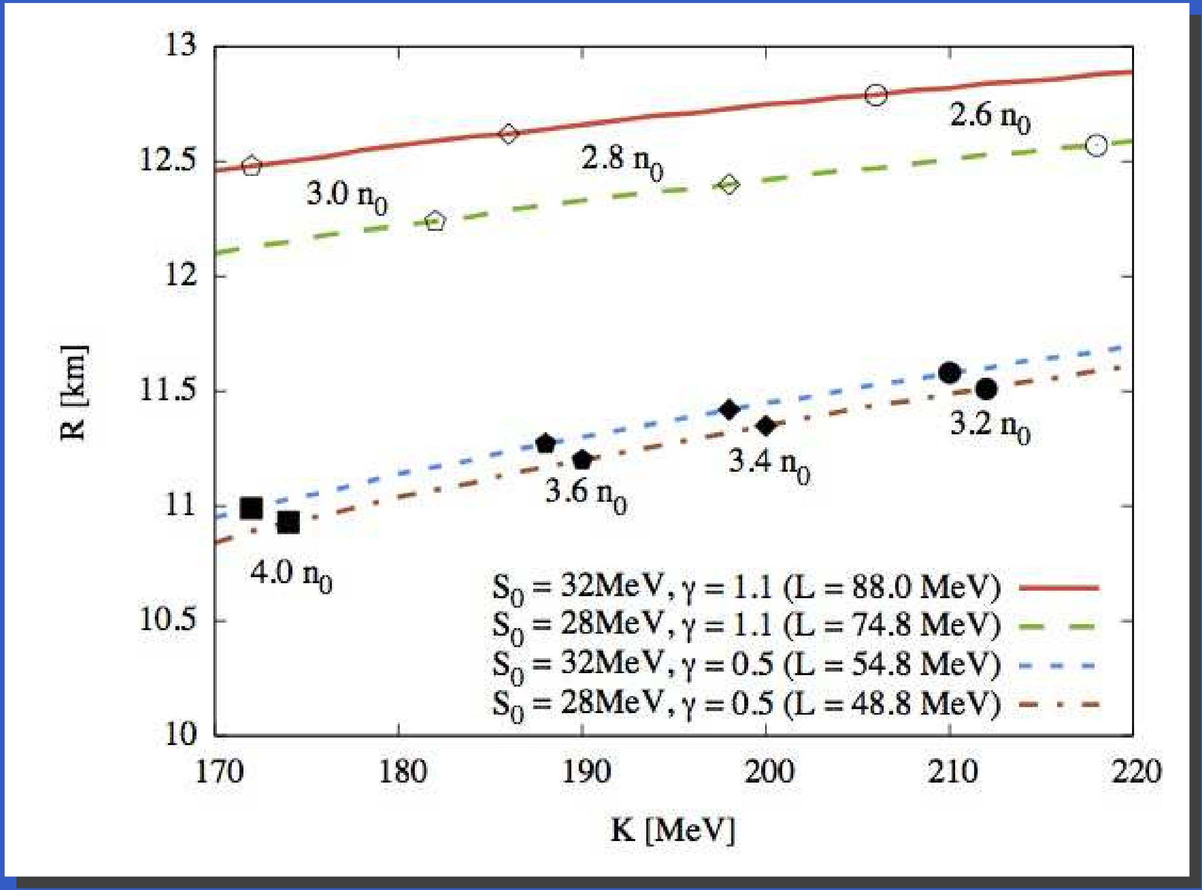
Maximum neutron star mass and compression modulus



(Weissenborn, Chatterjee, JSB 2011)

- relativistic mean-field model: stiffness of EoS controlled by m^*/m not the compression modulus K_0
- change in maximum mass for different compressibilities: at most $0.1 M_\odot$
- adopt stiffness parameter K from KaoS data analysis as a constraint on high density EoS only!

Low-Mass Neutron Star Radii and the Asymmetry Potential

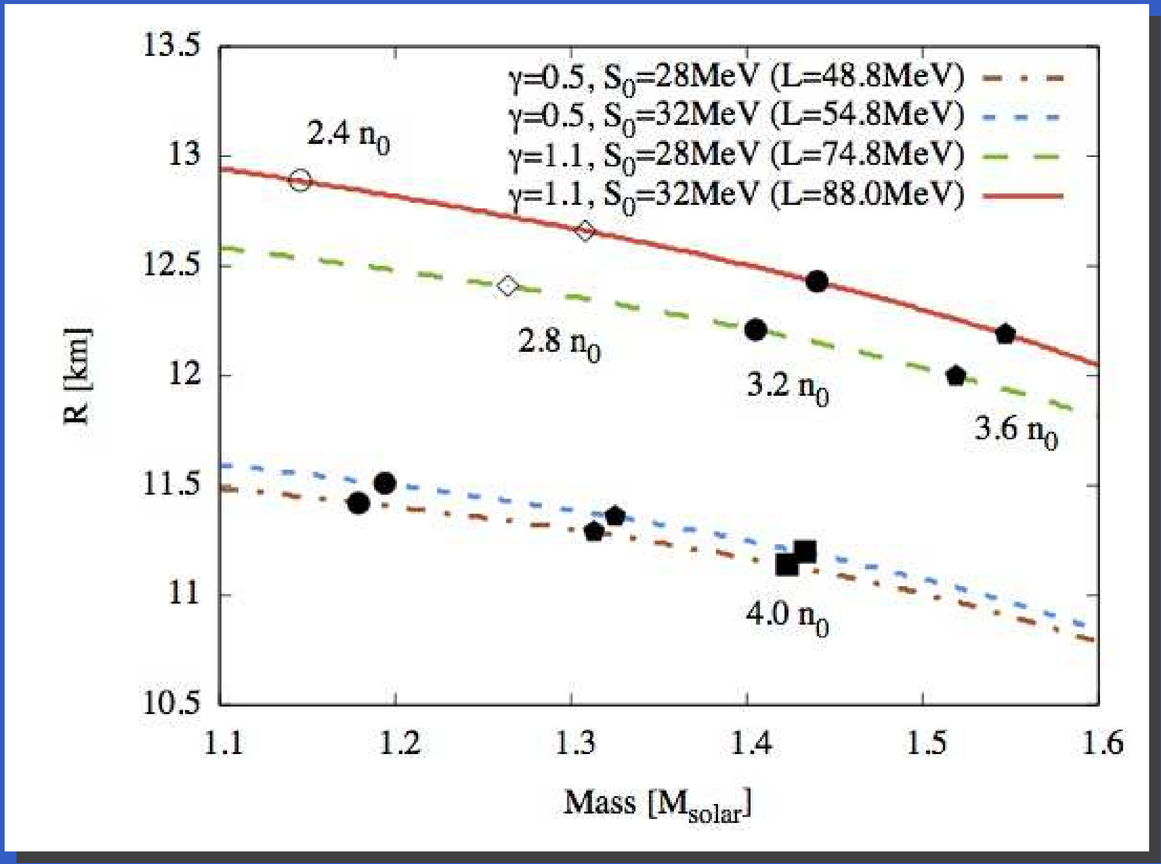


(Sagert, Tolos, Chatterjee, JSB, Sturm 2012)

- radii for different stiffness parameter (KaoS: $K < 200$ MeV)
- central density in a $1.25 M_{\odot}$ neutron star: around $3 n_0$
- radius mostly sensitive to density dependence γ of asymmetry energy

(Lattimer and Prakash (2001), Carriere, Horowitz, Piekarewicz (2003), Bao-An Li et al. . . .)

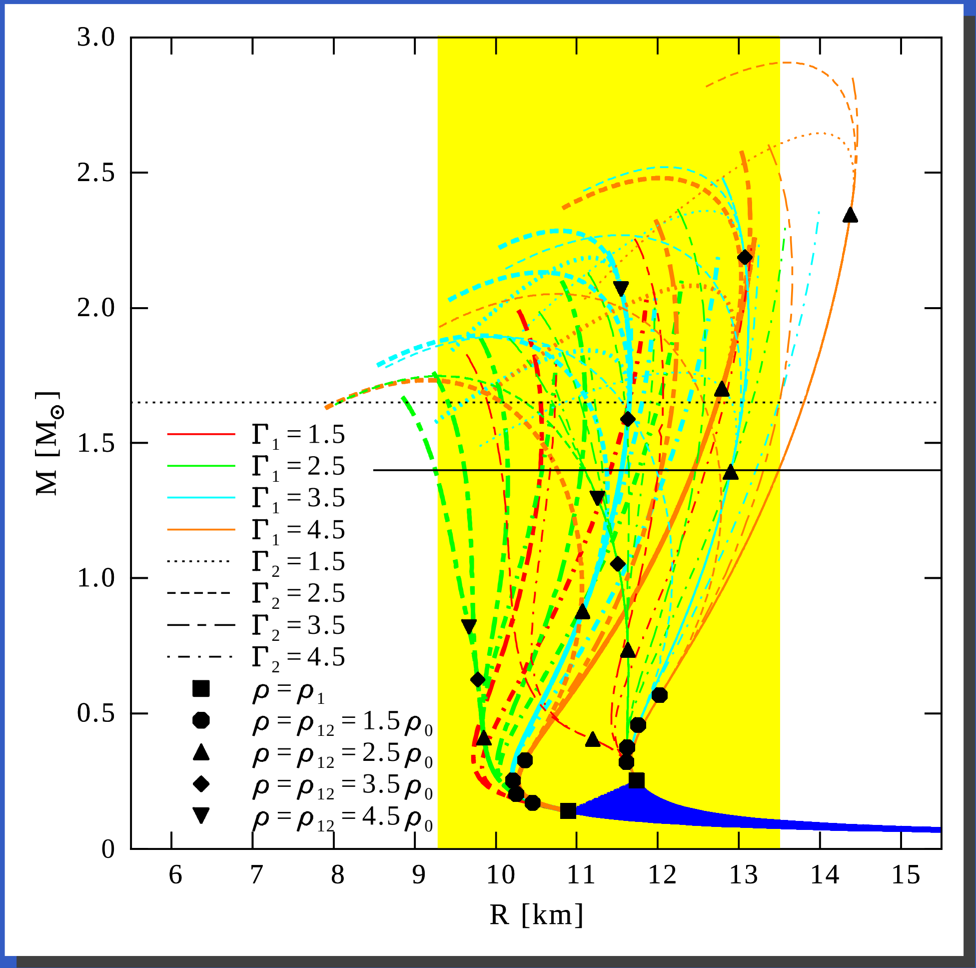
Neutron Star Radii and the Asymmetry Potential



(Sagert, Tolos, Chatterjee, JSB, Sturm 2012)

- radii for different masses and asymmetry potentials
- moderate change with mass, stronger dependence on density dependence γ of asymmetry energy
- constraint from KaoS data analysis reduces uncertainty in isospin independent part of the nuclear EoS

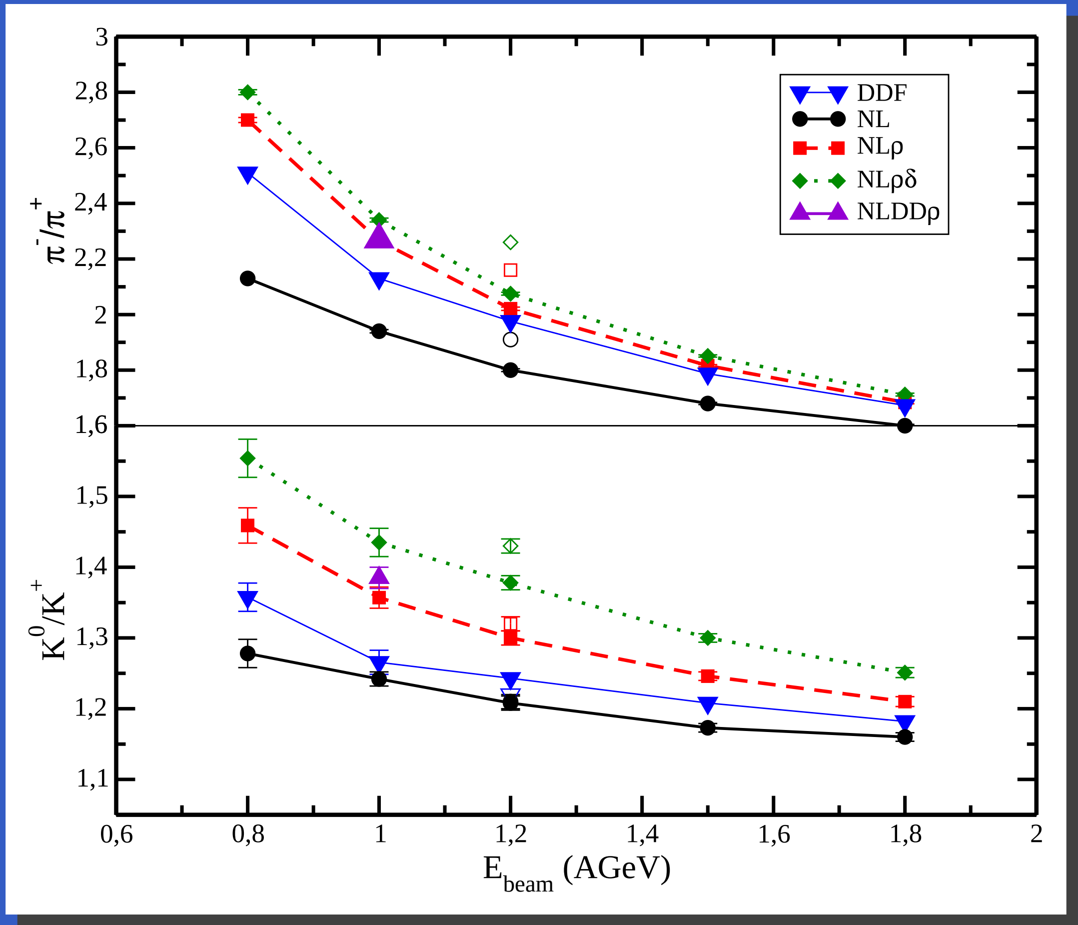
Constraints from chiral effective theory



(Hebeler, Lattimer, Pethick, Schwenk 2010)

- chiral effective theory for neutron matter with three-body forces
- extrapolate using different polytropes
- radii constraint to $R = 9.7 - 13.9$ km (corrected for neutron star crust)

A potential measure of the isospin potential

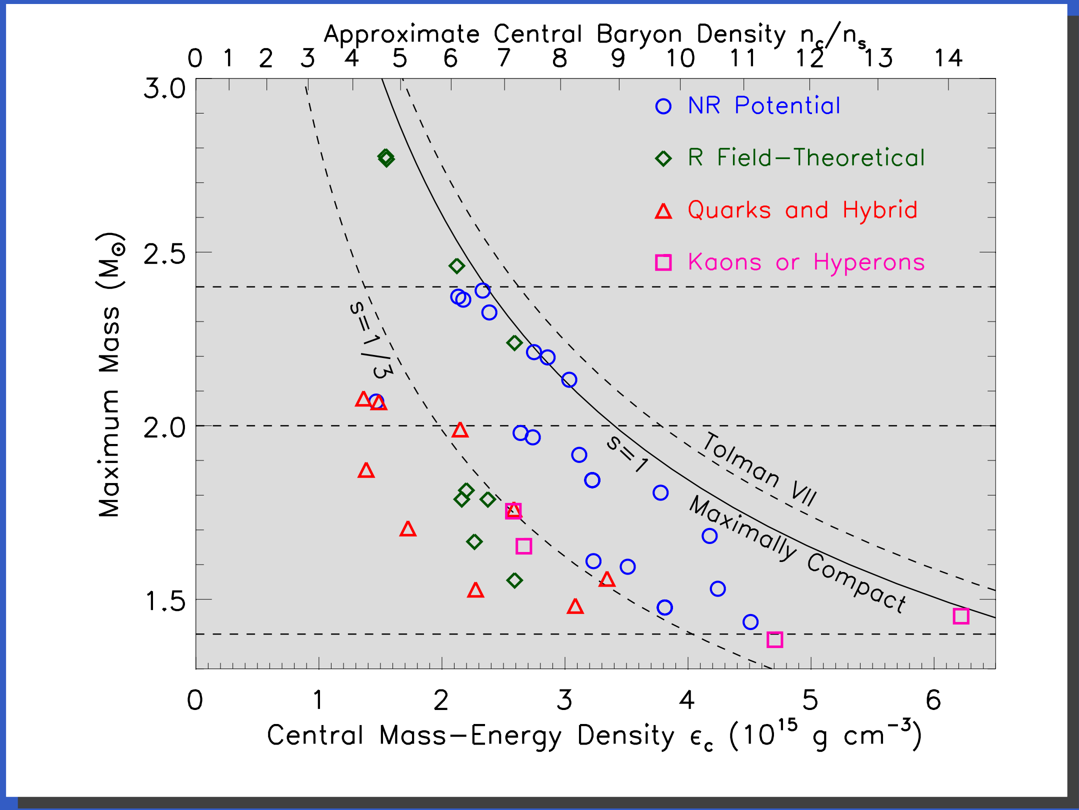


(Ferini, Gaitanos, Colonna, Di Toro, Wolter 2006)

- use different nucleon potentials with different asymmetry potentials
- particle ratios of kaons (pions) with different isospin: sensitive to different nuclear models

Implication II: Constraint on the Maximum Possible Neutron Star Mass

Maximum central density of a compact stars

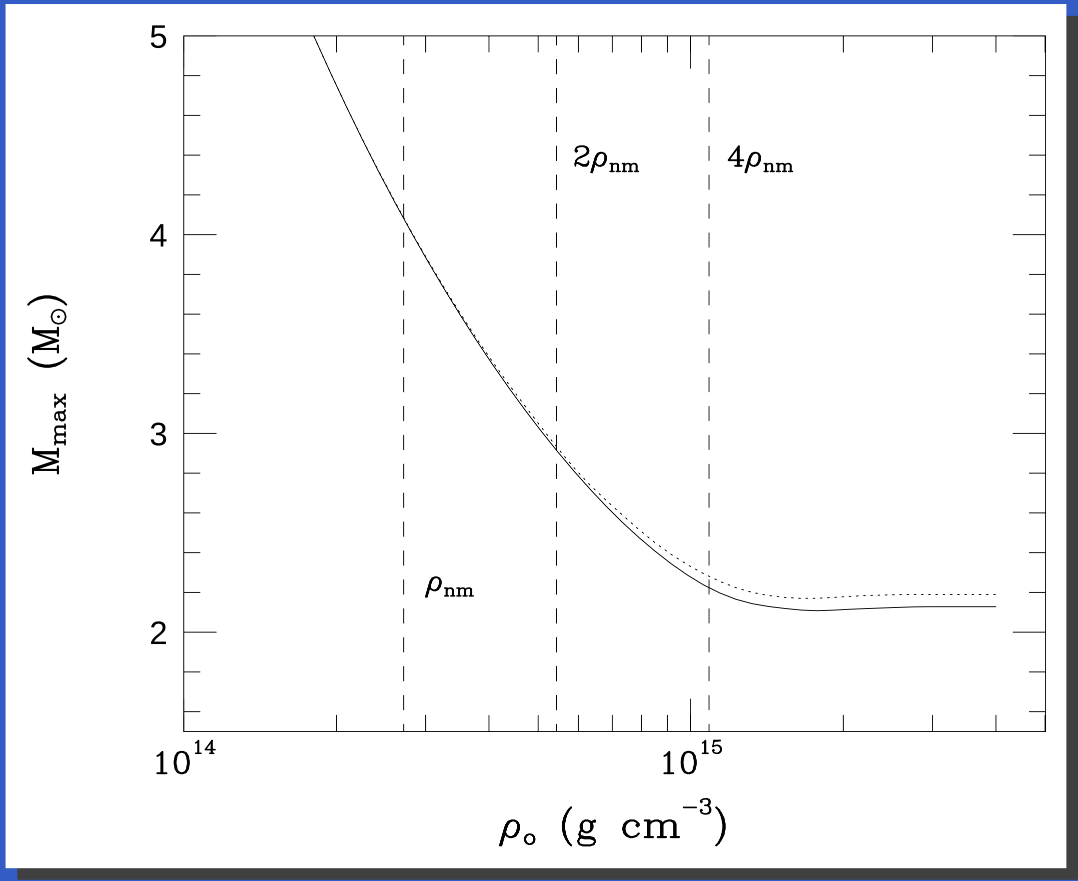


(Lattimer and Prakash 2011)

- maximally compact EoS: $p = s(\epsilon - \epsilon_c)$ with $s = 1$
- stiffest possible EoS (Zeldovich 1961)
- gives upper limit on compact star mass: $M_{\max} = 4.1 M_\odot (\epsilon_{\mathrm{sat.}}/\epsilon_f)^{1/2}$

  (Rhoades and Ruffini 1974, Hartle 1978, Kalogera and Baym 1996, Akmal, Pandharipande, Ravenhall 1998, Lattimer and Prakash 2011)

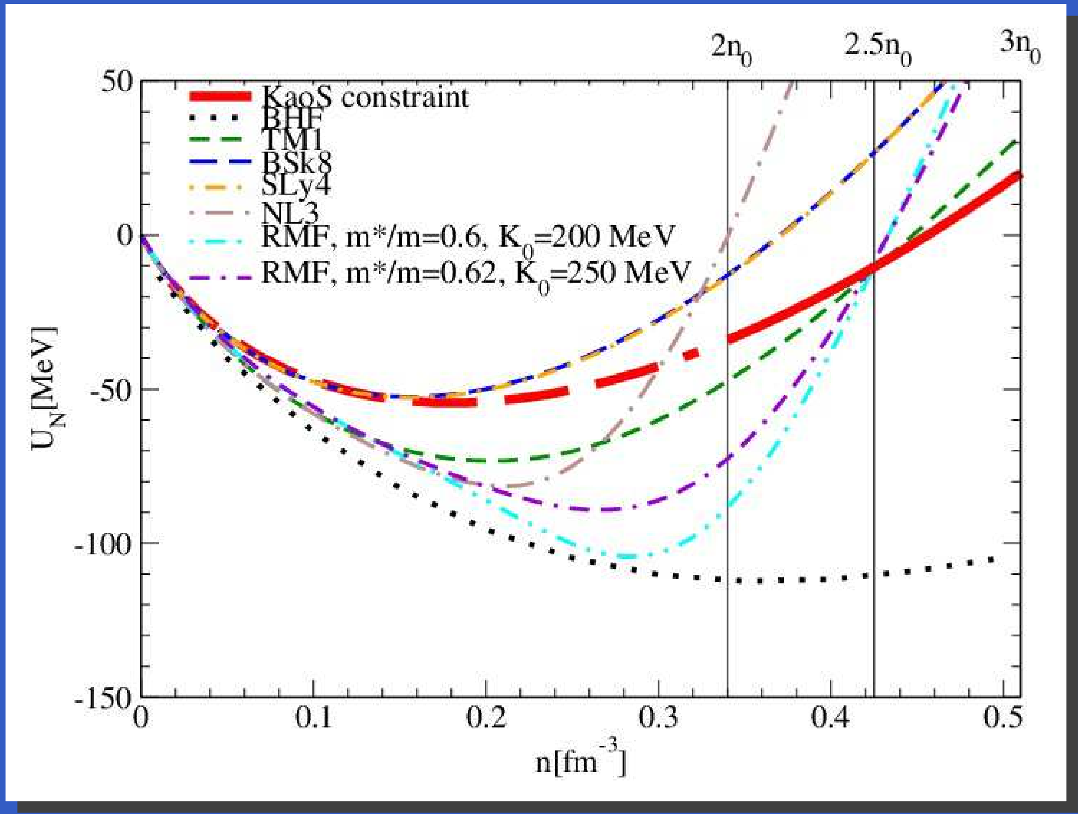
Maximum Mass from Causality Argument



(Kalogera and Baym 1996)

- use EoS from Wiringa, Fiks, Fabrocini 1988 (Argonne V_{14} potential)
- probed only up to normal nuclear matter density (at most)
- maximum possible mass due to causality: $M_{\max} = 4.1 M_\odot$ at $\epsilon_f = \epsilon_{\text{saturation}}$

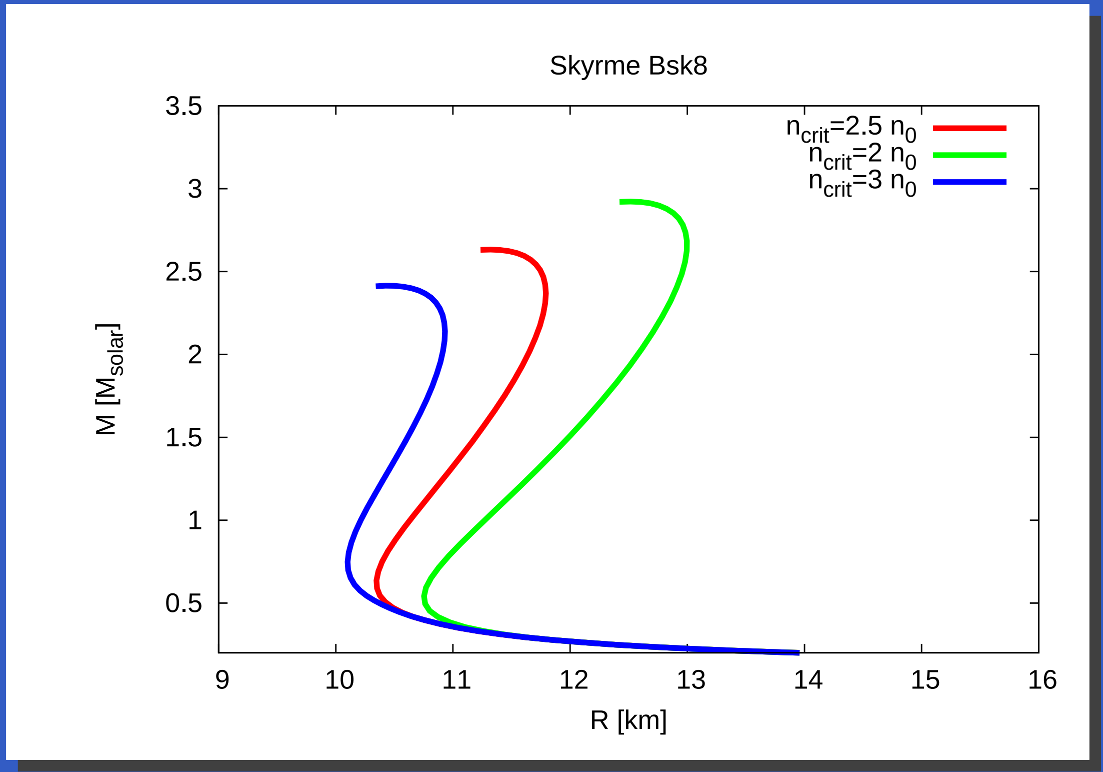
Constraint from heavy-ion data: nucleon potential at $2 - 3n_0$



(Sagert, Tolos, Chatterjee, JSB, Sturm 2012)

- input to transport simulations: nucleon potential
- kaon production is sensitive to densities of $n = 2 - 3n_0$ ($n_0 = 0.17$ fm^{-3})
- constraint: nucleon potential must be below the curve for the Skyrme model with $K = 200$ MeV at a fiducial density of $n_f = 2 \ldots 3n_0$

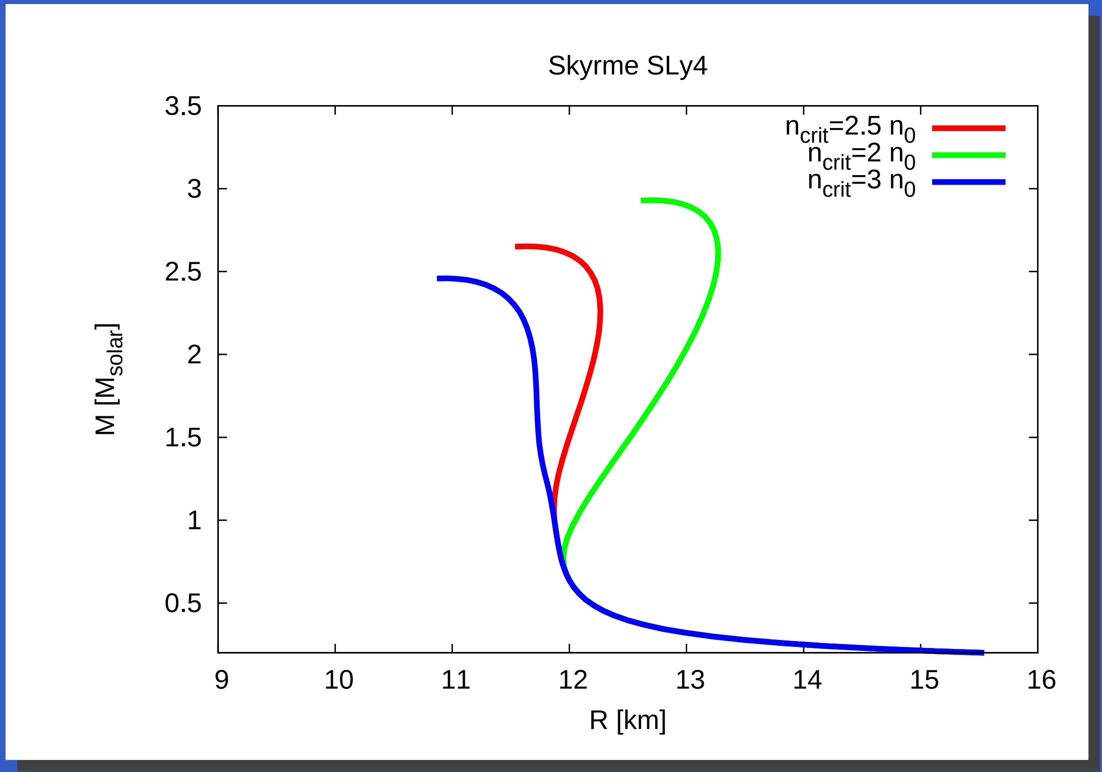
Maximum Masses of Neutron Stars – Causality



(Sagert, Tolos, Chatterjee, JSB, Sturm 2012)

- Skyrme parameter set BSK8: fitted to masses of all known nuclei
- above a fiducial density (determined from the analysis of the KaoS heavy-ion data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f
  Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\max} = 4.2 M_\odot (\epsilon_0/\epsilon_f)^{1/2}$

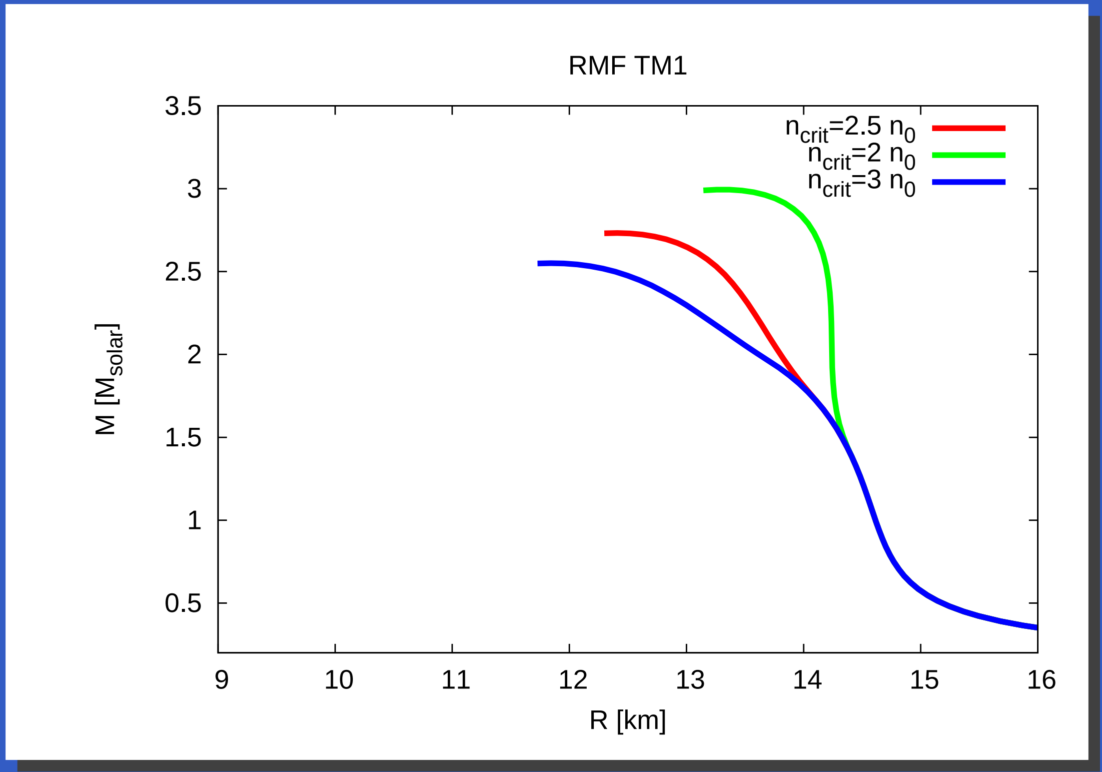
Maximum Masses of Neutron Stars – Causality



(Sagert, Tolos, Chatterjee, JSB, Sturm 2012)

- Skyrme parameter set Sly4: fitted to properties of spherical nuclei
- above a fiducial density (determined from the analysis of the KaoS heavy-ion data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f
  Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\rm max} = 4.2 M_\odot (\epsilon_0/\epsilon_f)^{1/2}$

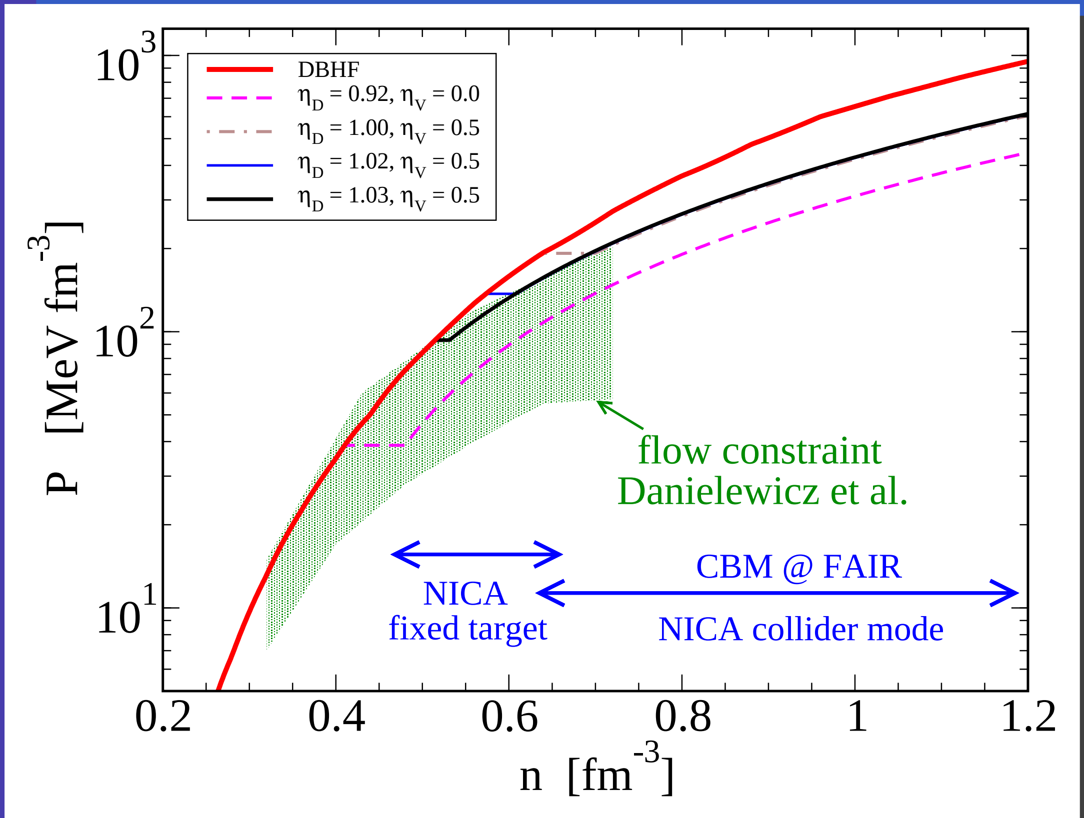
Maximum Masses of Neutron Stars – Causality

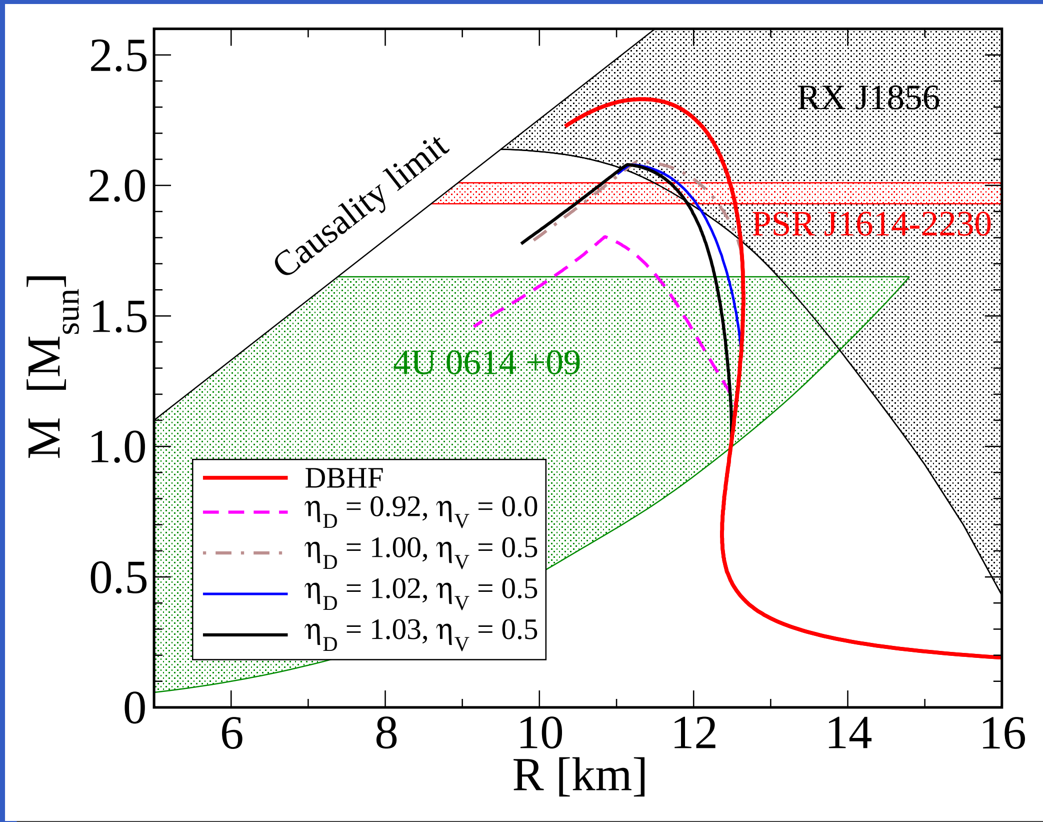


(Sagert, Tolos, Chatterjee, JSB, Sturm 2012)

- RMF parameter set TM1: fitted to properties of spherical nuclei
- above a fiducial density (determined from the analysis of the KaoS heavy-ion data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f
  Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\max} = 4.2 M_{\odot} (\epsilon_0/\epsilon_f)^{1/2}$

The Future: CBM@FAIR and NICA



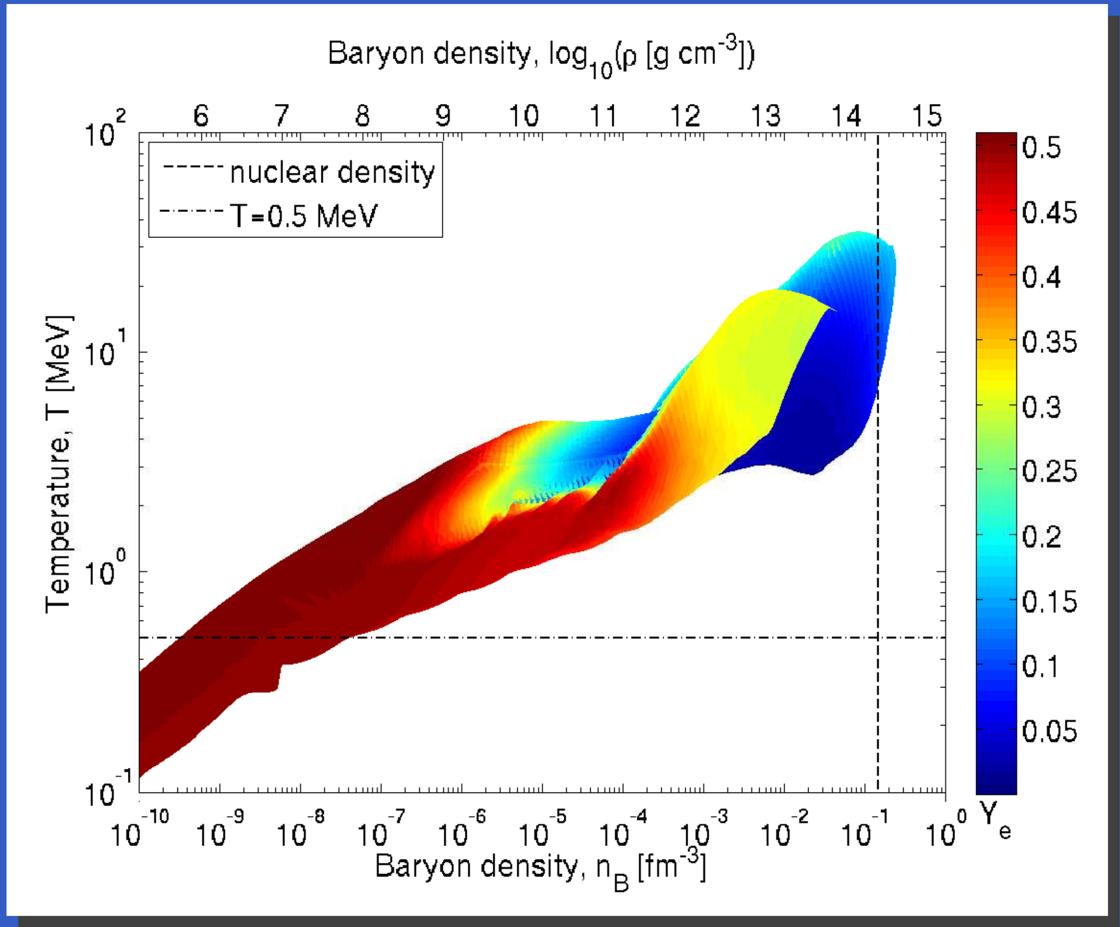


(Klähn, Blaschke, Weber 2011)

- left: equation of state and flow constraints,
  right: compatible mass-radius relations and astrophysical constraints
- higher baryon densities achieved at higher bombarding energy
- probing densities beyond $2 - 3n_0$

Symmetry Energy Impact on Core-Collapse Supernovae

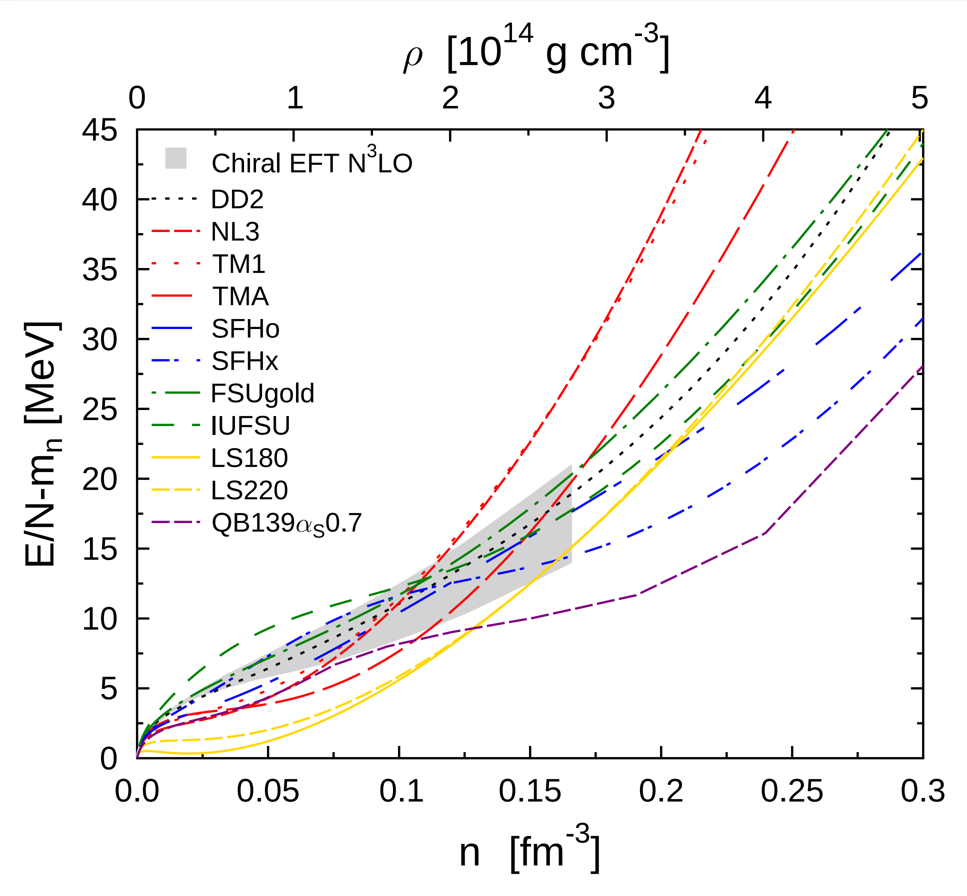
Phase Diagram for Supernova Simulations

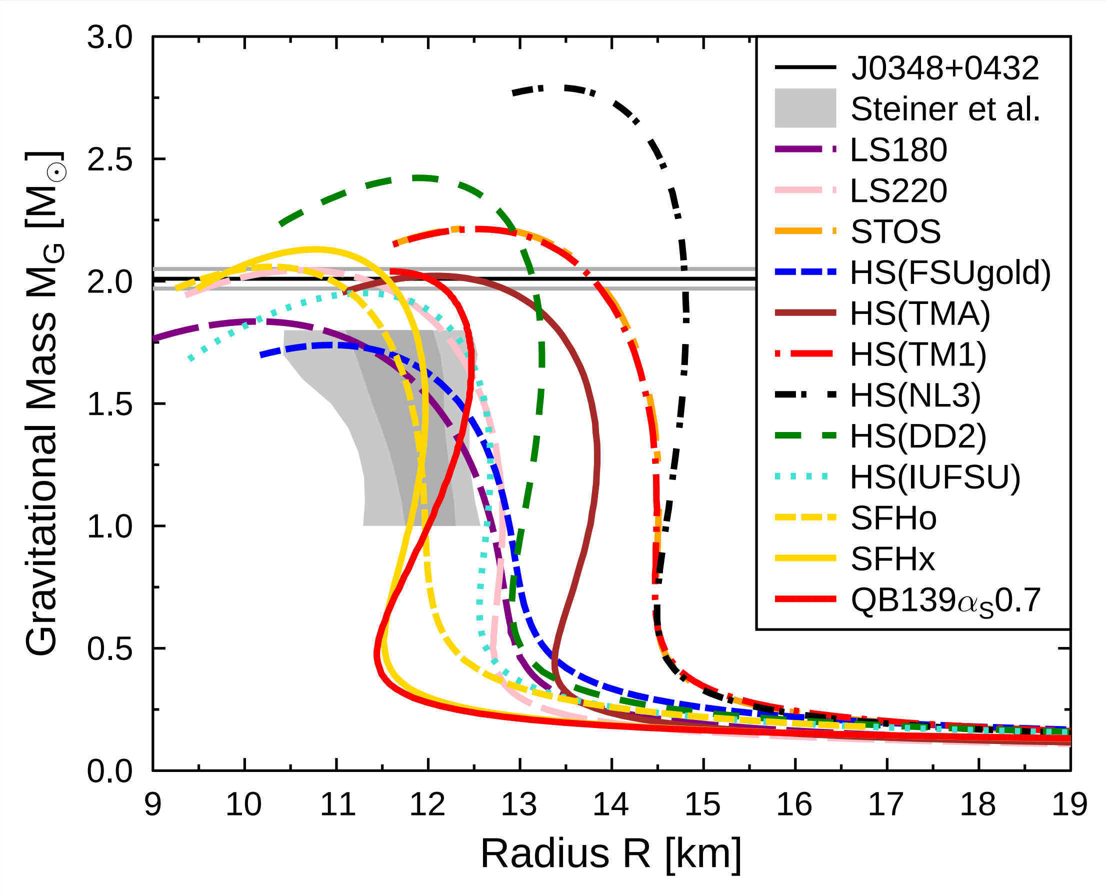


(Fischer, Hempel, Sagert, Suwa, JSB 2014)

- wide range in densities, temperatures and electron fraction needed for the EoS in core-collapse supernova simulations
- densities: $n = 10^{-10} - 10^{-1}$ fm^{-3}, temperatures: $T = 0.5 - 50$ MeV, electron to baryon fraction: $Y_e = 0 - 0.5$

Properties of available Supernovae EoS

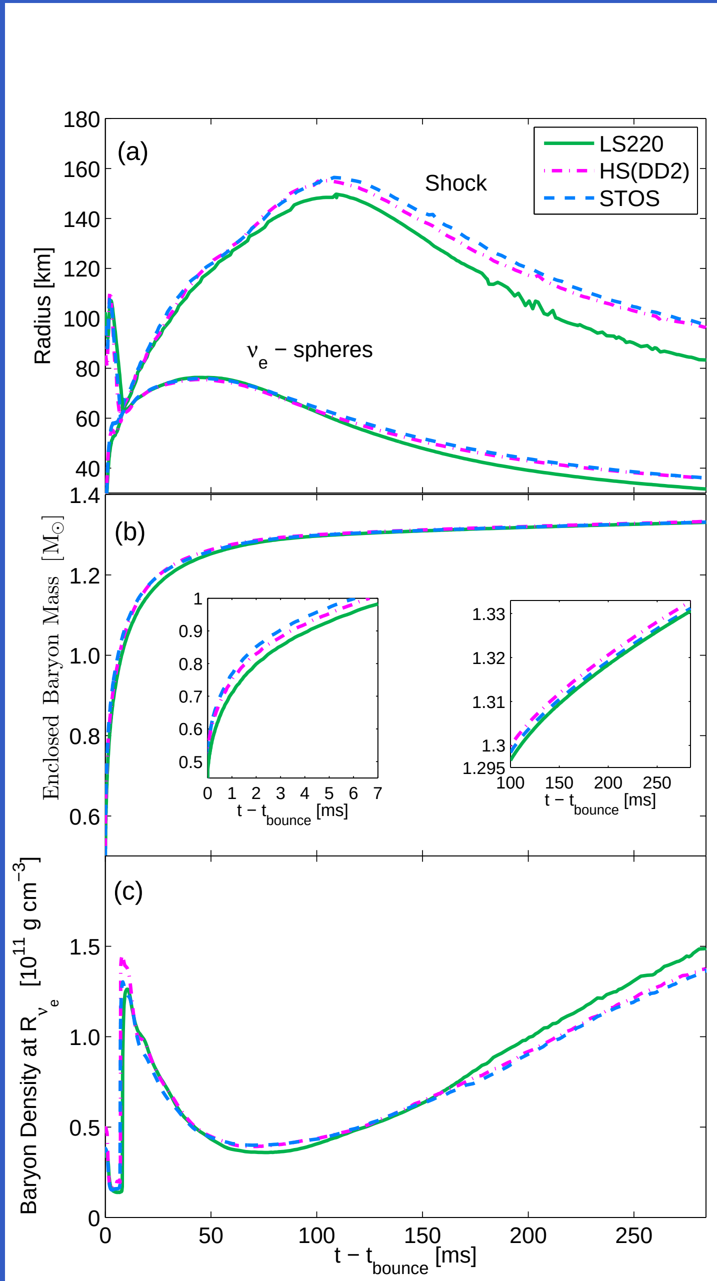




(Fischer, Hempel, Sagert, Suwa, JSB 2014)

- widely used: Lattimer and Swesty (LS220) and Shen et al. (STOS), fail to describe neutron matter (Krüger, Tews, Hebeler, Schwenk 2013)
- mass-radius relation depends on SLOPE of EoS (see e.g. IUFSU and LS220) which determines the pressure

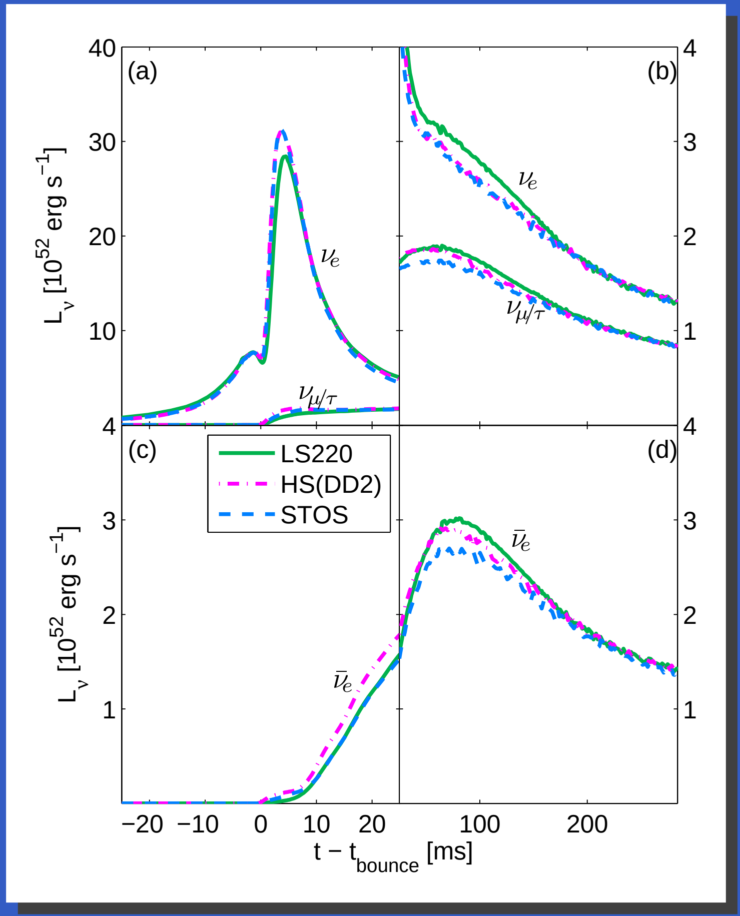
Results for Core-Collapse Supernova: Dynamics

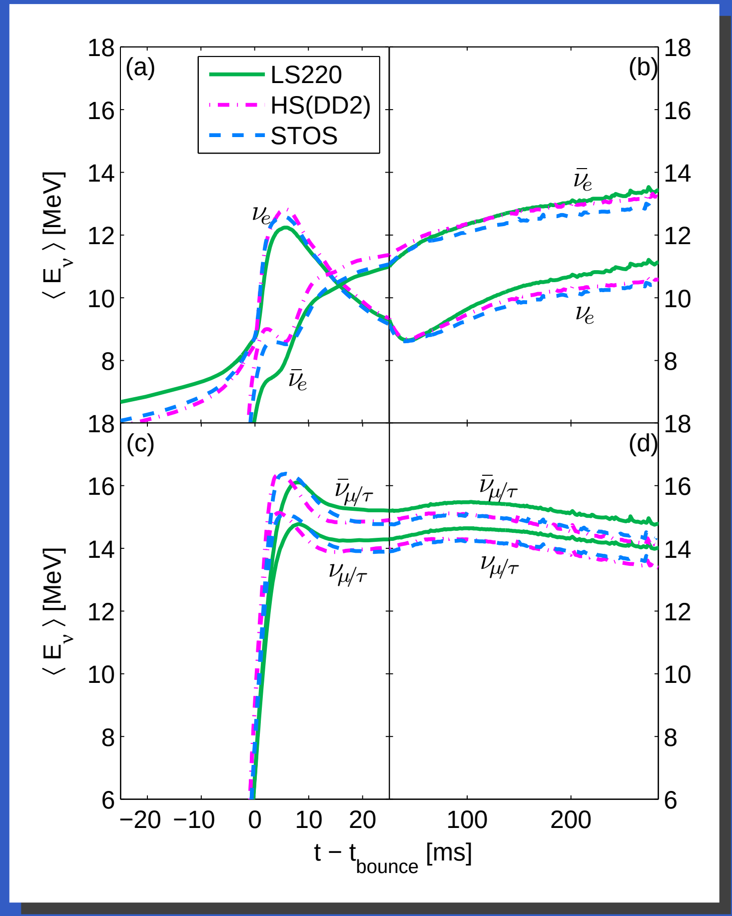


(Fischer, Hempel, Sagert, Suwa, JSB 2014)

- post-bounce evolution for shock radius, enclosed mass and baryon density at neutrino sphere
- shock radius turns around: no explosion in 1D
- radius of neutrino-sphere: decoupling of neutrinos
- neutrinos decouple around 10^{11} g cm^{-3} (energy dependent)
- small changes for different neutron matter EoS

Results for Core-Collapse Supernova: Neutrinos

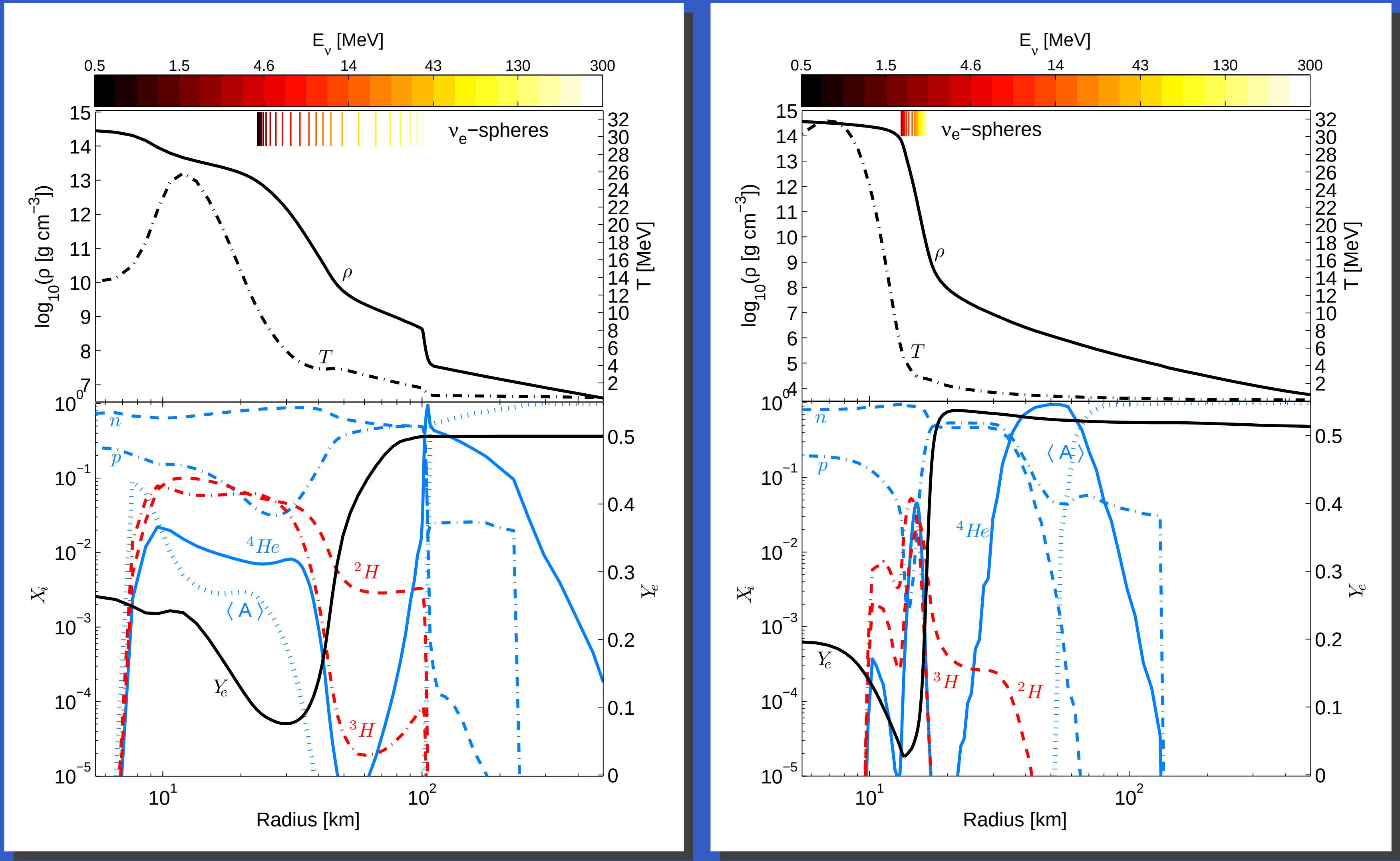




(Fischer, Hempel, Sagert, Suwa, JSB 2014)

- simulation in 1D with $11.2 M_\odot$ progenitor star
- small differences for different neutron matter EoS for the neutrino signal
- pressure of isospin symmetric part dominates due to high temperature

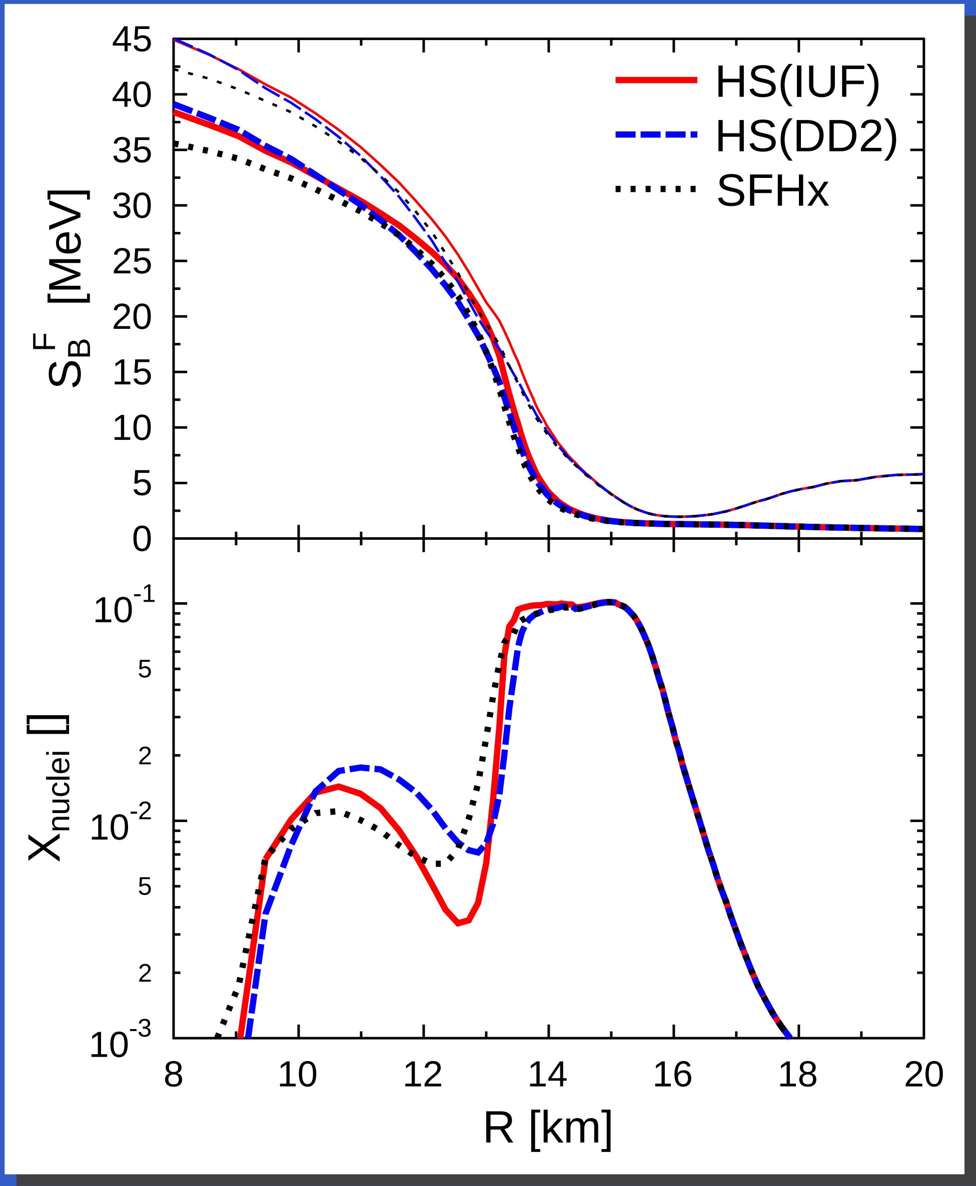
Results for Core-Collapse Supernova: Nuclei



(Fischer, Hempel, Sagert, Suwa, JSB 2014)

- particle and nuclei abundances for mass accretion phase (left: 250ms) and proto-neutron star deleptonization phase (right: 5s)

Abundance of Nuclei



(Fischer, Hempel, Sagert, Suwa, JSB 2014)

- consider isospin dependent part of the free energy (S_B^F) as expansion (thick lines) or difference of neutron to nuclear matter (thin lines)
- small changes in overall nuclear abundance as only moderate densities are involved

Summary:

- analysis of kaon production provides a constraint on the nuclear EoS (nucleon potential) at $2-3n_0$
- implications for neutron stars:
  - radii of light neutron stars: only controlled by asymmetry potential
  - maximum mass of neutron stars: lower than $3M_\odot$ due to causality arguments
- impact of symmetry energy on core-collapse supernovae:
  - small differences for neutrino signal
  - small effects in nuclear composition shortly after bounce
  - role of symmetry energy for proto-neutron star evolution at later times?

Thanks to:

- Debarati Chatterjee (Caen)
- Tobias Fischer (Wroclaw)
- Matthias Hempel (Basel)
- Irina Sagert (Los Alamos)
- Christian Sturm (GSI Darmstadt)
- Yudai Suwa (Kyoto)
- Laura Tolos (Barcelona)