Credit: NASA/Swift Dana Berry

# GW and ultra-dense matter

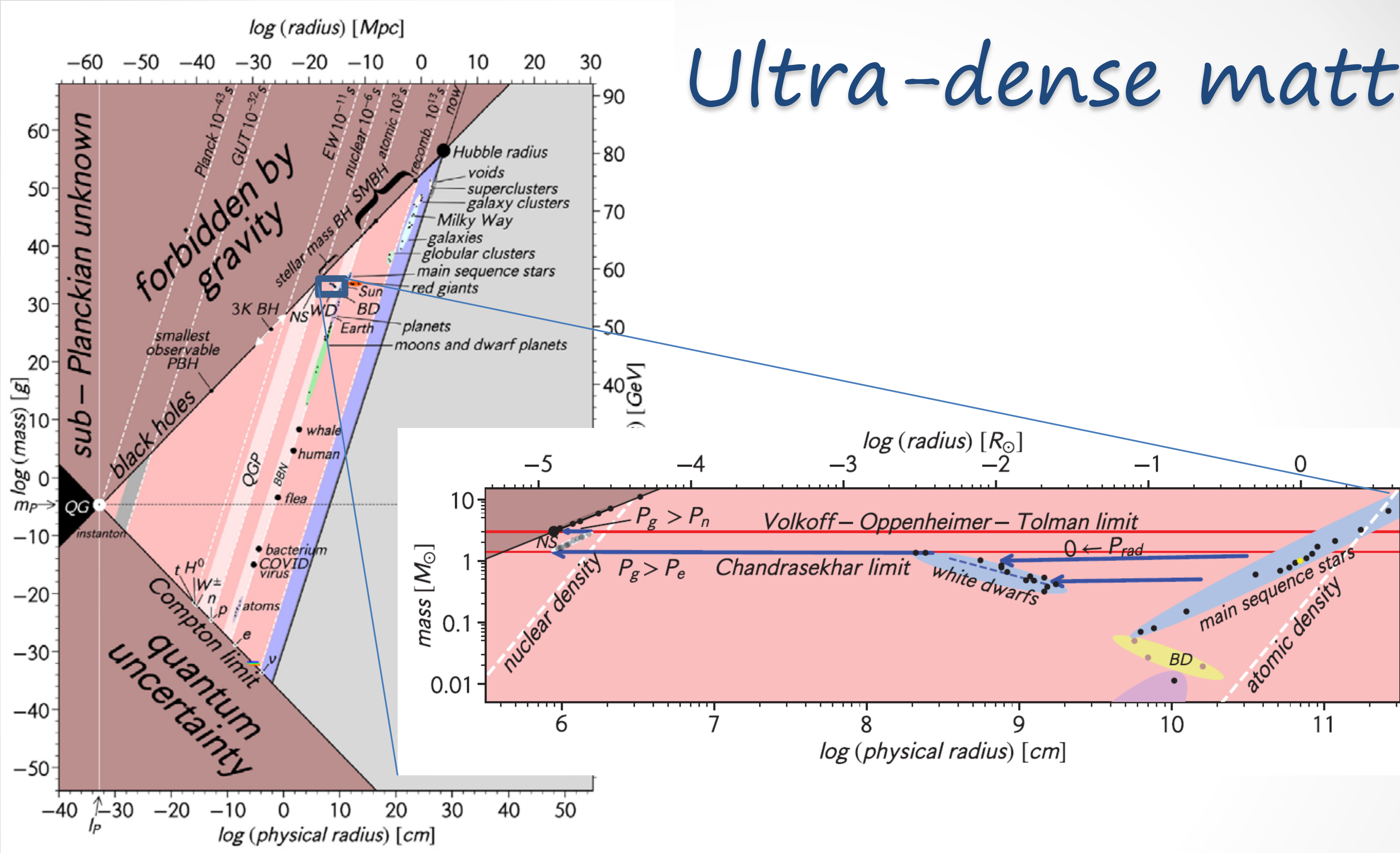
Francesca Gulminelli - Université de Caen-Normandie

3rd MaNiTou summer school on gravitational waves, June 30 – July 4, 2025

# Lecture plan

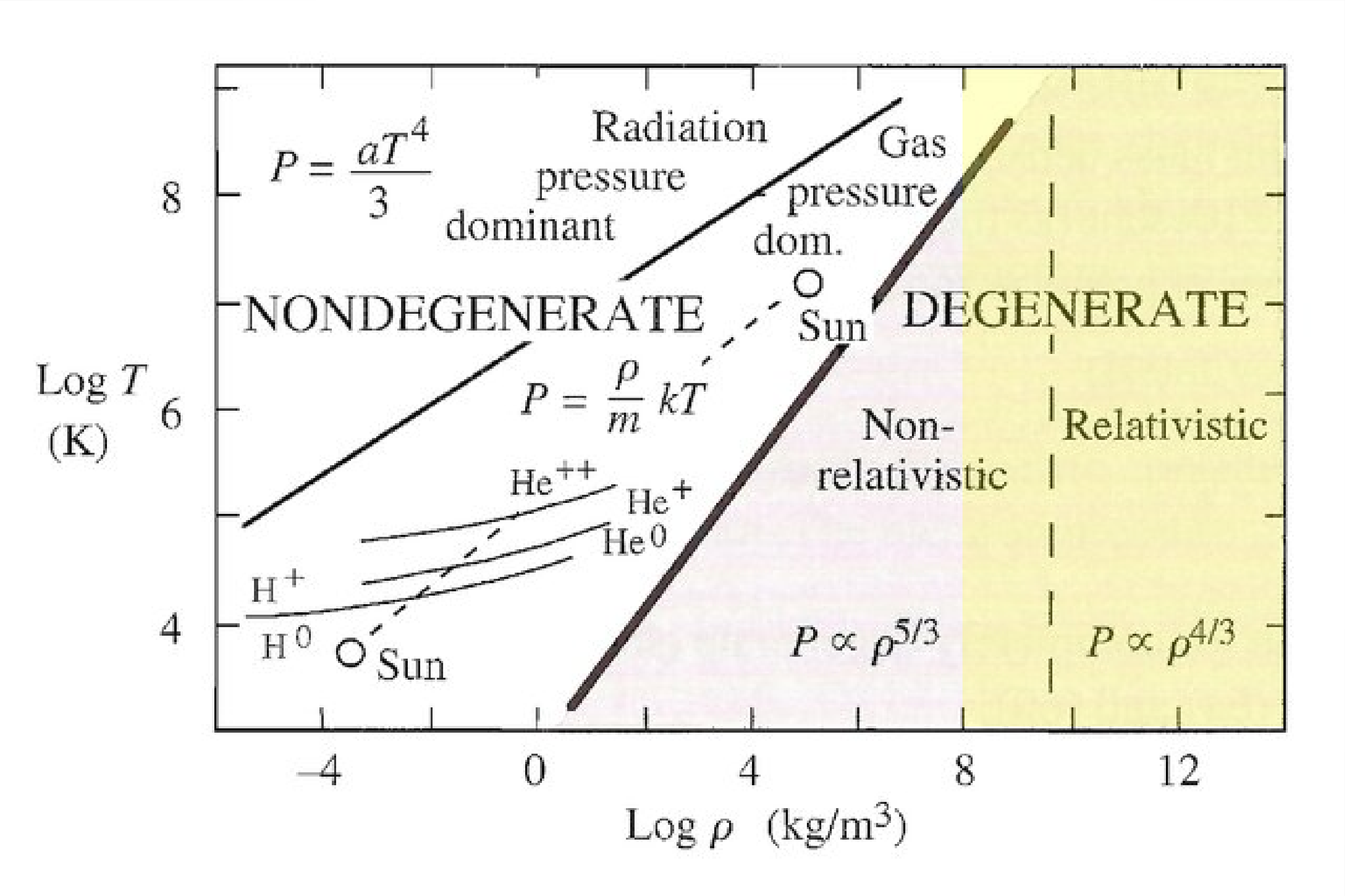
1. **Introduction: ultra-dense matter in the universe**
   a. **The sites**
   b. **The signals**
   c. **The big questions**
2. The gravitational wave probe for dense matter
   a. Neutron star modelling and the equation of state (EoS)
   b. Observations
   c. EoS and observables: constraining the parameters

# Ultra-dense matter



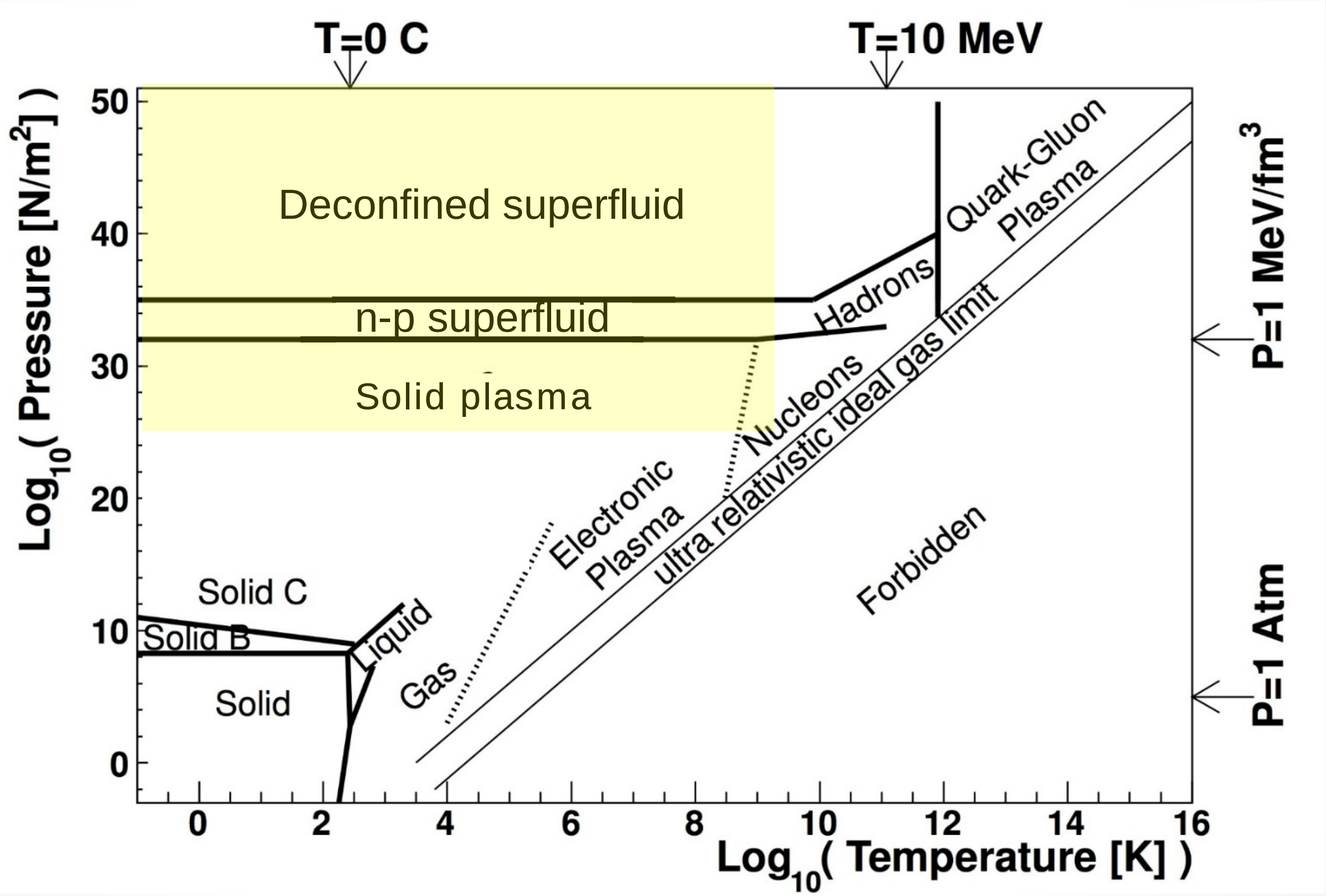

C.H.Lineweaver, V.M.Patel, Am.J.Phys.91 (2023) 819

# Ultra-dense matter




**Degenerate and relativistic at all temperatures**

# Ultra-dense matter

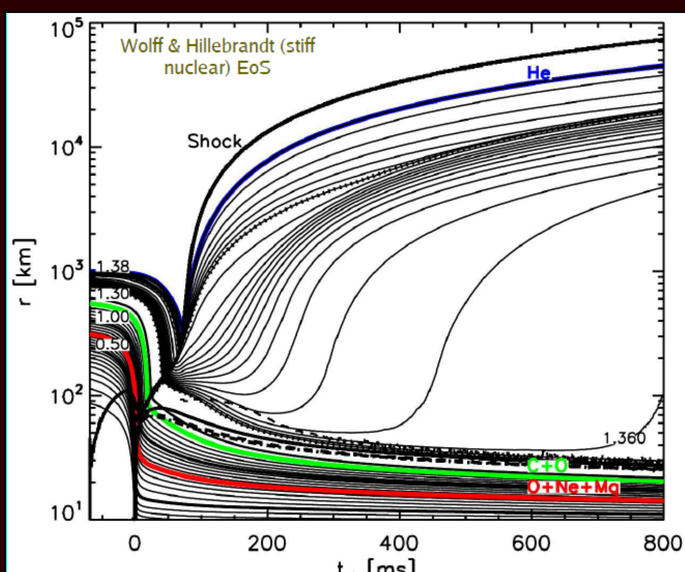


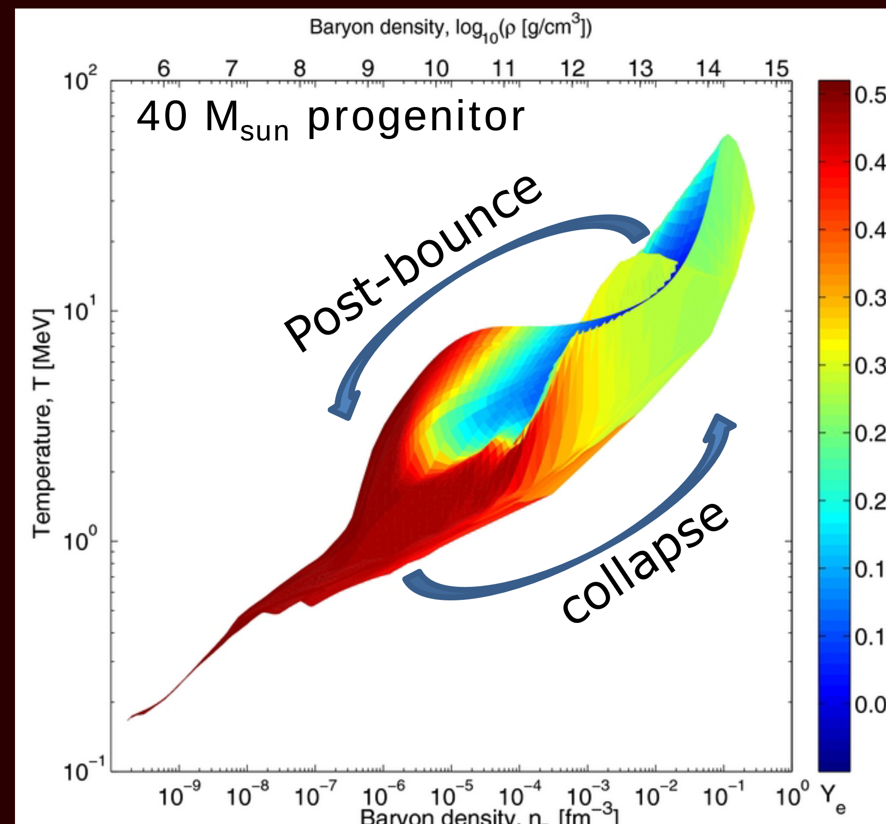

**Exotic constituents, exotic phases**

# Dense matter in the Universe: CCSN

*Supernova* remnant
in Puppis A
MIPS+XMM
IR Credit: NASA)

F.S.Kitaura et al, A&A 450 (06) 345

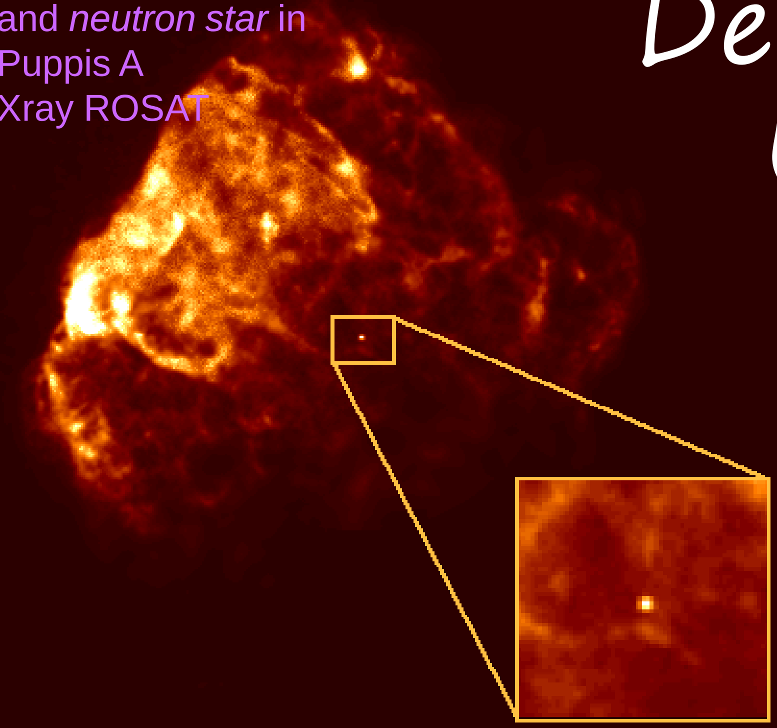


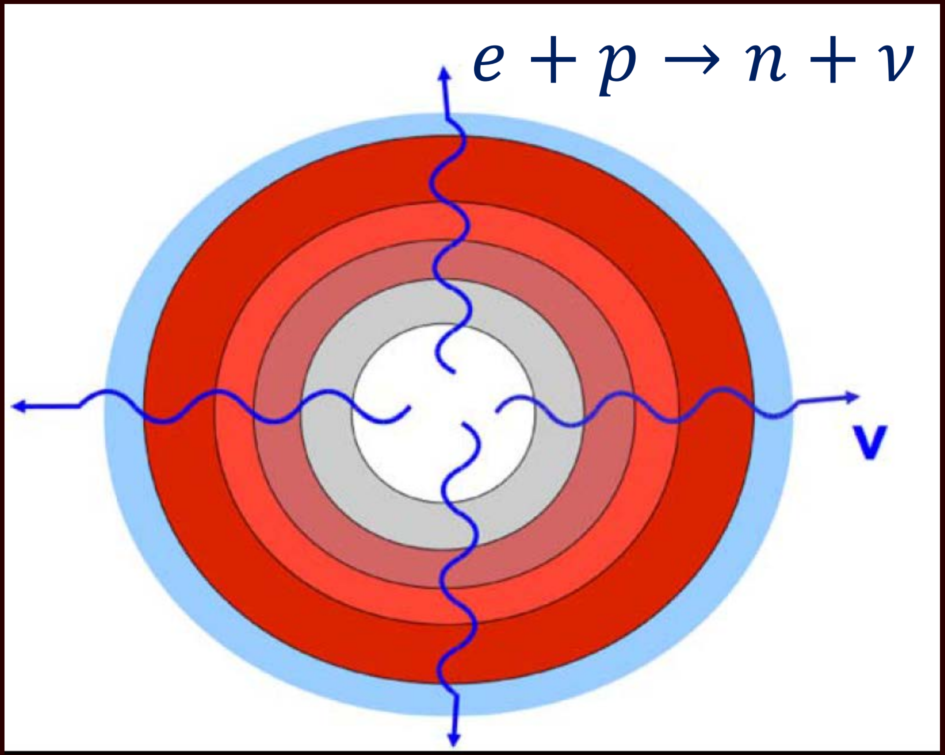



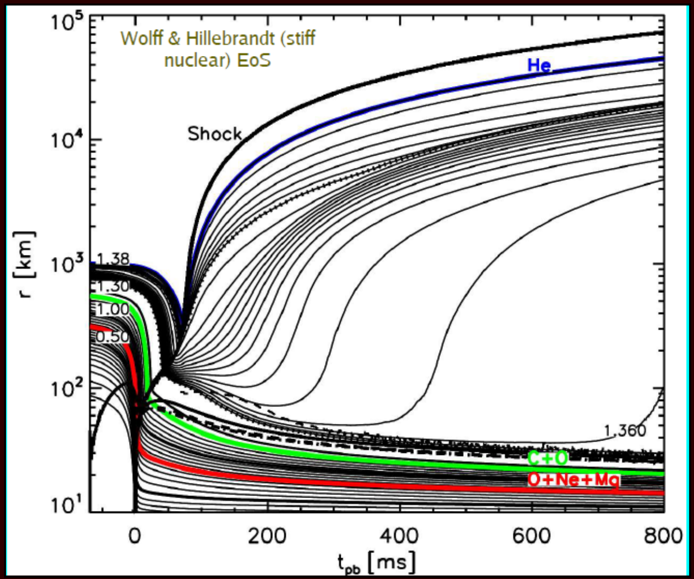

T.Fischer et al, 2011 ApJS **194** 39

*Supernova* remnant and *neutron star* in Puppis A
Xray ROSAT

# Dense matter in the Universe: PNS

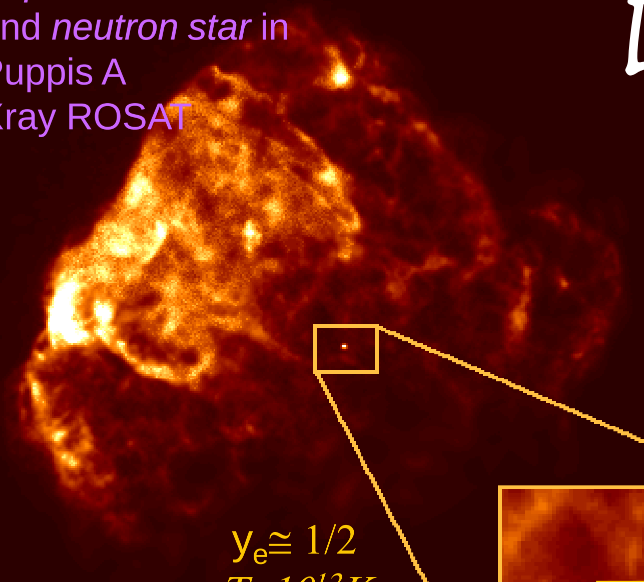




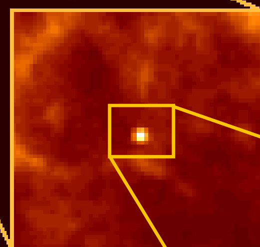



# Dense matter in the Universe: NS

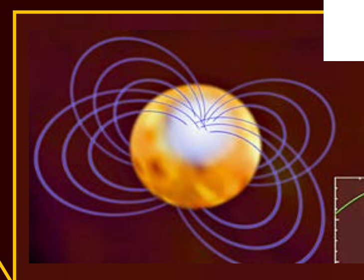
*Supernova* remnant and *neutron star* in Puppis A
Xray ROSAT



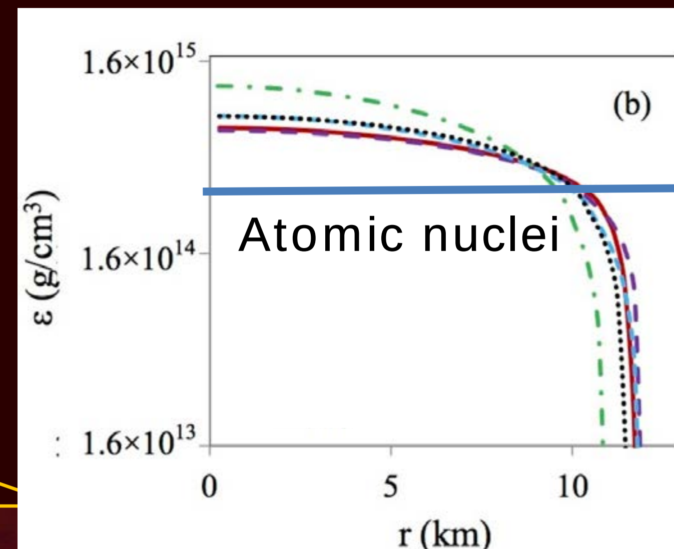
$y_e \cong 1/2$
$T{\sim}10^{12}K$

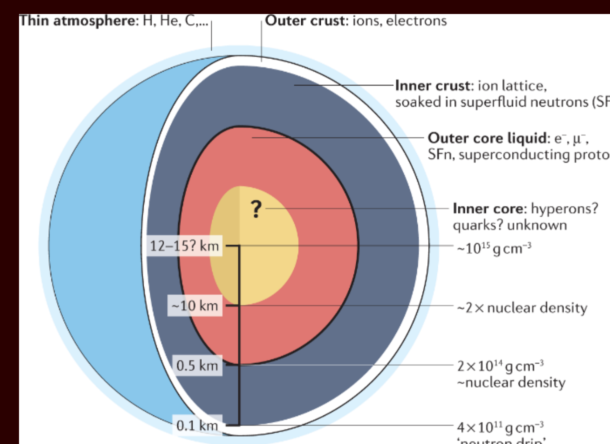


$y_e \cong 1/3$
$T{\sim}10^{11}K$



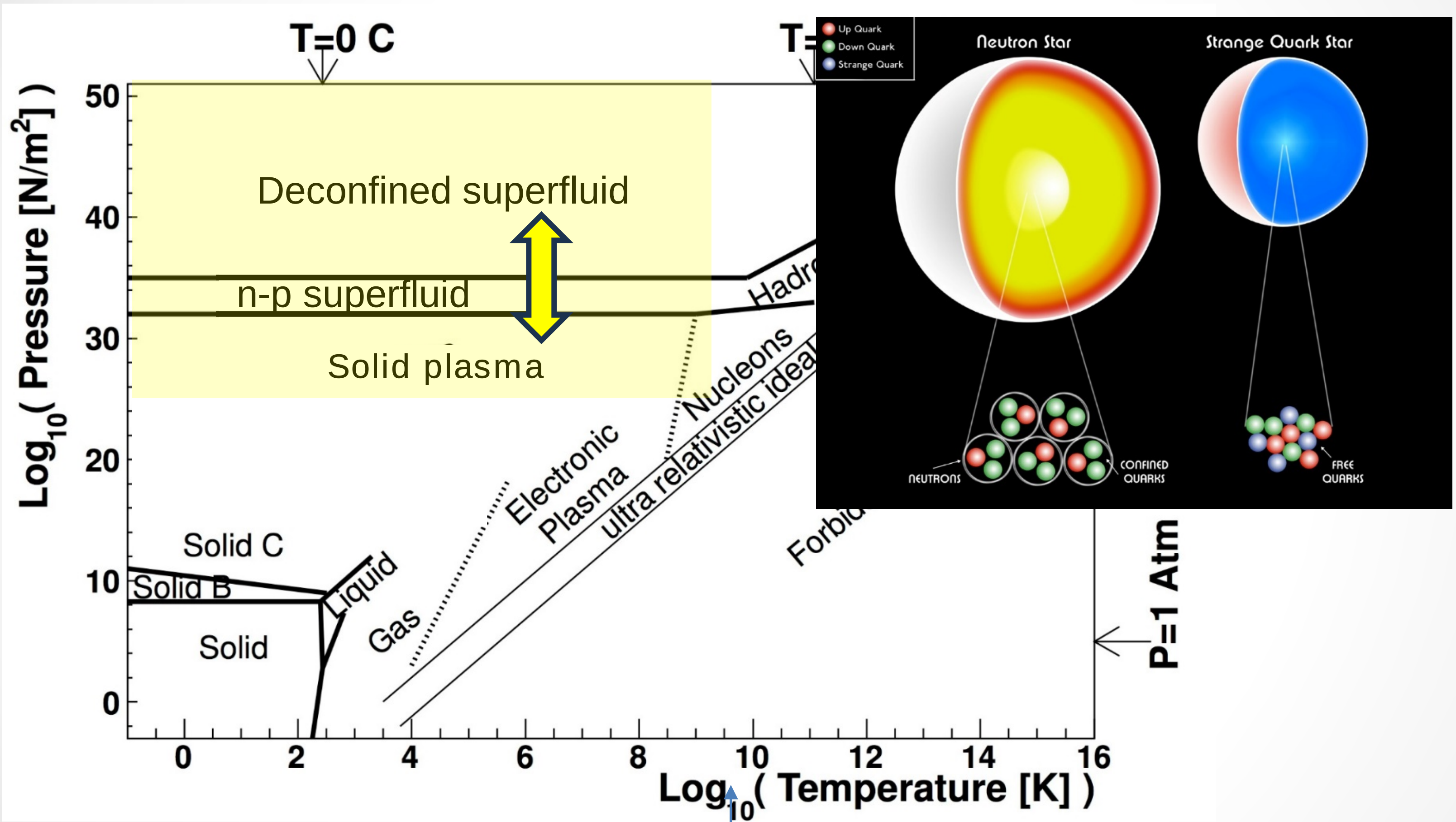
$y_e \cong 1/5$
$T{\sim}10^{6}K$




$$e + p \rightarrow n + \nu$$

# The phases of matter

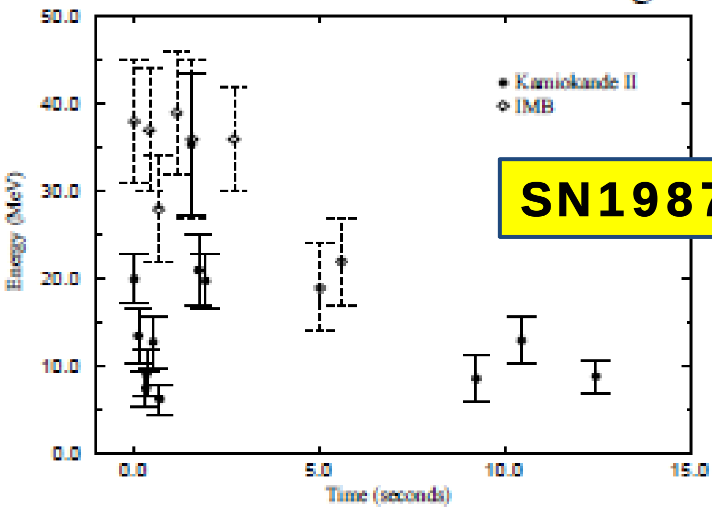



Credits: CXC/M.Weiss

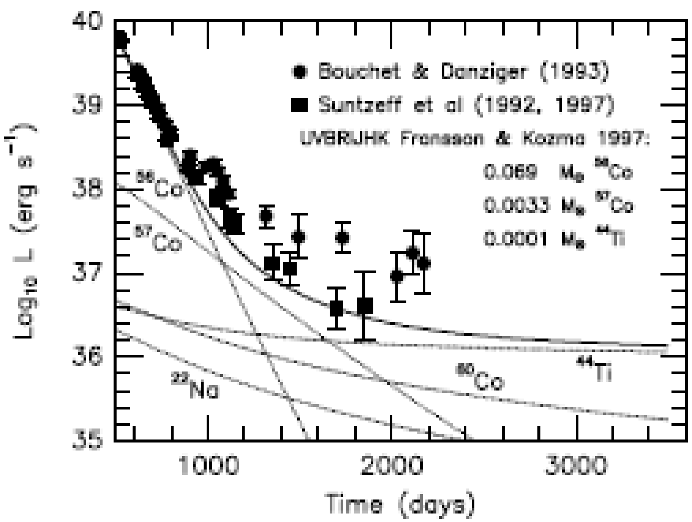
$k_B T = 1$ MeV

# CCSN Signals

neutrinos $E_\nu \approx 2.7 \times 10^{53}$ erg



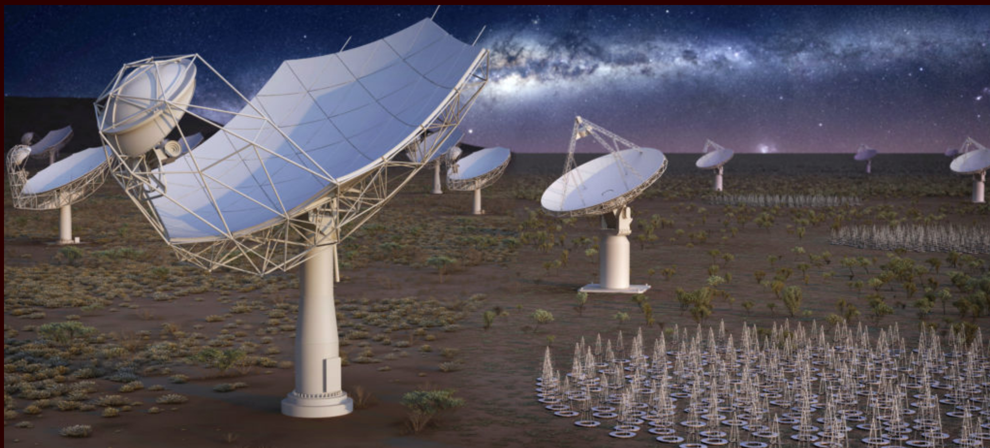

light curve




**SuperKamioKande @Kamioka**

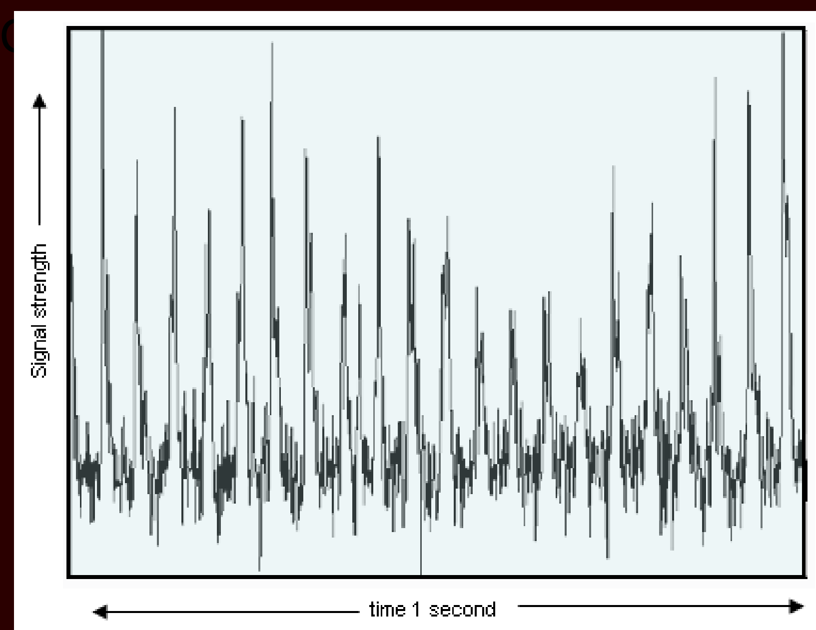
**DUNE @Stanford**

# Signals

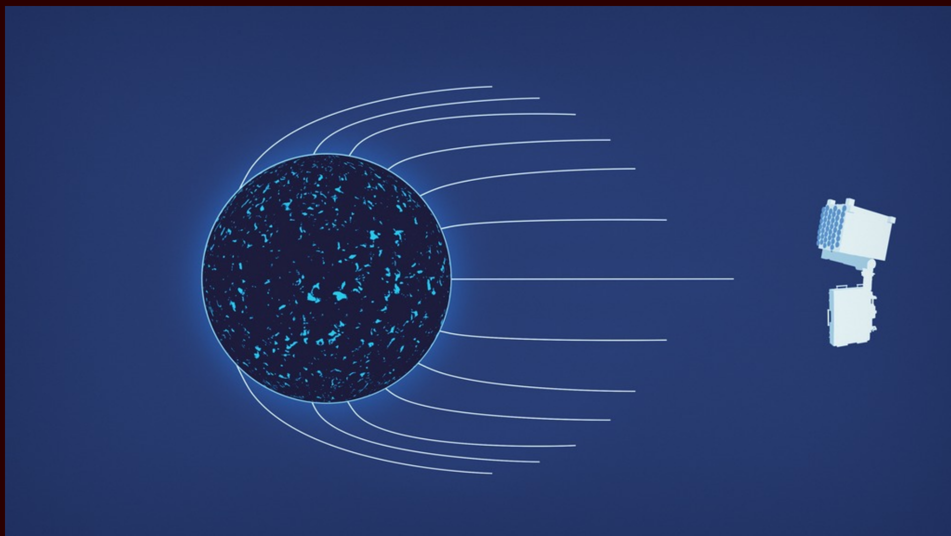


**SKA@ South Africa**

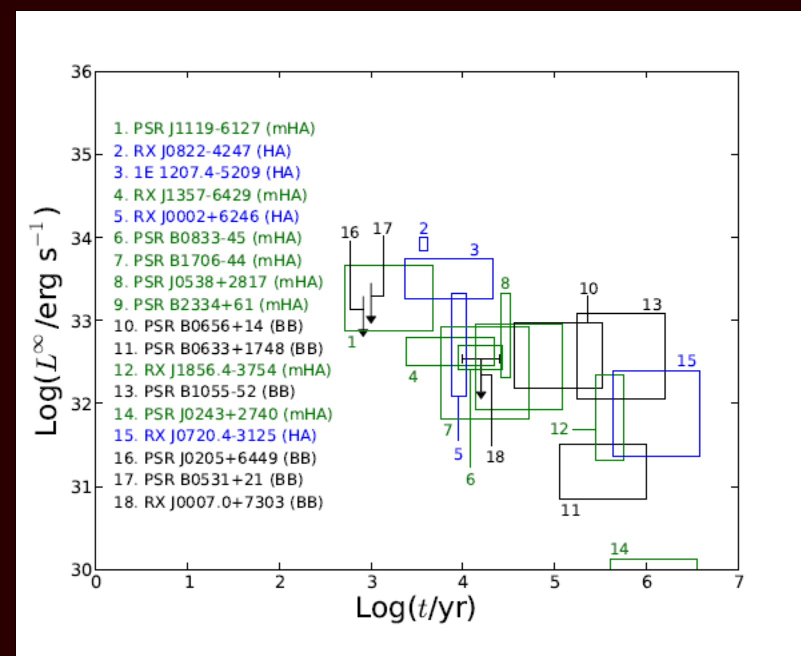
## Pulsars



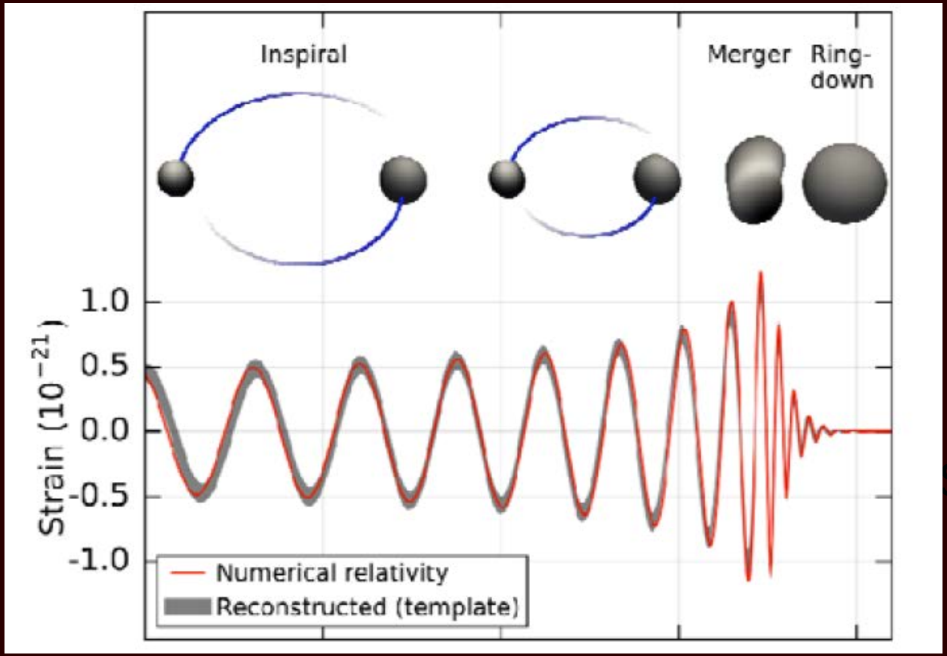
# Signals



## XR sources

# Signals

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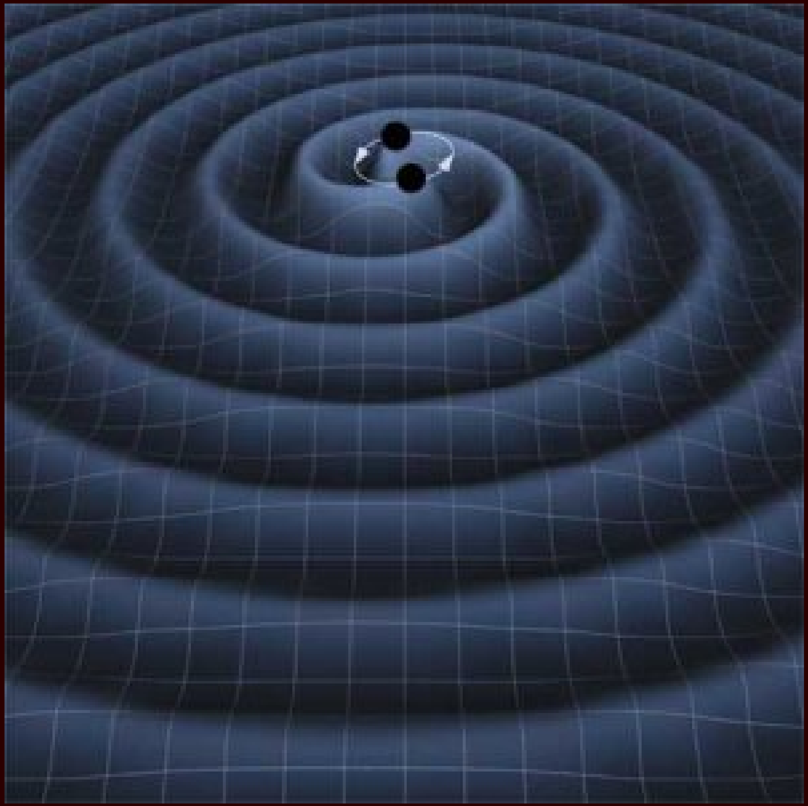
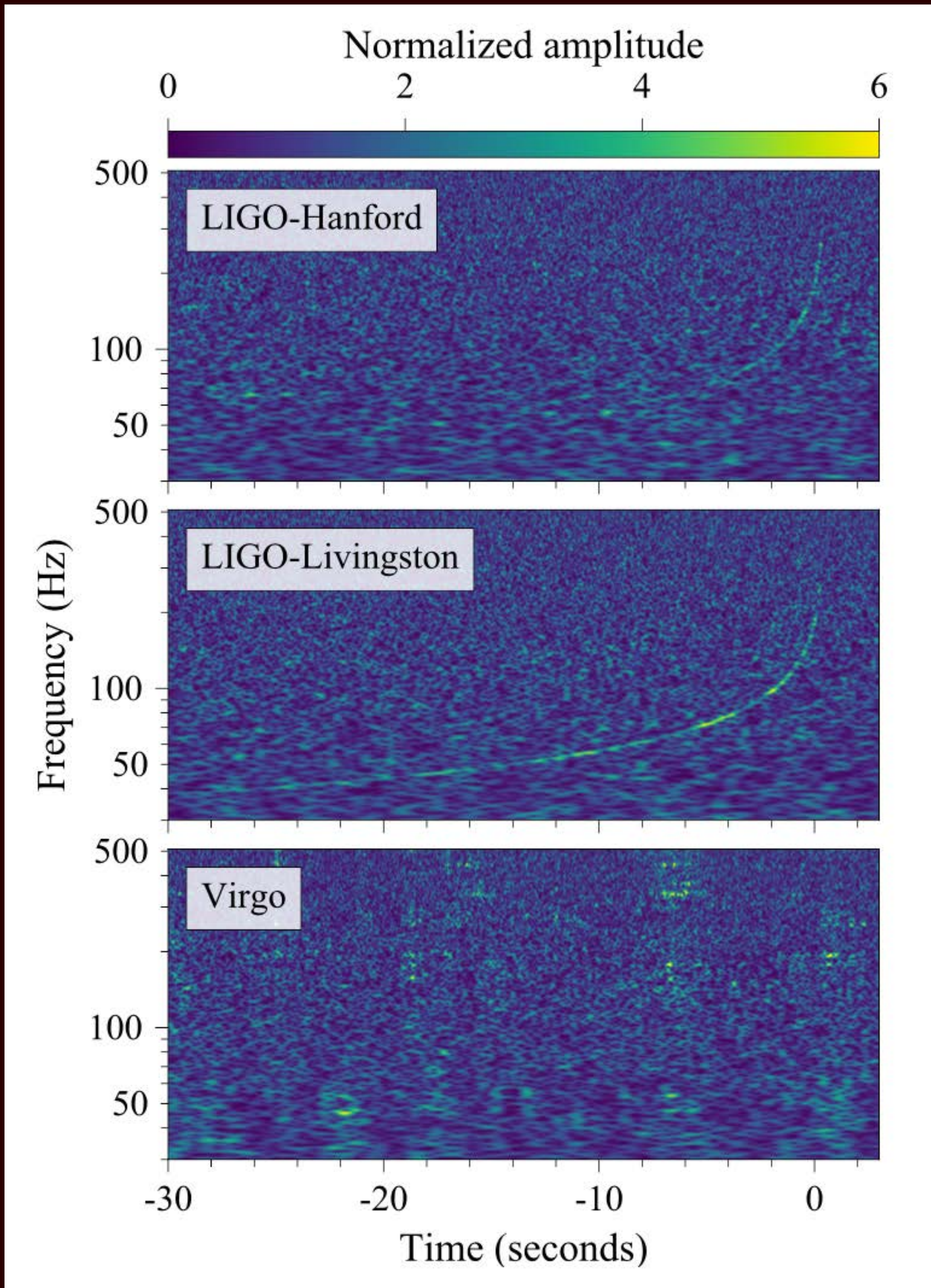


**Mergers**

# Signals




SN

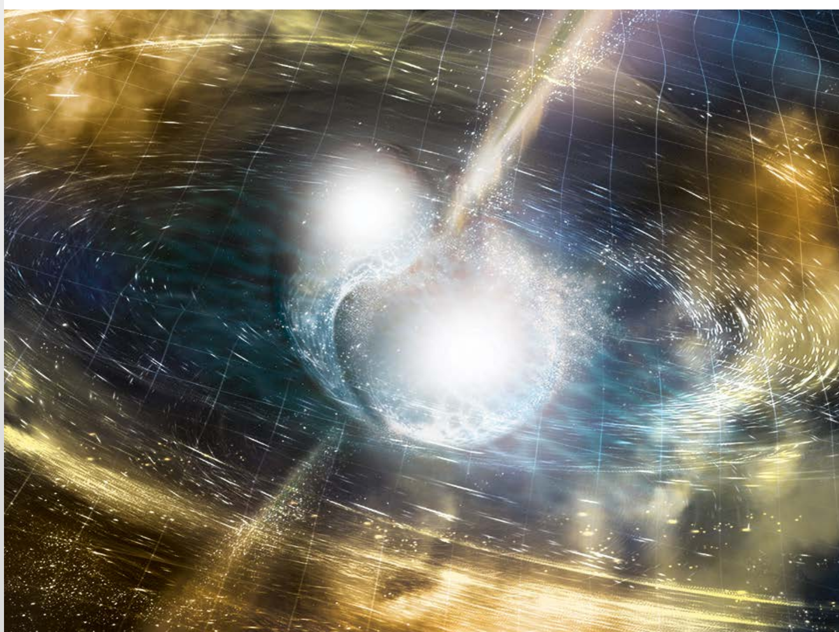
# Mergers

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9


# Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

*Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16*

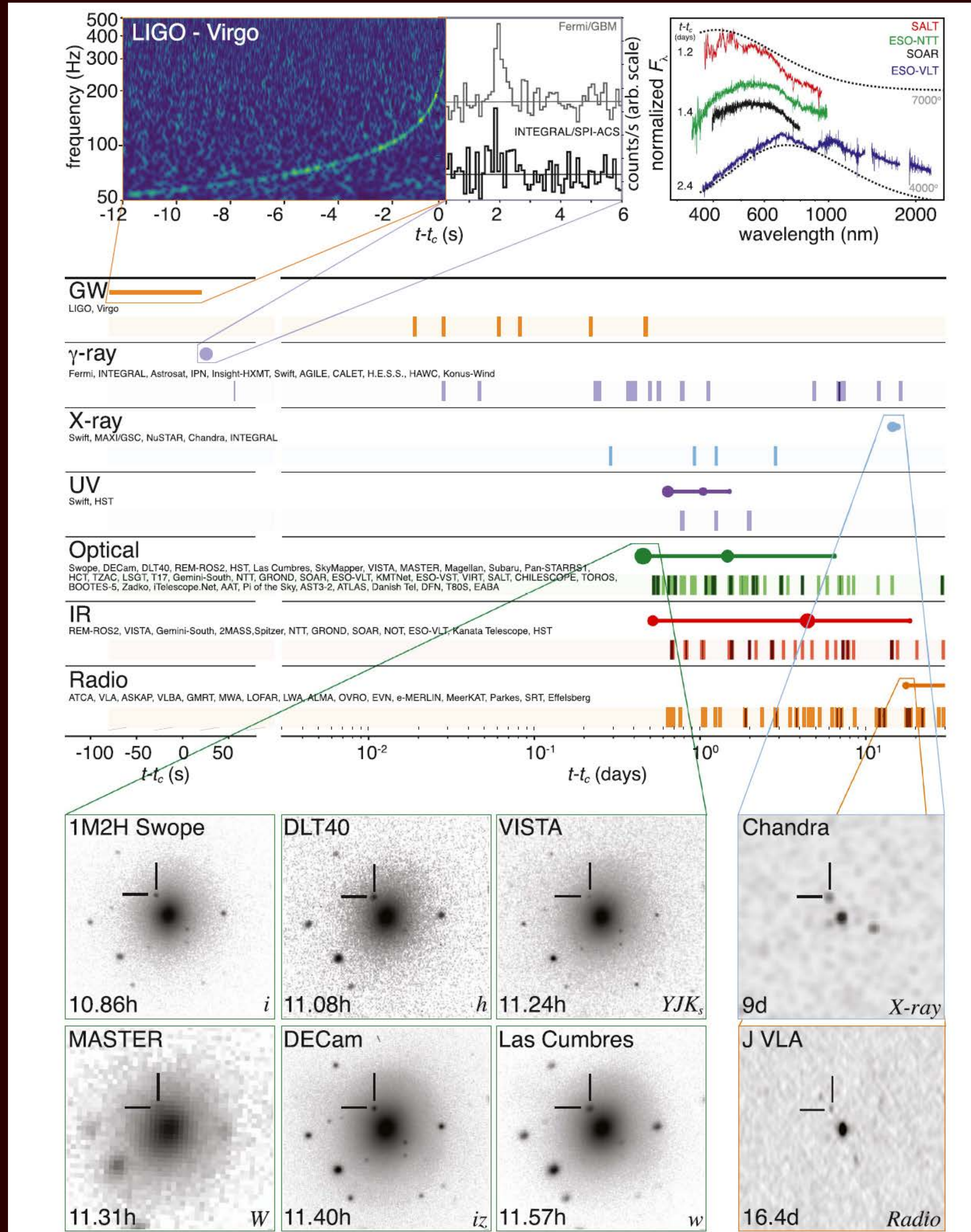


Foundation
Operated by Caltech and MIT

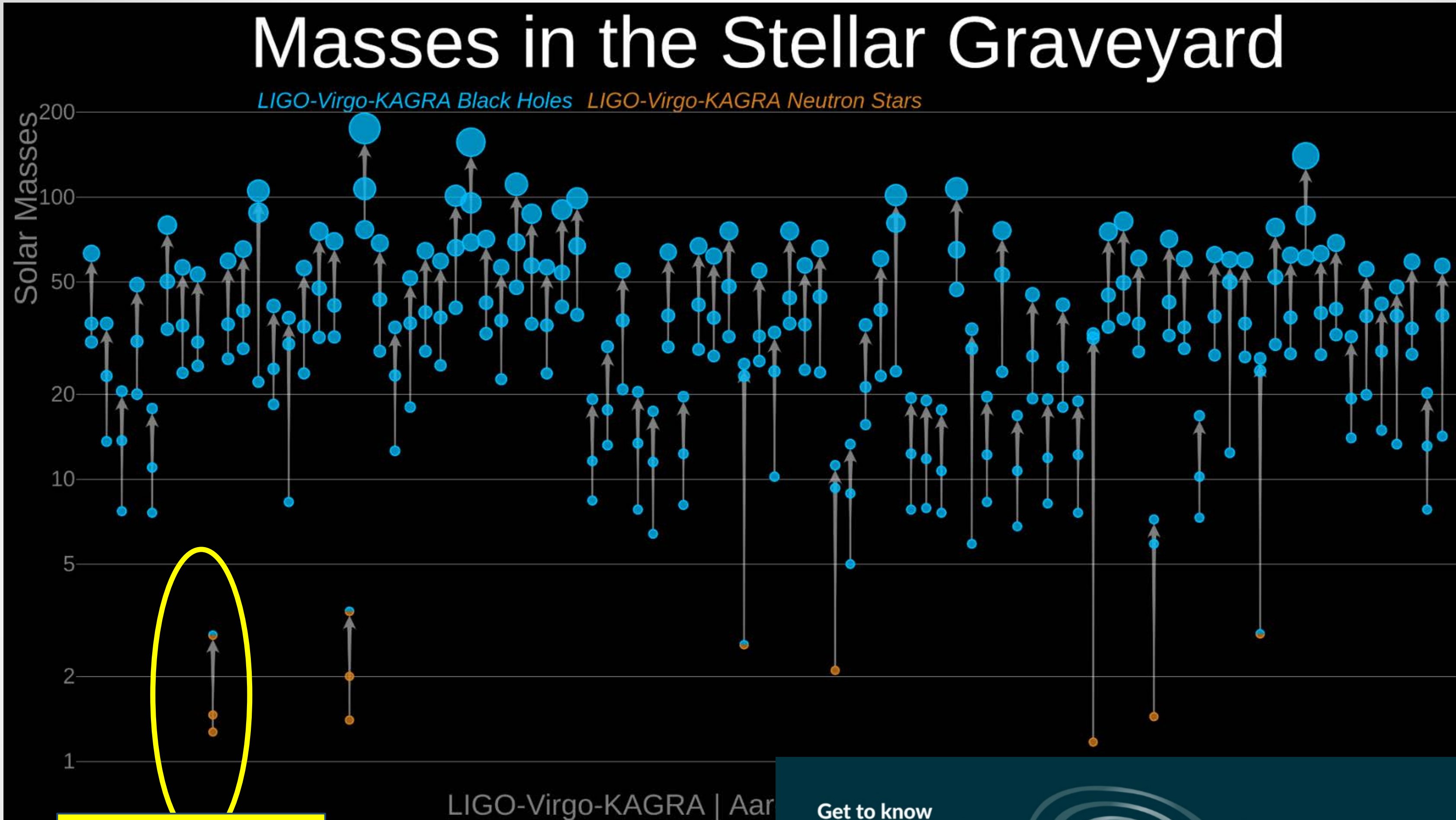
GW170817 Press Release

**LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars**

**Discovery marks first cosmic event observed in both gravitational waves and light.**

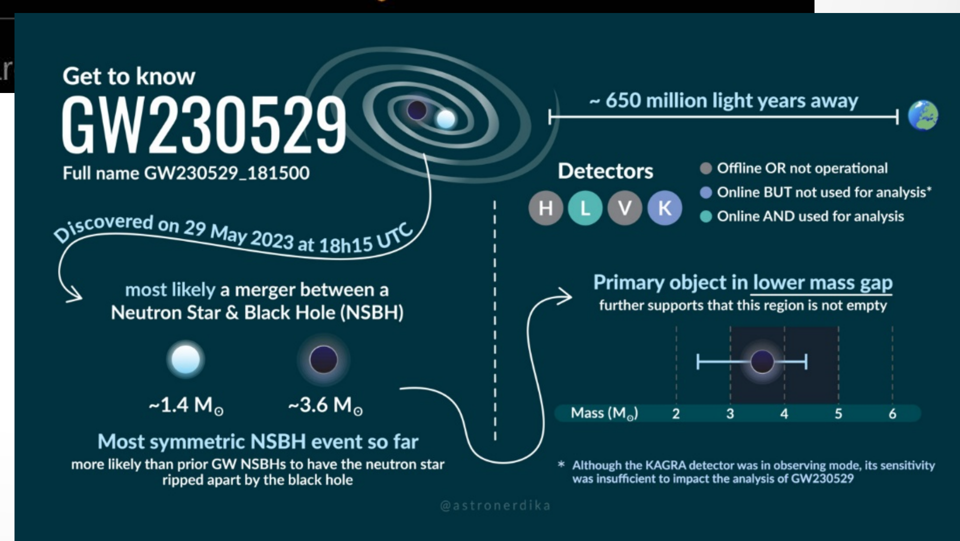


LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-t_c (s)
normalized F_λ
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-t_c (s)
t-t_c (days)
1M2H Swope 10.86h i
DLT40 11.08h h
VISTA 11.24h YJK_s
Chandra 9d X-ray
MASTER 11.31h W
DECam 11.40h iz
Las Cumbres 11.57h w
J VLA 16.4d Radio



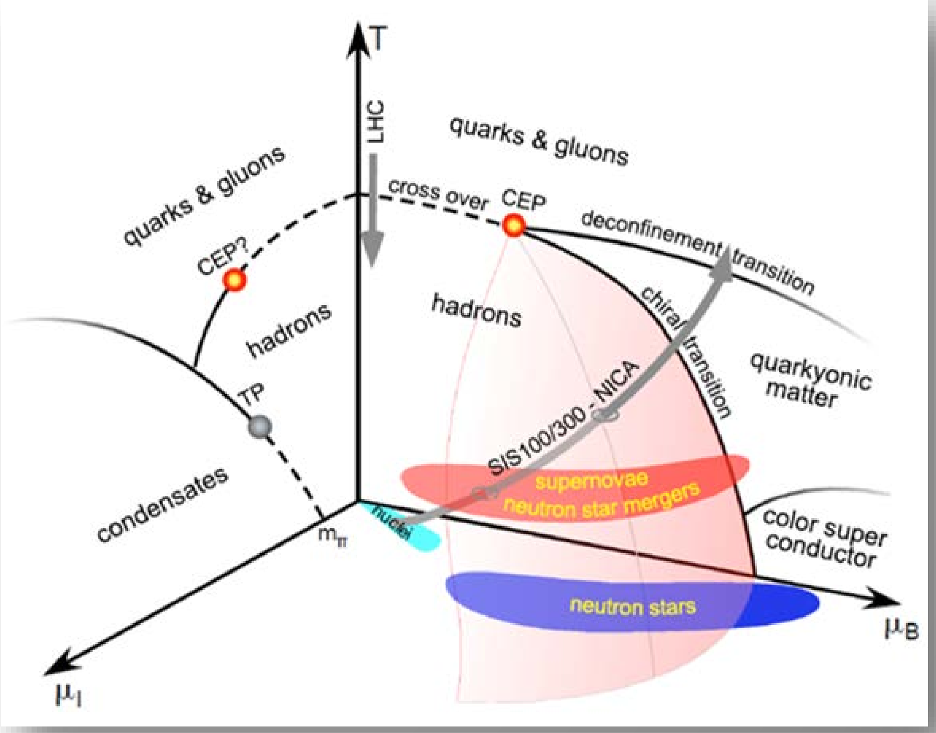

GW170817

# 10 years of LVK observations



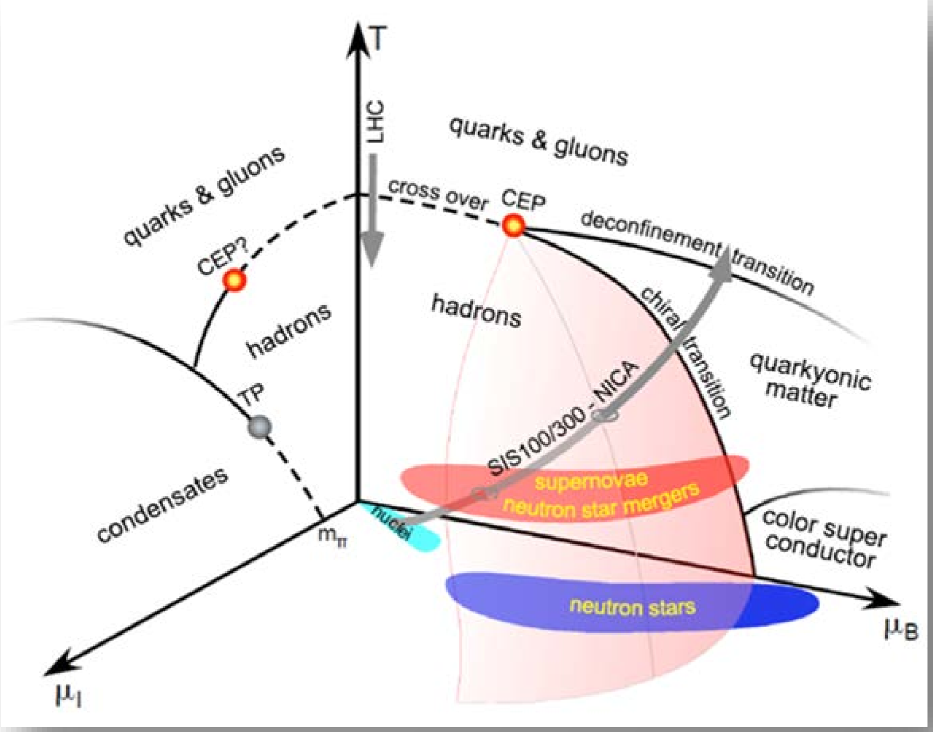
# *Dense matter: the Questions*

1. What is the internal structure of the dense matter in neutron stars, supernova cores and mergers?
2. How does this structure reflect into the observable signals?
3. What can we learn on the underlying nuclear and hadronic physics?



# *The message I would like to convey:*

Gravitational waves, and particularly the inspiral GW signal from NS mergers, opens the possibility of a **DIRECT** measurement of the QCD phase diagram



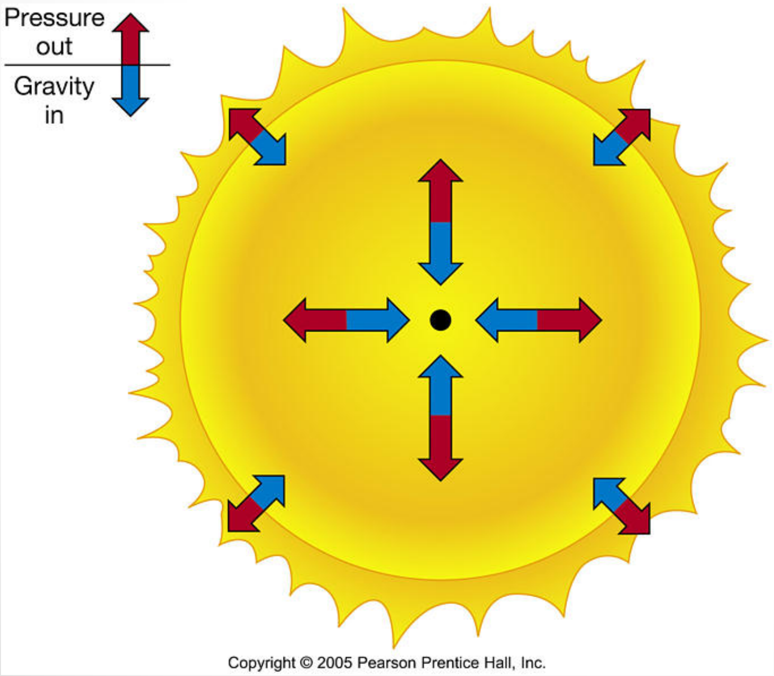
# *Lecture plan*

1. Introduction: ultra-dense matter in the universe
   a. The sites
   b. The signals
   c. The big questions
2. **The gravitational wave probe for dense matter**
   a. **Neutron star modelling and the equation of state (EoS)**
   b. **Observations**
   c. **EoS and observables: constraining the parameters**

# Modelling (Neutron) Stars: hydrostatics

- Self-gravitation => Tolman Oppenheimer Volkoff (1939):

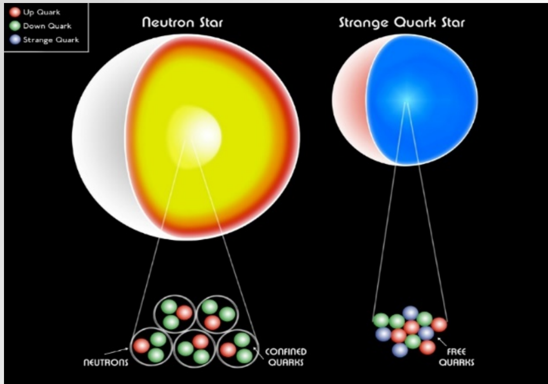
$$\frac{d\boldsymbol{P}(\boldsymbol{\rho})}{dr} = -\frac{G}{r^2}\left[\rho(r) + \frac{\boldsymbol{P}(\boldsymbol{\rho})}{c^2}\right]\left[m(r) + 4\pi r^3\frac{\boldsymbol{P}(\boldsymbol{\rho})}{c^2}\right]\left[1 - \frac{2Gm(r)}{rc^2}\right]^{-1}$$




$\forall\rho_c$
R=r(P=0)
M=m(r=R)

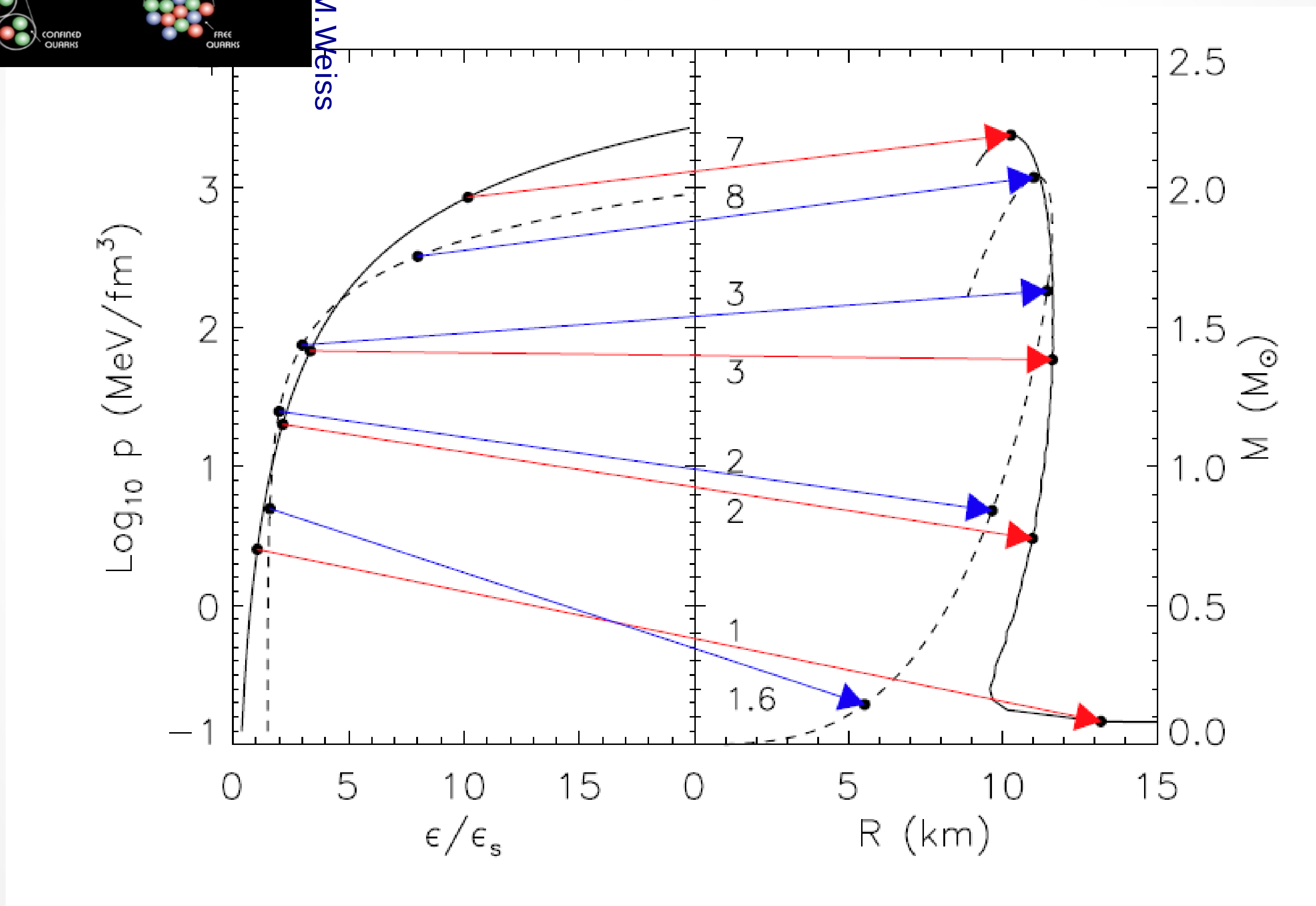
**Mass and radius**

**Needs ONLY $P(\rho)$ of NS matter**




Credits: CXC/M.Weiss

# $P(\rho) \Leftrightarrow M(R)$




J.Lattimer Ann.Rev.Nucl.Part.Sci 2012

# Modelling (Neutron) Stars: hydrostatics

- Influence of a second body => Thorne and Campolattaro (1967):

$$\frac{d^2H(r)}{dr^2} + \frac{dH(r)}{dr}\left[\frac{2}{r} + e^{\lambda(\boldsymbol{P}(\boldsymbol{\rho}))}\left(\frac{2m(r)}{r^2} + 4\pi r\left(\boldsymbol{P}(\boldsymbol{\rho}) - \rho(r)\right)\right)\right] + H(r)Q(\boldsymbol{P}(\boldsymbol{\rho})) = 0$$

$$\forall \rho_c$$

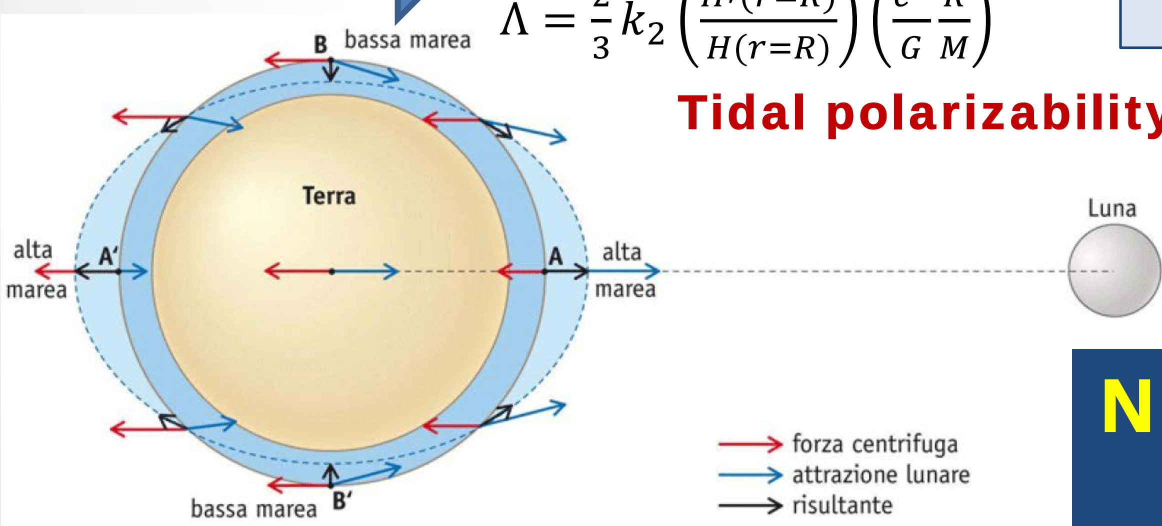
$$\Lambda = \frac{2}{3}k_2\left(\frac{H\prime(r=R)}{H(r=R)}\right)\left(\frac{c^2}{G}\frac{R}{M}\right)^5$$

**Tidal polarizability**

Quadrupole moment

Companion tidal field

$$\bar{\bar{Q}}^{(i)} = -\Lambda_i \bar{\bar{\mathcal{E}}}^{(j)}$$



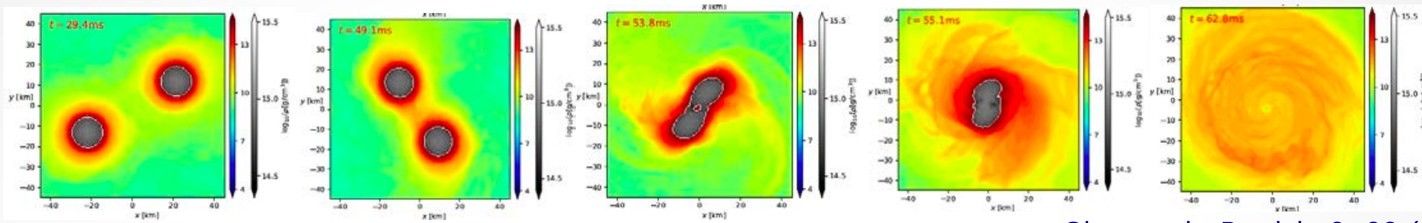

LIGO
Livingston

**Needs ONLY $P(\rho)$ of NS matter**

. West

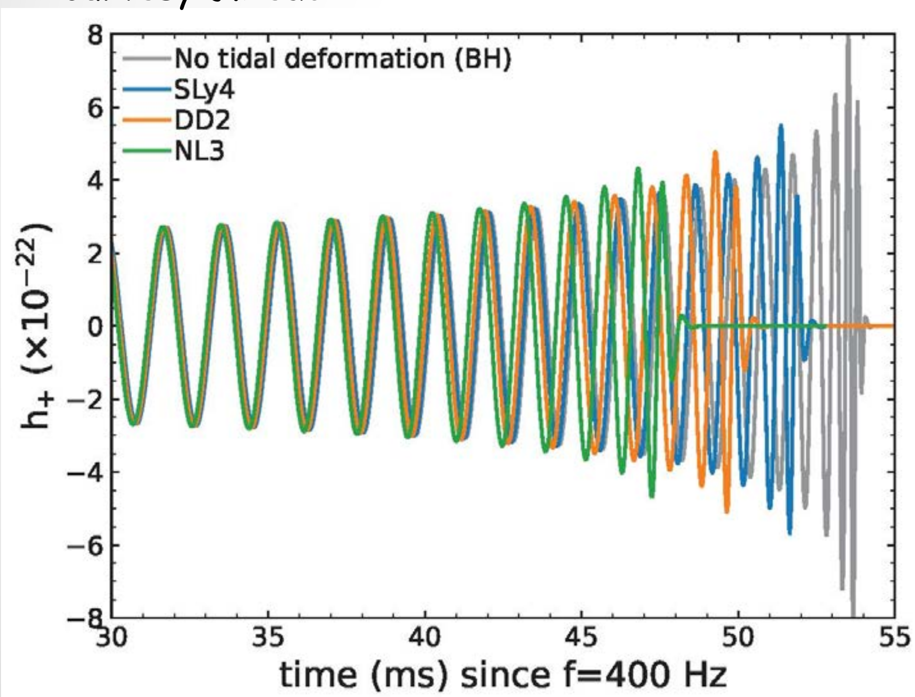
/

# Extraction of the tidal effects



Gieg et al., Particle 2, 23 (2019)

SEOBNRV4T_SURROGATE waveform,
Courtesy J.Read




R.Wade et al., PRD89(2014)103012

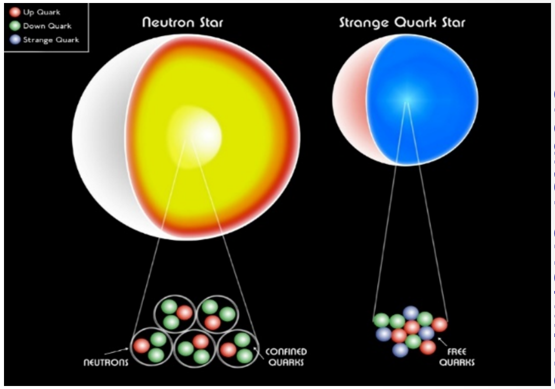
$$\delta\psi_{\rm tidal} = \frac{3}{128\eta x^{5/2}}\left[\left(-\frac{39}{2}\tilde{\Lambda}\right)x^5 + \left(-\frac{3115}{64}\tilde{\Lambda} + \frac{6595}{364}\sqrt{1-4\eta}\,\delta\tilde{\Lambda}\right)x^6\right]$$

$$(\Lambda_1, \Lambda_2) \leftrightarrow (\tilde{\Lambda}, \delta\tilde{\Lambda})$$

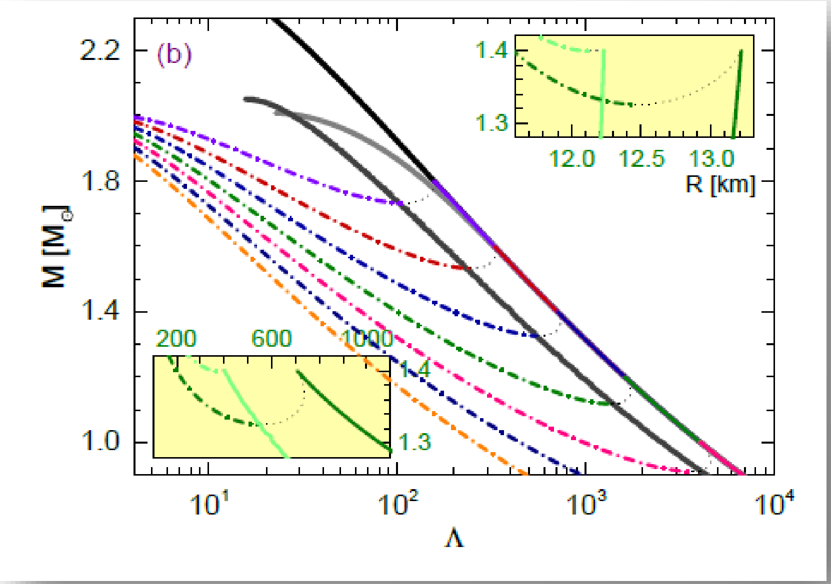
Tidal effects: modification of the gravitational waveform wrt a GR point-particle calculation, due to the star deformation just before merging

# ...a brief summary $\langle O \rangle \Leftrightarrow P(\rho)$

- GR imposes a 1-to-1 correspondence between the dense matter EoS and static properties of NS (M(R)- M(Λ))
- Different compositions => different M(Λ) => different gravitational signals!
- Systematics due to the astrophysical modelling in principle under control

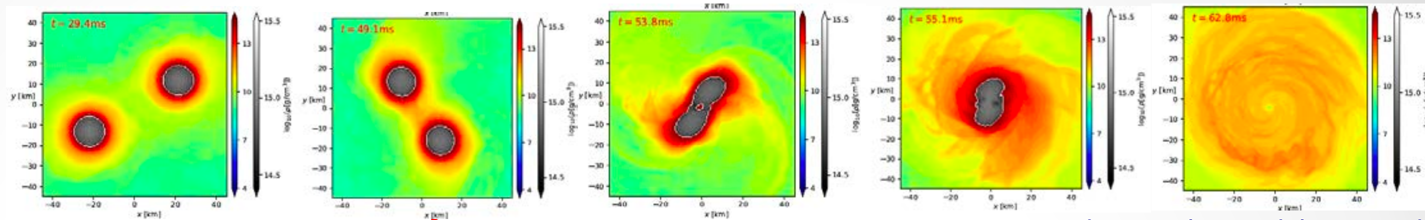



Credits: CXC/M.Weiss

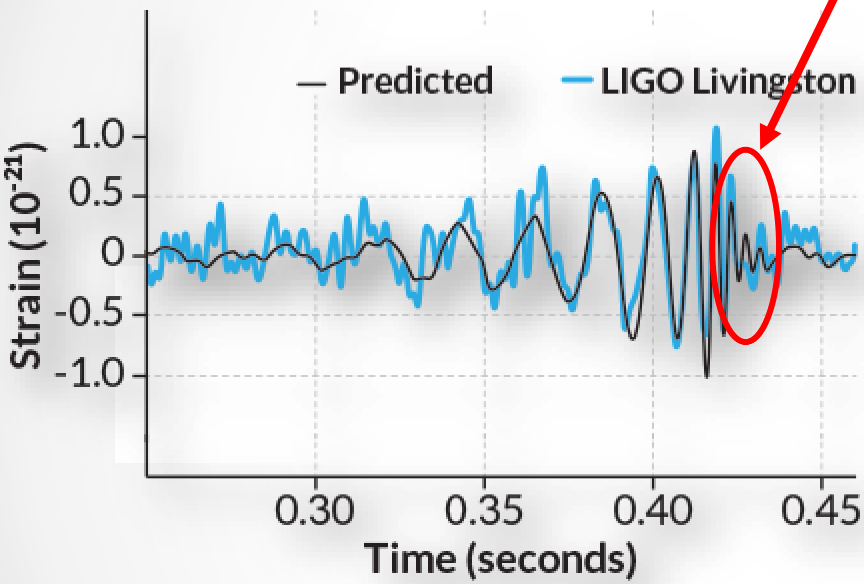



J.J.Li, A.Sedrakian, M.Alford, PRD101 (2020) 063022

# Problem I : the Λ info is hard to measure

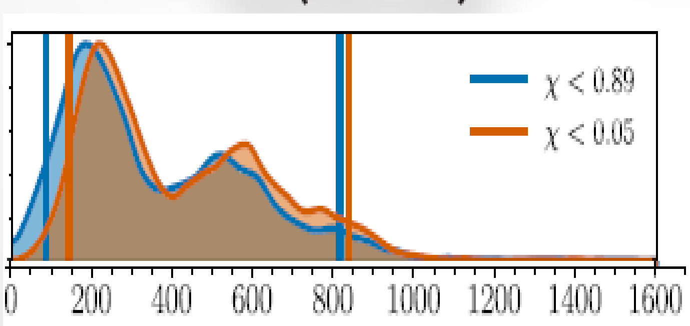


Gieg et al., Particle 2, 23 (2019




R.Wade et al., PRD89(2014)103012

$$\delta\psi_{\rm tidal} = \frac{3}{128\eta x^{5/2}}\left[\left(-\frac{39}{2}\tilde{\Lambda}\right)x^5 + \cancel{\left(-\frac{3115}{64}\tilde{\Lambda} + \frac{6595}{364}\sqrt{1-4\eta}\,\delta\tilde{\Lambda}\right)x^6}\right]$$




LVC, PRX 9 (2019), 011001

$$(\Lambda_1, \Lambda_2) \leftrightarrow (\tilde{\Lambda}, \delta\tilde{\Lambda})$$

=> Only the combined $\tilde{\Lambda}$ is measurable, and with error bars

# Problem II : no ab-initio theory of dense matter

## => Density Functional Approach

$\varepsilon_{tot} = \varepsilon_B + \varepsilon_L$ (baryons and leptons decoupled, leptons free FG)

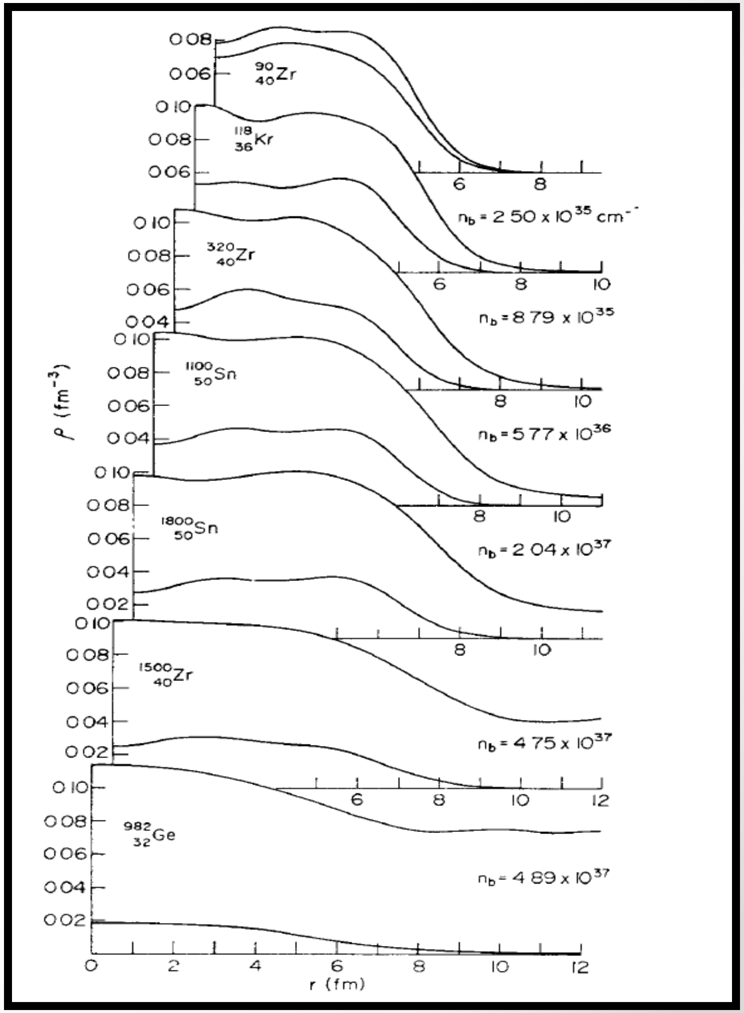
- **NS core:** $\rho_q(r) = \rho_q$ ($\forall$ q constituent)
  - **Effective single particles:** $e_q(k) = \sqrt{m_q^{*\,2} + k^2} + V_q(\rho_q, \rho_{q'})$

$\Rightarrow m_q^*$ , $V_q$ from a phenomenological Hamiltonian (Skyrme, Gogny,M3Y..) or Lagrangian (RMF)
$\Rightarrow$ Parameters fitted on nuclear data and/or ab-initio calculations
$\Rightarrow e(\rho_B, \rho_L, \rho_S) \quad P(\rho) = -\rho_B^2 \frac{\partial e}{\partial \rho_B}\Big|_{\mu_L=0,\mu_S=0,}$

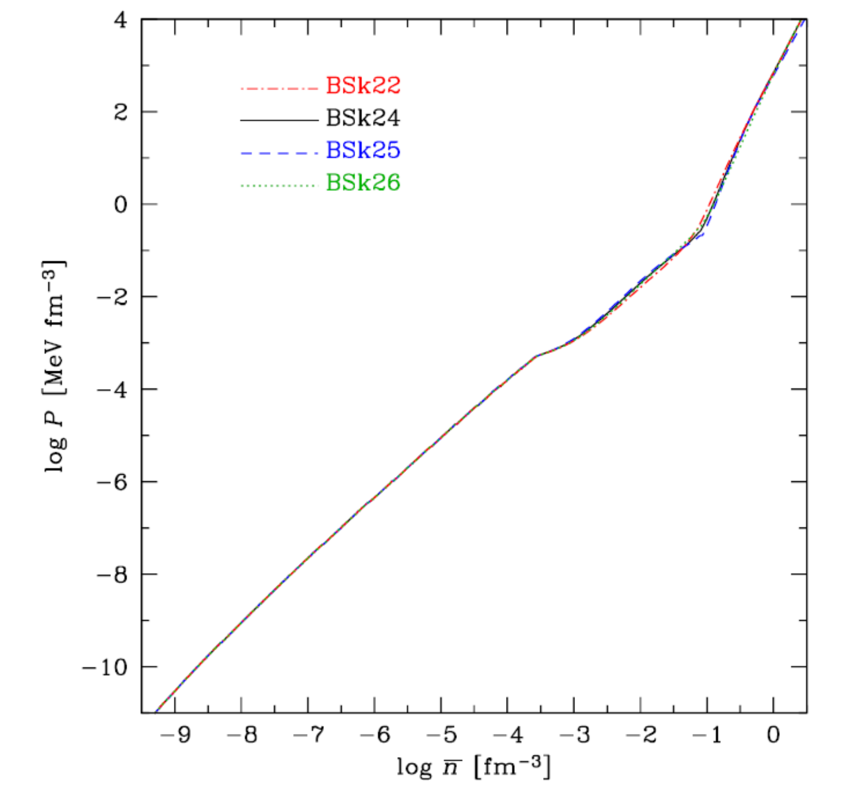
# Problem II : no ab-initio theory of dense matter

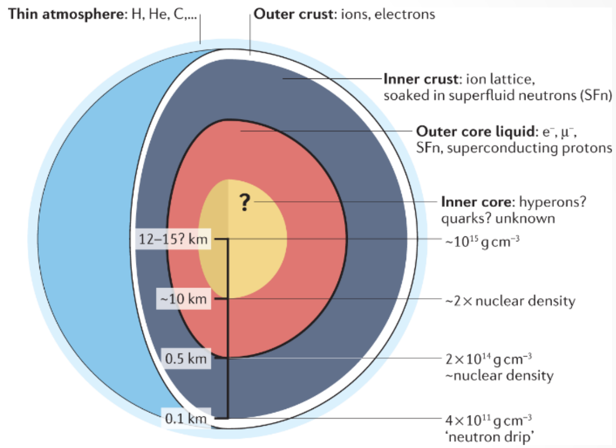
## => Density Functional Approach

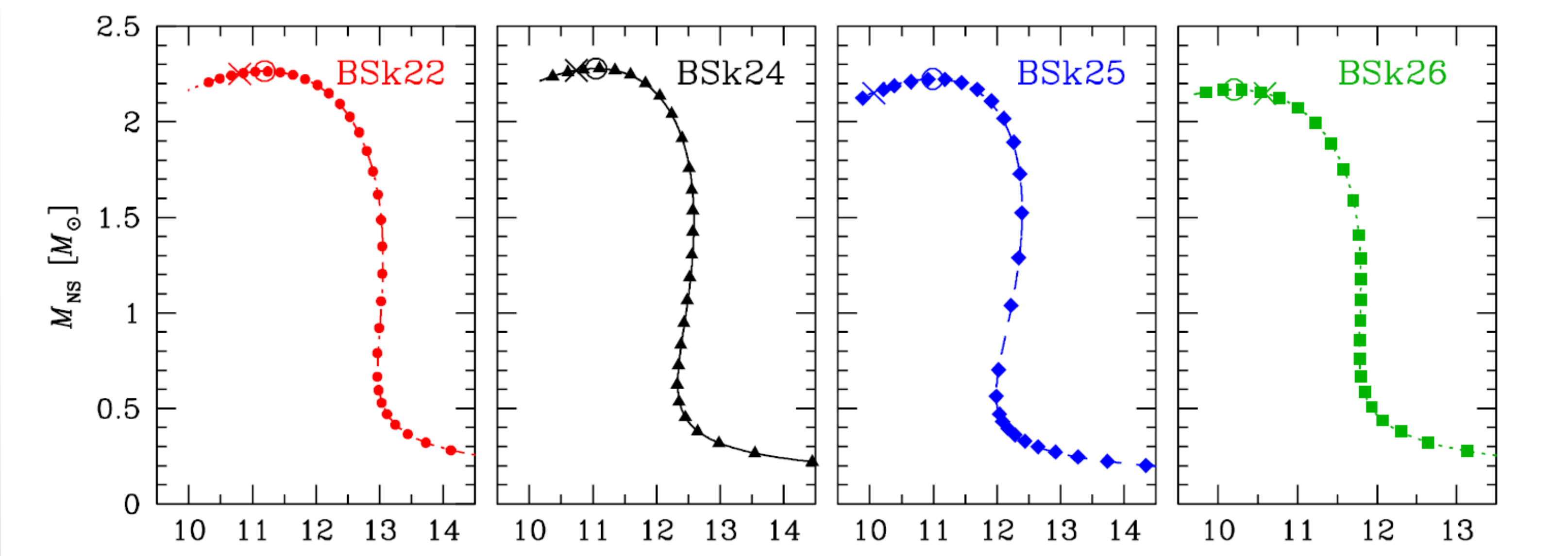
- **NS crust: q=n,p** variational calculation of the single particle wave-functions => $\rho_q(r)$ within the Hartree-Fock-(Bogoliubov) theory



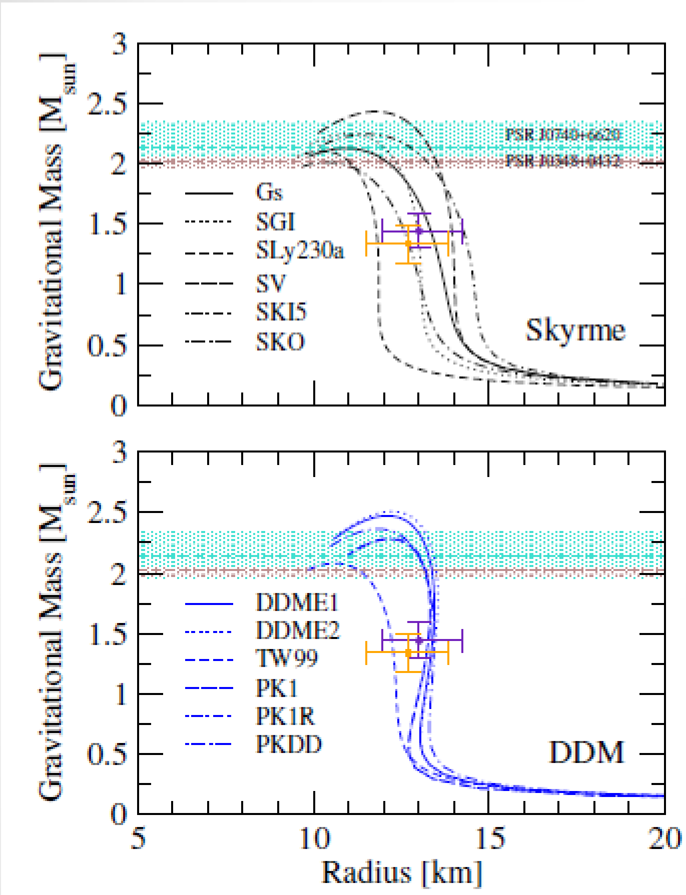
# An example: the Brussels-Montreal functionals BSK



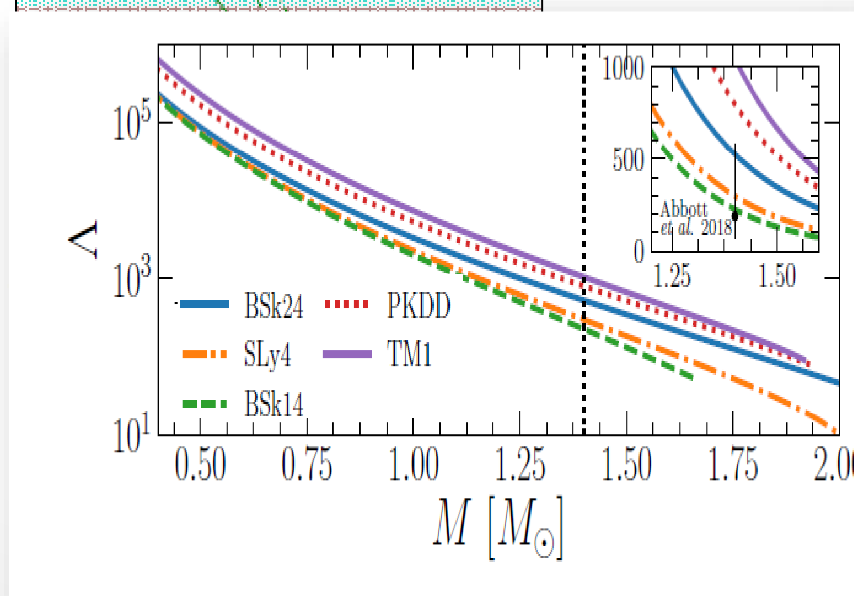



# Problem II : no ab-initio theory of dense matter

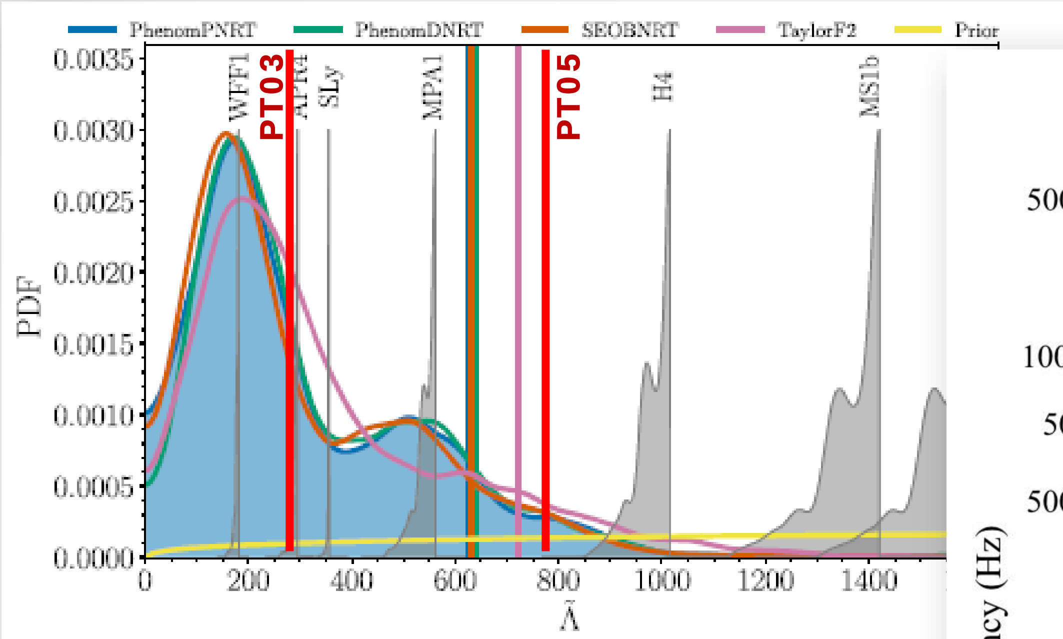



- **Model dependence: choice of functional form (Lagrangian versus Hamiltonian) and extrapolations lead to different predictions**

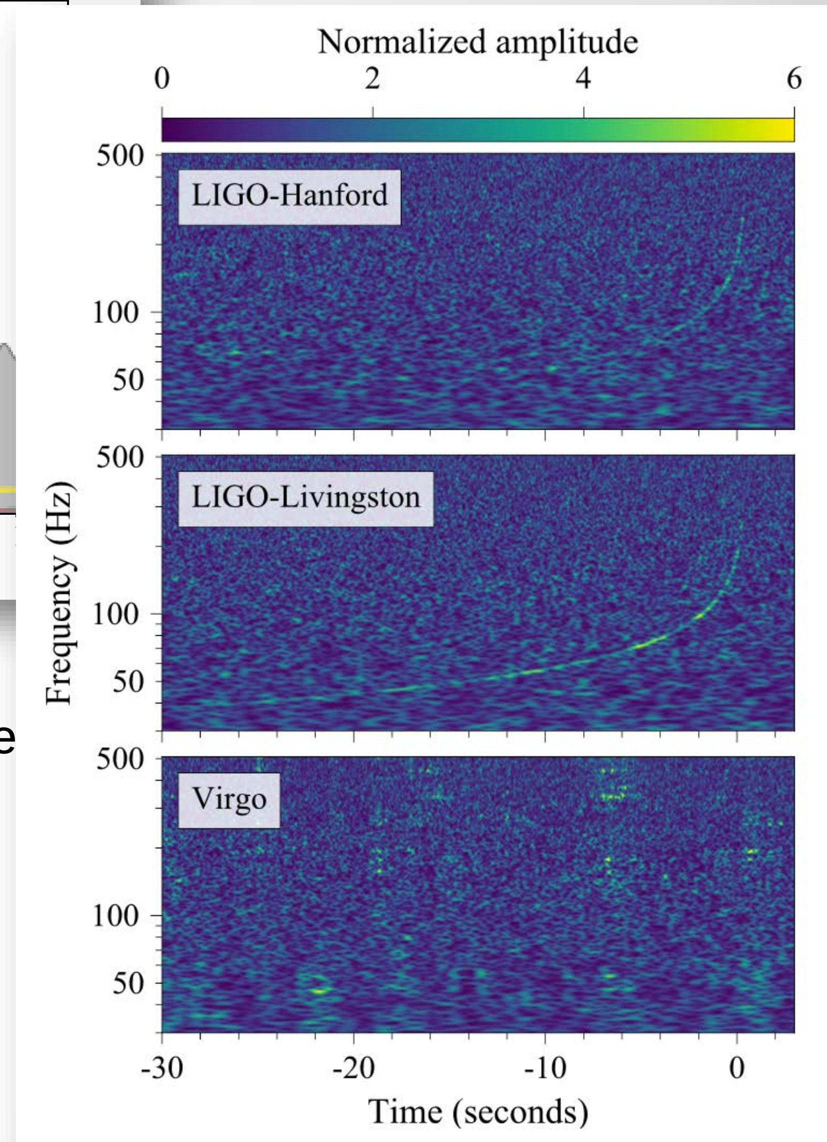



F.Burgio, I.Vidana, Universe 2020, 6, 119

# Present status: GW170817




LVC, APJL2017 & PRX9 2019




- The observation cannot discriminate

# Problem II : no ab-initio theory of dense matter

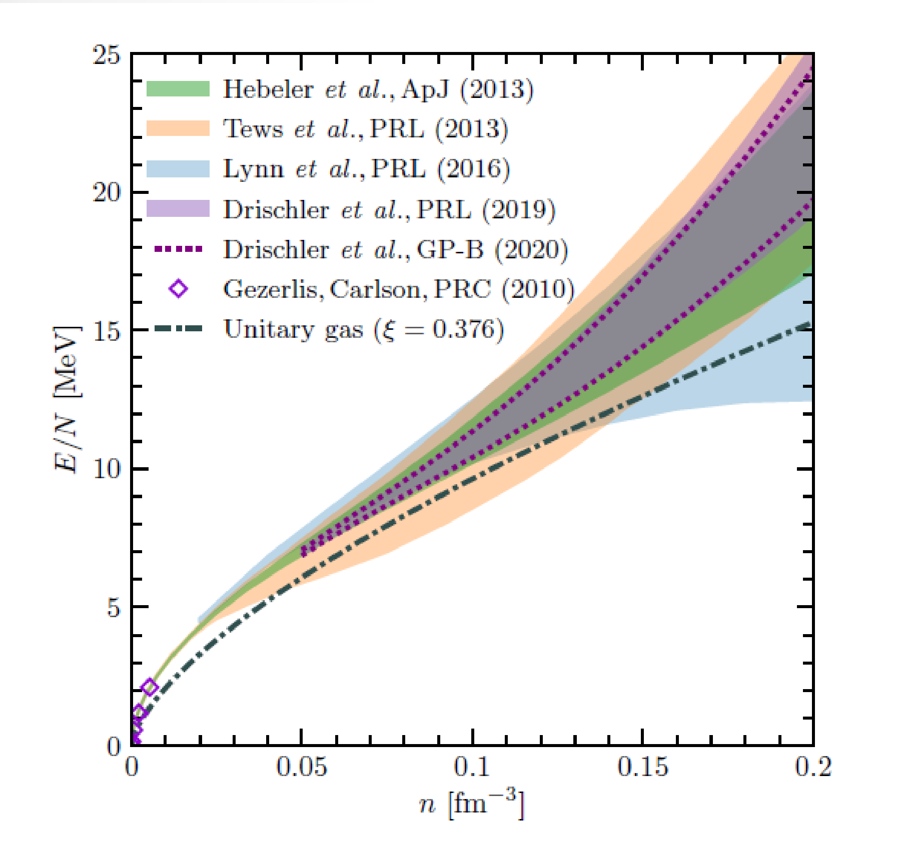
## => Nucleonic « ab-initio » approach

$\Rightarrow$ 2- and 3-body interactions from chiral perturbation theory
$\Rightarrow$ GS from beyond-MF many body techniques (variational, CC,MBPT,QMC...)

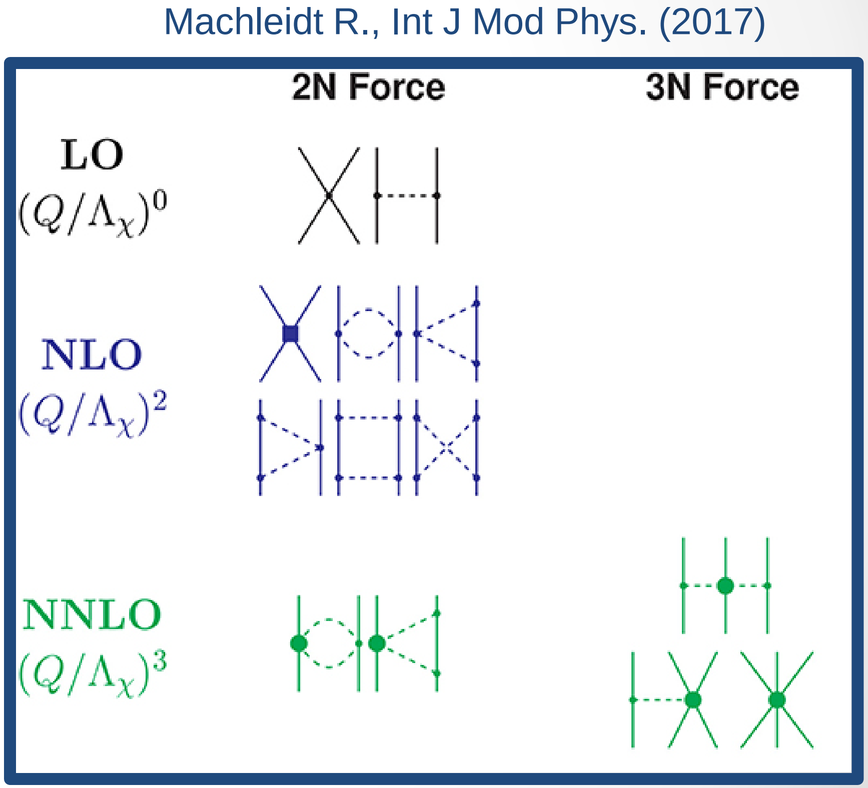
$\Rightarrow$ Contact terms fitted on scattering data and light nuclei
$\Rightarrow e(\rho_n, \rho_p) \quad P(\rho) = -\rho_B^2 \frac{\partial e}{\partial \rho_B}\Big|_{\mu_n - \mu_p = \mu_e,}$

# Nucleonic « ab-initio » approach

- **Diagrammatic expansion: controlled uncertainties!**
- **Still, power counting&regularization valid only up to ~ 1,5$\rho_0$**
- **Extrapolations needed**



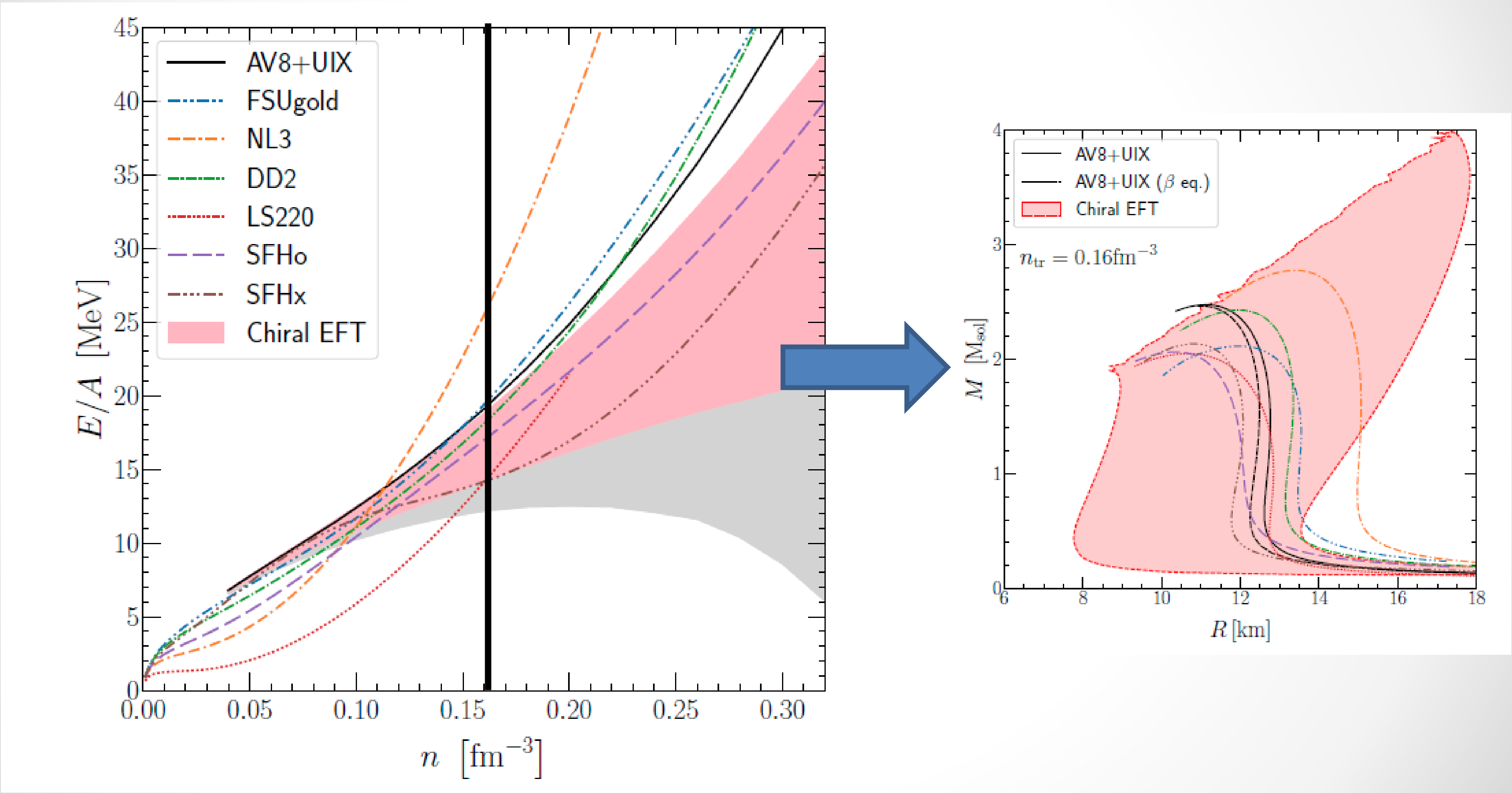

Machleidt R., Int J Mod Phys. (2017)



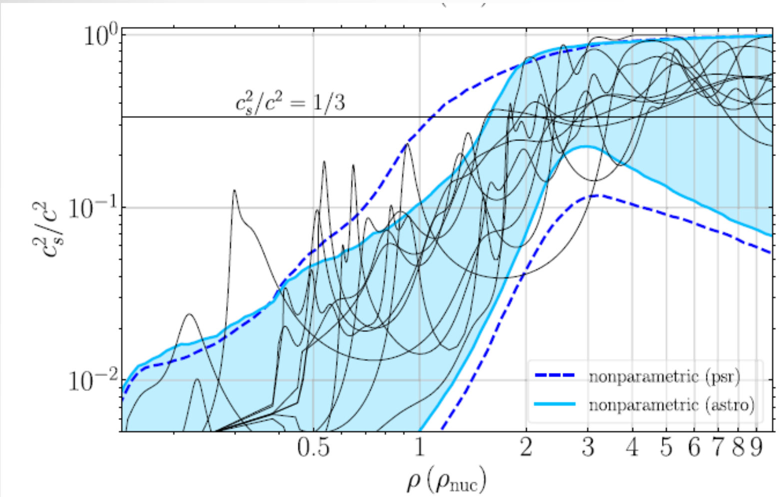

S. Huth, C. Wellenhofer, and A. Schwenk, Phys. Rev. C 103, 025803 (2021).

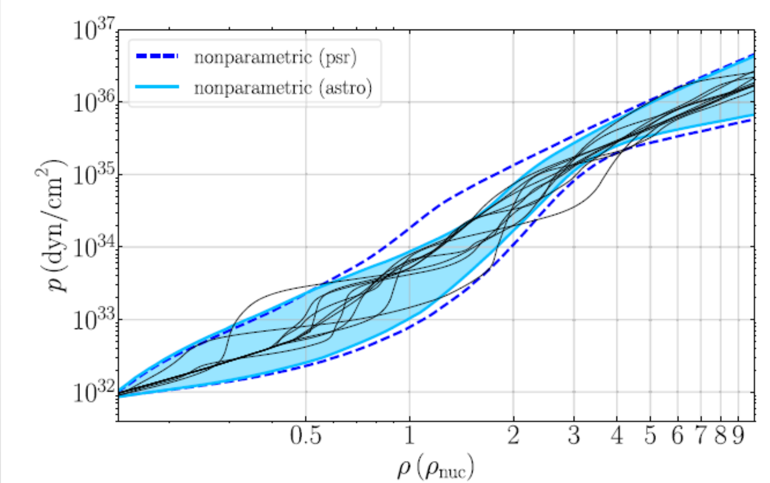
# Nucleonic « ab-initio » approach

Tews, Carlson, Gandolfi, Reddy 2018



# The inversion strategy




- Agnostic EoS only respecting causality and thermodynamical stability
- Example: non-parametric EoS from Gaussian Process

$$\phi(p) = \log\left(\frac{c^2}{c_s^2} - 1\right) = N\left(\mu(p_i), K(p_i, p_j)\right)$$

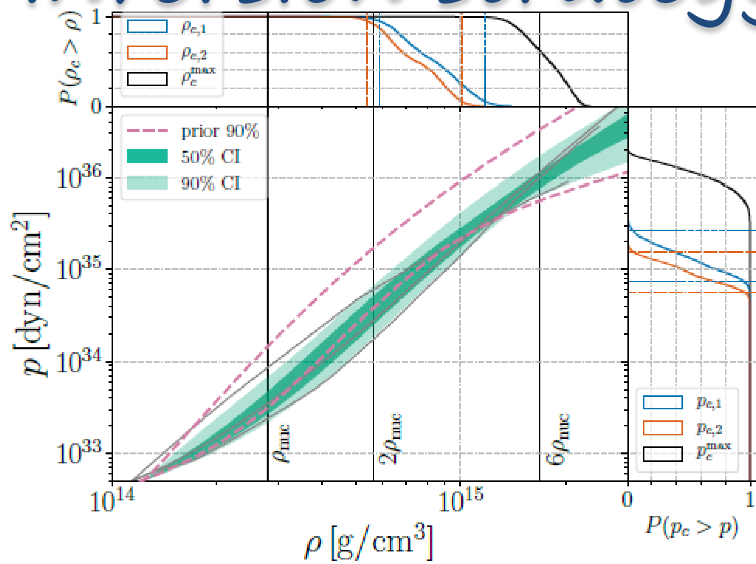
- Bayesian inference

$$P\left(EoS\middle|\vec{f}\right) = \frac{P(EoS)\prod_i P(f_i|EoS)}{P\left(\vec{f}\right)}$$

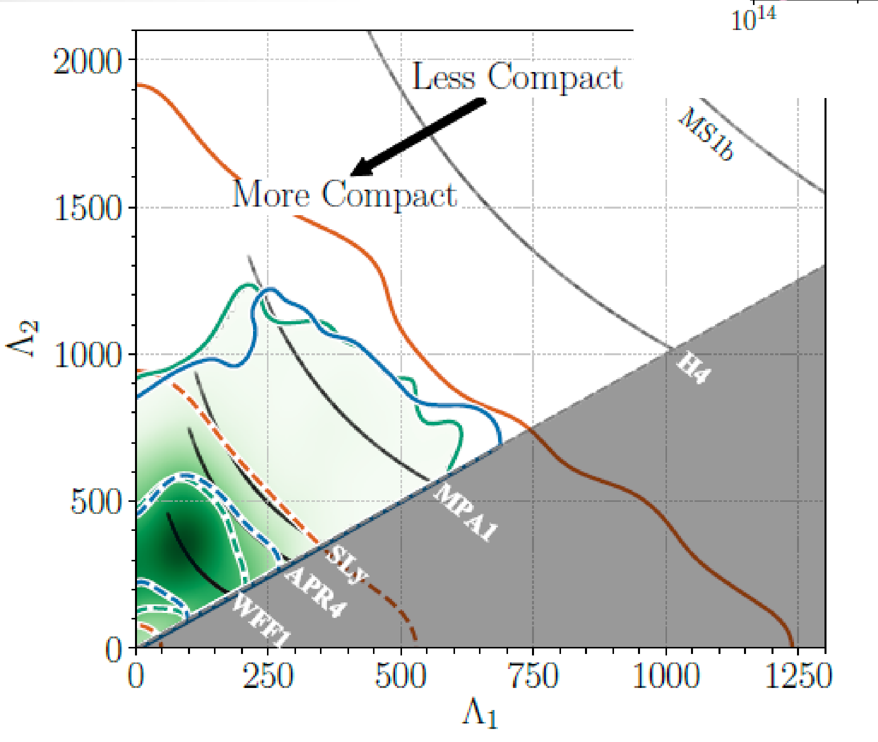
**$f_1$.** max.mass (radio)
**$f_2$.** tidal polarisability (GW)
**$f_3$.** radius (X-ray)

P. Landry and R. Essick, PRD 99, 084049 (2019)
I.Legred et al PRD105, 043016 (2022)

# The inversion strategy




A.Abbott et al, PRL 2018

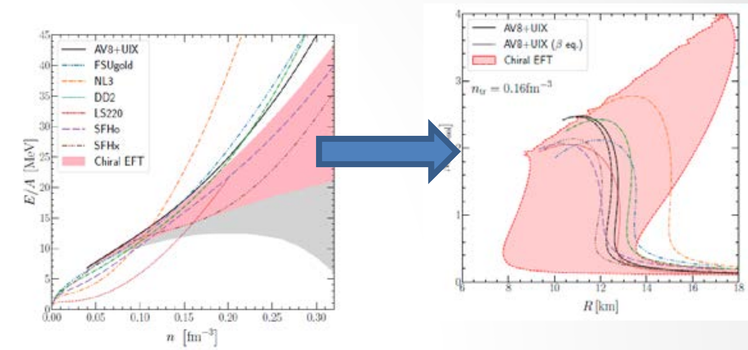



- (Almost) model independent evaluation of the EoS
- Still, we do not learn much about nuclear physics
- We do not exploit our nuclear physics knowledge either

# ...a brief summary $\langle O \rangle \Leftrightarrow P(\rho)$

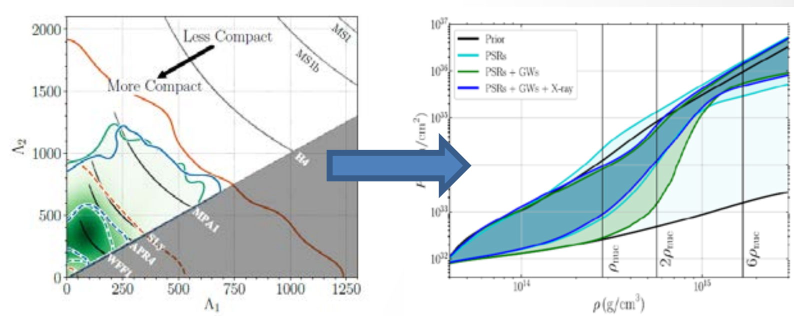
## The nuclear physicist viewpoint: $e(\rho_n,\rho_p) \Rightarrow P(\rho) \Rightarrow \langle O \rangle$

- Controlled dof, hypotheses and approximations, exp info included
- Still, the predictive power is limited




## The astrophysicist viewpoint: $\langle O \rangle \Rightarrow P(\rho)$

- Non-parametric representation: model independent evaluation of the EoS
- Still, we do not learn much about dense matter




# A nuclear-astrophysicist viewpoint: meeting in the middle...

# General EoS modelling: the syllabus

- An agnostic (parametric) representation $\cancel{P(\rho)}$ $e_{\vec{X}}(\rho_n, \rho_p)$: the variation of the parameter set $\vec{X}$ allows reproducing the different nuclear models and interpolating among them ~ 15 parameters – RMF and EDF versions
- The $X_i$ variation explores the equation of state space compatible with the hypothesis of a matter of neutrons and protons

A.Steiner et al ApJ 2010
A.Bulgac et al 2016
J.Margueron et al PRC 2018
Y. Lim, J.W. Holt, PRL 2018
C.Mondal et al, PRC 2022
P.Char et al, PRD 2023
G.Montefusco et al, A&A 2025
H.Koehn et al, PRX 2025
............................

$$P(\rho) = -\rho^2 \frac{\partial e(\rho_n,\rho_p)}{\partial \rho}\bigg|_{\mu_L=0}$$ and also

$y_e(\rho)|_{\mu_L=0}, P(\rho, y_e, T)$ for the SN and merger simulations

$$\boxed{r_i, BE_i} \Leftarrow \boxed{e_{\vec{X}}(\rho_n, \rho_p)} \Rightarrow \boxed{\mathrm{M, R}, \Lambda}$$

Laboratory observables

Nuclear model

Astronomical observables

# Bayesian Inference

$$P\left(EoS\middle|\vec{f}\right) = \frac{P(EoS)\prod_i P(f_i|EoS)}{P(\vec{f})}$$ (MCMC or Nested Sampling)

**f$_1$.** nuclear structure data
**f$_2$.** ab-initio theory (chiral)
**f$_3$.** HI collisions

**Nuclear physics**

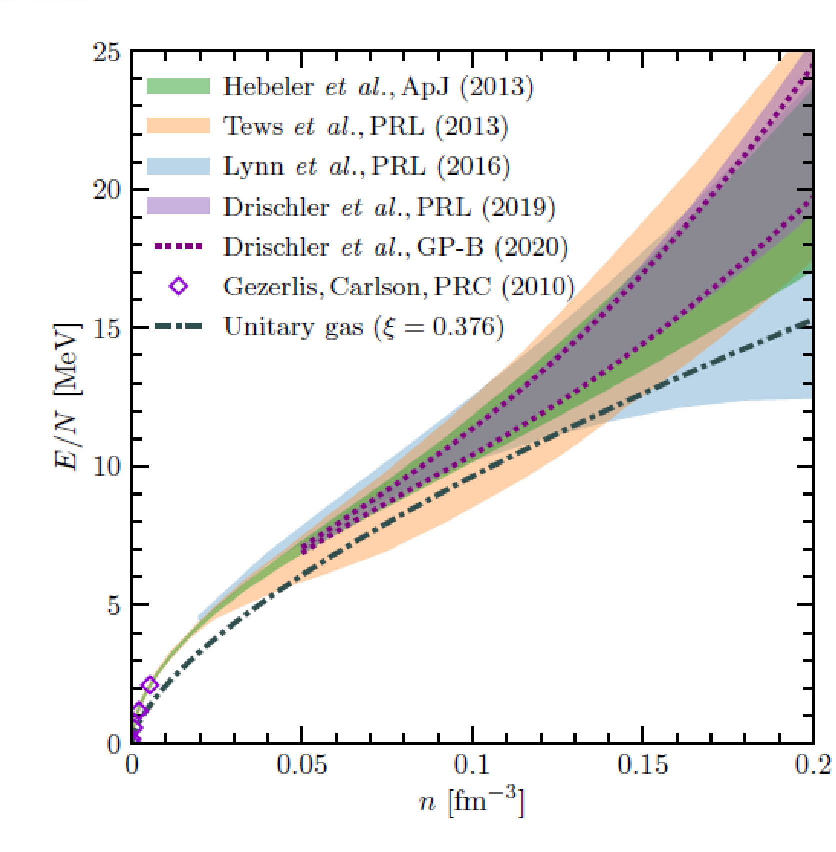
**f$_4$.** max.mass (radio)
**f$_5$.** tidal polarisability (GW)
**f$_6$.** radius (X-ray)
**f$_7$.** multi-messenger

**Astrophysics**

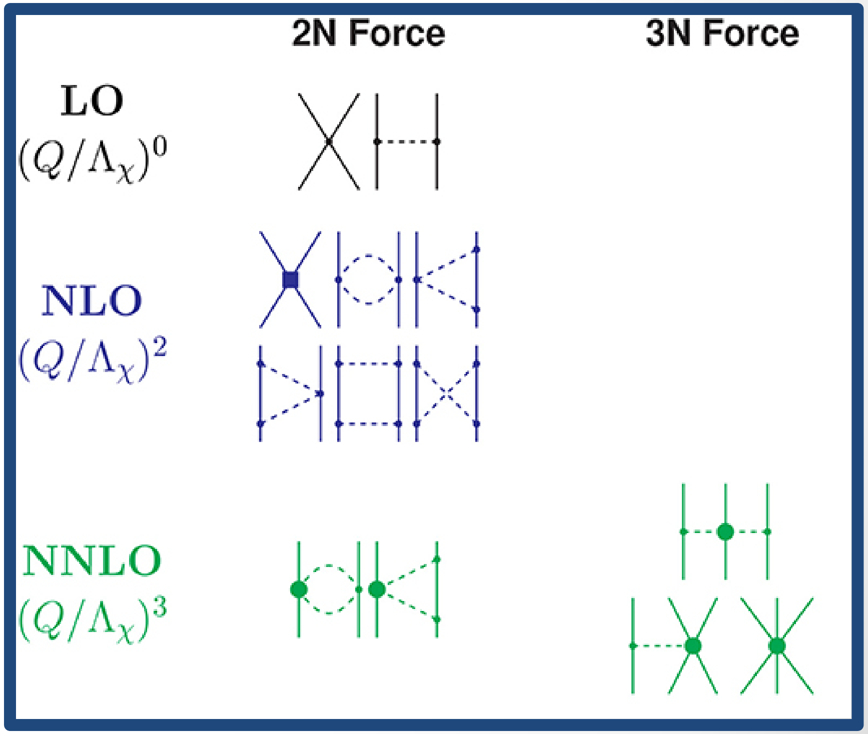
(3) PSR J0348+0432 M=2.01±0.04 $M_O$
(4) GW170817 $\widetilde{\Lambda}(M)$ LVK
(5) PSRJ0030+0451, PSRJ0740+6620 NICER (+ PSR10030-0451, PSRJ0614−3329)

# Ab-initio nuclear theory

- interaction from $\chi$-EFT, different many body methods (MBPT,AFMC)
  Diagrammatic expansion : controlled truncation errors
- Moment expansion! Only valid at low density




Machleidt R., Int J Mod Phys. (2017)



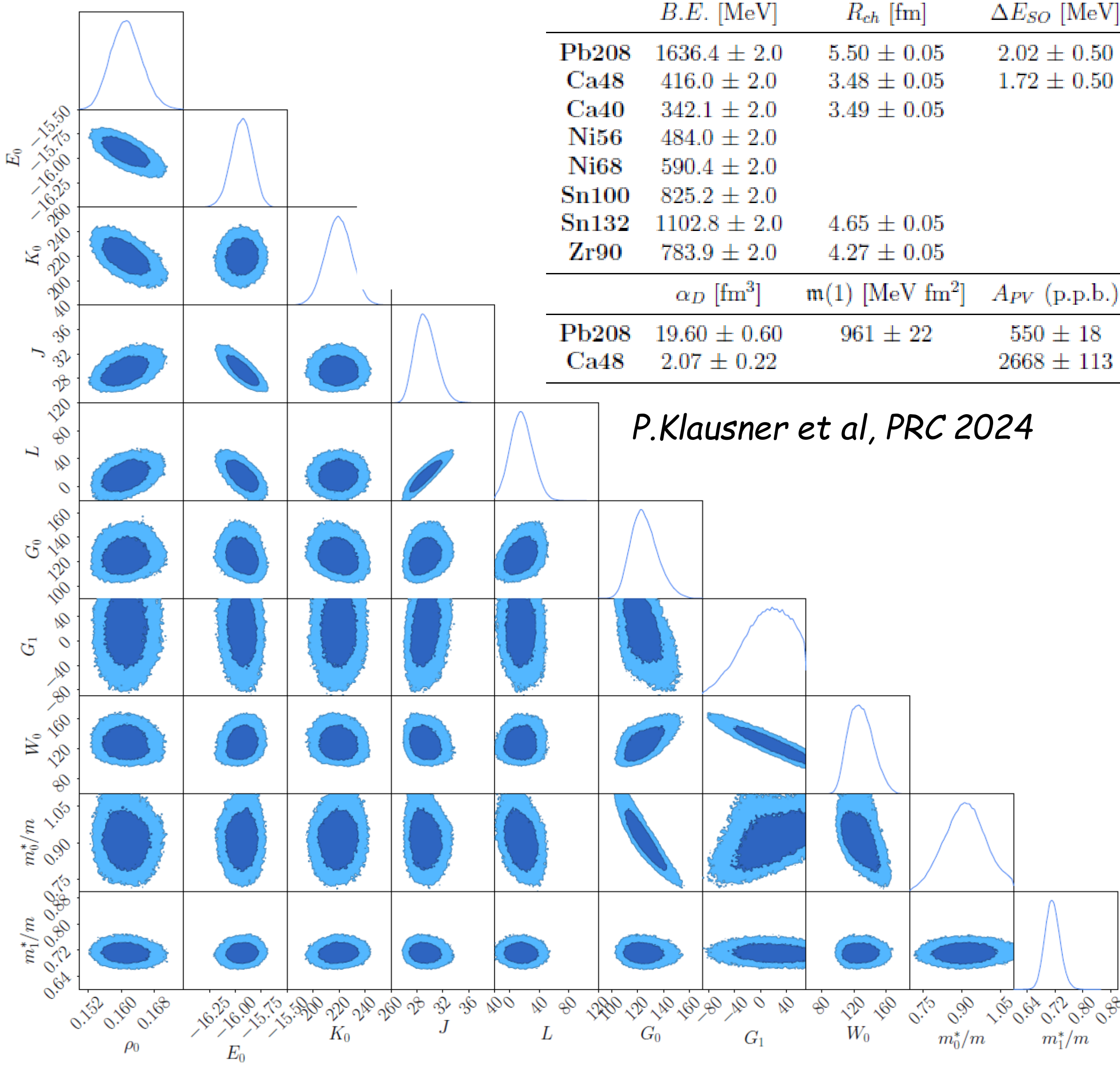

S. Huth, C. Wellenhofer, and A. Schwenk, Phys. Rev. C 103, 025803 (2021).

# Laboratory experiments

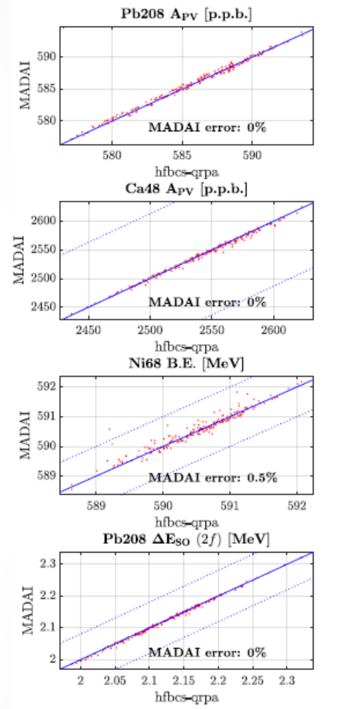
| | $B.E.$ [MeV] | $R_{ch}$ [fm] | $\Delta E_{SO}$ [MeV] | $E^{IS}_{GMR}$ [MeV] |
|---|---|---|---|---|
| **Pb208** | 1636.4 ± 2.0 | 5.50 ± 0.05 | 2.02 ± 0.50 | 13.5 ± 0.5 |
| **Ca48** | 416.0 ± 2.0 | 3.48 ± 0.05 | 1.72 ± 0.50 | |
| **Ca40** | 342.1 ± 2.0 | 3.49 ± 0.05 | | |
| **Ni56** | 484.0 ± 2.0 | | | |
| **Ni68** | 590.4 ± 2.0 | | | |
| **Sn100** | 825.2 ± 2.0 | | | |
| **Sn132** | 1102.8 ± 2.0 | 4.65 ± 0.05 | | |
| **Zr90** | 783.9 ± 2.0 | 4.27 ± 0.05 | | 17.7 ± 0.5 |

| | $\alpha_D$ [fm$^3$] | $\mathfrak{m}(1)$ [MeV fm$^2$] | $A_{PV}$ (p.p.b.) | $E^{IS}_{GQR}$ [MeV] |
|---|---|---|---|---|
| **Pb208** | 19.60 ± 0.60 | 961 ± 22 | 550 ± 18 | 10.9 ± 0.5 |
| **Ca48** | 2.07 ± 0.22 | | 2668 ± 113 | |

*P.Klausner et al, PRC 2024*

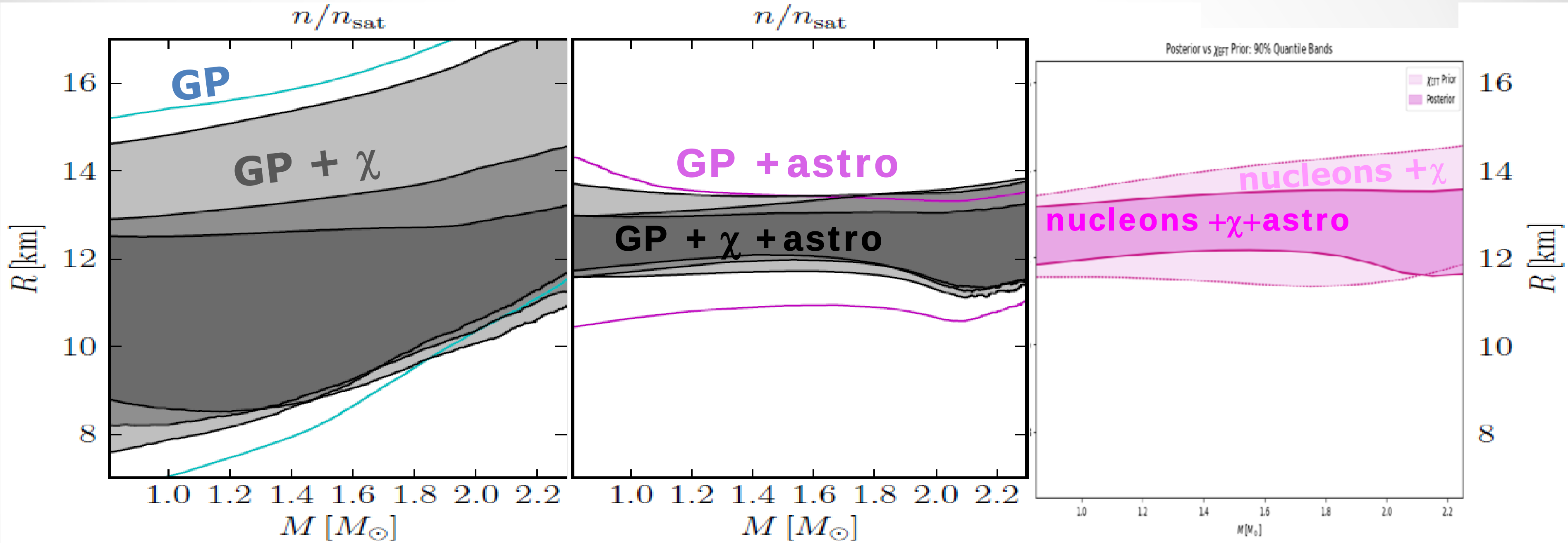



madai.phy.duke.edu



# Agnostic versus nucleonic

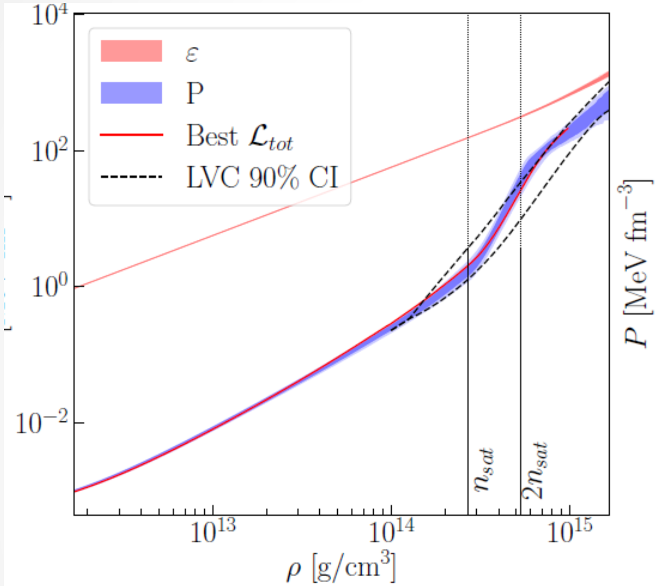
R.Essick et al, PRC 2020 G.Montefusco et al, A&A 2025

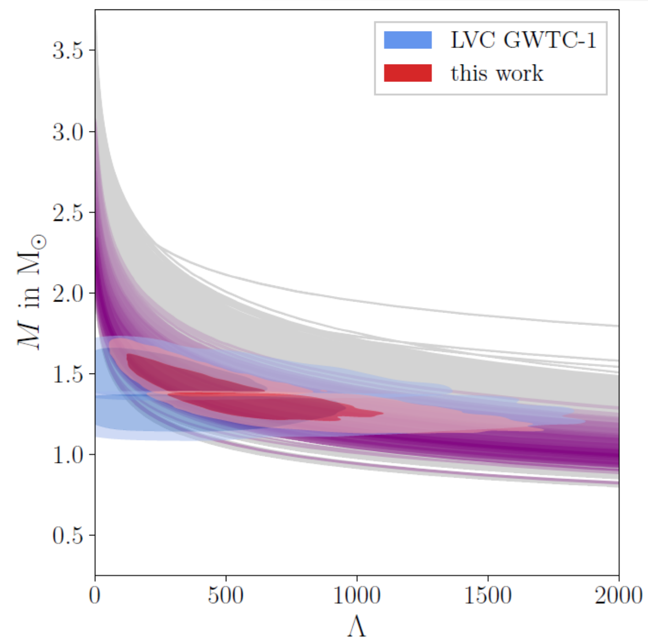



- Prior distributions are larger with agnostic models (GP)
- Distributions are very comparable with chiral (χ)+astro => the nucleonic models do cover all the parameter space compatible with the observations ! => the observations are compatible with a pure nucleonic composition

# Agnostic versus nucleonic

P.Klausner et al, ArXiV 2025

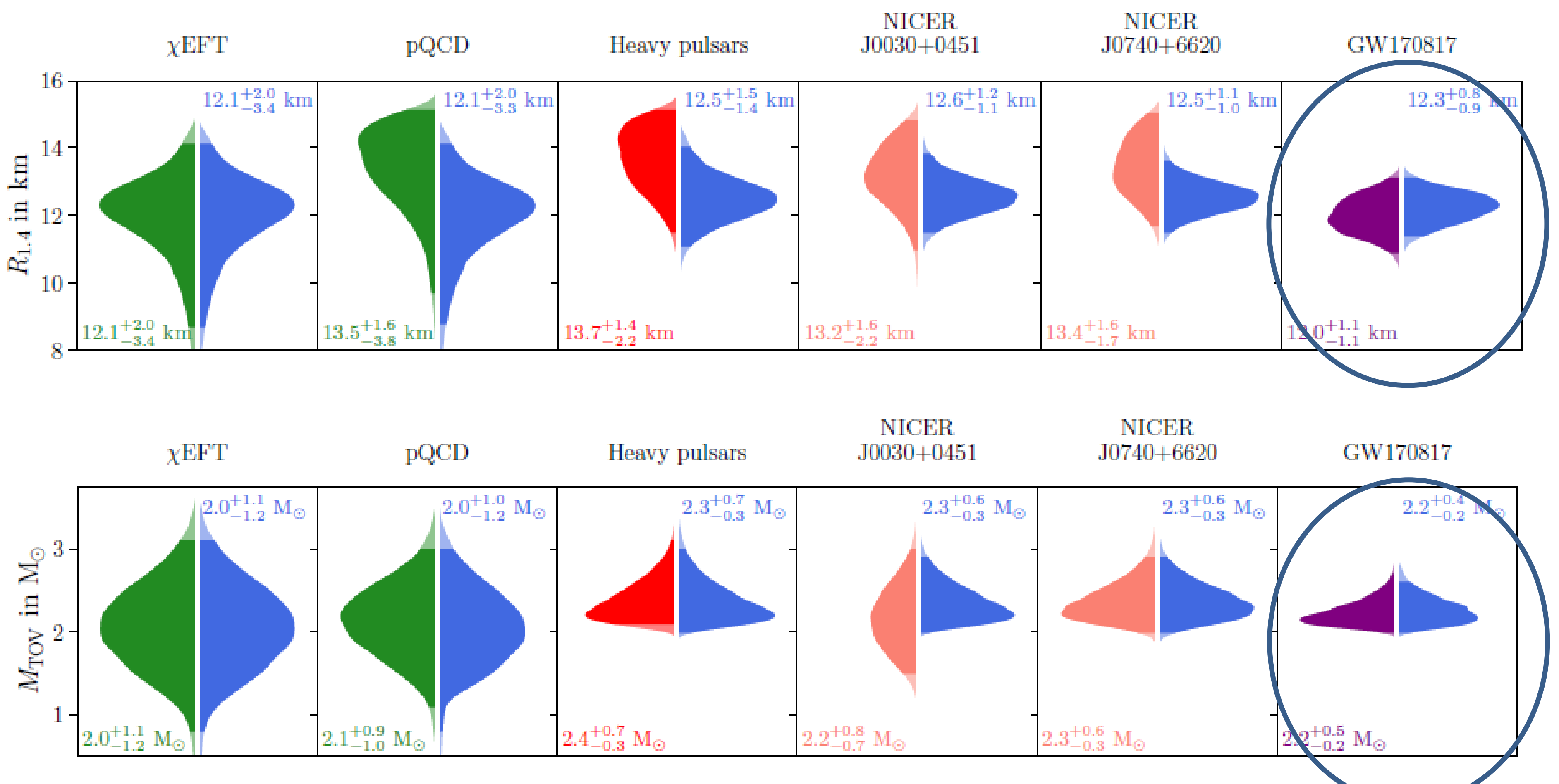



H.Koehn et al, PRX 2025

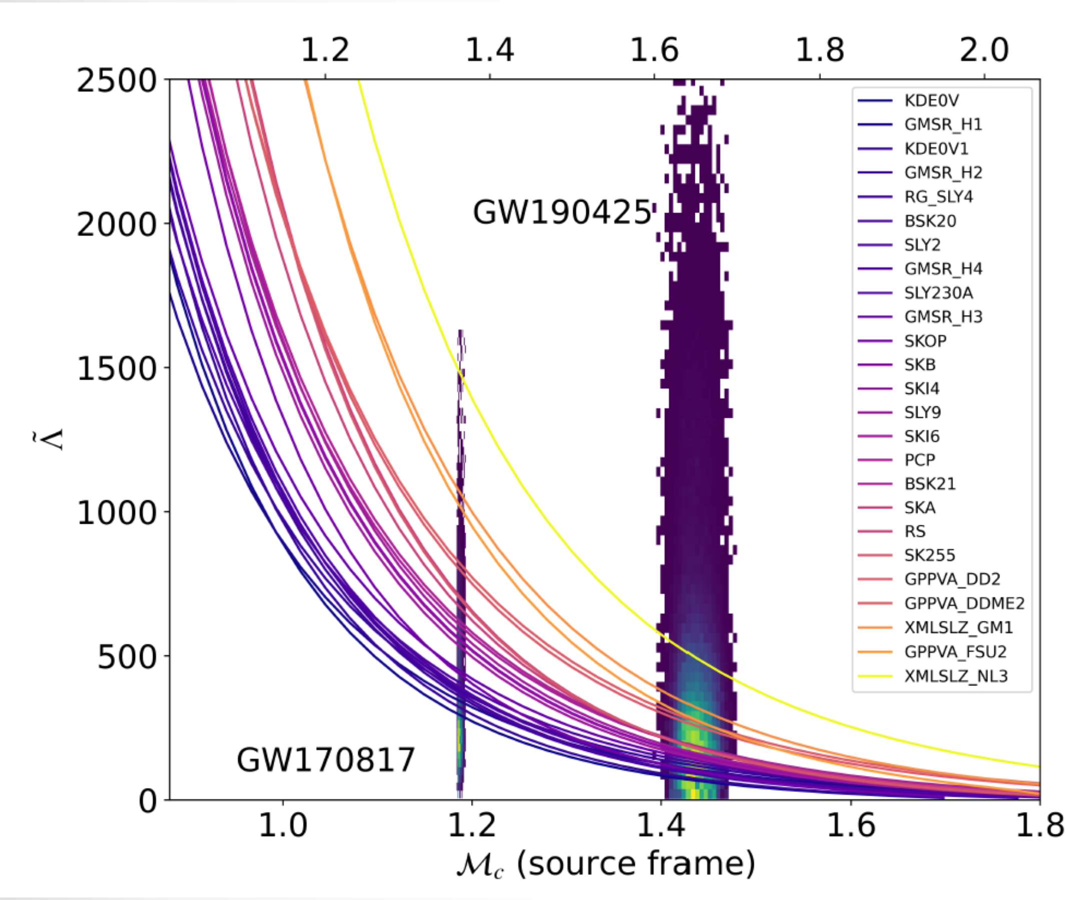
- Prior distributions are larger with agnostic models (GP)
- Distributions are very comparable with chiral ($\chi$)+astro => the nucleonic models do cover all the parameter space compatible with the observations ! => the observations are compatible with a pure nucleonic distribution
- **Distributions get shrinked when nuclear experiments are included => potential challenge of the nucleonic hypothesis!**

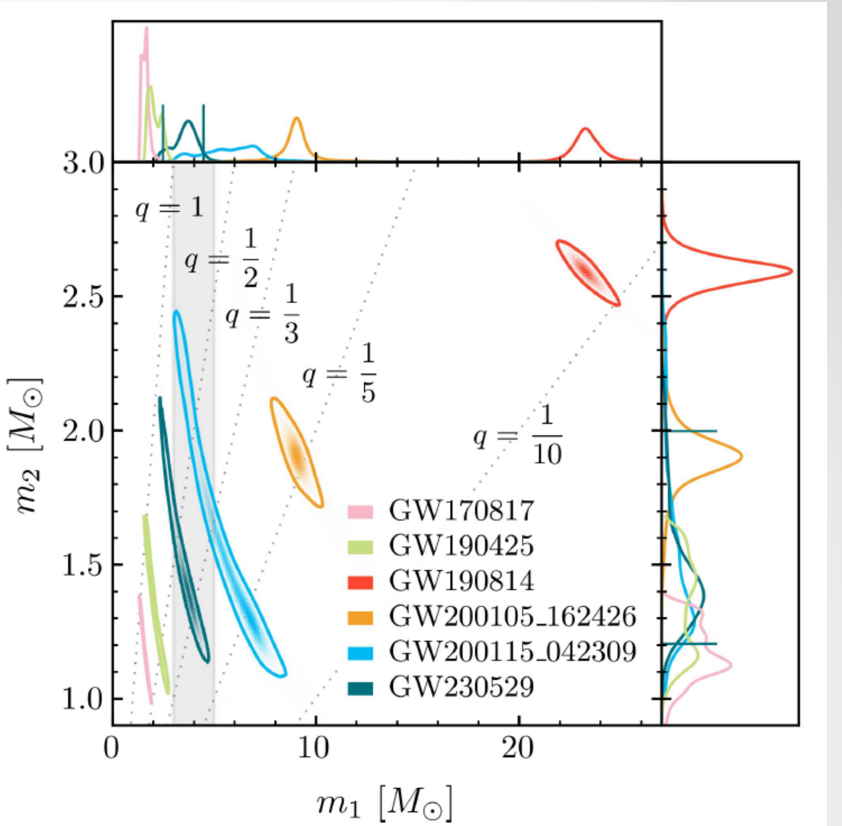
# The importance of the GW signal

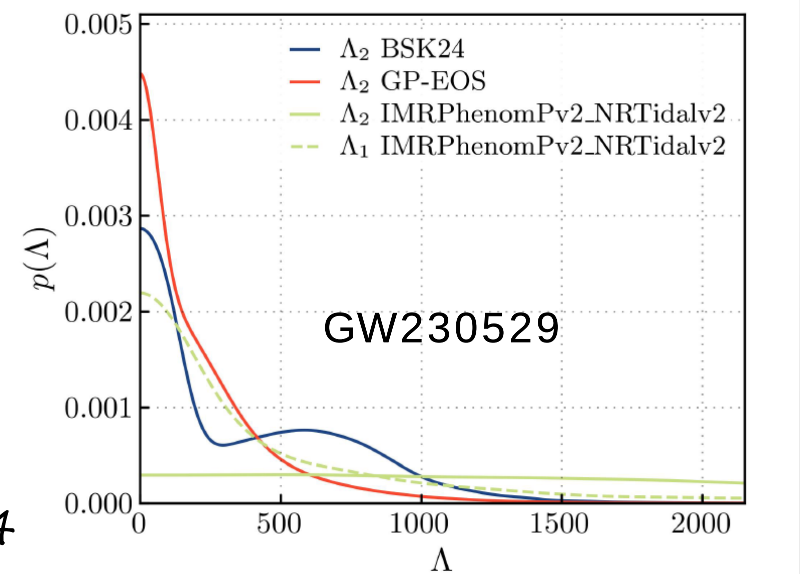



H.Koehn et al, PRX 2025

# GW info after GW170817

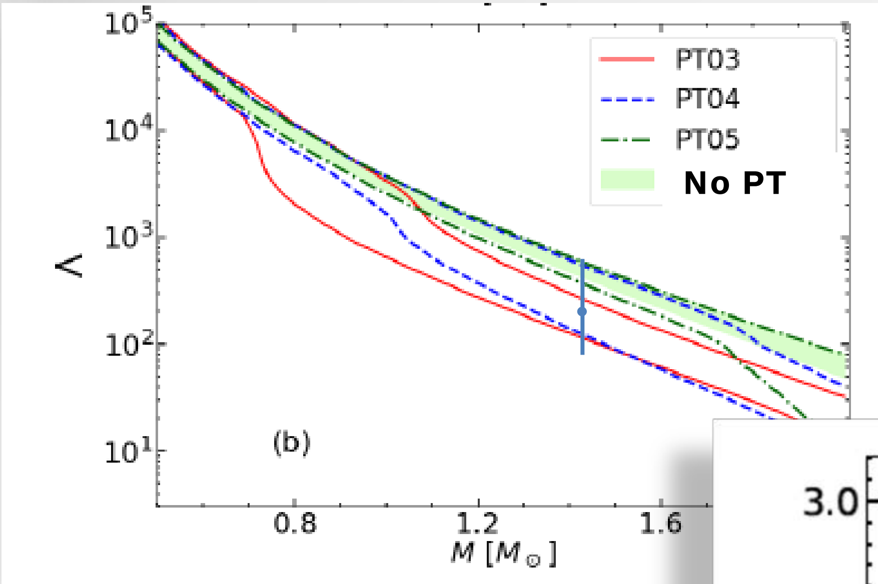


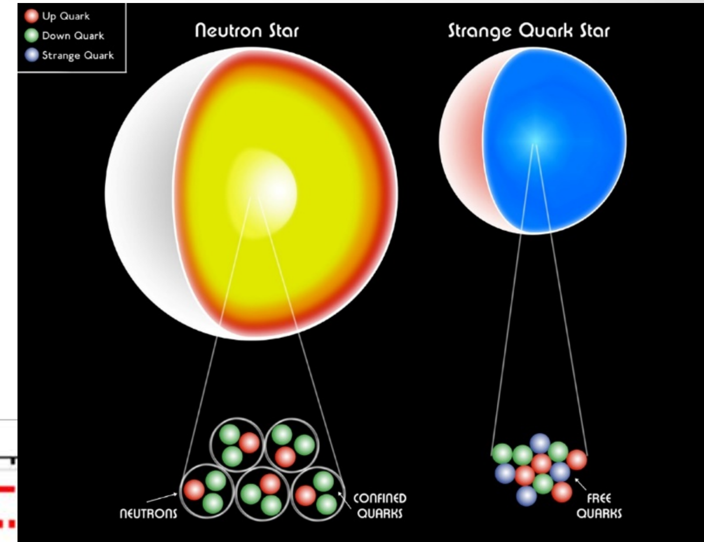



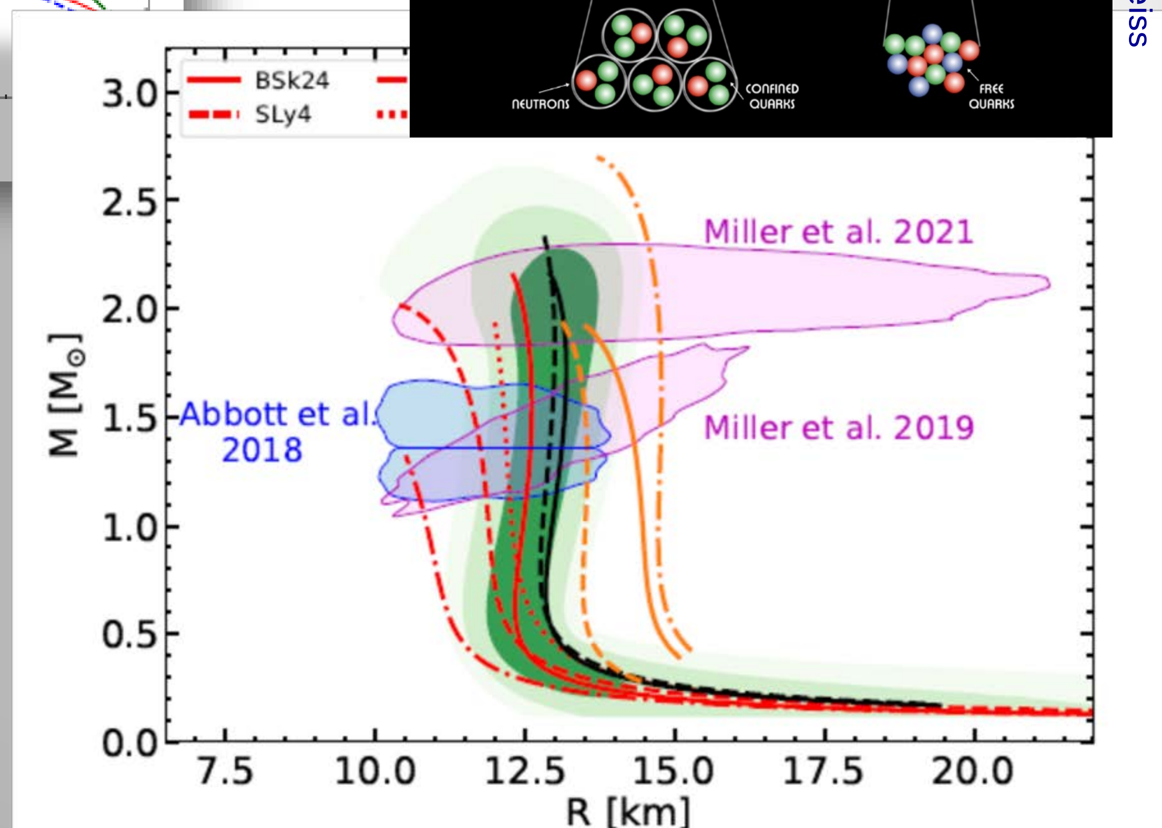

A.Abac et al, ApJL 2024

# Quarks in the core of neutron stars ?



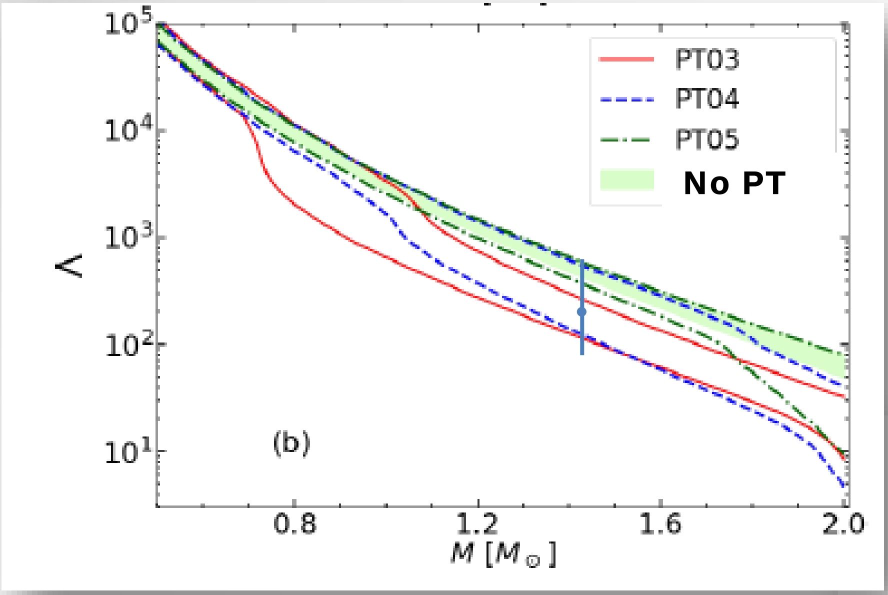

Credits: CXC/M.Weiss



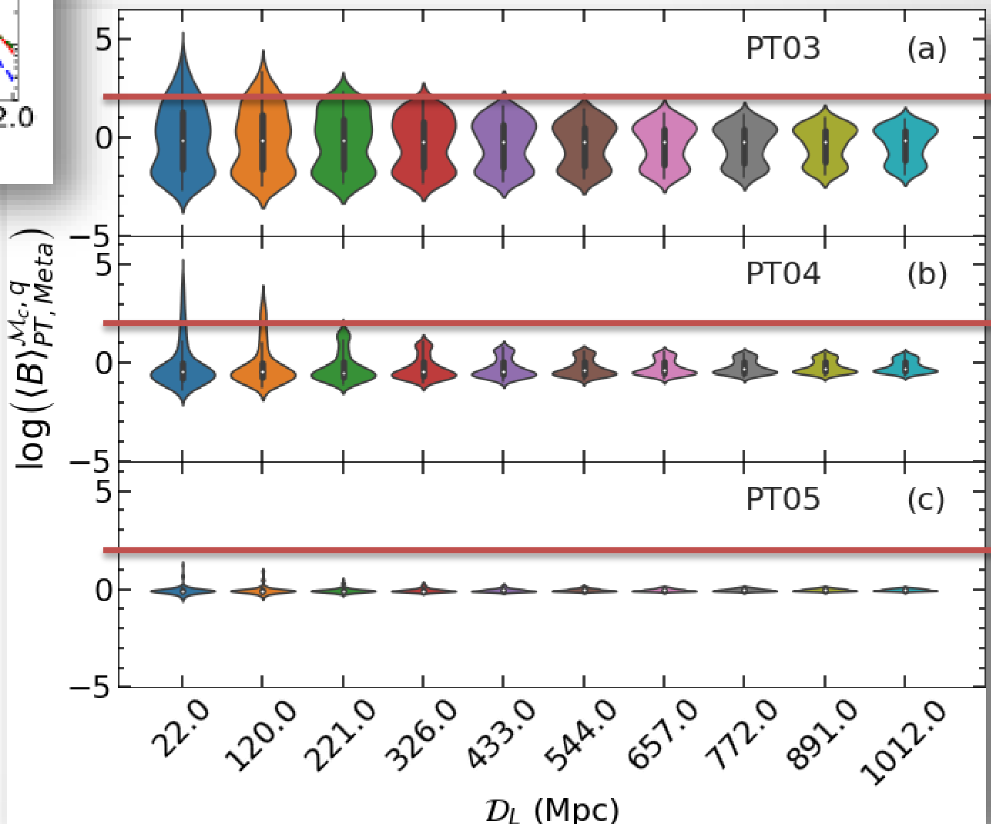

H.Dinh Thi et al, A&A 2021

- The observations are compatible with a pure nucleonic composition

# Quarks in the core of neutron stars ?




- The observations are compatible with a pure nucleonic composition
- Even with AdV+ sensitivity, only a very close detection would allow identifying deconfined matter, and only if the quark core is large



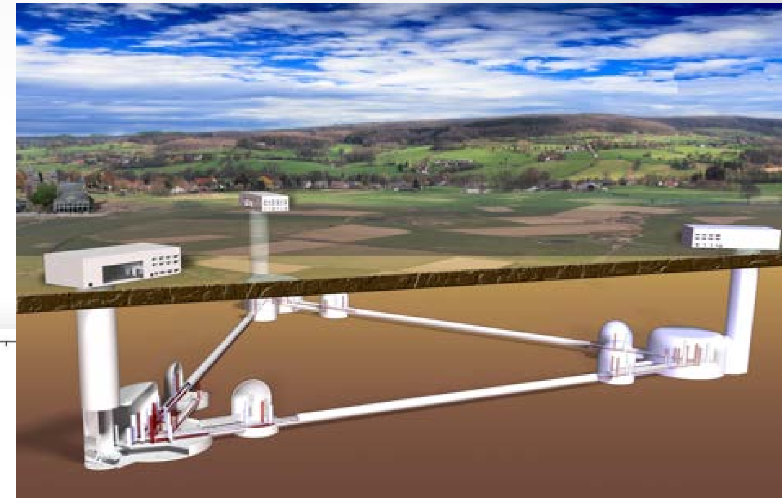

- Need to reduce the uncertainties!
  - New nuclear observables
  - Multiple detections with better SNR=> Einstein Telescope, Cosmic Explorer

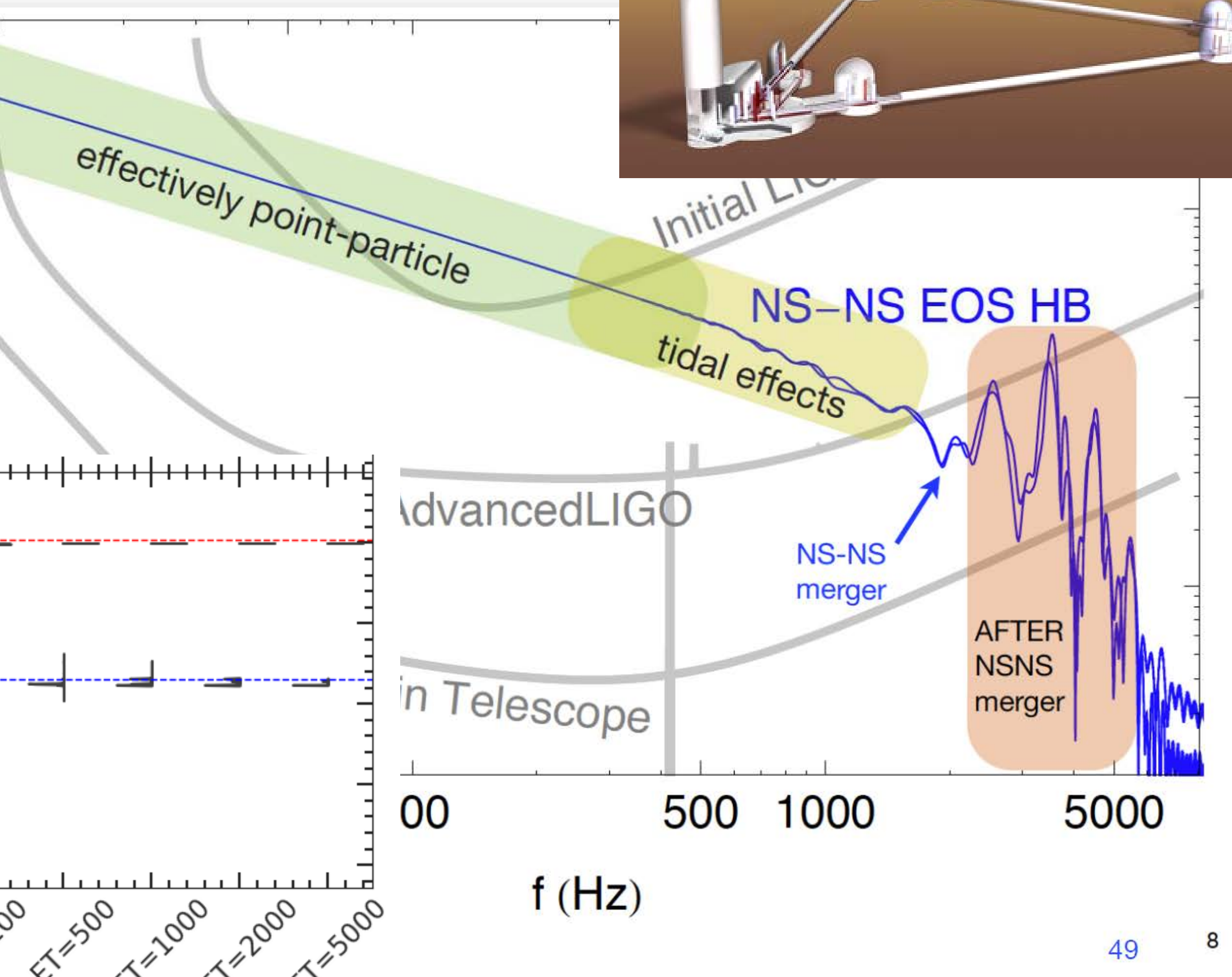
C.Mondal et al, MNRAS 2023

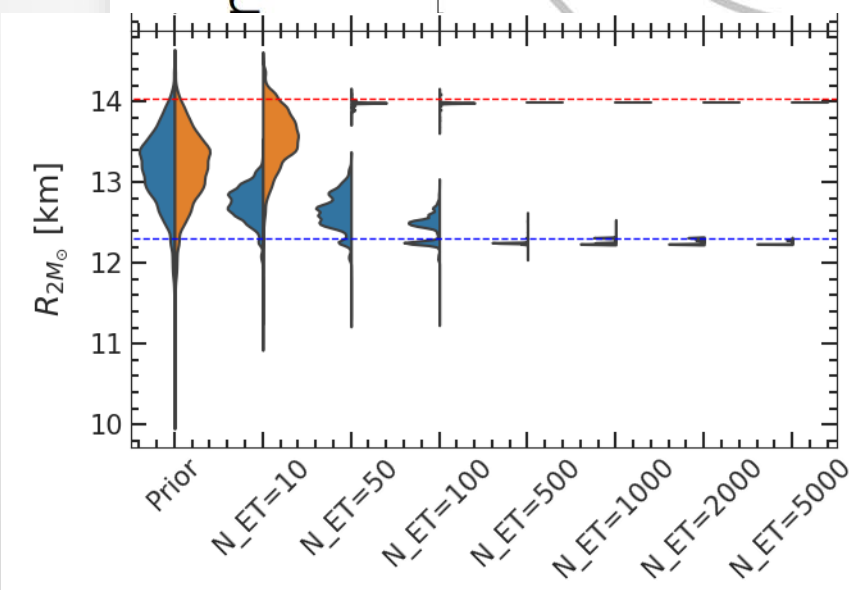
-

# The Einstein Telescope project

F.Iacovelli, C.Mondal et al, PRD 2023





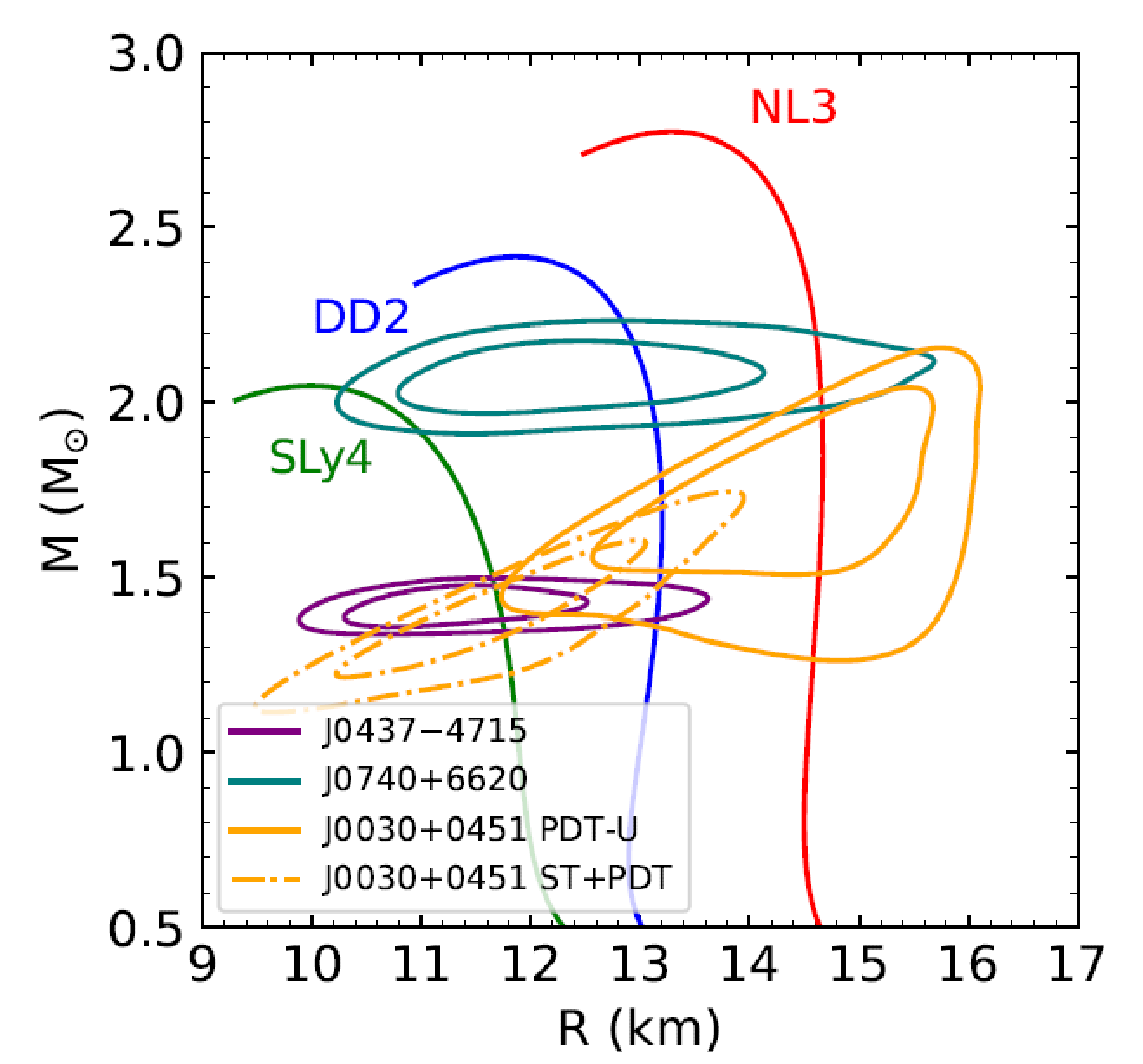



# Summary & Conclusions

- The Equation of State can be univocally mapped to the static properties of NS ⇔ to the GW signals from NS mergers
- No ab-initio model of nuclear matter for all densities! But Bayesian techniques allow controlled extrapolations of low density constraints from nuclear theory and experiments

  **=> No present indication of exotic degrees of freedom**
- Relatively tight observable prediction within the nucleonic hypothesis

  **=> A 1st order phase transition to deconfined matter can potentially be detected with 3G interferometers**



NL3
DD2
SLy4
J0437−4715
J0740+6620
J0030+0451 PDT-U
J0030+0451 ST+PDT
3.0
2.5
2.0
1.5
1.0
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9
10
11
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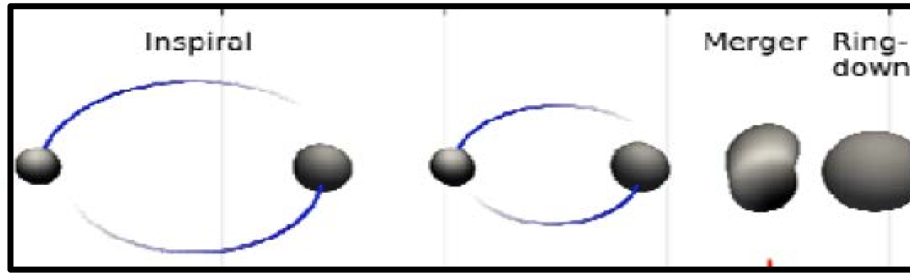
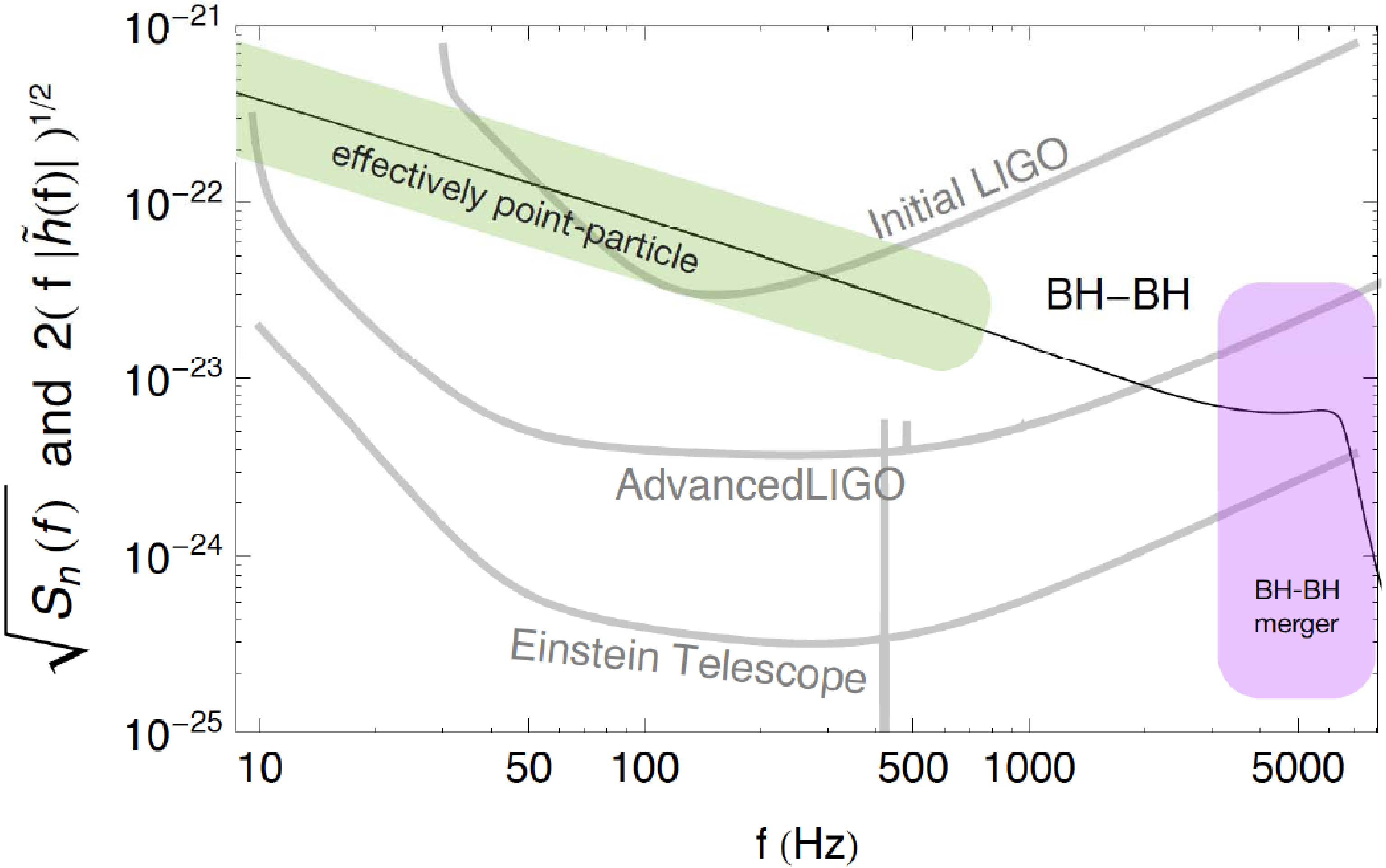
13
14
15
16
17
M ($M_\odot$)
R (km)

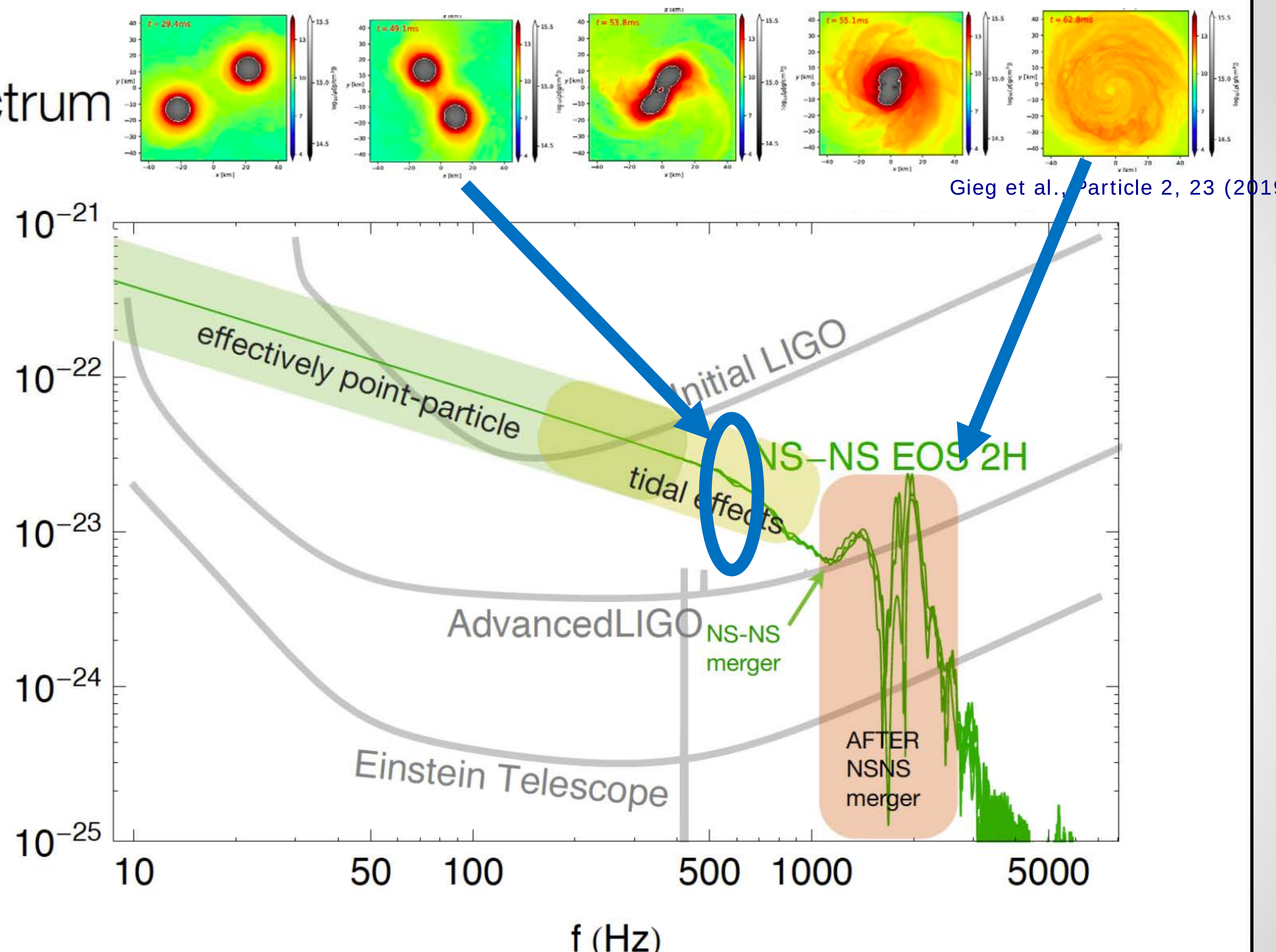
Spectrum of BBH inspiral,



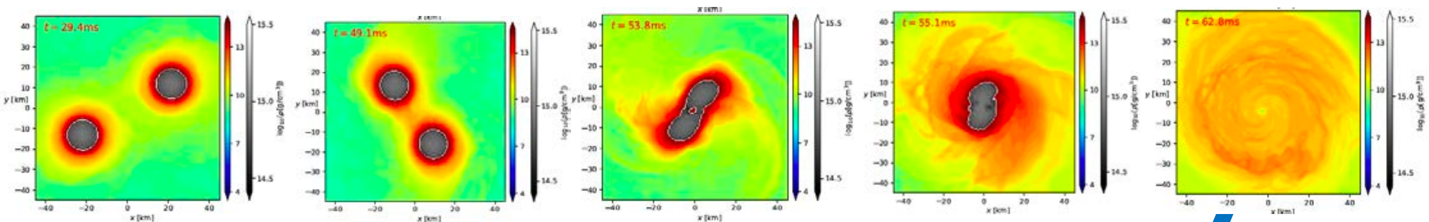

J. Read, CGWAS 2015

Spectrum

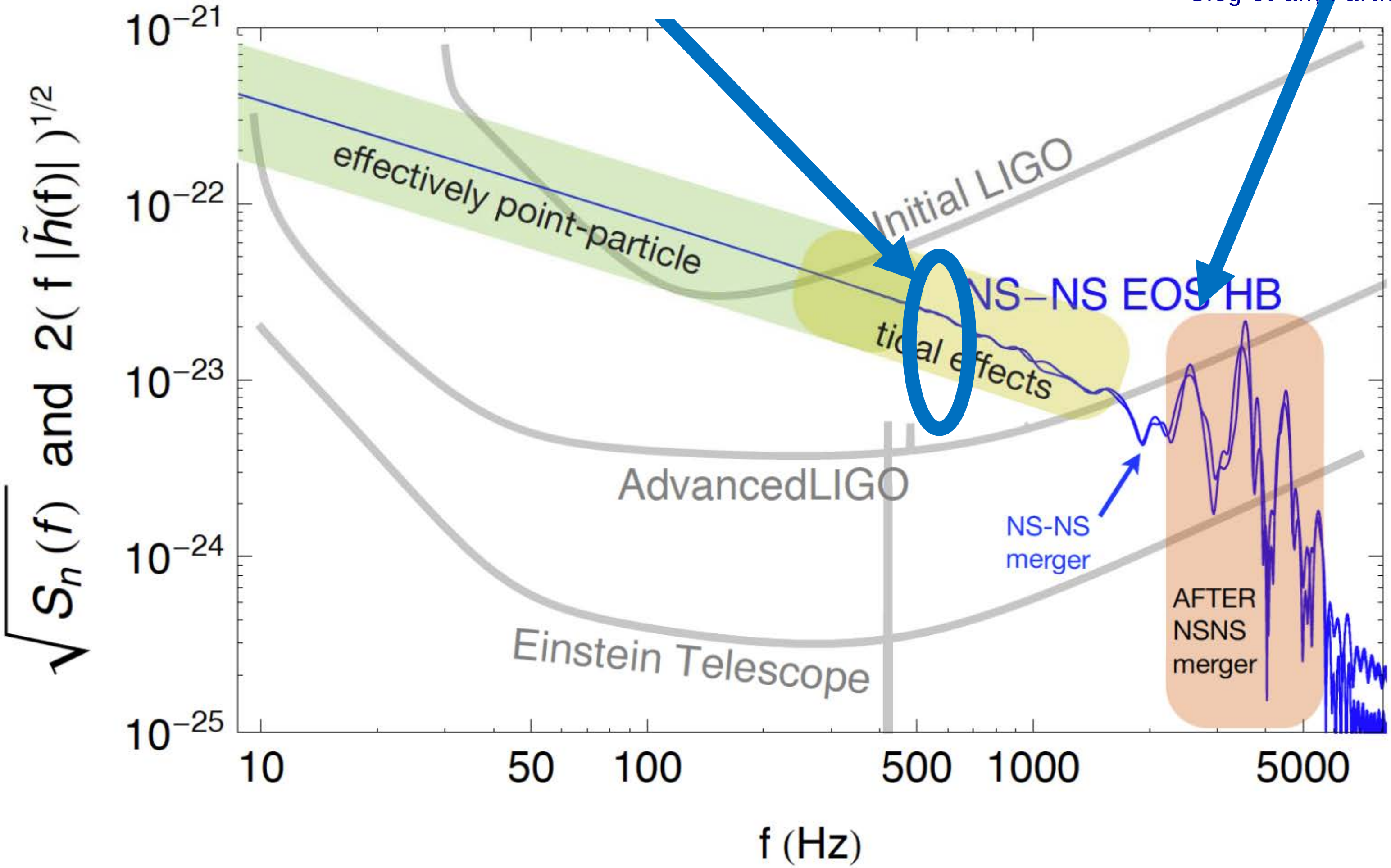



J. Read, CGWAS 2015

# Spectrum

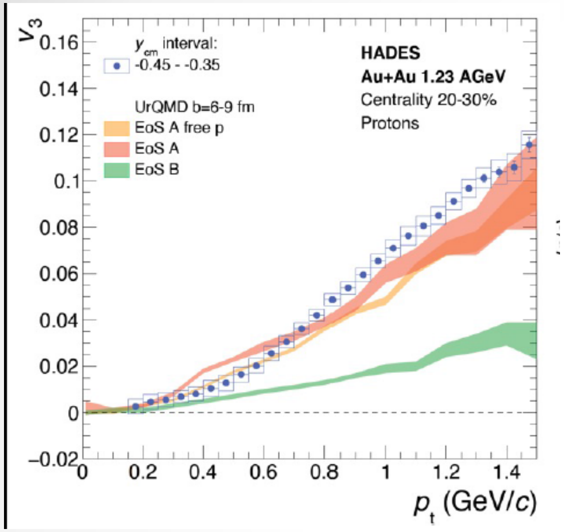


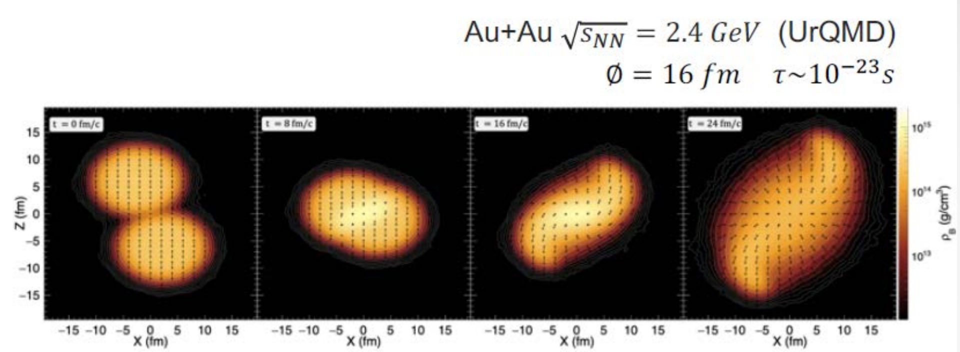
Gieg et al., Particle 2, 23 (2019



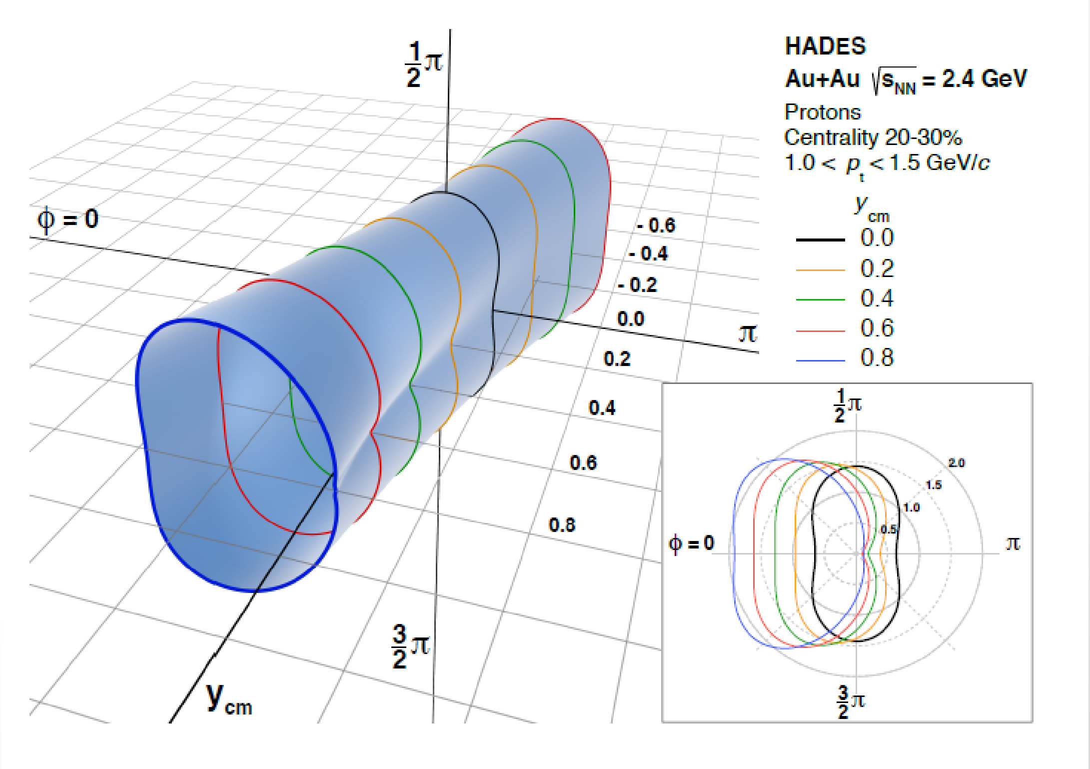

J. Read, CGWAS 2015

# The HI collisions probe




HADES collaboration
PRL 125 (2020) 262301



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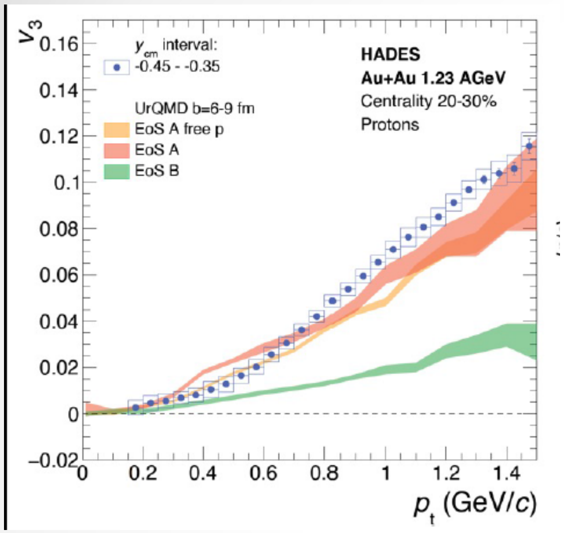
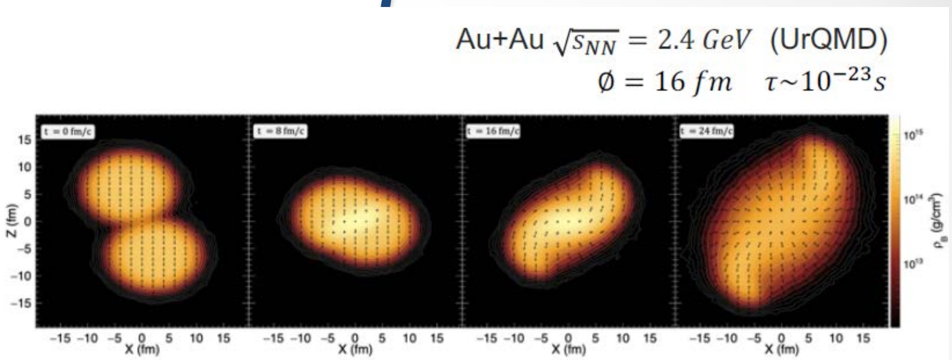
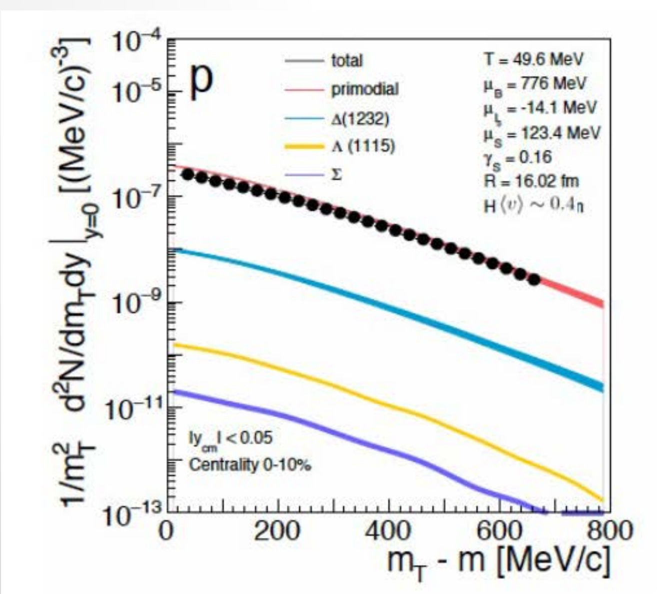
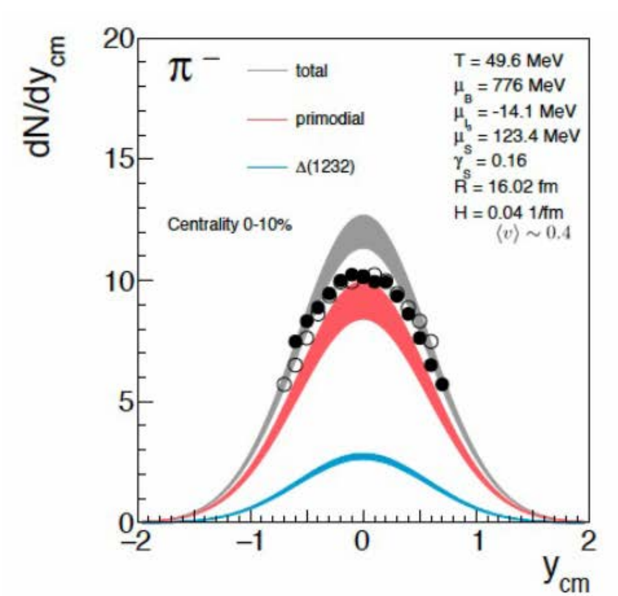


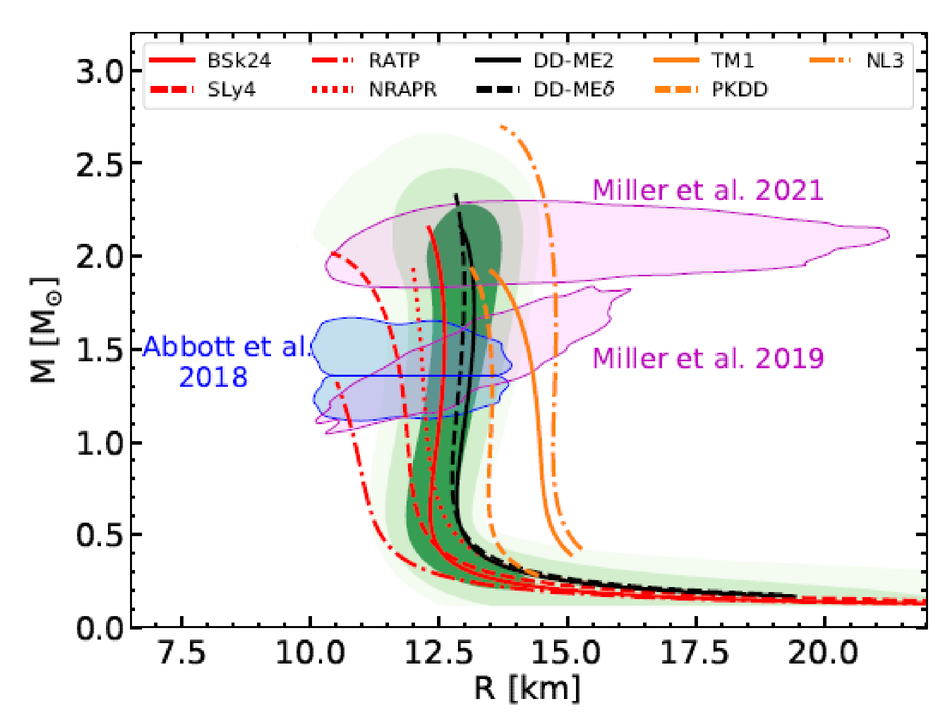




S.Harabasz PRC102 (2020) 054903



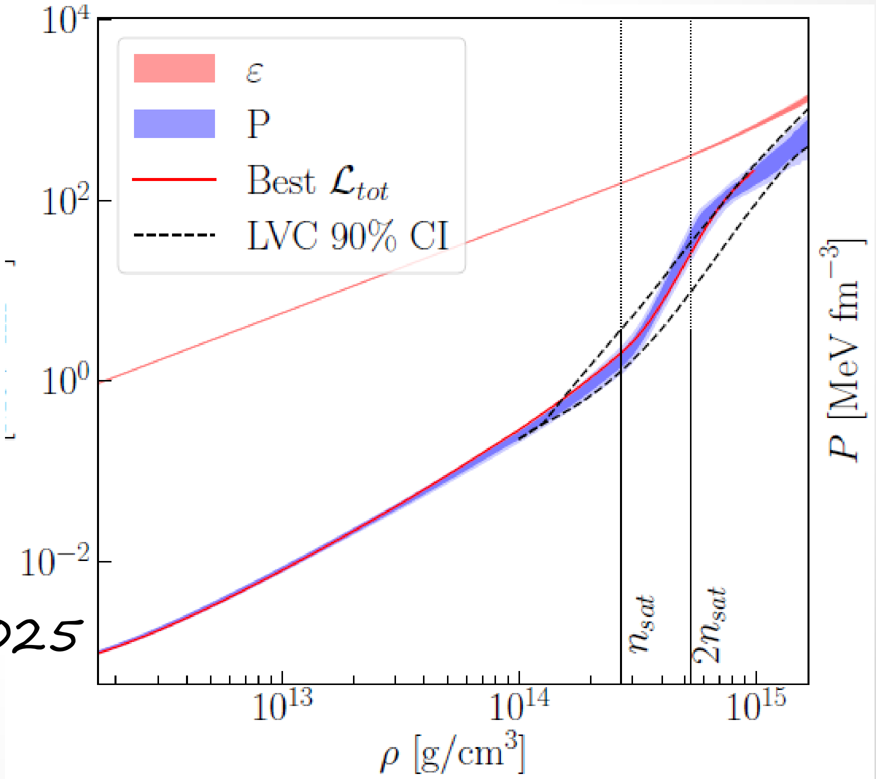



# Nuclear physics informed predictions



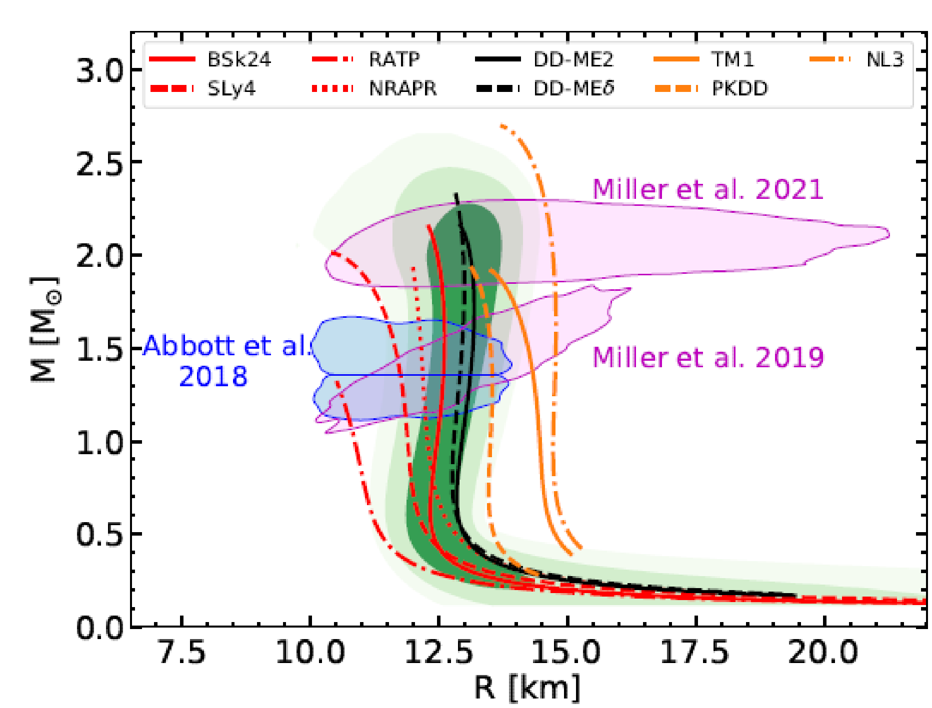

H.Dinh Thi et al, A&A 2021

- Nuclear constraints are very important up to ~2$n_{sat}$
- Many models can be excluded
- A neutrons and protons composition is compatible with the observations




P.Klausner et al, ArXiV 2025

# Nuclear physics informed predictions




H.Dinh Thi et al, A&A 2021

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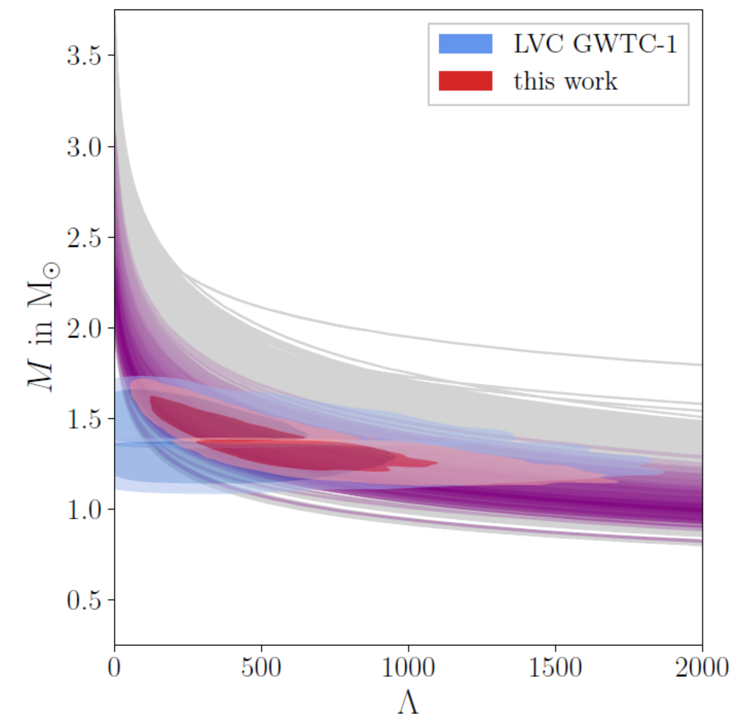
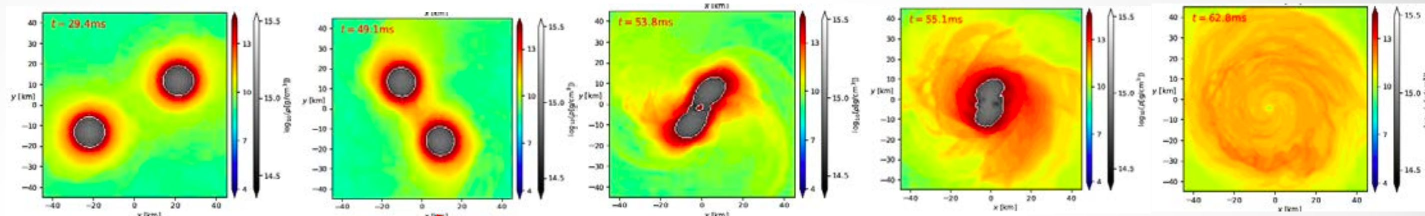
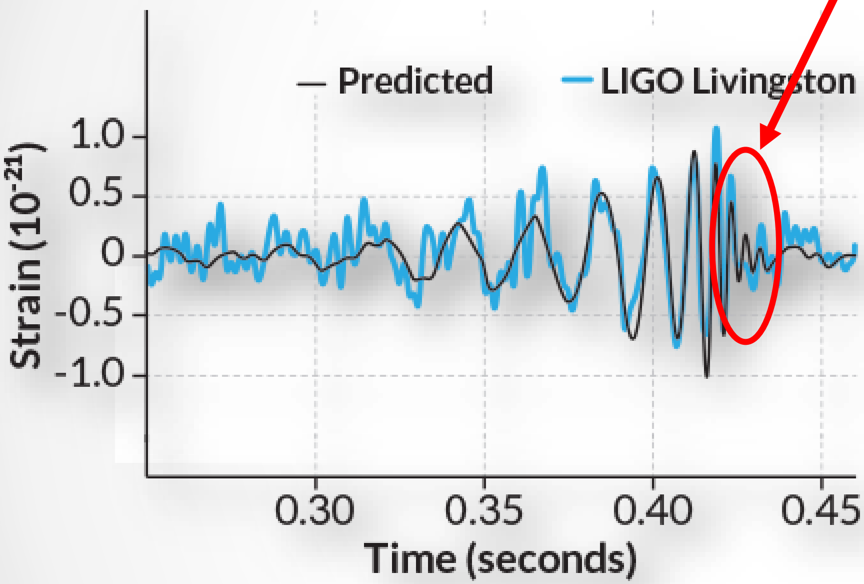


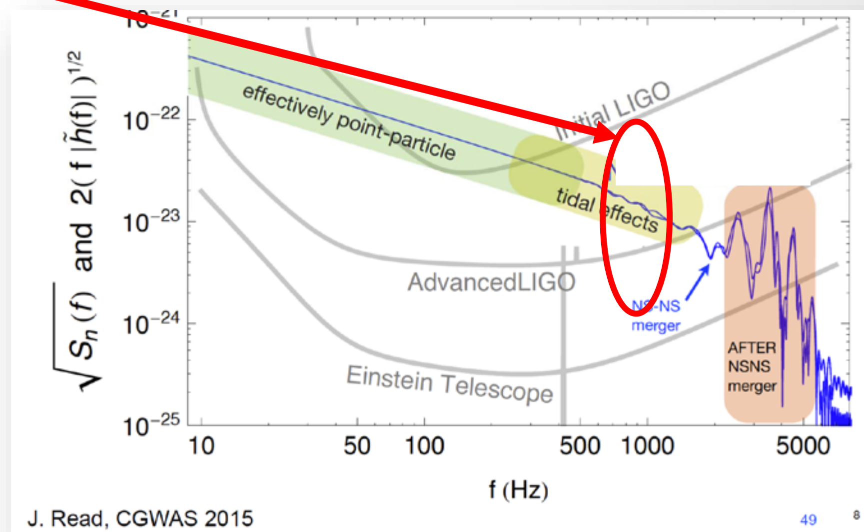

H.Koehn et al, PRX 2025

# Extraction of the tidal effects



Gieg et al., Particle 2, 23 (201

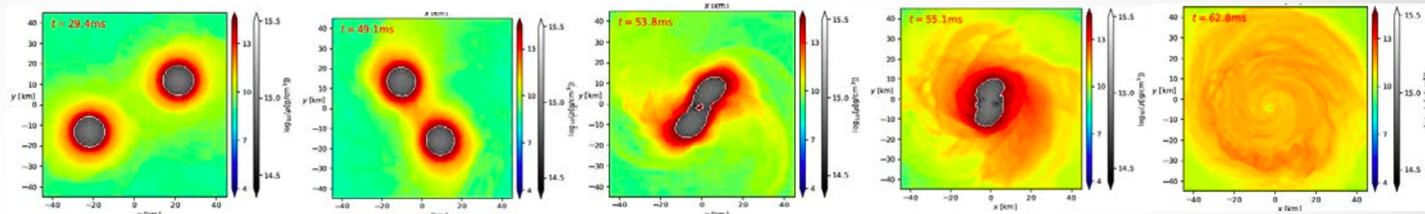


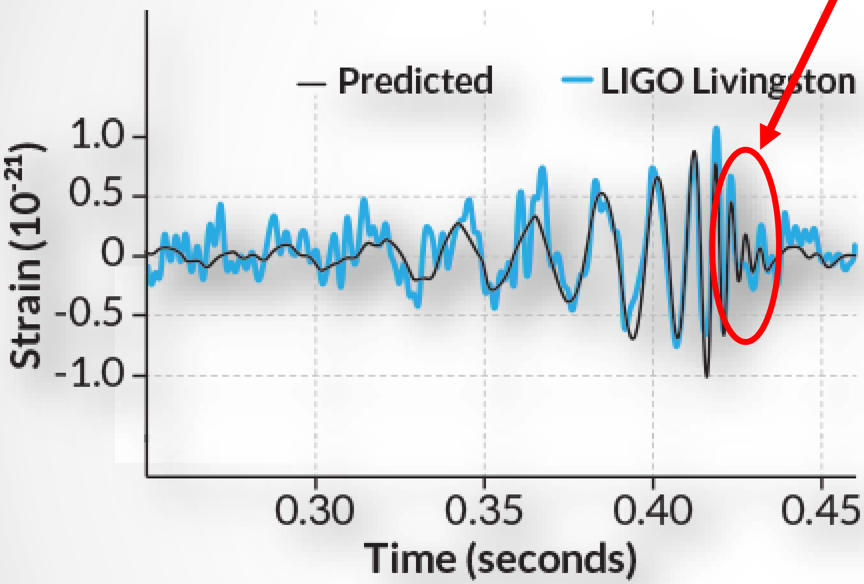

https://www.ligo.org/detections.php

Tidal effects: modification of the gravitational waveform wrt a GR point-particle calculation, due to the star deformation just before merging

# Extraction of the tidal effects



Gieg et al., Particle 2, 23 (201




$$\delta\psi_{\rm tidal} = \frac{3}{128\eta x^{5/2}}\left[\left(-\frac{39}{2}\tilde{\Lambda}\right)x^5\right.$$

Quadrupole moment

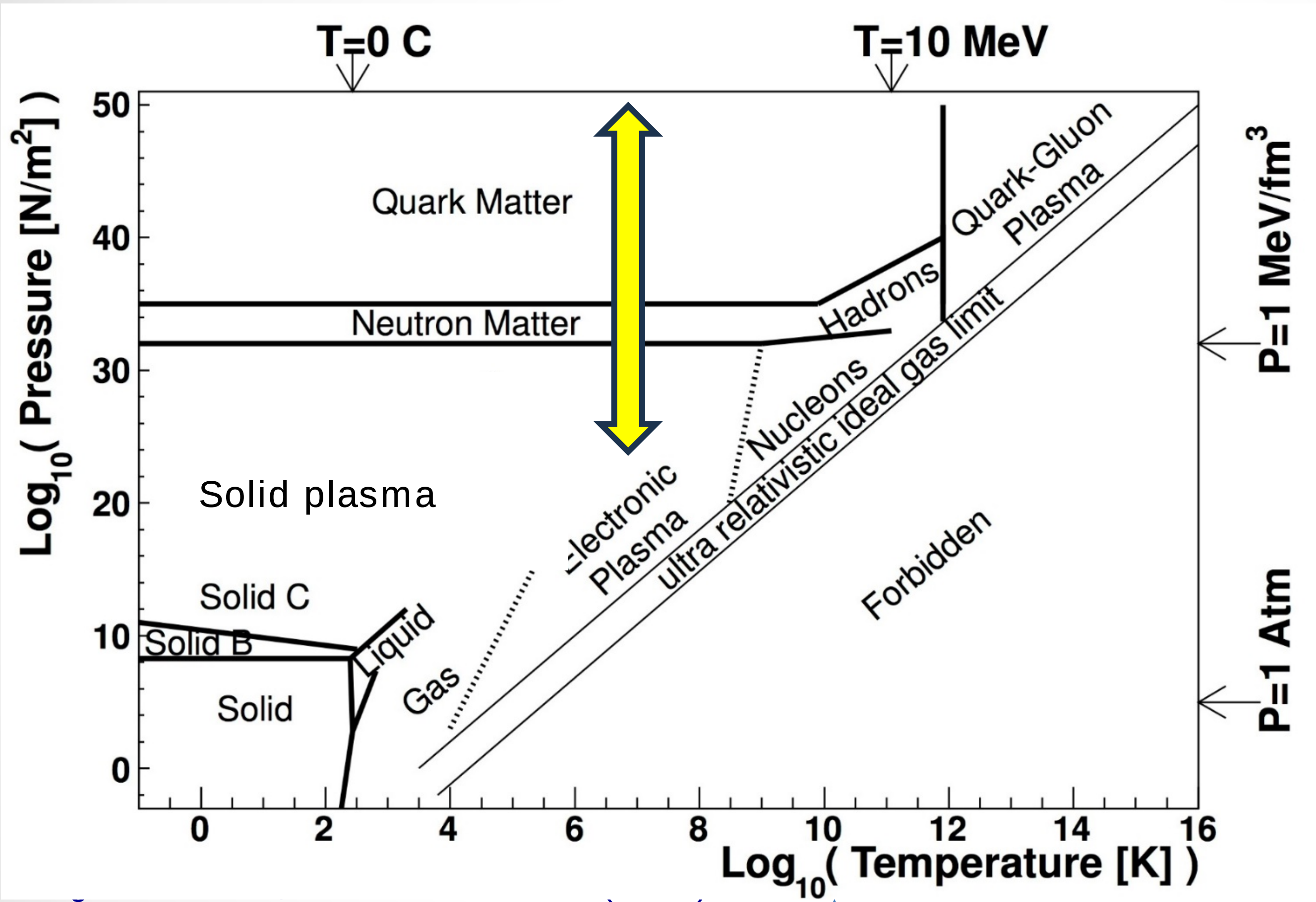
Companion tidal field

$$\bar{\bar{Q}}^{(i)} = -\Lambda_i \bar{\bar{\mathcal{E}}}^{(j)}$$

https://www.ligo.org/detections.php

Tidal effects: modification of the gravitational waveform wrt a GR point-particle calculation, due to the star deformation just before merging

# The phases of matter

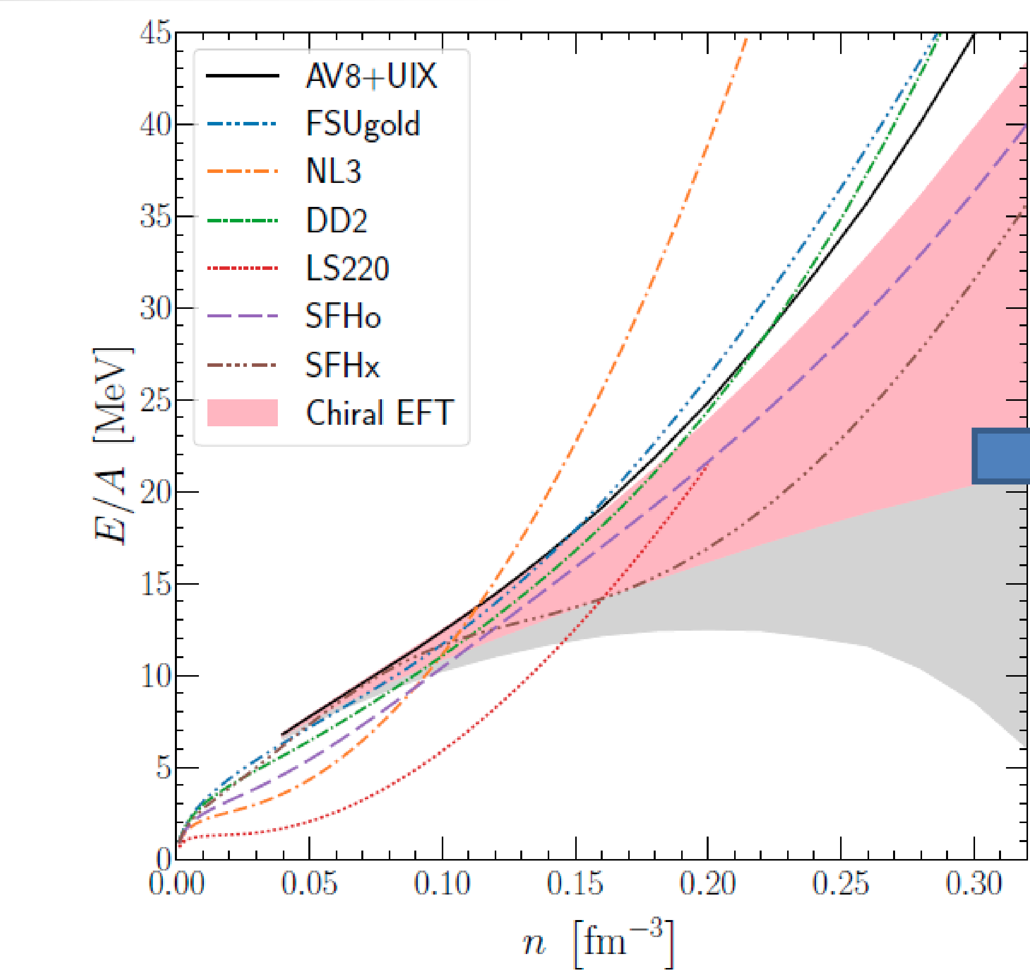


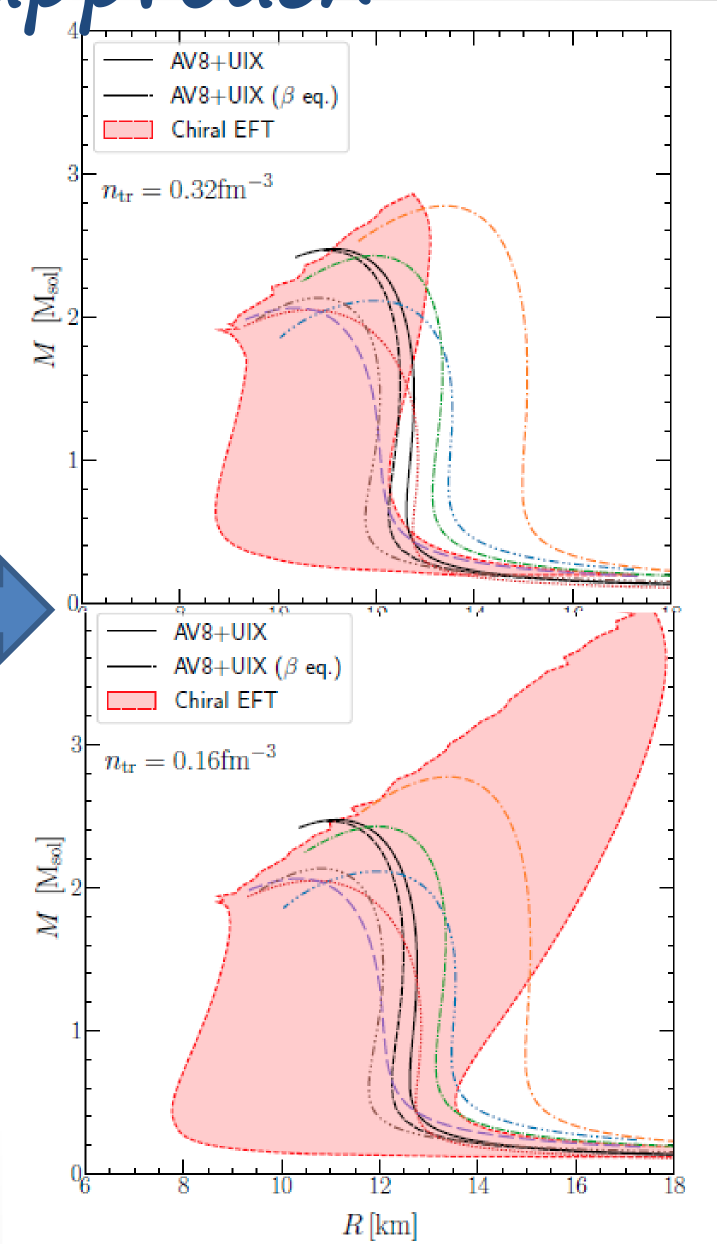

$k_B T$ = 1 MeV

**Where can ultra-dense matter be found in nature?**

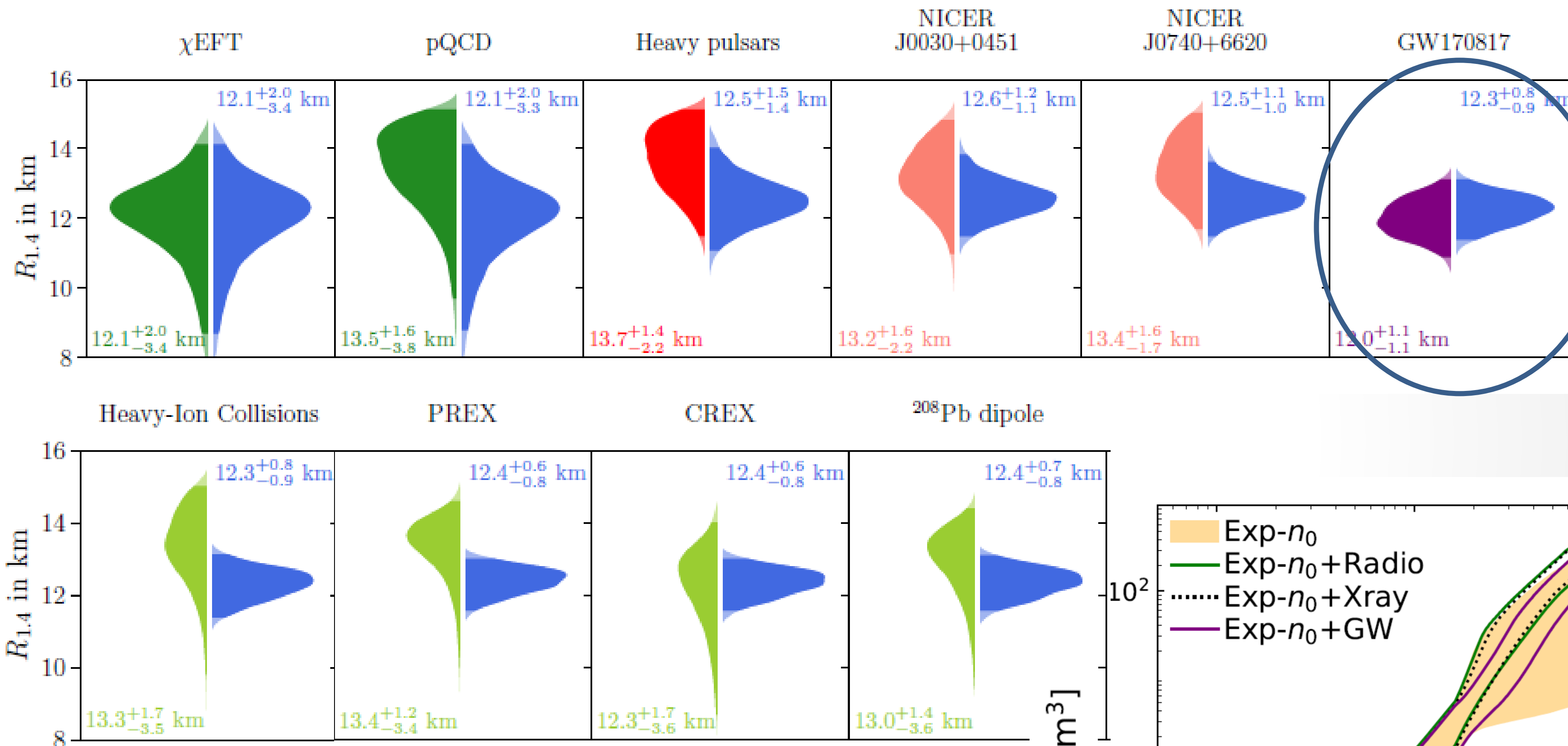
# Nucleonic « ab-initio » approach

Tews, Carlson, Gandolfi, Reddy 2018

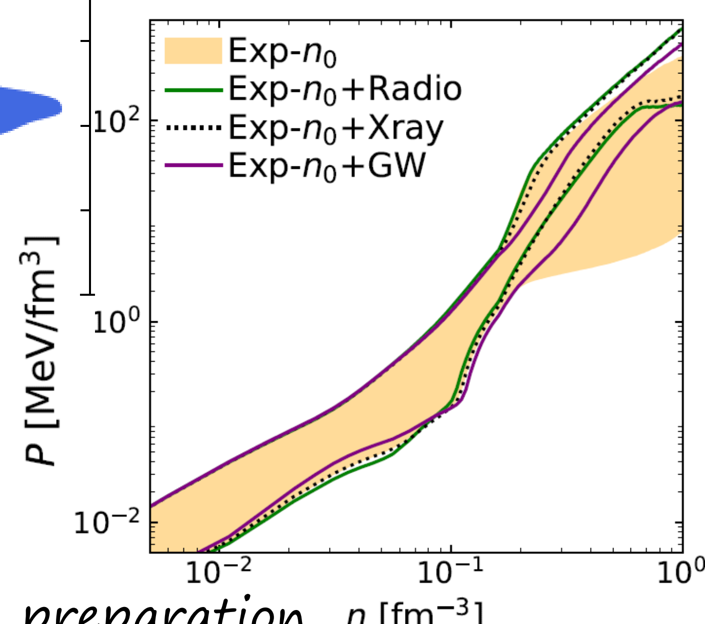


# Who determines what?



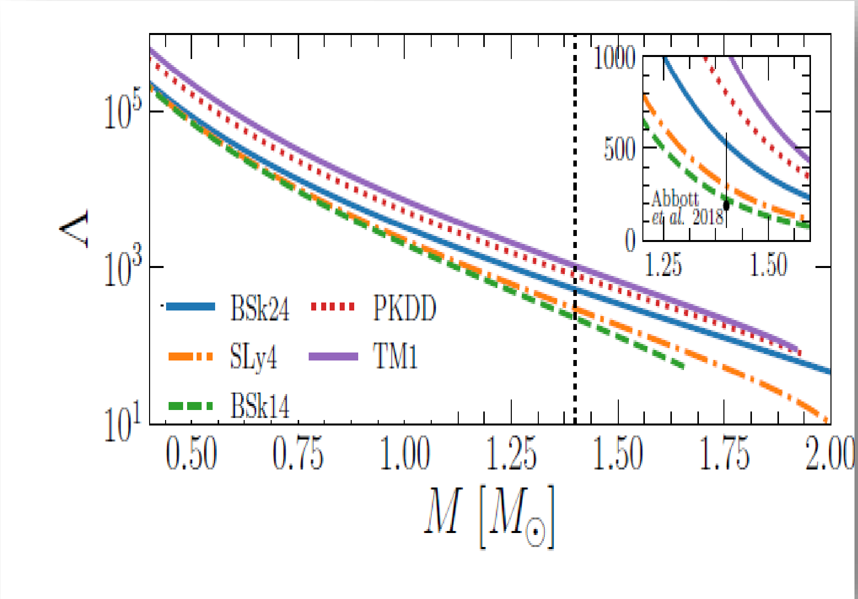

H.Koehn et al, PRX 2025

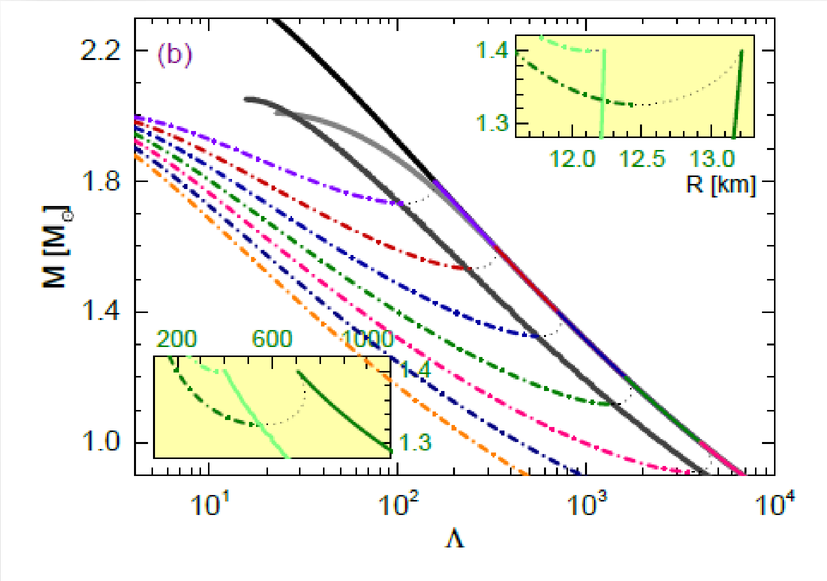


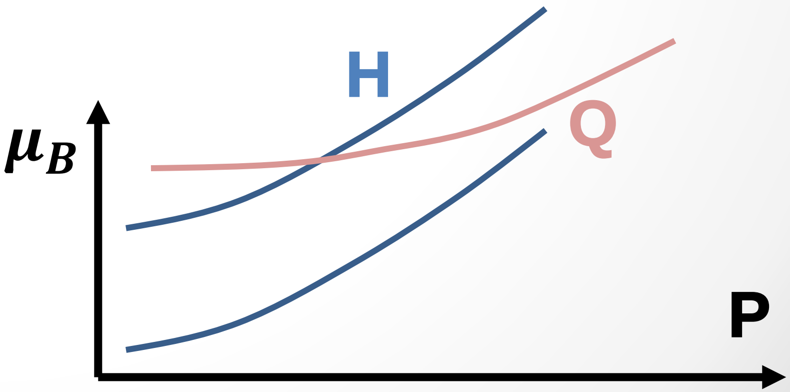

L.Suleiman et al, in preparation

# Problem II : no ab-initio theory of dense matter

- Hybrid stars: a first order phase transition between a nucleonic (RMF, Skyrme..) and a quark ((p)NJL, Bag, CSS…) EoS
- Huge uncertainties on both the Q and the H side!!




J.J.Li, A.Sedrakian, M.Alford, PRD101 (2020) 063022