become sex-specific through the emergence of a sex-determining gene (Fig. 1b). This is different from the standard model for the evolution of sex determination, but if we have learnt anything about sex-chromosome evolution, it is that there are multiple evolutionary routes[7] and no single model explains them all.

The *S. mediterranea* haplotypes potentially offer a remarkable system for studying the genes involved in the evolution of sex determination. Interestingly, Guo and colleagues propose that a fully hermaphroditic species has a region of the genome that is predisposed to being a sex chromosome, with no apparent evolutionary reason for it. What we do not know, however, is whether this region would actually become a sex chromosome. It might or it might not, and there are many sex-determining genes on other chromosomes that could evolve into sex chromosomes through the conventional model.

In support of the idea that chromosome 1 can evolve into a sex chromosome, the authors point to evolutionary conservation of gene content between the chromosome 1 haplotypes and the sex chromosomes in a distant relative, *Schistosoma mansoni* – the only flatworm for which a full genome sequence that has sex chromosomes is available. Broader comparative work could determine whether these haplotypes comprise sex chromosomes in other species. Genetic manipulation of the haplotypes in *S. mediterranea* could also be used to engineer chromosome 1 to become proper sex chromosomes. Such avenues offer exciting ways to determine the prevalence and mechanism of this route to sex determination.

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Nuclear physics

Diverse data tighten neutron-star constraints

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Analysis of data from astrophysical and terrestrial sources offers a promising way of narrowing the range of parameters that describe the extreme properties of neutron stars. **See p.276**

When two neutron stars spiral into each other, the object that results from their merger has an inner density that can be several times the density of an atomic nucleus (itself around 10 trillion times that of solid gold) and a temperature of around 100 billion degrees Celsius. Such events can therefore offer key information about the properties of matter at extreme densities and temperatures. However, the equations that describe ultradense matter cannot be solved exactly, and current numerical techniques cannot yet approximate the dense environment of a neutron star[1]. Progress in understanding these properties therefore requires collaboration between scientists in different fields, and assimilation of different types of data. This 'big science' approach is showcased to great effect on page 276, where Huth *et al.*[2] report a comprehensive analysis of neutron-star matter using astrophysical observations, experiments on heavy-ion collisions and nuclear-physics models.

Quantum chromodynamics is the fundamental theory that describes the subatomic particles called quarks and gluons, and their interactions. As such, the theory describes nuclear matter, and it gives rise to the nuclear equation of state, which governs the behaviour of the dense matter found in neutron stars. For example, the equation can reveal how the neutron stars' pressure varies with density and temperature. Theories developed to approximate quantum chromodynamics can account for matter with densities up to twice that of a nucleus, but above this value, the nuclear equation of state can be only constrained – not calculated exactly – using input from experiments and observations.

Some of the observations that Huth and colleagues considered came from a binary neutron-star merger that was first identified on 17 August 2017 through detection of the gravitational waves it had produced[3]. The discovery sparked a worldwide observing campaign in the hours and days that followed, resulting in the detection of many electromagnetic signals that were consistent with the radiation expected from the merger. This event heralded the dawn of the 'multi-messenger' astronomy era.

Whereas theory can determine the equation of state for matter at and below nuclear densities, these astrophysical observations proved crucial for inferring the parameters relevant for high densities. And Huth *et al.* found that data from experiments on collisions between gold nuclei had a pronounced impact on the nuclear equation of state at densities around 1.5 times that of a nucleus (Fig. 1). These data, which came from two experiments[4,5] performed in a synchrotron ion accelerator at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany, effectively bridged the gap between theory and astrophysical observations.

Huth *et al.* used Bayesian inference to combine all of these data with the theory in

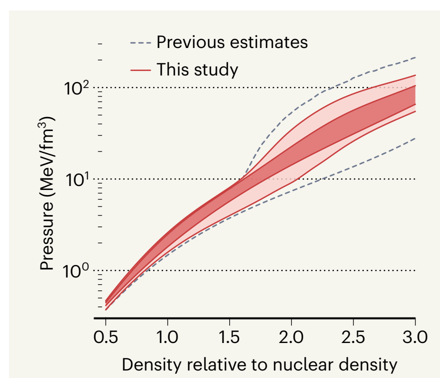

Figure 1 | Constraining the physics of neutron-star matter. Huth *et al.*[2] combined data from astrophysical observations and ion-collision experiments to improve estimates (with 68% and 95% confidence; red and pink shaded areas, respectively) of the parameters in the equation that describes the high-density environment of a merger of two neutron stars. The combined data were crucial for constraining parameters such as pressure (in megaelectronvolts per fm^3, where 1 fm is 10^{-15} m) above densities of around 1.5 times that of a nucleus, at which current nuclear-theory calculations become more uncertain than they are at nuclear densities. (Adapted from Fig. 1d of ref. 2.)

a consistent manner. The Bayesian approach involves estimating the most likely set of parameters of a model that gives rise to an observed or measured distribution of data. By including the collision data in their Bayesian analysis, the authors found that the most likely parameter values for pressure were increased, and that this, in turn, increased the most probable radii of neutron stars at densities comparable to those in the experiments. These inferred radii were consistent with measurements[6] of the mass and radius of neutron stars taken by NASA's Neutron Star Interior Composition Explorer at the International Space Station that were reported in 2019. This compatibility between constraints from terrestrial and astrophysical sources is impressive, and is bound to be crucial for further advances in our understanding of neutron-star matter.

Huth and colleagues' work shows that the results of experiments on collisions between heavy ions can do more than just tell us about the ions themselves – they can also provide powerful constraints on the neutron-star equation of state. It also demonstrates the value of combining these limits with previous constraints derived from systematic nuclear-theory calculations[7,8] and astrophysical observations. Indeed, the authors' analysis shows that the complementary approaches pursued in their study are remarkably consistent.

Crucially, the authors' work indicates that improved precision in heavy-ion collision experiments at low energies is required to better constrain the neutron-star equation of state. Luckily, the next generation of heavy-ion experiments will soon be available – for example, when construction of the Facility for Antiproton and Ion Research is completed at the GSI Helmholtz Centre for Heavy Ion Research. These experiments are expected to probe even larger densities than those analysed by Huth and co-workers. The team's study provides an excellent framework for combining the results of these endeavours with theory and astrophysical observations.

The analysis undertaken by Huth *et al.* is based on theoretical and computational approaches that are valid at nuclear densities, but become less applicable when extrapolated to densities a few times higher than nuclear density. One might therefore question what this work teaches us about the properties of nuclear matter at the extremely high densities that exist at the inner core of a neutron star. Is it possible that previously unknown exotic states of matter appear under the intense conditions present at the neutron-star core? Are there new types of phase transition? Unfortunately, Huth and colleagues' analysis cannot reveal the underlying nature of nuclear matter at such extremely high densities, but it has succeeded in putting tighter bounds on the nuclear equation of state at lower densities.

There is still much to explore with this approach. At high temperatures and very large densities, quarks are expected to transition from being bound to a phase in which they can move freely. Such effects are relevant for neutron-star merger simulations[9], but they are not included in Huth and colleagues' study. This key question in nuclear astrophysics research is thus left unanswered – as is the role of other types of exotic nuclear matter. However, with the advent of new experimental data in nuclear and gravitational-wave physics, answers might finally be on the horizon.

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