ROYAL HOLLOWAY UNIVERSITY OF LONDON

UK Research and Innovation

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Learning about neutron star (interior)s

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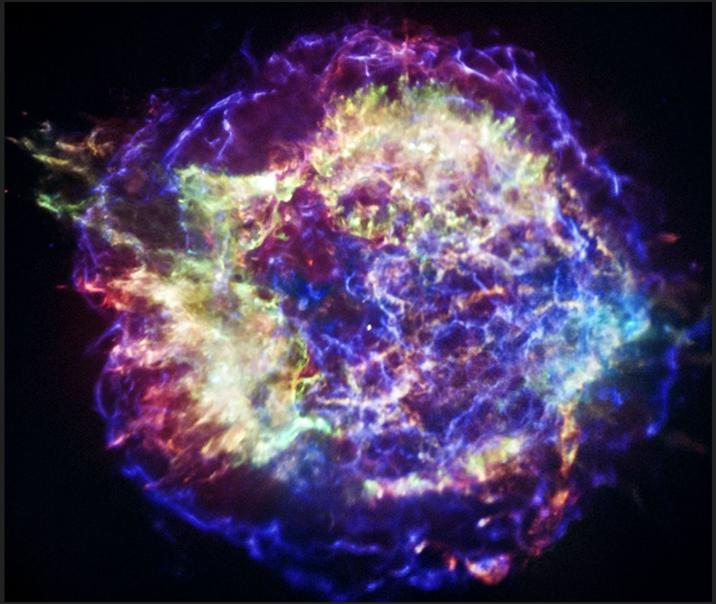
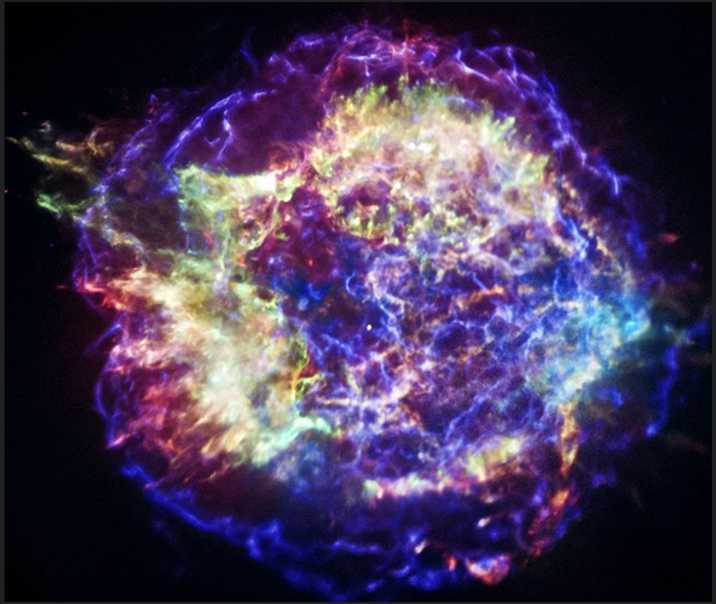
in collaboration with Stefano Ascenzi, Nanda Rea and many more



Cassiopeia A supernova remnant.
Credit: NASA/CXC/SAO

Overview

1. Setting the stage
2. “Standard observables”
3. Pulsar spin-up glitches
4. Neutron star cooling
5. Giant magnetar flares
6. Conclusions



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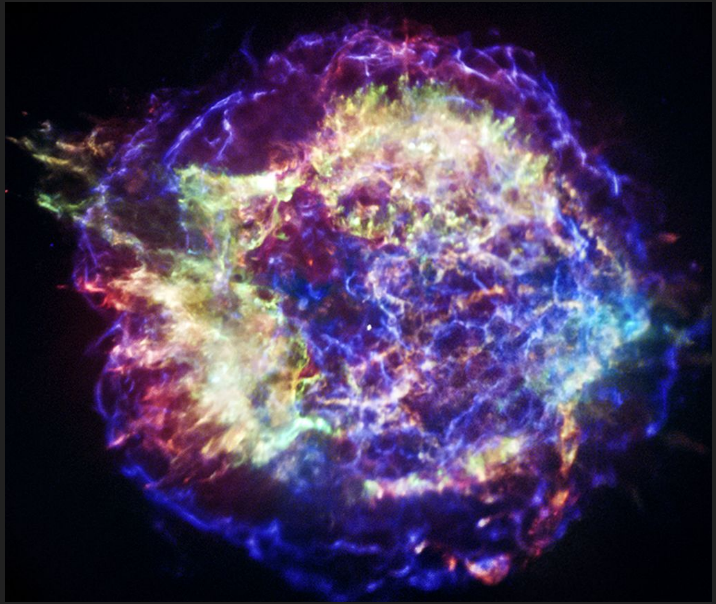

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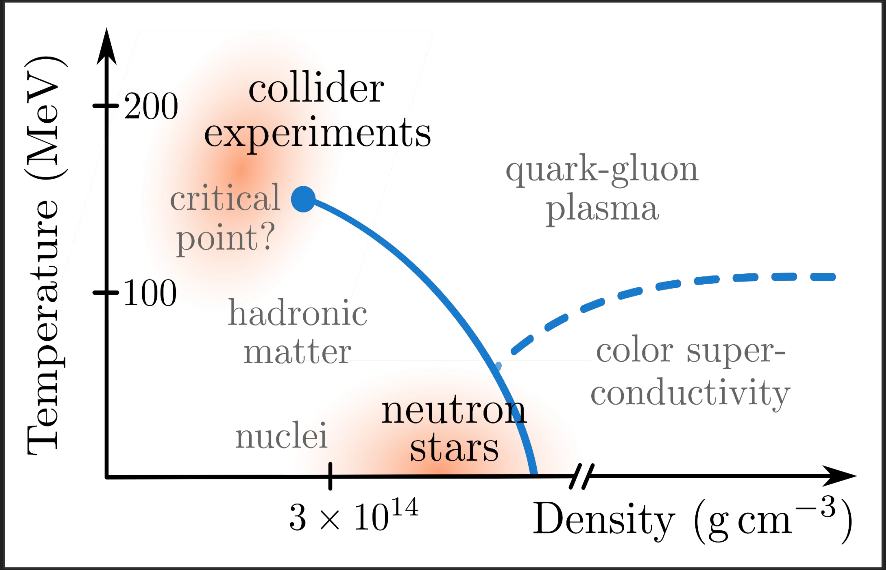
A quick overview of neutron stars (NSs)

- Formed in core-collapse super-novae of massive stars, NSs are compact objects that combine many extremes of physics.

NSs have masses of ~1-2 $M_\odot$ and radii of ~9-15 km.

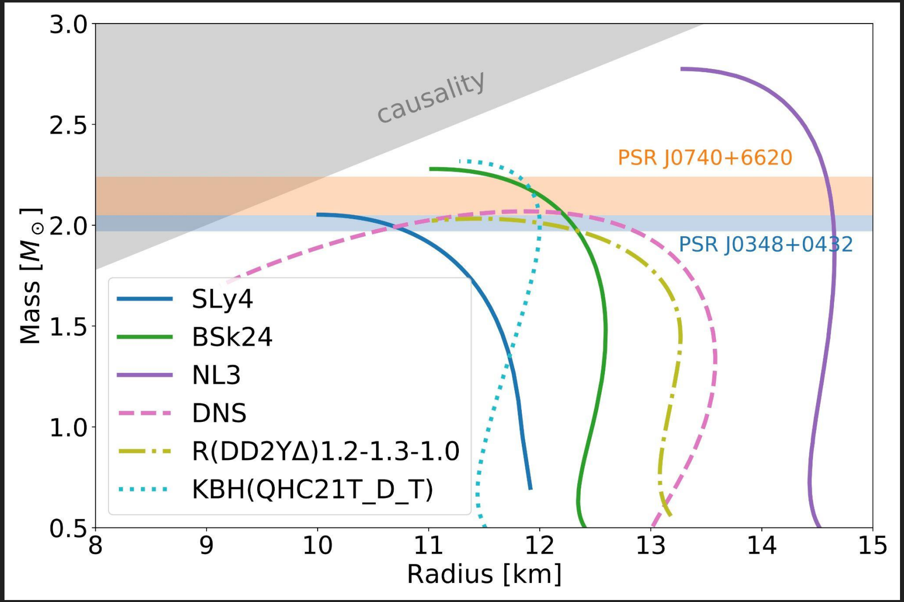
NSs are strong magnets with ~10^8-10^{15}G fields and fast rotators with periods ~10^{-3}-10s.

NSs are the only place in the Universe where we can probe the unknown equation of state (EoS) in the low-temperature, high-density regime.



Sketch of the QCD phase diagram showing the complementary regions probed by terrestrial collider experiments and NSs.

Global properties



M(R) curves for a range of EoSs. Solid lines represent nuclear EoSs, dashed/dashed-dotted lines those with hyperons and the dotted line shows a NS with a quark matter core (Ascenzi, Graber & Rea, 2024).

- One way to characterise neutron stars is by their global (macroscopic) properties. These, in turn, constrain the dense-matter EoS.

Mass

Radius

Tidal deformability

Compactness

Moment of inertia

Global properties are essential for nuclear physics and currently the primary focus of astrophysical dense-matter constraints.

Local properties

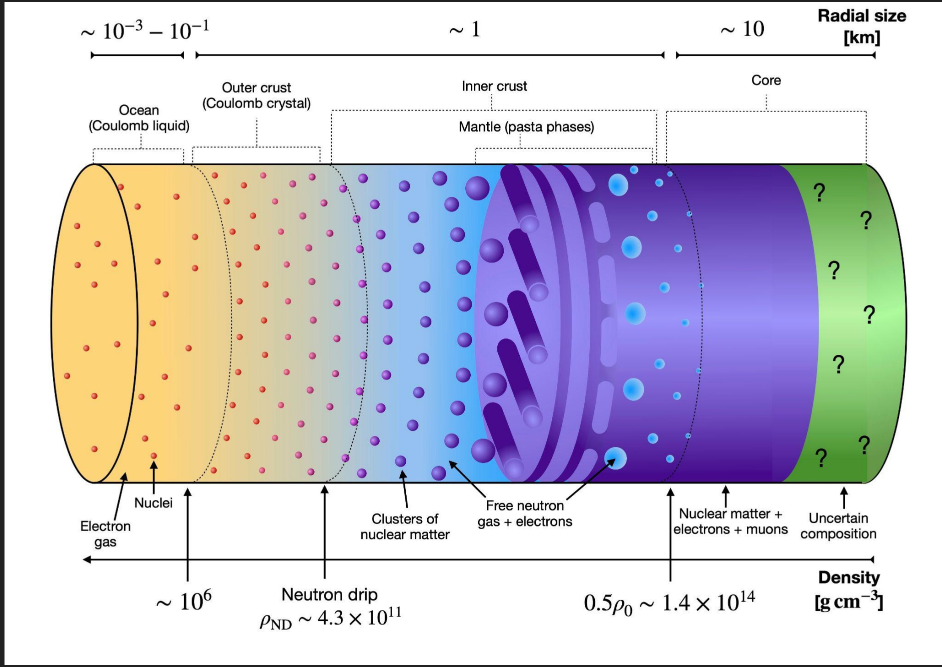
- Besides global features, NSs are also characterised by properties that do not take a single value, but typically vary across the stellar cross-section.

Magnetic field

Superfluid properties

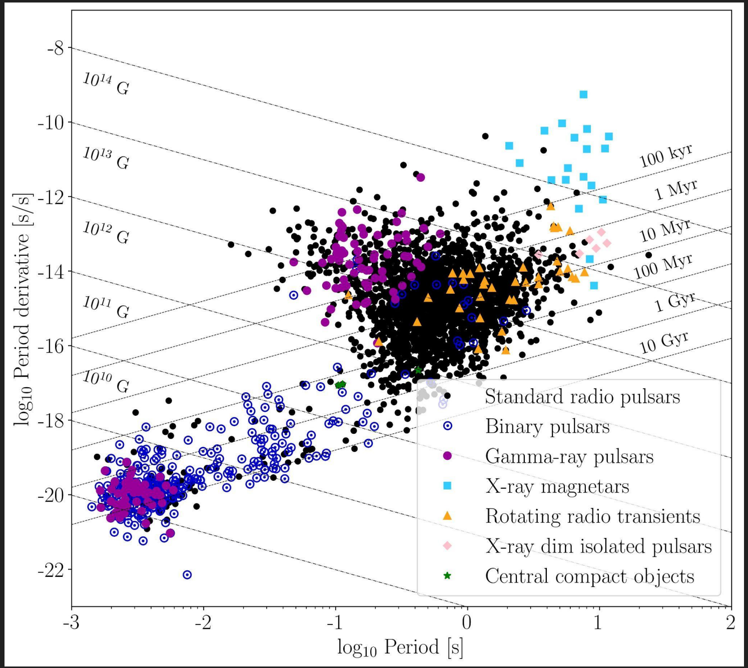
Crustal physics

Local physics are important when modelling dynamical processes, e.g., cooling, oscillations, B-field or rotational evolution.



Sketch of the NS structure (Ascenzi, Graber & Rea, 2024).

Neutron star diversity



Period period-derivative diagram of the pulsar population. Data taken from ATNF Pulsar Catalogue (Manchester et al. 2005).

- To probe (global & local) NSs properties, we take advantage of the fact that NSs are observed in a variety of environ-ments across the EM spectrum, e.g.:

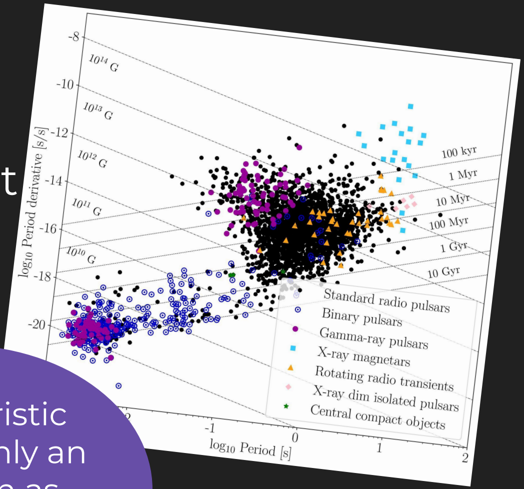
Millisecond pulsars are prime targets for mass and radius measurements via pulsar timing and pulse profile modelling, respectively.

Radio pulsars that undergo sudden spin-up glitches can help probing crustal physics.

Magnetars are strongly influenced by their magnetic fields.

Ages and magnetic fields

- NS magnetic field strengths and ages are typically not directly measured but instead inferred from pulsar timing (i.e., via P and $\dot{P}$ measurements).



We generally assume that NSs are rotating magnetic dipoles.

Based on dipolar spin-down, we can derive equations for the characteristic age and the dipolar field strength at the pole.

Characteristic ages are only an indication as they neglect field decay.

B-field estimates can vary by factor of ~5 based on assumption of NS magnetosphere and surface location.

$$\tau_c = \frac{1}{2}\frac{P}{\dot{P}} = 1.6 \times 10^7 \left(\frac{P}{1\,\mathrm{s}}\right)\left(\frac{\dot{P}}{10^{-15}\,\mathrm{s\,s^{-1}}}\right)^{-1}\,\mathrm{yr}$$

$$B_{\rm dip} \approx \sqrt{\frac{c^3 I_{\rm NS}}{\pi^2 R_{\rm NS}^6} P\dot{P}} \approx 1.7 \times 10^{12} \left(\frac{R_{\rm NS}}{10\,\mathrm{km}}\right)^{-3}\left(\frac{I_{\rm NS}}{10^{45}\,\mathrm{g\,cm^2}}\right)^{1/2}\left(\frac{\dot{P}}{10^{-15}\,\mathrm{s\,s^{-1}}}\right)^{1/2}\left(\frac{P}{1\,\mathrm{s}}\right)^{1/2}\,\mathrm{G}.$$

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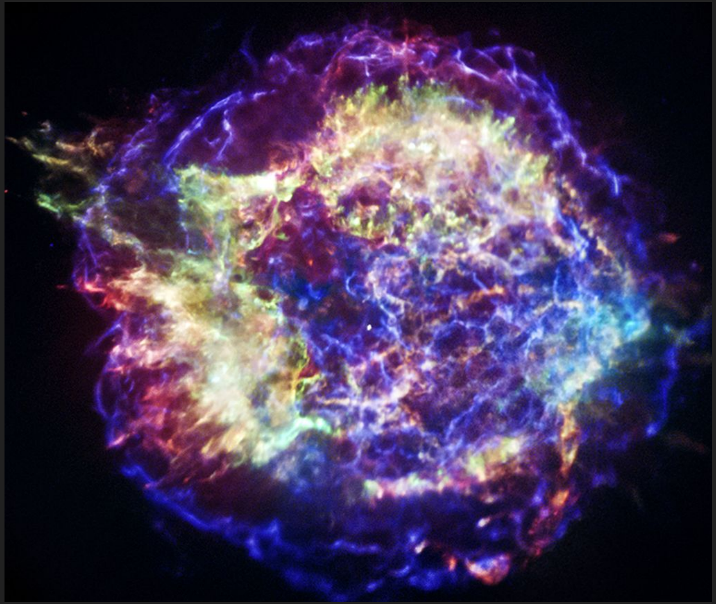

Cassiopeia A supernova remnant.
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Radio pulsar timing

- NSs emit regular electromagnetic pulses. We track this emision with telescopes to build up timing solutions and predict pulsar rotations.

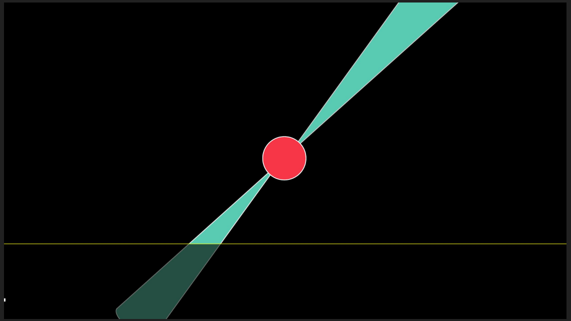


Illustration of pulsar lighthouse radiation. Credit: J. Christiansen

In some binary millisecond pulsars, relativistic effects of the orbital motion and propa-gation of radio waves are measured to high precision.

Precise measurements of Keplerian and post-Keplerian parameters allow us to constrain pulsar masses.

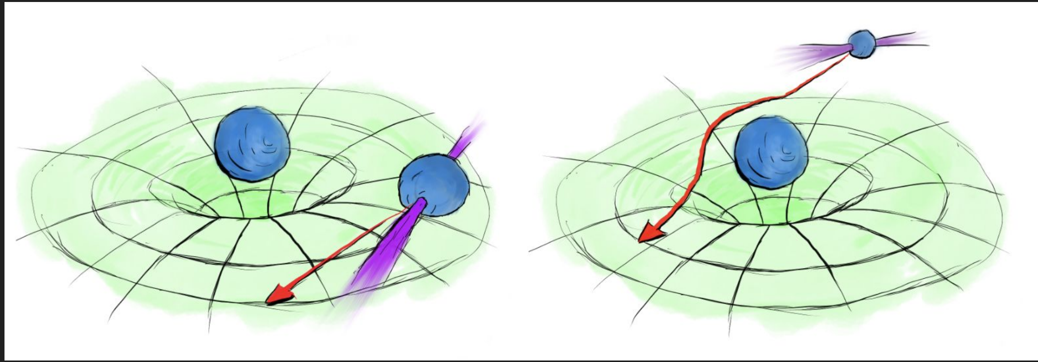
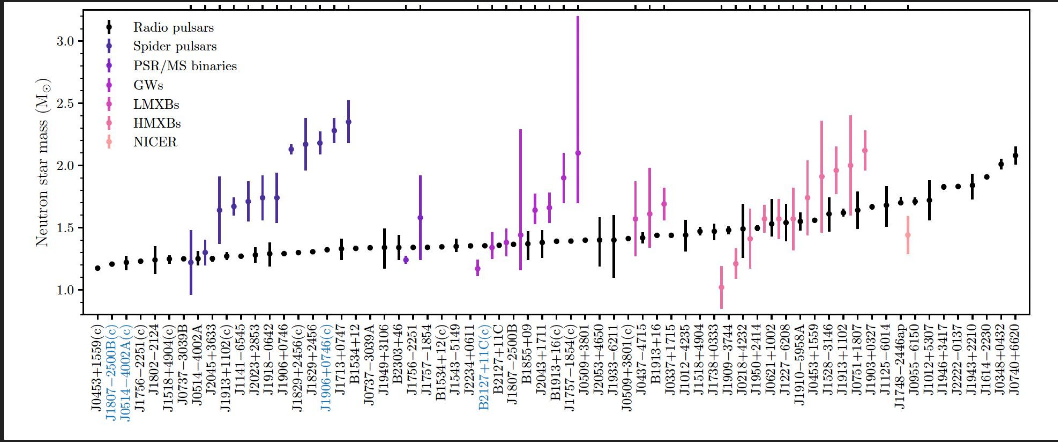


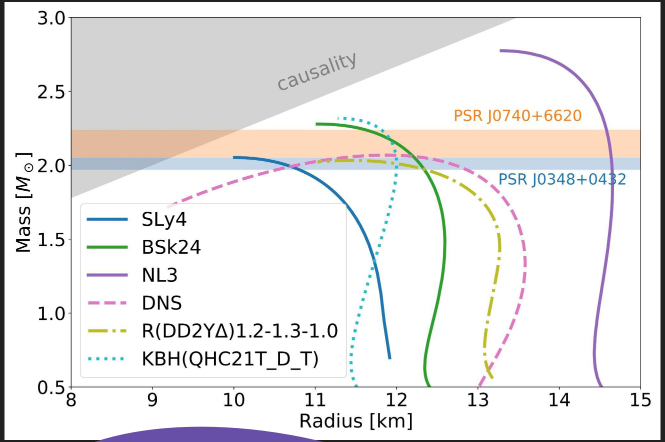
Illustration of the Shapiro delay. At superior conjunction, the companion's curvature introduces a time delay in the signal (Ascenzi, Graber & Rea, 2024).

Neutron star mass spectrum

- To date, high-precision pulsar timing has constrained 61 (65) NS masses. The heaviest source, PSR J0740+6620 (2.08 ± 0.07M☉), rules out the softest EoSs.



The observed NS mass spectrum with 68% confidence intervals combining data from You et al. (2025) and updated radio timing measurements from P. Freire. Credit: Marcus Lower



Any EoS with a maximum masses that falls below the most massive NS can be excluded.

Pulse-profile modelling in the X-rays

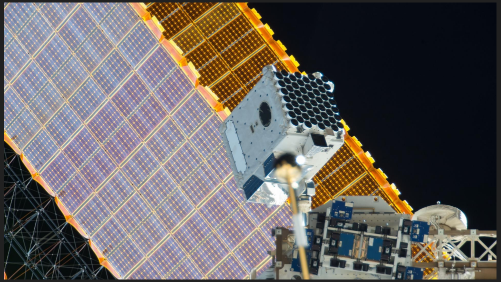
- NICER (Neutron Star Interior Composition Explorer) analyses the X-ray light curves emitted from rotating hotspots on NS surfaces.

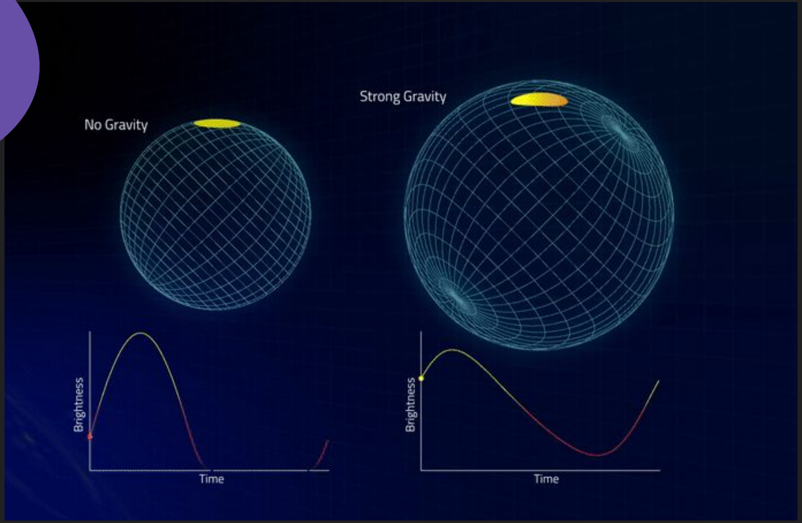
Pulse-profile modelling accounts for GR effects like light bending and Doppler shifts to simulate synthetic light curves.

Comparing theory with observations, we can infer masses and radii based on how the emission changes as the star rotates.

As NSs are so compact, we can see the hotspot emission from the "dark side".

Picture of NICER on the ISS (left) and illustration of the pulse profile emitted by hotspots in different gravitational fields (right). Credit: NASA Goddard





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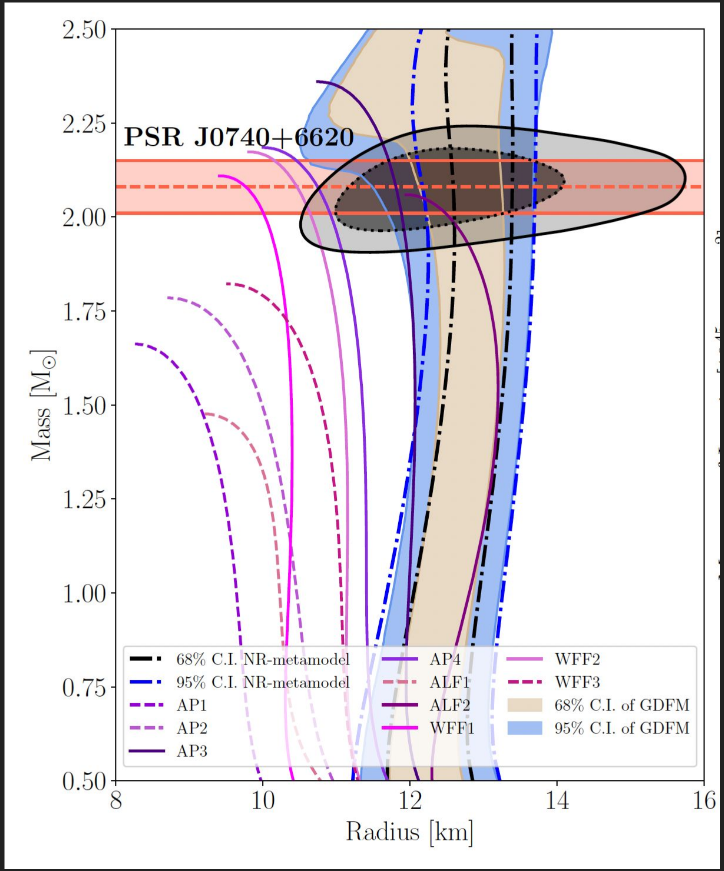
Mass-radius constraints



- While NICER can constrain masses and radii simultaneously, we obtain the best radius measurements for those millisecond pulsars where the mass is known from radio timing, e.g., for PSR J0740+6620.

Mass-radius relations for a range of EoSs and posteriors for relativistic (shaded brown/blue) and non-relativistic (dot-dashed brown/black) meta-model calculations. The grey shaded regions represent the 68% and 95% credible regions for the mass and radius of J0740+6620 from NICER measurements (Salmi et al., 2024a). Credit: Avishek Basu

The tightest M/R constraints today come from multi-wavelength observations in the radio and X-rays.

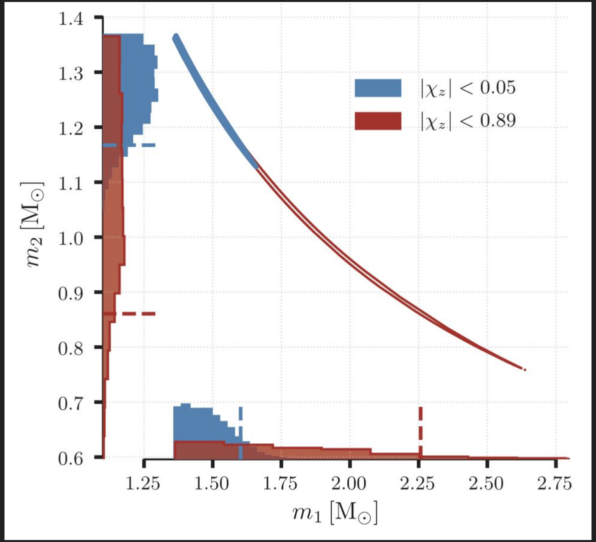
This also suggests that the EoS cannot be too soft!

Binary neutron star mergers

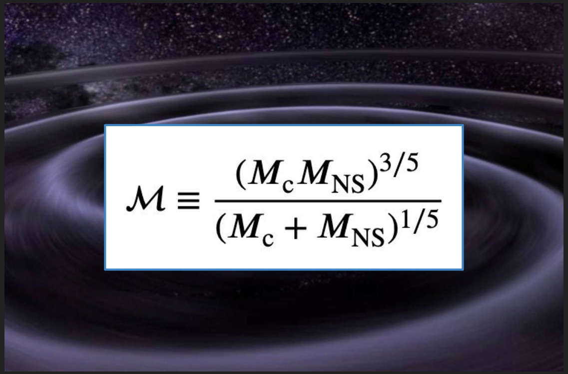
- The "newest" way to extract NS masses is from the gravitational waves signals of binary NS mergers.

The chirp signal depends on the chirp mass (roughly the geometric mean of the two component masses).

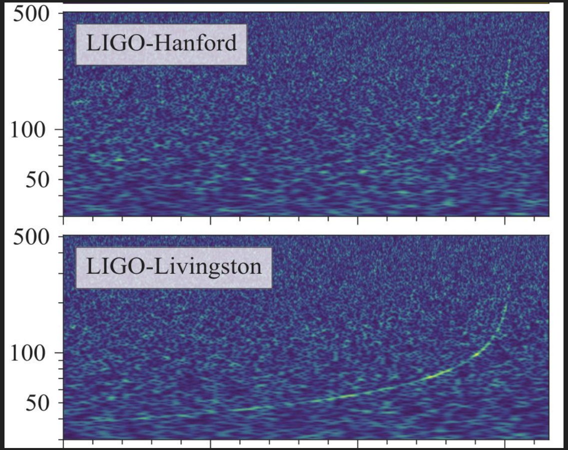
Measurements of the star's tidal properties also allow (weak) radius limits, ruling out the stiffest EoSs.



Mass posteriors for the component masses of GW170817 (Abbott et al., 2017).



$$\mathcal{M} \equiv \frac{(M_c M_{NS})^{3/5}}{(M_c + M_{NS})^{1/5}}$$



The merger of two NSs (top illustration by NASA Goddard) produces a characteristic chirp signal (bottom) in a gravitational wave detector (Abbott et al., 2017).

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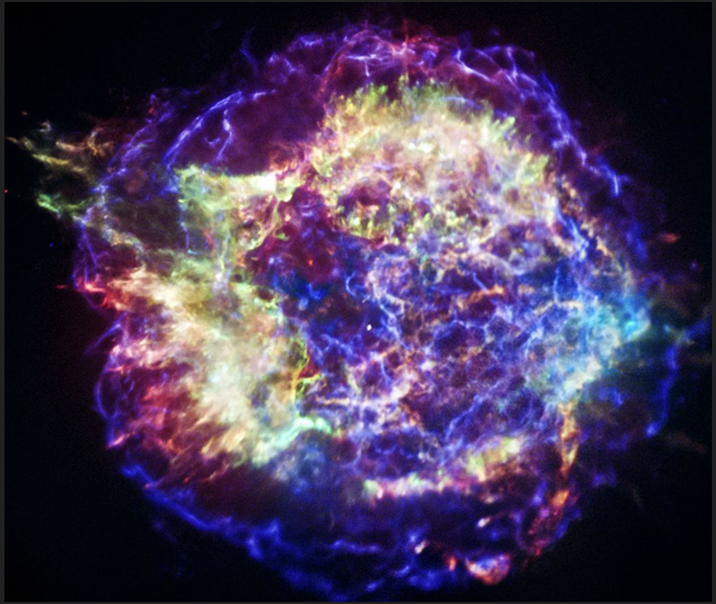

Cassiopeia A supernova remnant.
Credit: NASA/CXC/SAO

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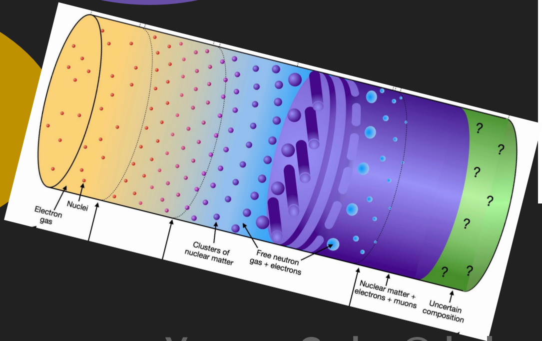
Macroscopic quantum states

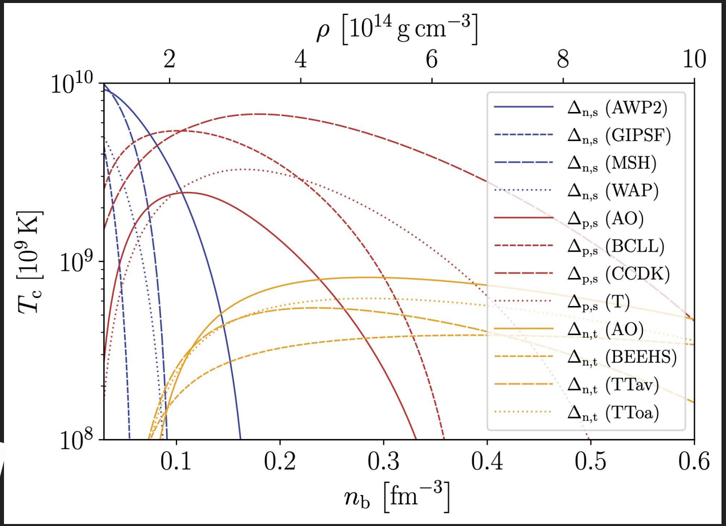
- Mature NSs with temperatures between 10^6-10^8K are cold in terms of their high densities and well below the nucleon Fermi temperatures (~10^{12}K).

Below critical temperatures T_c nucleons become unstable to Cooper pair formation.

NSs contain at least 3 macroscopic quantum states.

Superfluid (SF) neutrons influence the NS rotation, while super-conducting protons affect the stellar magnetism.

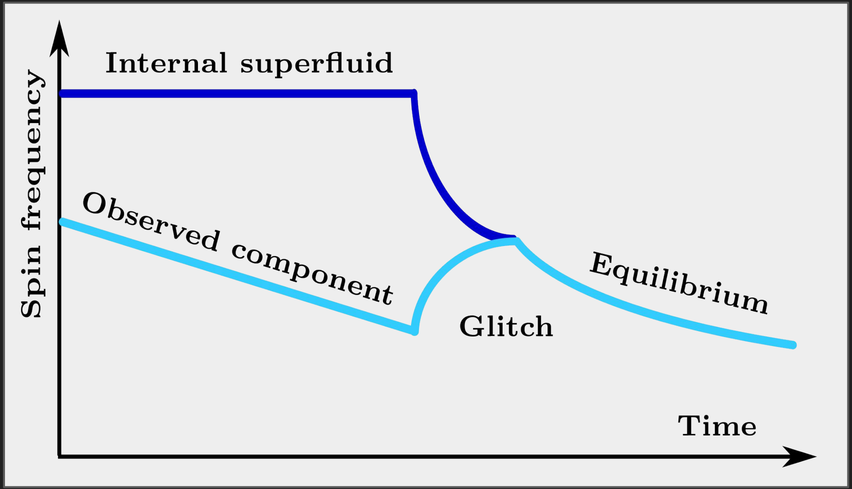




Transition temperatures for different energy gaps as a function of density for the NRAPR EoS (Ascenzi et al. 2024).

Sudden spin-ups

- Pulsar timing shows that the regular electromagnetic spin-down of NSs can be interrupted by sudden spin-ups, so-called pulsar glitches.



Sketch of the two-component pulsar glitch model.

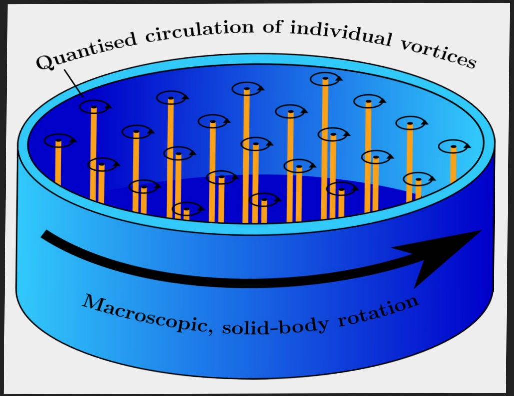
We have observed ~680 glitches in ~230 pulsars.

(Large) glitches are generally associated with the presence of super-fluids and explained in multi-component models.

While glitch statistics encode global NS properties, the shape of the glitch also gives information about local physics.

Vortex dynamics I

- Superfluids are characterised by a wave function $\Psi = \Psi_0 e^{i\varphi}$ satisfying a Schrödinger equation. This dictates $\mathbf{v}_{SF} = \hbar/m_c \nabla\varphi$ and $\boldsymbol{\omega} = \nabla \times \mathbf{v}_{SF} = 0$.



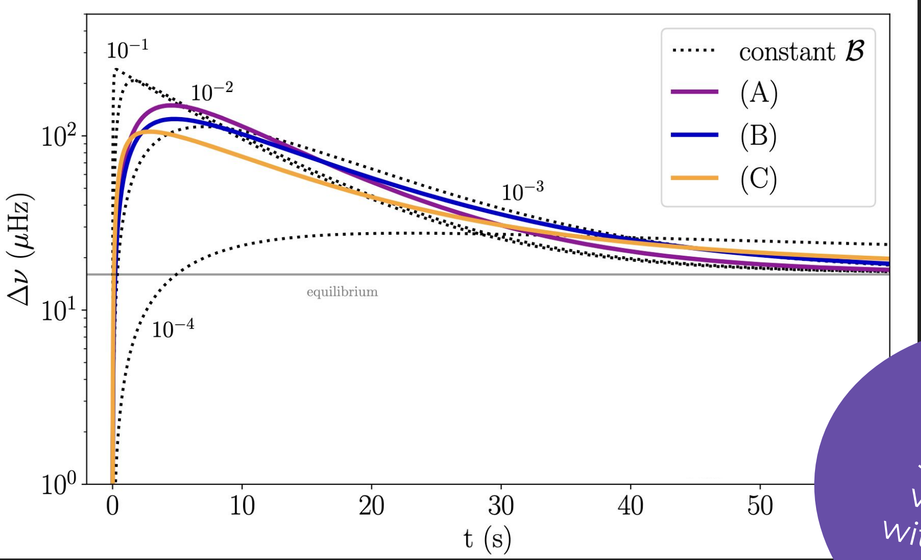
An array of quantised vortices mimics solid-body rotation on large scales.

Superfluids rotate by forming quantised vortices. Each vortex carries a quantum of circulation $\kappa = h/m_c$.

Vortices form an array that mimics solid-body rotation on large scales, i.e., $\omega = 2\Omega = N_v \kappa$.

We can imagine superfluid vortices as tiny rapidly rotating tornadoes (credit: NOAA Photo Library).

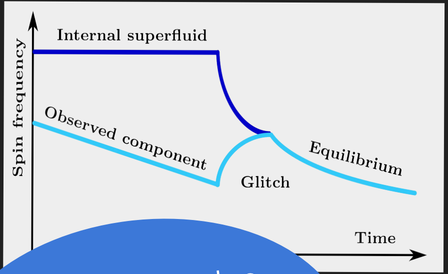
Vortex dynamics II



Glitch rises for a range of different prescriptions for the coupling of vortices in the NS crust (Graber et al. 2018).

- SF spin-down is impeded by pinning vortices to the crustal nuclei. The crustal SF can thus provide the angular momentum reservoir for the glitch.

Glitch rises are particularly sensitive to how vortices interact with their environments.



Glitches involve the catastrophic unpinning of billions of vortices.

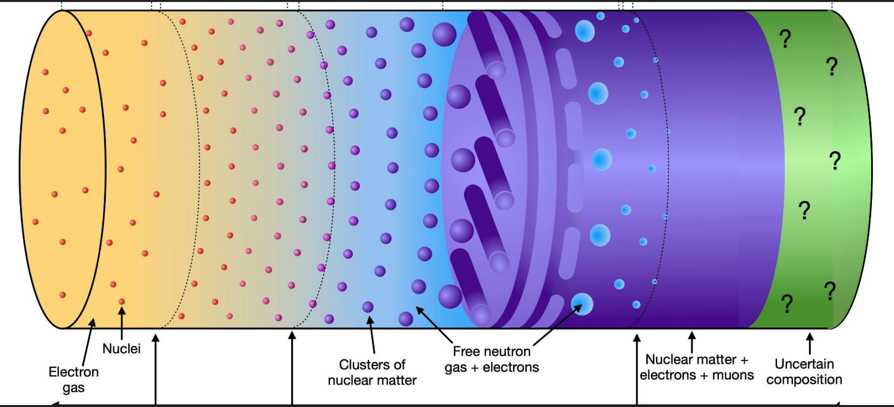
Crustal physics

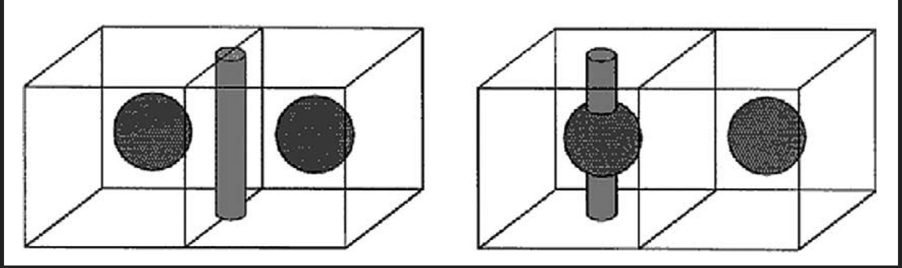
- Glitch morphology is not only affected by the properties of the vortices themselves but also the crustal physics.

Glitch shapes are affected by the baryon and SF densities, crustal lattice sizes and shapes, pinning inter-action, etc.

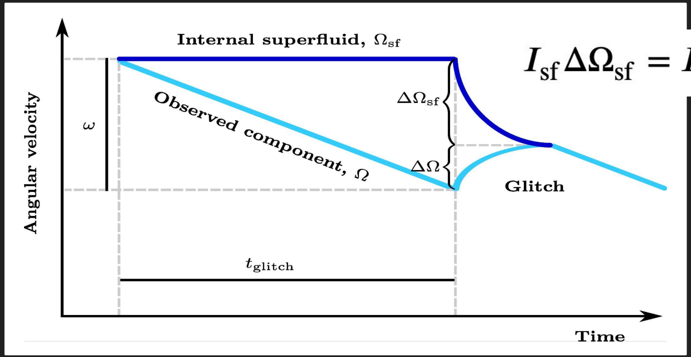
We currently do not have any glitch models that incorporate nuclear pasta!!

Better models will be crucial to use upcoming SKA data.





Two vortex-nucleus pinning configurations in the inner crust: interstitial pinning (left) and nuclear pinning (right) (Donati & Pizzochero 2004).

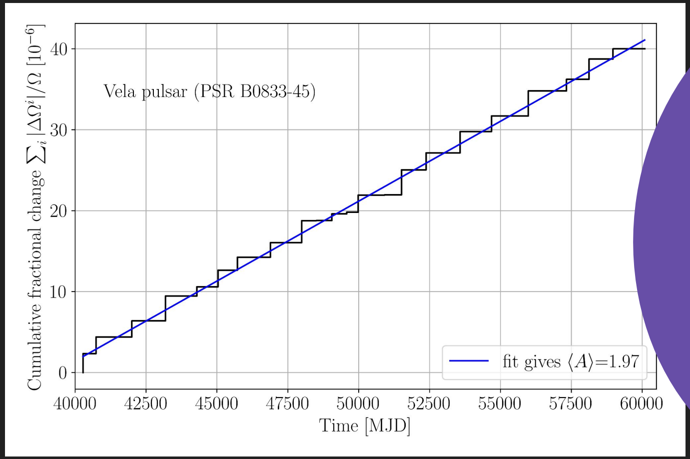


$$I_{sf}\Delta\Omega_{sf} = I_{obs}|\Delta\Omega|.$$

MoI constraints

- While individual glitches encode local physics, repeated large glitches constrain the NS moment of inertia (MoI).

$$\frac{I_{sf}}{I_{NS}} \approx 2\tau_c \frac{1}{t_{obs}} \sum_i^N \frac{|\Delta\Omega^i|}{\Omega} \equiv 2\tau_c \langle \mathcal{A} \rangle.$$



Cumulative fractional change of spin frequency for Vela pulsar with I_{sf}/I_{NS}~1.6%.

We combine angular momentum conservation with the average glitch activity <A> to estimate the fraction of the superfluid angular momentum reservoir.

Our I_{sf}/I_{NS} estimates range between ~0.5-5% in line with EoSs leading to ~2-8% MoI for inner crusts.

Model dependent and maybe missing physics (such as entrainment).

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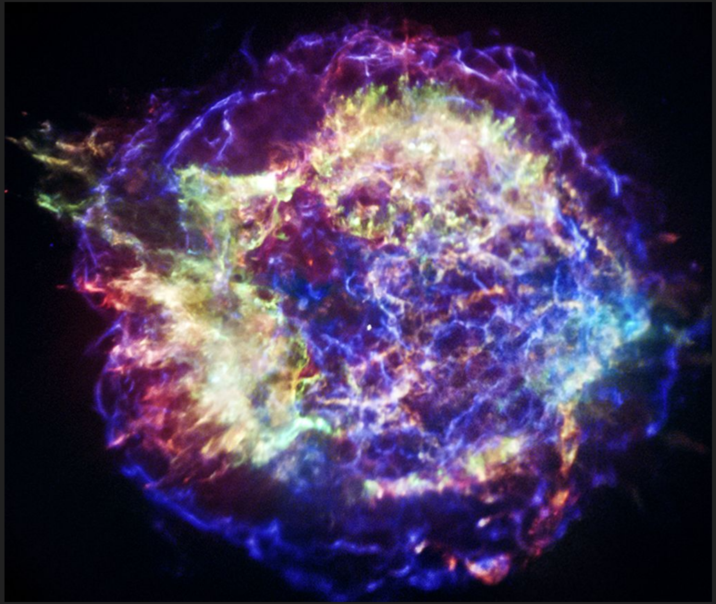

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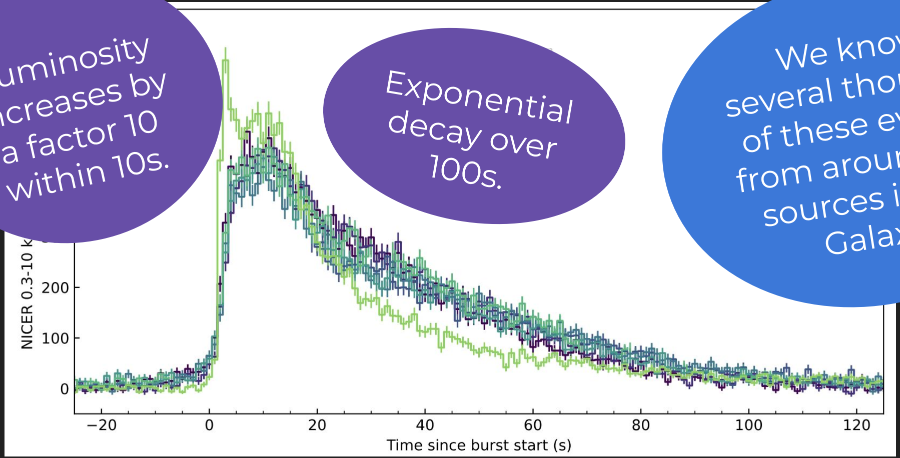
Burst mechanism

- NSs accreting from a main-sequence companion can accumulate so much matter onto their surfaces that a runaway fusion reaction is ignited causing thermonuclear bursts, observed in X-rays.

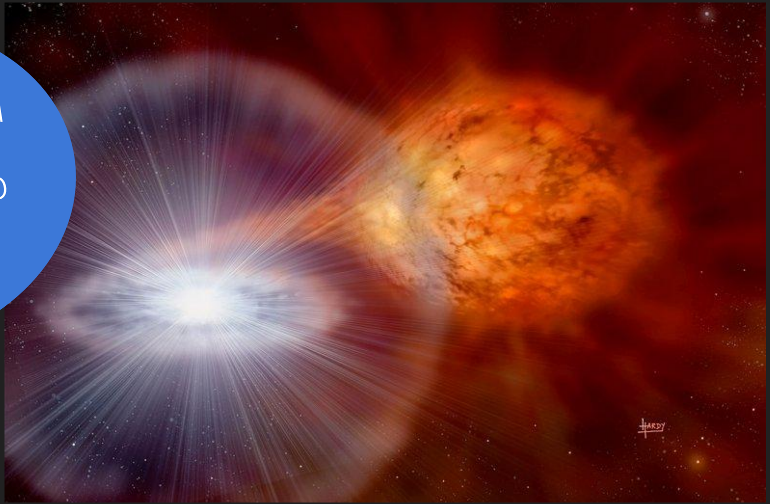
Luminosity increases by a factor 10 within 10s.

Exponential decay over 100s.

We know several thousand of these events from around 100 sources in the Galaxy.



7 X-ray burst of accreting X-ray MSP Swift J 1749.4-2807 observed with NICER in 2021 (Albayati et al. 2023).



Artist impression of a thermonuclear X-ray burst in a compact binary. Credit: David A. Hardy

Burst oscillations

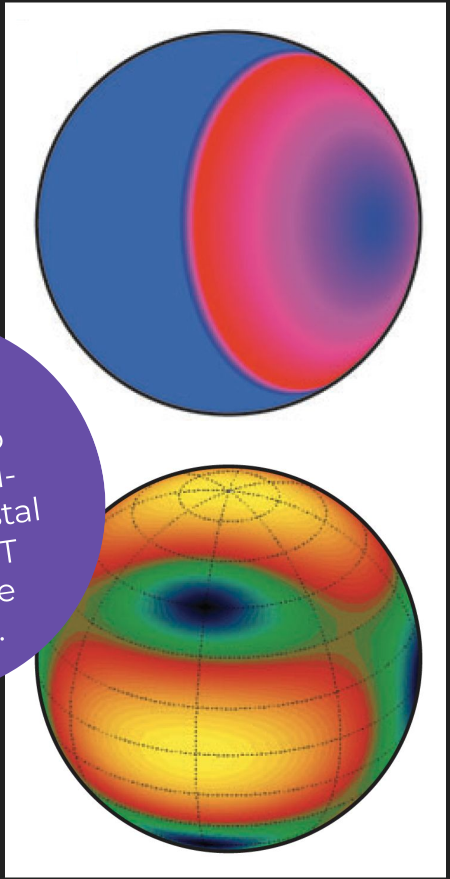
- Oscillations with frequencies ~10-600Hz are observed in the rises and decays of the bursts. They are associated with the NS rotation rate.

High-frequency oscillations are associated with small temperature anomalies, which cause localised ignition and subse- quent flame spreading.

Hot-spot models: burning in small region due to crustal field confinement.

Global-mode models: flame spreads and excites shallow, large-scale surface waves depending on crustal composition.

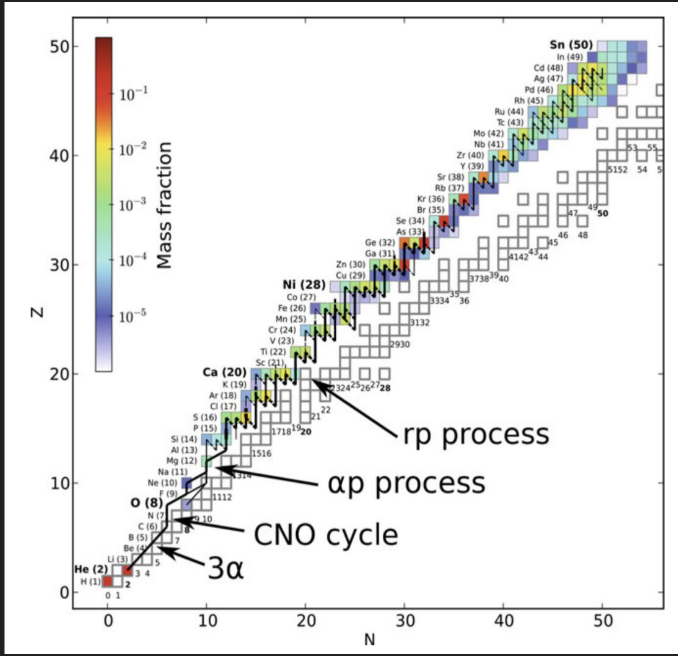
Gives qualitative insights into field configu- ration or crustal physics BUT models are complex.



Sketch of the hot-spot model (top) and the large-scale wave model (bottom) (Watts 2012).

Burning ashes

Flow of nuclear reactions between isotopes with N neutrons and Z protons for a solar accretion composition ~1ms into the burst. At this stage, most isotopes are unstable and β-decay (Galloway and Keek 2021).



- Ignition conditions and burst characteristics depend strongly on the thermal properties and composition of the crustal matter.

Composition of burning ashes left behind from explosions are not accessible due to burial by continued accretion.

Key input for burst models are detailed nuclear reaction chains.

To constrain the original crust composition, we can compare burst light curves and theoretical models.

Transient sources

- We can track the thermal evolution post-outburst to probe additional physics. In quiescence, luminosities drop significantly but are still much higher than for isolated, old neutron stars due to burning ashes reacting with the existing crust. This provides additional heat referred to as **deep crustal heating**.

Transient sources accrete from days to weeks and are typically in a steady-state post outburst.

$$L_{\text{neutrino}} + L_{\text{photon}} = L_{\text{crustal heating}} = Q \, \frac{\langle \dot{M} \rangle}{m_{\text{u}}},$$

Cooling processes (neutrinos from entire volume & photons from the surface) are balanced by deep crustal heating.

Combining observations with estimates for $\dot{M}$ and Q provided a strong hint for dUrca neutrino reactions in the first transiently accreting MSP.

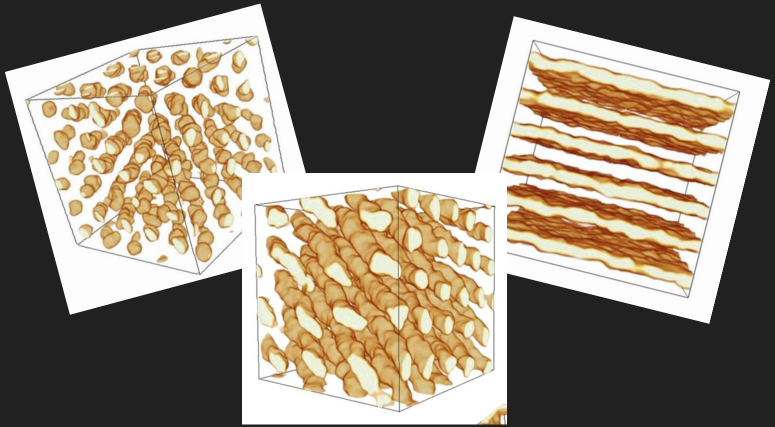
Quasi-persistent sources I

- These sources accrete from years to decades. Due to long accretion episodes, the crust is heated more and brought out of equilibrium with the core. By following the cooling, we can probe various aspects of crustal physics.

Short cooling timescales require a high thermal conductivity in the crust, which implies a "purification" process for impure burning ashes.

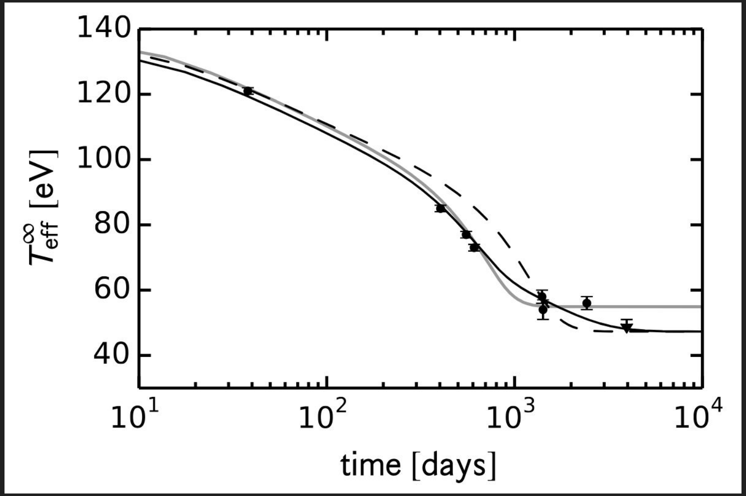
Many cooling curves require a localised highly resistive region in the inner crust, which is naturally explained by nuclear pasta.

High temperatures at the onset of quiescence suggest the need for an additional shallow heating source??



Nuclear pasta phases (gnocchi, spaghetti, lasagne) obtained from molecular dynamics calculations. Credit: M. E. Caplan, C. J. Horowitz

Quasi-persistent sources II



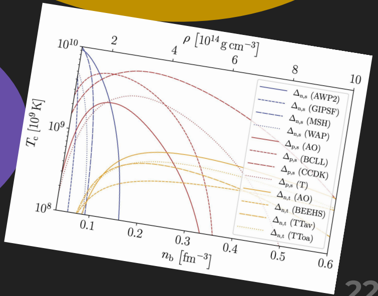
Cooling of MXB 1659-29 for Q_{imp}=2.5 throughout the crust and T_{core}=4 x 10^7K (grey), and Q_{imp}=20 in the pasta region, T_{core}=3 x 10^7K and two different gap models (black solid & dashed) (Deibel et al. 2015).

- The longer we observe quasi-persistent sources cooling post outburst, the deeper we probe into the star. For some sources, we can even probe the core.

Cooling curves are sensitive to SF. For SF neutrons, the heat capacity is suppressed leading to faster cooling.

Faster cooling at intermediate times suggests the presence of SF. The cooling curve is also sensitive to the gap.

Long-term monitoring suggests that some sources cannot contain large fractions of quarks, or core SF/SC.



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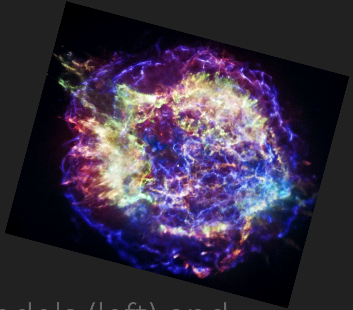
Cooling of isolated NSs



- Cooling observations also provide information about interiors of isolated NSs.

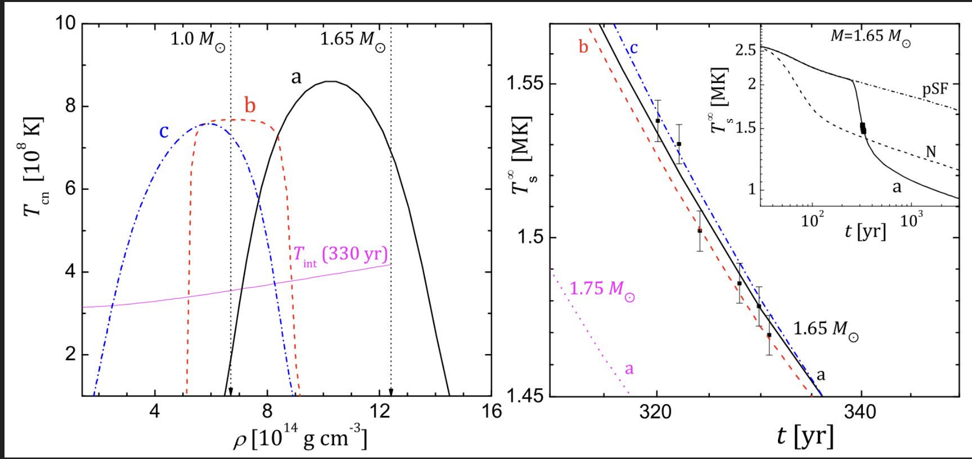
The most promising candidate is the young (~330yr) CCO in supernova remnant Cassiopeia A.

T_s appears to decrease faster than expected from standard neutrino cooling.

Extra neutrino emission could be due to recent onset of core neutron SF, which probes SF gap.

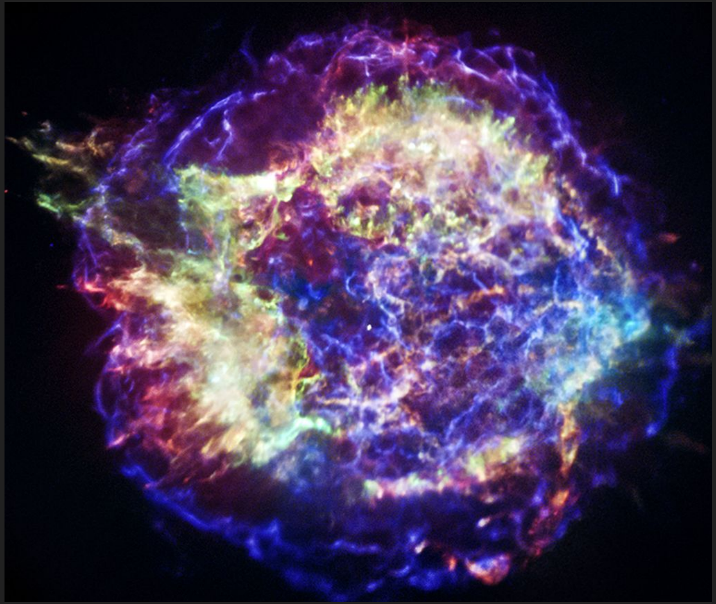
Note: temperature measurements are difficult!!

3 different neutron transition models (left) and corresponding cooling curves compared to Cas A observations (right) (Shternin et al. 2011).



Overview

1. Setting the stage
2. “Standard observables”
3. Pulsar spin-up glitches
4. Neutron star cooling
5. **Giant magnetar flares**
6. Conclusions



Cassiopeia A supernova remnant.
Credit: NASA/CXC/SAO

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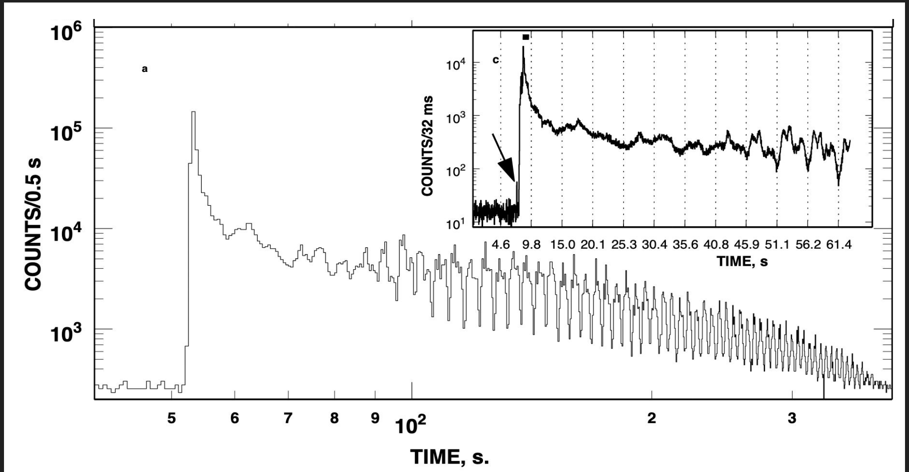
QPO observations

- Magnetars are those NSs with the strongest magnetic fields. Their decay and evolution drives the enigmatic activity (bursts, flares, etc.) of these sources.



1998 giant flare Ulysses observation of magnetar SGR 1900+14. The ~300s tail with a soft energy spectrum shows a clear periodicity at 5.16s (Hurley et al. 1998).

Three Galactic magentars have shown powerful giant flares with X-ray luminosities up to 10^{47} erg/s.

The flare tails show strong quasi-periodic oscillations (QPOs) with frequencies from tens of Hz to kHz.

QPOs are grouped into low- and high-frequency models below and above ~250Hz.

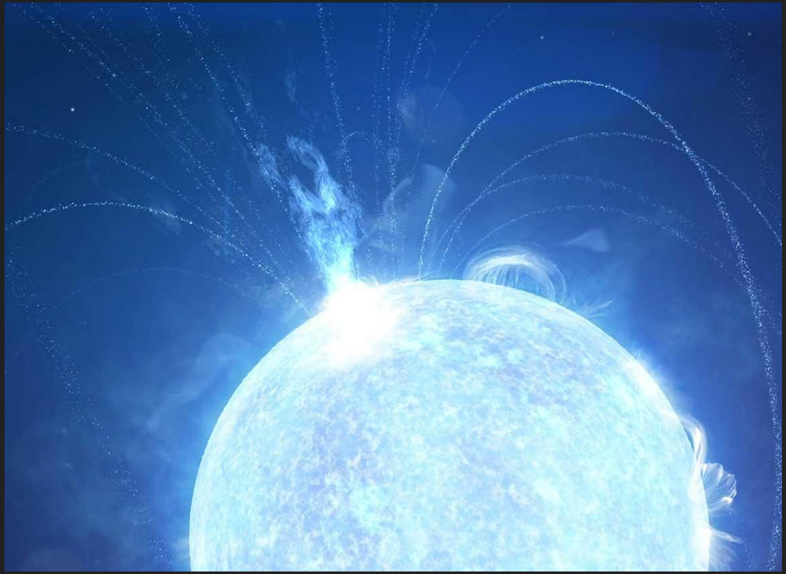
Giant flare & QPO mechanism

- The exact physical mechanism is not understood but we have an idea:

The burst trigger is associated with the slow build up of magnetic stresses and their subsequent catastrophic release.

Triggers: internal (large-scale MHD instabilities; crust quakes) or external (reconnections in magnetosphere)

The giant flare then excited internal oscillations sensitive to NS properties.



Artist's illustration of a magnetar eruption leading to a giant flare. Credit: NASA

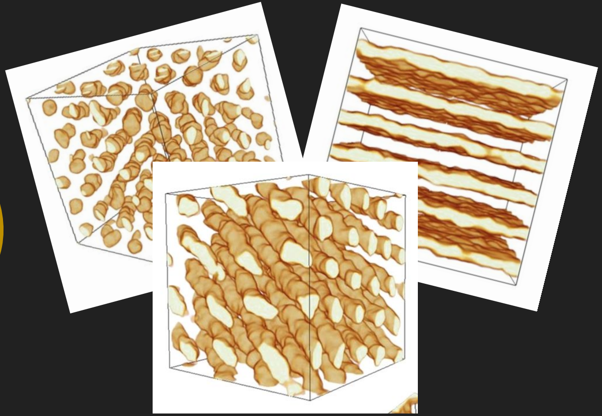
Probing crustal physics

- Initially, QPOs were interpreted as (discrete) torsional shear modes in the NS crust. QPO frequencies are, thus, sensitive to crustal physics. We can estimate the frequency of the fundamental mode in the inner crust as follows:

$$f_{\mathrm{s}} \simeq \frac{v_{\mathrm{s}}}{2\pi R_{\mathrm{NS}}} \approx 17.4 \left(\frac{\rho}{10^{14}\,\mathrm{g\,cm^{-3}}} \right)^{1/6} \left(\frac{Z}{38} \right) \left(\frac{A}{302} \right)^{-2/3} \left(\frac{1 - X_{\mathrm{n}}}{0.25} \right) \left(\frac{R_{\mathrm{NS}}}{10\,\mathrm{km}} \right)^{-1} \mathrm{Hz}.$$

The crustal shear speed is given as $(\mu_S/\rho)^{0.5}$, where the shear modulus is strongly dependent on the crustal microphysics.

Shear modulus calculations depend strongly on the lattice structure in the inner crust, i.e., the presence of nuclear pasta.



Probing magnetic field strengths

- A second hypothesis assumes that QPOs are (continuum) Alfvén oscillations of the strongly magnetised fluid core and thus probe the core magnetic field.

We can roughly estimate the frequency of the fundamental mode, which depends on the Alfvén speed.

$$f_A \simeq \frac{v_A}{4R_{NS}} \approx 7.1 \left(\frac{\rho_c}{10^{14}\,\mathrm{g\,cm^{-3}}} \right)^{-1/2} \left(\frac{B}{10^{14}\,\mathrm{G}} \right) \left(\frac{R_{NS}}{10\,\mathrm{km}} \right)^{-1} \mathrm{Hz},$$

v_A introduces a dependence on the mean magnetic field strength and the mass density of charged particles (which is only a fraction of the total density but dependent on superfluidity).

Mode frequencies also depend on the B-field geometry complicating a comparison further.

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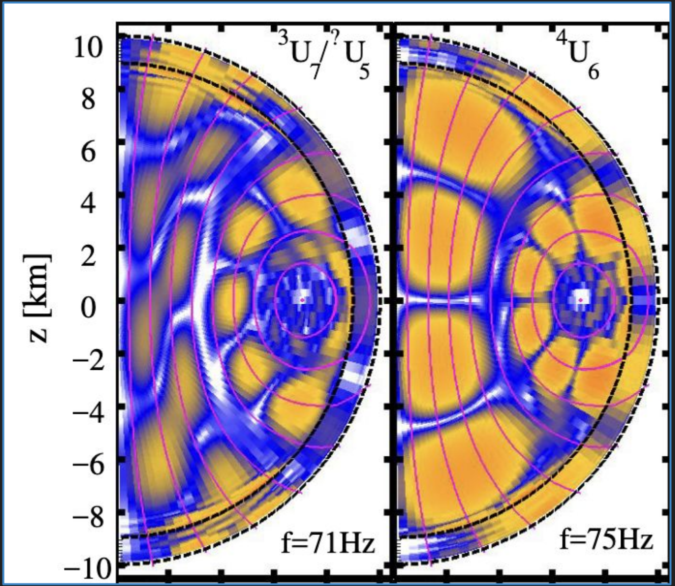
Realistic mode calculations

- The crustal vibrations are strongly damped as the B-field spreads the entire star and couples crustal oscillations to the Alfvén continuum in the core. QPOs are global magneto-elastic oscillations (Gabler et al. 2011, 2013, 2016).

Realistic mode frequencies now depend on the magnetic field, the shear speed and superfluid fraction.

Coefficient are fitted for a single numerical simulation.



Amplitude of discrete Fourier transform of velocity field of strongest QPOs (Gabler et al. 2016).

$$f_0 \simeq 2.8 X_{\mathrm{SF}}^{-0.55} \left(\frac{v_\mathrm{s}}{1.37 \times 10^8\ \mathrm{cm\ s^{-1}}} \right)^{1/2} + 0.66 X_{\mathrm{SF}}^{-0.33} \left(\frac{B}{10^{14}\ \mathrm{G}} \right) \mathrm{Hz},$$

Main issue: we need to identify a given frequency with a specific mechanism.

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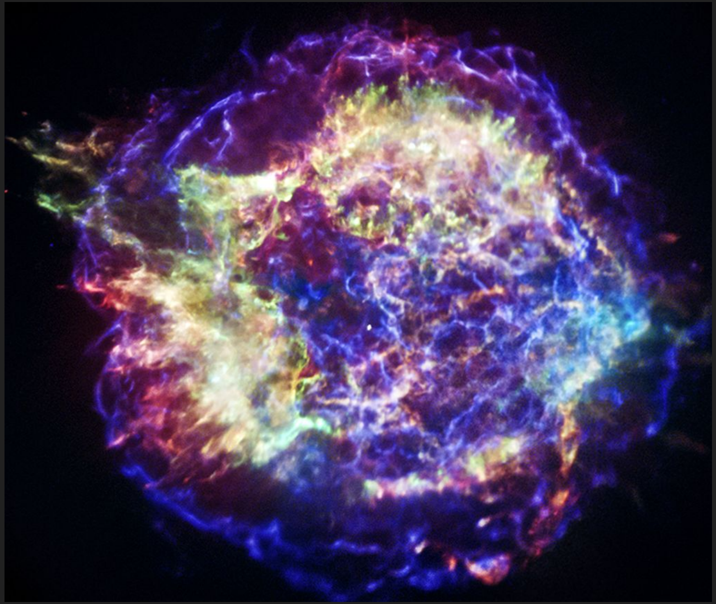


Cassiopeia A supernova remnant.
Credit: NASA/CXC/SAO

To summarise

NSs are unique laboratories that allow us to probe the low-temperature, high-density regime inaccessible on Earth.

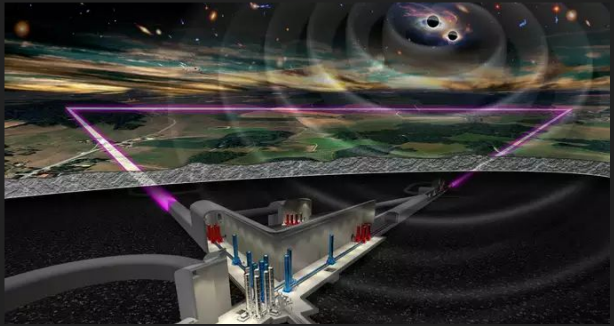
To date, scientific efforts have generally focused on measuring macroscopic (global) observables that probe the EoS.

Other observables probe non-local properties. Those are relevant for many dynamical phenomena, albeit strongly model dependent.

There are many more phenomena and I selected based on personal preference!!

The future is bright with new telescopes like the SKA, Einstein Telescope and NewAthena!!

Artist illustrations of the SKA (credit: SKAO) and ET (credit NIKHEF).



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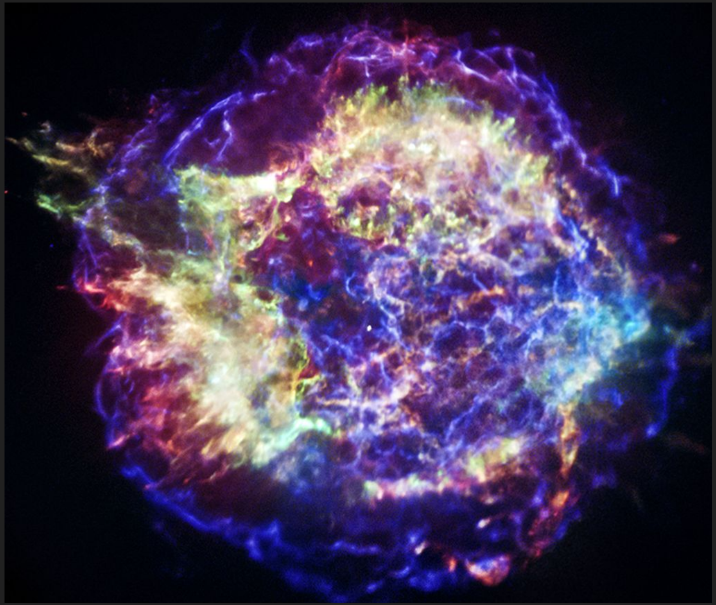
THANK YOU



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