Dense Matter

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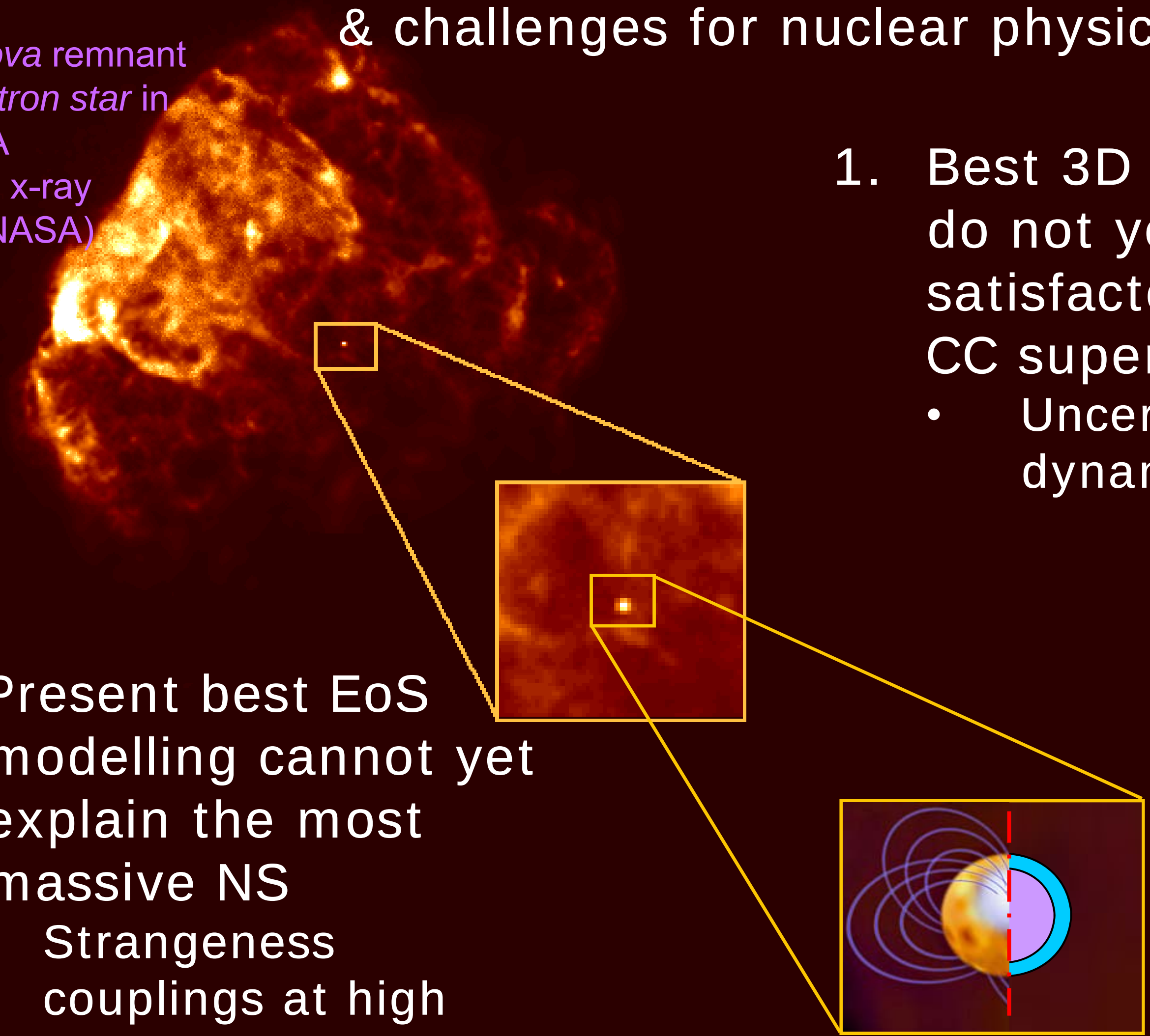
$<\rho> \sim\rho_0\sim 10^{14}$ g/cm^3

Nucleonic DoF

Dense matter in the universe

& challenges for nuclear physics

Supernova remnant and *neutron star* in Puppis A (ROSAT x-ray Credit: NASA)



1. Best 3D hydro simulations do not yet produce satisfactory explosions of CC supernova
   - Uncertainty in the ν dynamics

A

2. Present best EoS modelling cannot yet explain the most massive NS
   - Strangeness couplings at high density ?
   - Transition to quark matter ?

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3. The recent detection of GW by LIGO/VIRGO opens an exciting avenue of GW observation from compact objects
   - More binary NS merging
   - Continuous GW from deformed NS
   - R-modes in young sources
   - GW from SN

Dense matter in the universe
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Nuclear modelling needed !

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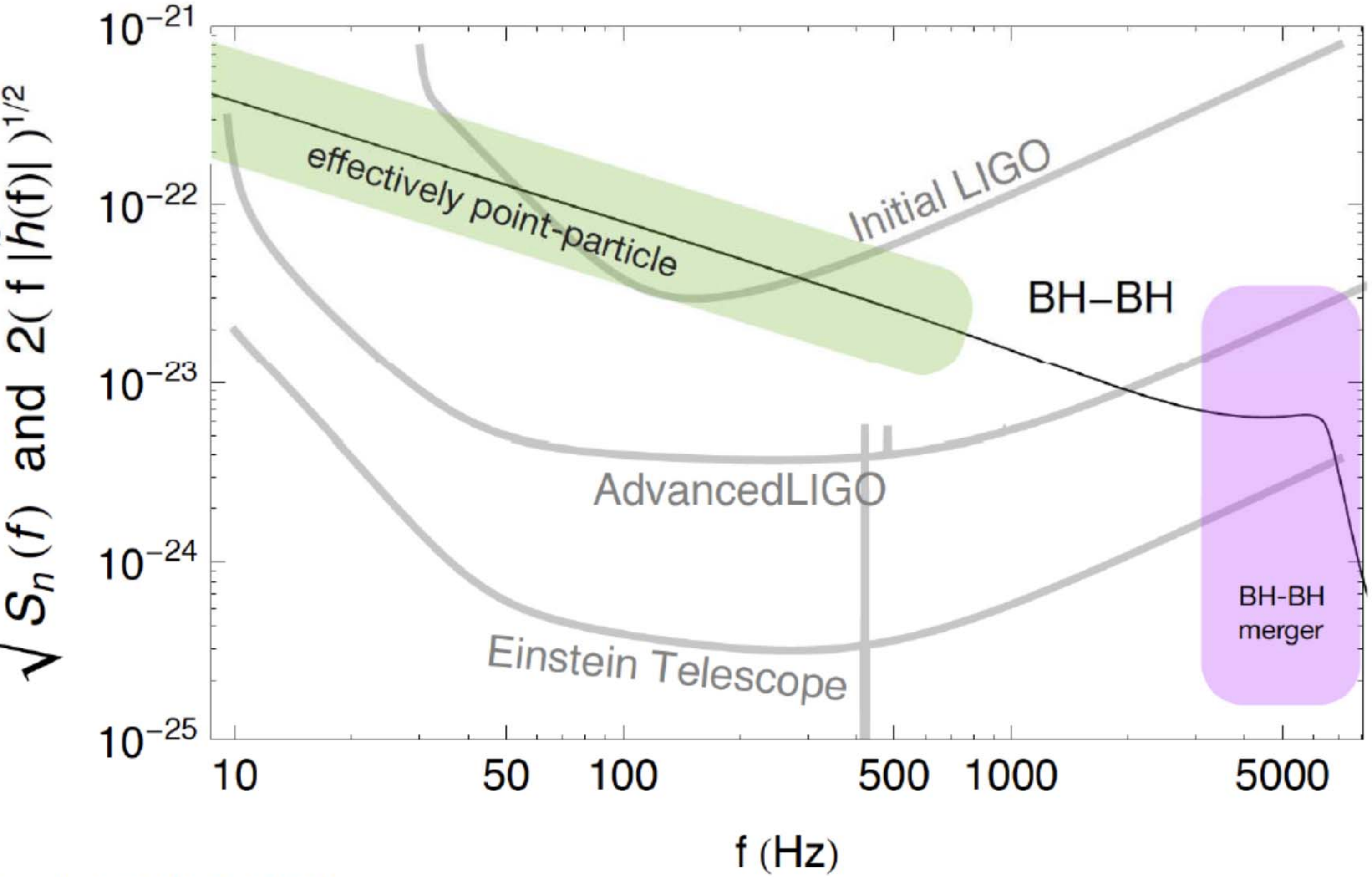
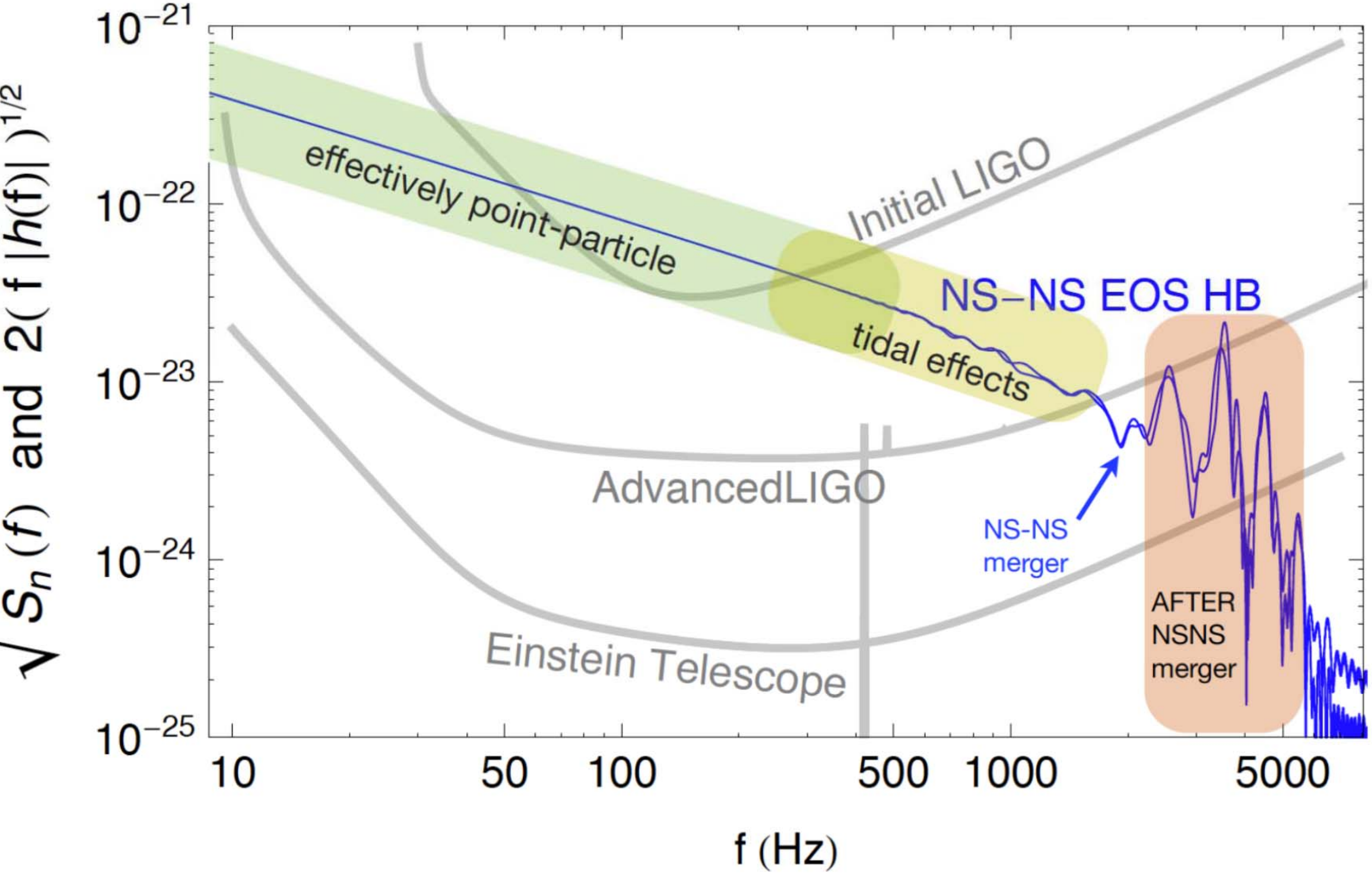
Spectrum of BBH inspiral, scale to 1.35-1.35, 45 Mpc



J. Read, CGWAS 2015

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



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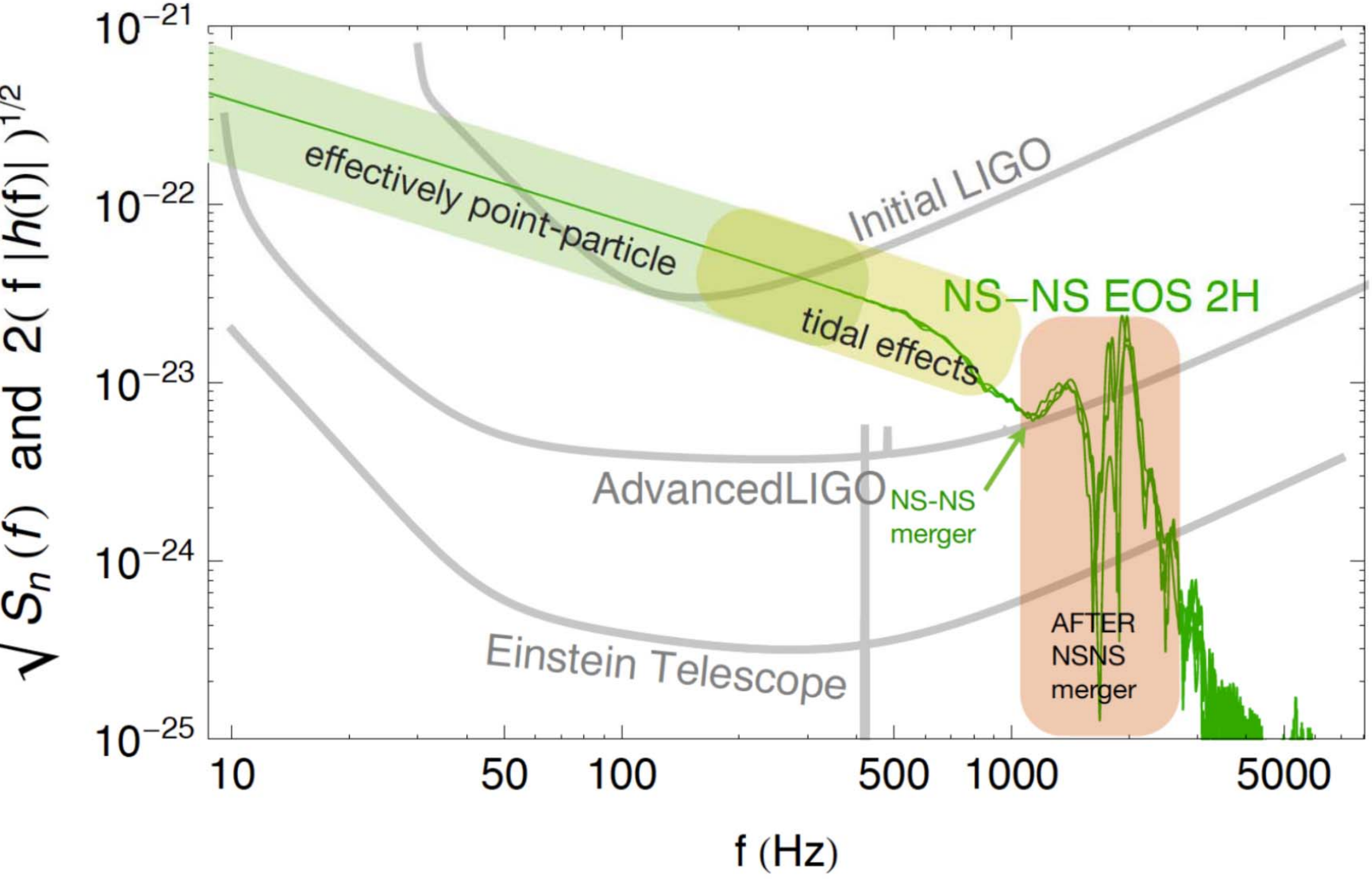

J. Read, CGWAS 2015

Astro Observable	Baryonic matter	Nuclear physics properties to be modelled	Key nuclear ingredients
SN collapse	Nuclei	Weak interaction out of equilibrium	Weak rates Masses
NS mass and radius	NM	Catalized matter Quark phase?	EoS Hyperon couplings
GW mergers R-modes	NM	F-peak Tidal properties	EoS
NS cooling Glitches	NM and nuclei	Solid-liquid transition	EoS Surface Pairing
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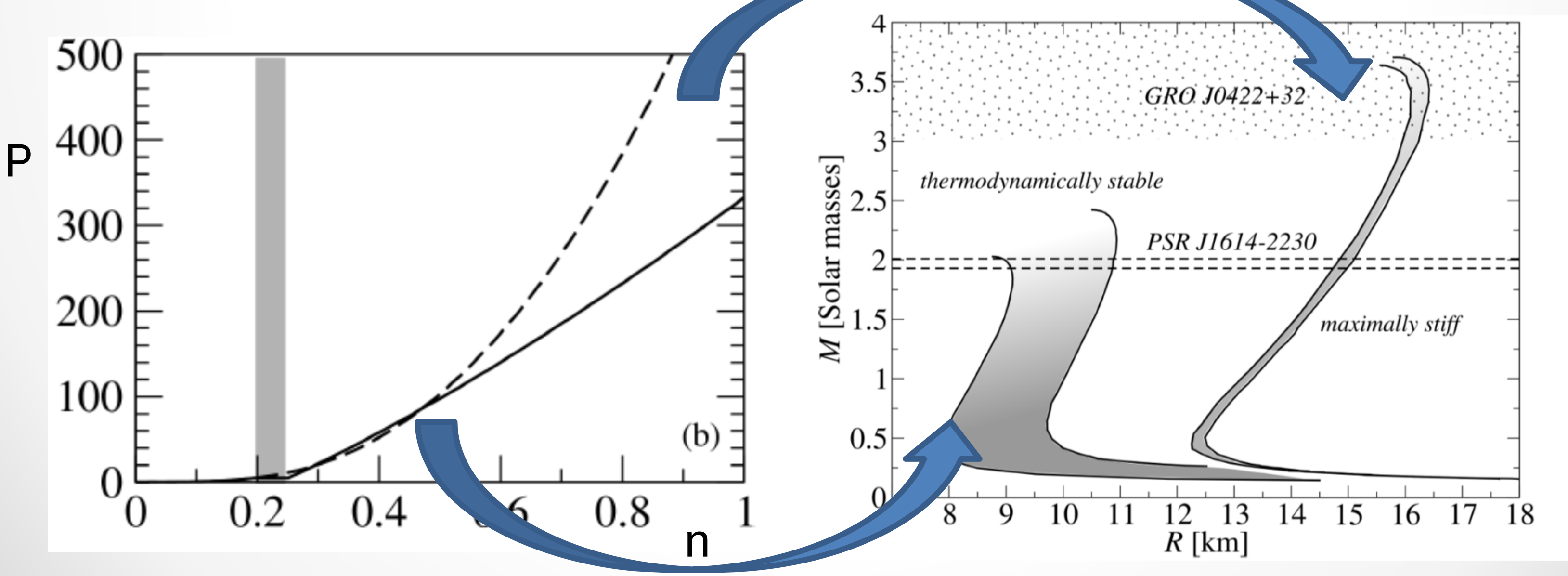
1)NS mass and radii

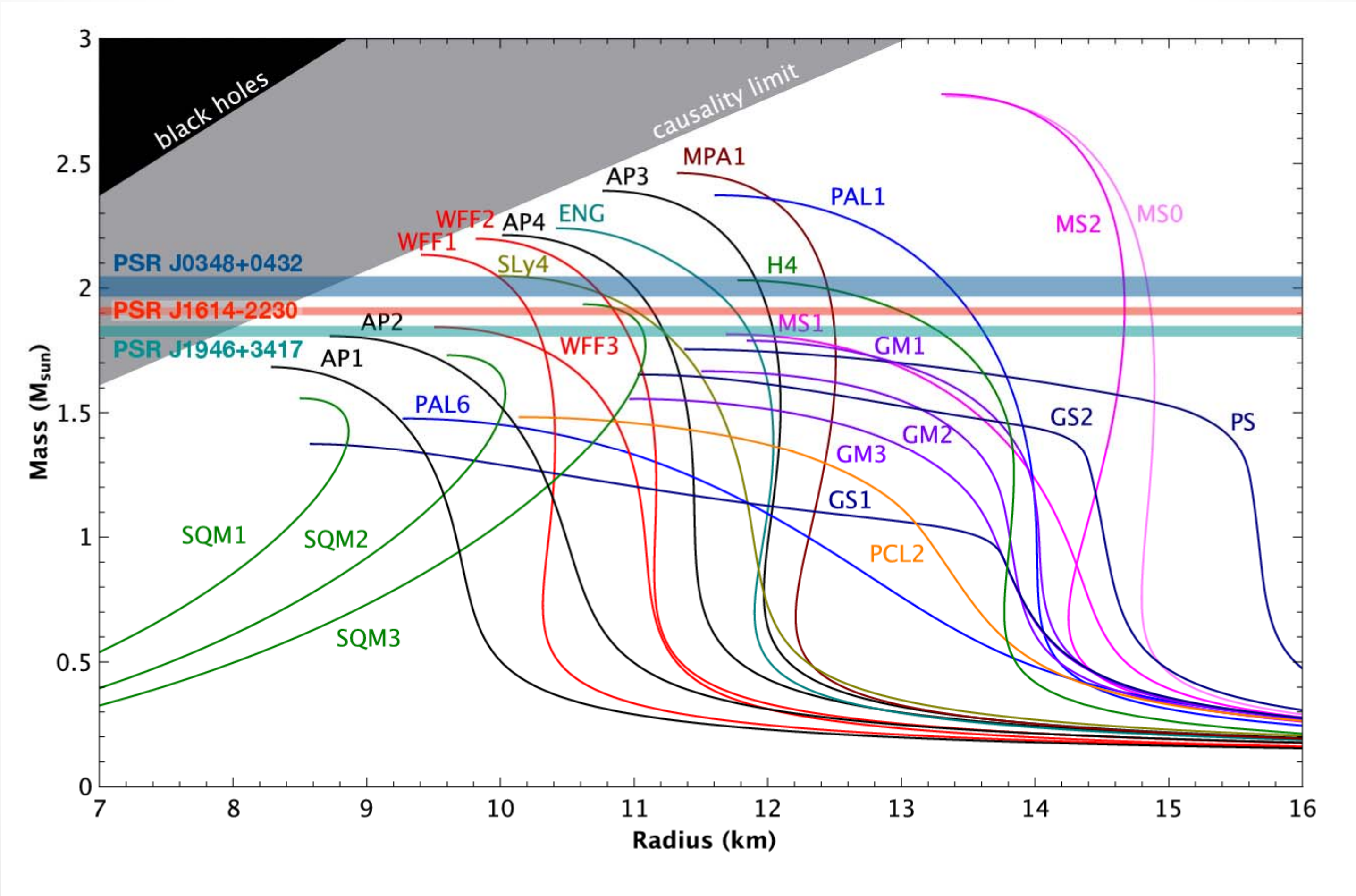
- Tolman Oppenheimer Volkoff: from general relativity

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

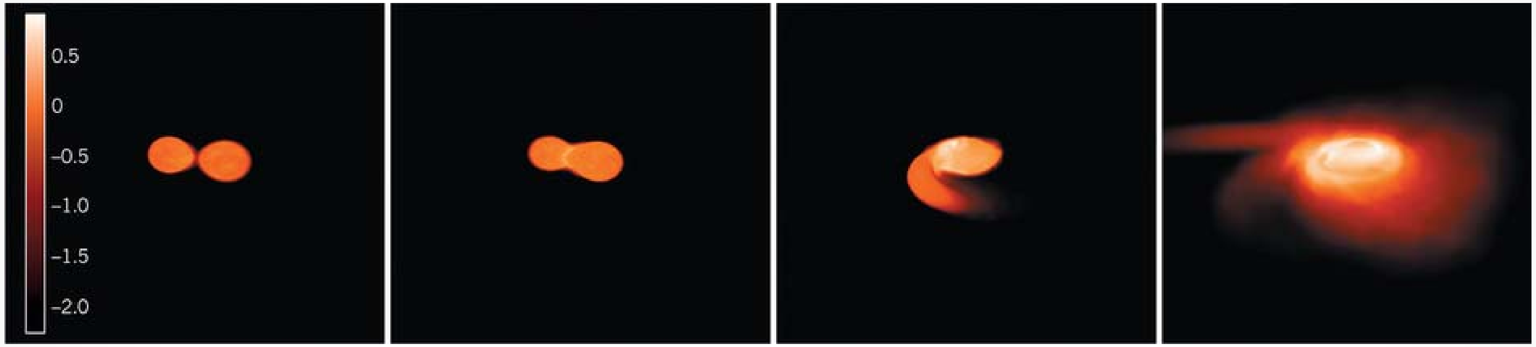


N.Chamel et al, A&A, 2013

1)NS mass and radii



2)NS mergers



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

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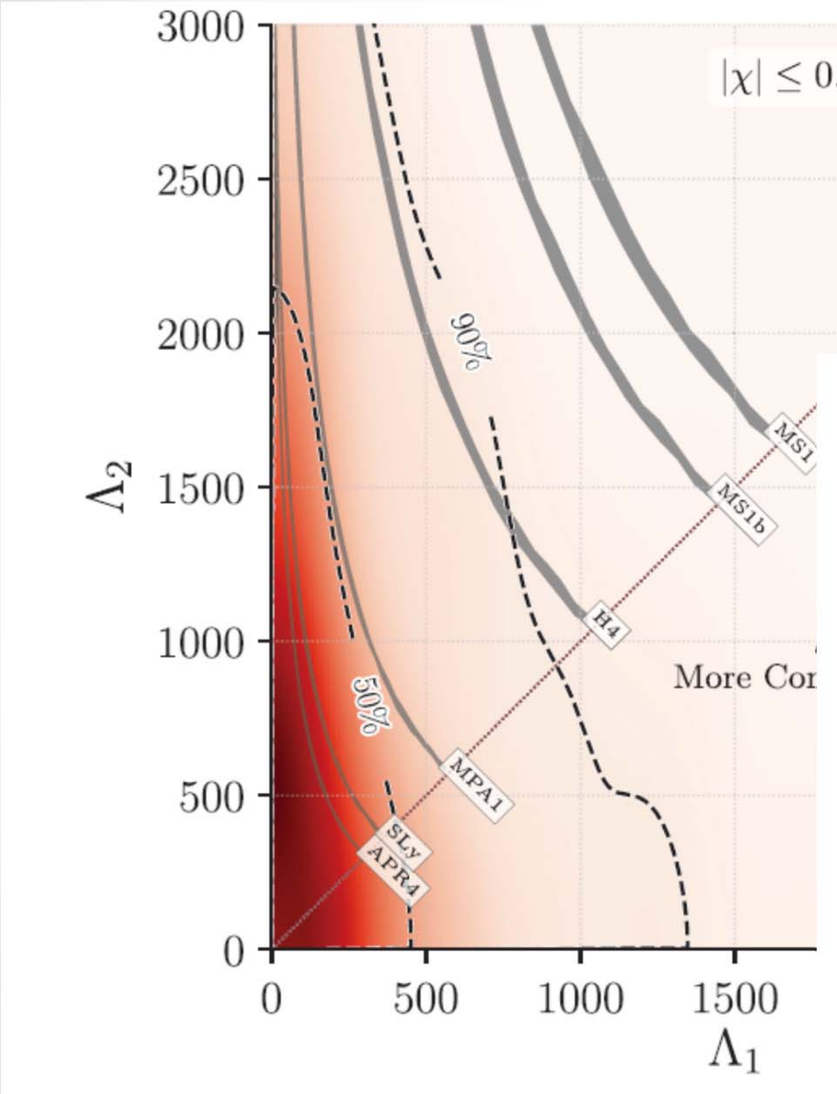
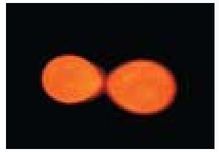
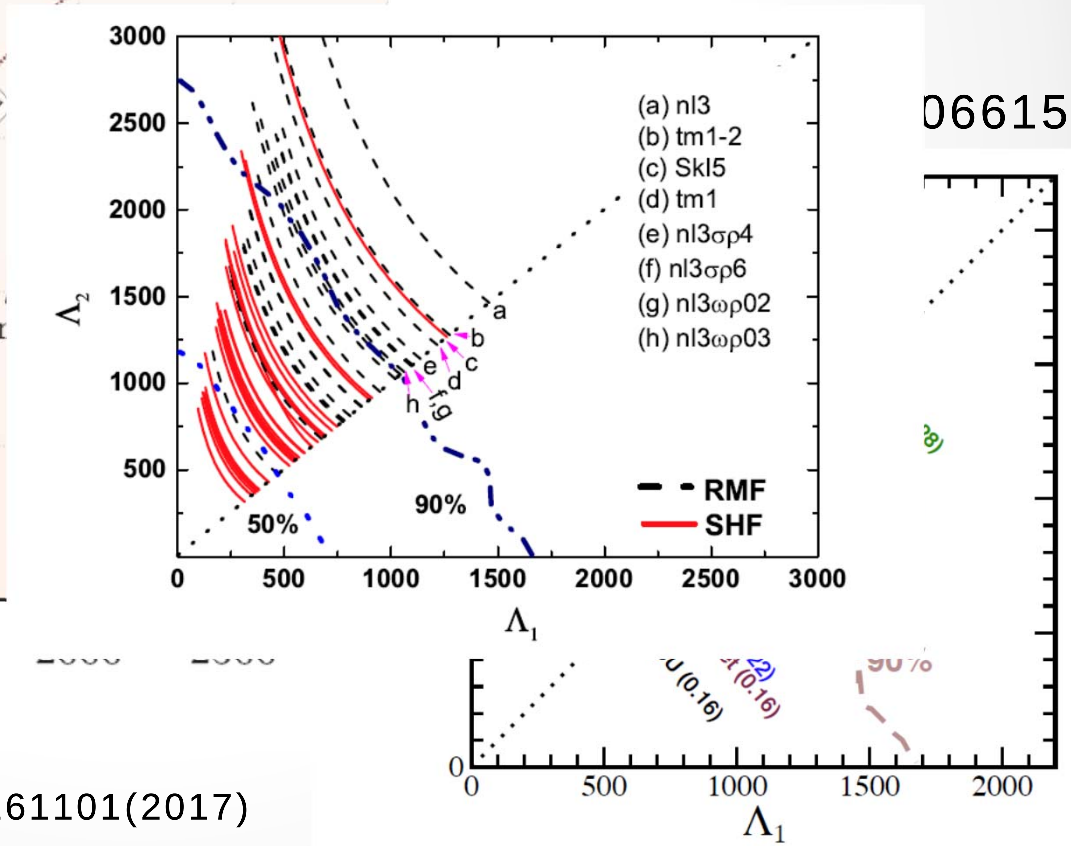
2)NS mergers





T.Malik ArXiv:180511963



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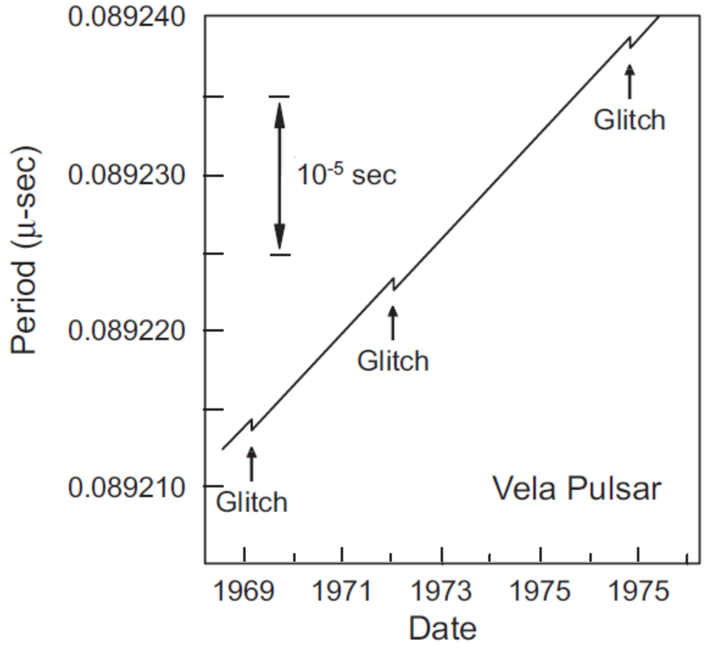
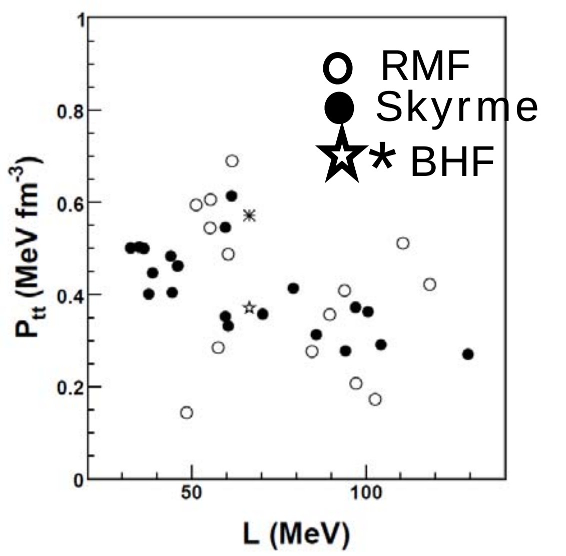
- B.Abbott et al. (LIGO) PRL 119,161101(2017)

3) Pulsar glitches



- Canonical interpretation: sudden unpinning of superfluid vortices due to the crust-core differential rotation
- Key parameter: crustal moment of inertia
- Can be evaluated from the TOV, if the crust-core transition pressure is known

- Strongly model dependent: requires the knowledge of the EoS **AND** of the surface energy of n-rich nuclei



C.Ducoin et al, PRC 2012

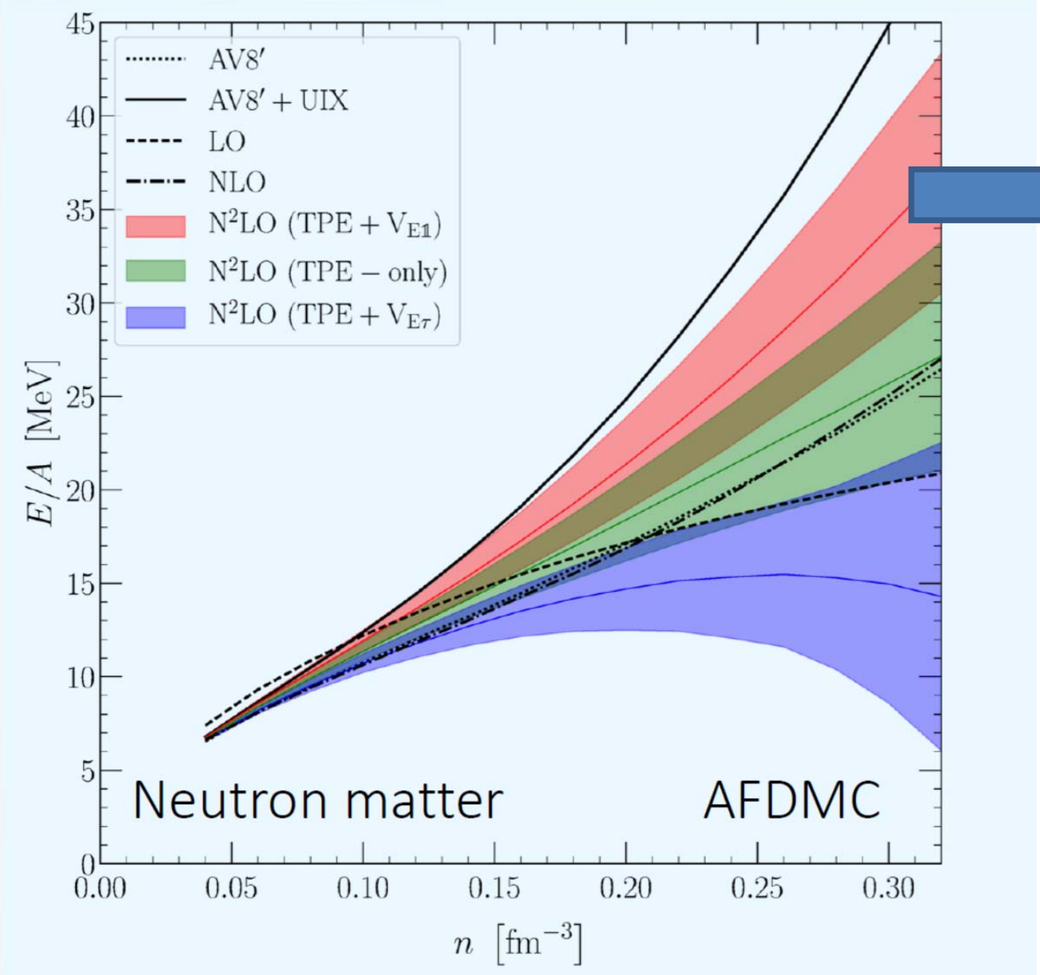
How to constrain the Equation of State?

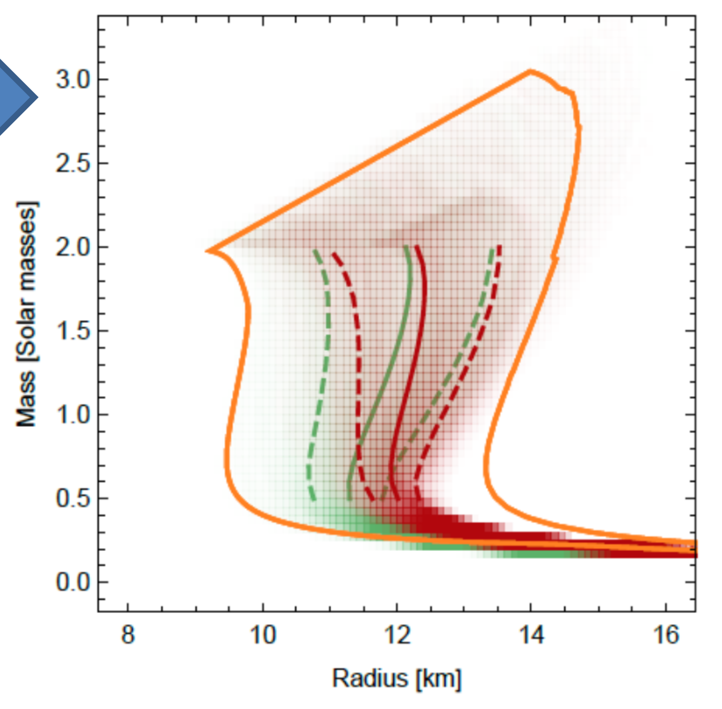
…

- Discriminate among models
- Quantify the reliability of the different models
- Predict astro observables with controlled uncertainty intervals

I - Constraining the EOS: ab-initio modelling

Tews, Carlson, Gandolfi, Reddy Astrophys.Journ. 2018

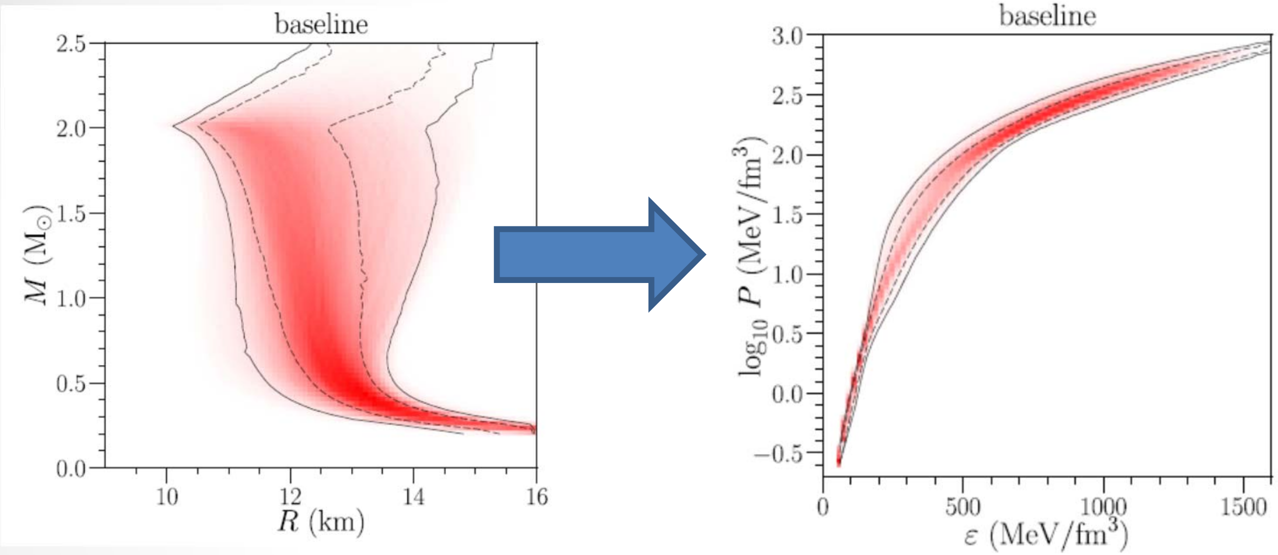




- Extrapolations needed above n_{sat}

II- Constraining the EoS: NS observation

A.W.Steiner et al, MNRAS 2018



- Low mass X-ray binaries in globular clusters
  - Atmosphere model?
  - Interstellar matter abundancies?
  - Hot spots?
  - Functional form of the EoS?

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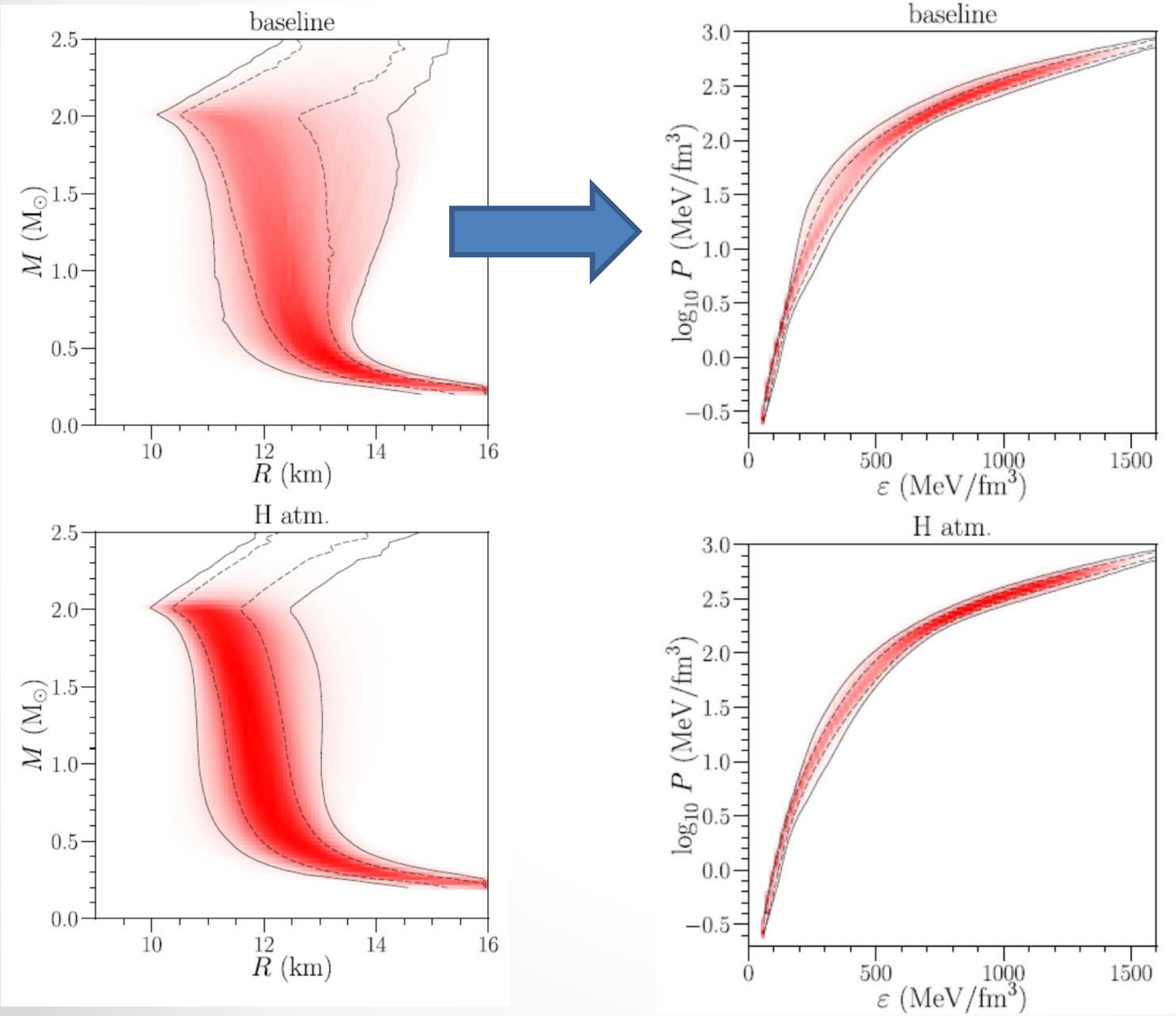
A.W.Steiner et al, MNRAS 2018



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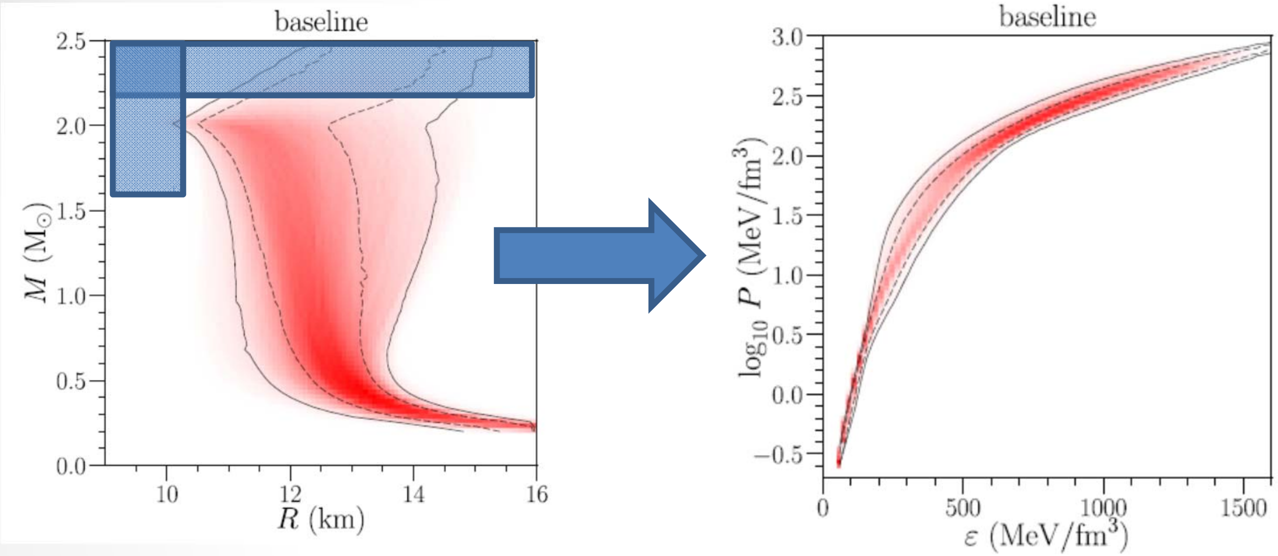


New constraints from GW170817 !

- A.Bauswein et al, ApJ (2017) R(M=1.6)>10.68 km
- L.Rezzolla et al, ApJ (2018) M<2.16 Mo

III- Constraining the EoS: J.Margueron, R.Casali FG PRC 2018

include nuclear physics empirical information

- Start from the energy functional $e(\rho,\delta)$ $\quad \left(P = -\frac{de}{d\rho^{-1}} = \rho\mu - \varepsilon\right)$
- Nuclear phenomenology is best known around saturation

$$\delta = \frac{\rho_n - \rho_p}{\rho}$$
$$x = \frac{\rho - \rho_0}{\rho_0}$$

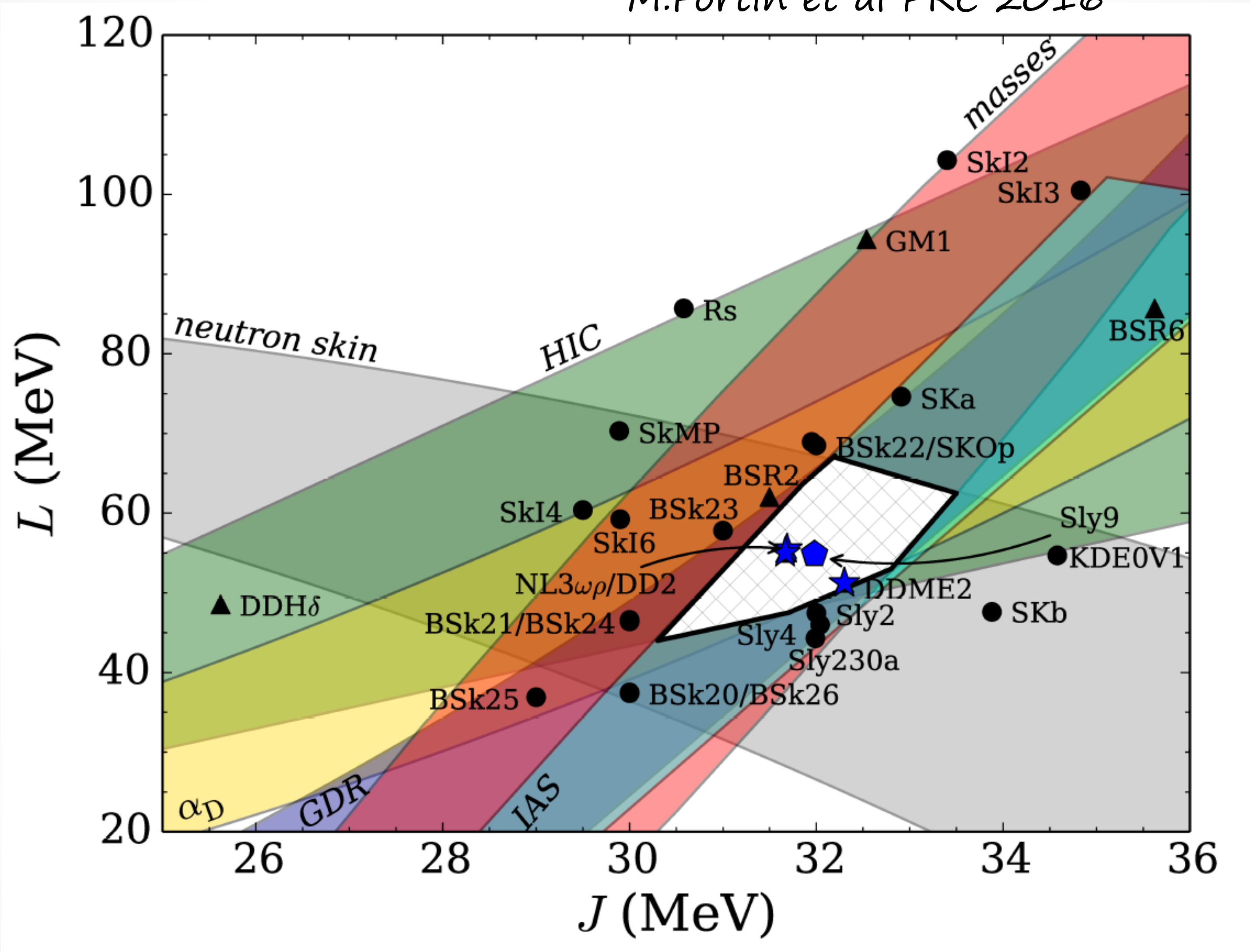
- Taylor expansion

$$e(\rho,\delta) = e_{IS}(\rho) + e_{IV}(\rho)\delta^2 + O(\delta^4)$$
$$= \left(\boldsymbol{E_0} + \frac{1}{18}\boldsymbol{K_0}x^2 + ..\right) + \left(\boldsymbol{J_{sym}} + \frac{1}{3}\boldsymbol{L_{sym}}x + \frac{1}{18}\boldsymbol{K_{sym}}x^2 + ..\right)\delta^2$$

- Empirical parameters $\left(E_0, \rho_0, K_0, J_{sym}, L_{sym}, K_{sym} \ldots\right)$ are strongly constrained by nuclear experiments (low order)

Empirical constraints

M.Fortin et al PRC 2016



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- Empirical parameters $(E_0, \rho_0, K_0, J_{sym}, L_{sym}, K_{sym} \ldots)$ are strongly constrained by nuclear experiments (low order)
- **Uncorrelated distribution of empirical parameters within nuclear physics uncertainty gives a physically founded prior**
- **Bayesian determination of the posterior**

Bayesian implementation of the constraints

- $\vec{X}$: parameter set; w: filter
- Bayes theorem:

$$\underbrace{P(\vec{X}|w)}_{\text{Posterior}} = \frac{\overbrace{P(w|\vec{X})}^{\text{Filter}}\overbrace{P(\vec{X})}^{\text{Prior}}}{P(w)}$$

$$\vec{X} = (E_0, \rho_0, K_0, J_0, L, \dots)$$

- Uncorrelated flat prior:

$$p_{prior}(\vec{X}) = \prod_{k=1}^{2(N+1)+3} f(X_k^{min}, X_k^{max}; X_k)$$

- Filters:
  - o **ab-initio EoS (LD)**
  - o **NS observation (HD)**
  - o **Nuclear masses**

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

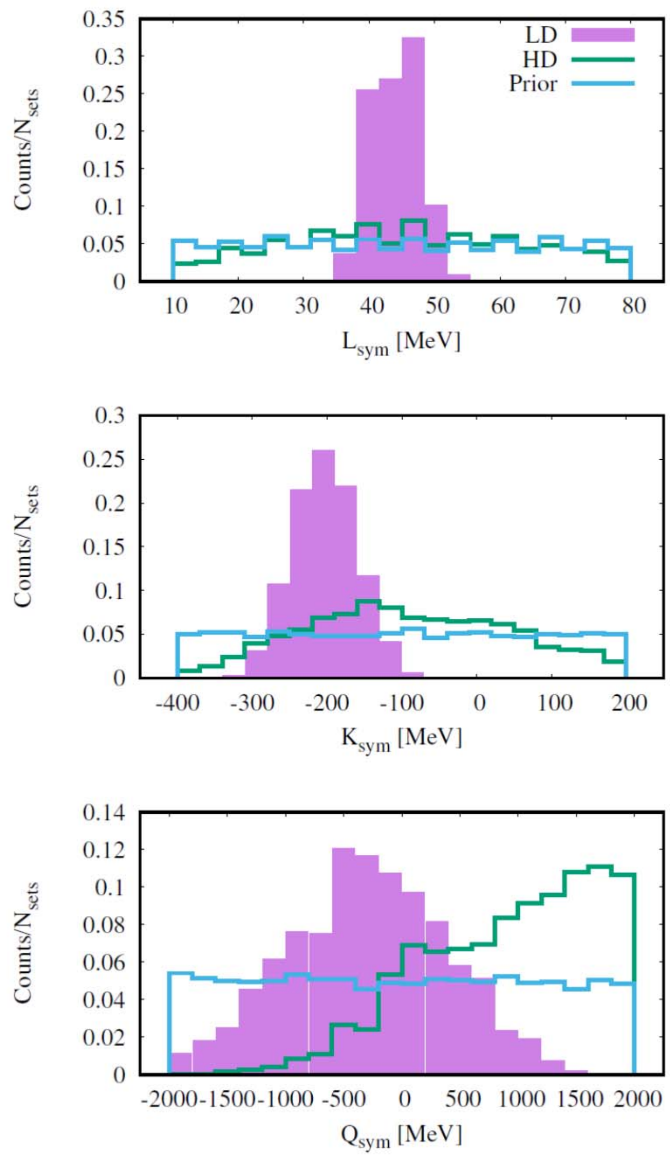
- Posterior calculation of observables:

$$p(Y) = \prod_{k=1}^{2(N+1)+3} \int_{X_k^{min}}^{X_k^{max}} dX_k Y(\vec{X}) p_{post}(\vec{X}),$$

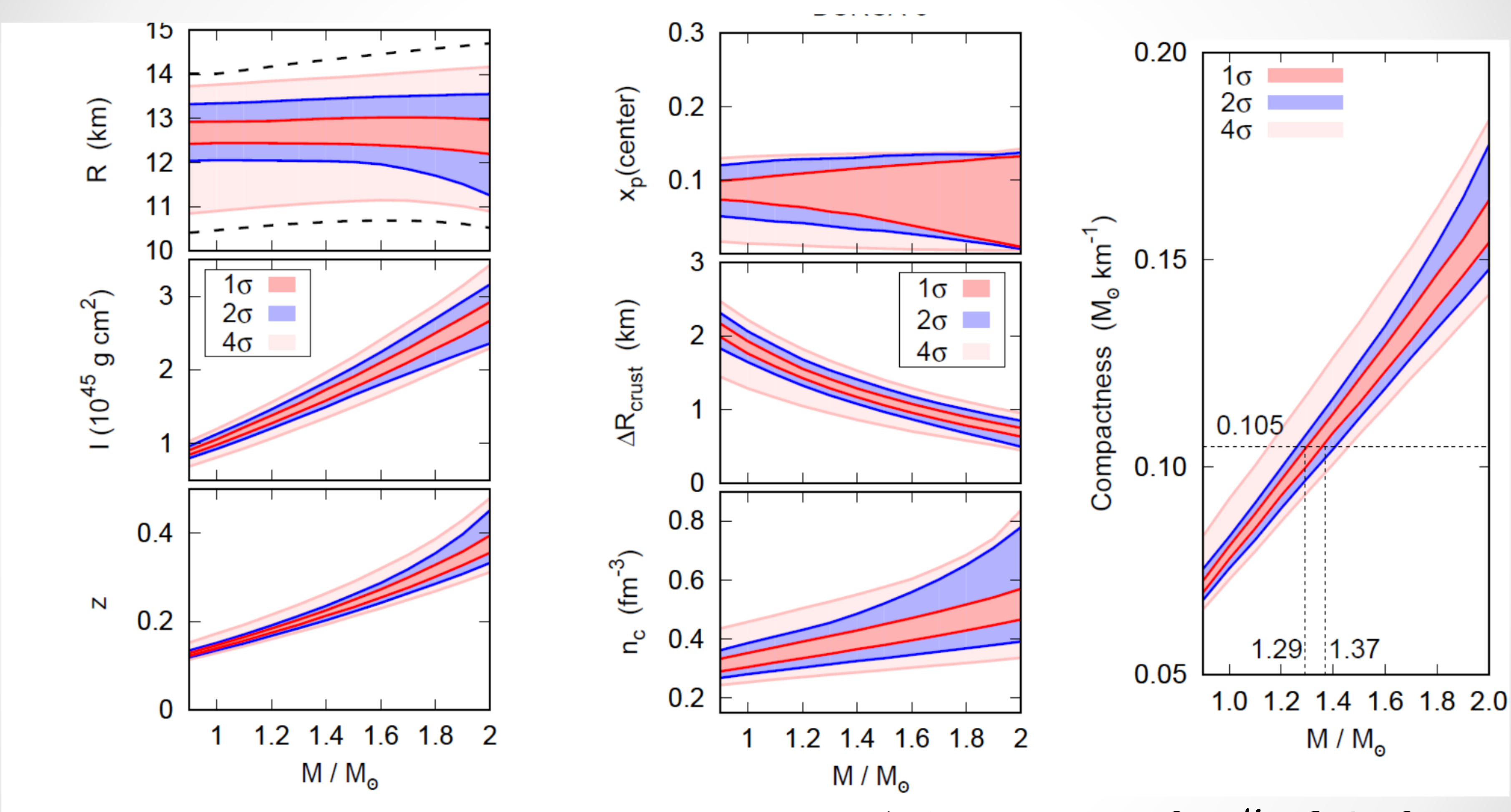
Bayesian implementation of the constraints

J.Margueron, R.Casali FG PRC 2018
T.Carreau et al, to be submitted

Parameter	Unit	Prior		HD		LD	
		Min	Max	Average	σ	Average	σ
n_{sat}	fm^{-3}	0.15	0.17	0.1600	0.0060	0.1641	0.0049
E_{sat}	MeV	-17	-15	-16.01	0.61	-15.29	0.25
K_{sat}	MeV	190	270	229	24	234	23
Q_{sat}	MeV	-1000	1000	200	535	-31	362
Z_{sat}	MeV	-3000	3000	1038	1233	-146	1728
E_{sym}	MeV	26	38	33.53	3.48	30.71	0.76
L_{sym}	MeV	10	80	45.45	17.97	43.66	3.68
K_{sym}	MeV	-400	200	-92	136	-202	42
Q_{sym}	MeV	-2000	2000	913	740	-253	673
Z_{sym}	MeV	-5000	5000	1463	2216	-114	2868
m^*_{sat}/m		0.6	0.8	0.70	0.06	0.70	0.06
$\Delta m^*_{sat}/m$		0.0	0.2	0.10	0.06	0.10	0.06
b		1	10	5.3	2.7	5.2	2.6



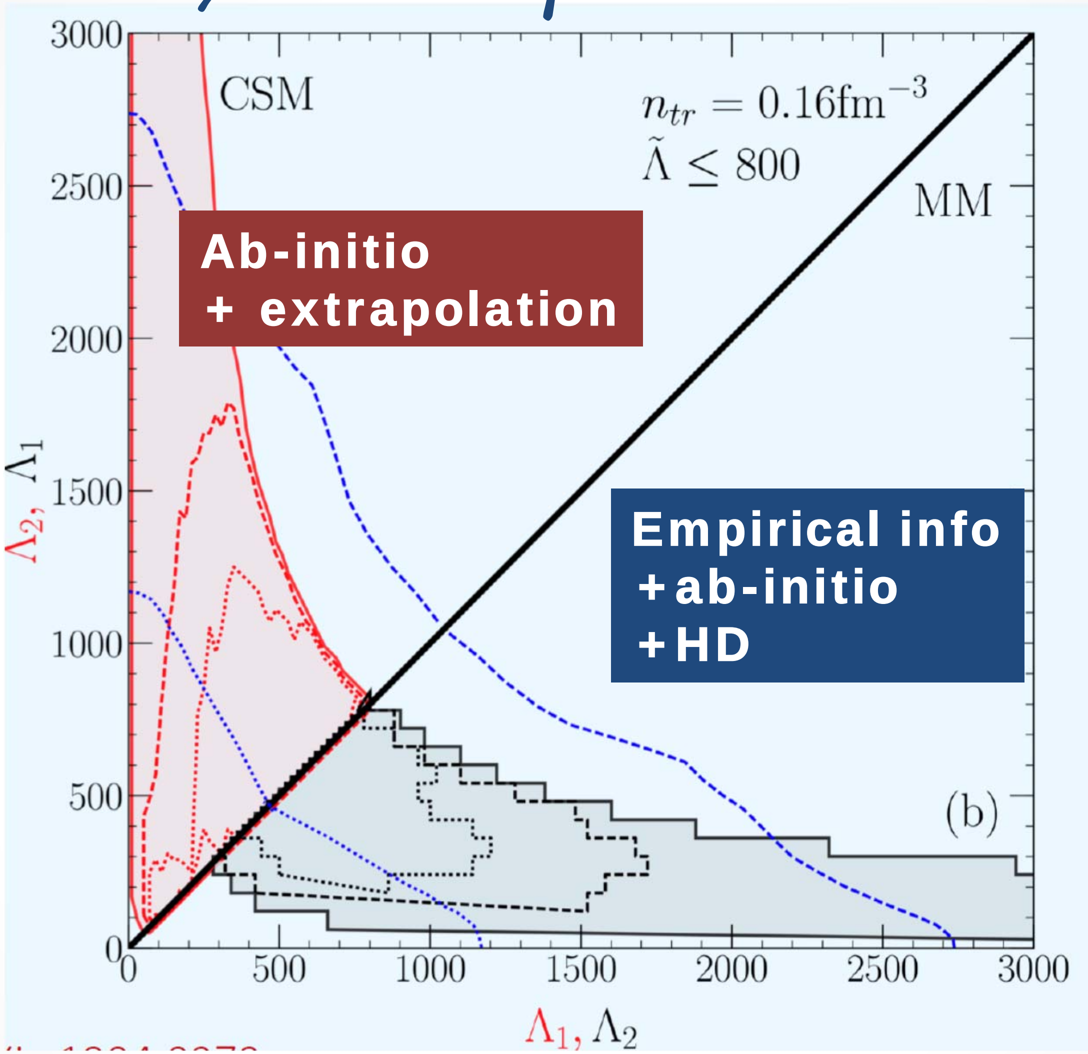
1) Static observables



J.Margueron, R.Casali FG PRC 2018

- Tighter bounds require further constraints on higher order parameters!

2) Tidal polarizability



I.Tews, J.Margueron, S.Reddy, arXiv:1804.0273

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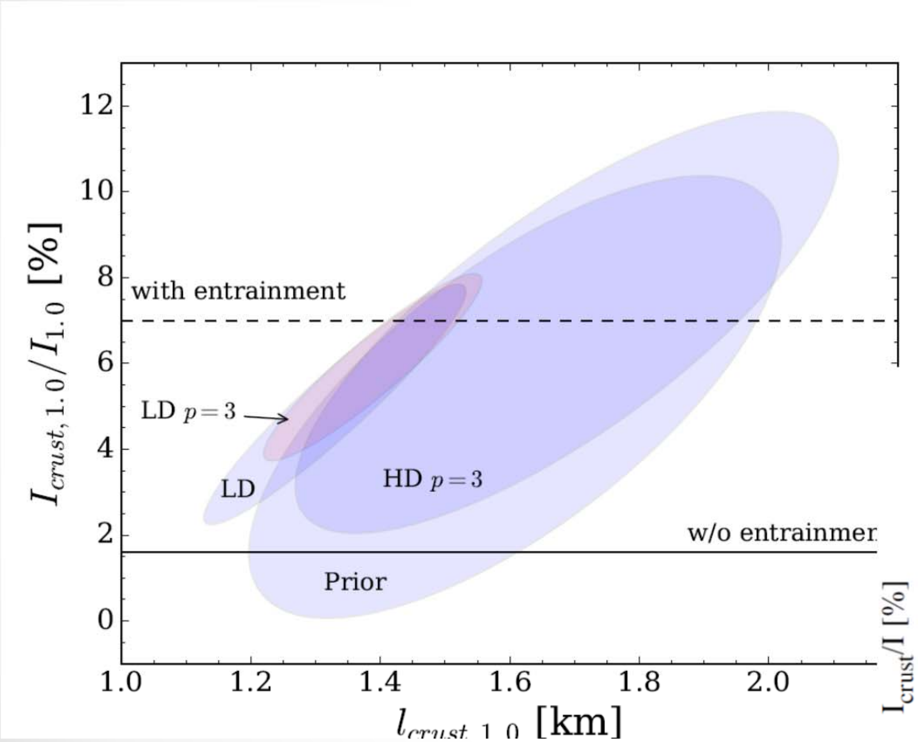
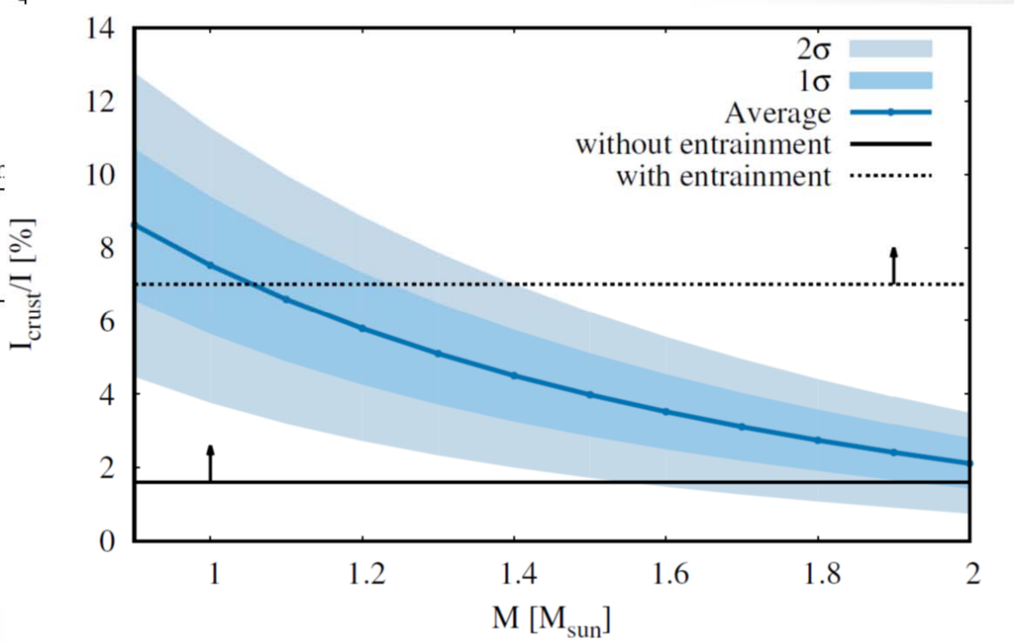
3) Pulsar glitches

T.Carreau et al, to be submitted





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$I_{crust}/I_{1.0}$

	n_{sat}	E_{sat}	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}	m^*/m	$\Delta m^*/m$	b	p	σ_0	b_s
LD p=3	-0.01	-0.02	0.17	-0.08	-0.05	-0.28	-0.38	0.48	0.78	-0.39	-0.02	0.05	-0.04	0.00	0.02	0.18
HD p=3	-0.03	0.24	0.27	-0.26	0.08	0.26	-0.04	-0.31	0.45	-0.12	-0.04	0.04	-0.11	0.00	-0.23	-0.03
LD	0.03	-0.20	0.14	-0.06	-0.03	-0.11	-0.24	0.31	0.53	-0.25	-0.02	0.04	-0.02	0.56	0.44	0.58
HD	-0.02	0.14	0.25	-0.24	0.08	0.25	-0.04	-0.29	0.41	-0.11	-0.03	0.04	-0.09	0.26	-0.09	0.18
Prior	0.02	0.12	0.18	-0.14	0.02	0.25	0.01	-0.45	0.49	-0.08	0.00	-0.12	-0.17	0.11	-0.09	0.10

- Tighter bounds require

further high density AND NUCLEAR SURFACE constraints!

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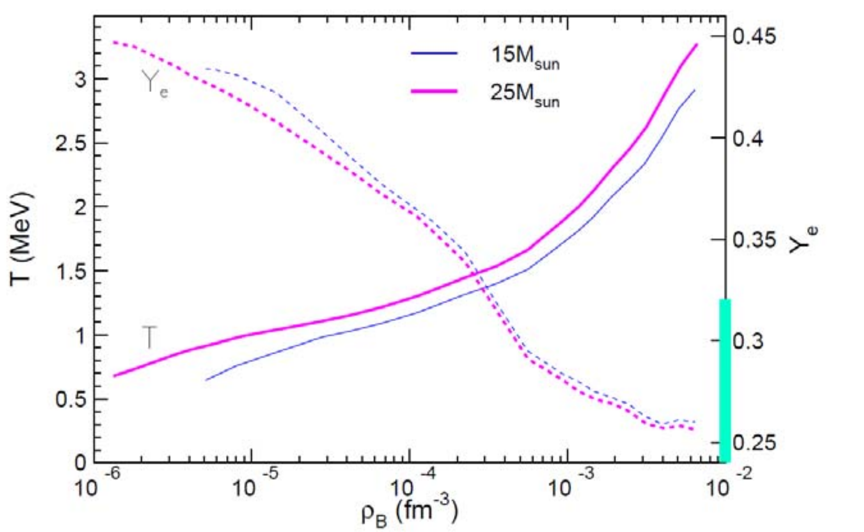
R-process Accretion	Nuclei	Strong interaction out of eq.	Strong&weak rates Fission Masses

=> Concerning the EoS, tighter bounds require constraining the high order isovector empirical parameters K_{sym}, Q_{sym}

Backup

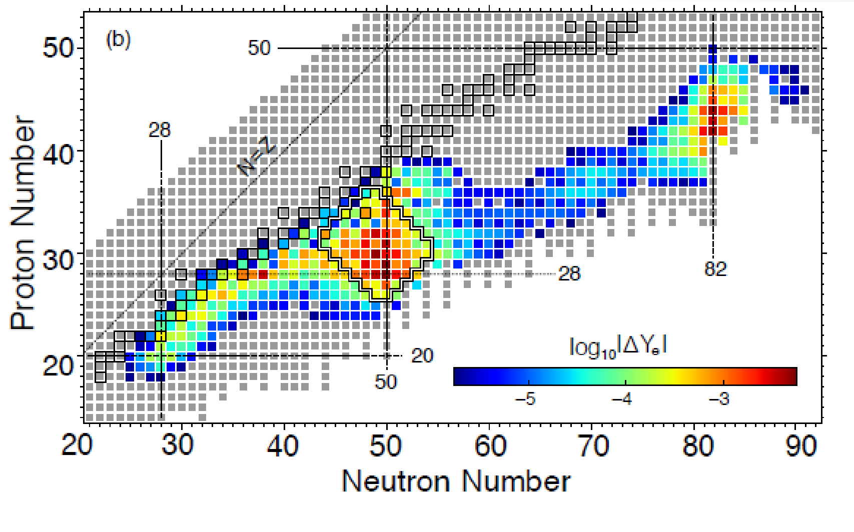
Electron capture and core collapse

- Matter becomes increasingly neutron-rich during core-collapse because of electron capture on nucleons and nuclei



C.Juodagalvis 2010

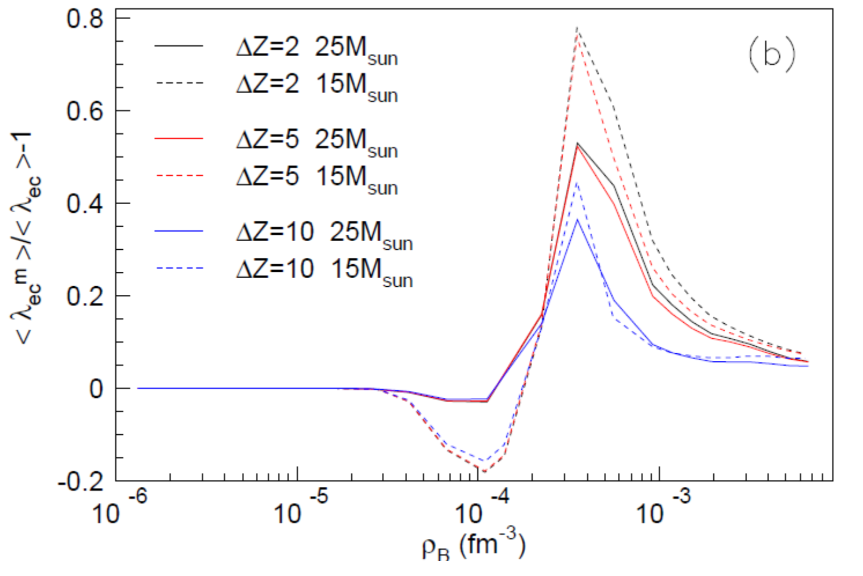
- In the late stage of the collapse, matter is essentially constituted by exotic nuclei around the N=50 and N=82 magic numbers

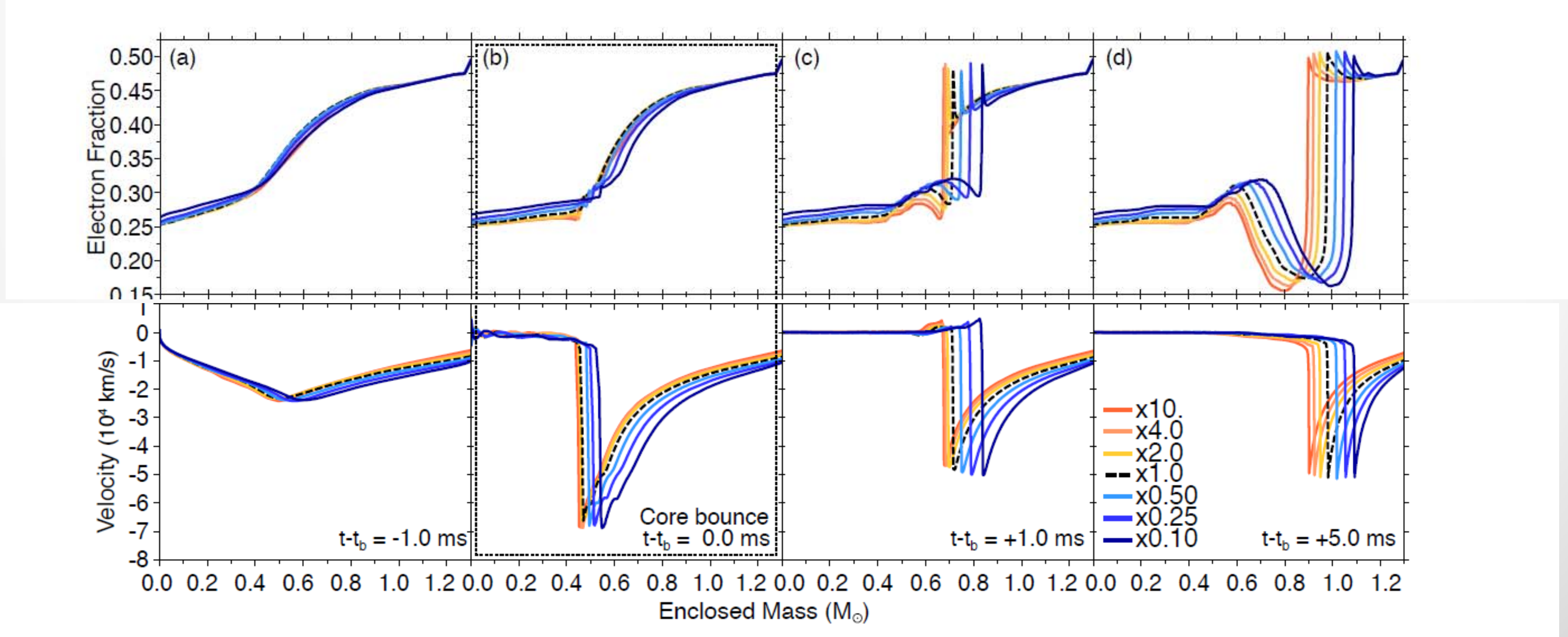


C.Sullivan 2015

Electron capture and core collapse

- The supernova evolution crucially depends on the e-capture rate.
- In turn, this depends on the mass of exotic N=50 nuclei and their β-decay properties.





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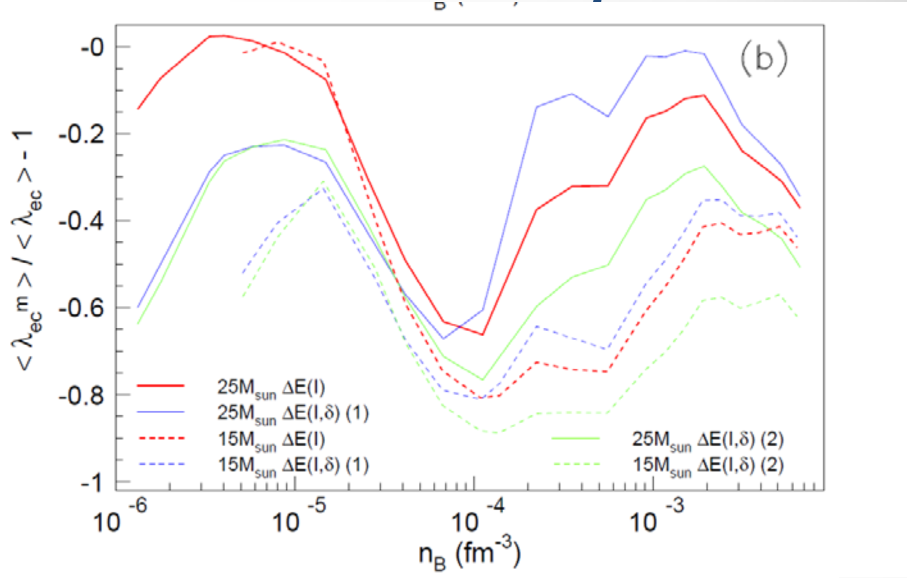
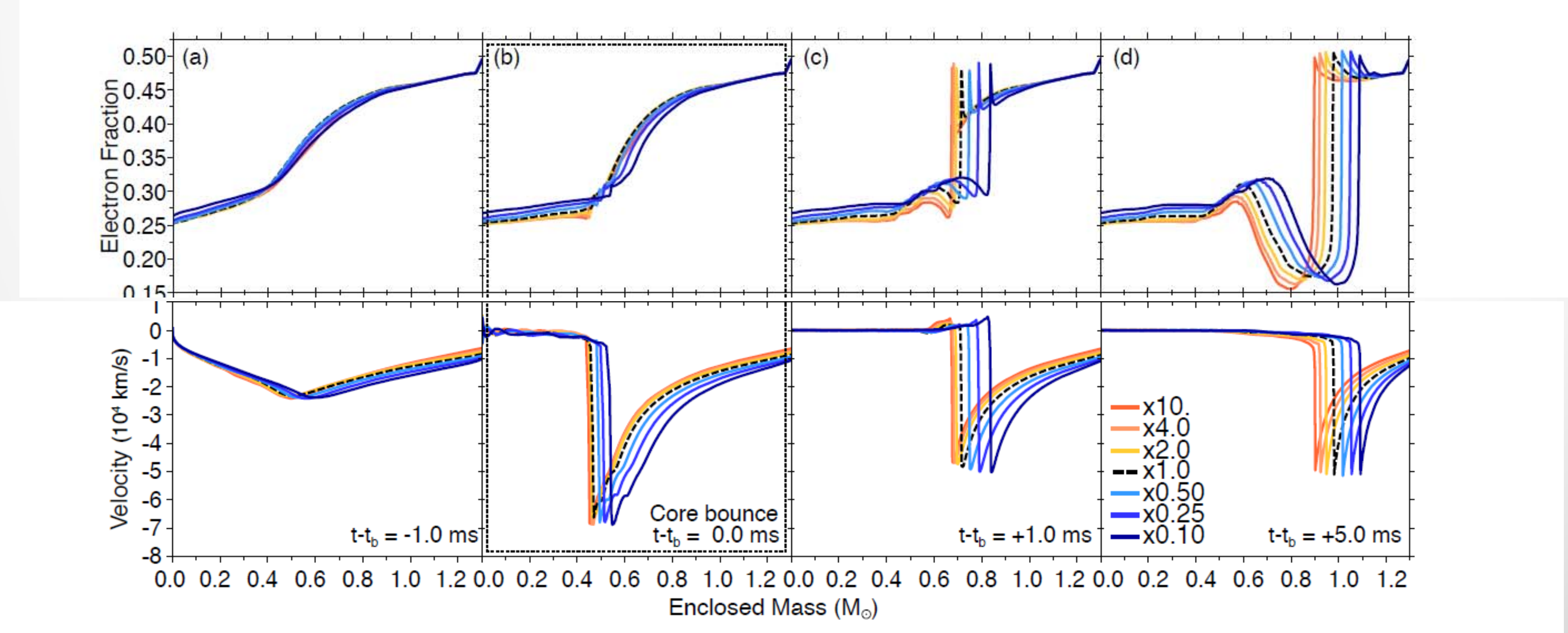
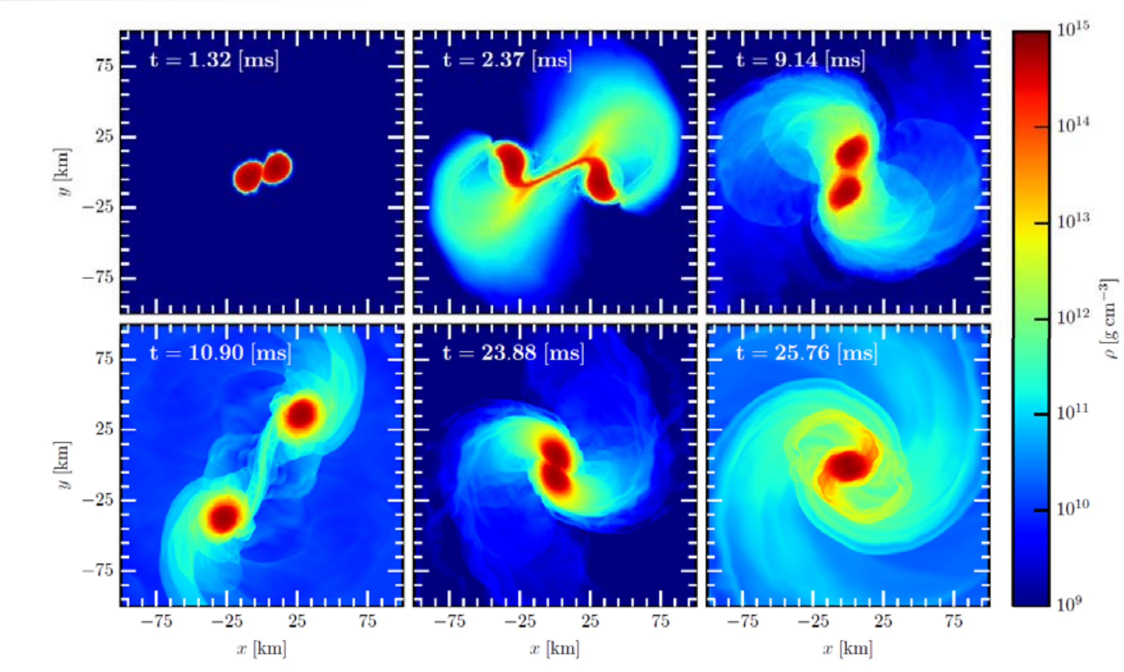


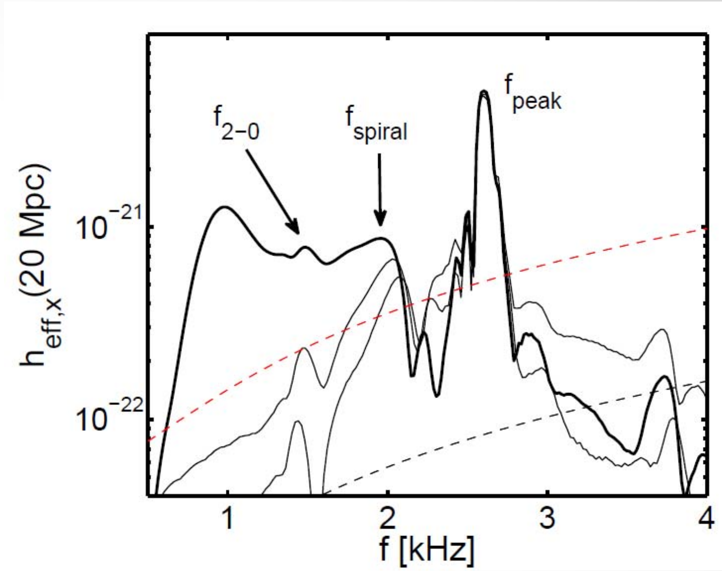


EoS and GW signals

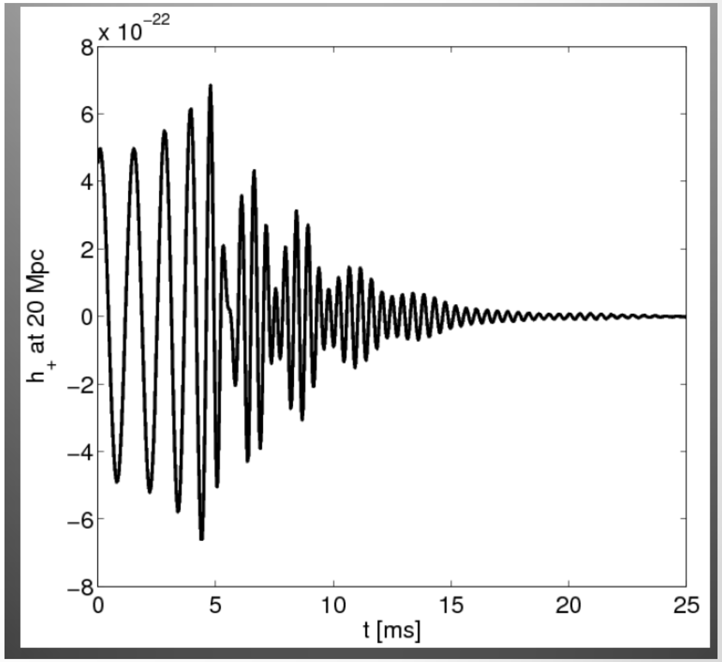
- Post-merger signals (~100-500 Hz)



A.Radice et al ArXiV 1601.02426

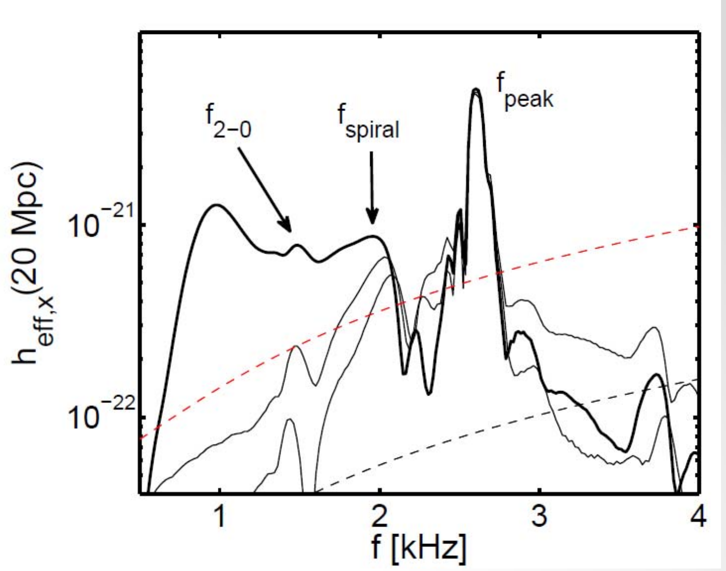


A.Bauswein, arXiV:1508.05493



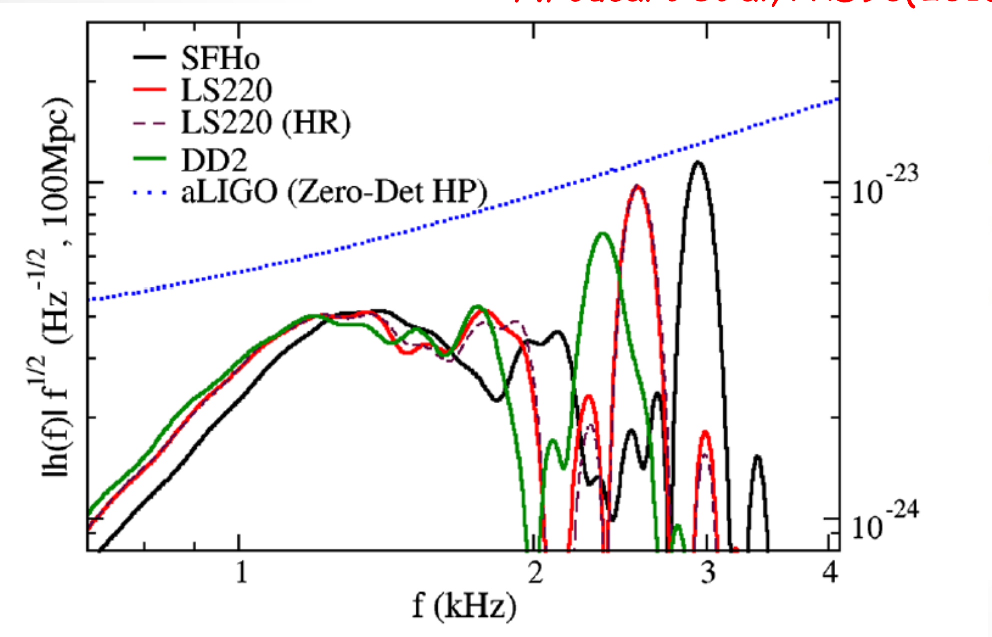
EoS and GW signals

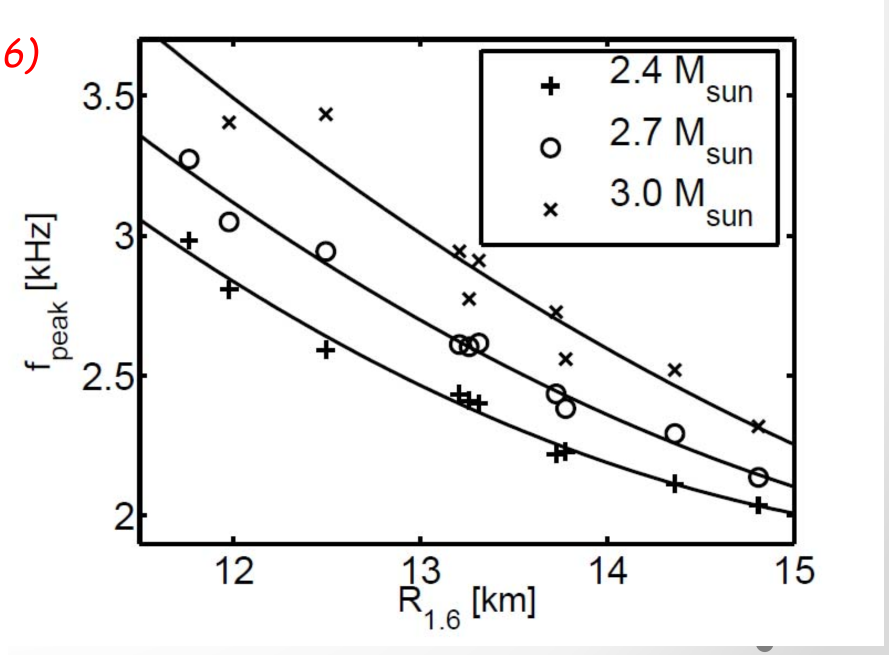
- Post-merger signals (~100-500 Hz)
  - fundamental quadrupole fluid mode (f-peak) of the differentially rotating post-merger remnant
  - Strongly correlated to the radius=>EoS



A.Bauswein, arXiV:1508.05493

F.Foucart et al, PRD93(2016)





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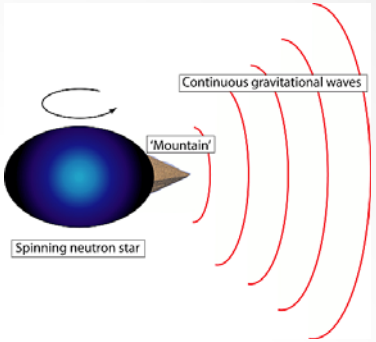
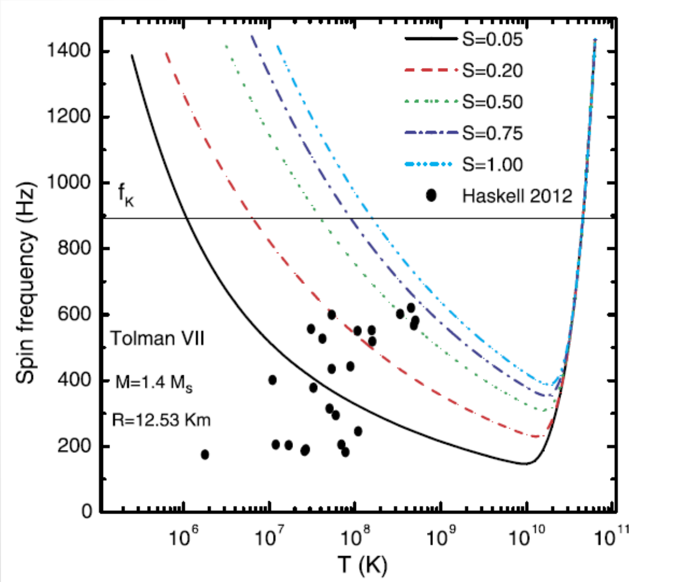
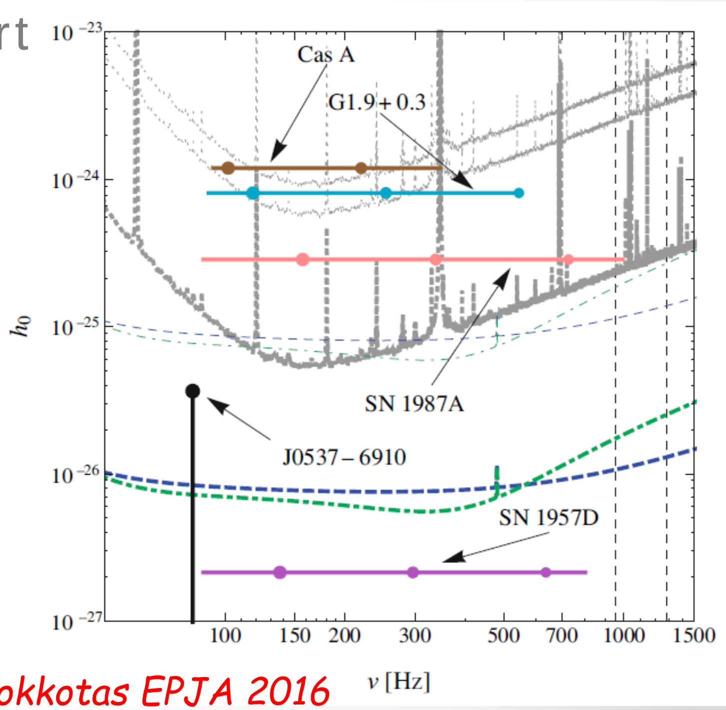


- Spinning NS with asymmetric deformations (~1-10 Hz)
  - Elastic strains in the crust or magnetic fields in the core
  - Too weak for aLIGO and ET
- Unstable r-modes in young sources (~100-500 Hz)
  - Undamped by viscous dissipation if T and ν are high enough
  - Potentially detectable + EM counterpart
  - Very complex modelling
-



C.C.Moustakidis, Astrophys.Space Sci. 2016



C.D.Kokkotas EPJA 2016

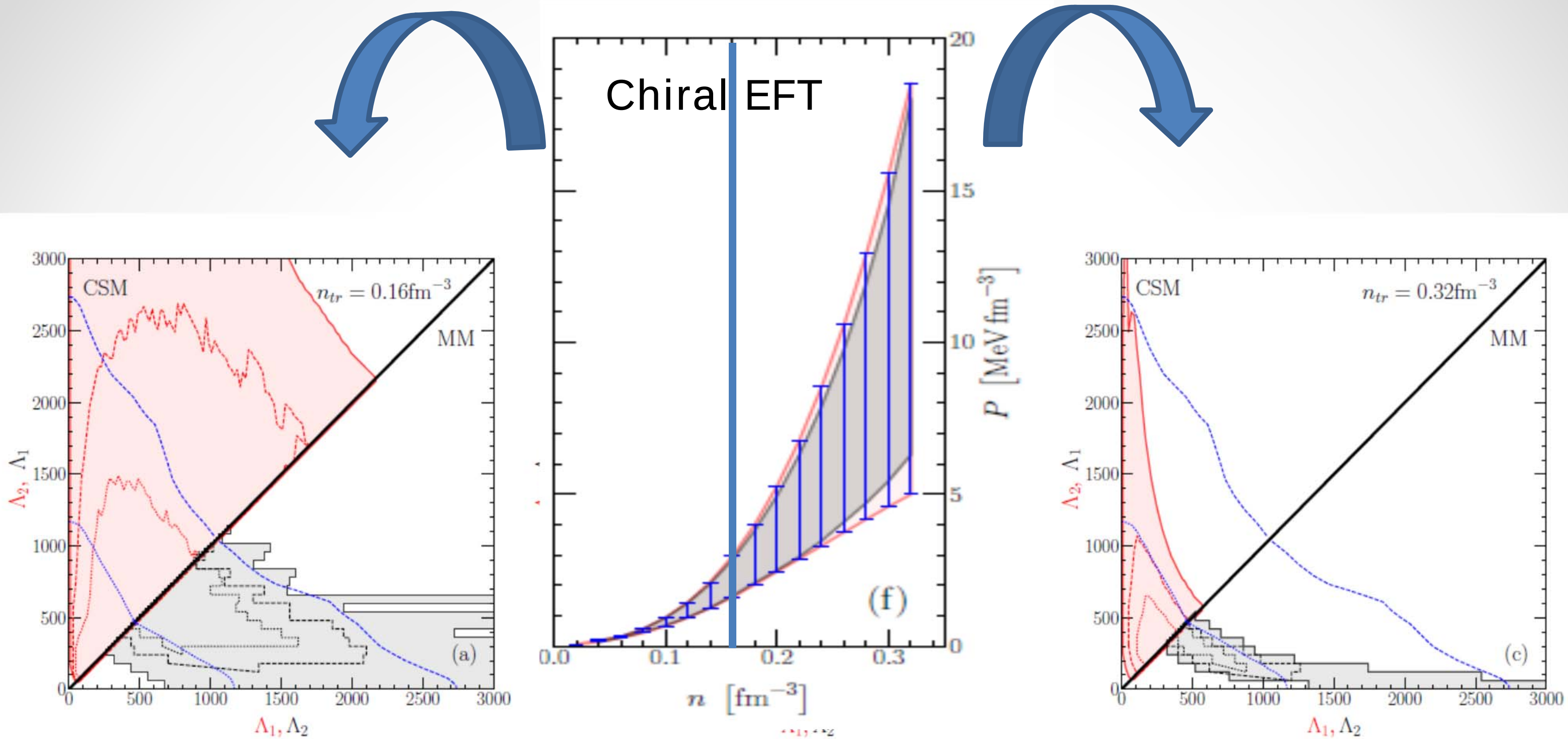


FIG. 1. Envelopes for the CSM (red) and the MM (black) for the correlation of the tidal polarizabilities Λ_1 and Λ_2 of the two compact stars in GW170817. We show: panel (a) the results for $n_{\rm tr} = n_{\rm sat}$ and no constraint on $\tilde{\Lambda}$, panel (b) for $n_{\rm tr} = n_{\rm sat}$ when 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).

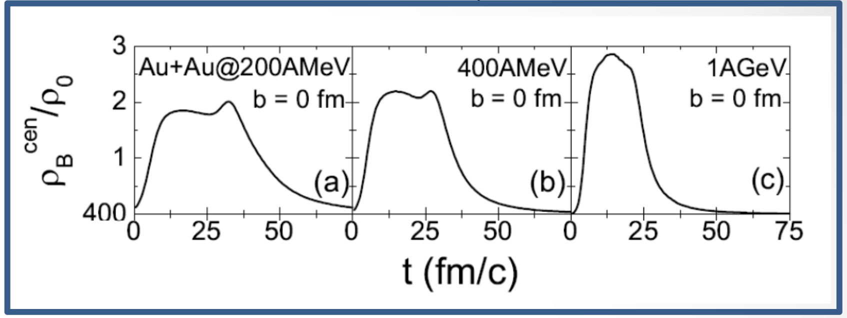
I.Tews, J.Margueron, S.Reddy, INT-PUB-18-014

Drastic improvement if
the high density EoS is constrained!

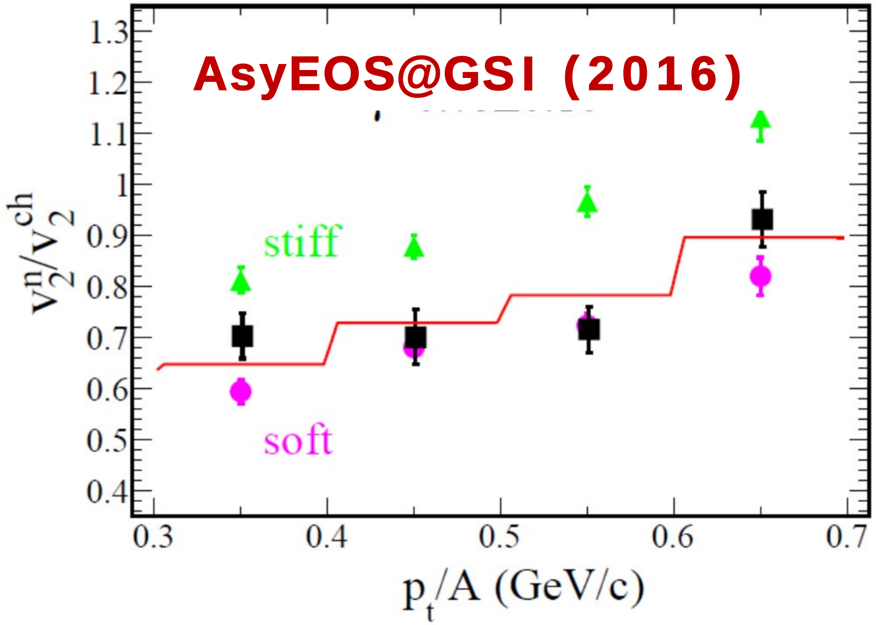
How to further constrain the high density EoS?

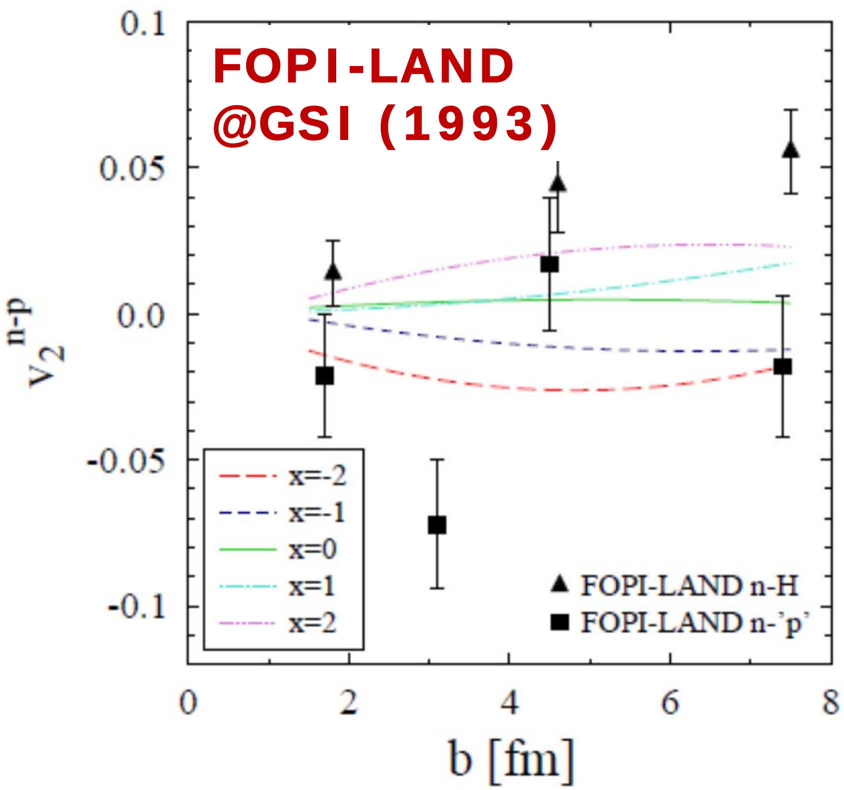
Strategy I: high density constraints

J.Xu, PRC 2013



P.Russotto et al,PRC 2016

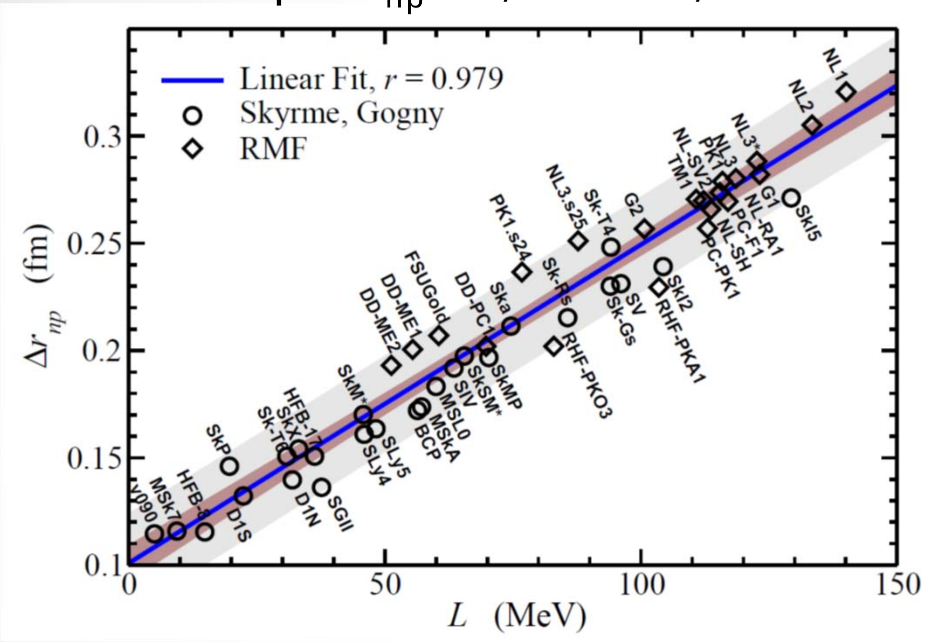




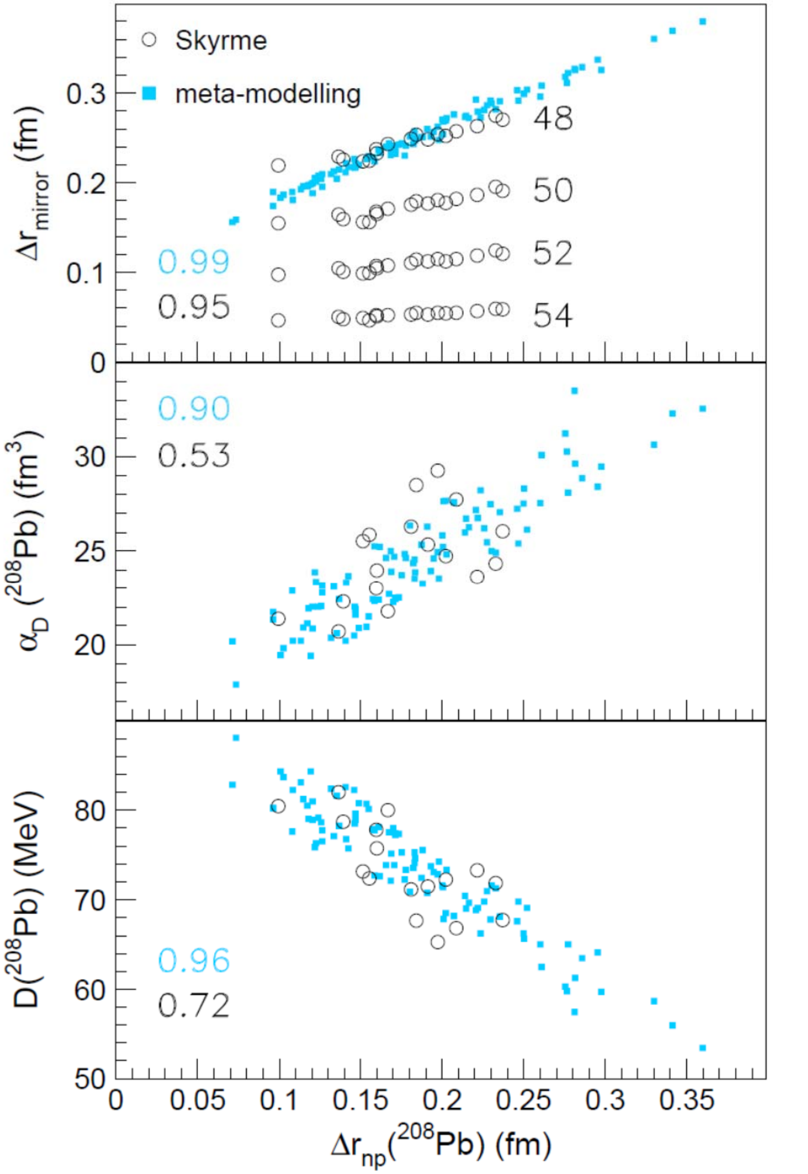
Differential elliptic flow for Au+Au 400 A.MeV

Strategy II: high precision

Exp: Δr_{np}= 0,1318-0,3072



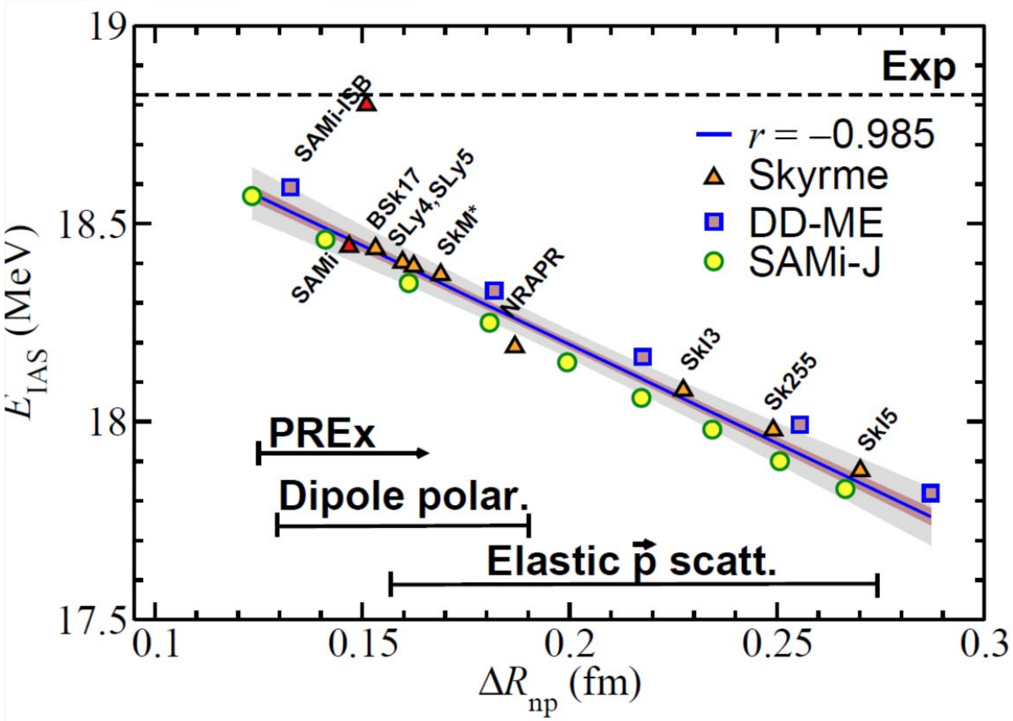
F.G, A.Raduta 2018



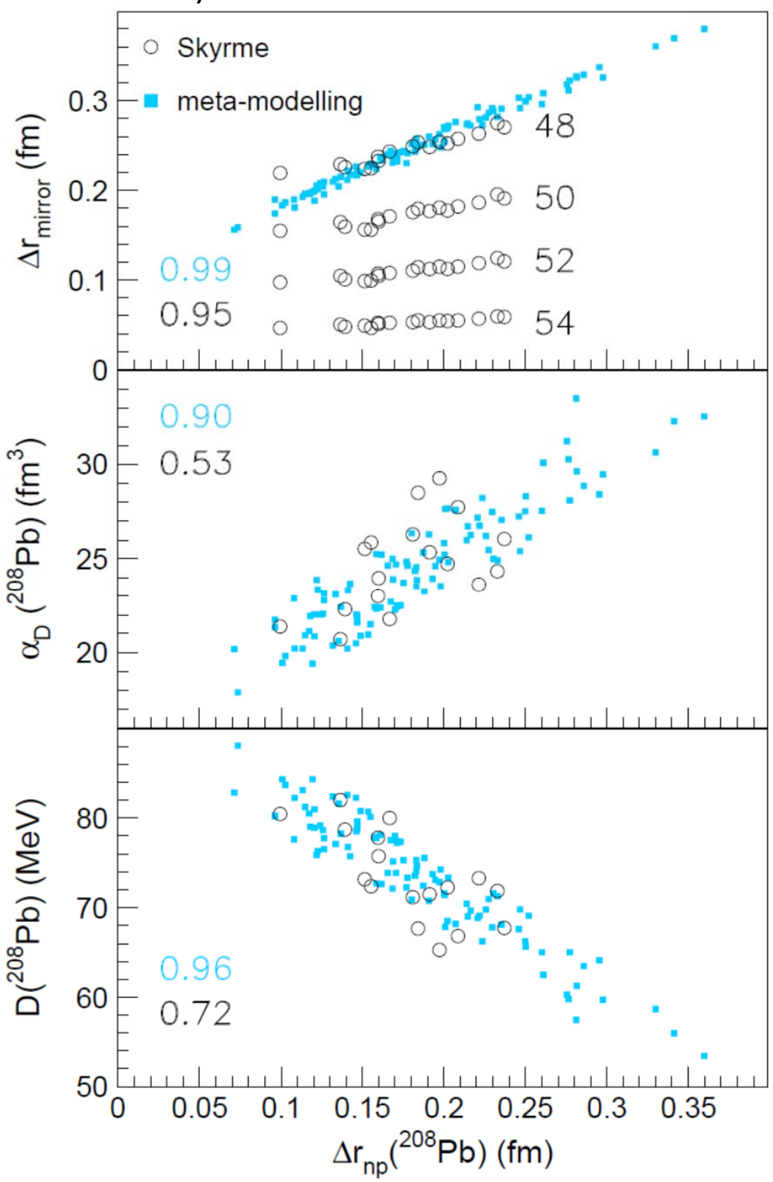
X.Vinas et al 2014
P.G.Reinhard, W.Nazarewicz 2016
D.Chatterjee, F.G. 2017
J.Yang, J.Piekarewicz 2017

Strategy II: high precision

F.G, A.Raduta 2018



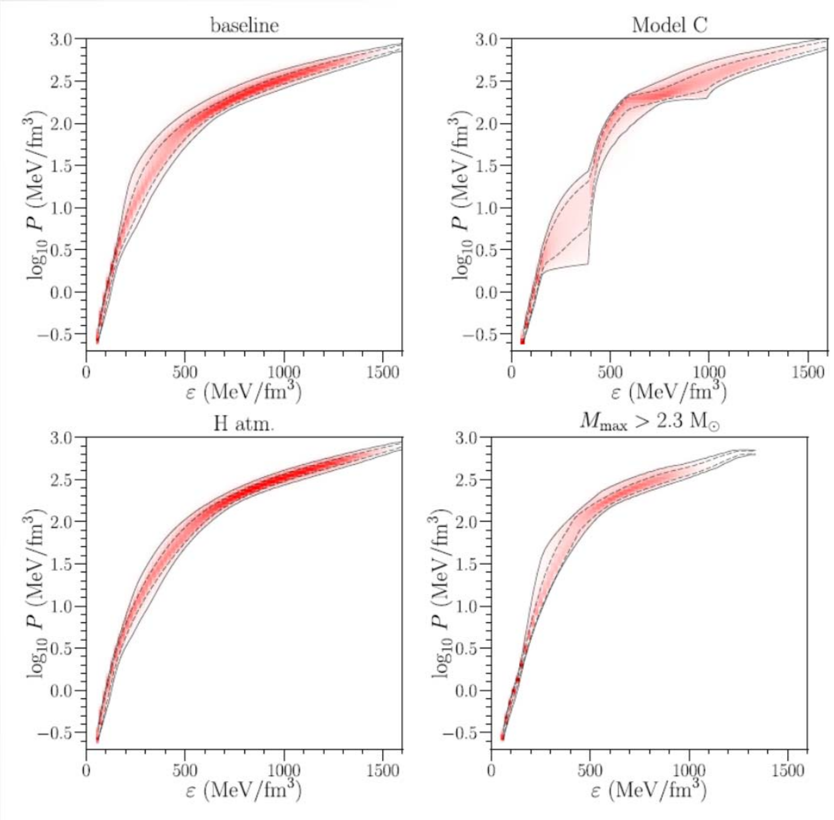
X.Roca-Maza, G.Colo, H.Sagawa 2018

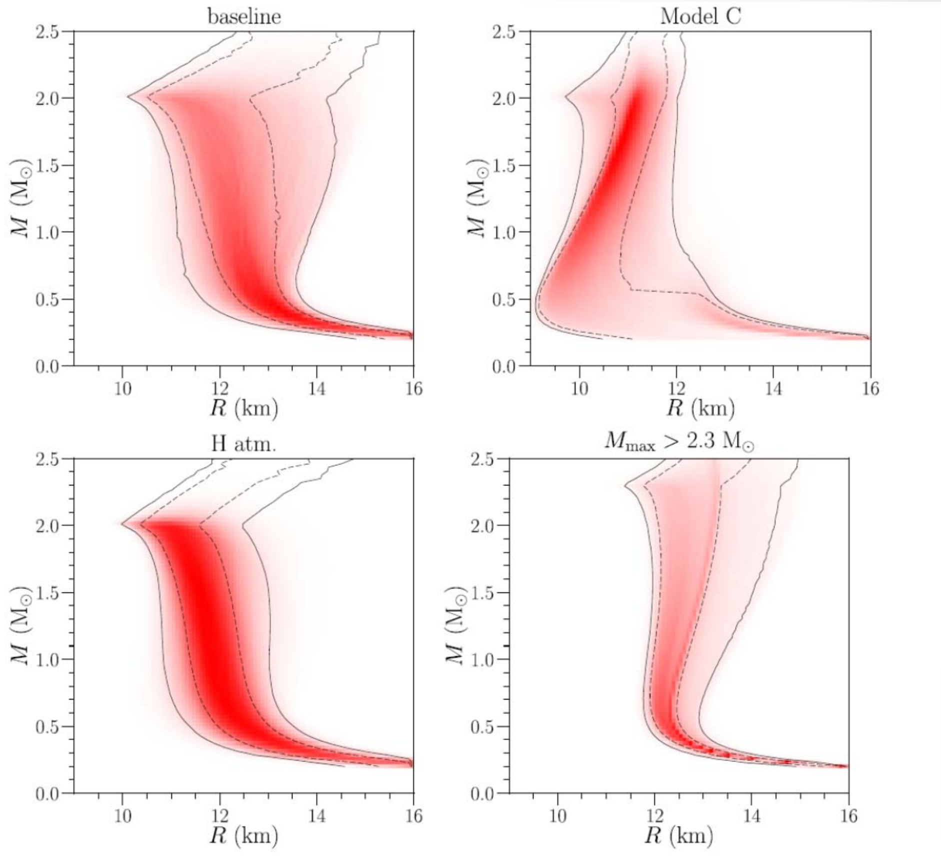


Recent review: X.Roca-Maza, N.Paar Prog.Part.Nuc.Phys.2018

Constraining the EoS: NS observation

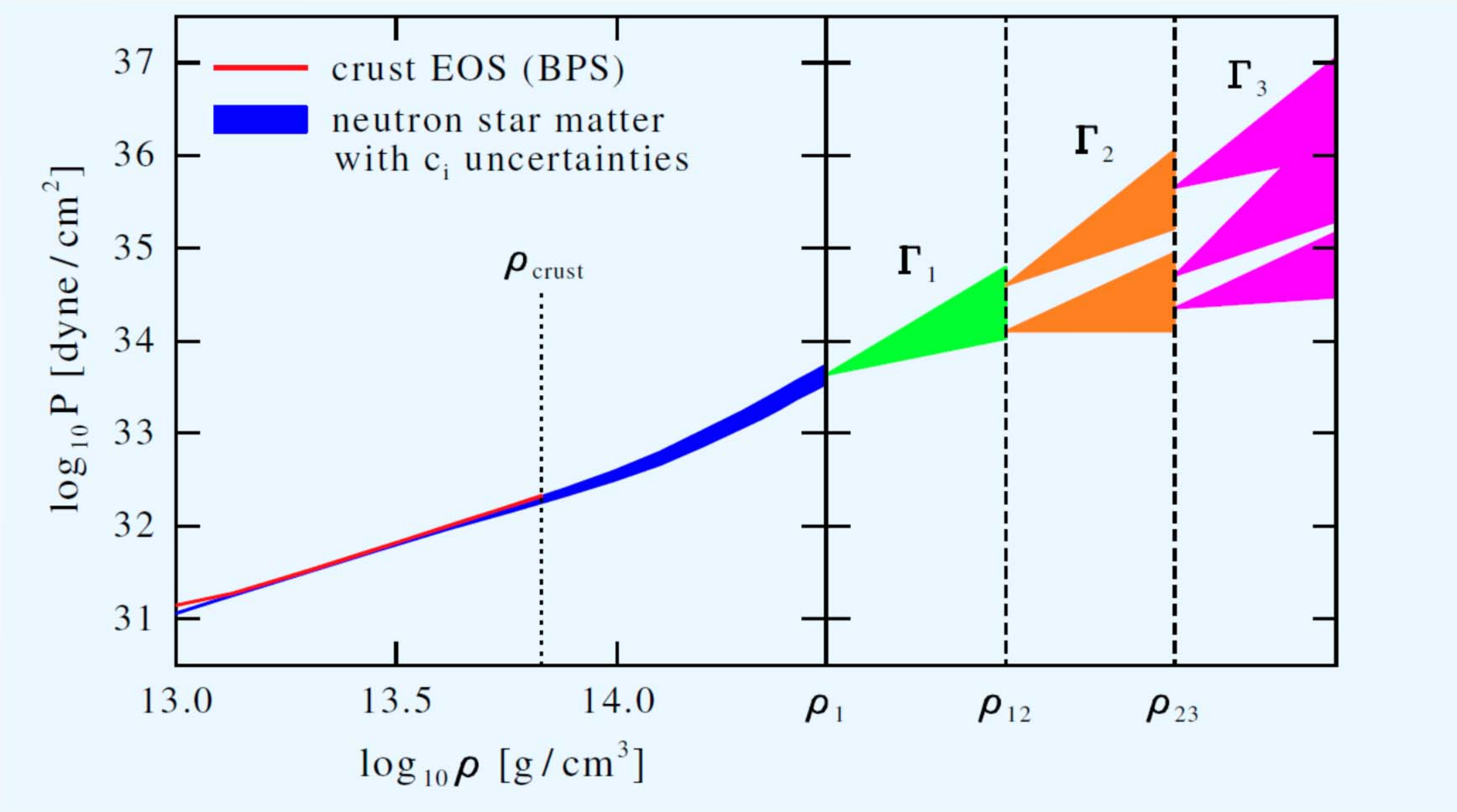
A.W.Steiner et al, MNRAS 2018





Model C: Piecewise polytropic expansion Steiner Lattimer Brown ApJ 2013

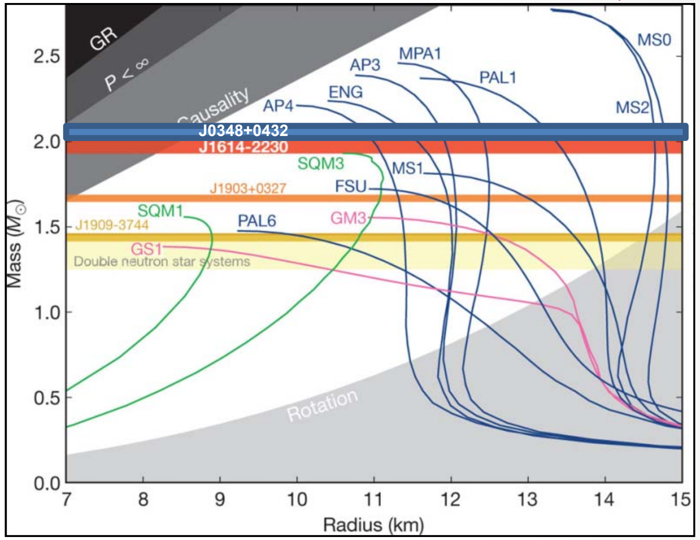
Constraining the EoS: NS observation



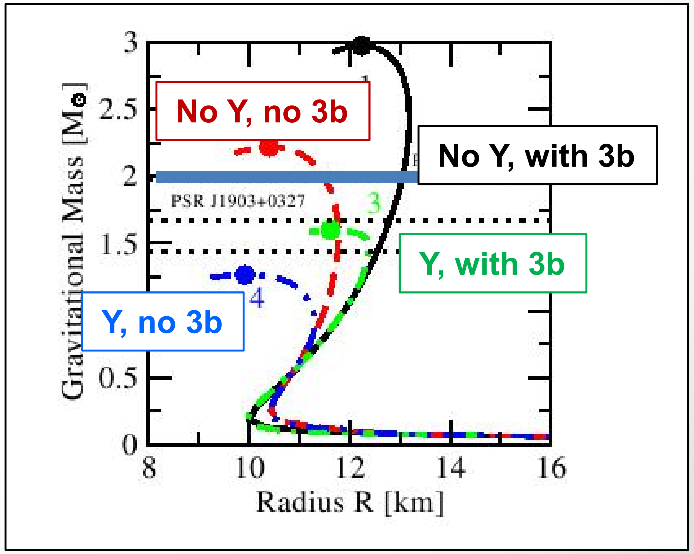
Piecewise polytropic expansion Steiner Lattimer Brown ApJ 2013

NS mass and the hyperon puzzle

P. Demorest et al., Nature 467 1081 (2010).
J. Antoniadis et al., Science, 340, 6131 (2013).



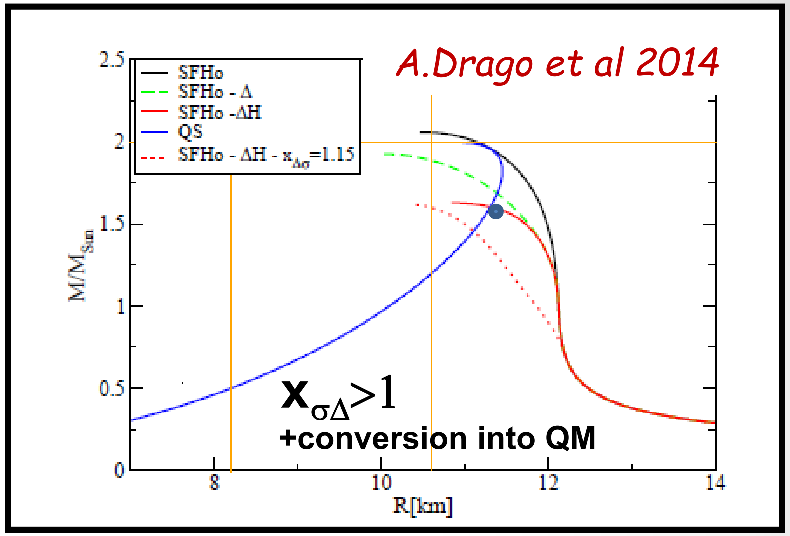
- The highest mass is associated to the highest central density.
- If $\mu(\rho) > m_Y c^2 + U_Y$, hyperon Y should appear
- The appearence of a new degree of freedom softens the EoS=>reduces the mass
- $2M_O$ neutron star should not exist if U_Y is calculated with microscopic BHF based on experimental bare interactions

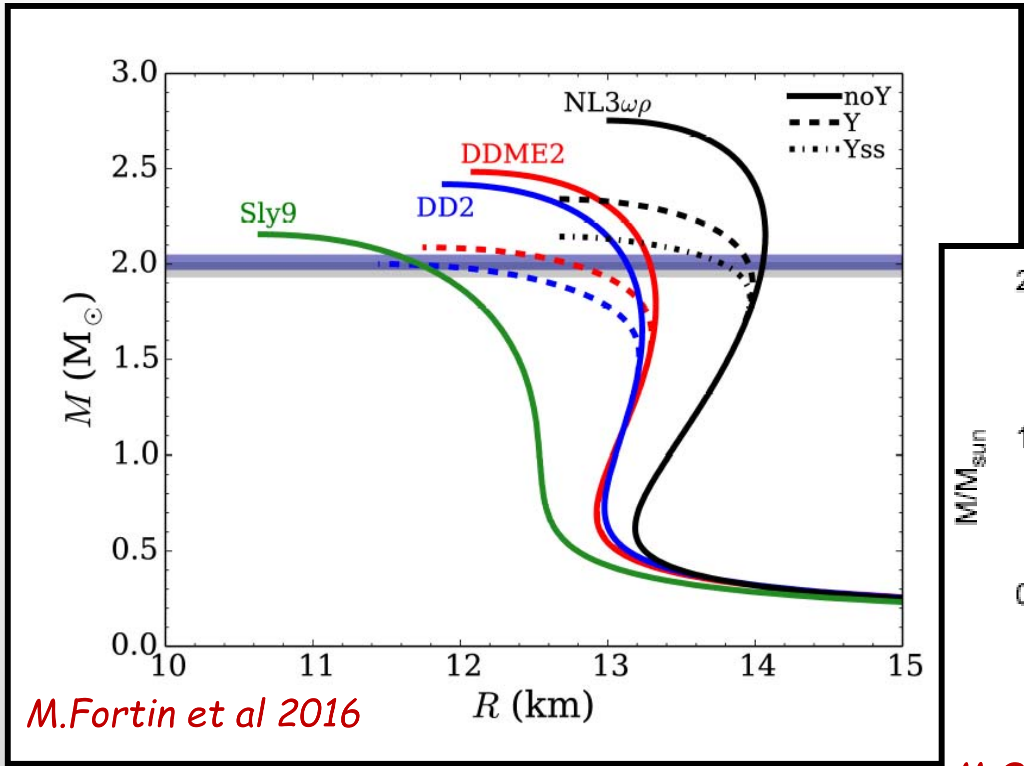


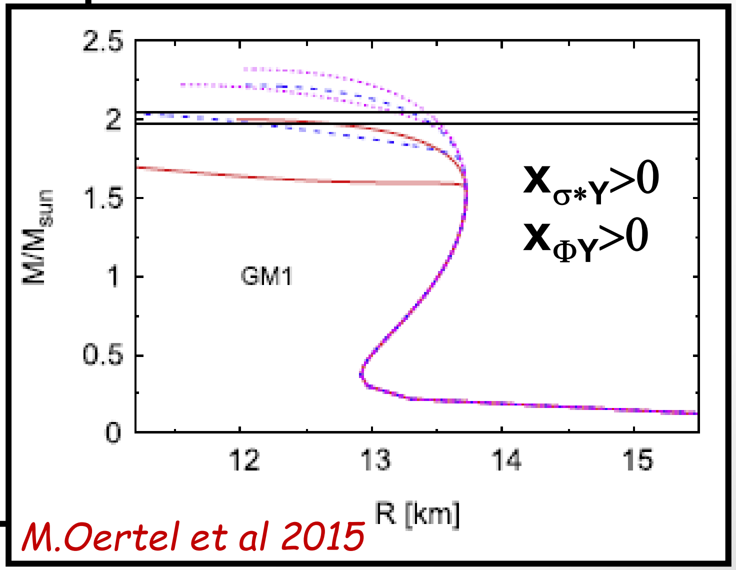
I.Vidana et al, Europhys.Lett.94:11002,2011

The hyperon puzzle: solutions

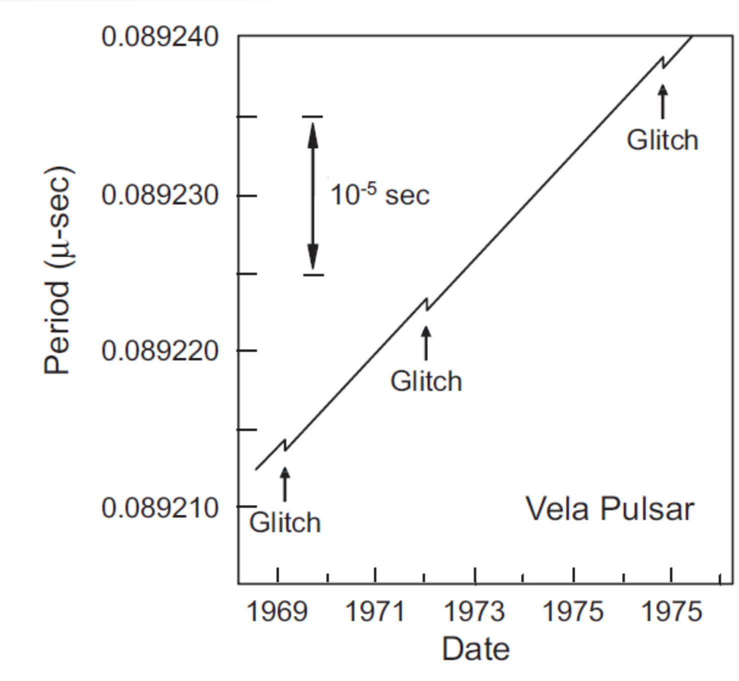
- Stiffening of the EoS above rho0?
- New strangeness couplings at high density ?
- Transition to quark matter ?





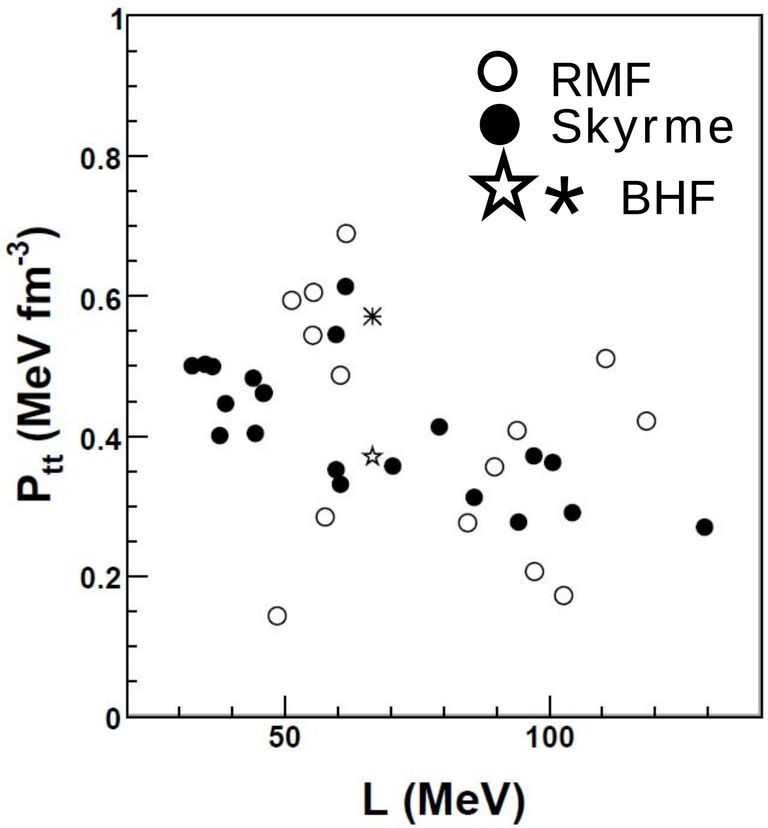


Pulsar glitches



- In some pulsars "glitches" are observed where the spin rate suddenly jumps to a higher value
- Glitches indicate some internal rearrangement has altered the rotation rate by a small amount.
- Sudden unpinning of the superfluid vortices from the crystal lattice during the slowing down due to the differential rotation between the fast vortices and the slow star
- Angular momentum transfer to the star which spins up

Pulsar glitches



C.Ducoin et al, PRC 2012

- $I_c/I>0.07$ to explain Vela data

$$I \equiv \frac{J}{\Omega} = \frac{8\pi}{3}\int_0^R r^4 e^{-\nu(r)}\frac{\bar{\omega}(r)}{\Omega}\frac{\left(\mathcal{E}(r)+P(r)\right)}{\sqrt{1-2GM(r)/r}}dr$$

$$I_{\rm crust} = \frac{8\pi}{3}\int_{R_t}^R r^4 e^{-\nu(r)}\widetilde{\omega}(r)\frac{\left(\mathcal{E}(r)+P(r)\right)}{\sqrt{1-2GM(r)/r}}dr\ .$$

$\Rightarrow P_t>0.5$ MeV fm^{-3}

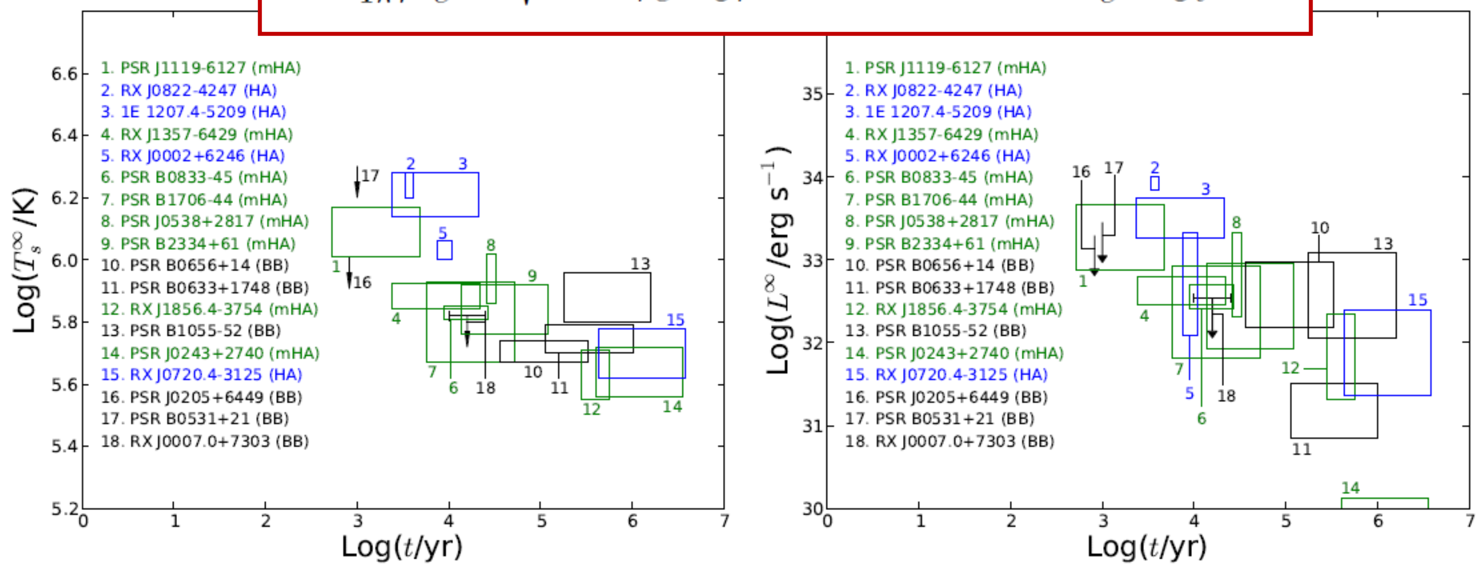
Results are extremely model dependent

Neutron star cooling

- Neutron stars are born hot, and cool down via neutrino emission
- Cooling curve can be inferred from luminosity measurements via atmosphere modelling
- Cooling depends on the neutrino emissivity and the heat capacity

$$\frac{L_r}{4\pi\kappa r^2} = -\sqrt{1-\frac{2Gm}{rc^2}}\,e^{-\Phi_g}\frac{\partial}{\partial r}\left(Te^{\Phi_g}\right) ,$$

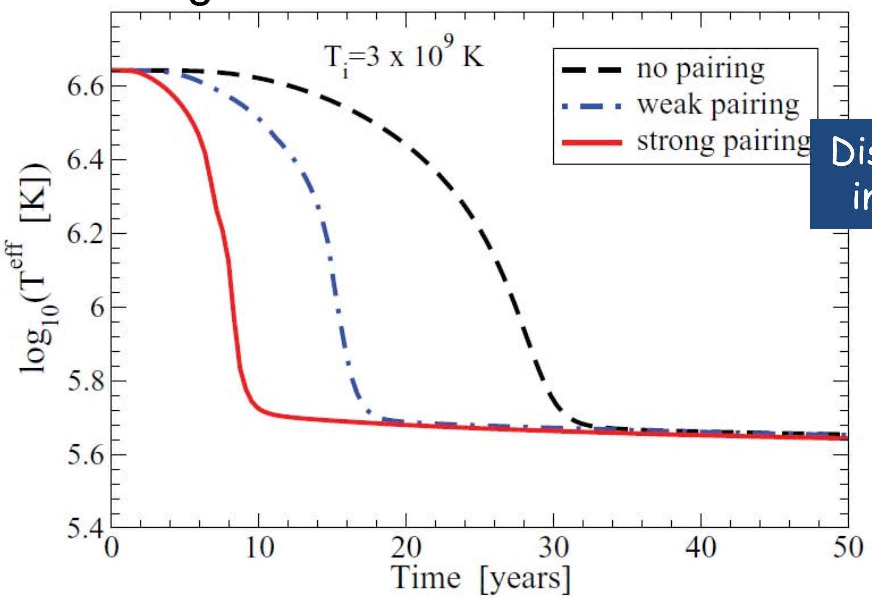
$$\frac{1}{4\pi r^2 e^{2\Phi_g}}\sqrt{1-\frac{2Gm}{rc^2}}\,\frac{\partial}{\partial r}\left(e^{2\Phi_g}L_r\right) = -Q_\nu - \frac{C_v}{e^{\Phi_g}}\frac{\partial T}{\partial t} ,$$



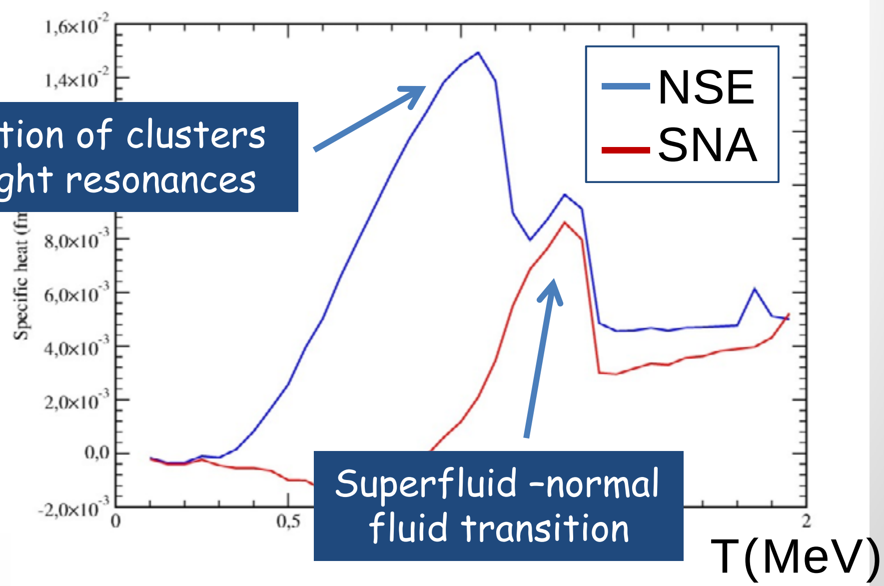
Neutron star cooling

- The cooling of very hot proto-neutron star is dominated by the heat capacity of the crust
- $^1S_0$ n- superfluidity is the key ingredient, but in-medium effects on the cluster distributions can play a role
- Unfortunately observations are not available

J.Margueron 2005



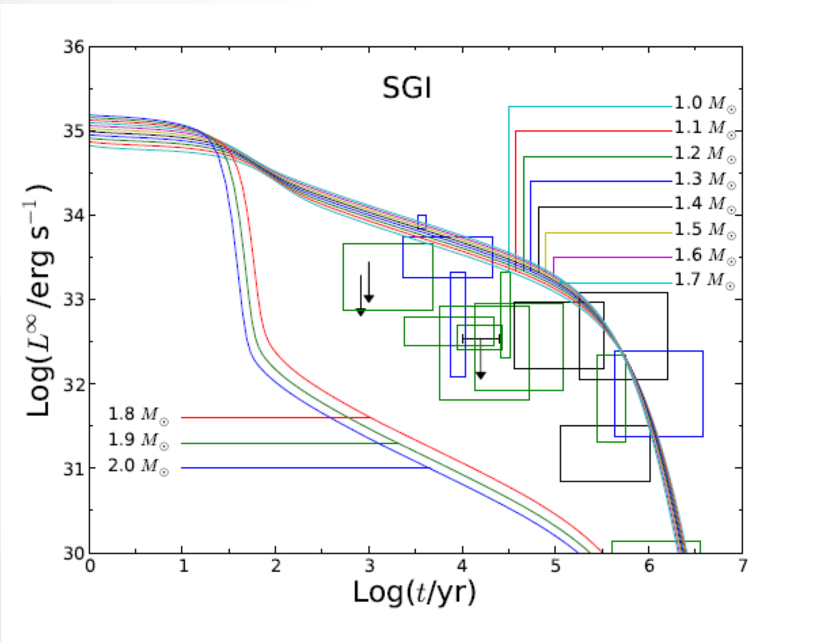
S.Burrello 2016



Neutron star cooling

- The ν emissivity dramatically depends on the possibility of DURCA: $n \rightarrow p + e + \nu$ and $p + e \rightarrow n + \nu$
- Momentum conservation implies $p_{Fn}(\rho) \leq p_{Fp}(\rho) + p_{Fe}(\rho)$ => needs a minimum proton fraction
- The minimum proton fraction allowing DURCA is determined by the EoS
- Enhanced cooling seems excluded, but the subject is still under debate

Lim 2015



Fortin 2016