

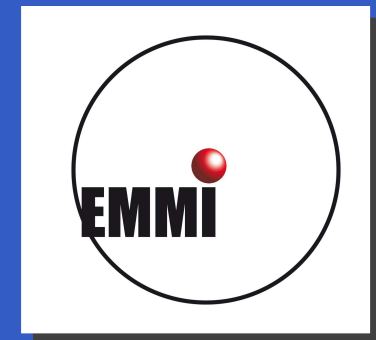
Strangeness in Astrophysics and Cosmology

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RUPRECHT-KARLS-
UNIVERSITÄT
HEIDELBERG



International Conference on Strangeness in Quark Matter
September 28 - October 2, 2009, Buzios, Brasil

Parallel session 08 about astrophysics on Thursday:

- Strange quark matter and colour superconductivity: quarkyonic matter
⇒ talk by David Blaschke
- Supernova matter: signal for the phase transition to strange quark matter
⇒ talk by Irina Sagert
- Evolution of proto-neutron stars: the appearance of a new strange phase
⇒ talk by Giuseppe Pagliara
- How to produce strange quark matter: nucleation
⇒ talk by Bruno Mintz

Outline

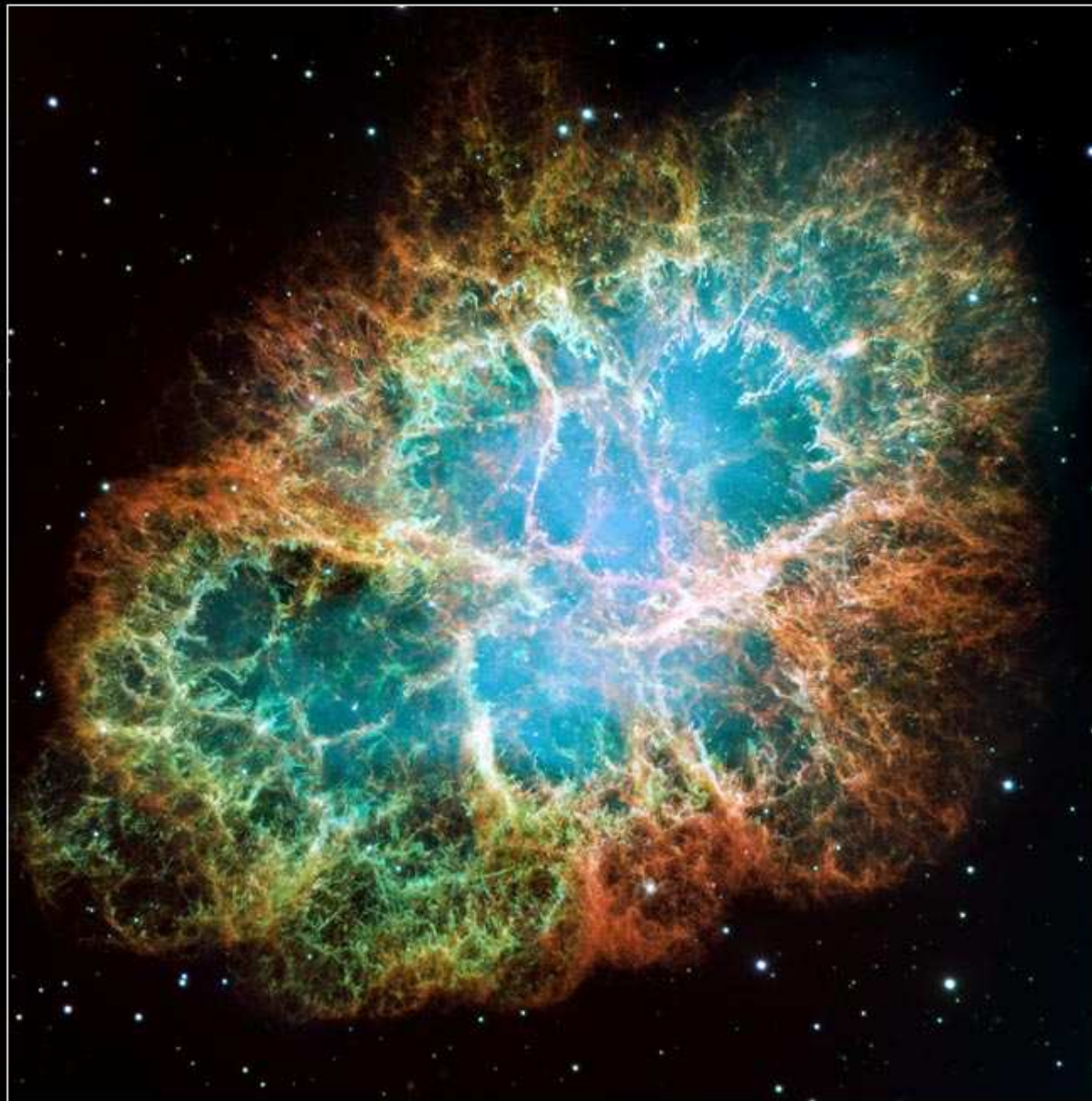
- Introduction
- Maximum mass of neutron stars:
causality constraints using heavy-ion data
- Gravitational wave emission from rotating
neutron stars:
the viscosity of strange quark matter
- Neutron star mergers:
the flux of strangelets in cosmic rays
- Early universe:
phase transition from strange quark matter
- Summary

Introduction

Neutron Stars

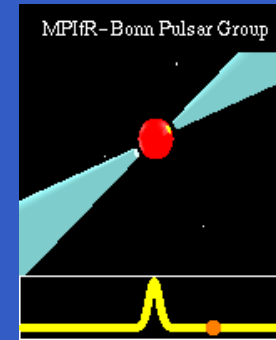
Crab Nebula ■ M1

HST ■ WFPC2



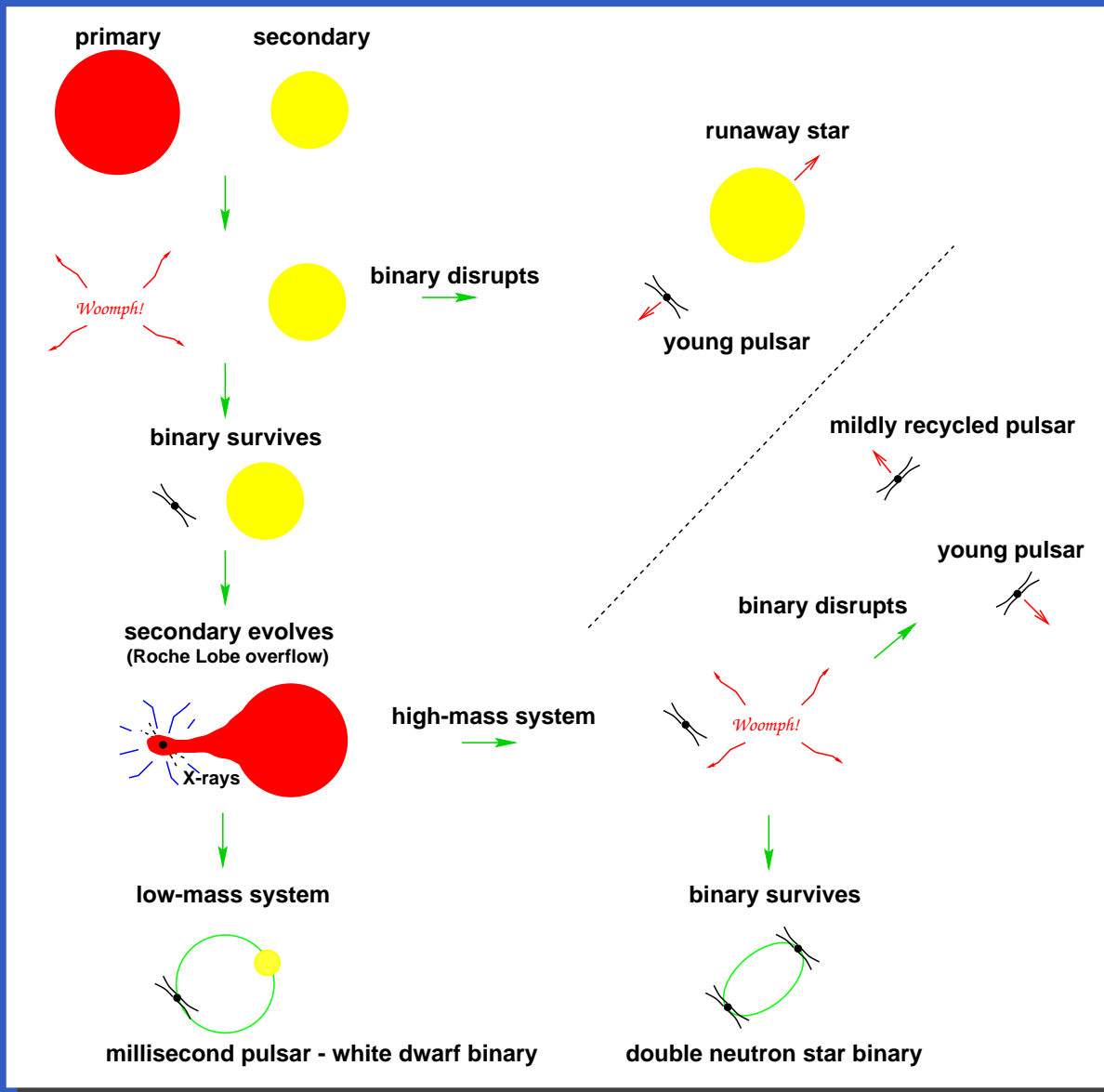
NASA, ESA, and J. Hester (Arizona State University)

STScI-PRC05-37



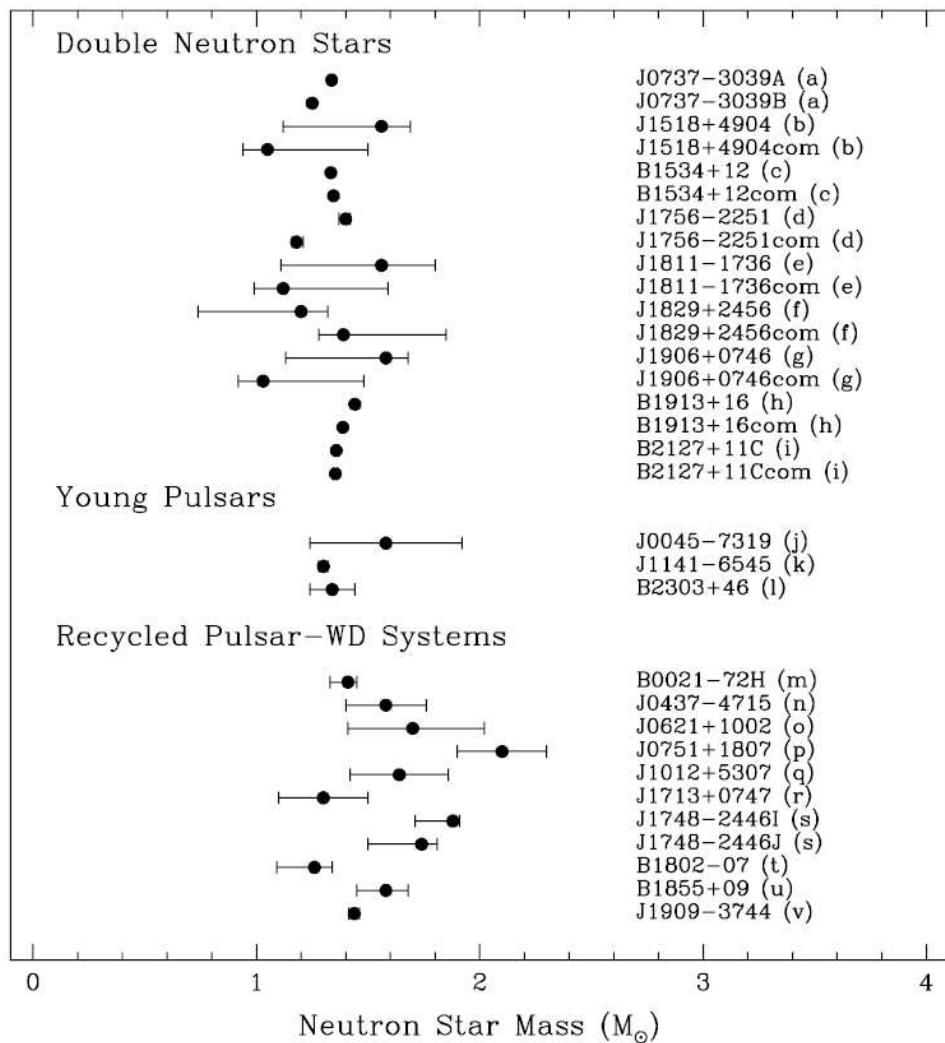
- produced in core collapse supernova explosions
- compact, massive objects: radius ≈ 10 km, mass $1 - 2M_{\odot}$
- extreme densities, several times nuclear density: $n \gg n_0 = 3 \cdot 10^{14} \text{ g/cm}^3$
- in the middle of the crab nebula: a pulsar, a rotating neutron star!

How to create binary pulsars (Lorimer 2008)



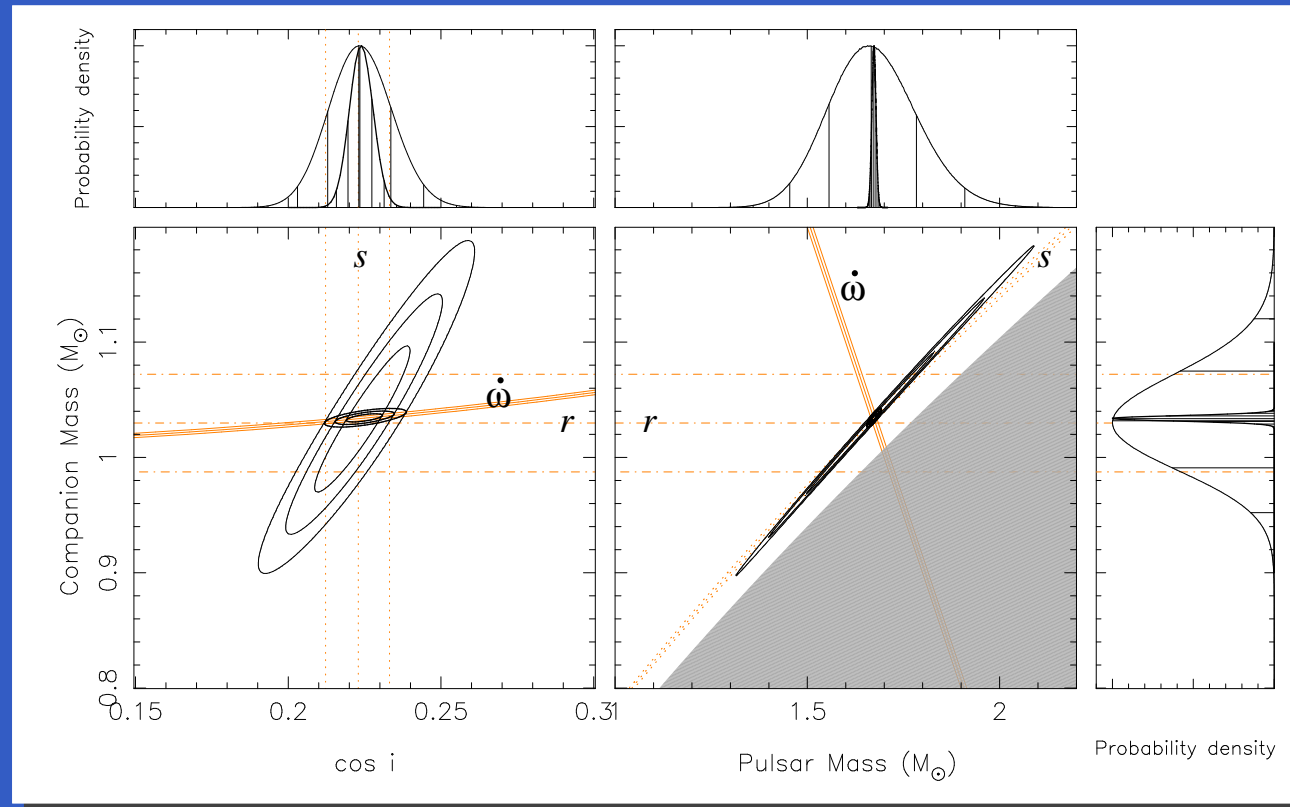
- start with two stars, one with at least $8M_{\odot}$
- first supernova creates a neutron star
- neutron star is spun up by accreting matter from the companion star
- companion star might become a white dwarf or another neutron star

Masses of Pulsars (Stairs 2006)



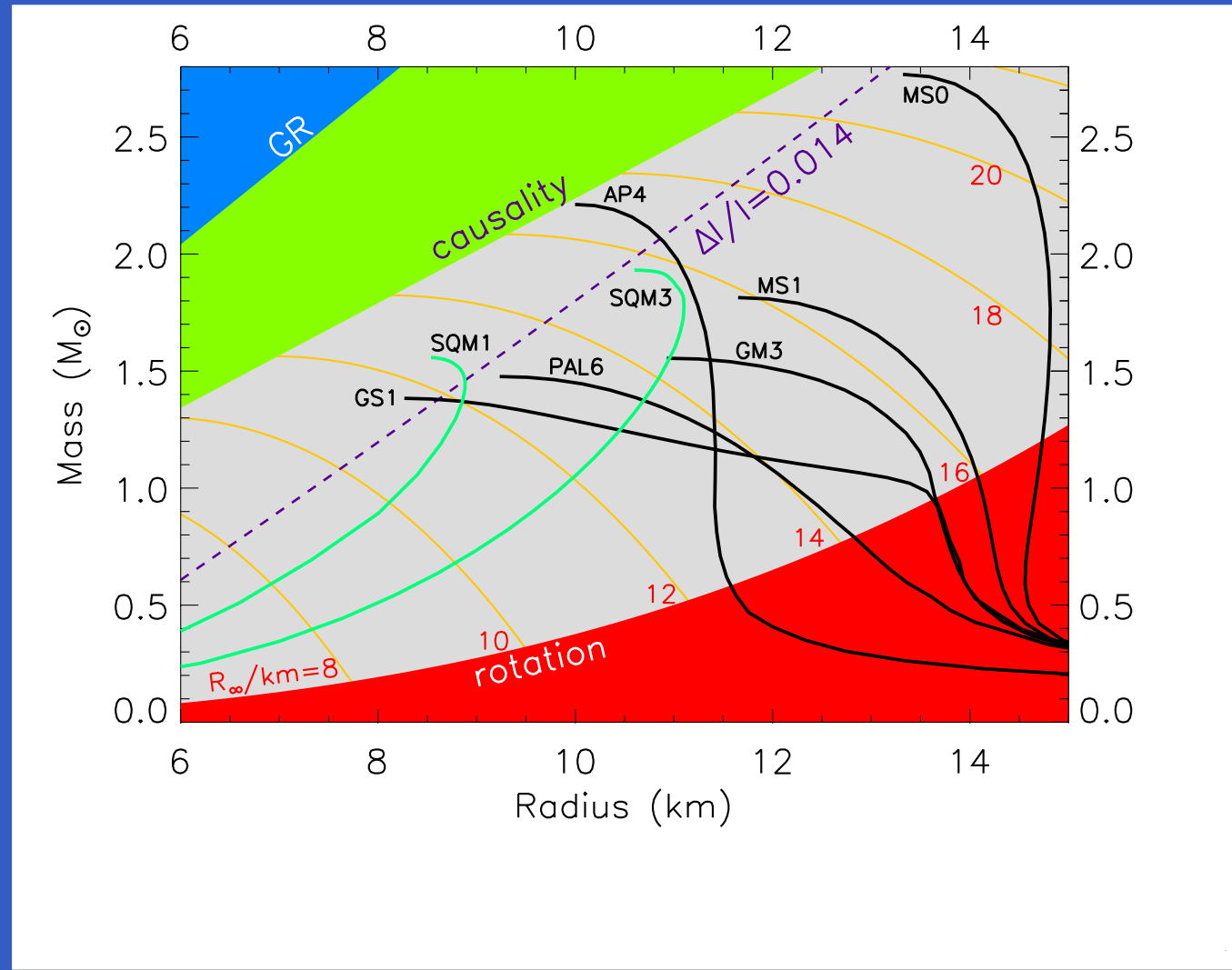
- more than 1800 pulsars known with 140 binary pulsars
- best determined mass:
 $M = (1.4414 \pm 0.0002)M_{\odot}$
 Hulse-Taylor pulsar
 (Weisberg and Taylor, 2004)
- mass of PSR J0751+1807 corr.
 from $M = (2.1 \pm 0.2)M_{\odot}$ to
 $M = (1.14 - 1.40)M_{\odot}$
 (Nice et al. 2008)
- mass of PSR J1903+0327
 (not finalized yet):
 $M = (1.67 \pm 0.01)M_{\odot}$
 (Freire et al. 2009)

Mass measurement of pulsar PSR 1903+0327 (Freire 2009)



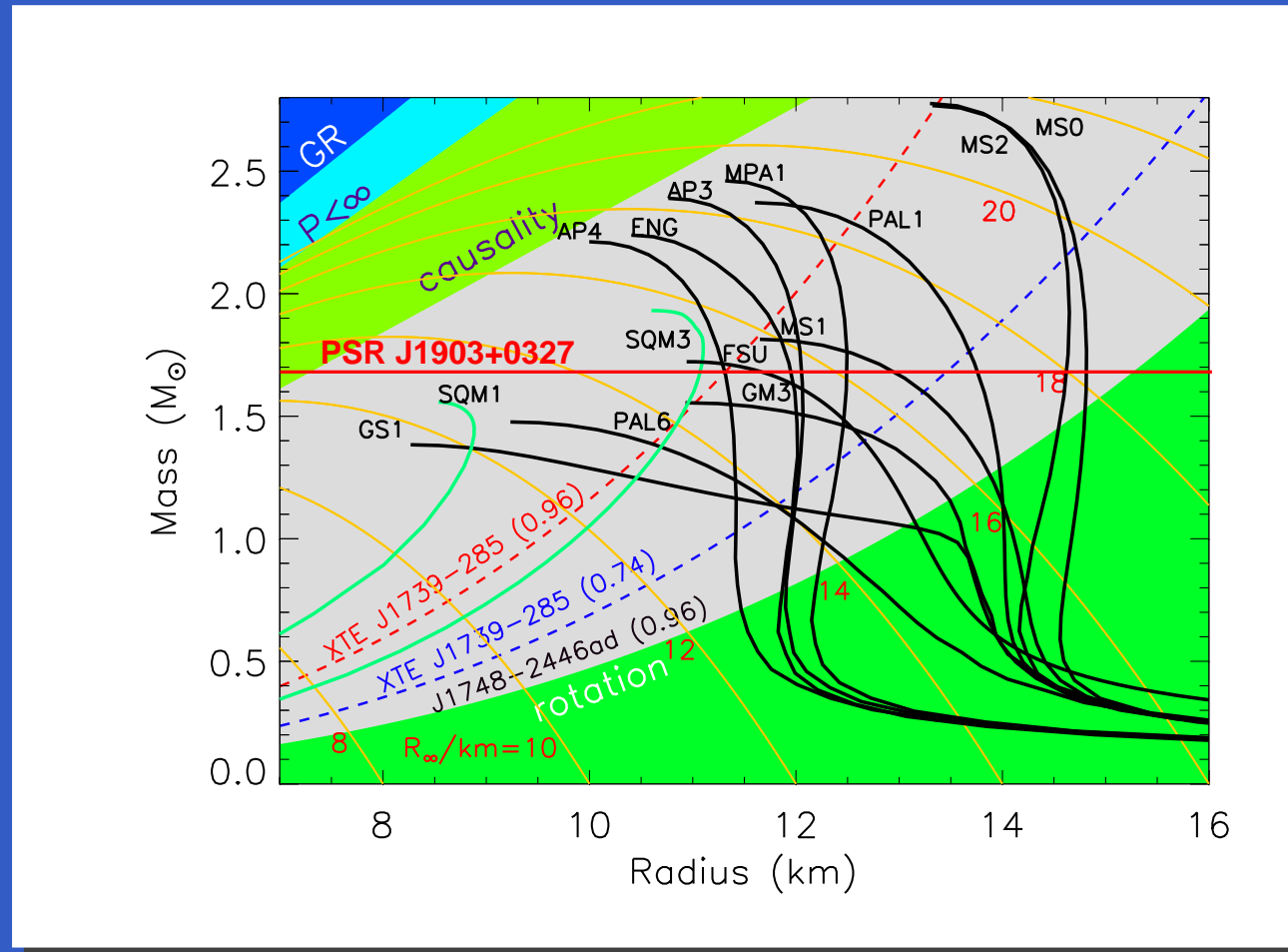
- measure post-Keplerian parameters from pulsar timing
- Shapiro delay parameters r and s alone constrain $M = (1.67 \pm 0.11)M_{\odot}$
- combined with periastron advance $\dot{\omega}$: $M = (1.67 \pm 0.01)M_{\odot}$
- rotation of the companion star could influence $\dot{\omega}$
(follow-up observation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

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



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

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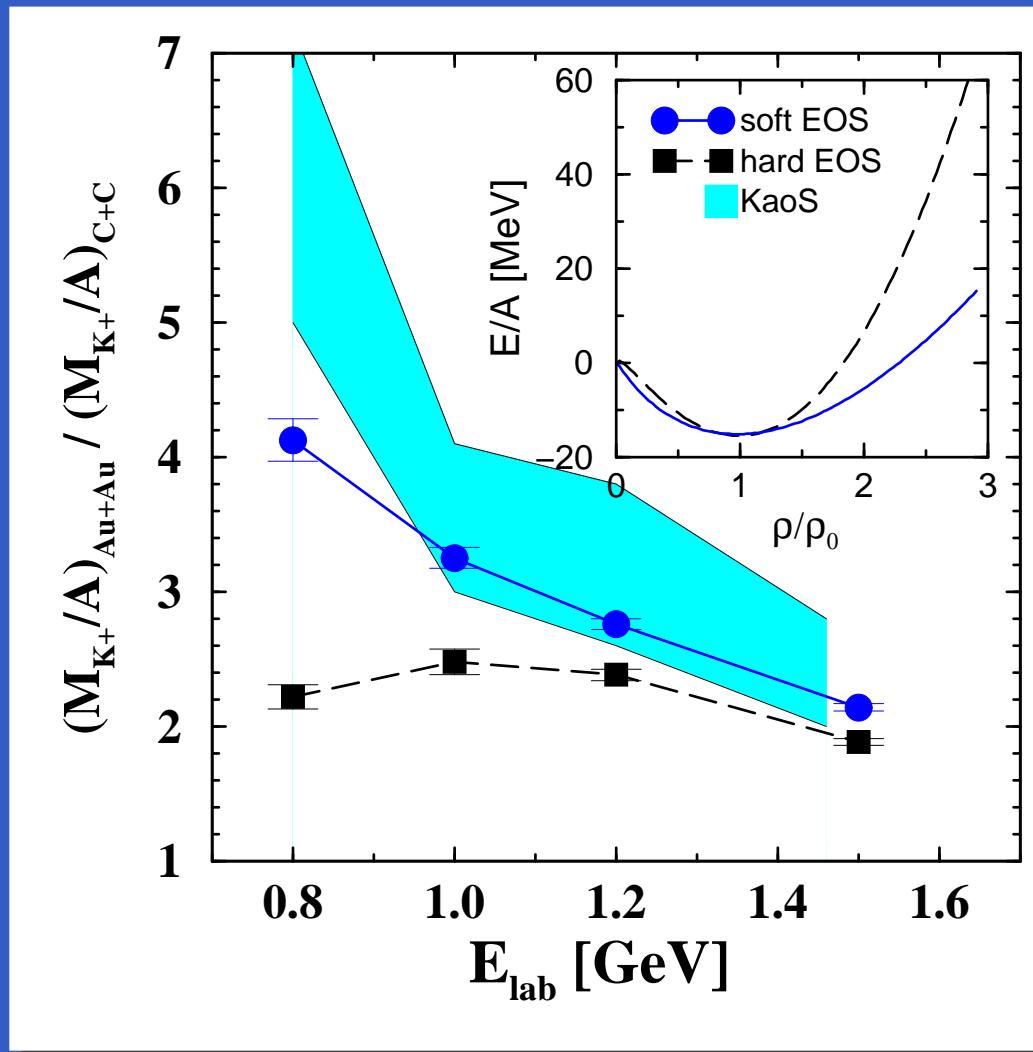
• causality limit for EoS: $R > 3GM$

• mass limit from PSR 1903+0327 (Freire et al. 2009): $M = (1.67 \pm 0.01)M_{\odot}$

Maximum mass of neutron stars: causality constraints using heavy-ion data

(Irina Sagert, JSB, Christian Sturm, 2009)

Kaon production in heavy-ion collisions



Sturm et al. (KaoS collaboration), PRL 2001

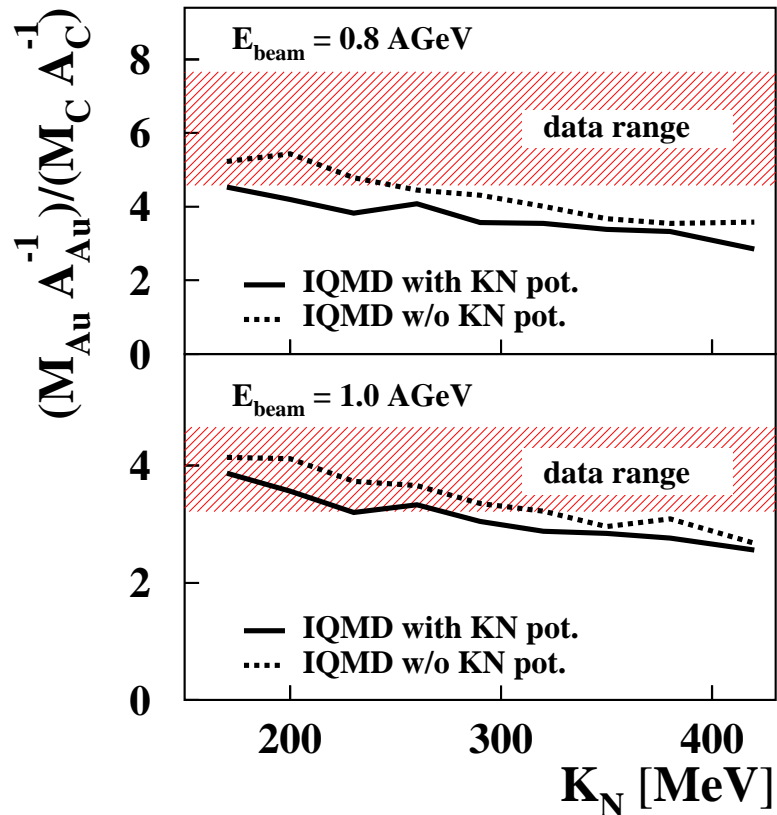
Fuchs, Faessler, Zabrodin, Zheng, PRL 2001

- Kaons produced by associated production:
 $NN \rightarrow N\Lambda K, NN \rightarrow NNK\bar{K}$
- in-medium processes (rescattering): $\pi N \rightarrow \Lambda K, \pi\Lambda \rightarrow N\bar{K}$
- nuclear matter is compressed up to $3n_0!$
- long mean-free path of kaons: kaons can escape high density matter

Confirmed KaoS data analysis: the nuclear EoS is soft!

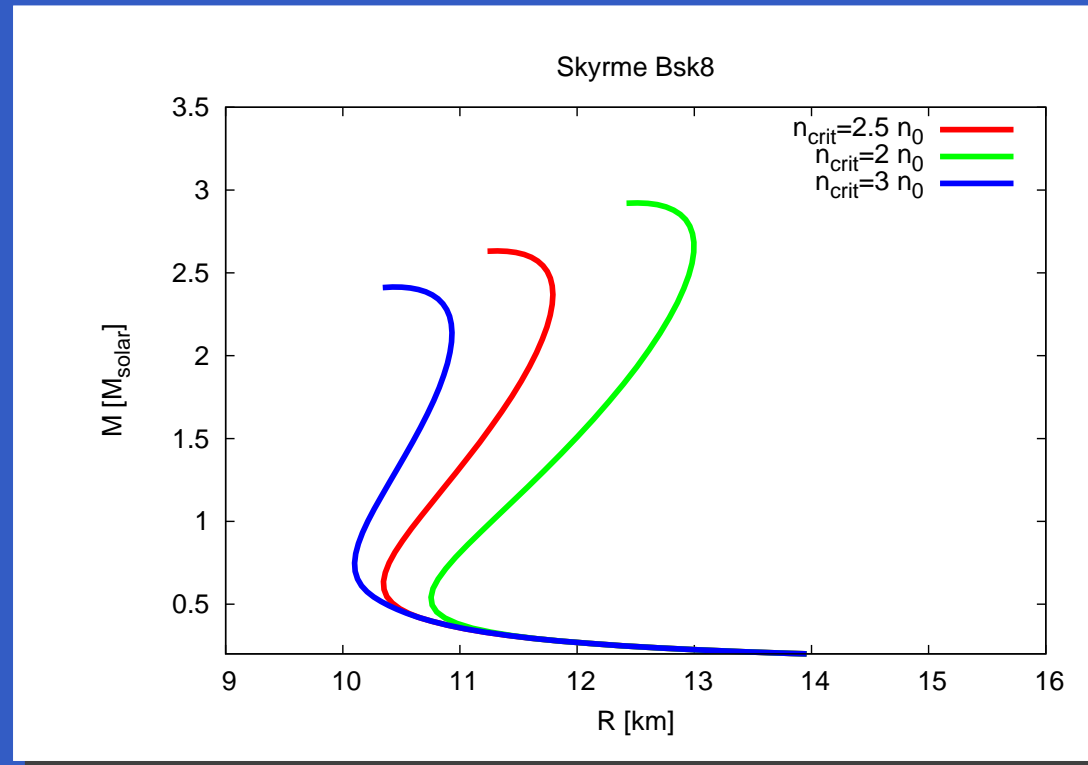
The **KAO S** Collaboration

- kaon production (K^+) in heavy-ion collisions at subthreshold energies
- double ratio: multiplicity per mass number for C+C collisions and Au+Au collisions at 0.8 AGeV and 1.0 AGeV (rather insensitive to input parameters)
- only calculations with a compression modulus of $K_N \approx 200$ MeV can describe the data (Hartnack, Oeschler, Aichelin, PRL 2006; KaoS collaboration, 2007)



\implies the nuclear equation of state is **SOFT!**

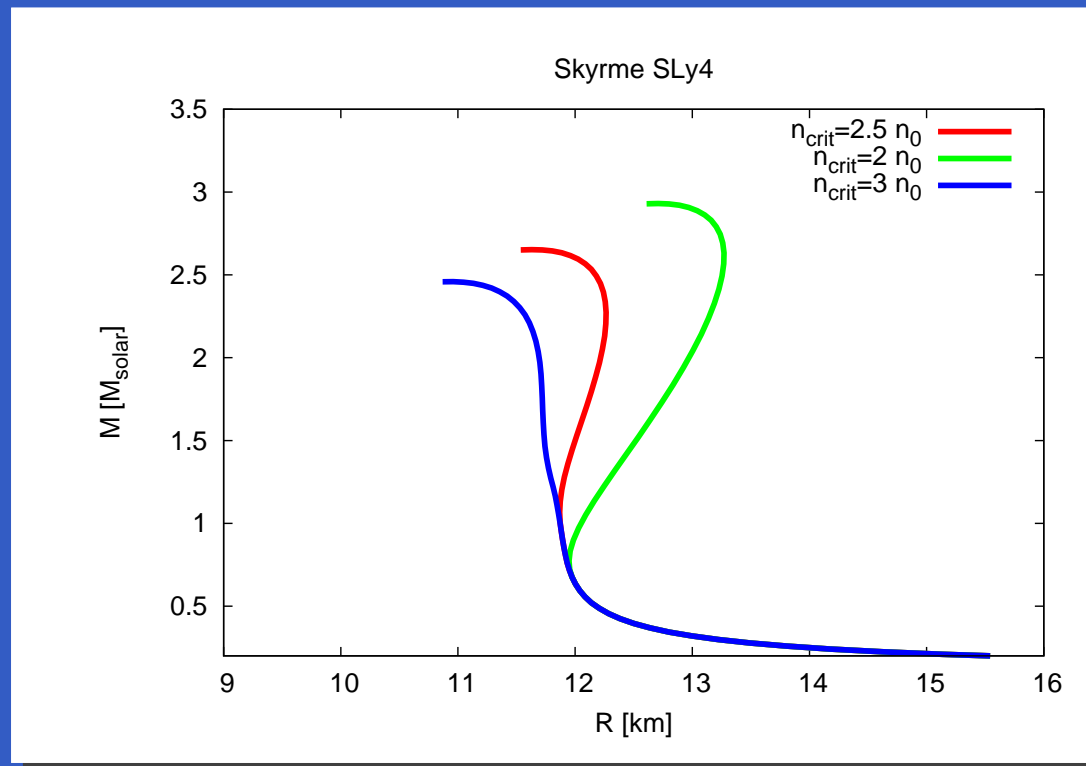
Maximum Masses of Neutron Stars – Causality



(Irina Sagert)

- Skyrme parameter set BSK8: fitted to masses of all known nuclei
- above a fiducial density (determined from the data analysis of the KaoS data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f
Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\max} = 4.2M_{\odot}(\epsilon_0/\epsilon_f)^{1/2}$
- \implies new upper mass limit of about $2.7M_{\odot}$ from heavy-ion data!

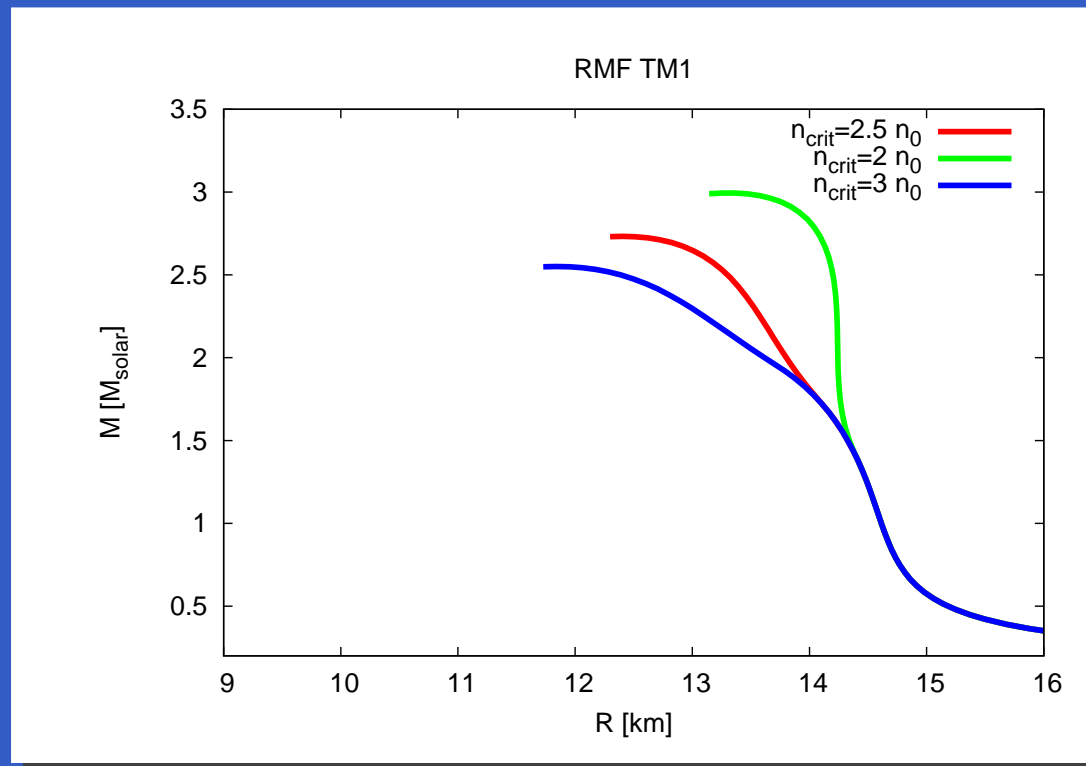
Maximum Masses of Neutron Stars – Causality



(Irina Sagert)

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

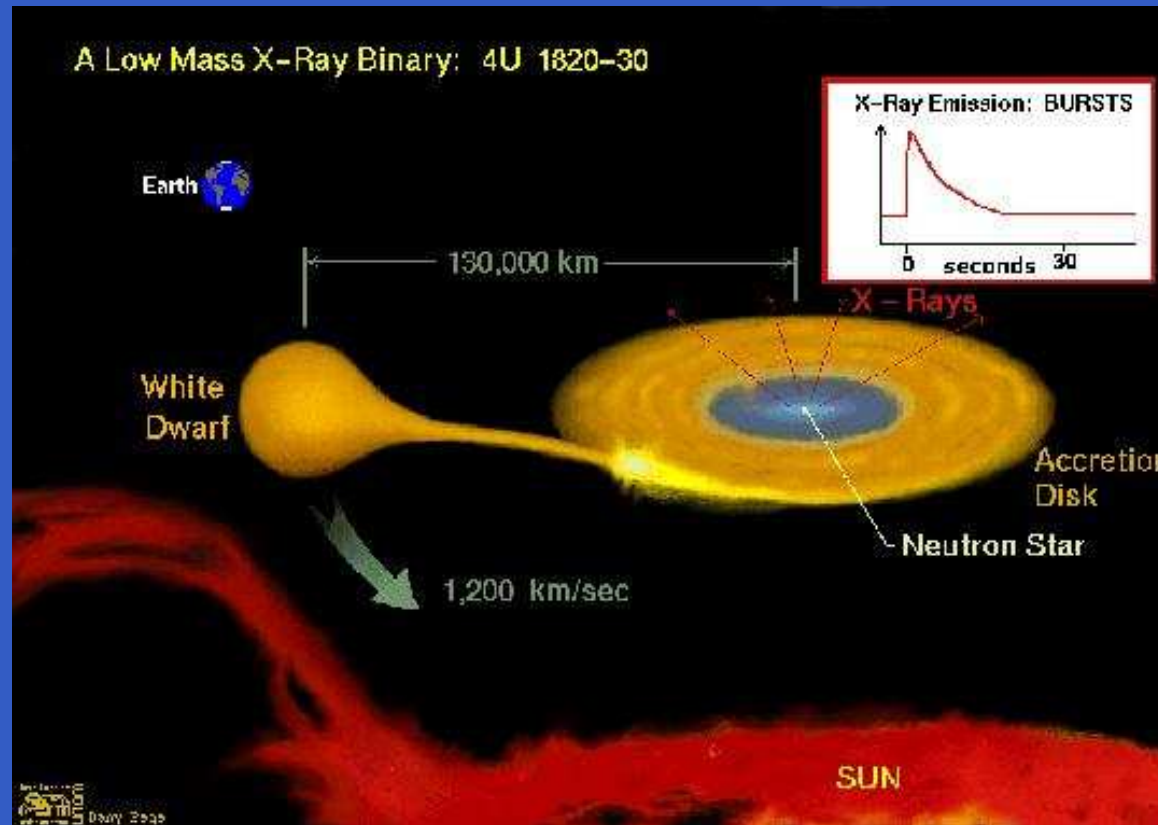


(Irina Sagert)

- RMF parameter set TM1: fitted to properties of spherical nuclei
- above a fiducial density (determined from the data analysis of the KaoS data) transition to stiffest possible EoS
- causality argument: $p = \epsilon - \epsilon_c$ above the fiducial density ϵ_f
Rhoades, Ruffini (1974), Kalogera, Baym (1996): $M_{\text{max}} = 4.2 M_{\odot} (\epsilon_0 / \epsilon_f)^{1/2}$
- \implies new upper mass limit of about $2.8 M_{\odot}$ from heavy-ion data!

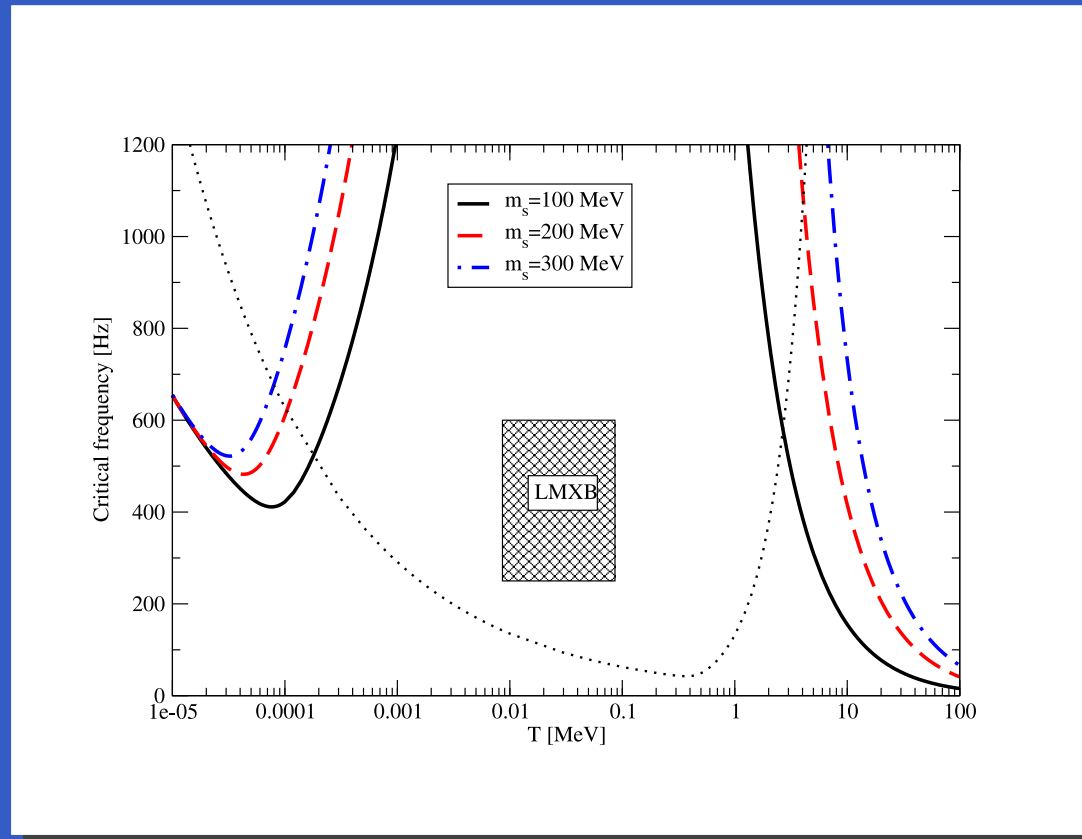
Gravitational wave emission from rotating neutron stars: the viscosity of strange quark matter

X-Ray burster



- binary systems of a neutron star with an ordinary star or a white dwarf
- low-mass x-ray binary (LMXB): neutron star with a low mass companion
- accreting matter falls onto the neutron star: release of x-rays in a burst
- typical temperatures in the neutron star of $T = 10 - 100$ keV

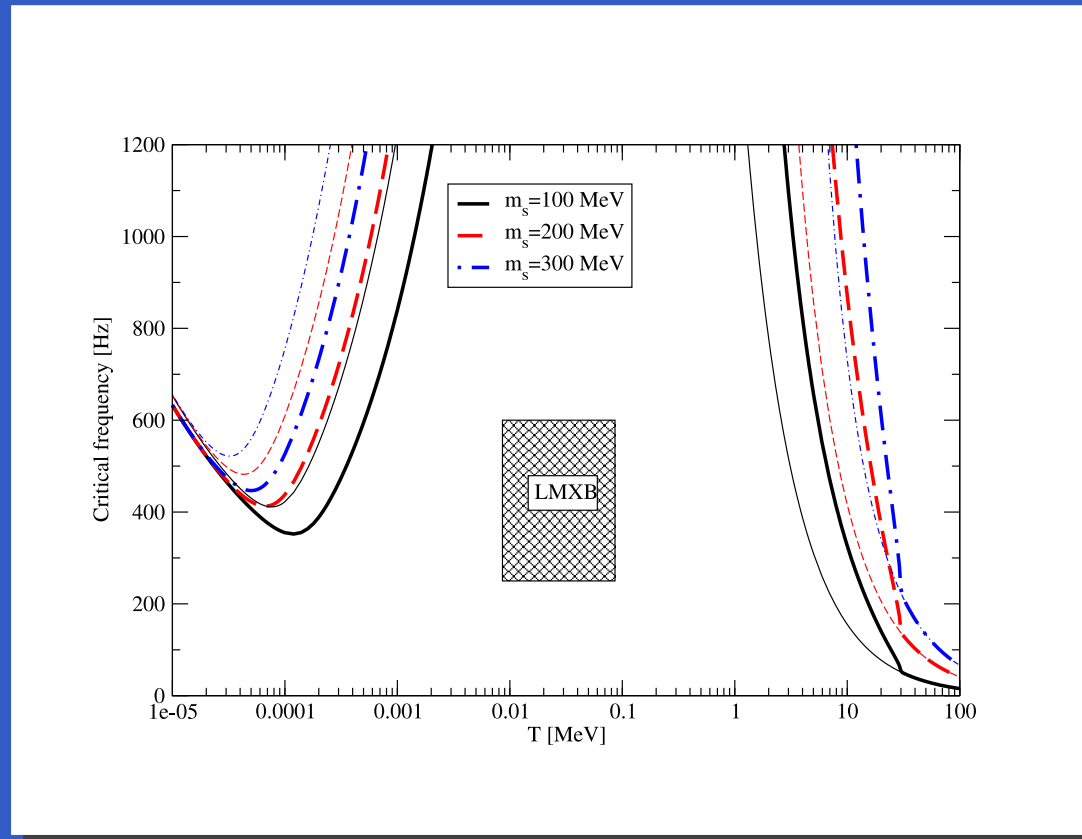
R-mode instability for rotating neutron stars (SQM)



(Sad, Shovkovy, Rischke 2007; Sad 2008)

- oscillations brings the matter out of β -equilibrium
- restore equilibrium by bulk and shear viscosity from weak processes
- quark contributions increase the stability window in temperature and frequencies (dotted line: nuclear matter)

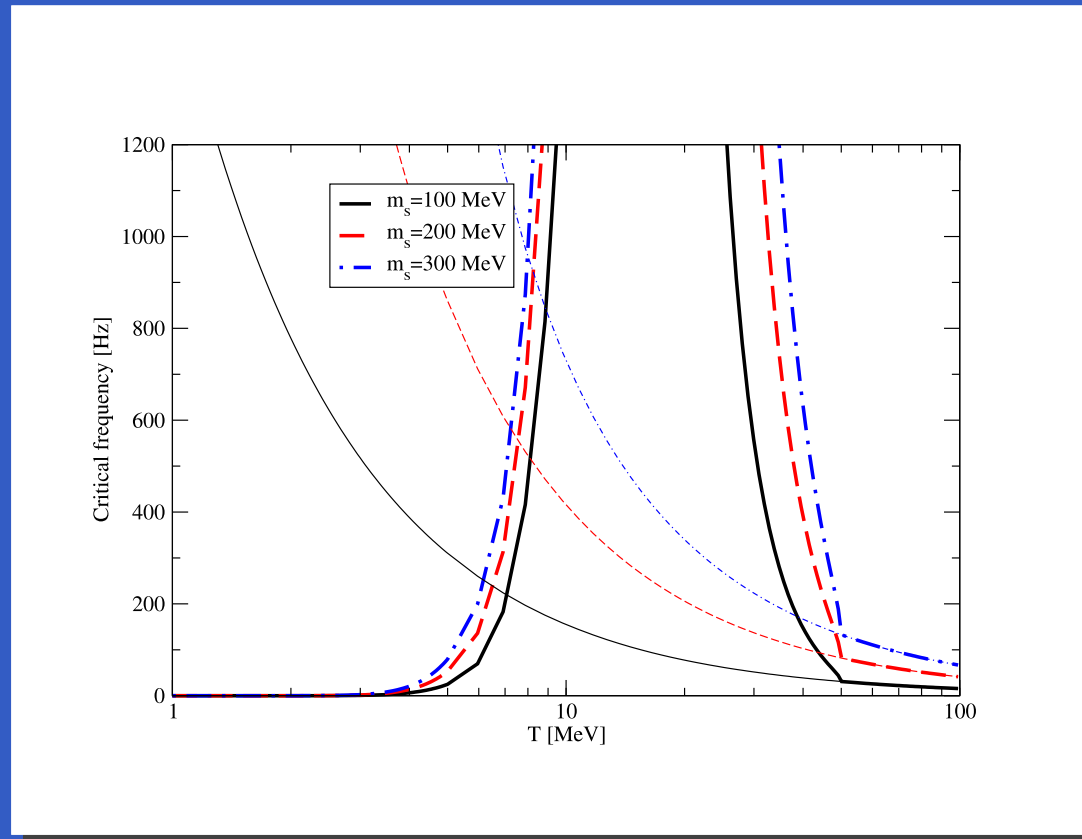
R-mode instability for rotating neutron stars (2SC)



(Sad, Shovkovy, Rischke 2007; Sad 2008)

- pairing of two quark flavours and two colours (2SC phase)
- still unpaired quarks left: similar results compared to free case
- compatible with data on low-mass x-ray binaries (LMXB)

R-mode instability for rotating neutron stars (CFL)



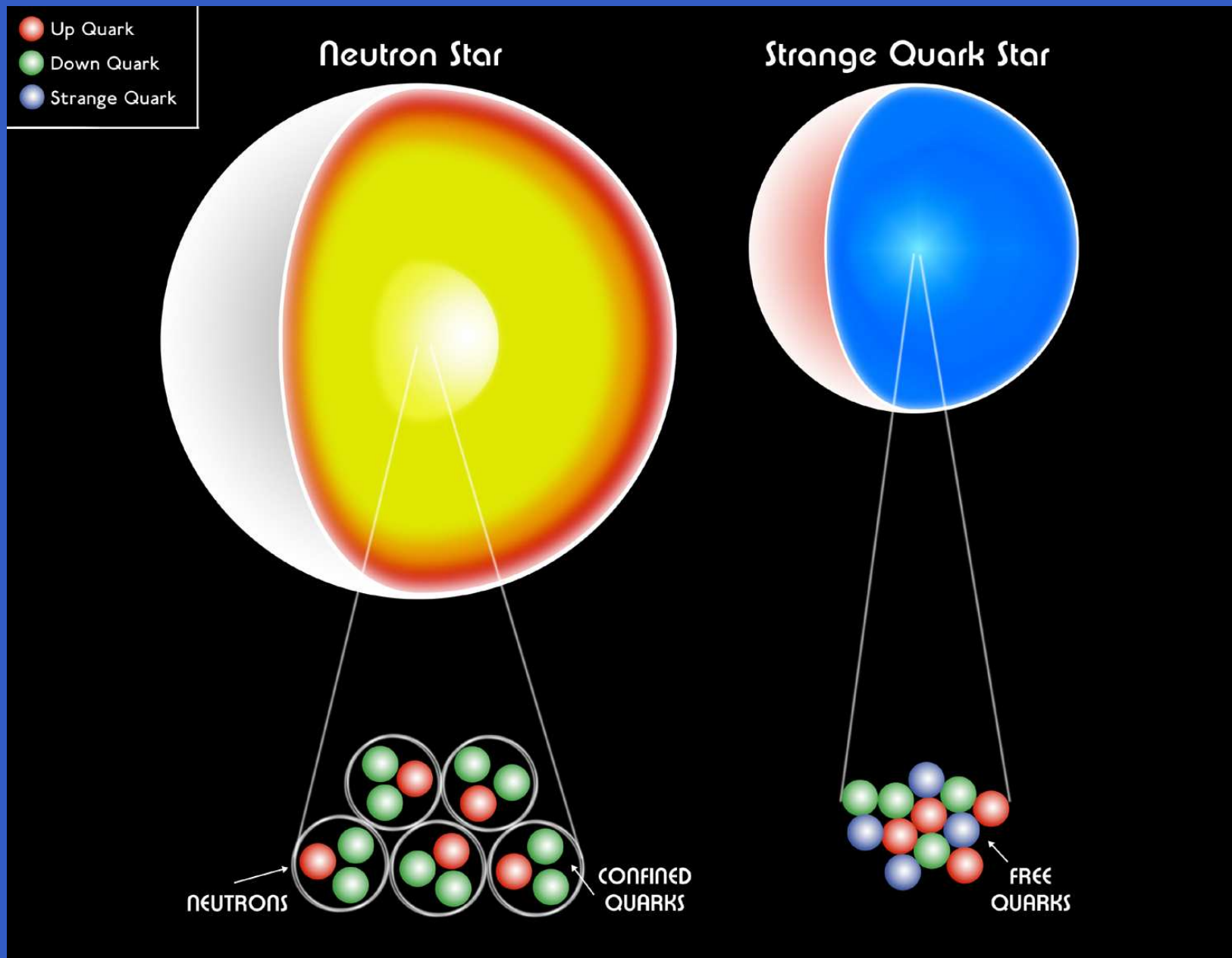
(Sad, Shovkovy, Rischke 2007; Sad 2008)

- pairing of all quarks of all flavour and colour (CFL phase)
- reaction rates are suppressed, instability window is considerably broader
- impact on evolution of young pulsars and accreting neutron stars!

Neutron star mergers: the flux of strangelets in cosmic rays

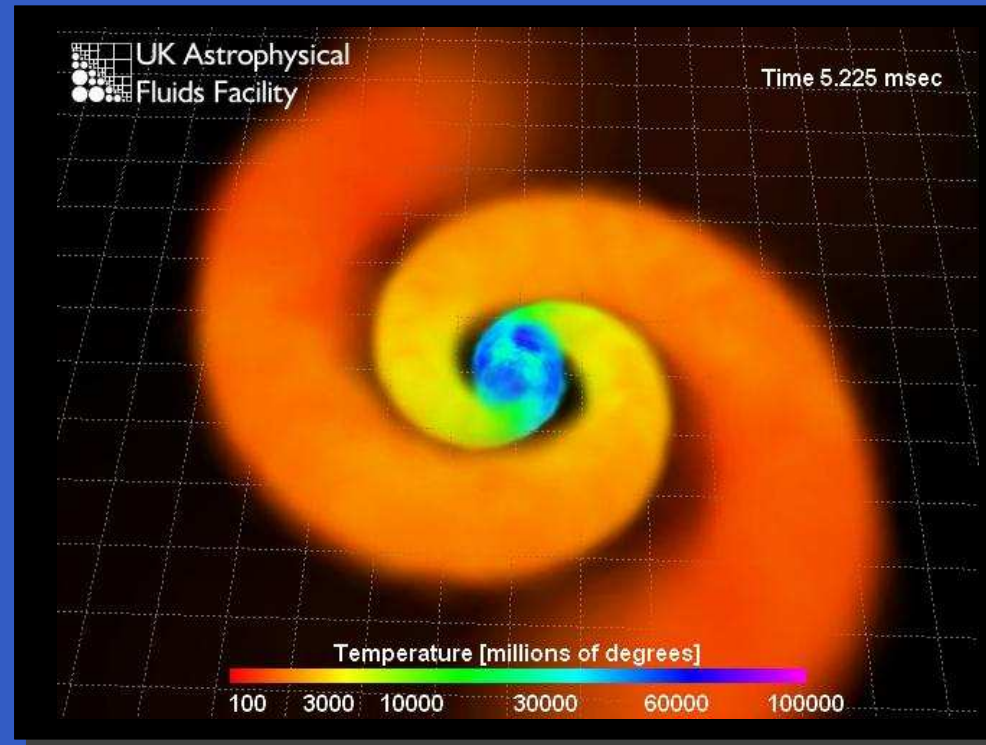
(Bauswein, Oechslin, Janka, Pagliara, JSB, Hohle, Neuhäuser
PRL 2009)

Neutron Star versus Strange (Quark) Star



(Chandra X-Ray Center, 2002)

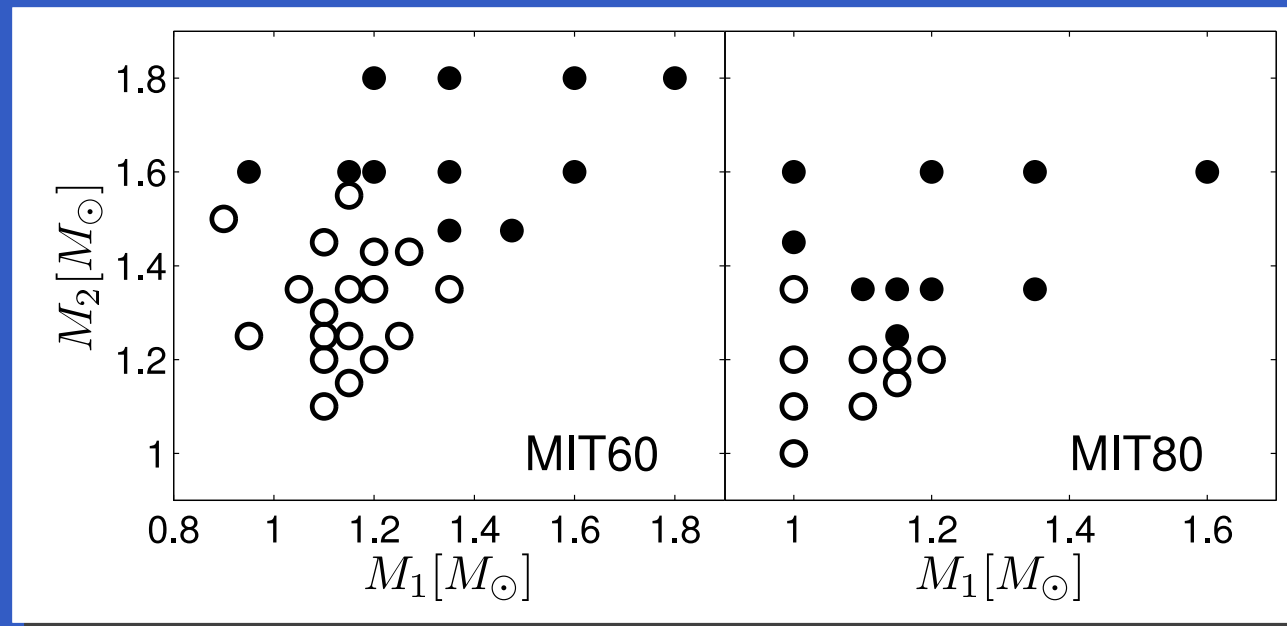
Neutron star merger simulation



(Stephan Rosswog)

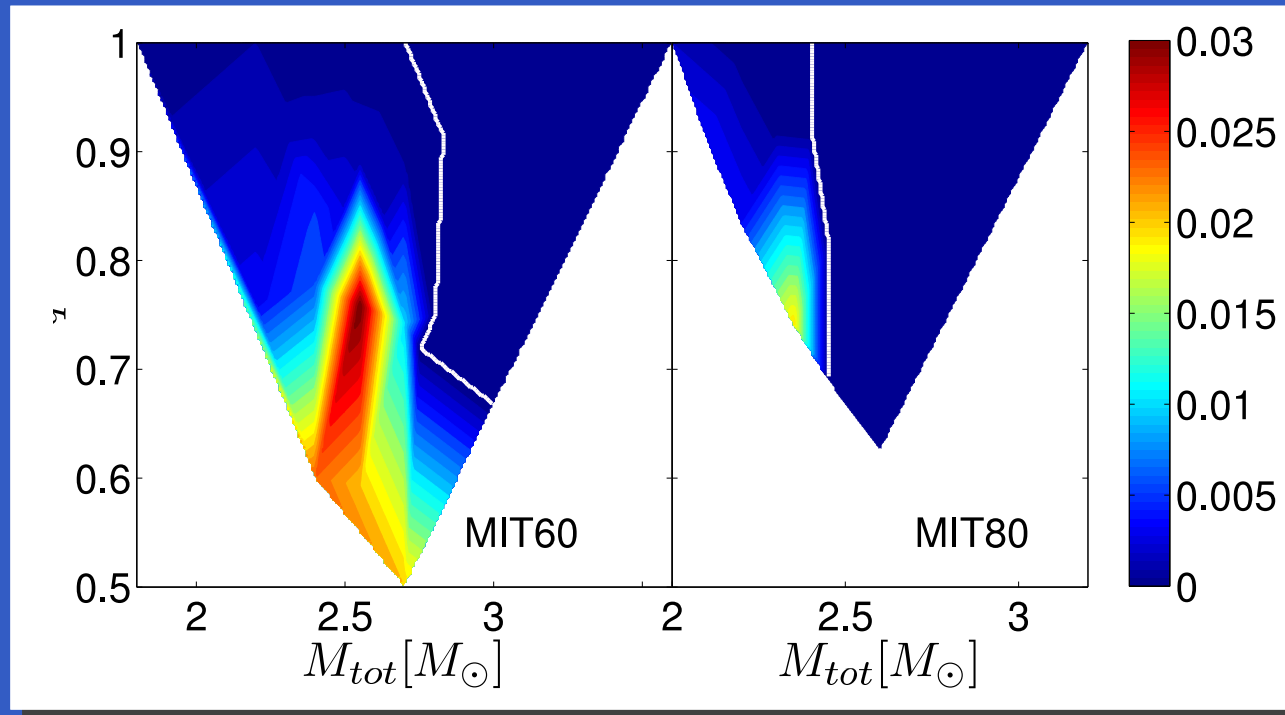
- consider absolutely stable strange quark matter: strange stars are selfbound and can coexist with ordinary neutron stars
- simulate collisions of two strange stars (3D relativistic smoothed particle hydrodynamics with approximate treatment of GR)
- typical timescales: milliseconds, matter is in β -equilibrium

Simulation of strange star mergers



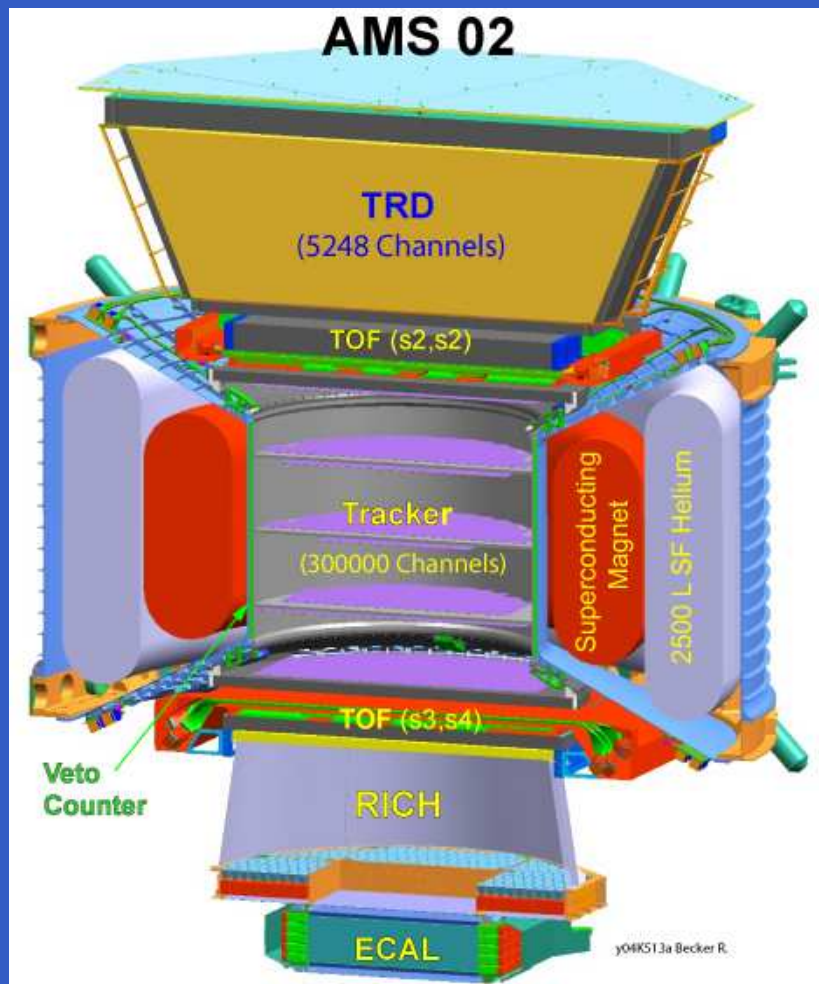
- bag constants of $B=60$ and 80 MeV/fm^{-3} (MIT60 and MIT80), both get absolutely stable strange quark matter
- different initial masses
- two different outcomes:
 - a) immediate collapse to a black hole (filled dots)
 - b) formation of a hypermassive object stabilized by differential rotation (open circles)

Strange star mergers: results



- ejected mass in M_{\odot} (strangelets) for different mass ratios $q = M_1/M_2$ and total mass M_{tot}
- estimated total strangelet mass ejected: $(1.4 \dots 2.8 \cdot 10^{-4})M_{\odot}$ for MIT60 and zero for MIT80!
- possibility that no strangelets are seen in cosmic rays although strange stars exist!

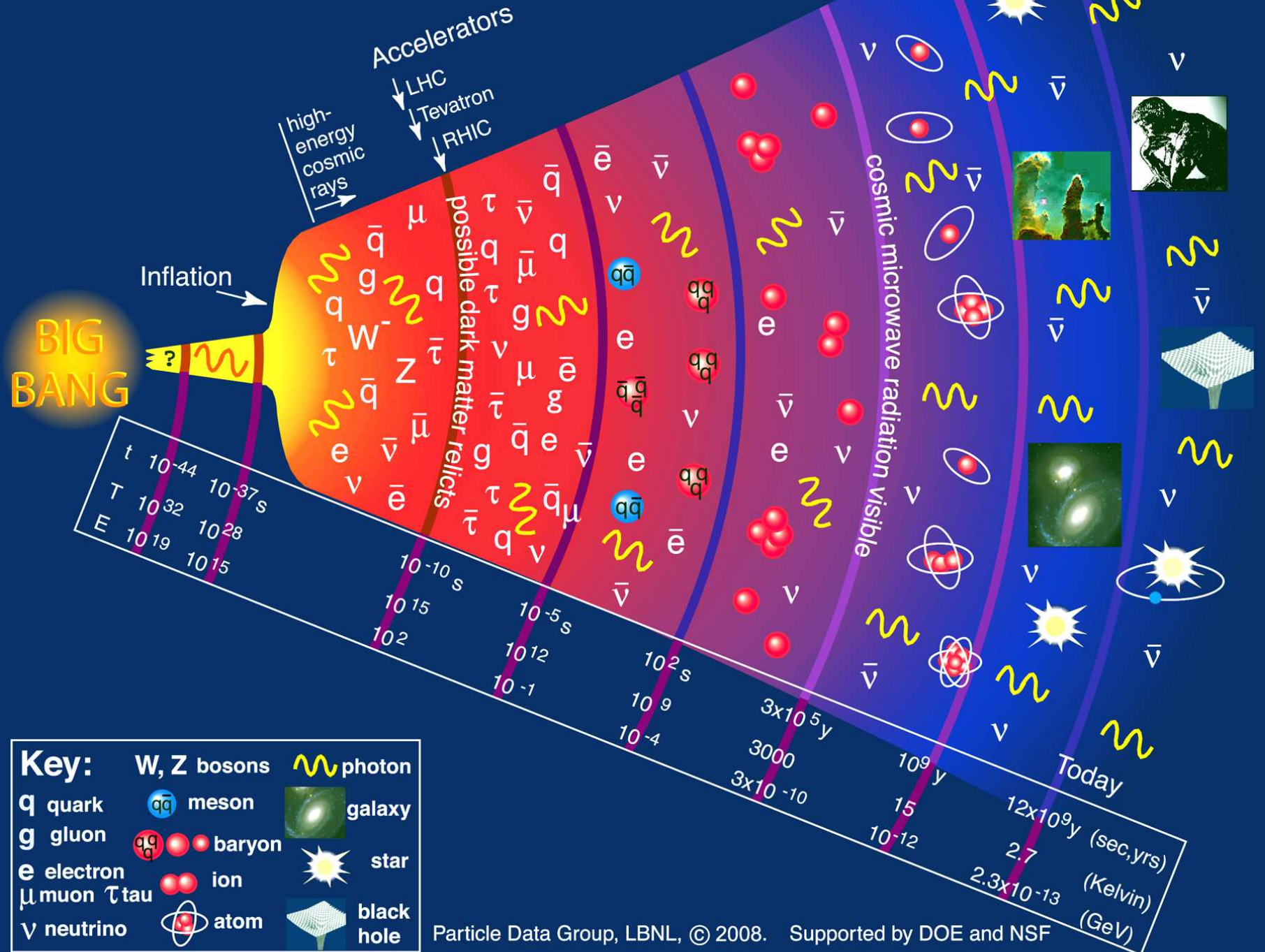
Alpha Magnetic Spectrometer AMS



AMS will measure the strangelet flux in cosmic rays
(at the ISS in 2010)

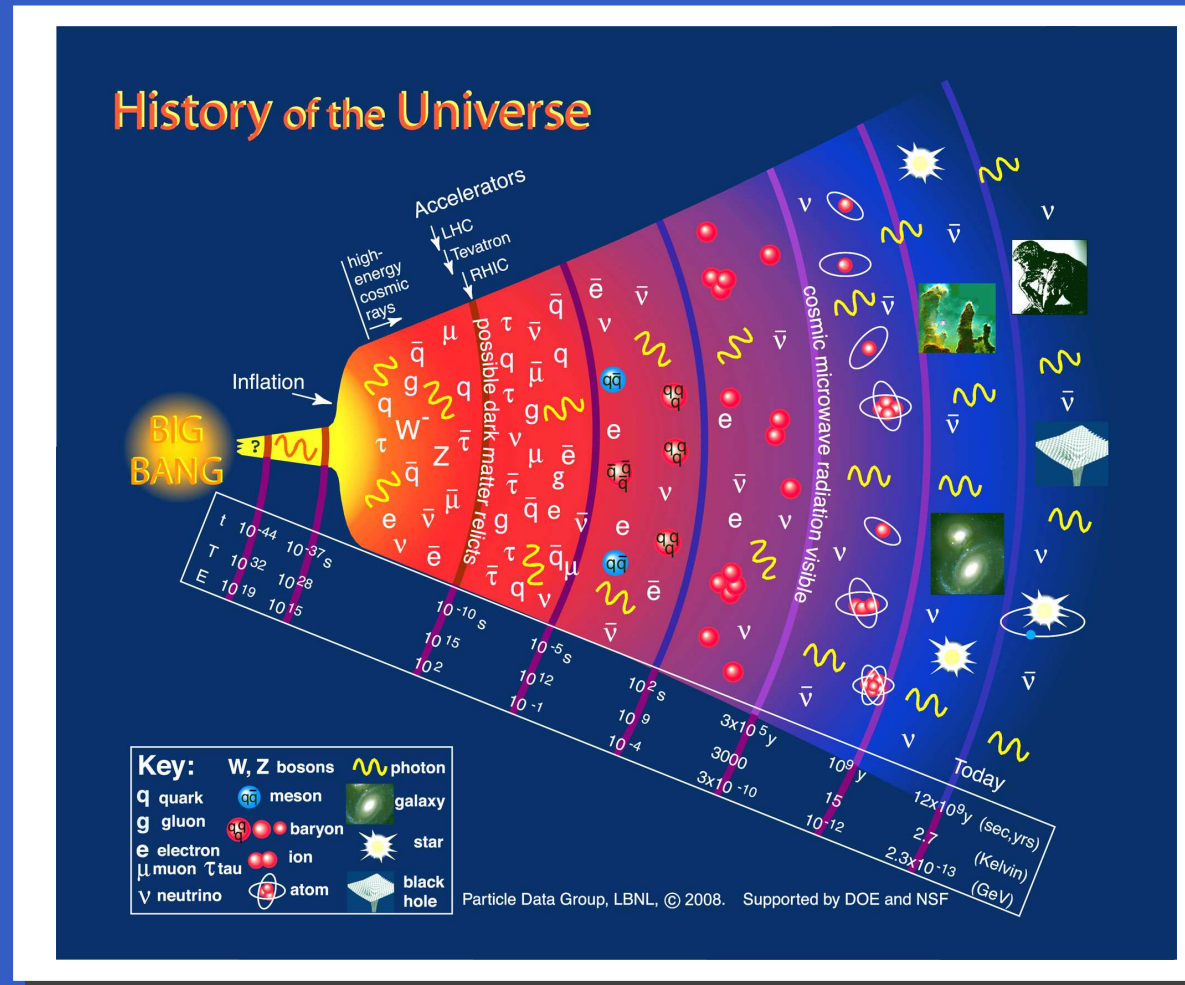
Early universe: phase transition from strange quark matter

History of the Universe



Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

History of the early universe



- Early universe: temperature increases with scale parameter as a^{-1}
- at $t = 1$ s to 3 minutes: BBN ($T = 0.1$ to 1 MeV)
- at $t \approx 10^{-5}$ s: QCD phase transition ($T \approx 170$ MeV)
- at $t \approx 10^{-10}$ s: electroweak phase transition ($T \approx 100$ GeV)

Standard cosmology

from microwave background radiation and big bang nucleosynthesis:

$$n_B/s \sim n_B/n_\gamma \sim \mu/T \sim 10^{-9}$$

note: baryon number per entropy is conserved

⇒ early universe evolves along $\mu \sim 0$

⇒ crossover transition, nothing spectacular, no cosmological signals

Friedmann equation for radiation dominated universe:

$$H^2 = \frac{8\pi G}{3} \rho \sim g(T) \frac{T^4}{M_p^2}$$

$g(T)$: effective number of relativistic degrees of freedom at T

Hubble time (true time $t = 3t_H$ for radiation dominated universe):

$$t_H = \frac{1}{H} \sim g^{-1/2} \frac{M_P}{T^2} \implies \frac{t}{1 \text{ sec}} \sim \left(\frac{1 \text{ MeV}}{T} \right)^2$$

A little inflation at the QCD phase transition

what happens if the early universe passes through a first order phase transition?

- is this possible? \implies Yes! no contradiction with present data
- could this be observable? \implies Yes! by gravitational waves

1st order phase transition \implies false metastable vacuum

\implies de Sitter solution \implies (additional small) inflationary period

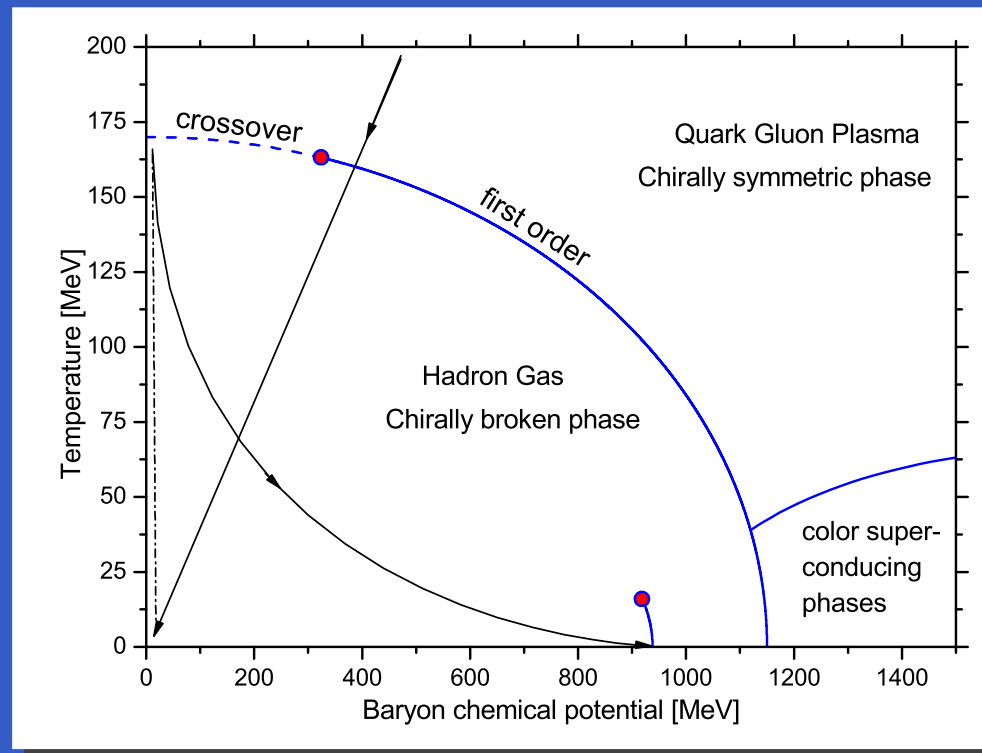
$$H = \dot{a}/a \sim M_p^{-1} \rho_v^{1/2} = H_v = \text{const.} \rightarrow a \sim \exp(H_v \cdot t)$$

just a few e-folds is enough (standard inflation needs $N \sim 50$):

$$\left(\frac{\mu}{T}\right)_f \approx \left(\frac{a_i}{a_f}\right)^3 \left(\frac{\mu}{T}\right)_i$$

Hence $(\mu/T)_i \sim \mathcal{O}(1)$ for just $N = \ln(a_f/a_i) \sim \ln(10^3) \sim 7$

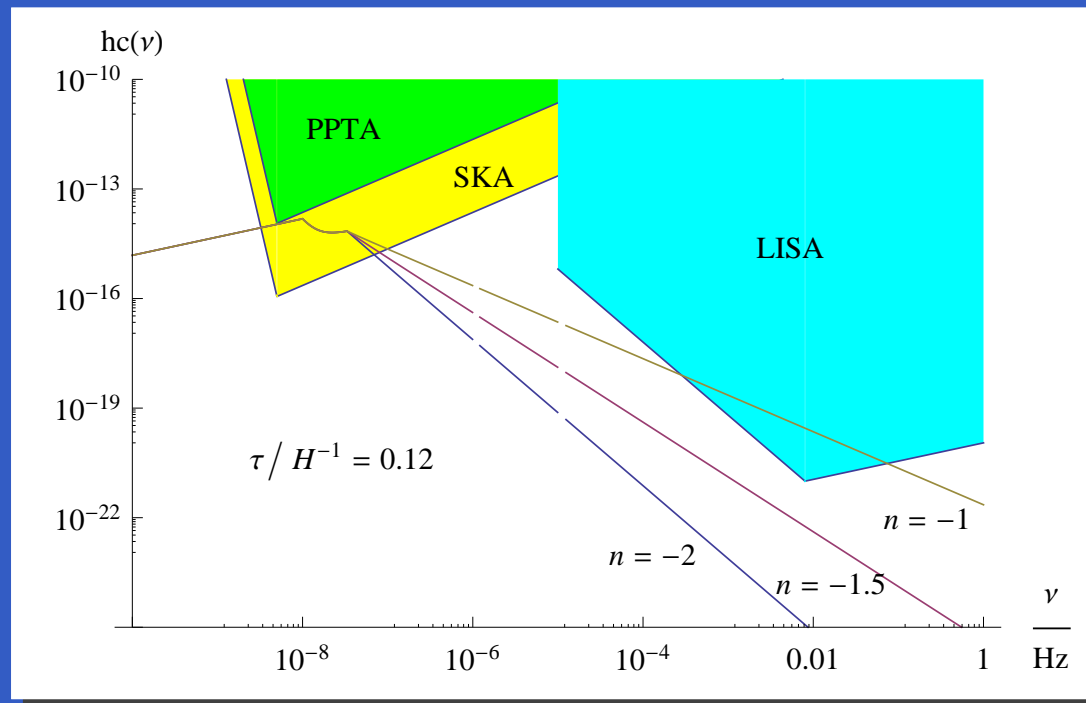
A little inflation in the QCD phase diagram



(Boeckel and JSB, arXiv:0906.4520)

- start with $\mu/T \sim 1$ (possible for e.g. Affleck-Dine baryogenesis)
- universe trapped in false vacuum at the transition line
- supercooling and dilution with $\mu/T = \text{const.}$
- decay to the true vacuum state \rightarrow reheating to $T \sim T_c$ so that $\mu/T \sim 10^{-9}$
- then standard cosmological evolution to BBN

Cosmological signal in gravitational waves!



(Till Boeckel)

- first order transition produces tensor perturbations → gravitational waves
- frequency scale given by (redshifted) horizon scale at the transition point $\nu_{\text{peak}} \sim H \cdot T_{\gamma,0}/T \sim T/M_p \cdot T_{\gamma,0} \sim 10^{-7}$ Hz, amplitude $h \sim a/a_0 \sim 10^{-12}$
- amplitude scales as $h(\nu) \propto \nu^{-1/2}$ for $\nu < H$ (white noise) and as $h(\nu) \propto \nu^{-2 \dots -1}$ for $\nu > H$ (multi bubble collisions) (Kamionkowski, Kosowsky, Turner 1994, Huber, Konstandin 2008)

Cosmological implications of a first order transition

- gravitational wave background:
observable with pulsar timing and LISA
- cold dark matter density is diluted by 10^{-9}
→ need different WIMP annihilation cross section as
 $\Omega_{\text{CDM}} \sim \sigma_{\text{weak}}/\sigma_{\text{ann}}$ or larger WIMP mass (probed by LHC!)
- large-scale structure modified up to $M \sim 10^9 M_{\odot}$
(without QCD inflation only up the horizon mass $\sim 10^{-9} M_{\odot}$)
- generation of the seeds of (extra)galactic magnetic fields:
observed today in our galaxy $B \sim 10^{-5}$ G,
extragalactic $B \sim 10^{-7}$ G
need primordial seed fields of $B = 10^{-30} \dots 10^{-10}$ G
→ possible within the standard model again!

Summary

- constraints on nuclear EoS from kaon production gives a new upper mass limit for neutron stars of $M_{\max} = 2.7M_{\odot}$
- gravitational wave emission is sensitive to microphysical properties of strange quark matter
- strange star mergers: no strangelets in cosmic rays does not rule out strange stars
- 1st order transition could have happened in the early universe
⇒ impact on gravitational wave background, structure formation, cold dark matter densities ...