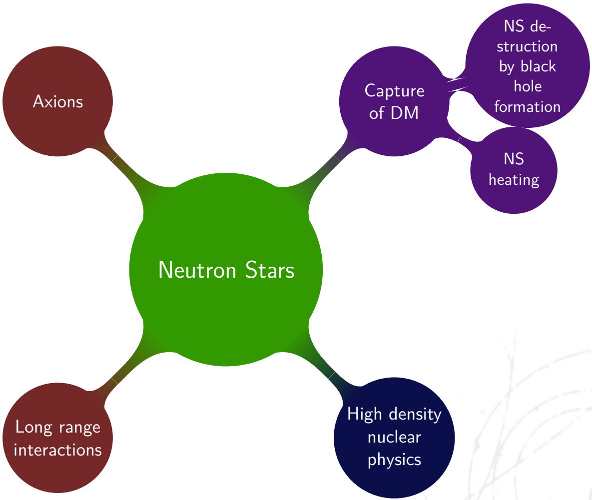
New Physics from Neutron Stars

Raghuveer Garani

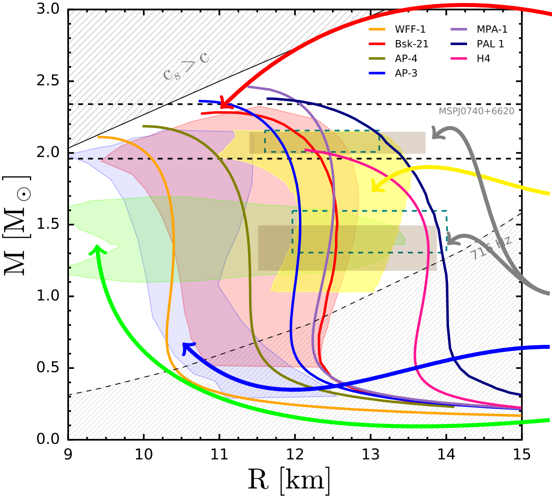
INFN
Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

Window to New (and nuclear) Physics



Nuclear physics close to saturation

What do we know about neutron stars?



combined fits
Raithel et al. '18

GW+hadronic EoS
Most et al. '18

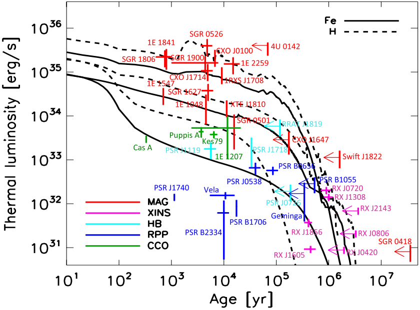
NICER: Miller et al.
+ Riley et al. '19 '21

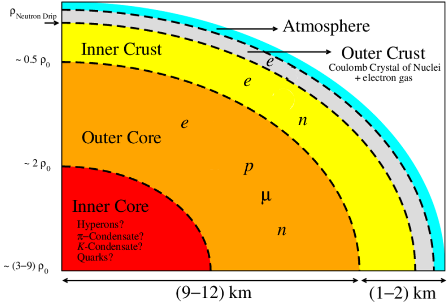
pulsars: Özel et al. '16

LIGO: Abbott et al. '18

Chatterjee et al. 2205.05048

NS luminosity and composition





Viganó et al. '13 & Potekhin '12

Much about NS interiors unknown

Most measurements of surface properties till date are from X-ray telescopes.

Possible exotic phases

in the NS core

- Color superconductivity review: Alford et al. '08
- Mass-radius relation: only the M-R information insufficient
- Tidal deformability: GW wave form different if there is a step in the density profile. Depends on surface tension at interface.
- Cooling: Early times dominated by exotic phases. Need to observe proto-neutron stars in the neutrino channel.
- Pulsar spins: r-mode instabilities

More data

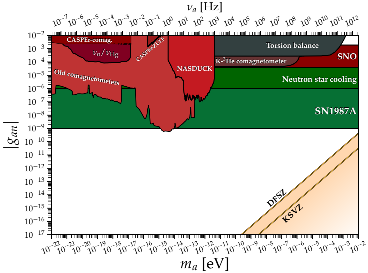
multi-messenger approach could lead the way

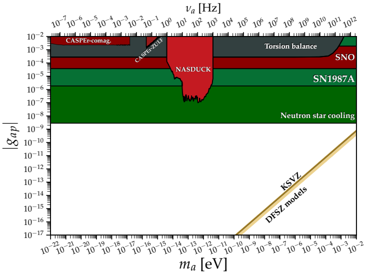
Axion searches

Axion Searches

Emissions and cooling

- Hot NS cool by Urca, modified Urca process $(n + n \to p + n + e^- + \bar{\nu}_e)$
- Additional energy losses $\implies$ significantly alter minimal cooling paradigm (e.g. $n + n \to n + n + a$)

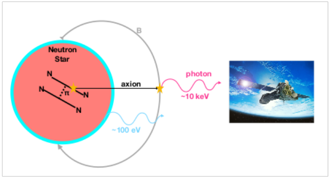


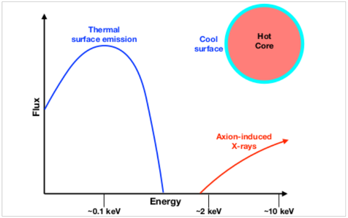


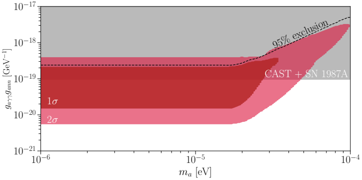
https://cajohare.github.io/AxionLimits/
Hanhart et al. '00, Sedrakian '16, Hook et al. '18, Peng et al. '18, Beznogov et al. '18, Fischer et al. '21, Buschmann et al. '21 + + +

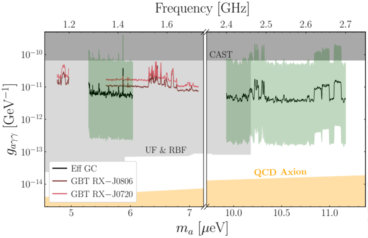
Axion Searches

Non-thermal emissions - Chandra and XMM newton









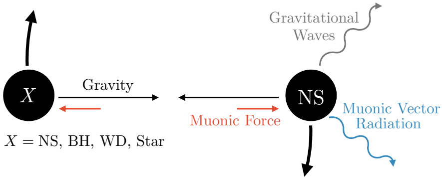
Hook et al. '18, Buschmann et al. '19, Foster et al. '20, Bondarenko et al. '22 + +

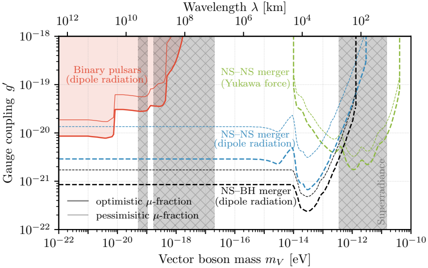
Searches for long range forces

Long range forces

Schematic

- Binary mergers: long range forces modify GW waveform
- PTA+GW detectors





Nelson et al. '18, Poddar et al. '20, Dror et al. '20, Xu '21, Berryman et al. '22 ,Snowmass (2203.14915)

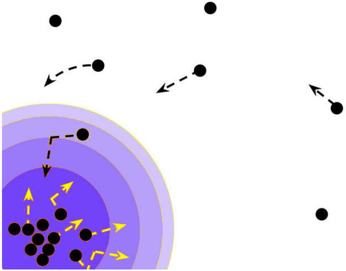
Dark Matter searches

Capture of DM

Schematic

- If DM (χ) has a non vanishing $\sigma_{\chi T}$, it can be captured in celestial objects. Press and Spergel '85, Griest and Seckel '86, Gould '87, Goldman et.al. '89
- Dynamics governed by the equation

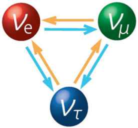
$$\frac{\mathrm{dN}_\chi}{\mathrm{dt}} = C - E\,\mathrm{N}_\chi - A\,\mathrm{N}_\chi^2$$

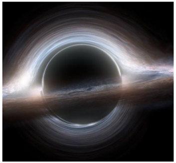


Capture of DM

Possible signals

Neutrinos Press and Spergel '85, Griest and Seckel '86, Gould '87 + +



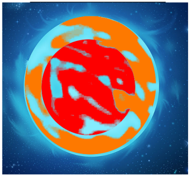


Black Hole formation

Goldman et al. '89, Kouvaris et al.'10 '11 '12,

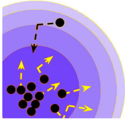
McDermott et al. '12 + +

Heating cold and old objects



Kouvaris '07, '10, Bertone et al. '08,

McCullough et al. '10, Baryakhtar et al. '



Capture of DM

Comparison

- Sufficiently weak, $\sigma n_\star R_\star \sim 1$
- Geometric cross section, $\sigma_\star = \pi R_\star^2 / N$
- The maximal capture rate

$$C_\star = \pi R_\star^2 \left(1 + \frac{v_e^2}{v_\infty^2}\right) \left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right) v_\infty$$

	$\sigma_\star$ [cm^2]	$\sim M_{\rm max}$/Gyr
Sun	10^{-35}	$10^{-11} {\rm M}_\odot$
White Dwarf	10^{-39}	$10^{-19} {\rm M}_\odot$
Neutron Star	10^{-45}	$10^{-15} {\rm M}_\odot$

Heating of NS due to DM capture

Ways to heat up cold and old NS

- Kinetic Heating: Infalling DM heats up the neutron star. Potentially observable by James Webb Space Telescope Baryakhtar et.al. '17, Raj et.al. '17, Bell et.al. '18

$$T_{\rm kin}^{\rm max} \simeq 1700K \left(\frac{C}{C_\star}\right)^{1/4} \left(\frac{\rho_{\sf DM}}{0.4{\rm GeV/cm^3}}\right)^{1/4}.$$

- Annihilations: If DM capture and annihilation are in equilibrium Kouvaris '07, Kouvaris et.al. '10

$$T_{\sf ann}^{\rm max} \simeq 2480K\,[\rho_{\sf DM}/(0.4{\rm GeV/cm^3})]^{0.25}$$

- Maximal heating: Kinetic+annihilation (KA) at geometric values of cross section $\sim 10^{-45}$ cm^2

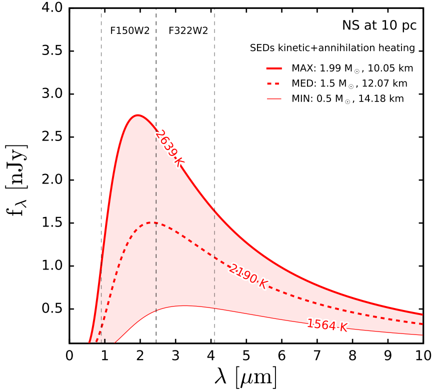
$$T_{\rm KA}^{\infty} \approx 2518\ {\rm K}\left[\frac{\alpha_{\rm KA}}{0.33}\left(\frac{\rho_\chi}{0.42\,{\rm GeV/cm^3}}\right)\left(\frac{220\,{\rm km/s}}{{\rm v}_\star}\right){\rm Erf}\left(\frac{270\,{\rm km/s}}{{\rm v_d}}\frac{{\rm v}_\star}{220\,{\rm km/s}}\right)\right]^{1/4},$$

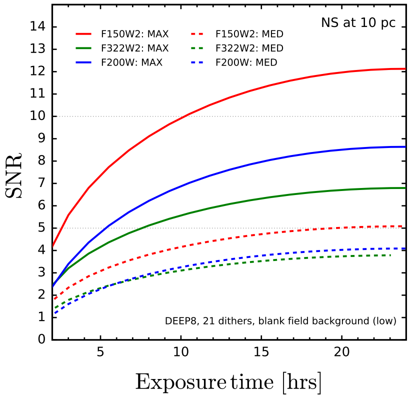
with,

$$\alpha_{\rm KA} = \frac{\gamma(\gamma^2-1)}{\gamma^4}$$

Heating of NS due to DM capture

Signals at James Webb Space Telescope





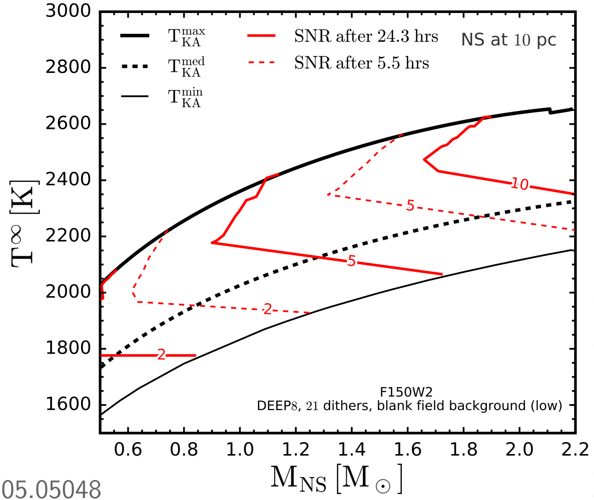
Chatterjee et al. 2205.05048

SNR > 10 achievable within 15 hrs of exposure!

Best sensitivity for broad band filter F150W2

Heating of NS due to DM capture

The whole range



Chatterjee et al. 2205.05048

Conclusions and Outlook

- Neutron stars are cool!
- Better understanding of NS $\implies$ robust constraints on new physics
- Using JWST exposure time calculator we demonstrate warm NS in the local bubble ~ 2500 K detectable by JWST
- Observation of cold NS $\implies$ constraints on DM $+$ better understanding of NS evolution.