

Constraints on Neutron Star Properties from KaoS Heavy-Ion Data

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HEIDELBERG



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Work done in collaboration with:

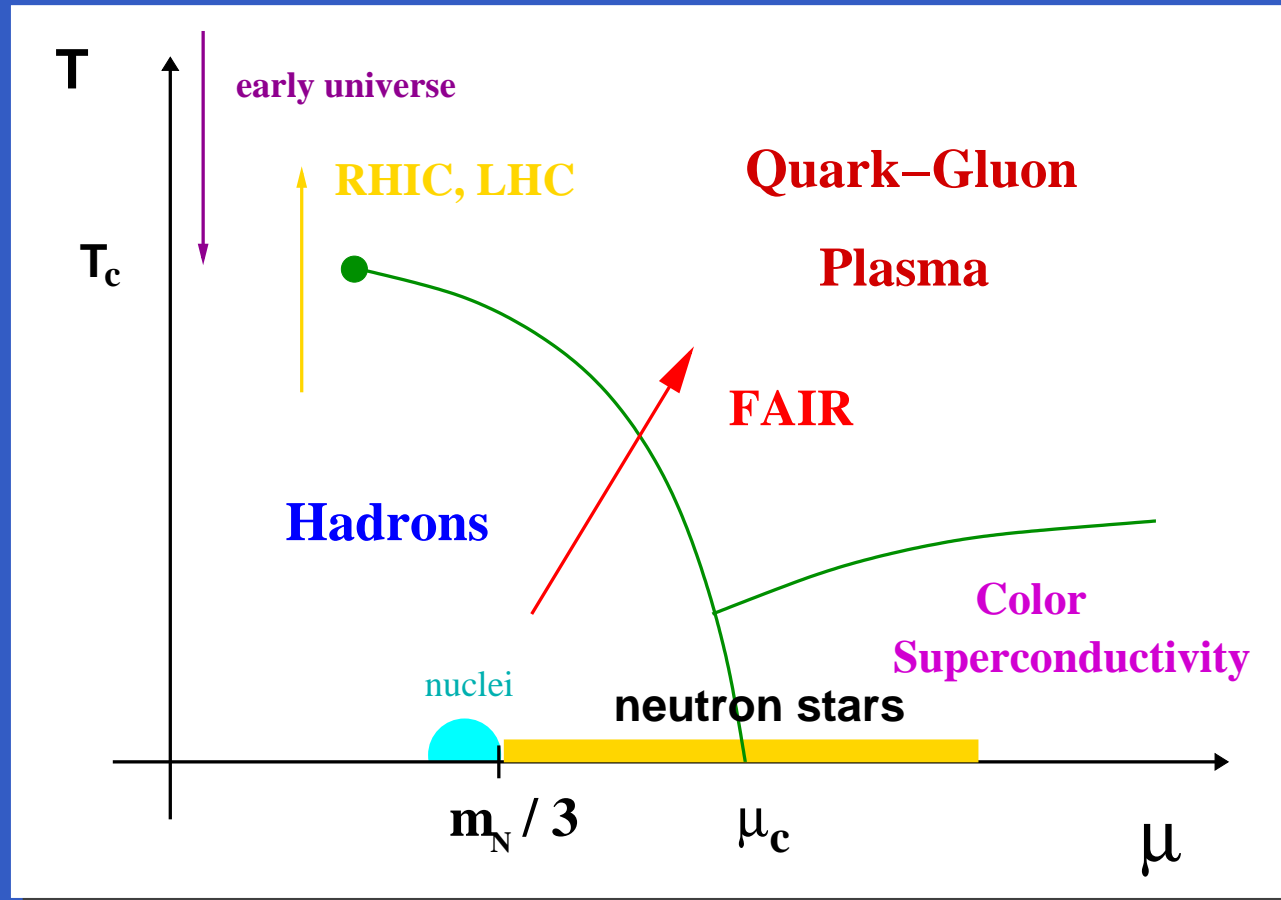
Irina Sagert, Laura Tolos, Debarati Chatterjee,
and Christian Sturm

e-Print: [arXiv:1111.6058](https://arxiv.org/abs/1111.6058) [astro-ph.SR], PRC in press

Outline

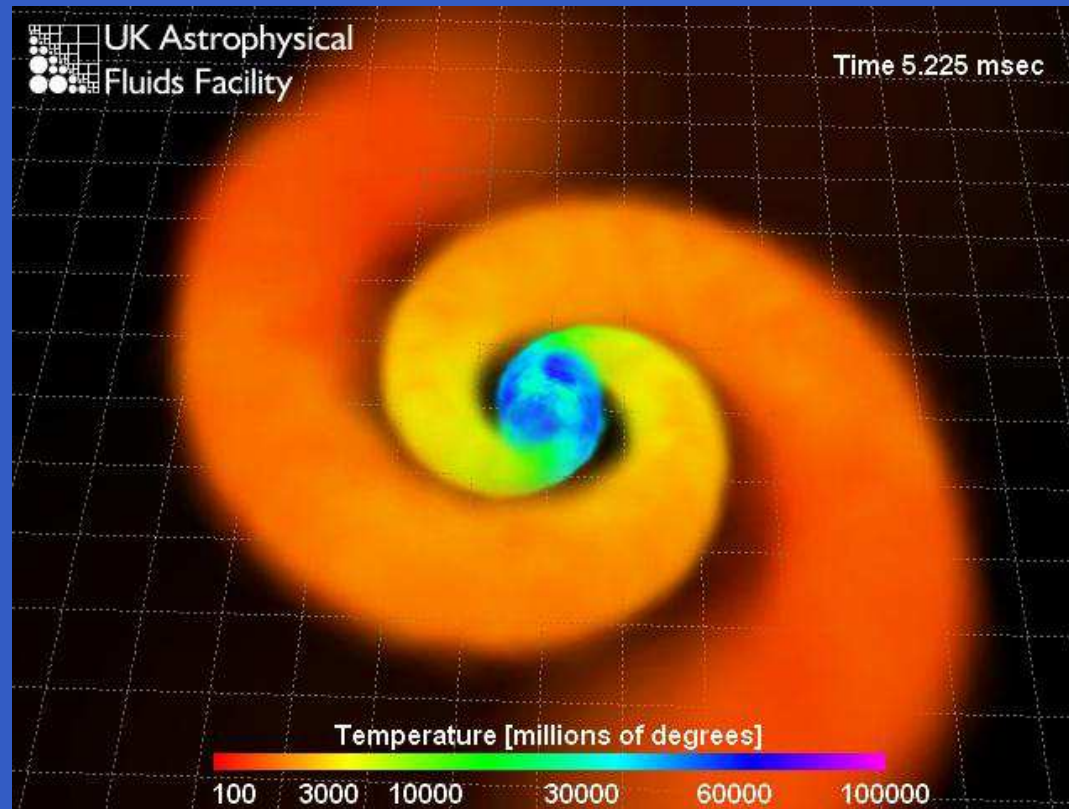
- Introduction: Neutron Star Masses
- Nuclear EoS from kaon production in heavy-ion collisions
- Implications for neutron stars:
 - Neutron star radii for light neutron stars
 - Maximum possible neutron star mass
- Summary

Phase Diagram of Quantum Chromodynamics QCD



- Early universe at zero density and high temperature
- neutron star matter at small temperature and high density
- first order phase transition at high density (not deconfinement!)
- probed by heavy-ion collisions at GSI, Darmstadt (FAIR)

Nuclear Equation of State as Input in Astrophysics

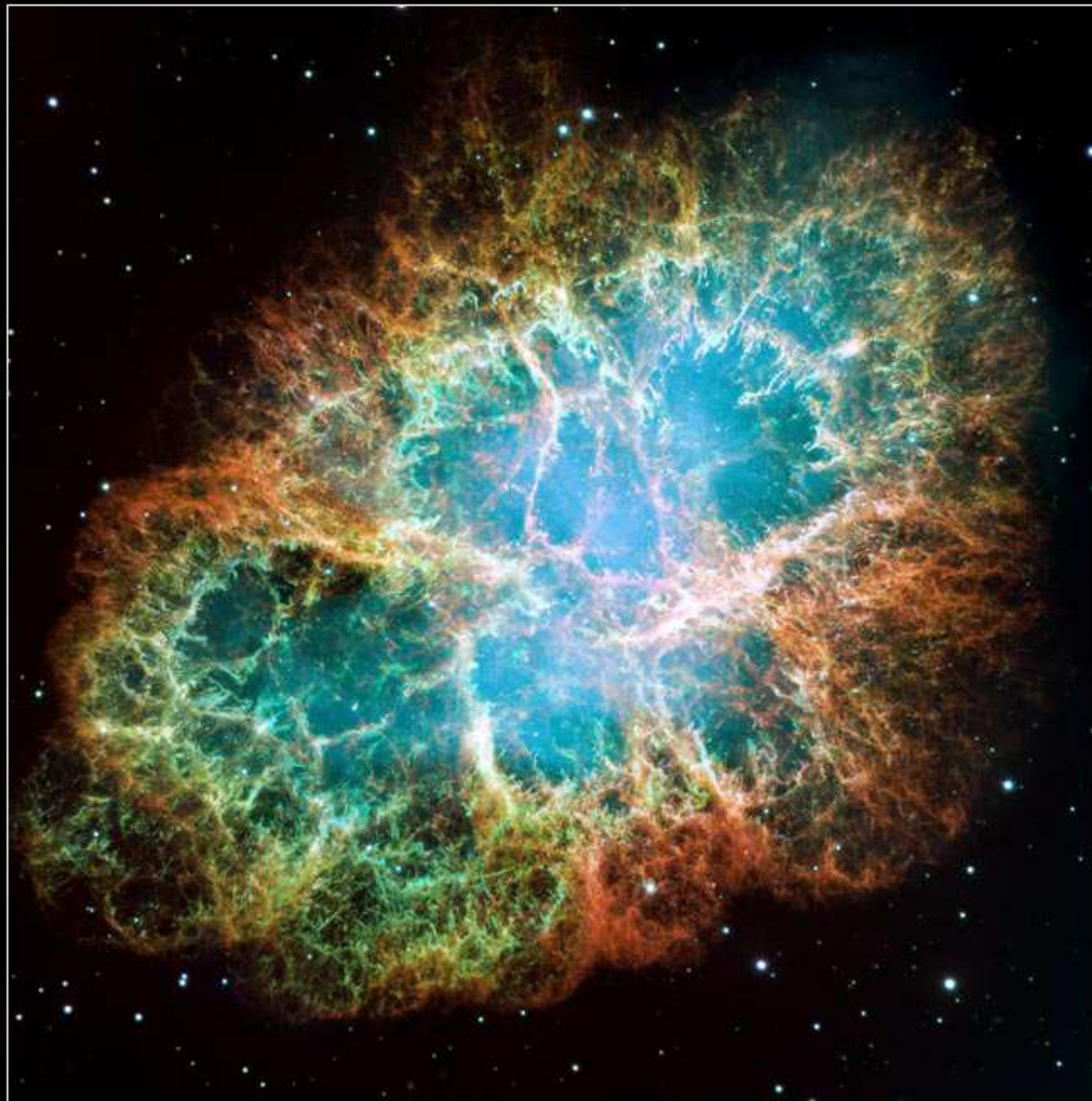


- supernovae simulations: $T = 1\text{--}50$ MeV, $n = 10^{-10}\text{--}2n_0$
- proto-neutron star: $T = 1\text{--}50$ MeV, $n = 10^{-3}\text{--}10n_0$
- global properties of neutron stars: $T = 0$, $n = 10^{-3}\text{--}10n_0$
- neutron star mergers: $T = 0\text{--}100$ MeV, $n = 10^{-10}\text{--}10n_0$

Neutron Stars

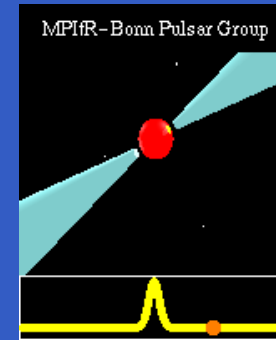
Crab Nebula ■ M1

HST ■ WFPC2



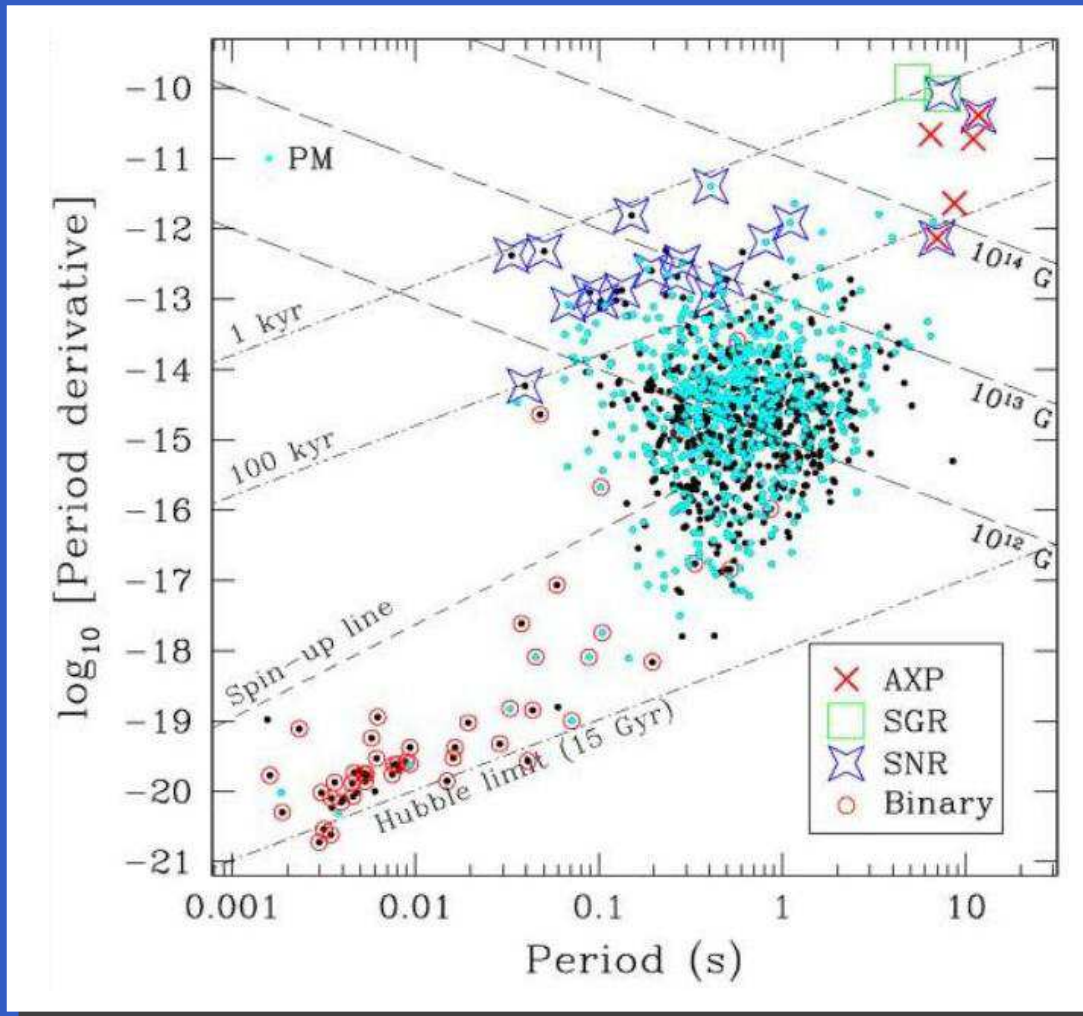
NASA, ESA, and J. Hester (Arizona State University)

STScI-PRC05-37



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

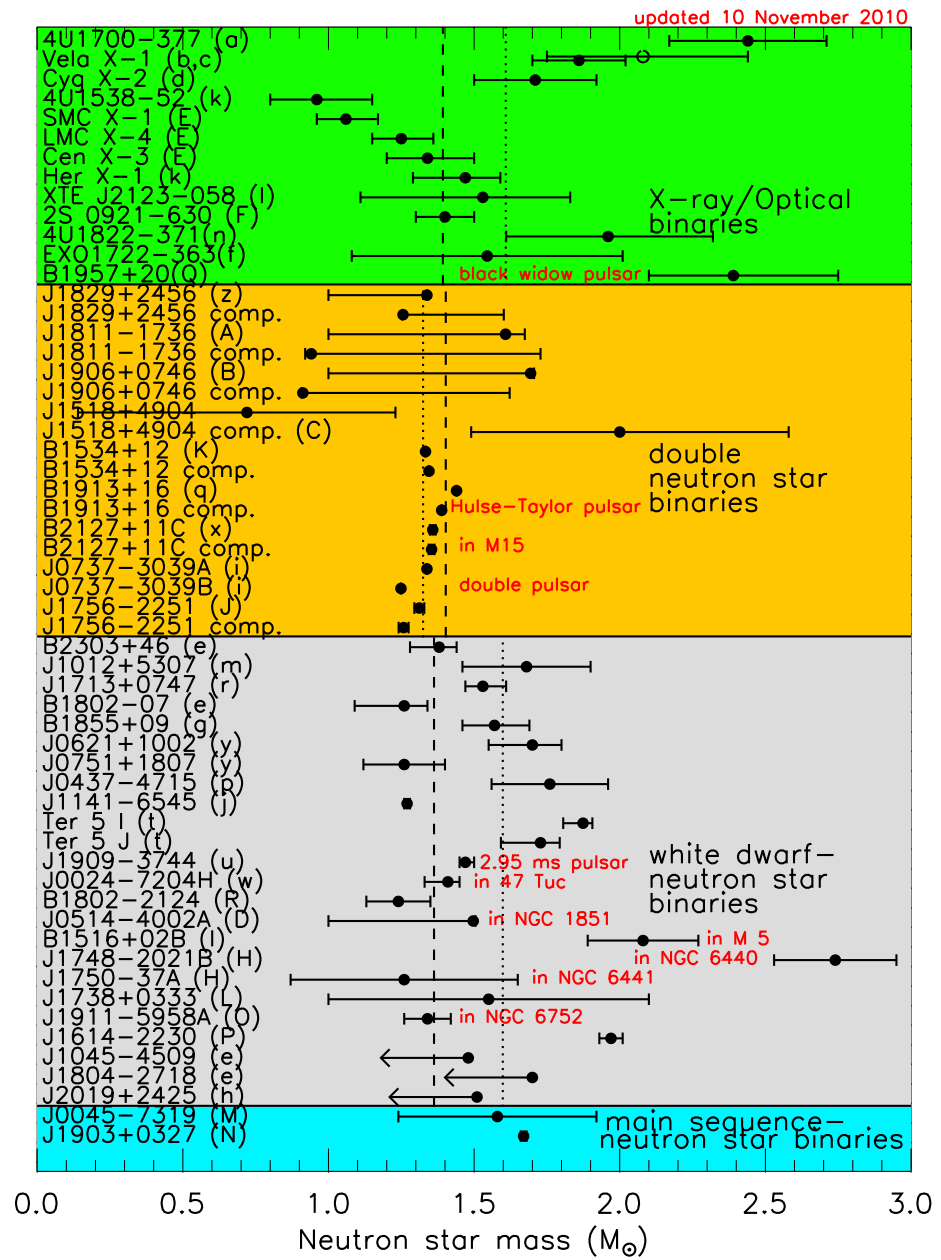
The Pulsar Diagram



(ATNF pulsar catalog)

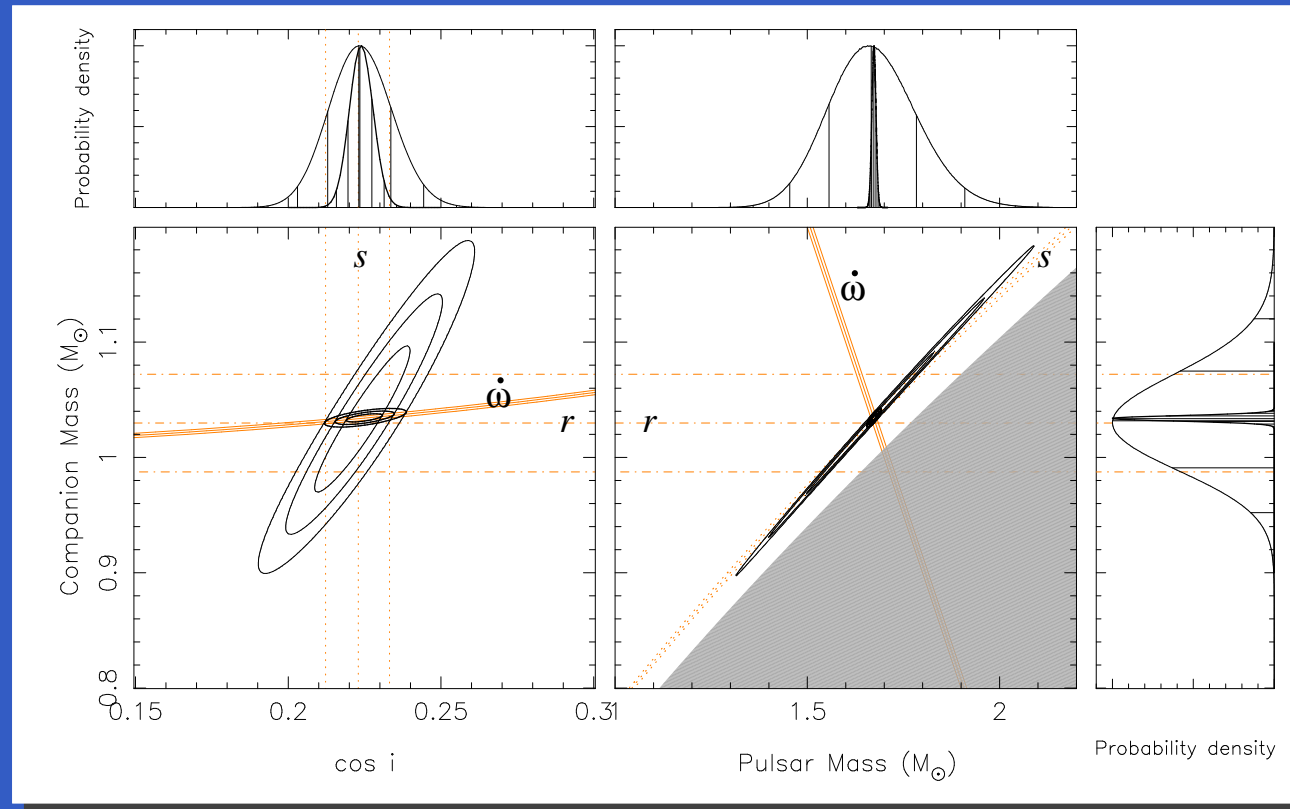
- the diagram for pulsars: period versus period change ($P-\dot{P}$)
- dipole model for pulsars:
characteristic age: $\tau = P/(2\dot{P})$
and magnetic field
 $B = 2 \cdot 10^{19} (P \cdot \dot{P})^{1/2}$ Gauss
- anomalous x-ray pulsars: AXP,
soft-gamma ray repeaters:
SGR, young pulsars in
supernova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

Masses of Pulsars (Lattimer and Prakash 2011)



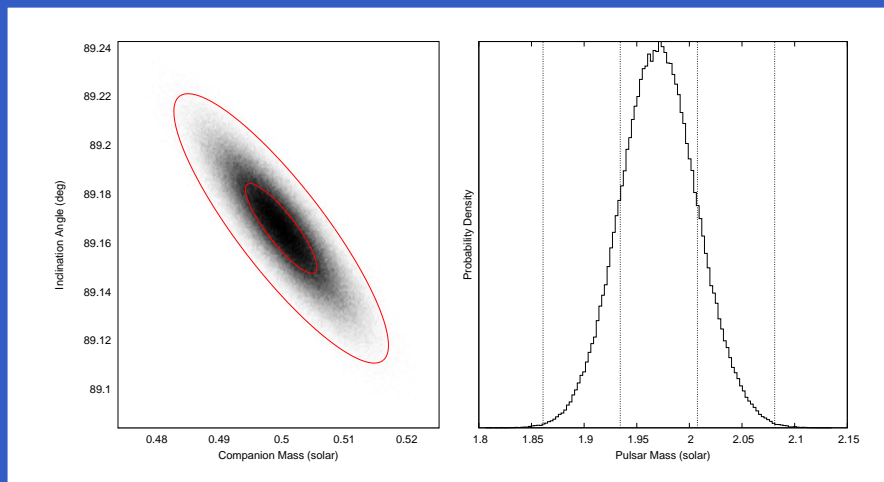
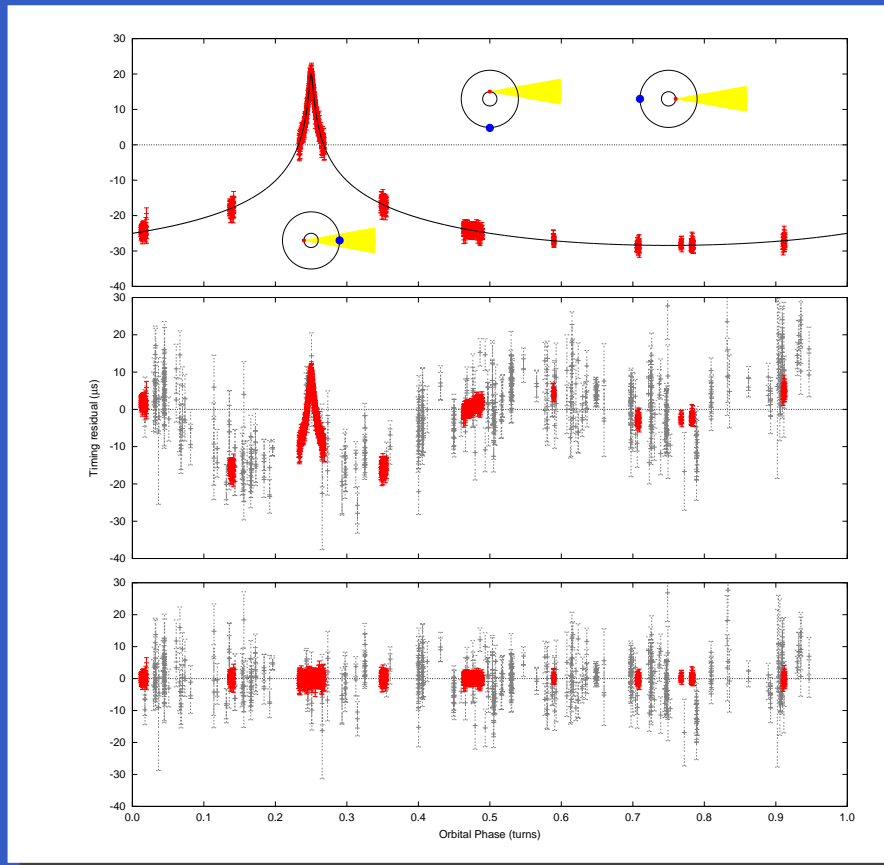
- nearly 2000 pulsars known with 140 binary pulsars
- best determined mass:
 $M = (1.4414 \pm 0.0002) M_{\odot}$
 Hulse-Taylor pulsar
 (Weisberg and Taylor, 2004)
- very high mass of
 $M = (2.74 \pm 0.21) M_{\odot}$ for
 PSR 1748-2021B
 (statistical analysis in inclination angle)
 (Freire et al. 2007)

Mass measurement of pulsar PSR J1903+0327 (Freire 2009)



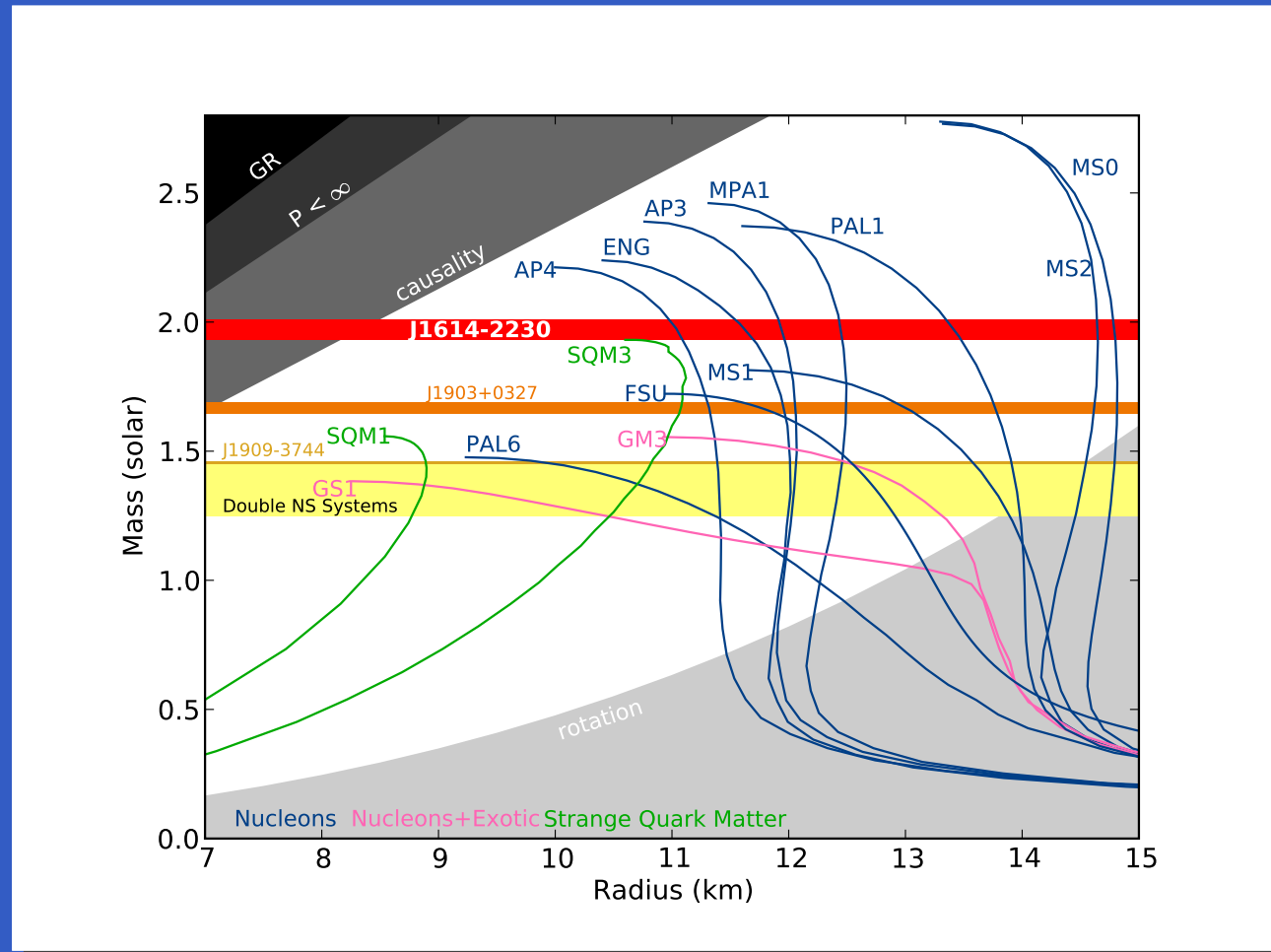
- measure post-Keplerian parameters from pulsar timing
- Shapiro delay parameters r and s alone constrain $M = (1.67 \pm 0.11)M_{\odot}$
- combined with periastron advance $\dot{\omega}$: $M = (1.67 \pm 0.01)M_{\odot}$
- rotation of the companion star could influence $\dot{\omega}$
(follow-up observation with Hubble planned)

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!

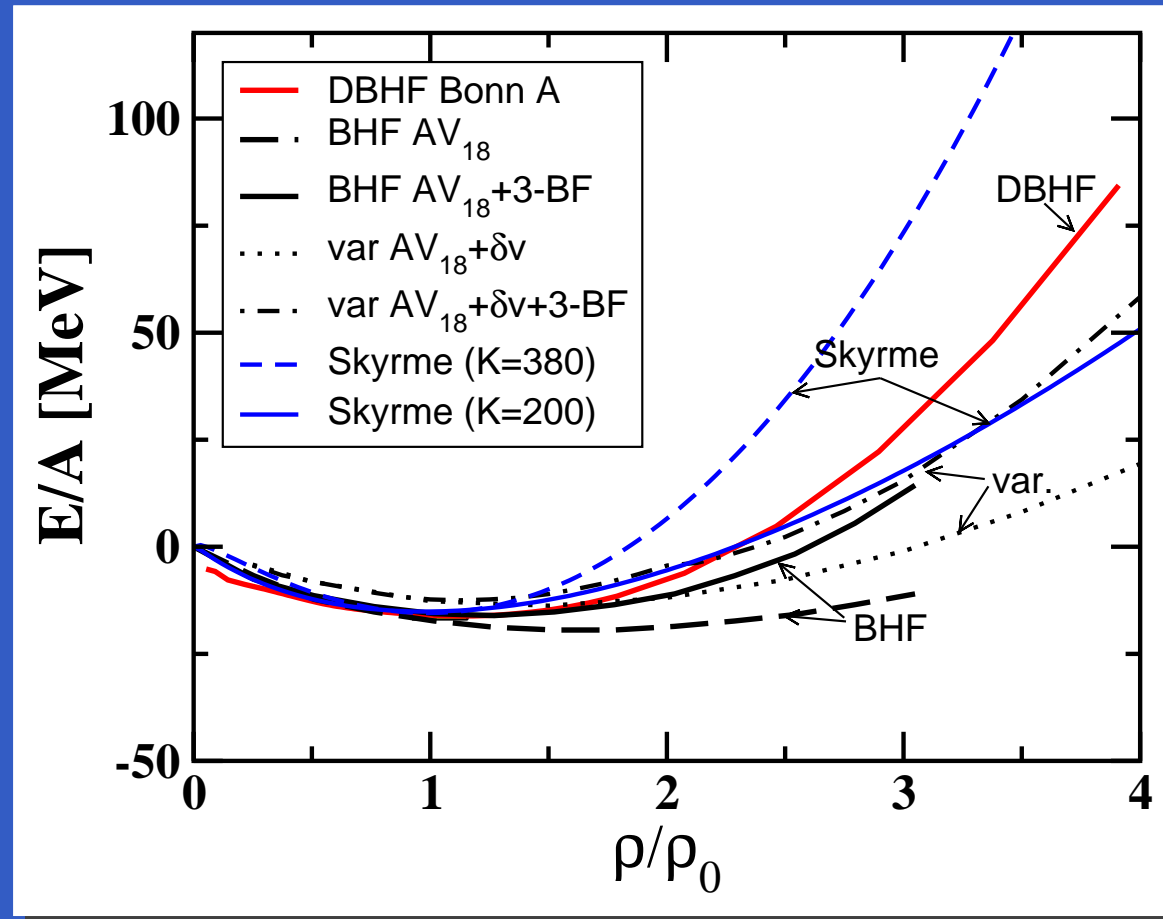
Constraints on the Mass–Radius Relation (Lattimer and Prakash 2004)



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

Kaon Subthreshold Production in Heavy-Ion Collisions

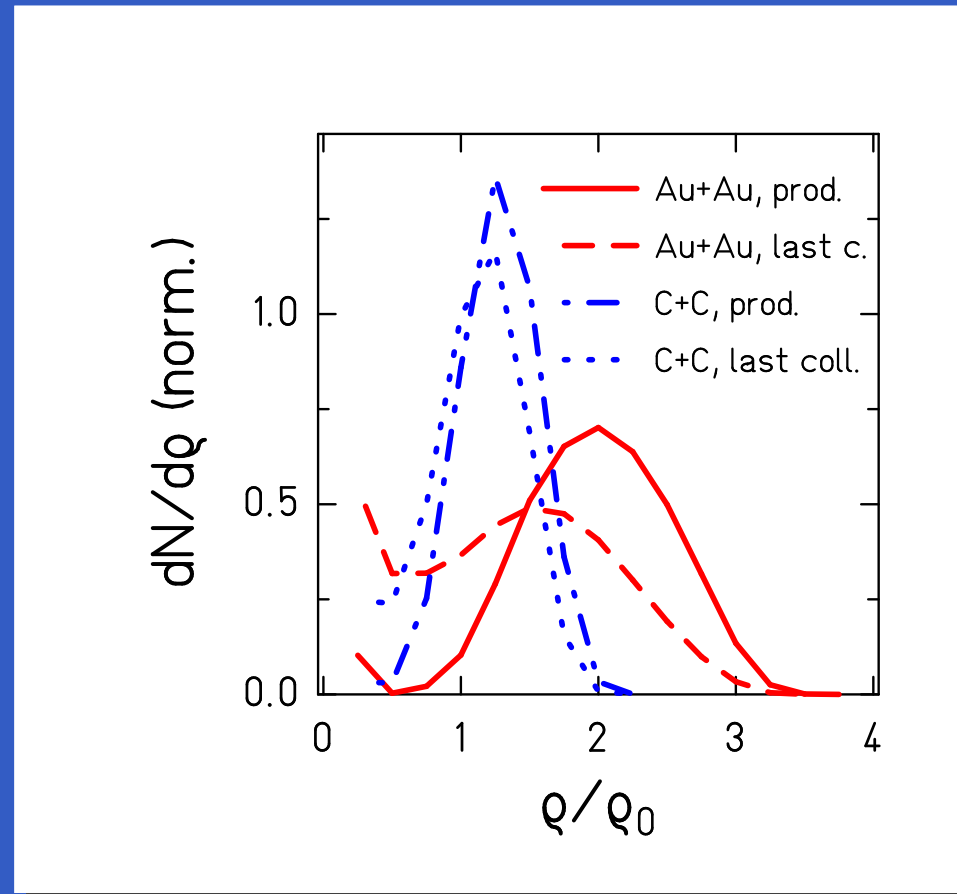
Input to transport models: the nucleon potential



(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

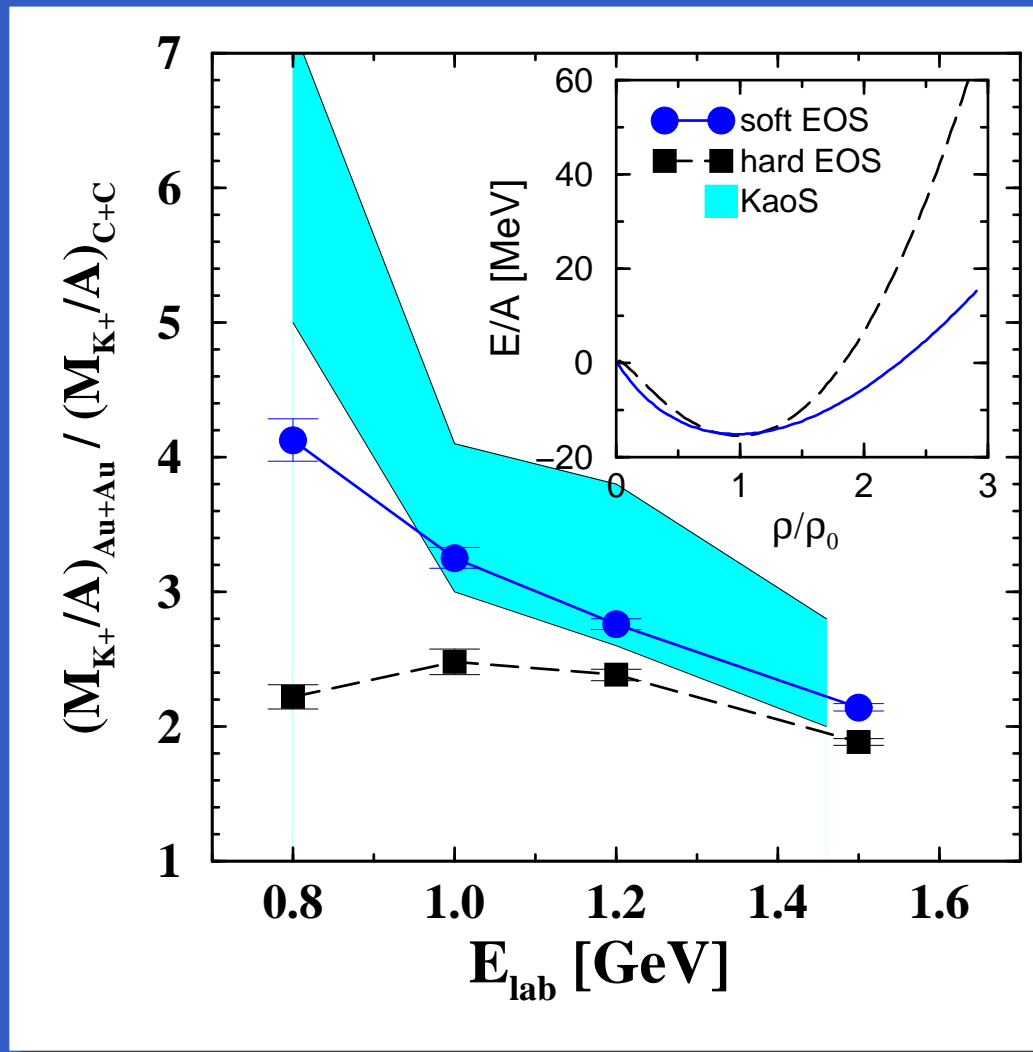
Heavy-ion collisions: density range probed with kaons



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

- kaon production by associated production: $NN \rightarrow N\Lambda K$, $NN \rightarrow NNK\bar{K}$
- 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

Kaon production in heavy-ion collisions

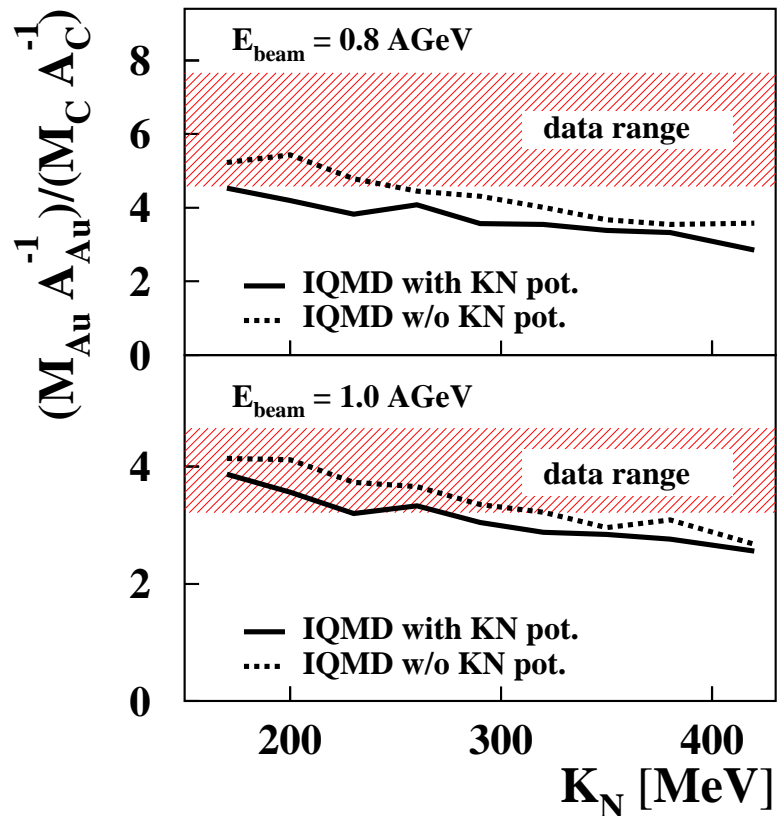


- nuclear matter is compressed up to $2 - 3n_0!$
- long mean-free path of kaons: kaons can escape high density matter
- clear trend indicating high compression
→ a soft EoS

Sturm et al. (KaoS collaboration), PRL 2001

Fuchs, Faessler, Zabrodin, Zheng, PRL 2001

Confirmed KaoS data analysis: the nuclear EoS is soft!



Forster et al. (KaoS collaboration) 2007

Hartnack, Oeschler, Aichelin, 2006

⇒ the nuclear equation of state is **SOFT!**

- 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

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):

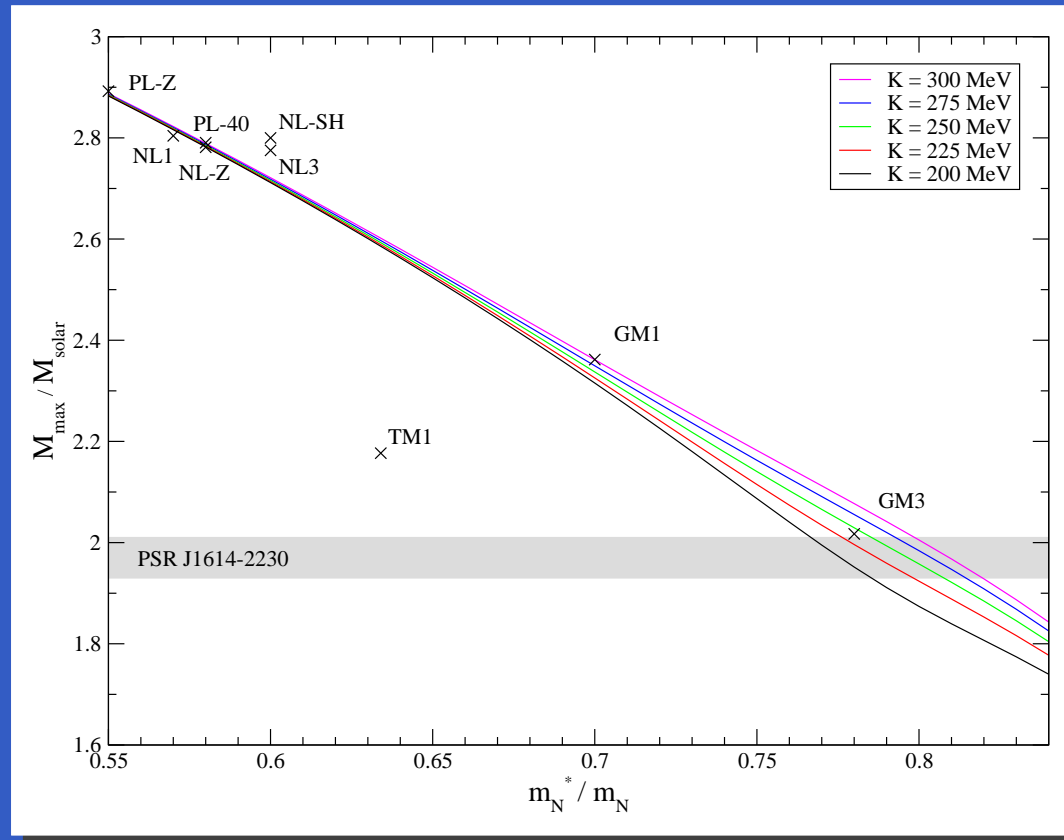
$$\epsilon/n = m_N + E_0^{kin} + \frac{A}{2} \cdot u + \frac{B}{\sigma + 1} u^\sigma + S_0 \cdot u^\gamma \cdot \left(\frac{n_n - n_p}{n} \right)^2$$

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

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

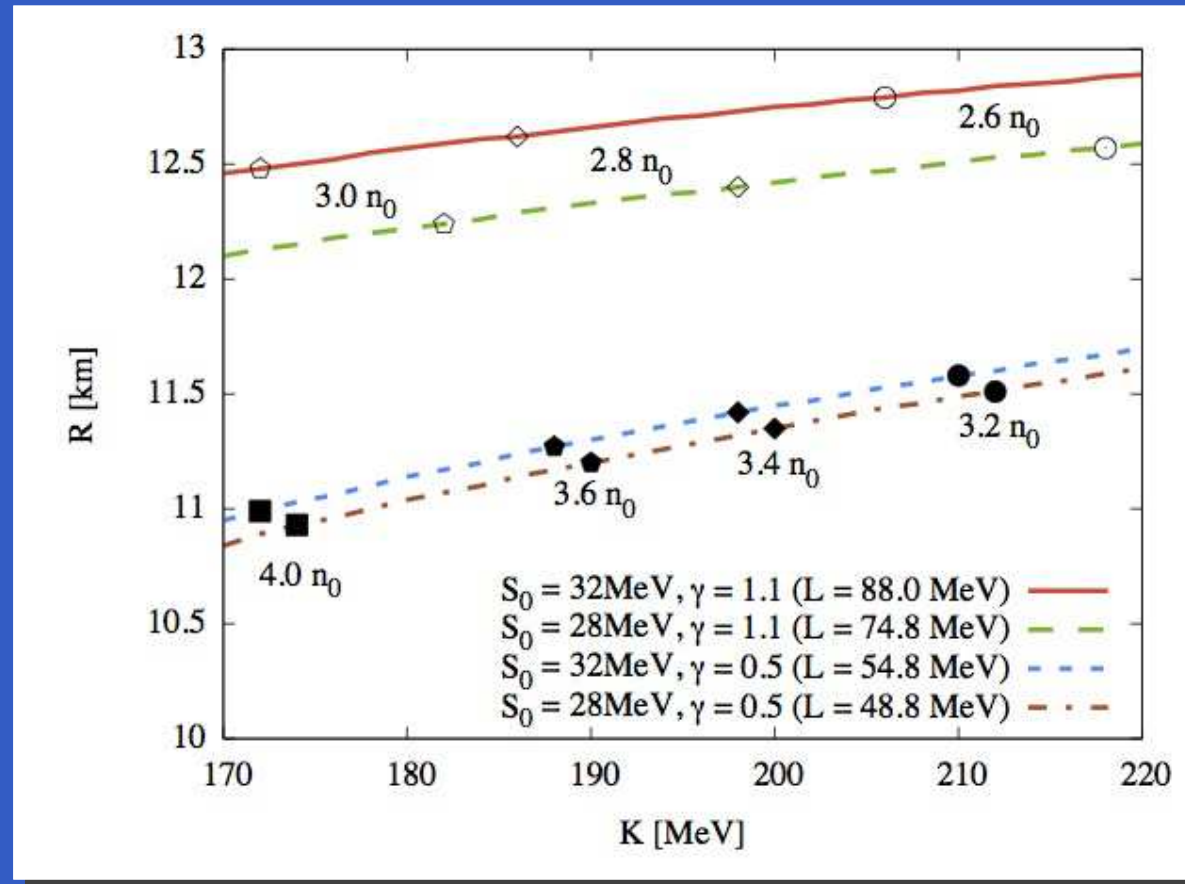
Maximum neutron star mass and compression modulus



(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 $0.1M_{\odot}$
- adopt stiffness parameter K from KaoS data analysis as a constraint on high density EoS only!

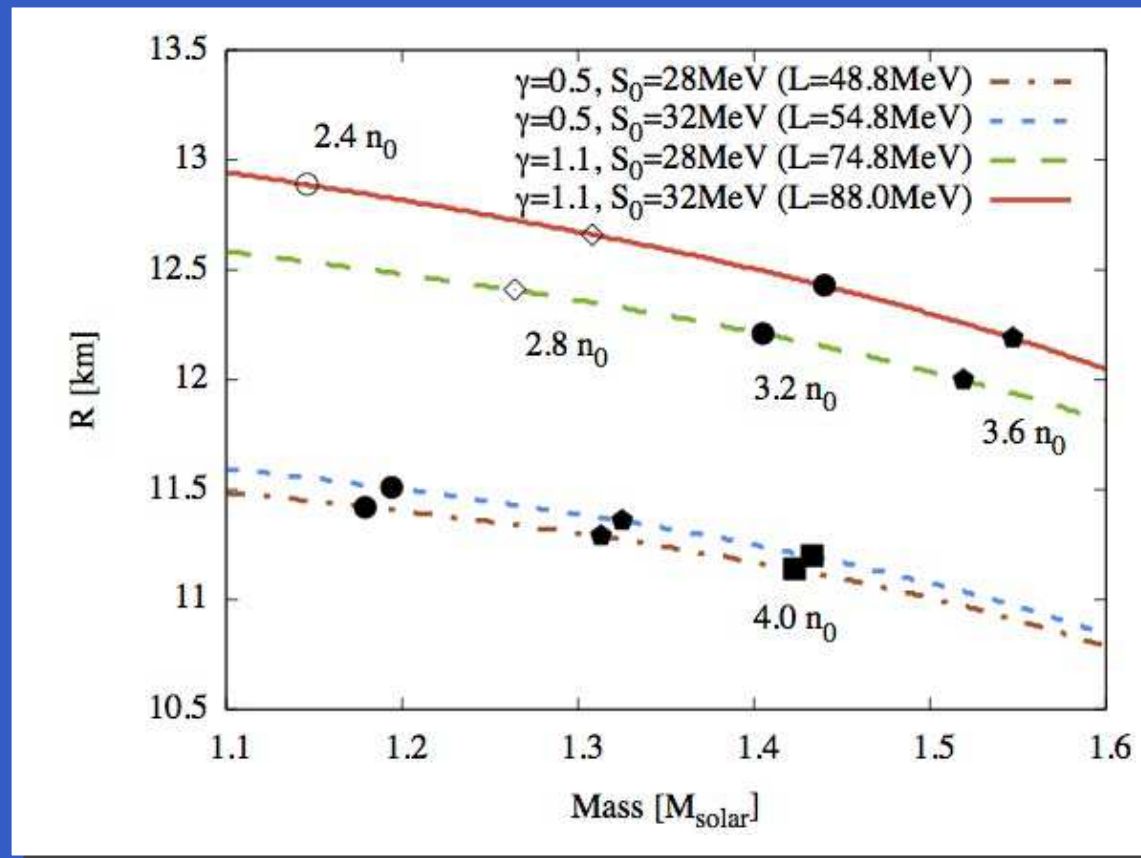
Low-Mass Neutron Star Radii and the Asymmetry Potential



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

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

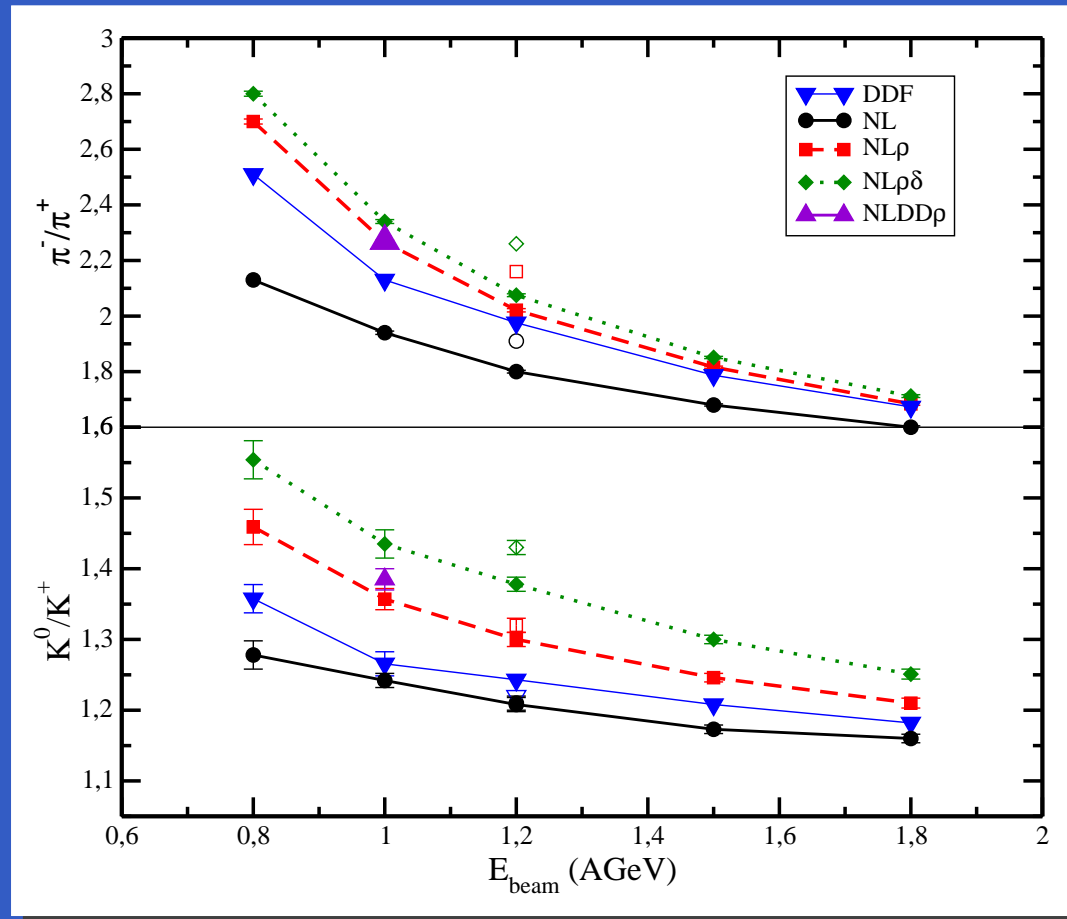
Neutron Star Radii and the Asymmetry Potential



(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

A potential measure of the isospin potential

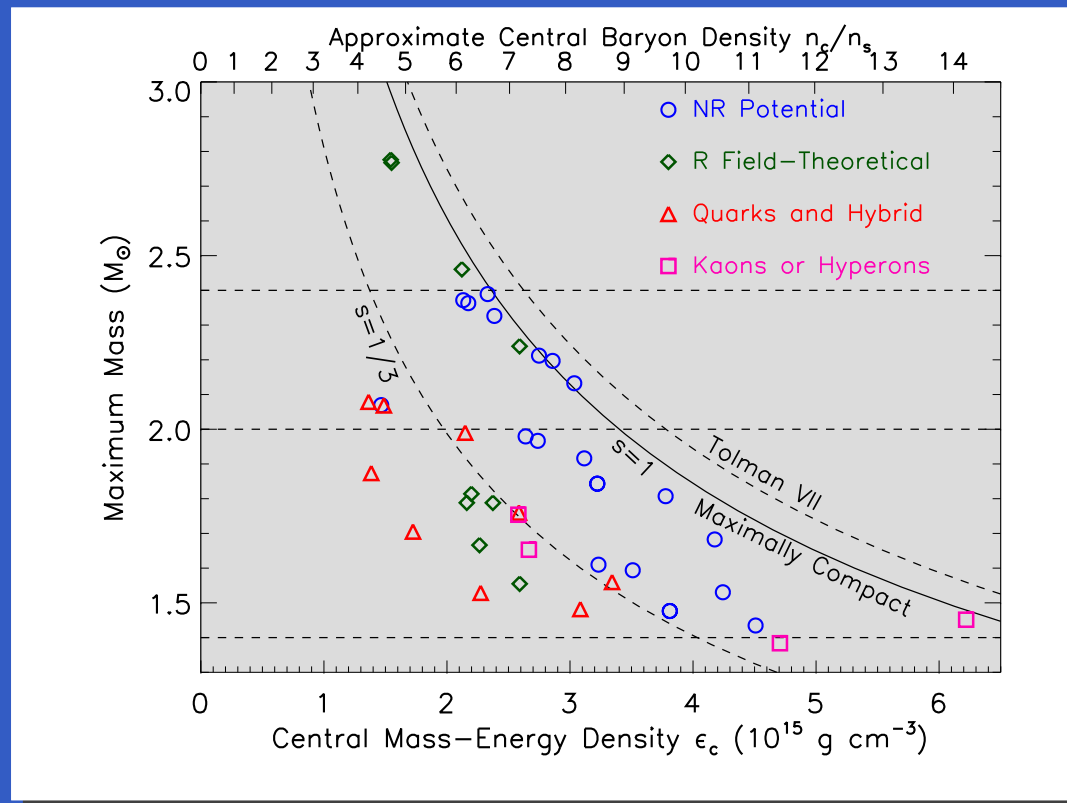


(Ferini, Gaitanos, Colonna, Di Toro, Wolter 2006)

- 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

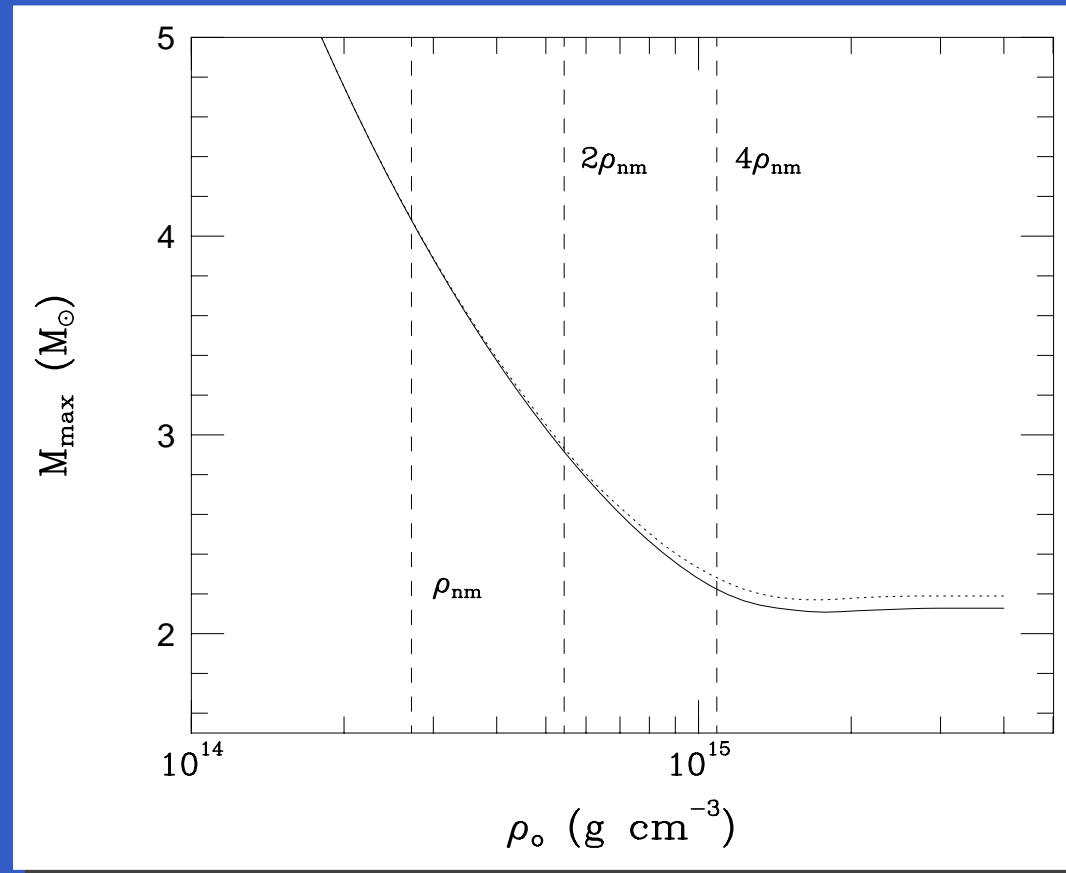
Maximum central density of a compact stars



(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: $M_{\max} = 4.1M_{\odot}(\epsilon_{\text{sat.}}/\epsilon_f)^{1/2}$
(Rhoades and Ruffini 1974, Hartle 1978, Kalogera and Baym 1996, Akmal, Pandharipande, Ravenhall 1998, Lattimer and Prakash 2011)

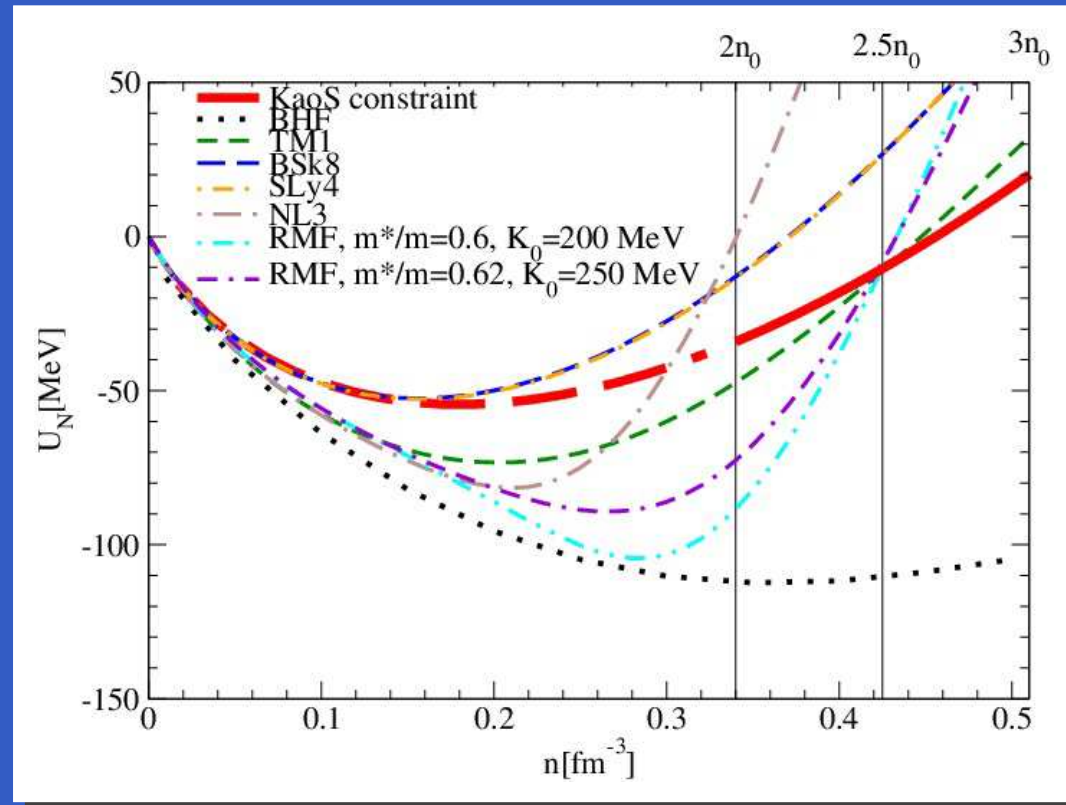
Maximum Mass from Causality Argument



(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: $M_{\max} = 4.1M_{\odot}$ at $\epsilon_f = \epsilon_{\text{saturation}}$

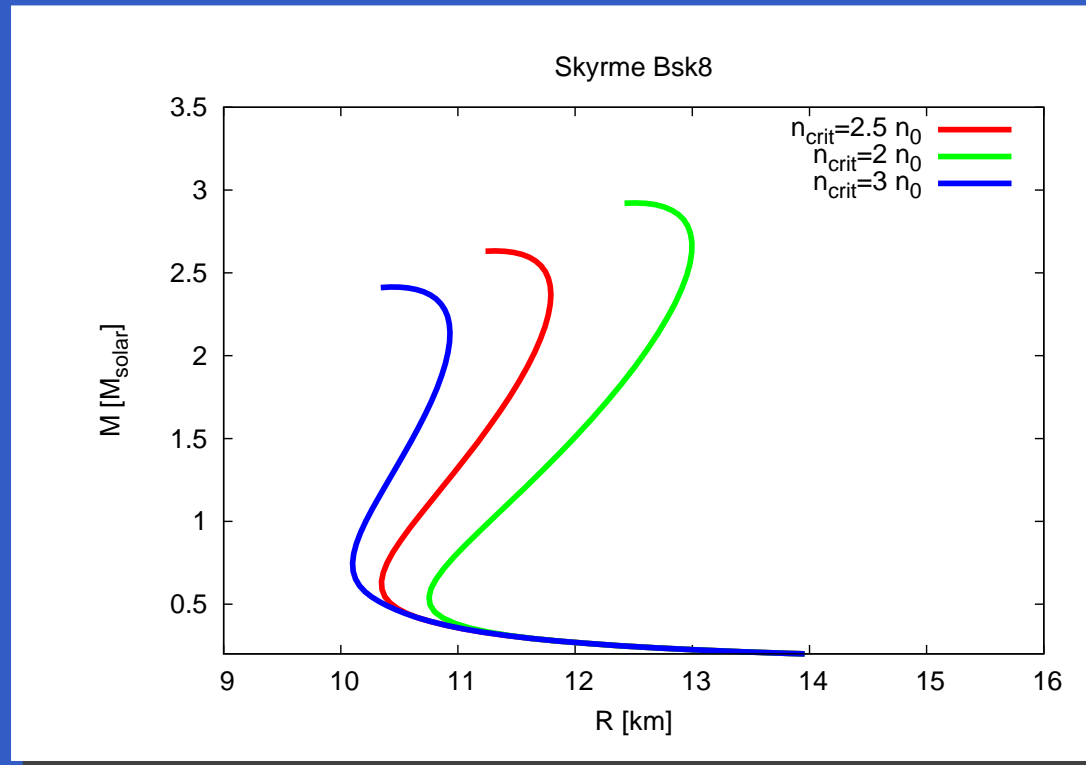
Constraint from heavy-ion data: nucleon potential at $2 - 3n_0$



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

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

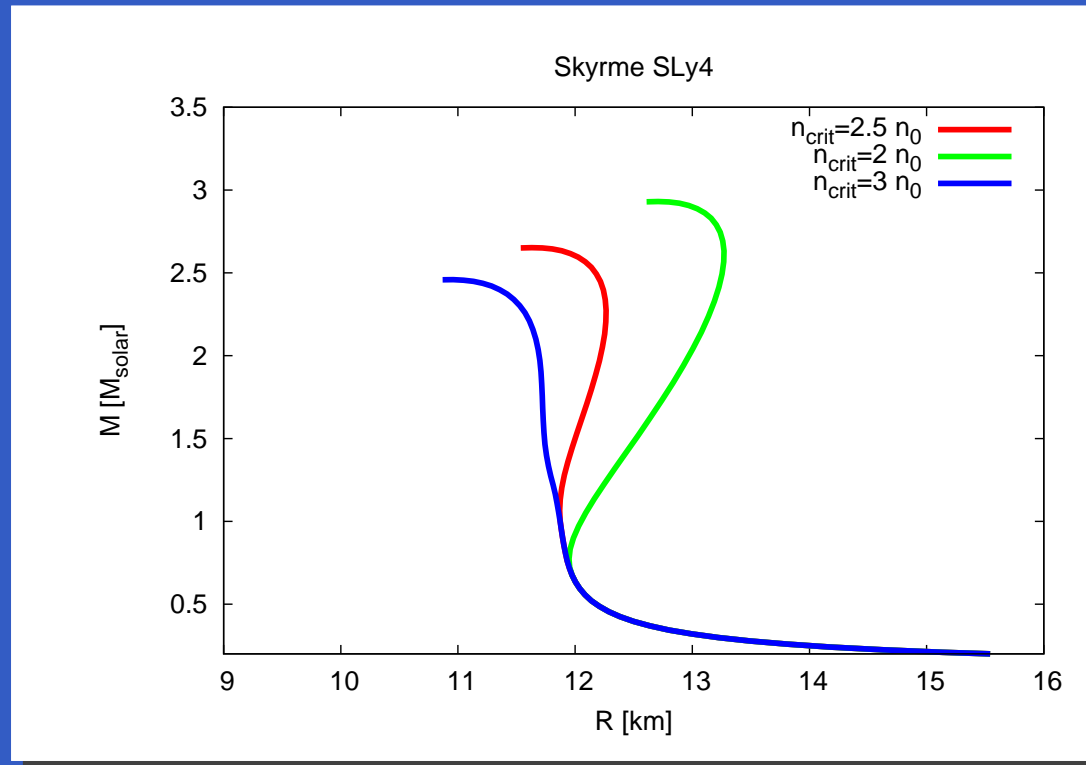
Maximum Masses of Neutron Stars – Causality



(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): $M_{\text{max}} = 4.2M_{\odot}(\epsilon_0/\epsilon_f)^{1/2}$

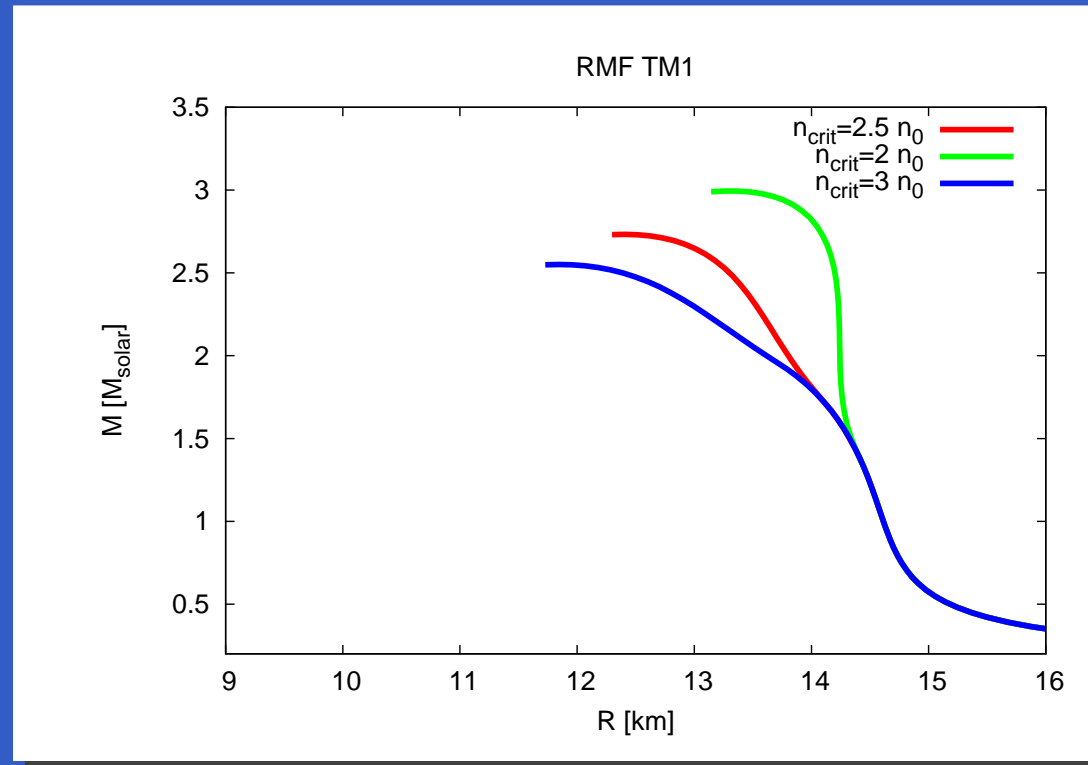
Maximum Masses of Neutron Stars – Causality



(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): $M_{\text{max}} = 4.2 M_{\odot} (\epsilon_0 / \epsilon_f)^{1/2}$

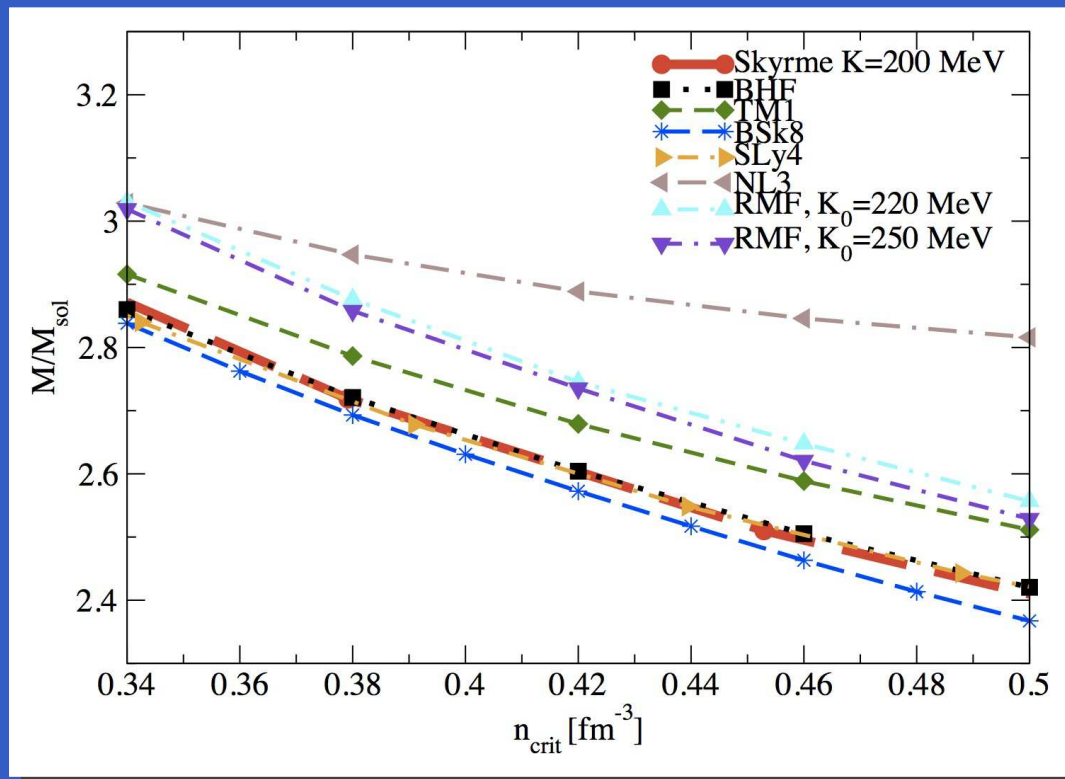
Maximum Masses of Neutron Stars – Causality



(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): $M_{\text{max}} = 4.2M_{\odot}(\epsilon_0/\epsilon_f)^{1/2}$

Constraint for neutron stars: causality plus heavy-ion data



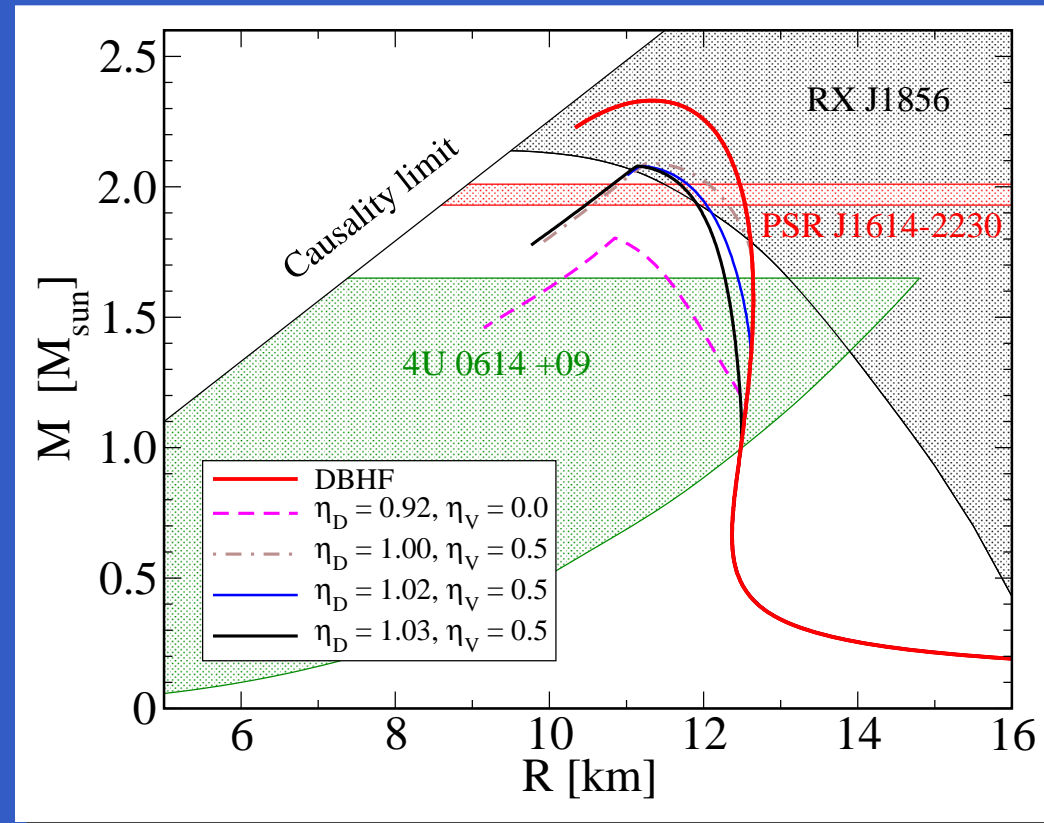
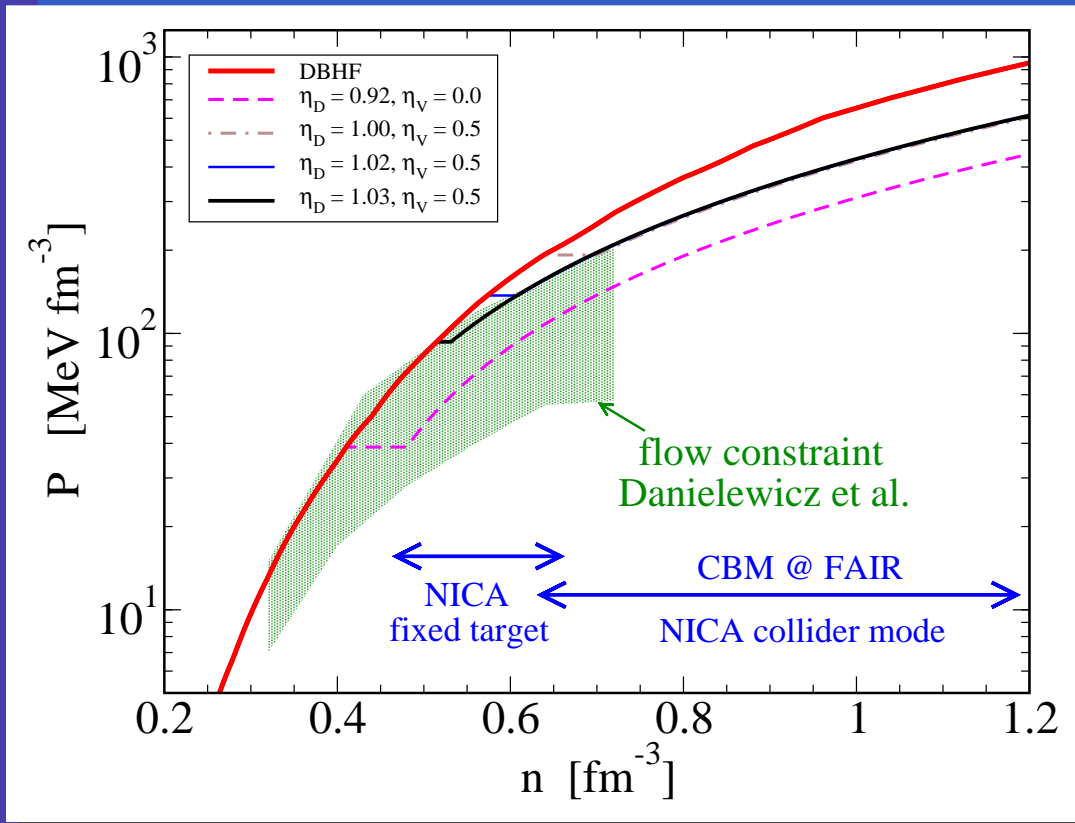
(Sagert, Tolos, Chatterjee, JSB, Sturm 2012)

- maximum mass for neutron stars versus the fiducial density
- same trend for various allowed nuclear models (NL3 is too stiff!)
- main difference: the density dependence of the asymmetry energy
- overall upper limit of a maximum mass of $M_{max} = 3M_{\odot}$ for $n_f = 2n_0$

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
- strong interplay between heavy-ion physics and astrophysics

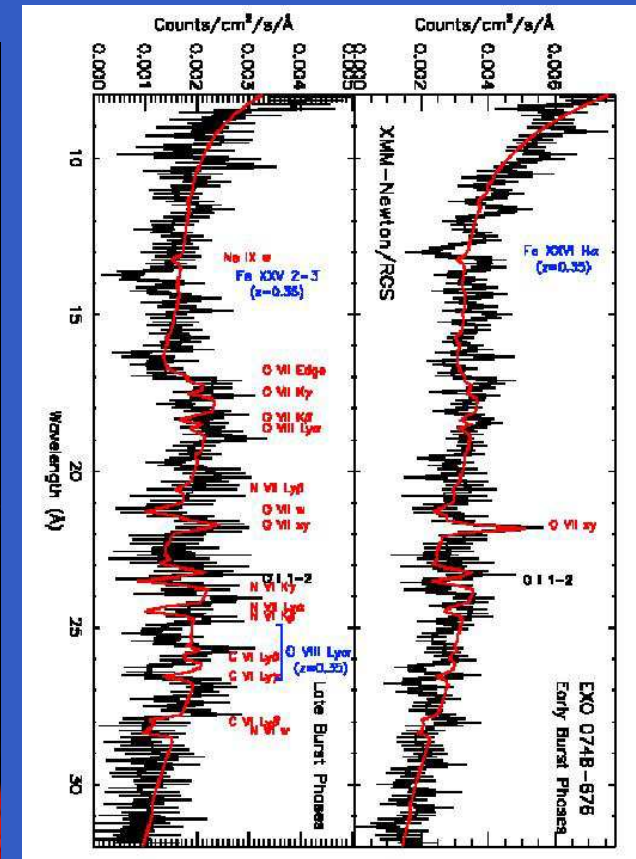
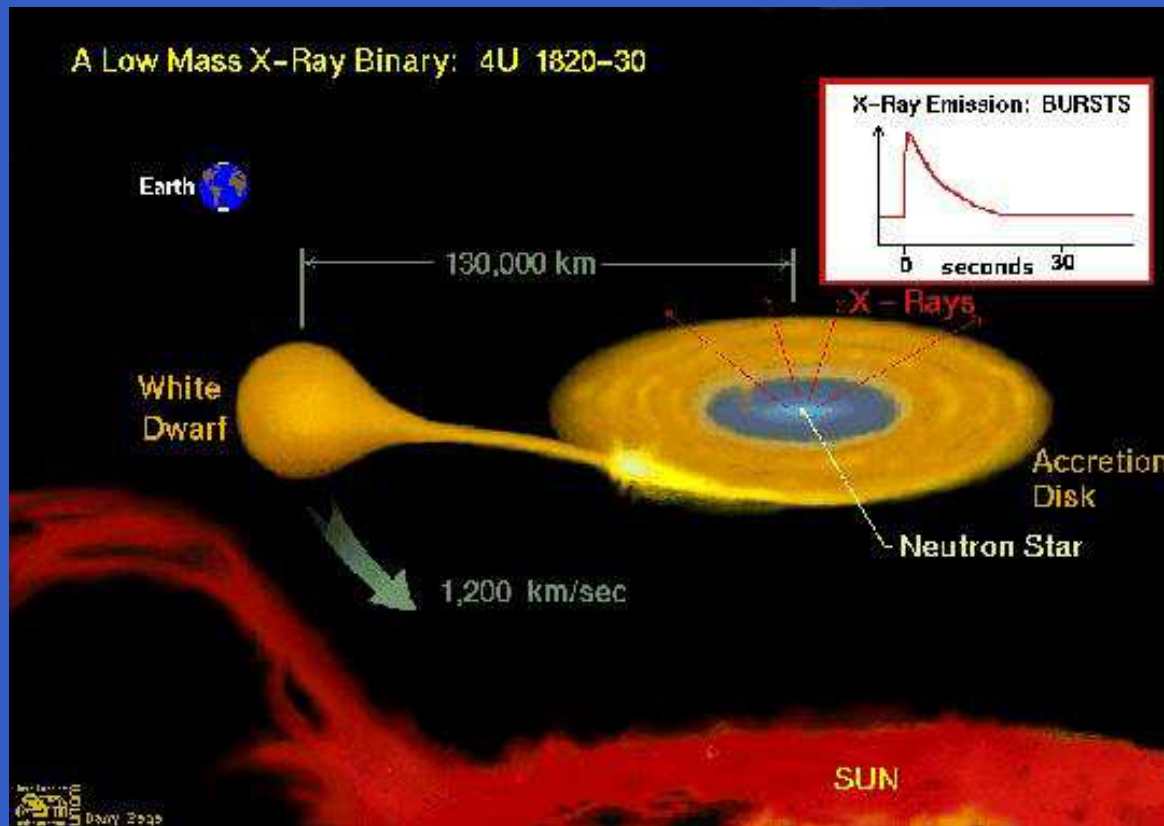
The Future: CBM@FAIR and NICA



(Klähn, Blaschke, Weber 2011)

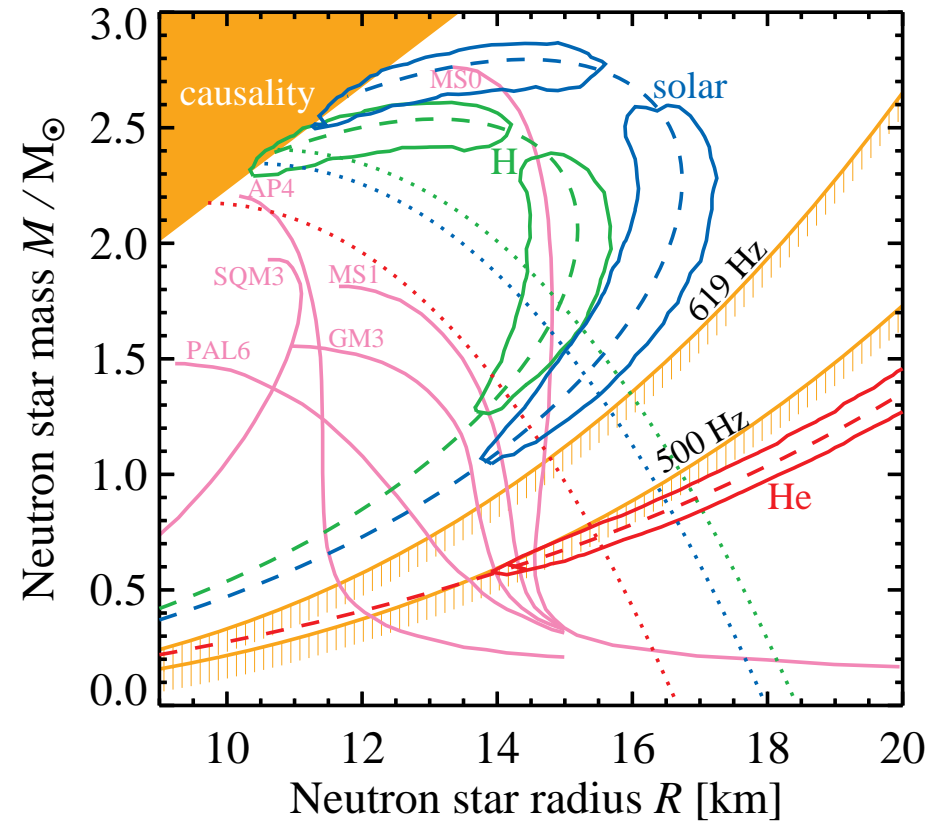
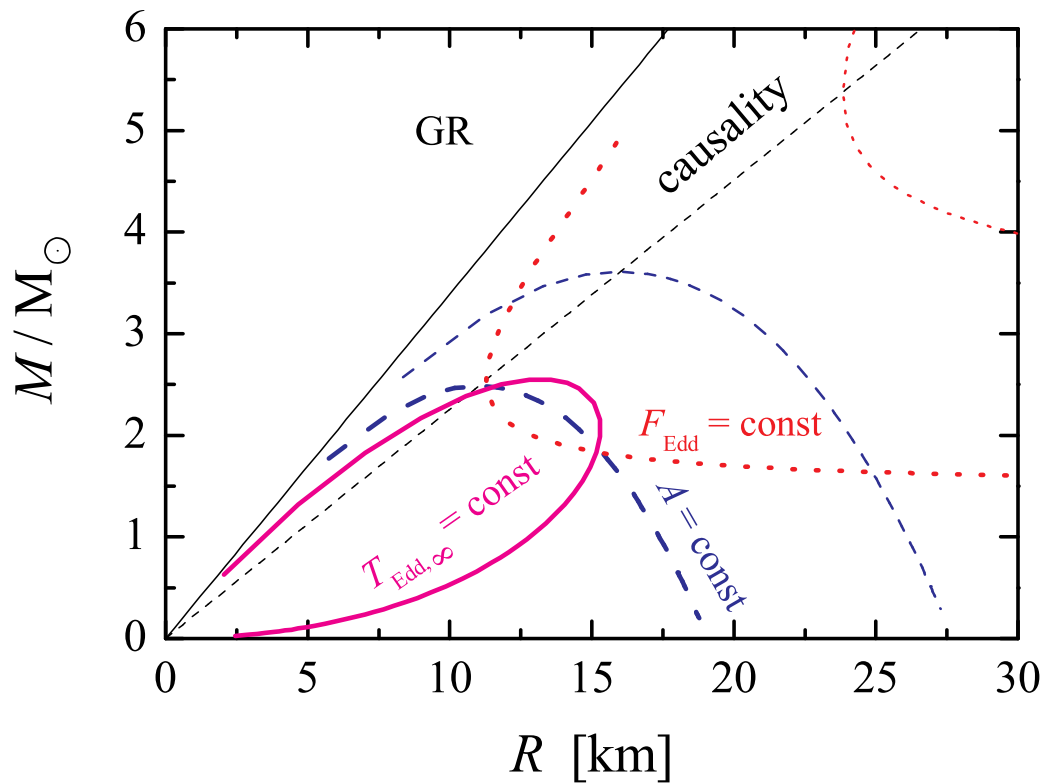
- left: equation of state and flow constraints, right: compatible mass-radius relations and astrophysical constraints
- higher baryon densities achieved at higher bombarding energy
- probing densities beyond $2 - 3n_0$

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

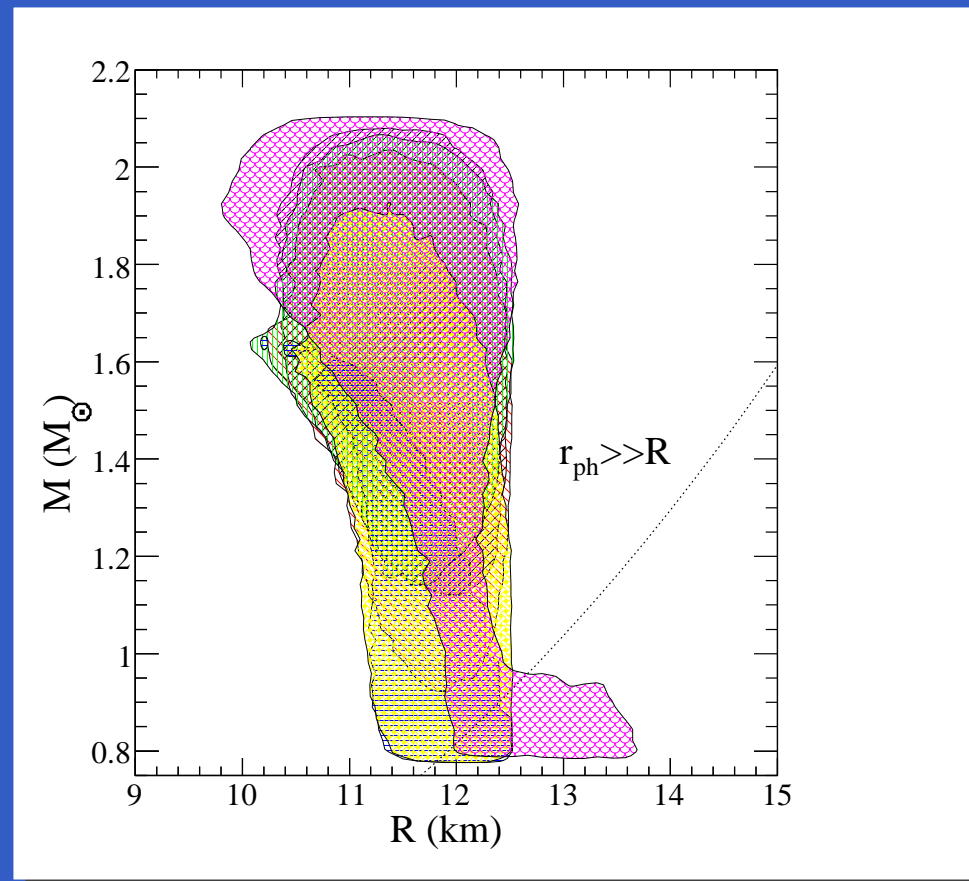
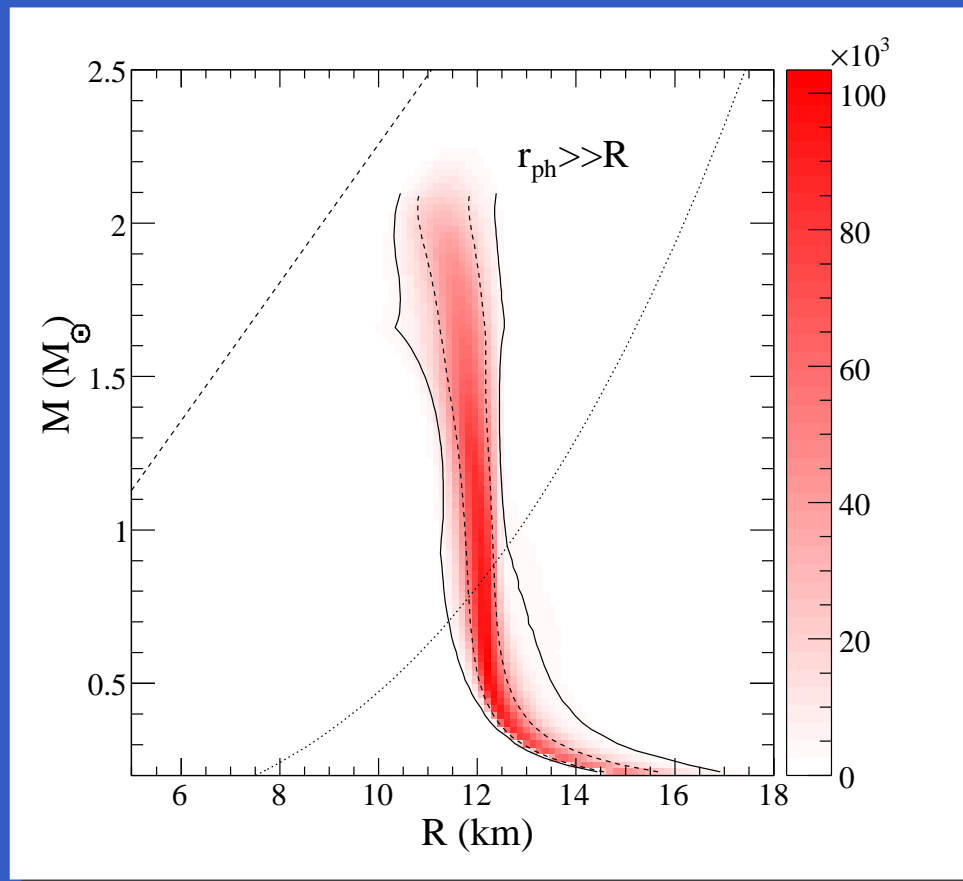
Fits to X-Ray Burster Spectra



(Suleimanov, Poutanen, Revnivtsev, Werner 2011)

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

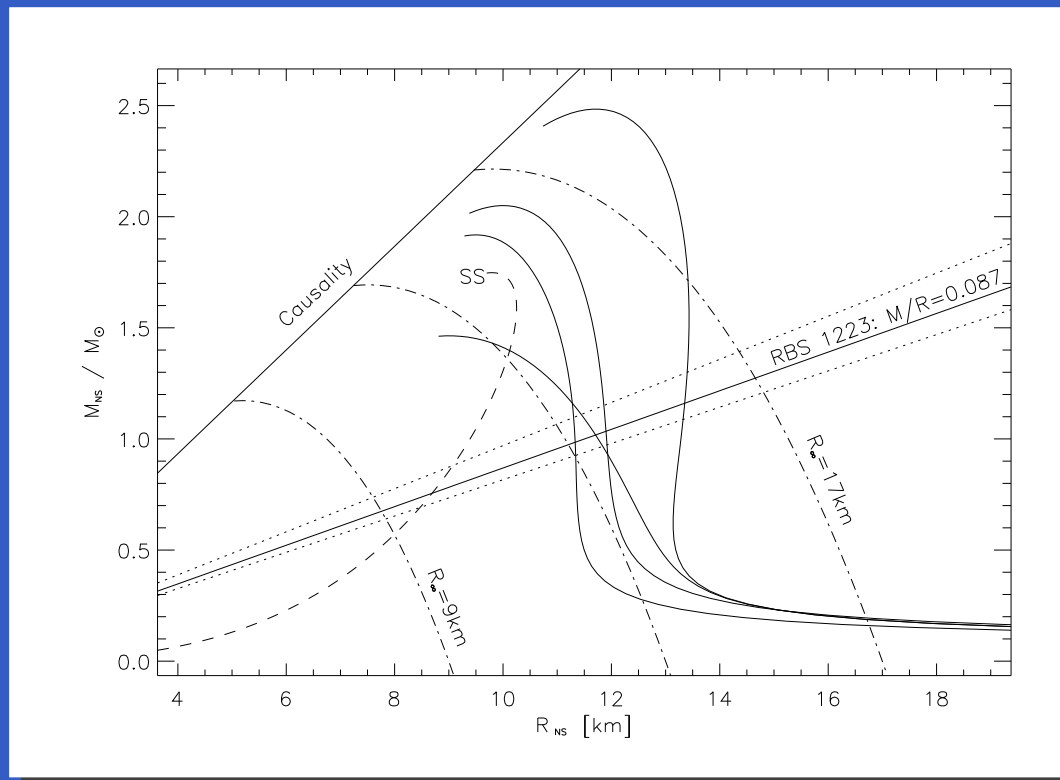
Mass-Radius Constraints from X-Ray Burster and Binaries



(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)

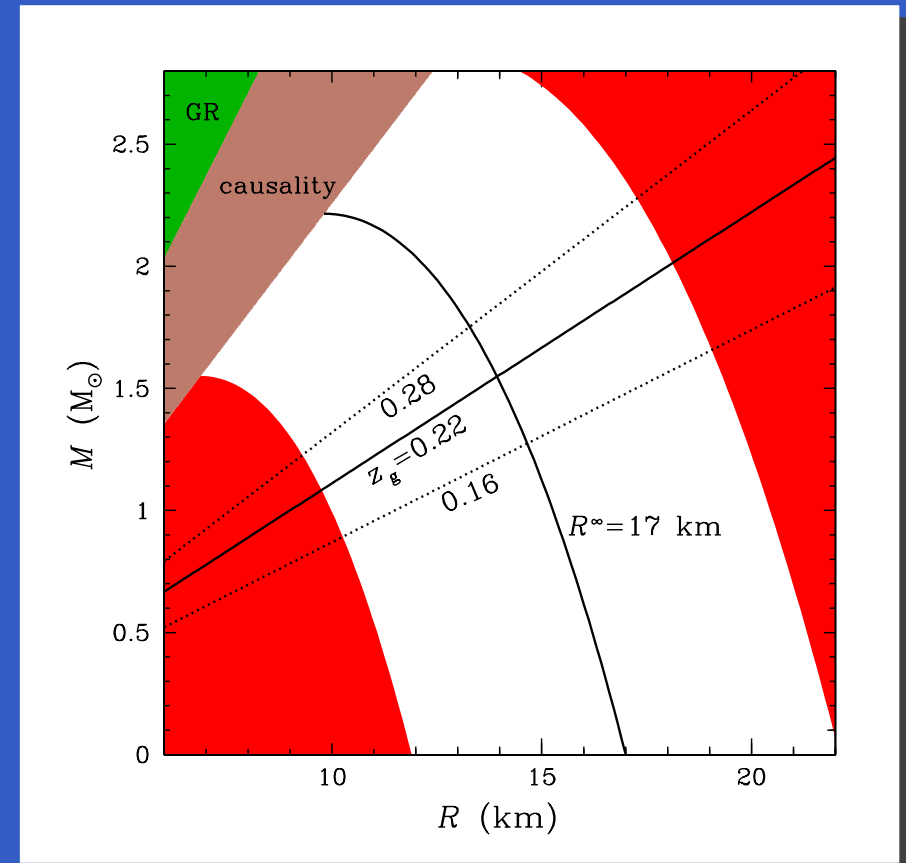
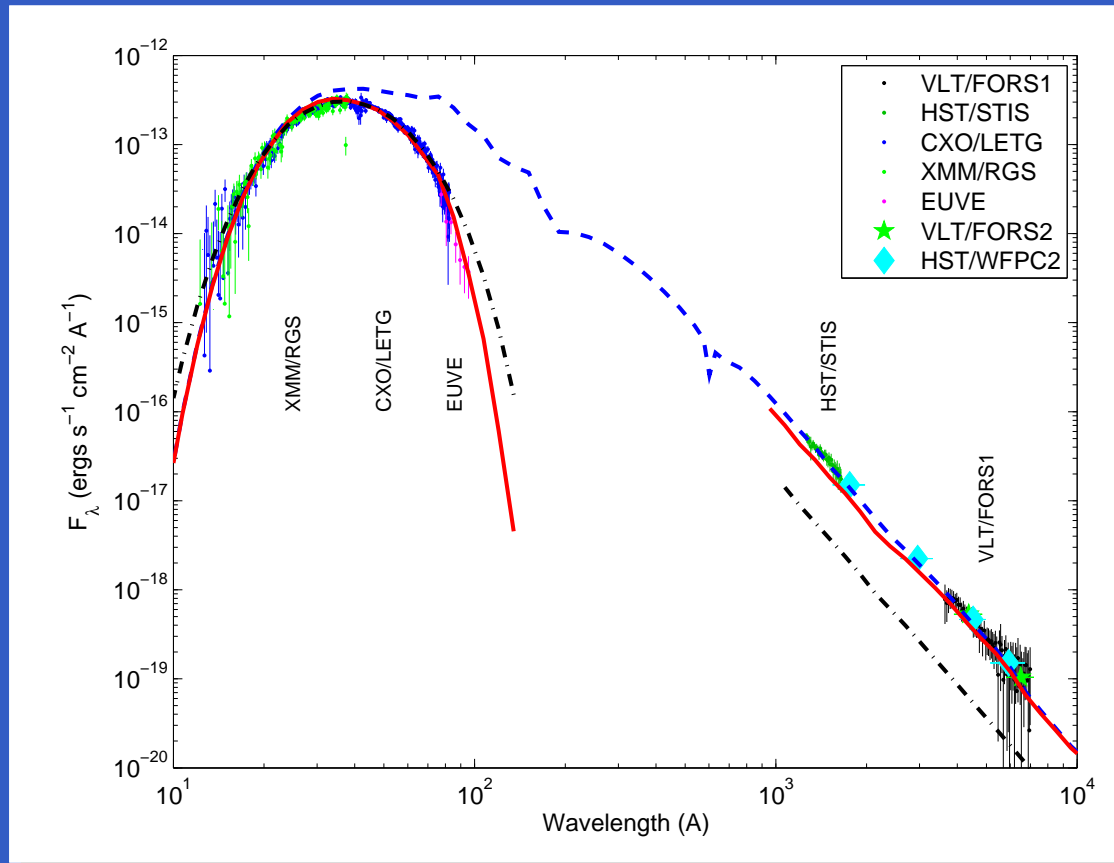
Mass-Radius Constraints from Isolated Neutron Stars



(Hambaryan, Suleimanov, Schwabe, Neuhäuser, Werner, Potekhin 2011)

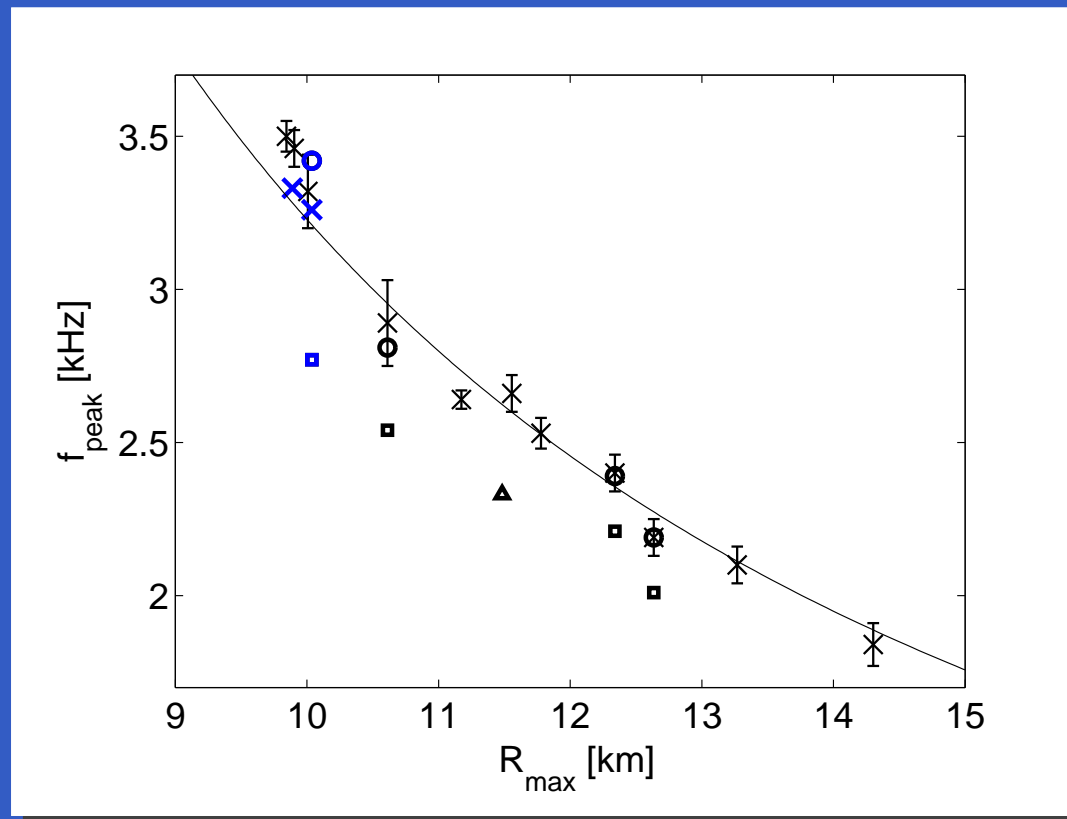
- isolated neutron star, pulses in x-rays
- phase space resolved x-ray spectroscopy
- fit to geometry of hot spot etc. including redshift z
- resulting compactness: $(M/M_{\odot})/(R/\text{km}) = 0.087 \pm 0.004$
- indication for a stiff equation of state

RXJ 1856: Neutron Star or Quark Star? (Trümper et al. (2003), Ho et al. (2007))



- two-component blackbody: small soft temperature, so as not to spoil the x-ray
- this implies a rather LARGE radius so that the optical flux is right!
- lower limit for radiation radius: $R_\infty = R/\sqrt{1 - 2GM/R} = 17 \text{ km}$ ($d/140 \text{ pc}$)
- from parallax measurement: distance $d = 123(+11, -15) \text{ pc}$
(Walter, Eisenbeiss, Lattimer, Kim, Hambaryan, Neuhäuser 2011)

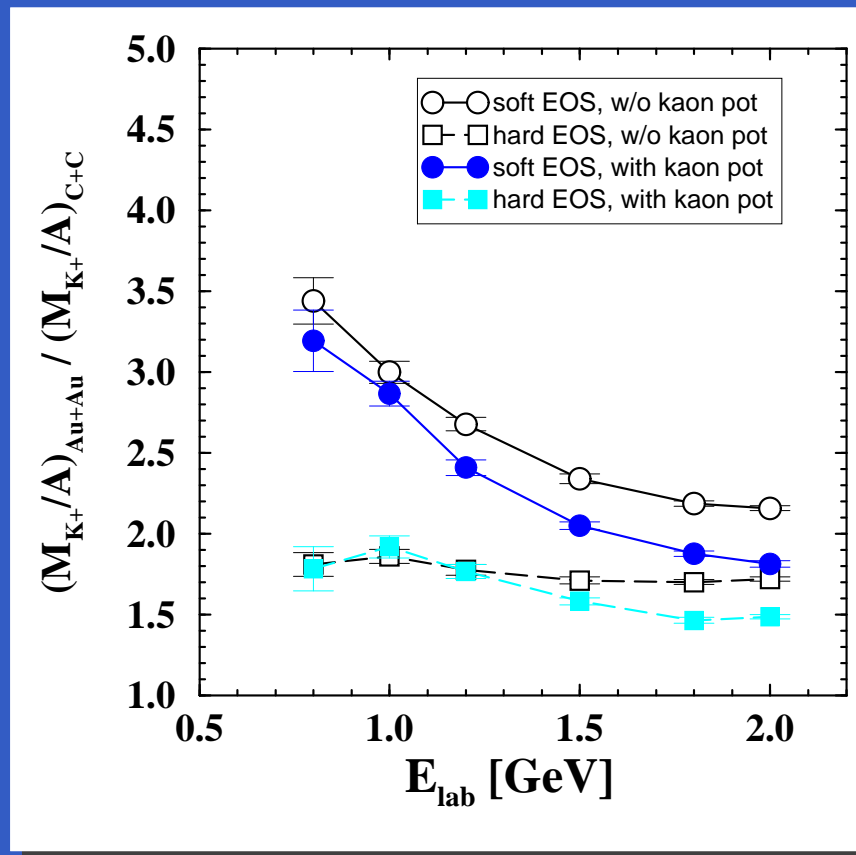
Neutron Star Radii from Neutron Star Mergers



(Bauswein and Janka, 2012)

- neutron star merger simulation with 3D smoothed particle hydro code using conformal flatness approximation
- strong correlation with peak frequency in gravitational waves and neutron star radius rather insensitive to masses of neutron stars
- measurable with advanced LIGO in a few years

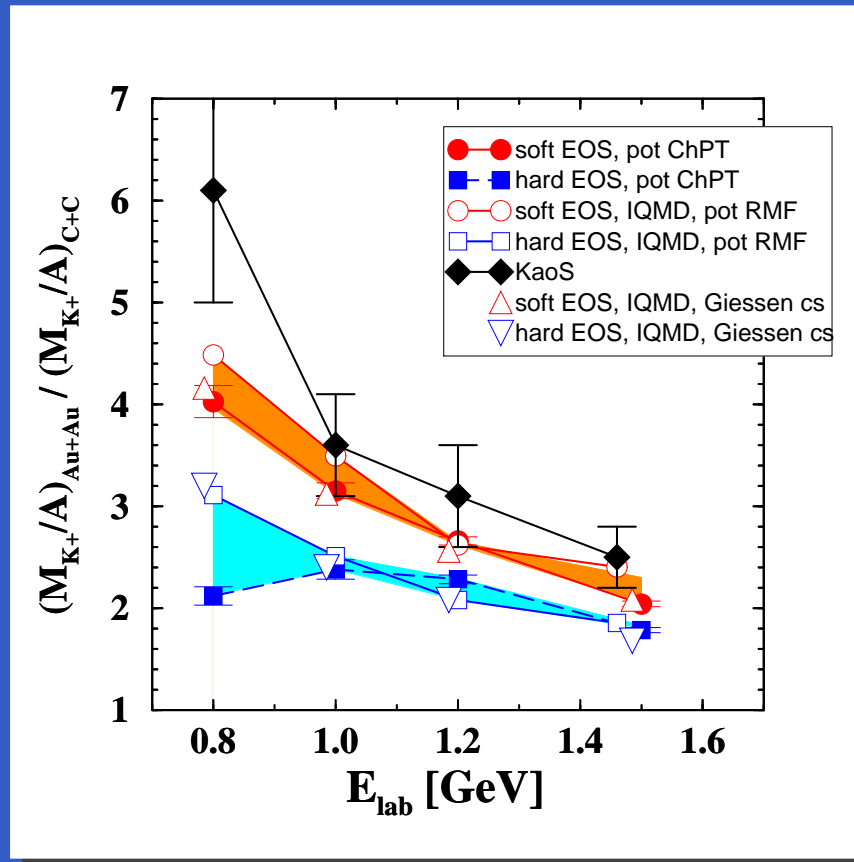
Effect of kaon potentials on double ratio



(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 \rightarrow 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!