Probing the equation of state of dense matter with neutron stars

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Objets compacts et nouvelle physique,
Paris (France), 28-29 June 2022

Outline

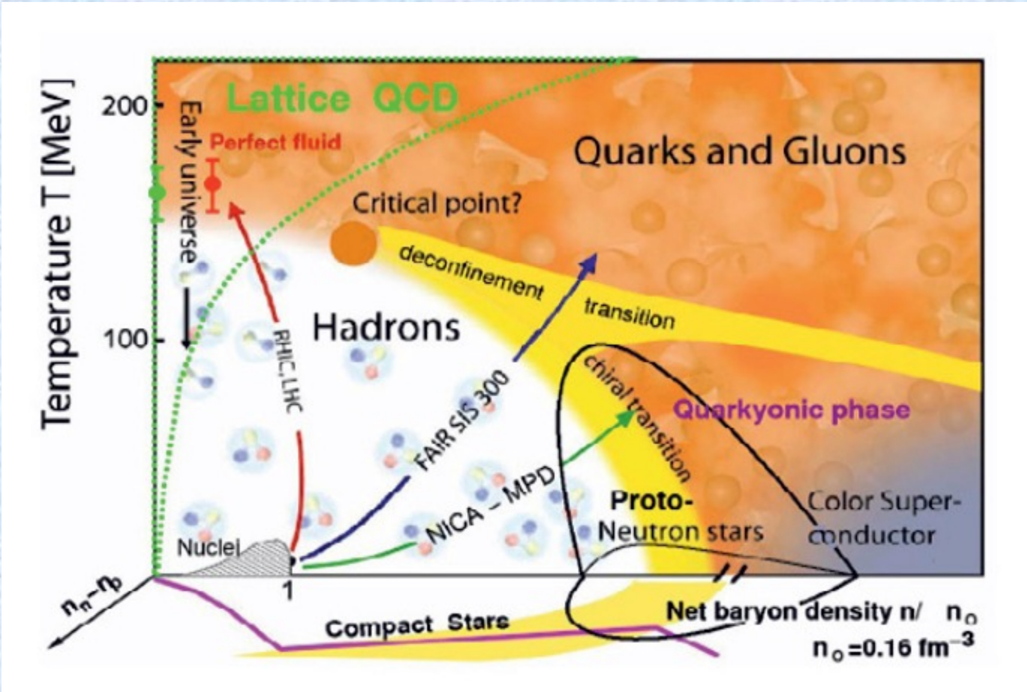
- Introduction
  - Microscopic to macroscopic modelling
- Equation-of-state (EoS) modelling
  - Approaches to the EoS
  - EoS and neutron-star (NS) properties
  - What do we know on the EoS ?

    → Constraints from nuclear physics (and astrophysics)
- Conclusions

N.B.: In this talk, $T = 0$ and beta-equilibrium matter

→ OK for mature NSs and for inspiral phase in NS mergers

Probing extreme conditions in NSs



Kekelidze et al., EPJ Web of Conf. 70, 00084 (2014)

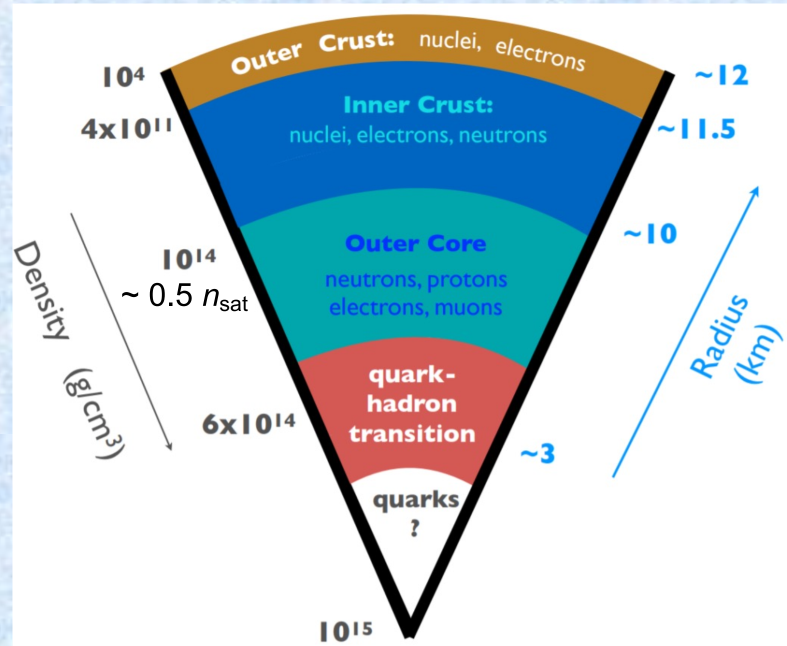


Image Credit: 3G Science White Paper

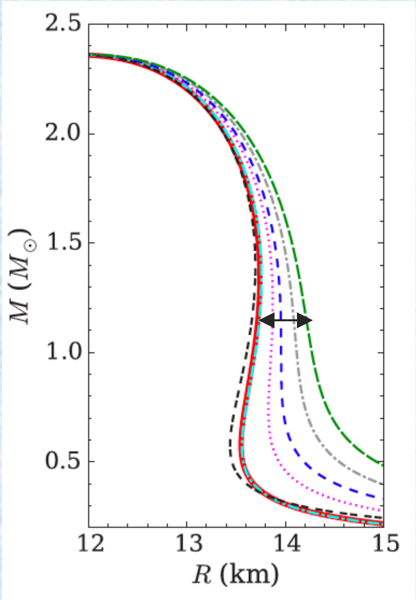
different states of matter spanned in NSs !
→ inhomogeneous, homogeneous, “exotic” particles (?)
+ superfluidity, magnetic field, etc.

→ not all conditions can be probed in terrestrial labs → theoretical models !

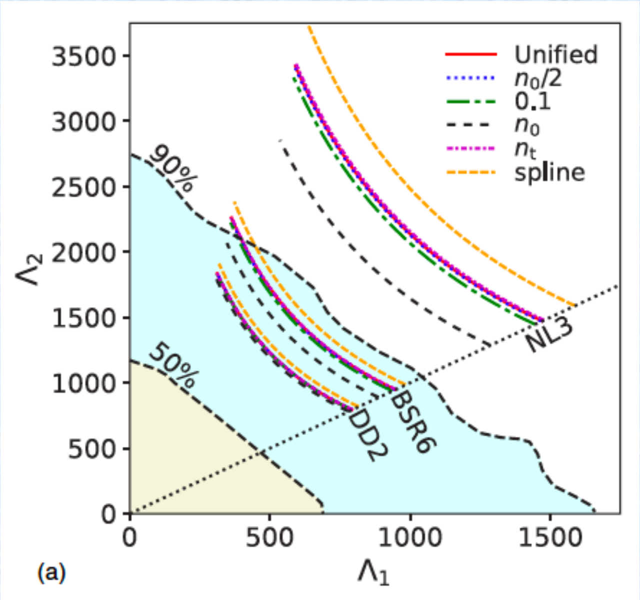
Why a <u>unified</u> treatment ?

Unified treatment of finite nuclei & infinite matter
→ same nuclear model employed in different regions of star

- Challenging because of wide range of density, isospin asymmetry (and temperature)
- Challenging because different states of matter (cluster, “pasta”, homogeneous matter)
- But: <u>essential to avoid spurious non-physical effects in numerical modelling</u>

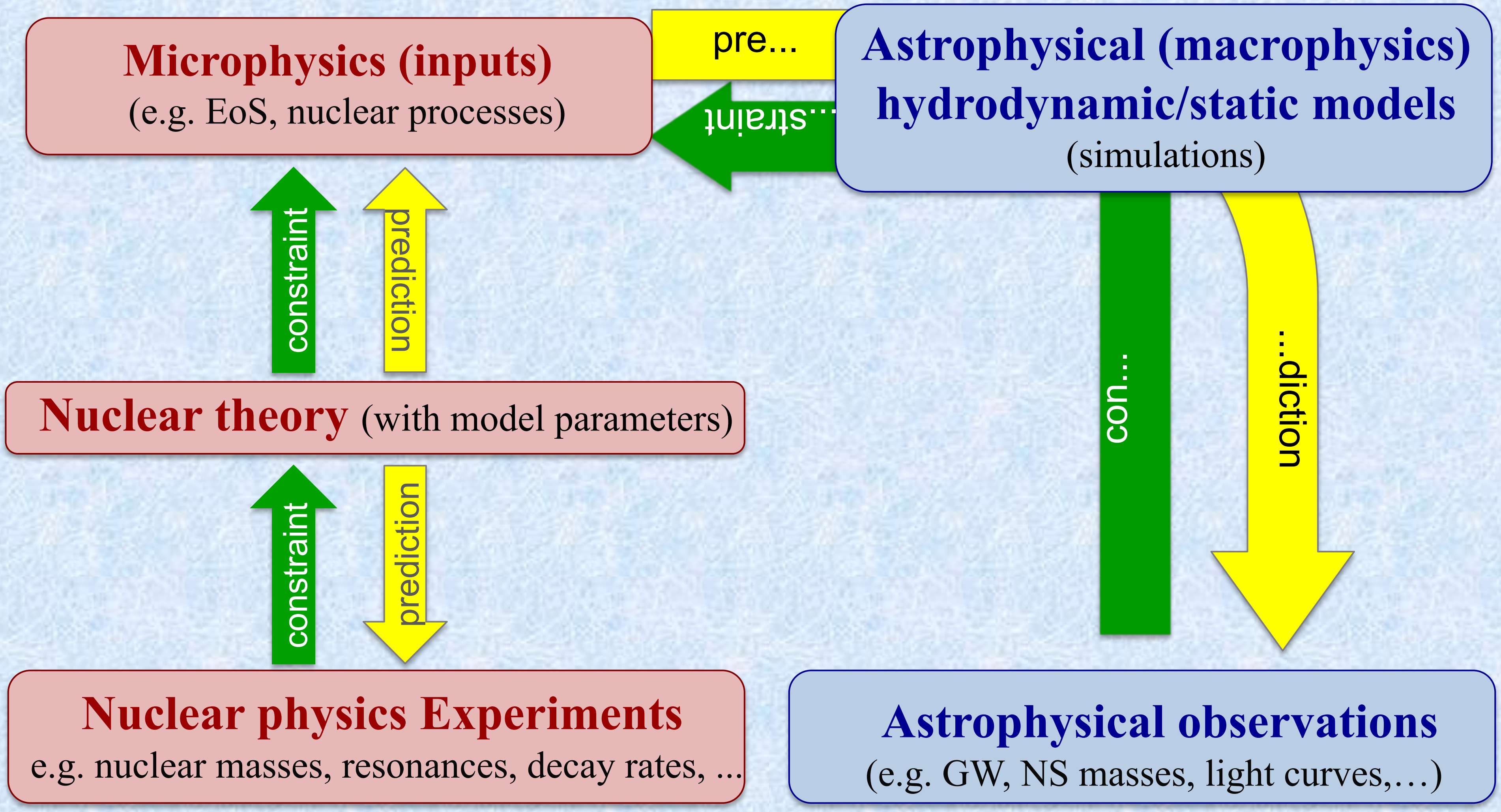


Fortin et al., PRC 94, 035804 (2016)



Suleiman et al., PRC 104, 015801 (2021)

Micro to macro through modelling



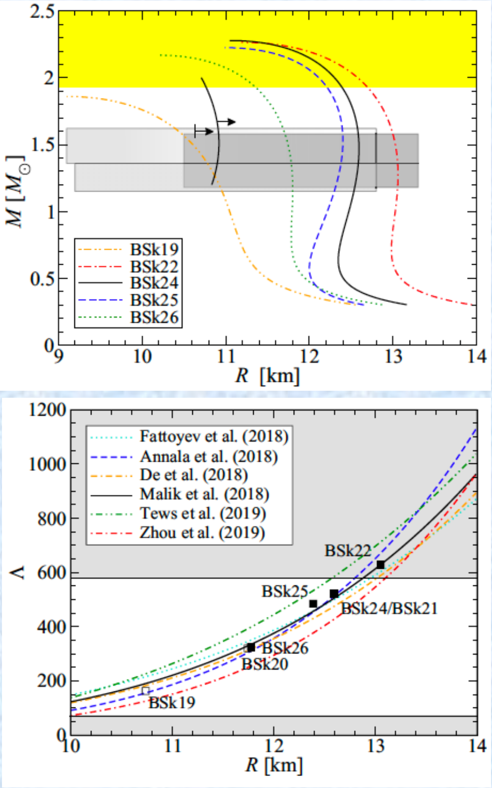
EoS ←→ NS (static) observables

- **TOV → *M*(*R*)**

$$\frac{\mathrm{d}P(r)}{\mathrm{d}r} = -\frac{G\rho(r)\mathcal{M}(r)}{r^2}\left[1+\frac{P(r)}{c^2\rho(r)}\right] \times\left[1+\frac{4\pi P(r)r^3}{c^2\mathcal{M}(r)}\right]\left[1-\frac{2G\mathcal{M}(r)}{c^2 r}\right]^{-1}$$

$$\mathcal{M}(r) = 4\pi\int_0^r \rho(r')r'^2\mathrm{d}r'$$

+ EoS $P(\rho)$ →



Perot et al., PRC 100, 035801 (2019)

- **+ eq. for *y*(*r*) → Λ(*M*), Λ(*R*)**

$$r\frac{dy}{dr}+y(r)^2+F(r)y(r)+Q(r)=0$$

→ Love number k_2 → $\Lambda = \frac{2}{3}k_2\left[\frac{Rc^2}{GM}\right]^5$

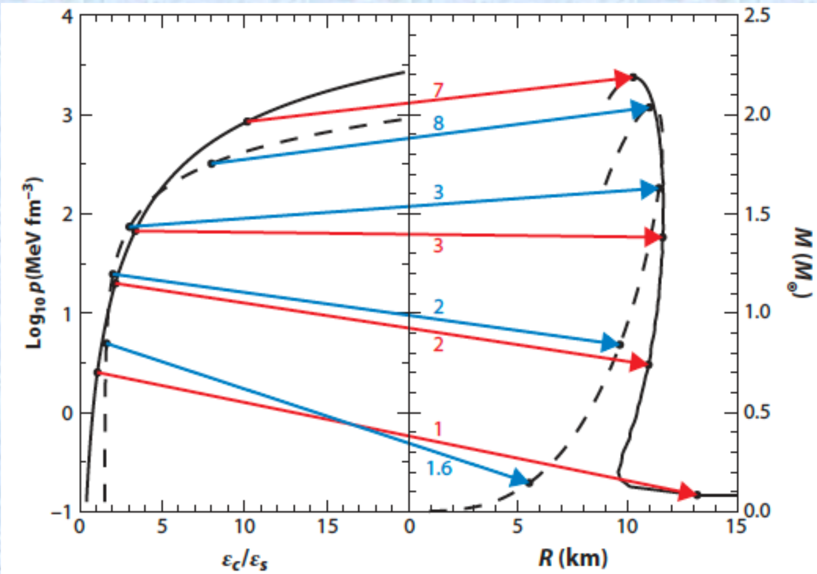
$$\tilde{\Lambda} = \frac{16}{13}\frac{(M_1+12M_2)M_1^4\Lambda_1+(M_2+12M_1)M_2^4\Lambda_2}{(M_1+M_2)^5}$$

tidal contribution to GW phase evolution (quadrupole moment) enters in 5PN (see L. Bernard's talk)

N.B.: GR in slow rotation limit w/o magnetic field !

see e.g. Haensel et al. 2007 (Springer); Hinderer et al., PRD 81, 123016 (2010); Blanchet, Liv. Rev. Relat. 17, 2 (2014)

EoS and NS properties (1)

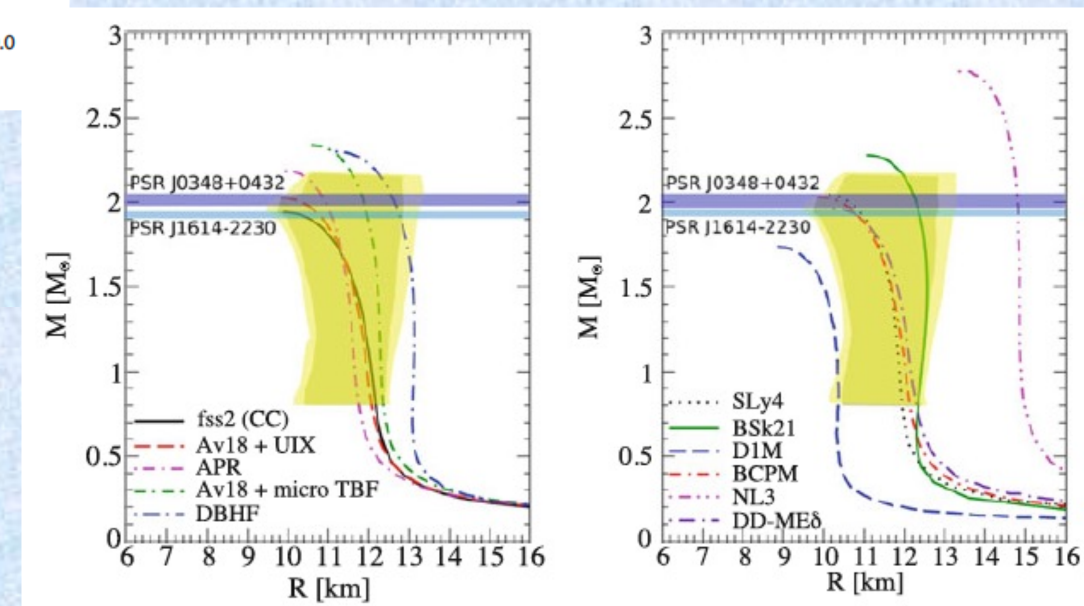


Lattimer, Annu. Rev. Part. Nucl. Sci. 62, 485 (2012)

- ✓ GR → one-to-one correspondence EoS ←→ NS static properties $M(R)$, $\Lambda(M)$… (non-rotating mature NS)
- ✓ Different EoSs ←→ different NS properties ←→ different GW signals
  ? → trace back to EoS and composition ?

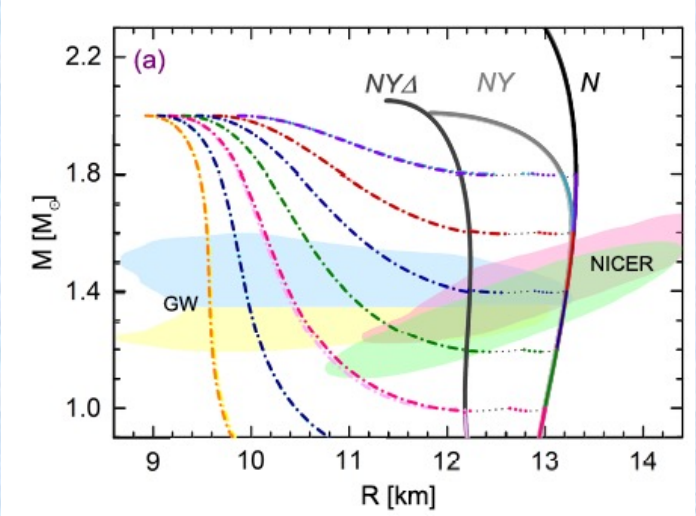
<u>but</u>:

- ✗ EoS model dependent !
- ✗ <u>no</u> ab-initio dense-matter calculations in all regimes → phenomenological models
- ✗ composition ←→ EoS → $M(R)$?

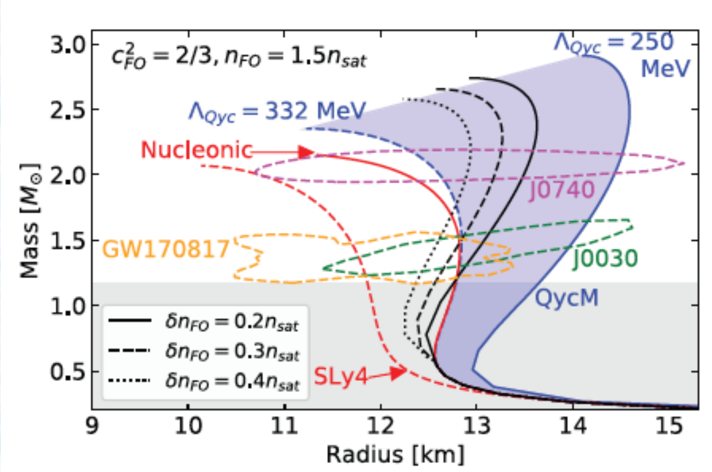


Burgio & Fantina, ASSL 457, 255 (2018)

EoS and NS properties (2)

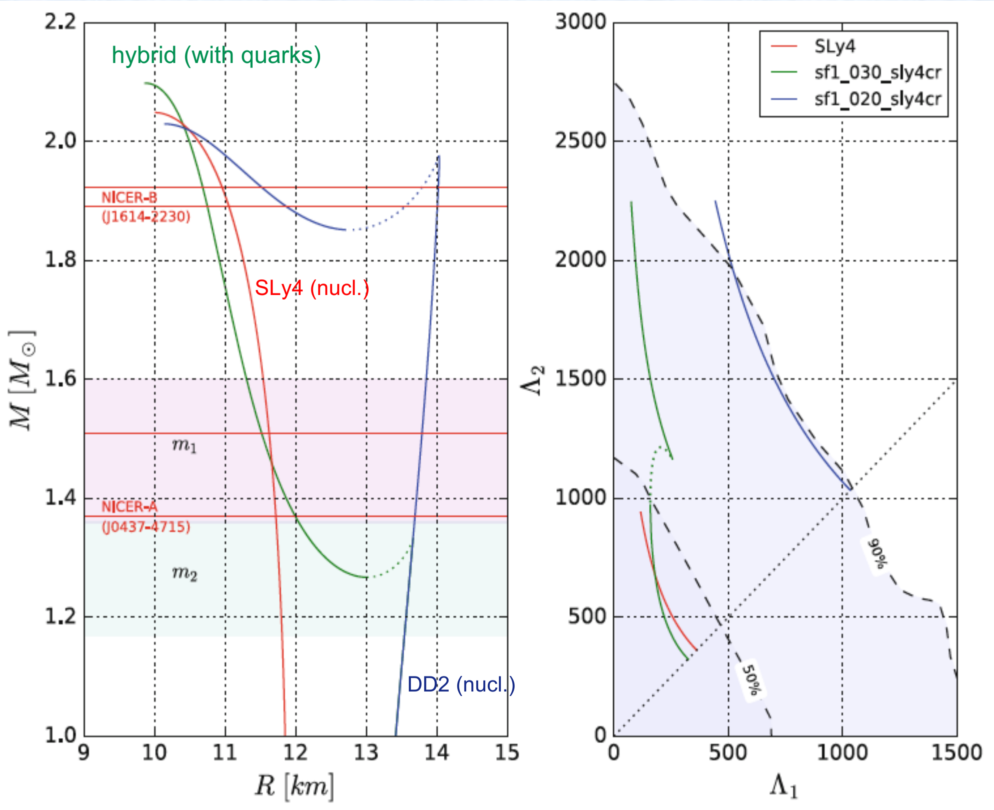


Li et al., PRD 101, 063022 (2020)



Somasundaram & Margueron, EPL 138, 14002 (2022)

- Role of "exotic" degrees of freedom?
  Hyperons → softer EoS
  Quarks → not clear
- "Masquerade" effect



Blaschke & Chamel, ASSL 457, 337 (2018)

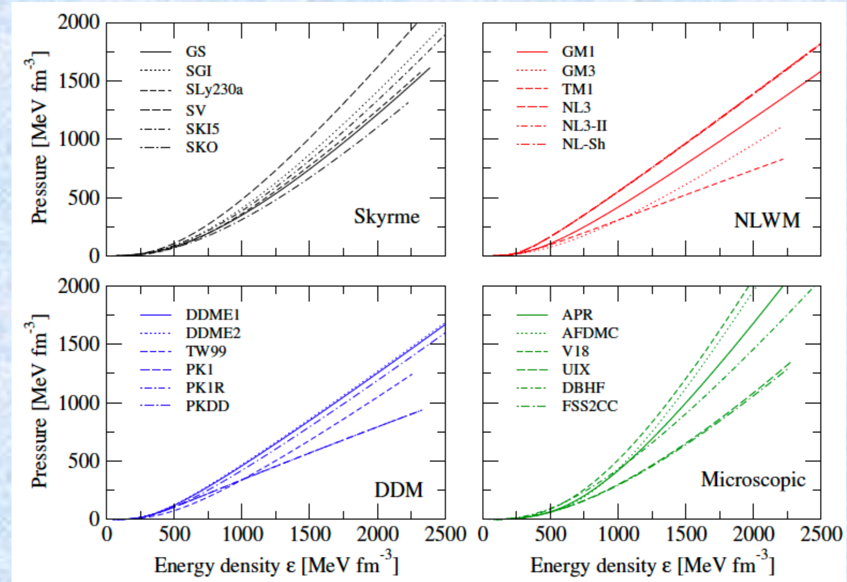
EoS: different approaches

- **Ab-initio ("microscopic") approaches**
  based on quantum many-body theories from realistic nuclear interactions (variational methods, (D)BHF, chiral EFT, Monte-Carlo, Green's func., …)
  → usually restricted to homogeneous matter (core)

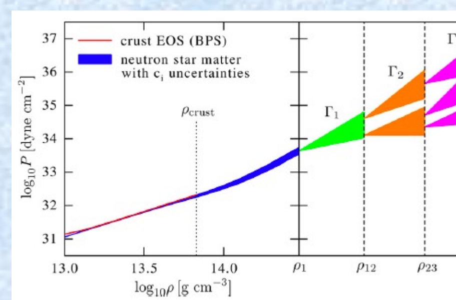
- **Phenomenological approaches**
  based on effective interactions with parameters adjusted to reproduced nuclear properties (EDF e.g. Skyrme/Gogny, meta-models, …)
  → also applicable for inhomogeneous matter (crust + core)

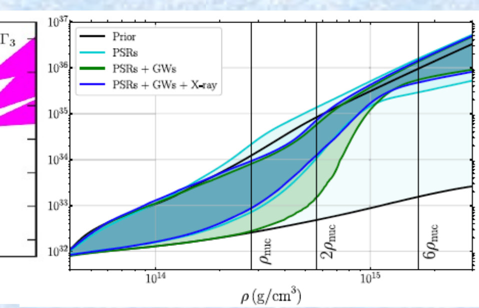
- **Agnostic (non-parametric) approaches**
  - Piecewise polytropes
  - Speed-of-sound models
  - Spectral functions
  - Gaussian processes

  → but what about info on composition?



Burgio & Vidana, Universe 6, 119 (2020)





Hebeler et al., ApJ 773, 11 (2013) Landry et al. PRD 101, 123007 (2020)

for a review see e.g. Haensel et al. 2007 (Springer), Oertel et al., Burgio & Fantina, ASSL 457, 255 (2018)
Agnostic approaches, e.g. PP: Reed et al. PRD 2009, Hebeler et al. ApJ 2013, Annala et al. PRL 2018; CSM: Tews et al. ApJ 2018, Tan et al. PRL 2020; SF: Lindblom 2010, Lindblom & Indik 2014; GP: Landry et al. PRD 2020, Essick et al. PRD 2020,…

EoS: meta-model (nucleons only)

- **Meta-model** approach for nucleons : flexible functional (“quasi” agnostic)
  → expansion in density and asymmetry around n_{sat} and $\delta = 0$ (with m^*_q included)

$$\epsilon_B(n,\delta) \approx n \sum_{m=0}^{4} \frac{1}{m!} \left(\left.\frac{d^m e_{\rm sat}}{dx^m}\right|_{x=0} + \left.\frac{d^m e_{\rm sym}}{dx^m}\right|_{x=0} \delta^2 \right) x^m$$

$$x = (n - n_{\rm sat})/3n_{\rm sat}$$

$$\delta = (n_n - n_p)/n$$

Empirical parameters (bulk) $\boldsymbol{X}_{\rm sat,sym} = E_{\rm sat}, K_{\rm sat}, Q_{\rm sat}, E_{\rm sym}, L_{\rm sym}, K_{\rm sym}, \ldots$

- If one wants to model the crust → + surface and Coulomb term (CLDM)
  → surface parameters (σ_0, $\sigma_{0,c}$, β, b_s, p)

~ 15 – 20 parameters

- Apply filters in Bayesian analysis

$$p_{\rm post}(\vec{X}) = \mathcal{N}\, w_{\rm LD}(\vec{X})\, w_{\rm HD}(\vec{X})\, e^{-\chi^2(\vec{X})/2}\, p_{\rm prior}(\vec{X})$$

Low-Density filters
→ ab-initio (EFT)
(e.g. Drischler et al, PRC 93, 054316 (2016))

High-Density filters
→ causality, stability, $M_{\rm NS,max}$, $e_{\rm sym} > 0$
(NICER, tidal from GW)

nuclear masses (AME2016)
→ surf. param. (σ_0, $\sigma_{0,c}$, β, b_s, p)

flat non-informative prior
→ span large parameter space

see e.g. Bulgac et al., PRC 97, 044313 (2018), Margueron et al., PRC 97, 025805 (2018), Carreau et al, EPJA 55, 188 (2019), Tews et al., EPJ A 55, 97 (2019), Dinh Thi et al., A&A 654, A114 (2021), Dinh Thi et al., EPJA 57, 296 (2021); Essick et al., PRC 104, 065804 (2021), …

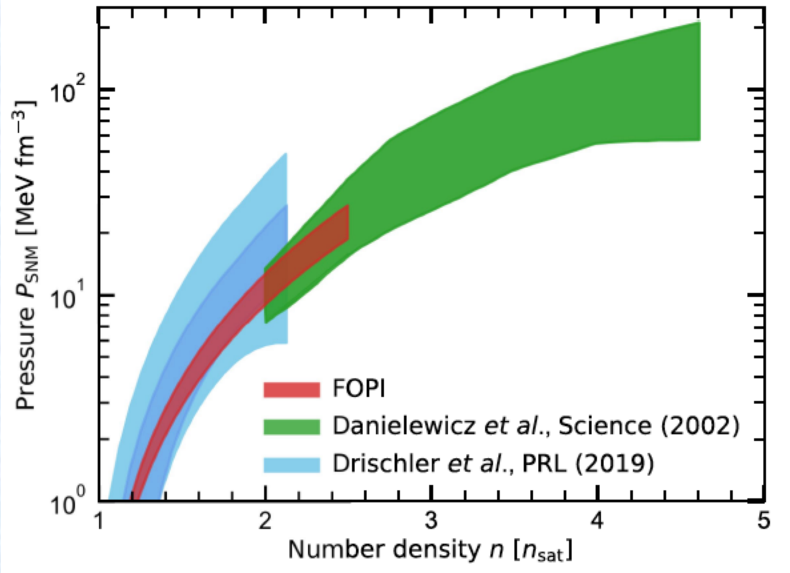
How can we get constraints?

Nuclear physics exp./ theory

- Measure of **nuclear properties**:
  - masses and radii of nuclei
  - collective modes, polarizability
  - neutron skins, HIC, flows

  etc …
- **ab-initio calculations**

→ **"low" density** (better in nucleonic sector)



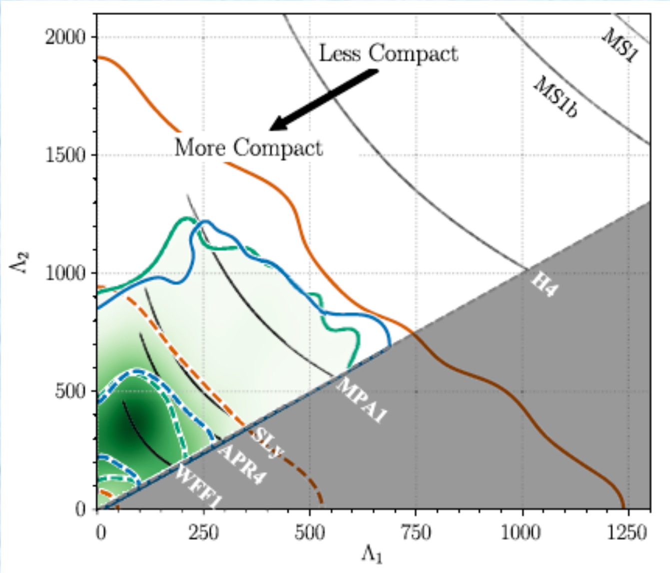
Huth et al., Nature 606, 276 (2022)

Astrophysical observations

- Measure of **NS properties:**
  - NS masses and radii (NICER)
  - rotational frequency, oscillation modes
  - cooling, moment of inertia

  etc …
- **Gravitational waves**

→ **"high" density**



Abbott et al., PRL 121, 161101 (2018)

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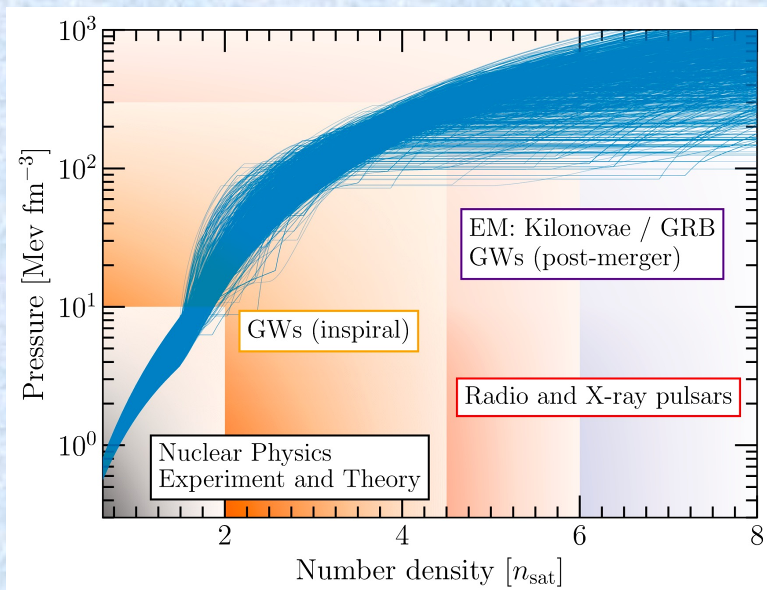
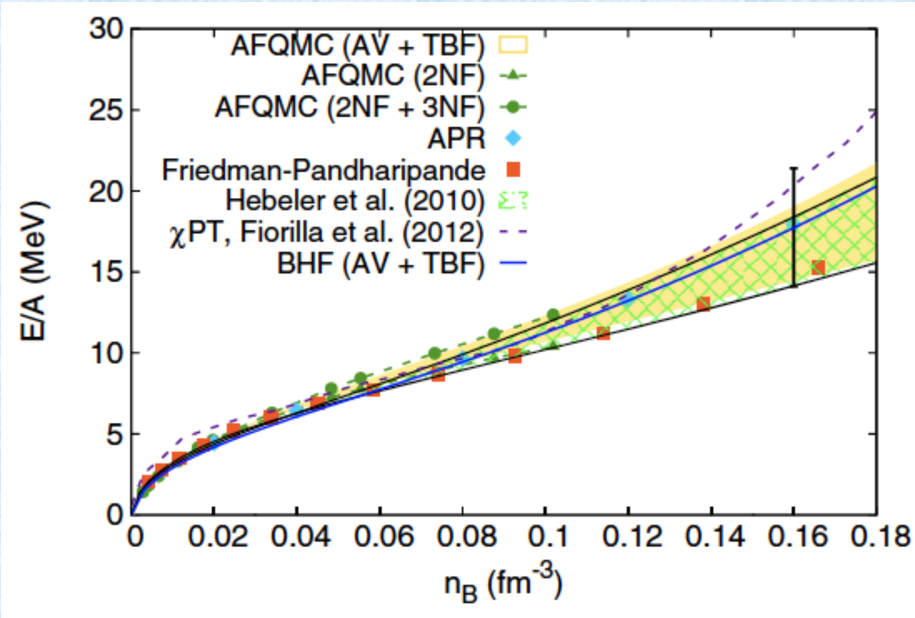


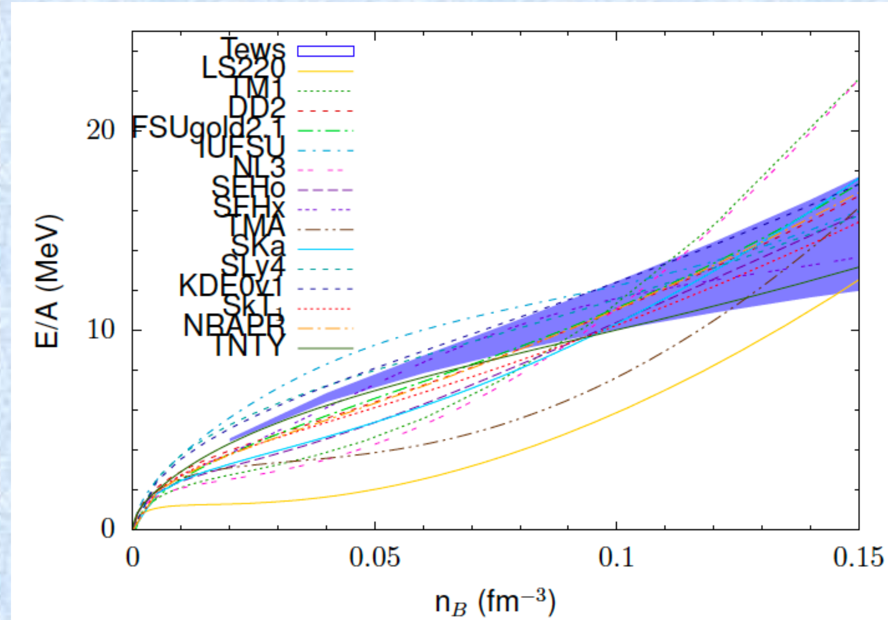
Pang et al., arXiv:2205.08513 (2022)

N.B.: rectangles only qualitative,
→ EoS dependence !

Constraints from nucl. phys.: theo

PURE NEUTRON MATTER





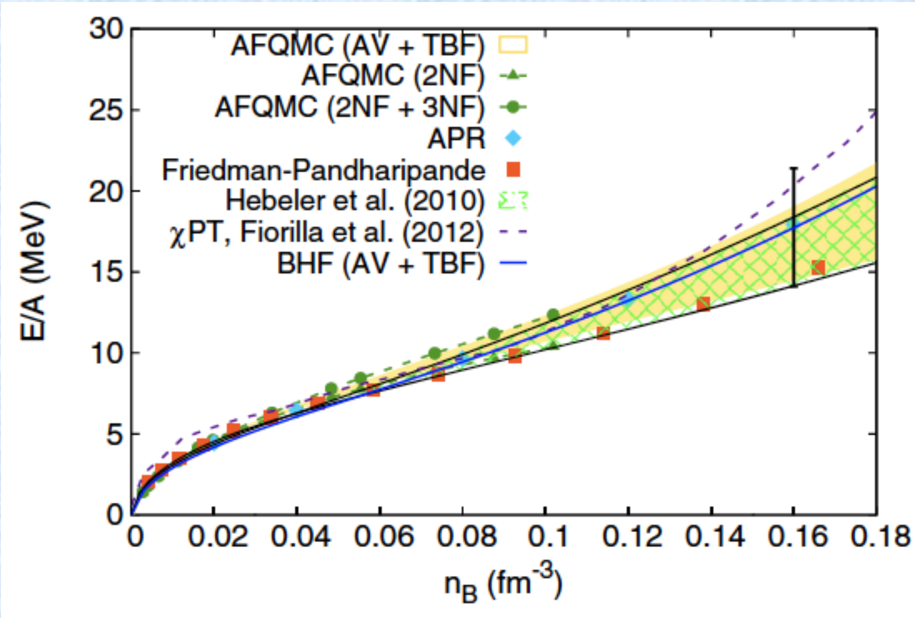
Oertel et al., Rev. Mod. Phys. 89, 015007 (2017)

Figure courtesy of M. Oertel

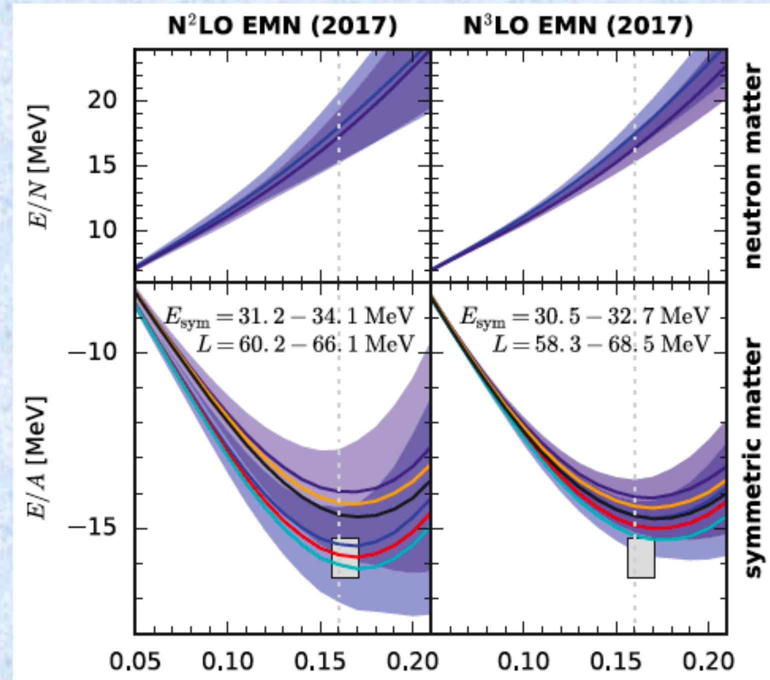
→ **Not all popular models agree with ab-initio constraints!**

Constraints from nucl. phys.: theo

PURE NEUTRON MATTER



Oertel et al., Rev. Mod. Phys. 89, 015007 (2017)

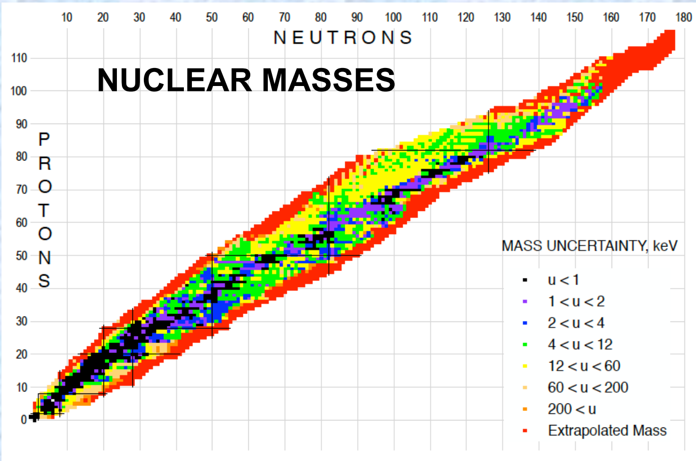


Drischler et al., PPNP 121, 103888 (2021)

→ Reasonable agreement of ab-initio (PNM) up to ~ saturation density
→ PNM calculations benchmark for phenomenological models

N.B.: for symmetric matter (ab-initio): (i) saturation point difficult to obtain ; (ii) larger uncertainties ; (iii) cluster formation at subsaturation

Constraints from nucl. phys.: exp

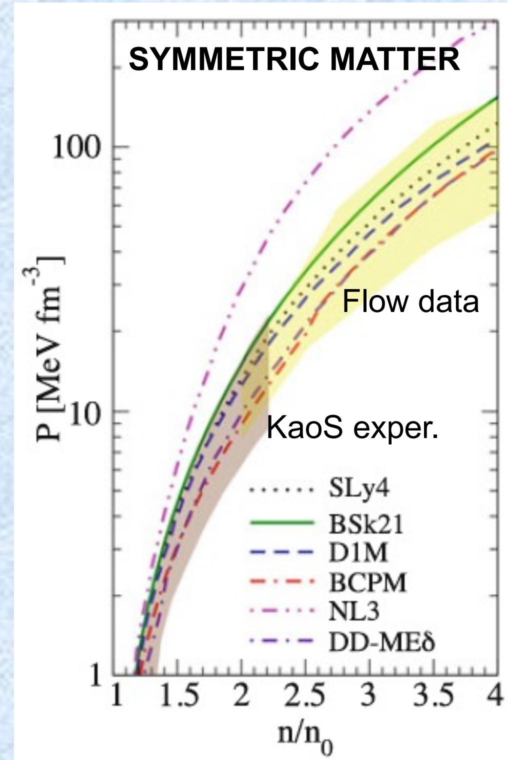


Kondev et al., Chin. Phys. C 45, 030001 (2021)

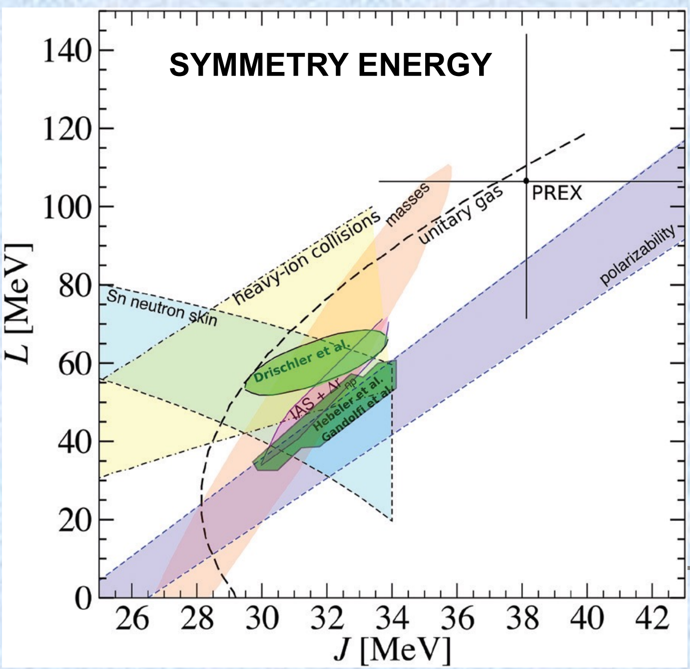
→ Constraints at "low" densities
  → low-order parameters

→ Constraints more on "symmetric" matter

→ Not always "clear" constraints
  → "tension"



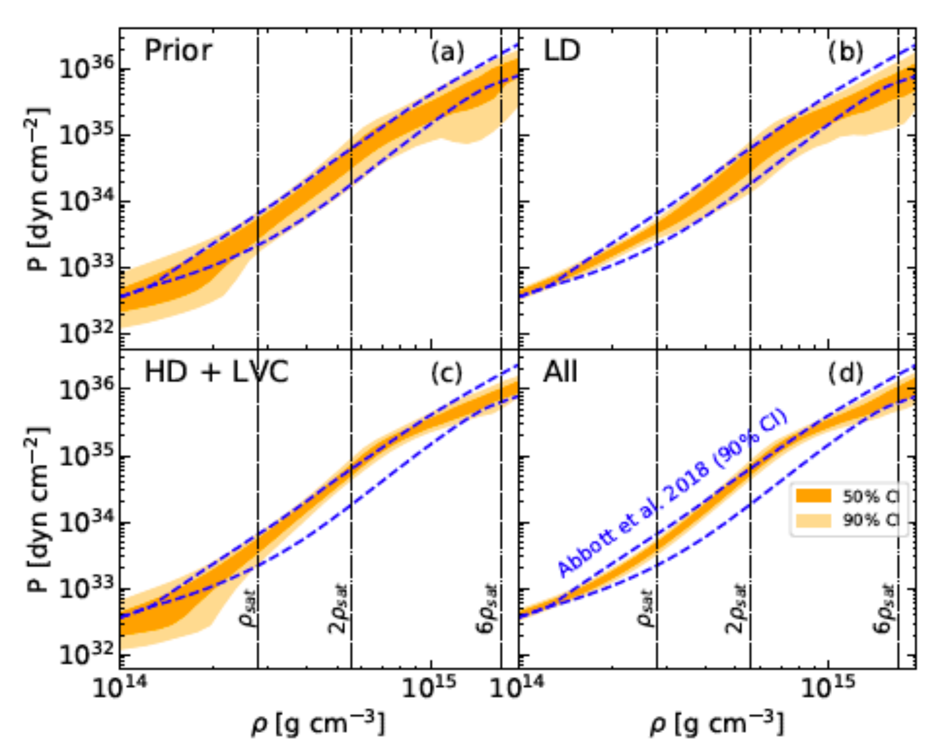
Burgio & Fantina, ASSL 457, 255 (2018)
(Flow: Danielewicz et al., Science 2002
KaoS: Lynch et al., PPNP 2009)



Gulminelli & Fantina, Nucl. Phys. News 31, 9 (2021)

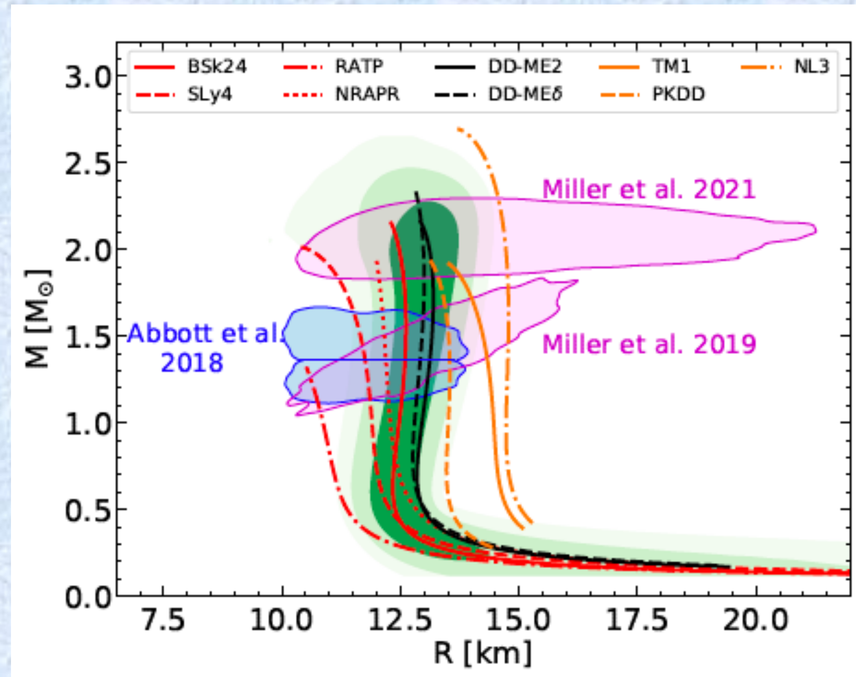
N.B.: deduced constraints are often *not* raw data, but combined with models
→ model dependence of constraints !

EoS : effect of LD/HD constraints



Dinh Thi et al., Universe 7, 373 (2021)

LD (EFT calc.) → low-density (nucl.phys.)
HD → high-density (astro)
(causality, M_{max}, NICER, GW)



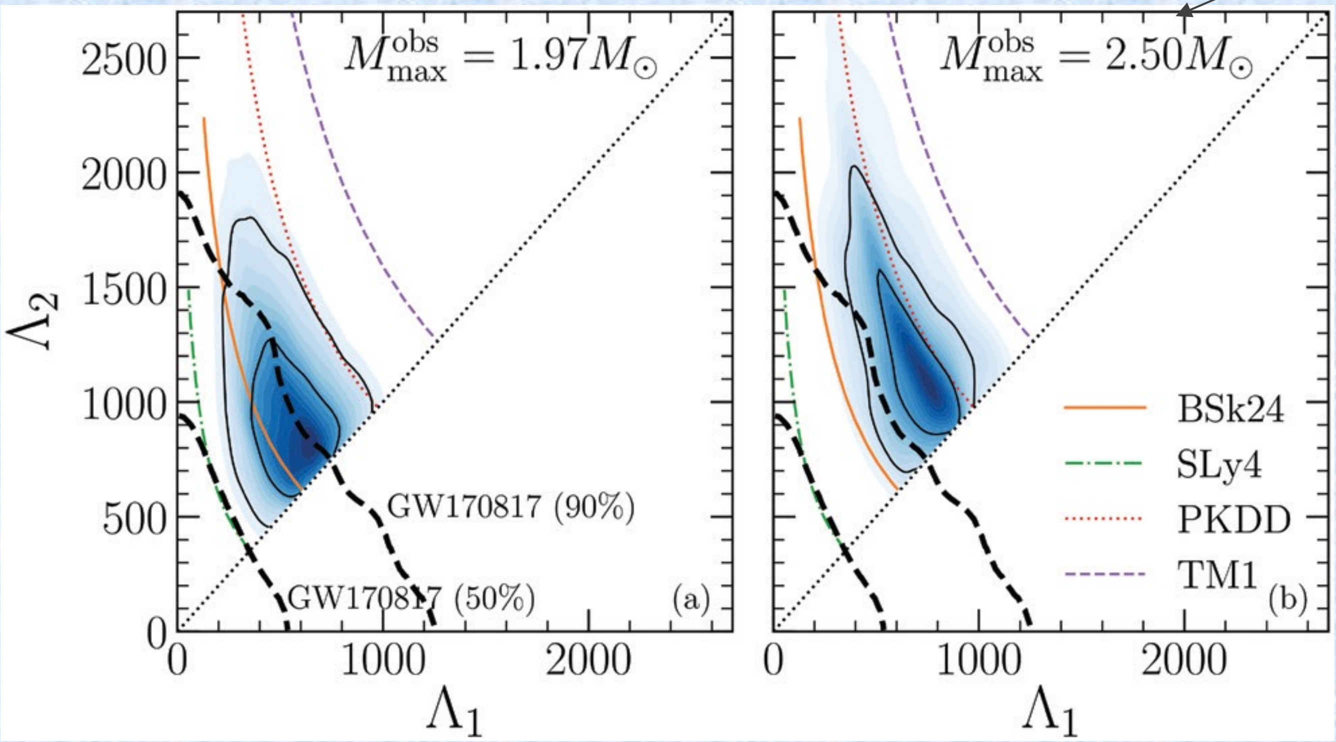
Dinh Thi et al., A&A 654, A114 (2021)

→ posterior compatible with observations
but: some popular models are not !

→ nucleonic hp compatible with observations

Challenge for nucleonic hp? (1)

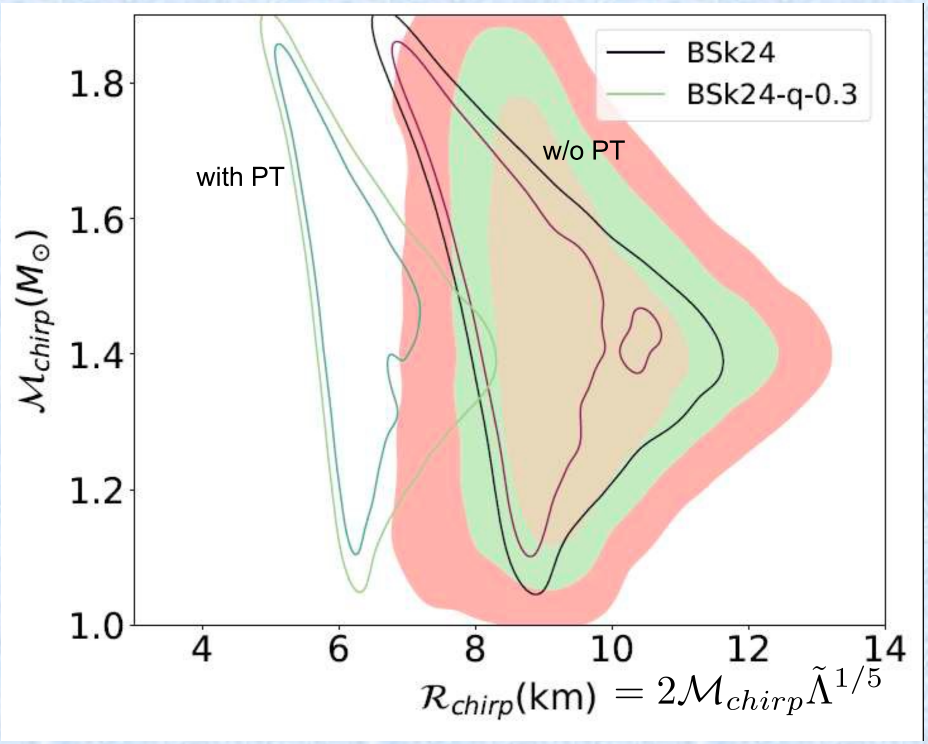
GW190426 ?

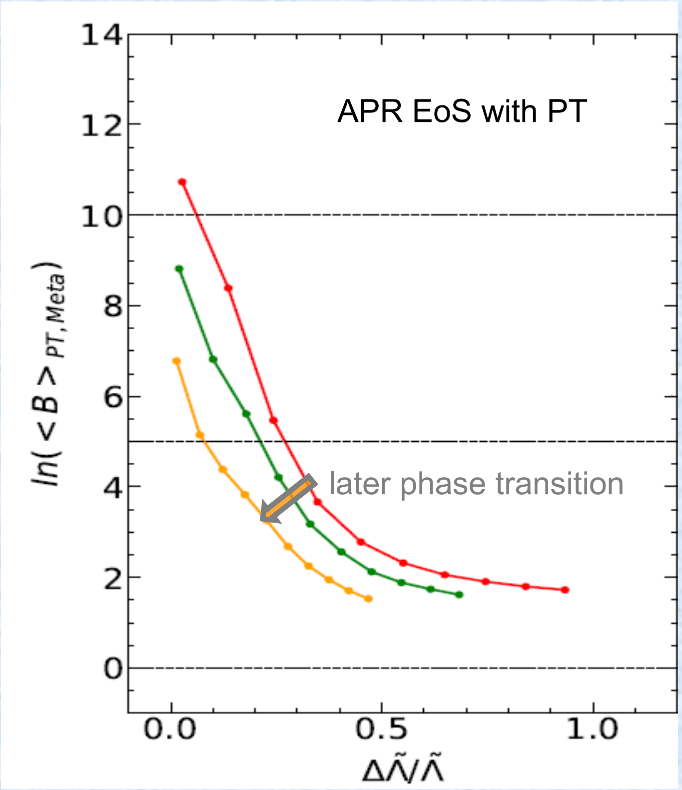


Gulminelli & Fantina, Nucl. Phys. News 31, 2 (2021)
T. Carreau, PhD Thesis (2020)

→ posterior (nucleonic matter) compatible with observations
but: if M_{max} ~ 2.5 M_{sun} → challenge for nucleonic hypothesis !
→ meta-model (nucleonic) can be used as null hp

Challenge for nucleonic hp? (2)





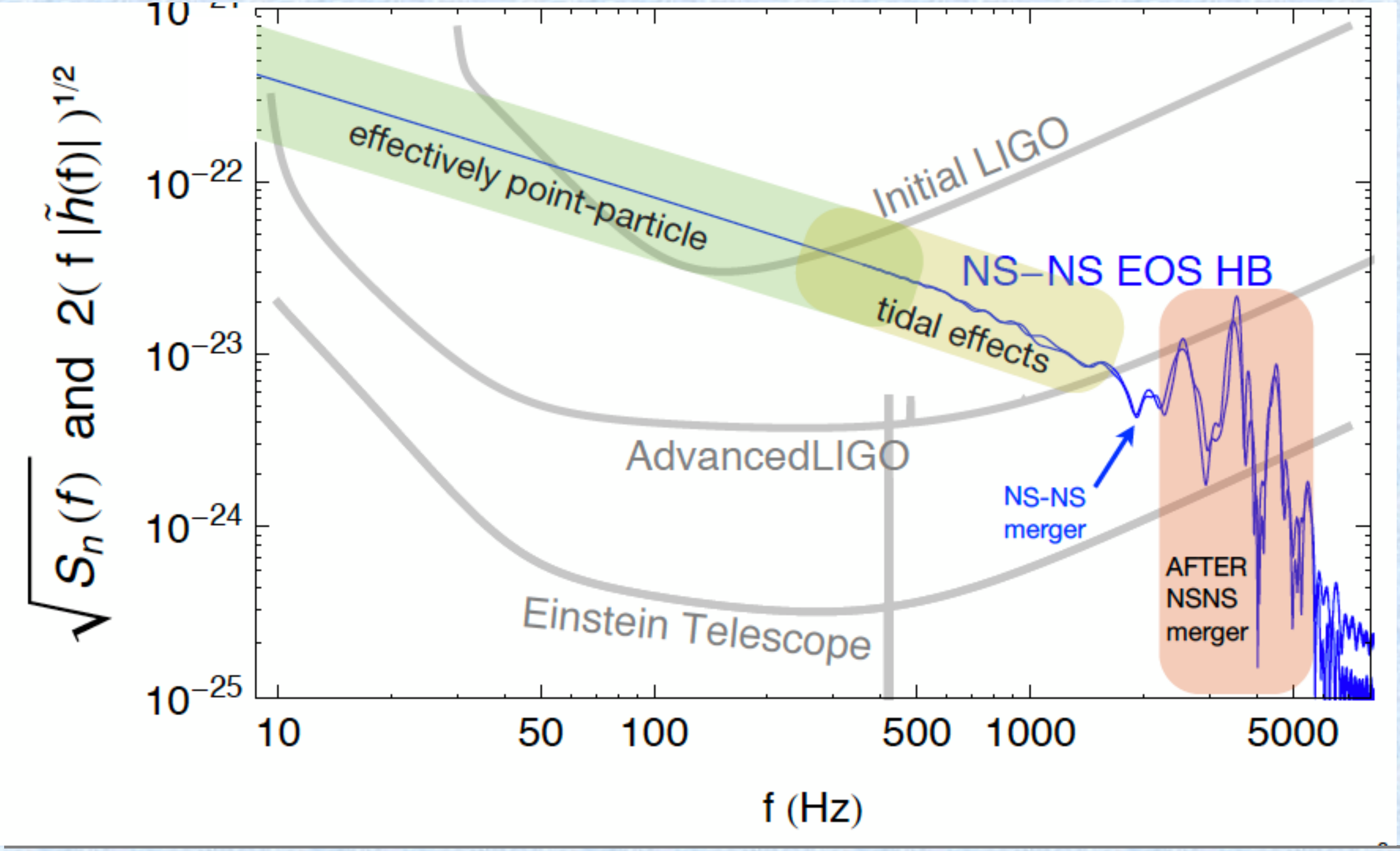
Figures courtesy of C. Mondal

→ if Λ precisely enough measured → phase transition (PT) may be detectable

but: if transition is not “early” enough ?

BNS and (future) GW detection

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



Read, CGWAS lecture (2015)

BNS and (future) GW detection

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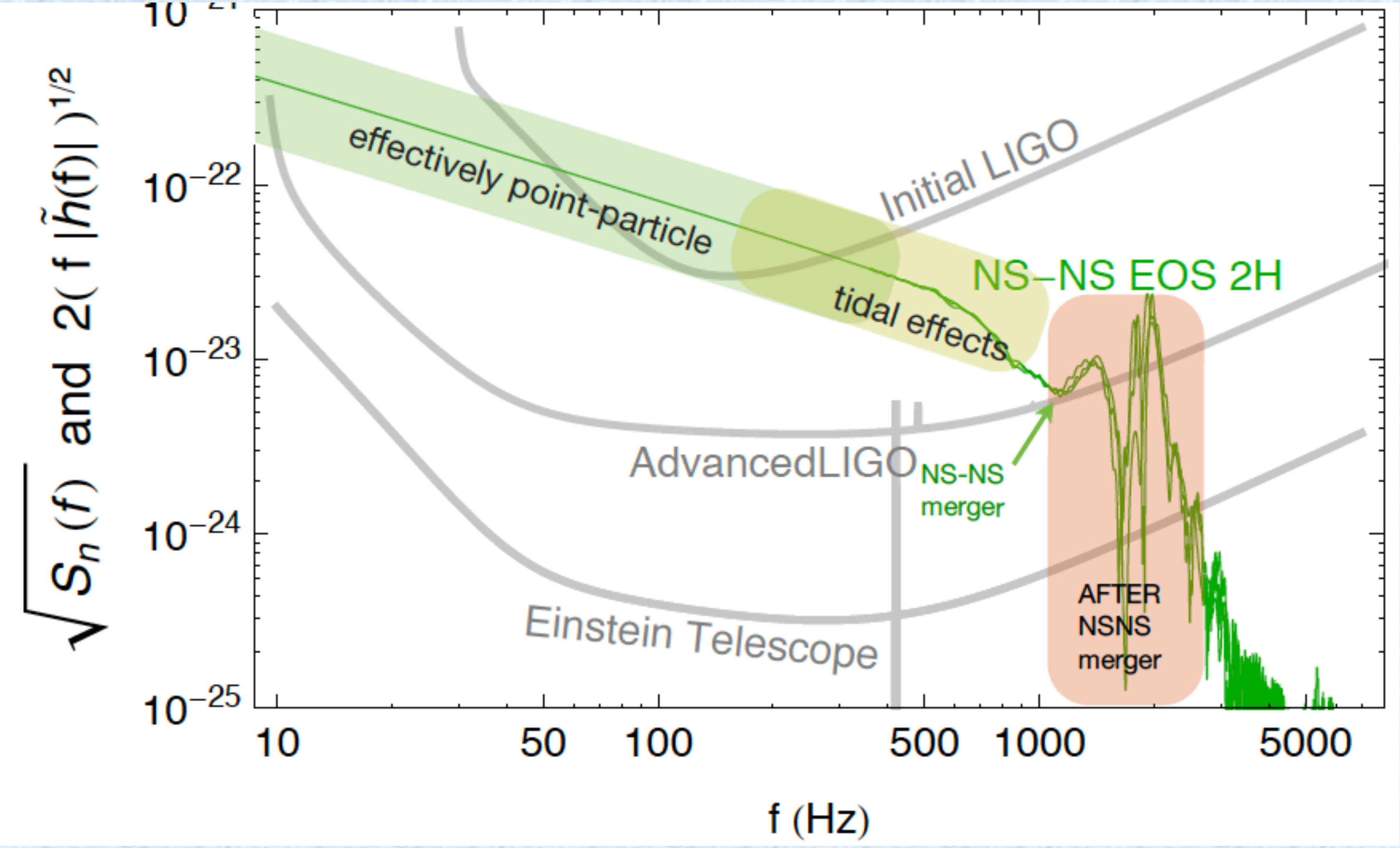
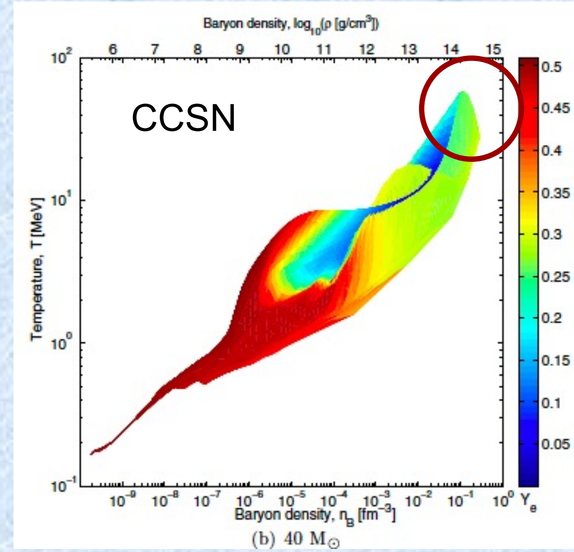


Read, CGWAS lecture (2015)

Finite T in BNS mergers / CCSN

✓ Finite T , high density met in **CCSN and BNS mergers (post-merger)**
→ additional degrees of freedom ? Effect on dynamics ?

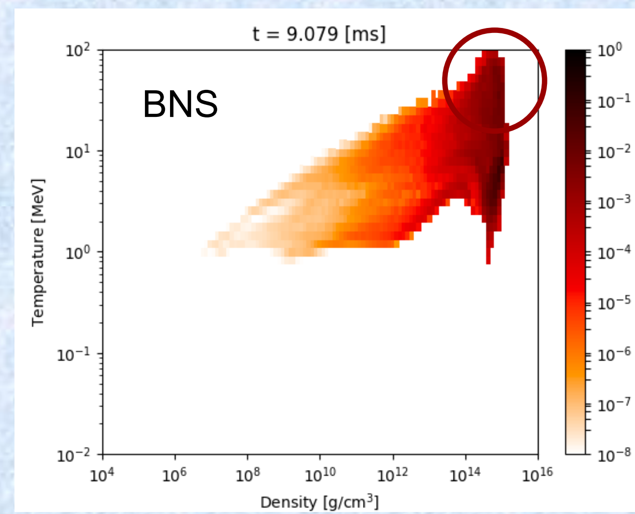
Temperature	$0 \text{ MeV} \leq T < 150 \text{ MeV}$
Baryon number density	$10^{-11} \text{ fm}^{-3} < n_B < 10 \text{ fm}^{-3}$
Electron fraction	$0 < Y_e < 0.6$



Fischer et al., ApJSS 194, 39 (2011)

✗ Consistent treatment of phase transitions challenging
✗ Extension of many-body methods and extrapolation of predictions not trivial (e.g. parameters of nuclear – phenomenological – models usually fitted at T=0)
✗ Hydro effects (SASI, …)

→ see J. Guilet's talk



➢ Need of a *unified* "general purpose" EoS (and composition) in very wide thermodynamic conditions
➢ Implementation in numerical simulations

Perego et al., EPJA 55, 124 (2019)

for a review e.g. Oertel et al., Rev. Mod. Phys. 89, 015007 (2017); Burgio & Fantina, ASSL 457, 255 (2018)

Conclusions

- Nuclear physics (experiments + theory) + *astrophysical observations*
  → constraints on dense-matter properties
  → constraints on (phenomenological) models & EoS

- Nuclear physics (theo + exp) gives constraints up to ~ 1.5 n_{sat}
  → predicted observables quite robust (with uncertainties)
  → possibility of exploring new physics ?

- Uncertainties in high-density part of EoS
  → blurring of different effects ?

- No present compelling indication of “exotic” particles in NSs
  → observations not informative enough to support/rule out phase transition
  → future observations ?

- Static properties: if GR → possible “extraction” of EoS (with uncertainties)
- Dynamic properties → need of complex (multi-D, hydro) simulation
  → computationally challenging, dependence on different inputs


Thank you