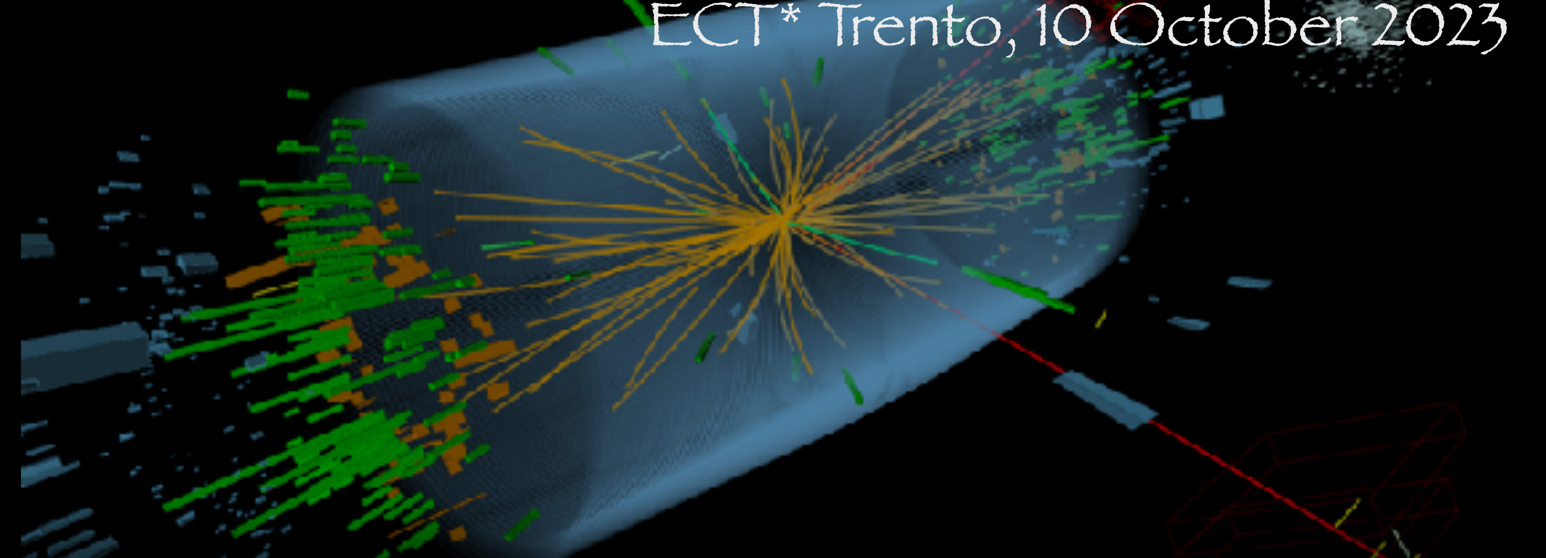
ROCKSTAR: Towards a ROadmap of the Crucial measurements of Key observables in Strangeness reactions for neutron sTARs equation of state

ECT* Trento, 10 October 2023



Probing hyperons in Neutron Stars using Multimessenger data

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Associate Professor,

Inter-University Centre for Astronomy & Astrophysics, Pune, India

Chair, LIGO-India Education & Public Outreach

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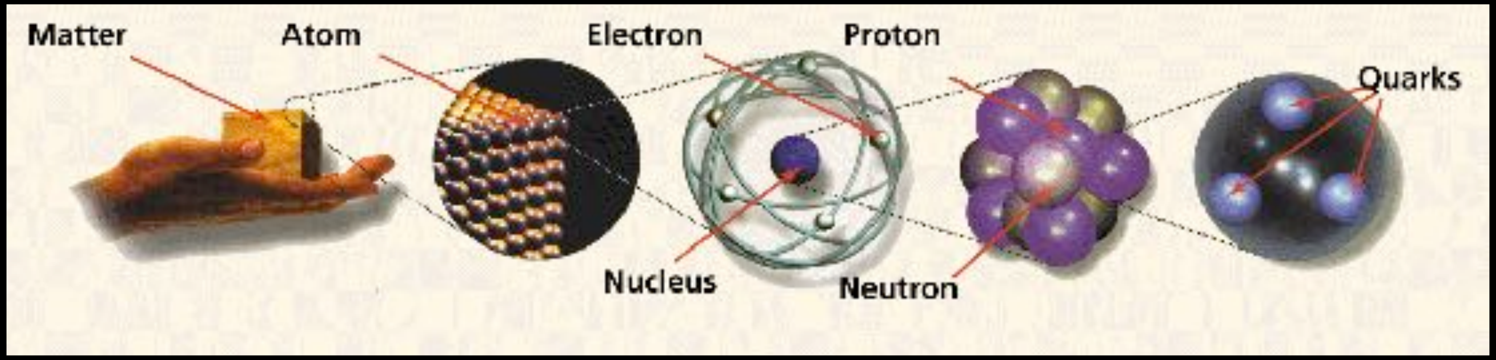
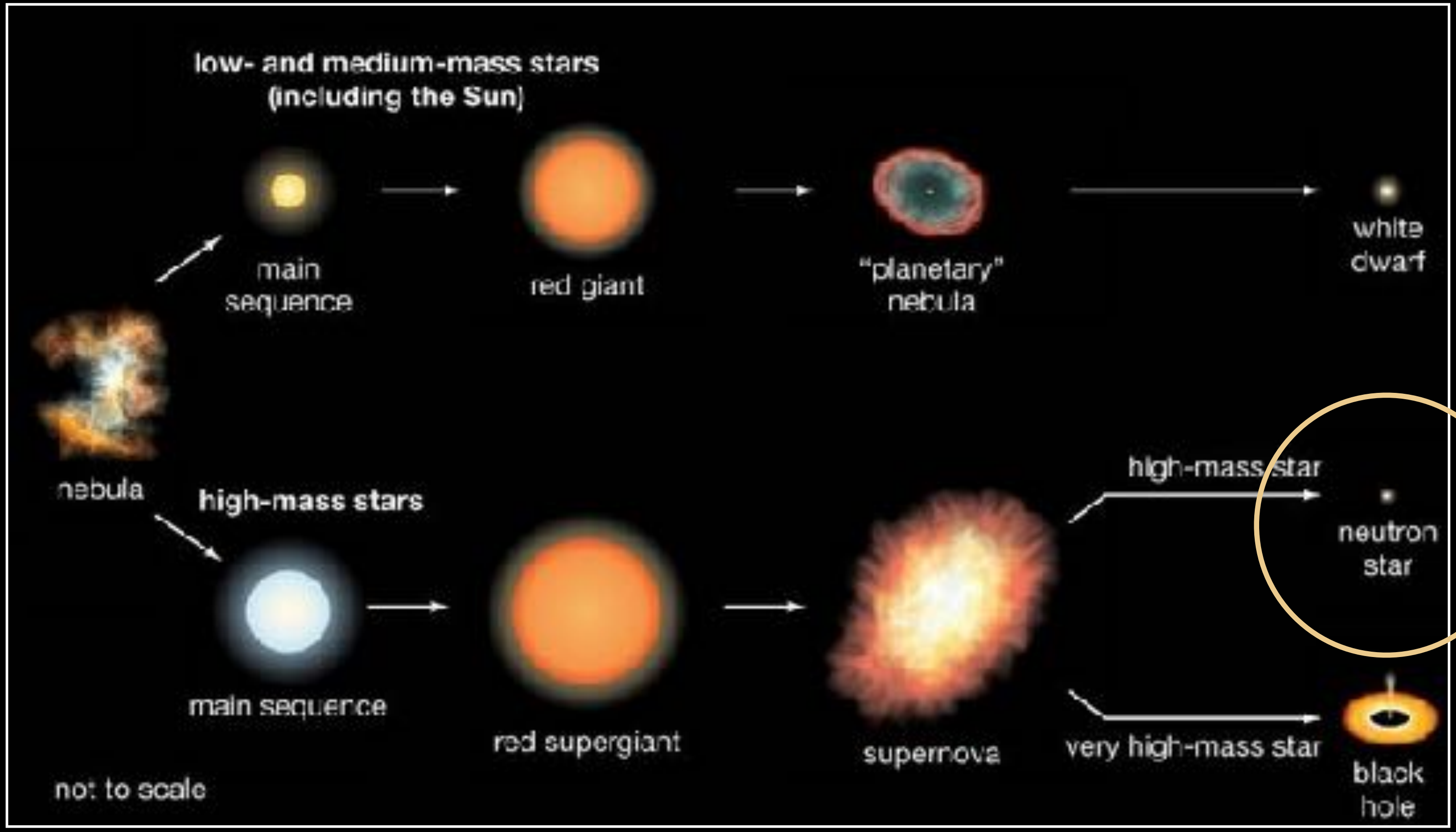
Jürgen Schaffner-Bielich (Goethe Uni Frankfurt)

Isaac Vidaña (INFN Catania)

Prashanth Jaikumar, Vinh Tran (California State University Long Beach)

Neutron Stars: Laboratories of Extreme Physics





Credit: Encyclopædia Britannica

NEUTRON STAR FACTSHEET

MASS ~ $2 \times M_{sol}$

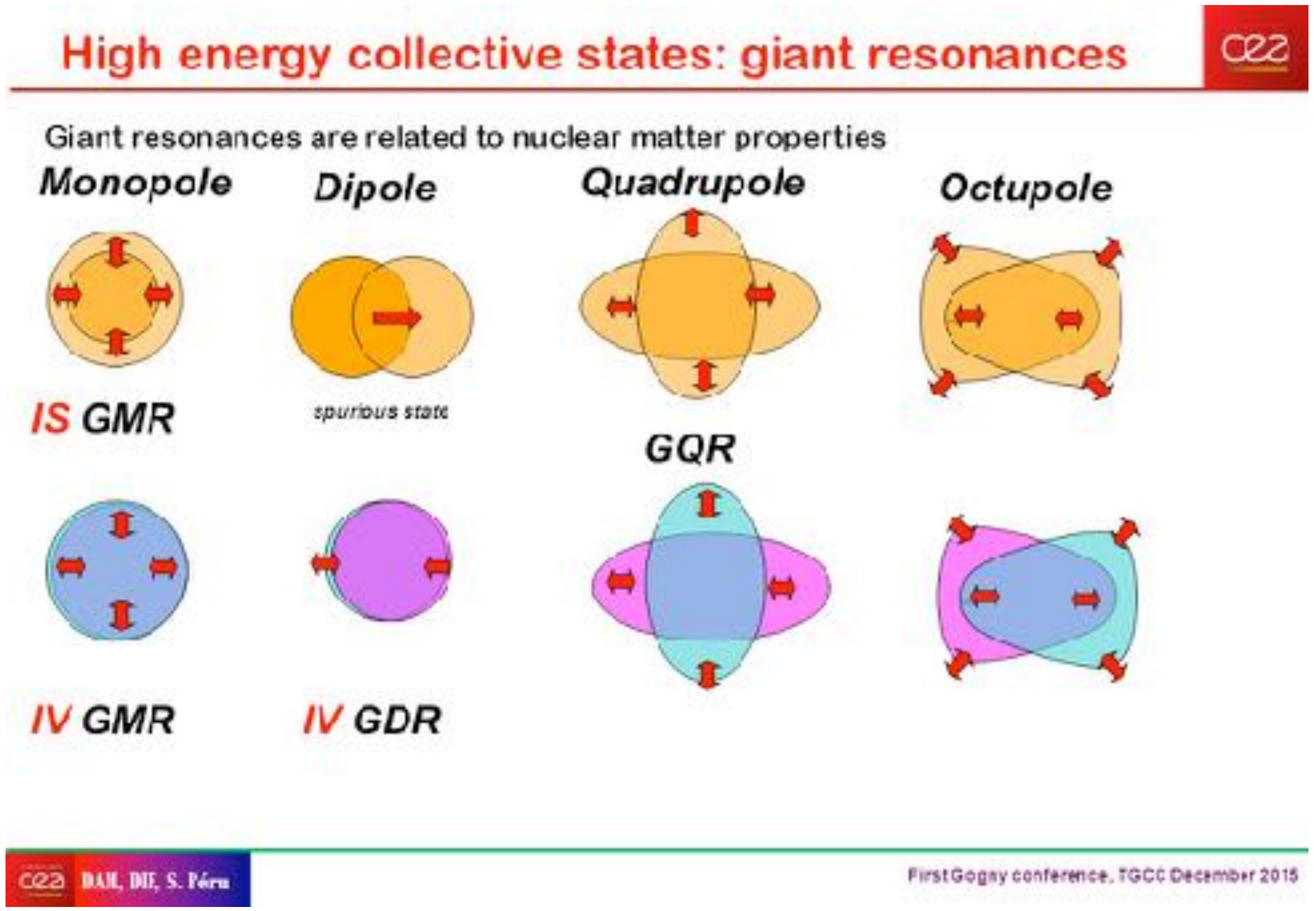
RADIUS ~ 10 km

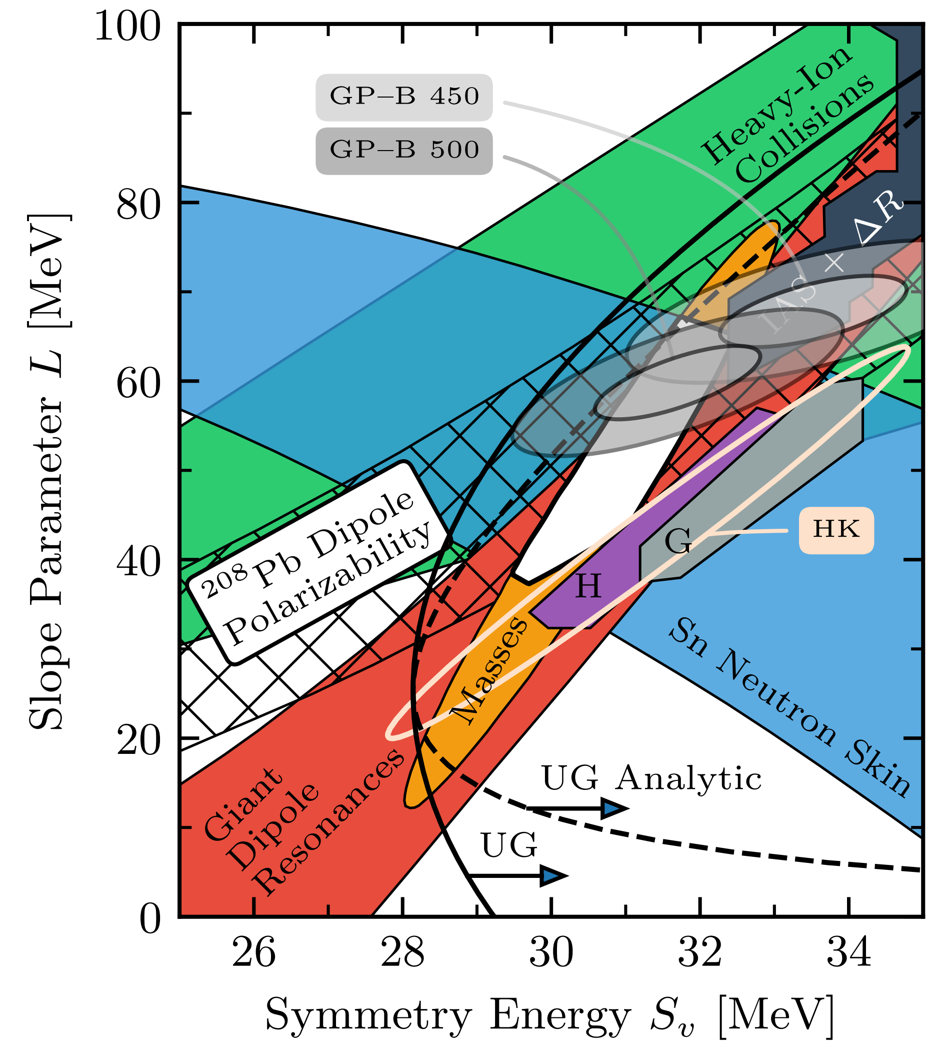
DENSITY ~ 2-10x nuclear density

TEMPERATURE ~ 10^9-10^{11} K

MAGNETIC FIELD ~ 10^{12} - 10^{15} G

Nuclear experiments





Credit: Drischler+ 2021

Nuclear Empirical Observables

$n_{sat}, E_{sat}, K_{sat}, E_{sym}, L_{sym}, K_{sym}$

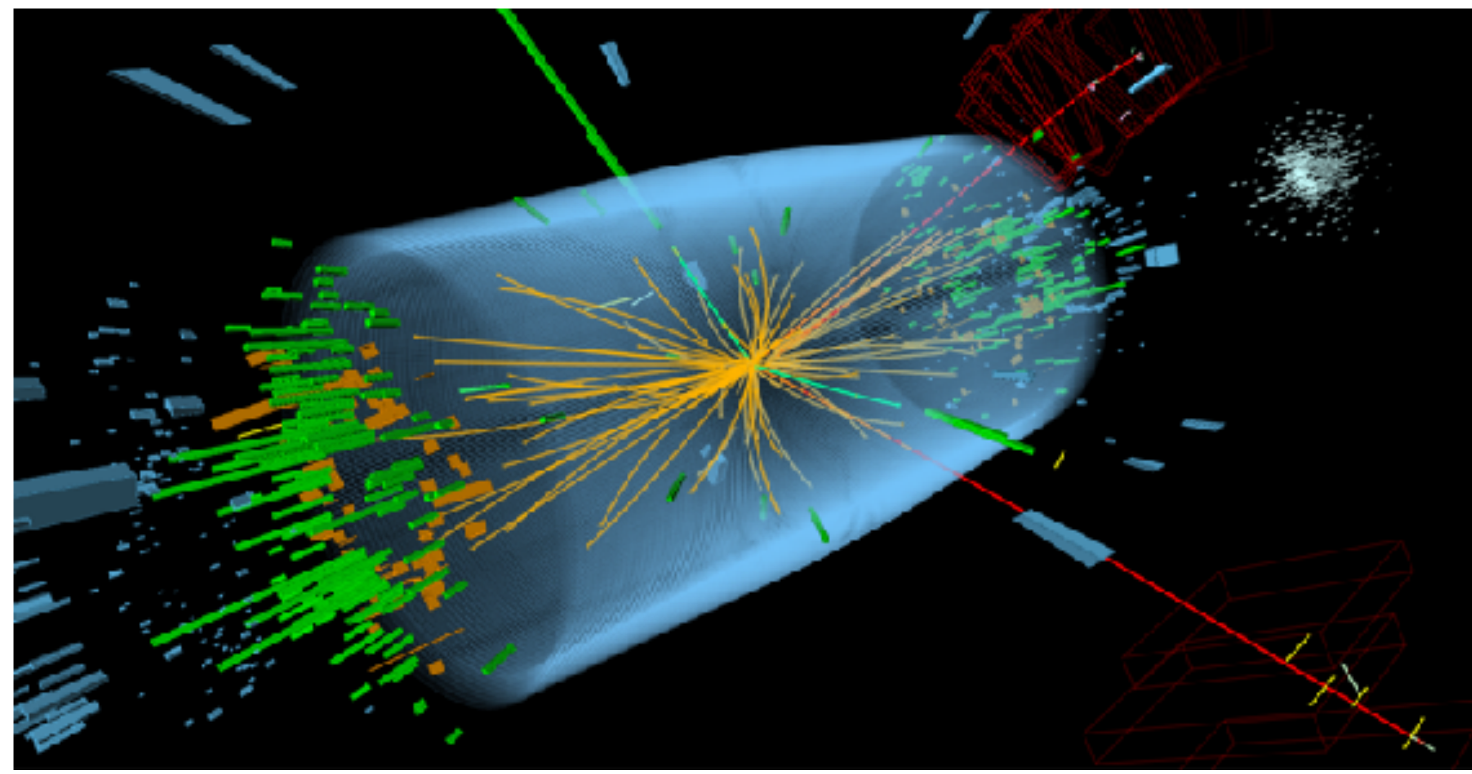
- From n skin thickness of ^{208}Pb, ^{48}Ca (PREX,CREX)
- From electric dipole polarizability α_D
- From giant dipole resonance (GDR) of ^{208}Pb
- From measured nuclear masses
- From isobaric analog states (IAS)

Heavy ion collision experiments

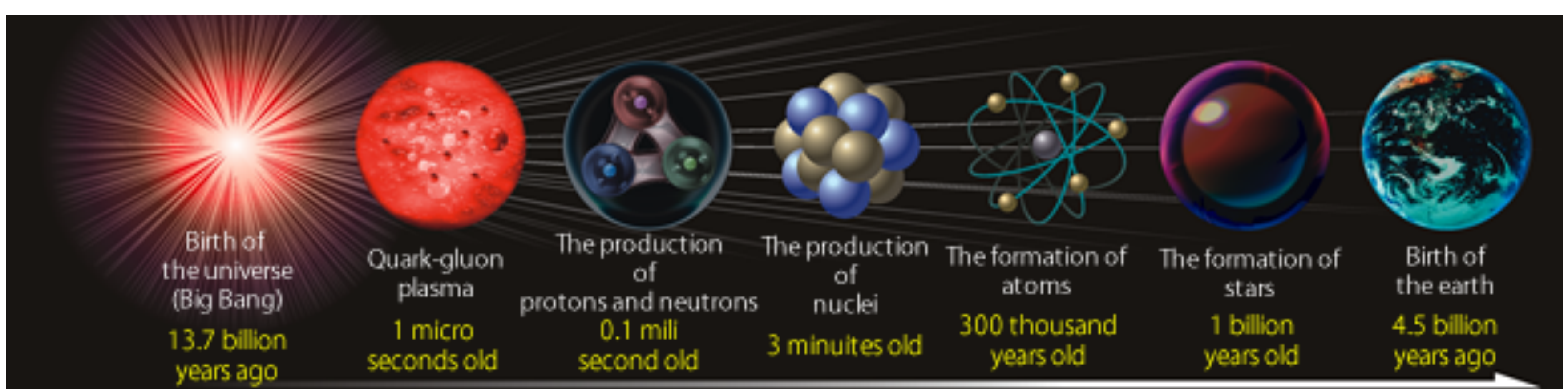
GANIL
GRAND ACCELERATEUR NATIONAL D'IONS LOURDS
LABORATOIRE COMMUN DSM/CEA-IN2P3/CNRS

GSI
GSI Helmholtzzentrum für Schwerionenforschung

FAIR
FAIR — Facility for Antiproton and Ion Research in Europe

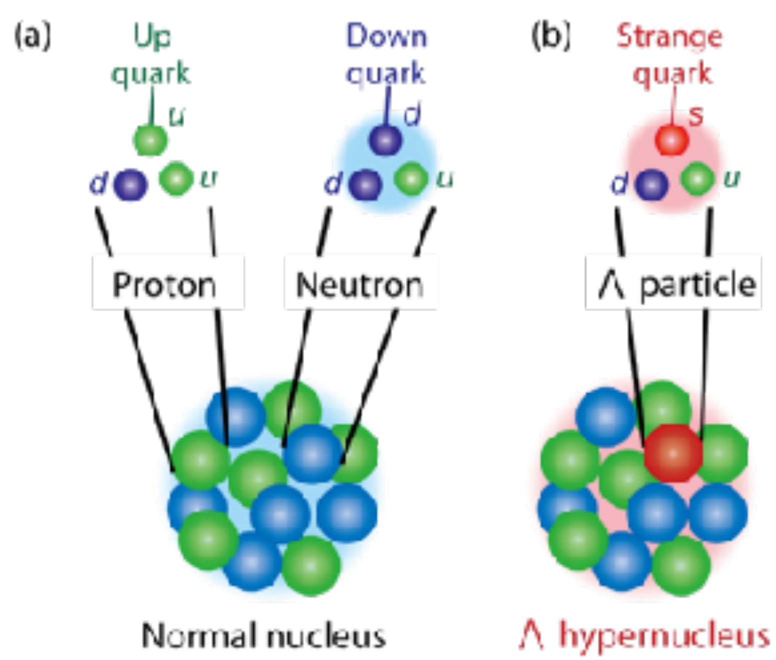


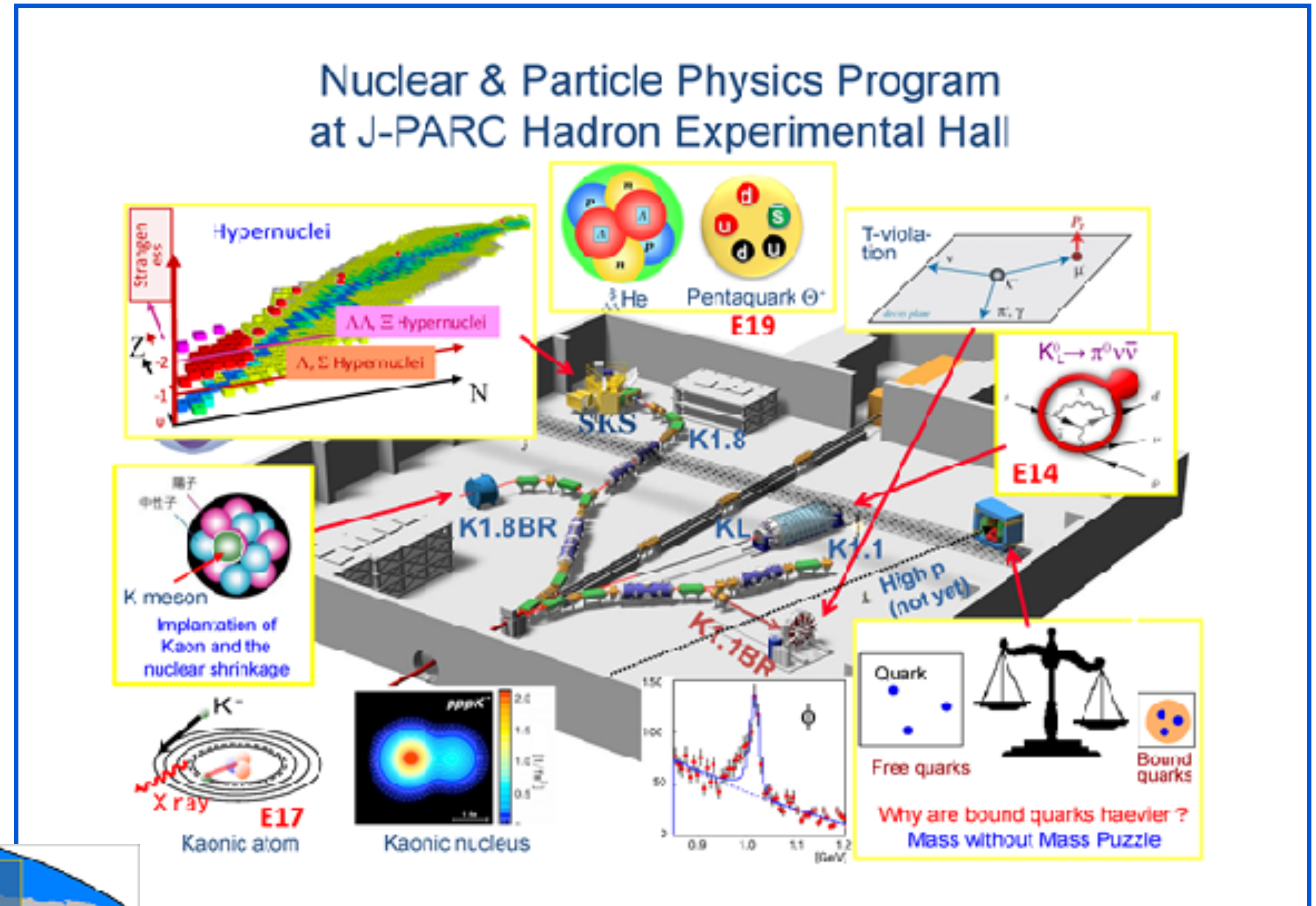
CBM

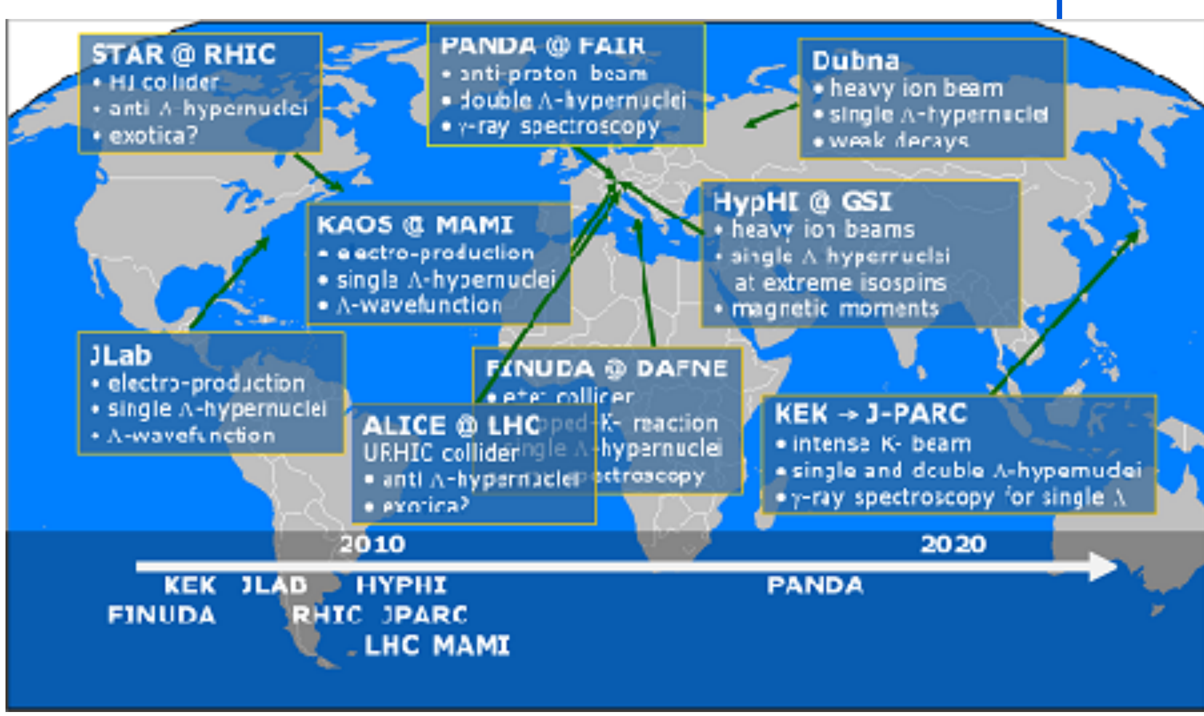


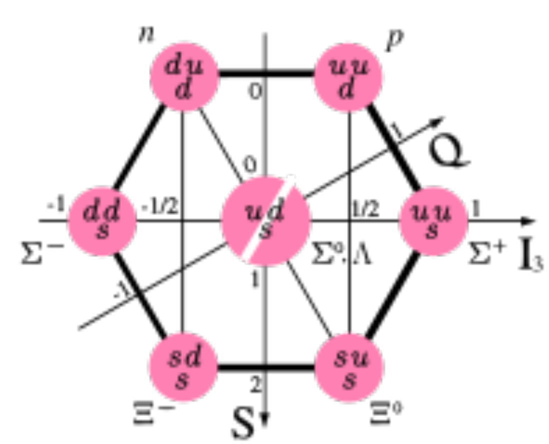
CERN

Hypernuclear experiments



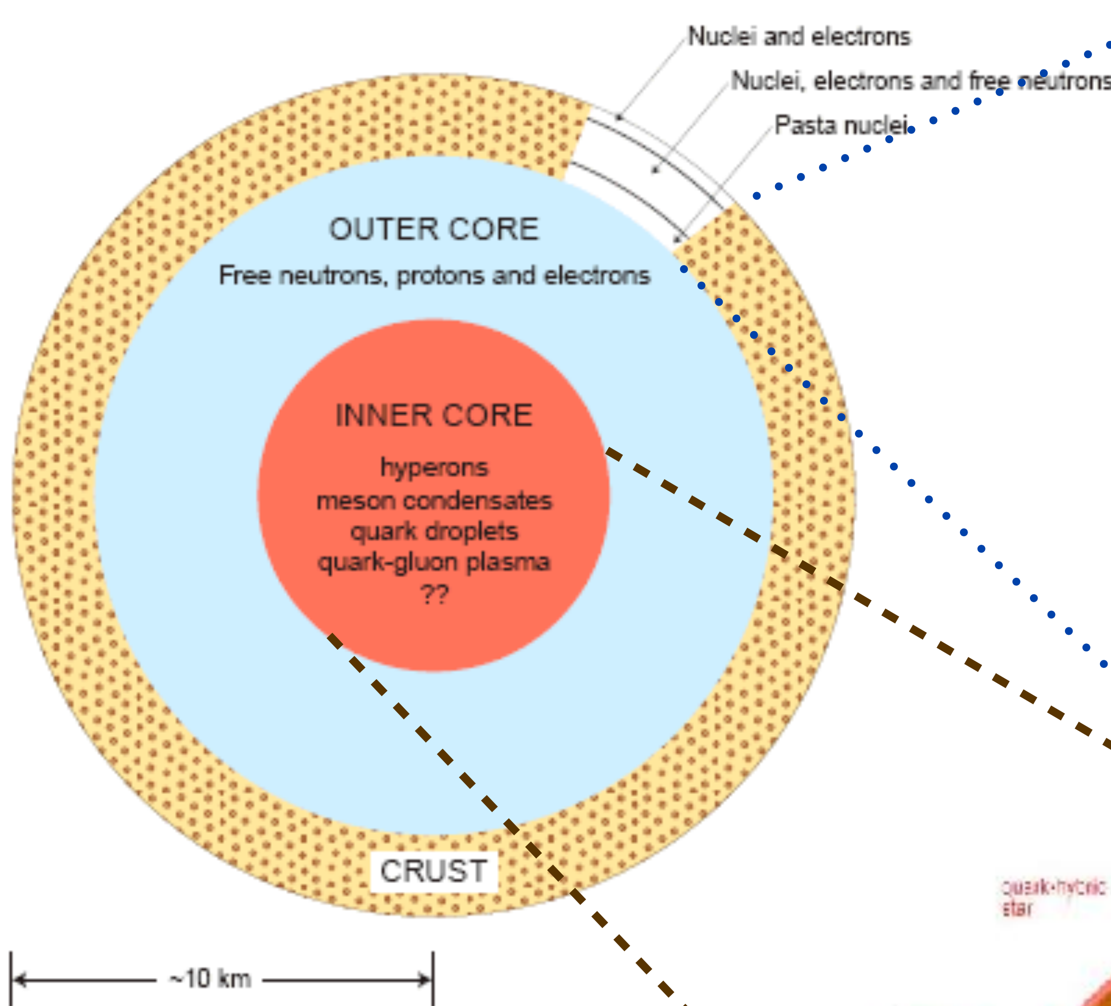


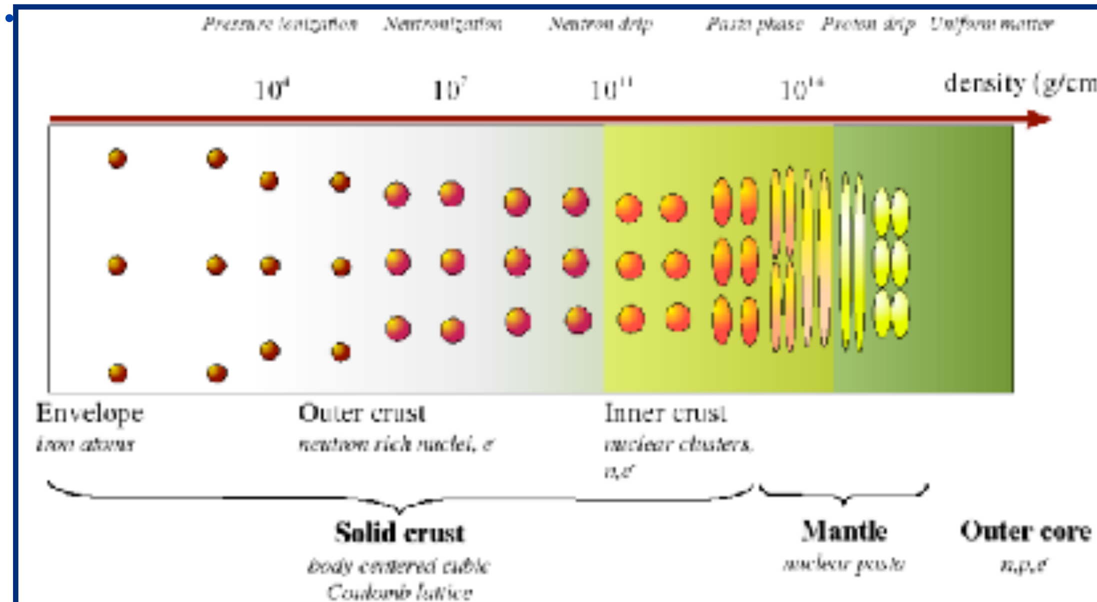




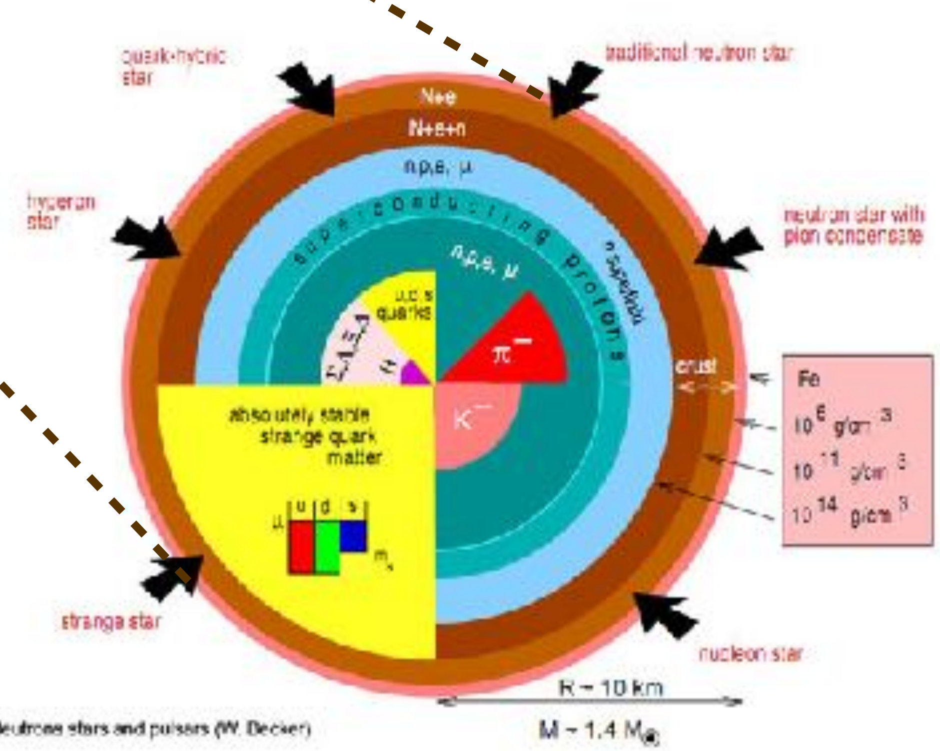
The Neutron Star interior

Credit: G. Baym



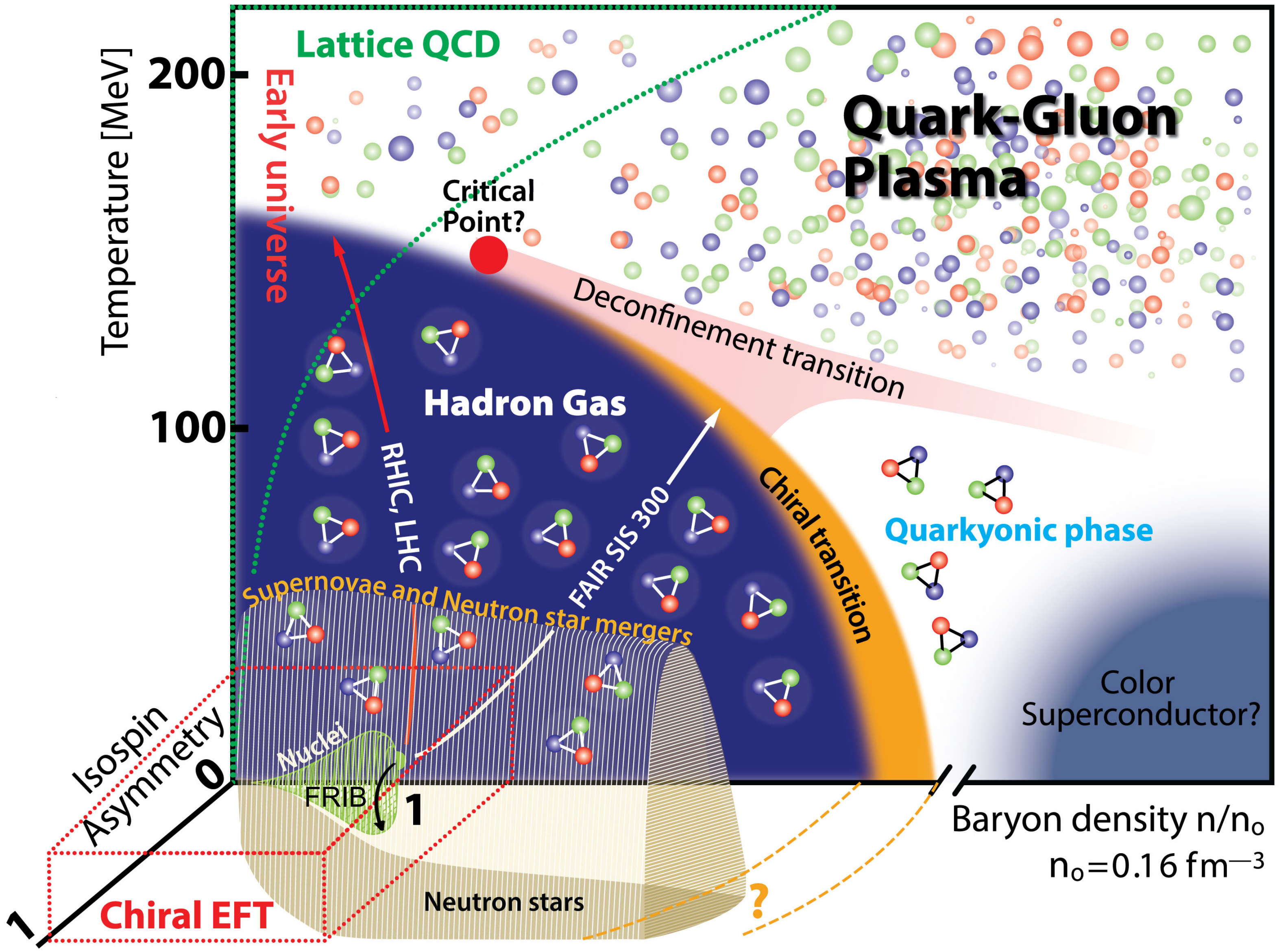


Credit: Chamel & Haensel, Physics of Neutron Star Crusts. Living Rev. Relativ. 11, 10 (2008)



Source : Neutron stars and pulsars (W. Becker)

Phase diagram of QCD (Quantum Chromodynamics)



- Nuclear theory
- Nuclear experiments
- Hypernuclear experiments
- Heavy-ion collision experiments
- Lattice QCD
- Perturbative QCD

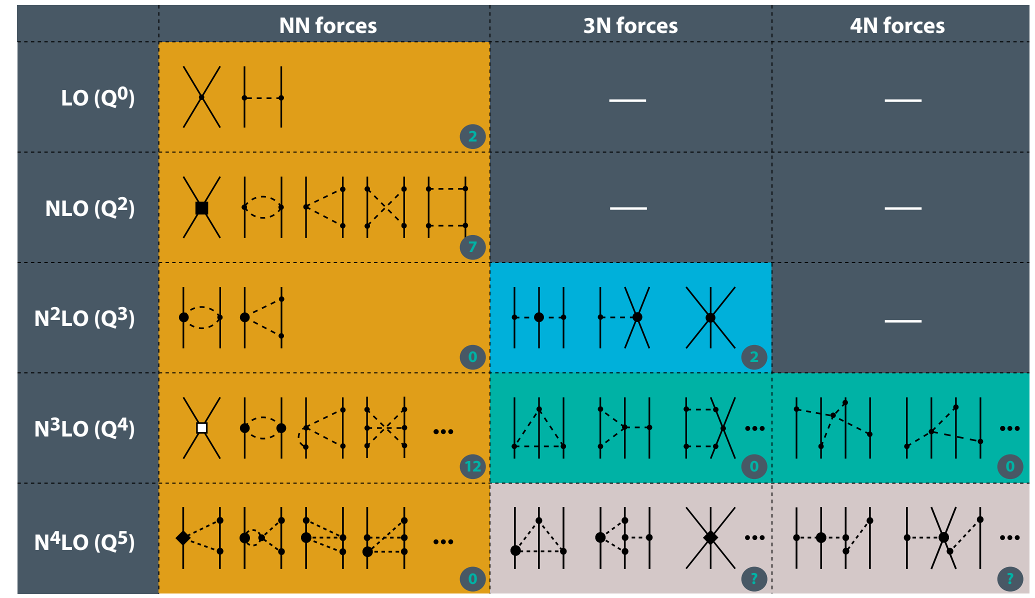
NS Equation of State (EoS): Theoretical models

- Microscopic models (realistic N-N interactions)
  - Meson exchange (e.g. Brueckner Hartree Fock models)
  - Chiral perturbation theory

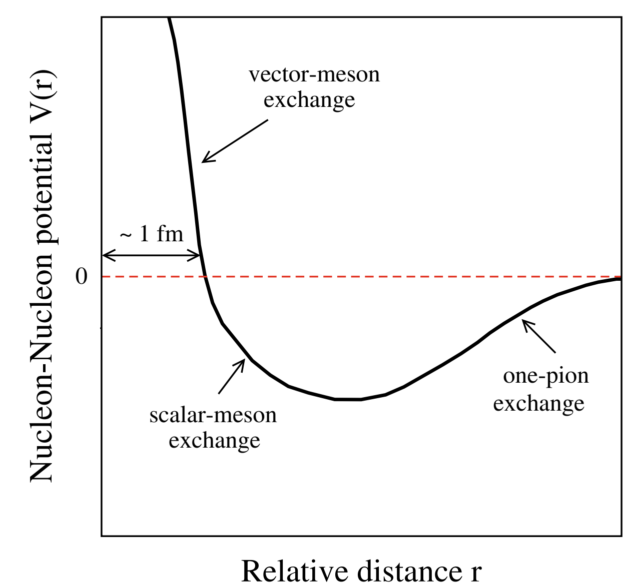
- Phenomenological models
  - Effective density dependent interactions
  - Parameters adjusted to reproduce nuclear and hypernuclear observables

- Non-relativistic (Skyrme interactions)

- Relativistic Mean Field Models (RMF)
  - baryon-baryon interaction mediated by meson exchange
  - nucleonic couplings fitted to properties of bulk nuclear matter (GL, GM1) or to properties of nuclei (NL3,TM1, FSUGold)
  - hyperonic couplings fixed by symmetry relations and hypernuclear data



C. Drischler, J.W. Holt and C. Wellenhofer
Annual Review of Nuclear and Particle Science
Vol. 71 (2021)



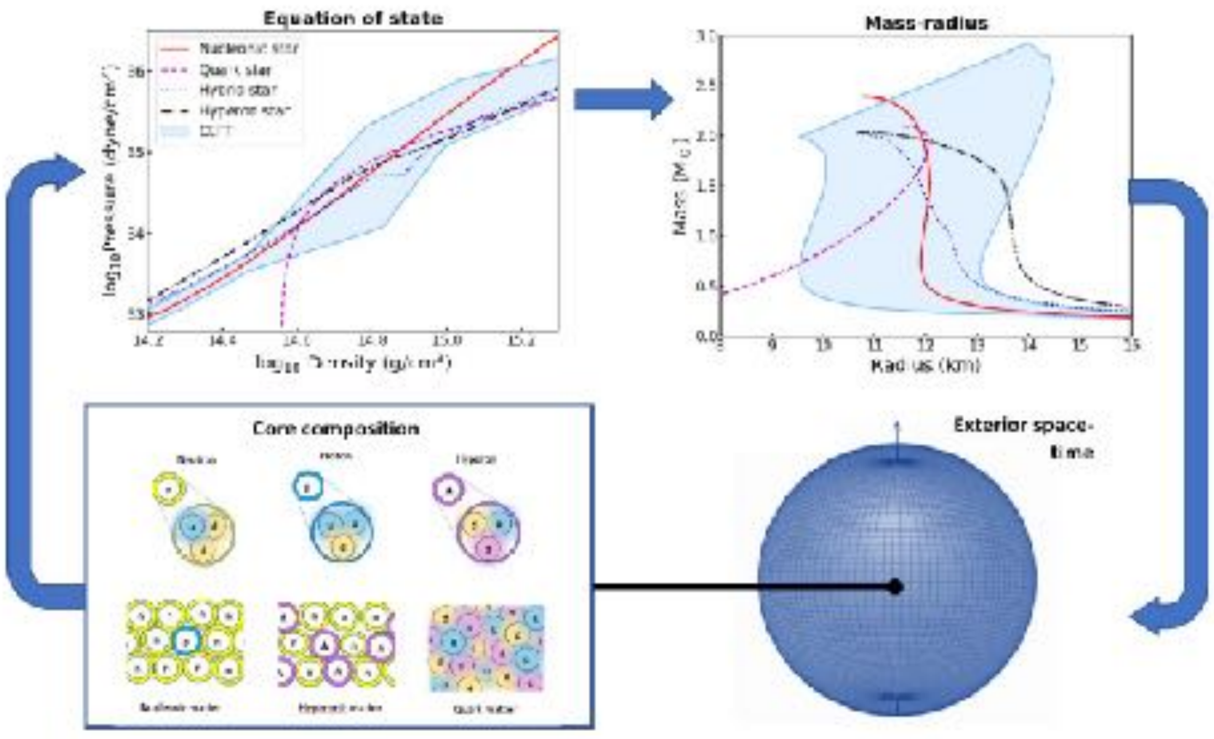
radial profile of NN-potential

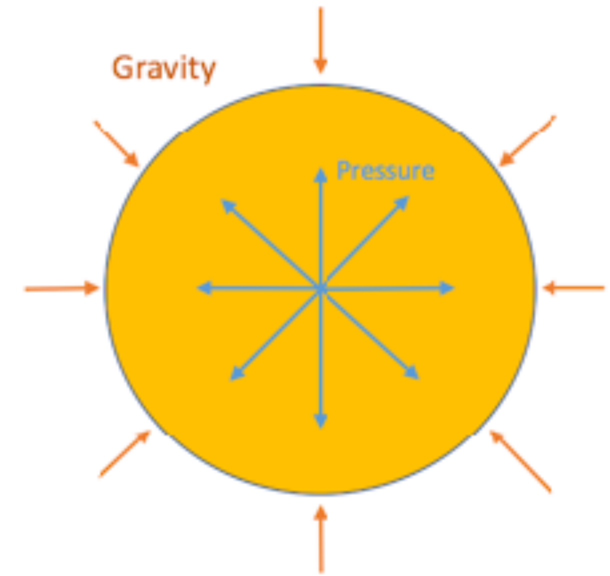
"Equations of state for supernovae and compact stars"
M. Oertel, M. Hempel, T. Klähn, S. Typel,
Rev. Mod. Phys. 89 (2017) 015007

"Hyperons: the strange ingredients of the nuclear equation of state"
Isaac VIdaña, Proc. R. Soc. A.474 (2018) 20180145

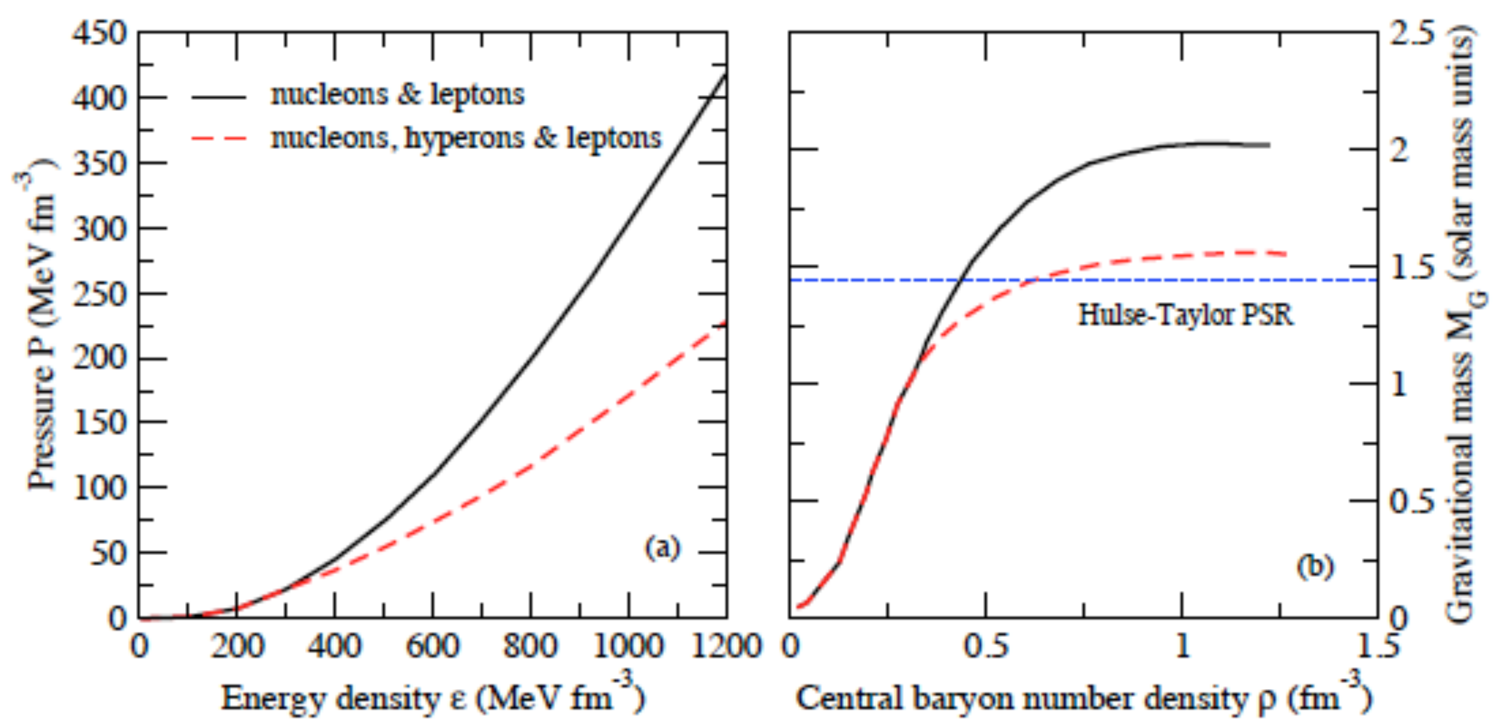
EoS and M-R relation

Credit: Astro2020 Science White Paper





Credit: J. Stayner



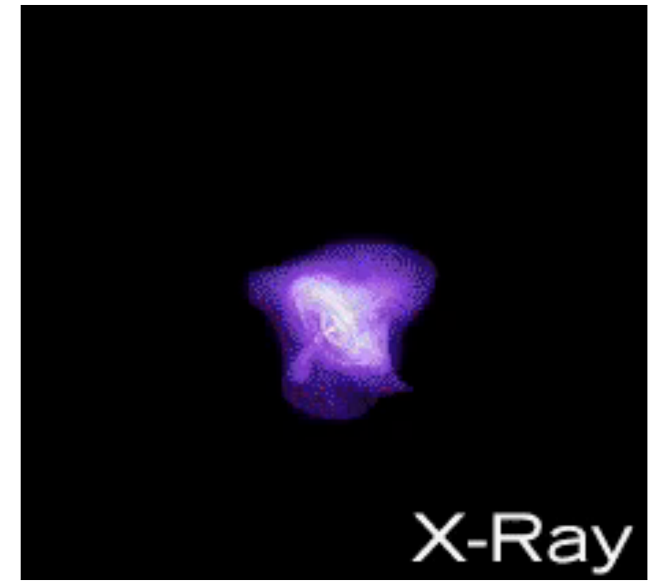
D.C. & I. Vidaña EPJA 52 (2016)

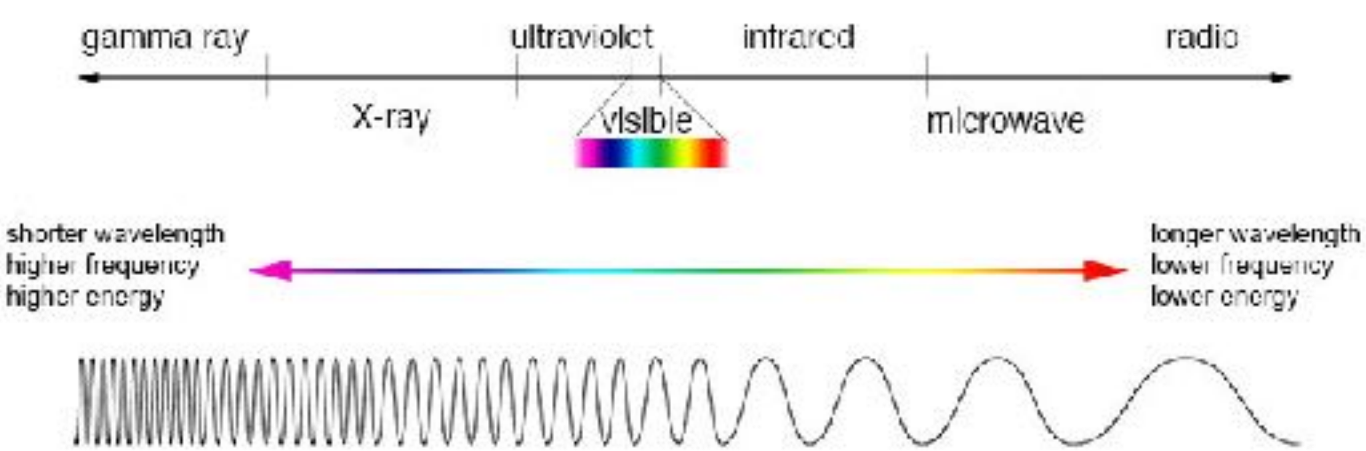
Multi-Wavelength Astrophysical Observations

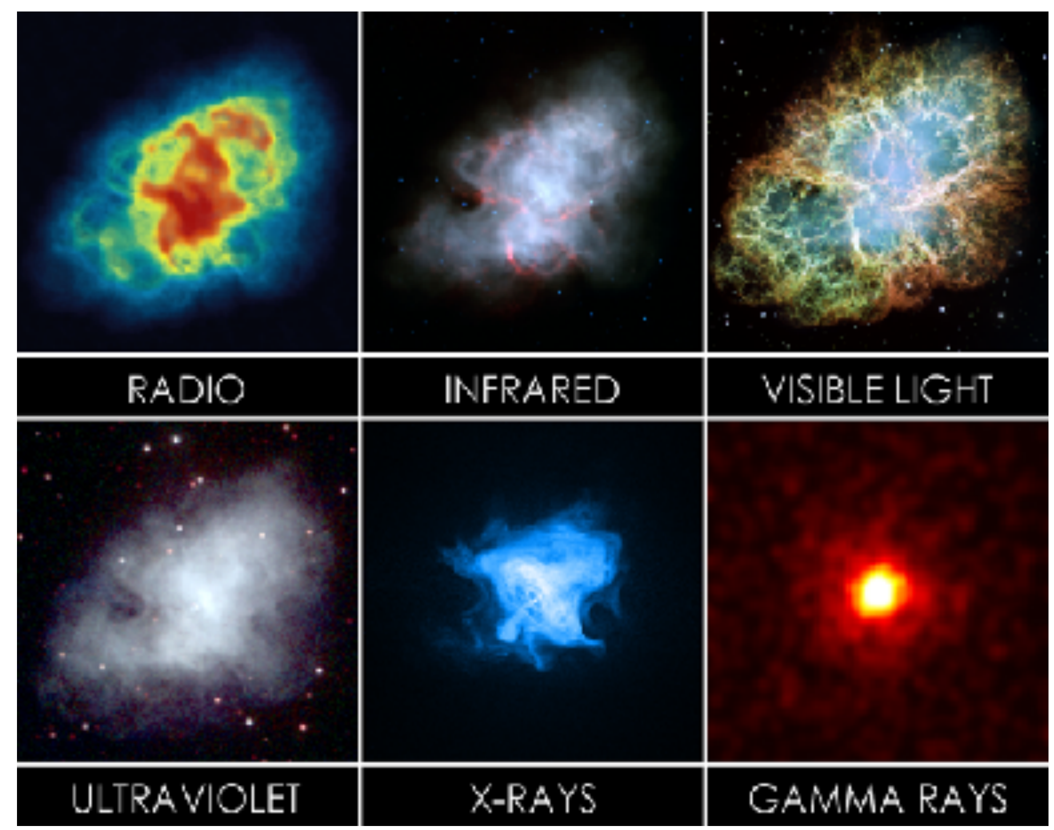
Gamma (INTEGRAL, Fermi, CTA, THESEUS)

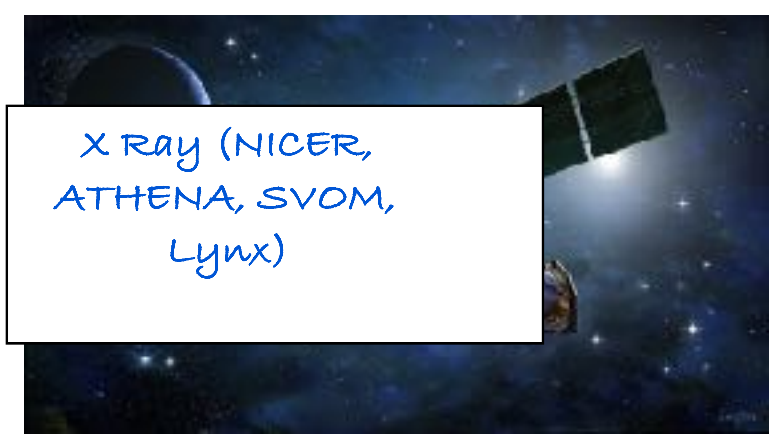
Multi-Wavelength (AstroSat)

Radio (uGMRT, SKA)

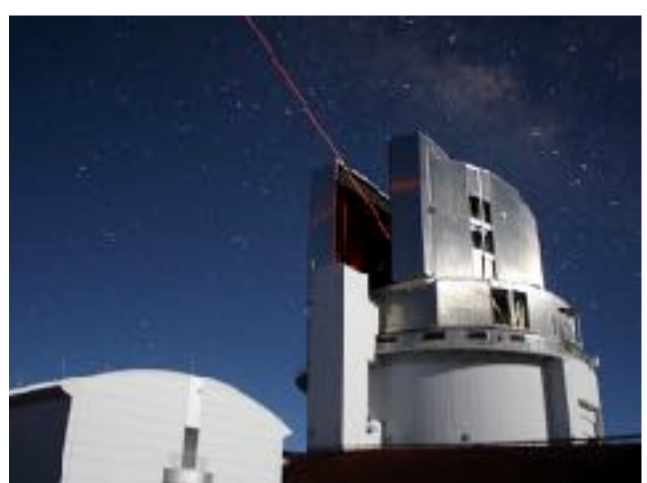






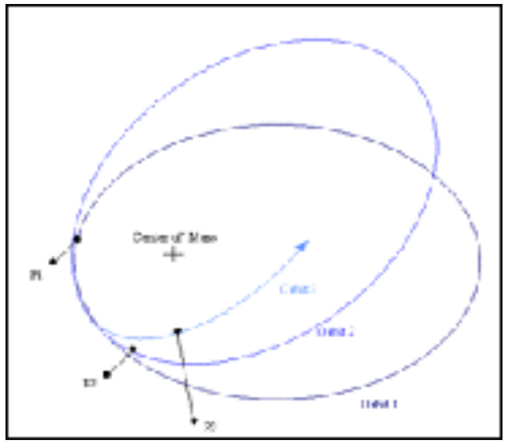


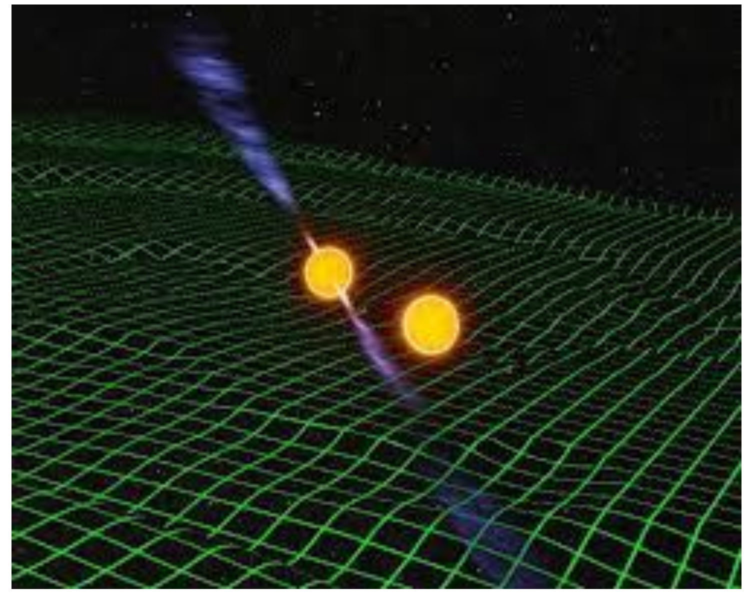
X Ray (NICER, ATHENA, SVOM, Lynx)

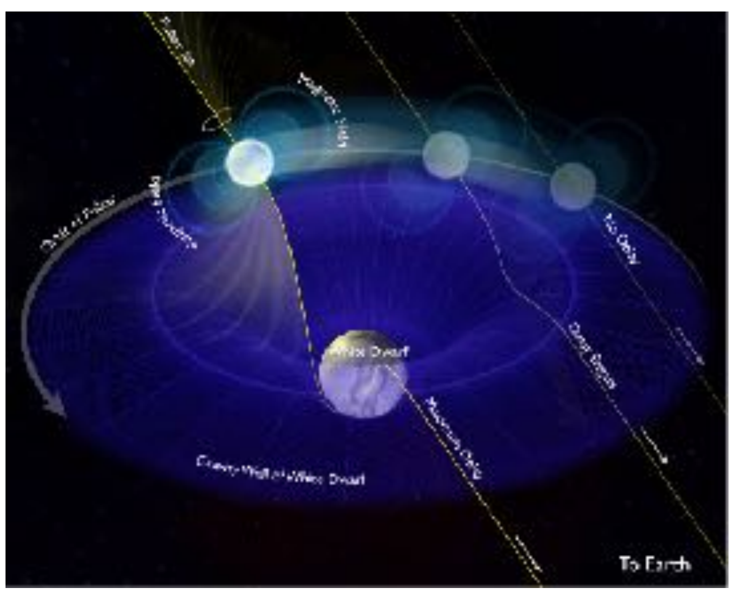


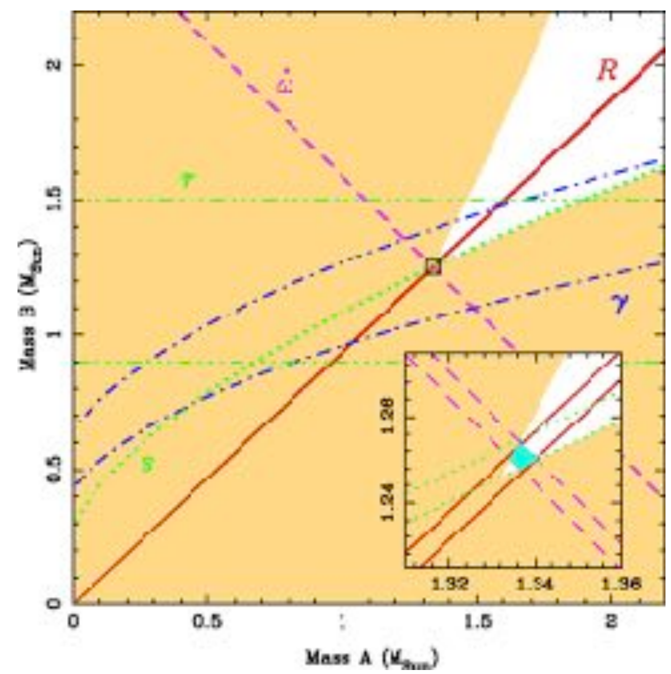
Optical/ Infrared (LSST, TMT)

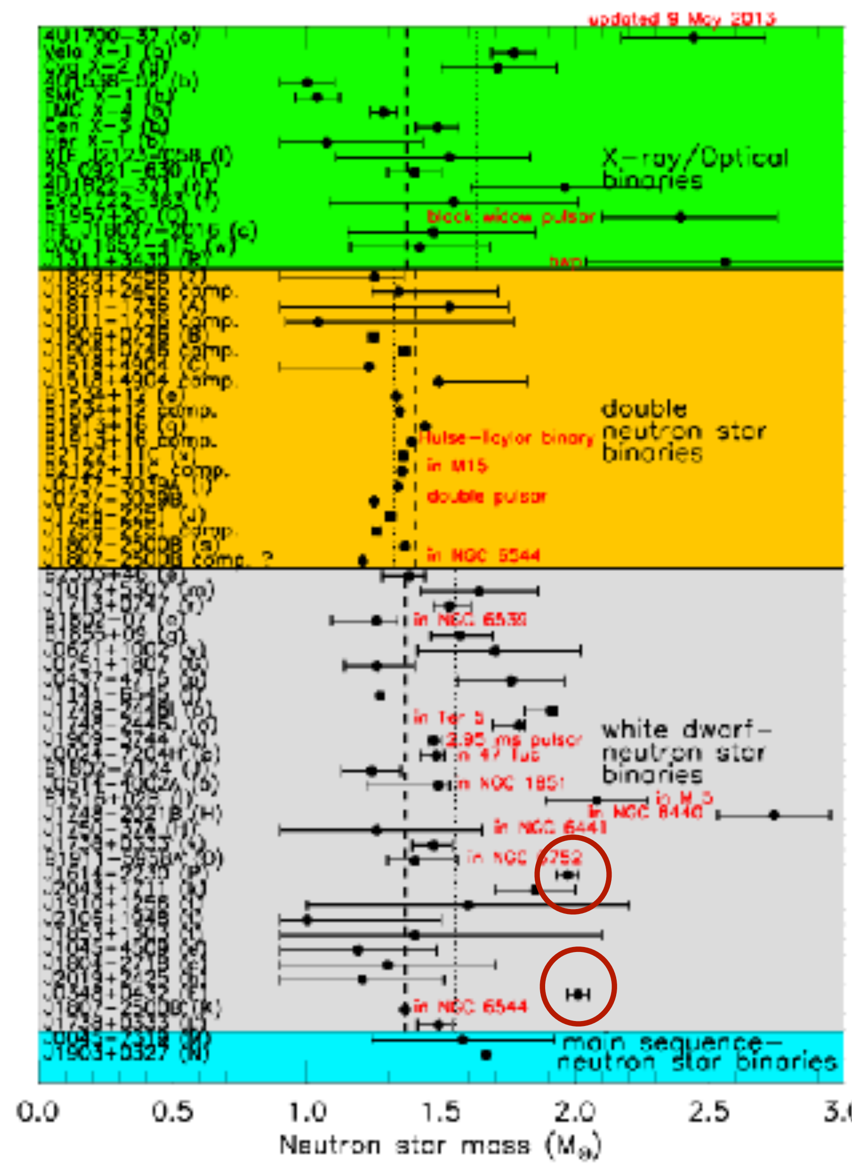
Constraining the NS Mass











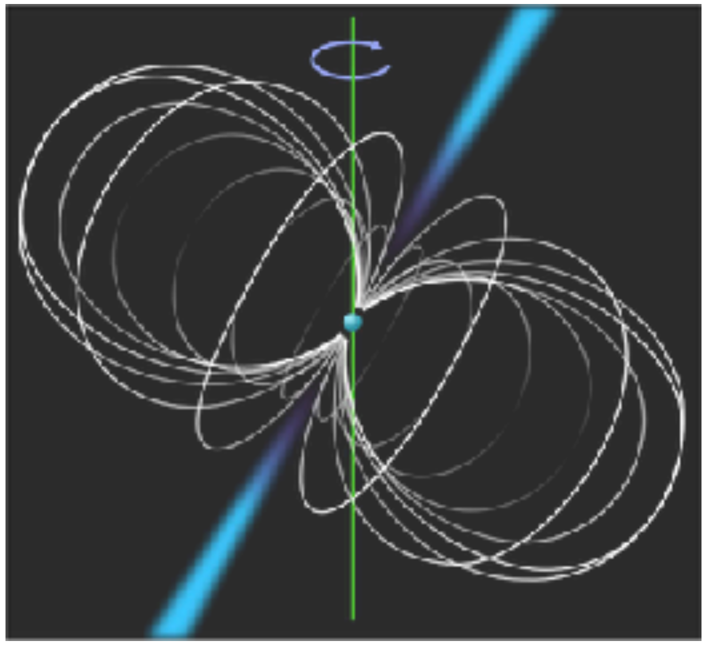
M^{max}(theo) > M^{max}(obs)

Credit: Lattimer (2019)

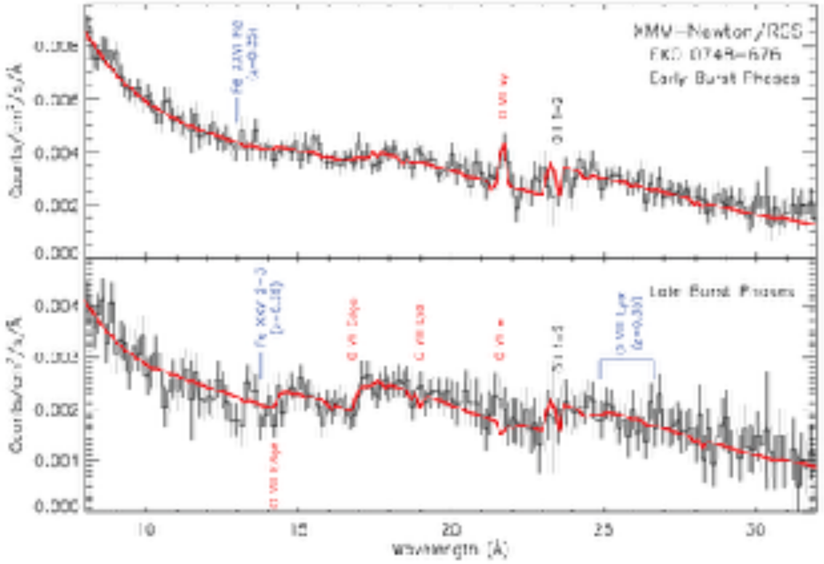
Constraining the NS Radius

- Thermonuclear X-ray bursts (photospheric radius expansion)
- Burst oscillations (rotationally modulated waveform)
- Fits of thermal spectra to cooling neutron stars
- kHz QPOs in accretion disks around neutron stars
- Precession in relativistic binaries (double pulsar J0737)

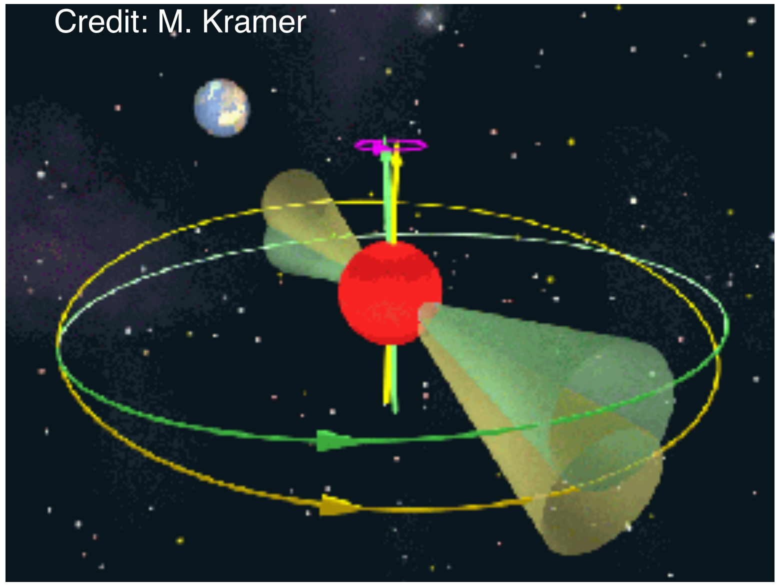
Credit: David A. Hardy



Credit: Watts



Credit: Cottam (2008)

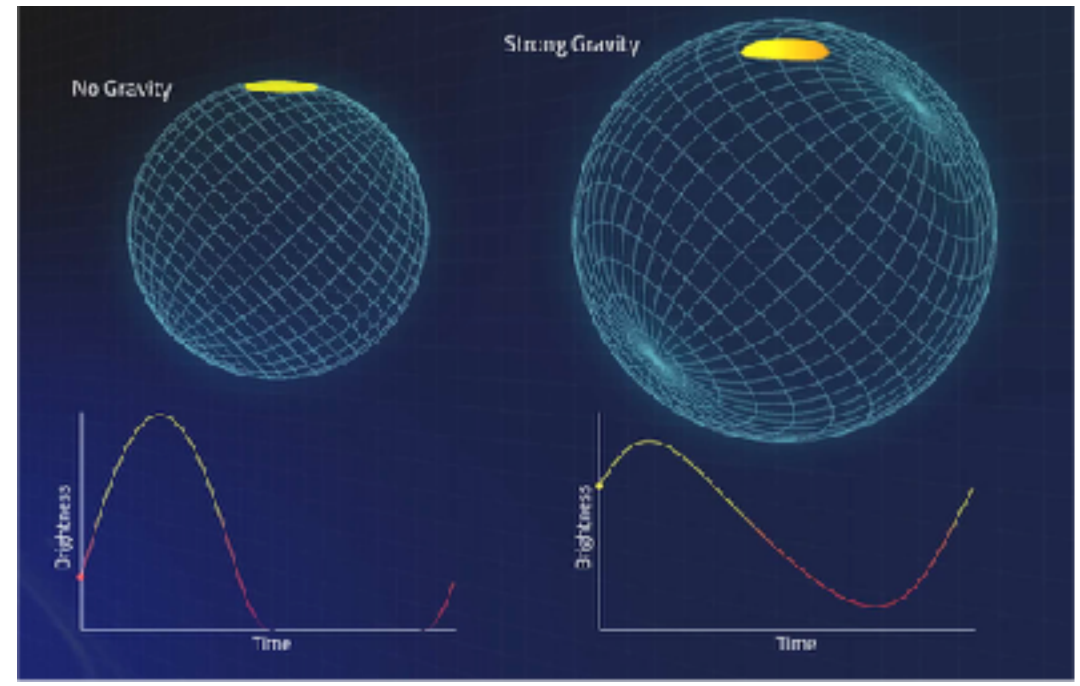


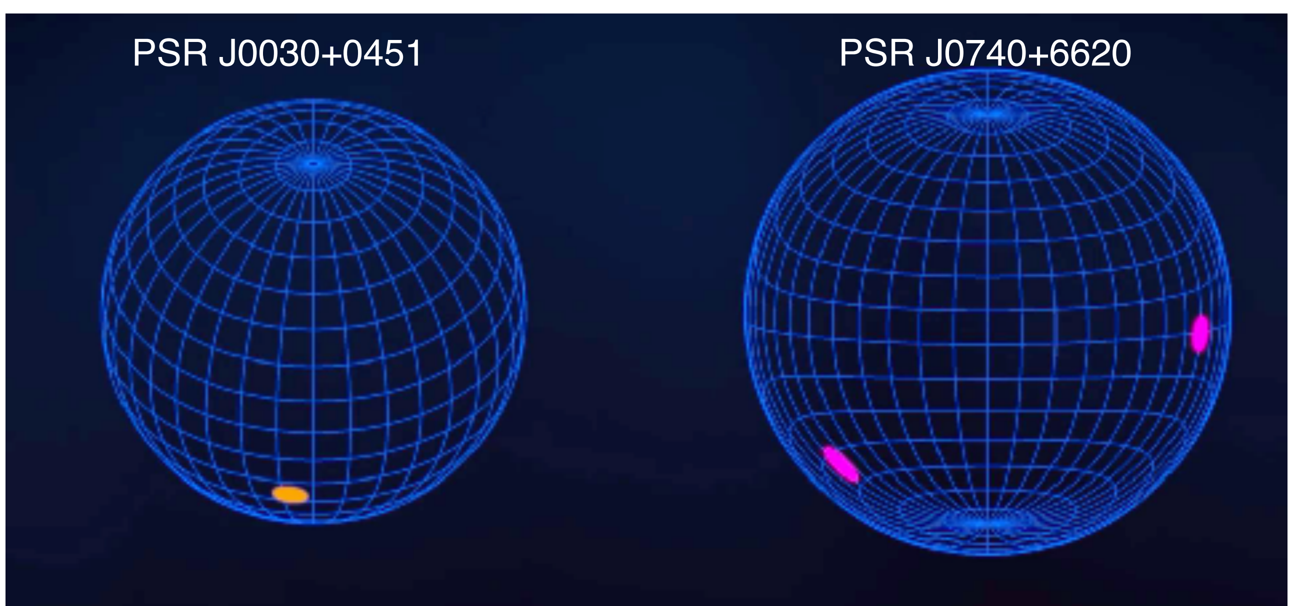
Credit: M. Kramer

Constraining the NS Radius

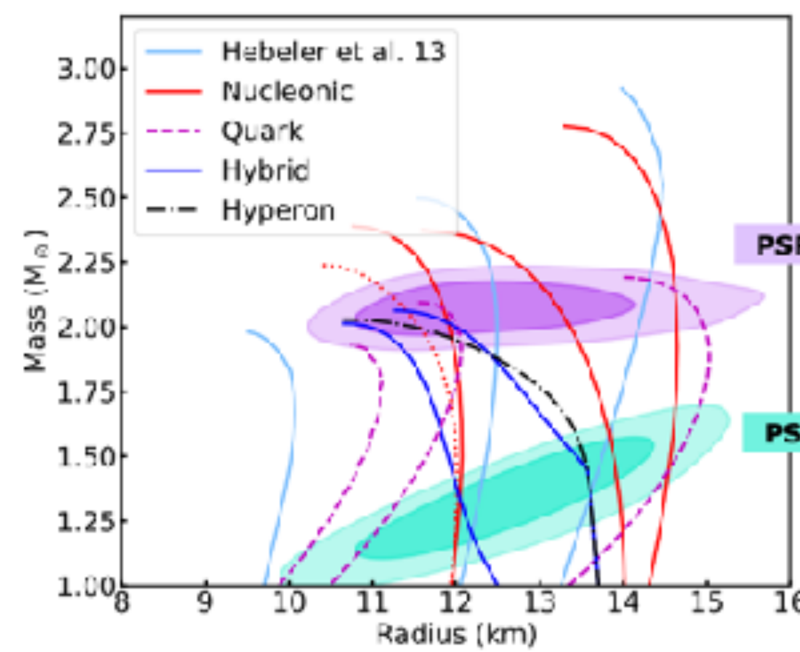
- Thermonuclear X-ray bursts (photospheric radius expansion)
- Burst oscillations (rotationally modulated waveform)
- Fits of thermal spectra to cooling neutron stars
- kHz QPOs in accretion disks around neutron stars
- Precession in relativistic binaries (double pulsar J0737)
- **Pulse Profile Modelling (NICER)**

Credit: NASA





Credit: S. Morsink/NASA



$2.08 \pm 0.07 M_{\odot}$

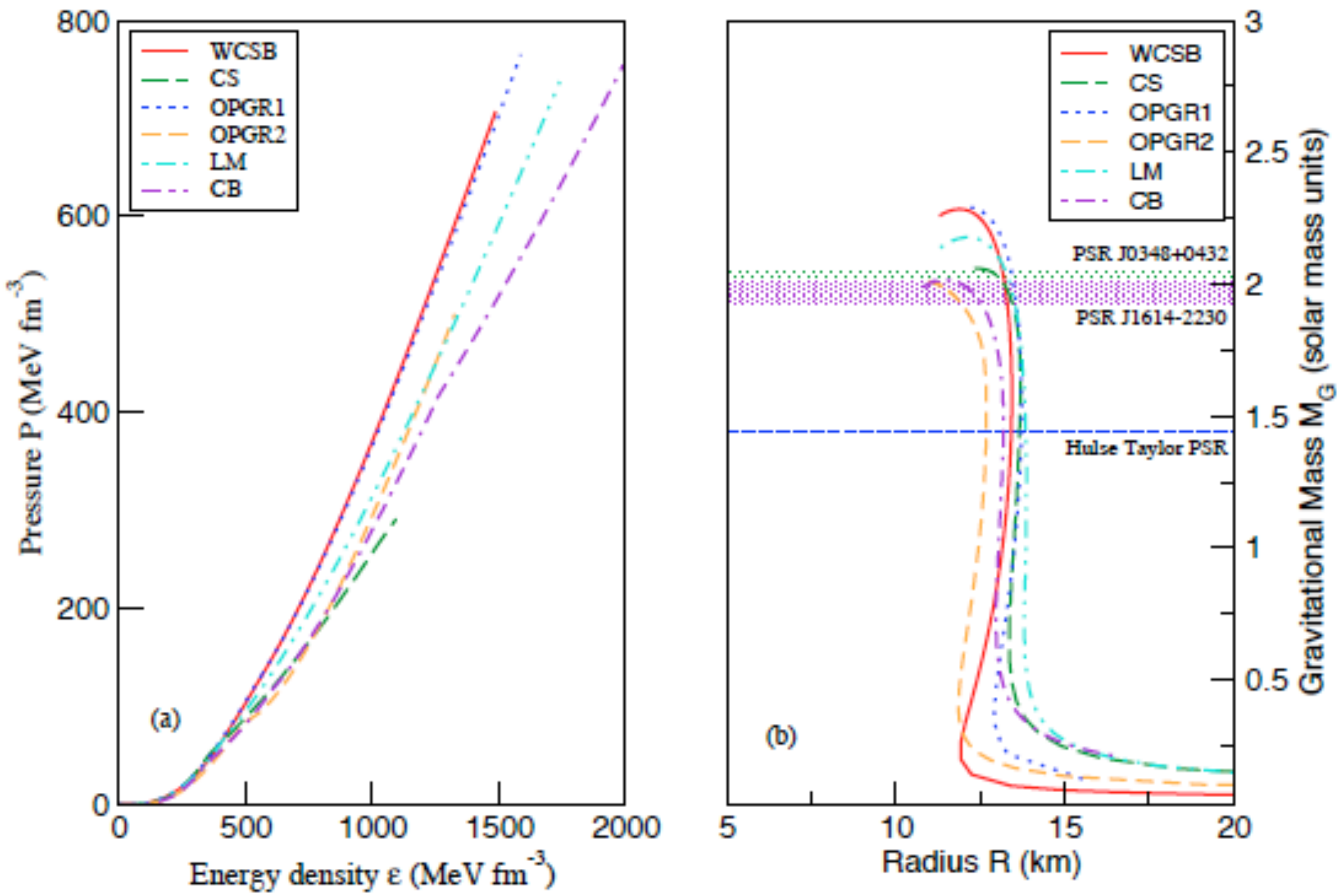
$12.35 \pm 0.75\, km$

Miller+ ApJL 918 (2021)

Credit: Anna Watts

Solving the hyperon puzzle : Role of vector repulsion

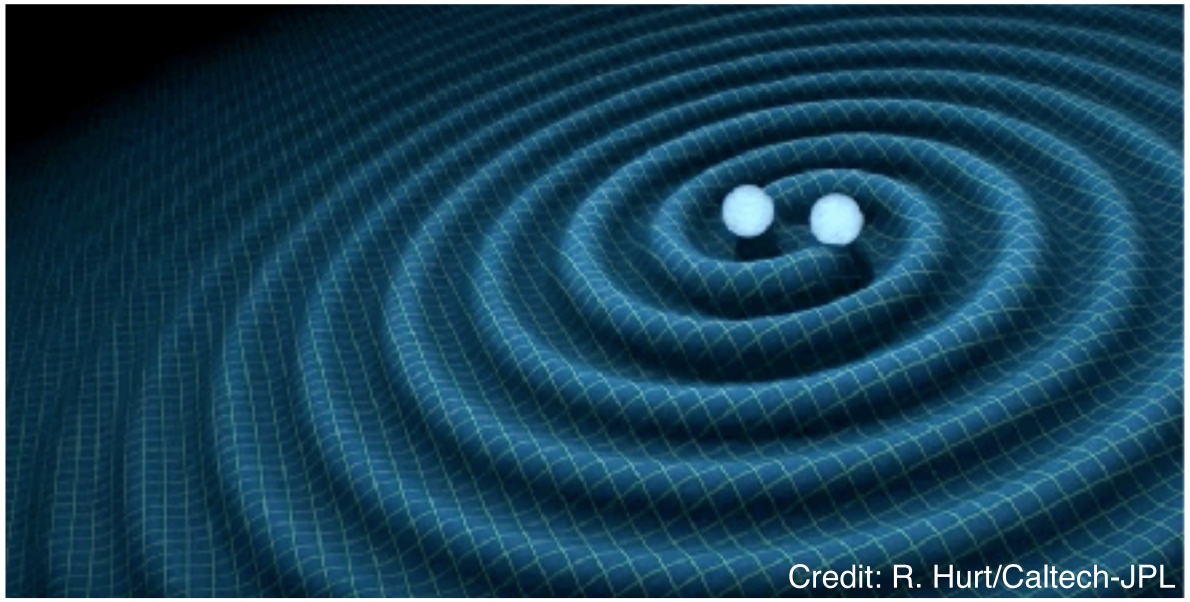
"Do hyperons exist in the interior of neutron stars?"
D.C. & I. Vidaña EPJA 52 (2016)



S.Weissenborn, D.C. and J. Schaffner-Bielich, NPA 881 (2012); PRC 85 (2012)
Colucci and Sedrakian PRC 87 (2013)
Oertel Providencia Gulminelli and Raduta, J.Phys. G 42 (2015)
Lopes and Menezes PRC 89(2014)
Char and Banik PRC 90 (2014)

See recent works by C. Providência, M. Oertel, A. Sedrakian,..

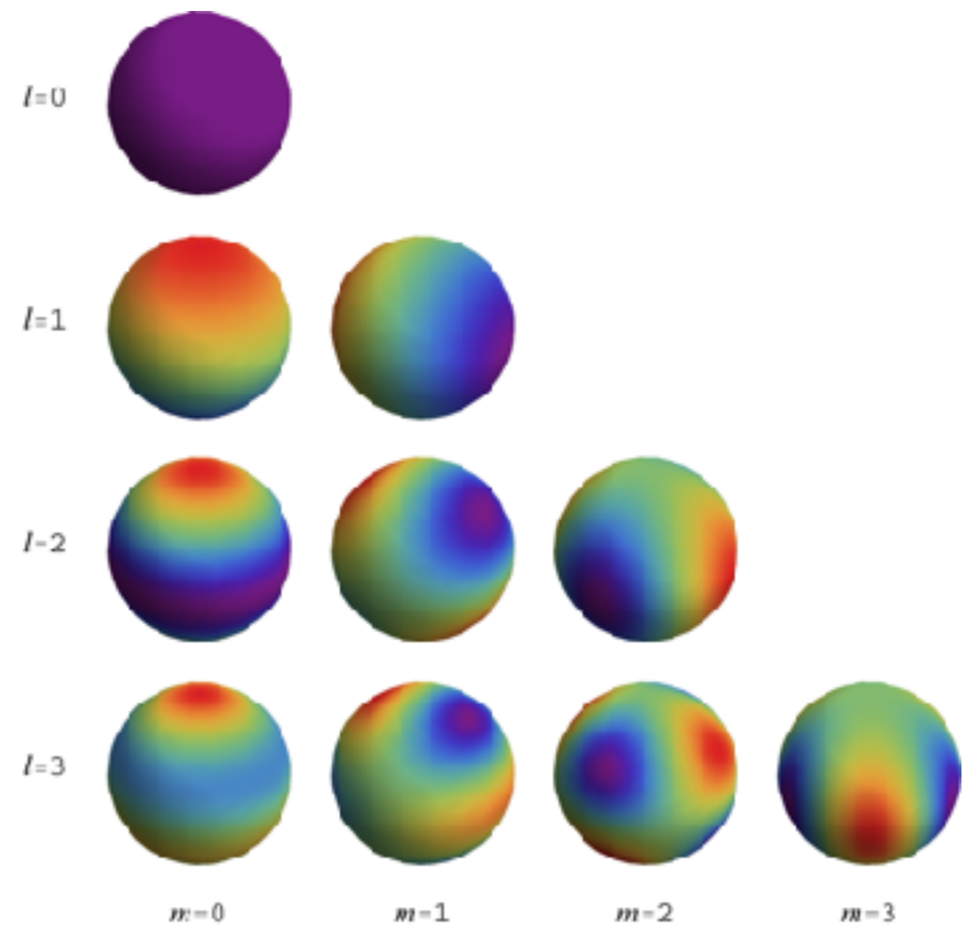
Neutron Stars as Gravitational Wave Sources



Binary NS mergers

Non-axisymmetric Oscillations:
- f-modes: fundamental modes
- p-modes: pressure
- g-modes: buoyancy
- r-modes: Coriolis force
- w-modes: space-time

Isolated NSs



Credit: Pnigouras & Kokkotas (2016)

Can we use GWs from NS oscillation modes to constrain hyperons in NSs?

QNMs in isolated NSs or post-merger remnant

Time varying quadrupole (rotating, deformed or oscillating NSs)

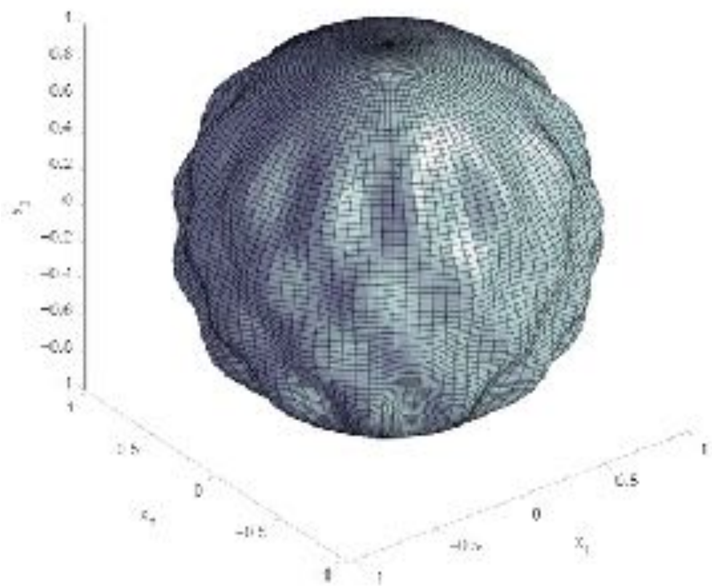


Fig.: R. Nilsson

Non-axisymmetric Oscillations:

- f-modes: fundamental (~ KHz)
- p-modes: pressure
- g-modes: buoyancy
- r-modes: Coriolis force ($\sim \Omega_s/2\pi$)
- w-modes: space-time

- **"Constraining dense matter physics using f-mode oscillations in neutron stars"**, S. Jaiswal & D.C, Physics 2021, 3, 302
- **"Effect of hyperons on f-mode oscillations in neutron stars"** B. K. Pradhan & D.C., Phys. Rev. C 103, 035810 (2021)
- **"General relativistic treatment of f-mode oscillations of hyperonic stars"** B. K. Pradhan, D. C., M. Lanoye and P. Jaikumar, arXiv:2203.03141 (accepted in Phys Rev C)
- **"Impact of updated Multipole Love numbers and f-Love Universal Relations in the context of Binary Neutron Stars"**, B. K. Pradhan, A. Vijaykumar, D.C. Phys. Rev. D 107, 2023

See talk by Bikram K. Pradhan

Nuclear EoS and F-modes

S. Jaiswal & D.C, Physics 2021, 3, 302

Relativistic Mean Field (RMF) model:

interaction Lagrangian → EoS

Calibration of the Model :

isoscalar coupling constants fixed to
- nuclear saturation density n_{sat}
- binding energy per nucleon E_{sat}
- incompressibility K_{sat}
- effective nucleon mass m^*/m

isovector coupling constants function of
- symmetry energy & its slope E_{sym}, L_{sym}

Isoscalar couplings :

$n_{sat} \approx 0.15\text{–}0.16\ \text{fm}^{-3}$

$E_{sat} \approx -16.5$ to -15.5 MeV

$K_{sat} \approx 240\text{–}280$ MeV

$m^*/m \approx 0.55 - 0.75$

Isovector couplings:

functions of J_{sym} and L_{sym}

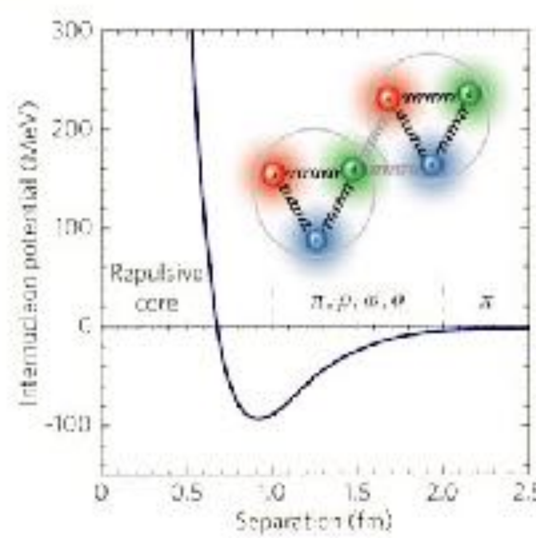
$E_{sym} \approx 30 - 32$ MeV

$L_{sym} \approx 50 - 60$ MeV

$$\mathcal{L} = \sum_B \bar{\psi}_B \left(i\gamma^\mu \partial_\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu \omega^\mu - g_{\rho B}\gamma_\mu \vec{I}_B \cdot \vec{\rho}^\mu \right) \psi_B + \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) - U_\sigma$$
$$+ \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}(\vec{\rho}_{\mu\nu} \cdot \vec{\rho}^{\mu\nu} - 2 m_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu) + \Lambda_\omega (g_{\rho N}^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu)(g_{\omega N}^2 \omega_\mu \omega^\mu)$$
$$+ \sum_Y \bar{\psi}_Y (g_{\sigma^* Y}\sigma^* - g_{\phi Y}\gamma_\mu \phi^\mu)\psi_Y + \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2}(\partial_\mu \sigma^* \partial^\mu \sigma^* - m_{\sigma^*}^2 \sigma^{*2})$$
$$+ \sum_{\ell = \{e^-, \mu^-\}} \bar{\psi}_\ell (i\gamma^\mu \partial_\mu - m_\ell)\psi_\ell$$

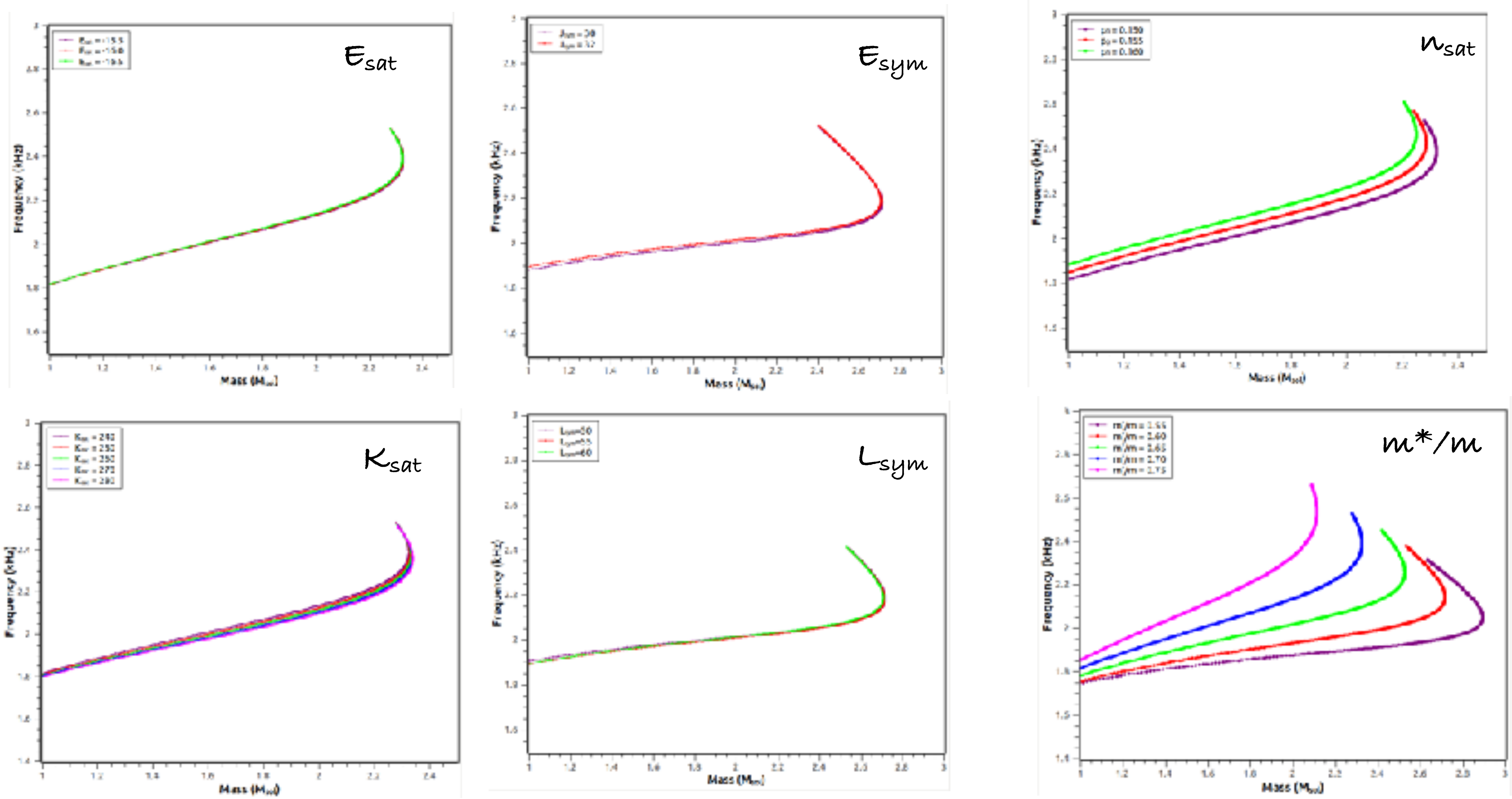
$$U_\sigma = \frac{1}{3} b m_N (g_{\sigma_N}\sigma)^3 + \frac{1}{4} c (g_{\sigma_N}\sigma)^4$$

Nuclear saturation properties



Sensitivity study

S. Jaiswal & D.C, Physics 2021, 3, 302



The saturation density plays a non-negligible role, while the uncertainties in other parameters does not affect the f-mode frequencies

- The **effective nucleon mass** is the dominant empirical saturation parameter that determines the f-mode frequencies

Within Cowling approximation

Do hyperons affect F-modes?

B. K. Pradhan & D.C., Phys. Rev. C 103, 035810 (2021)

- **RMF model:** interaction Lagrangian
  → EoS

- **Calibration of the Model :**
  - hyperon-vector meson couplings fixed by SU(6) symmetry of quark model
  - hyperon-sigma meson couplings fixed to hyperon depth in nuclear matter
  - hyperon strange-scalar meson fixed by hyperon potential depths in hyperon matter

Isoscalar couplings :

- $n_{sat} \approx 0.16\ \mathrm{fm}^{-3}$
- $E_{sat} \approx -16$ MeV
- $K_{sat} \approx 240$ MeV
- $m^*/m \approx 0.55 - 0.75$

Isovector couplings:

functions of J_{sym} and L_{sym}

- $J_{sym} \approx 32$ MeV
- $L_{sym} \approx 60$ MeV

$$\mathcal{L} = \sum_B \bar{\psi}_B (i\gamma^\mu \partial_\mu - m_B + g_{\sigma_B}\sigma - g_{\omega_B}\gamma_\mu \omega^\mu - g_{\rho_B}\gamma_\mu \vec{I}_B . \vec{\rho}^\mu)\psi_B + \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) - U_\sigma + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu}$$

$$-\frac{1}{4}(\vec{\rho}_{\mu\nu}.\vec{\rho}^{\mu\nu} - 2 m_\rho^2 \vec{\rho}_\mu . \vec{\rho}^\mu) + \Lambda_\omega (g_{\rho_N}^2 \vec{\rho}_\mu . \vec{\rho}^\mu)\,(g_{\omega_N}^2 \omega_\mu \omega^\mu) + \mathcal{L}_{YY} + \mathcal{L}_\ell ,$$

$$U_\sigma = \frac{1}{3} b m_N (g_{\sigma_N}\sigma)^3 + \frac{1}{4} c (g_{\sigma_N}\sigma)^4$$

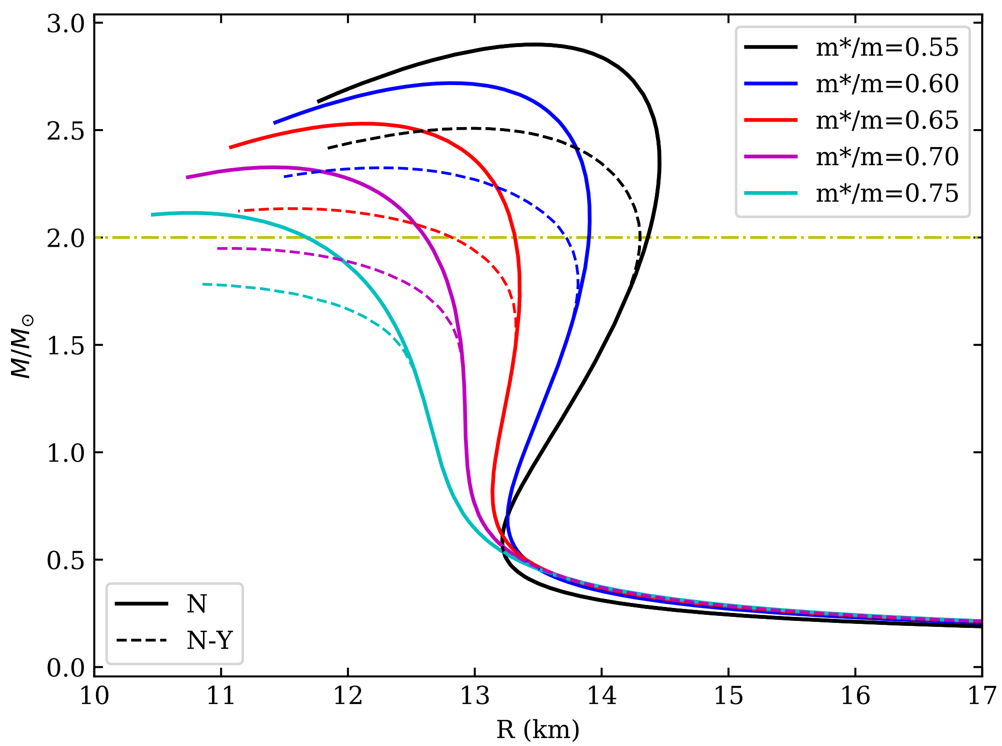
$$\mathcal{L}_{YY} = \sum_Y \bar{\psi}_Y (g_{\sigma^* Y}\sigma^* - g_{\phi Y}\gamma_\mu \phi^\mu)\psi_Y + \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu$$

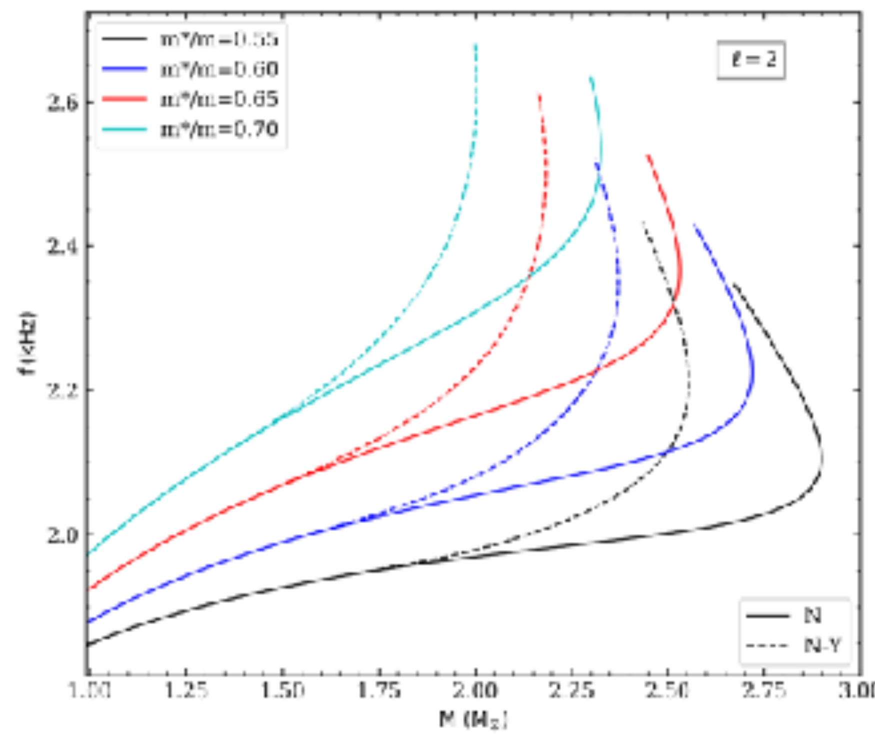
$$-\frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2}(\partial_\mu \sigma^* \partial^\mu \sigma^* - m_{\sigma^*}^2 \sigma^{*2})$$

$$\mathcal{L}_\ell = \sum_{\ell = \{e^-, \mu^-\}} \bar{\psi}_\ell (i\gamma^\mu \partial_\mu - m_\ell)\psi_\ell .$$

$U_\Sigma^{(N)} = +30,\ U_\Lambda^{(N)} = -30$ and $U_\Xi^{(N)} = -18$ MeV

$U_{\Sigma}^{(N)} = +30,\ U_{\Lambda}^{(N)} = -30$ and $U_{\Xi}^{(N)} = -18$ MeV

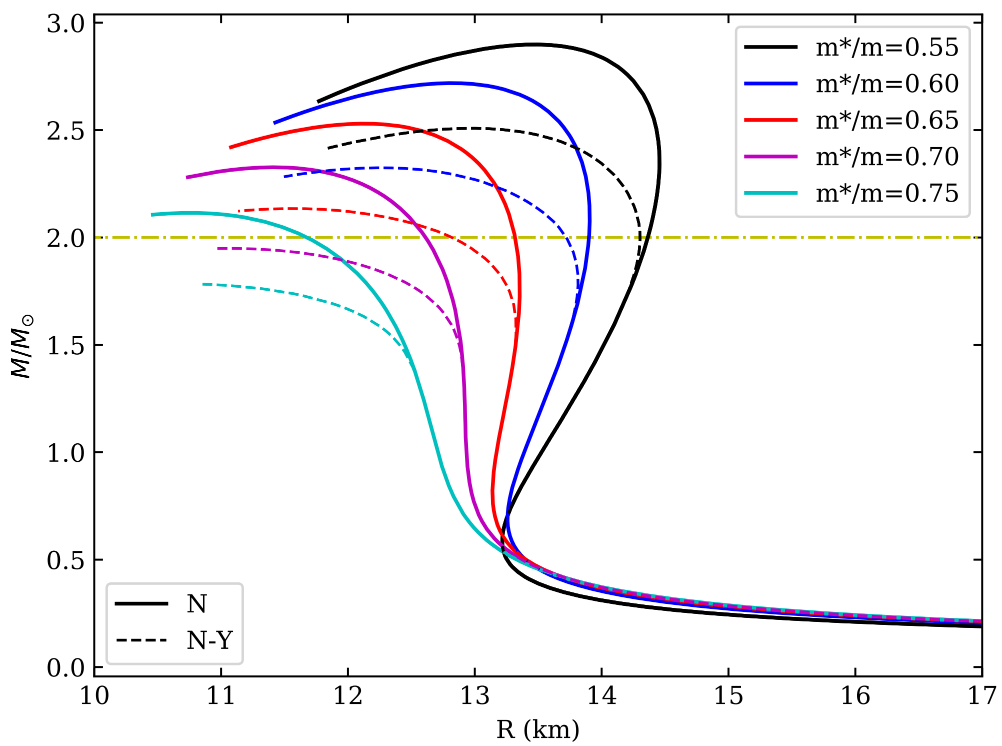


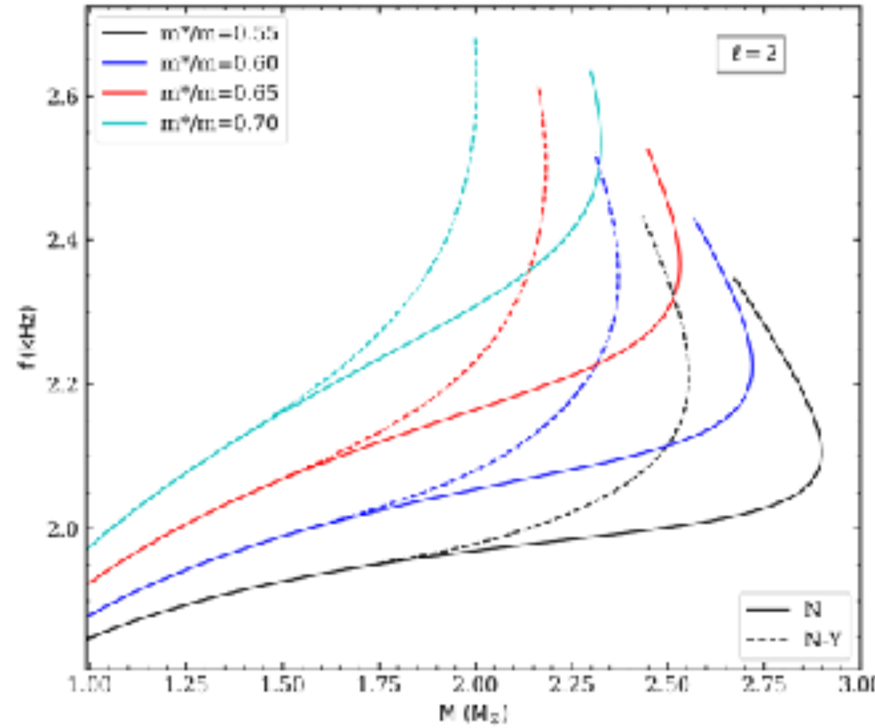


Within Cowling approximation

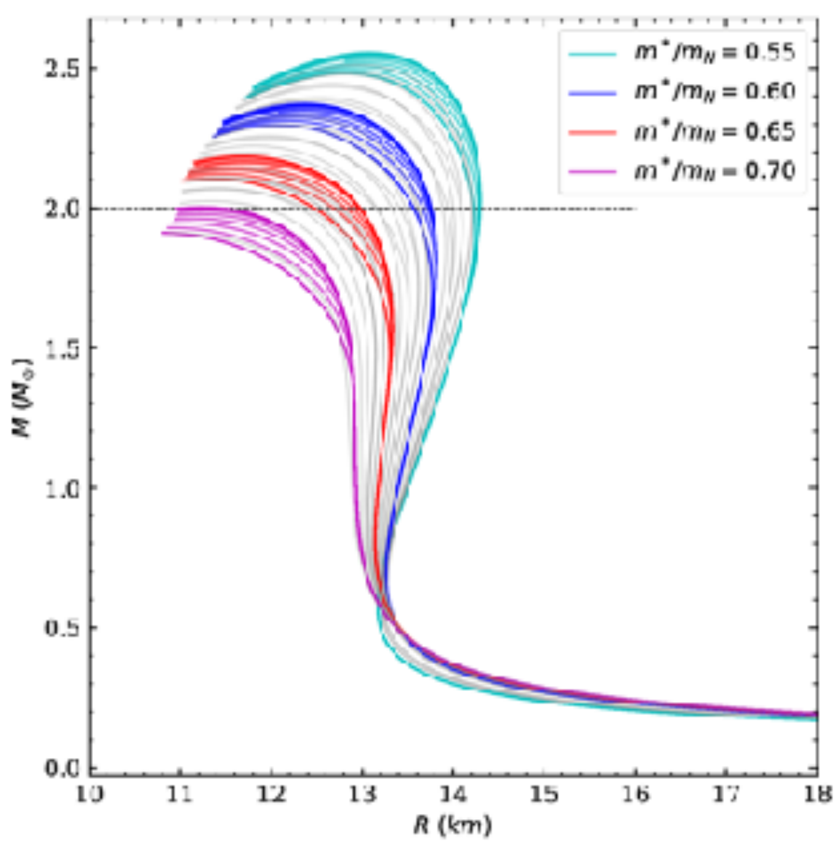
B. K. Pradhan & D.C., Phys. Rev. C 103, 035810 (2021)

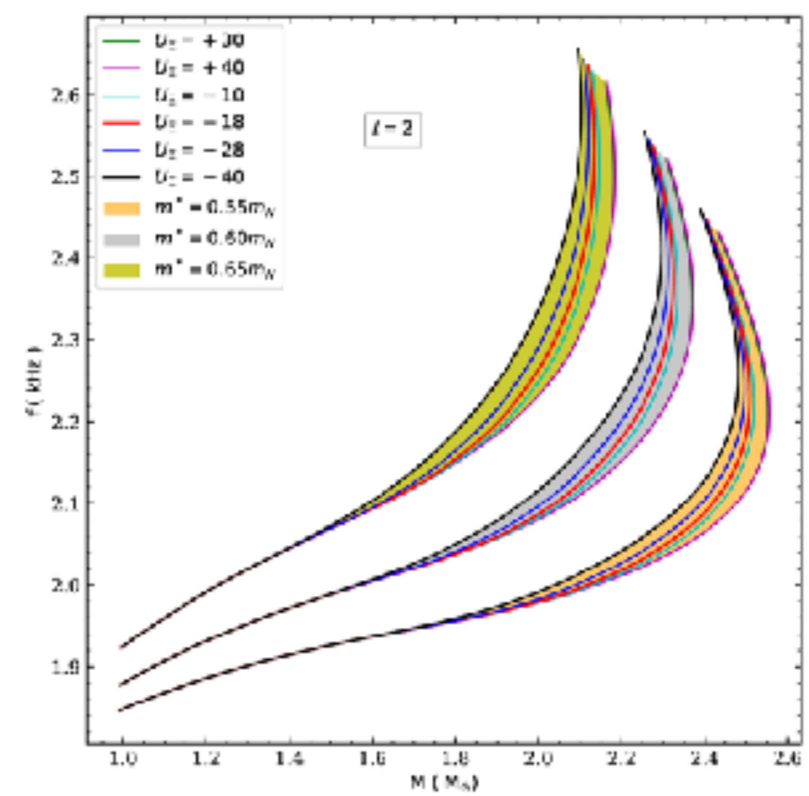
$U_\Sigma^{(N)} = +30,\ U_\Lambda^{(N)} = -30$ and $U_\Xi^{(N)} = -18$ MeV





U_Ξ^N -40 MeV to +40 MeV.

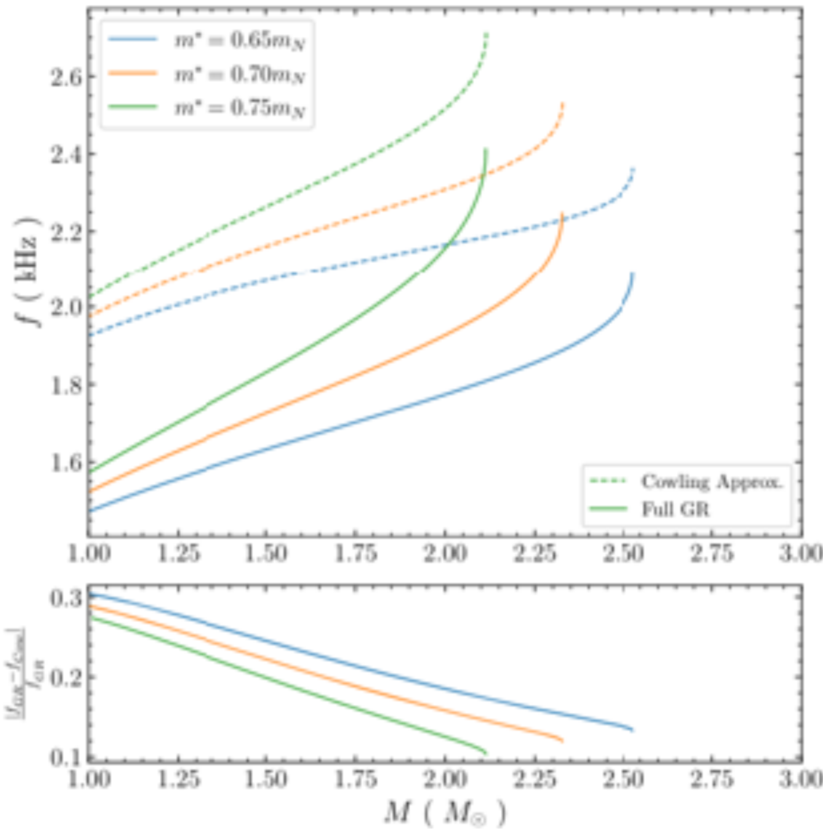


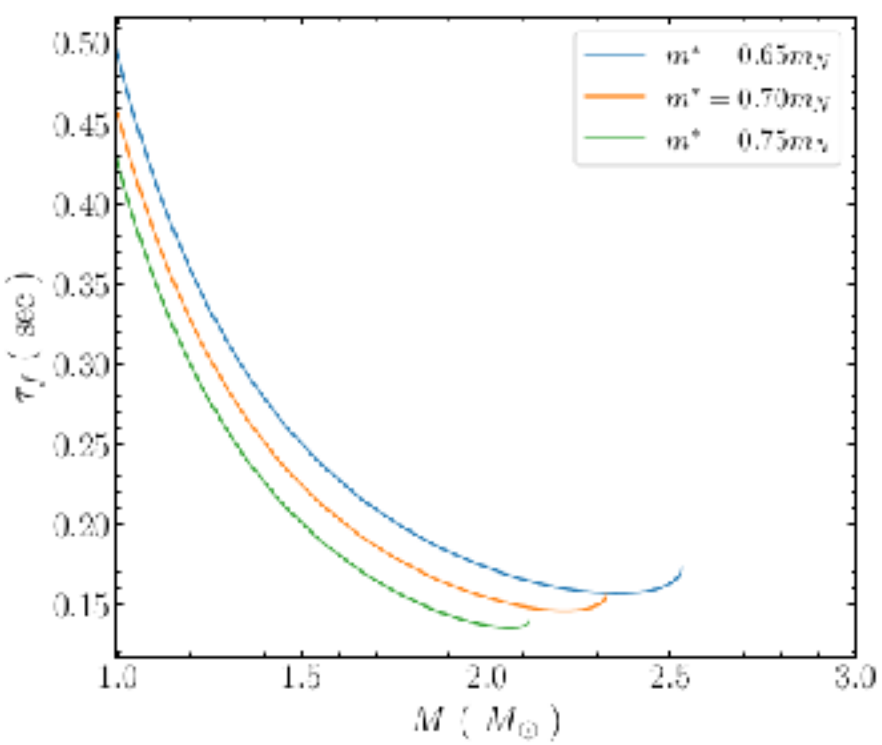


Within Cowling approximation

B. K. Pradhan & D.C., Phys. Rev. C 103, 035810 (2021)

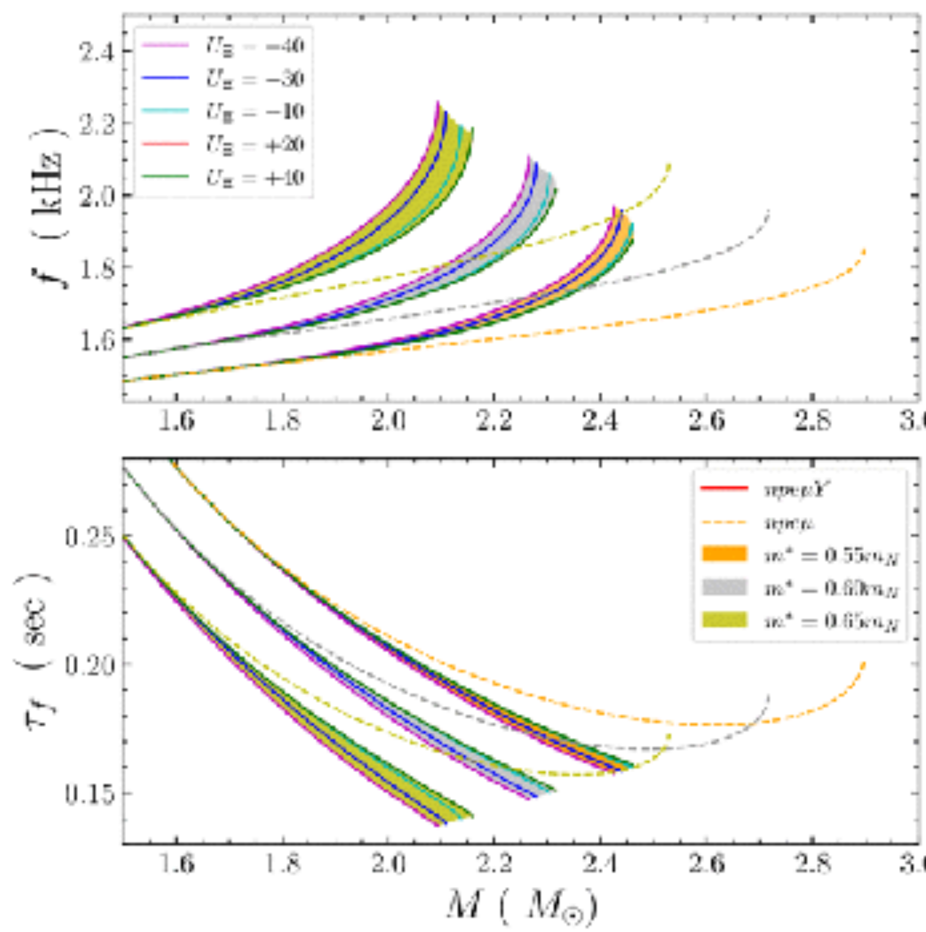
FROM COWLING APPROXIMATION TO FULL GR





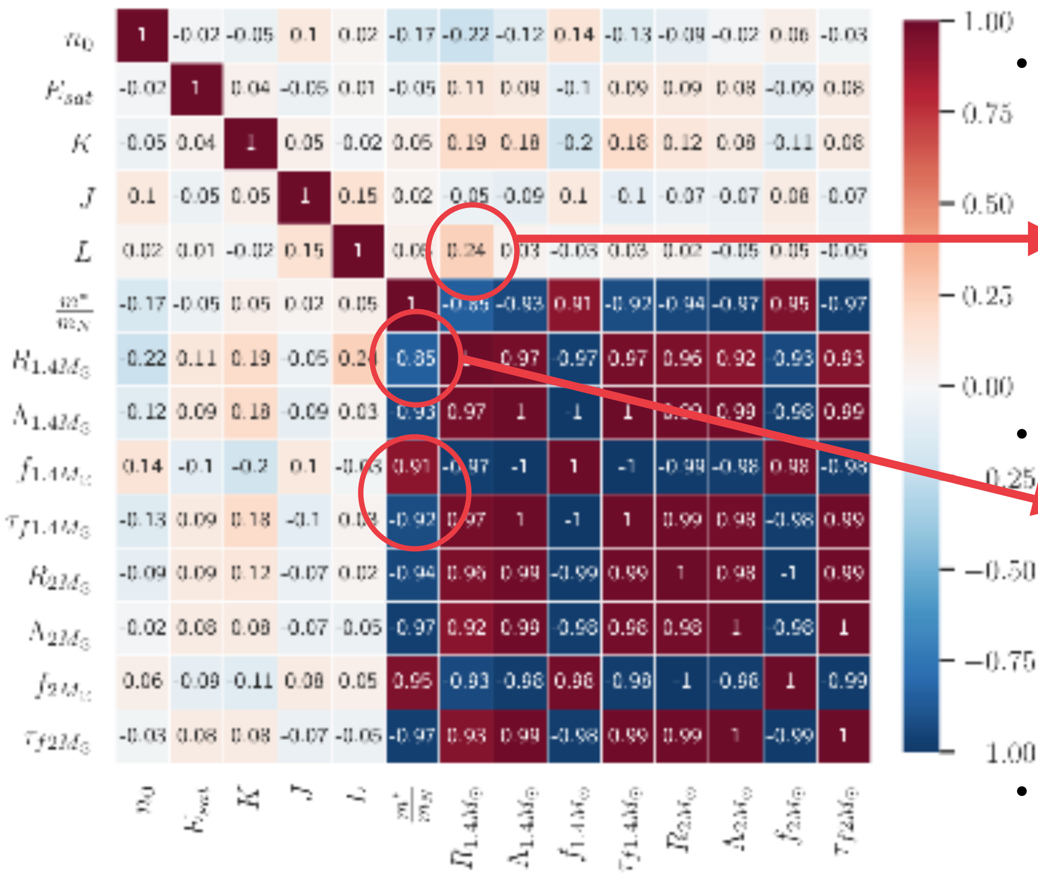
B. K. Pradhan, D. C., M. Lanoye and P. Jaikumar, Phys. Rev. C 106, 015805 (2022)

- The frequency and damping time of quadrupole f-mode oscillations of hyperonic stars are found to be in the range of 1.47–2.45 kHz and 0.13–0.51 s respectively
- Cowling approximation can introduce an error in the mode frequency of 10-30%
- Error decreases with increasing mass (f-mode is peaked near the surface)



CORRELATION STUDIES

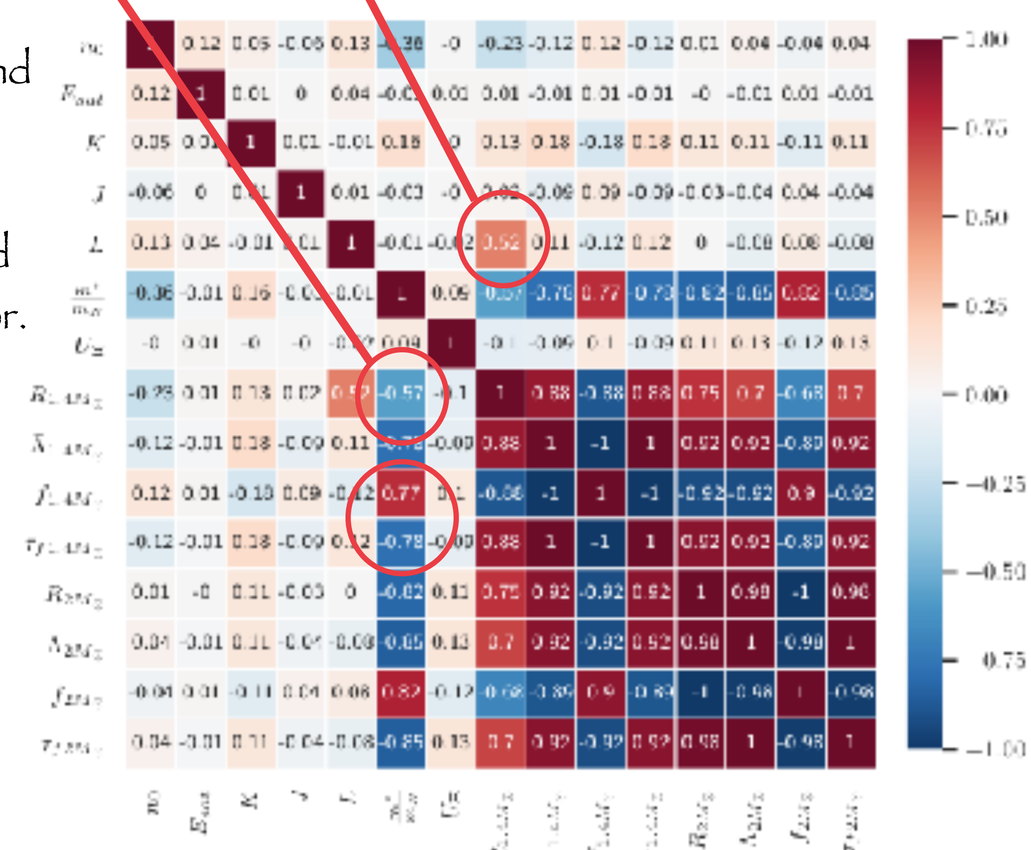
B. K. Pradhan, D. C., M. Lanoye and P. Jaikumar, Phys. Rev. C 106, 015805 (2022)



Nucleonic

- Correlation between L_{sym} and radius of $1.4M_{\odot}$ star increases when compared to the nucleonic case (from 0.24 to 0.52)
- The correlation between m^* and R of $1.4M_{\odot}$ decreases from 0.85 to 0.57 compared to the nucleonic case
- Effective mass shows strong correlation with mode characteristics (frequency and damping time)
- Correlations between U_{Ξ} and mode characteristics are poor.

Hyperonic



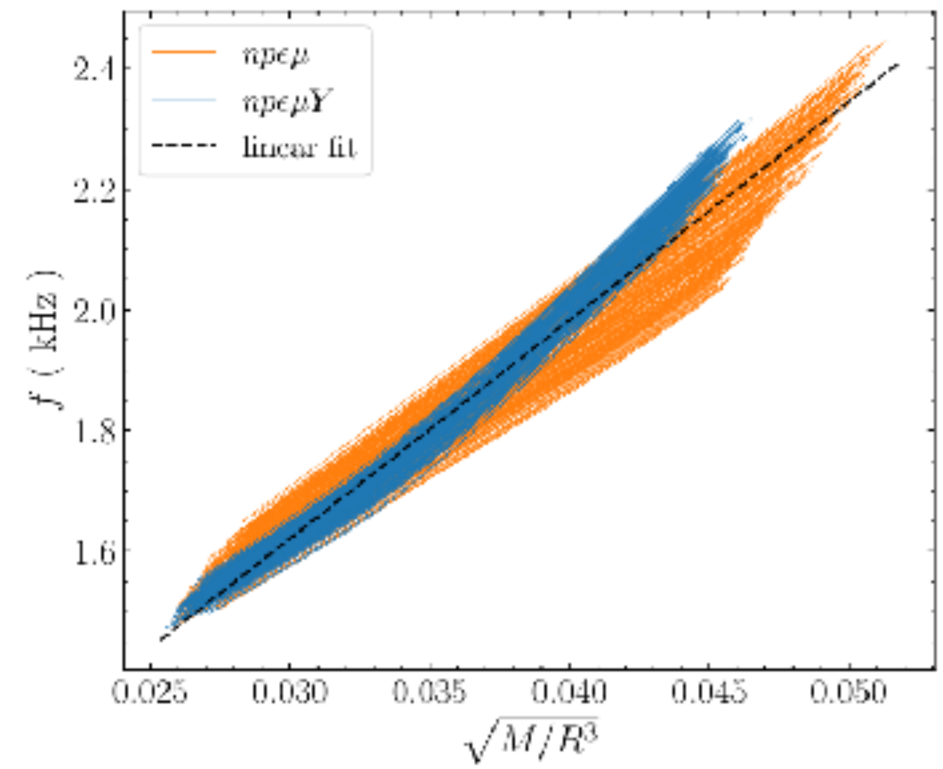
Asteroseismology and Universal Relations

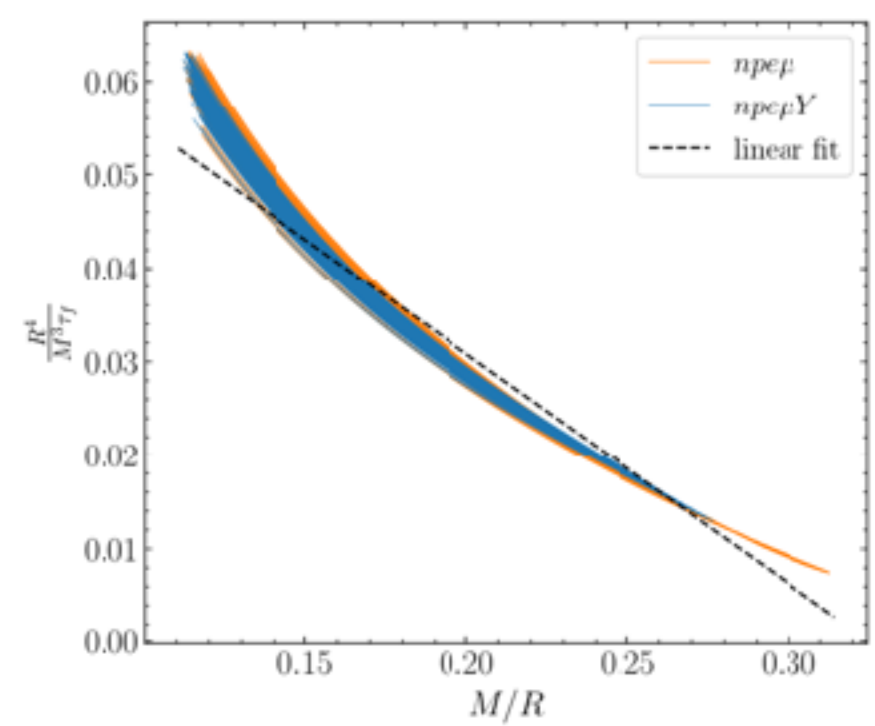
$$f(\mathrm{kHz}) = a_r + b_r\sqrt{\frac{M}{R^3}},$$

$$\frac{R^4}{M^3\tau_f} = a_i + b_i\frac{M}{R}.$$

Reference	a_r (kHz)	b_r (kHz × km)
Andersson and Kokkotas [38]	0.22	47.51
Benhar and Ferrari [68]	0.79	33
D.Doneva *et al.* [25]	1.562	25.32
Pradhan and Chatterjee [40]	1.075	31.10
This work	0.535	36.20

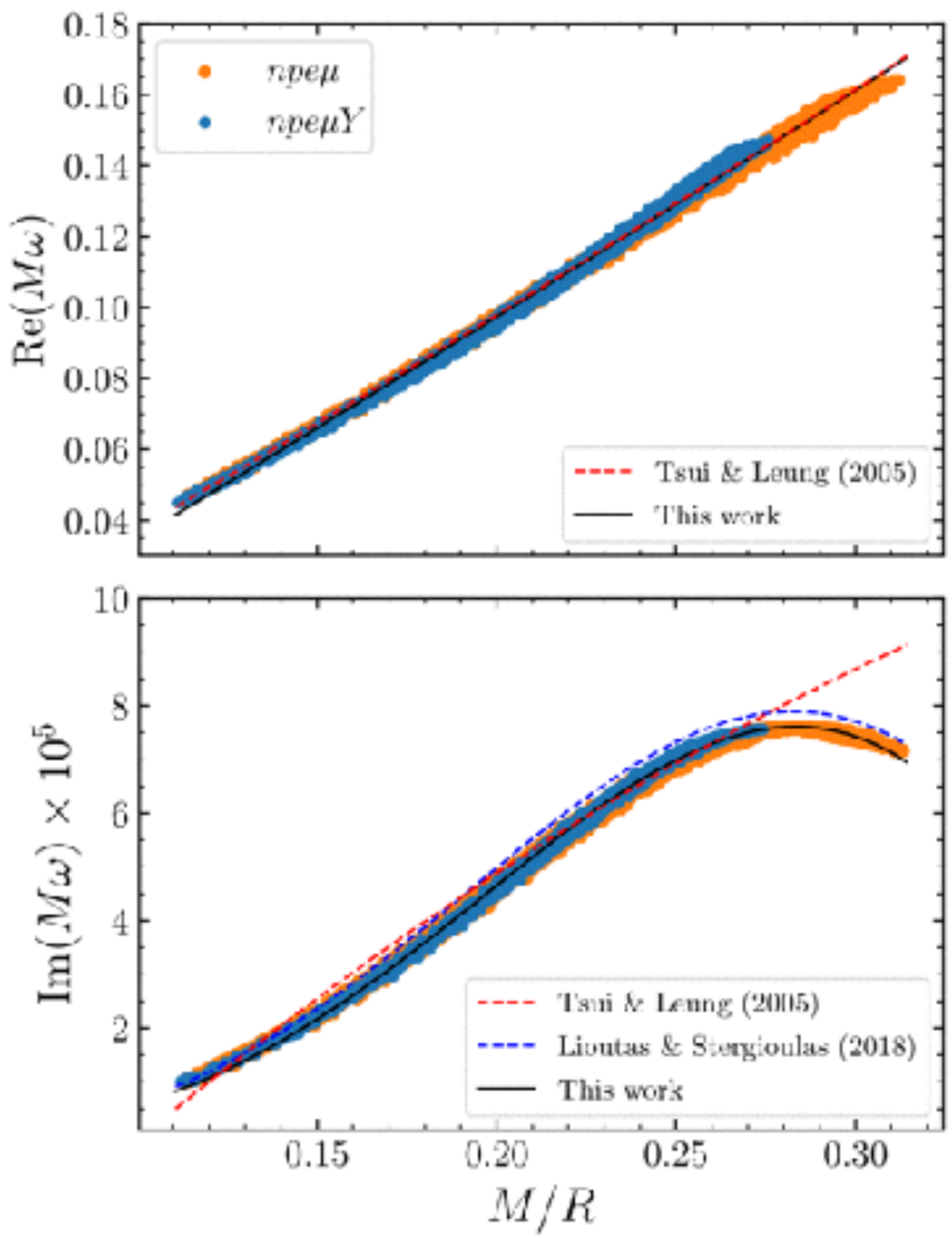
Reference	a_i	b_i
Andersson and Kokkotas [38]	0.086	−0.267
Benhar and Ferrari [68]	0.087	−0.271
This work	0.080	−0.245





B. K. Pradhan, D. C., M. Lanoye and P. Jaikumar,
Phys. Rev. C 106, 015805 (2022)

Asteroseismology and Universal Relations



B. K. Pradhan, D. C., M. Lanoye and P. Jaikumar, Phys. Rev. C 106, 015805 (2022)

$$\mathrm{Re}(M\omega) = a_0\left(\frac{M}{R}\right)^2 + a_1\frac{M}{R} + a_2,$$

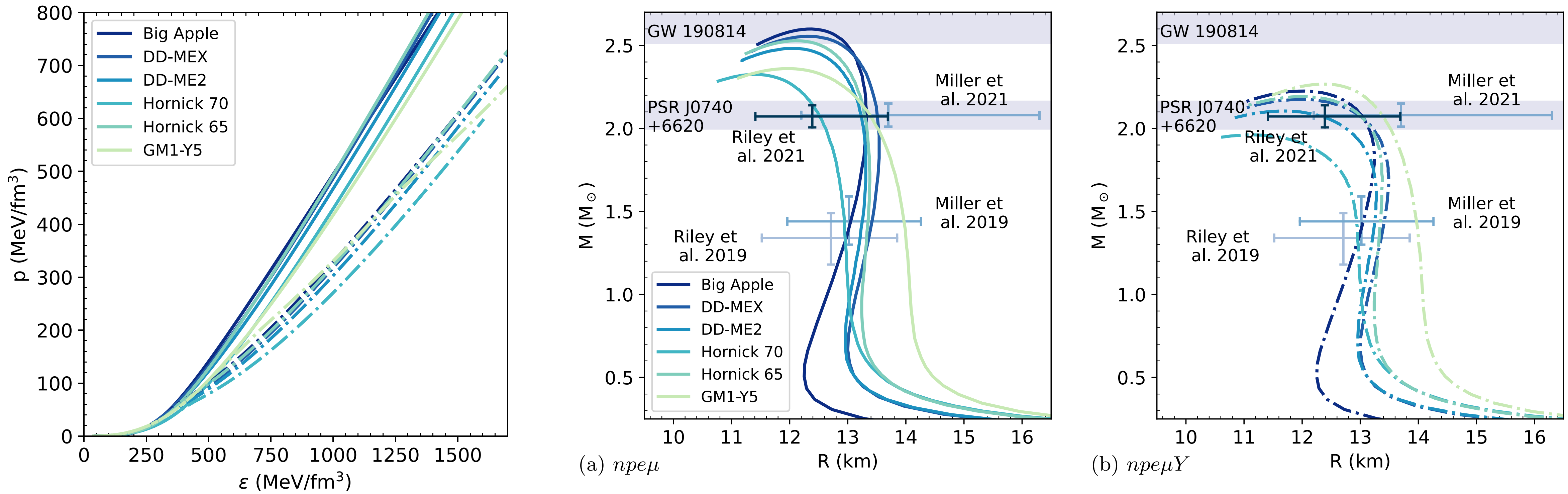
$$\mathrm{Im}(M\omega) = b_0\left(\frac{M}{R}\right)^4 + b_1\left(\frac{M}{R}\right)^5 + b_2\left(\frac{M}{R}\right)^6.$$

	Re($M\omega$)		Im($M\omega$)
a_0	0.079 ± 0.002	b_0	$(9.836 \pm 0.003) \times 10^{-2}$
a_1	0.599 ± 0.001	b_1	$(-4.448 \pm 0.002) \times 10^{-1}$
a_2	$-0.026 \pm 8 \times 10^{-5}$	b_2	$(4.915 \pm 0.004) \times 10^{-1}$

Can we use GWs from NS oscillation modes to constrain the nuclear EoS?

Non-axisymmetric Oscillations:
- f-modes: fundamental (~ KHz)
- p-modes: pressure
- g-modes: buoyancy
- r-modes: Coriolis force ($\sim \Omega_s/2\pi$)
- w-modes: space-time

"g-mode Oscillations in Neutron Stars with Hyperons",
V. Tran, S. Ghosh, N. Lozano, D. C., P. Jaikumar,
Phys. Rev. C 108 (2023) 015803



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"g-mode Oscillations in Neutron Stars with Hyperons",
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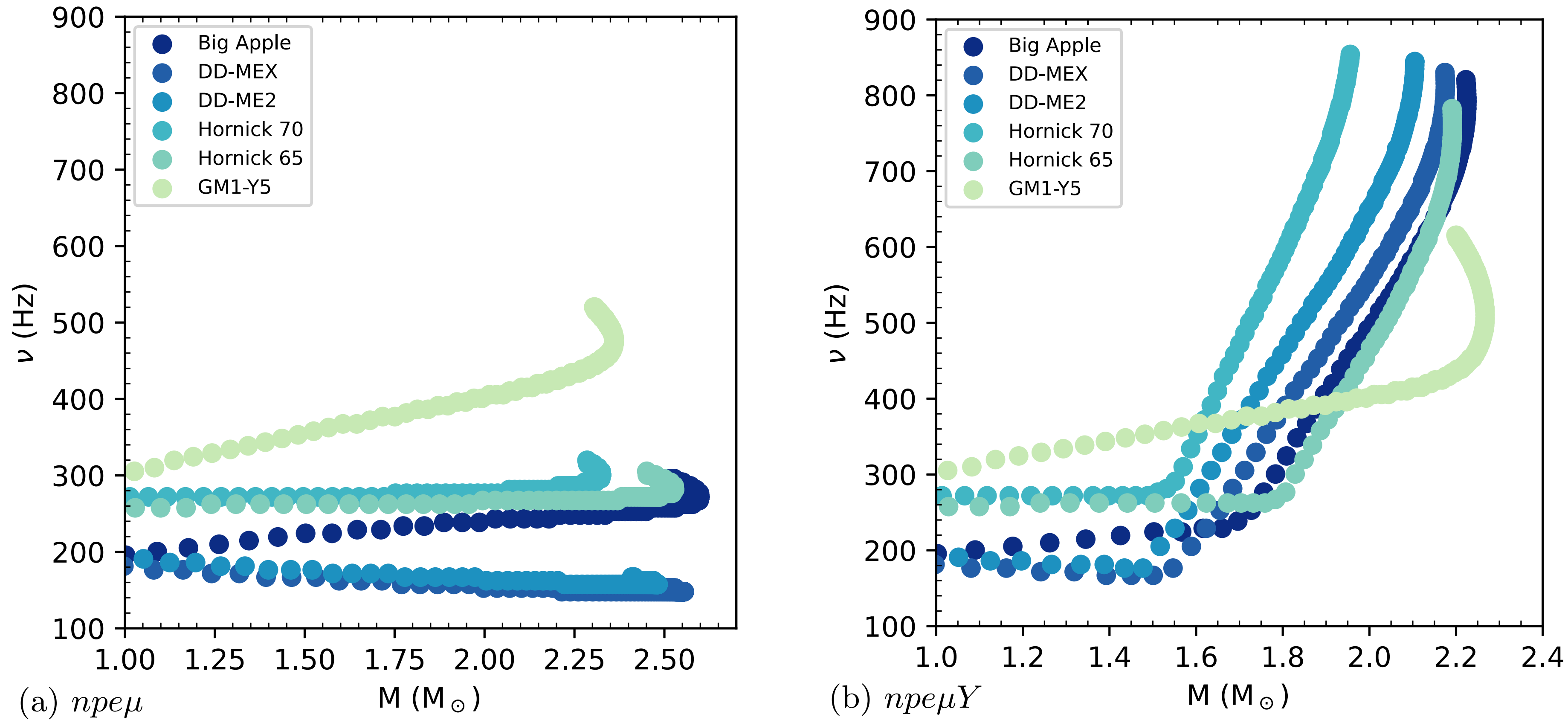
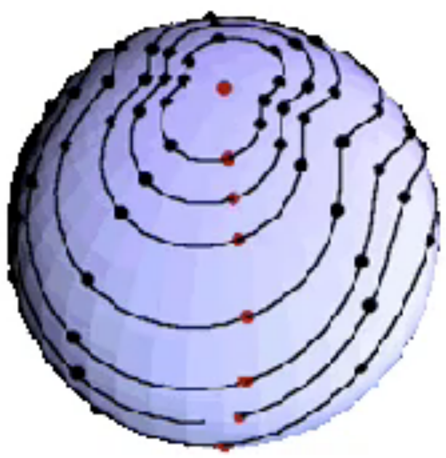
Phys. Rev. C 108 (2023) 015803

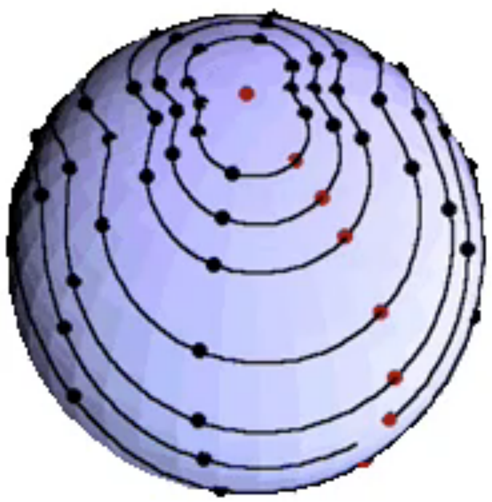


- A sharp rise in the **g-mode** frequencies upon the onset of strange baryons.
- Should g modes be observed in the near future, their frequency could be used to test the presence of hyperonic matter in the core of neutron stars

Neutron Stars and R-mode instability



co-rotating



inertial

Image: L. Rezzolla

- R-modes generic to all rotating neutron stars
- Unstable by the CFS mechanism: R-mode amplitude grows under the effect of gravitational radiation-reaction; sources of GW
- Damped by (shear, bulk) viscosity, depend on NS composition

- Shear viscosity from momentum transport due to particle scattering
- Bulk viscosity from variation in pressure and density when the system is driven away from chemical equilibrium

$$p - \bar{p} = -\zeta \nabla \cdot \bar{u}$$

- timescale associated with growth/dissipation
  $\tau_{BV,SV} \gg \tau_{GR}$: r-mode unstable, star spins down
  $\tau_{BV,SV} \ll \tau_{GR}$: r-mode damped, star can spin rapidly

$$\frac{1}{\tau} = -\frac{1}{\tau_{GR}} + \frac{1}{\tau_{SV}} + \frac{1}{\tau_{BV}}$$

Hyperons and R-modes

- Leptonic weak processes involving nucleons

direct Urca process:

$$n \to p + e^- + \bar{\nu}_e$$
$$p + e^- \to n + \nu_e$$

modified Urca process:

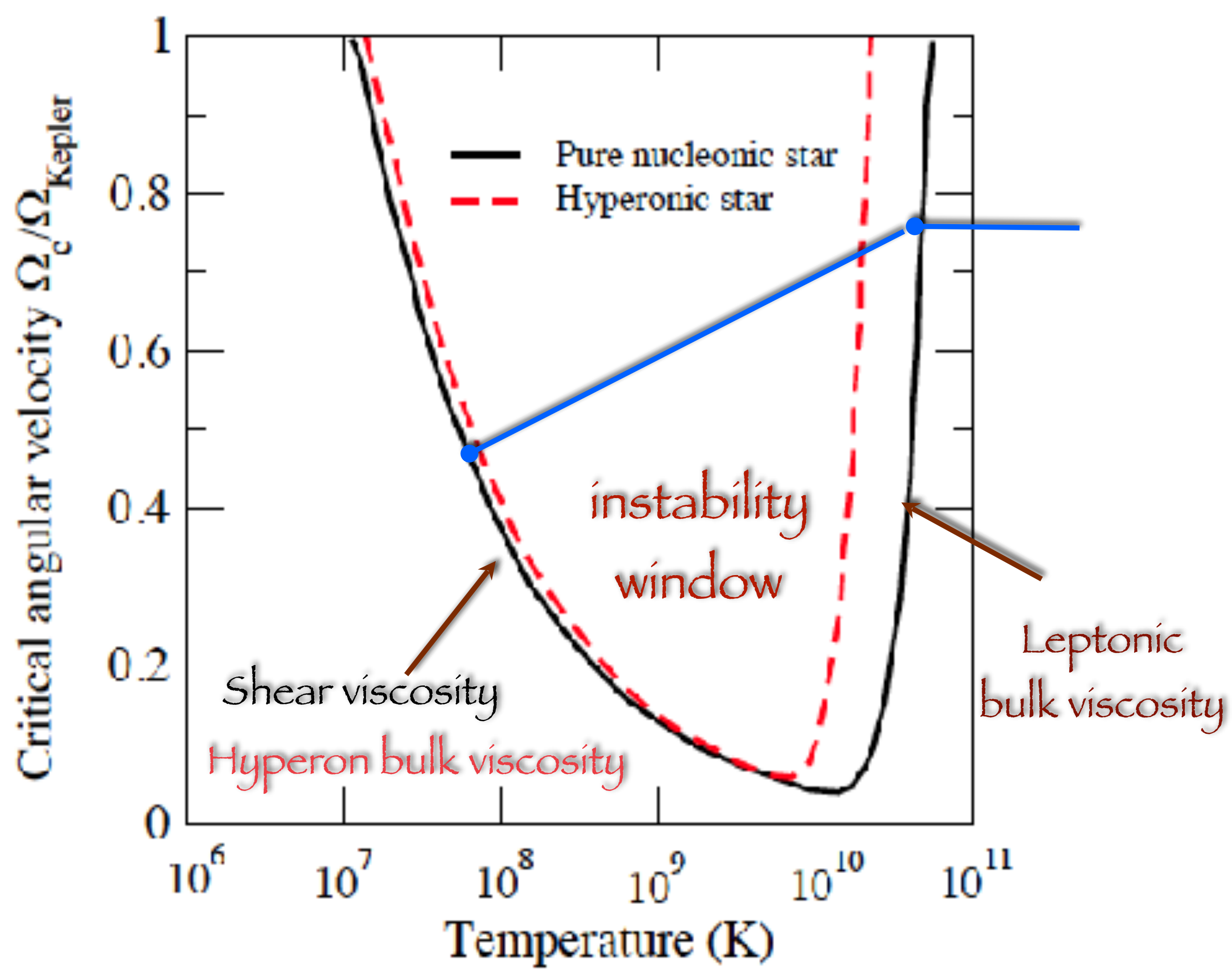
$$n + N \to p + e^- + \bar{\nu}_e + N$$
$$p + e^- + N \to n + \nu_e + N$$

- Non-leptonic processes involving hyperons, Bose condensates or quarks

$$n + p \leftrightarrow p + \Lambda$$
$$n + n \leftrightarrow n + \Lambda$$

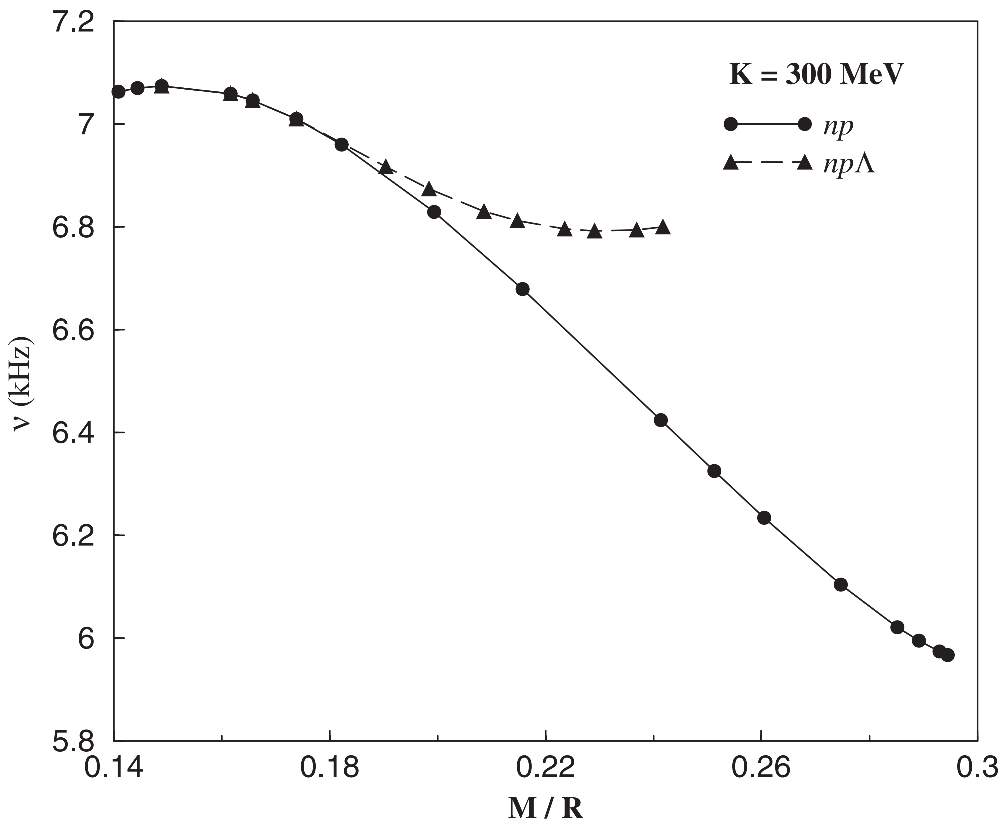
D.C. & I. Vidaña EPJA 52 (2016)

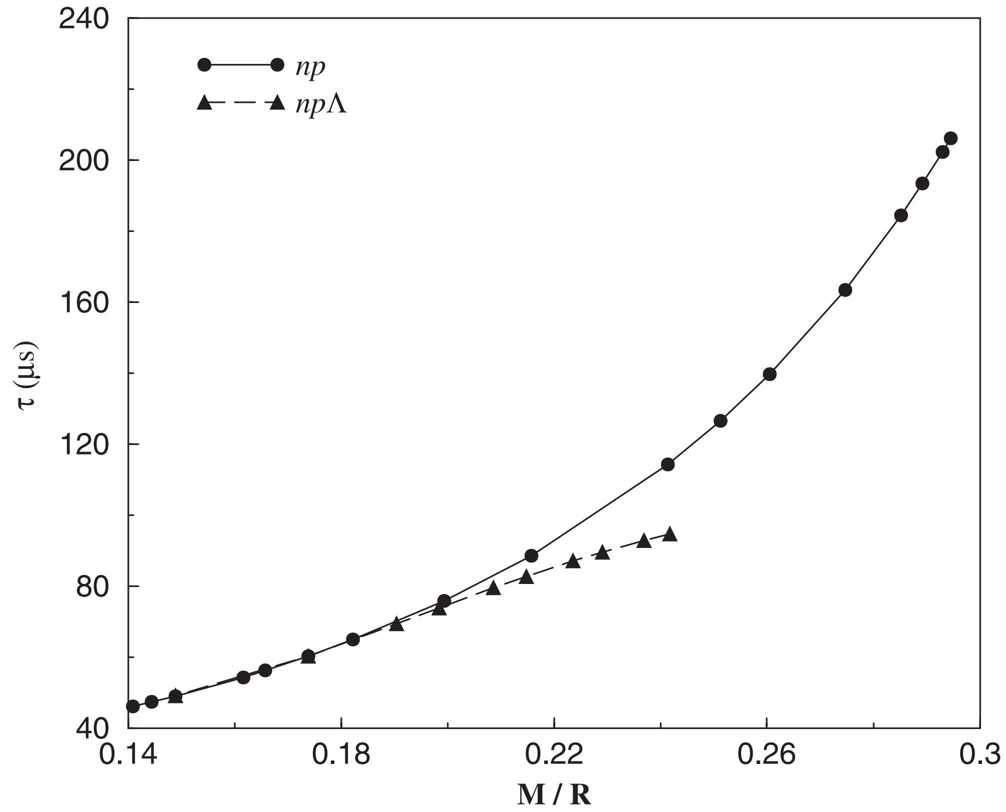
See recent works by B. Haskell, N. Andersson, W. C. G. Ho, M. Alford, K. Schwenzer,..



D.C. and D. Bandyopadhyay,
Phys. Rev. D 74 (2006)
Astrophys. Space Sci. 308 (2007)
Phys. Rev. D 75 (2007)
Ap. J. 680 (2008)
J. Phys. G 35 (2008)
PoS (NIC X) (2008) 181

Hyperons and axial w-modes



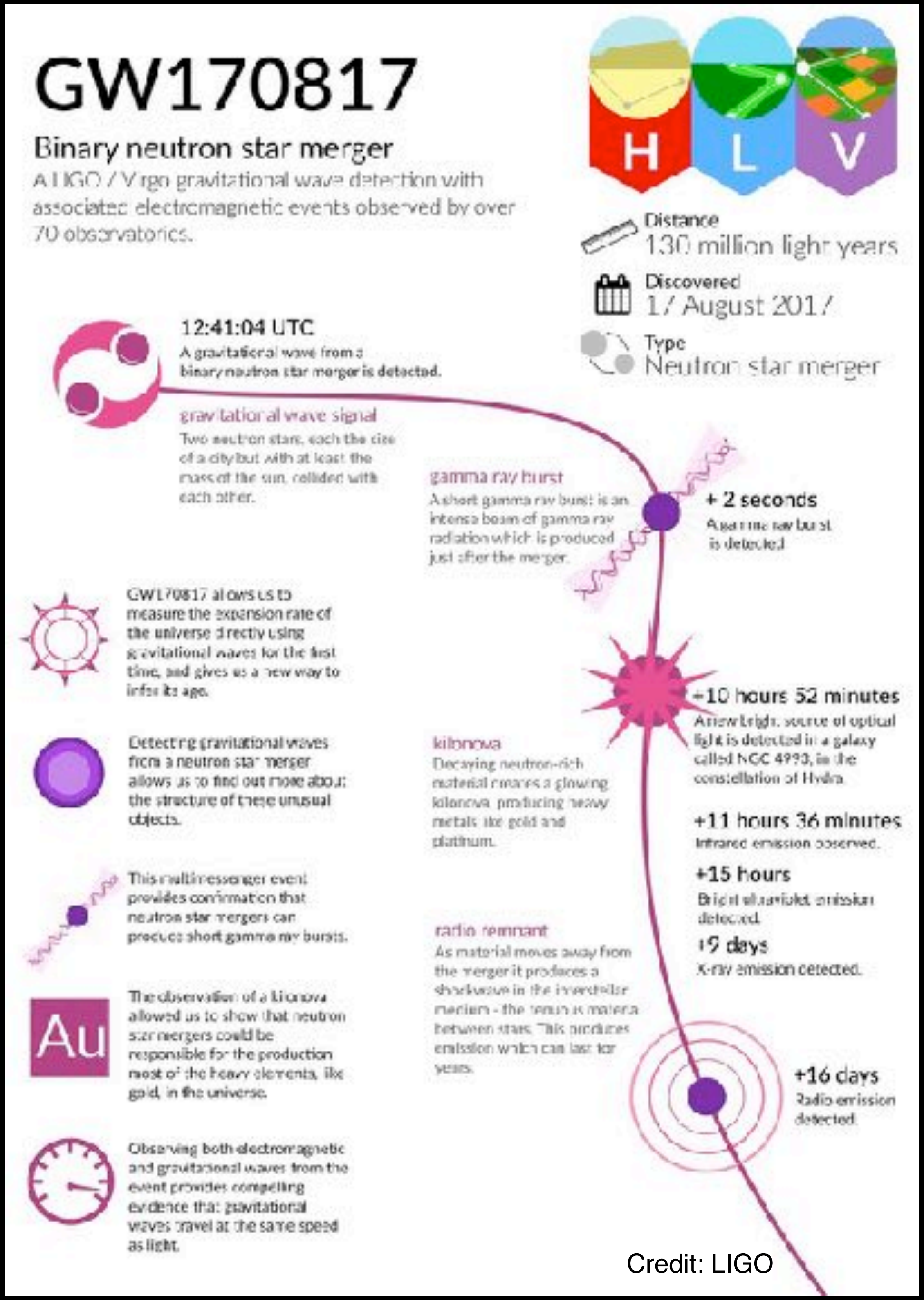


- Frequency and damping time for different EoSs can be calculated as functions of NS structure parameters such as M, R and compactness M/R
- Hyperons result in higher frequencies and lower damping times of first axial w modes than those of nucleonic matter
- Detection of w-mode frequencies can constrain composition of NSs

D.C. and D. Bandyopadhyay, PRD 80 (2009)

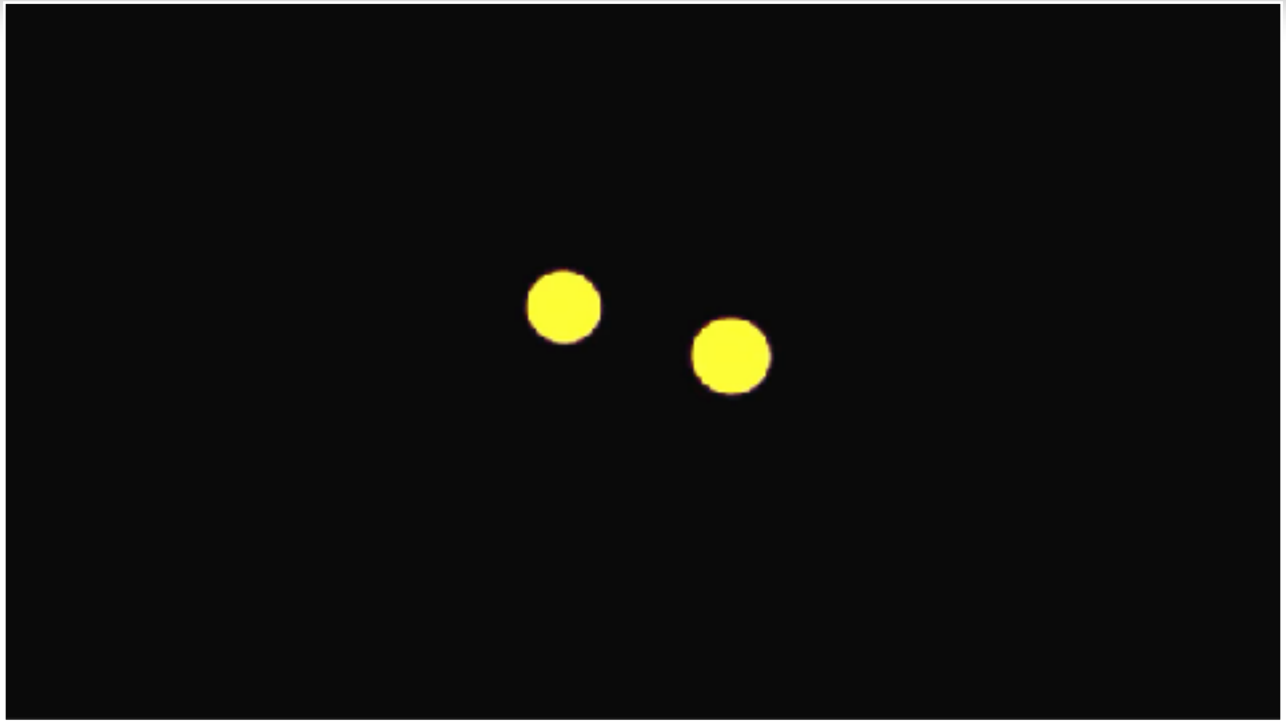
Binary Neutron Star mergers

Credit: NASA's Goddard Space Flight Center/CI Lab



Credit: LIGO

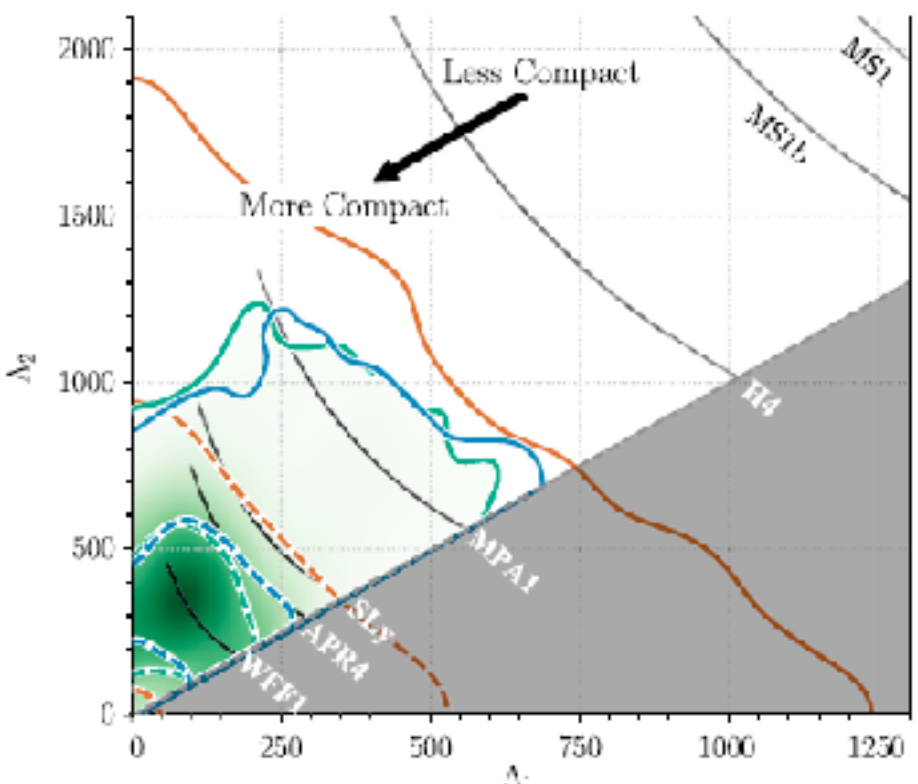
Tidal deformability and EoS



Tidal deformability

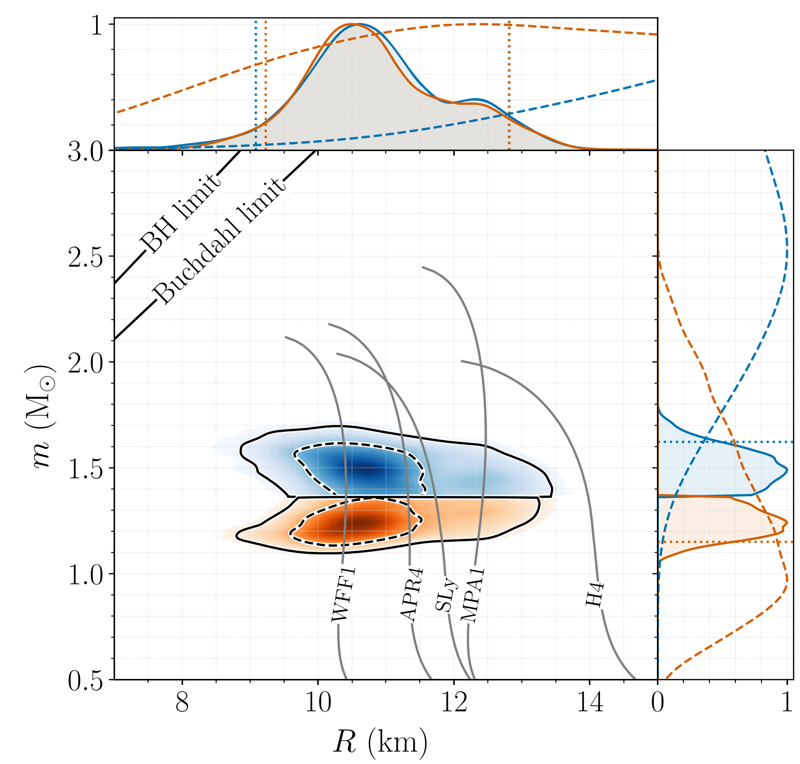
$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5$$

k_2 = tidal love number



Abbott et al. PRL 121 (2018)

$\Lambda_{1.4} < 800$ $R_{1.4} \lesssim 13.5\,\mathrm{km}$



Abbott et al. PRL 119 (2017)

$\Lambda_{1.4} = 190^{+390}_{-120}$

Can we use hints from Multi-disciplinary Physics to probe the Neutron Star interior?

1. **"Imposing multi-physics constraints at different densities on the Neutron Star Equation of State"**
S Ghosh, D. C. & J. Schaffner-Bielich,
Eur. Phys. J. A 58, 37 (2022)

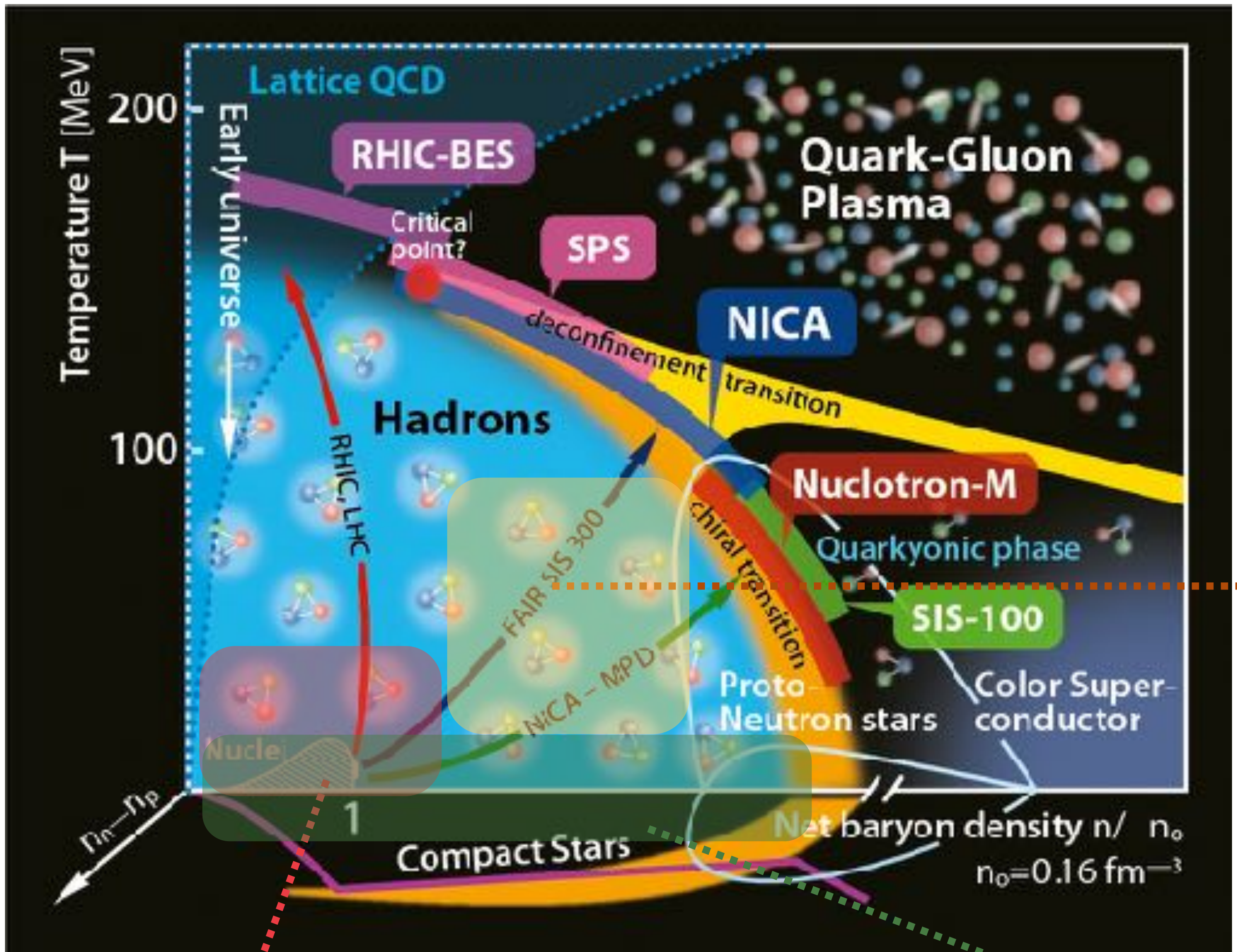
Nucleonic Matter

2. **"Multi-physics constraints at different densities to probe nuclear symmetry energy in hyperonic neutron stars"**
S Ghosh, B.-K. Pradhan, D. C. & J. Schaffner-Bielich,
Front. Astron. Space Sci. 9, 864294 (2022)

Hyperon Matter

Motivation:

- Multi-physics constraints at different density regimes to constrain the nuclear parameter space
- Investigate possible correlations between empirical nuclear parameters & astrophysical observables



Heavy-ion collision experiments

KaoS experiment
FOPI experiment
ASY-EOS experiment
$n/n_0 \sim 1 - 3$

NS astrophysical data

GW data

Nuclear experimental data

Chiral Effective Field Theory

Maximum Mass PSR J0740+6620

Tidal deformability from GW170817
large n/n_0

Radius from NICER
PSR J0030+0451, J0740+6620

S. Ghosh, D. C., J. Schaffner-Bielich, EPJA 58 (2022)

Methodology

- Microscopic description: Phenomenological Relativistic Mean Field (RMF) model
  Strong interaction mediated by scalar, vector and isovector mesons
  Interaction among hyperons is mediated by the exchange of strange vector (ϕ) meson
  We also vary hyperon-isovector coupling y from 0 to SU(6).

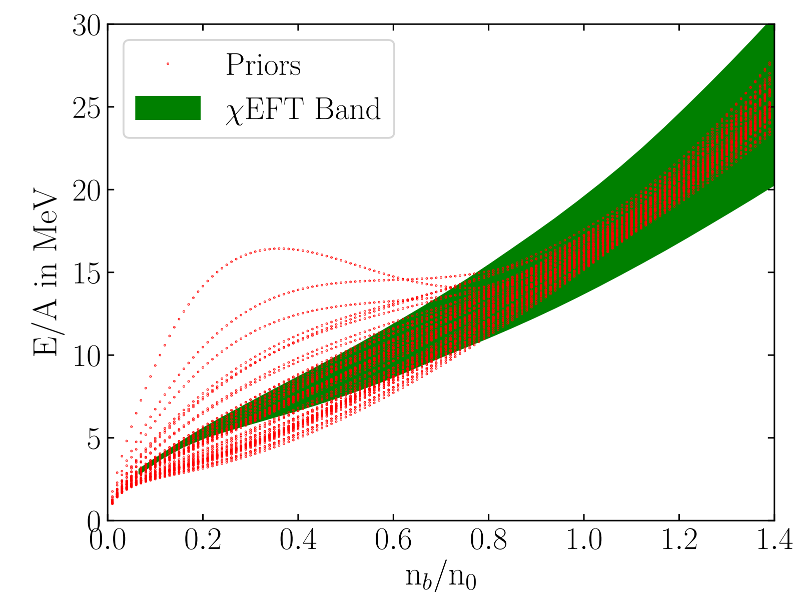
Hornick,.., Schaffner-Bielich, Phys Rev C 98 (2018)

$$\begin{aligned}
\mathcal{L} &= \sum_B \bar{\psi}_B \left(i\gamma^\mu \partial_\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu \omega^\mu - g_{\rho B}\gamma_\mu \vec{I}_B . \vec{\rho}^\mu \right) \psi_B + \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) - U_\sigma \\
&+ \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}(\vec{\rho}_{\mu\nu} . \vec{\rho}^{\mu\nu} - 2 m_\rho^2 \vec{\rho}_\mu . \vec{\rho}^\mu) + \Lambda_\omega (g_{\rho N}^2 \vec{\rho}_\mu . \vec{\rho}^\mu)(g_{\omega N}^2 \omega_\mu \omega^\mu) \\
&+ \sum_Y \bar{\psi}_Y (g_{\sigma^* Y}\sigma^* - g_{\phi Y}\gamma_\mu \phi^\mu)\psi_Y + \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2}(\partial_\mu \sigma^* \partial^\mu \sigma^* - m_{\sigma^*}^2 \sigma^{*2}) \\
&+ \sum_{\ell=\{e^-,\mu^-\}} \bar{\psi}_\ell (i\gamma^\mu \partial_\mu - m_\ell)\psi_\ell \qquad (
\end{aligned}$$

- Range of nuclear empirical parameters

n_0 (fm^{-3})	E_{sat} (MeV)	K_{sat} (MeV)	E_{sym} (MeV)	L_{sym} (MeV)	m^* (m_N)	U_Λ (MeV)	U_Σ (MeV)	U_Ξ (MeV)	y
0.14	-16.2	200	28	40	0.55	-30	0	-30	0
0.17	-15.8	300	34	70	0.75	-30	30	0	1

Nucleonic   Hyperonic

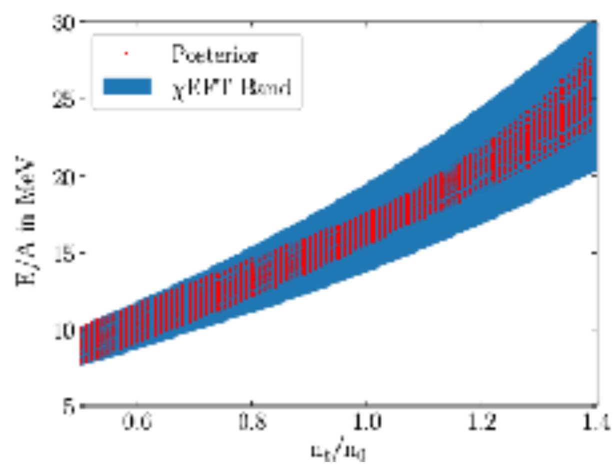


S. Ghosh, D. C., J. Schaffner-Bielich, EPJA 58 (2022)

Bayesian posterior distributions

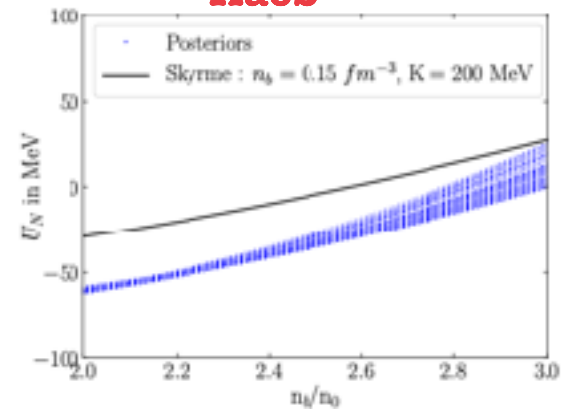
S. Ghosh, D. C., J. Schaffner-Bielich, EPJA 58 (2022)

- Uniform prior of the nuclear parameters.
- Likelihood functions are filter functions appropriately chosen from physical constraints at different densities
- Posterior is used to explore correlations

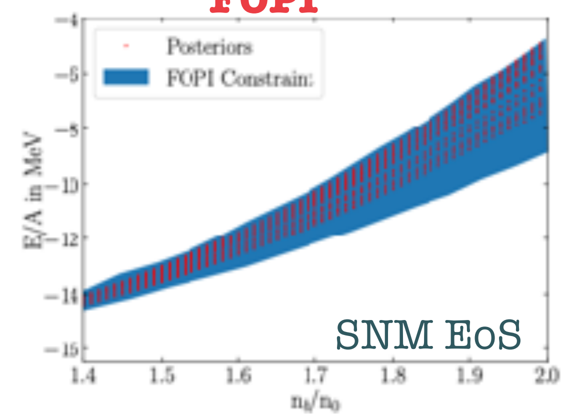


Low density : Chiral EFT

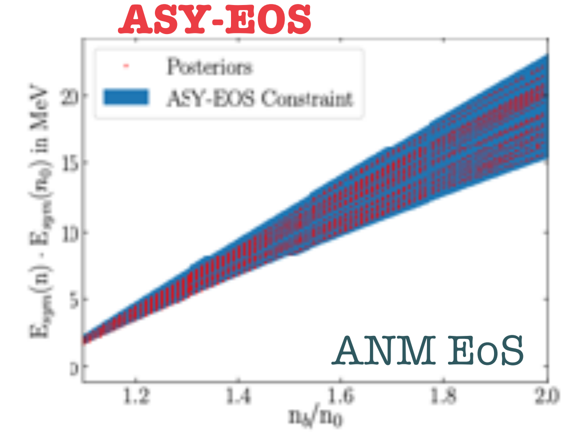
KaoS



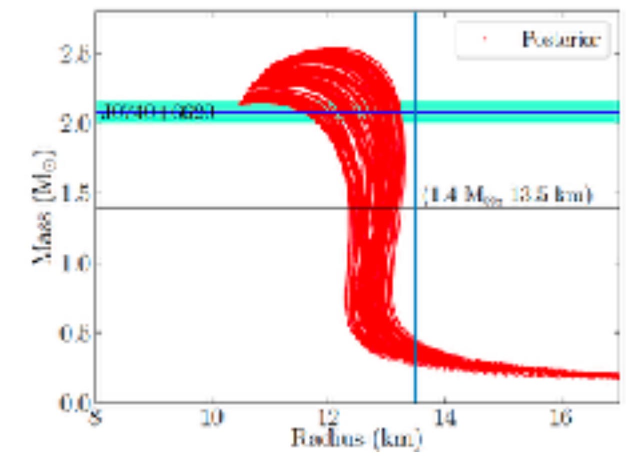
FOPI

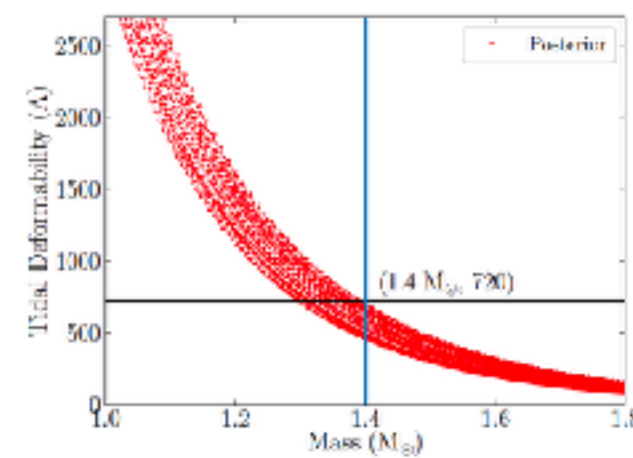


ASY-EOS



Intermediate density:
Heavy ion collision (HIC) experiments



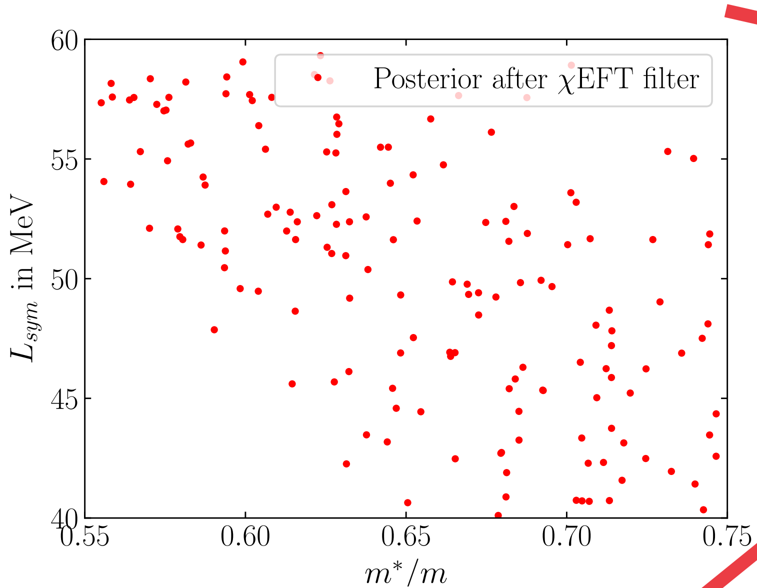


High density: Multi-messenger observations (EM+GW)

Correlations: nuclear matter

S. Ghosh, D. C., J. Schaffner-Bielich, EPJA 58 (2022)

See also S. Huth et al., Nature 606 (2022)



- No points at low L_{sym} and small m^*/m
- Hugenholtz van-Hove theorem

- Strong correlation between symmetry energy and its slope at saturation density but they are weakened after applying the HIC filters

- Radius of 1.4 solar mass NS has low correlation with slope of symmetry energy but high correlation with effective mass

- Nuclear saturation density has good correlation with the effective mass and the astrophysical observables

- High correlation between the astrophysical observables

ChiEFT+Astro

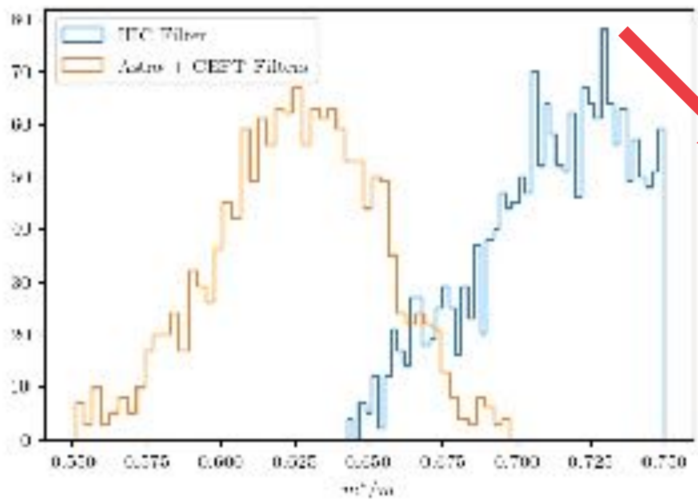
	n_0	E_{sat}	K_{sat}	E_{sym}	L_{sym}	m^*/m	$R_{1.4M_\odot}$	$\Lambda_{1.4M_\odot}$	$R_{2M_\odot}$	$\Lambda_{2M_\odot}$
n_0	1	0.03	0.08	0.21	0.11	0.45	0.47	0.31	[illegible]	0.09
E_{sat}	0.03	1	0.02	0.07	0.01	0.01	0.01	[illegible]	0.01	0.01
K_{sat}	0.08	0.02	1	0.08	0.03	[illegible]	0.17	0.21	0.05	0.01
E_{sym}	0.21	0.07	0.08	1	0.73	0.06	0.03	0.14	0.08	0.13
L_{sym}	0.11	0.01	0.03	0.73	1	0.2	0.38	0.2	[illegible]	0.14
m^*/m	0.45	0.01	0.19	0.06	0.2	1	[illegible]	0.58	0.72	0.81
$R_{1.4M_\odot}$	0.47	0.01	0.17	0.03	0.38	0.43	1	0.95	0.91	0.84
$\Lambda_{1.4M_\odot}$	0.31	0.01	0.21	0.14	0.2	0.58	0.95	1	0.97	0.94
$R_{2M_\odot}$	0.21	0.01	0.05	0.08	0.22	0.72	0.91	0.97	1	0.98
$\Lambda_{2M_\odot}$	0.09	0.01	0.01	0.13	0.14	0.81	0.84	0.94	0.98	1

ChiEFT+Astro+HIC

	n_0	E_{sat}	K_{sat}	E_{sym}	L_{sym}	m^*/m	$R_{1.4M_\odot}$	$\Lambda_{1.4M_\odot}$	$R_{2M_\odot}$	$\Lambda_{2M_\odot}$
n_0	1	0	0.26	0.3	0.44	0.61	0.79	0.64	0.4	0.25
E_{sat}	0	1	[illegible]	[illegible]	0.03	0.07	0.03	0.05	0.06	0.07
K_{sat}	0.26	0.06	1	0.07	0.28	0.39	0.33	0.29	0.06	0.04
E_{sym}	0.3	0.15	0.07	1	0.36	0.04	0.3	0.35	0.3	0.29
L_{sym}	0.44	0.03	0.28	0.36	1	0.48	0.36	0.17	0.01	0.14
m^*/m	0.61	0.07	0.39	0.04	0.48	1	0.08	0.14	0.45	0.6
$R_{1.4M_\odot}$	0.79	0.03	0.33	0.3	0.36	0.08	1	0.97	0.84	0.73
$\Lambda_{1.4M_\odot}$	0.64	0.05	0.29	0.35	0.17	0.14	0.97	1	0.94	0.87
$R_{2M_\odot}$	0.4	0.06	0.06	0.3	0.01	0.45	0.84	0.94	1	0.98
$\Lambda_{2M_\odot}$	0.25	0.07	0.04	0.29	0.14	0.6	0.73	0.87	0.98	1

Correlations: hyperon matter

S Ghosh, B.K. Pradhan, D. C. & J. Schaffner-Bielich, Front. Astron. Space Sci. 9, (2022)



Inclusion of hyperon shifts the posterior of effective mass to a lower value to satisfy the astrophysical constraints. But HIC filters favours higher m* value. Inclusion of hyperon generates a tension between astrophysical and HIC constraints

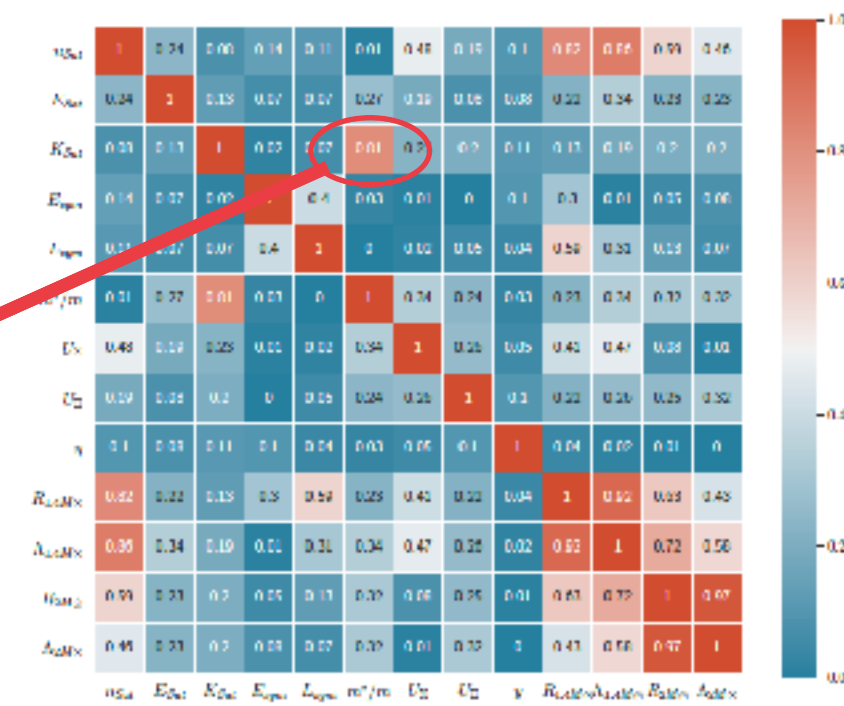
- Strong correlation between symmetry energy and its slope at saturation density after CEFT filter but they are weakened after applying the HIC filters

Radius of 1.4 solar mass NS has low correlation with slope of symmetry energy

Increase in correlation between effective mass and incompressibility due to the KaoS filter.

No correlation between the hyperon potentials and astrophysical observables.

ChiEFT+Astro

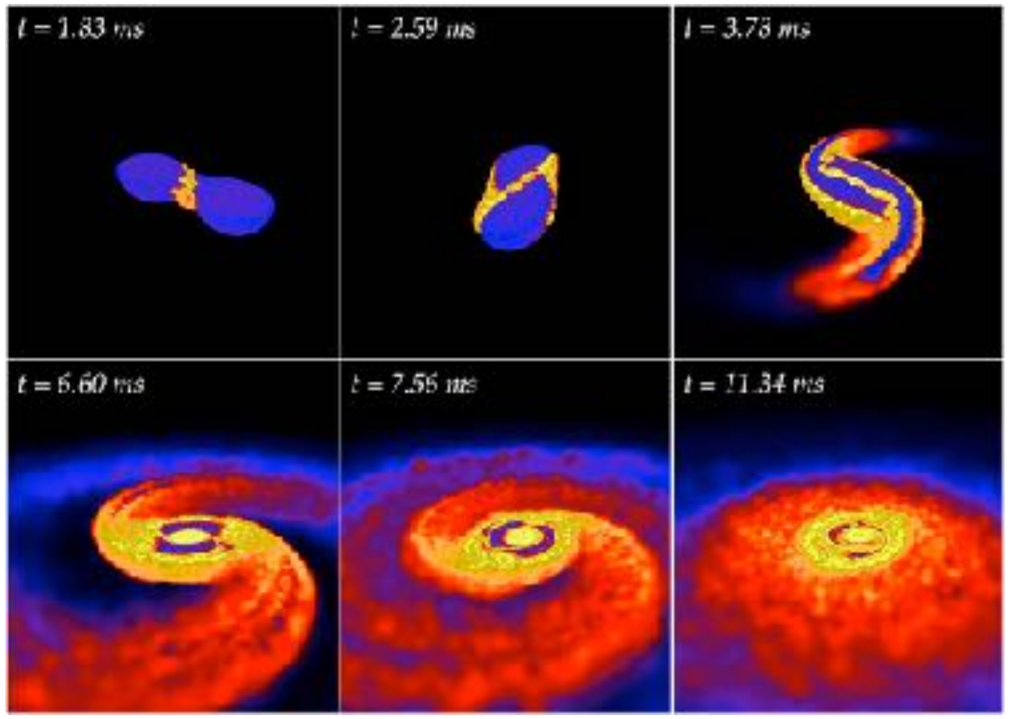


ChiEFT+Astro+HIC

➢ Constrained parameter space -> informed choice of parameters in astrophysical and numerical relativity simulations

➢ This work : among nuclear empirical parameters, saturation density and effective nucleon mass are essential parameters to vary

Tidal heating in BNS inspiral



Credit: Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen)

"Tidal Heating as a direct probe of Strangeness inside NS matter",
S. Ghosh, B. K. Pradhan and D.C., arXiv:2306.14737

- During the binary inspiral, viscous processes in NS matter can damp out the tidal energy induced by the companion and convert this to thermal energy to heat up the star

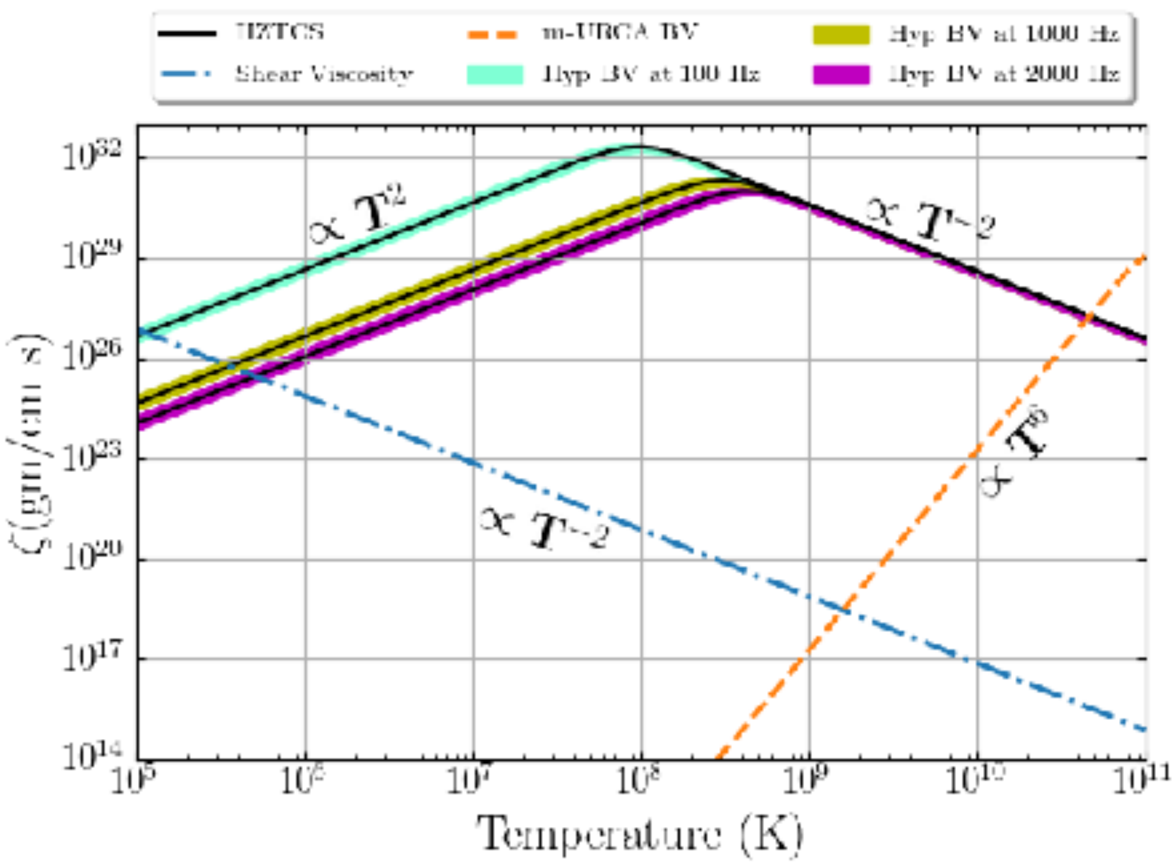
  Flanagan et al. PRD 77,021502(R) (2008)

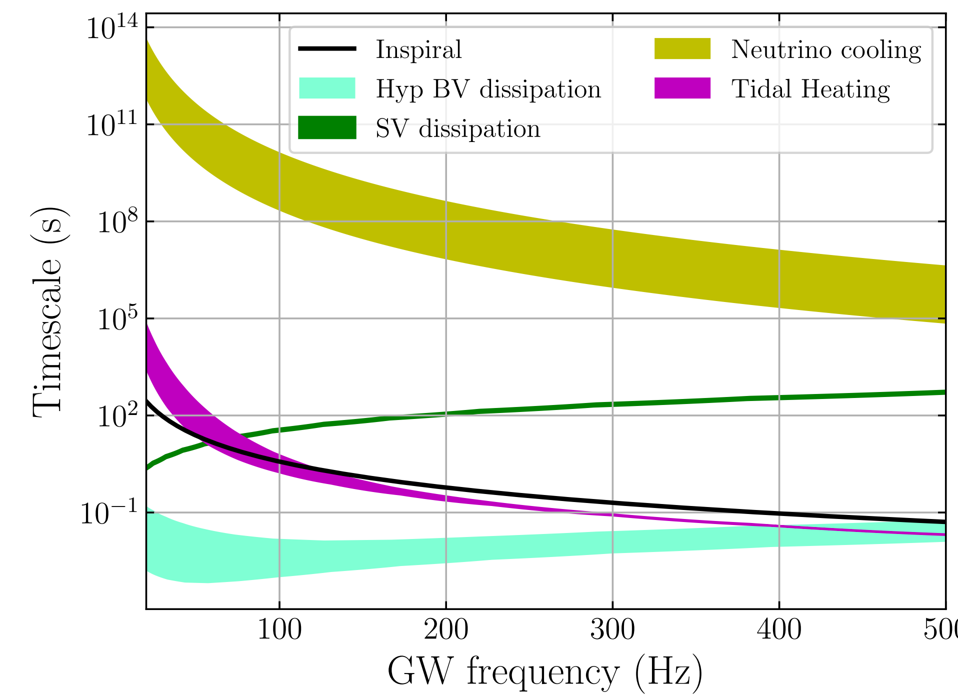
- This tidal heating due to normal neutron matter viscosity is too small to have any significant effect, and is therefore neglected
  Bildsten & Cutler, ApJ 400(1992), D. Lai MNRAS 270(1994)

Hyperon bulk viscosity and Tidal heating

S. Ghosh, B. K. Pradhan and D.C., arXiv:2306.14737

$n + p \longleftrightarrow p + \Lambda$

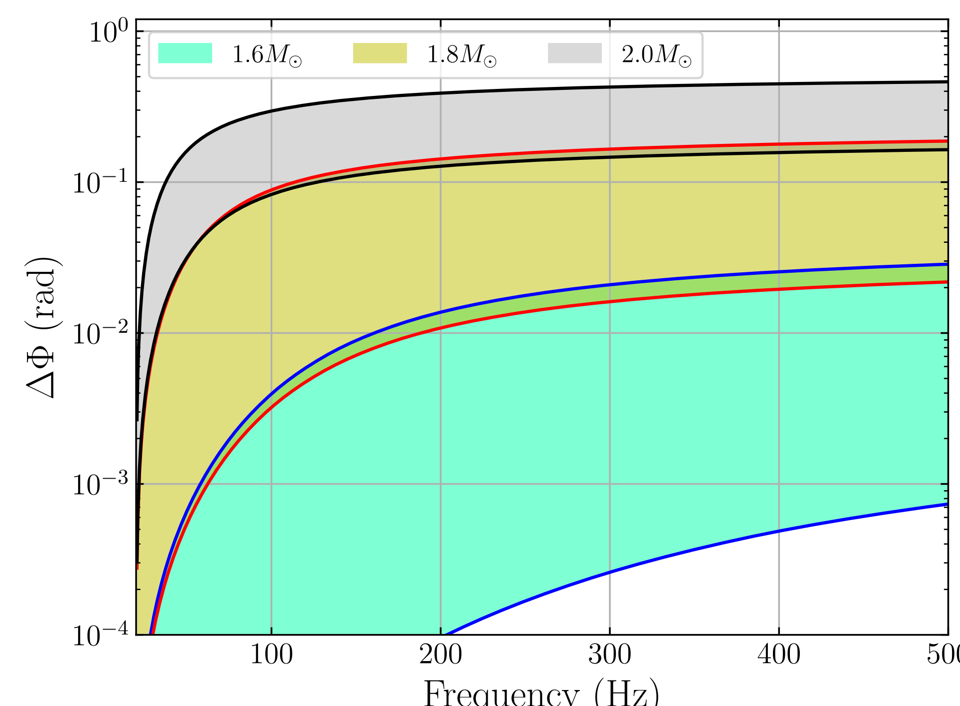




- Hyperon bulk viscosity in the core is high enough to heat the star up to 0.1-1 MeV during the inspiral, but not high enough to require inclusion of thermal corrections to the EoS

- The dissipated energy can induce a net phase difference ~ 10^{-3} - 0.5 rad depending on component masses

- Tidal heating due to bulk viscosity arising from hyperons is significant and its detection may indicate the presence of hyperons inside NS core



Detailed Post-Newtonian calculation is ongoing!

Hyperons and ProtoNS cooling

- Leptonic weak processes involving nucleons

  direct Urca process:

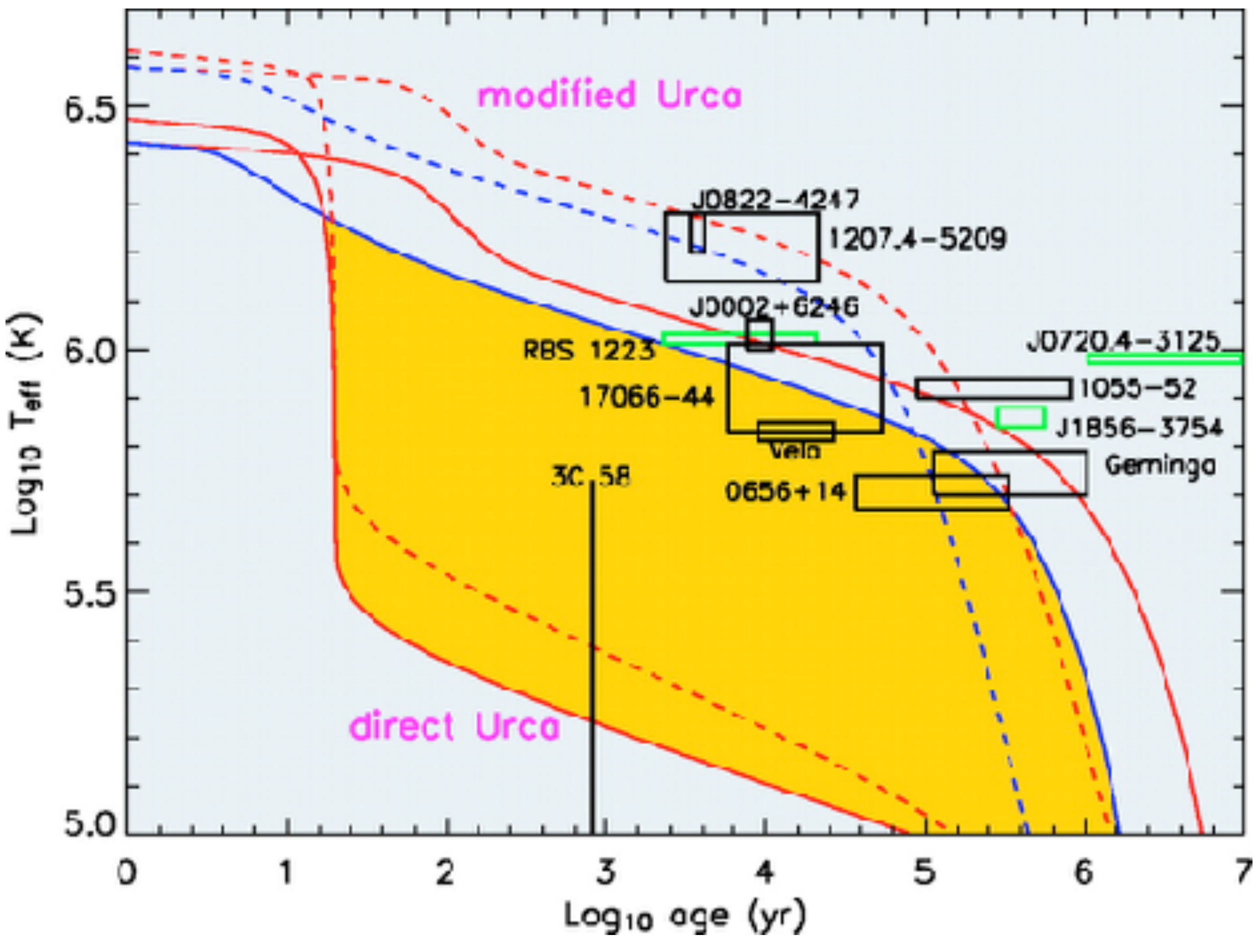
$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$p + e^- \rightarrow n + \nu_e$$

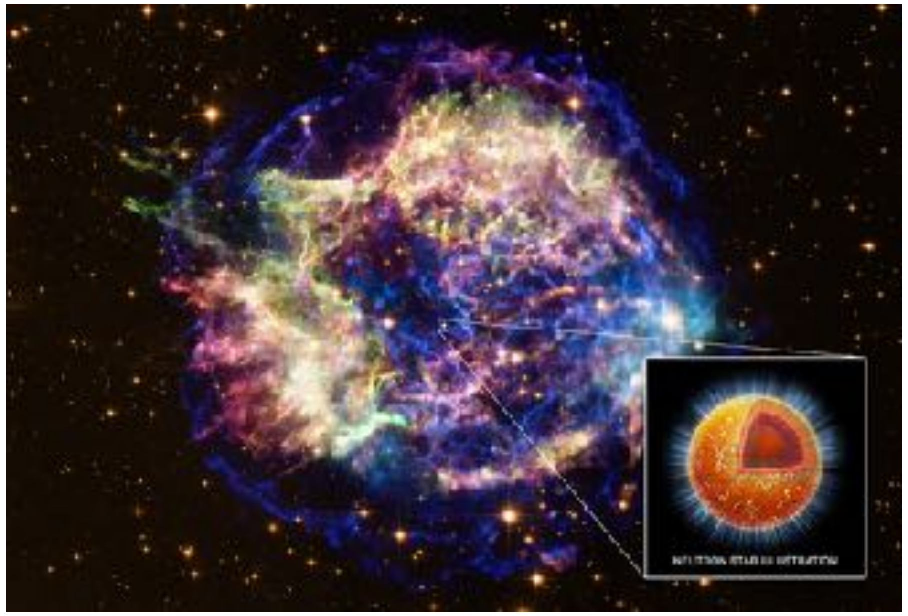
  modified Urca process:

$$n + N \rightarrow p + e^- + \bar{\nu}_e + N$$
$$p + e^- + N \rightarrow n + \nu_e + N$$

- Leptonic weak processes involving hyperons, Bose condensates or quarks

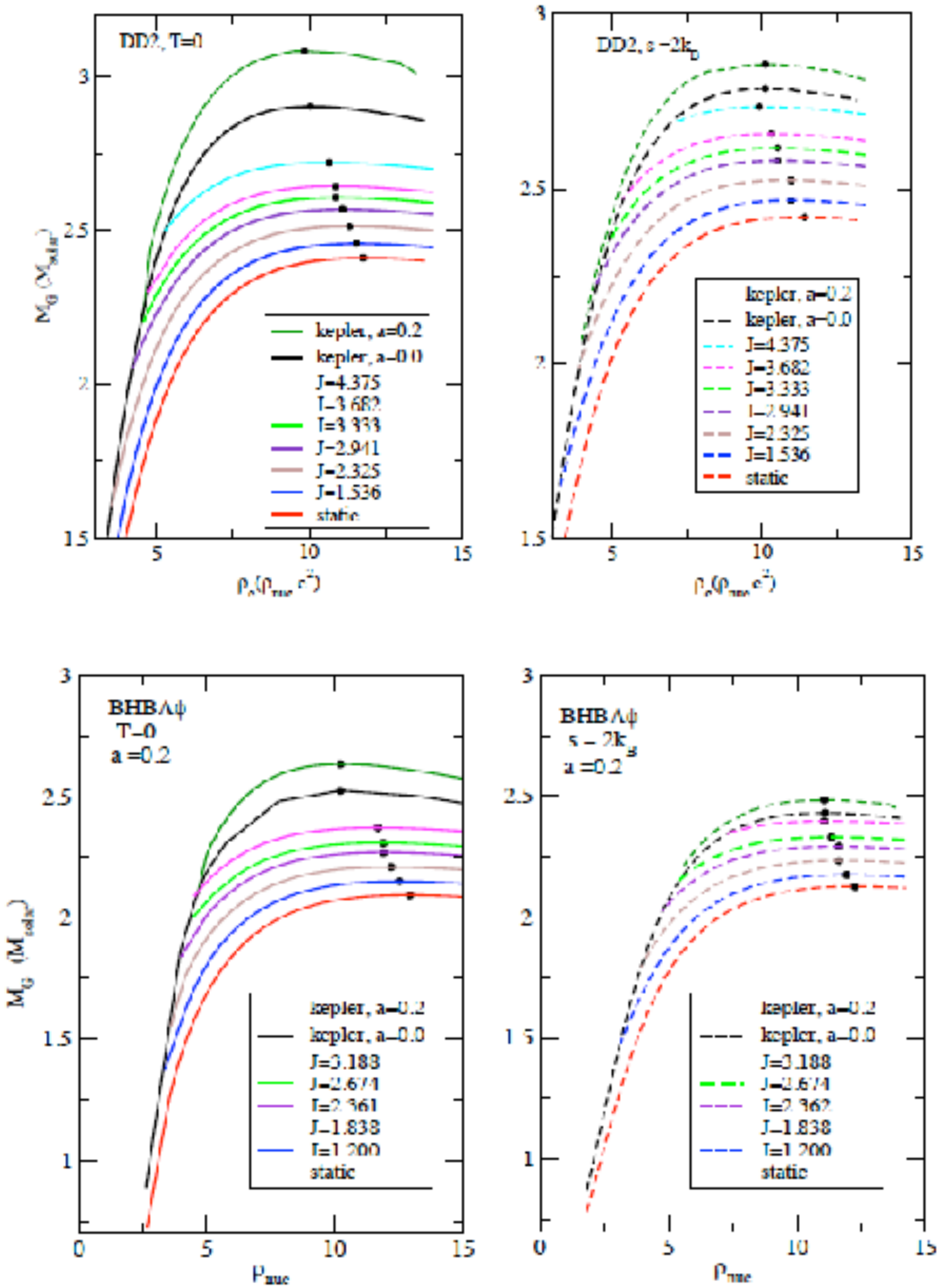
$$Y \rightarrow B + l + \bar{\nu}_l$$

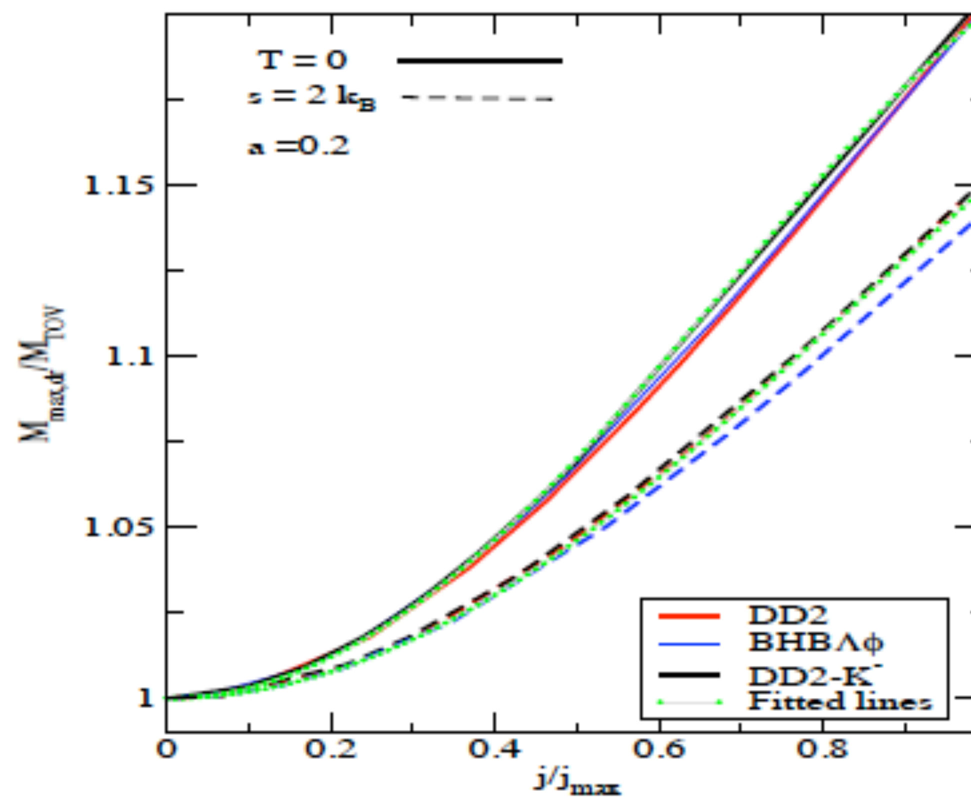




D.C. & I. Vidaña EPJA 52 (2016)

Hyperons and stability of BNS merger remnants



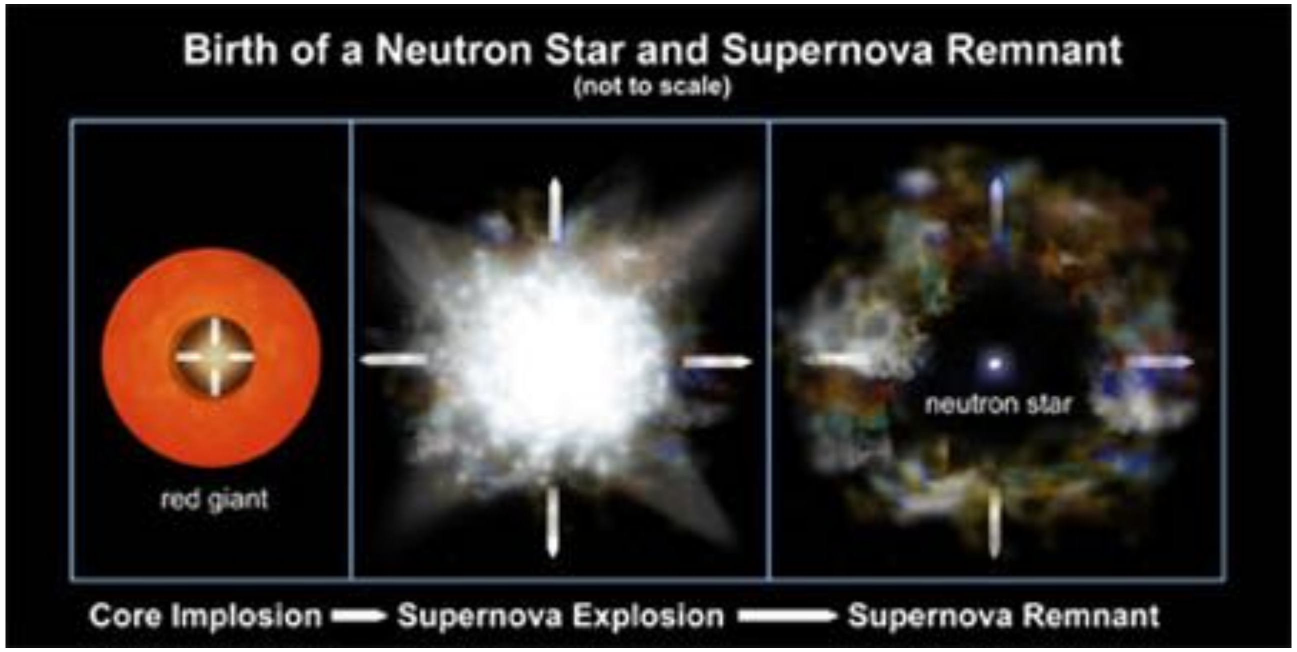


$$\frac{M_{max,dr}}{M_{TOV}} = 1 + b_1(a)(\frac{j}{j_{max}})^2 + b_2(a)(\frac{j}{j_{max}})^4$$

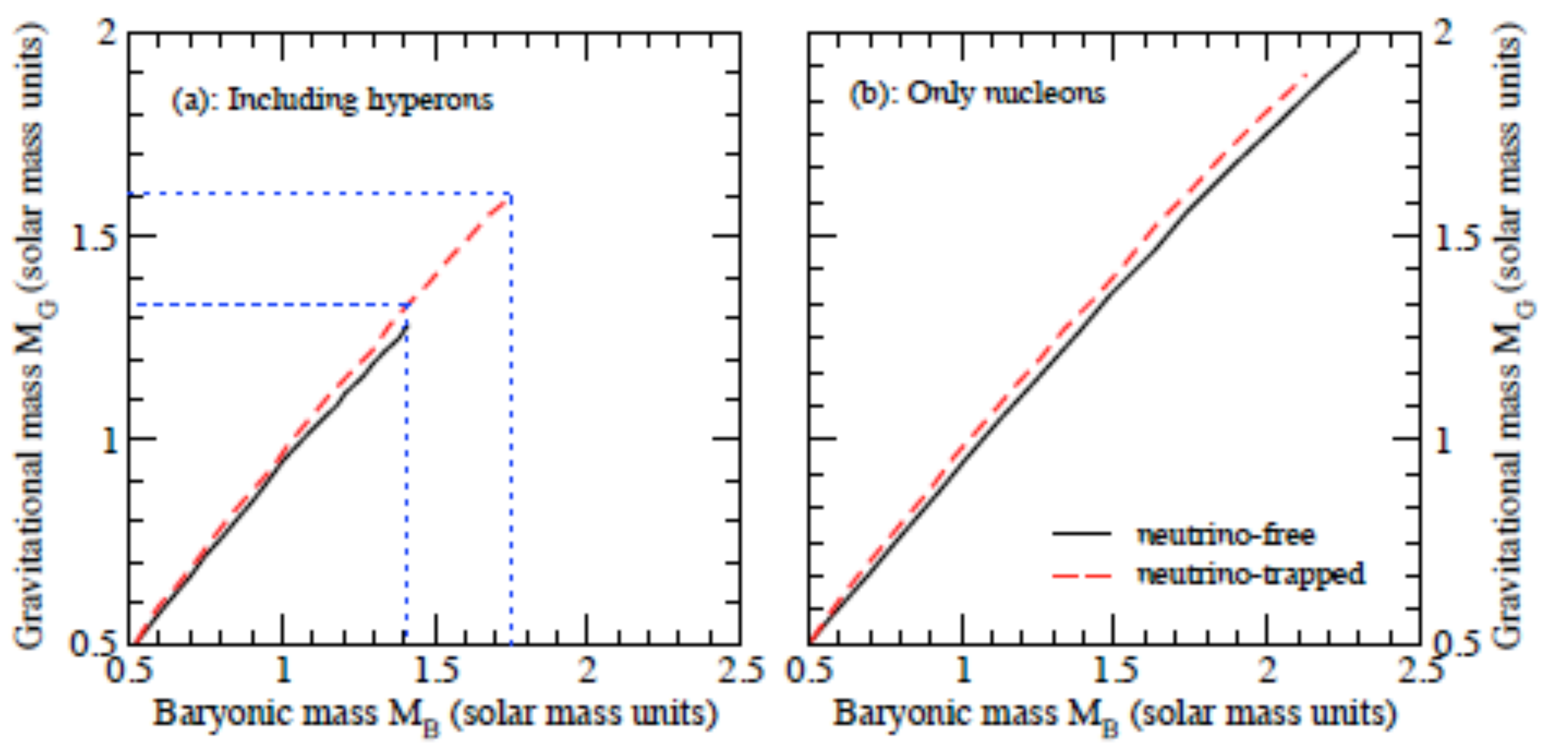
$b_1 = 0.30735(0.1964)$ and $b_2 = -0.10671(-0.04671)$

“Signatures of Strangeness in Neutron Star Merger Remnants“
K. P. Nunna, S. Banik and D.C., *ApJ* 896 (2020) 109

Hyperons and Blackhole formation during SNE



M_G vs M_B for neutrino-free and neutrino-trapped matter



D.C.& I. Vidaña EPJA 52 (2016)

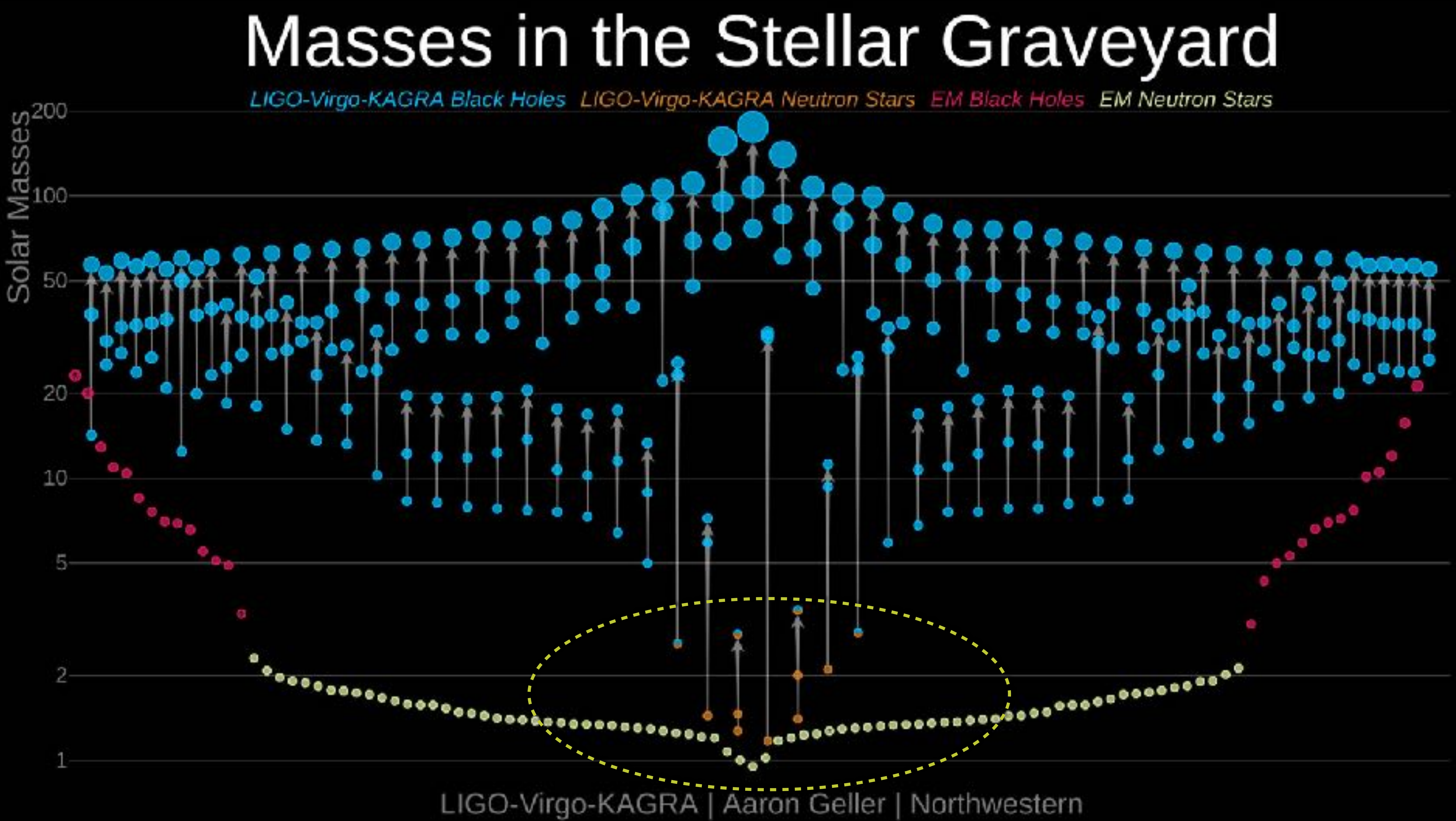
Important conclusions

- The appearance of hyperons in the NS core significantly affect unstable oscillation modes (f-,p-,g-,w- and r-modes) and consequently GW emission
- For f-modes, it may be difficult to distinguish signatures of hyperons from those of nucleonic NSs from future GW detections, given the present uncertainties in EoS models with hyperons
- If g-modes be observed in the near future, their frequency could be used to test the presence of hyperonic matter in the core of neutron stars
- Multidisciplinary physics from nuclear theory, heavy-ion collisions and multi-messenger astrophysical observations impose important constraints on the parameter space of EoS models for nucleonic and hyperonic matter
- Hyperon bulk viscosity may lead to significant tidal heating during the inspiral phase of BNS mergers, which may indicate the presence of hyperons in NSs

Still open questions to be addressed in the future

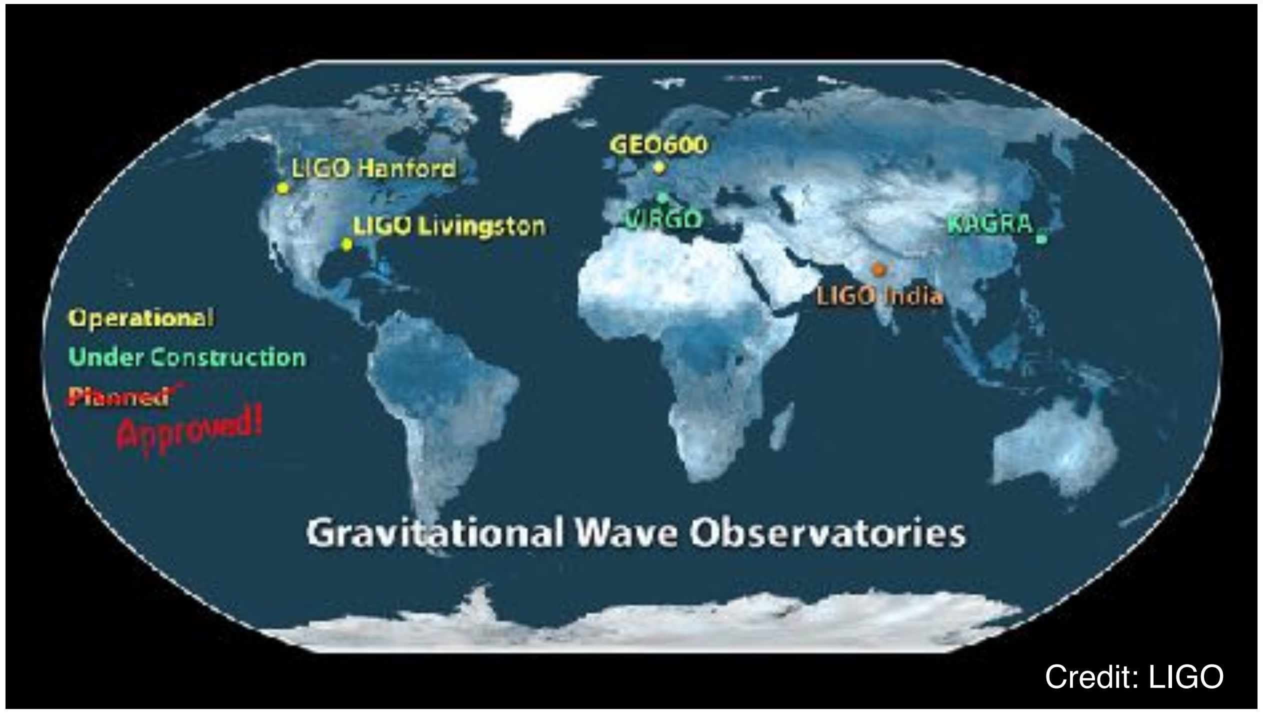
- Further systematic studies of effects of hyperons on various NS astrophysical observable properties required
- Improved constraints on the parameter space of EoS models describing hyperons and hyperon-hyperon interaction from future multi-messenger (EM+GW) observations of NSs, isolated or in binary
- Future nuclear and hyper nuclear experiments to improve understanding of N-N, Y-N and Y-Y interaction, which are important ingredients of EoS models
- Future heavy-ion experiments at intermediate energies to improve our understanding of the EoS of dense matter at densities beyond 4-5 saturation nuclear density

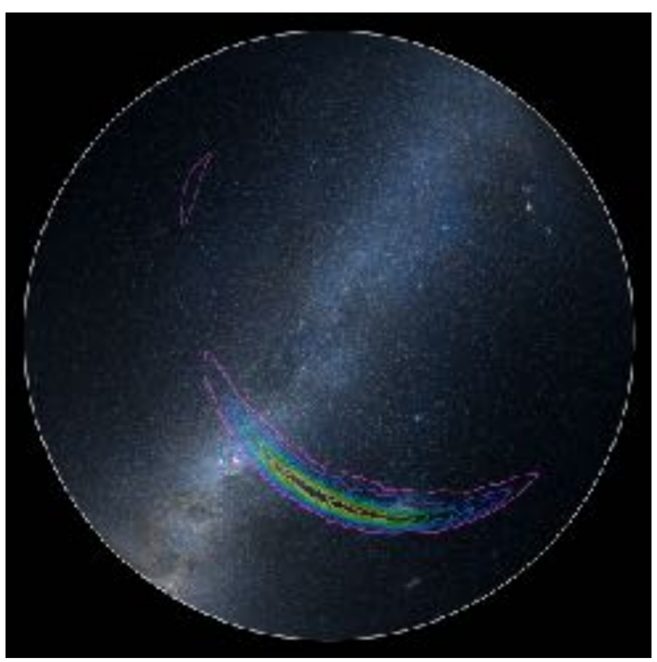
LVK discoveries until O3

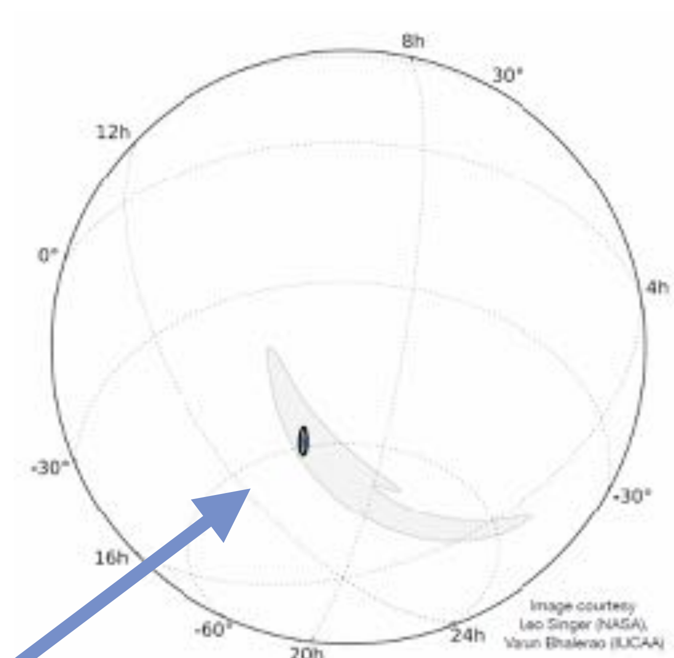


Credit: LIGO

Current generation of GW detectors

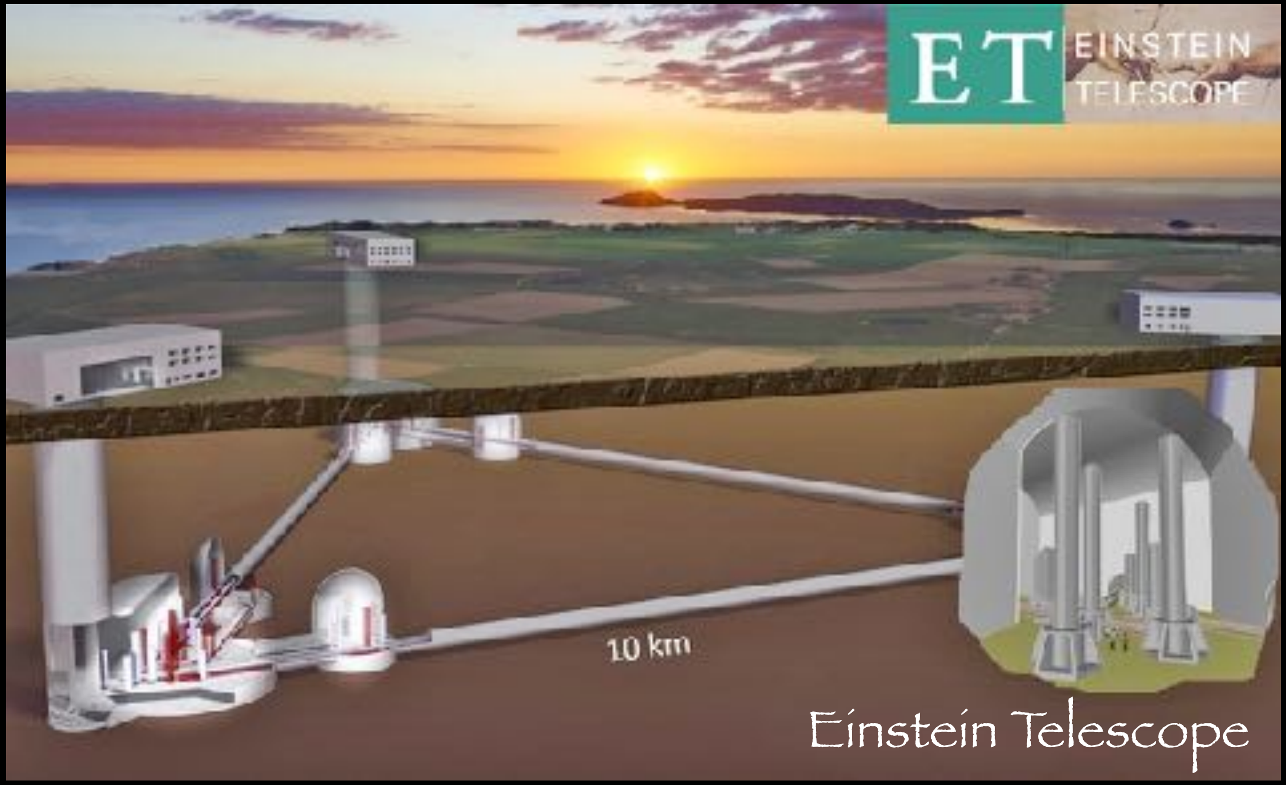


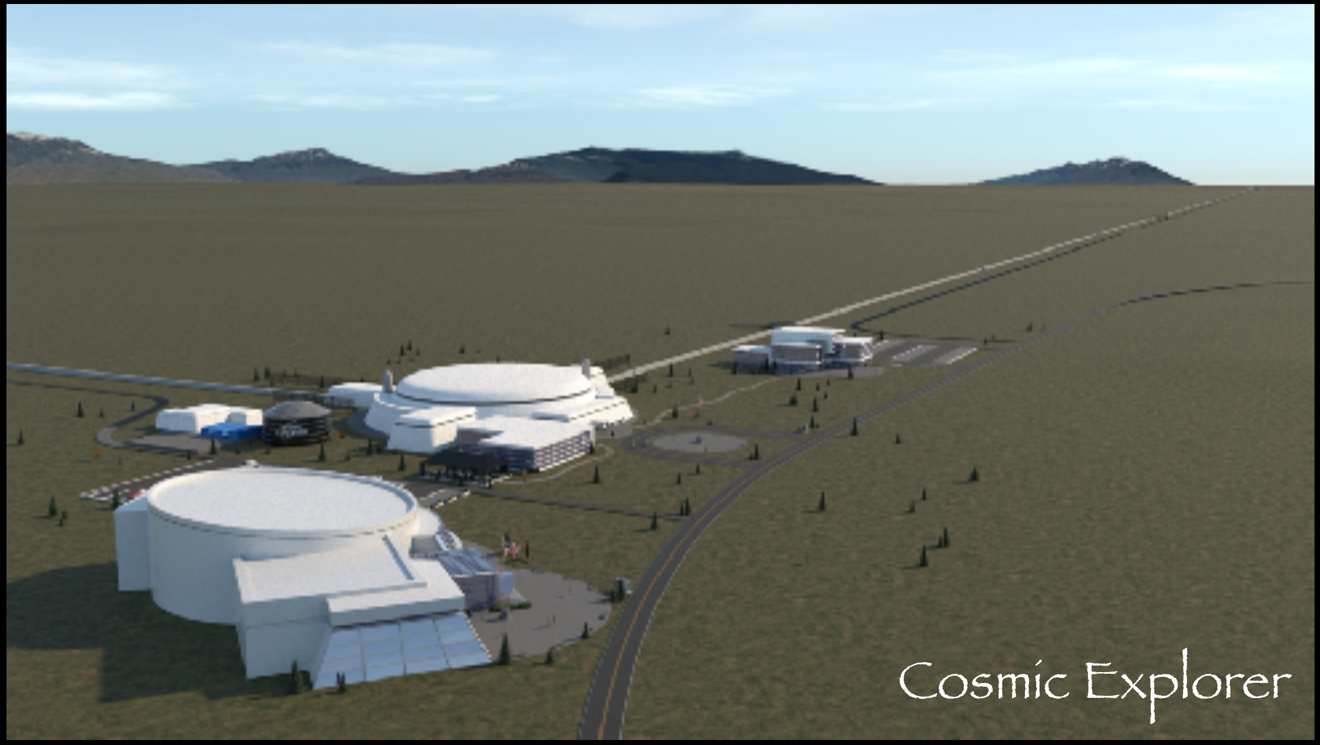


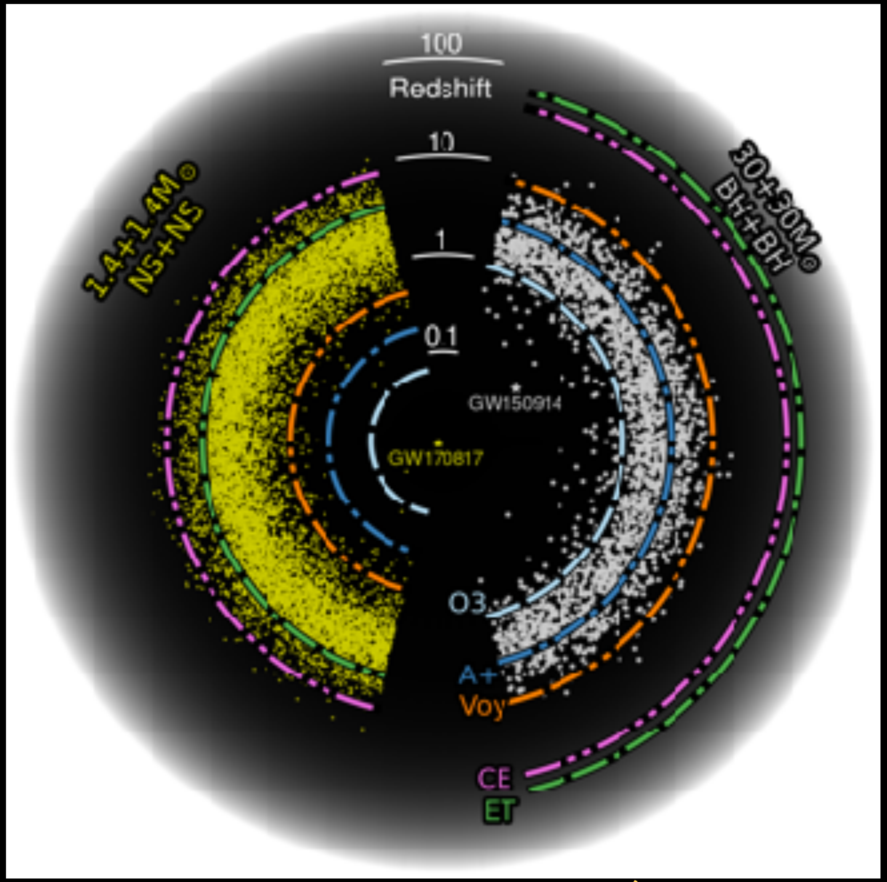


Improvement in localisation of GW150914 with LIGO-India

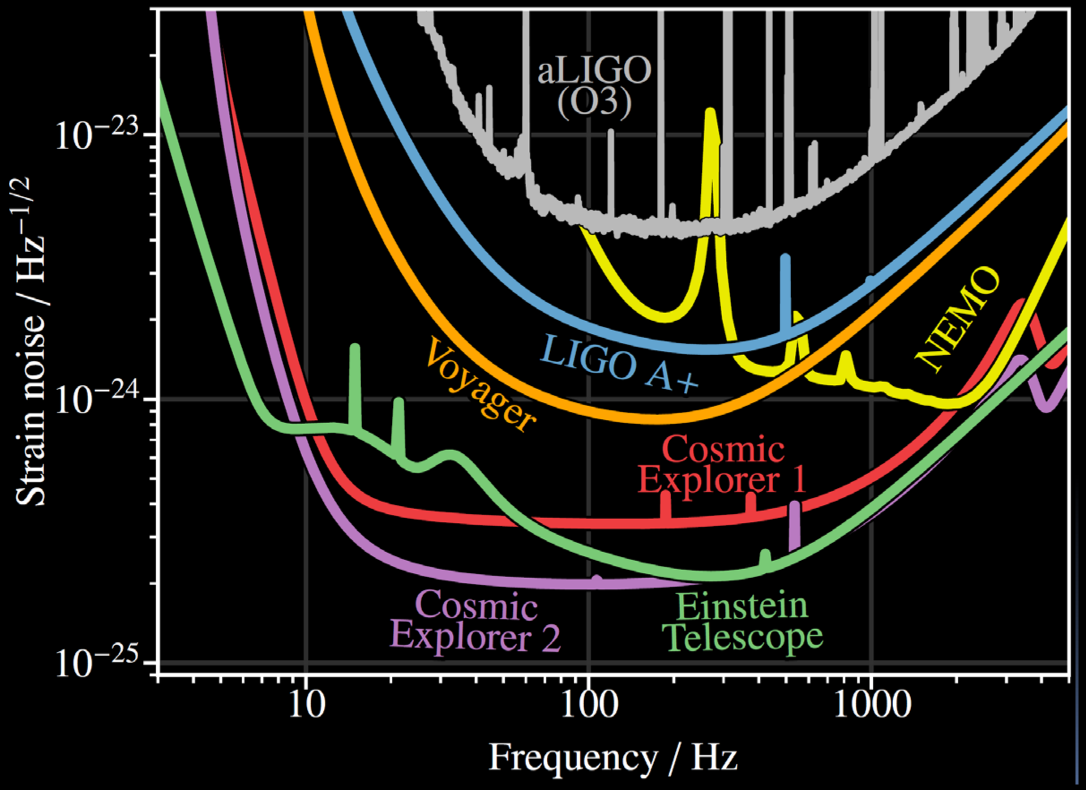
The Future: 3G GW detectors







www.cosmicexplorer.org

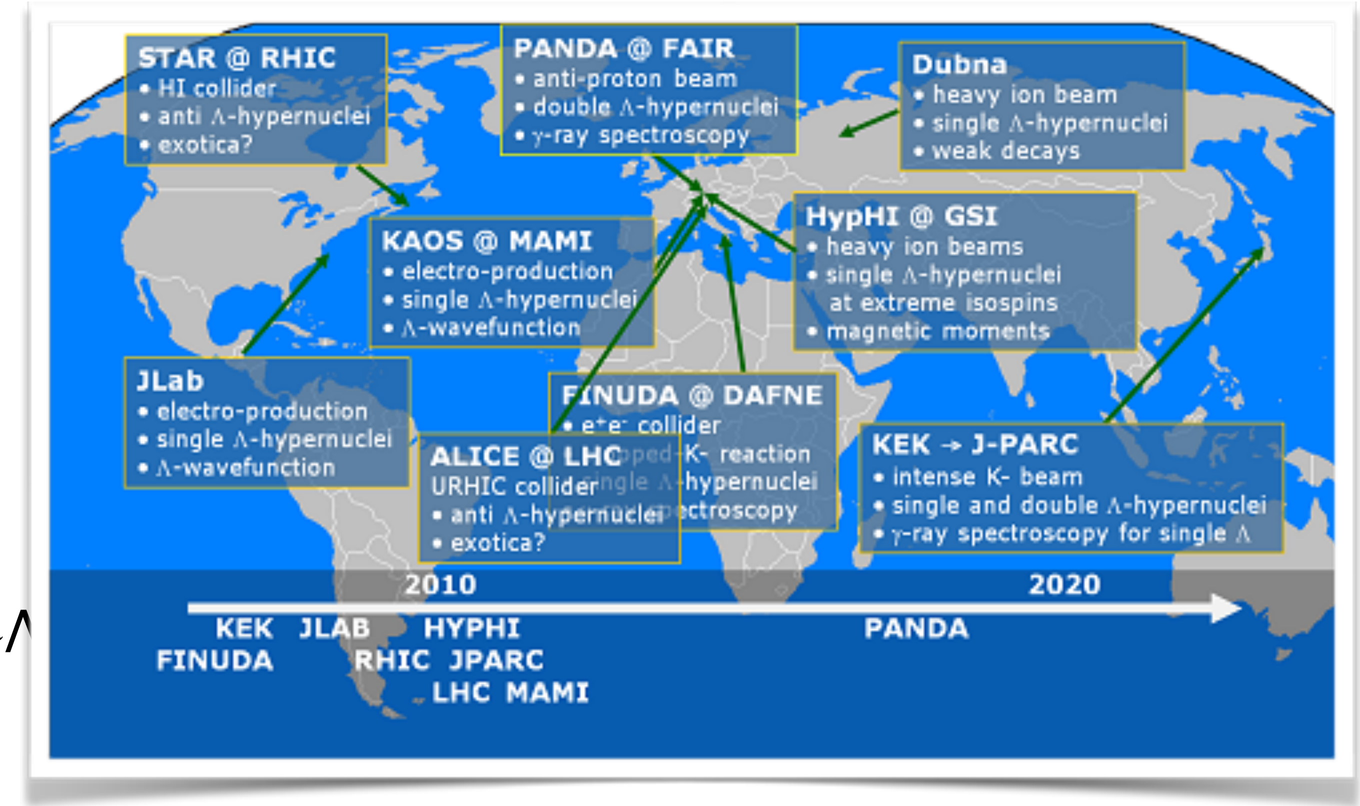


Credit: ET collaboration

Future nuclear and hypernuclear experiments

- N-N interaction : fairly well known
  - scattering data
  - measured properties of nuclei
- Y-N interaction : poorly constrained
  - short lifetime of Y
  - low intensity beam flux
  - ΛN and ΣN scattering events ~ 600
- Y-Y interaction : hardly any constraints
  - no scattering data
- Hypernuclei (YN bound systems)
  - 40 single Λ-hypernuclei and few double-Λ
  - no Σ hypernuclei confirmed yet

LHC@CERN
FAIR@GSI
NICA@JINR



Strangeness exchange reactions (CERN, BNL, KEK, J-PARC)

$$K^- + {}^AZ \rightarrow {}^A_\Lambda Z + \pi^-$$

Associate production reactions (BNL, KEK, GSI)

$$\pi^+ + {}^AZ \rightarrow {}^A_\Lambda Z + K^+$$

Electro-production reactions (JLAB,MAMI-C)

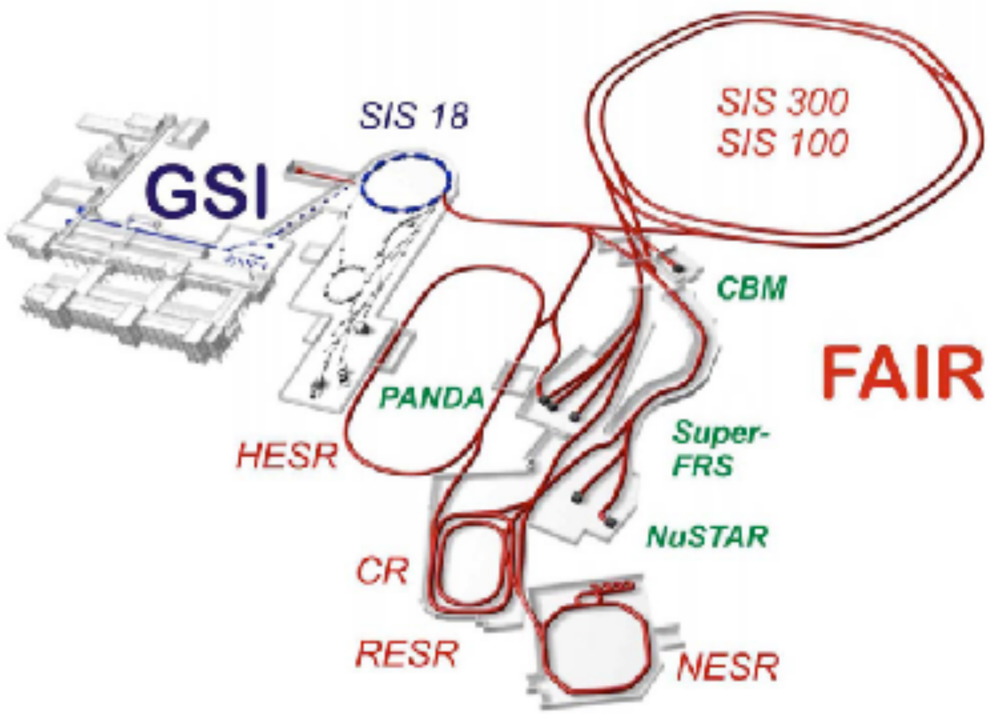
$$e^- + {}^AZ \rightarrow e^- + K^+ + {}^A_\Lambda(Z-1)$$

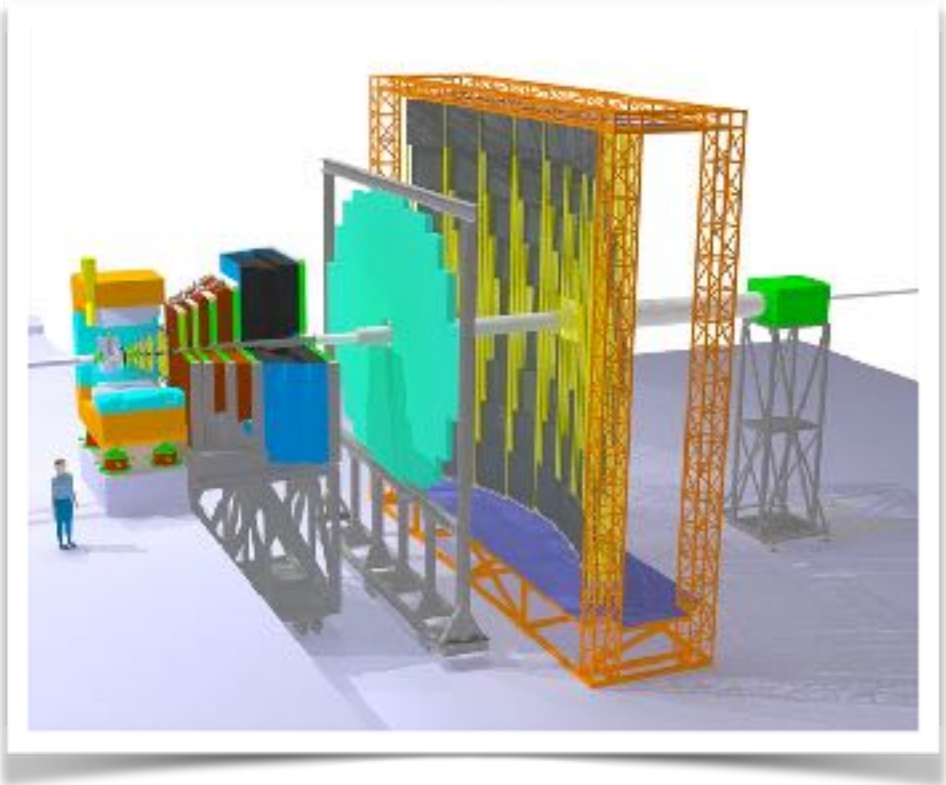
BNL
KEK
J-PARC
GSI

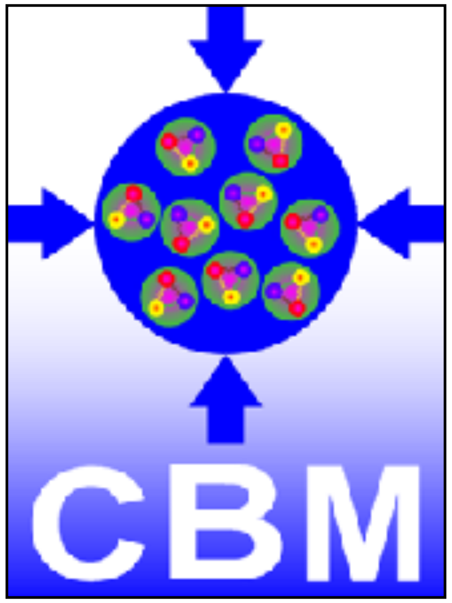
Future heavy-ion experiments

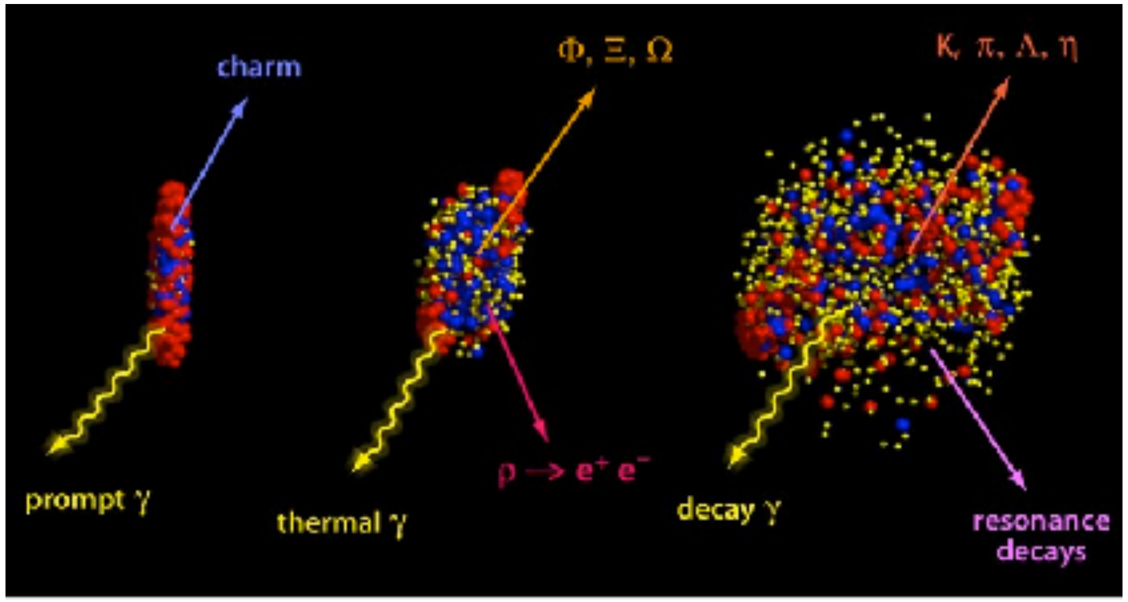
NA60+@CERN
CBM@FAIR
MPD@NICA
SPES@INFN

FAIR — Facility for Antiproton and Ion Research in Europe









Thank you! Questions?