Credit: NASA/Swift Dana Berry

UNIVERSITÉ
CAEN
NORMANDIE

IN2P3
Les deux infinis

the Neutron Stars EoS

The contribution of nuclear physics to the interpretation of GW signals from ultra-dense matter

Francesca Gulminelli - Université de Caen-Normandie

European Summer School on Experimental Nuclear Astrophysics ,
16-22 June, 2024

Lecture plan

1. Introduction: dense matter in the universe
    1. The sites
    2. The signals
    3. The big questions
2. Neutron star mergers and the Equation of State
    1. Observations
    2. Hydrostatics and the EoS
    3. EoS and observables: constraining the parameters

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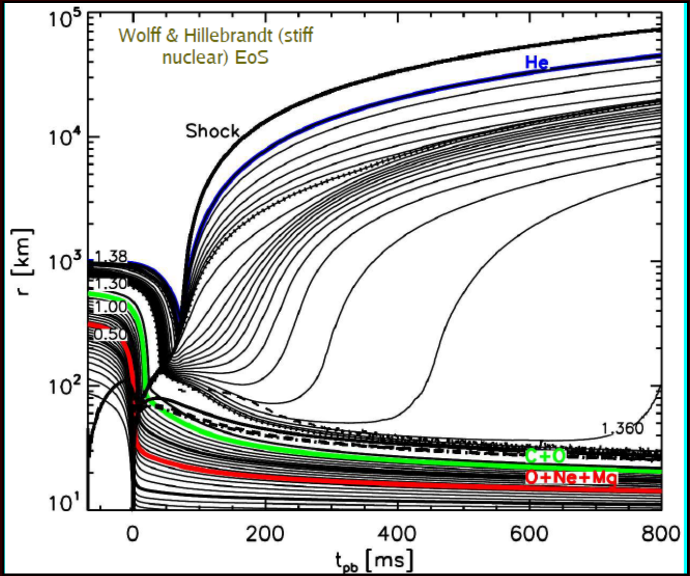
Dense matter in the Universe: CCSN

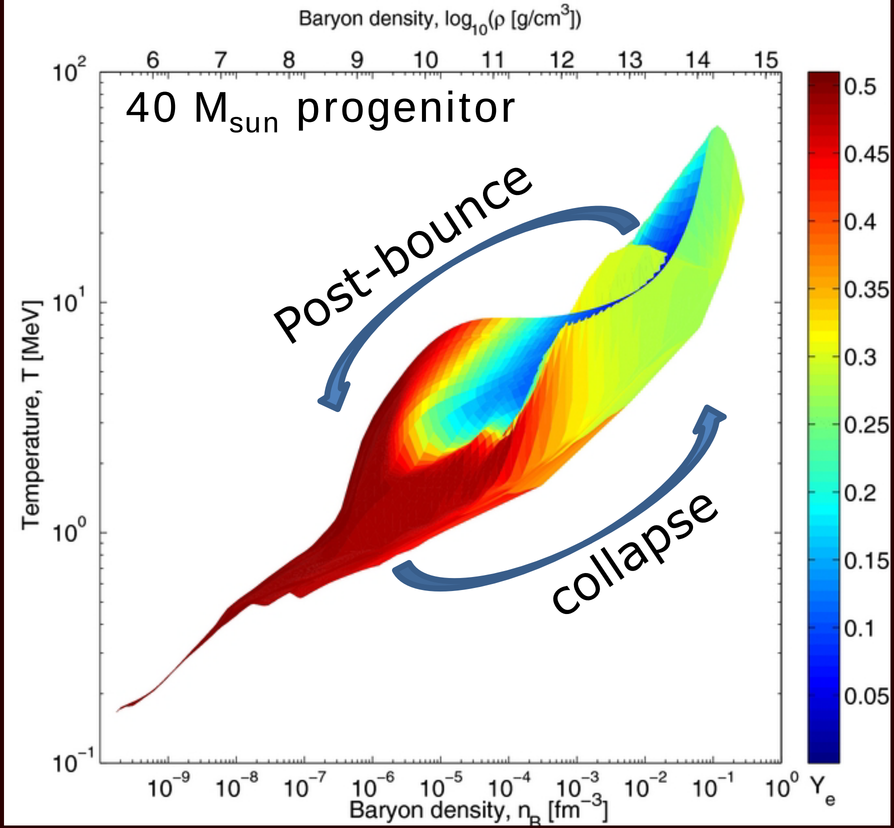
Supernova remnant

in Puppis A
MIPS+XMM
IR Credit: NASA)

A

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

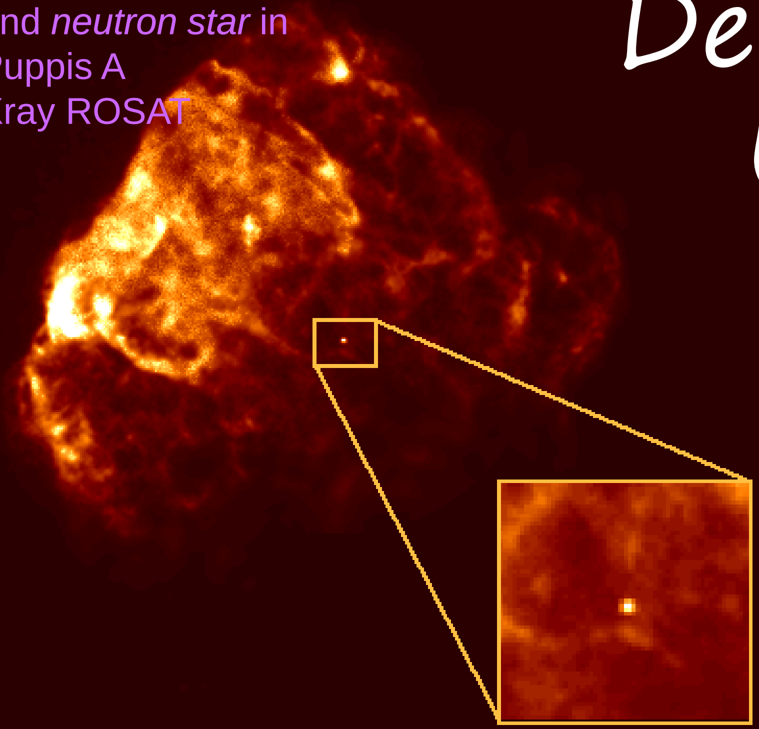


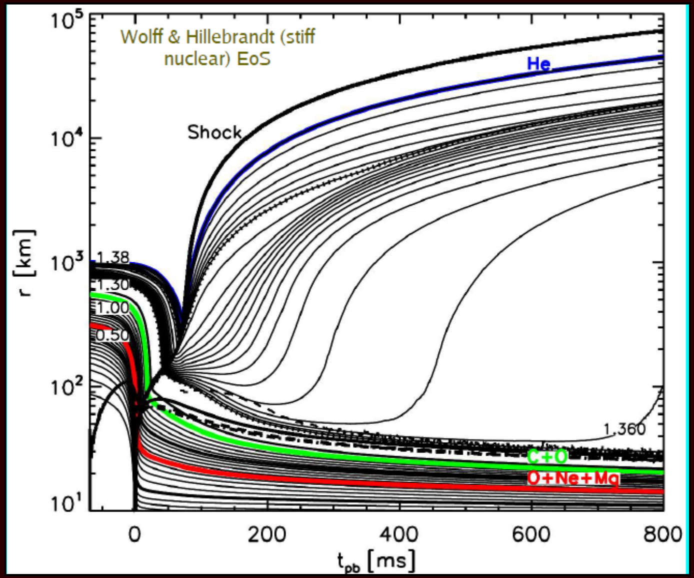


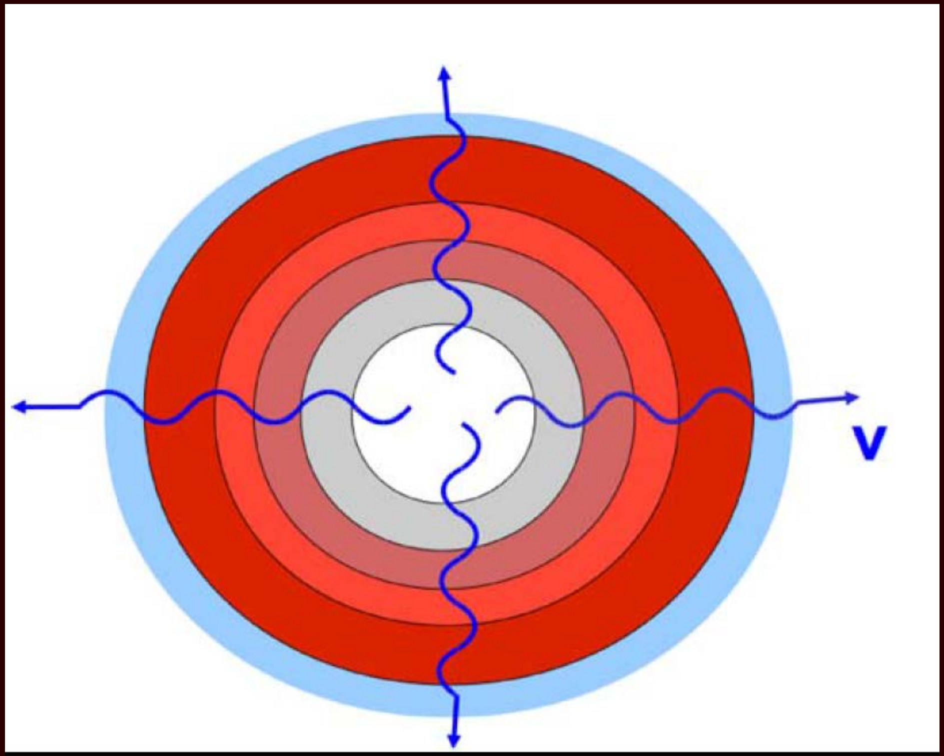
T.Fischer et al, 2011 ApJS **194** 39

Dense matter in the Universe: PNS

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

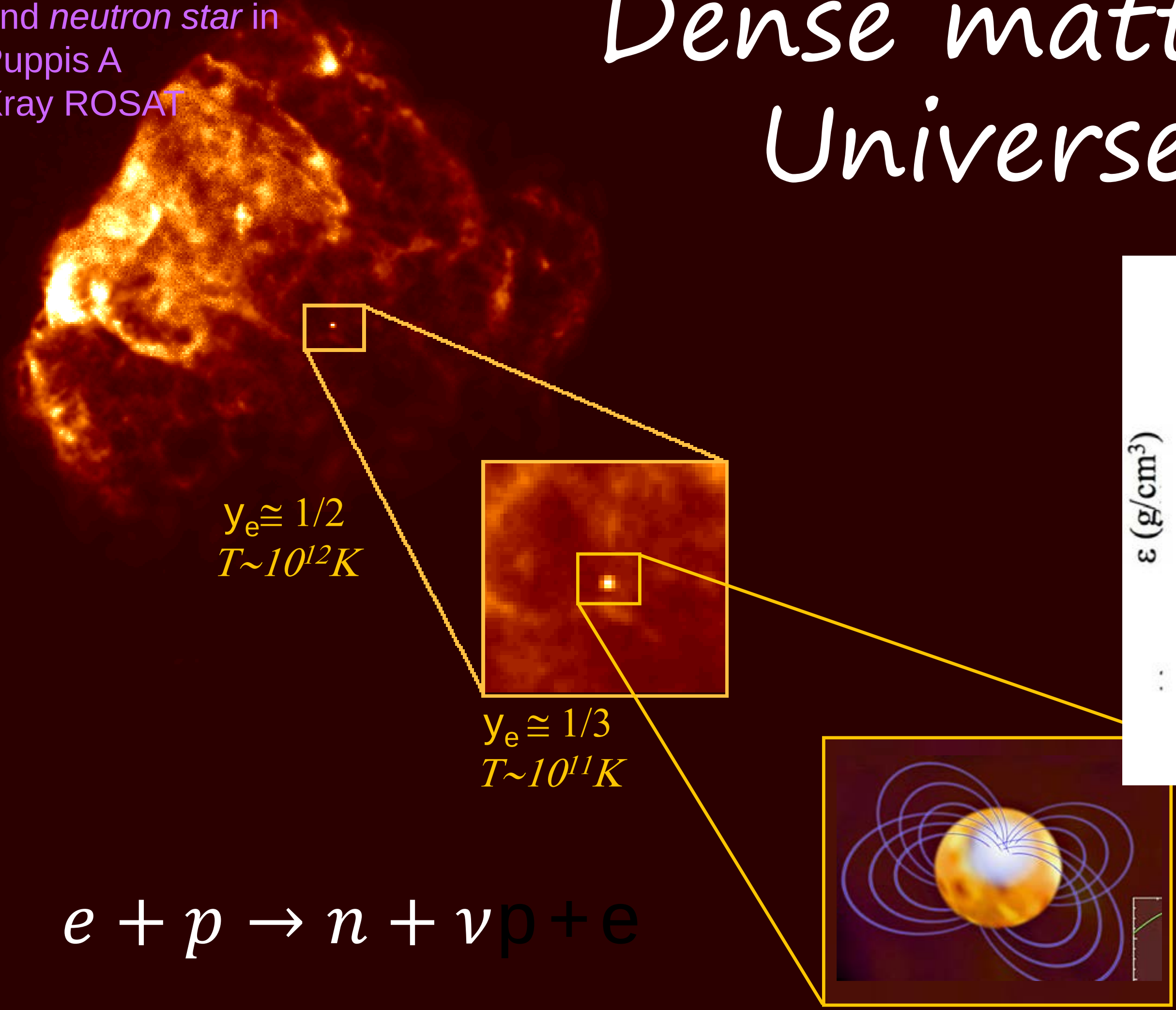






Dense matter in the Universe: NS

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

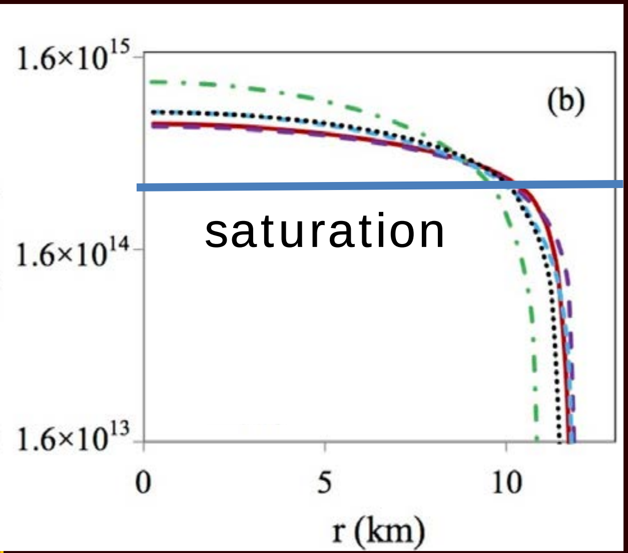


$y_e \cong 1/2$
$T \sim 10^{12} K$

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

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

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



in the
NS

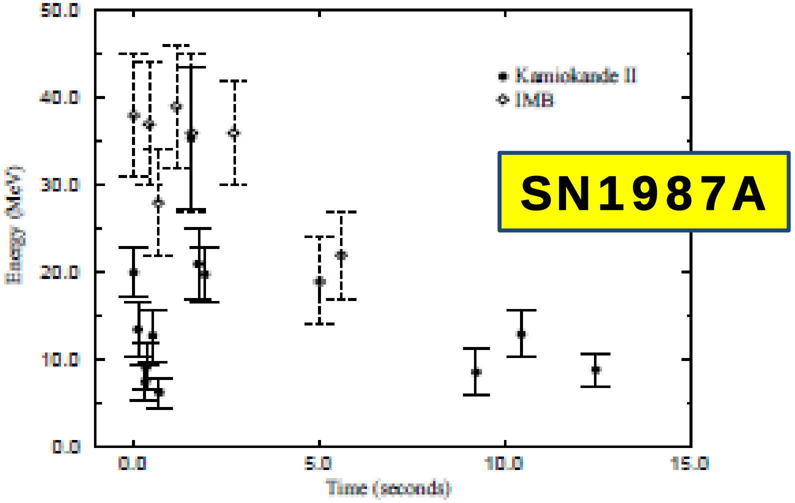
pact star binaries
ever stable in GR
oalescence into a
assive NS and/or
llapse into a BH

, visualisation R. West
ovies/nsmerger/

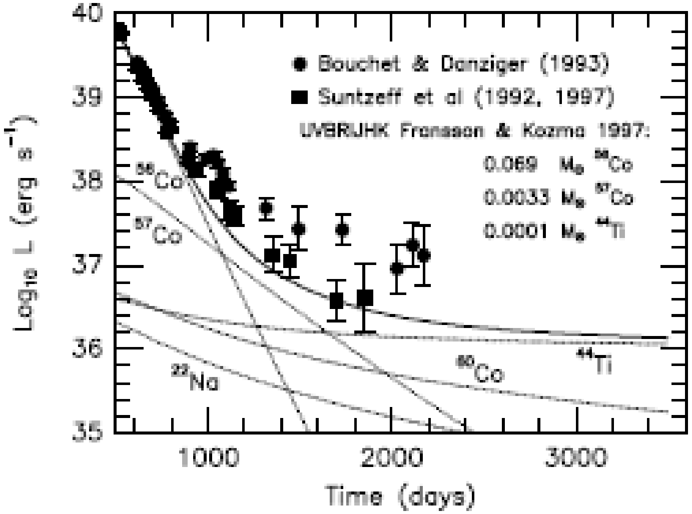
CCSN

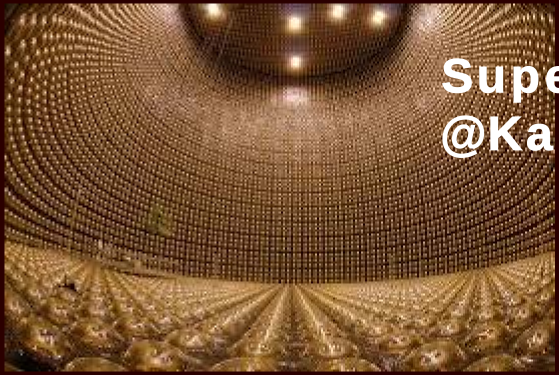
Signals

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



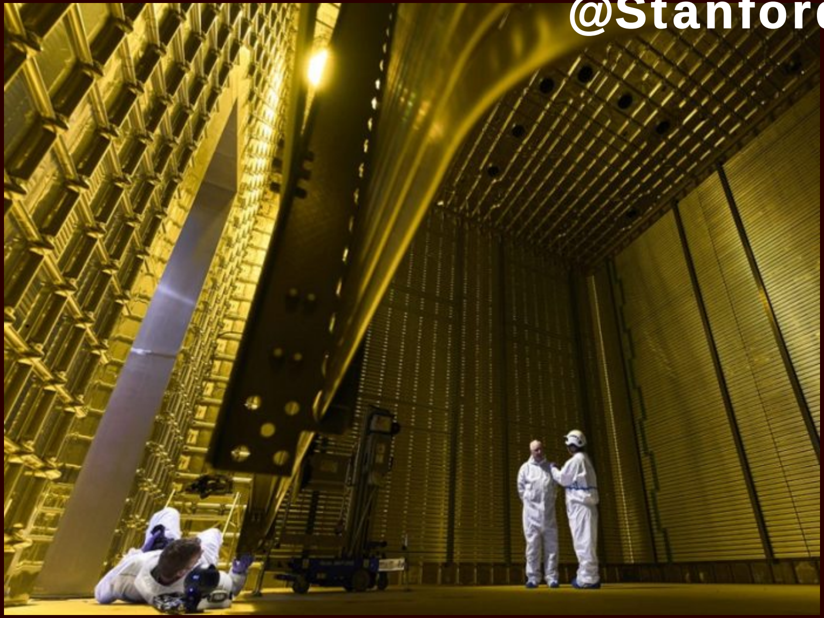
light curve



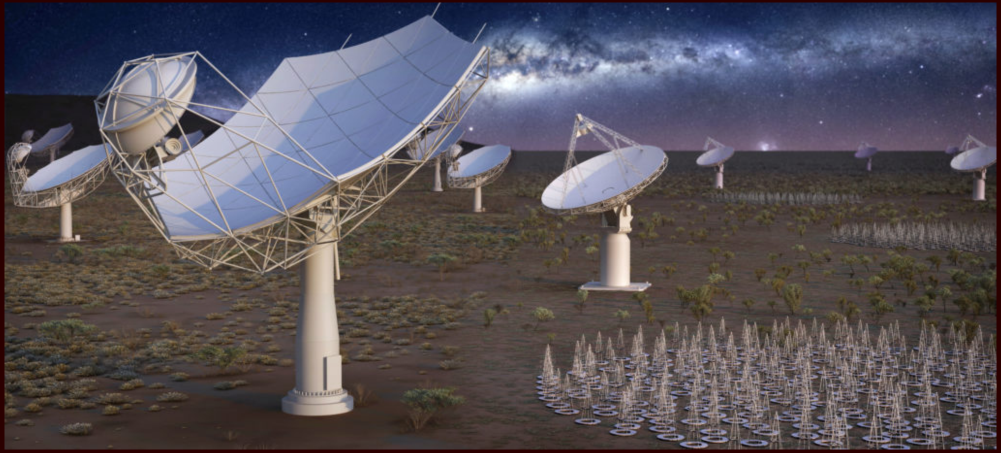


SuperKamioKande @Kamioka

DUNE @Stanford

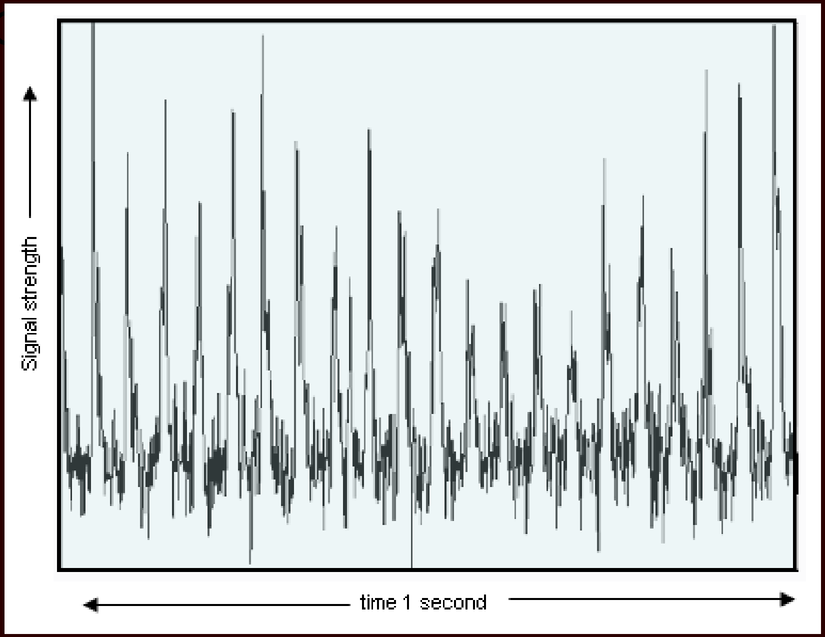


Signals

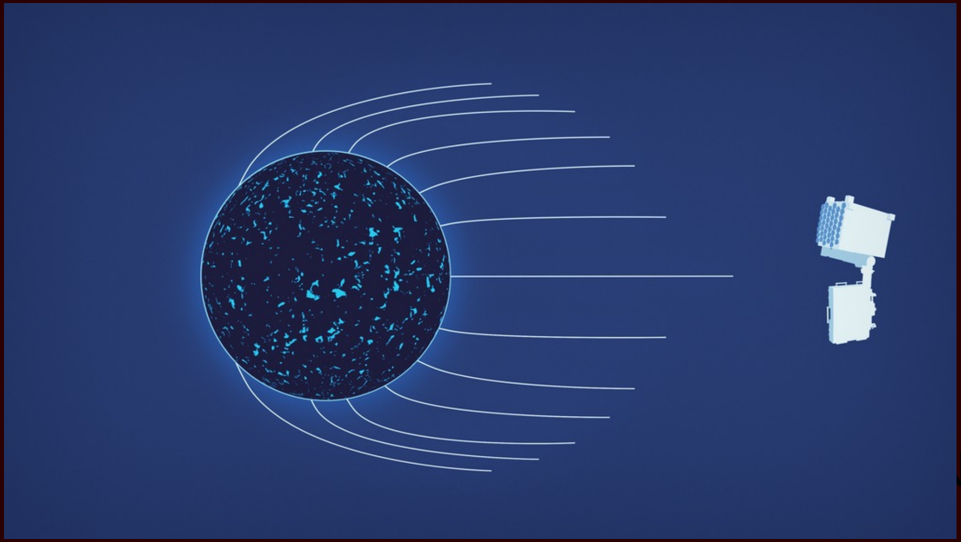


SKA@ South Africa

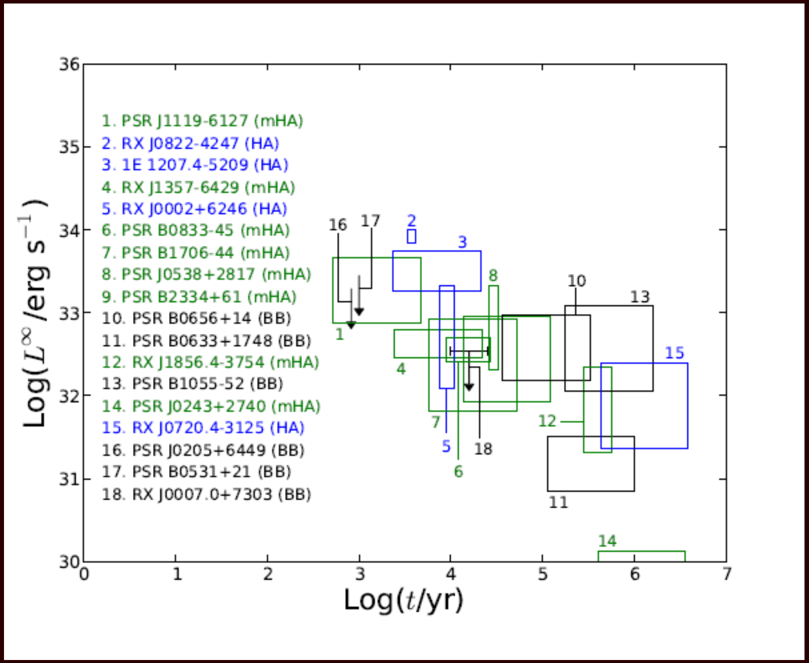
Pulsars

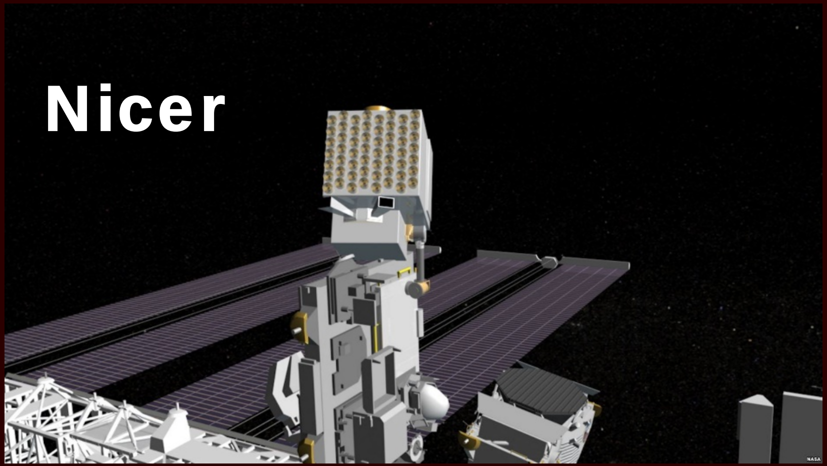


Signals

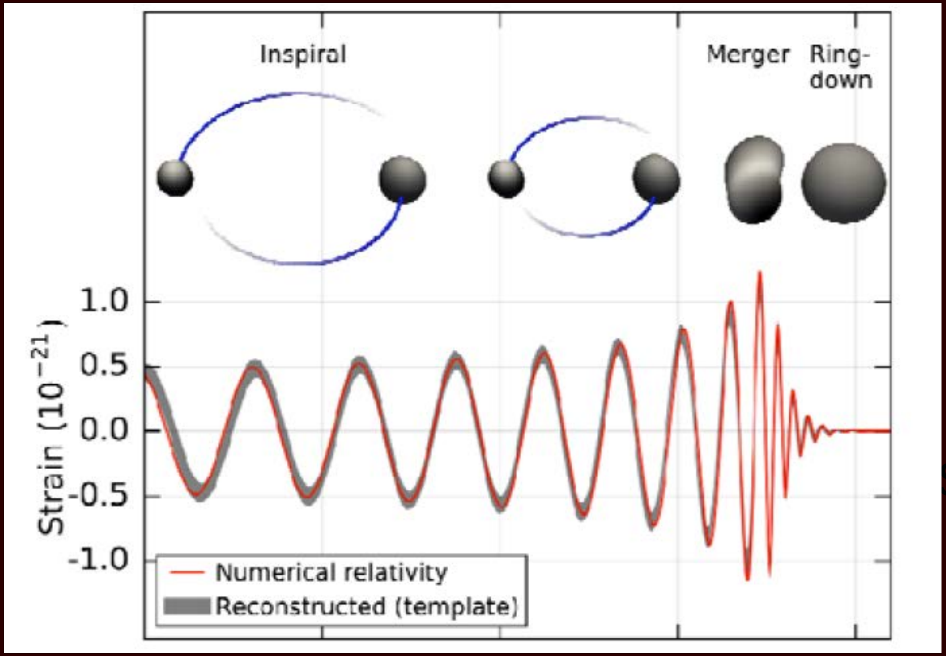


XR sources

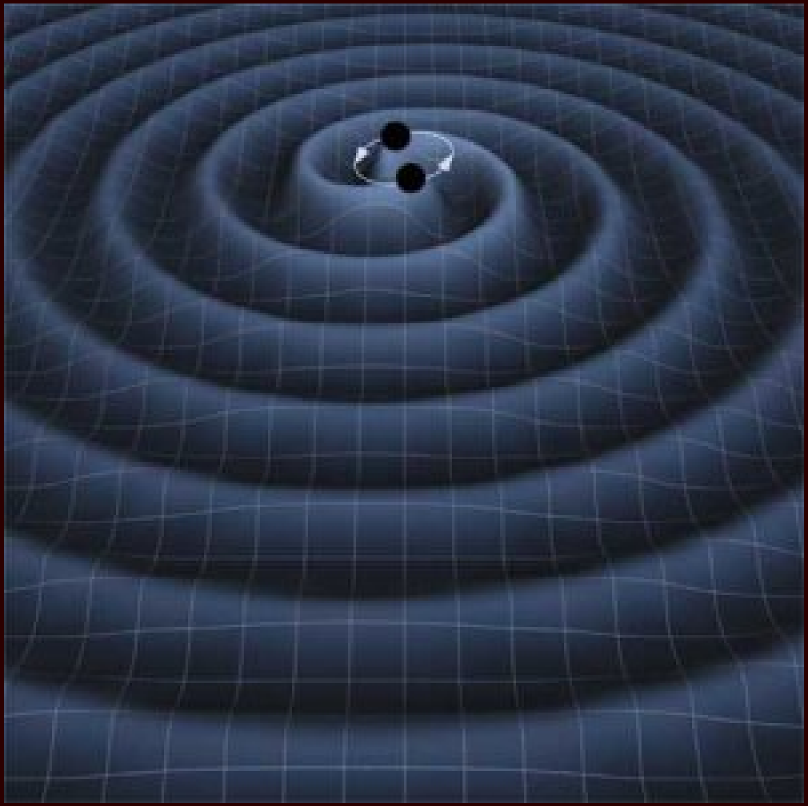




Signals

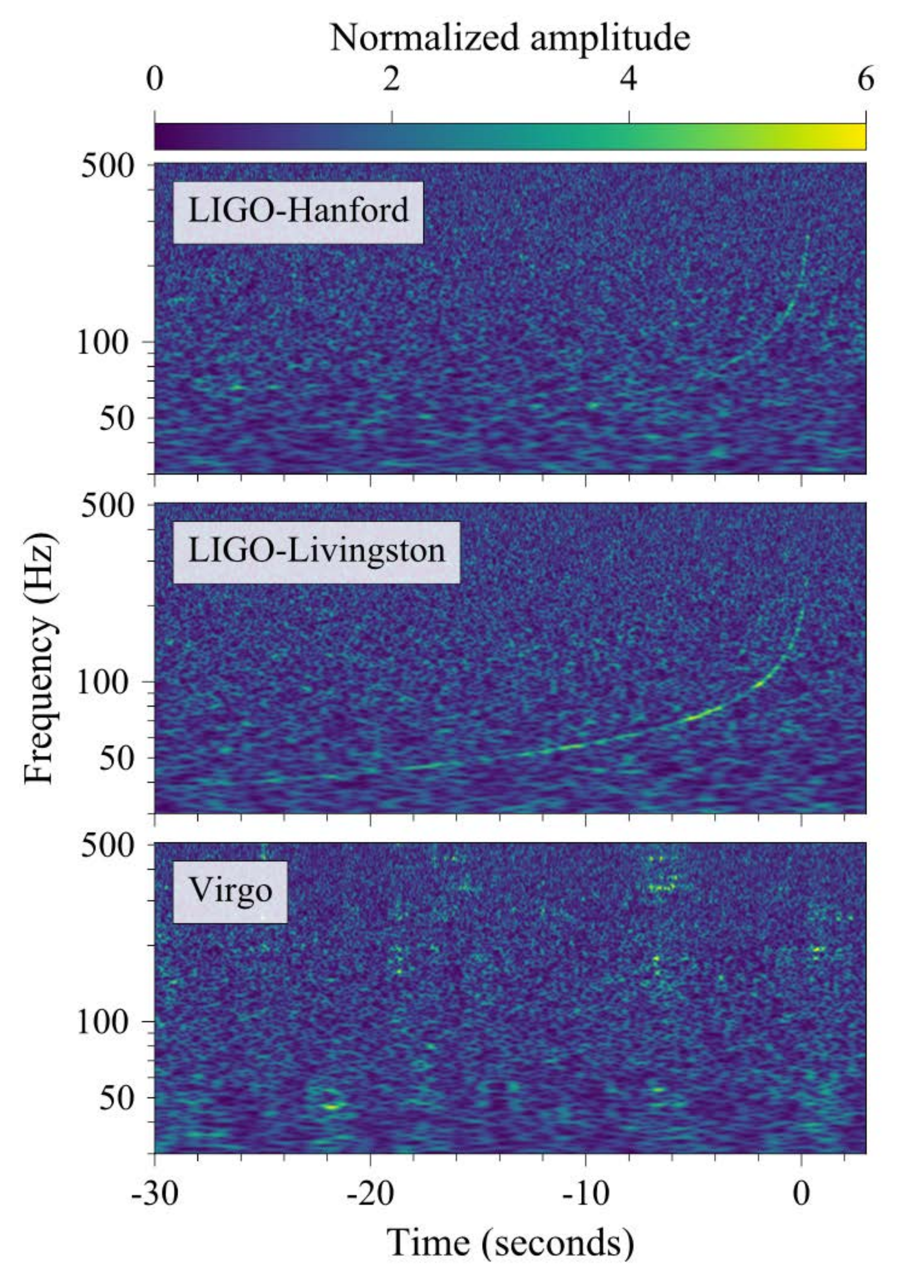


SN



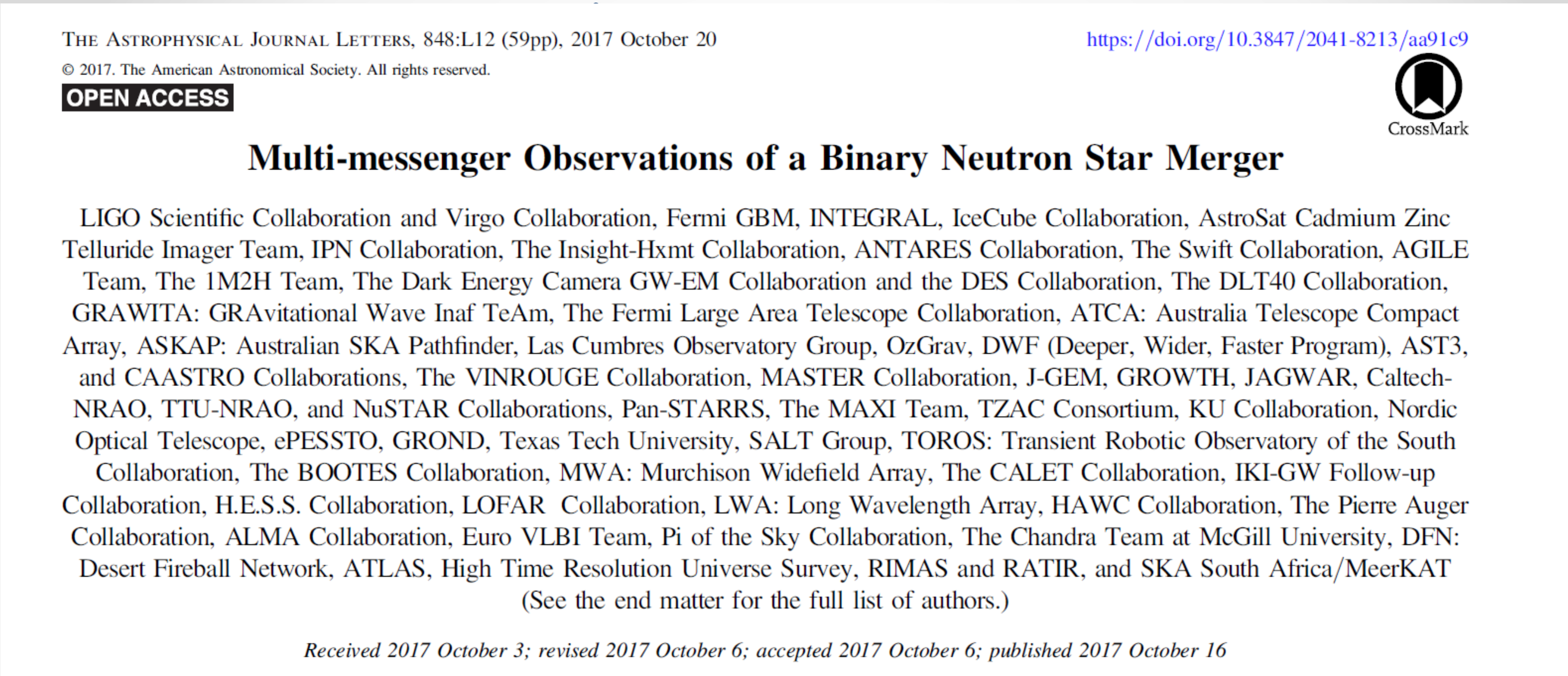
Mergers

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.)

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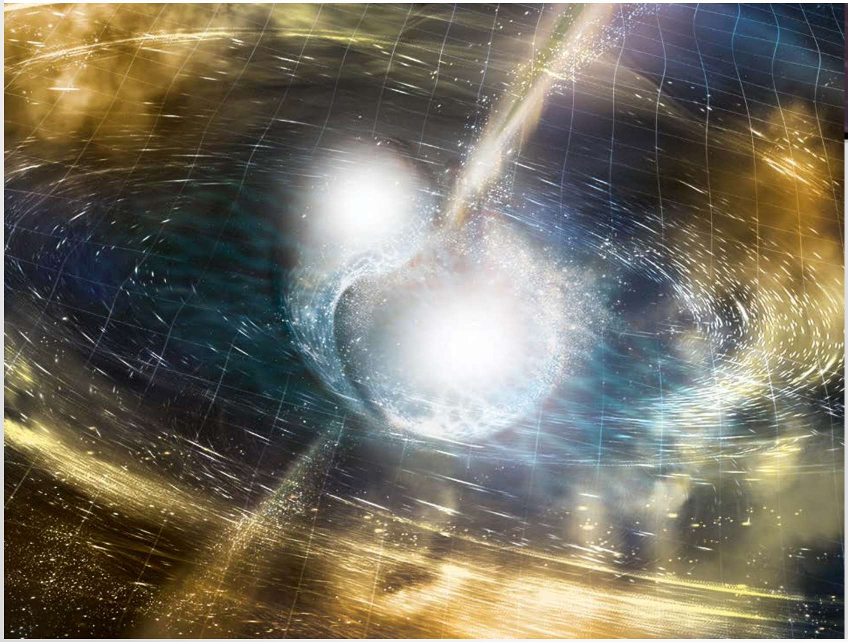
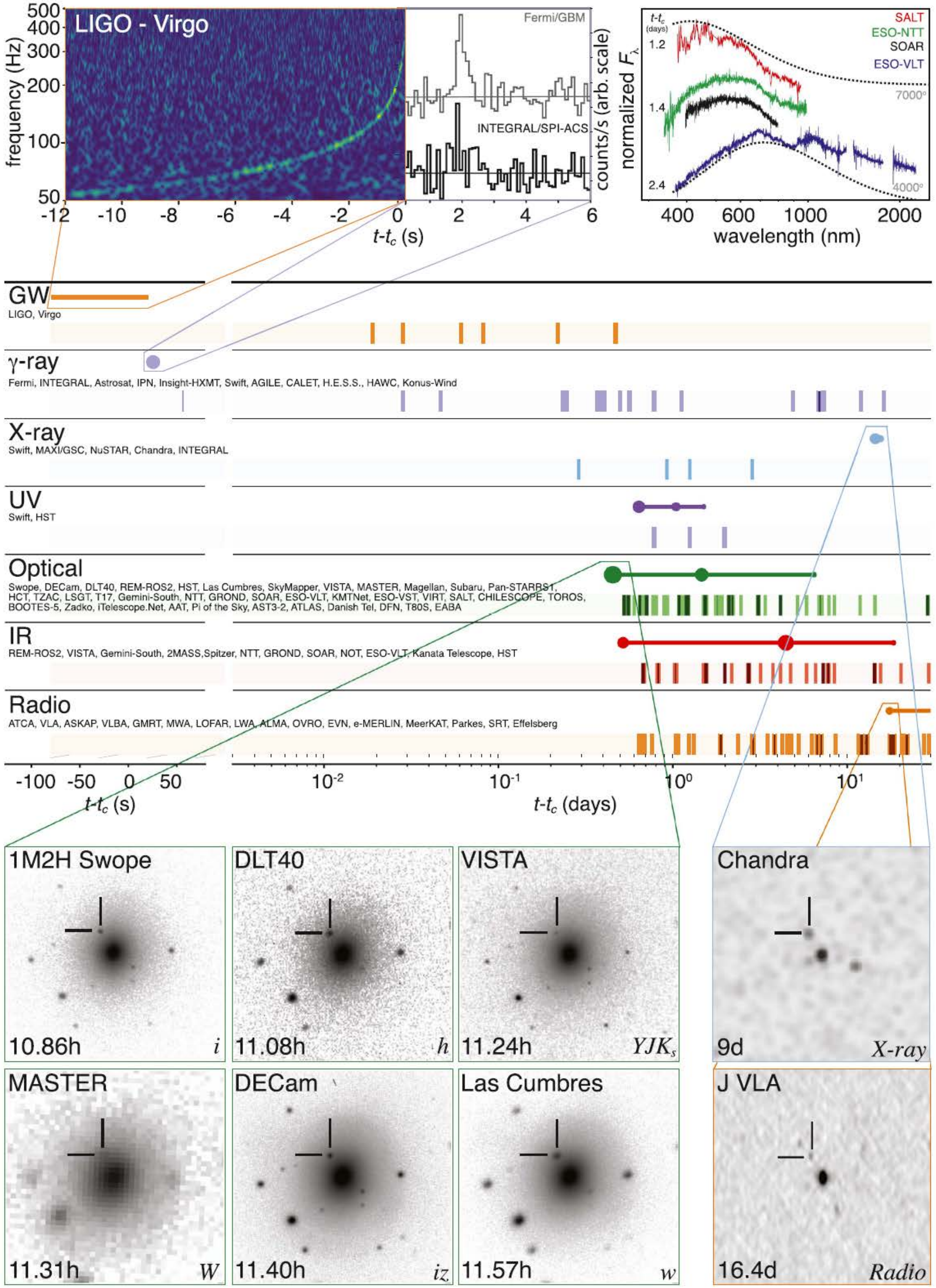


Foundation
Operated by Caltech and MIT

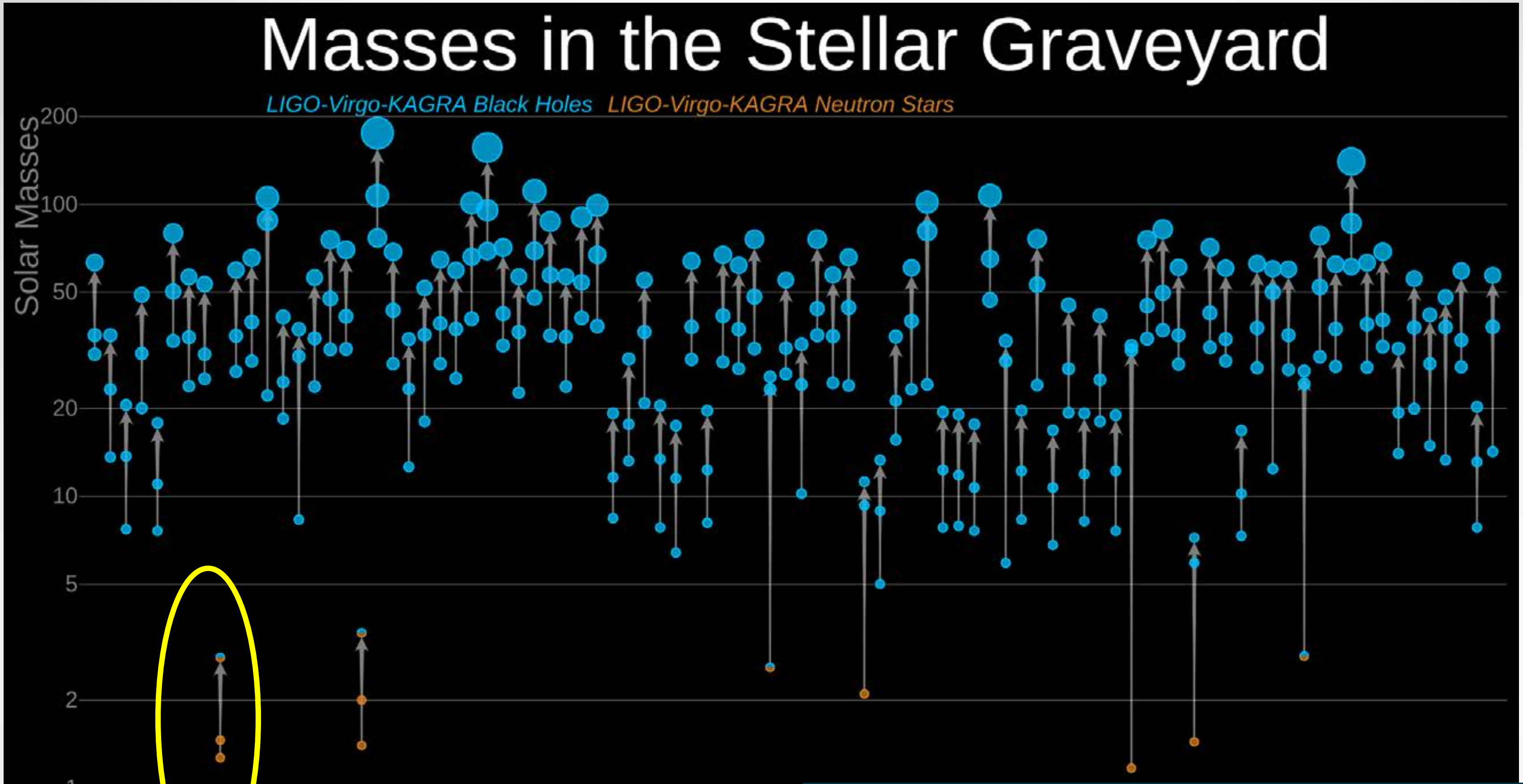
GW170817 Press Release

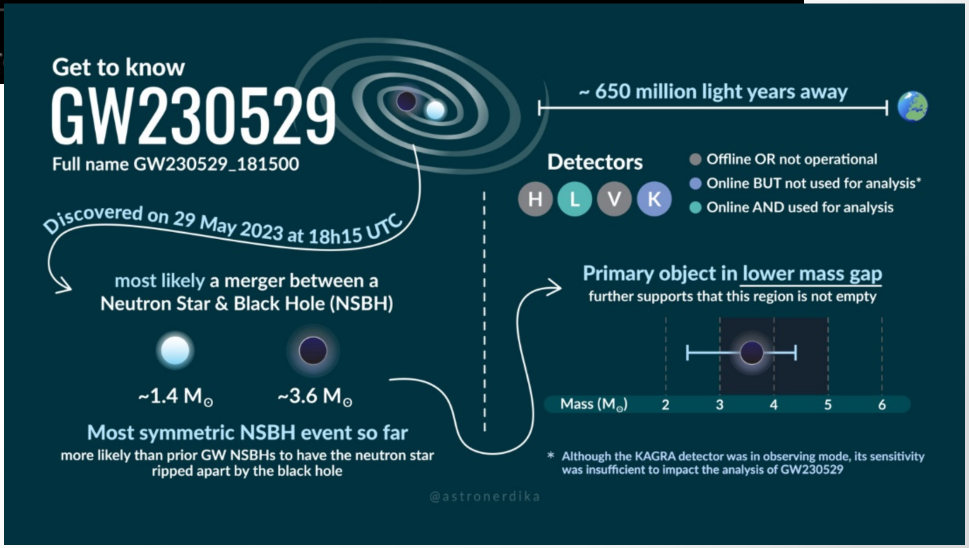
LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars

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


LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
-12
-10
-8
-6
-4
-2
0
2
4
6
t-t_c (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
normalized F_λ
t-t_c (days)
1.2
1.4
2.4
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
400
600
1000
2000
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
-100
-50
0
50
t-t_c (s)
10^{-2}
10^{-1}
10^{0}
10^{1}
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

5 years of LVK observations




Get to know

GW230529

Full name GW230529_181500

~ 650 million light years away

Discovered on 29 May 2023 at 18h15 UTC

most likely a merger between a Neutron Star & Black Hole (NSBH)

~1.4 M☉ ~3.6 M☉

Most symmetric NSBH event so far

more likely than prior GW NSBHs to have the neutron star ripped apart by the black hole

Detectors

H L V K

- Offline OR not operational
- Online BUT not used for analysis*
- Online AND used for analysis

Primary object in lower mass gap

further supports that this region is not empty

* Although the KAGRA detector was in observing mode, its sensitivity was insufficient to impact the analysis of GW230529

@astronerdika

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?**
4. **Can we explain the origin of elements beyond Fe via r-process nucleosynthesis in CCSN&BNS?**

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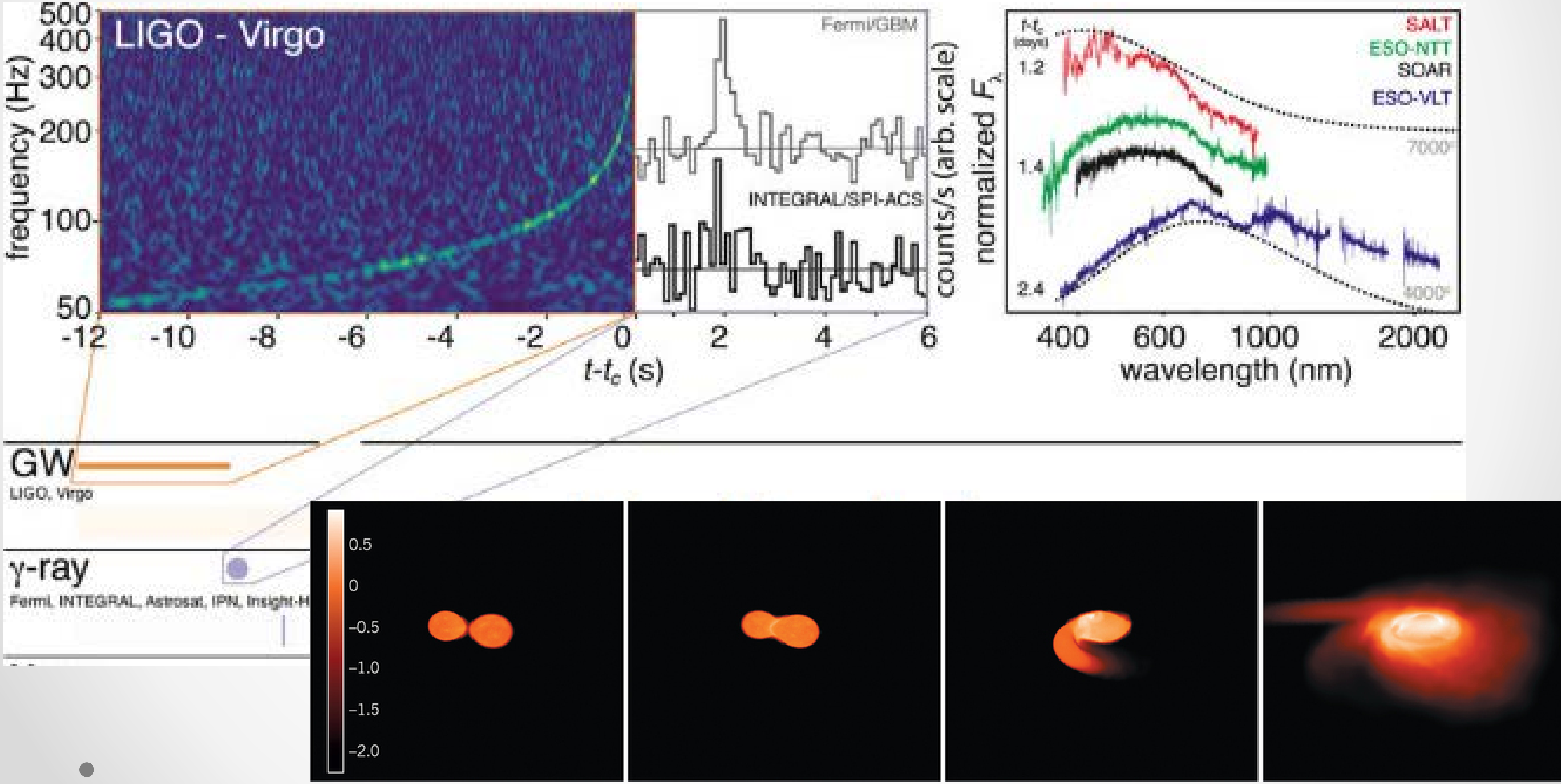
Merging of neutron stars:

GW170817 – GRB170817A – AT2017gfo

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



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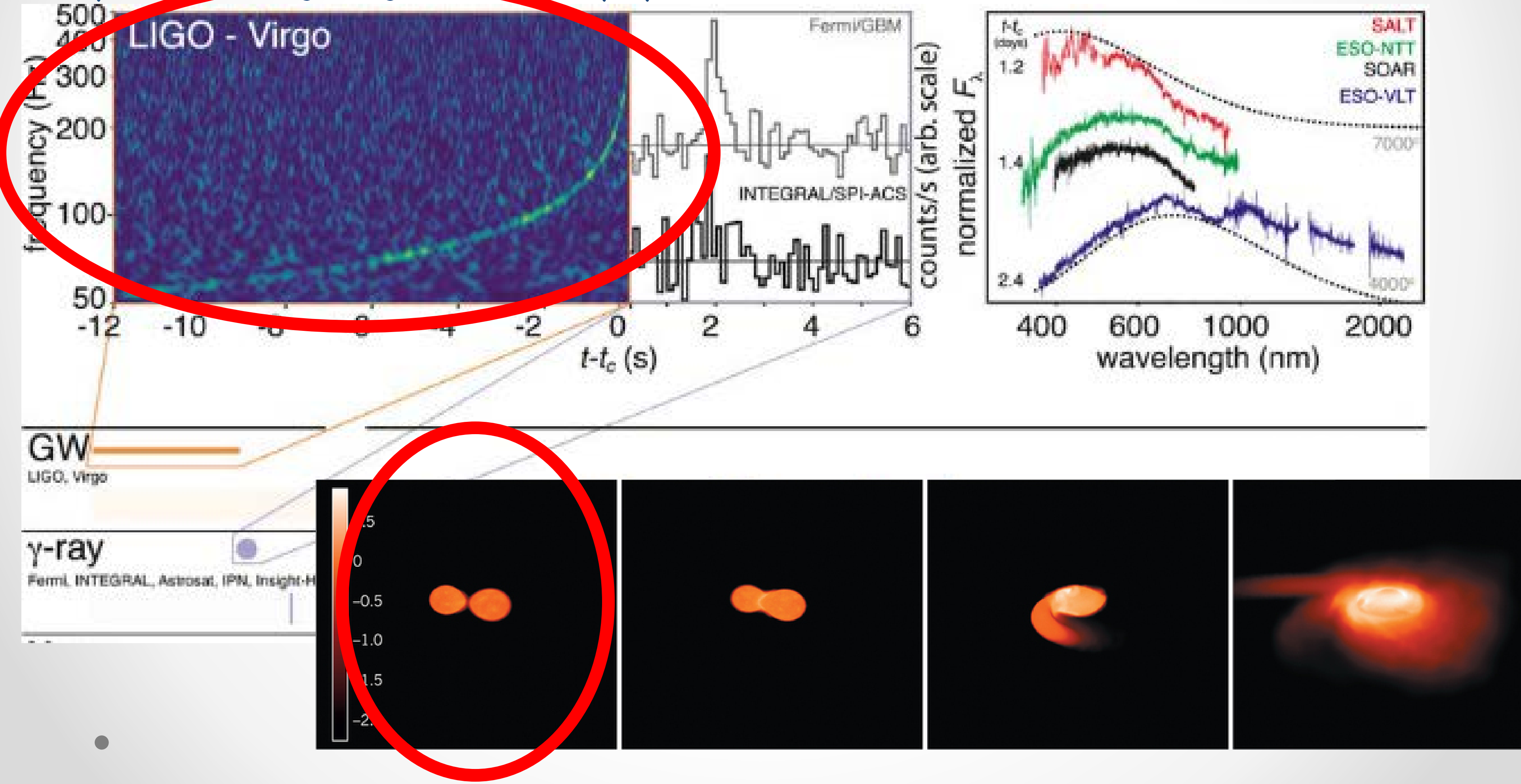
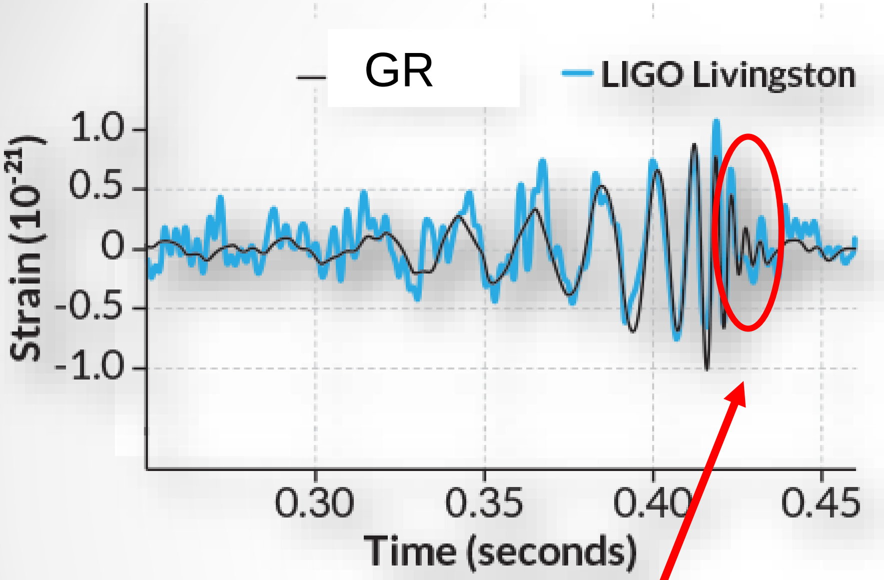


Merging of neutron stars:

Tidal polarisability



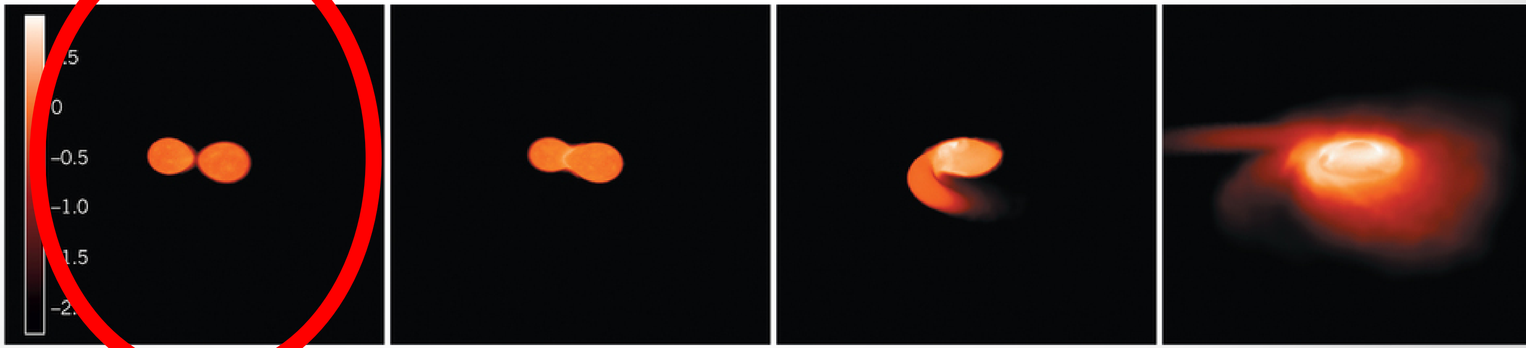
https://www.ligo.org/detections.php

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

Quadrupole moment

Companion tidal field

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



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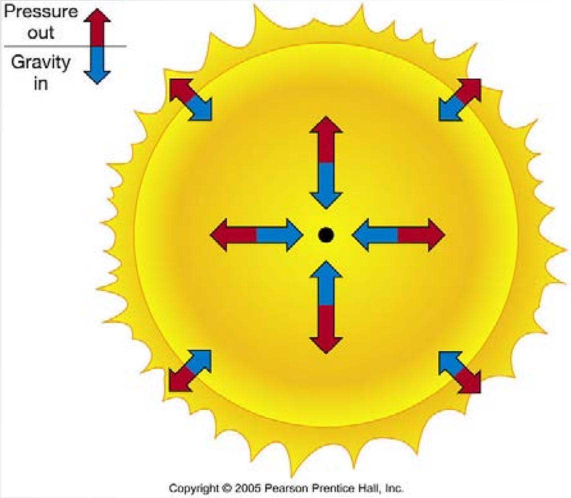
The Equation of State



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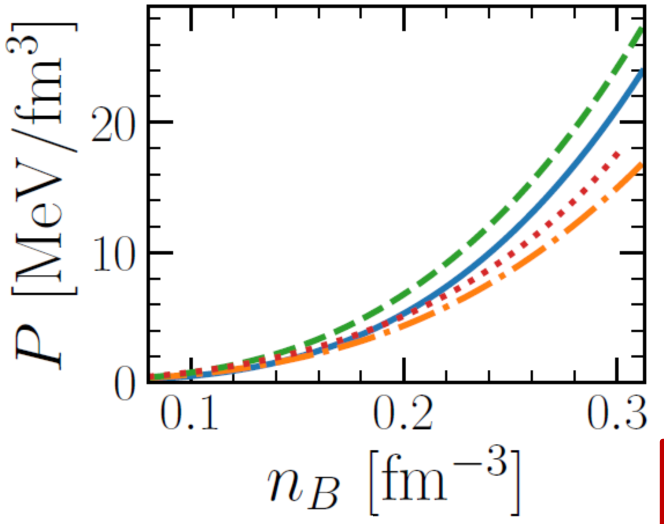
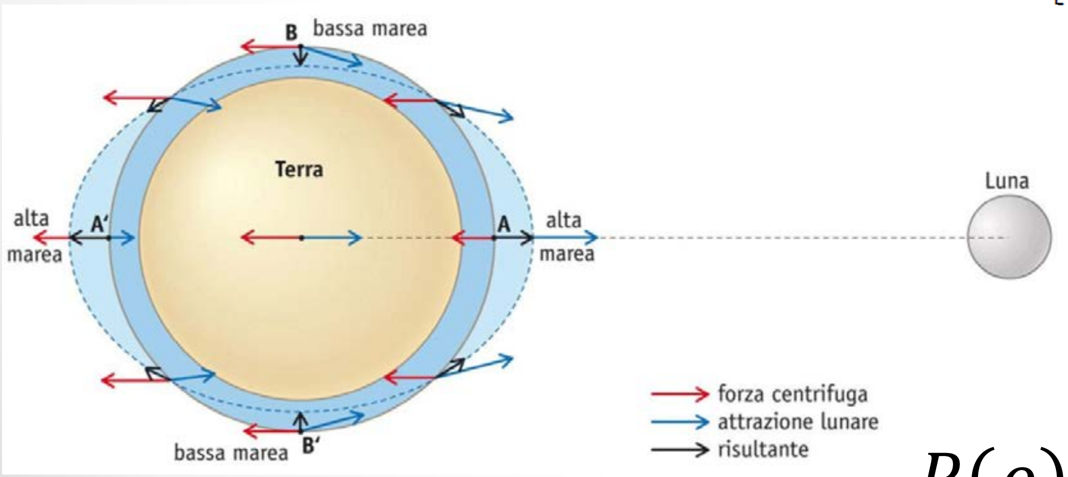


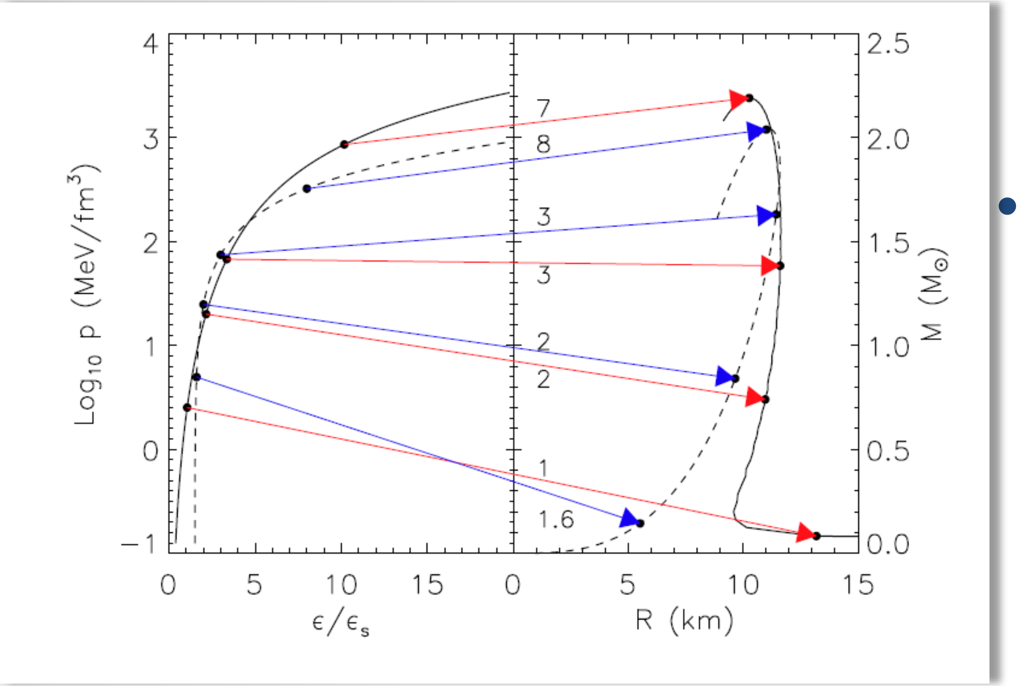


Nuclear model

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

EoS&GW

- The tidal information from the inspiral GW signal is ***uniquely*** determined by the nuclear Equation of State $\boldsymbol{P}(\boldsymbol{\rho})$
- Indeed, GR imposes a 1-to-1 correspondence between the nuclear EoS and all static properties of NS (M(R)- M(Λ))

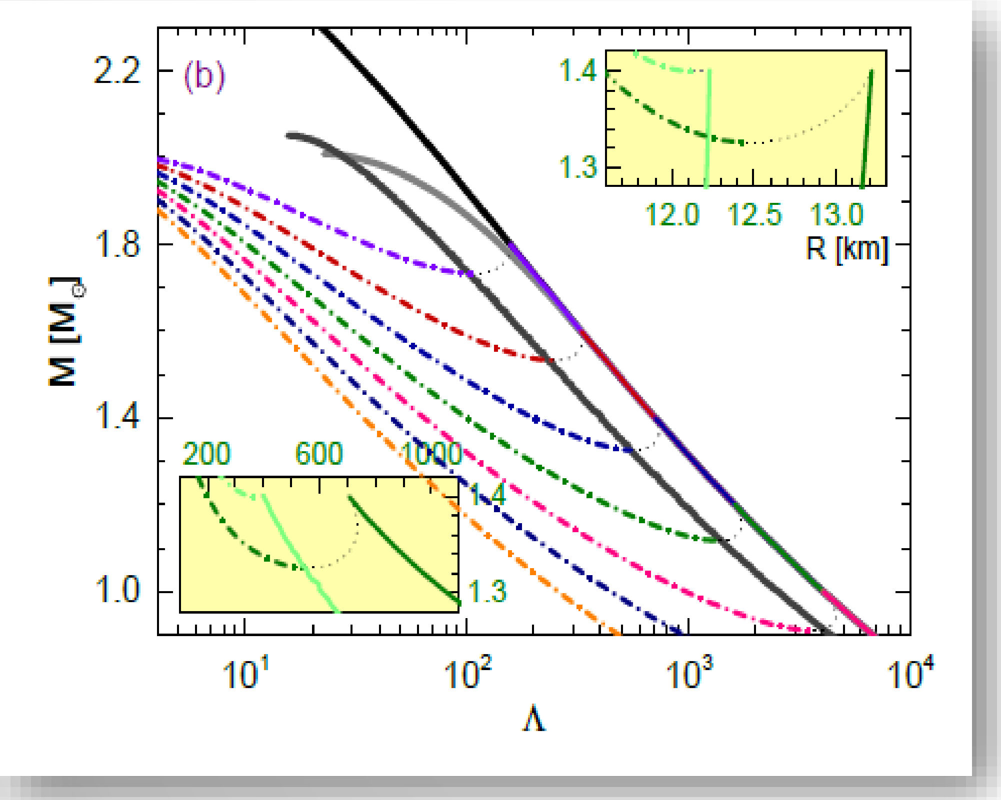


J.Lattimer Ann.Rev.Nucl.Part.Sci (2012)

$$\Lambda = \frac{2}{3G} k_2 R^5$$

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

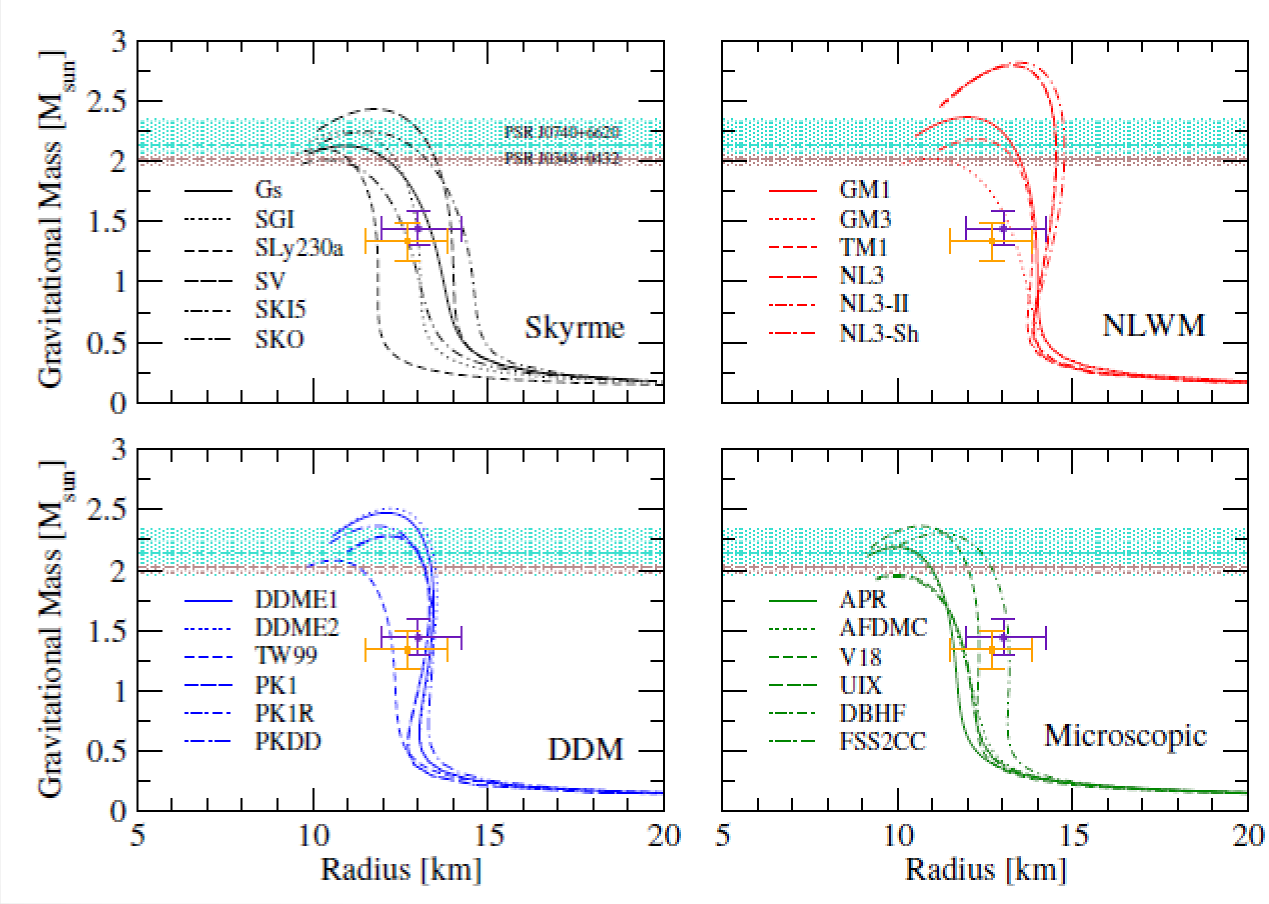
EoS&GW



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

- The tidal information from the inspiral GW signal is *___uniquely___* determined by the nuclear Equation of State $P(\rho)$
- Indeed, GR imposes a 1-to-1 correspondence between the nuclear EoS and all static properties of NS ($M(R)$ - $M(\Lambda)$)
- Different models => different $M(\Lambda)$ => different gravitational signals!
- Systematics due to the astrophysical modelling in principle under control

Problem : no ab-initio theory of dense matter

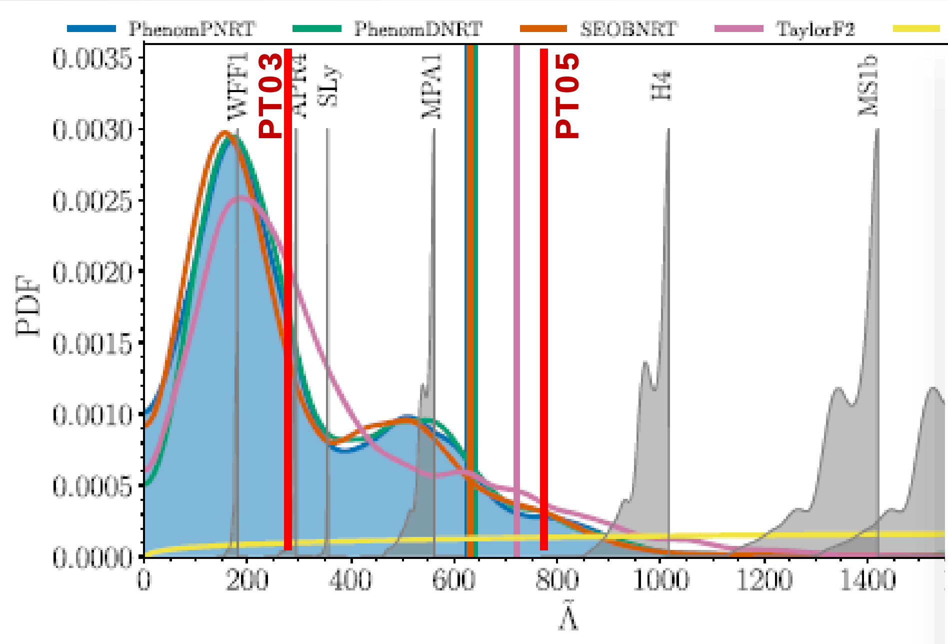


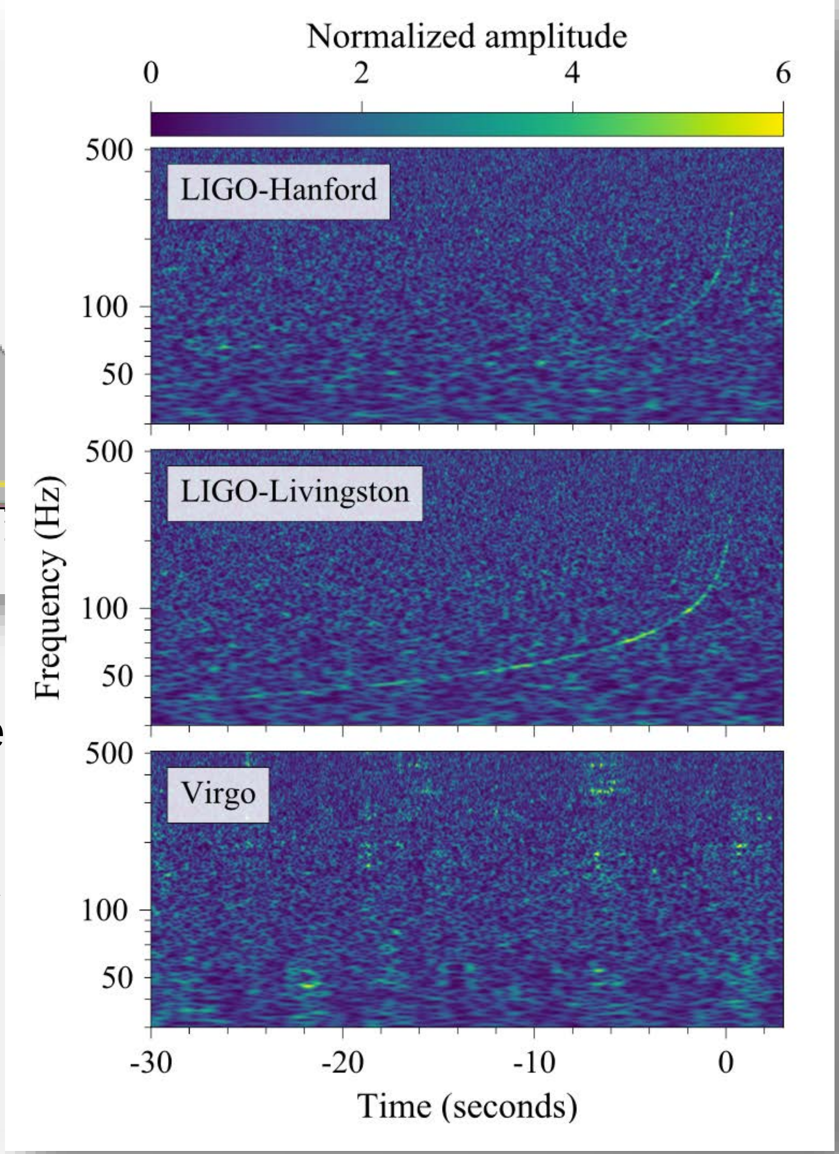
Max masses:
Demorest et al, Nature **2010**
Antoniadis et al, Science **2013**

Mass-radii:
Riley et al, ApJ **2019**
Miller et al, ApJ **2019**

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

Present status: GW170817

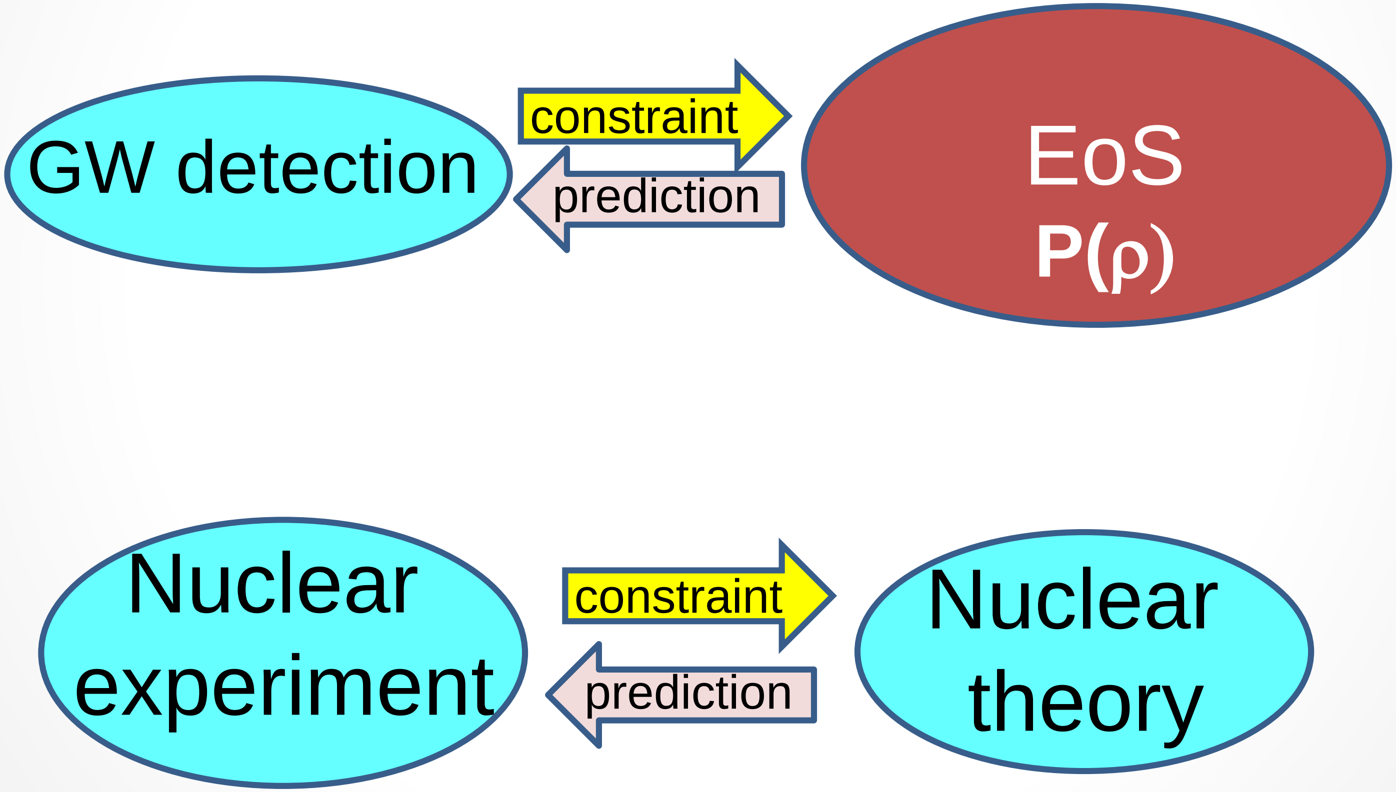




LVC, APJL2017 & PRX9 2019

- The observation cannot discriminate (yet)

=> How can we quantify the reliability of a given EoS model?



GW detection

constraint

prediction

EoS

P(ρ)

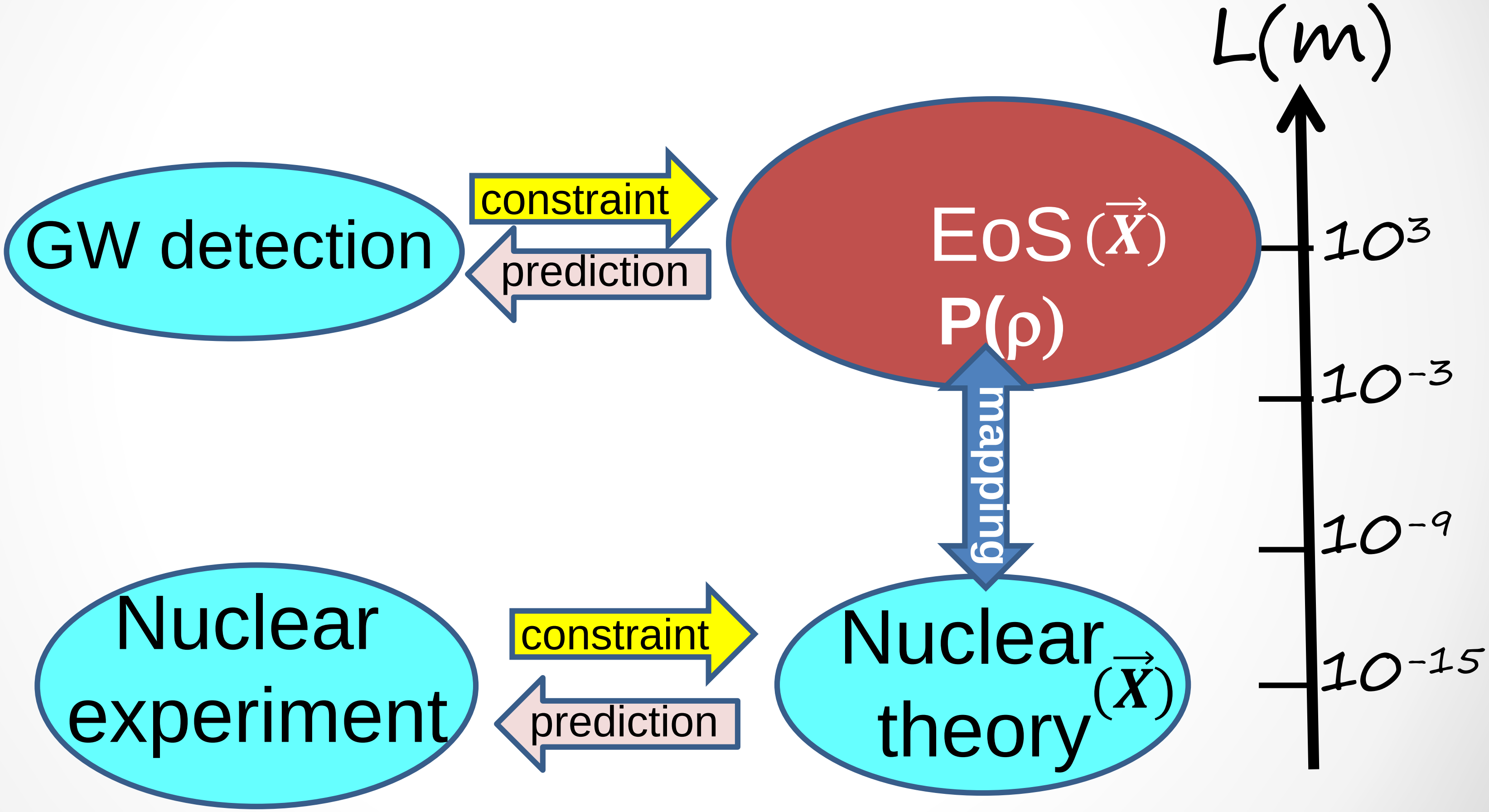
Nuclear experiment

constraint

prediction

Nuclear theory

Jumping across the scales!



GW detection

constraint

prediction

EoS $(\vec{X})$

P(ρ)

mapping

Nuclear experiment

constraint

prediction

Nuclear theory $(\vec{X})$

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 effective 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

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

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
…………………………

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

Laboratory observables

Nuclear model

Astronomical observables

Bayesian Inference

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

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)

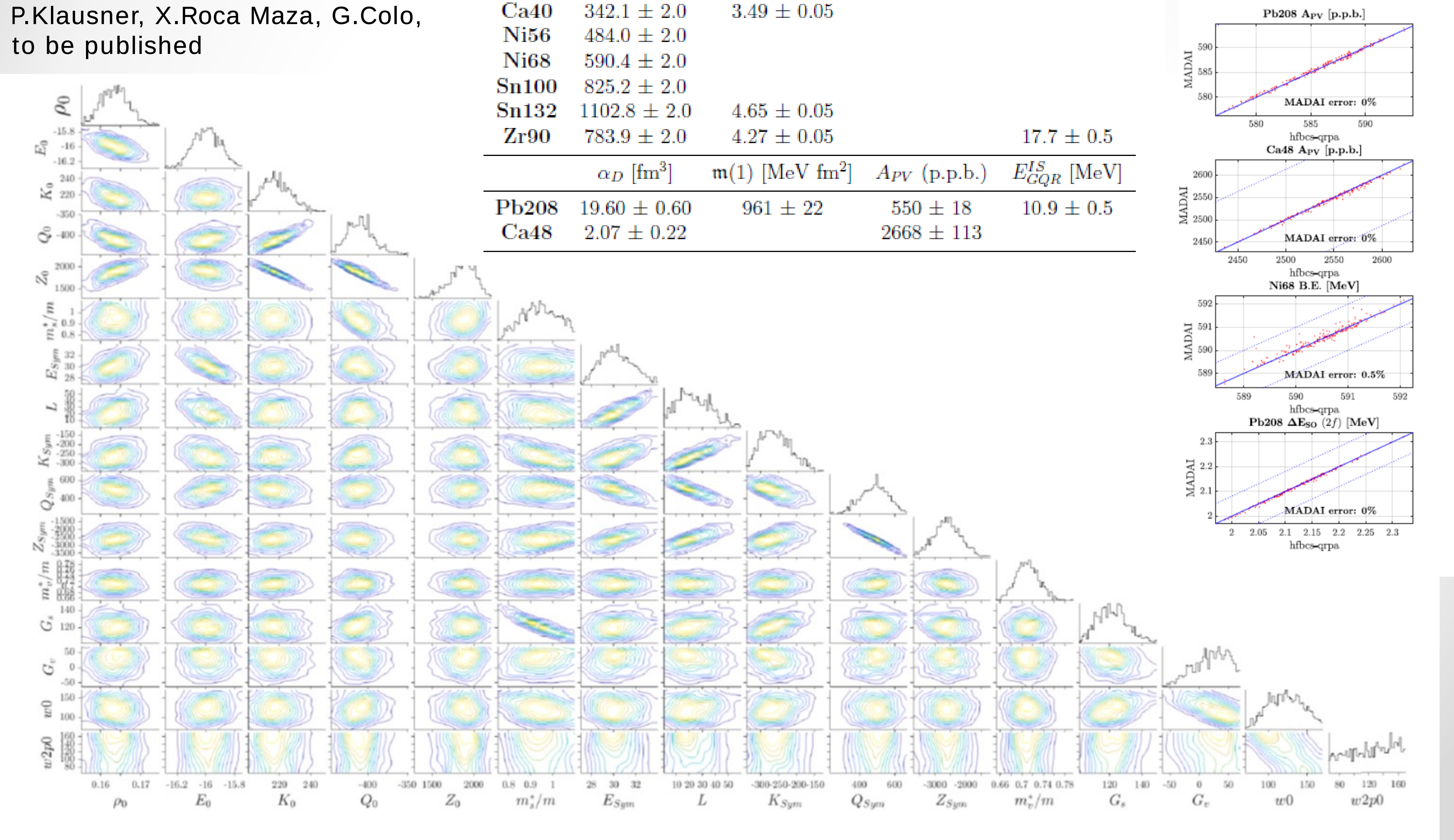
Astrophysics

(3) PSR J0348+0432 M=2.01±0.04 M_O
(4) GW170817 $\widetilde{\Lambda}(M)$ LVK
(5) PSR J0030+0451, PSR J0740+6620 NICER

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	

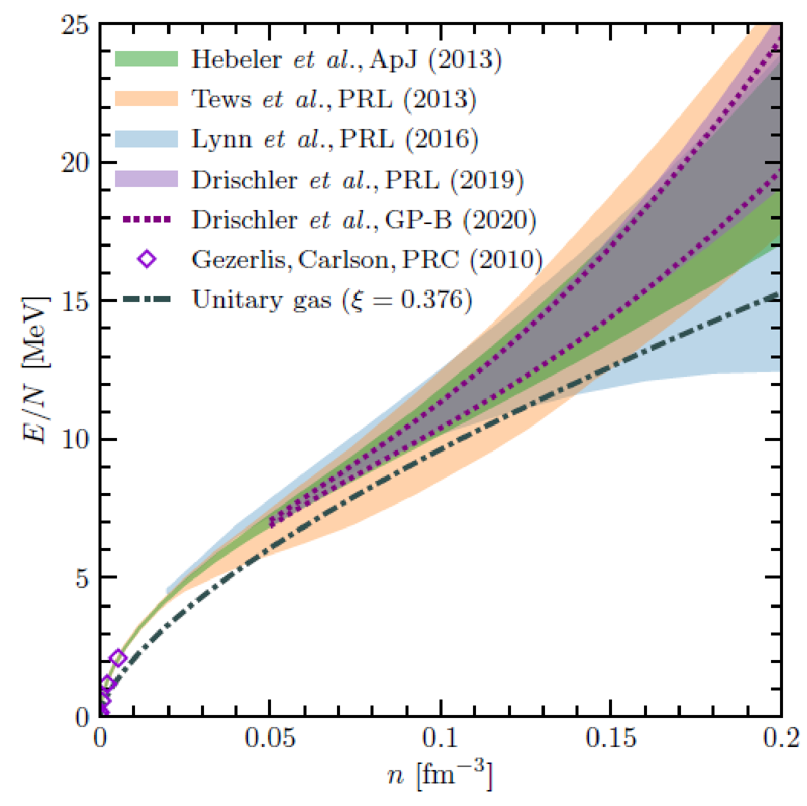
P.Klausner, X.Roca Maza, G.Colo,
to be published



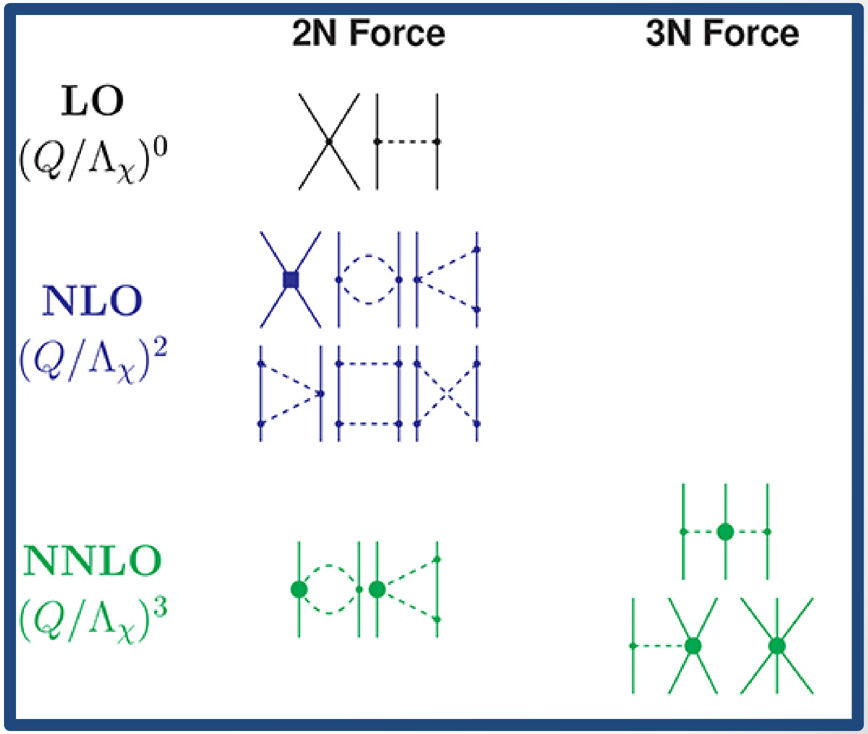
madai.phy.duke.edu

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

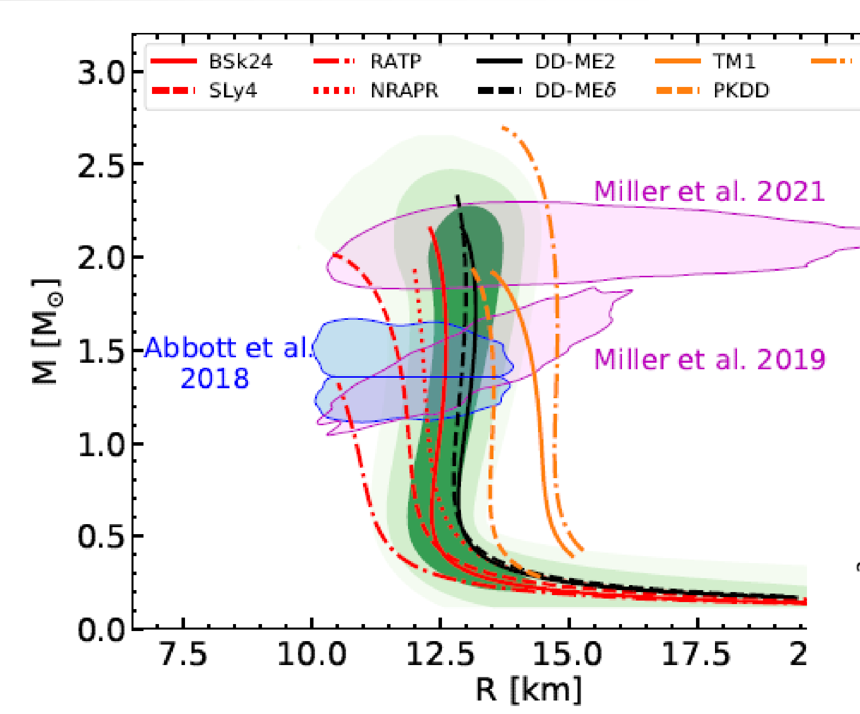


Machleidt R., Int J Mod Phys. (2017)



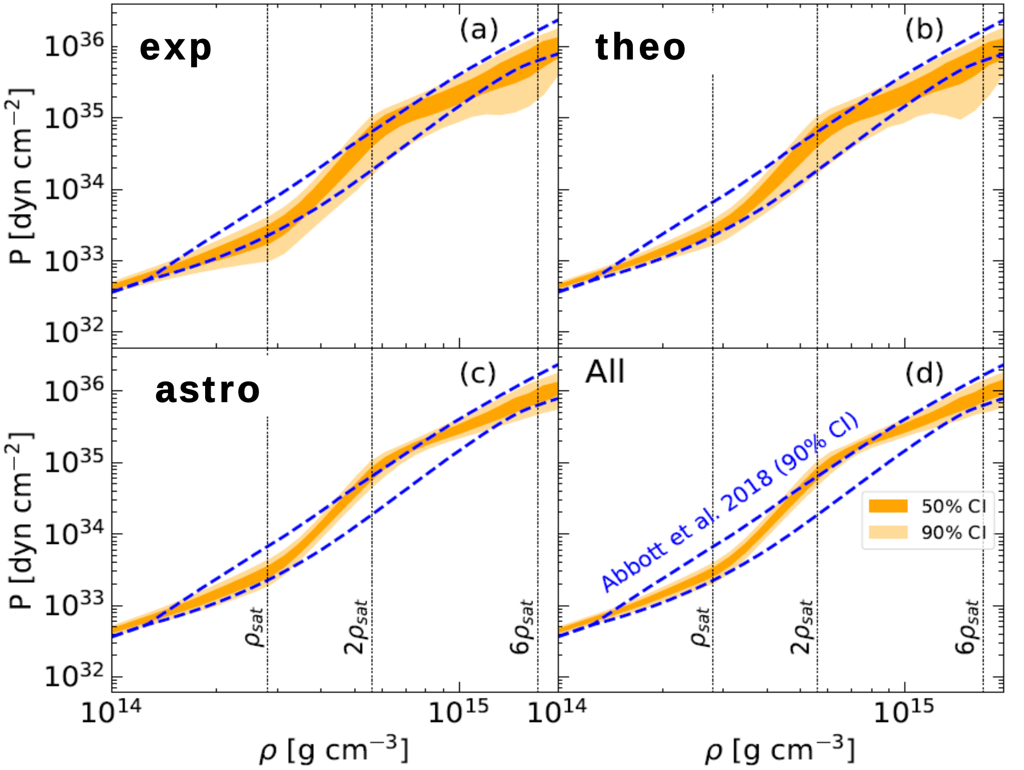
S. Huth, C. Wellenhofer, and A. Schwenk, Phys. Rev. C 103, 025803 (2021).

Nuclear physics informed predictions

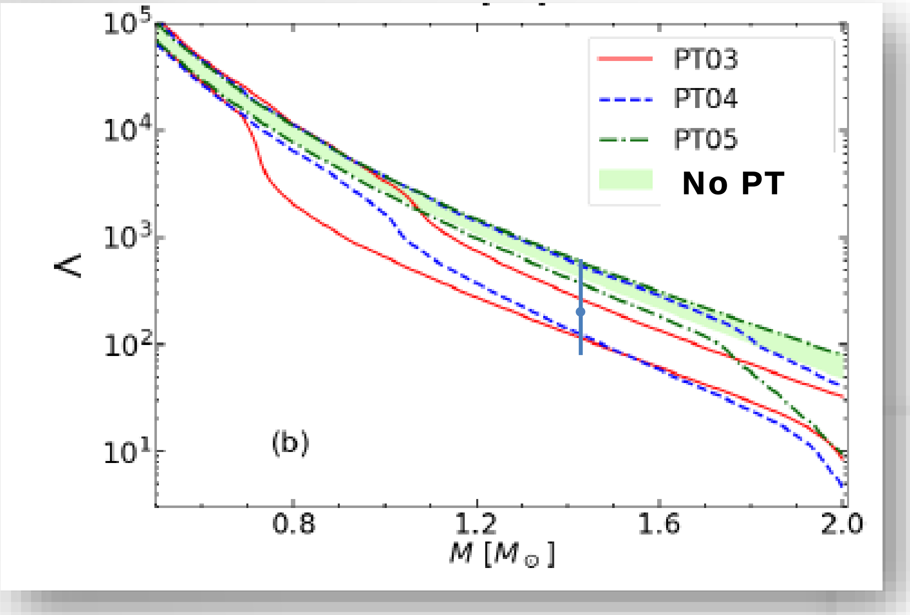


H.Dinh Thi et al, A&A 2021

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

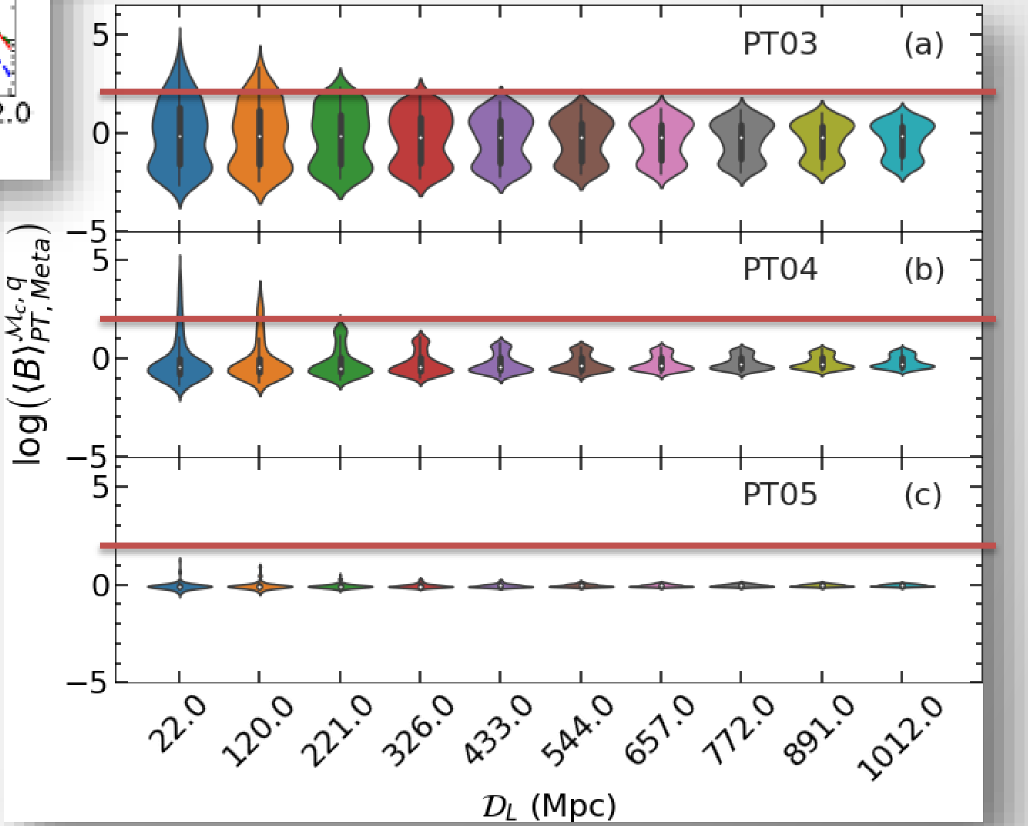


Quarks in the core of neutron stars ?



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

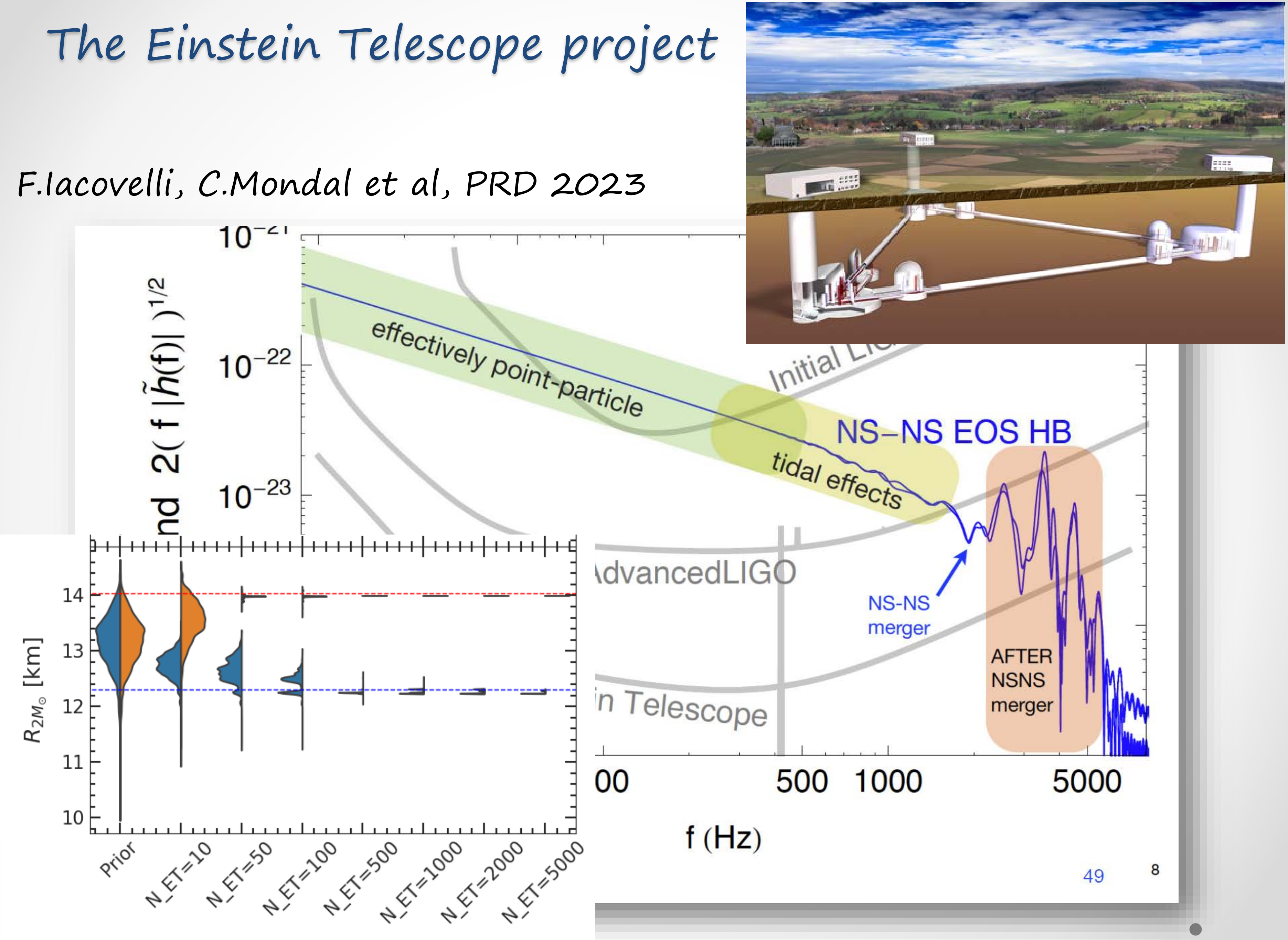
C.Mondal et al, MNRAS 2023



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

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