
Credit: NASA/Swift Dana Berry

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IN2P3
Les deux infinis

Unveiling the structure of ultra-dense matter

Synergy between nuclear physics and gravitational waves

Francesca Gulminelli - Université de Caen-Normandie

Congrès Général des 150 ans de la SFP, 3-7Juillet, 2023

plan

1. Neutron stars and gravitational waves
2. Gravitational waves and the equation of state of dense matter
3. The contribution of nuclear physics
4. Future perspectives

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1. **Neutron stars and gravitational waves**
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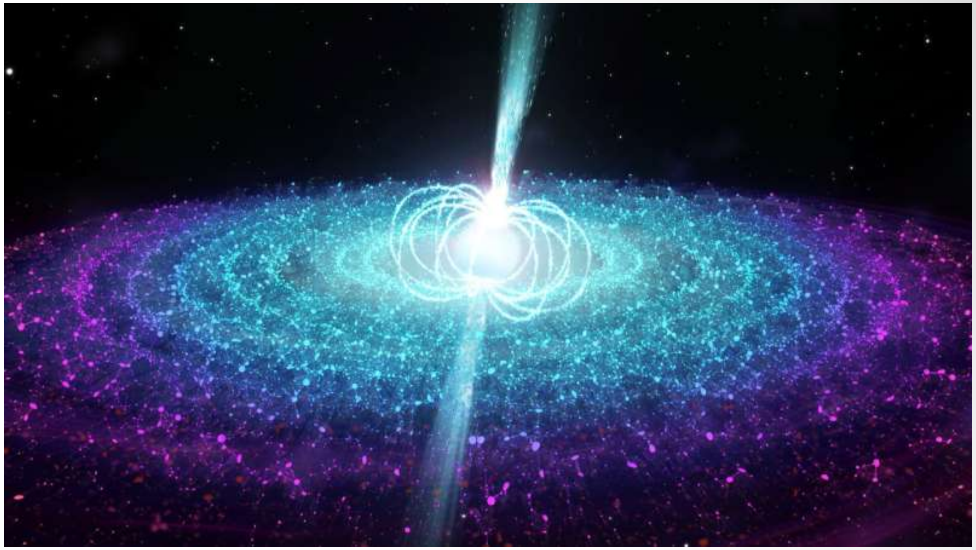
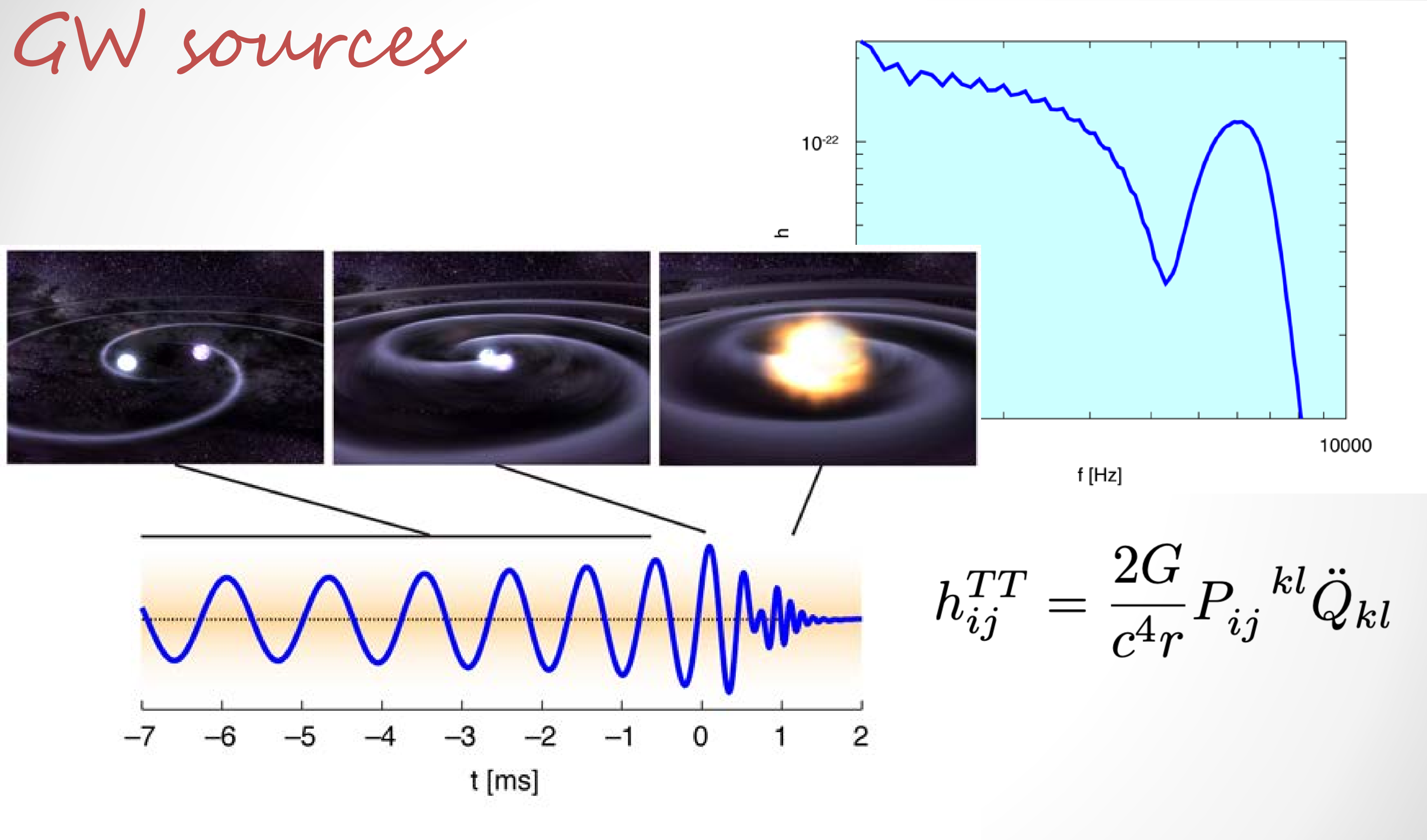
Neutron stars record list

Credit: ICRAR/Univ. Amsterdam.



- The objects which spin the fastest $\nu=716$ Hz => $v_{equator} \sim c/4$
- The highest speed of the galaxy $v=1083$ km/s
- The most intense magnetic fields $H>10^{14}$ Gauss
- The densest matter of the universe $\rho \sim 10^{14}$ g/cm^3
- The only place where:
  - neutrinos can be trapped
  - quarks might be deconfined

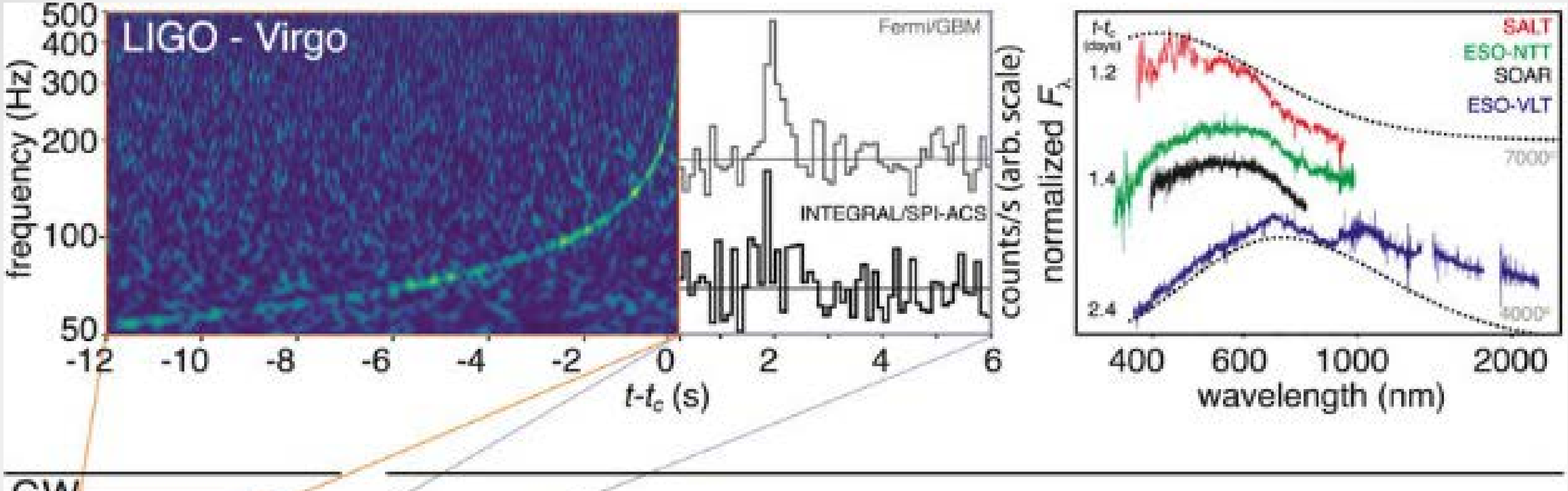
Neutron star binaries: GW sources



$$h_{ij}^{TT} = \frac{2G}{c^4 r} P_{ij}{}^{kl} \ddot{Q}_{kl}$$

Source: NASA&A.Stonebraker, adapted from PRL 104, 141101

GW170817 by LVC



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

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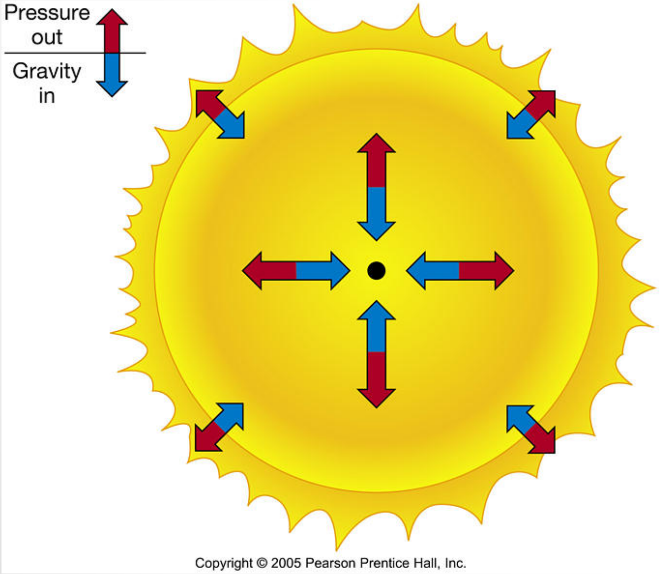
Modeling (neutron) stars: hydrostatics

- Equilibrium of a self-gravitating object
  => Tolman Oppenheimer Volkoff (1939):

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



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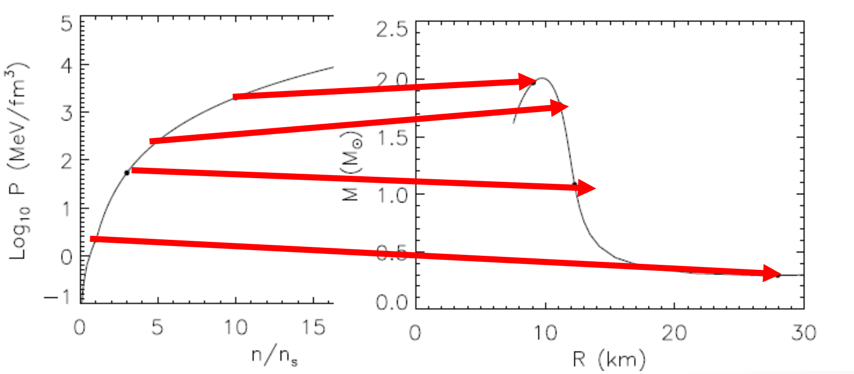


Equilibrium radius for each mass

Only depends on the EoS $P(\rho)$

Modeling (neutron) stars: hydrostatics

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

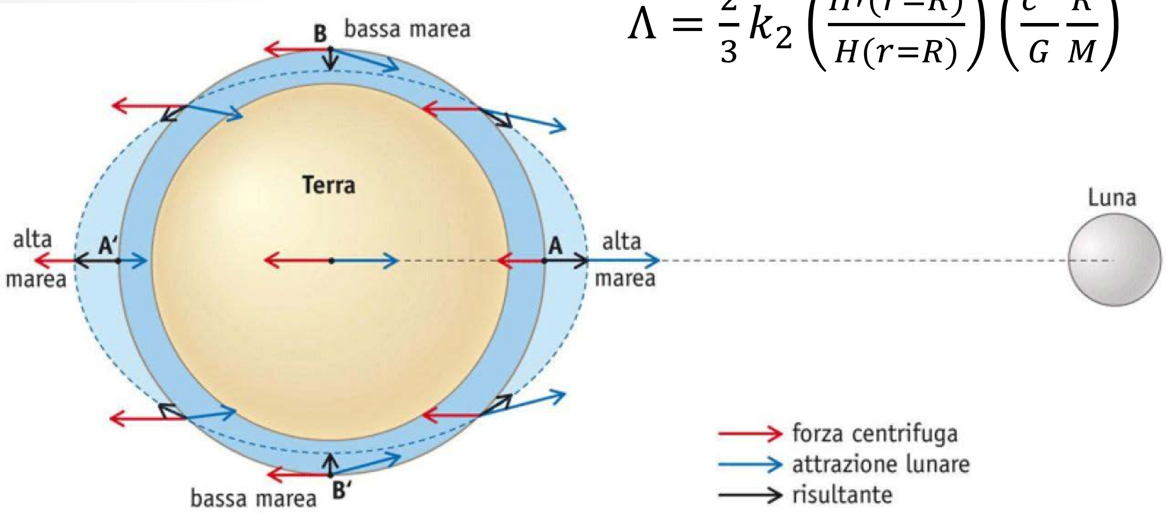
$$\frac{d^2H(r)}{dr^2}+\frac{dH(r)}{dr}\left[\frac{2}{r}+e^{\lambda(\boldsymbol{P(\rho)})}\left(\frac{2m(r)}{r^2}+4\pi r\left(\boldsymbol{P(\rho)}-\rho(r)\right)\right)\right]+H(r)Q(\boldsymbol{P(\rho)})=0$$

$\forall\rho_c$

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

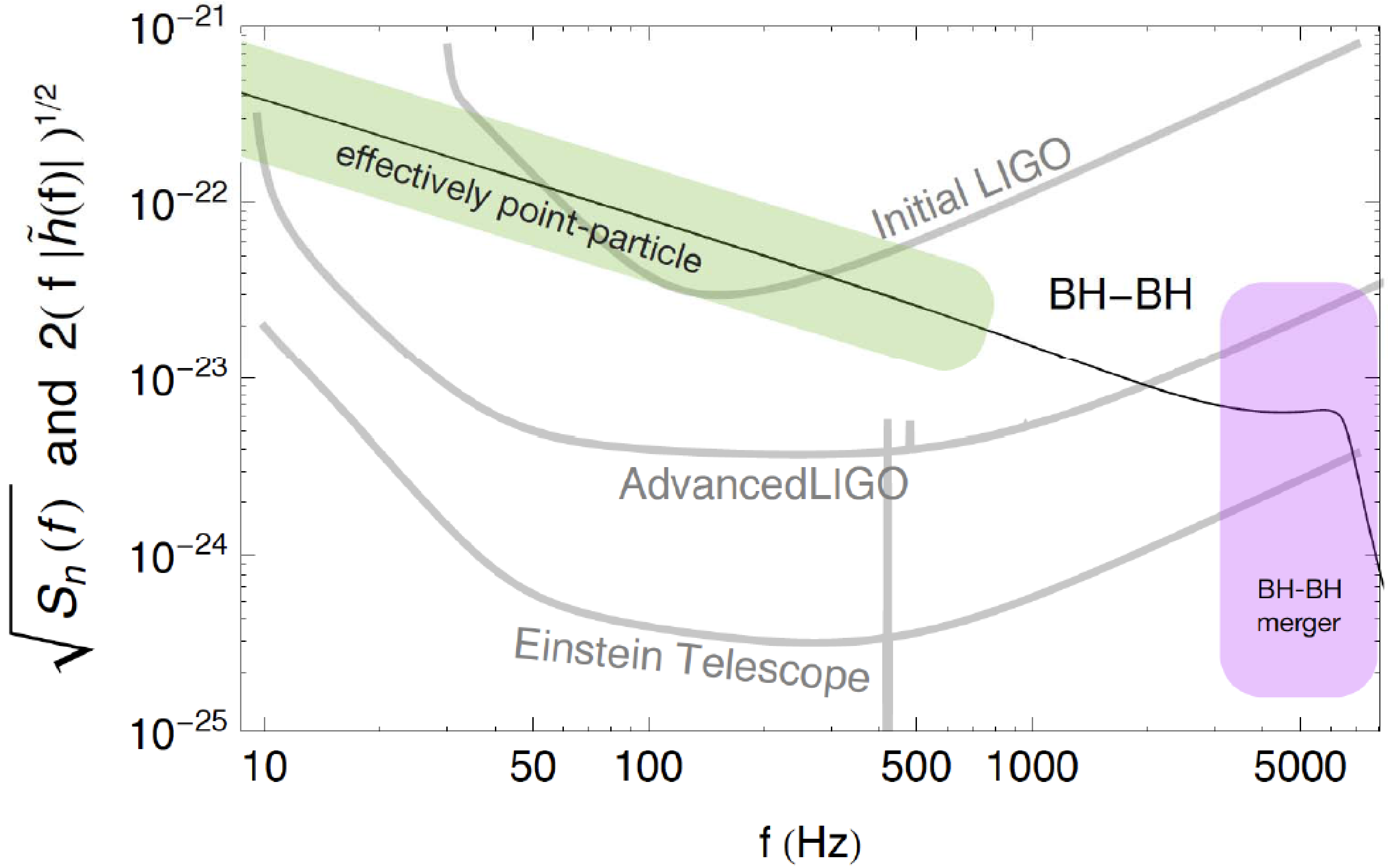
Tidal polarisability

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



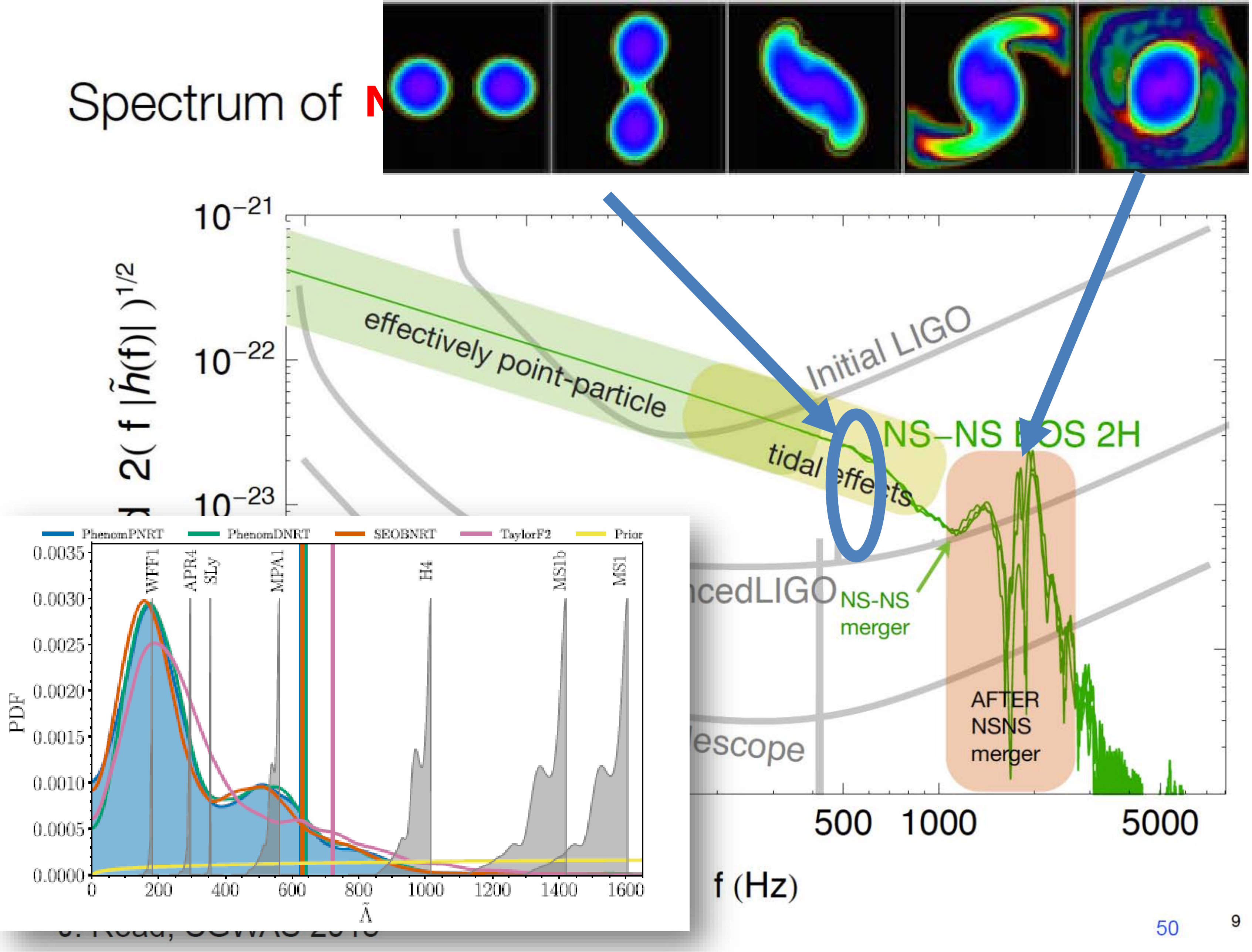
Only depends on the EoS $P(\rho)$

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



J. Read, CGWAS 2015

Spectrum of



LVC, PRX9 2019

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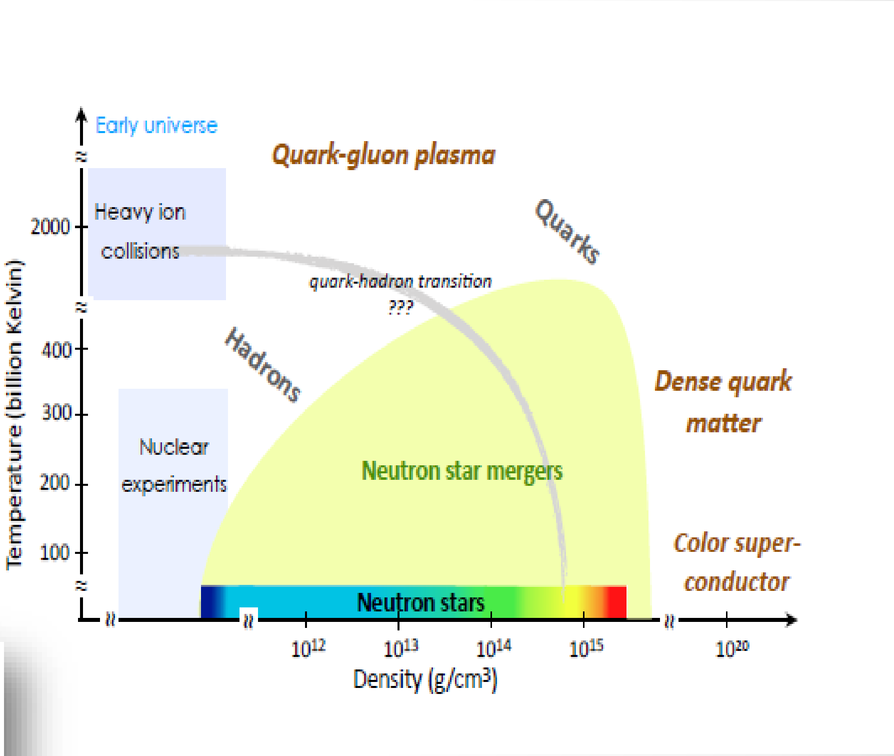
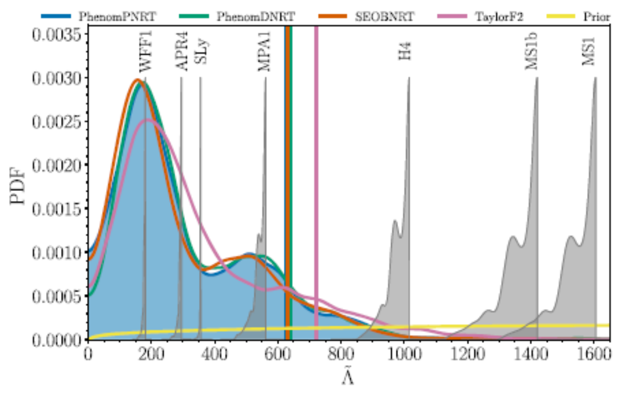
Neutron star EoS and nuclear physics

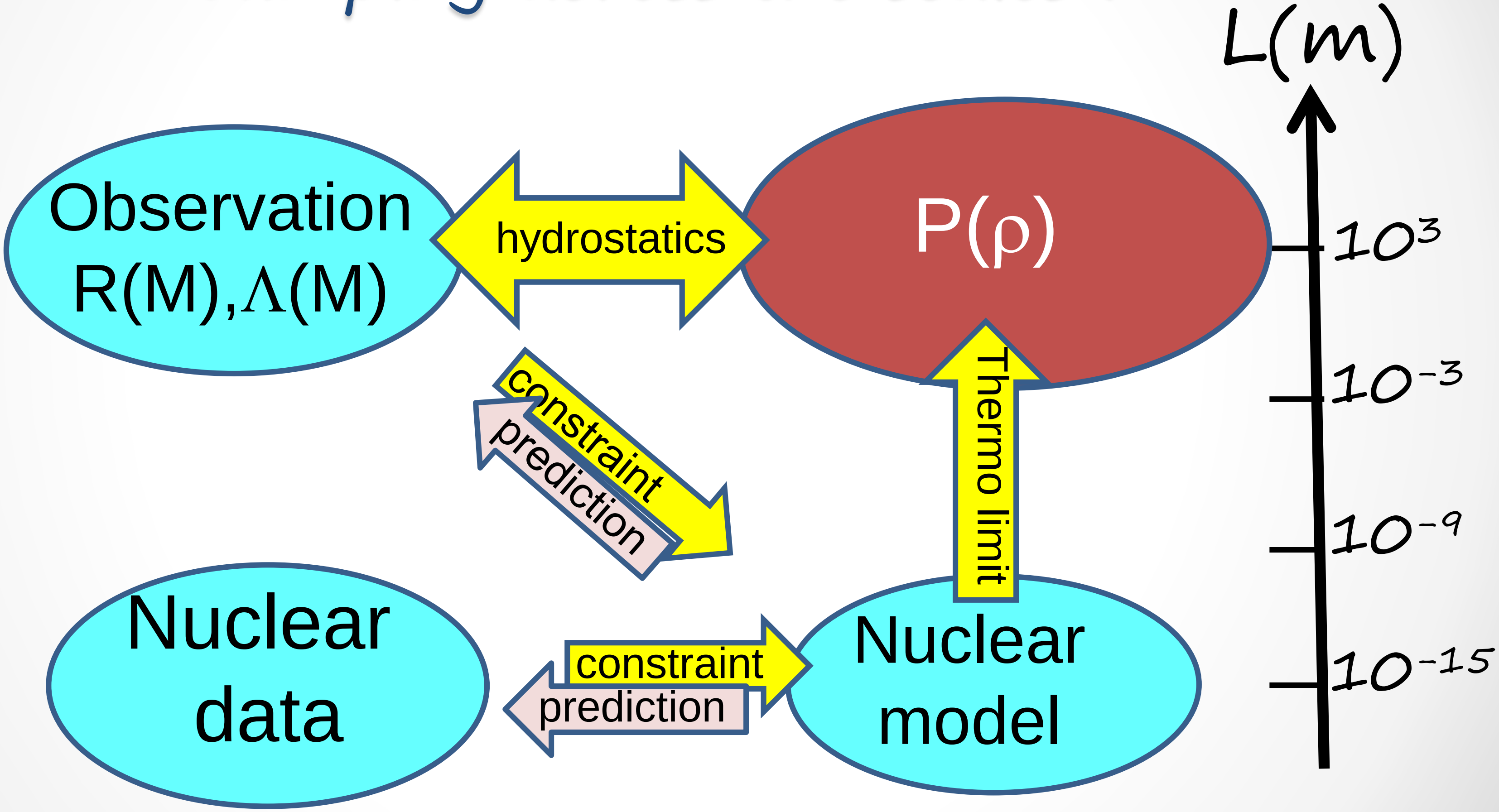
- M~1.4M$_O$, R~12 km => density as the one inside the atomic nucleus=> nuclear degrees of freedom (hadrons or quarks) in strong interaction
- The strong interaction is described by the standard model of particle physics, but no solution exists for dense matter
- Effective models of neutrons and proton





JCAP03(2020)050
Science case for the Einstein Telescope

Jumping across the scales ?



Observation $R(M), \Lambda(M)$

hydrostatics

$P(\rho)$

constraint

prediction

Thermo limit

Nuclear data

constraint

prediction

Nuclear model

Jumping across the scales: the syllabus

- An effective model of the relevant densities (neutrons and protons) gives a prediction for the EoS $P(\rho) = -\rho^2 \left.\frac{\partial e(\rho_n,\rho_p)}{\partial \rho}\right|_{\mu_L=0}$
- A flexible analytic representation $e_{\vec{X}}(\rho_n, \rho_p)$: the variation of the parameter set $\vec{X}$ allows reproducing the effective models and interpolating among them ~ 15 parameters
- The X_i variation explores the equation of state space compatible with the hypothesis of a matter of neutrons and protons

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

Laboratory observables

EoS analytic representation

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

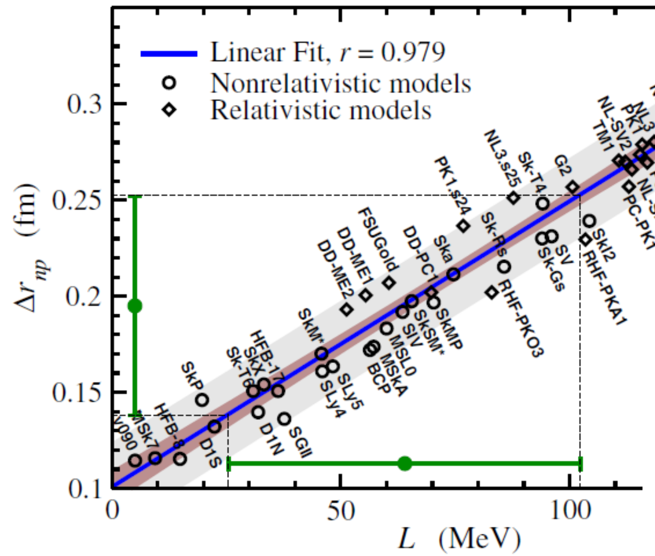
(1) Huang et al, 2016 AME mass table, Angeli&Marinova, ADNDT 2013
(2) χEFT Drischler et al PRC 2016
(3) PSR J0348+0432 M=2.01$\pm$0.04 $M_{\odot}$
(4) GW170817 $\tilde{\Lambda}(M)$ LVK
(5) PSR J0030+0451, PSR J0740+6620 NICER

Laboratory experiments

example: neutron skin of ^{208}Pb

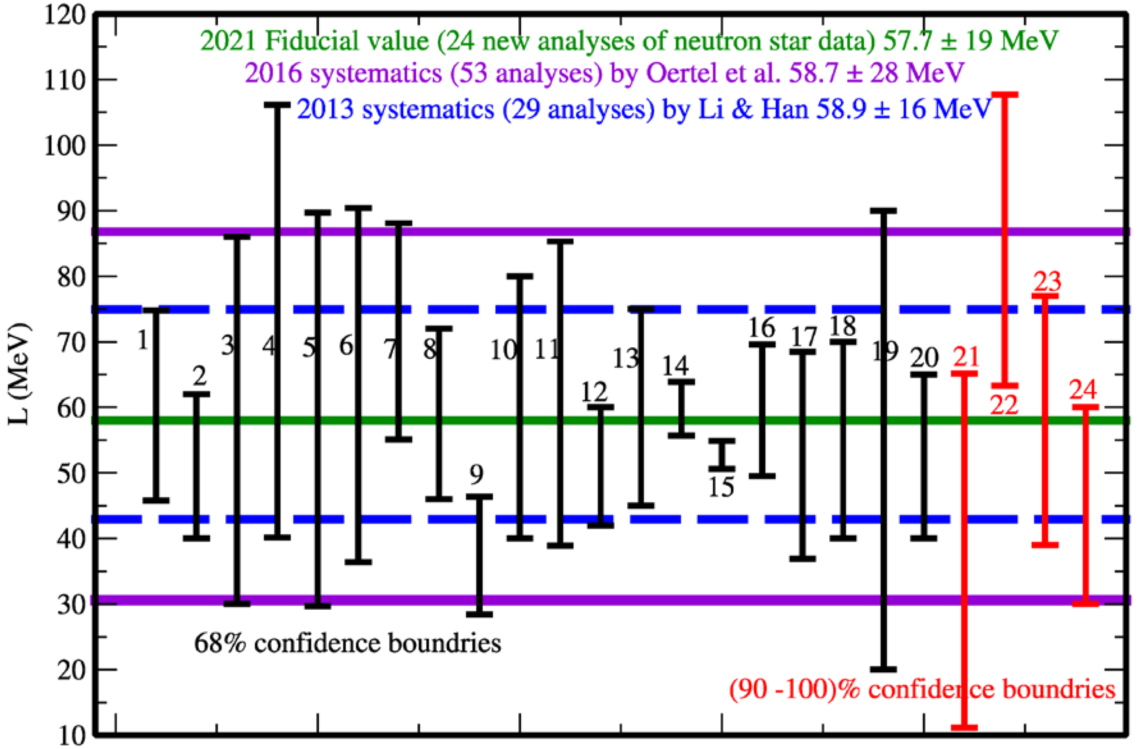
$$\vec{X} = \{E_0, K, E_{sym}, L, K_{sym}, \ldots\}$$

$$P\left(f_i = \Delta r \middle| \vec{X}\right) \propto e^{-\frac{\left(\Delta r - \Delta r(\vec{X})\right)^2}{\sigma_{\Delta r}^2}}$$



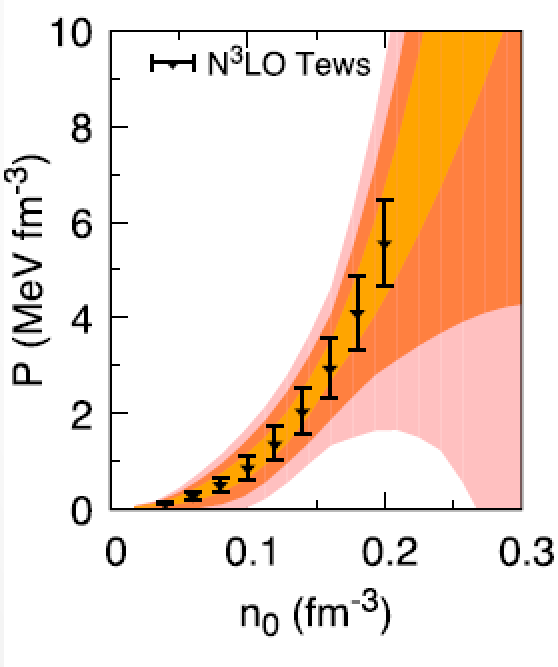
X.Roca-Maza et al PRL 2011

B.An Li et al, Universe 2021, 7(6), 182

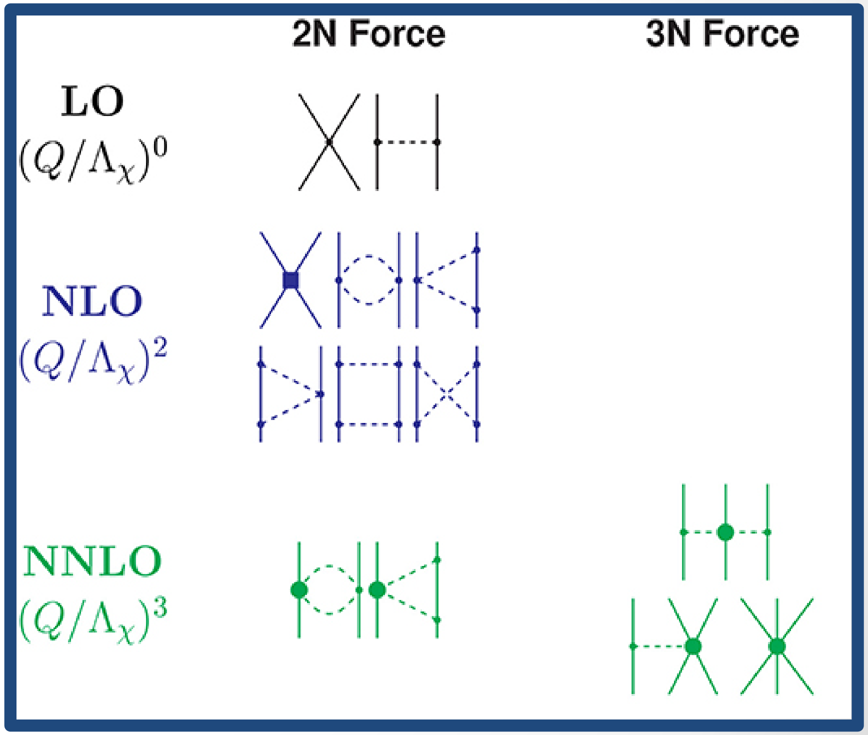


Chiral perturbation theory

- **The « ab-initio » nuclear theory**
- **Perturbative expansion : controled truncation errors**
- **Moment expansion! Only valid at low density**

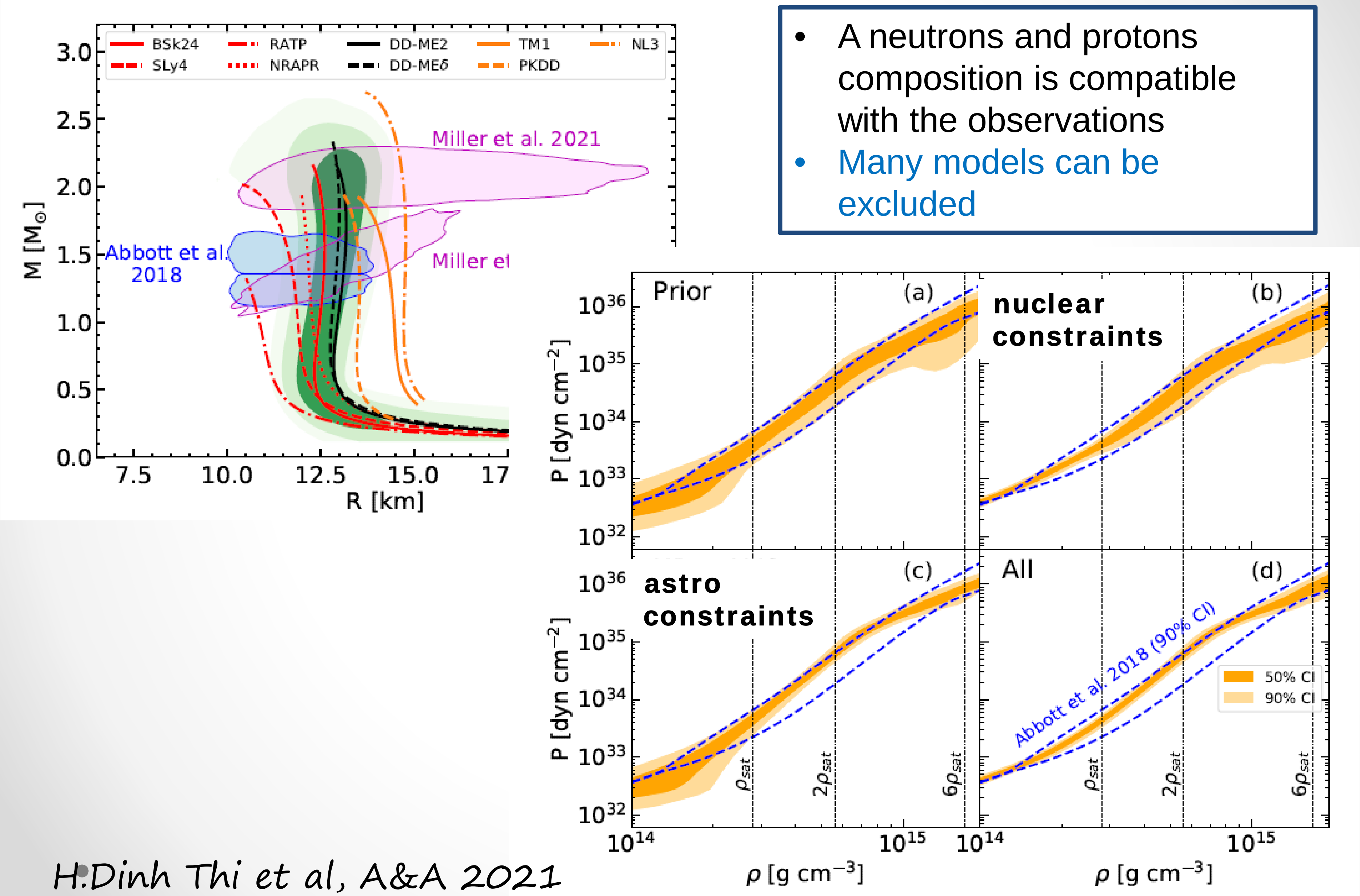


Machleidt R., Int J Mod Phys. (2017)



I. Tews, T. Krüger, K. Hebeler, and A. Schwenk, Phys. Rev. Lett. **110**, 032504 (2013).
C. Drischler, K. Hebeler, and A. Schwenk, Phys. Rev. C **93**, 054314 (2016).

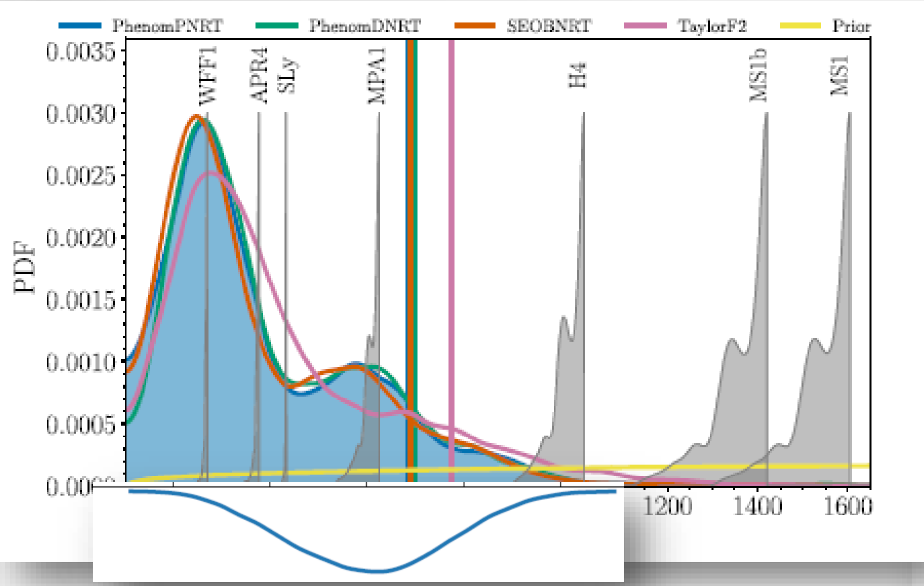
The nuclear physics predictions



- A neutrons and protons composition is compatible with the observations
- Many models can be excluded

H.Dinh Thi et al, A&A 2021

The nuclear physics predictions



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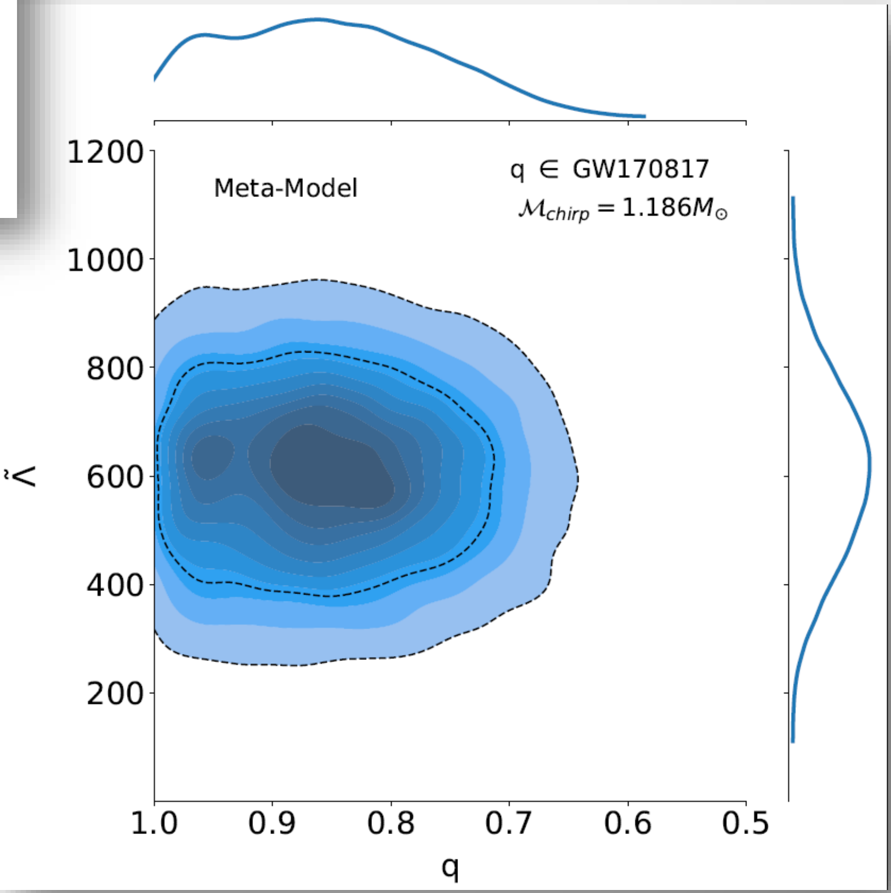

LVC, PRX9 2019
H.Dinh Thi et al, A&A 2021
And Universe **2021**, 7(10), 373

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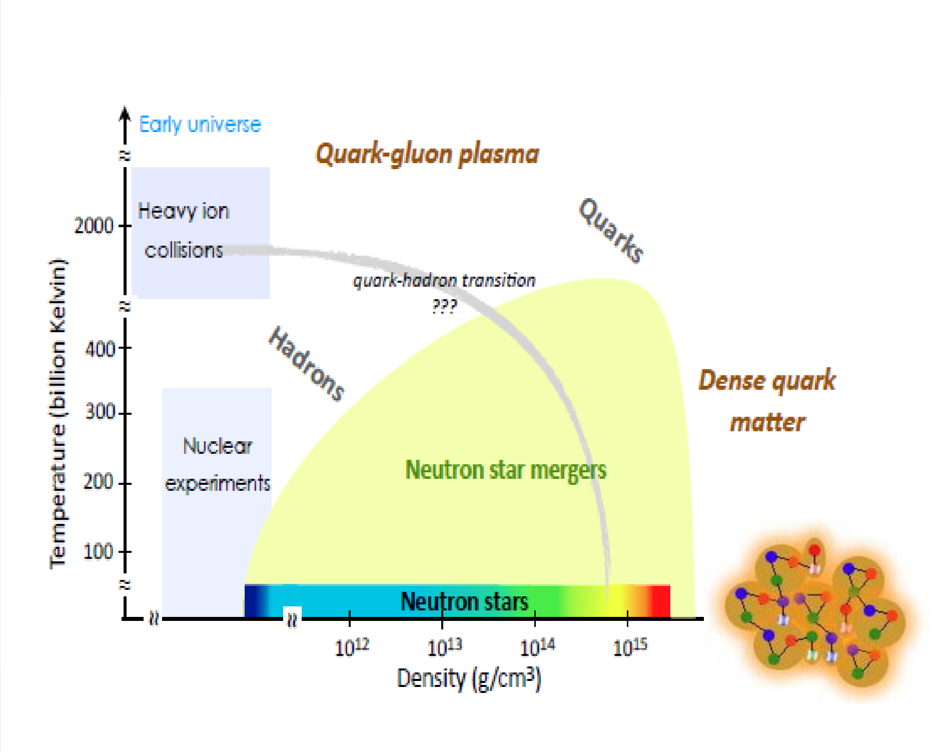
Quarks in the core of neutron stars?



JCAP03(2020)050
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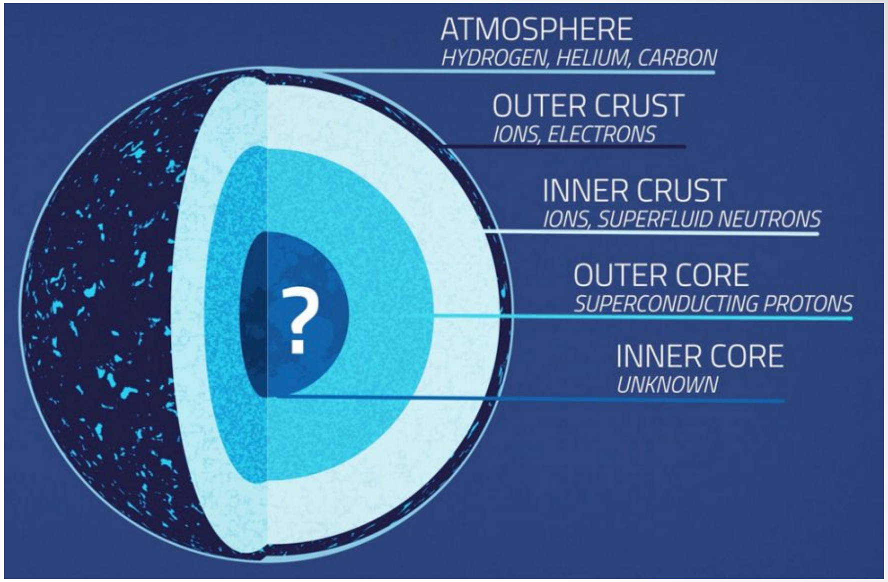
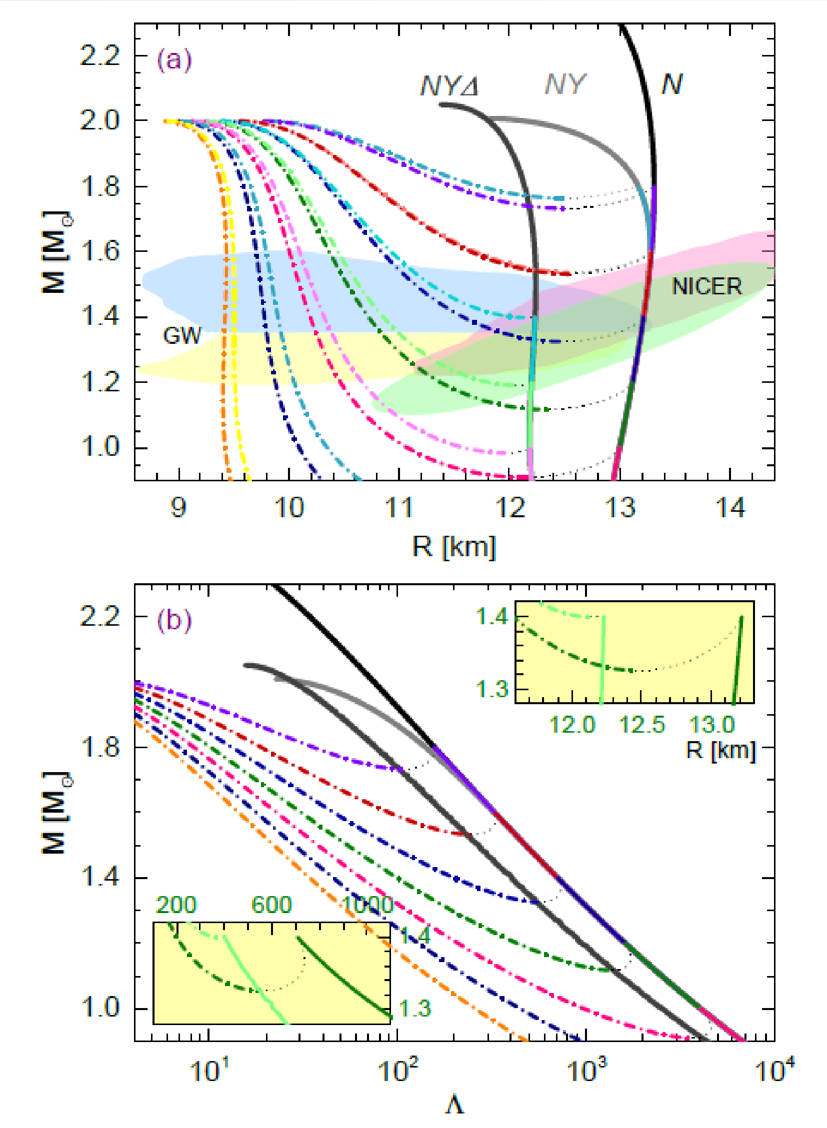


- At high density, matter could be deconfined

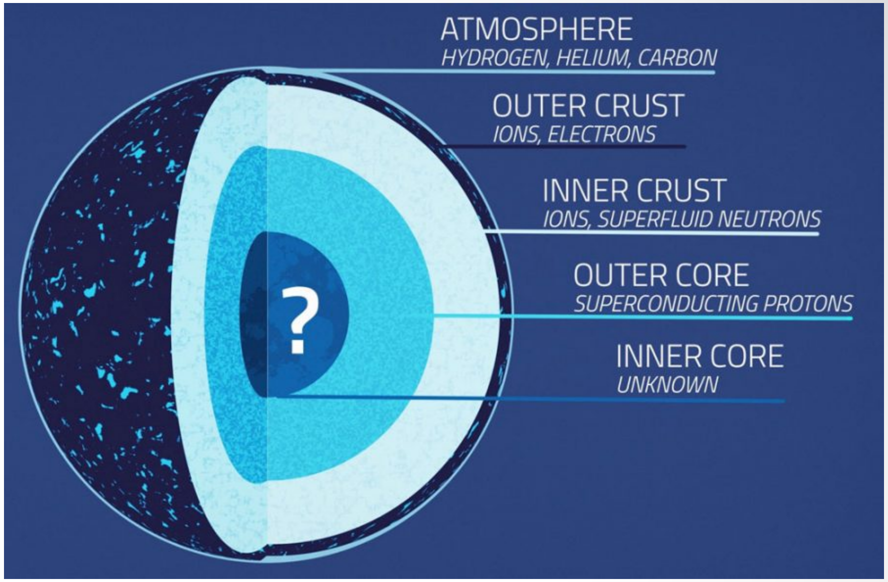
tude dans

e nulle: peut-on
se une composition
nucléonique?

Quarks in the core of neutron stars ?



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

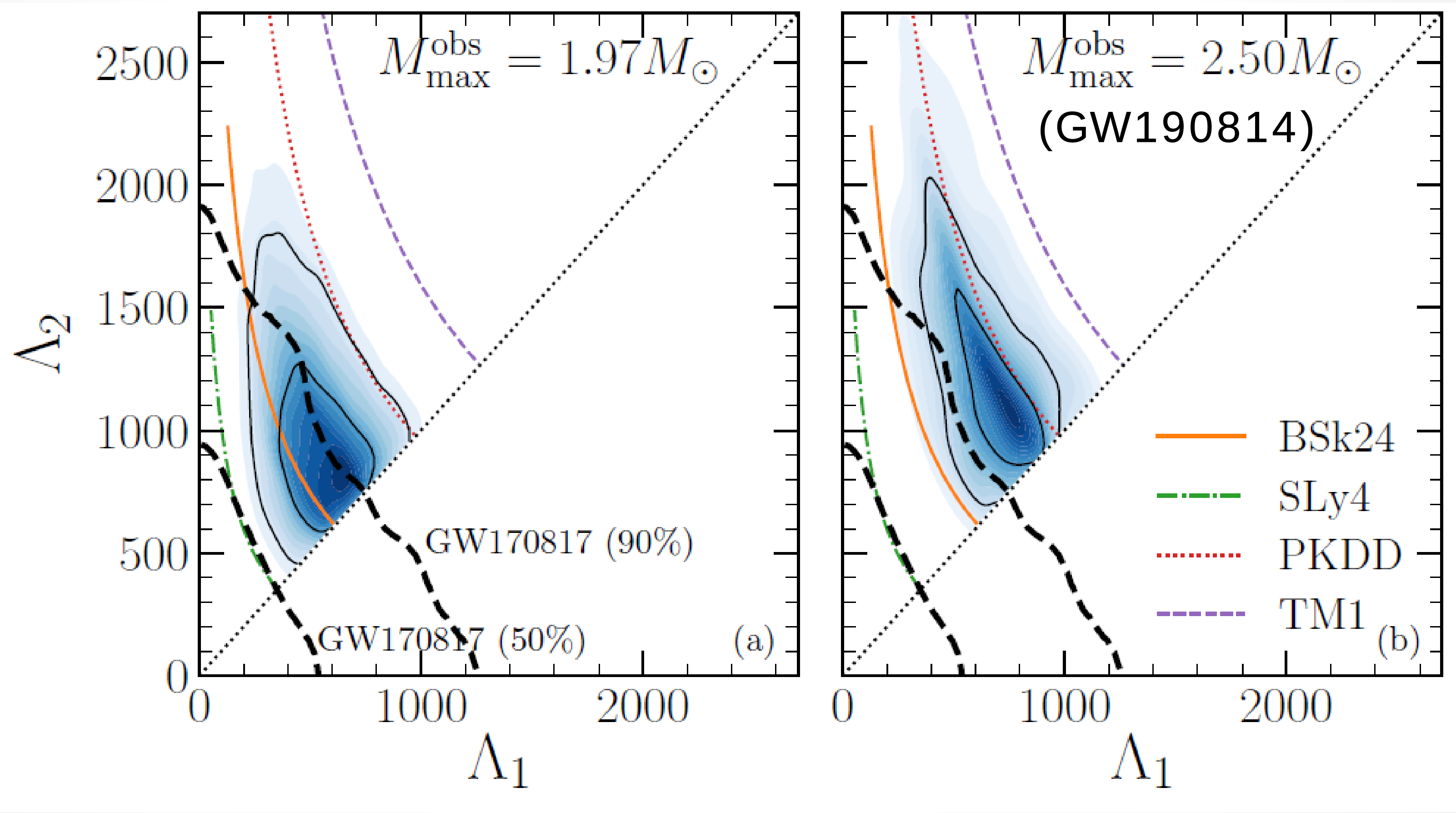


- At high density, matter could be deconfined
- Big uncertainty in the models
- Null hypothesis: can we exclude a nucleonic composition?

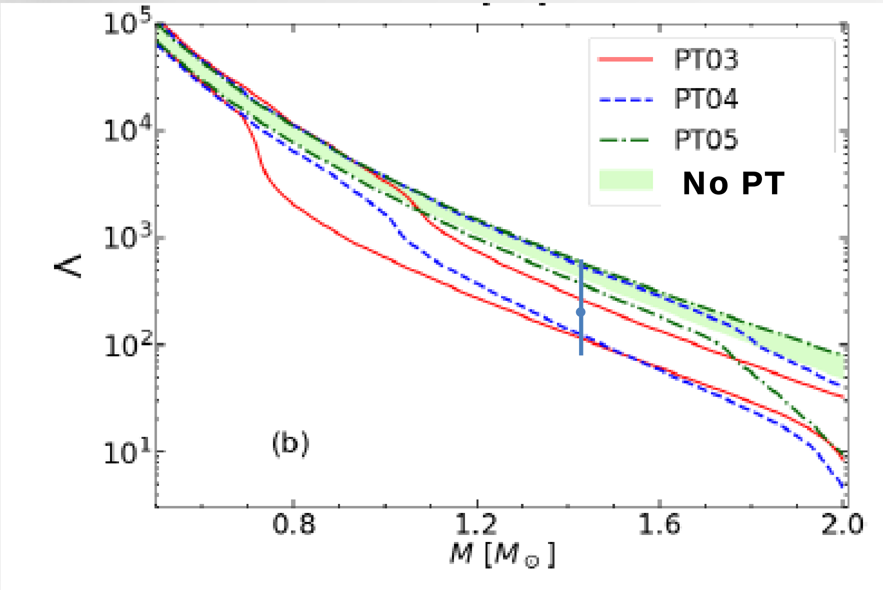
Quarks in the core of neutron stars ?

- A neutrons and protons composition is compatible with the observations
- But a great discovery potential

F.G., A.F.Fantina,NPN 2021

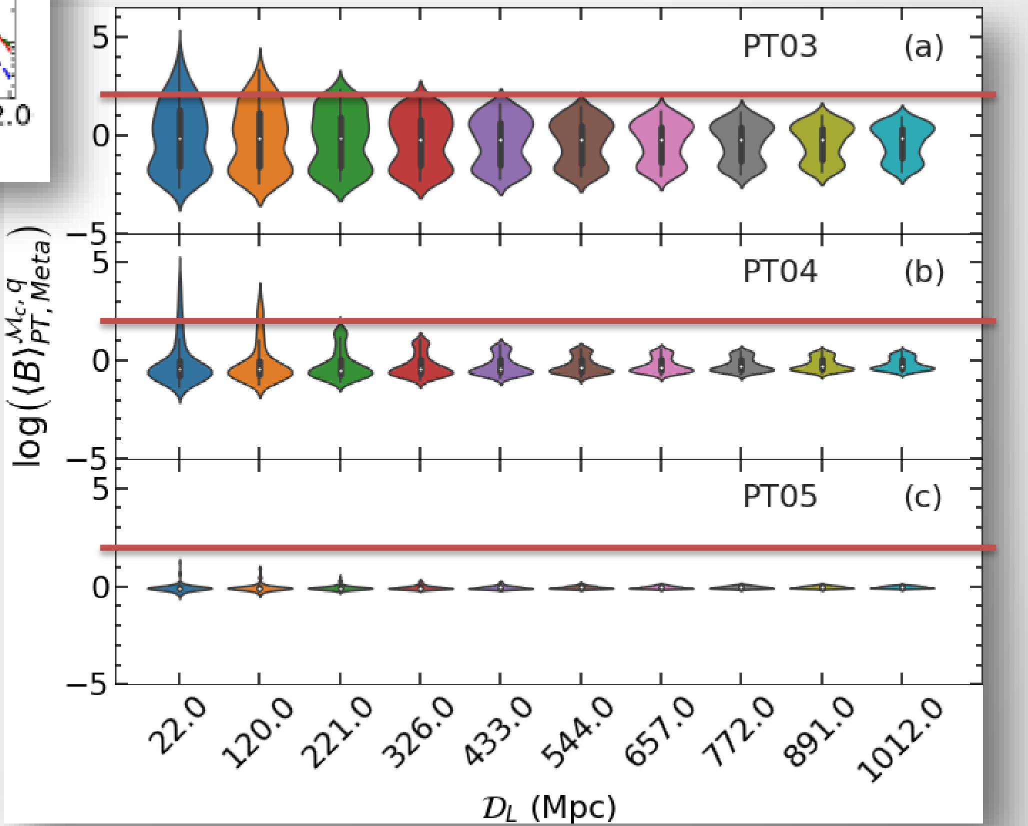


Quarks in the core of neutron stars ?

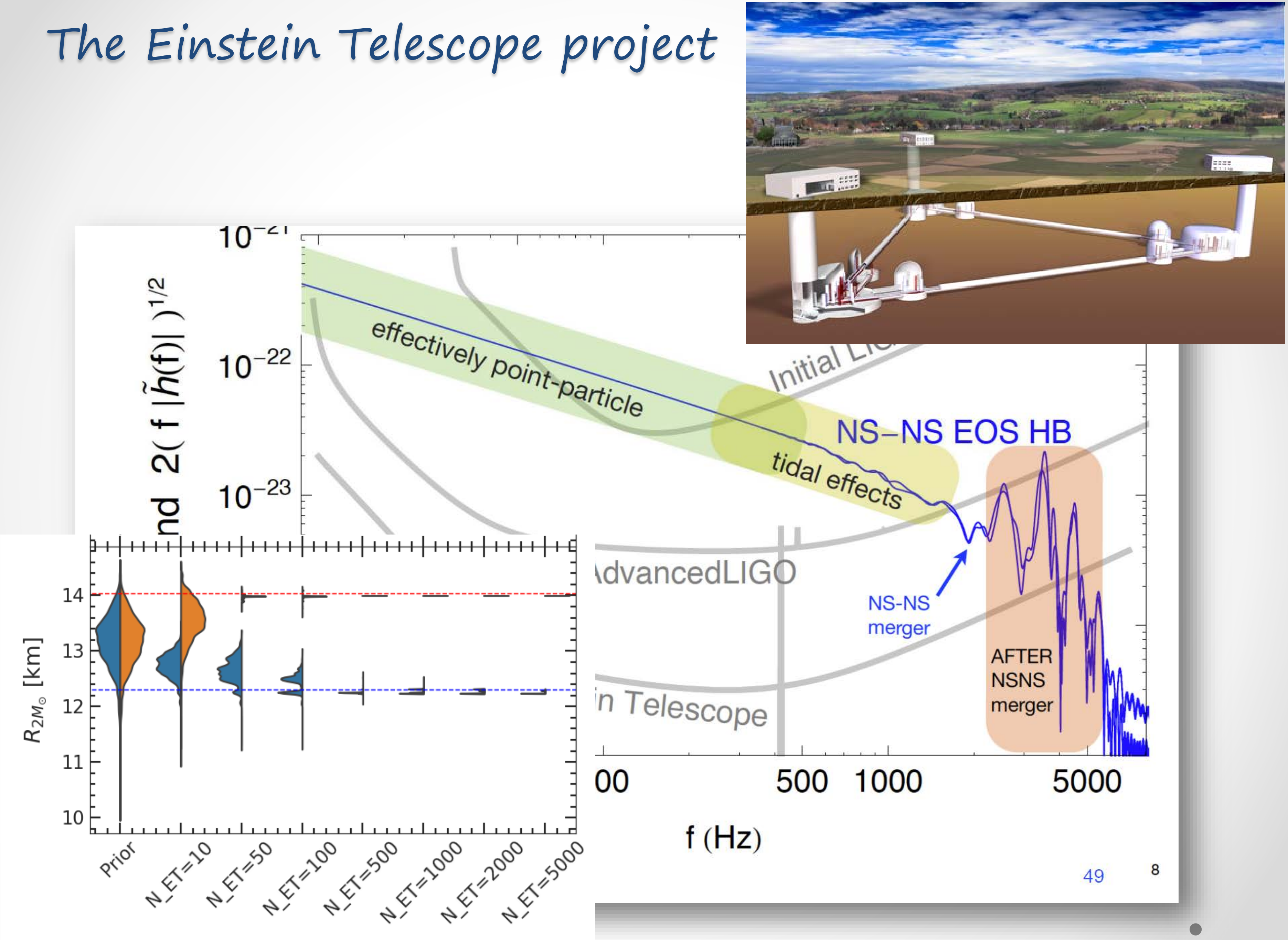


- Only a very close detection would allow identifying deconfined matter, and only if the quark core is large

- Need to reduce the uncertainties!
    - New nuclear observables =>GANIL/Spiral2, FRIB
    - Progress in theory
    - New detections with better SNR=> Einstein Telescope, Cosmic Explorer



The Einstein Telescope project



Conclusions

- Gravitational waves: a new probe to explore ultra-dense matter
- Important synergies between nuclear physics and astrophysics since the first observation of a neutron star merger GW170817
- No evidence of deconfined matter (quark-gluon plasma) in the neutron star core, but exciting discoveries ahead

Cyril FRÉSILLON / CNRS Photothèque

L'histoire de(s) découverte(s)

- **1934:** Prediction Baade&Zwicky
- **1967:** Découverte des pulsars
  Bell&Hewish (prix Nobel 1974)

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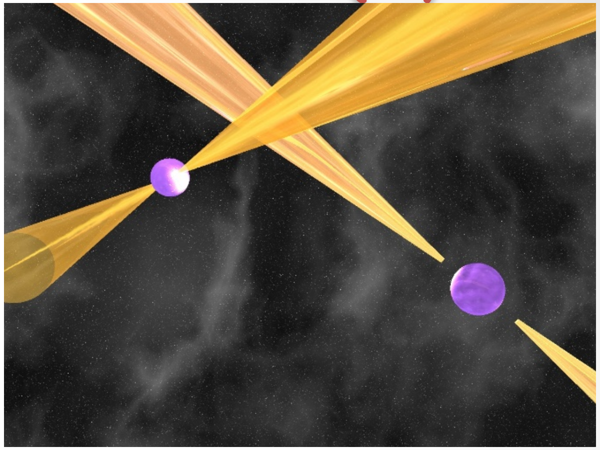

Credit: M. Kramer, Univ. Manchester

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  1993: d'ondes gravitationnelles (OG)
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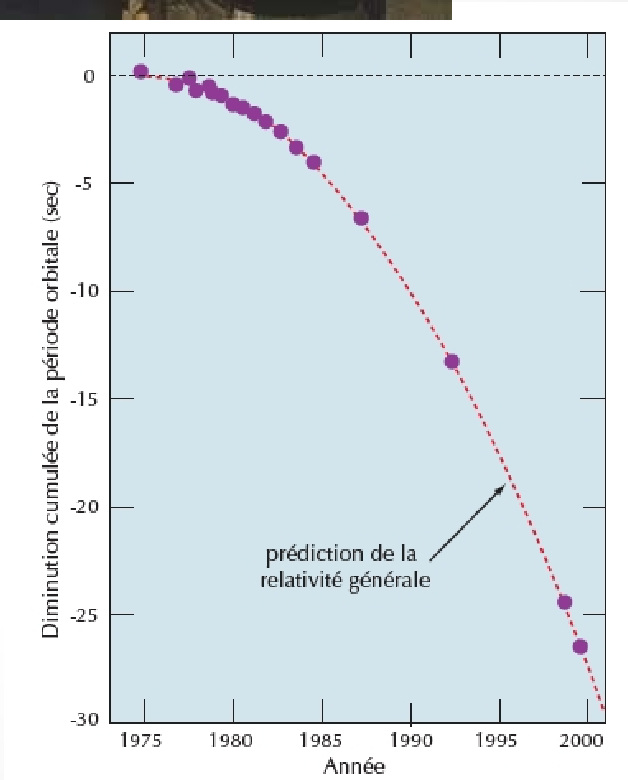

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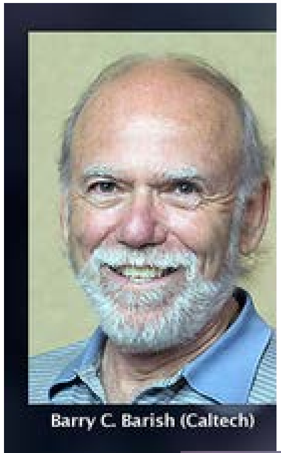
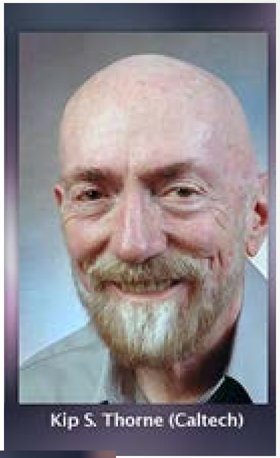
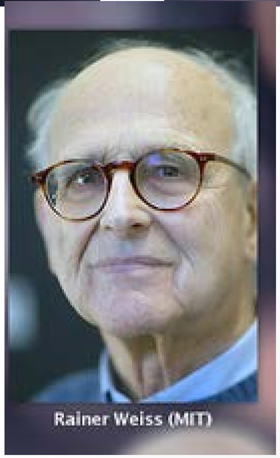
- **1974:** Première détection d’une binaire de pulsar (Hulse-Taylor)
- **1975-1993:** Mise en évidence indirecte d’ondes gravitationnelles (OG) Hulse&Taylor (prix Nobel 1994
- **2015:** Première détection d’OG d’une binaire de trous noirs (LIGO -Virgo, prix Nobel 2017)
- **2017:** Première détection d’OG d’une binaire d’étoiles à neutrons
- **2023:** Début du quatrième run d’observation LVK

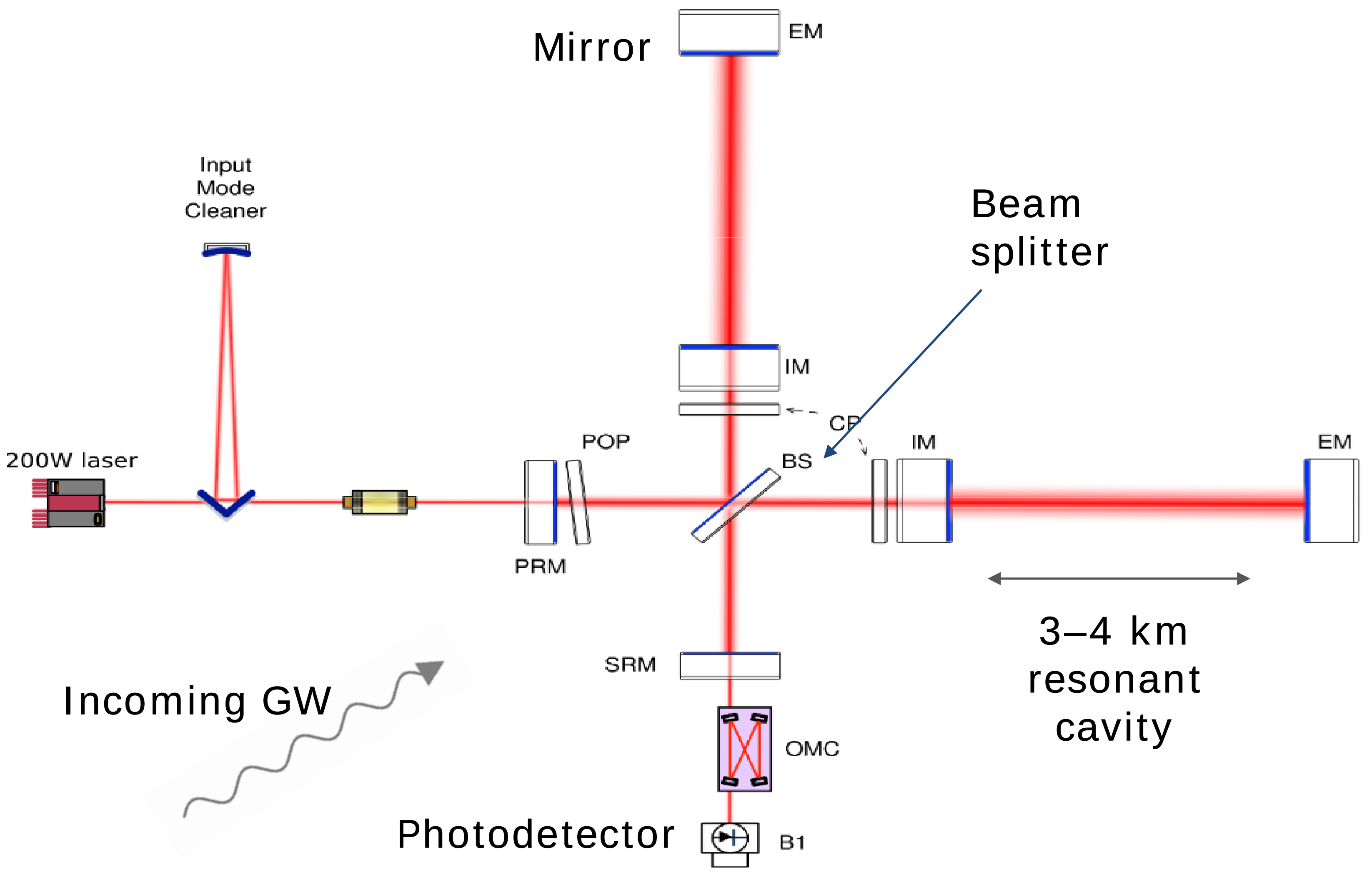

Barry C. Barish (Caltech)


Kip S. Thorne (Caltech)


Rainer Weiss (MIT)

La détection d'OG

interféromètre Michelson-Fabry-Perot



Mirror

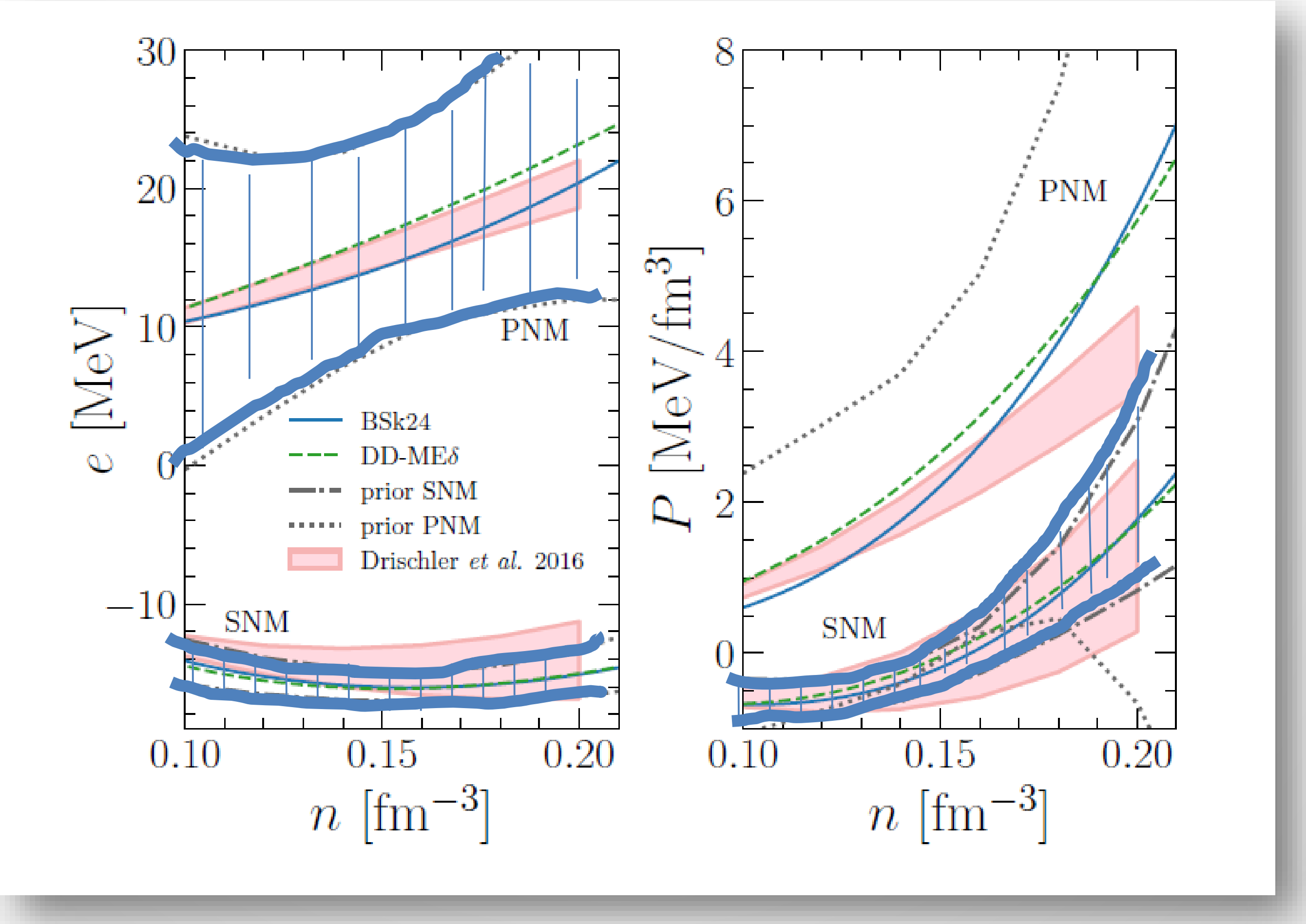
Beam splitter

3–4 km resonant cavity

Incoming GW

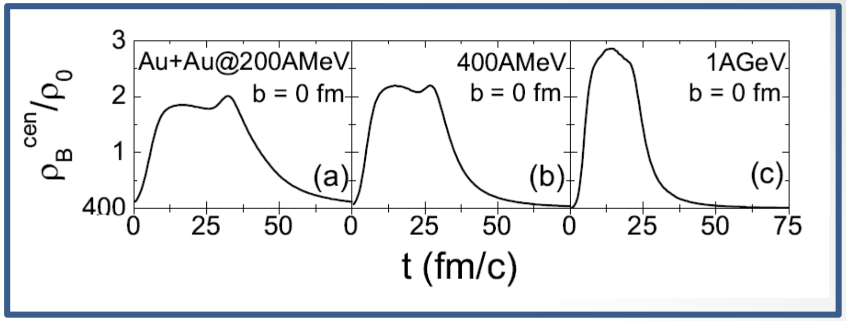
Photodetector

Contraintes expérimentales et théoriques

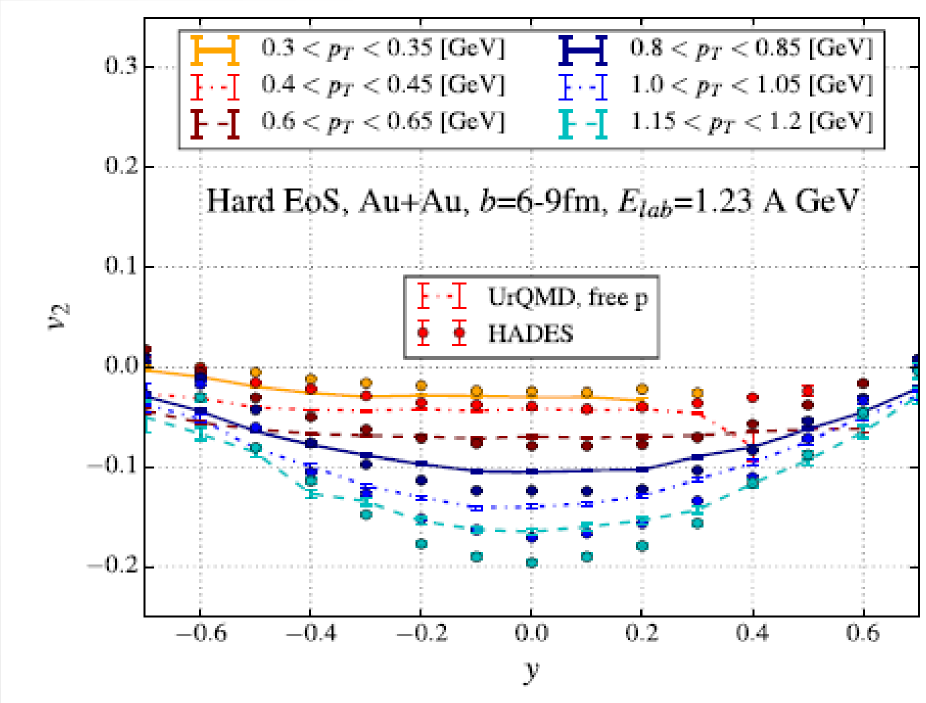


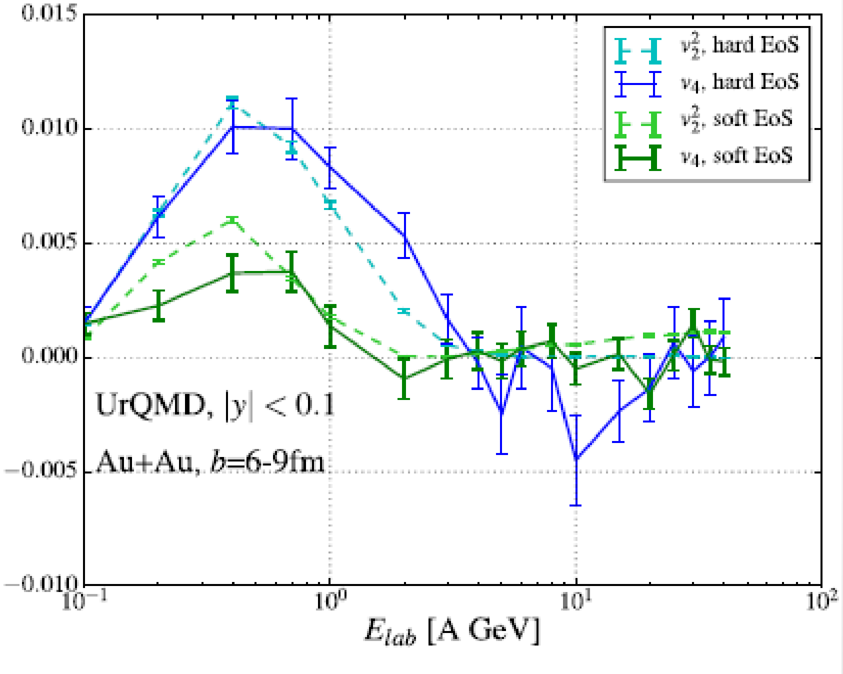
Tighter constraints from high energy experiments ?

J.Xu, PRC 2013



Elliptic flow @ HADES:
Transport model versus data





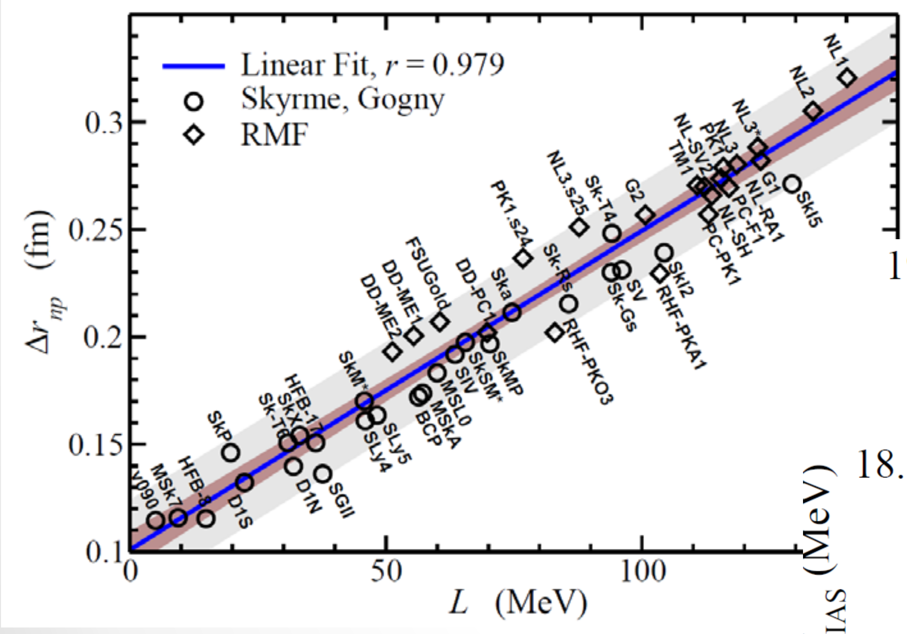
P.Hillmann et al., JPG 47 (2020) 055101

Strategy II: high precision

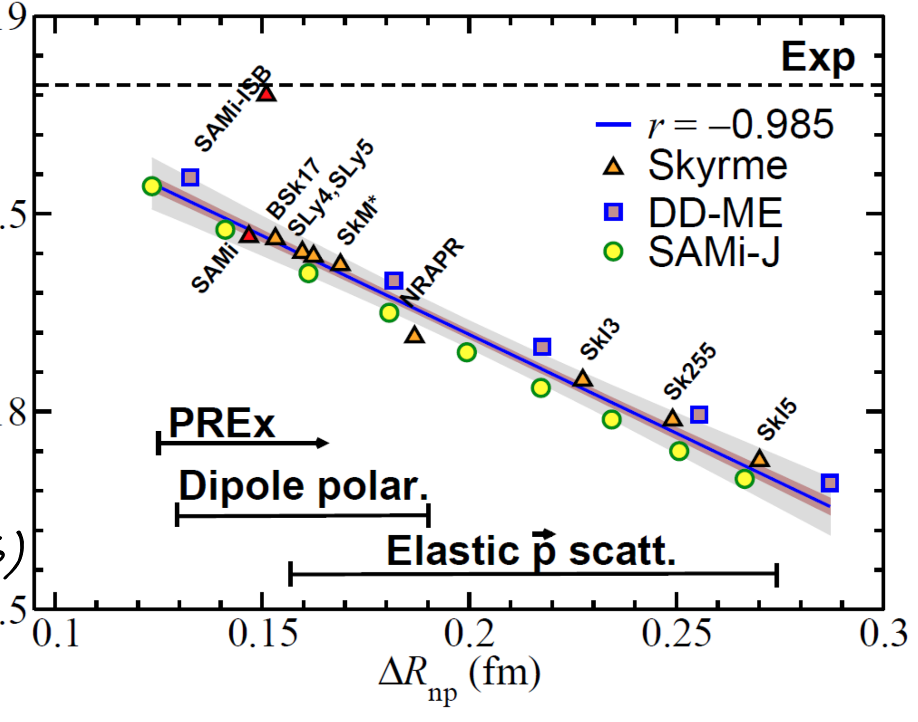
Isovector probes with stable nuclei:

- Skin
- IAS
- GDR response
- Isospin transport in HIC (INDRA/FAZIA)

Exp: Δr_{np}= 0,1318-0,3072



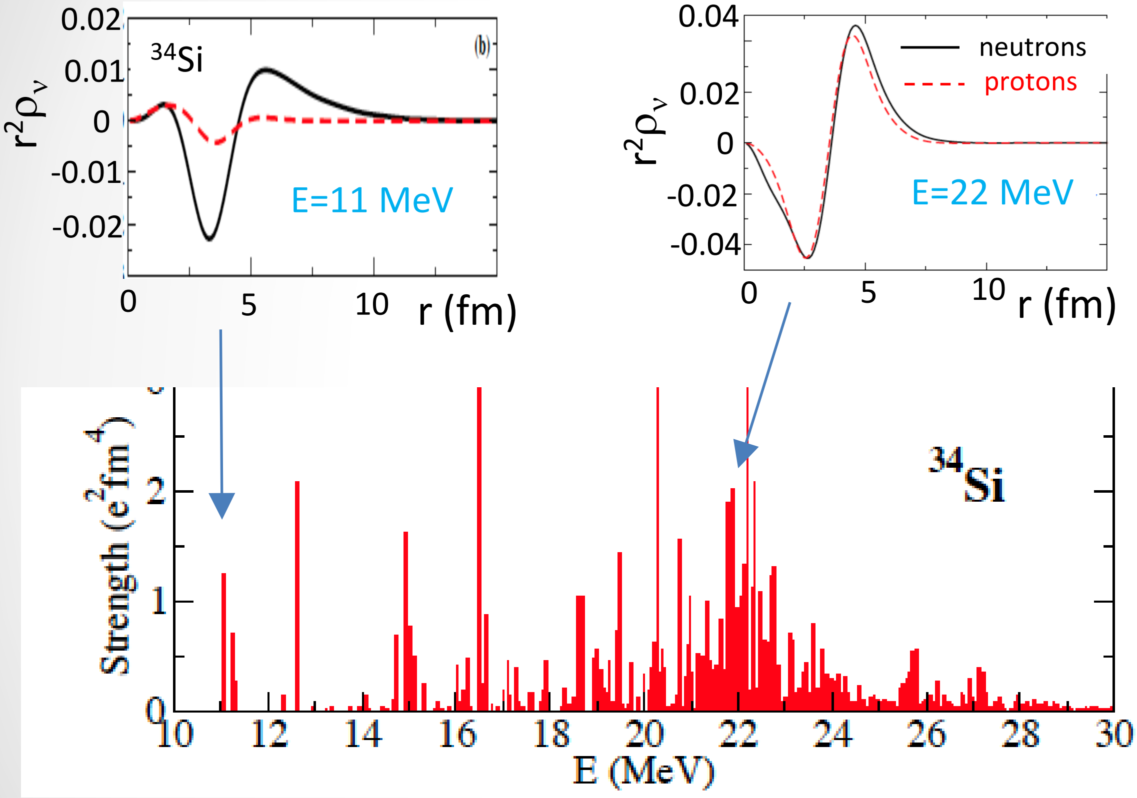
X.Roca-Maza, G.Colo, H.Sagawa (2018)



X.Vinas et al (2014)
P.G.Reinhard, W.Nazarewicz (2016)
J.Yang, J.Piekarewicz (2017)

Strategy III: new probes

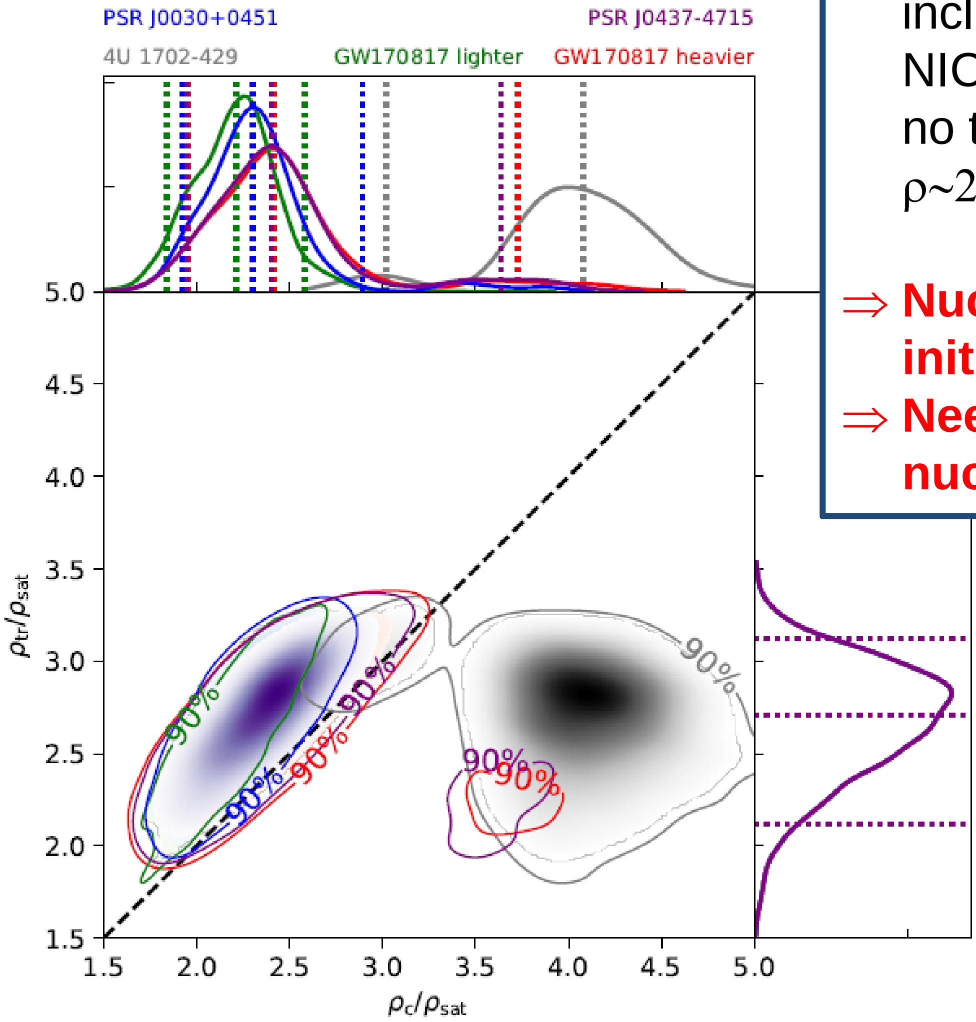
SSRPA calculations



Isoscalar probes in exotic nuclei:

- Soft monopole

D.Gambacurta, Phys. Rev. C ***100****, 014317 (2019)*



- « Reasonable » agnostic modeling of a 1st order phase transition including both LIGO/VIRGO and NICER data as constraints, predicts no transitions below densities $\rho \sim 2{,}5\rho_0$

⇒ **Nuclear physics is valid, but ab-initio modeling is not…**

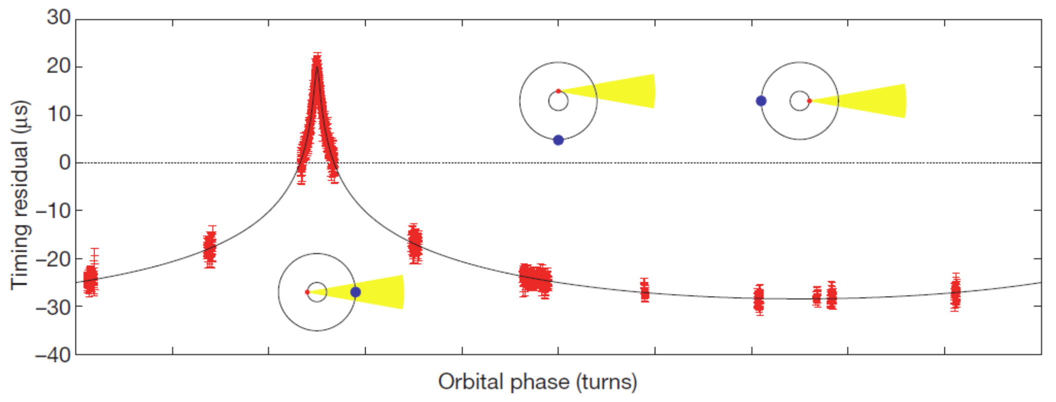
⇒ **Need of more constraining nuclear data for $\rho_0 < \rho < 2\rho_0$**

S.P.Tang et al., arXiv:2009.05719v1

Neutron Stars: today

Today: about 2000 Neutron Stars known in the Milky Way and Large Magellanic Cloud

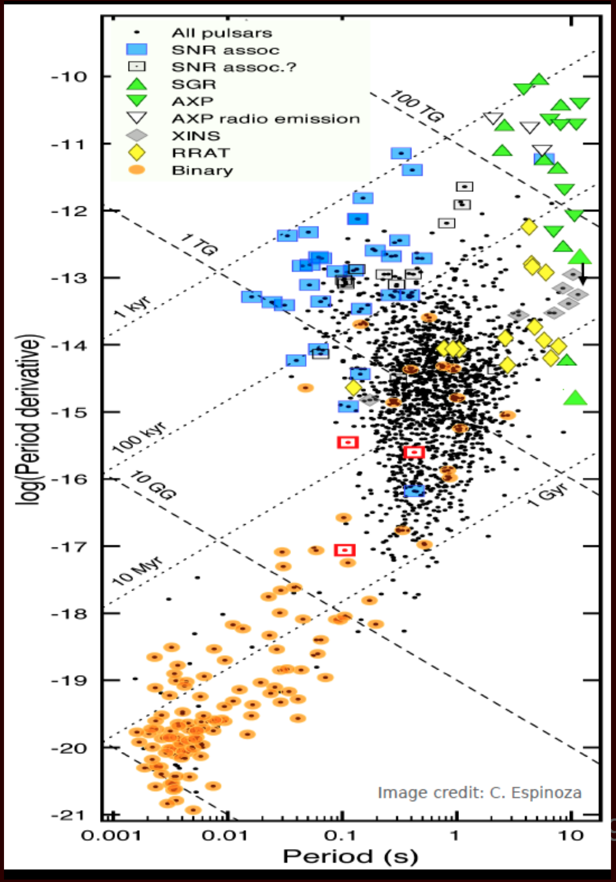
P. Demorest et al., Nature (2010)
M(PSR J1614)=1.97 +/- 0.04
J.Antoniadis et al., Science (2013).
M(PSR J0348)=2.01 +/- 0.04
H.Cromartie et al. Nature As. (2019)
M(PSR J0740)=2.14+/- 0.1



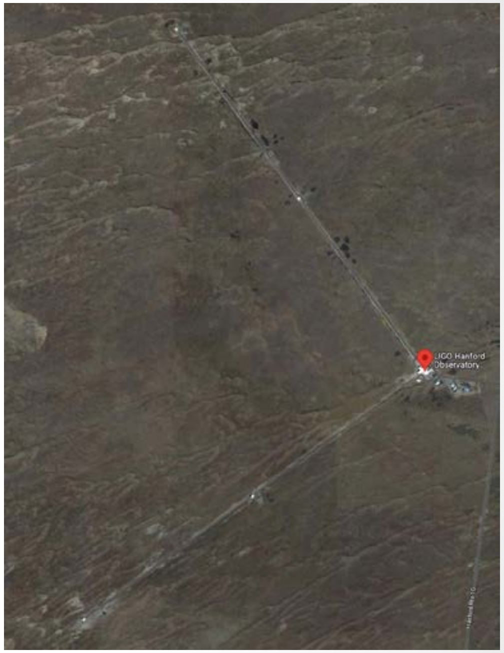
...supermassive objects: challenge for the strong interaction

N.Rea et al., ApJ (2013).
B(SGR 0418) = 6x10^{12} G

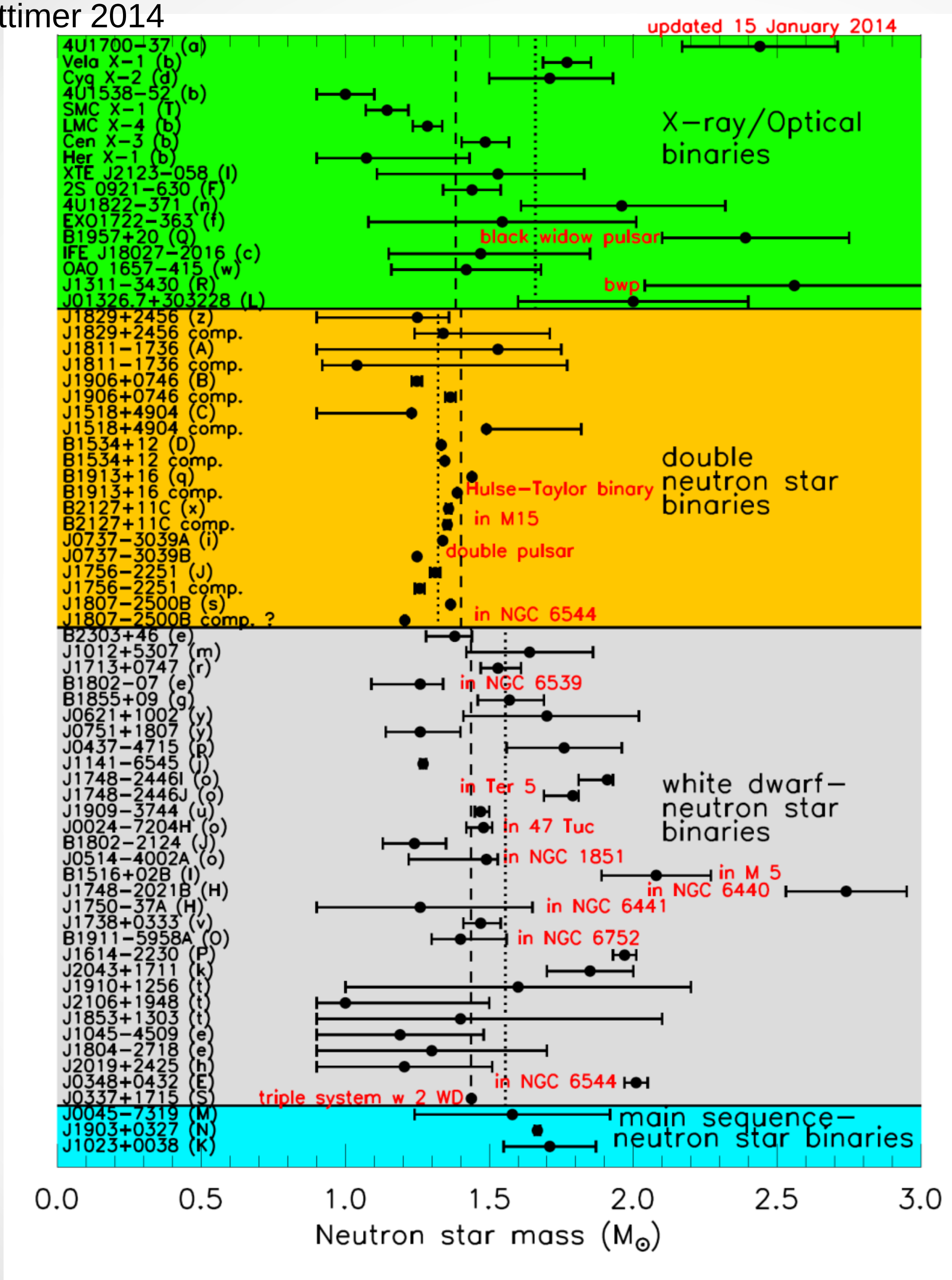
...SGR,pulsar,magnetars: unified picture

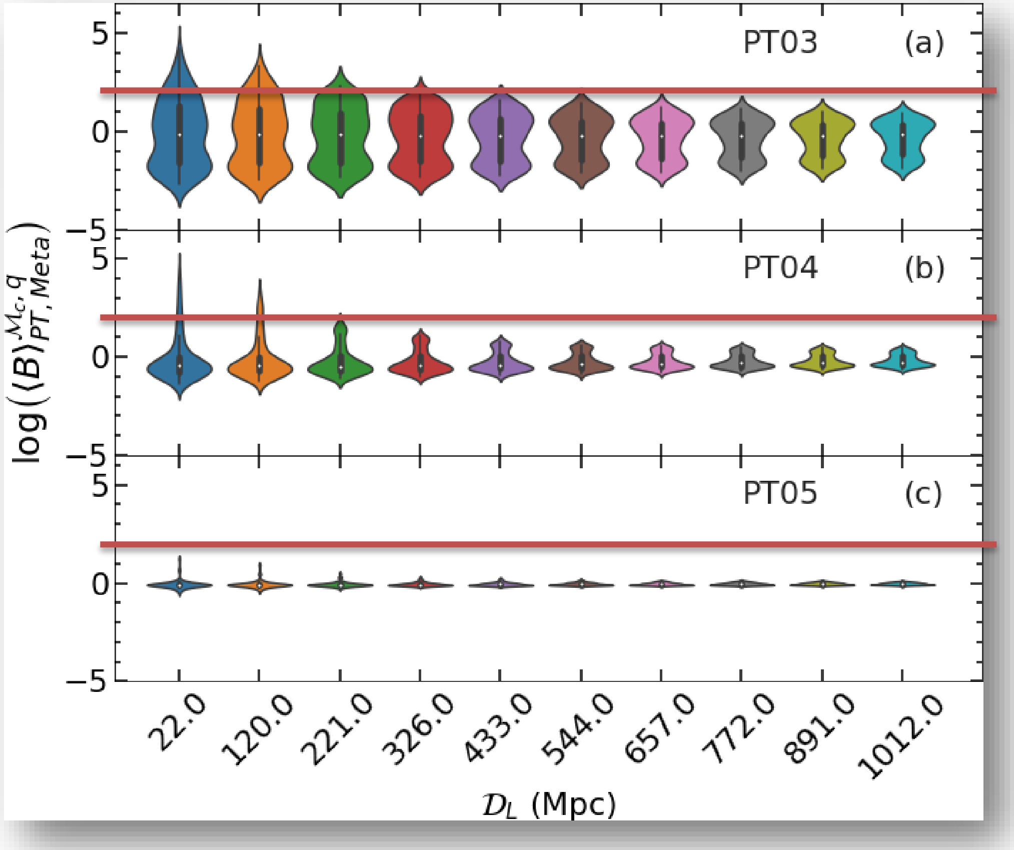


GW detectors: the present network



Jim Lattimer 2014

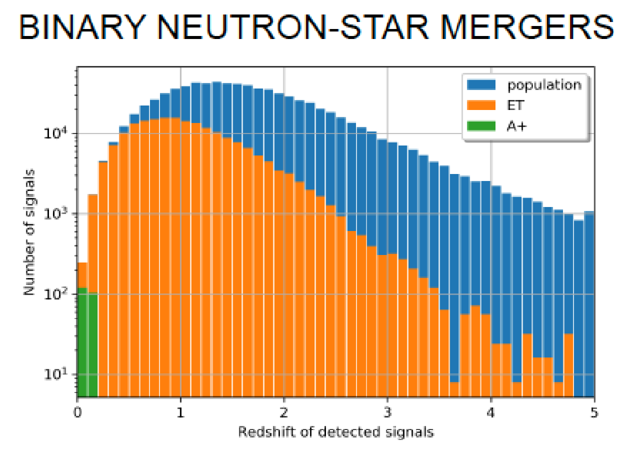


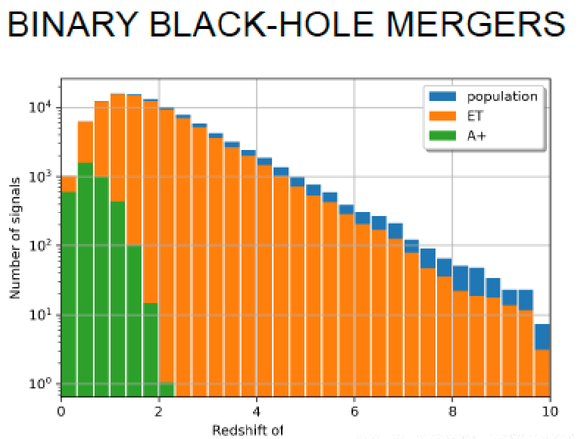


$$log\left(\langle B\rangle^{\mathcal{M}_0,q_0}_{PT,nucl}\right) = \int d\tilde{\Lambda}\, P_0^{GW}(\tilde{\Lambda}) log\left[\frac{P_0^{n_t}(\tilde{\Lambda})}{P_0^{nucl}(\tilde{\Lambda})}\right]$$

=> High detectability potential of a density jump with G3 detectors for an EARLY phase transition

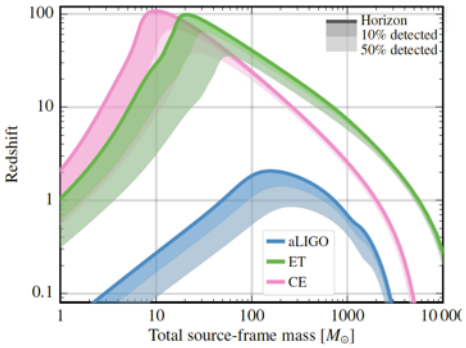
ET sensitivity

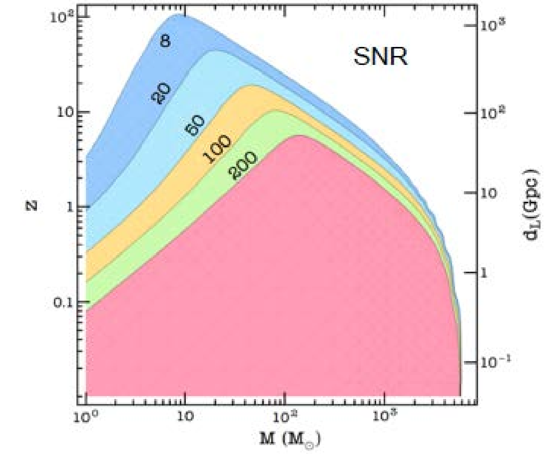

BINARY NEUTRON-STAR MERGERS


BINARY BLACK-HOLE MERGERS

- 10^5-10^6 BBH detections per year
- 10^4-10^5 BNS detections per year among which ~10-100 with EM counterparts
- High SNR events
- Overlapping events

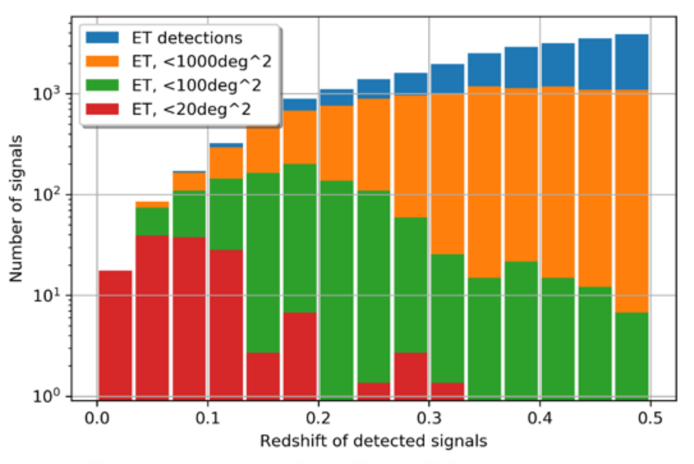
~1 detection every 30s



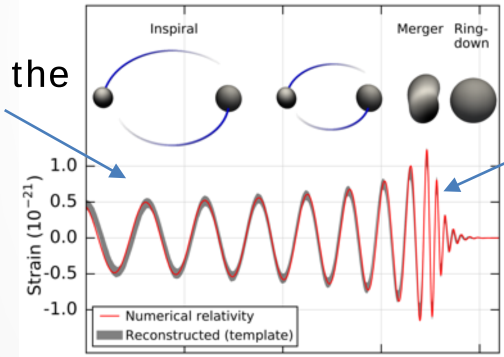


ET sensitivity

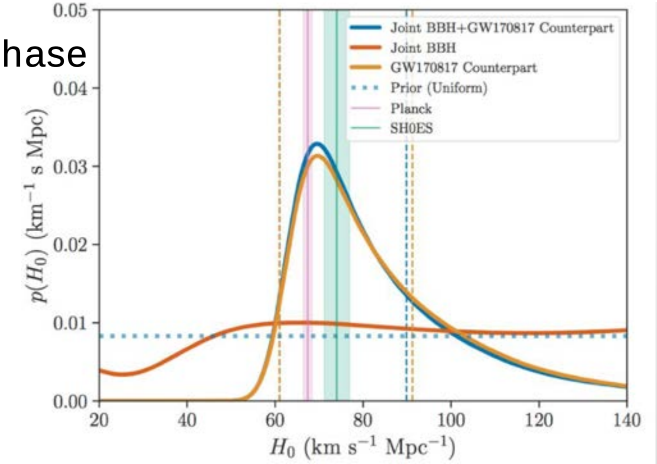
- **BNS detection with EM counterparts and localization precision < 20 deg^2** : o(10-100) per year
- Overlap with many BBH signals
- Potentially, very long signals
- ET will be able to provide alerts few hours before the merger



Identify early the inspiral ...



... and provide alert before the merger phase



- And with ~500 BNS-EM detection, we can reach Planck resolution on H_0 measurement