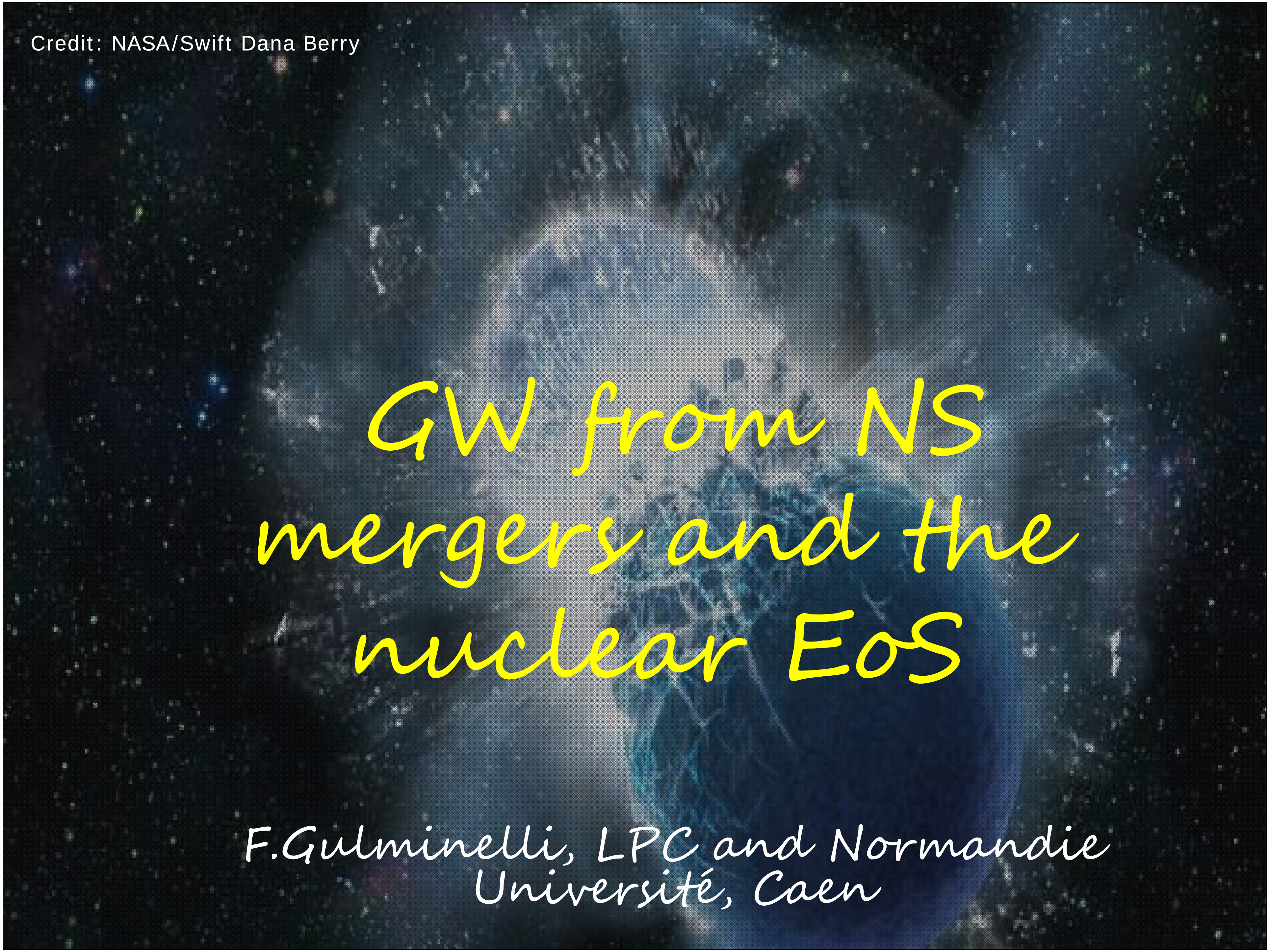


GW from NS mergers and the nuclear EoS

F.Gulminelli, LPC and Normandie Université, Caen

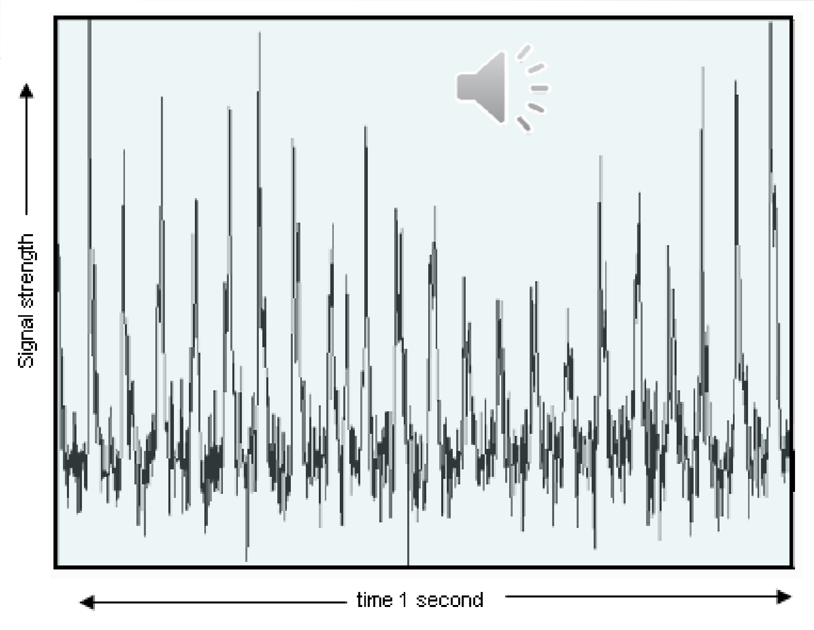
Libération
100
SUD OUEST
Pourquoi l'observation d'une fusion d'étoiles à neutrons est une découverte majeure
Photographie com
neutrons au centre
étoiles à neutrons
Photo NASA/HST/
Hester et al.
ASTRONOMIE
ouest france
Espace. La fusion de deux étoiles à neutrons observée pour la première fois
la Repubblica.it
SCIENZE
C'è una miniera d'oro nello
The New York Times
SCIENCE
LIGO Detects Fierce Collision of Neutron Stars for the First Time
ZEIT ONLINE
Gravitationswellen
Das nächste große Ding der Astronomie
Le Monde
S'abonner dès 1€
Publié Le 16.10.2017 à 16h06
Des étoiles à neutrons secouent la Terre

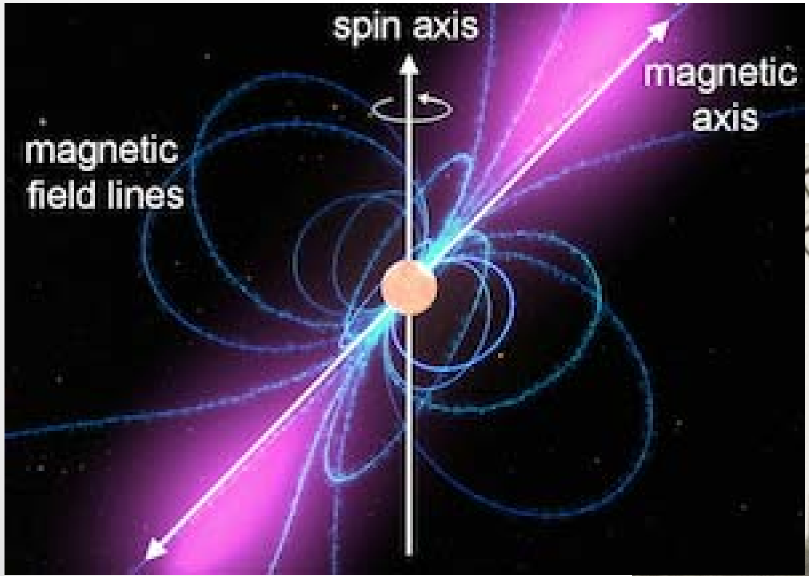
GW from NS mergers and the nuclear EoS

- Neutron stars and NS mergers: present status and predictions
- The 17/8/2017 multi-messenger event
- Modelling NS: the nuclear EoS and the GW signal
- The present status of the EoS and perspectives

NS discovery: LGM-1

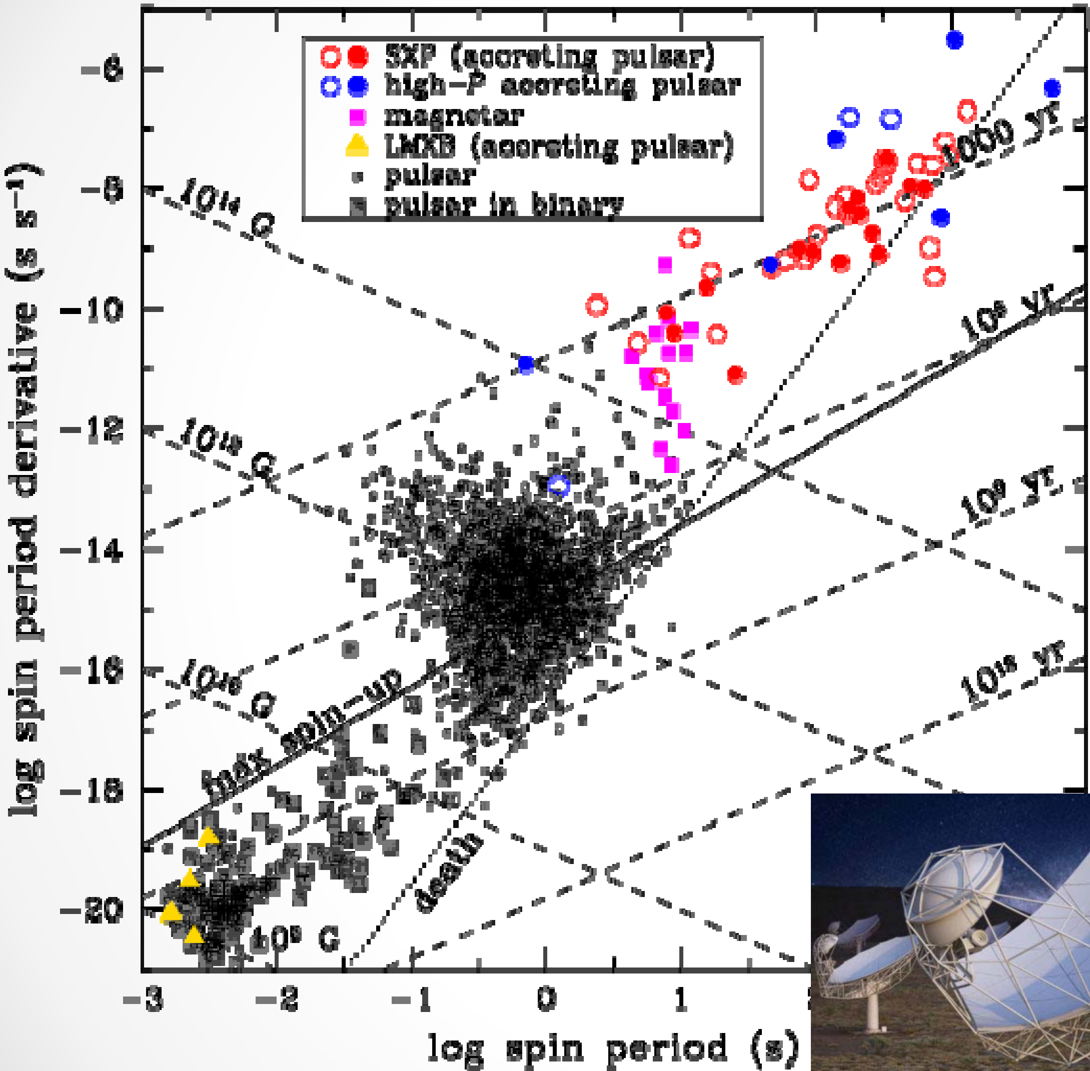
Jocelyn Bell
& Antony Hewish
(Nobel 1974)



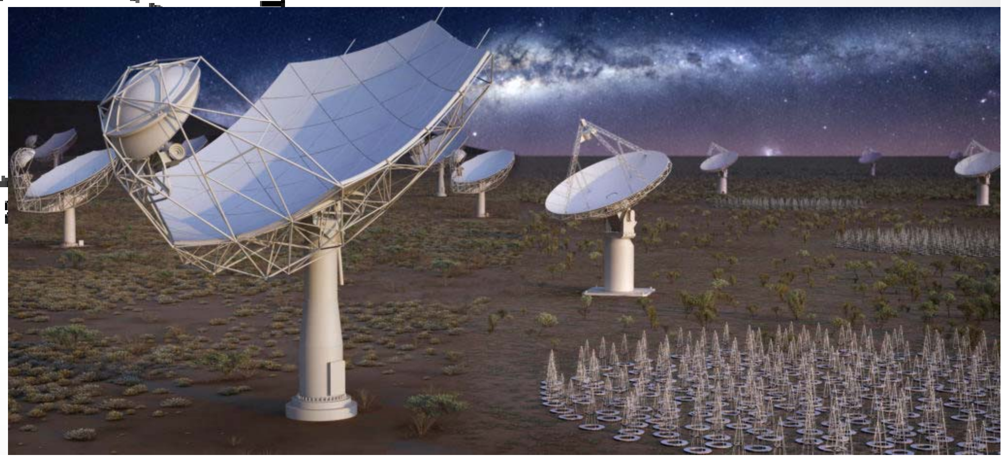


Credit: NASA/Goddard Space Flight Center Conceptual Image Lab

Today:

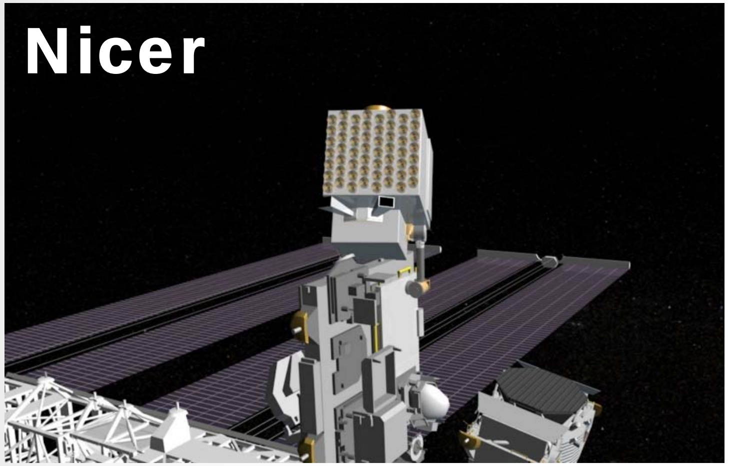


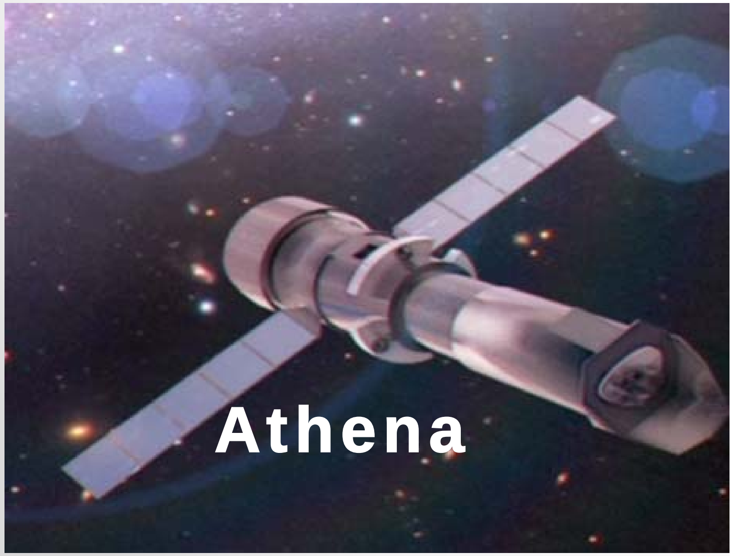
~2000 stars known in the galaxy
~100.000 expected (SKA)

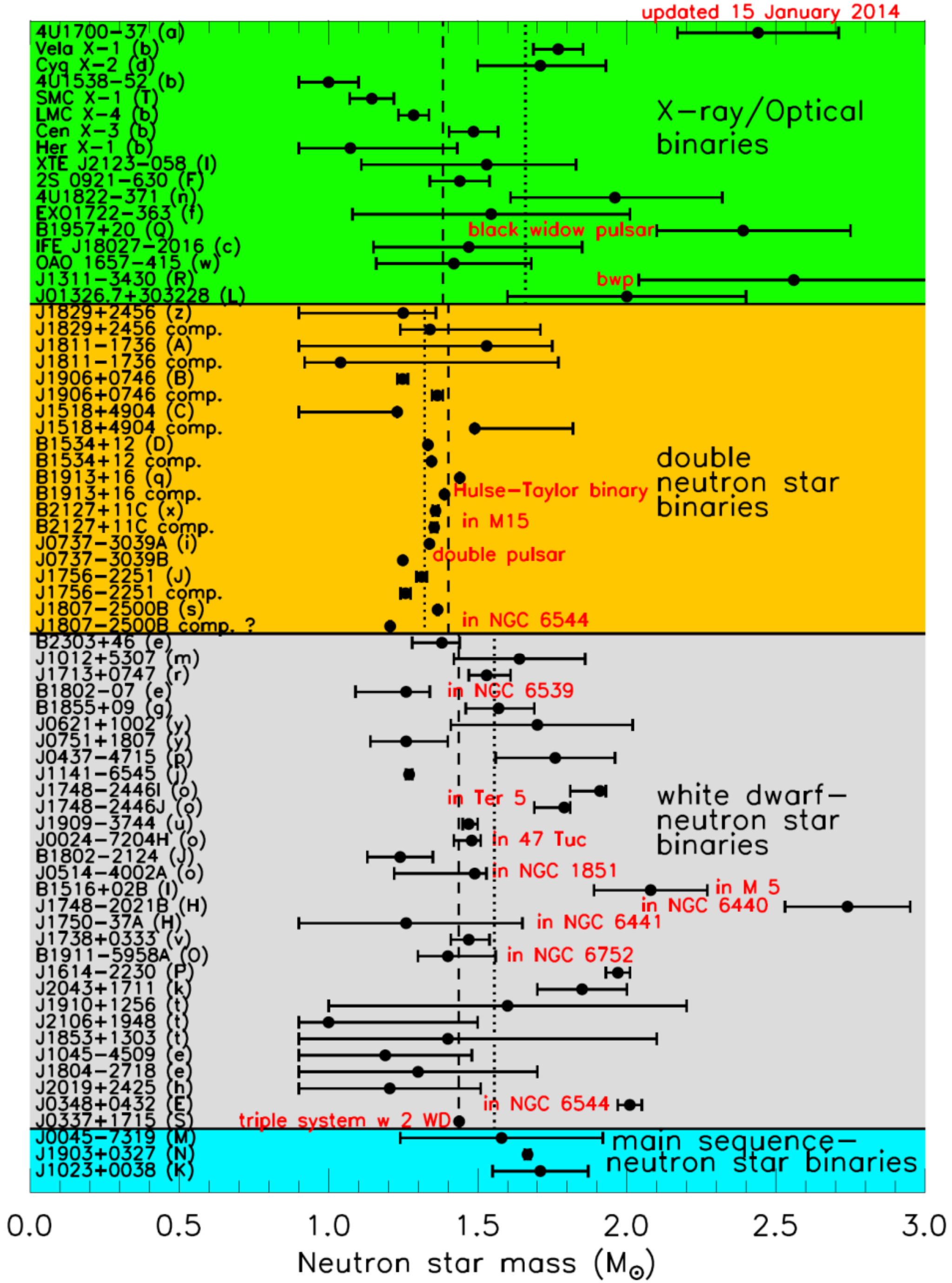


$M \sim M_{sun} \sim 10^{30}$ kg
$R \sim 10$ km
$n \sim M/R^3 \sim 10^{18}$ kg/l

Jim Lattimer 2014



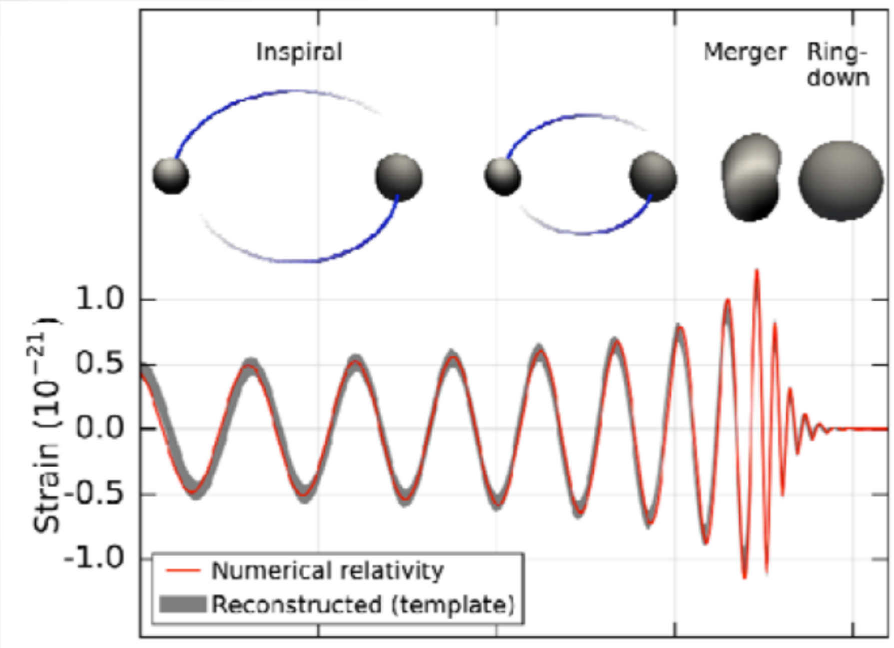


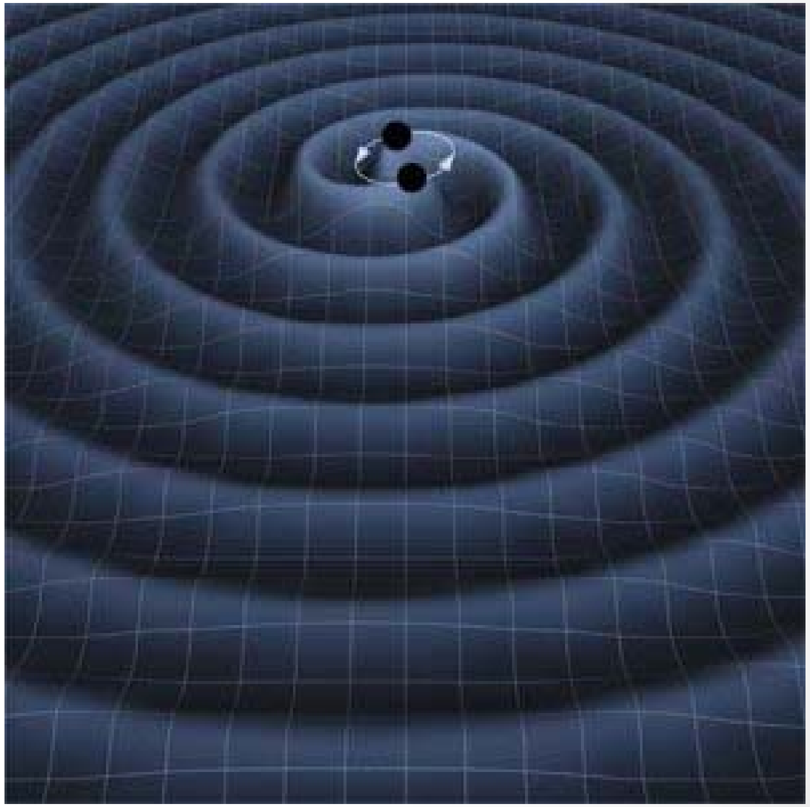


Before 17/08/2017 : Predictions on NS binaries

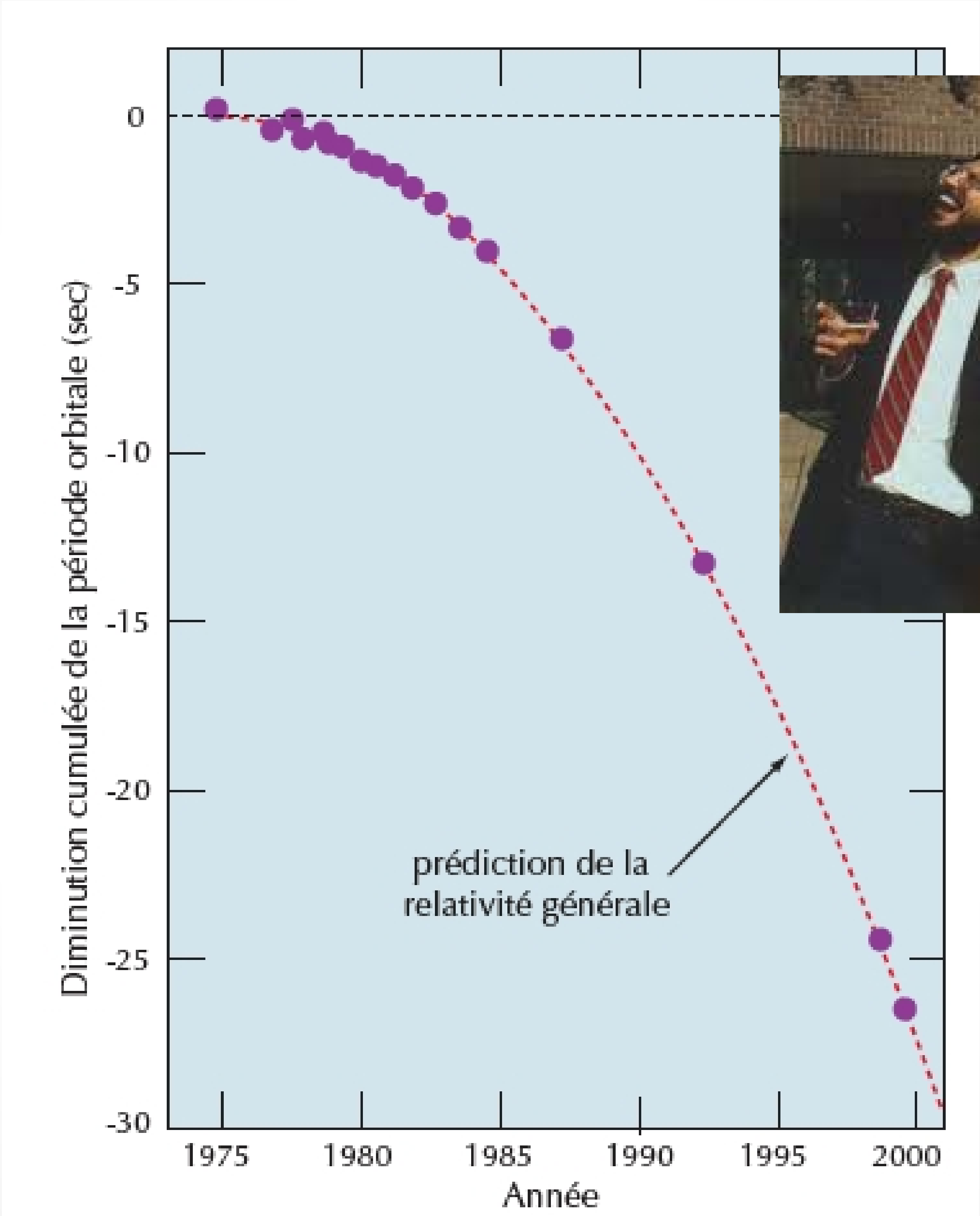
- Gravitational Waves
- X-ray bursts
- Short γ–ray bursts
- R-process
- kilonova

Binary NS-NS systems : gravitational waves sources

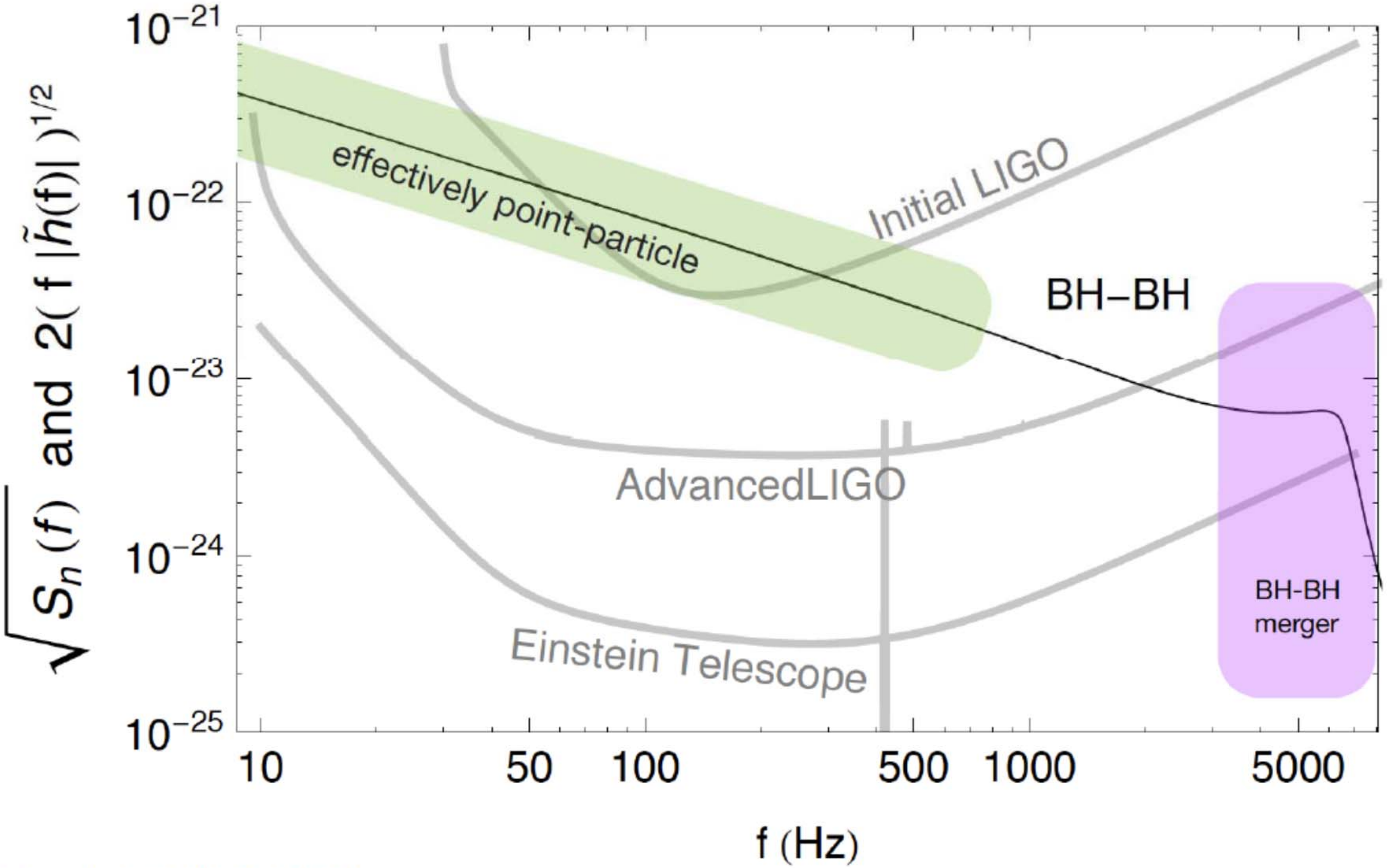




Russel Hulse & Joseph Taylor:
Indirect discovery of GW
(Nobel 1993)

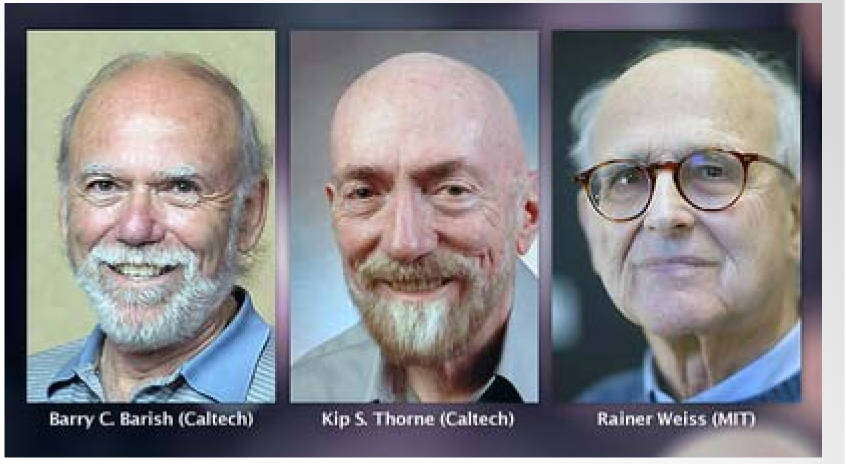


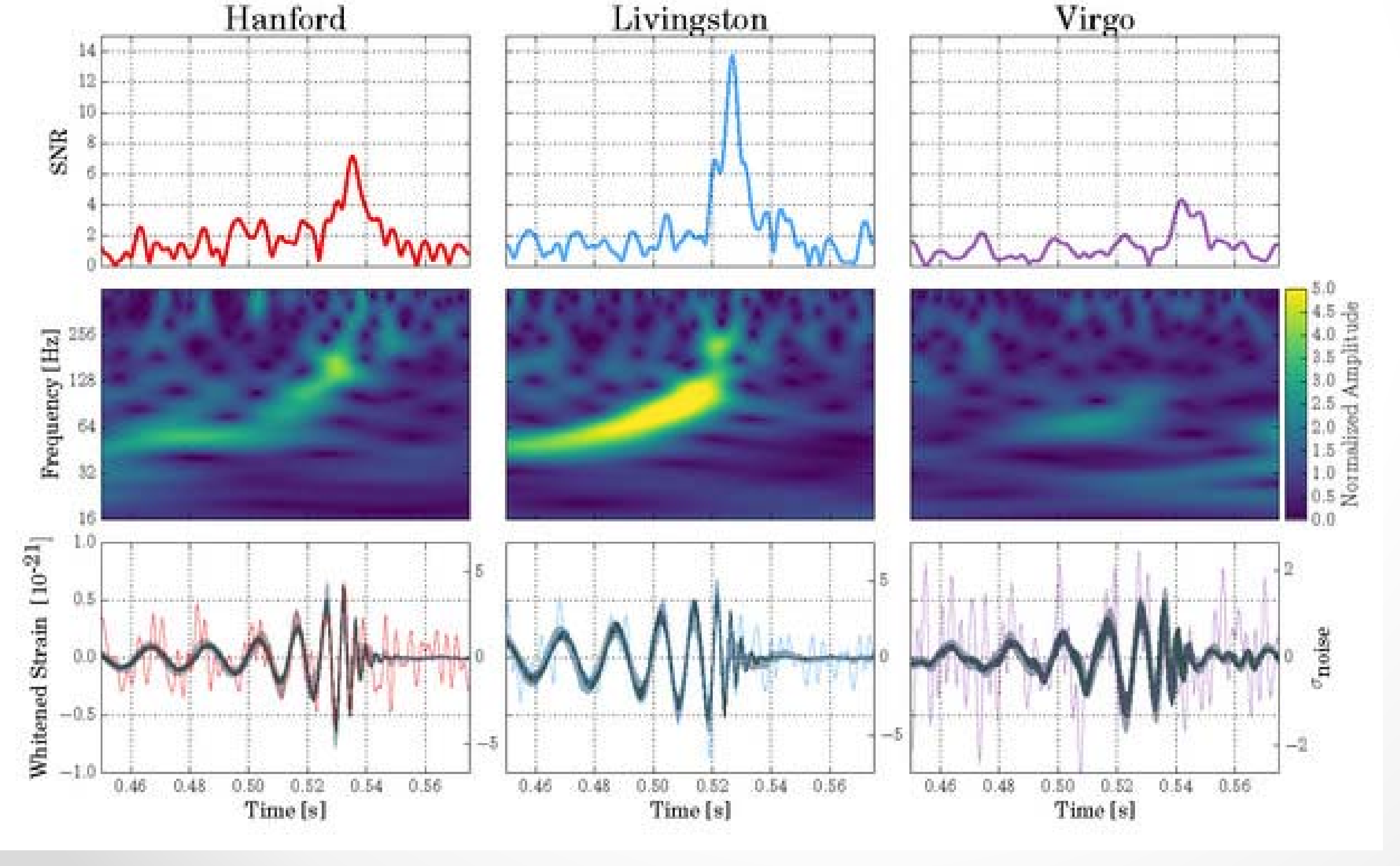
Spectrum of BBH inspiral, scale to 1.35-1.35, 45 Mpc



J. Read, CGWAS 2015

2015, september 14: first direct detection of GW (Nobel 2017)





THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa91c9

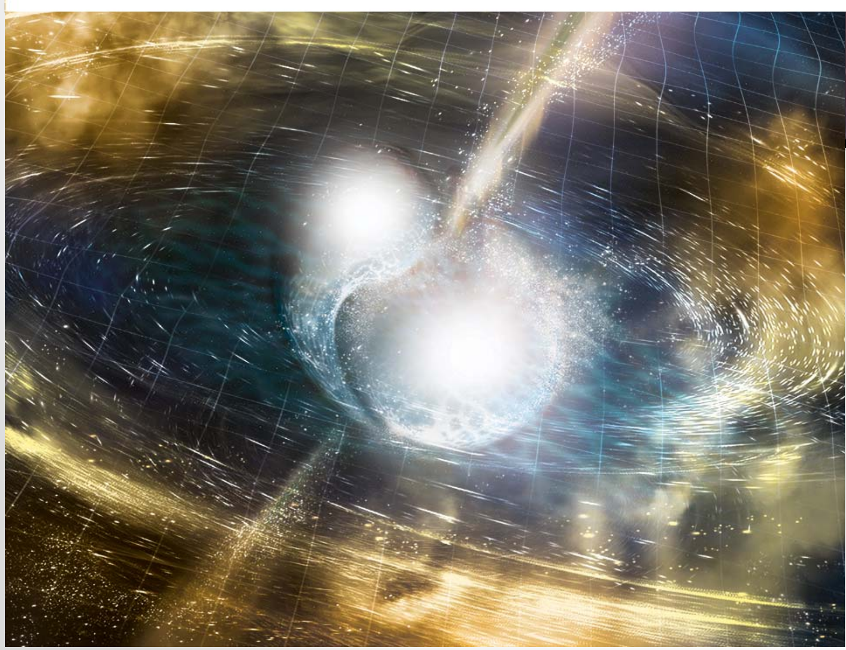
OPEN ACCESS

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

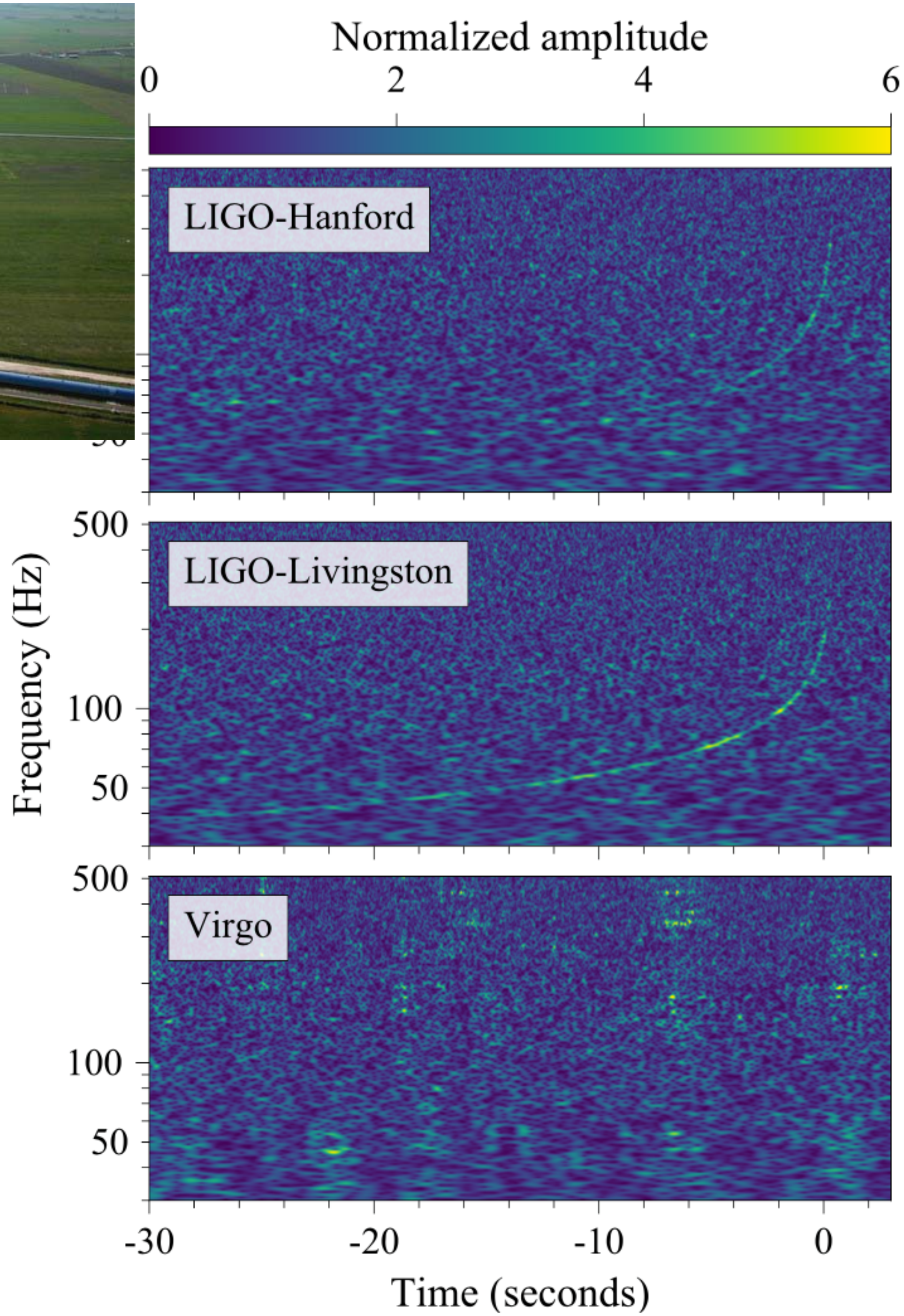
Foundation
Operated by Caltech and MIT



GW170817 Press Release

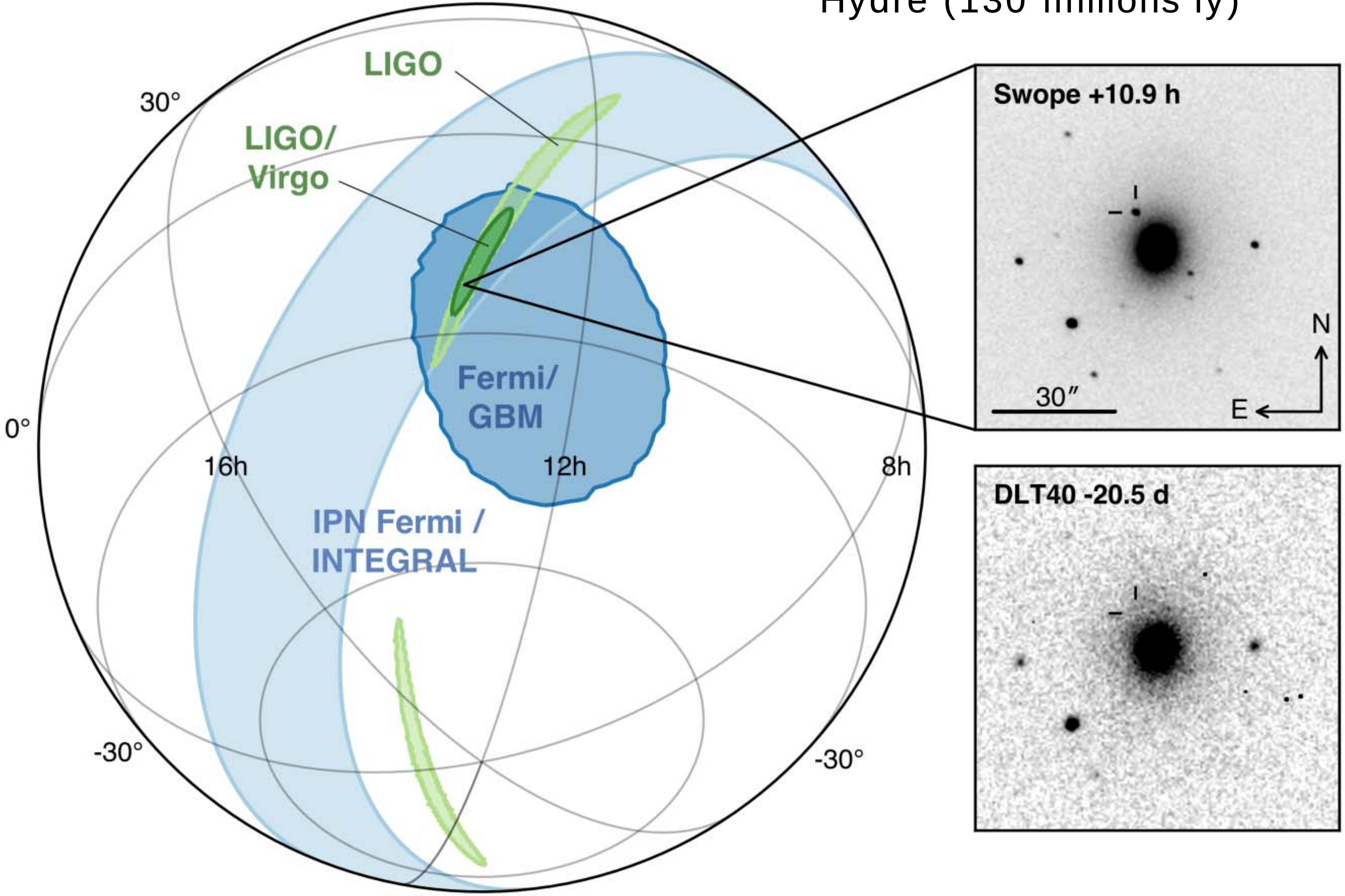
LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars

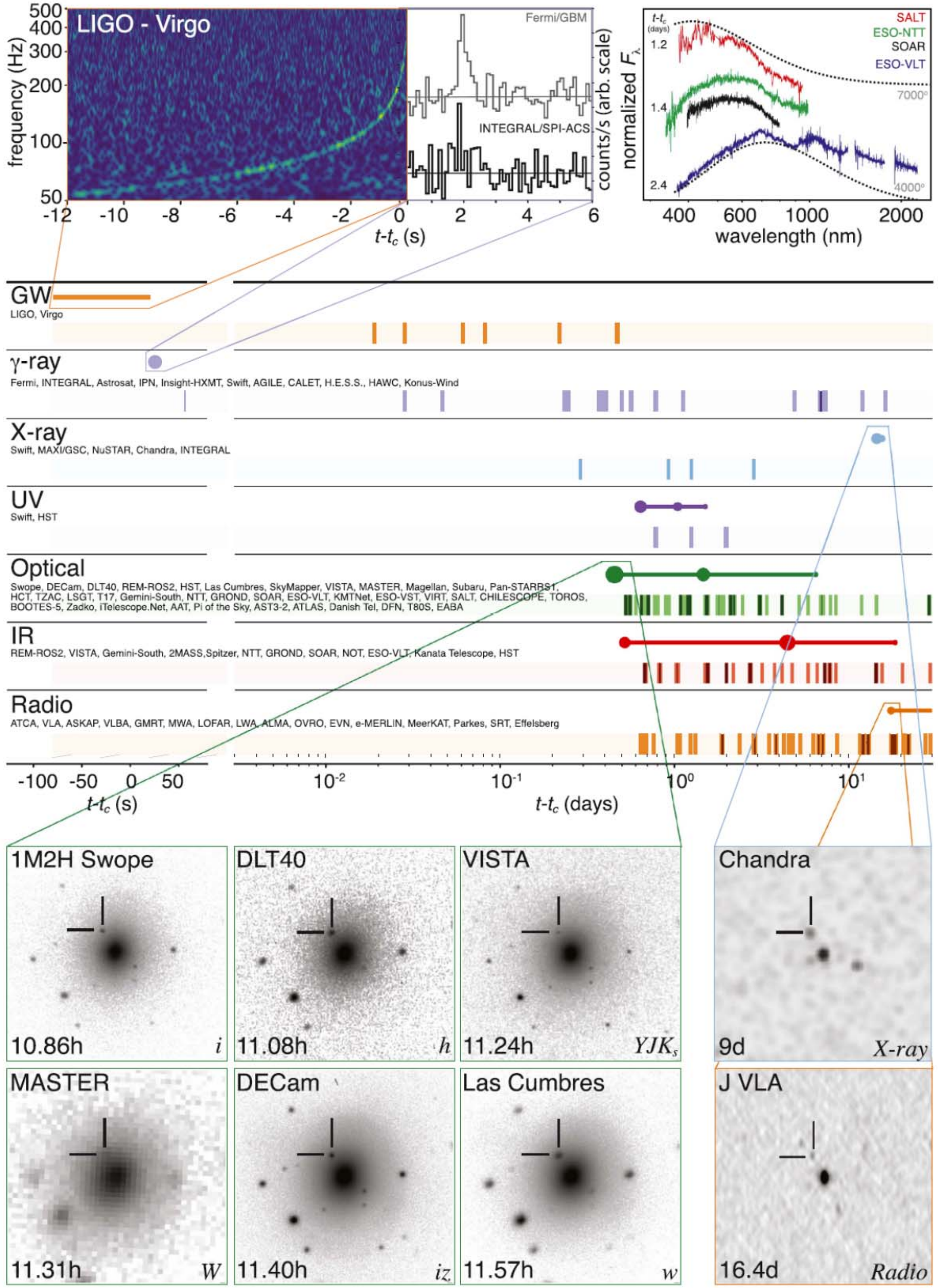
Discovery marks first cosmic event observed in both gravitational waves and light.



Normalized amplitude
0
2
4
6
LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
500
100
50
-30
-20
-10
0
Time (seconds)

NGC4993 :
Hydre (130 millions ly)





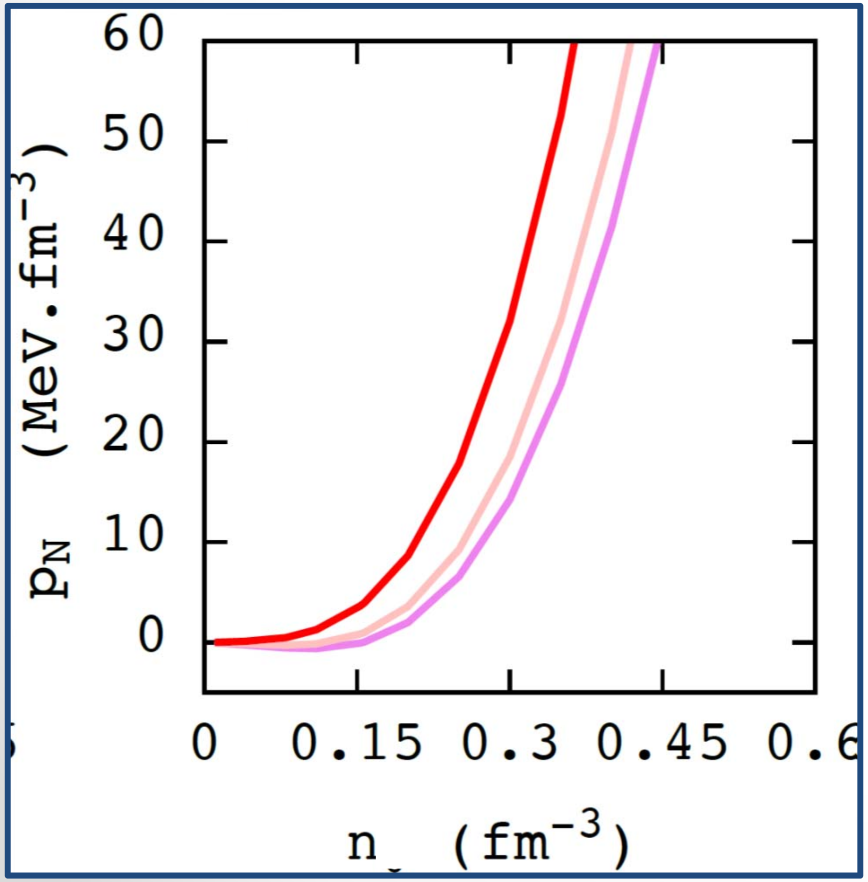
LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-t_c (s)
SALT
ESO-NTT
SOAR
ESO-VLT
normalized F_λ
wavelength (nm)
7000°
4000°
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, 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 YJKs
Chandra 9d X-ray
MASTER 11.31h W
DECam 11.40h iz
Las Cumbres 11.57h w
J VLA 16.4d Radio

GW from NS mergers and the nuclear EoS

- Neutron stars and NS mergers: present status and predictions
- The 17/8/2017 multi-messanger event
- **Modelling NS: the nuclear EoS and the GW signal**
- The present status of the EoS and perspectives

The Equation of State

- Condensed matter: $P(n,T) = n^2 \frac{\partial e}{\partial n}$



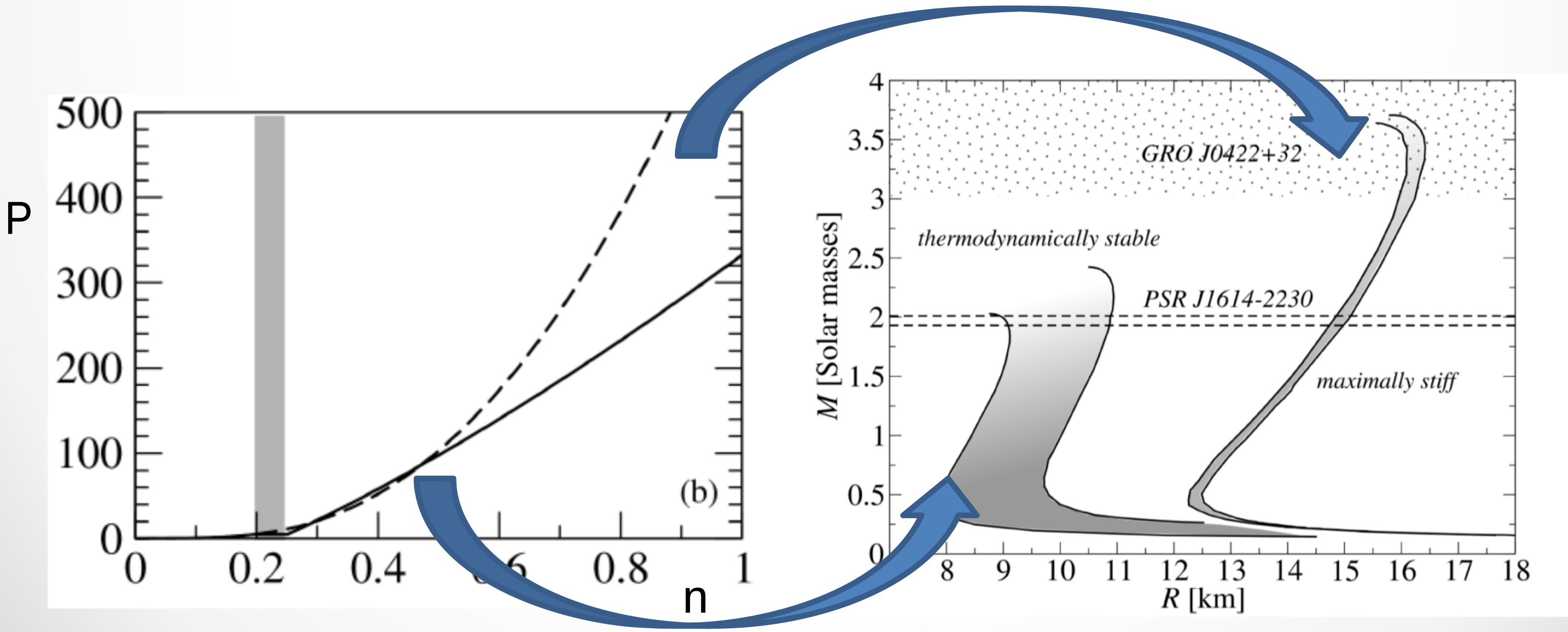
Neutron stars:
M~M$_{sun}$ ~10^{30} kg
R~10 km
n~M/R^3 ~ 10^{18} kg/l

$\Rightarrow$ Nuclear interaction is needed to compute the pressure
$\Rightarrow$ An effective theory for the nuclear energy functional

Modelling Neutron stars: hydrostatics

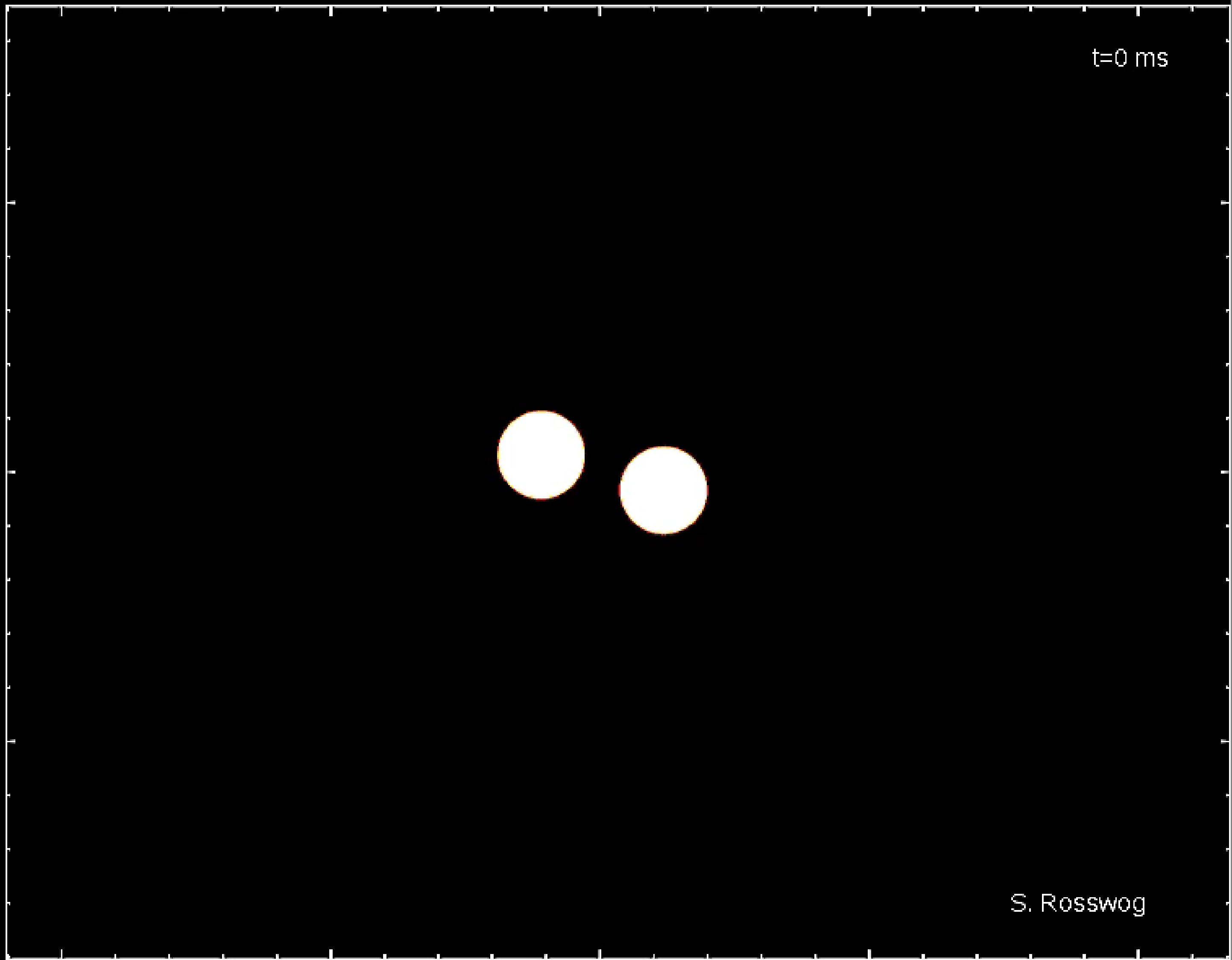
- Tolman Oppenheimer Volkoff: from general relativity

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



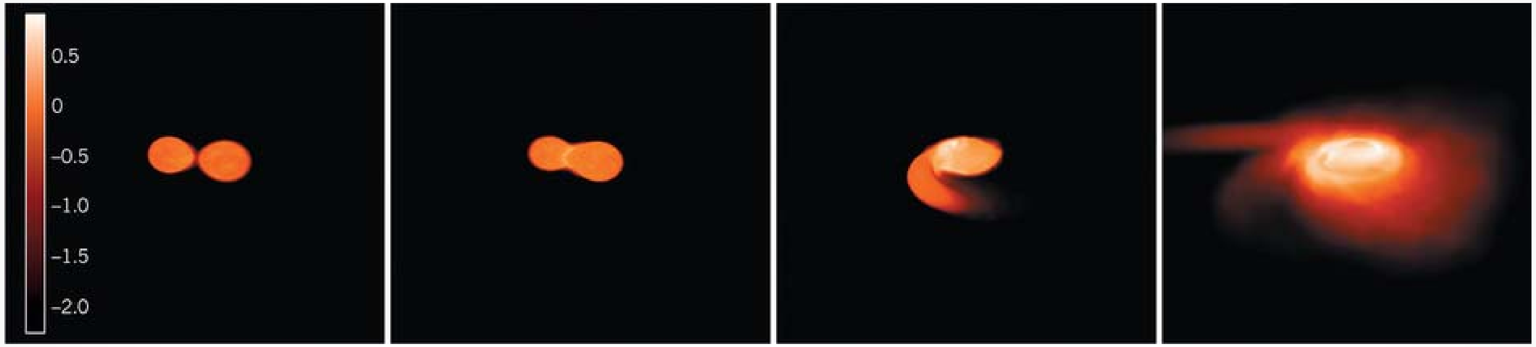
N.Chamel et al, A&A, 2013

Modelling NS mergers: hydrodynamics



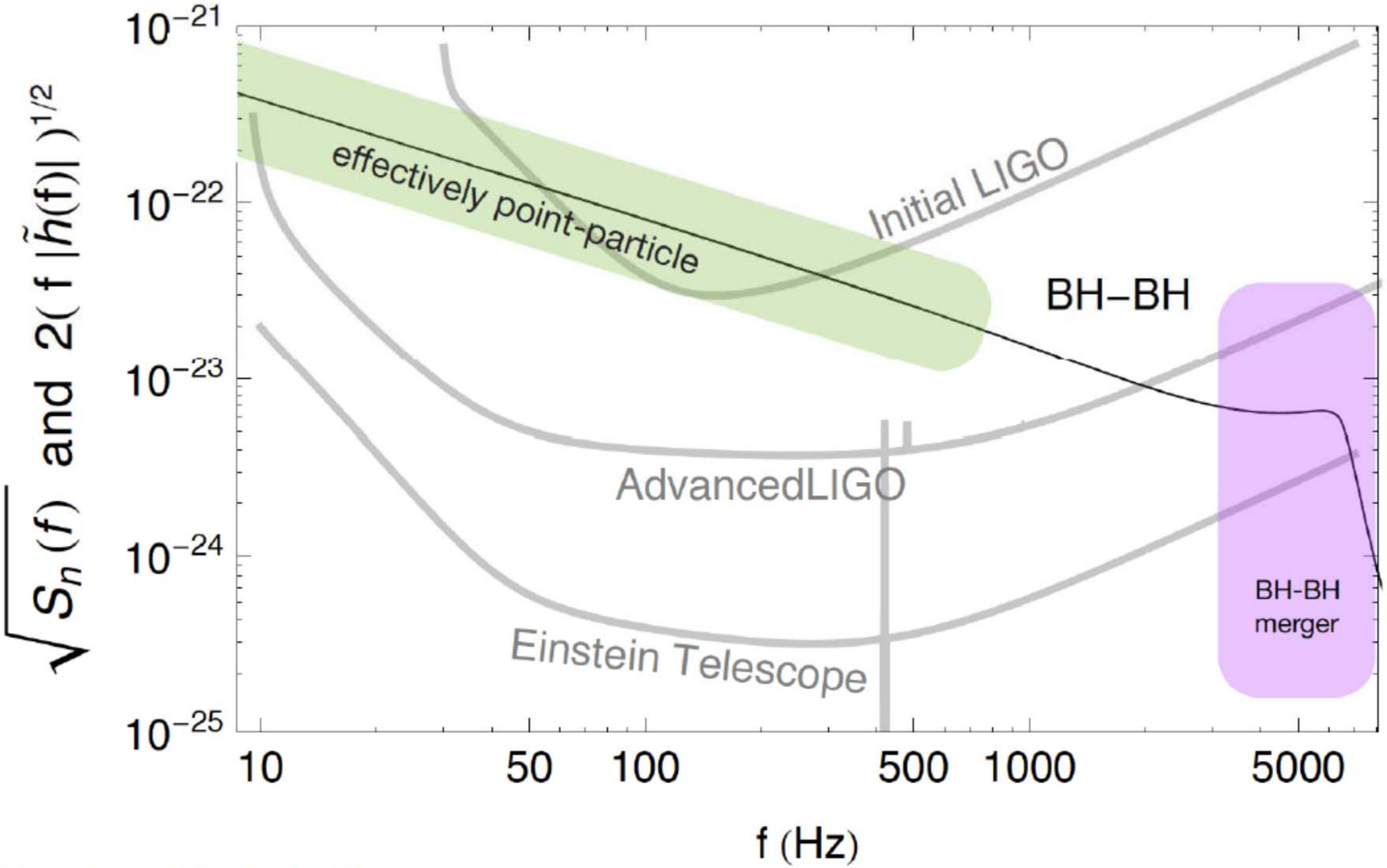
S. Rosswog, T. Piran and E. Nakar, MNRAS 430, 2585 (2013)
T. Piran, E. Nakar and S. Rosswog, MNRAS 430, 2121 (2013)

Tidal polarizability



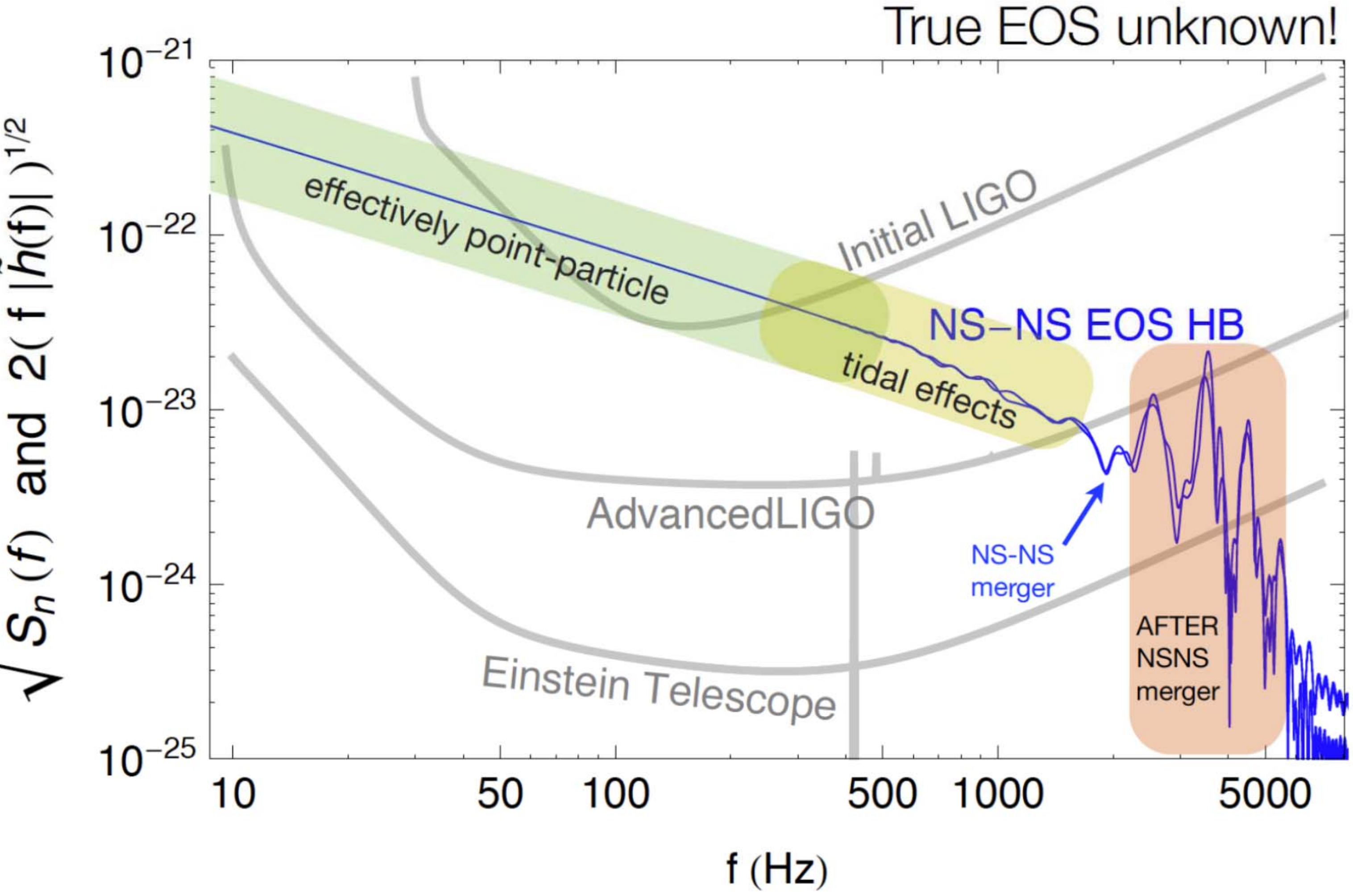
- The tidal field of the companion induces a mass quadrupole moment which accelerates the coalescence
- Coalescence time is determined by the tidal polarizability $\Lambda = \frac{2}{3} k_2 \left(\frac{c^2}{G} \frac{R}{M} \right)^5$

Spectrum of BBH inspiral, scale to 1.35-1.35, 45 Mpc



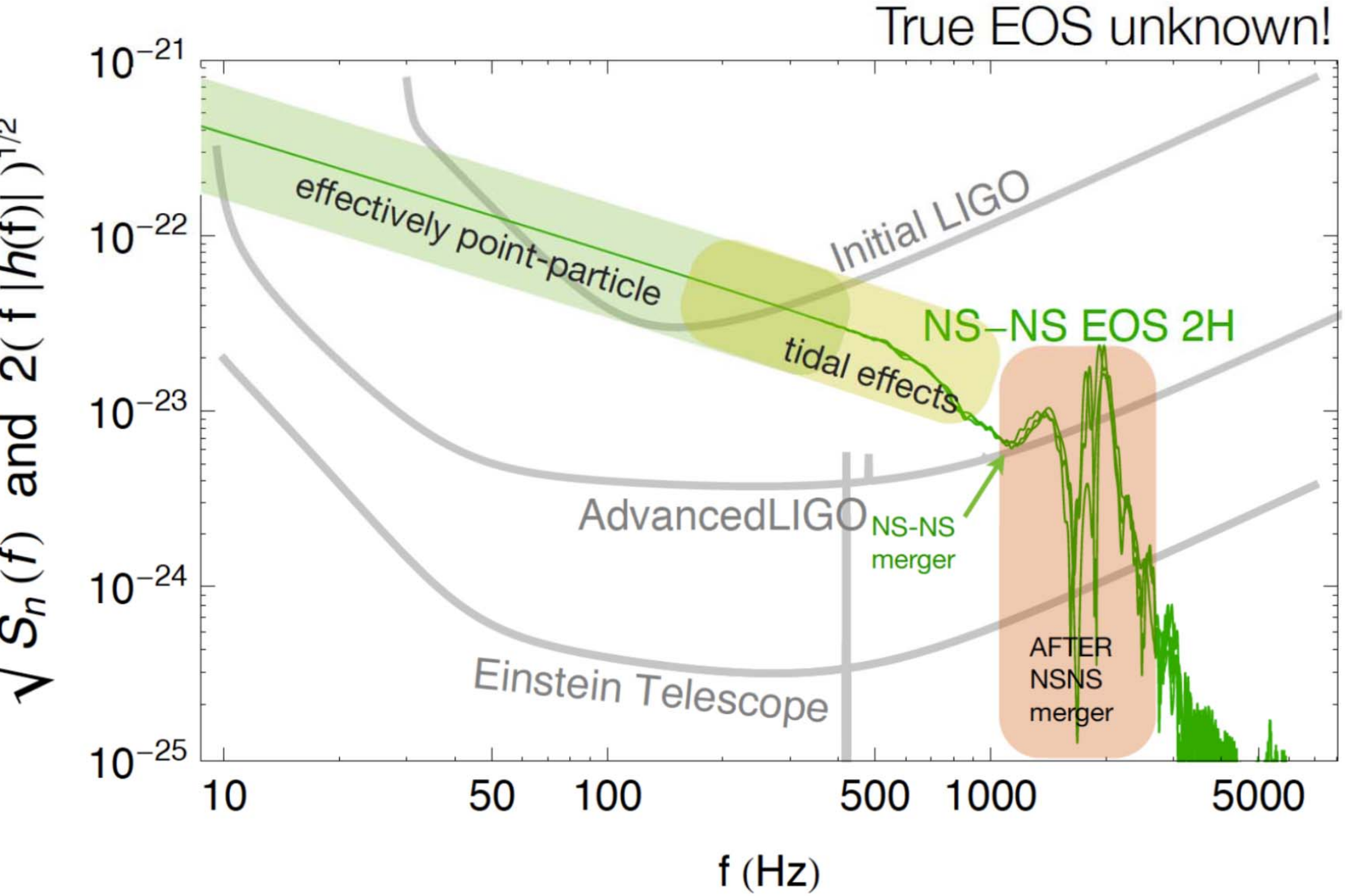
J. Read, CGWAS 2015

Spectrum of NS-NS inspiral, 1.35-1.35, 45 Mpc



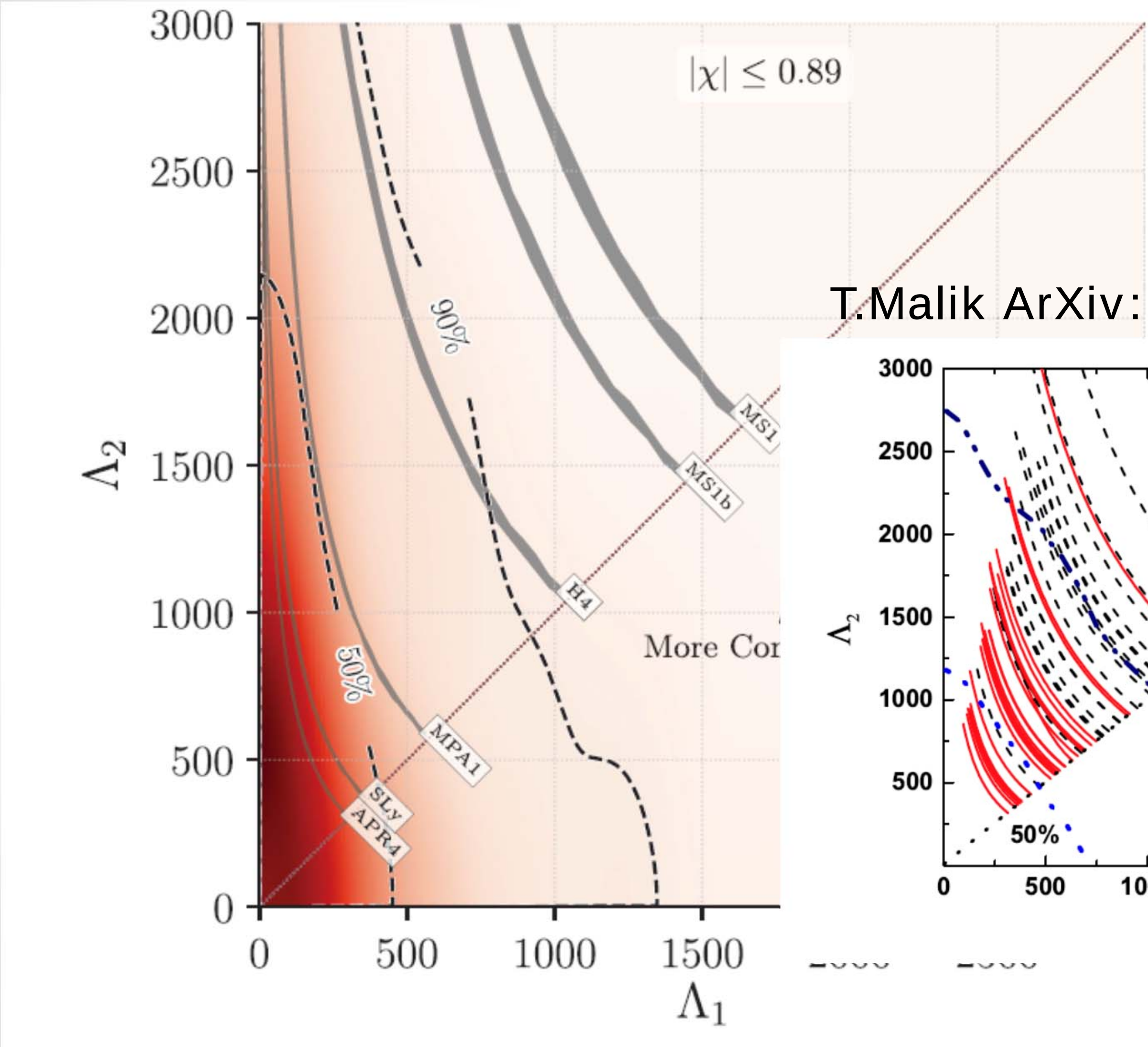
J. Read, CGWAS 2015

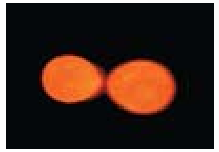
Spectrum of NS-NS inspiral, 1.35-1.35, 45 Mpc



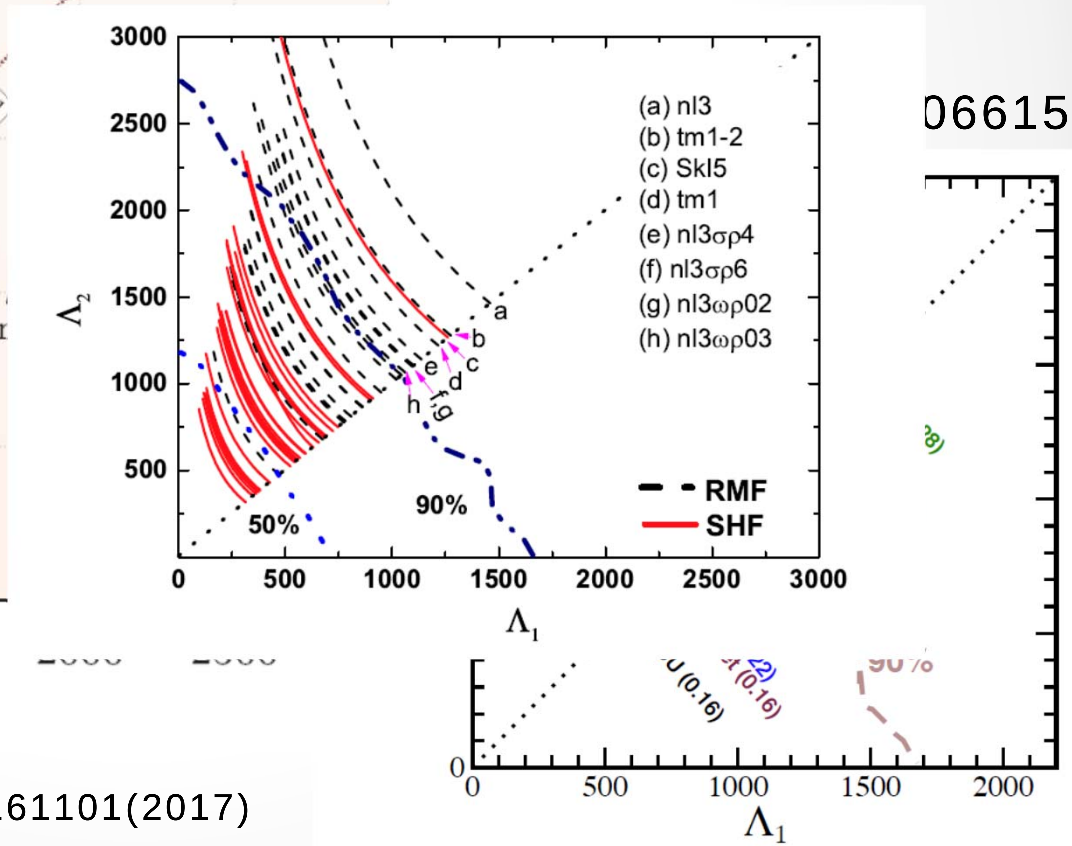
J. Read, CGWAS 2015

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





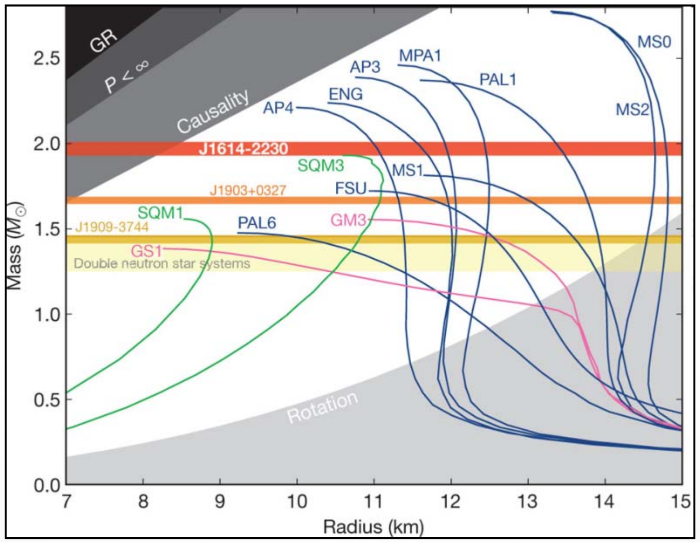
T.Malik ArXiv:180511963



06615

- B.Abbott et al. (LIGO) PRL 119,161101(2017)

How to recognize the « true » EoS model?



The contribution of nuclear experiments

$$\delta = \frac{n_n - n_p}{n}$$

$$x = \frac{n - n_0}{n}$$

- **Definition of empirical parameters**

  - The EoS is the derivative of the energy functional $e(n_p, n_n)$ *energy per baryon*

  - In the absence of a phase transition, the functional can be written as a Taylor expansion

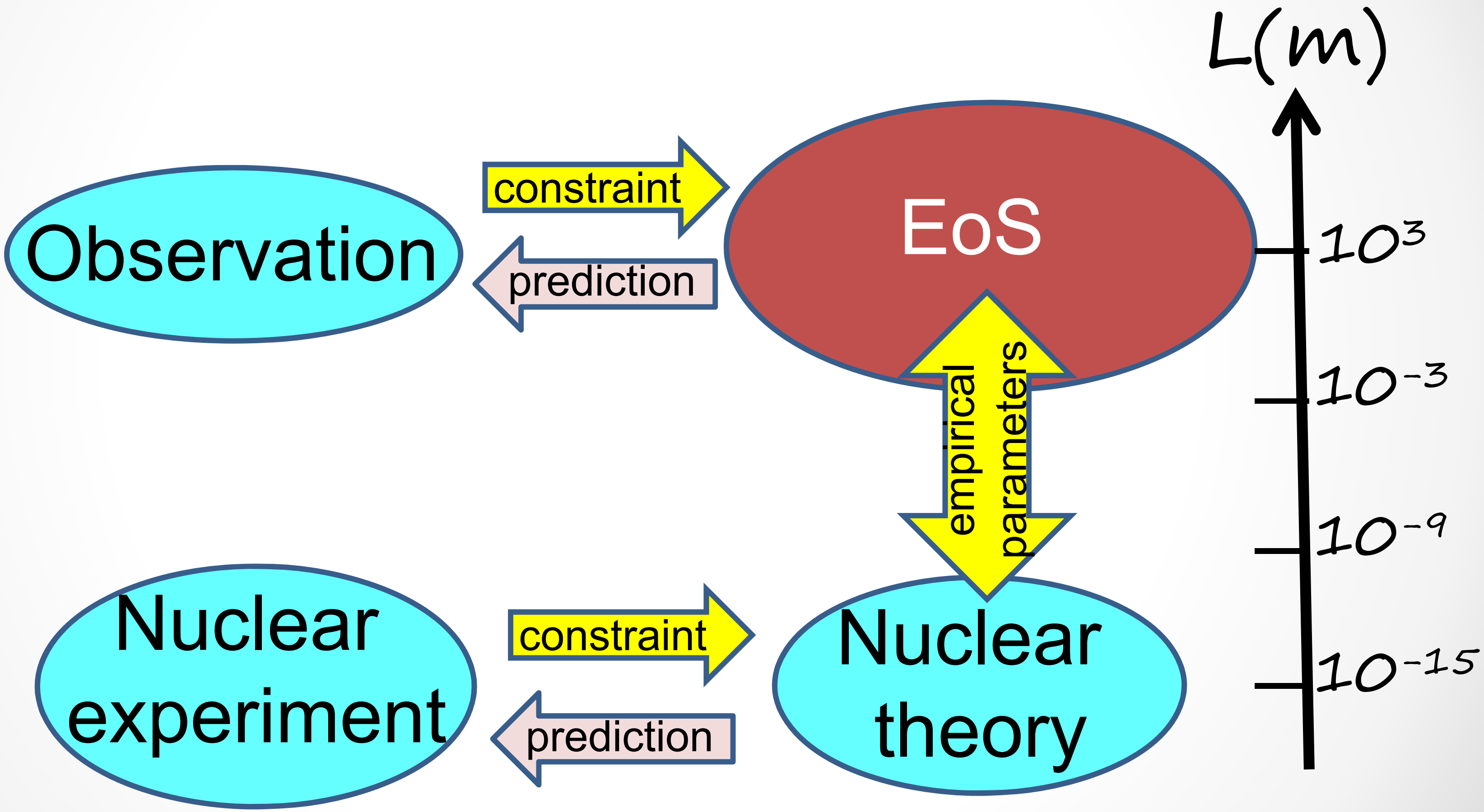
$$e(n,\delta) = e_{IS}(n) + e_{IV}(n)\delta^2 + O(\delta^4)$$

$$= \left(\boldsymbol{E_0} + \frac{1}{18}\boldsymbol{K_0}x^2 + O(x^3)\right) + \left(\boldsymbol{J_0} + \frac{1}{3}\boldsymbol{L}x + \frac{1}{18}\boldsymbol{K_{sym}}x^2 + O(x^3)\right)\delta^2$$

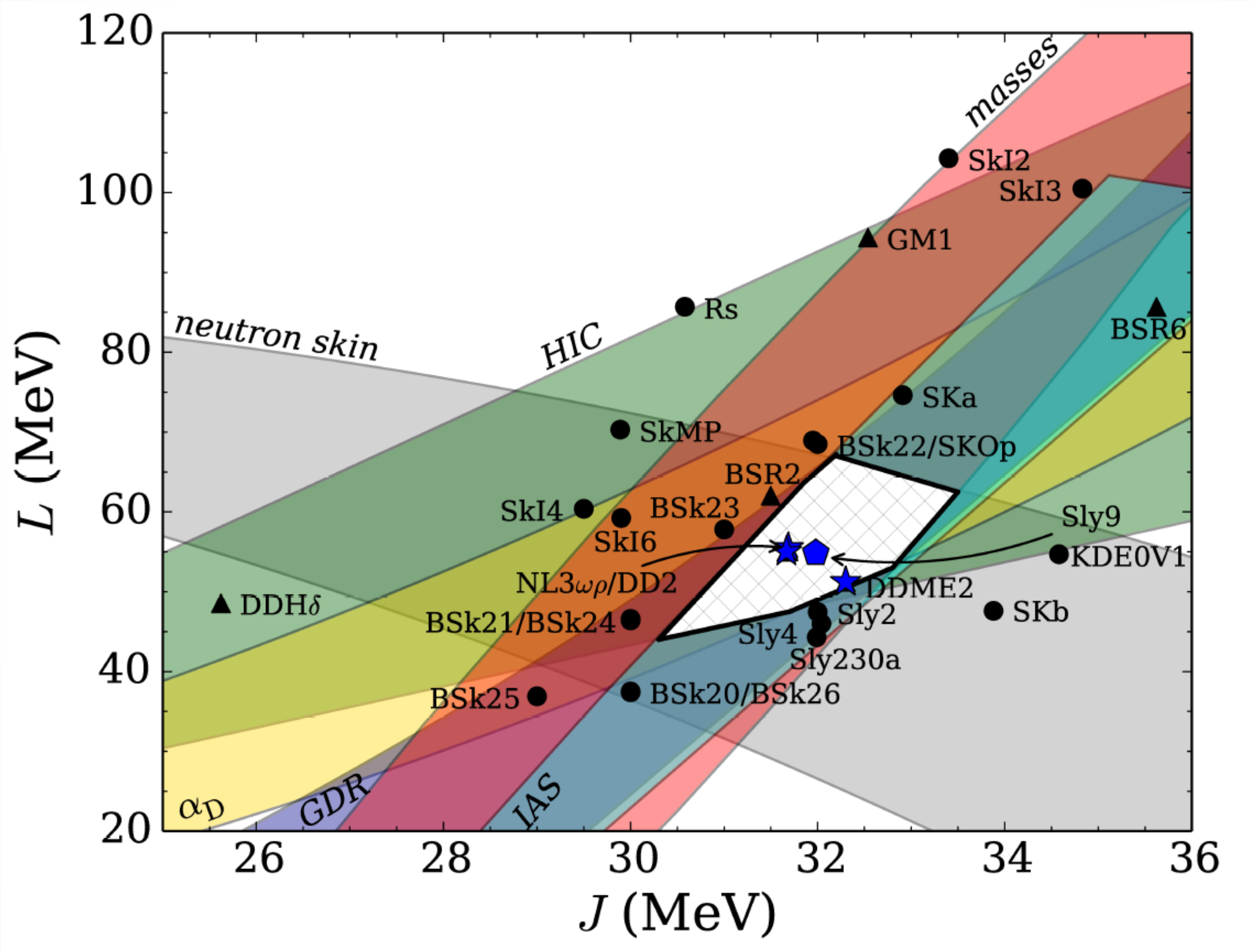
  - The expansion coefficients (empirical parameters)can be constrained comparing the functional predictions with data,

Constraining the empirical parameters:

jumping across the scales!

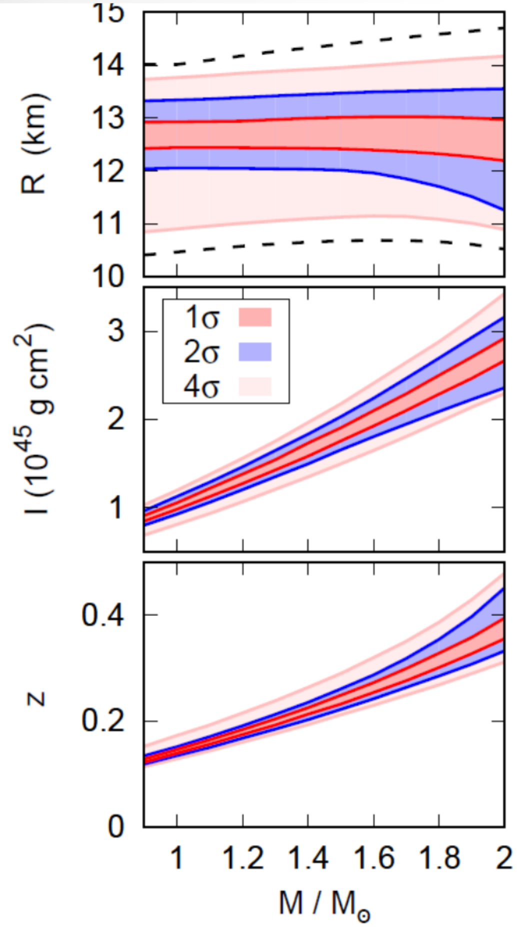


Experimental constraints



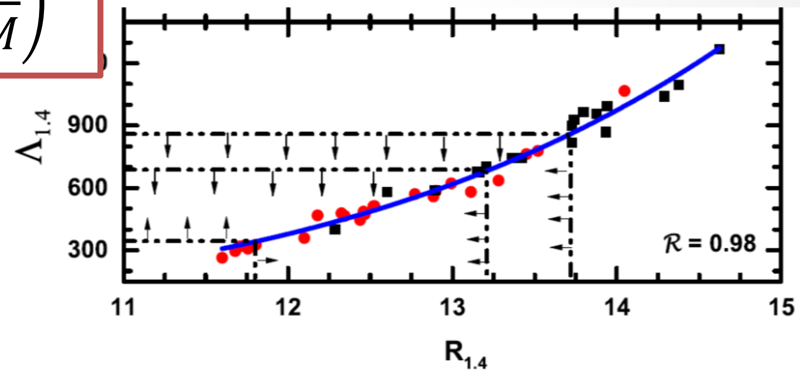
M.Fortin et al, PRC 2016

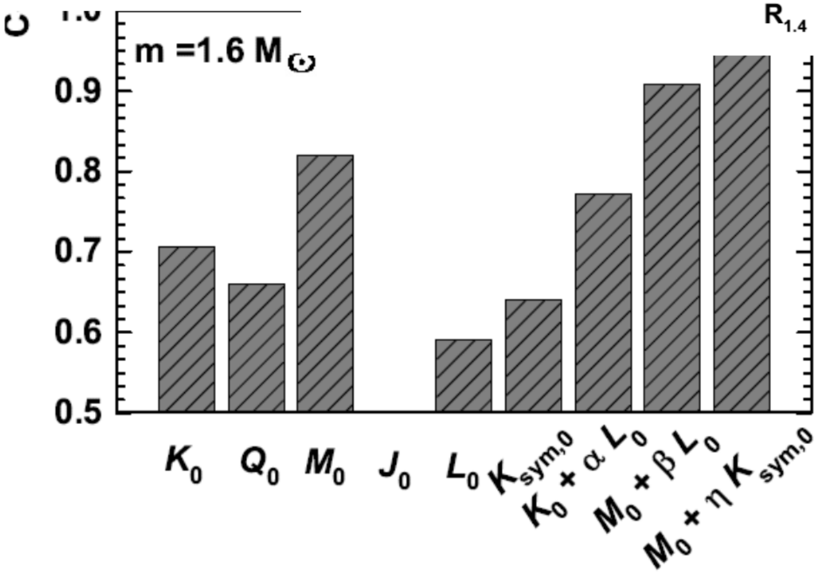
Present status of the predictions



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

T.Malik ArXiv:180511963





J. Margueron, R.Casali and F. Gulminelli, PRC97(2018)025805
PRC97(2018)025806

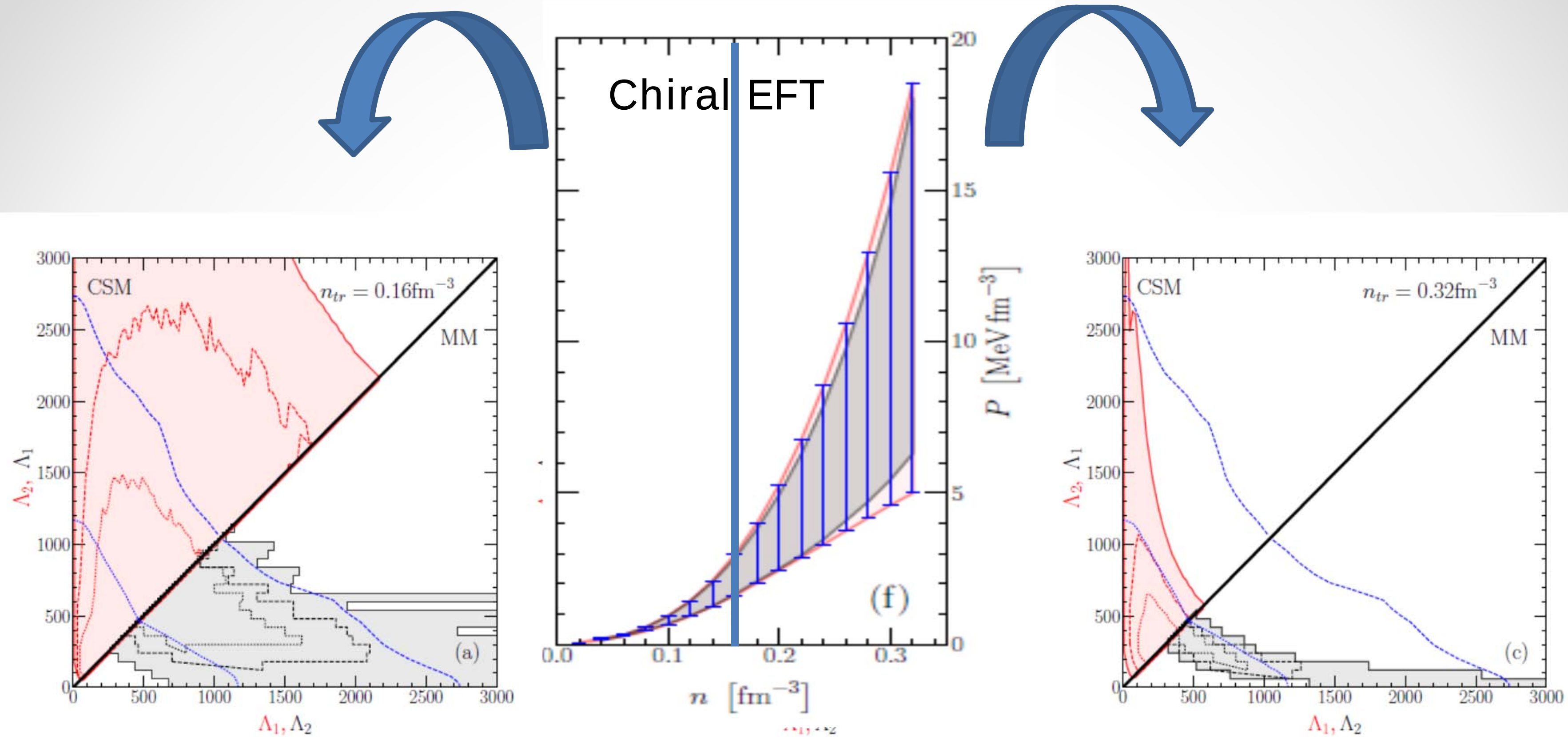


FIG. 1. Envelopes for the CSM (red) and the MM (black) for the correlation of the tidal polarizabilities Λ_1 and Λ_2 of the two compact stars in GW170817. We show: panel (a) the results for $n_{\rm tr} = n_{\rm sat}$ and no constraint on $\tilde{\Lambda}$, panel (b) for $n_{\rm tr} = n_{\rm sat}$ when additionally enforcing $\tilde{\Lambda} < 800$, and panel (c) for $n_{\rm tr} = 2n_{\rm sat}$ and no constraint on $\tilde{\Lambda}$. We also show the 90% (dashed lines) and 50% (dotted lines) probability contours for the MM (black lines), the CSM (red lines), and compare to the corresponding 90% and 50% contours from the LV analysis (blue lines).

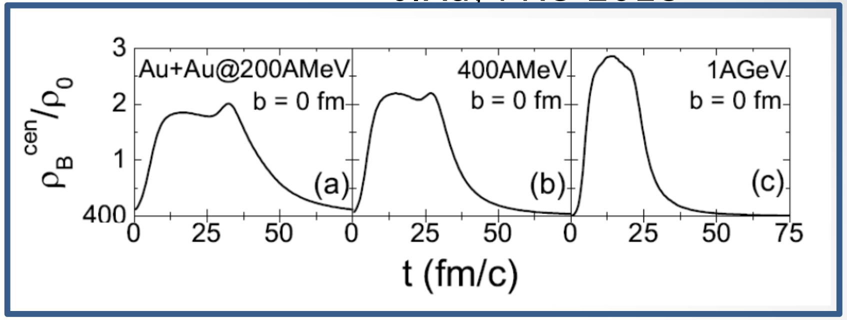
I.Tews, J.Margueron, S.Reddy, INT-PUB-18-014

Drastic improvement if
the high density EoS is constrained!

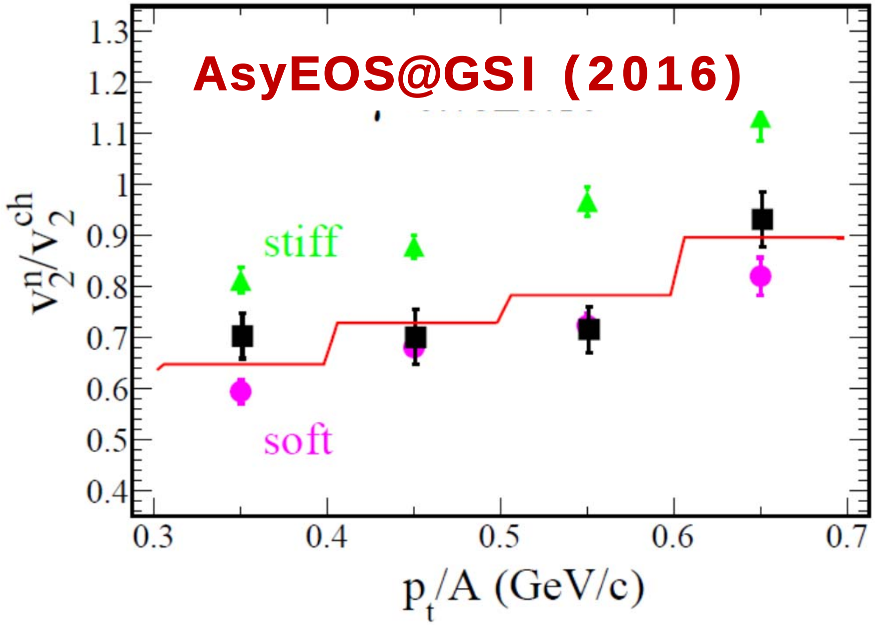
How to further constrain the high density EoS?

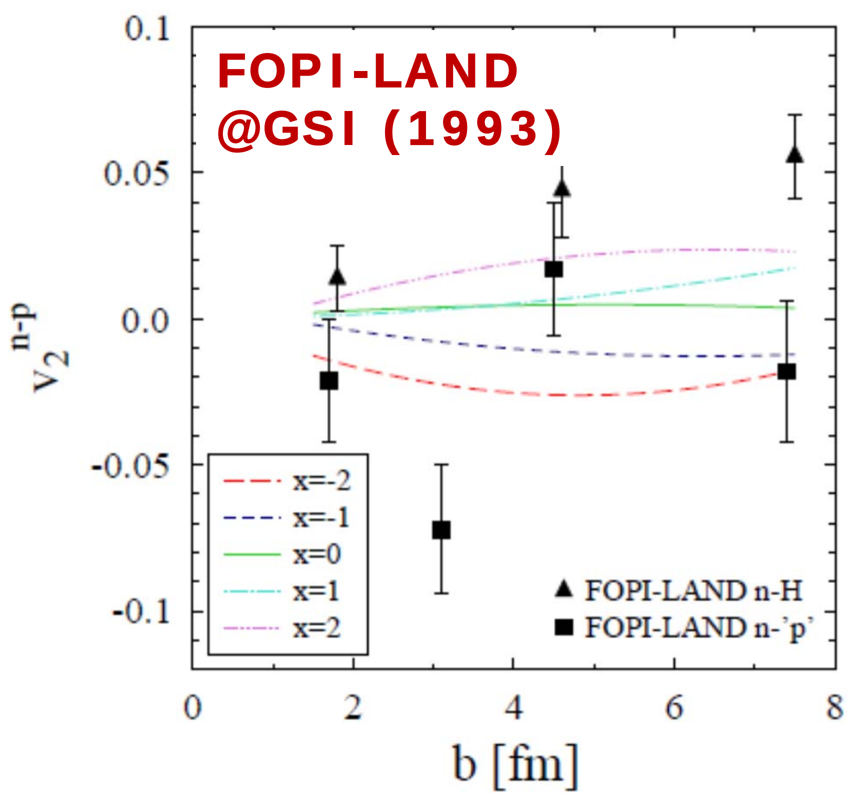
Strategy I: high density constraints

J.Xu, PRC 2013



P.Russotto et al,PRC 2016

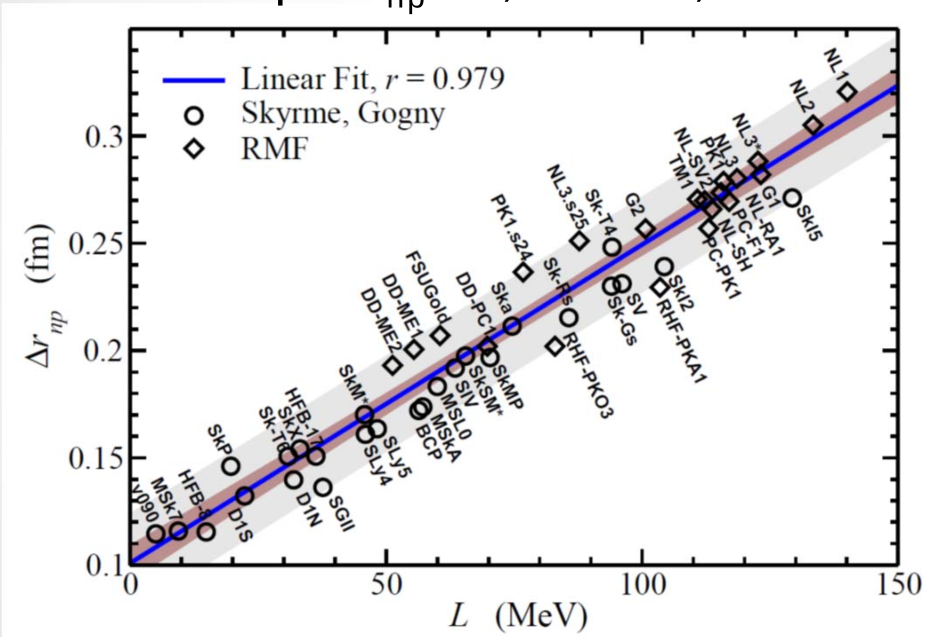




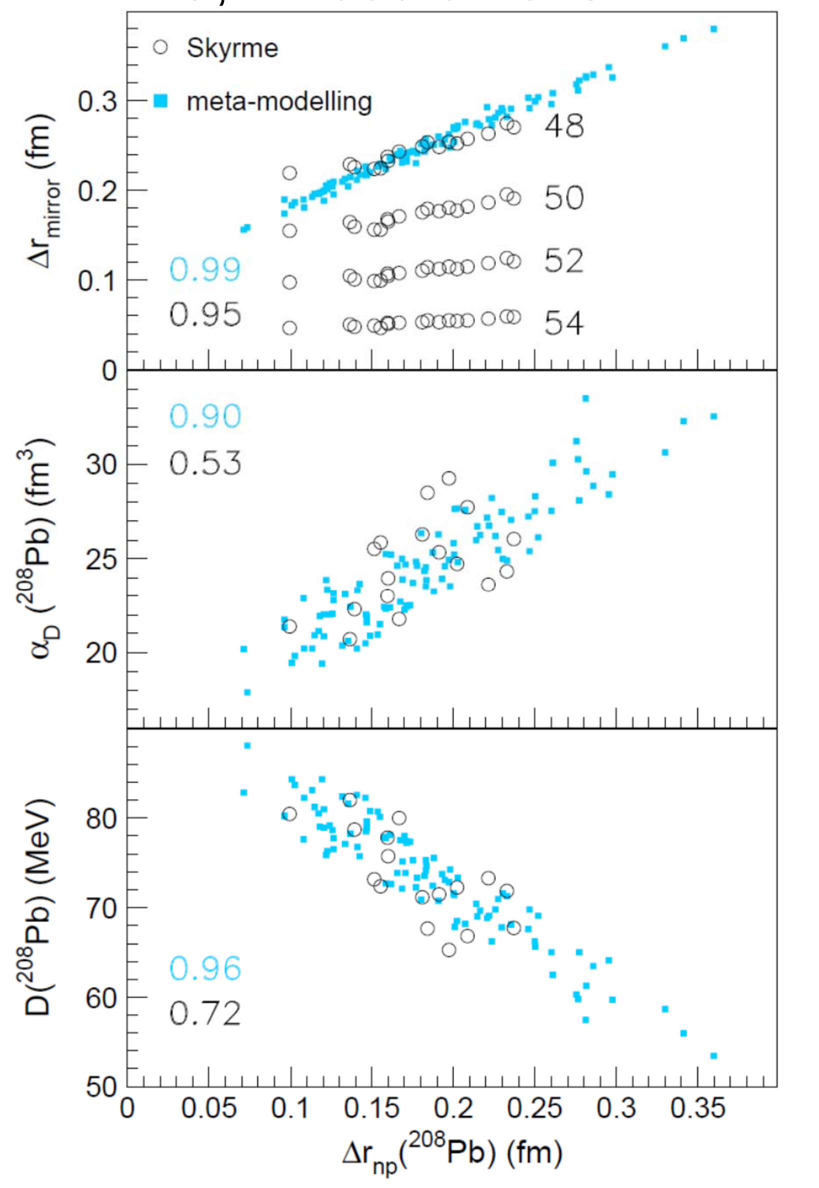
Differential elliptic flow for Au+Au 400 A.MeV

Strategy II: high precision

Exp: Δr_{np}= 0,1318-0,3072

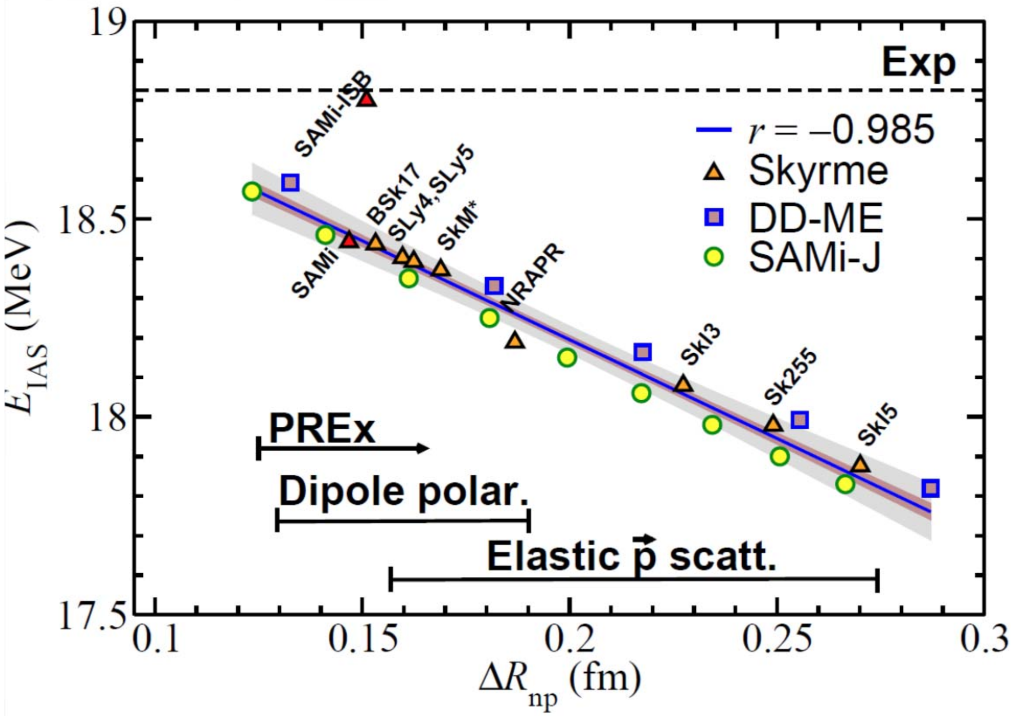


F.G, A.Raduta 2018



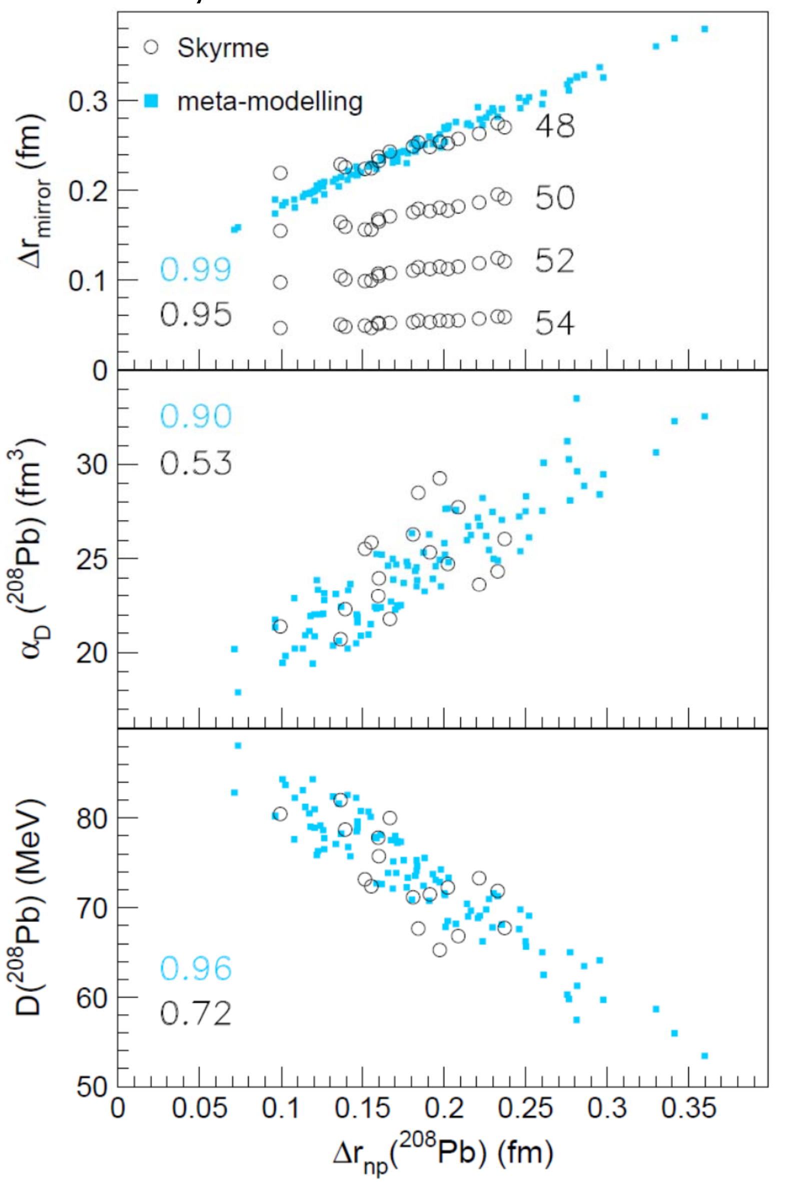
X.Vinas et al 2014
P.G.Reinhard, W.Nazarewicz 2016
D.Chatterjee, F.G. 2017
J.Yang, J.Piekarewicz 2017

Strategy II: high precision



X.Roca-Maza, G.Colo, H.Sagawa 2018

F.G, A.Raduta 2018



- Recent review: X.Roca-Maza, N.Paar Prog.Part.Nuc.Phys.2018 •

Conclusions

- The multi-messanger 17/08/17 NS merger observation has spectacularly confirmed all the théoretical predictions on NS mergers
- GW are a new observable for the nuclear EoS
- Advances on the nuclear EoS require better constraints on high order derivatives
  - Data at supersaturation density (HIC)
  - Precision measurements at subsaturation (skin, isovector collective modes)
  - Theory (ab-initio modelling, phase transition)