Credit: NASA/Swift Dana Berry

UNIVERSITÉ CAEN NORMANDIE

IN2P3 Les deux infinis

GW and dense matter

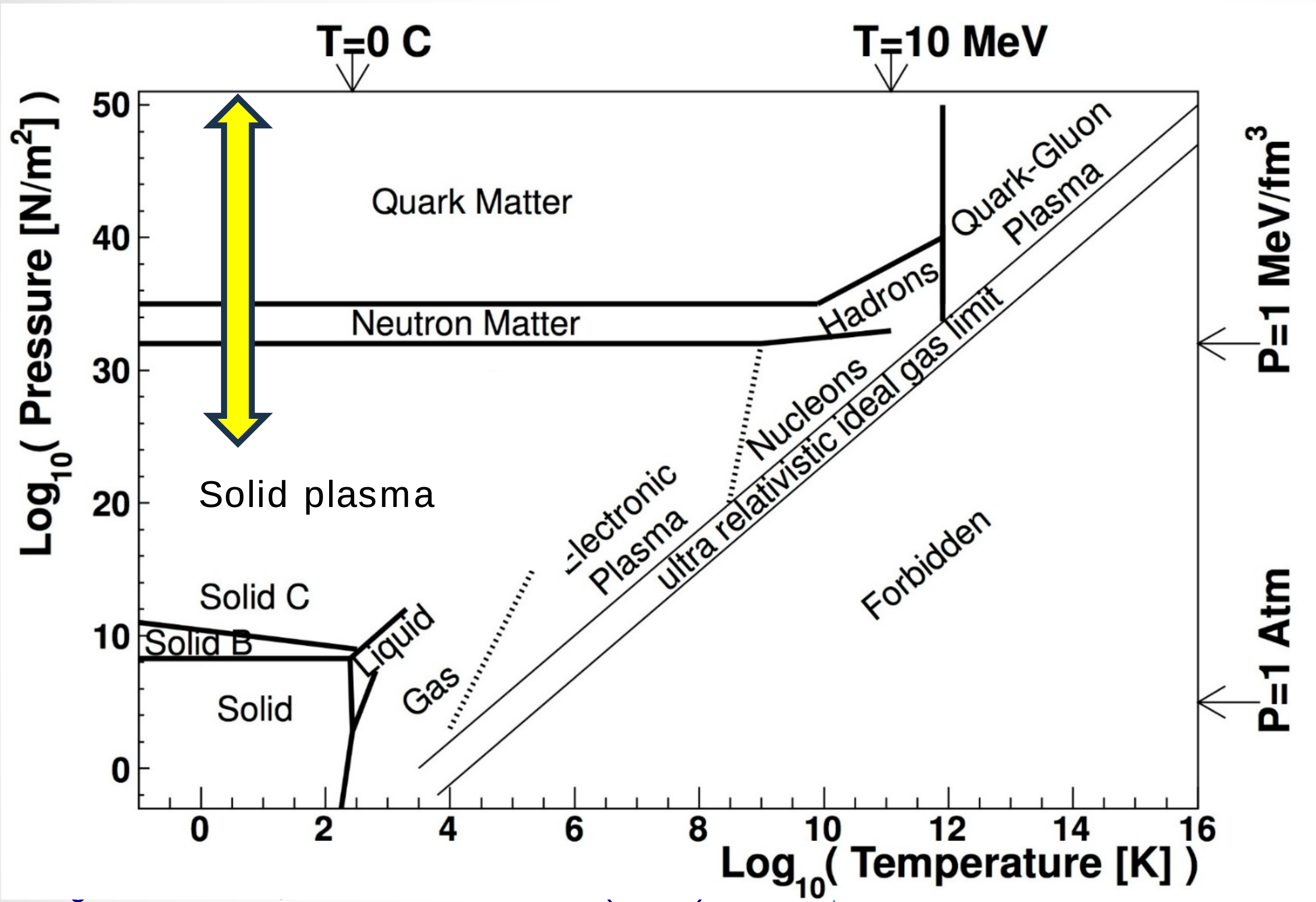
Francesca Gulminelli - Université de Caen-Normandie

3rd MaNiTou summer school on gravitational waves, 1-6 July, 2024

Lecture plan

1. **Introduction: 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

The phases of matter



$k_B T = 1$ MeV

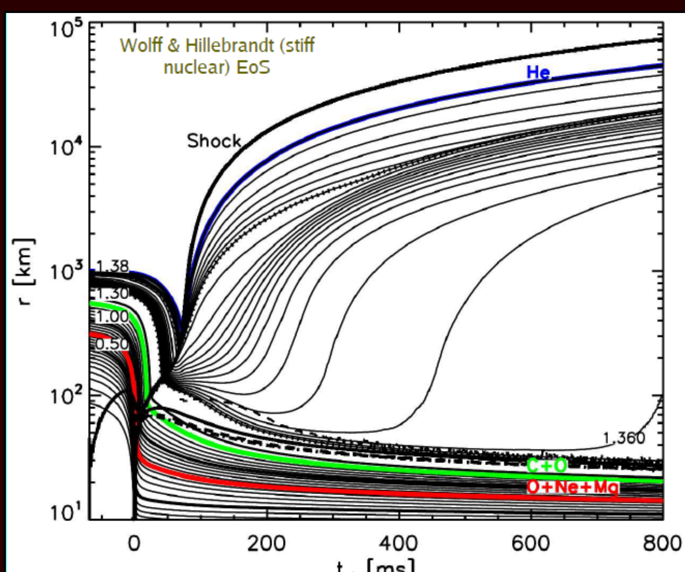
Where can ultra-dense matter be found in nature?

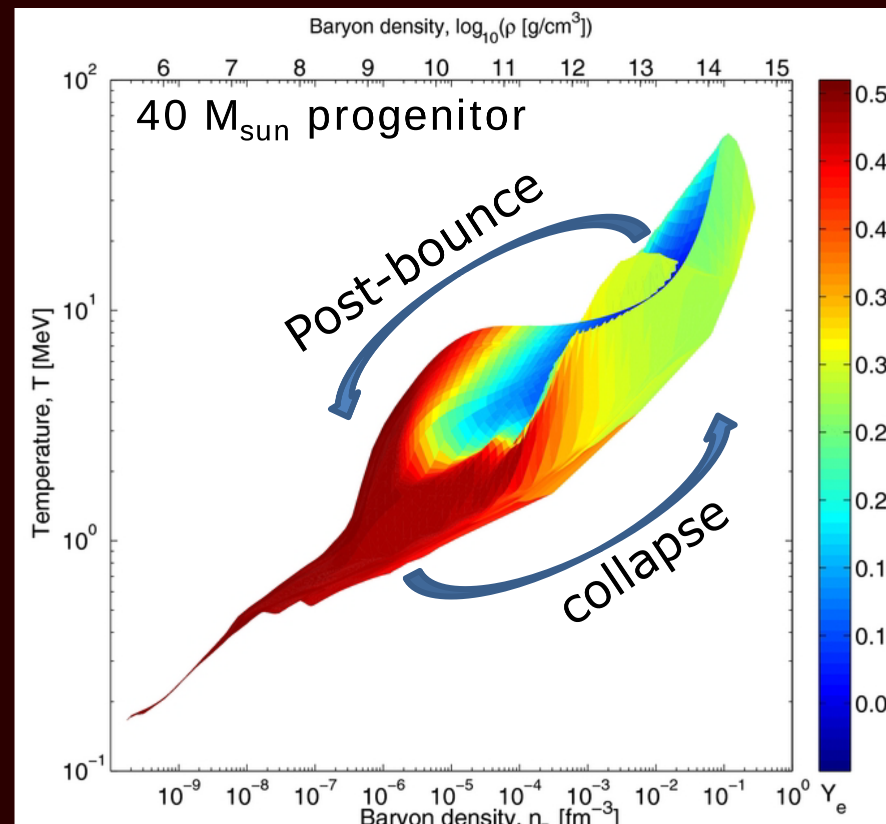
Dense matter in the Universe: CCSN

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

A

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

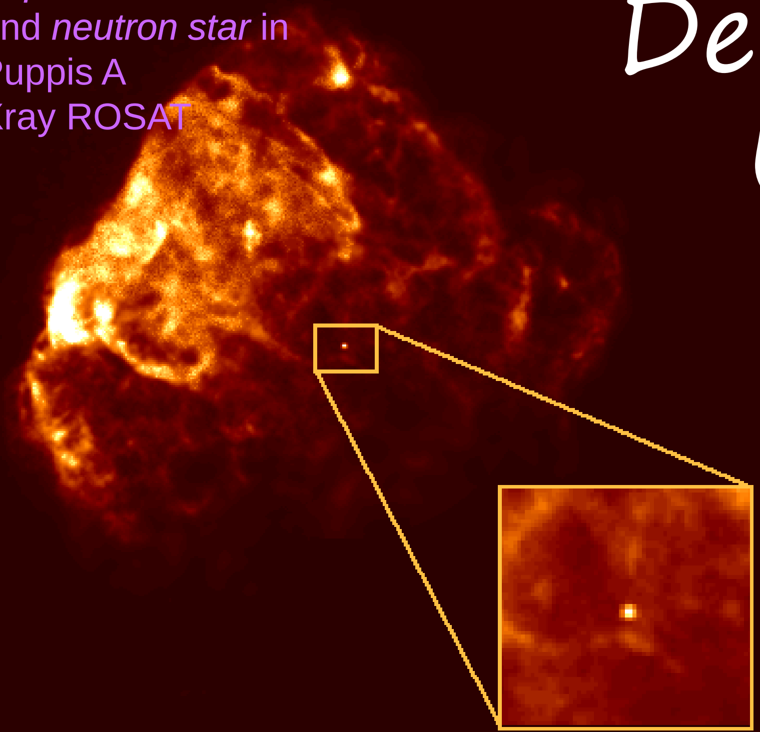


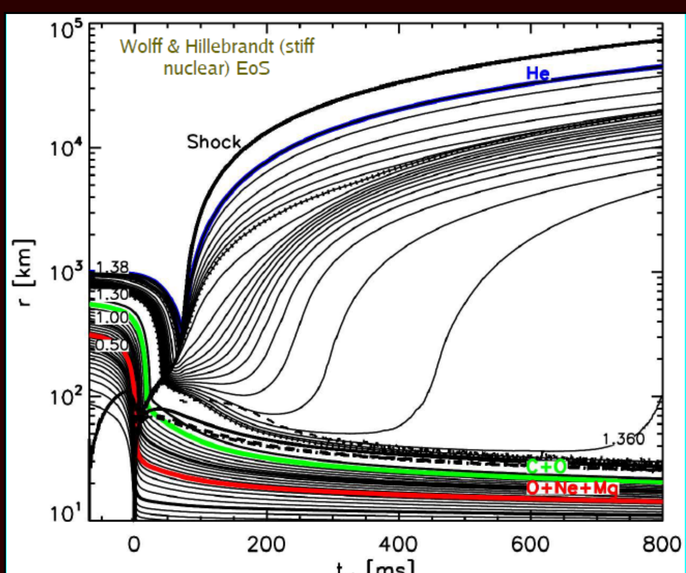


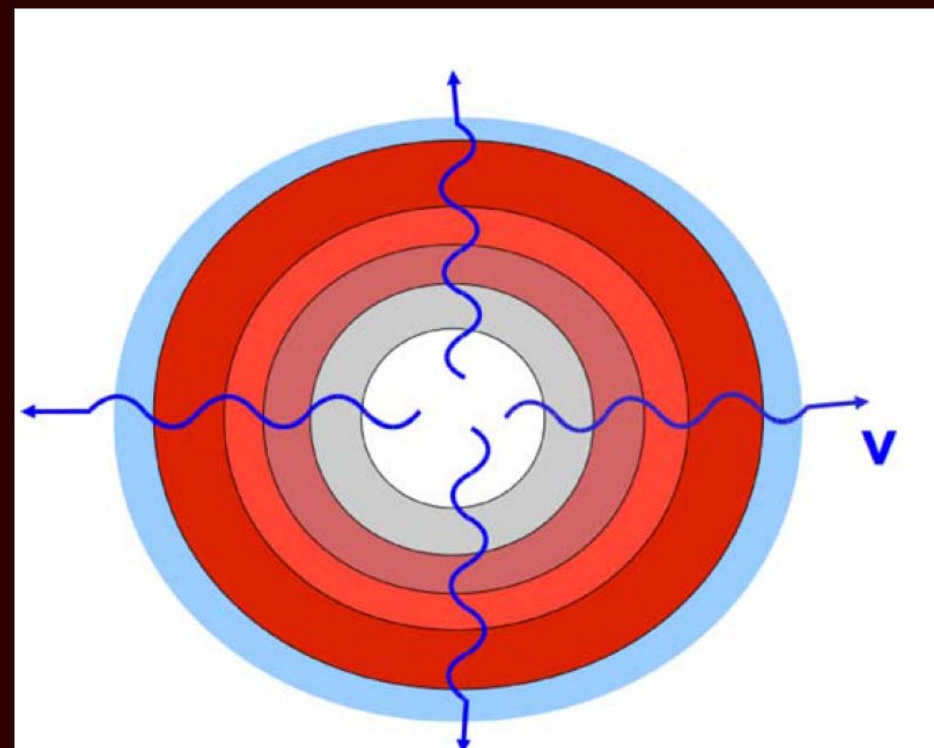
T.Fischer et al, 2011 ApJS **194** 39

Dense matter in the Universe: PNS

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

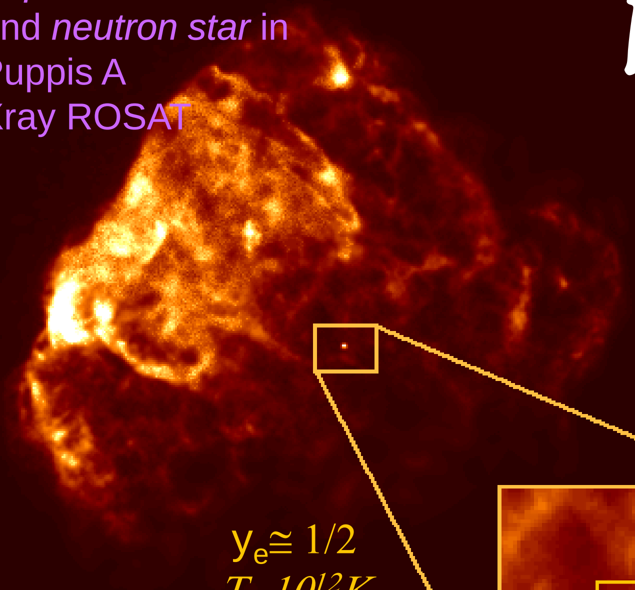




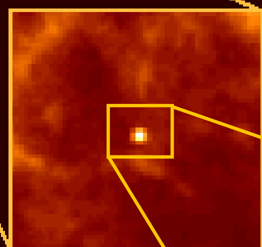


Dense matter in the Universe: NS

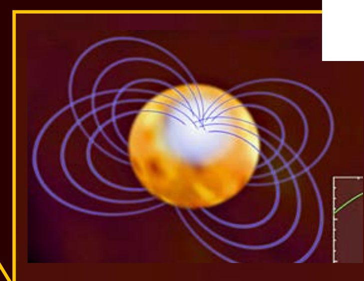
Supernova remnant and *neutron star* in Puppis A Xray ROSAT



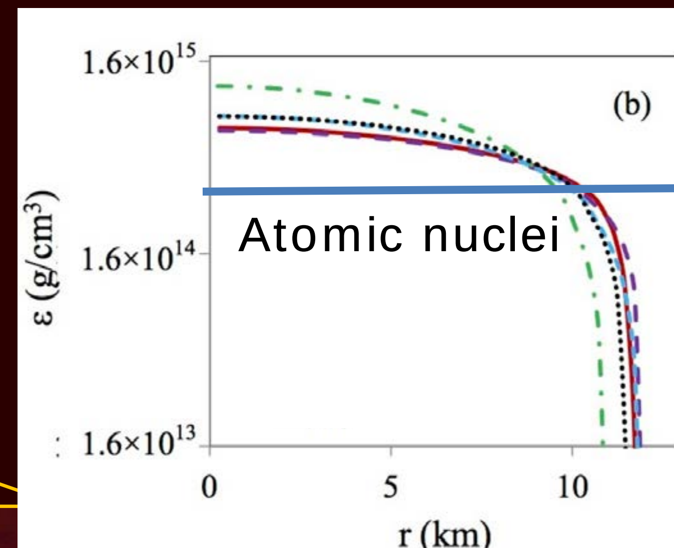
$y_e \cong 1/2$
T~10^12^K



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

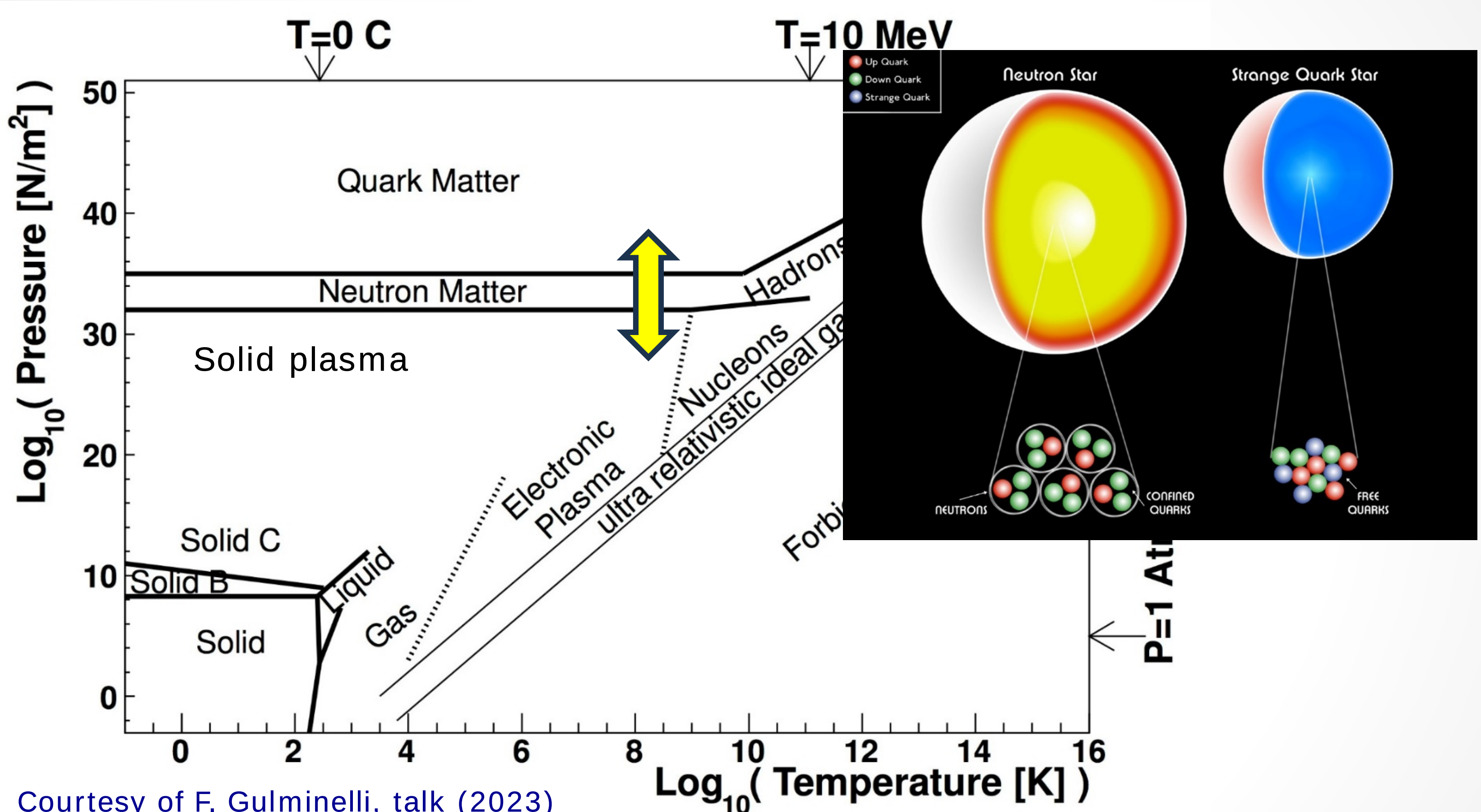


$y_e \cong 1/5$
$T{\sim}6K$



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

The phases of matter



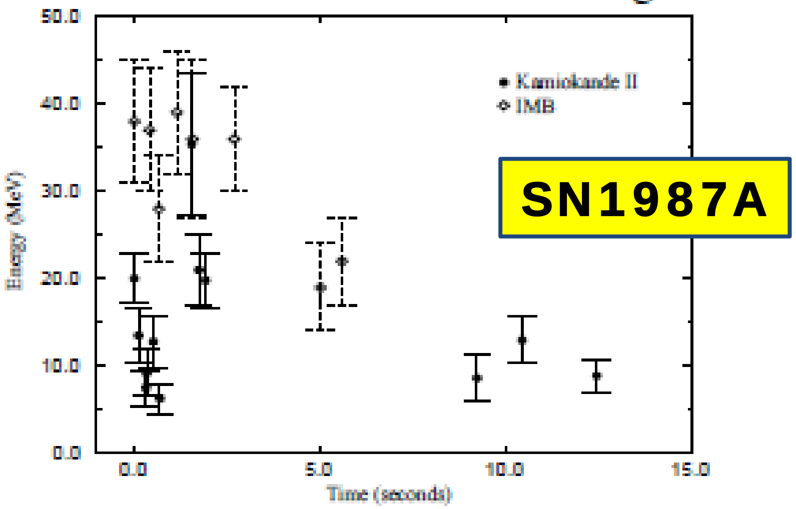
Credits: CXC/M.Weiss

Courtesy of F. Gulminelli, talk (2023)

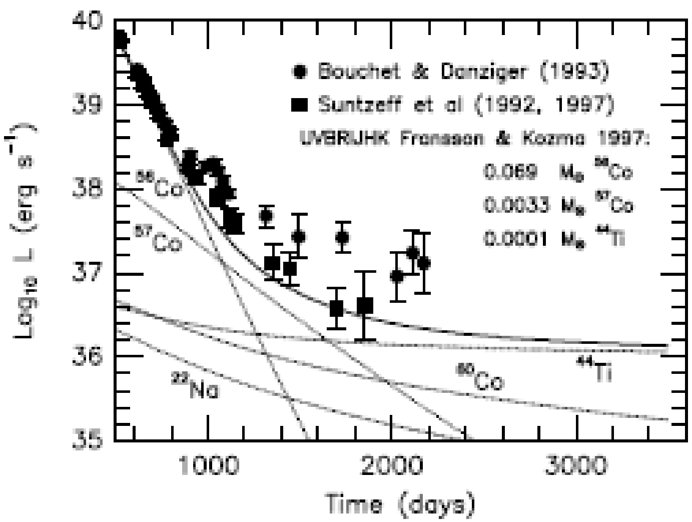
$k_B T = 1$ MeV

CCSN

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



light curve

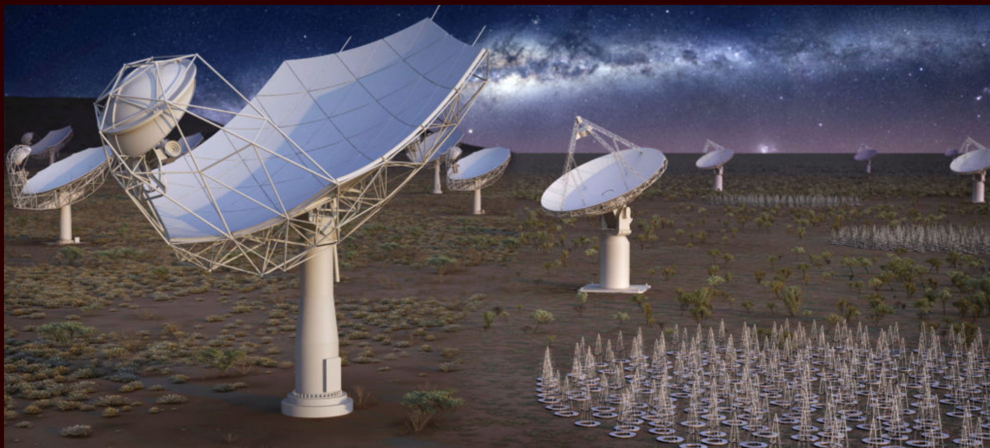


Signals

SuperKamioKande
@Kamioka

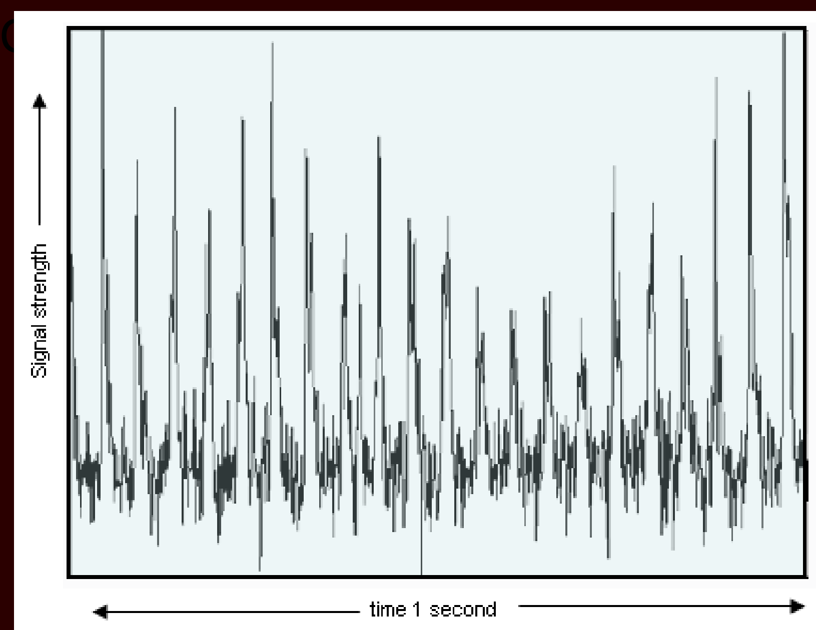
DUNE
@Stanford

Signals

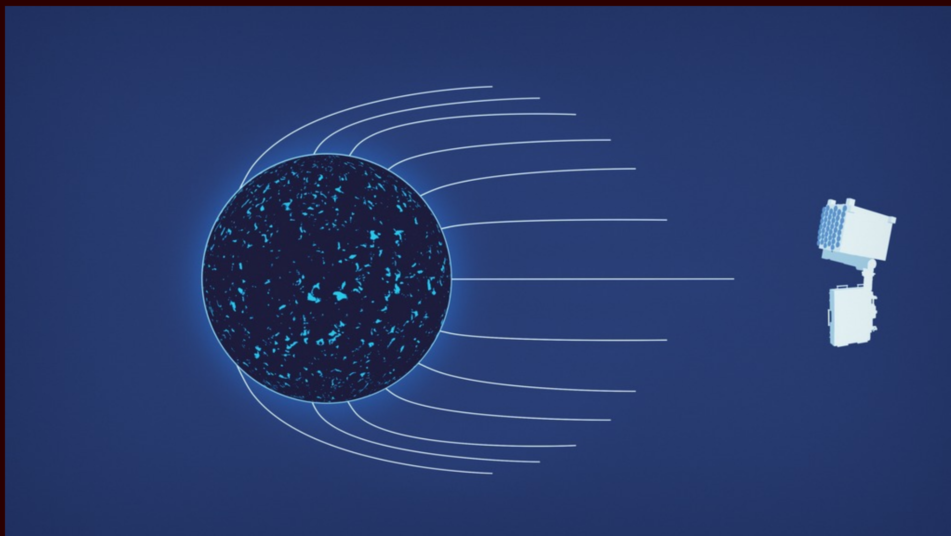


SKA@ South Africa

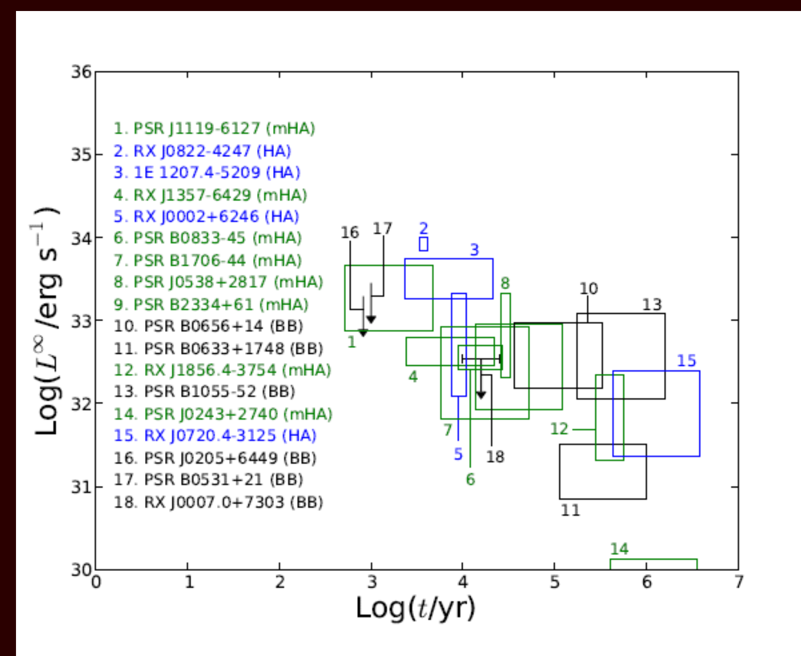
Pulsars



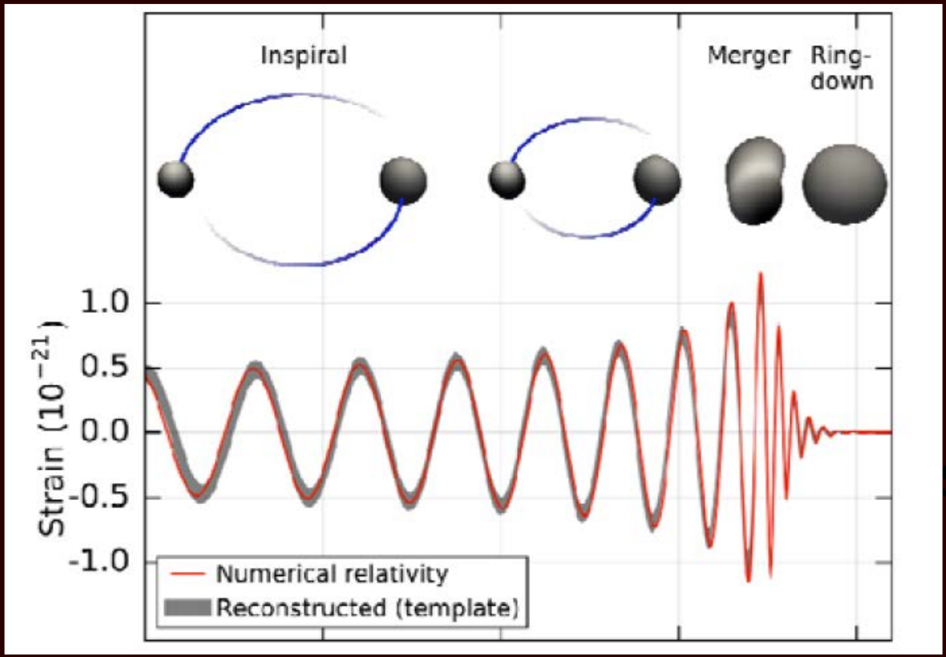
Signals



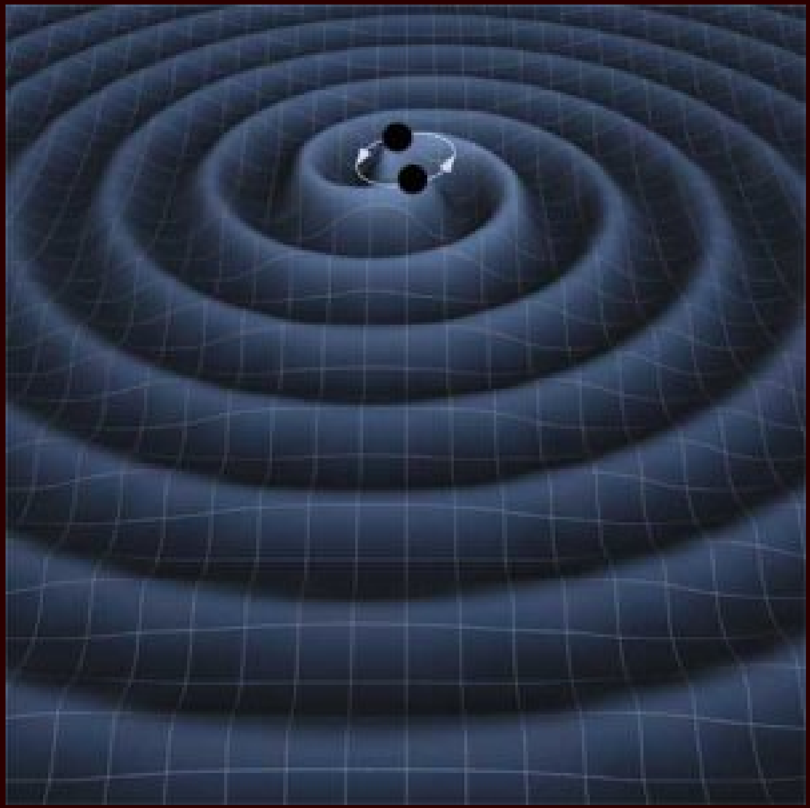
XR sources



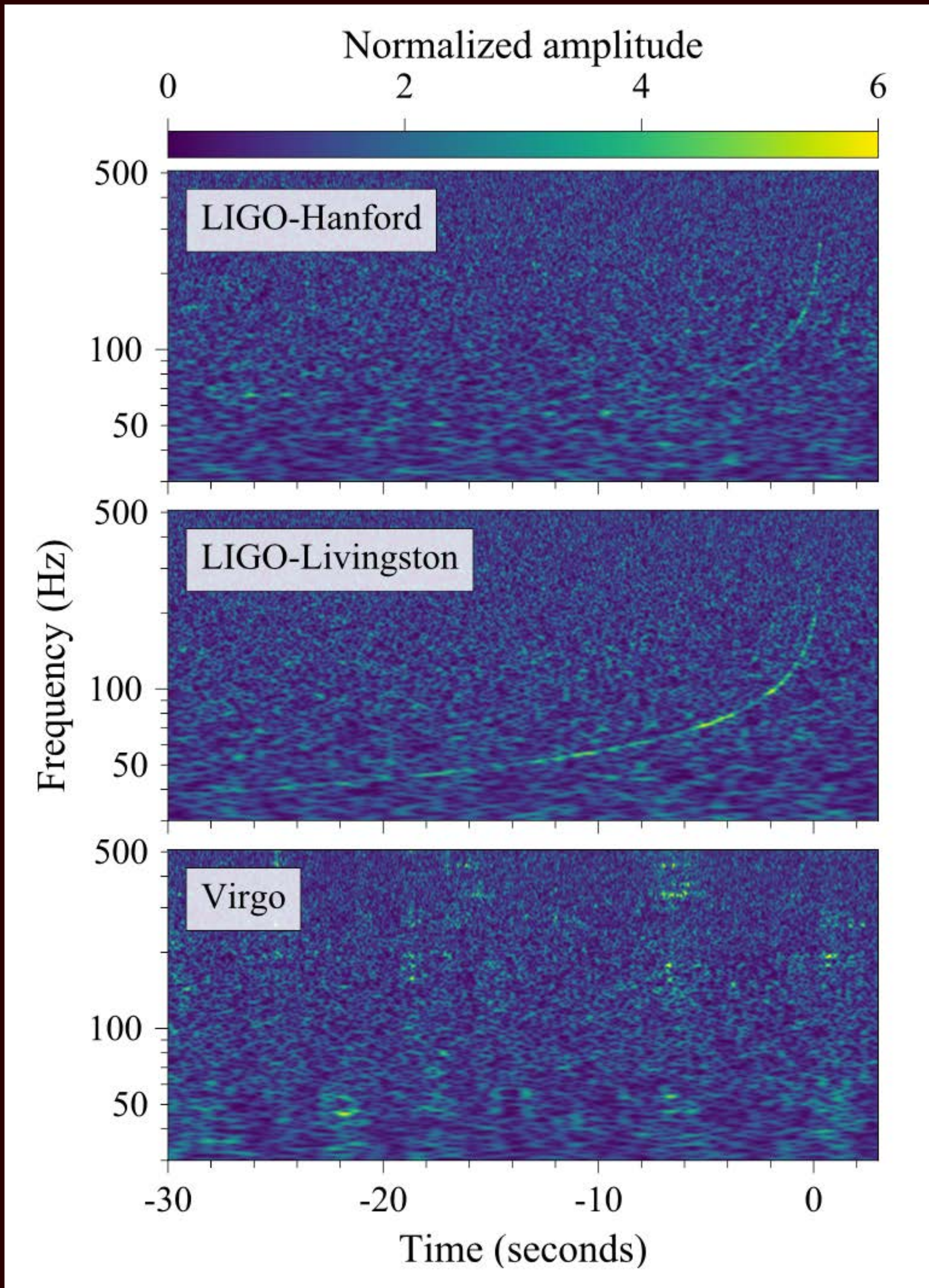
Signals



SN



Mergers



Signals

SN

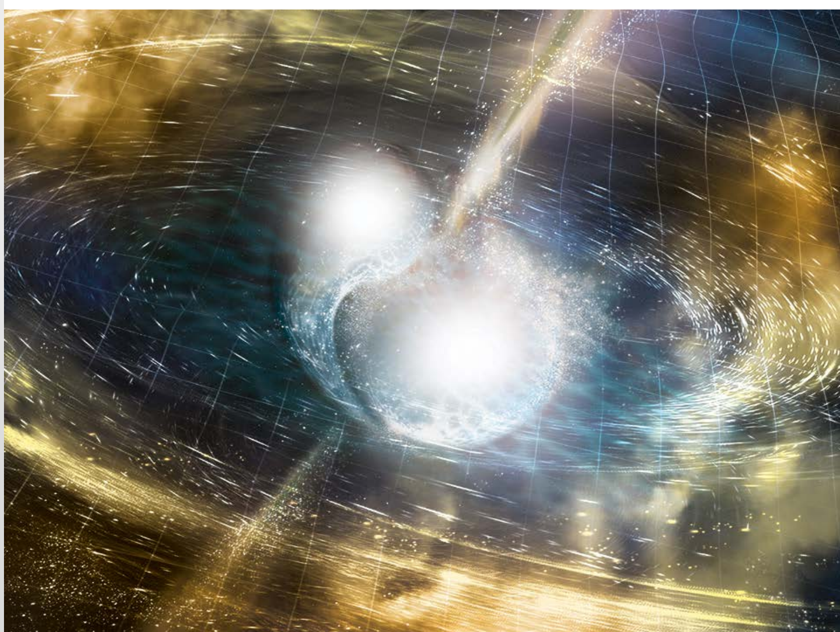
Mergers

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

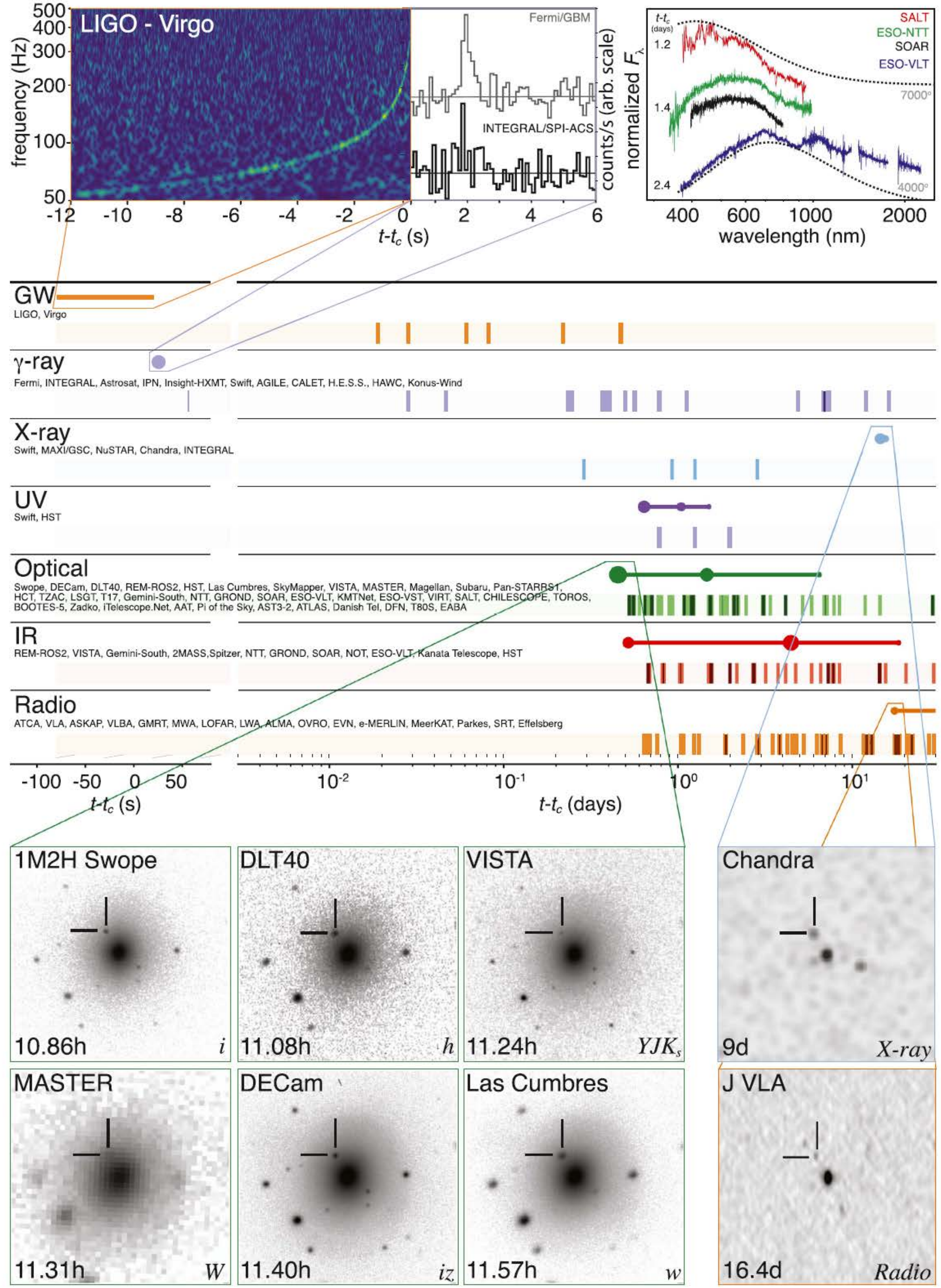


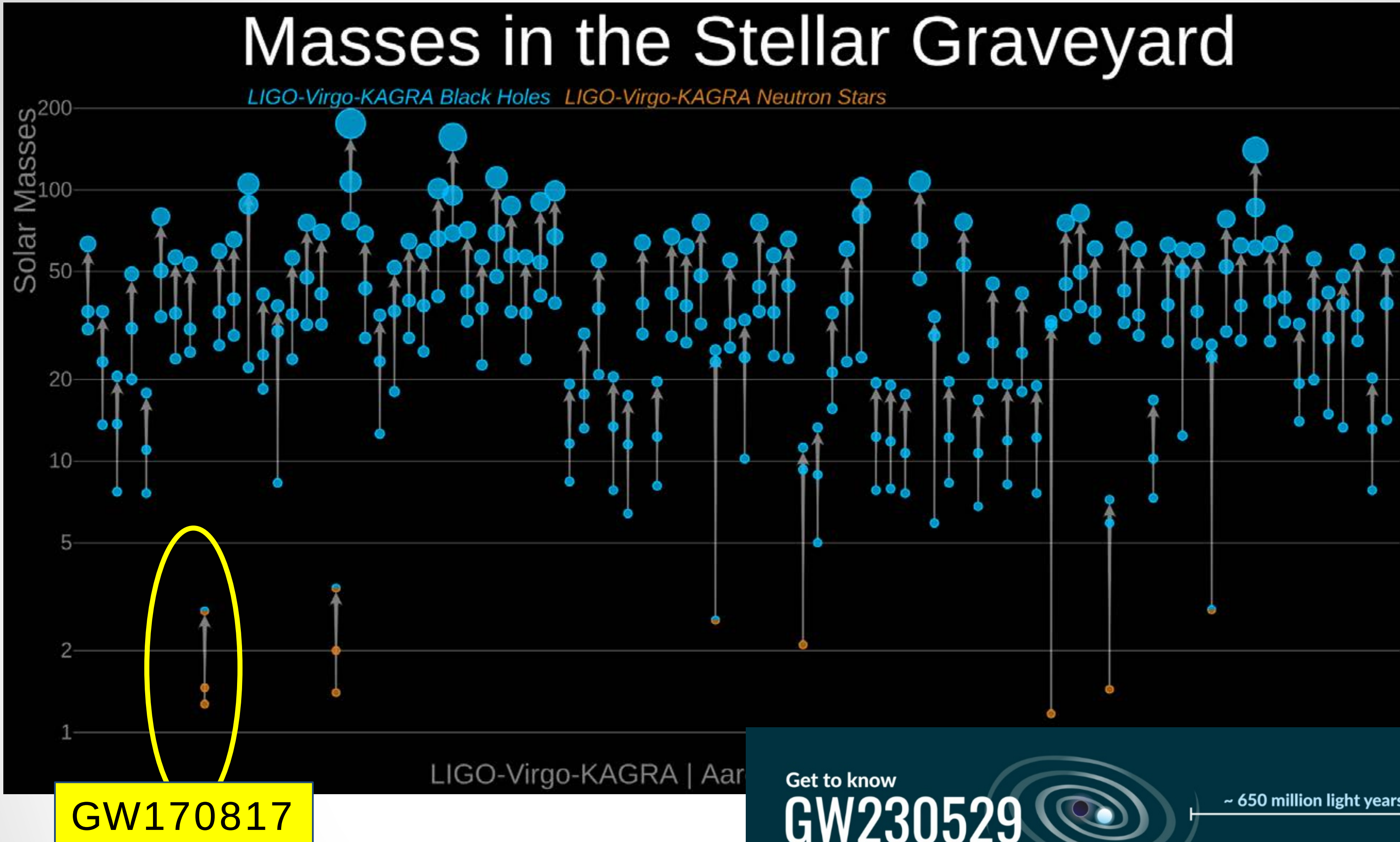
Foundation
Operated by Caltech and MIT

GW170817 Press Release

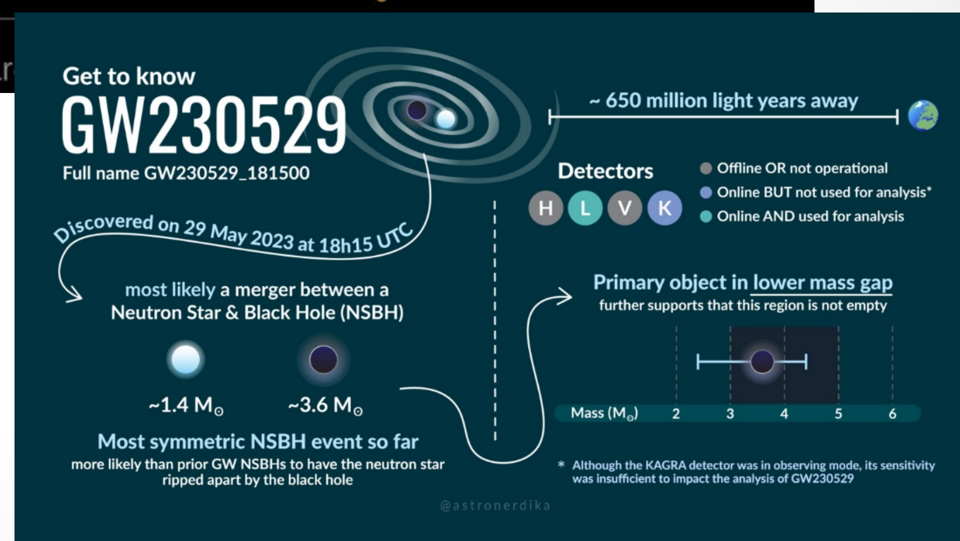
LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars

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
t-t_c (days)
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
DLT40
11.08h
VISTA
11.24h
YJK_s
Chandra
9d
X-ray
MASTER
11.31h
DECam
11.40h
iz
Las Cumbres
11.57h
J VLA
16.4d
Radio

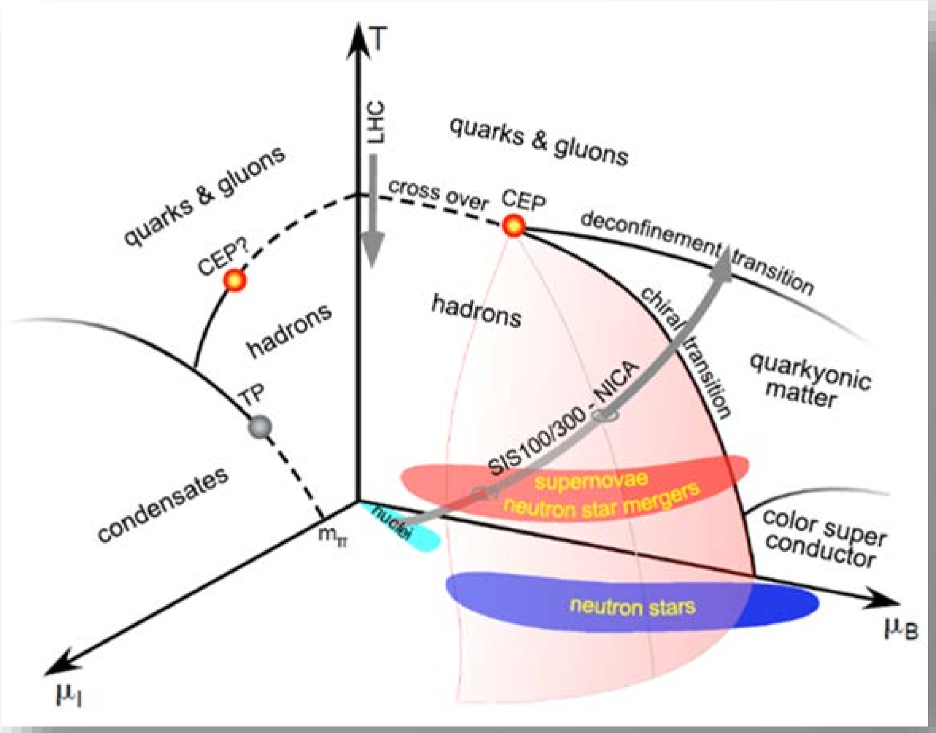


5 years of LVK observations



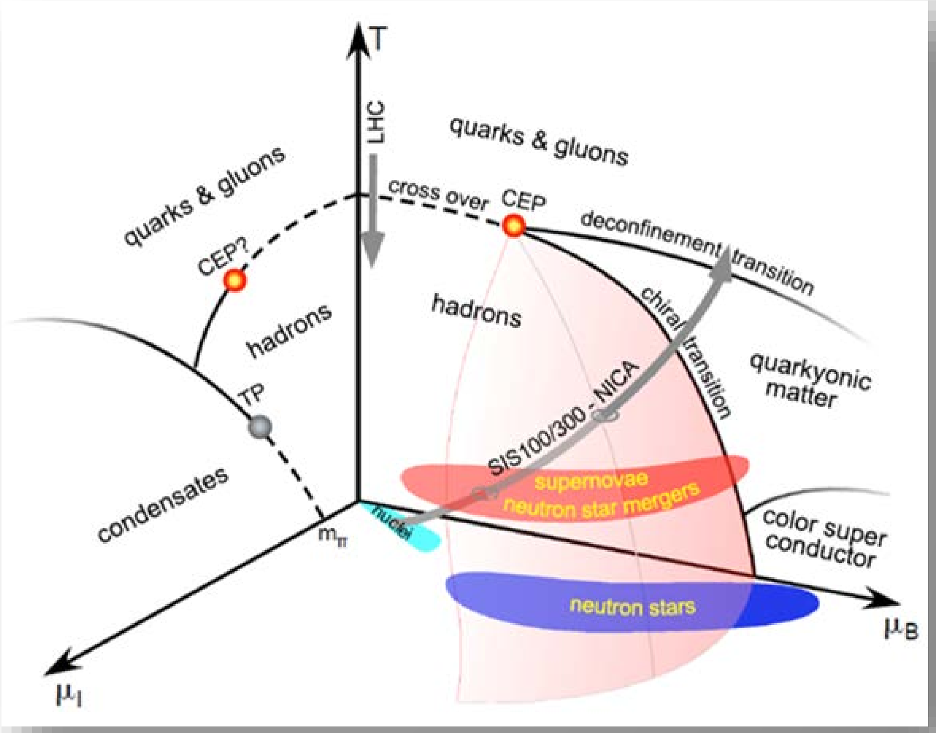
Dense matter: the Questions

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



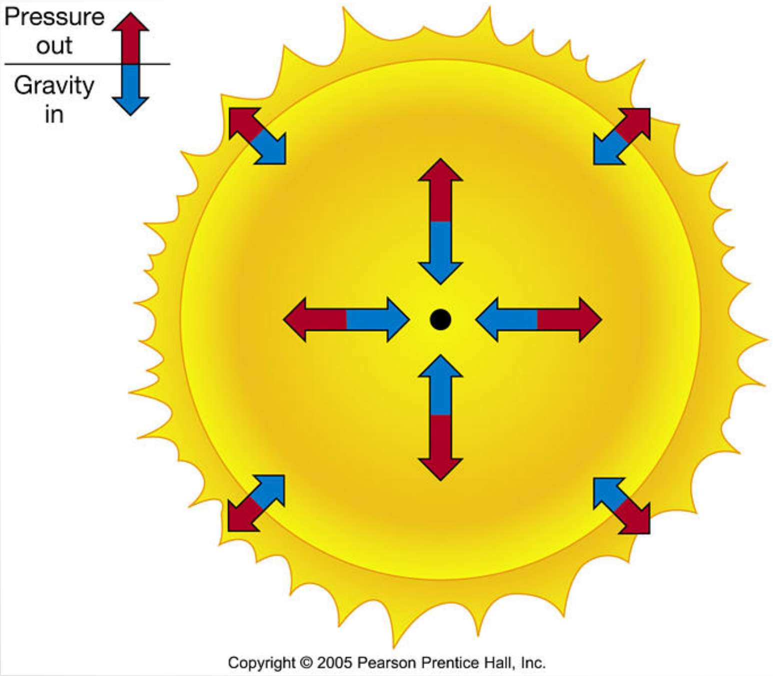
Lecture plan

1. Introduction: 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):

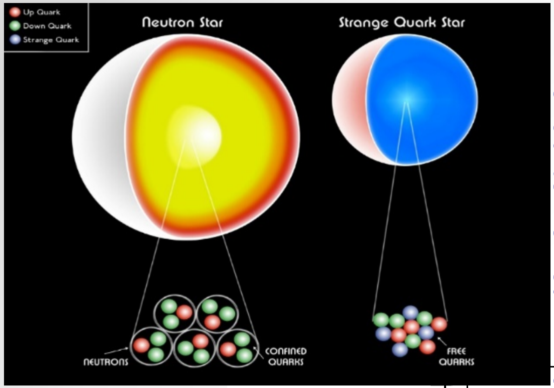
$$\frac{d\boldsymbol{P}(\boldsymbol{\rho})}{dr} = -\frac{G}{r^2}\left[\rho(r) + \frac{\boldsymbol{P}(\boldsymbol{\rho})}{c^2}\right]\left[m(r) + 4\pi r^3 \frac{\boldsymbol{P}(\boldsymbol{\rho})}{c^2}\right]\left[1 - \frac{2Gm(r)}{rc^2}\right]^{-1}$$



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

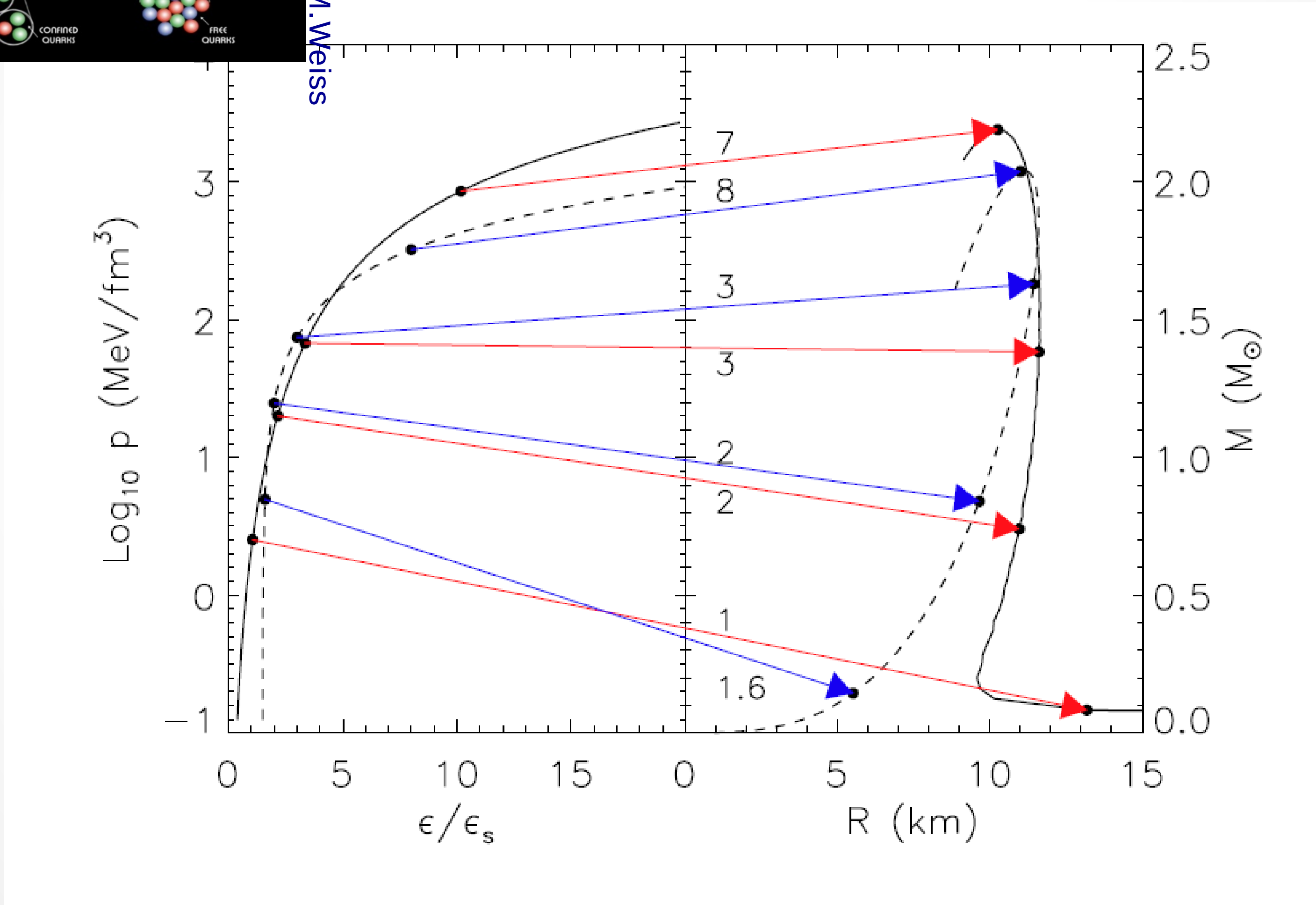
Mass and radius

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

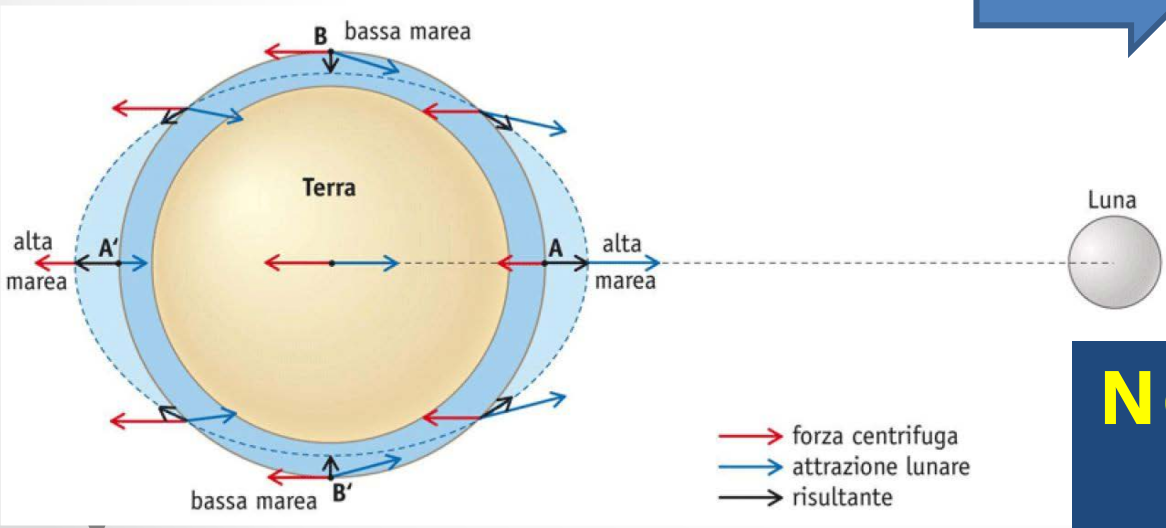
- Influence of a second body => Thorne and Campolattaro (1967):

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

$$\forall \rho_c$$

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

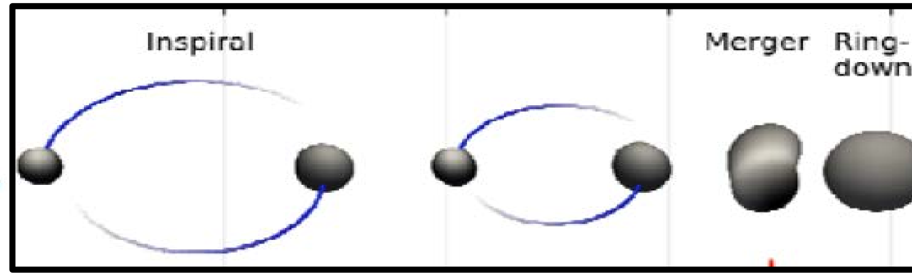
Tidal polarizability

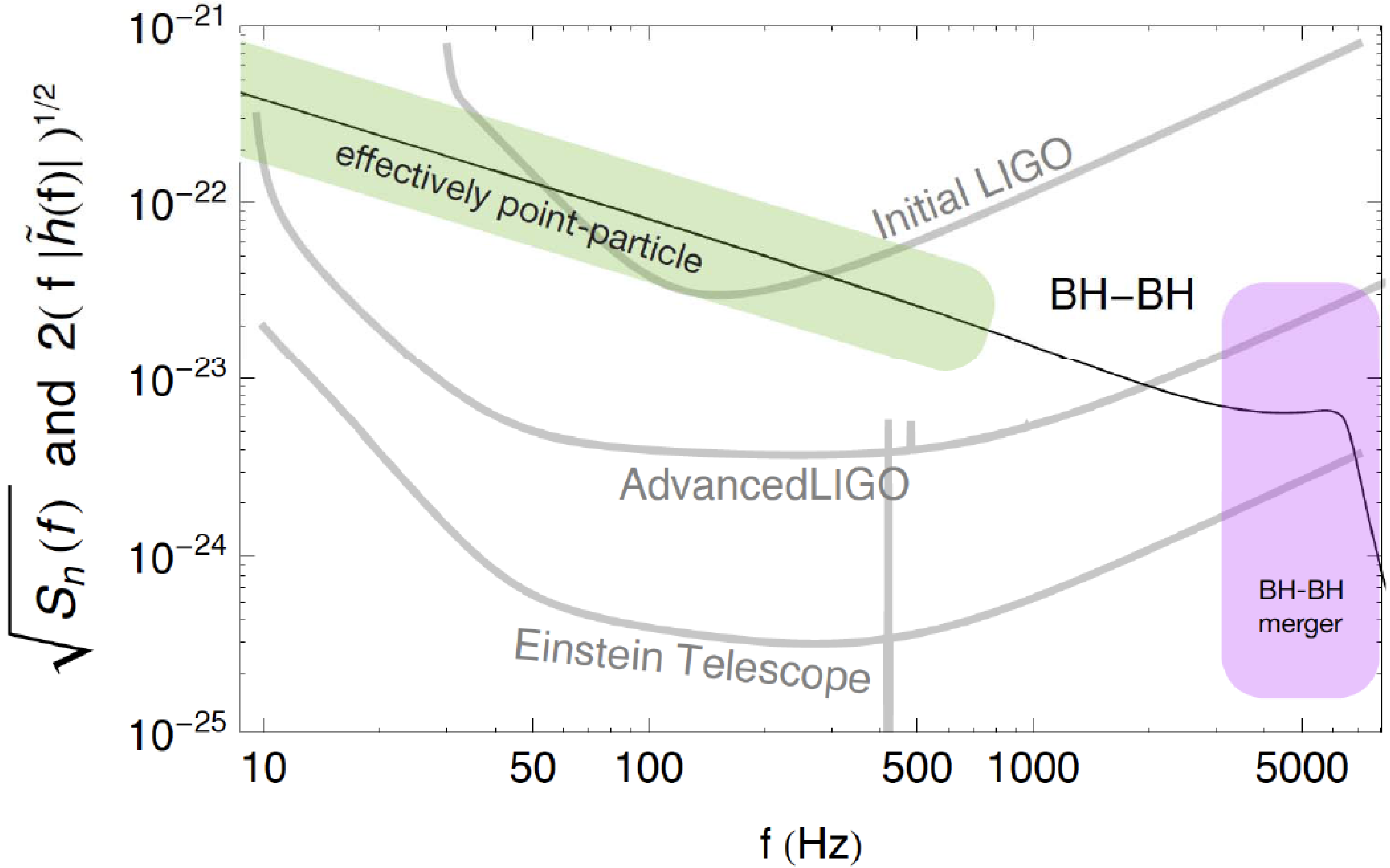


Needs ONLY $P(\rho)$ of NS matter

. West

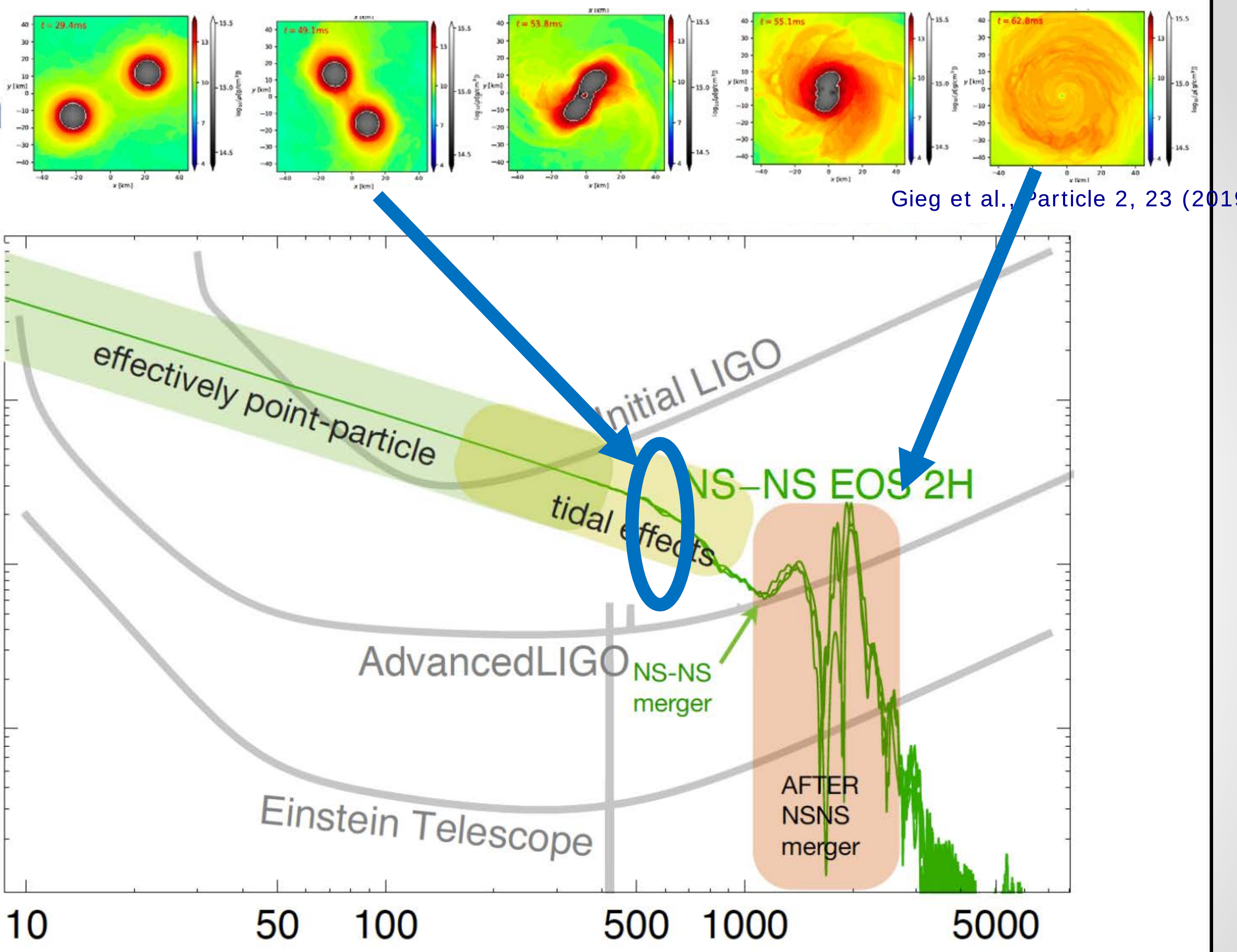
Spectrum of BBH inspiral,





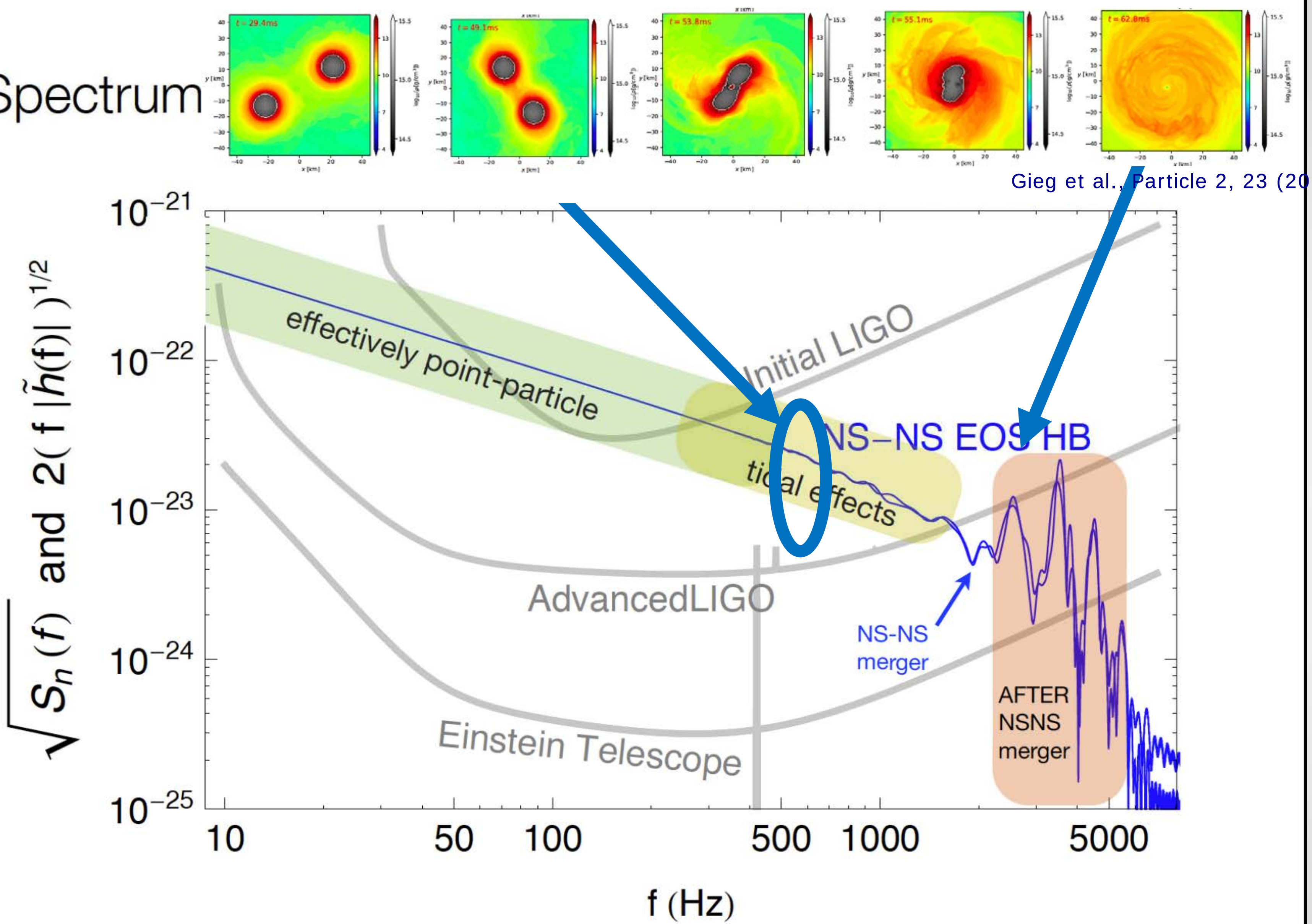
J. Read, CGWAS 2015

Spectrum



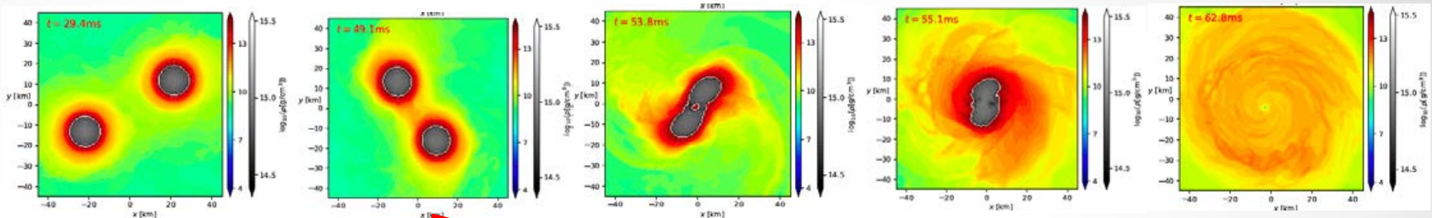
J. Read, CGWAS 2015

Spectrum

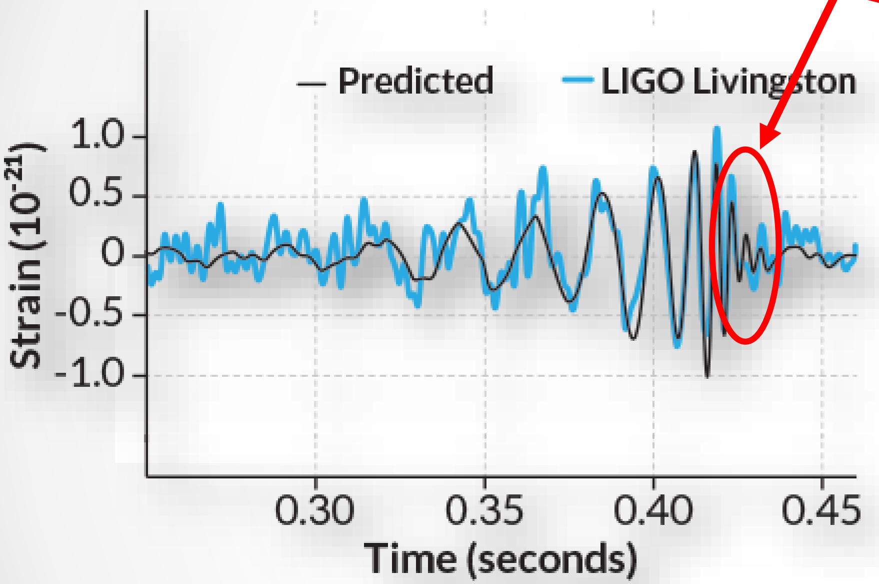


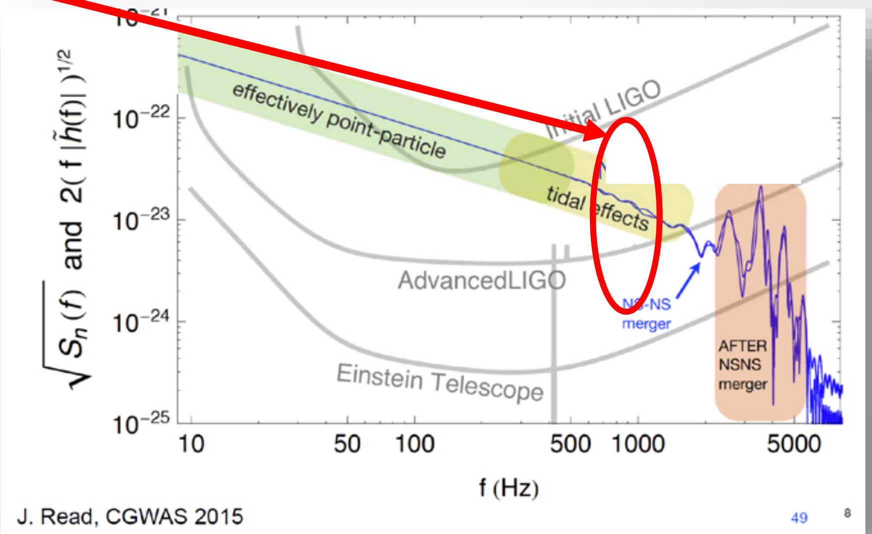
J. Read, CGWAS 2015

Extraction of the tidal effects



Gieg et al., Particle 2, 23 (201

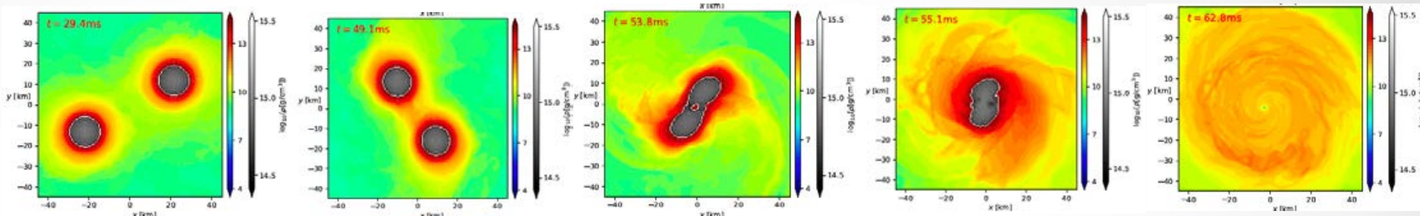




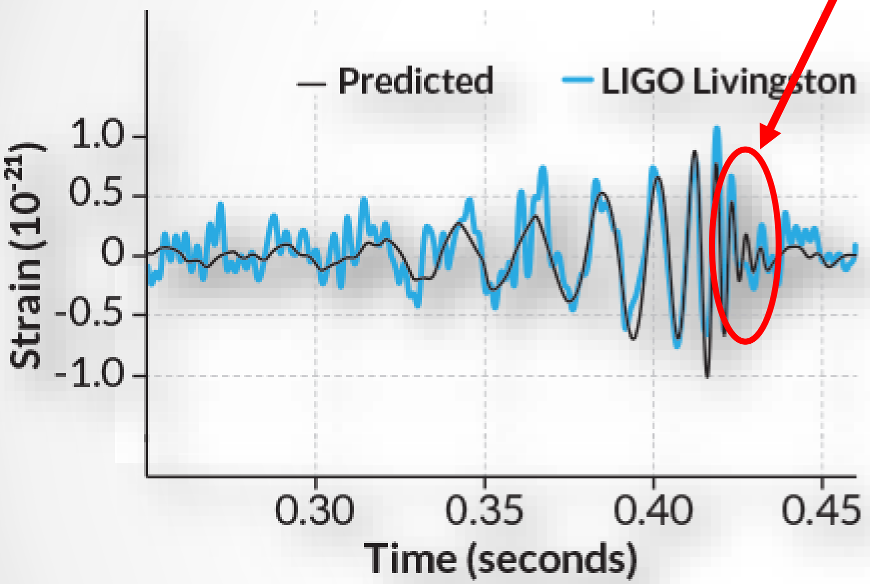
https://www.ligo.org/detections.php

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



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

Quadrupole moment

Companion tidal field

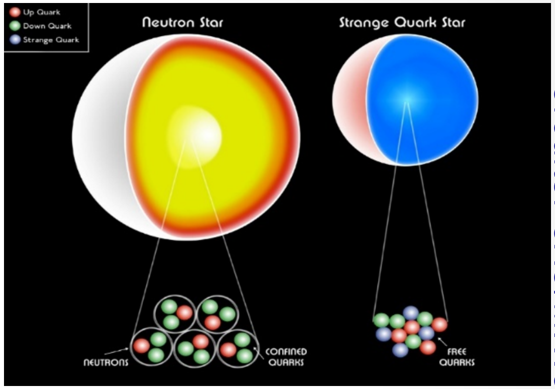
$$\bar{\bar{Q}}^{(i)} = -\Lambda_i \bar{\bar{\mathcal{E}}}^{(j)}$$

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

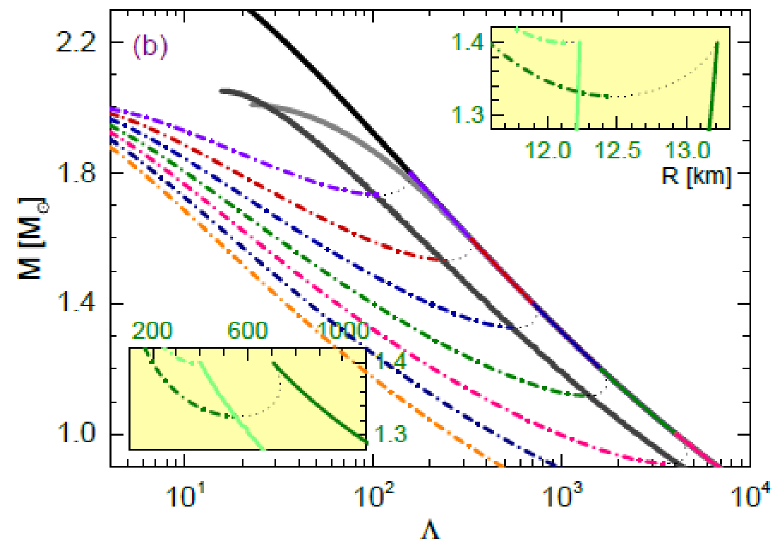
Tidal effects: modification of the gravitational waveform wrt a GR point-particle calculation, due to the star deformation just before merging

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

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

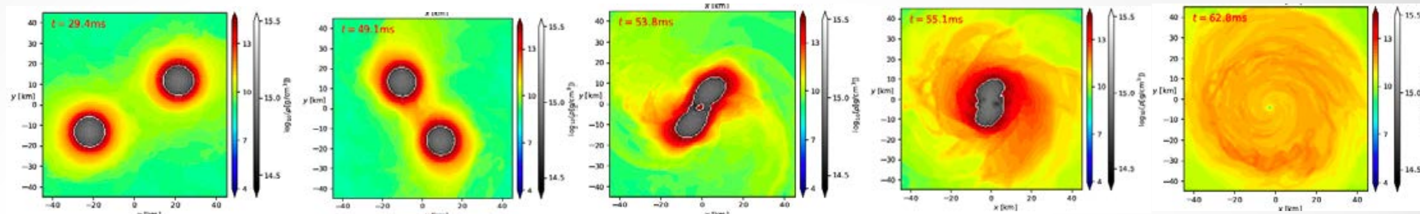


Credits: CXC/M.Weiss

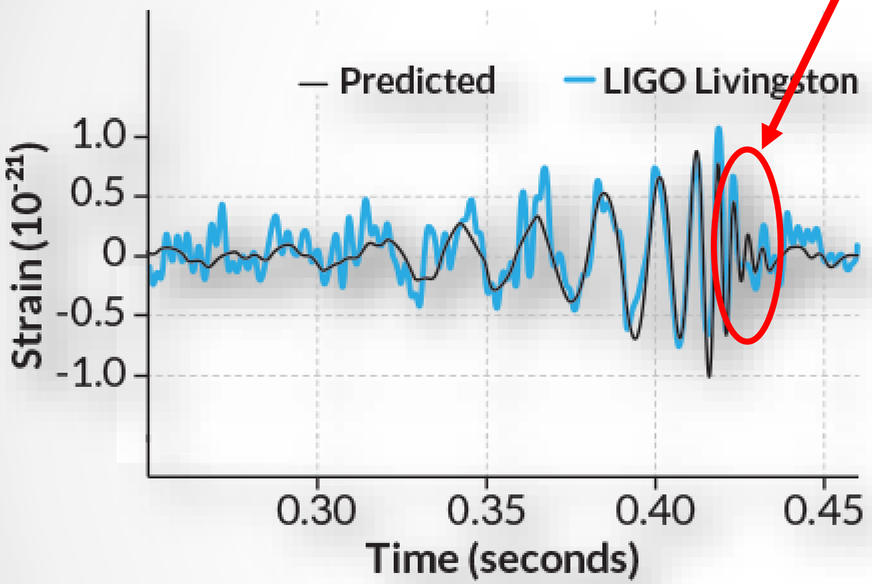


J.J.Li, A.Sedrakian, M.Alford, PRD101 (2020) 063022

Problem I : the Λ info is hard to measure



Gieg et al., Particle 2, 23 (201



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

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

Quadrupole moment

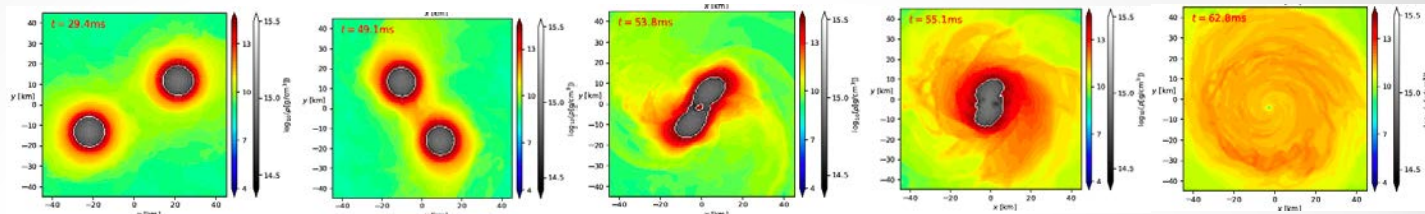
Companion tidal field

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

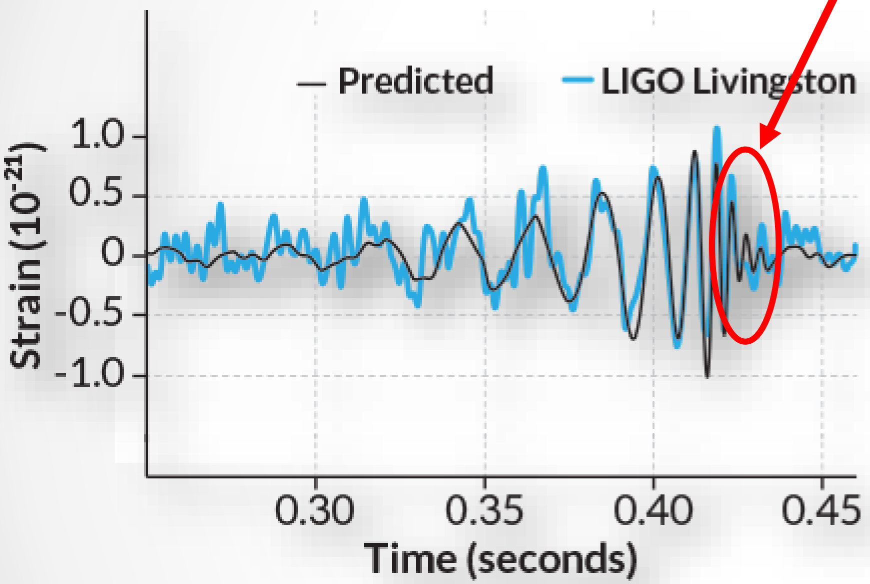
$$(\Lambda_1, \Lambda_2) \leftrightarrow (\tilde{\Lambda}, \delta\tilde{\Lambda})$$

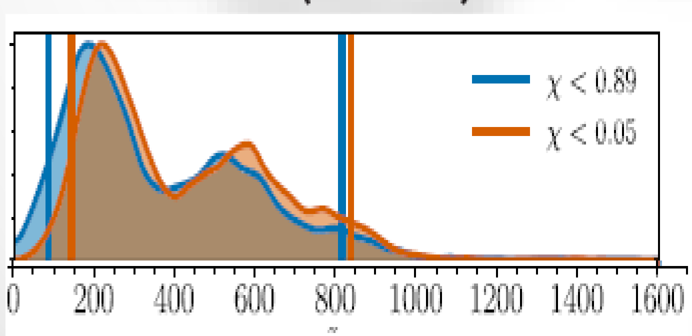
=> Only the combined $\tilde{\Lambda}$ is measurable, and with error bars

Problem I : the Λ info is hard to measure



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





LVC, PRX 9 (2019), 011001

Quadrupole moment

Companion tidal field

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

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

=> 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)

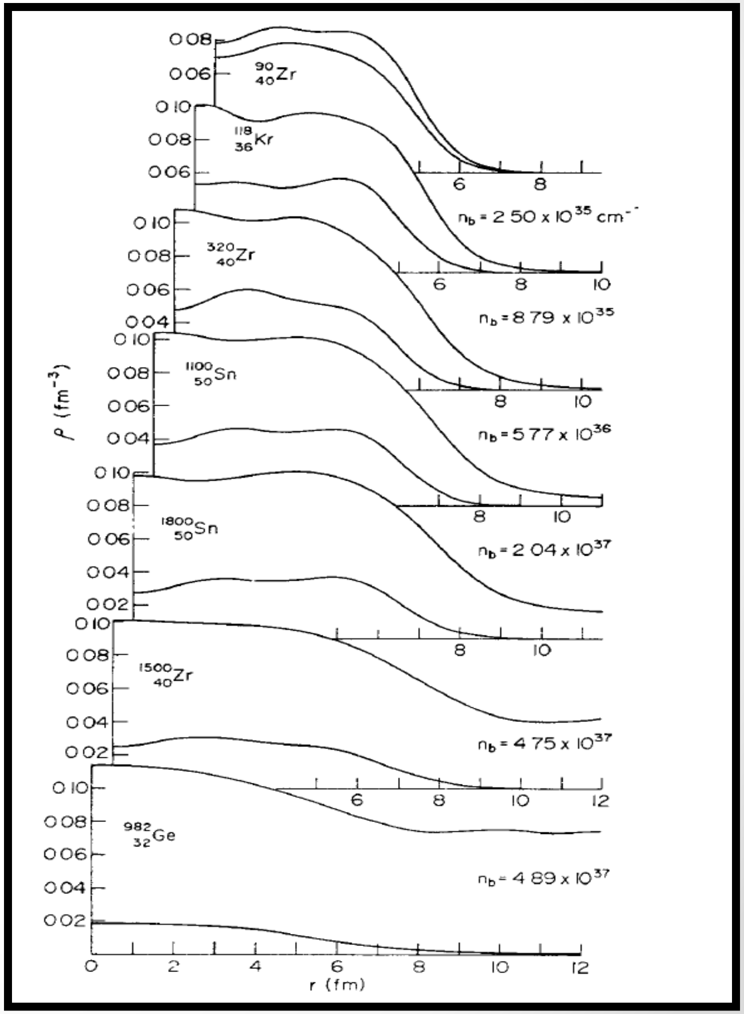
- **NS core:** $\rho_q(r) = \rho_q$ ($\forall$ q constituent)
  - **Effective single particles:** $e_q(k) = \sqrt{m_q^{*\,2} + k^2} + V_q(\rho_q, \rho_{q'})$

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

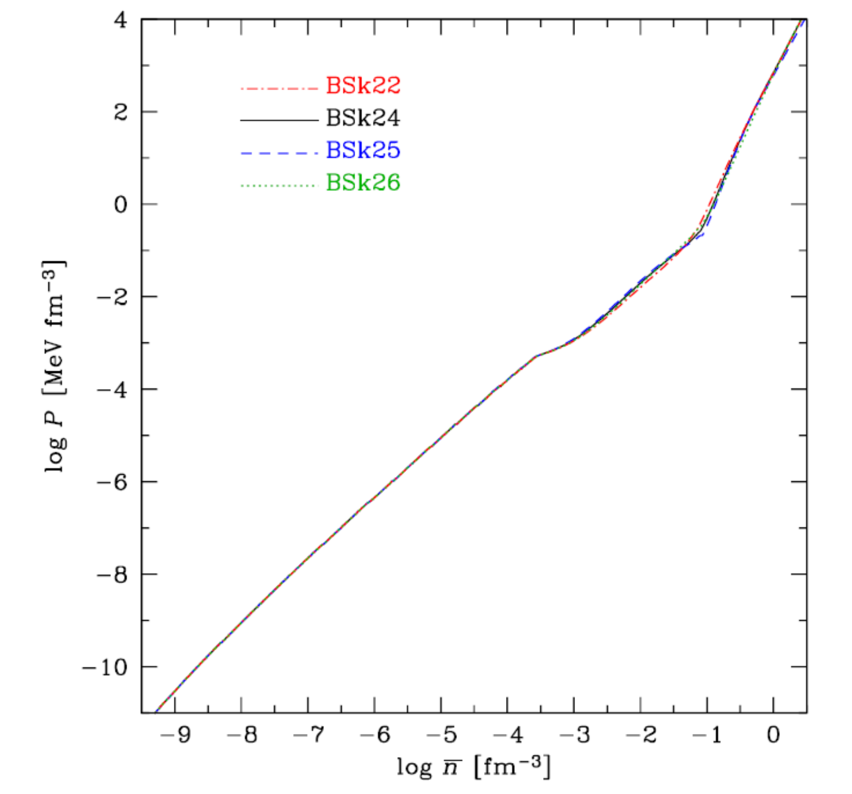
Problem II : no ab-initio theory of dense matter

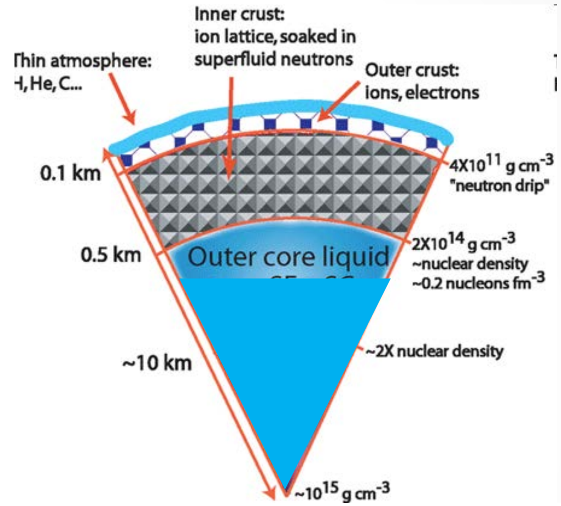
=> Density Functional Approach

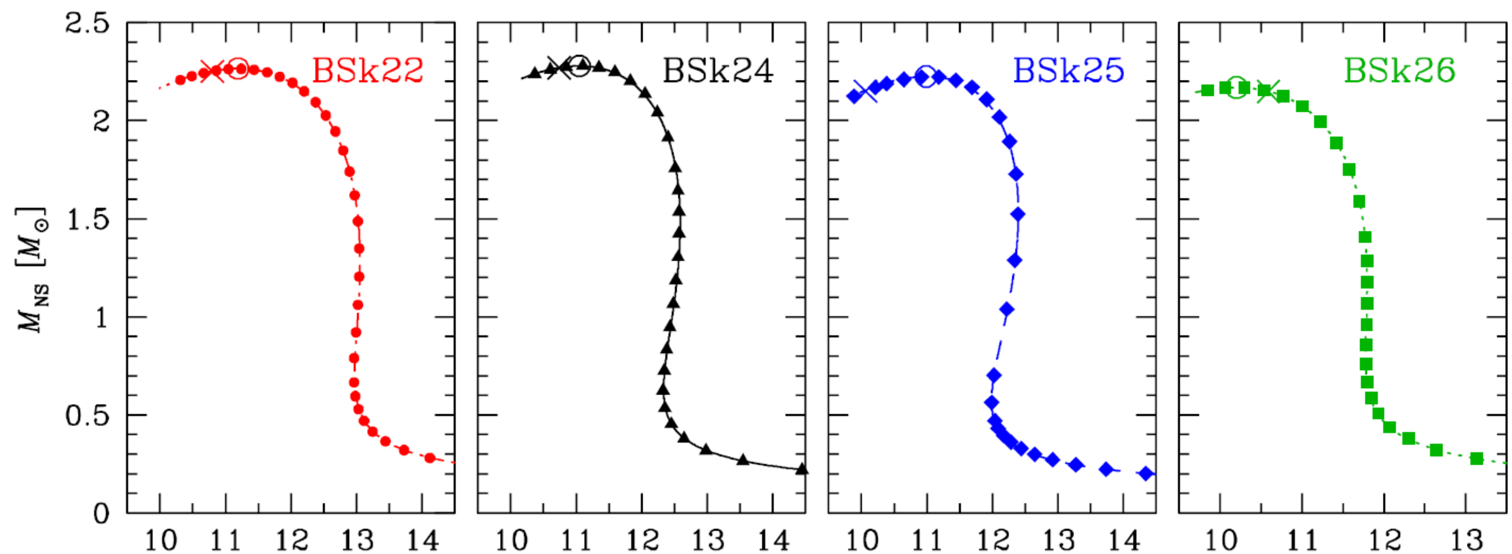
- **NS crust: q=n,p** variational calculation of the single particle wave-functions => $\rho_q(r)$ within the Hartree-Fock-(Bogoliubov) theory



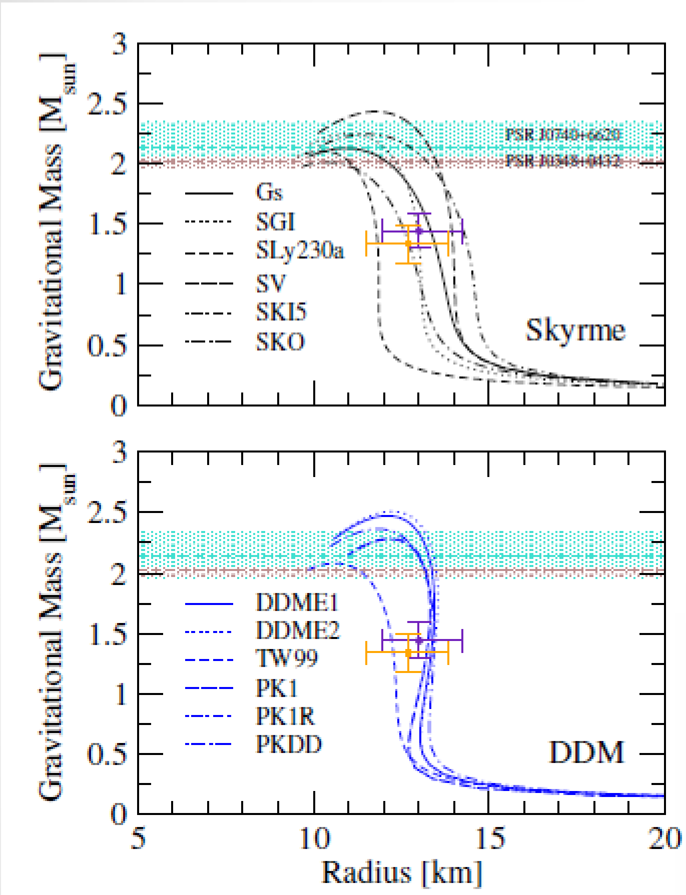
An example: the Brussels-Montreal functionals BSK



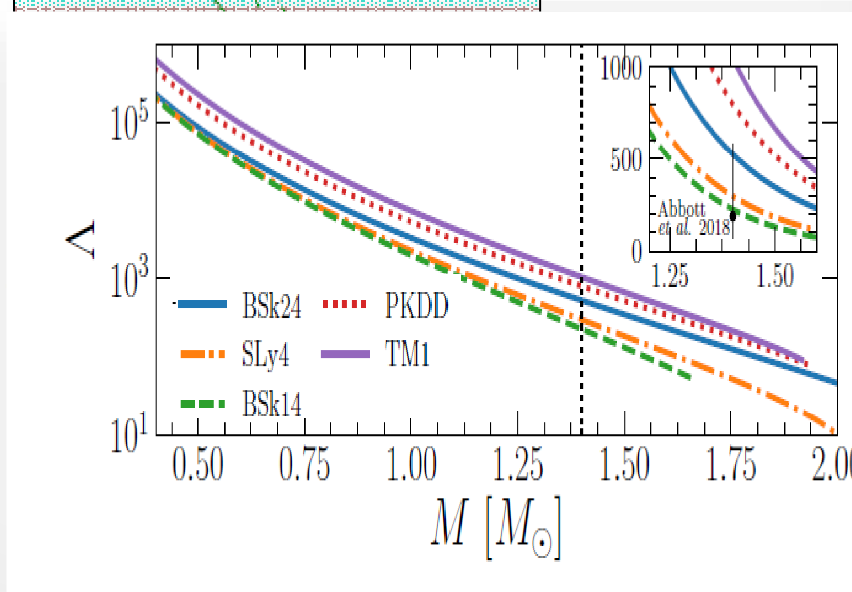




Problem II : no ab-initio theory of dense matter



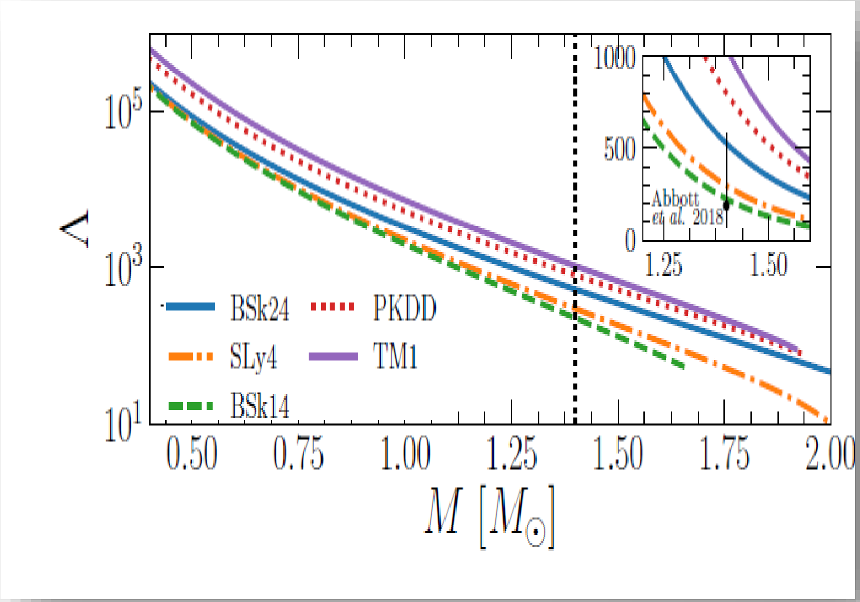
- **Model dependence: choice of functional form (Lagrangian versus Hamiltonian) and fitting protocol lead to different predictions**

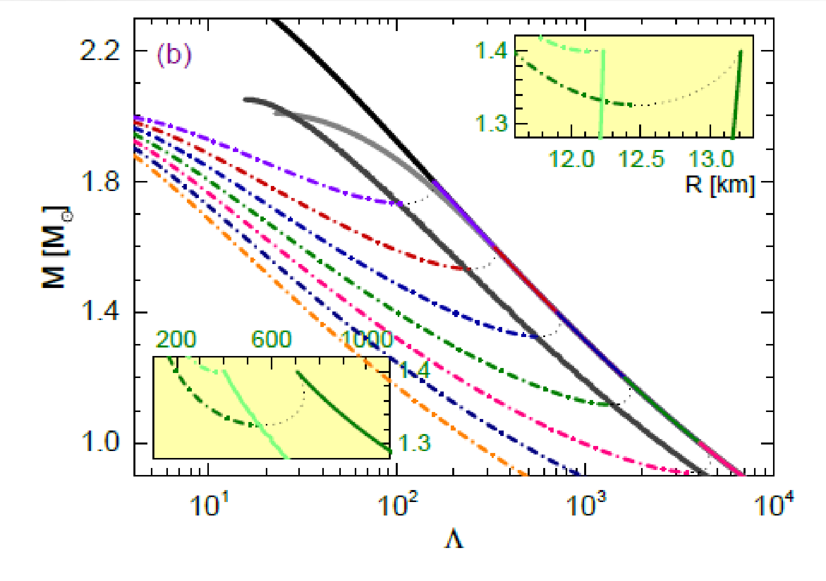


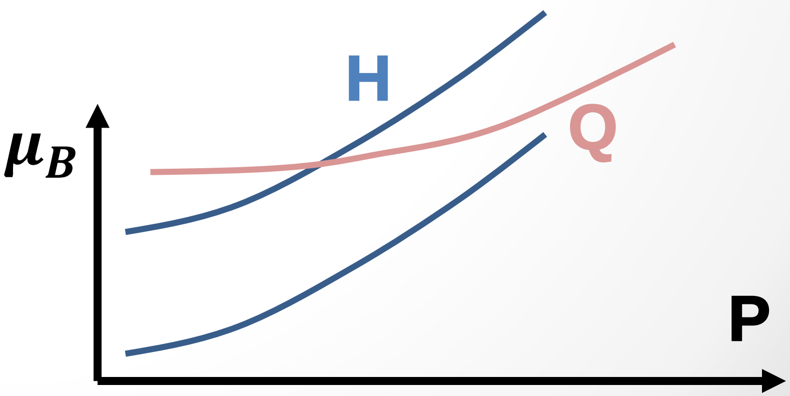
F.Burgio, I.Vidana, Universe 2020, 6, 119

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!!

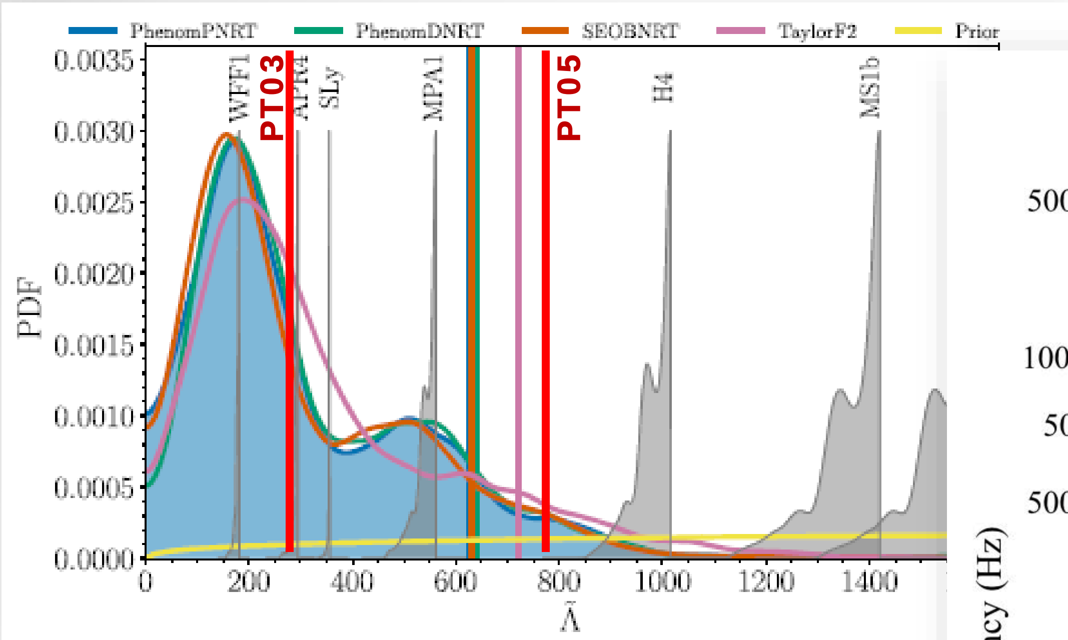


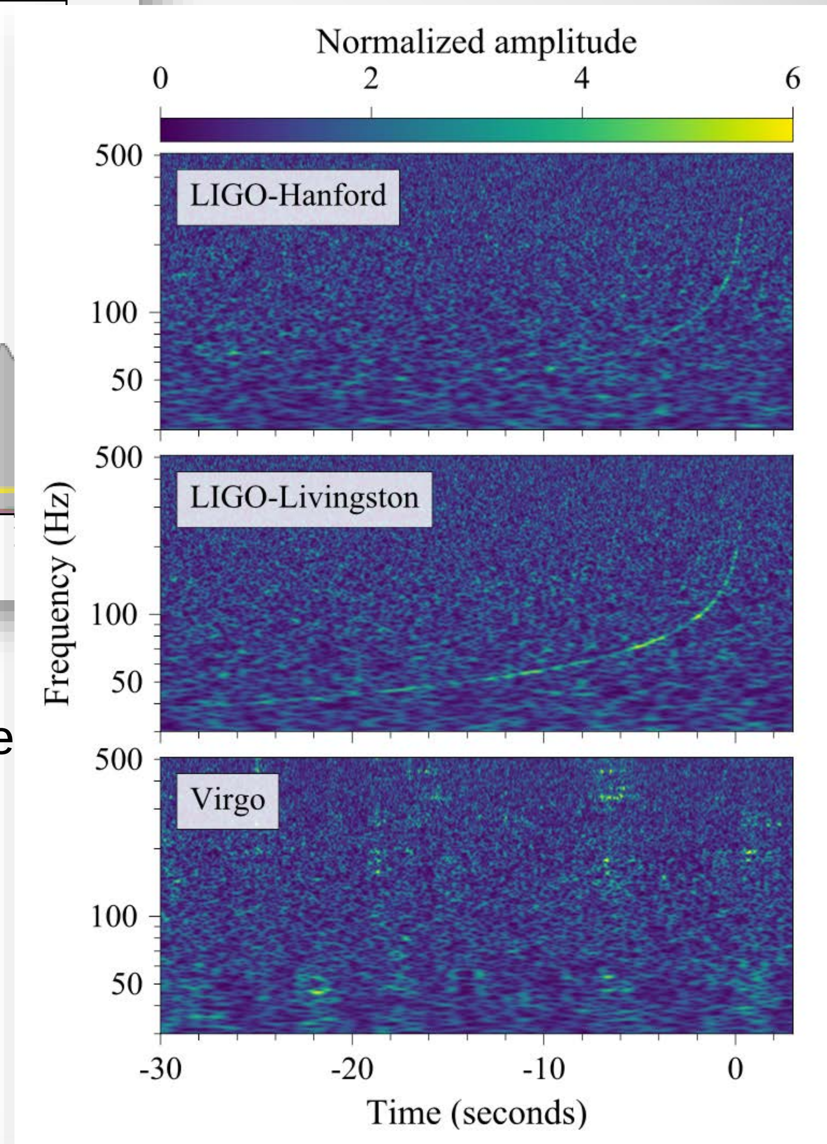




J.J.Li, A.Sedrakian, M.Alford, PRD101 (2020) 063022

Present status: GW170817





LVC, APJL2017 & PRX9 2019

- The observation cannot discriminate

Problem II : no ab-initio theory of dense matter

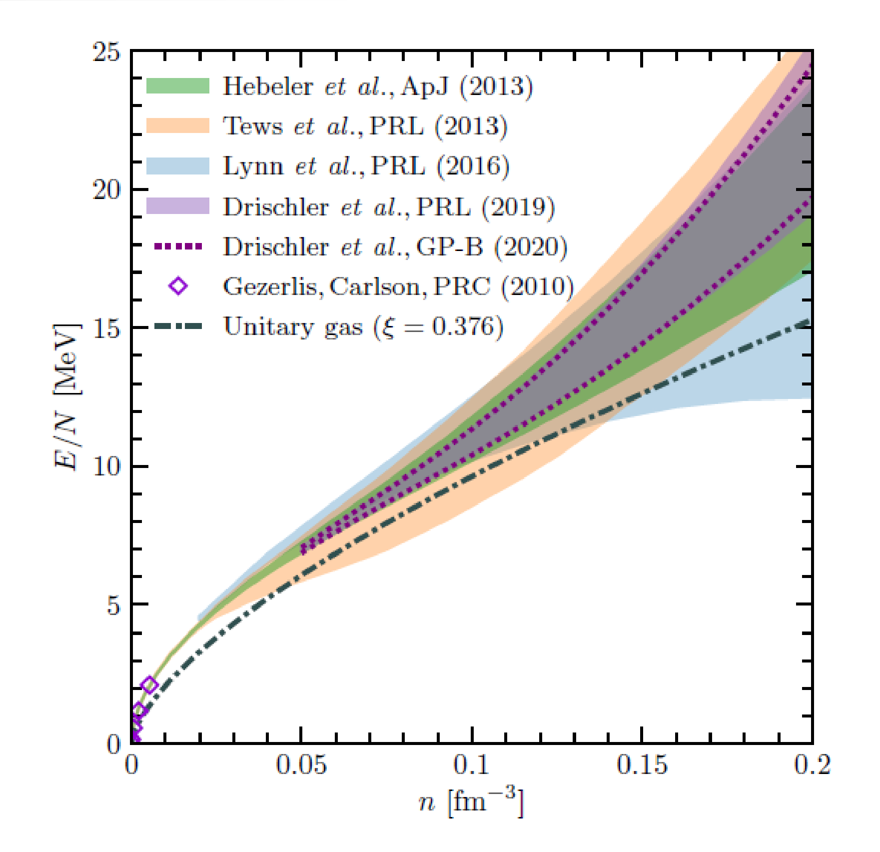
=> Nucleonic « ab-initio » approach

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

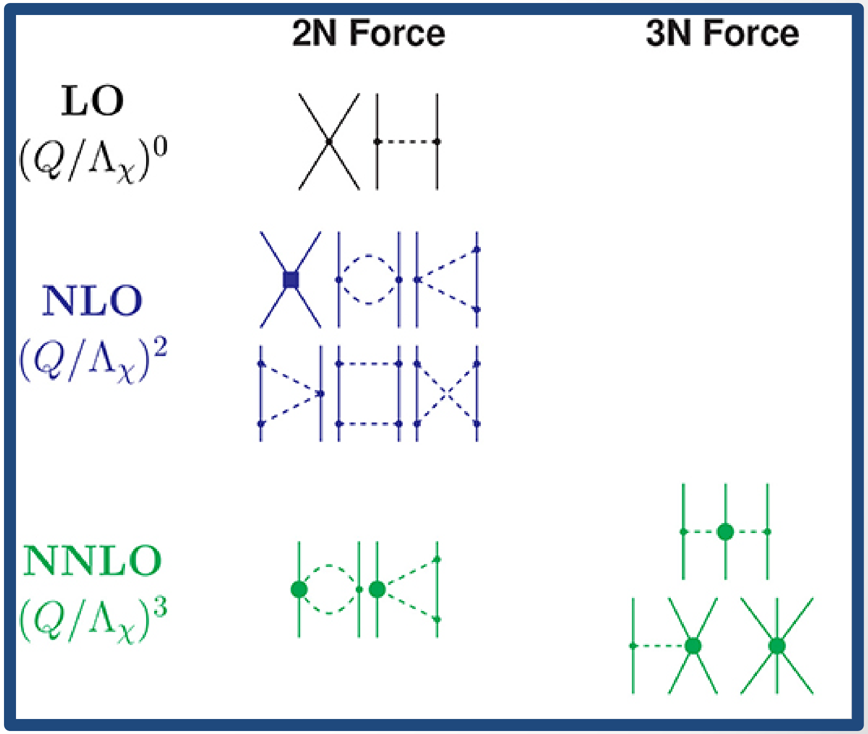
⇒ Coupling constants fitted on scattering data and light nuclei
⇒ $e(\rho_n, \rho_p)$ $P(\rho) = -\rho_B^2 \frac{\partial e}{\partial \rho_B}\Big|_{\mu_n - \mu_p = \mu_e,}$

Nucleonic « ab-initio » approach

- Diagrammatic expansion: controlled uncertainties!
- Still, power counting&regularization valid only up to ~ $2\rho_0$
- Extrapolations needed



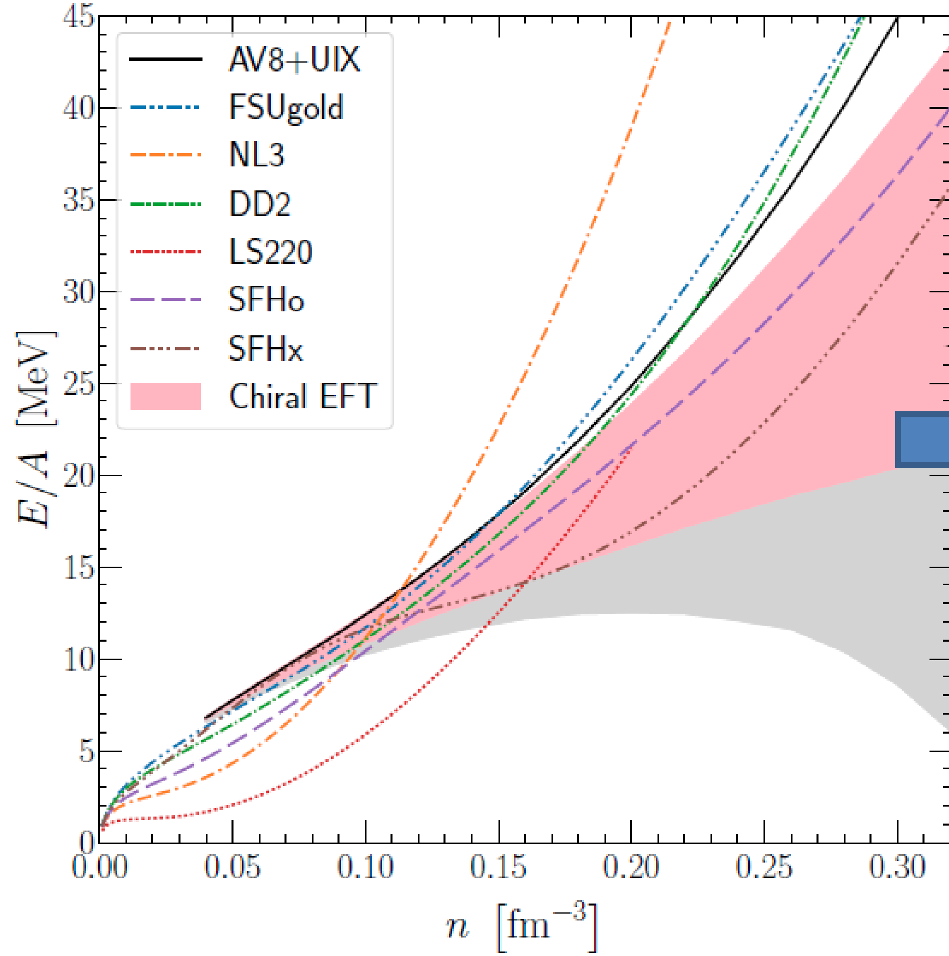
Machleidt R., Int J Mod Phys. (2017)

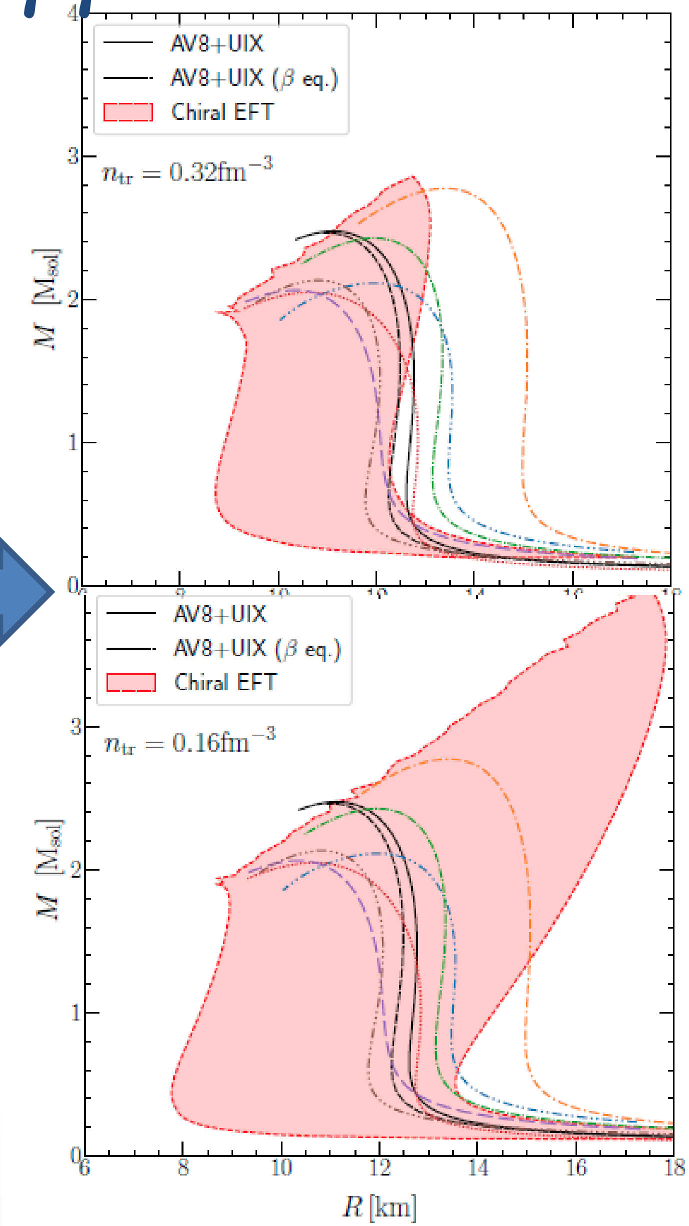


- S. Huth, C. Wellenhofer, and A. Schwenk, Phys. Rev. C 103, 025803 (2021).

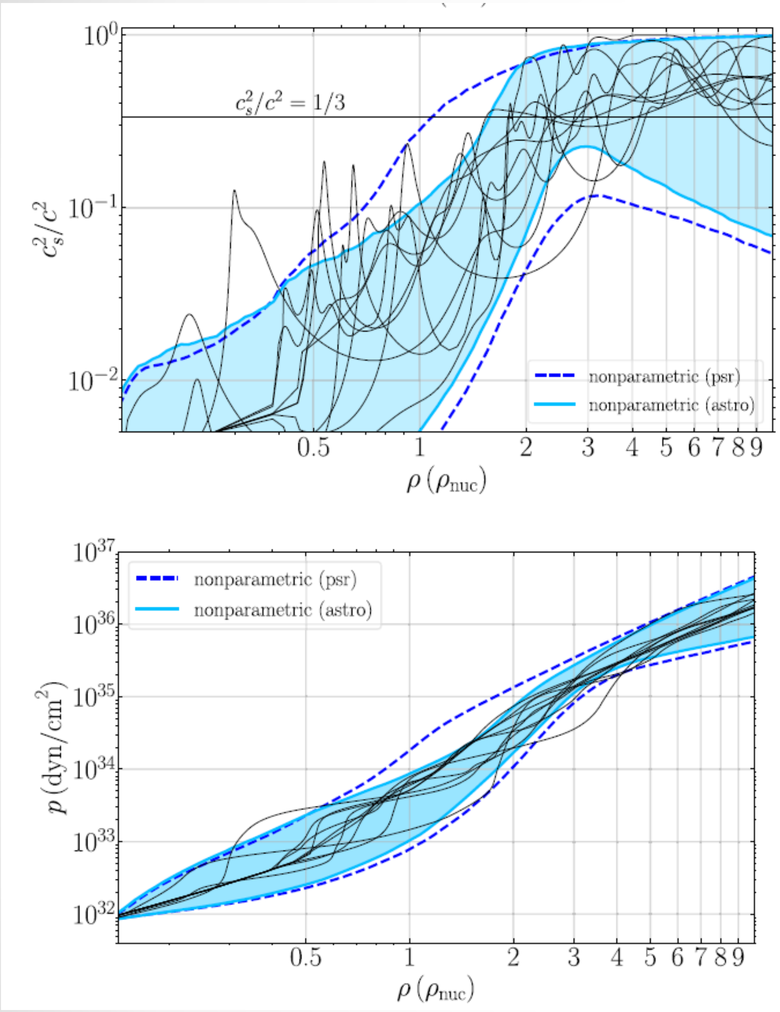
Nucleonic « ab-initio » approach

Tews, Carlson, Gandolfi, Reddy 2018





The inversion strategy



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

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

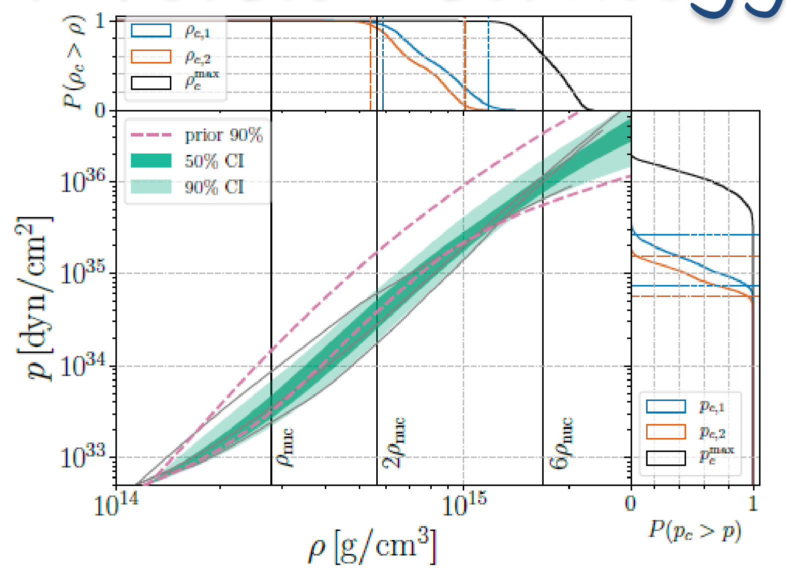
- Bayesian inference

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

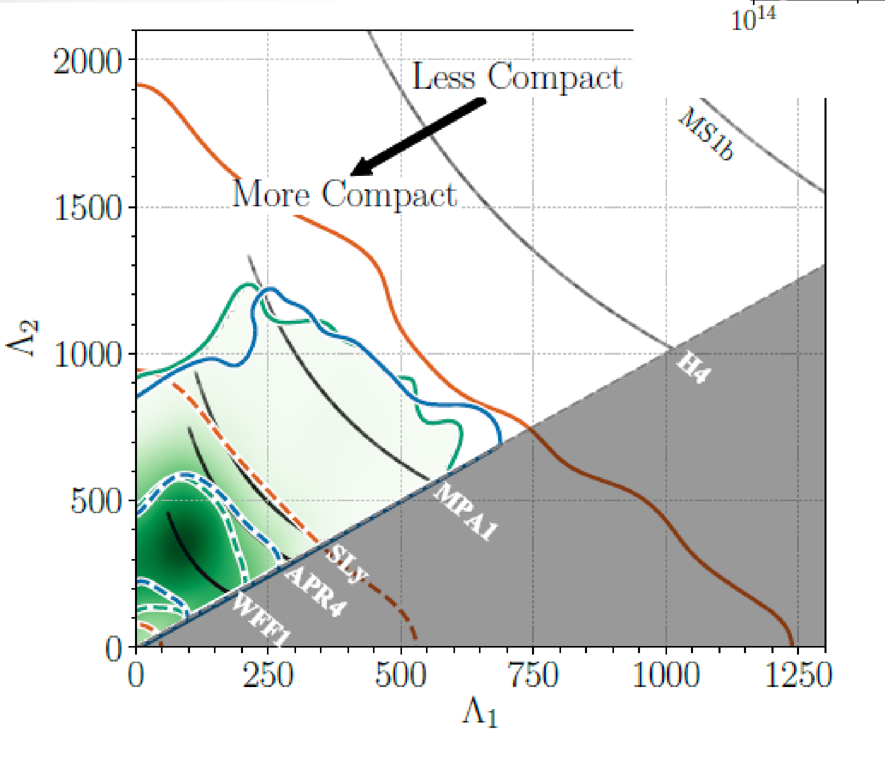
f_1. max.mass (radio)
f_2. tidal polarisability (GW)
f_3. radius (X-ray)

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

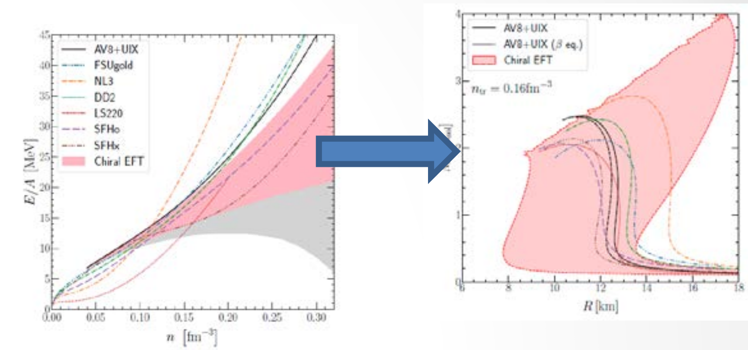


- (Almost) model independent evaluation of the EoS
- Still, we do not learn much about nuclear physics
- We do not exploit our nuclear physics knowledge either

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

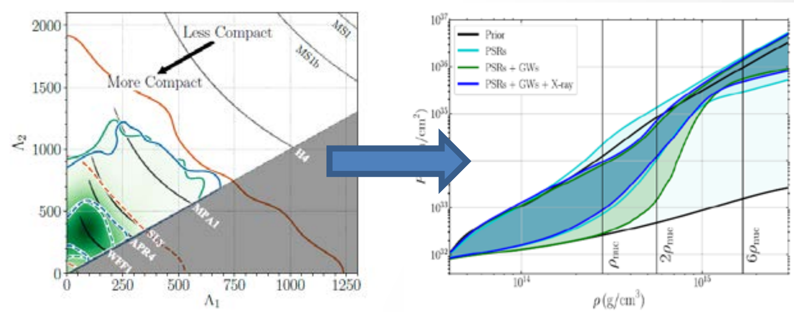
The nuclear physicist viewpoint: $e(\rho_n,\rho_p) \Rightarrow P(\rho) \Rightarrow \langle O \rangle$

- Controlled dof, hypotheses and approximations, exp data 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 nuclear physics



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

General EoS modelling: the syllabus

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

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

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
…………………………

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

Laboratory observables

~~EoS~~
Nuclear model

Astronomical observables

Bayesian Inference

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

f_1. nuclear data
f_2. ab-initio theory

Nuclear physics

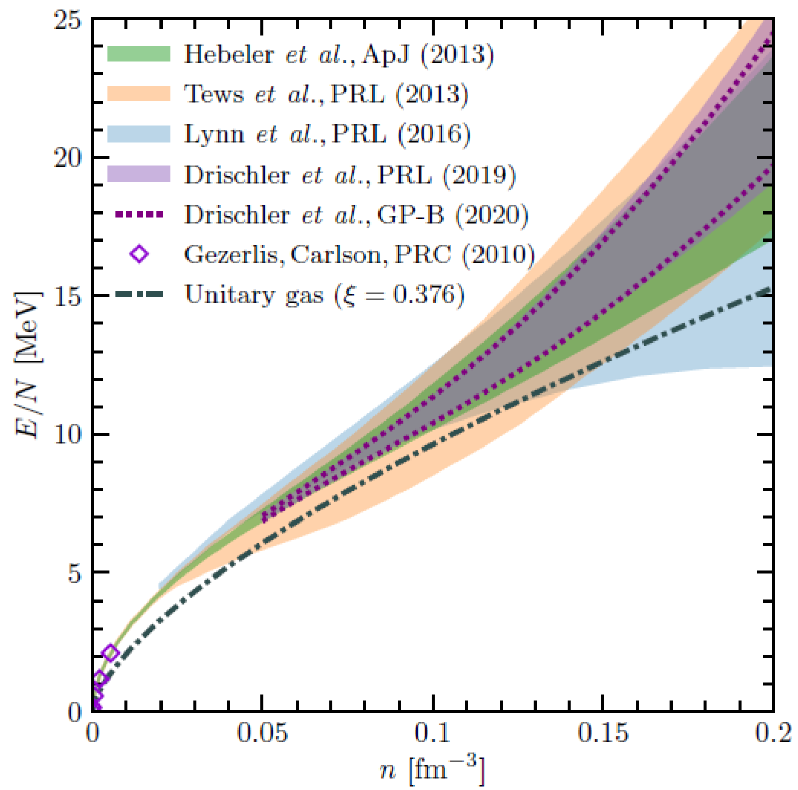
f_3. max.mass (radio)
f_4. tidal polarisability (GW)
f_5. radius (X-ray)

Astrophysics

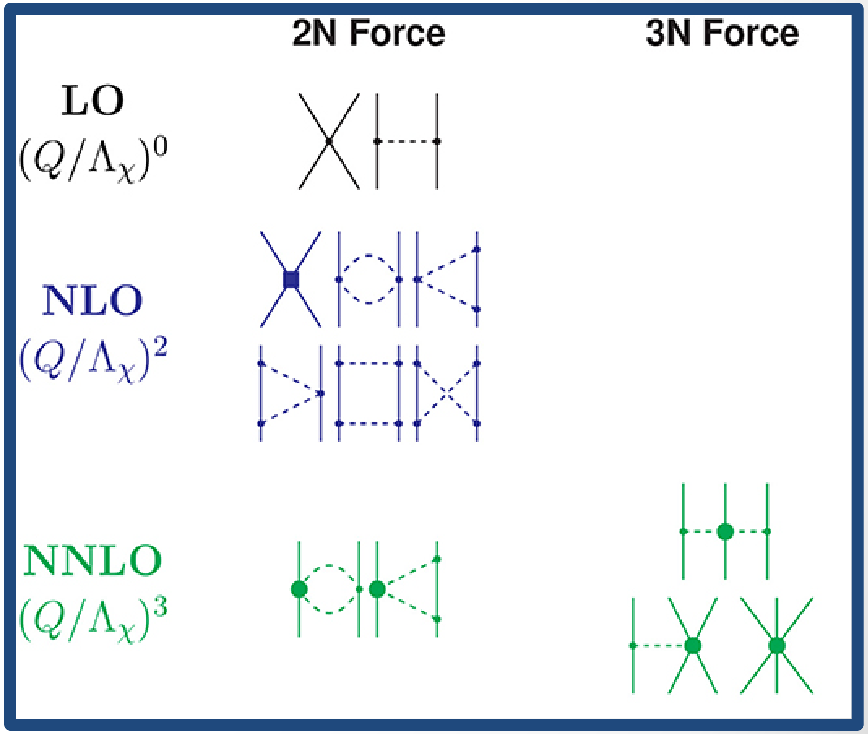
(3) PSR J0348+0432 $M=2.01\pm0.04\ M_{\odot}$
(4) GW170817 $\tilde{\Lambda}(M)$ LVK
(5) PSR J0030+0451, PSR J0740+6620 NICER

Ab-initio nuclear theory

- interaction from χ-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)



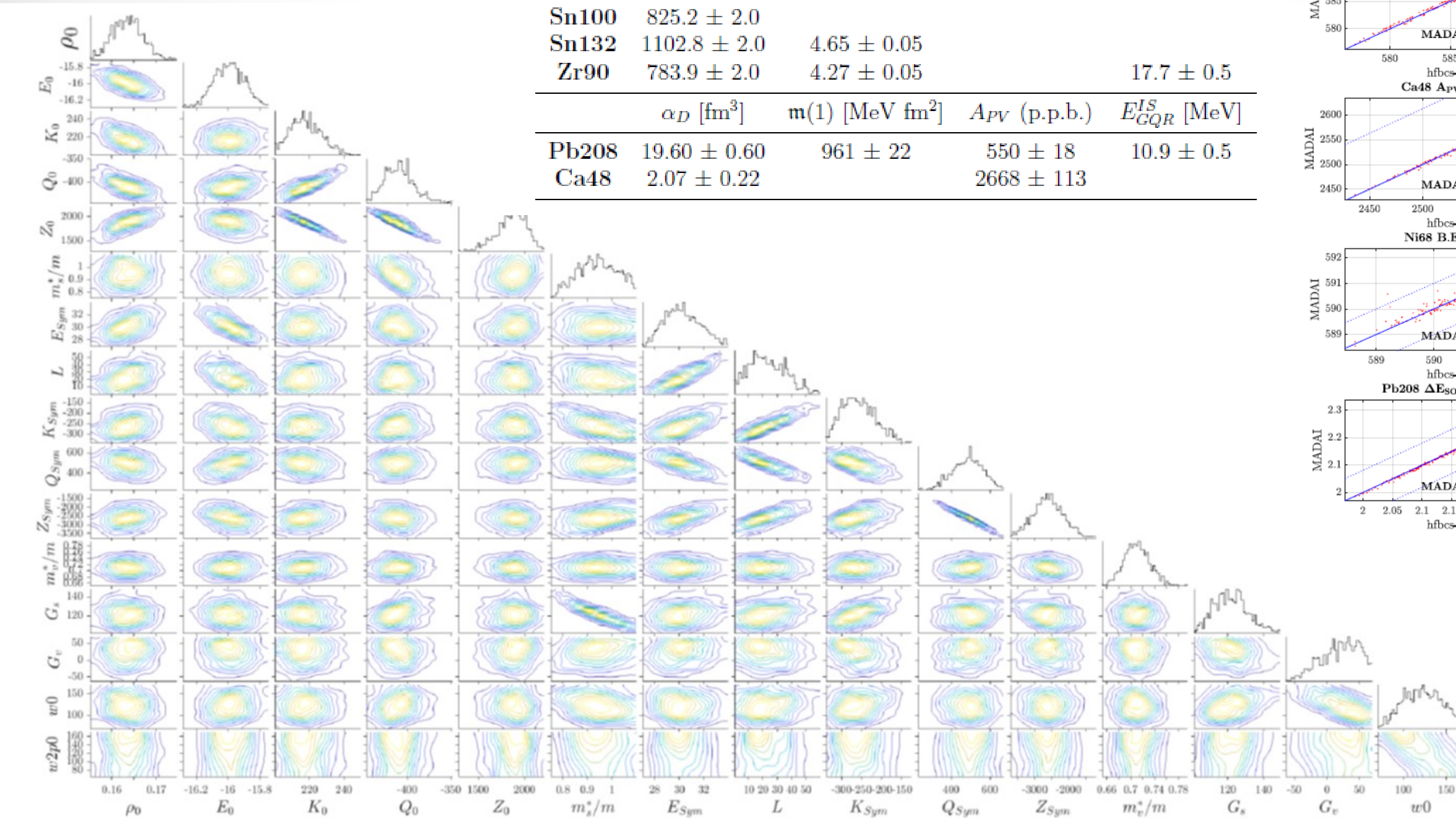
S. Huth, C. Wellenhofer, and A. Schwenk, Phys. Rev. C 103, 025803 (2021).

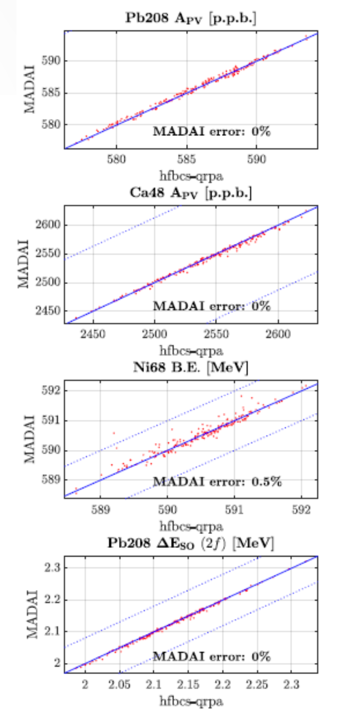
Laboratory experiments

	$B.E.$ [MeV]	R_{ch} [fm]	ΔE_{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
	α_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	

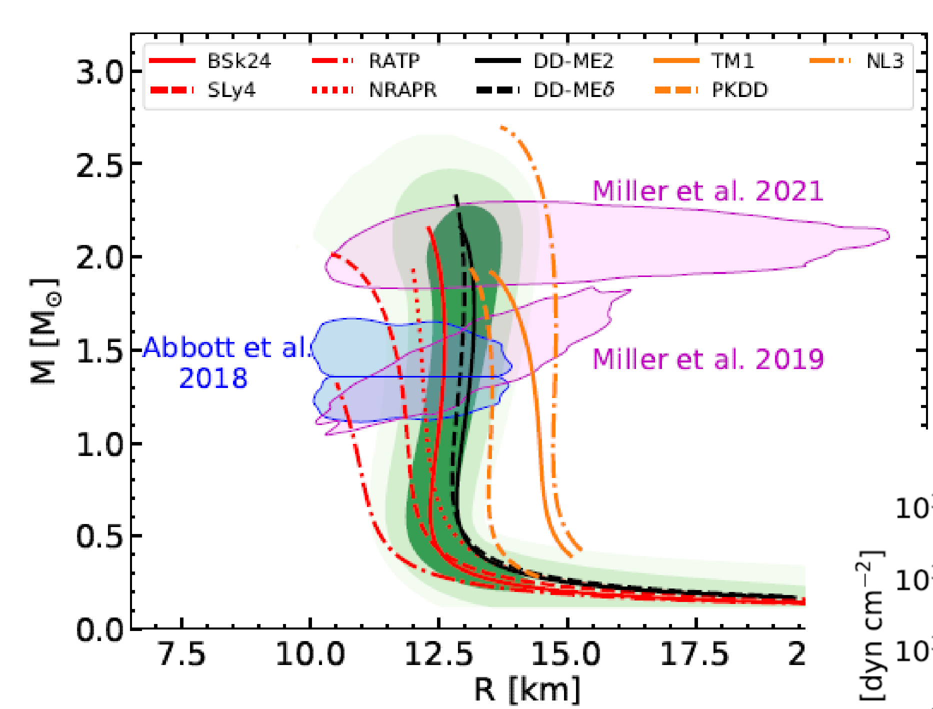
madai.phy.duke.edu

P.Klausner, X.Roca Maza, G.Colo, to be published



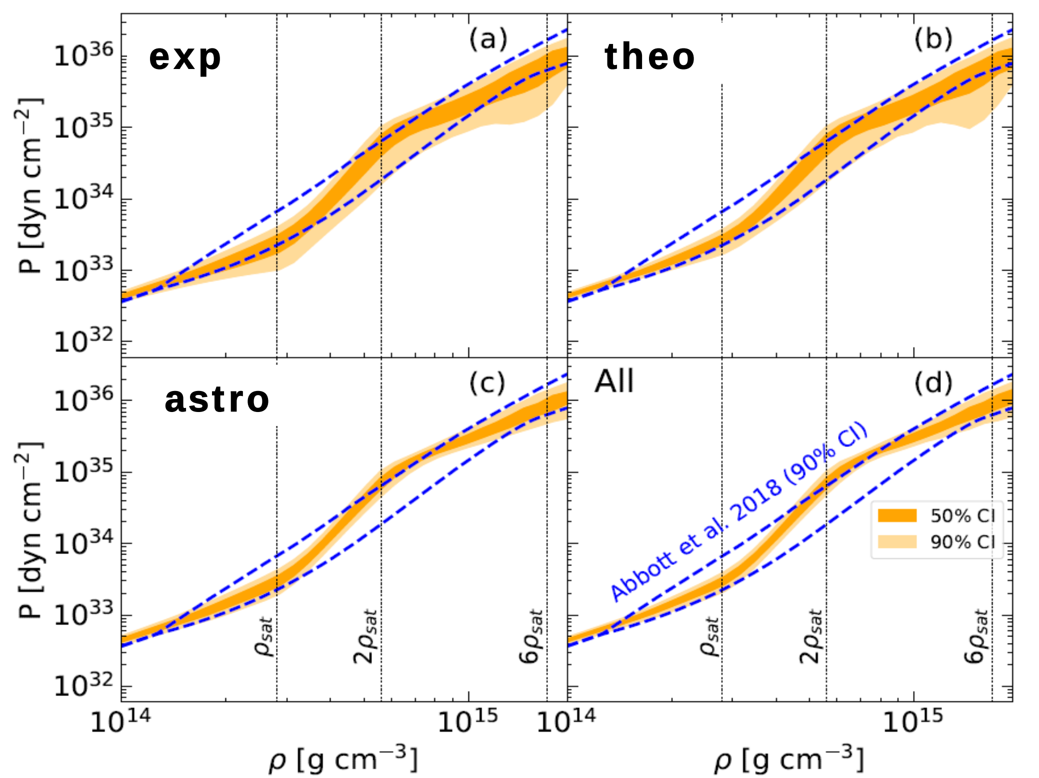


Nuclear physics informed predictions

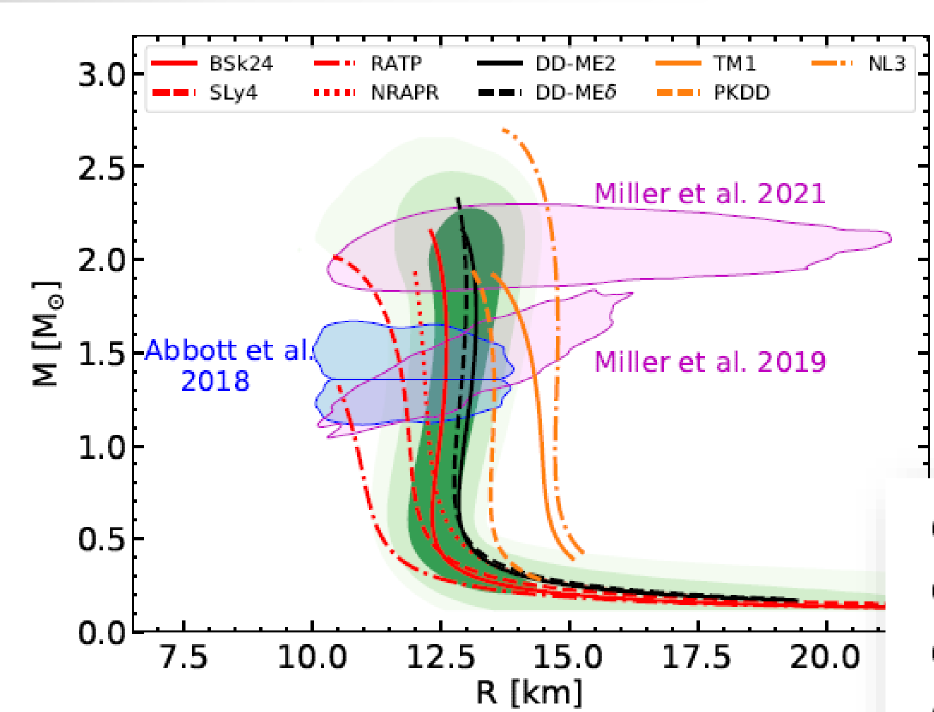


H.Dinh Thi et al, A&A 2021

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



Nuclear physics informed predictions



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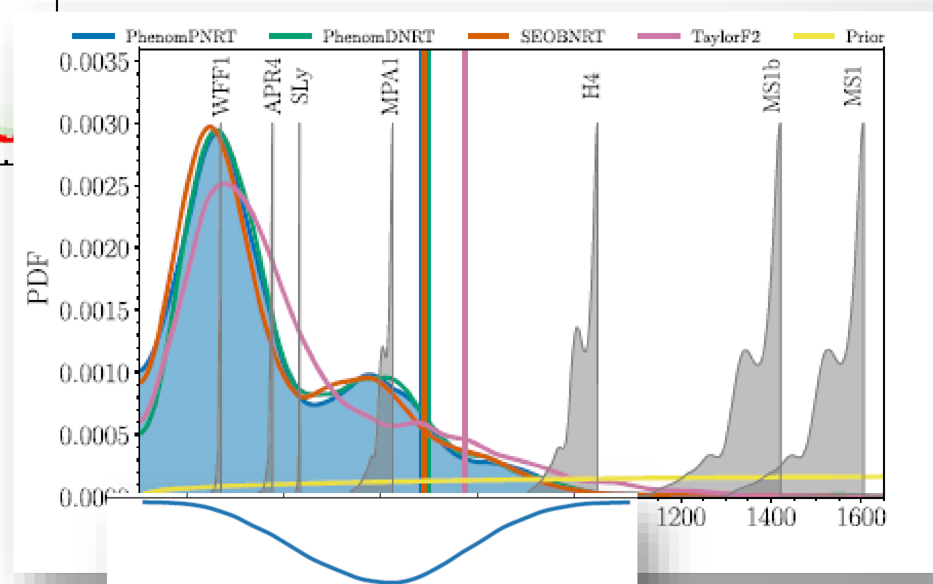
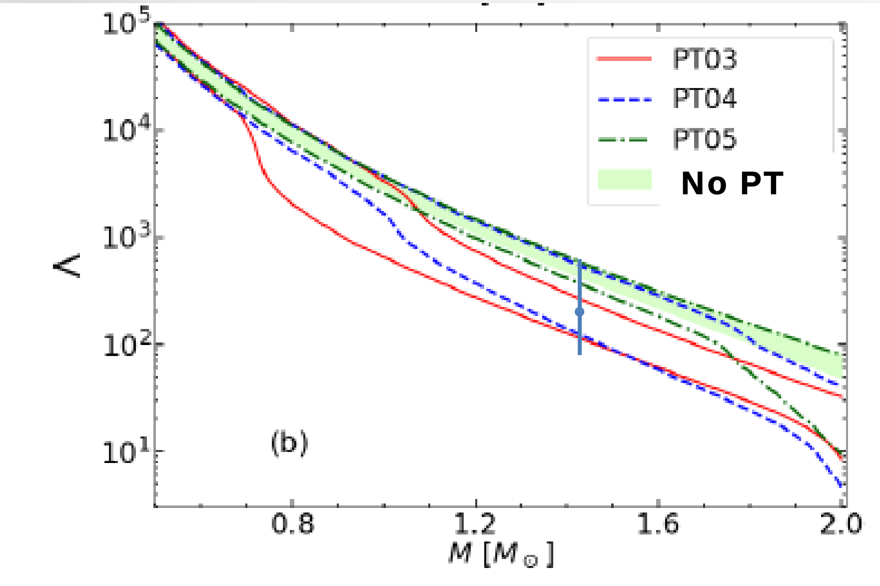
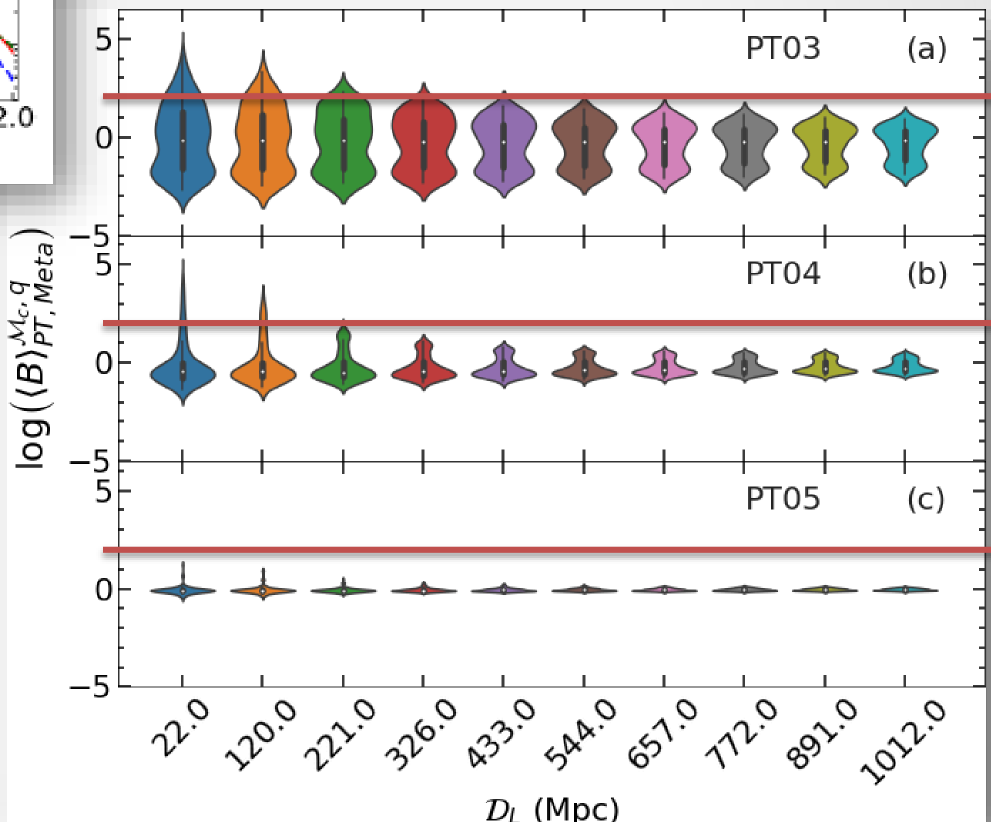


Quarks in the core of neutron stars ?



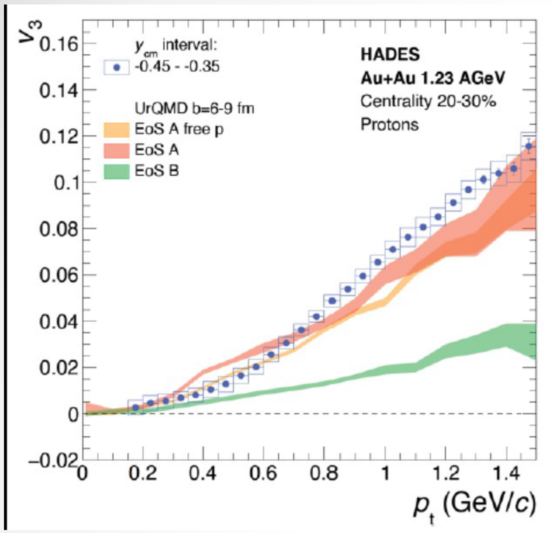
- Even with AdV+ sensitivity, only a very close detection would allow identifying deconfined matter, and only if the quark core is large

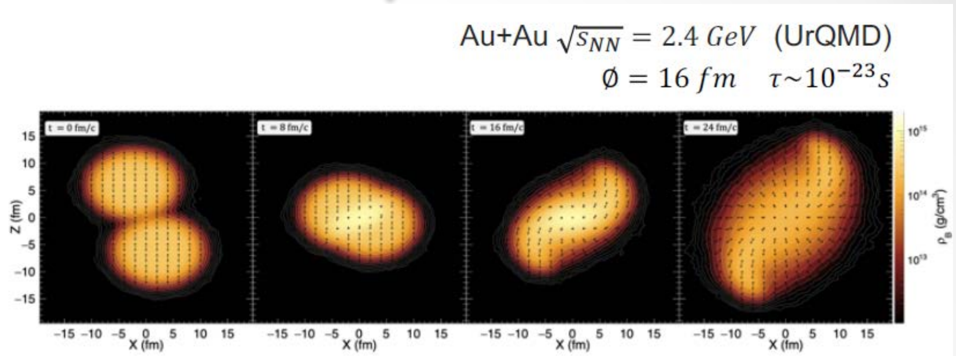
C.Mondal et al, MNRAS 2023

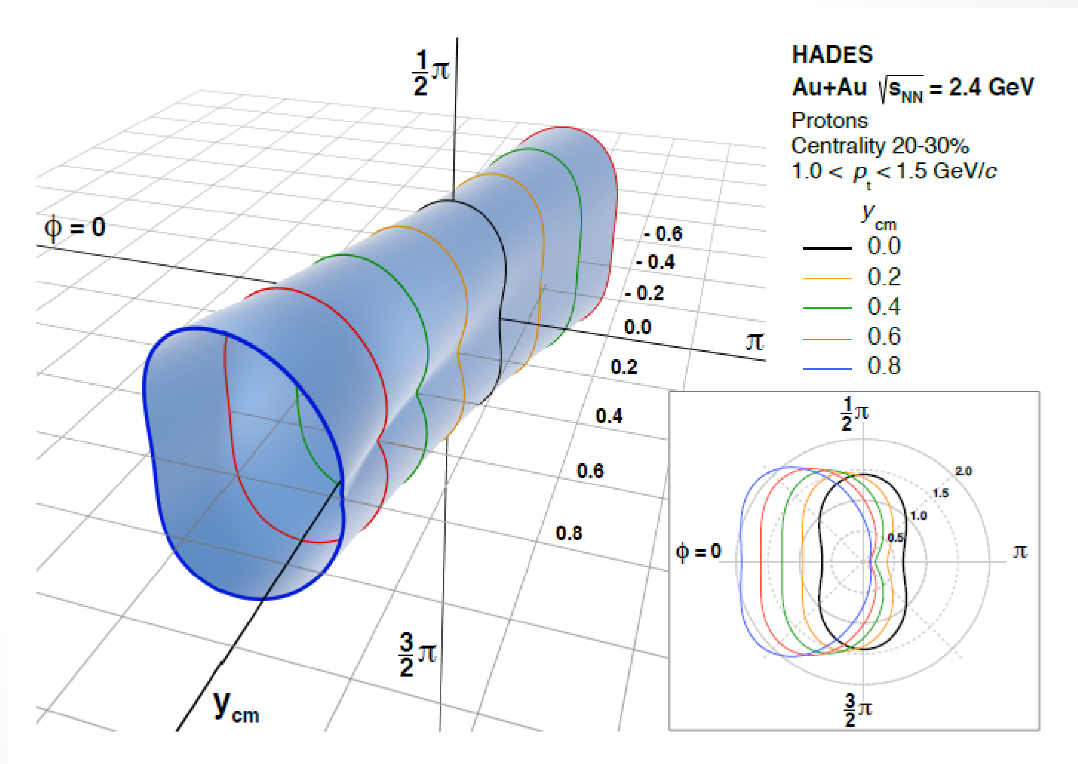


- Need to reduce the uncertainties!
  - New nuclear observables
  - Multiple detections with better SNR=> Einstein Telescope, Cosmic Explorer

The HI collisions probe

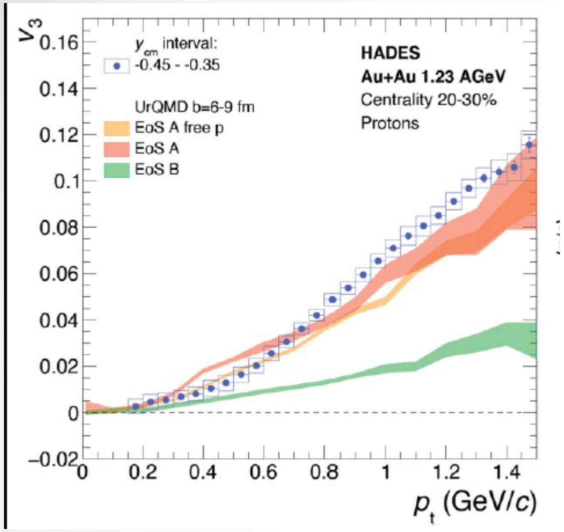


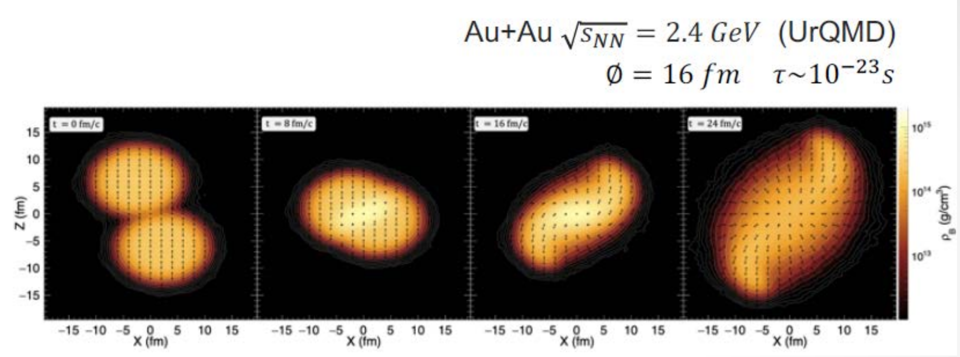




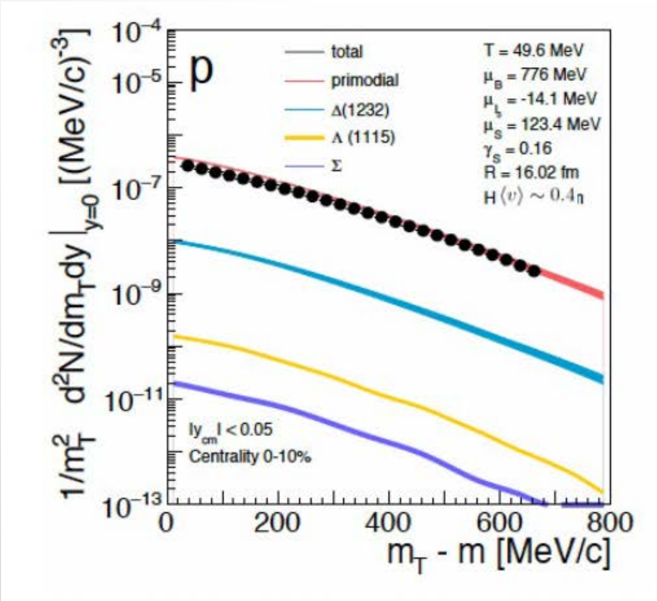
HADES collaboration
PRL 125 (2020) 262301

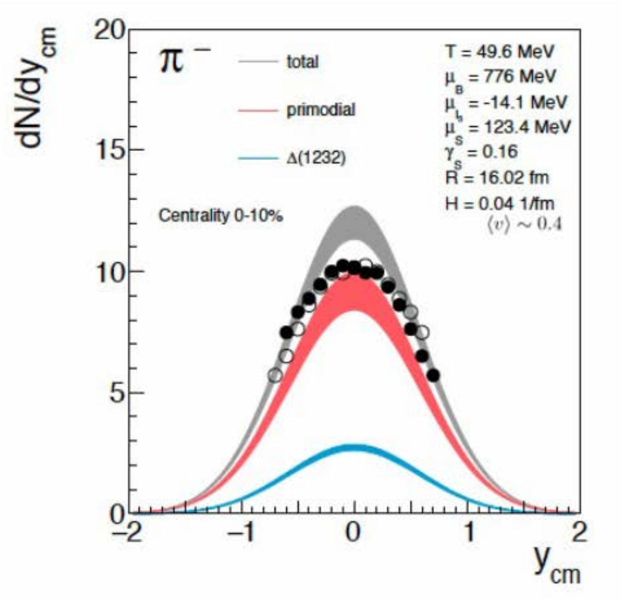
The HI collisions probe





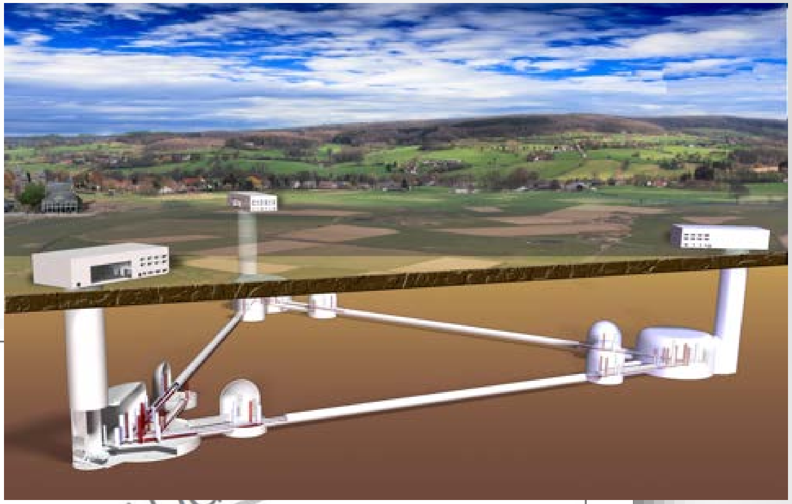
S.Harabasz PRC102 (2020) 054903

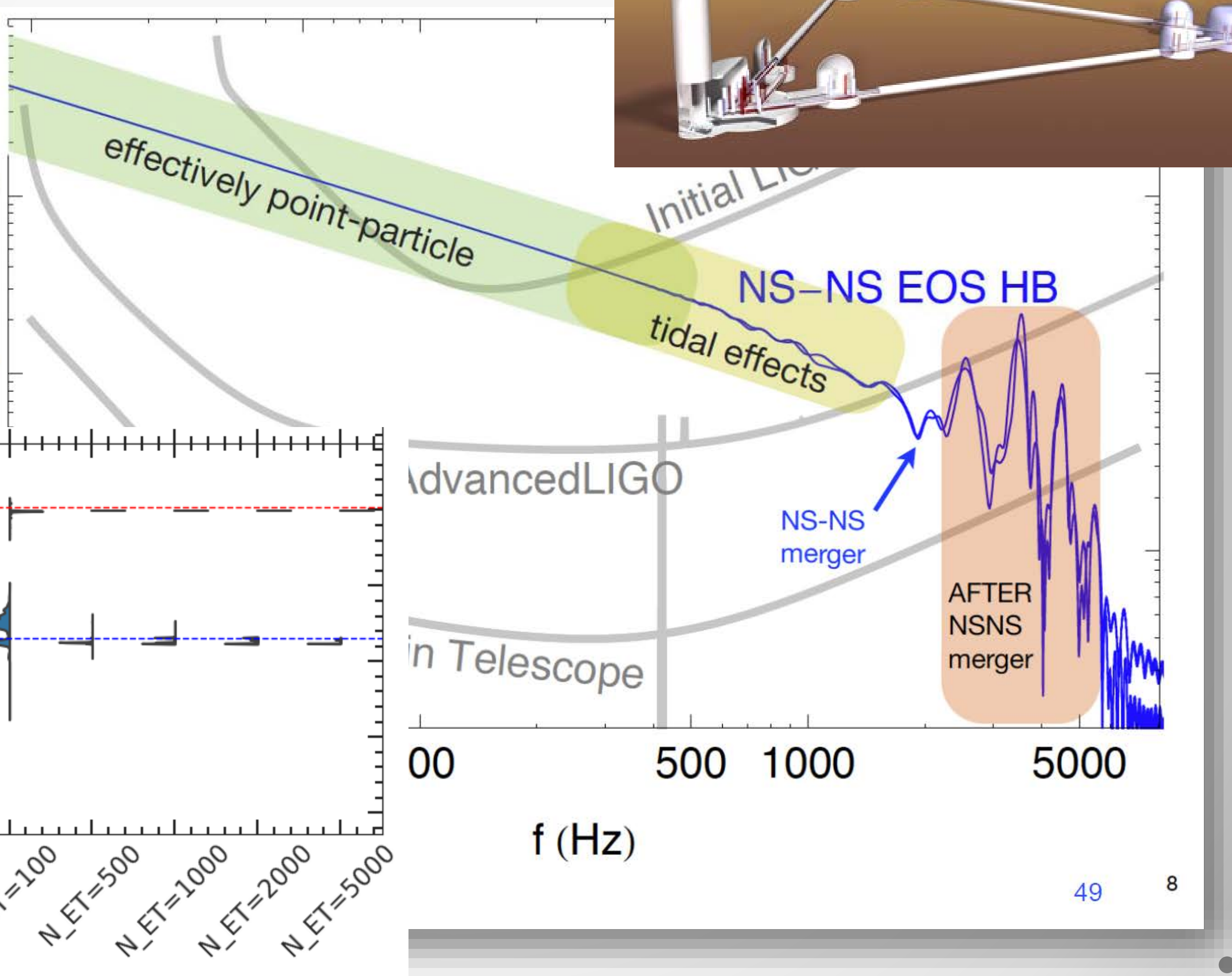


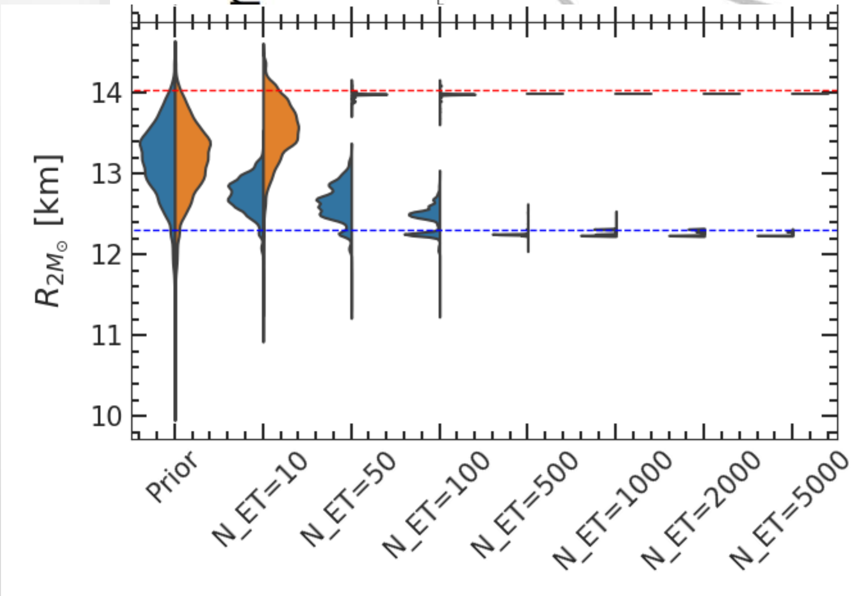


The Einstein Telescope project

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