The nEoS sets from hadron physics alone

Felipe J. Llanes-Estrada
& Eva Lope-Oter
(earlier collaborators,
Mark Alford & Andreas Windisch)

25/Feb/2021
COMPOSE2021 workshop
at Barcelona's avatar
Prerecorded talk available at
https://youtu.be/5FGpVDpD8kU

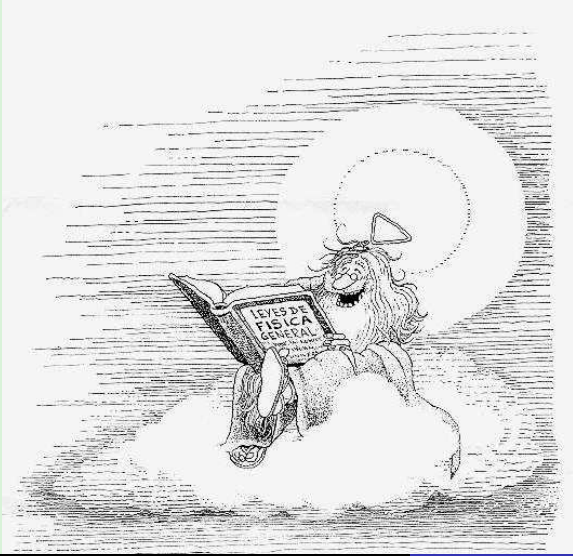
Outline

Testing Einstein's GR and constraining modifications

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Very well tested at solar-system (weak field)
- Well tested in binary pulsars (weak field)
- Tests starting near black holes and N^* mergers (strong field)
- Gravitational wave propagation

$\frac{c_g - c}{c} < 10^{-15}$!! but Einstein failed Unified Field Theory...



(As this cartoon by Quino illustrates)

But all are tests of the LHS

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Need to assess the Neutron Star interior!

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Need to assess the Neutron Star interior!

Distinguishing Nuclear matter- from Gravitational- effects

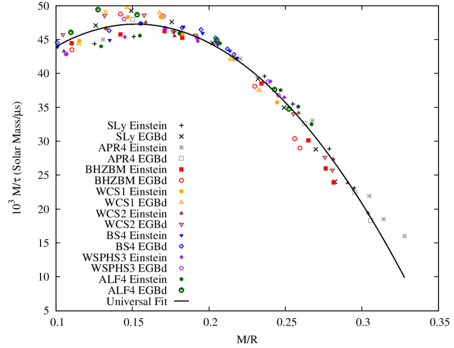
The strong equivalence principle difficults assigning corrections to either T or G
Example: cosmological constant

$$G_{\mu\nu} + \lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Same problem in neutron stars

So here an example from home

N-Star oscillation frequency against mass



Can displace the curve with both EOS and theory

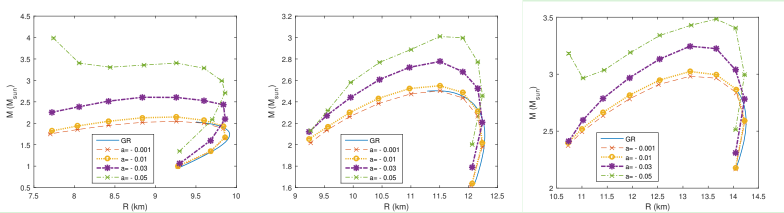
EITHER test the EoS

OR test GR

but not both

(Blázquez-Salcedo, González-Romero and Navarro-Lérida @ UCM)

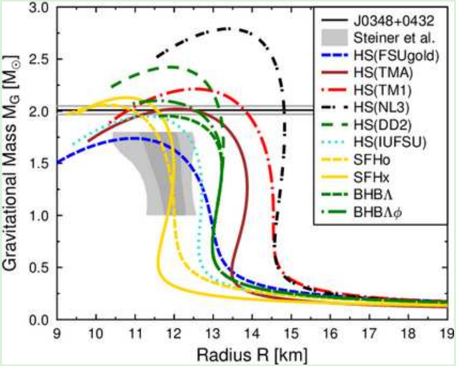
$R + aR^2$ gravity: N-star mass increased for large a



- State equations of Hebeler *et al.* APJ**773**:11 (2013)
- Matching to exterior Schwarzschild (careful: lot of energy there)
- Find heavier stars
- Can also find twin branches from modified gravity

(M. Aparicio Resco et al., Phys. Dark Universe 2016; also works by Odintsov and coll. and Yazadjev & Doneva)

But same effect upon changing the EoS



https://astro.physik.unibas.ch/people/matthias-hempel/equations-of-state.html

Therefore, need to control Hadron input

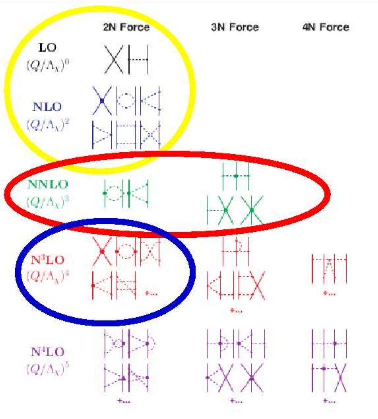
What is $T_{\mu\nu}$ in a neutron star?
(purely from hadron theory)

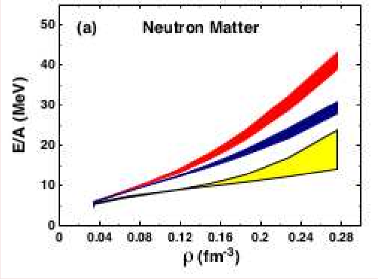
Outline

René Descartes taught us

The first was never to accept anything for true which I did not clearly know to be such; that is to say, carefully to avoid precipitancy and prejudice, and to comprise nothing more in my judgment than what was presented to my mind so clearly and distinctly as to exclude all ground of doubt.

NNLO+ part of N^3LO

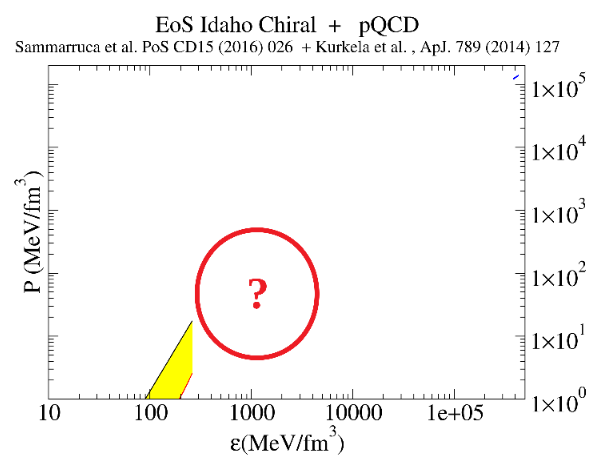




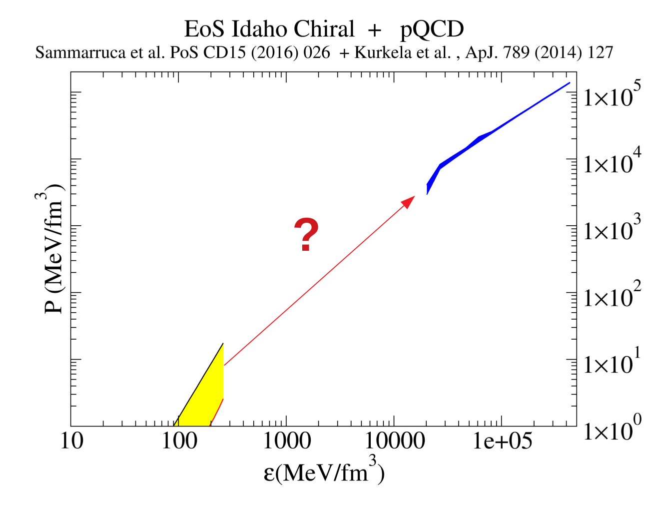
From N^3LO only 2-body part
(to add 3-body, need to refit triton)

Sammarruca *et al.* (INFN-Idaho) Proc. of Science Chiral Dynamics 15 026 (2016)

But the bulk of a neutron star has higher density

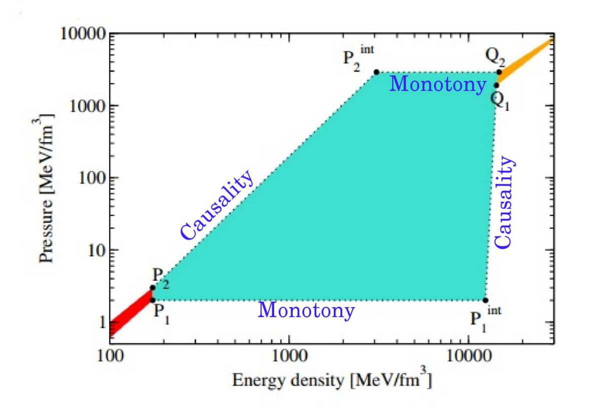


4) EoS from asymptotically high density with pQCD

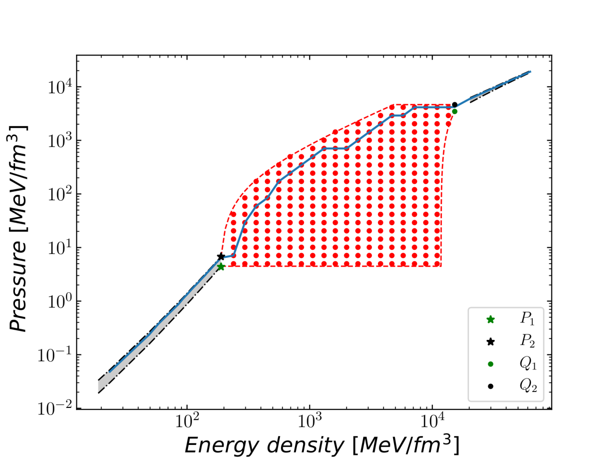


Also A.Kurkela *et al.*, PRD **81** (2010) 105021

Maximum allowed region from first principles

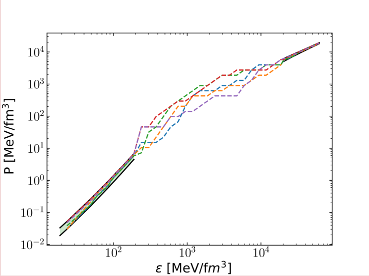


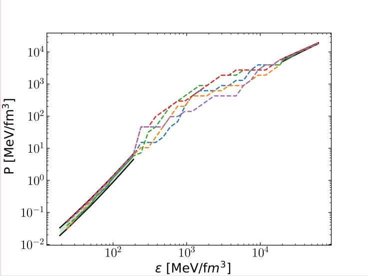
Interpolation with Von Neumann's rejection



At all points, $c_s \in [0, 1]$

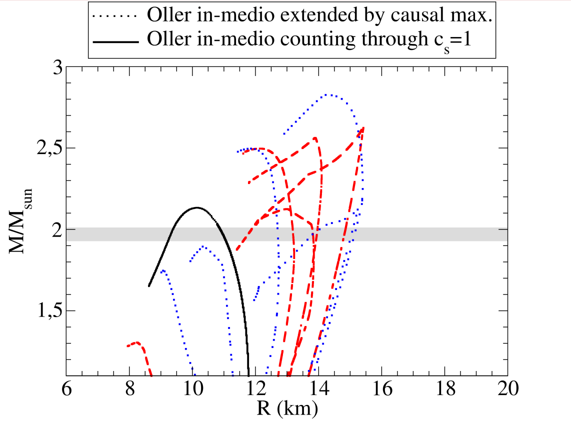
Outcome: bands depending on low-ChPT input



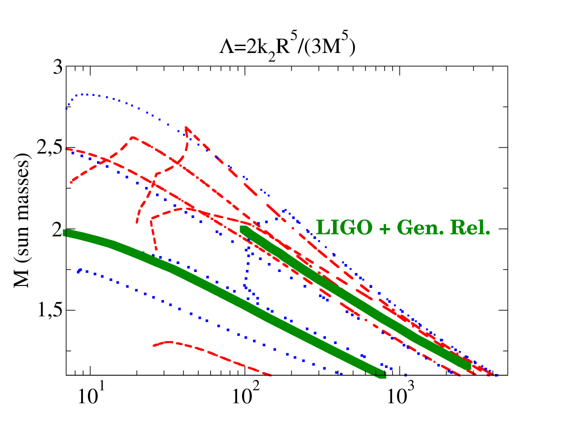


Low P: ChPT   High P: pQCD

Example use: mass-radius diagram in GR

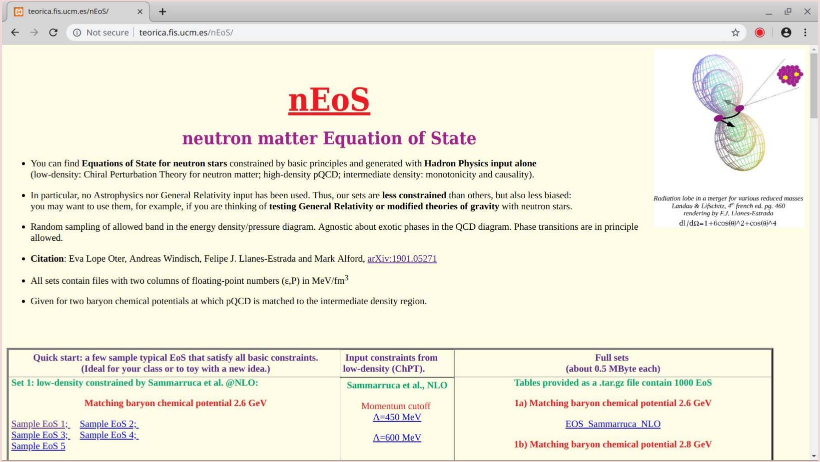


Example use: Tidal deformability



(Green band from aLIGO GW170817 + General Relativity)

Website http://teorica.fis.ucm.es/nEoS



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nEoS

neutron matter Equation of State

- You can find **Equations of State for neutron stars** constrained by basic principles and generated with **Hadron Physics input alone** (low-density: Chiral Perturbation Theory for neutron matter; high-density pQCD; intermediate density: monotonicity and causality).
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- Given for two baryon chemical potentials at which pQCD is matched to the intermediate density region.

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Landau & Lifschitz, 4th french ed. pg. 460
rendering by F.J. Llanes-Estrada
dI/dΩ=1+6cos(θ)^2+cos(θ)^4

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You find ten sets with several subsets

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Sample EoS 3; Sample EoS 4; Sample EoS 5		
Set 7: low-density constrained by Drischler et al.; **Matching baryon chemical potential 2.6 GeV.** Sample EoS 1; Sample EoS 2; Sample EoS 3; Sample EoS 4; Sample EoS 5. **Matching baryon chemical potential 2.8 GeV.** Sample EoS 1; Sample EoS 2; Sample EoS 3; Sample EoS 4; Sample EoS 5.	**Drischler et al.** Lower boundary of allowed band Upper boundary of allowed band	**Tables provided as a .tar.gz file contain 1000 EoS** **7a) Matching baryon chemical potential 2.6 GeV** EOS_Drischler **7b) Matching baryon chemical potential 2.8 GeV** EOS_Drischler
Set 8: low-density constrained by Holt and Kaiser @ NLO **Matching baryon chemical potential 2.6 GeV.** Sample EoS 1; Sample EoS 2; Sample EoS 3; Sample EoS 4; Sample EoS 5 **Matching baryon chemical potential 2.8 GeV** Sample EoS 1; Sample EoS 2; Sample EoS 3; Sample EoS 4; Sample EoS 5	**Holt and Kaiser, NLO** Λ= 450 MeV Λ= 500 MeV	**Tables provided as a .tar.gz file contain 1000 EoS** **8a) Matching baryon chemical potential 2.6 GeV** EOS_Holt_NLO **8b) Matching baryon chemical potential 2.8 GeV** EOS_Holt_NLO
Set 9: low-density constrained by Holt and Kaiser @(partly) N2LO **Matching baryon chemical potential 2.6 GeV.** Sample EoS 1; Sample EoS 2; Sample EoS 3; Sample EoS 4; Sample EoS 5 **Matching baryon chemical potential 2.8 GeV** Sample EoS 1; Sample EoS 2; Sample EoS 3; Sample EoS 4; Sample EoS 5	**Holt and Kaiser (partly) N^2LO** Λ= 450 MeV Λ= 500 MeV	**Tables provided as a .tar.gz file contain 1000 EoS** **9a) Matching baryon chemical potential 2.6 GeV** EOS_Holt_N2LO **9b) Matching baryon chemical potential 2.8 GeV** EOS_Holt_N2LO
Set 10: low-density constrained by Holt and Kaiser @(partly) N3LO **Matching baryon chemical potential 2.6 GeV.** Sample EoS 1; Sample EoS 2; Sample EoS 3; Sample EoS 4; Sample EoS 5 **Matching baryon chemical potential 2.8 GeV** Sample EoS 1; Sample EoS 2; Sample EoS 3; Sample EoS 4;	**Holt and Kaiser (partly) N^3LO** Λ= 450 MeV Λ= 500 MeV	**Tables provided as a .tar.gz file contain 1000 EoS** **10a) Matching baryon chemical potential 2.6 GeV** EOS_Holt_N3LO **10b) Matching baryon chemical potential 2.8 GeV** EOS_Holt_N3LO

Typical EoS: (ϵ, P) in $\mathrm{MeV/fm^3}$

teorica.fis.ucm.es/nEoS/EOSDA ×

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129.98814999999999	0.88627831040382377
138.77703000000000	1.0067072546076774
147.58109999999999	1.1345698052811621
157.42316000000000	1.2865097931456566
166.32536999999999	1.4311267364072799
175.25260000000000	1.5839618105316162
182.23185000000001	1.7069770472764969
192.24266000000000	1.8937927473735807
200.29506000000001	2.0486767668199537
209.39793000000000	2.2320486152791976
217.52753999999999	2.4010001828050611
225.68101999999999	2.5763892392539982
233.89724000000001	2.7599845266127589
283.89724000000012	5.2290906814847204
347.92600012114980	11.467426043511406
426.39548577612896	16.981882641947934
522.56258579971848	37.241366642514407
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784.85556119003115	179.10394798456952
961.86794939495633	265.23146640256567
1178.8028241405937	392.77599160525551
1444.6641028801523	581.65413656966984
1770.4864014658999	581.65413656966984
2169.7930276846600	581.65413656966984
2659.1572683590816	581.65413656966984
3258.8902663275585	861.36001644577516

What you can download

- A few loose EoS for a toy idea or a class
- gZipped packages with 1000 sets each for research runs
- Or source code to do-it-yourself (at your peril)

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Systematic sensitivity

- Two values of pQCD starting point:

$$\mu_B \simeq 2.6,\ 2.8\ \text{GeV}$$

- Several ChPT calculations (Sammarruca *et al.*, Hu *et al.*, Drischler *et al.*, Holt and Kaiser, at available orders of perturbation theory.)
- Two values of ChPT momentum cutoff:

$$\Lambda = 0.45,\ 0.5\ \text{GeV}$$

or similar, when available.

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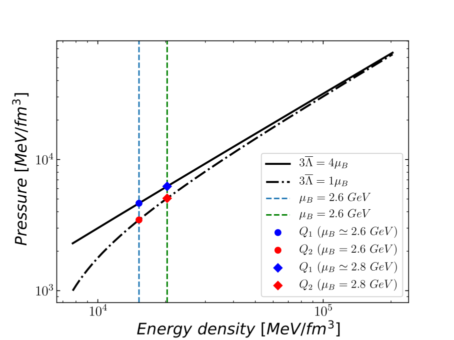
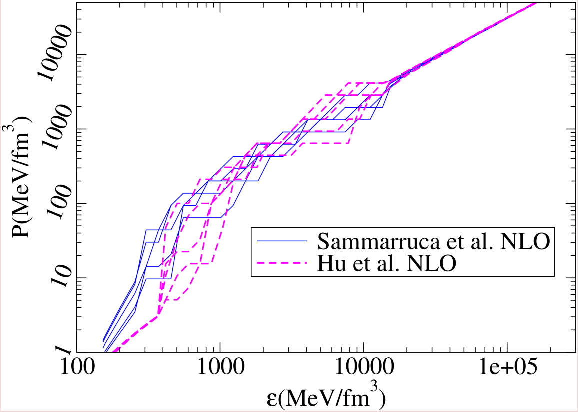
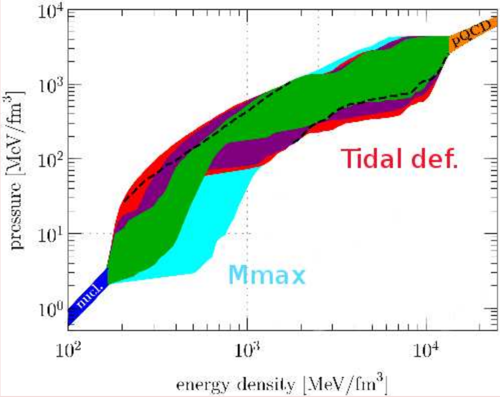
Choice of pQCD starting point



Differences with other sets: nEoS knows no astrophysics



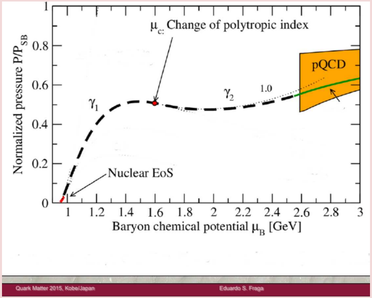
EOS from first principles + mass + tidal constraints

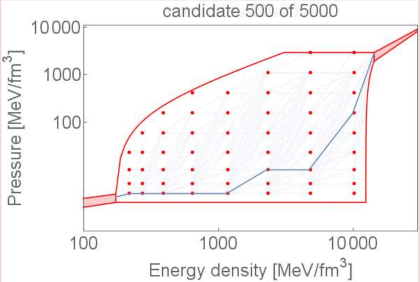


Kurkela *et al.* 1711.02644

If you can assume General Relativity, this work is way tighter but to *constrain beyond GR theories*, visit the nEoS webpage!

Interpolation between low and high P





Polytropic $P \propto \rho^\gamma$ vs. nEoS linear interpolation ($\gamma = 0, 1$)

nEoS more naturally allows for 1st order phase transitions

Outline

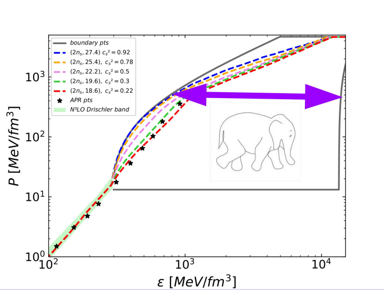
Diagnostic for progress

- Specific latent heat L in a phase transition (pure number in natural units)

Substance/transition	L
He-3 superfluid	$1.5\ \mu$J/mol $= 5.5 \times 10^{-24}$
Ice-water	79.7 cal/g $= 3.71 \times 10^{-12}$
Nuclear evaporation	8 MeV/A $= 8.5 \times 10^{-3}$
Neutron star matter?	$O(0.1)$?

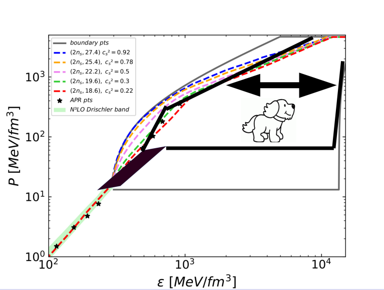
Maximum L in a possible (unknown) phase transition

$$L = \frac{\Delta E}{N M_N} = P_{\rm hadron} \frac{(\varepsilon_{exotic} - \varepsilon_{hadron})}{\varepsilon_{exotic}\varepsilon_{hadron}}$$

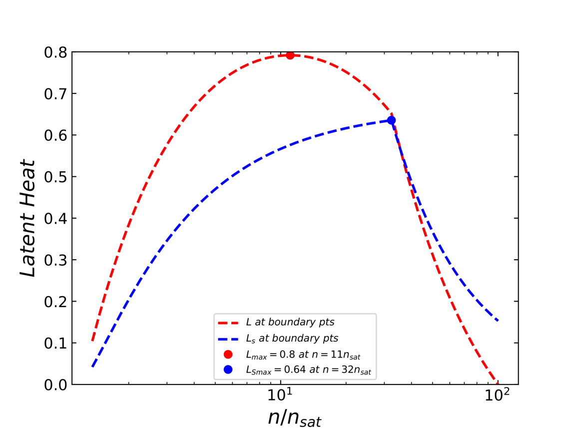


Maximum L in a possible (unknown) phase transition

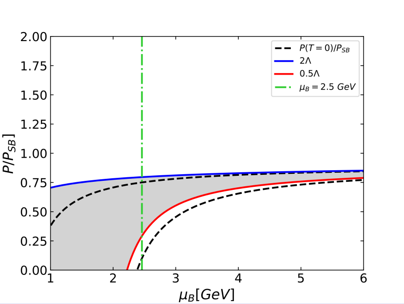
- If the ChPT & pQCD computations improve...

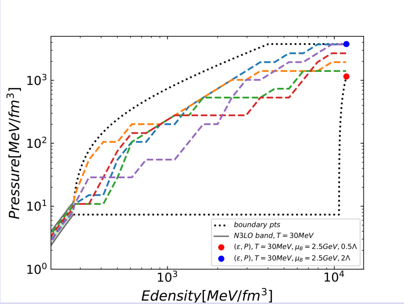


Current status from nEoS: L dependence on transition ε



Finite temperature





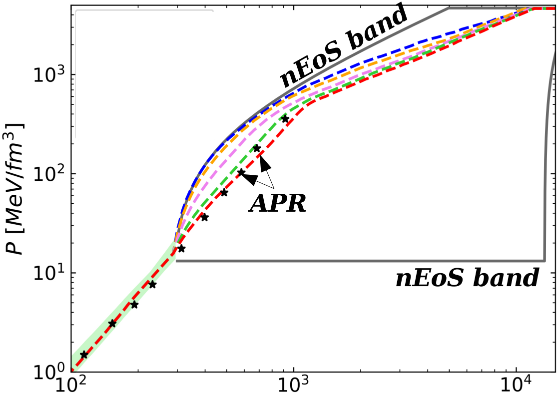
Time to reissue a nEoS 2.0?

- New ChPT computations appearing, finite T, improve sampling...
- Not well known setup, small return on our effort (Alford et al. JPG 2018)

Outline

Conclusions

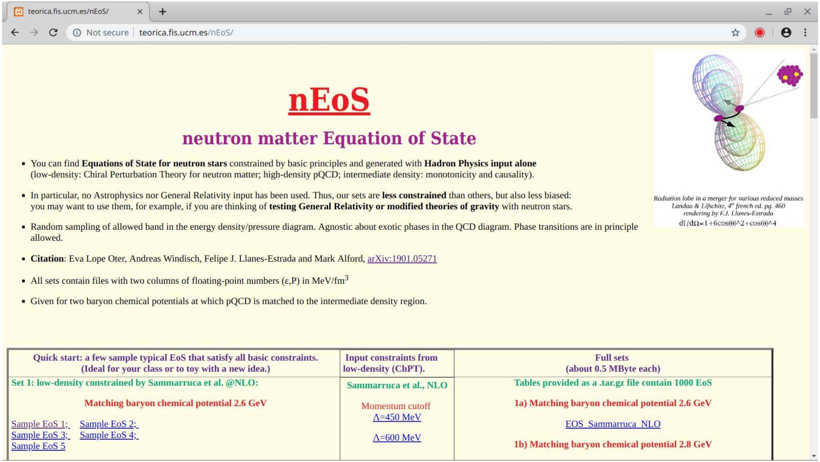
- If you test modified gravity with a conventional EoS,
  you are missing out



Conclusions

- To fully test the Einstein's equations, we need *the interior* of neutron stars
- To discriminate between field and matter effects, we need first-principles predictions of $T_{\mu\nu}$, saliently $P(\rho)$
- We have collected the state of the art information thereof in the nEoS project

Website http://teorica.fis.ucm.es/nEoS



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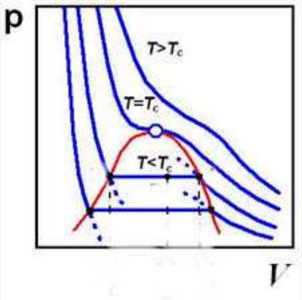
Backup Slides

Monotony: derivative is positive or null



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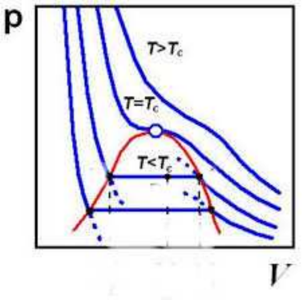

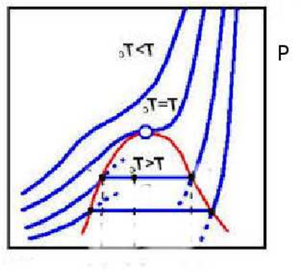

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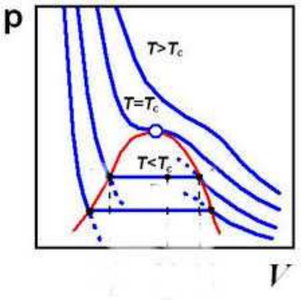
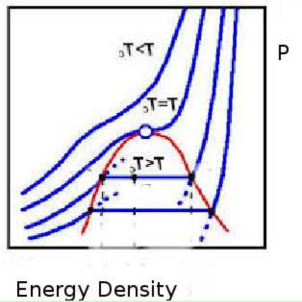
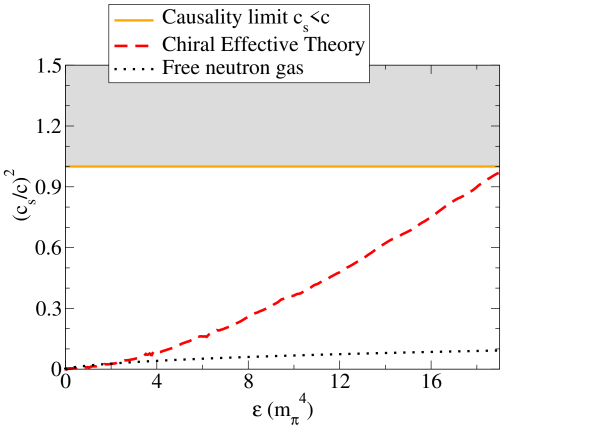




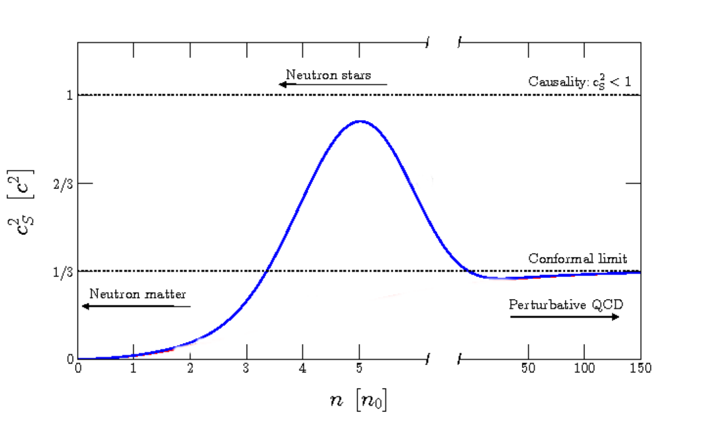
$P(\rho)$ will be below whatever Neutron Matter computation yields

Anything "exotic" beyond neutrons is a softener
1st order phase transition → latent heat → zero derivative

Hardness limited by causality: $c_s = \sqrt{dP/d\rho} \leq c$

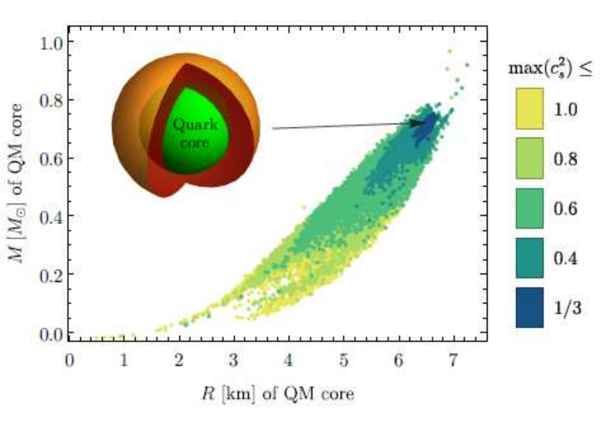


The conformal value is a red herring: $c_s^2 > 1/3$ seems necessary



Graph from McLerran and Reddy, Phys.Rev.Lett. 122 (2019), 122701

Small exception to $c_s^2 > 1/3$ by Helsinki group



Graph from Annala *et al.* arXiv:1903.09121 [astro-ph.HE]