130 Million Years ago, in a galaxy equally far away

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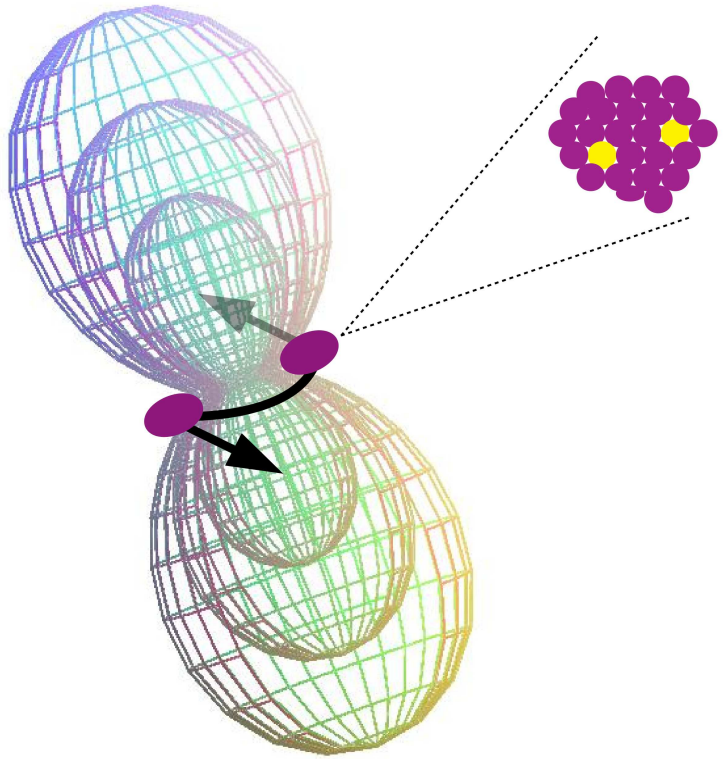
Gravitational radiation from neutron star merger



Radiation lobe in a merger for various reduced masses
Landau & Lifschitz, 4th french ed. pg. 460
rendering by F.J. Llanes-Estrada

$$dI/d\Omega = 1 + 6\cos(\theta)\text{^}2 + \cos(\theta)\text{^}4$$

One needs to know...

- Nuclear physics
- Particle physics
- General relativity
- Numerical analysis ...

So that requires a giant of physics
Which is, of course, **the chairman**.
(Need extra time to fit some slides)

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Equation of State for modified gravity studies at neutron stars

Felipe J. Llanes-Estrada

Universidad Complutense de Madrid, Departamento de Física Teórica

Ongoing work in collaboration with Eva Lope Oter & Ivan Sayago (@UCM), Mark Alford and Andreas Windisch (@ WU St. Louis)

26th/6/2018 Strong and Electroweak Matter, Barcelona

Neutron star mergers are a testbed for General Relativity

Hadron physics input (this talk: Eq. of State)

Providing an EoS with minimum bias

Do not assume GR: a software implementation

Outline

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Amazing: γ delayed 1.7sec in a 130 Mly travel

- Little matter in the way (Compton scattering): galaxy's edge
- GWs and light have precisely the same speed to 10^{-15}
- But where does the delay come from?

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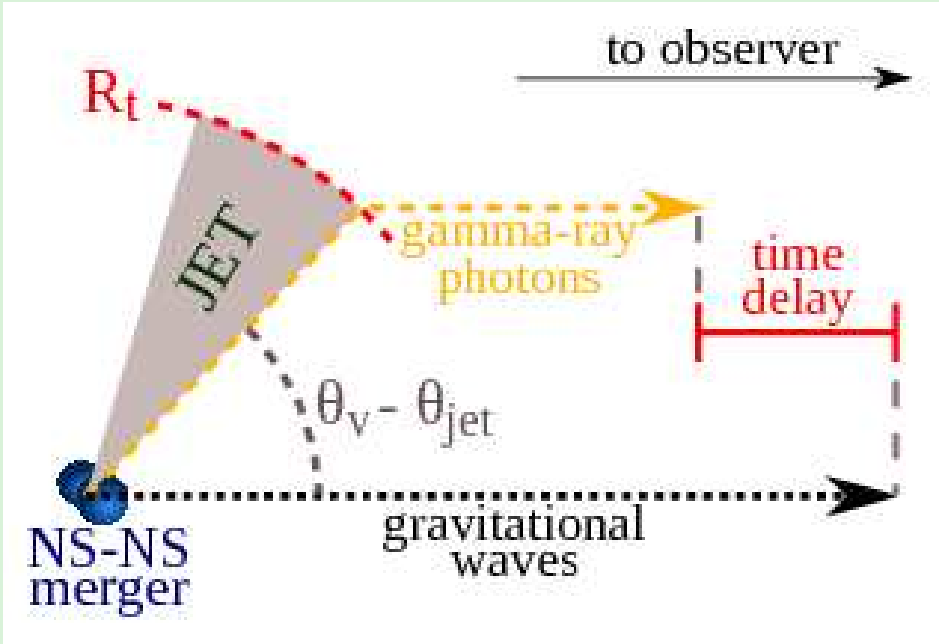
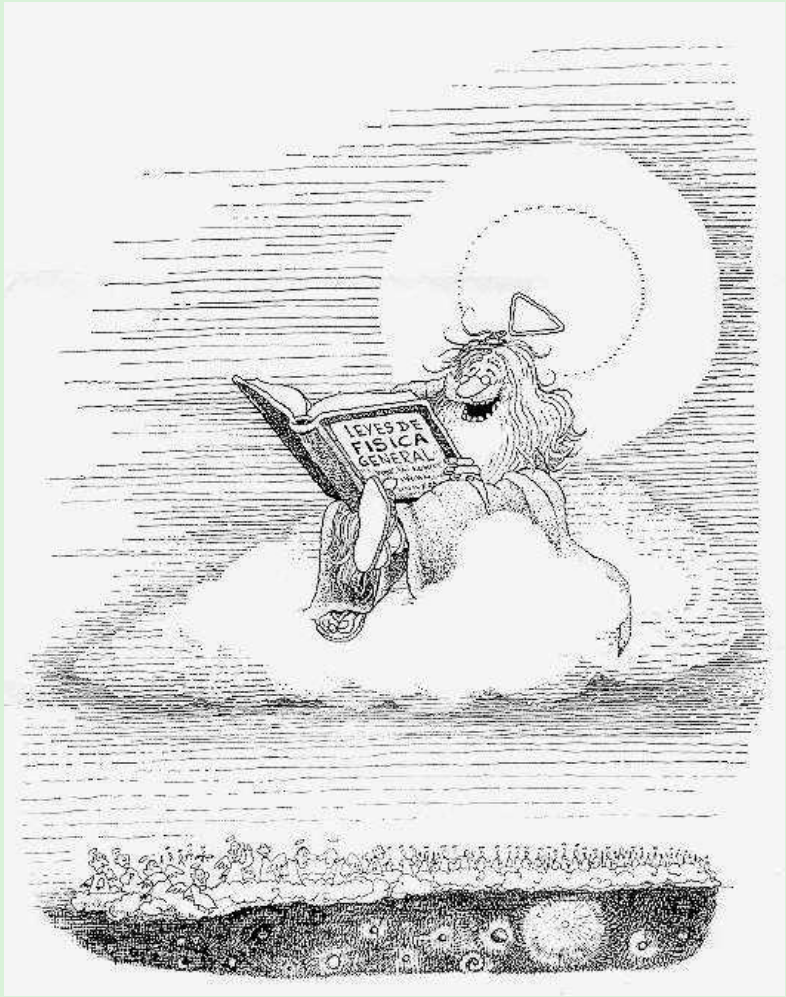


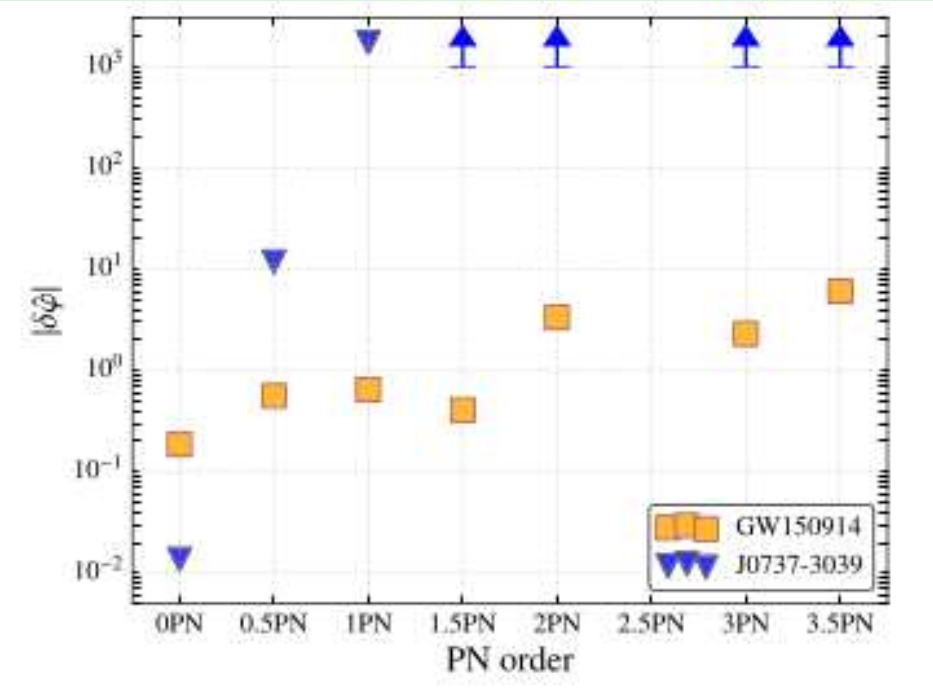
Whether jet or fireball, the instant when matter becomes transparent is delayed arxiv:1711.03112

10^{-15}!! and Einstein failed to find a Unified Field Theory...



(As this cartoon by Quino illustrates)

LIGO is testing General Relativity



Post-Newtonian coeffs. constrained 10^3 better with their BH-BH than with earlier binary-pulsar orbital period measurement

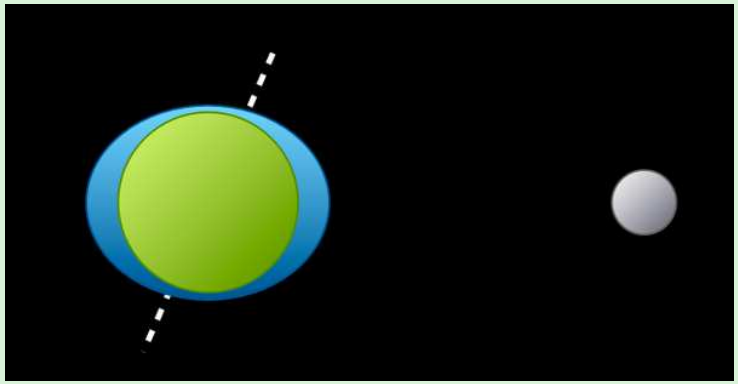
LIGO scientific coll. PRL**116** 221101 (2016)

Coming to GW170817: Tidal deformability

Upper bound

$$\Lambda = \frac{2}{3} k_2 \left((c^2/G)(R/m) \right)^5 \leq 800$$

(low spin priors; could be 1400)



Constraint on allowed equations of state...
if you assume General Relativity

Distinguishing Nuclear matter- from Gravitational- effects

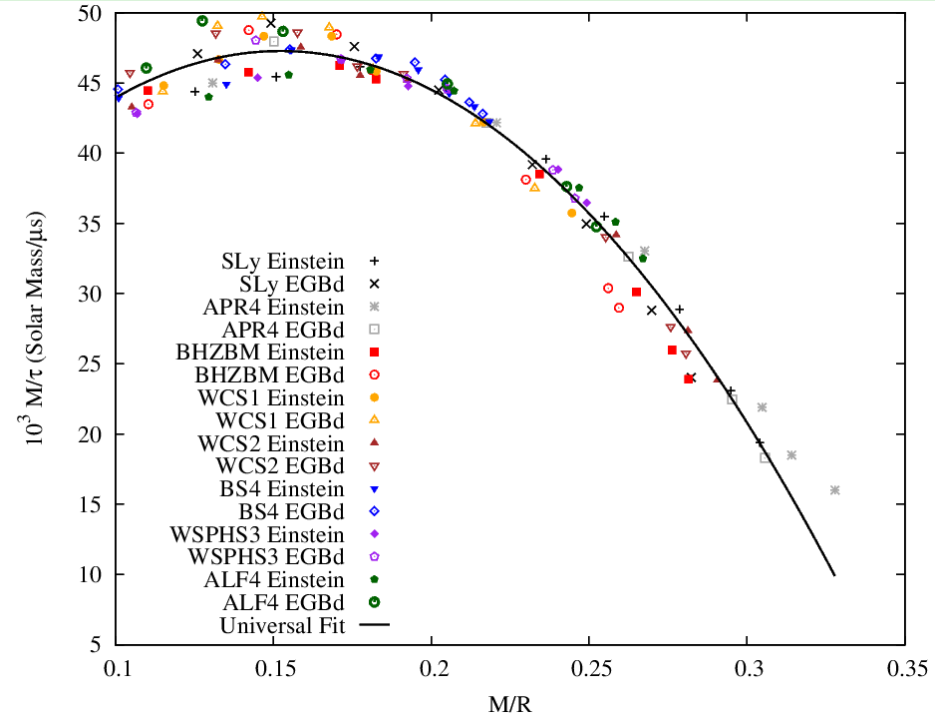
The strong equivalence principle difficults assigning corrections to either T or G
Example: cosmological constant

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

Same problem in neutron stars

So here an example from home

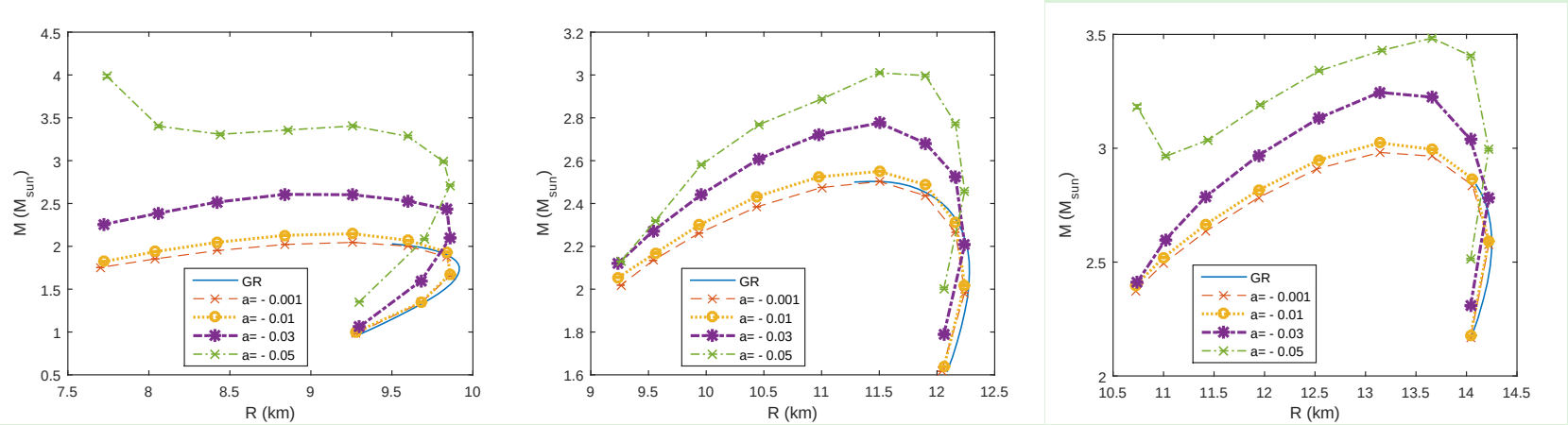
N-Star oscillation frequency against mass



Can slide up or down the curve with both EOS and theory

EITHER test the EoS
OR test GR but not both
(F. Navarro from UCM et al.)

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



- State equations of Hebeler *et al.* APJ**773**:11 (2013)
- Matching to exterior Schwarzschild (careful: lot of energy there)
- Find heavier stars

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

Outline

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What we gain with NS mergers

Retarded metric for a linear wave ($t' = t - |\mathbf{x} - \mathbf{y}|/c$)

$$\bar{h}_{\alpha\beta}(t, \mathbf{x}) = \frac{4G}{c^4} \int d^3\mathbf{y} \frac{T_{\alpha\beta}(t', \mathbf{y})}{|\mathbf{x} - \mathbf{y}|}$$

$T_{\alpha\beta}(t', \mathbf{y})$, that's us!

$$T = \underbrace{T^{(0)}}_{\text{Perfect, isotropic EOS } P(\rho))} + T^{\text{dissipative}} + T^{\text{anisotropic}}$$

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Input to numerical relativity simulations

Quote off numerical relativity work (Parma-Louisiana 1605.03424)

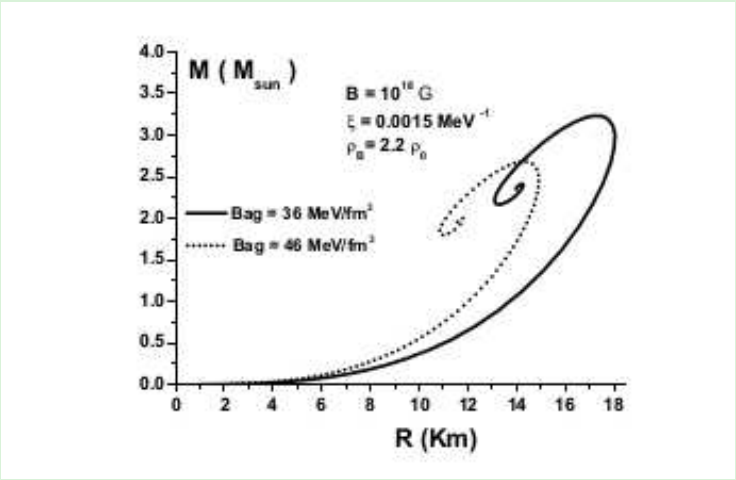
"The true EOS for nuclear matter in an environment similar to a neutron star is still not known. (...) We thus have to simulate the effect of different plausible EOSs on observable quantities, in the hope to learn about the EOS indirectly through observations."

Standard in that field:
Akmal, Pandharipande and Ravenhall, PRC**58** 1804 (1998)
(basically, Argonne potential + some 3-body force)

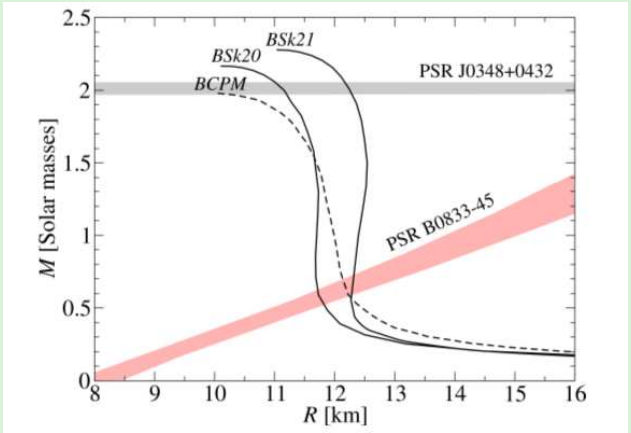
Also used: Skyrme-Lyon interaction (Douchin, Haensel arXiv:astro-ph/0111092),
Hyperon EOS by Lackey, Nayyar, and Owen, PRD**73** 024021 (2006),

Muller and Serot, PRC**52** 2072 (1995).

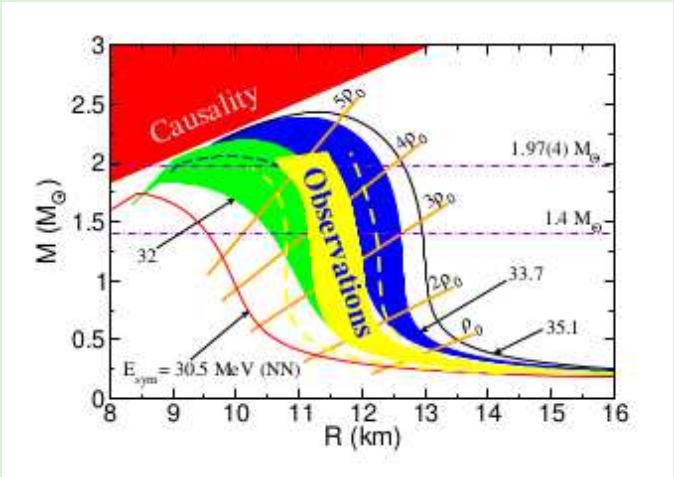
Static observables: Mass and radius



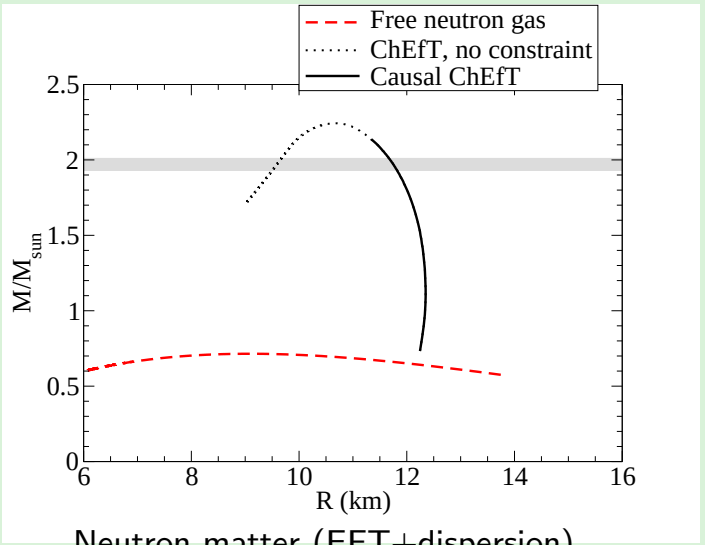
Quark matter + B
1608.00602 Fogaca et al (Navarra)



Neutron matter (Skyrme+HFB)
1607.05943 Chamel

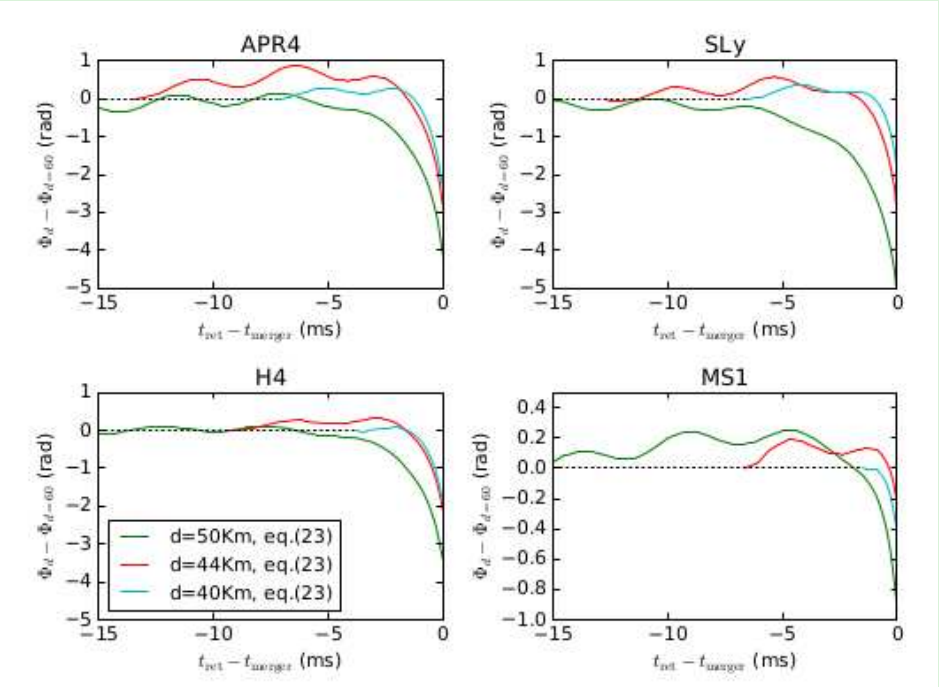


Neutron matter Argonne+Urbana+QMC
1307.5815 Gandolfi *et al.*



Neutron matter (EFT+dispersion)
PRC**85** 012801 (2012) Dobado *et al.*

GW predictions hampered by EOS



For example, uncertainty in predicting the phase, but also

$O(15\%)$ uncertainty in predicting the merging time,
$O(25\%)$ uncertainty for the $h_{\rm max}$ amplitude,
$O(50\%)$ uncertainty in the peak frequency emitted after merging,
$O(100\%)$ uncertainty in the total radiated energy.

1605.03424; but not systematic uncertainties

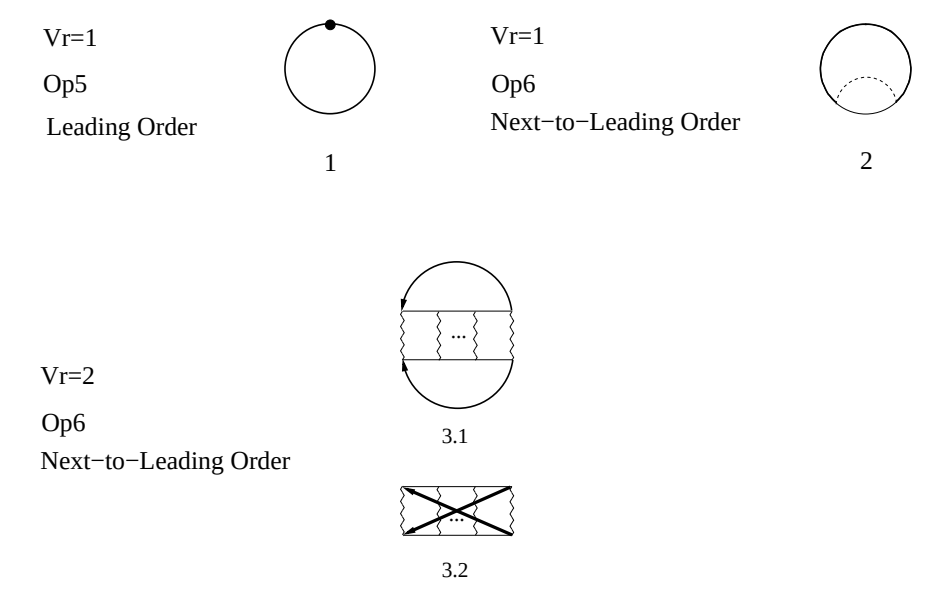
Can hadron physics control the EOS?

Check perturbative convergence

Chiral counting of nucleon forces *in medio*

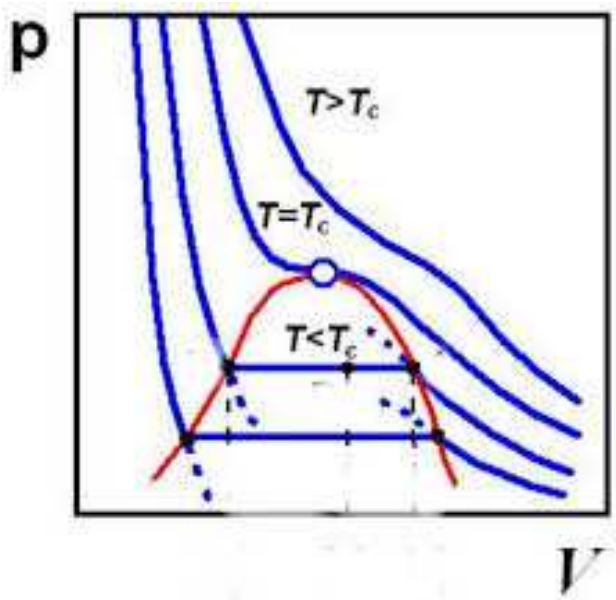
Modern calculations in EFT+unitarity

Neutron stars: large Fermi momentum $\Longrightarrow$ EFT with pions



(Lacour, Oller and Meissner Ann. Phys. **326** (2011) 241, consistent power counting in nuclear matter)

Changes of phase soften the EOS



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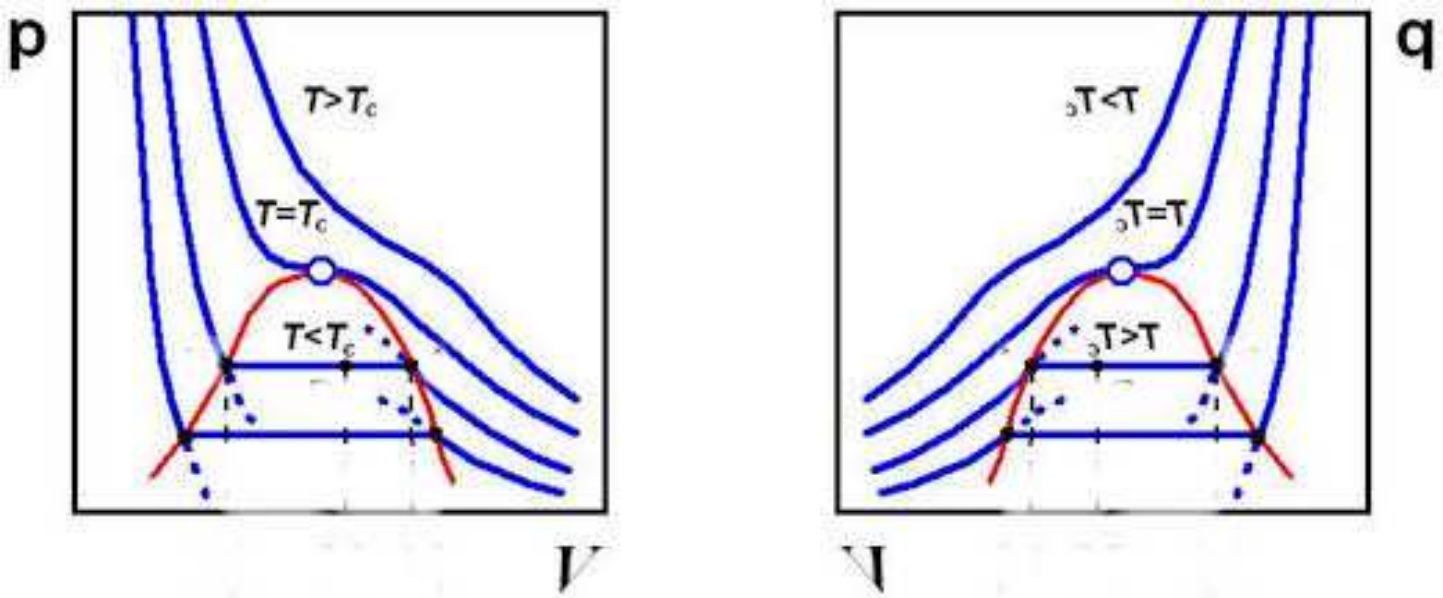

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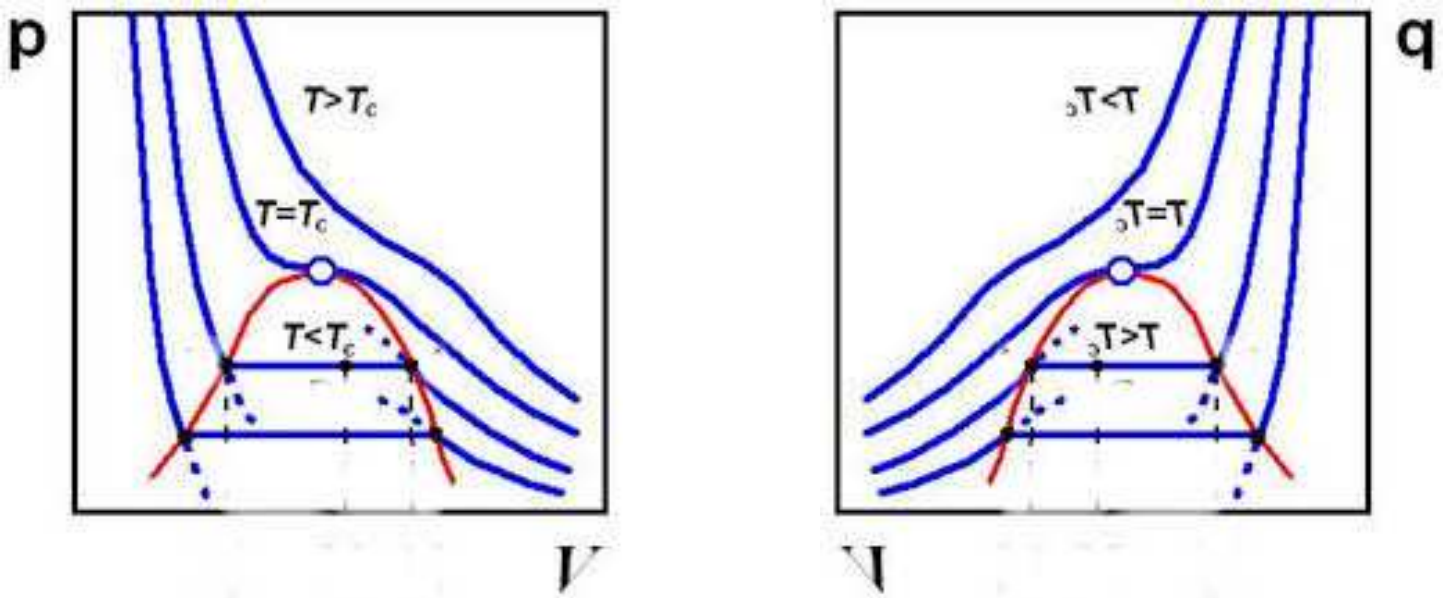
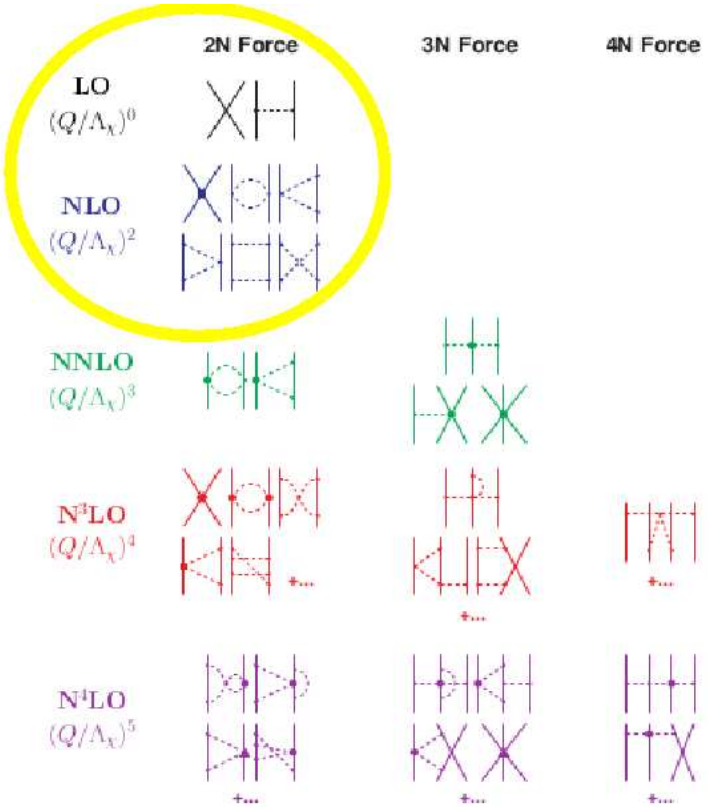
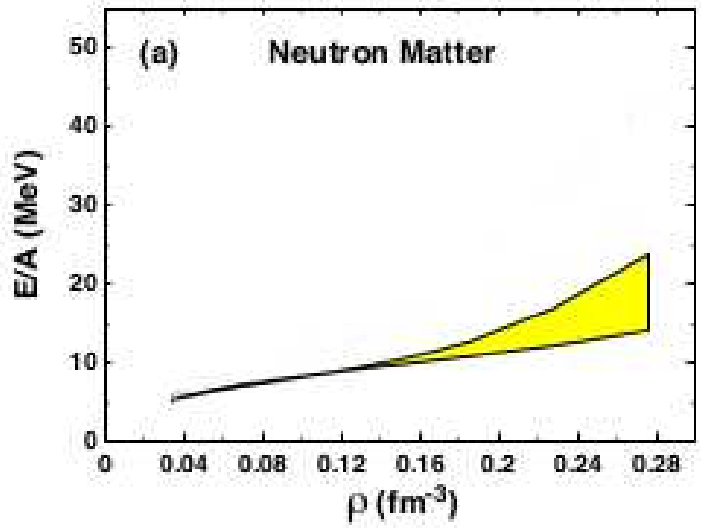


$P(\rho)$ will be below whatever Neutron Matter computation yields

Anything "exotic" beyond neutrons is a softener

LO+NLO

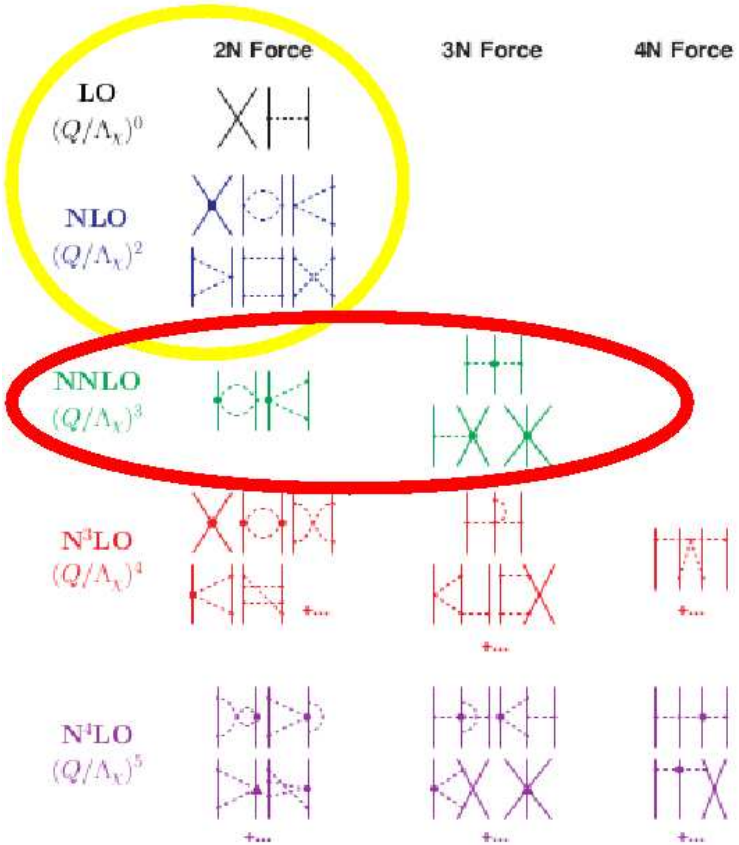


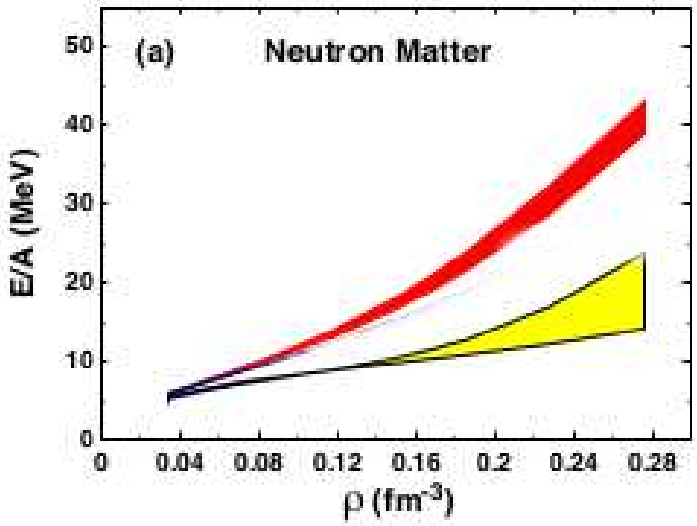


Cutoff variation (450-600) MeV

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

NNLO

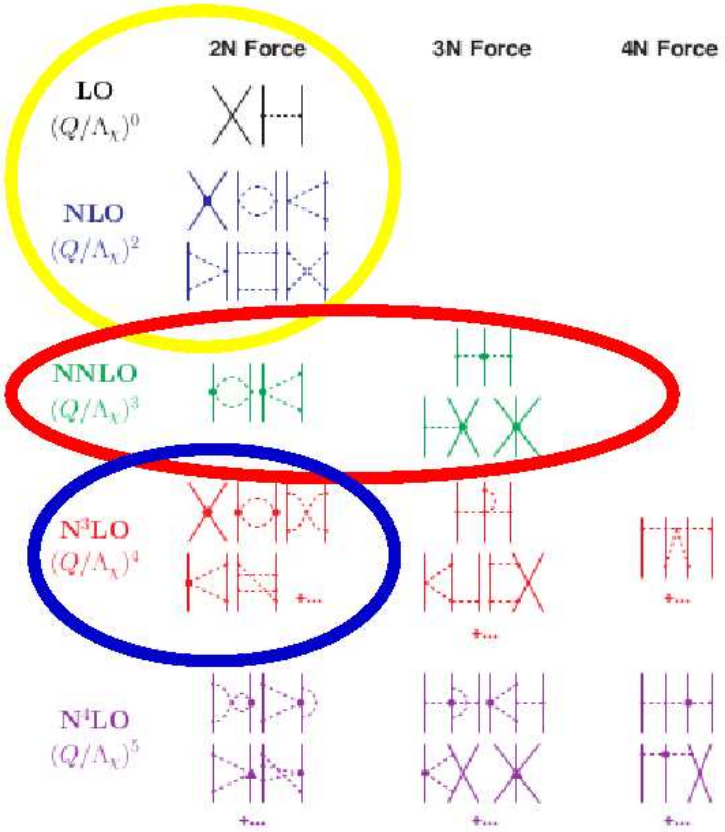


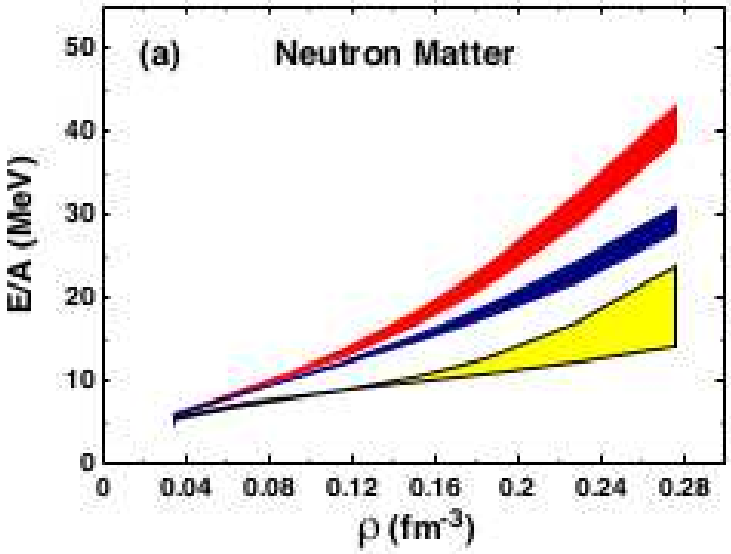


3-body force: local density approx.
Not a full Bethe-Faddeev computation

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

NNLO+ part of N^3*LO*

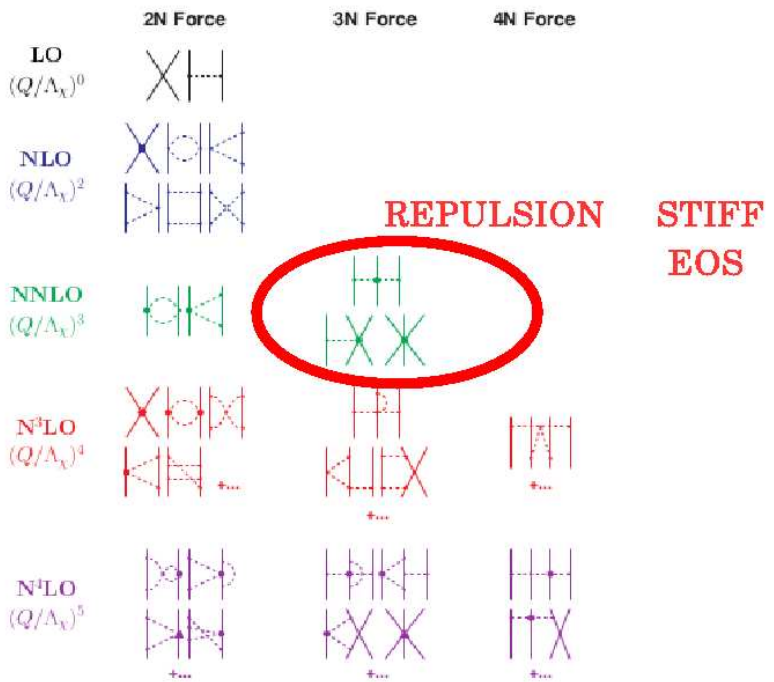




From N^{3}LO only 2-body part (to add 3-body, need to refit triton)

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

One thing is sure



2-body 3-body

This group will extend the 2-body force to N^{4}LO soon (ask Entem)

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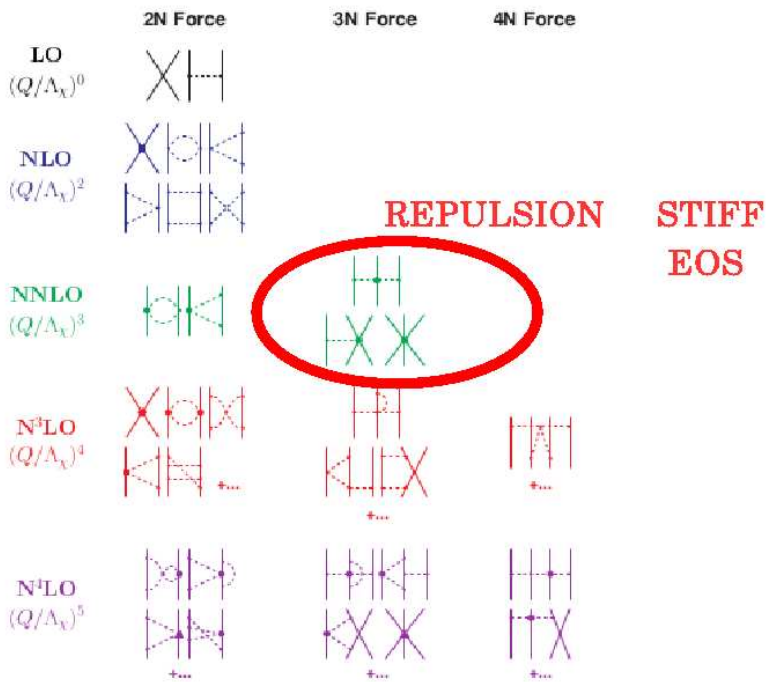

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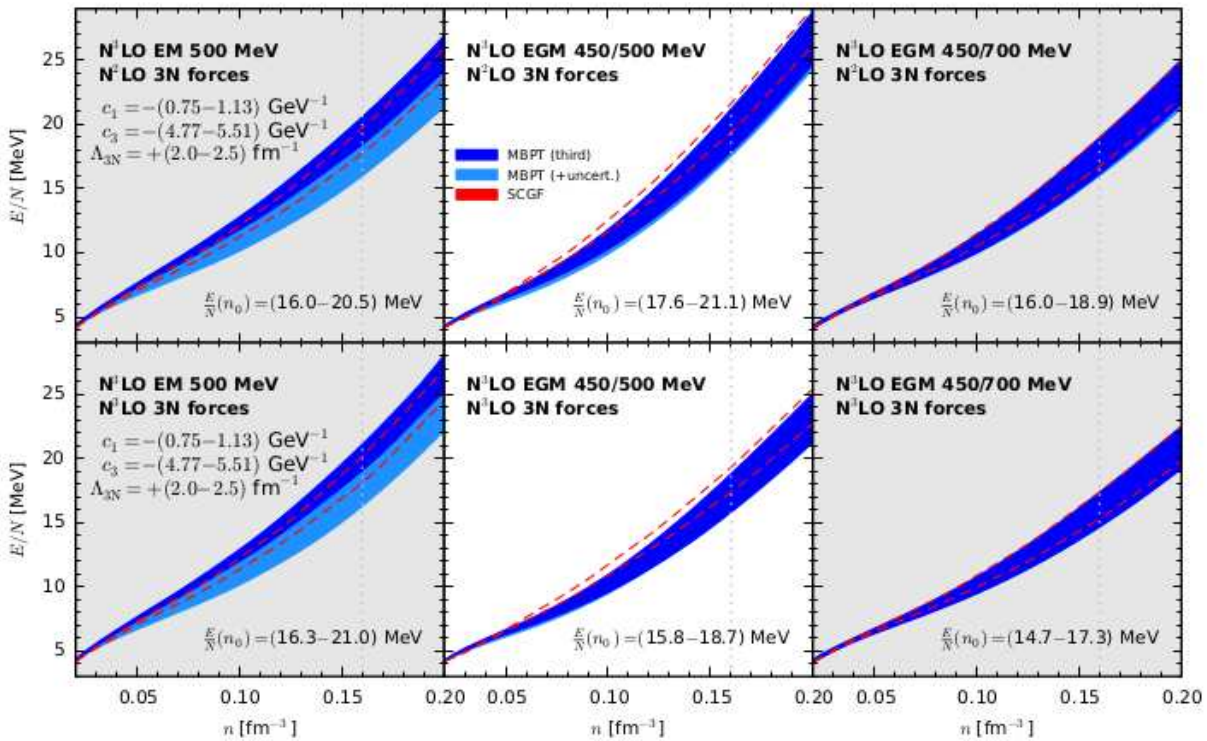

C. Drischler *et al.* (Schwenk) 1608.05615

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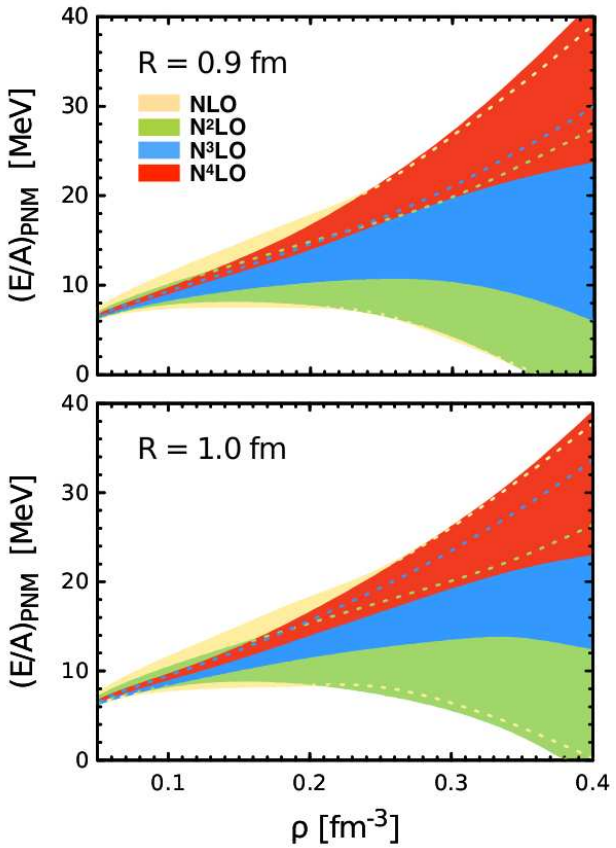

J. Hu *et al.* (Meissner) 1612.05433

Neutron star cores beyond reliability of χpt

- Typically you cannot trust theory past $k_F \simeq 400 - 600$ MeV
- But k_F in heavy $2M_\odot$ stars could easily reach 800 MeV-1 GeV.

Sometimes: EoS extrapolated with polytrope functions $P = c\rho^\gamma$

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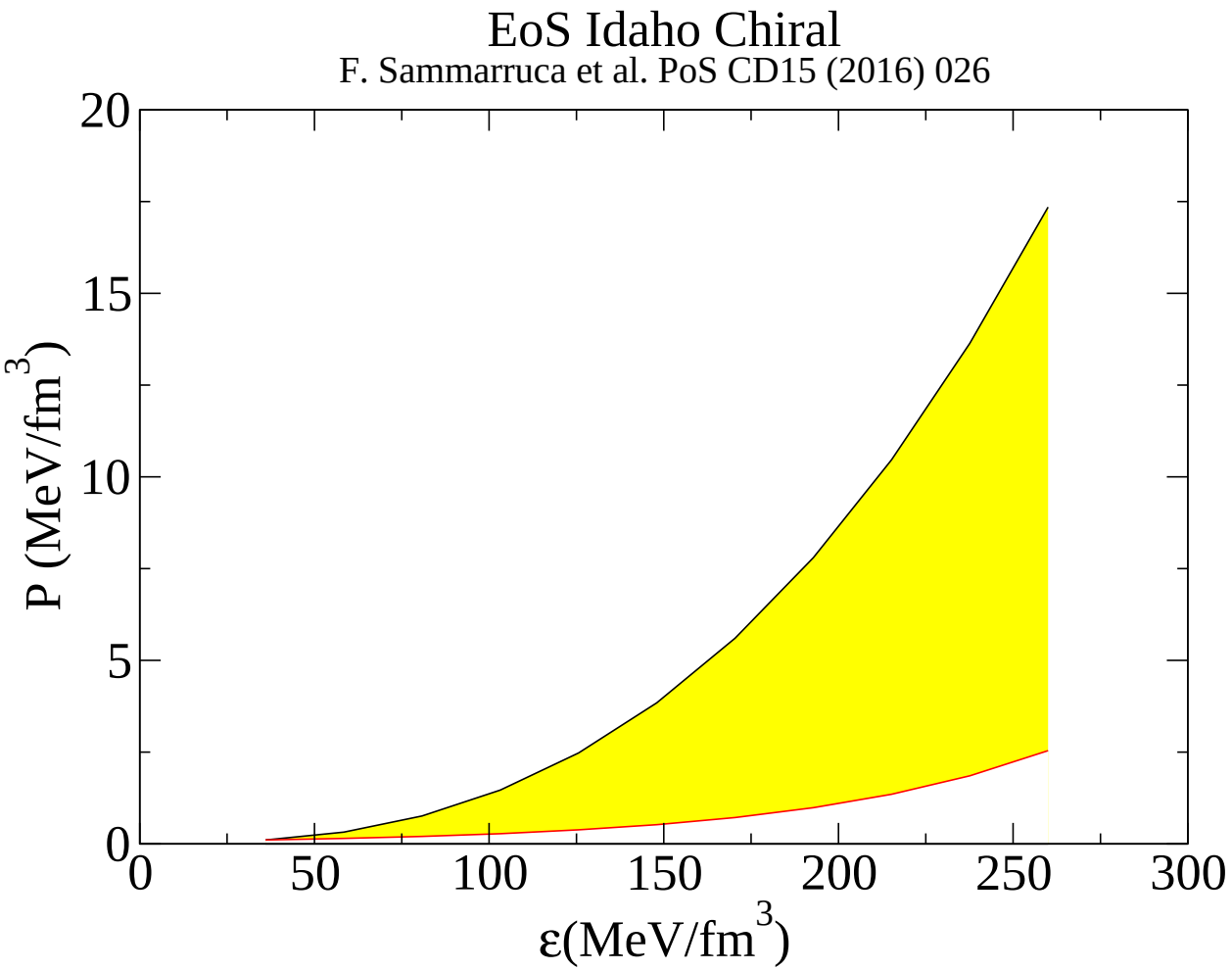
Do not assume GR: a software implementation

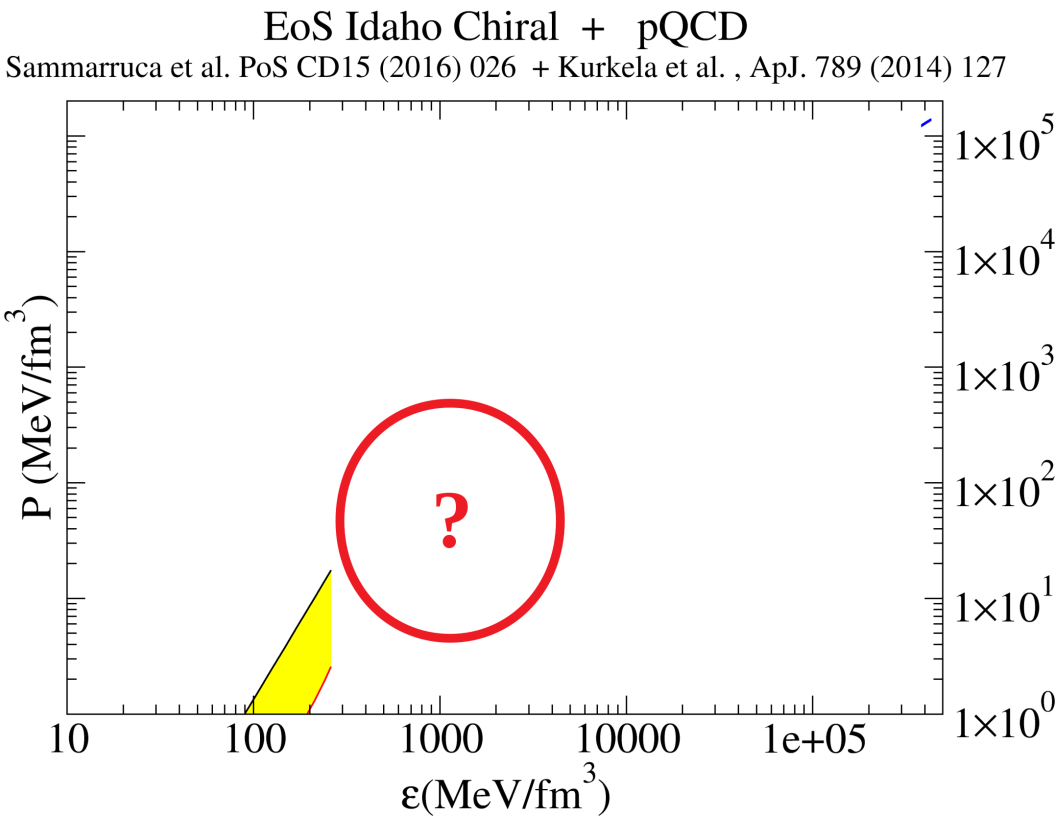
René Descartes taught us

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.

A little above nuclear density, e.g. NNLO Idaho EoS

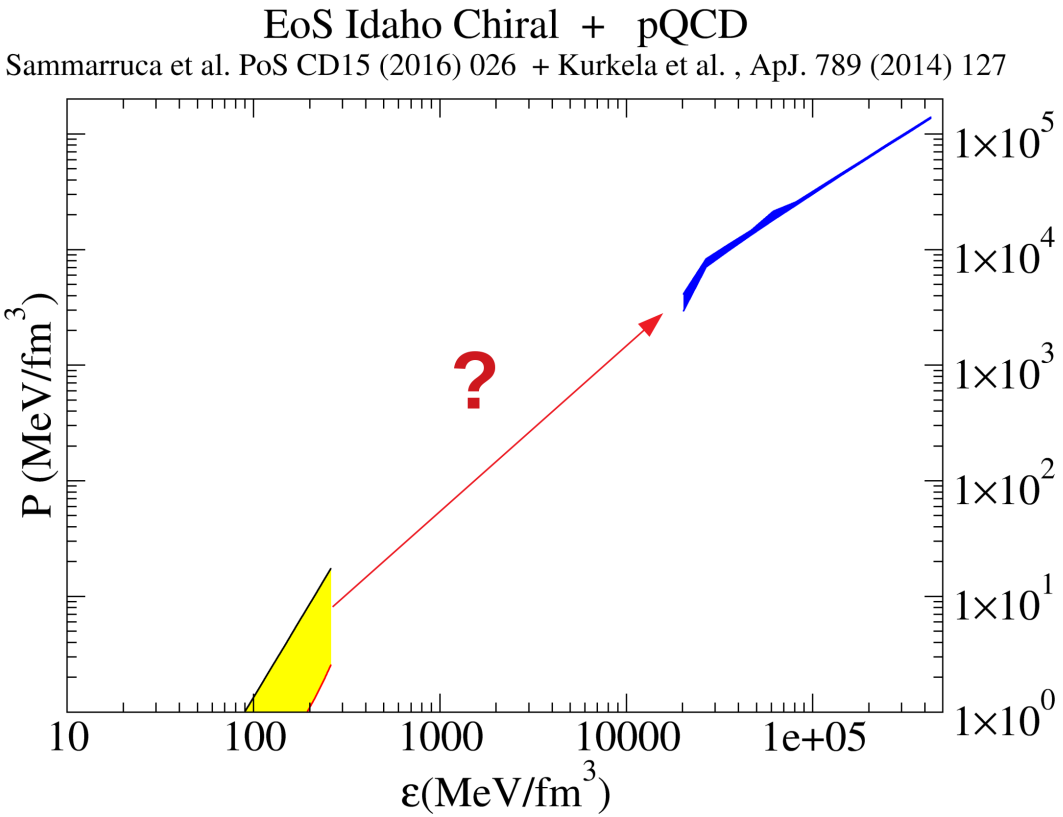


But the bulk of a neutron star has higher density

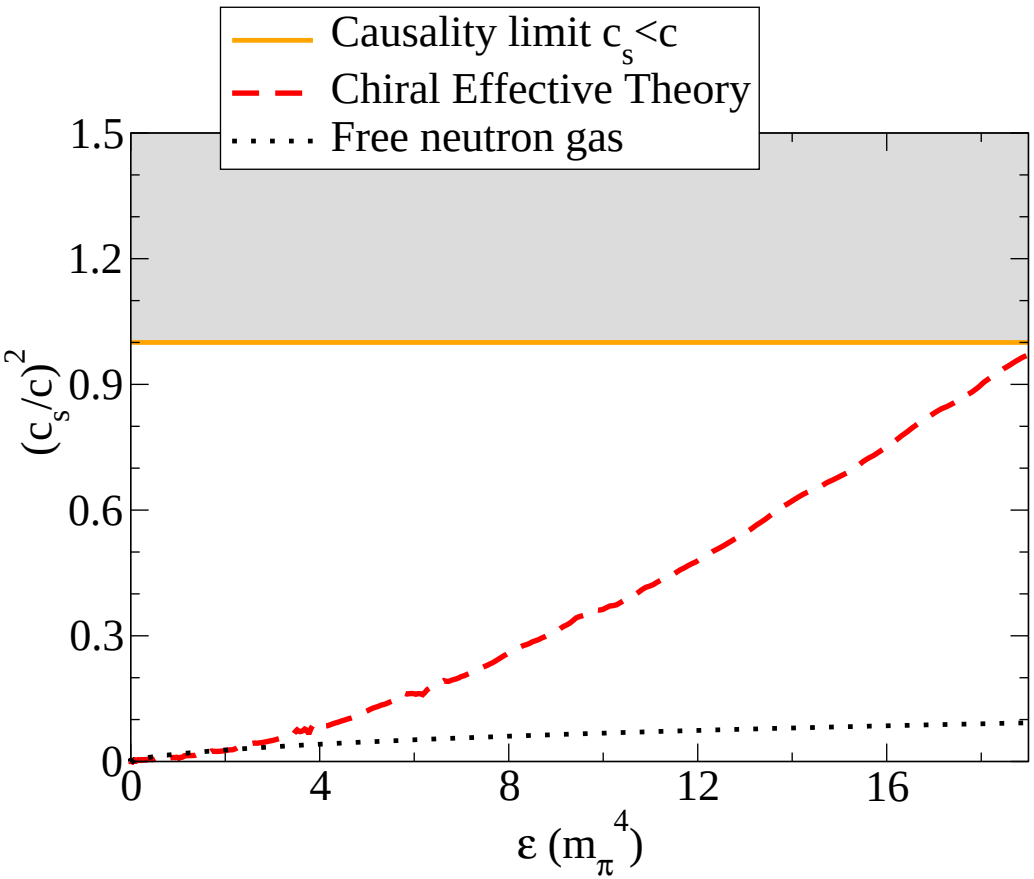


How to use the EoS from asymptotically high density?

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



Causality: $c_s \leq c$



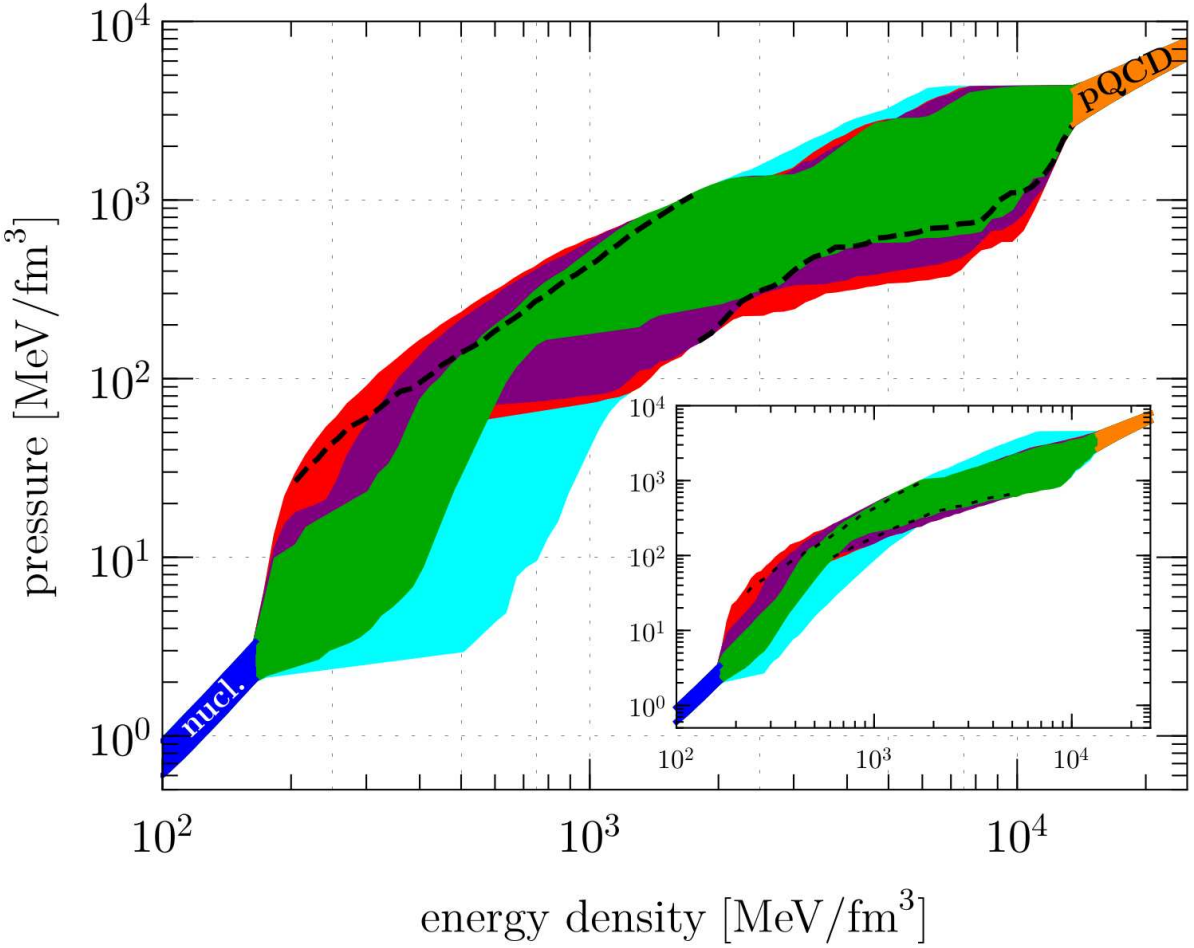
(Note χEFT has repulsion built in:
it exceeds $c_s^2 = 1/3$ but that's ok)

Monotonicity

$$\frac{dP}{d\epsilon} \geq 0 \rightarrow \quad c_s^2 \geq 0$$

(Less fundamental but credible: quarks are fermions)

EOS from first principles + mass + tidal constraints



Kurkela *et al.* 1711.02644 (assumes General Relativity)
(see slides of T. Gorda)

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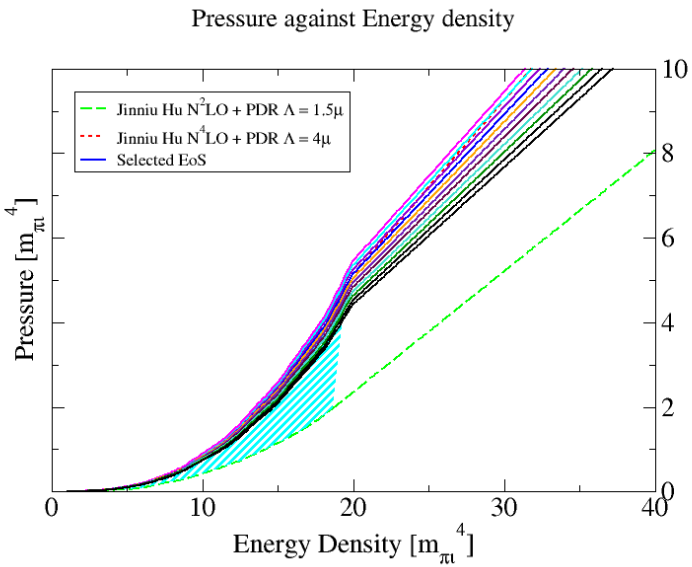
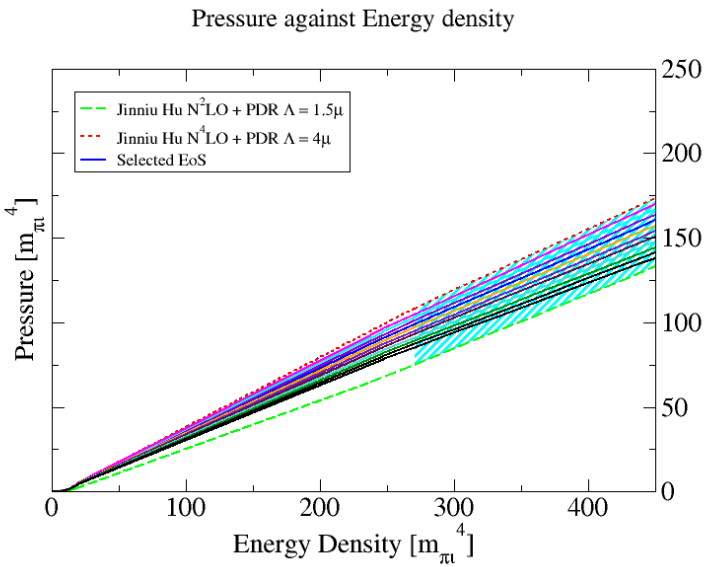
Do not assume GR: a software implementation

What we want to avoid

Simple parametrization interpolating the two bands

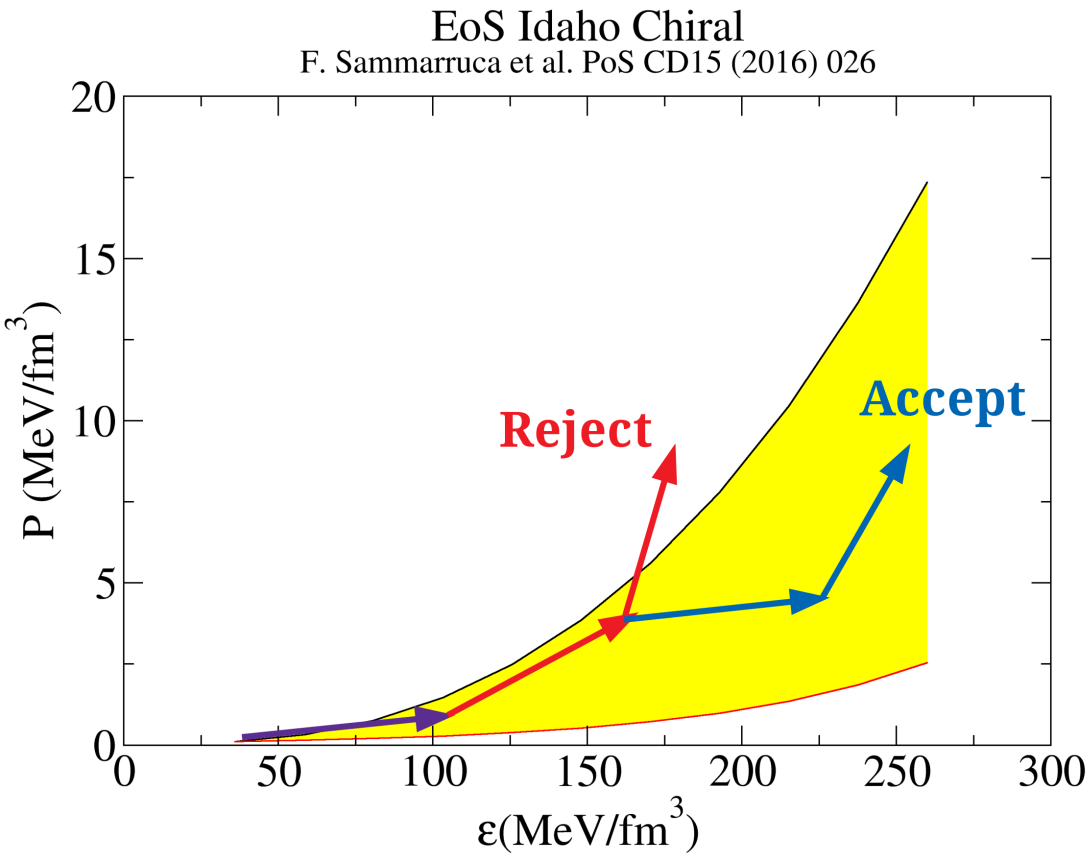




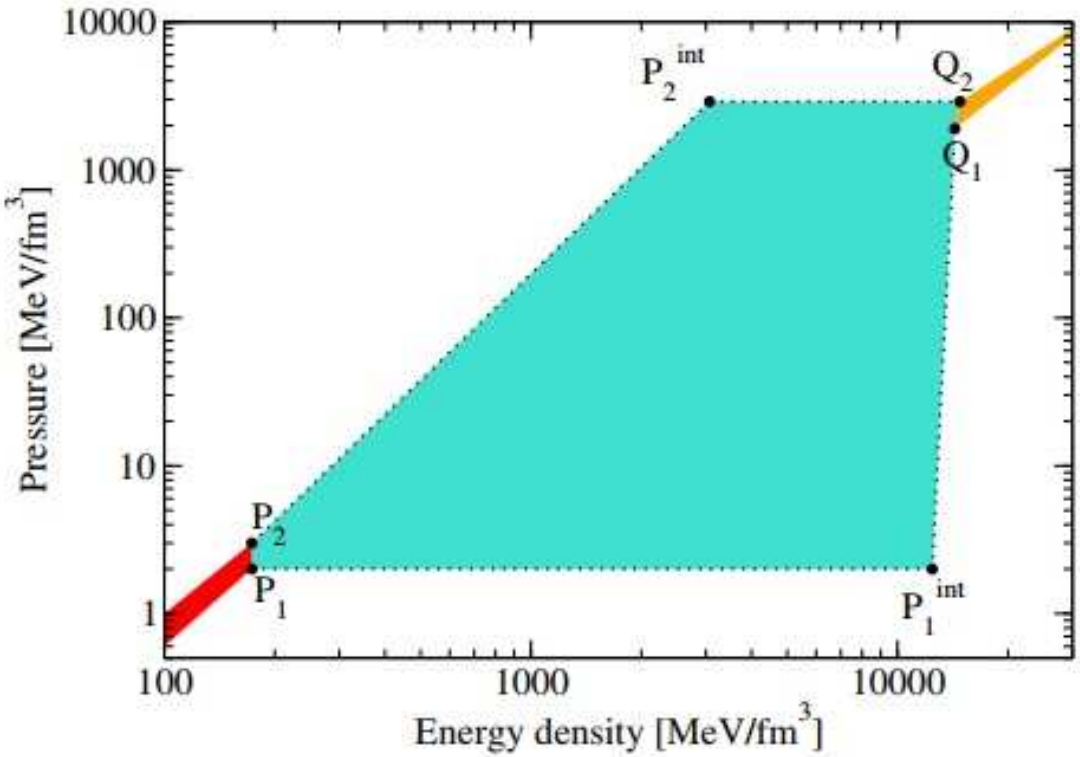
Uncontrolled systematic error from the parametrization

Advance from $\epsilon = 0$ with Von Neumann's rejection

Unbiased; inefficient but simple (less bugs)



Same through middle band interpolating low-high energy



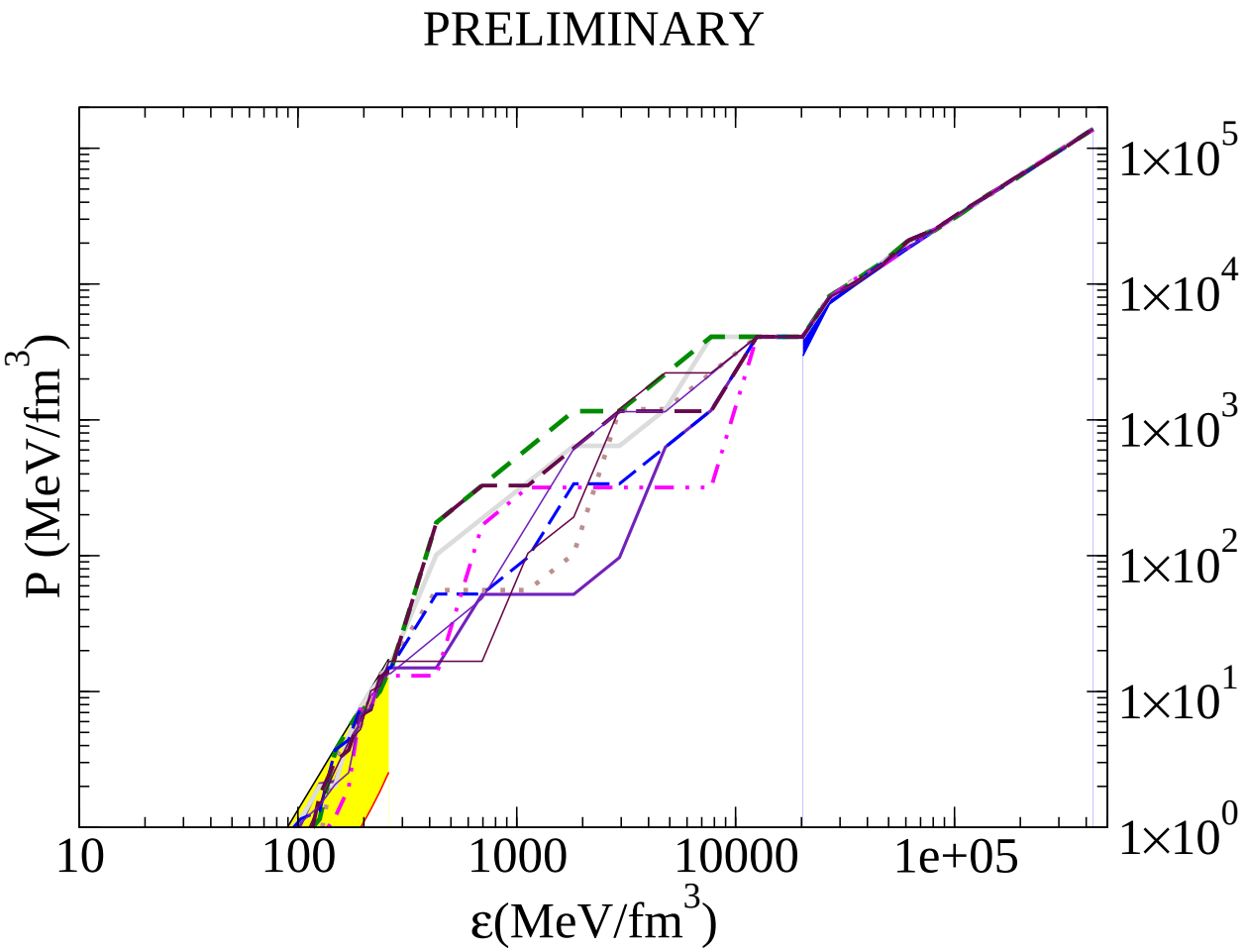
Fortran code

- Advance with random step & reject if outside the band; start over
- Parameters: $\Lambda_{\rm low}$ for the chiral theory, $\Lambda_{\rm high}$ *forpQCD*

Advantages of the method

- State of the art EoS that *do not* assume General Relativity (ideal to check extensions thereof)
- Systematic errors from countings
- New information **from QCD** available? No problem, we substitute our low-ϵ/high-ϵ bands

Example: 10 EOS on a sparse grid on the stiff side



How to deliver 100-1000 EoS candidates to a user?

- Give us the ϵ-grid,
  we return P on it?
- We give a callable function and interpolate our own grid? (e.g. pdfs)
- We develop a web interface?
  Or clean up and release the code?

Send us an email with your needs!

How to deliver 100-1000 EoS candidates to a user?

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  Or clean up and release the code?

Send us an email with your needs!

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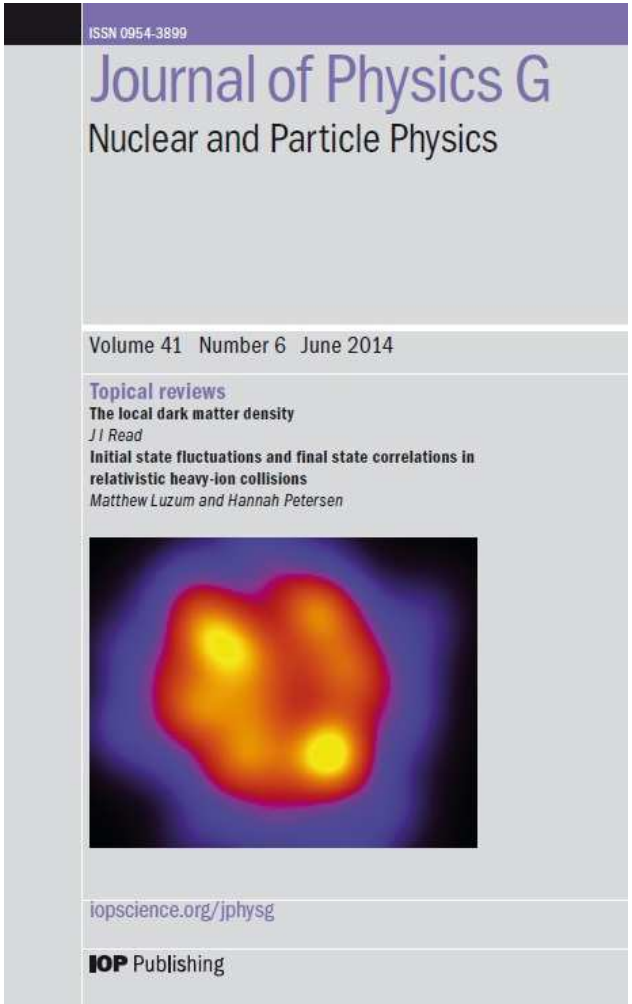
Are working on these things? consider...



Journal of Physics G focus issue

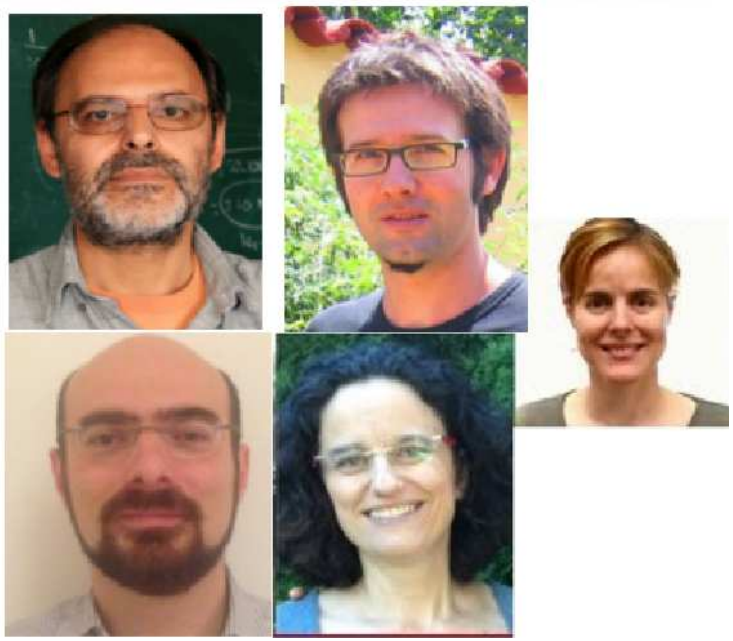
Hadrons and Gravitational Waves after GW170817

Approved and open for submissions any day now

Cosmocaixa is a shelter for theorists

Because there are no stars in Barcelona's night sky

They are organizing the workshop



THANK YOU!

Equation of State for modified gravity studies at neutron stars

Felipe J. Llanes-Estrada

Universidad Complutense de Madrid, Departamento de Física Teórica

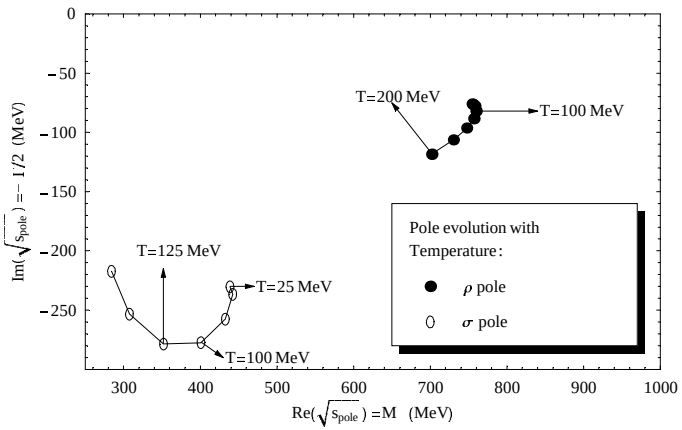
Ongoing work in collaboration with Eva Lope Oter & Ivan Sayago (@UCM), Mark Alford and Andreas Windisch (@ WU St. Louis)

26th/6/2018 Strong and Electroweak Matter, Barcelona

Spare slides

Effect of finite T?

- Mergers: temperatures of $O(60)$ MeV
- At this level, $T \sim m_\pi \ll m_n$ (can use chiral counting at low ϵ)
- A. Dobado et al. PRC2002 teaches us that m_ρ, m_σ are unaffected



Low energy dynamics controlled by M, not Γ: T is not the most urgent concern.

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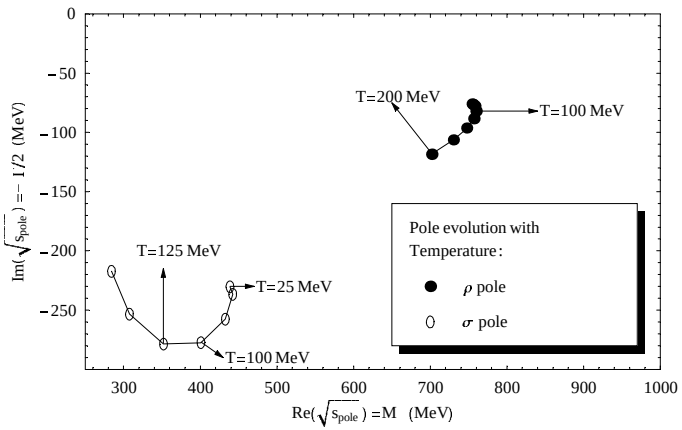

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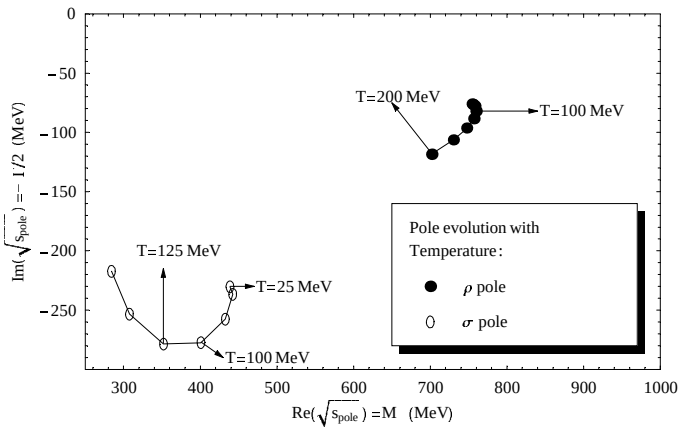

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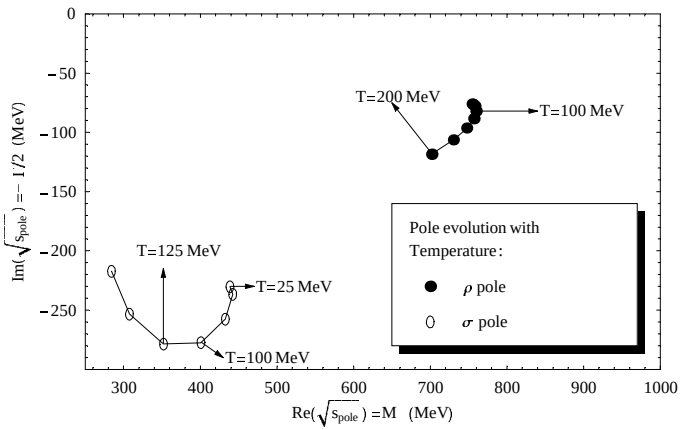
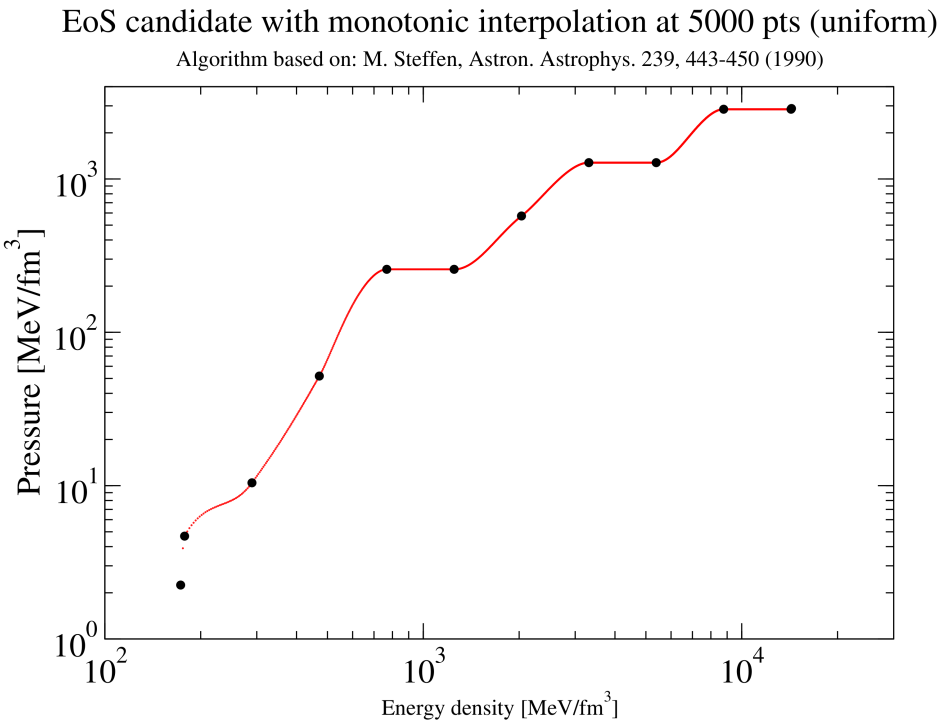


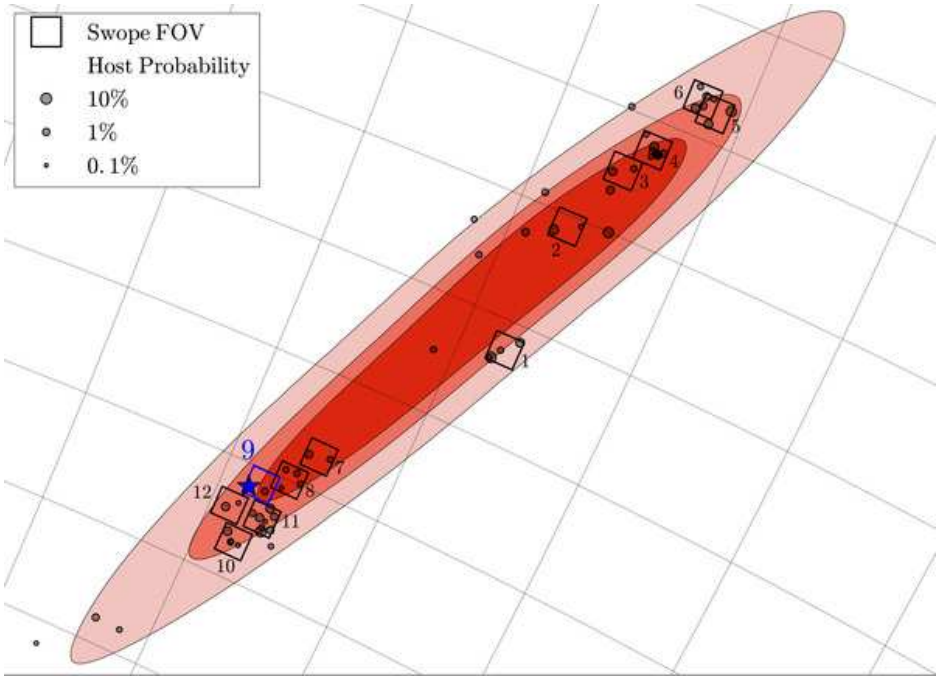
Low energy dynamics controlled by M, not Γ: T is not the most urgent concern.

Interpolate between ρ grid points with Steffen's method



A&A **239**, 443-450 (1990). Plot by A. Windisch

Are the EM and GW pulses from the same source?



(1M2H Team/UC Santa Cruz & Carnegie Observatories/Ryan Foley)

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There is about one γ-ray burst per day. What a coincidence in the sky...

Distance to source: GW 40^{+8}_{-14} MPc Electromagnetic 44^{3}_{7} MPc (associated galaxy)

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Tolman-Oppenheimer-Volkoff equation

General Relativistic Hydrostatic equilibrium
(static, spherical body)

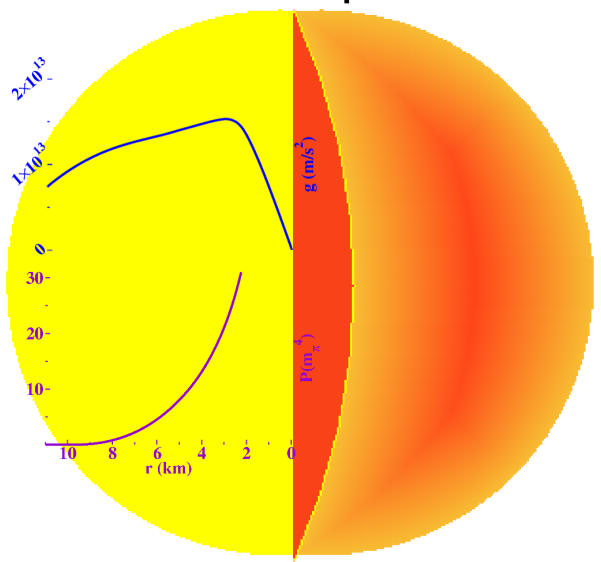
$$\frac{dP}{dr} = -\frac{G_N}{r^2}\frac{(\varepsilon(r)+P(r))(M(r)+4\pi r^3 P(r))}{1-\frac{2G_N M(r)}{r}} .$$

+ EOS + Mass: $M_{GR} = \int_0^{R_\odot} 4\pi r^2 \epsilon(r) \mathrm{d}r$

Compare with
Newtonian Hydrostatic equilibrium

$$dP = -\frac{G_N M(r)}{r^2}\frac{dM}{dA}$$

Pressure profile



Maximum mass for a given eq. of state

- Hydrostatic equilibrium:
  pressure compensates weight of upper layers
- Causality limits the achievable pressure, $c^2 \geq c_s^2 = \frac{dP}{d\rho}$
- But nothing limits the amount of matter falling on the star
- ρ increases until P picks up
- When $R_* < R_{\rm Schwarzschild} = 2M_*$, Gen. Rel. predicts collapse
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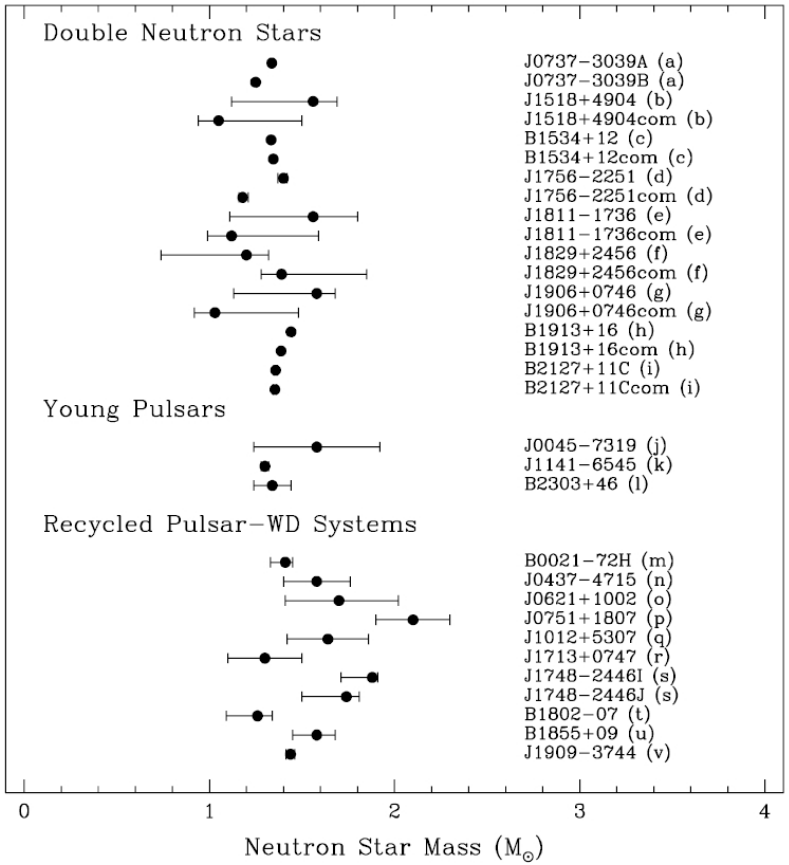
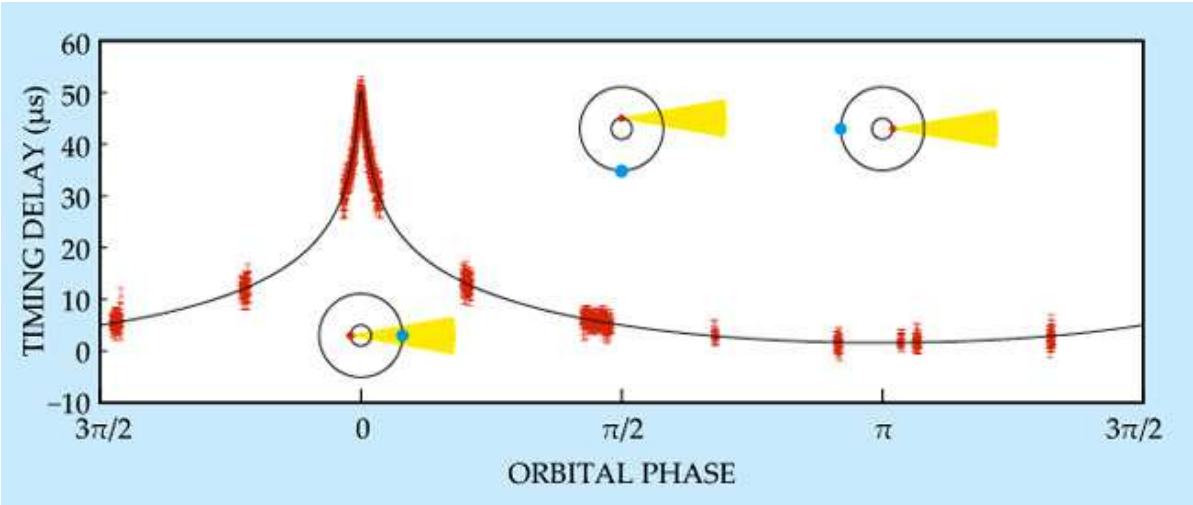
Measured pulsar masses before 2010



PRC77 065803 (2008)

Two-solar mass neutron star

Shapiro delay: allows for absolute measurement of the mass (Demorest et al. Nature 2010)



$$\Delta t = -\log(1 - \hat{n}_1 \cdot \hat{n}_2)\frac{R_s}{c}$$

Confirmed with 2nd example (binary orbital data), Antoniadis *et al.* Science **340** 1233232 (2013)

Bounds on the maximum

- All neutron stars have masses less than an (unknown) EOS-dependent maximum
- The gravitational-wave event is claimed to bind that maximum from above:
- $M_{\rm max} < 2.17 M_\odot$

1710.05938 from the radiation of the ejecta (not "red" enough)
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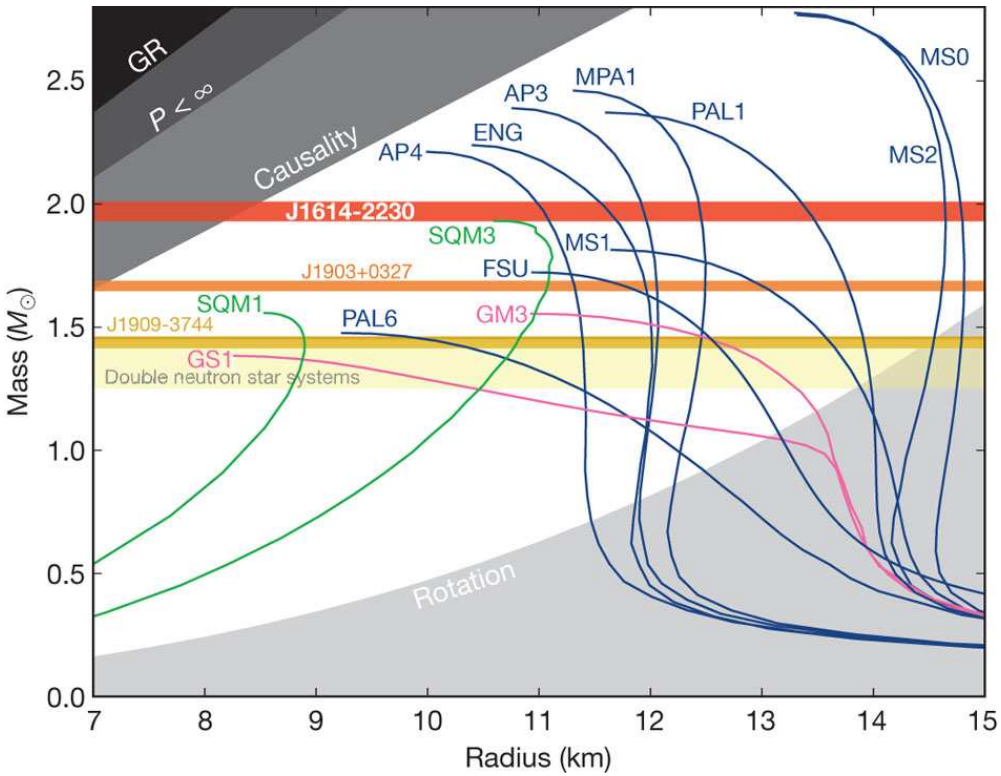
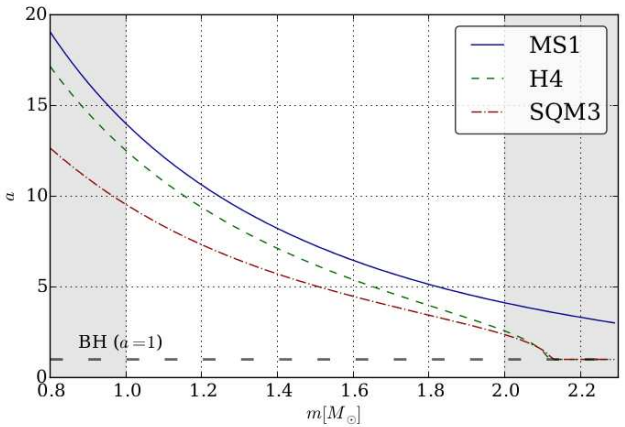
Used back then to exclude many models



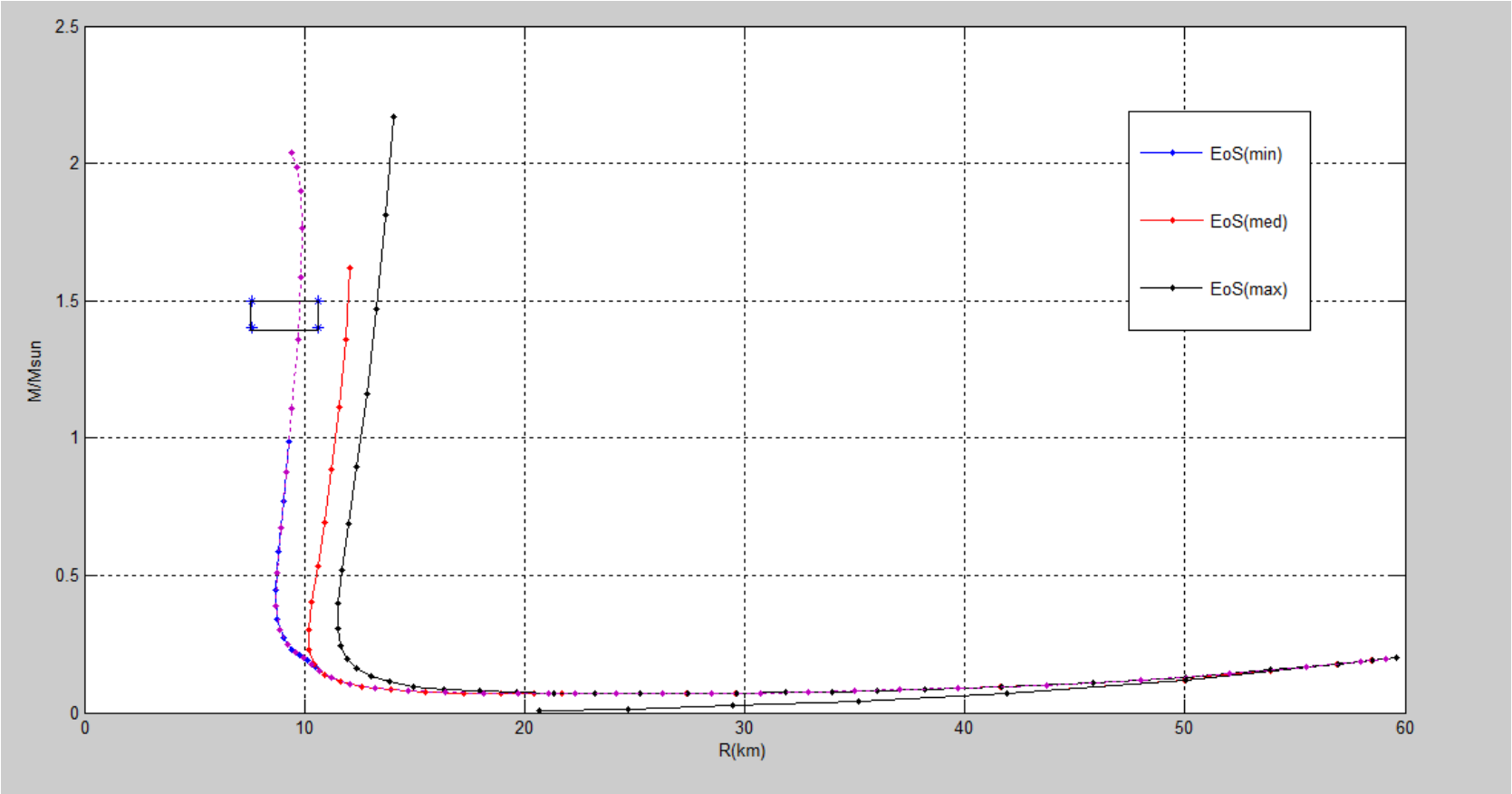
Static observables:

Bulk properties (very much like nuclear physics): M, R, I, Quadrupole moment Q, . . . ,
but also T, $\tau_{\rm cooling}$, Tidal deformability $Q_{ij} = \lambda E_{ij}$

Theory prediction of Q/J^2 quadrupole moment for three equations of state

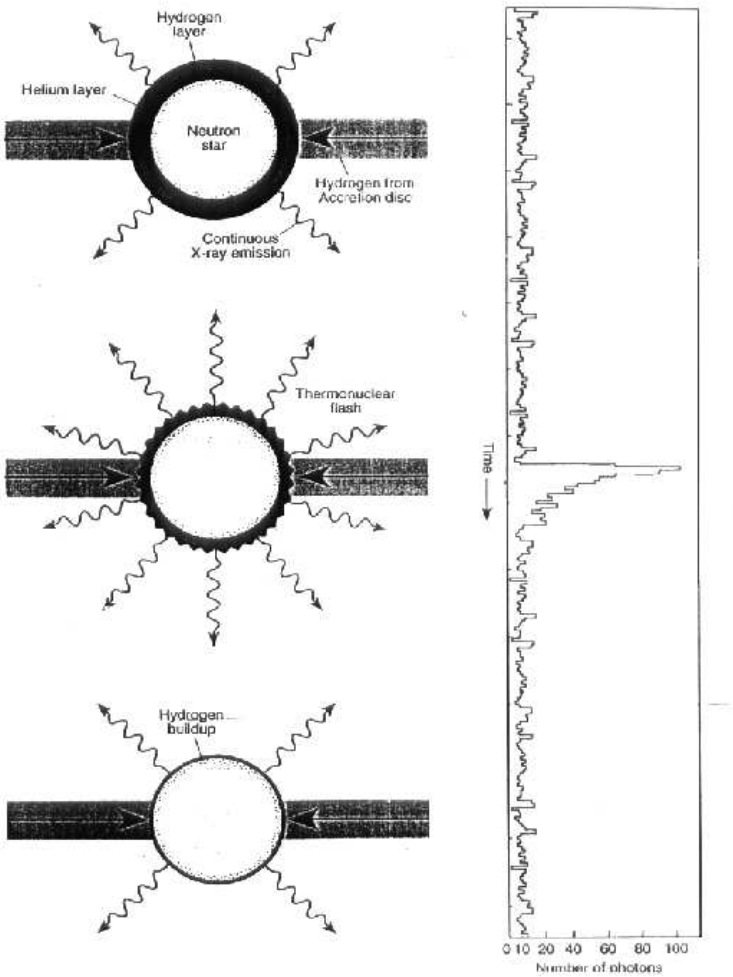


$M(R)$ quite vertical for $1.4M_\odot$: a measurement fixes EOS



The three EOS of Hebeler *et al.* (Schwenk), APJ **773** 11 (2013)

Radii from quiescent X-ray sources



(Picture from Ben Williams, UW)

1. X-ray spectrum $\Longrightarrow$ temperature T
2. $L_{\text{apparent}}\, d^2 = L R^2$
3. Luminosity to size $L = \sigma(\pi R^2) T^4$

$$\boxed{R = 9.4 \pm 1.2 km}$$

Guillot and Rutledge APJ**796**,1 (2014).

Typical radii calculated with GR: $R \simeq 11 - 13 km$

New light U-boson exchange? (1509.02128)

Other attempts to measure radii

Problems:

- Atmosphere of star and interstellar gas absorb X-rays
- Bad thermal spectrum

Try methods with different systematics

- Thermonuclear burst sources $R = (10.4 - 12.9)\mathrm{km}$
- Gravitational radiation

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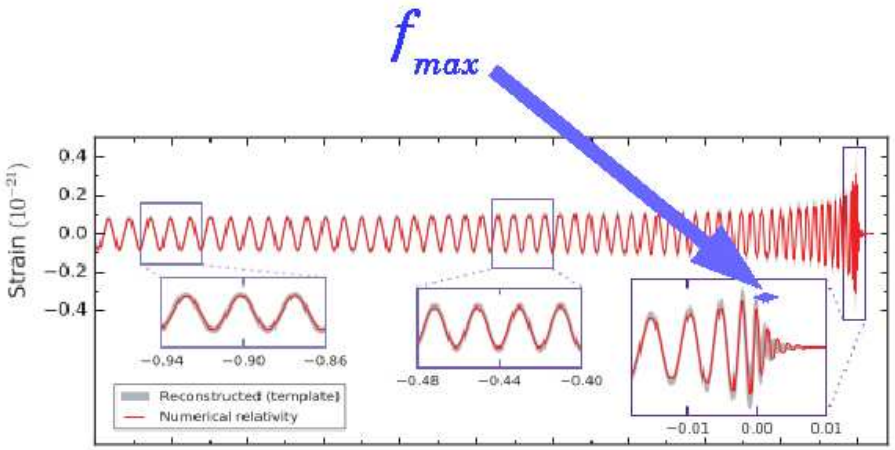

After merger:

Numerical relativity + EOS $\Longrightarrow$ Maximum frequency reads off the radius

Hoaw fast can you spin a bar?

Kaneyama *et al.* PRD**93**, 123010 (2016)

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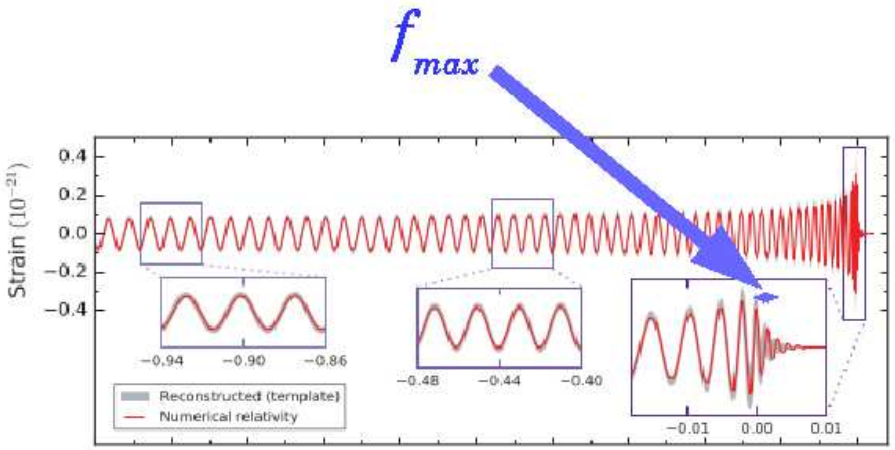

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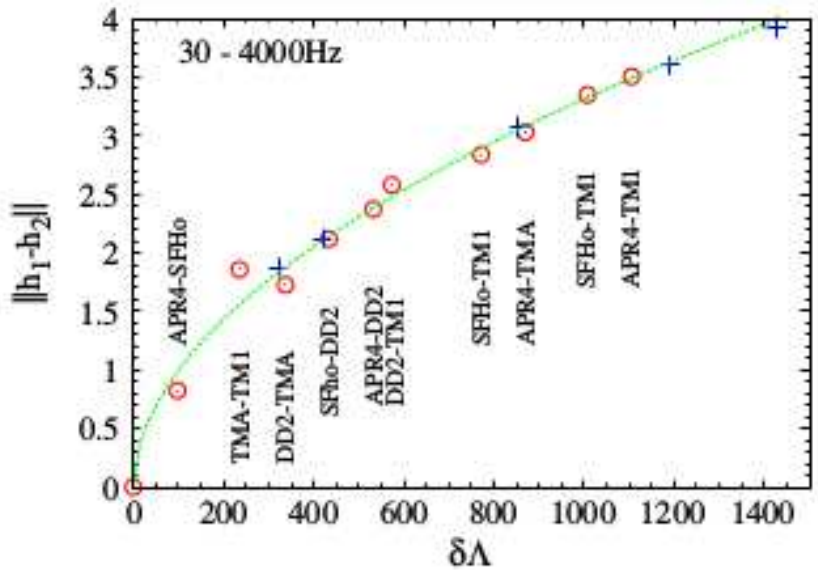
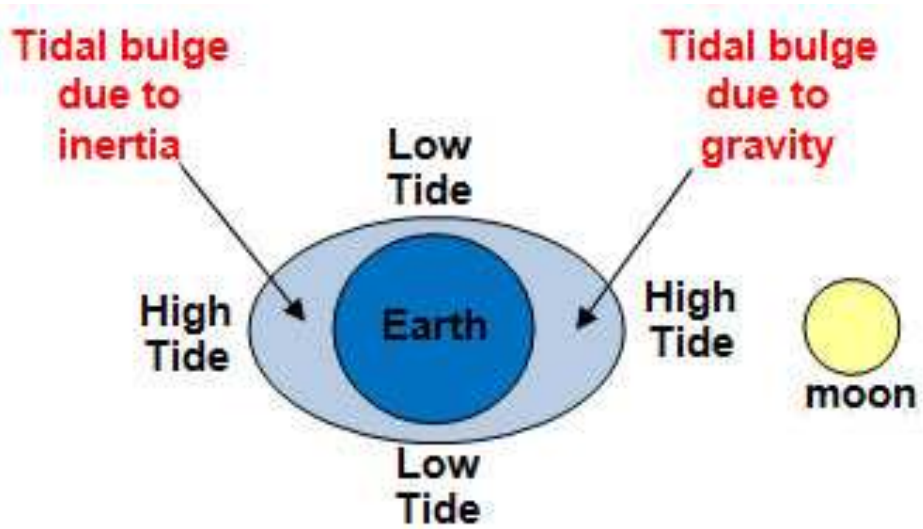
Simulations $\Longrightarrow$ Tidal deformability λ $\Longrightarrow$ R

$$\frac{\delta R/0.91\mathrm{km}}{R/13\mathrm{km}} = \frac{\delta\lambda/400}{\lambda/1000}$$

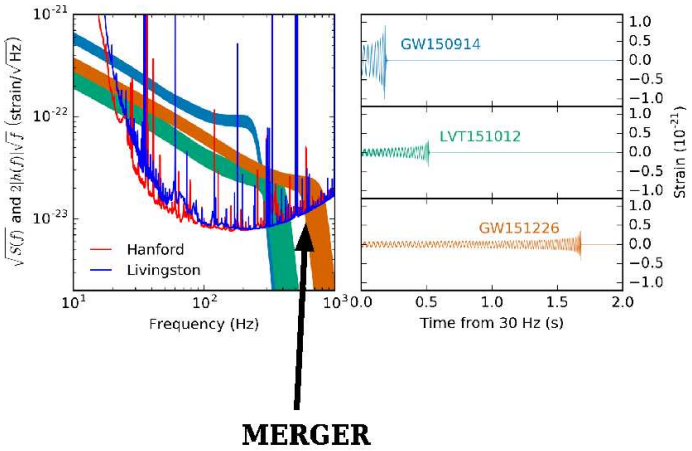




Extraction comparing simulated gravitational waveforms h_1 and h_2

Hotokezaka *et al.*, PRD**93**, 064082 (2016) for $M = 1.35 M_\odot$

Frequency maximum would closely track tidal deformability



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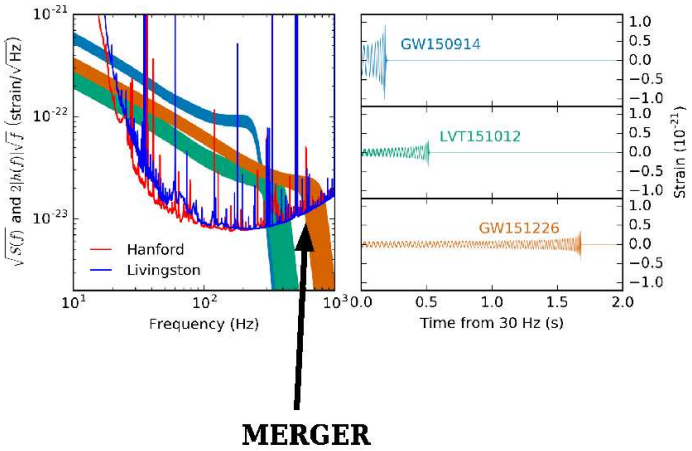

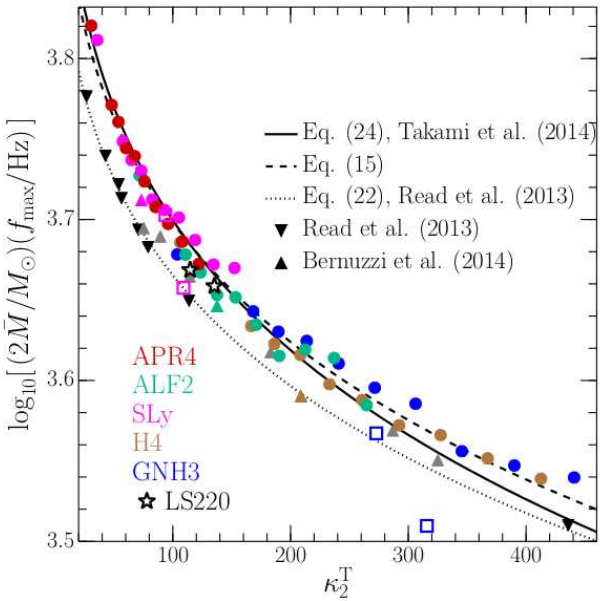

Rezzolla and Takami, 1604.00246

Other effects: waves in flat space

(Tight bounds because

$$\frac{t_{\text{propagation}}}{t_{\text{generation}}} \sim \frac{\text{Distance}}{\text{Source mass}}$$

- Scalar (third) polarization $h = \begin{pmatrix} h_0 + h_+ & h_x \\ -h_x & h_0 - h_+ \end{pmatrix}$
- Depending on the sign of a in aR^2
  1. Dispersion relation with a mass $m_R^2 = \frac{1+f_{rR}(0)}{3f_{rrR}(0)}$ (Ligo already constrains it to $m_R < 10^{-22}$eV see P. Bicudo, 1602.04337)
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