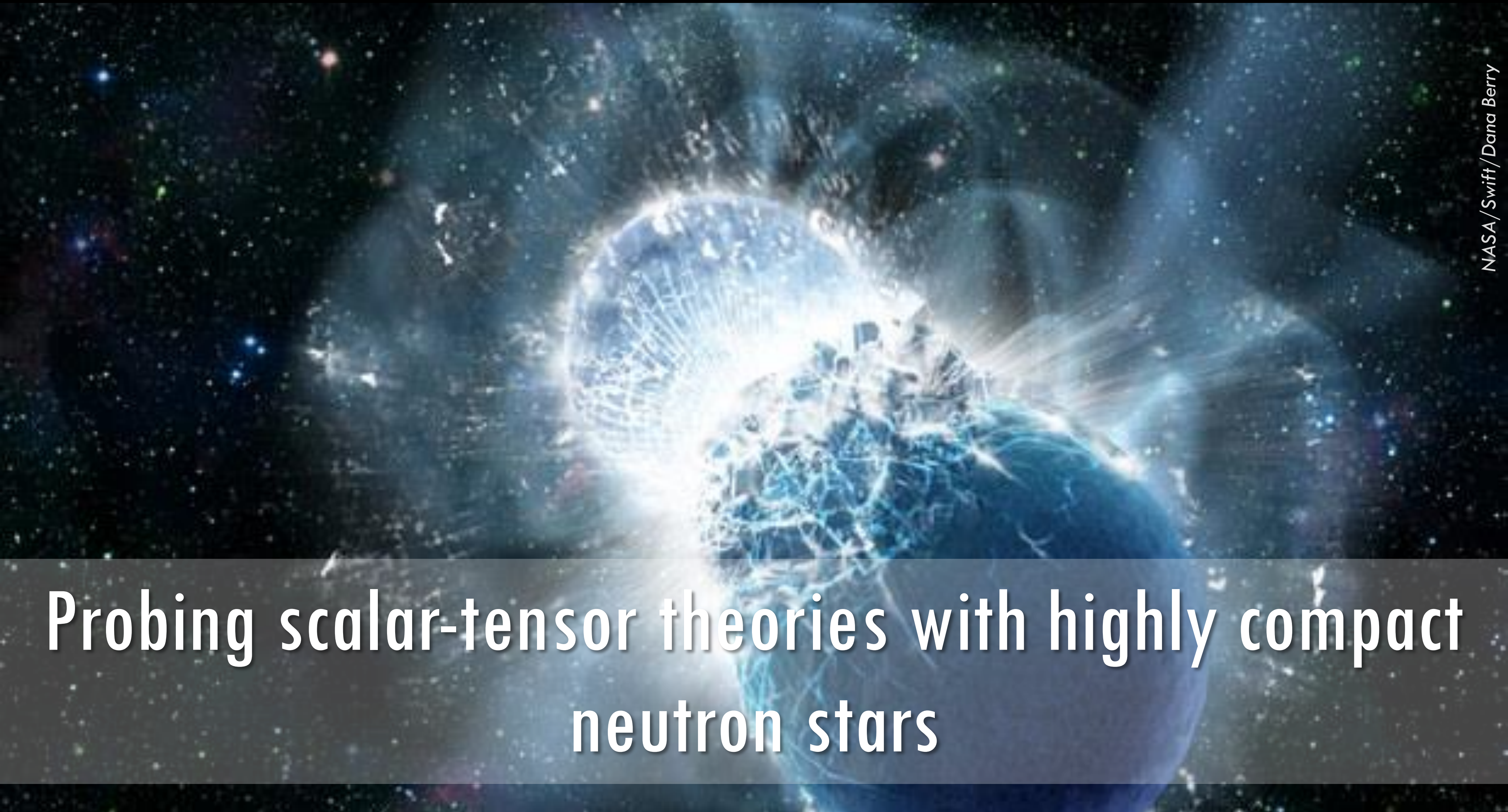
Black Holes and Neutron Stars in Modified Gravity, Nov 18th 2019, Meudon - France



NASA/Swift/Dana Berry

Probing scalar-tensor theories with highly compact neutron stars

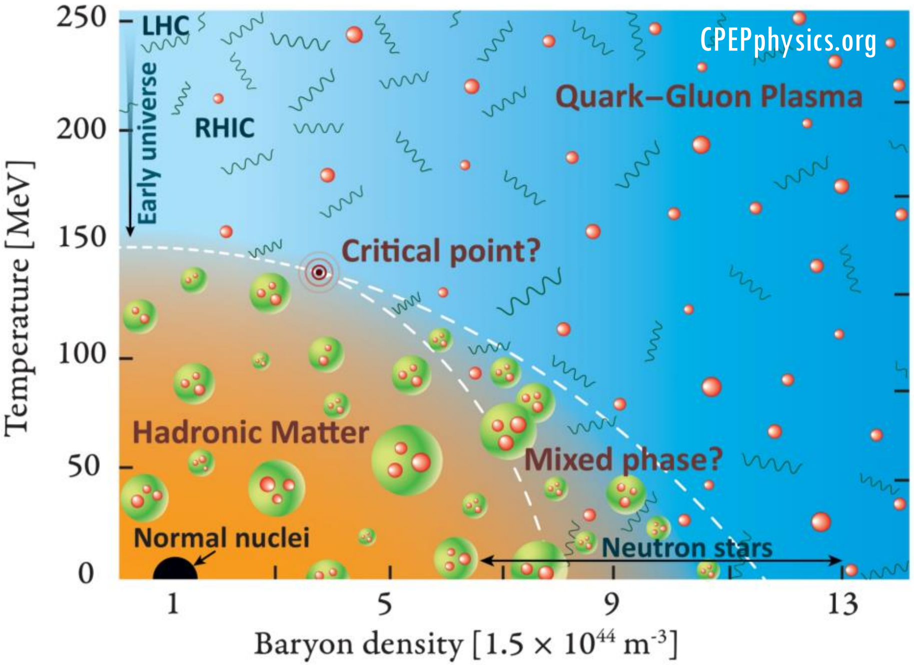
Raissa F. P. Mendes

UFF – Rio de Janeiro, Brazil

Neutron stars: most compact (material) objects in Nature

Neutron stars: most compact (material) objects in Nature

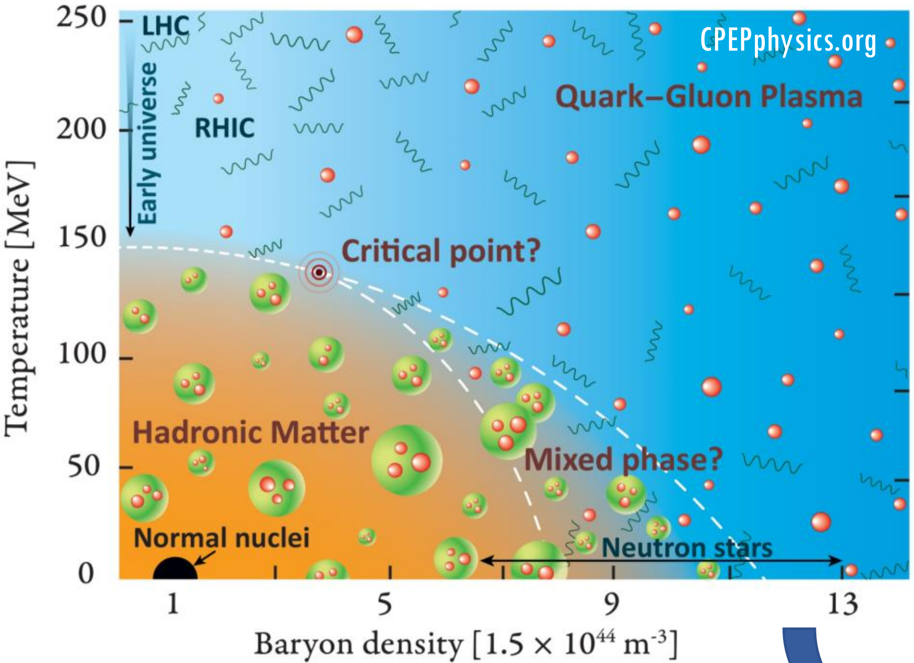
Rich microphysics

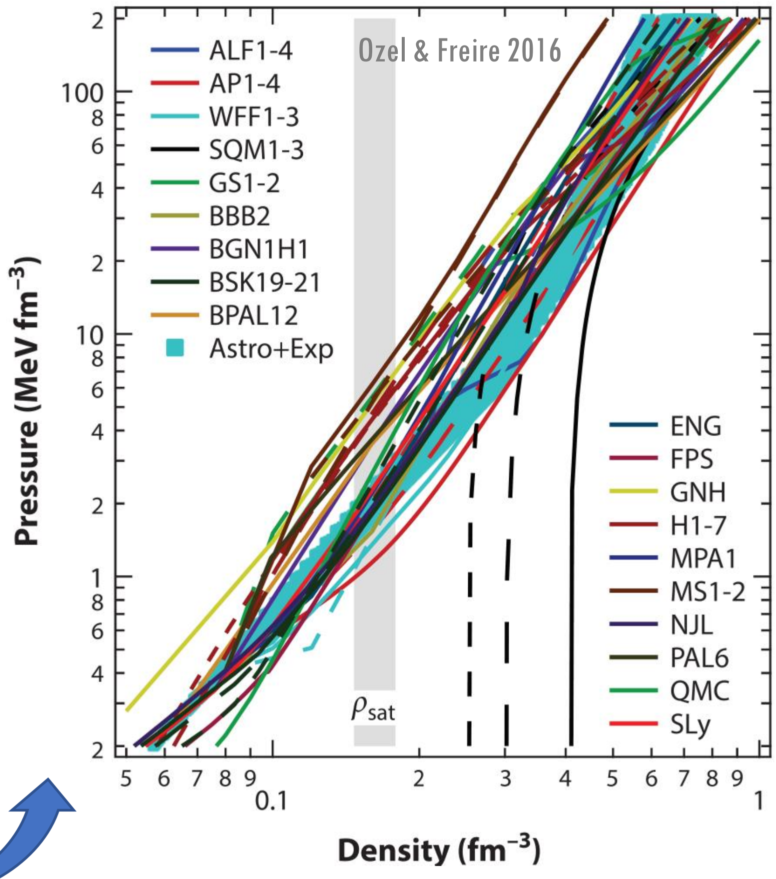


Neutron stars: most compact (material) objects in Nature

Rich microphysics

- NS as labs for nuclear physics





nuclear physics modeling

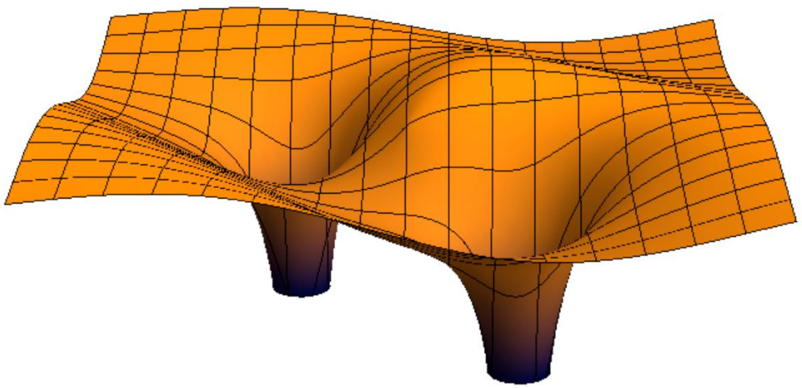
Neutron stars: most compact (material) objects in Nature

Rich microphysics

- NS as labs for nuclear physics

Strong gravity

- NS as labs for fundamental physics and testing GR



Nuclear physics *vs* modified gravity

PART 1: THE CURSE OF NS MICROPHYSICS

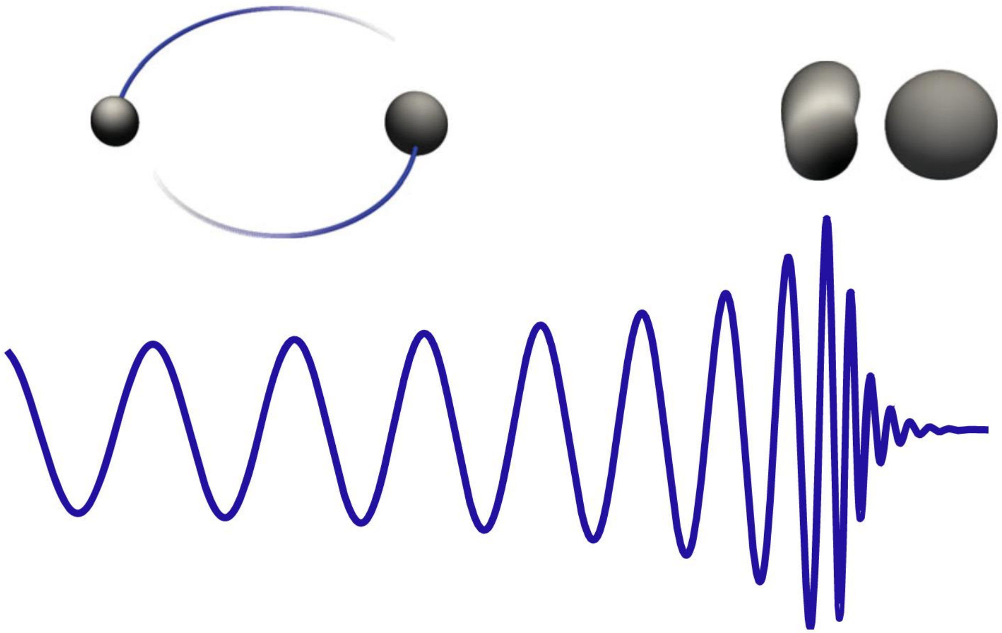
And how to circumvent it

PART 2: THE BOONS OF NS MICROPHYSICS

And how to harness them

PART 1: The ‘curse’ of neutron star microphysics

Gravity/EOS degeneracies



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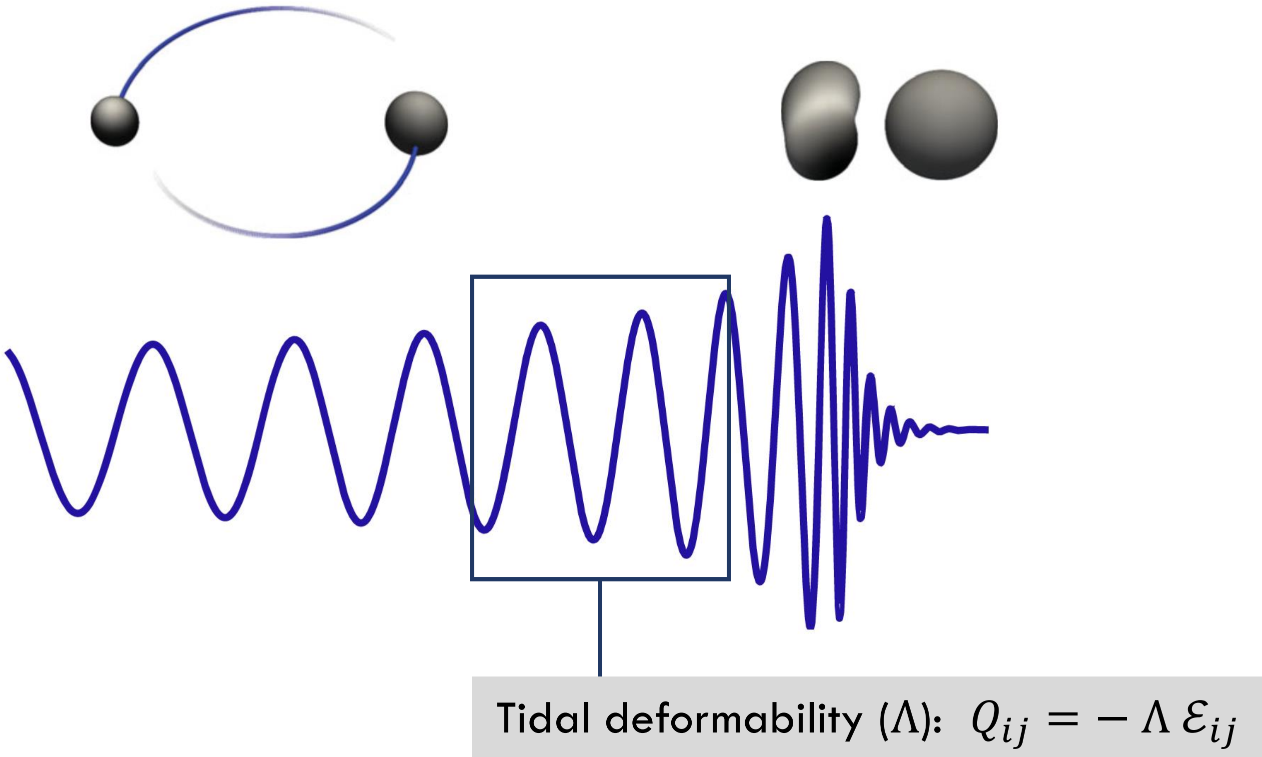

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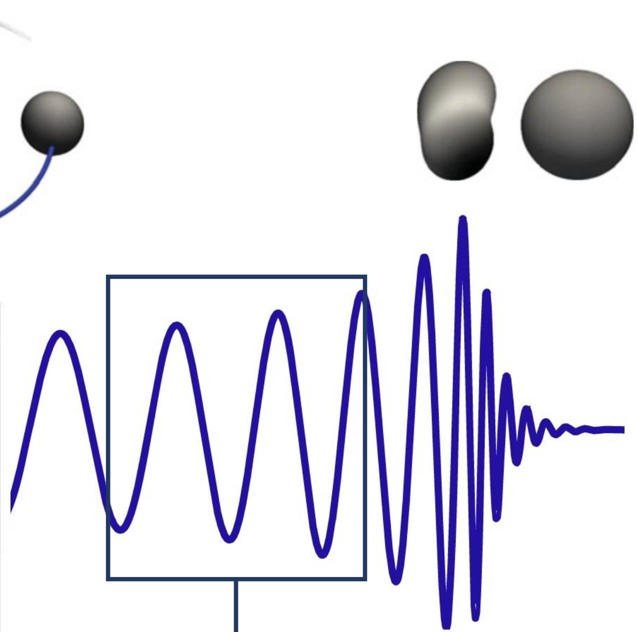
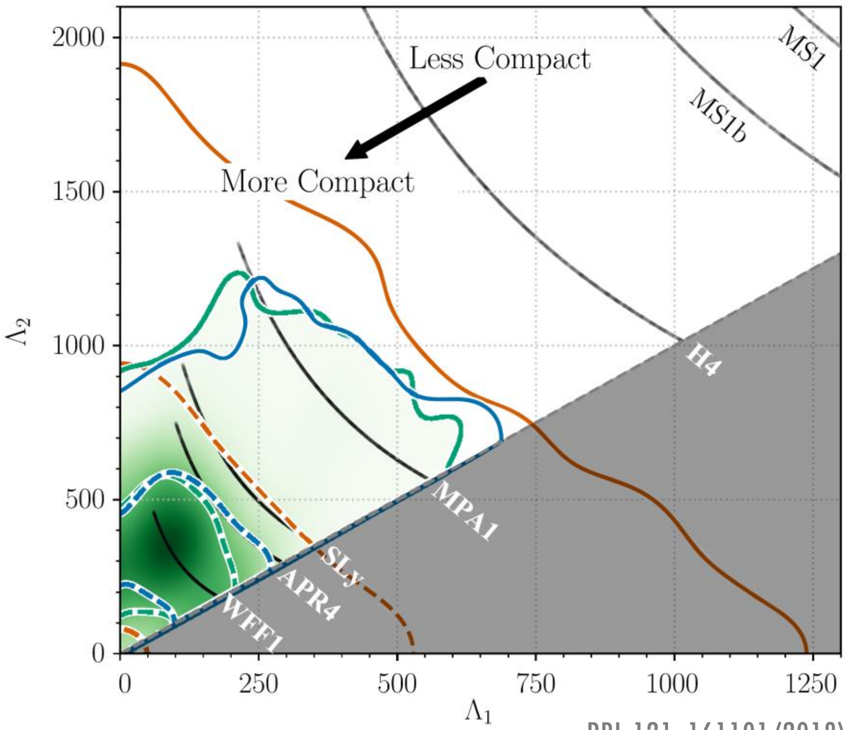
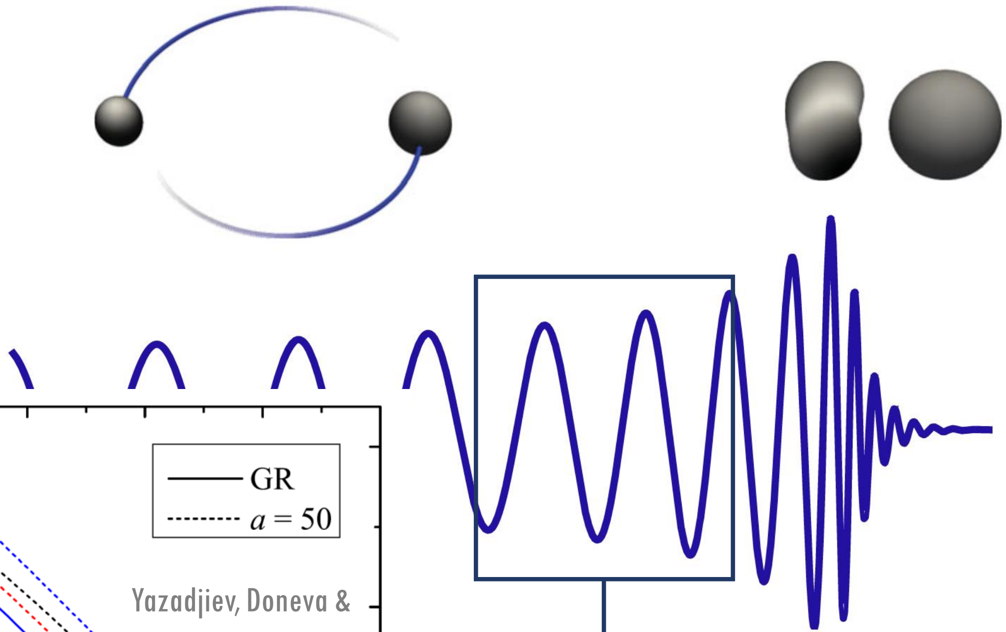


Tidal deformability (Λ): $Q_{ij} = -\Lambda\,\mathcal{E}_{ij}$



PRL 121, 161101 (2018)

Gravity/EOS degeneracies



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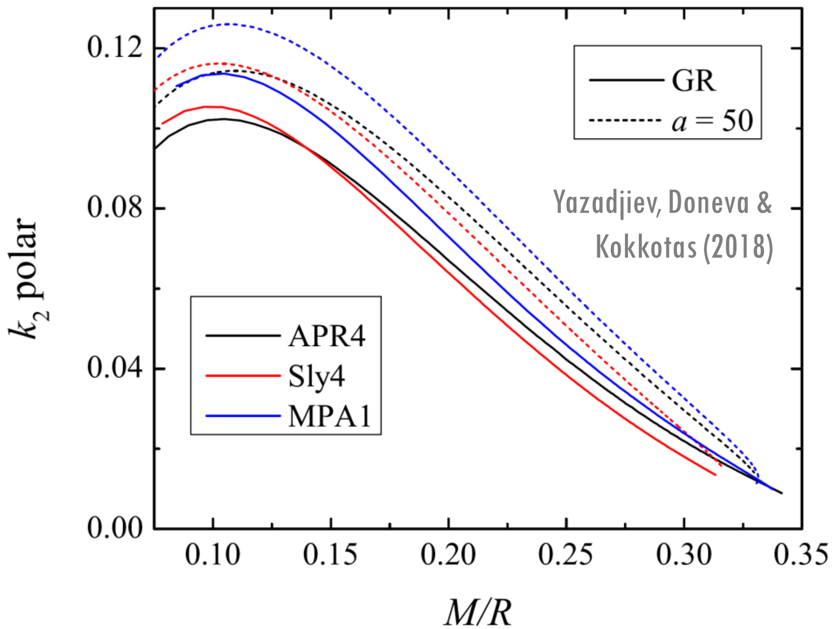
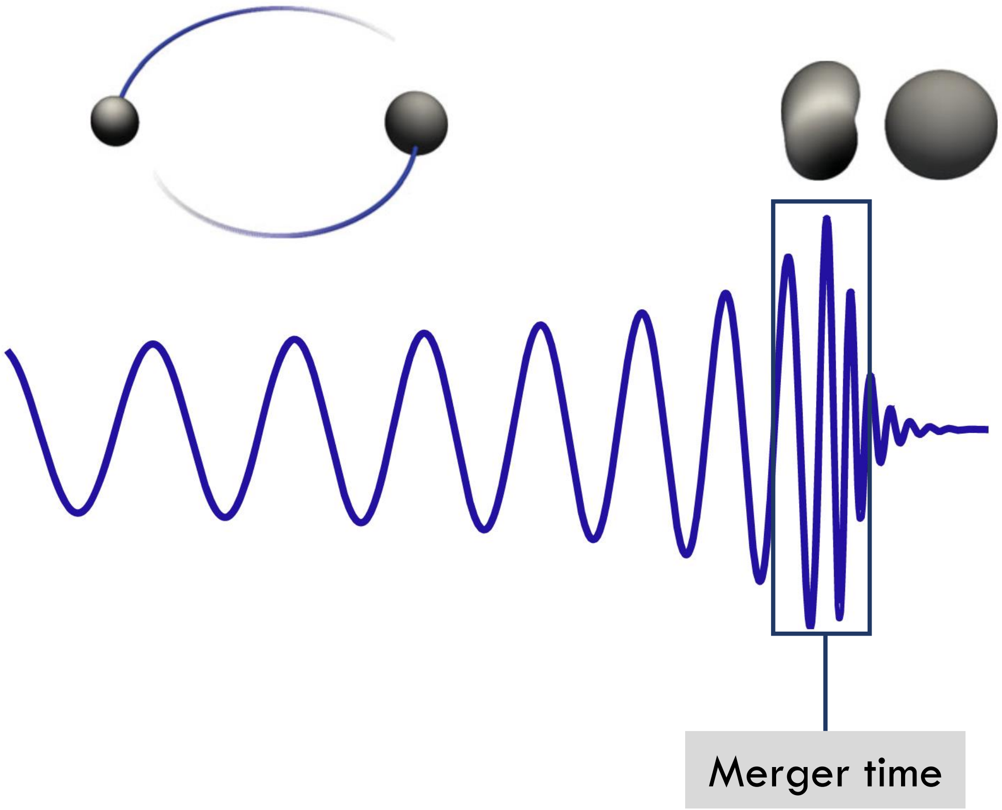


Yazadjiev, Doneva & Kokkotas (2018)

Gravity/EOS degeneracies



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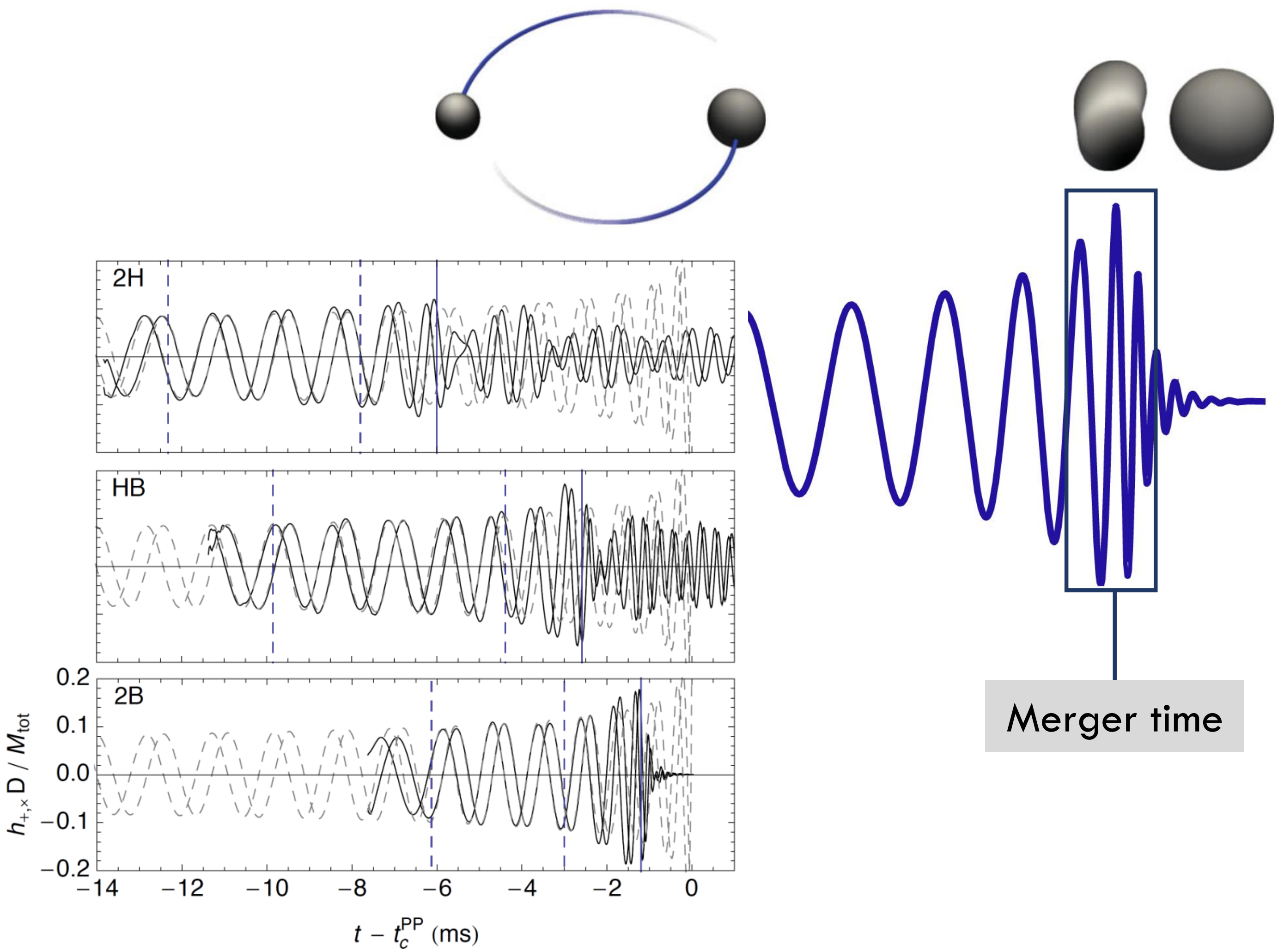

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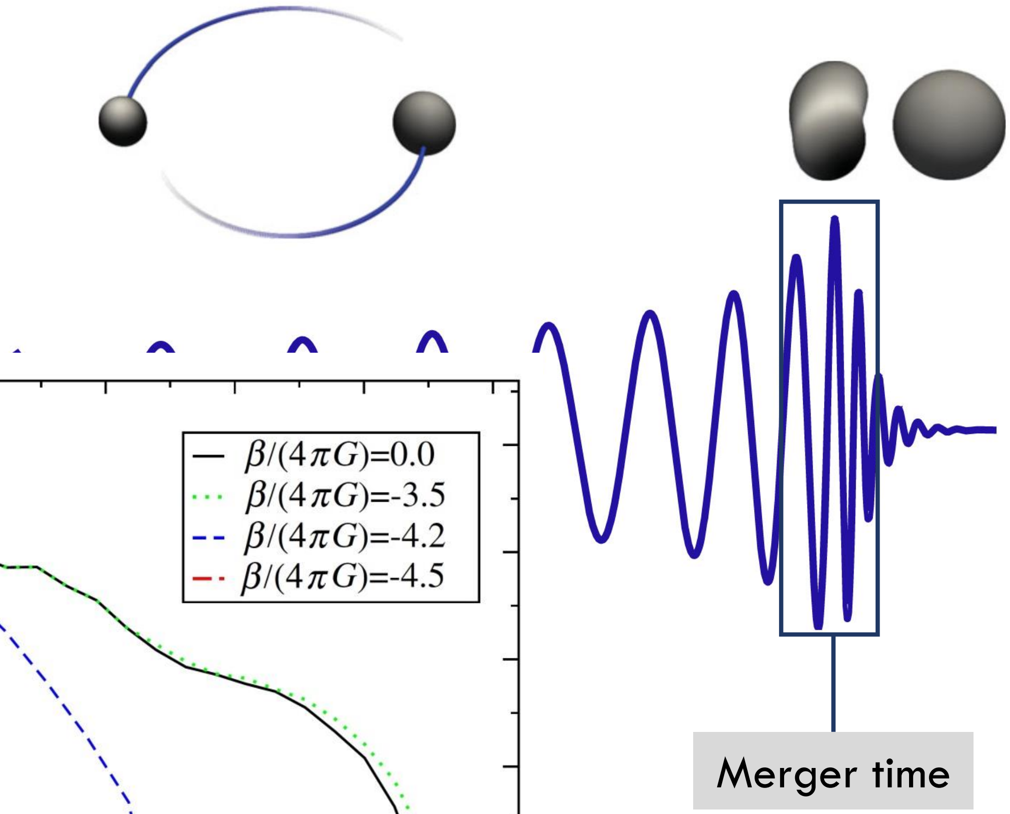

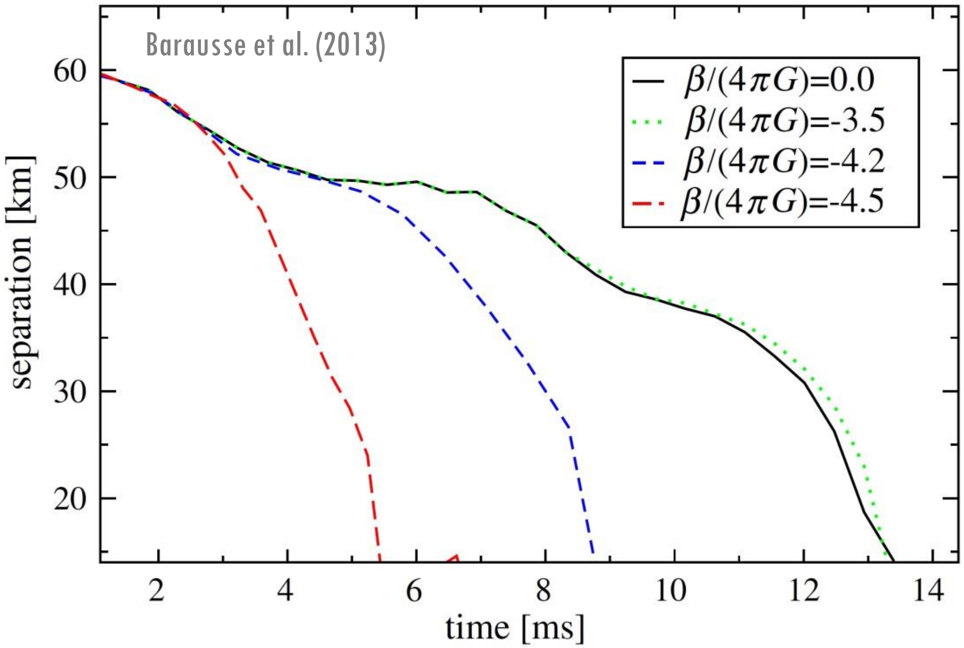

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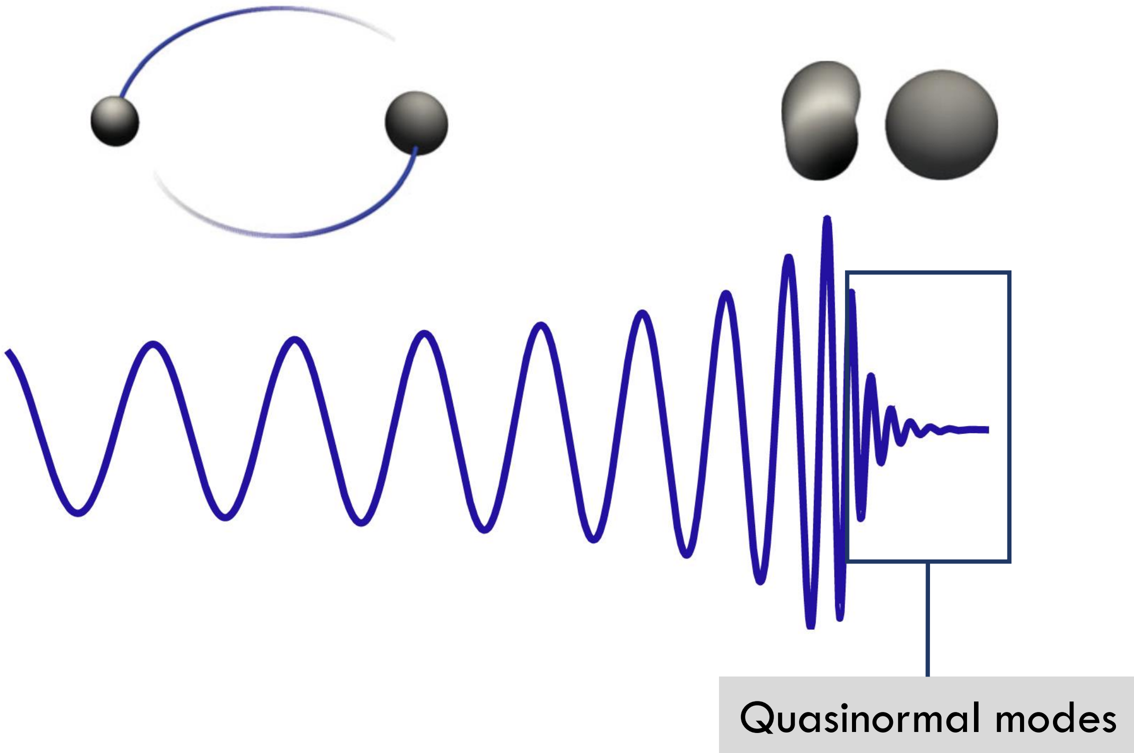

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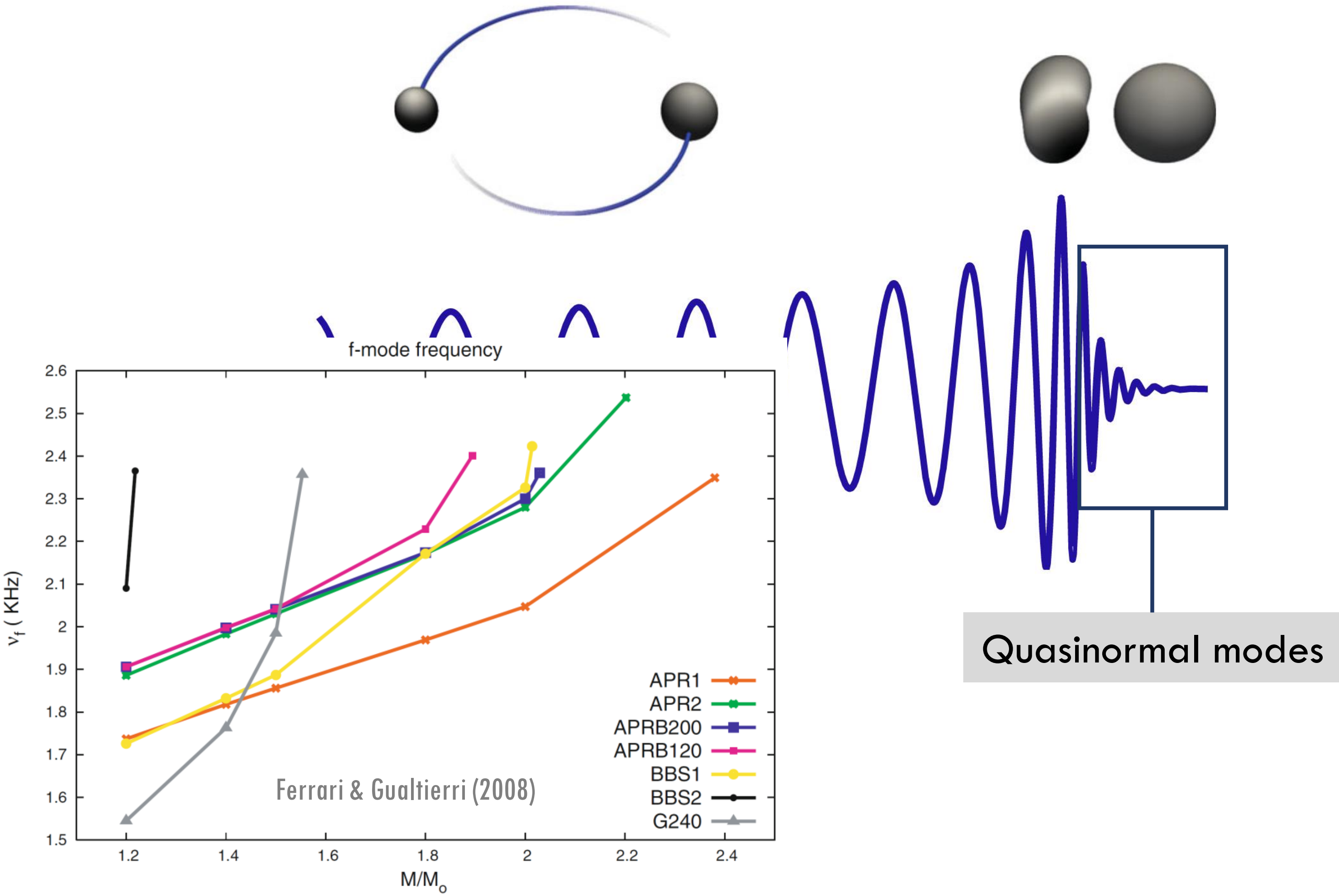

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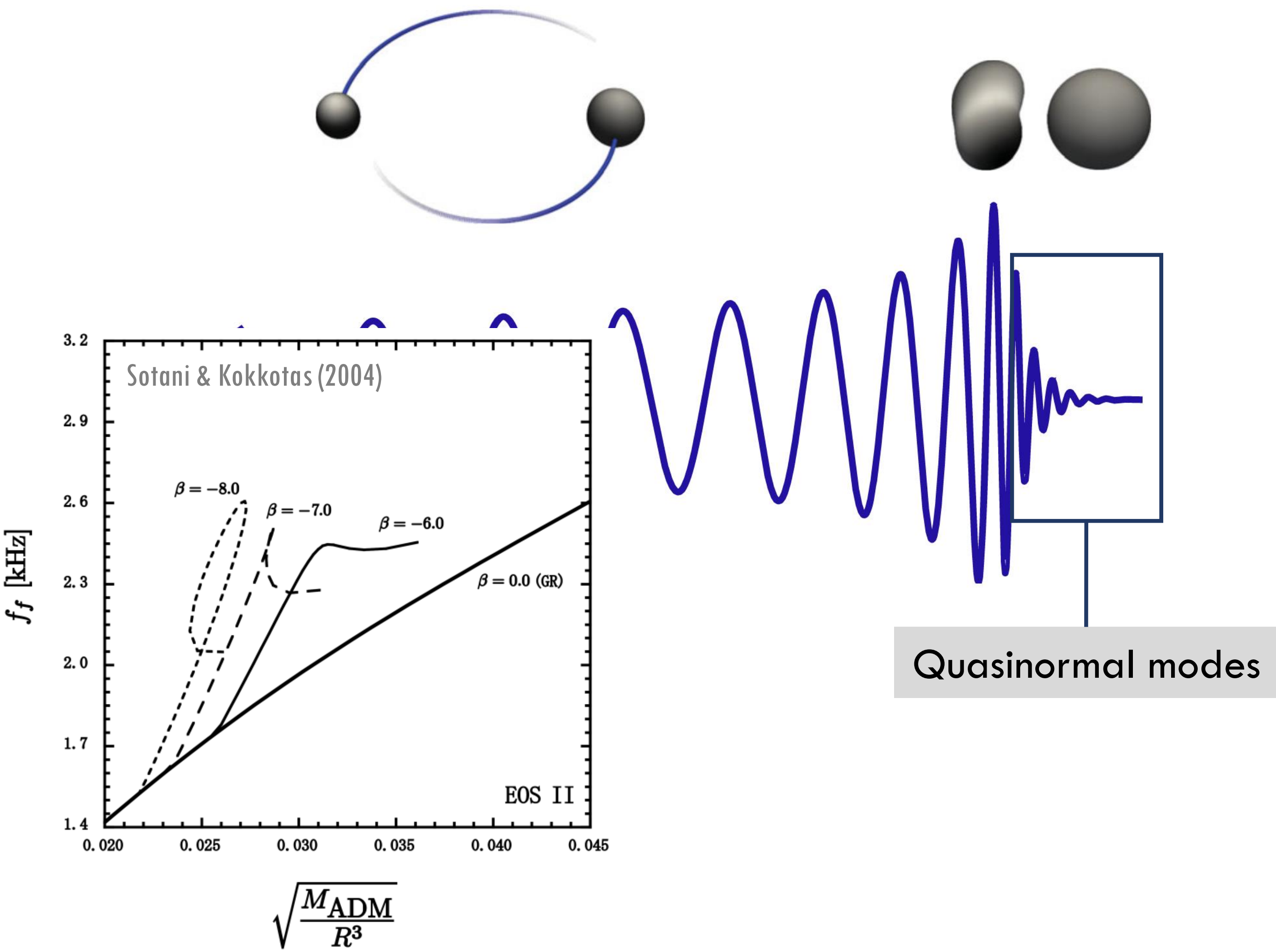

Gravity/EOS degeneracies: a way to circumvent them

Mendes & Ortiz, PRL 120, 201104 (2018)

Gravity/EOS degeneracies: a way to circumvent them

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Modified theories of gravity may not only *shift* the frequencies of NS QNMs, but also *introduce entirely new families of modes*, with no counterpart in GR, and which may be sufficiently well-resolved in frequency as to allow for a clear detection.

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* Expected!

Newtonian star

General-relativistic star

$$\{\omega_i^{(N)}\} \longrightarrow \left\{\omega_i^{(R)}\right\} = \left\{\omega_i^{(N)} + \delta\omega_i + i\Delta_i\right\}$$

+ *w-modes*!

Set-up: scalar-tensor theories (STTs)

- Natural, mathematically consistent and simple extensions to GR

$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-\tilde{g}}\left[F(\Phi)\tilde{R} - Z(\Phi)\,\tilde{g}^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi\right] + S_m\left[\Psi_m;\ \tilde{g}_{\mu\nu}\right] \quad (Jordan)$$

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- Examples:
  - Jordan-Brans-Dicke: $F(\Phi) = \Phi$, $Z(\Phi) = \omega_{BD}/\Phi$.
  - “Standard” NMC scalar: $F(\Phi) = 1 - \xi\Phi^2$, $Z(\Phi) = 8\pi$.

Set-up: scalar-tensor theories (STTs)

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$$g_{\mu\nu} = F(\Phi)\,\tilde{g}_{\mu\nu} = a(\phi)^{-2}\tilde{g}_{\mu\nu}$$

$$\phi = \phi(\Phi)$$

$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\left[R - 2g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\right] + S_m\left[\Psi_m; a(\phi)^2 g_{\mu\nu}\right]\quad (Einstein)$$

Set-up: scalar-tensor theories (STTs)

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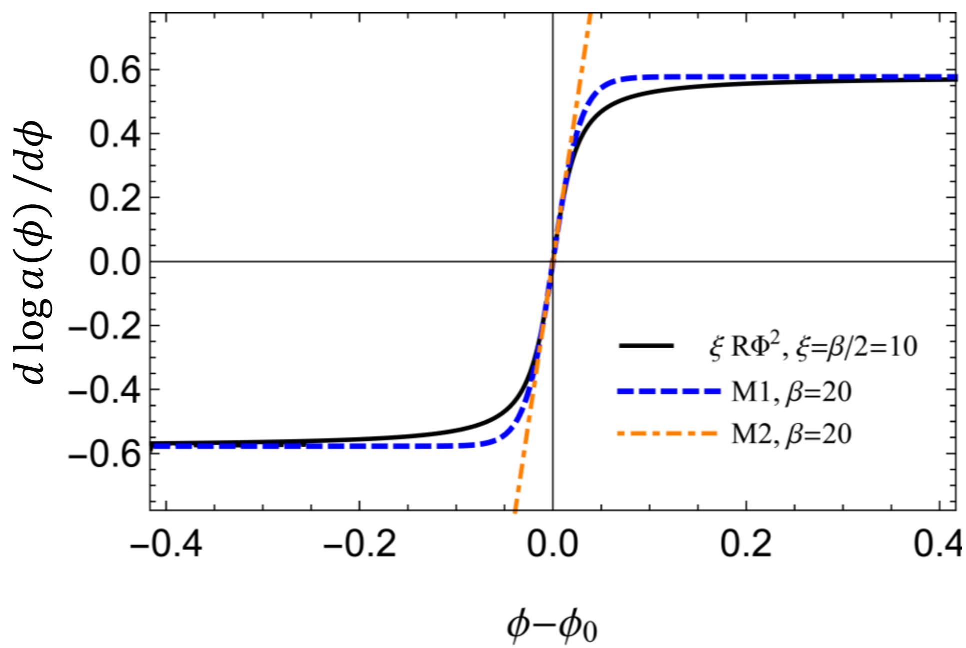
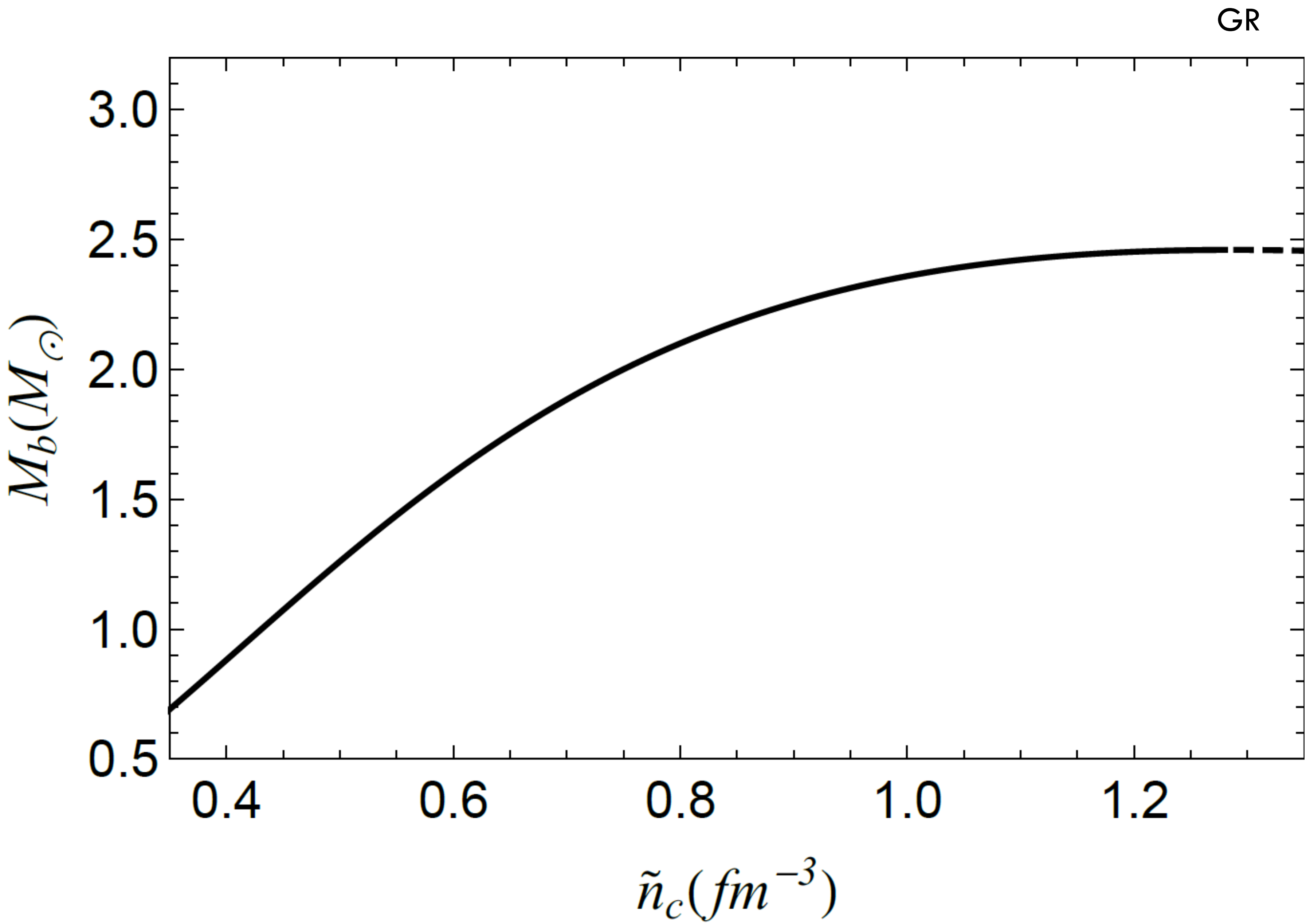
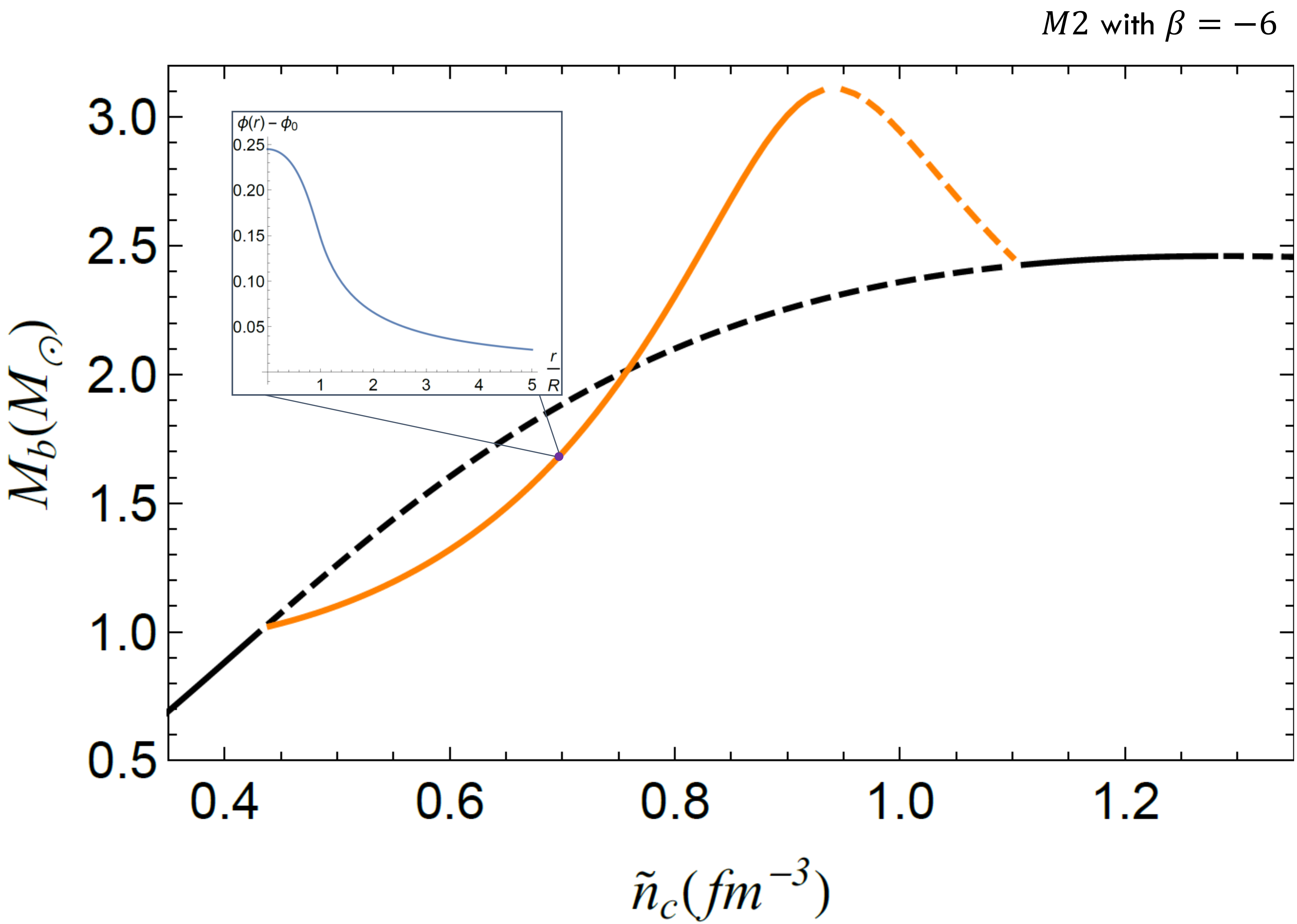
Model 1: $a(\phi) = \cosh\left[\sqrt{3}\,\beta\,(\phi - \phi_0)\right]^{1/(3\beta)}$

Model 2: $a(\phi) = \exp\left[\beta\,\frac{(\phi-\phi_0)^2}{2}\right]$



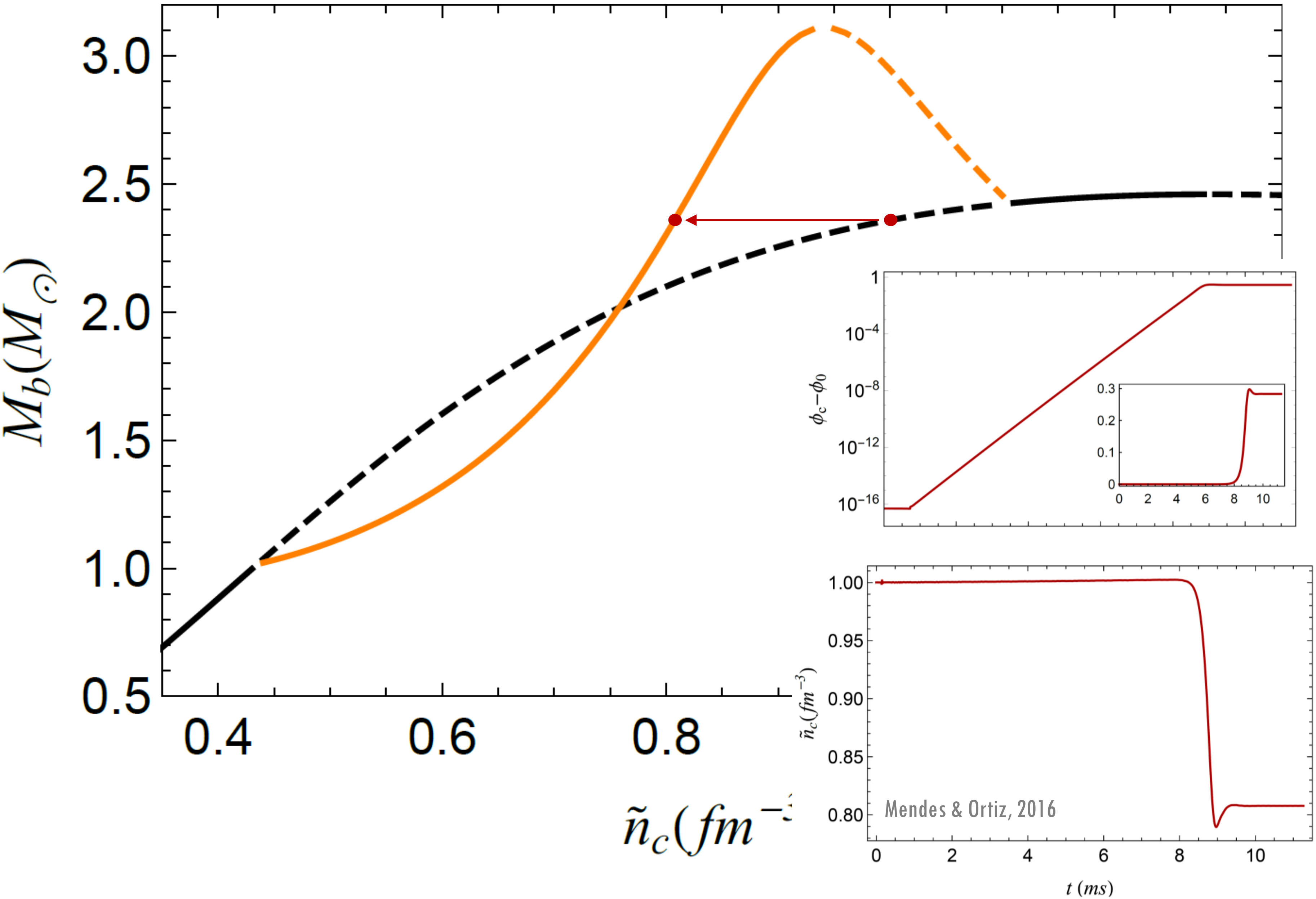


GR
3.0
2.5
2.0
1.5
1.0
0.5
$M_b(M_\odot)$
0.4
0.6
0.8
1.0
1.2
$\tilde{n}_c(fm^{-3})$



M2 with β = −6
φ(r) − φ0
0.25
0.20
0.15
0.10
0.05
1
2
3
4
5
r/R
3.0
2.5
2.0
1.5
1.0
0.5
0.4
0.6
0.8
1.0
1.2
$M_b(M_\odot)$
$\tilde{n}_c(fm^{-3})$

$M2$ with $\beta = -6$



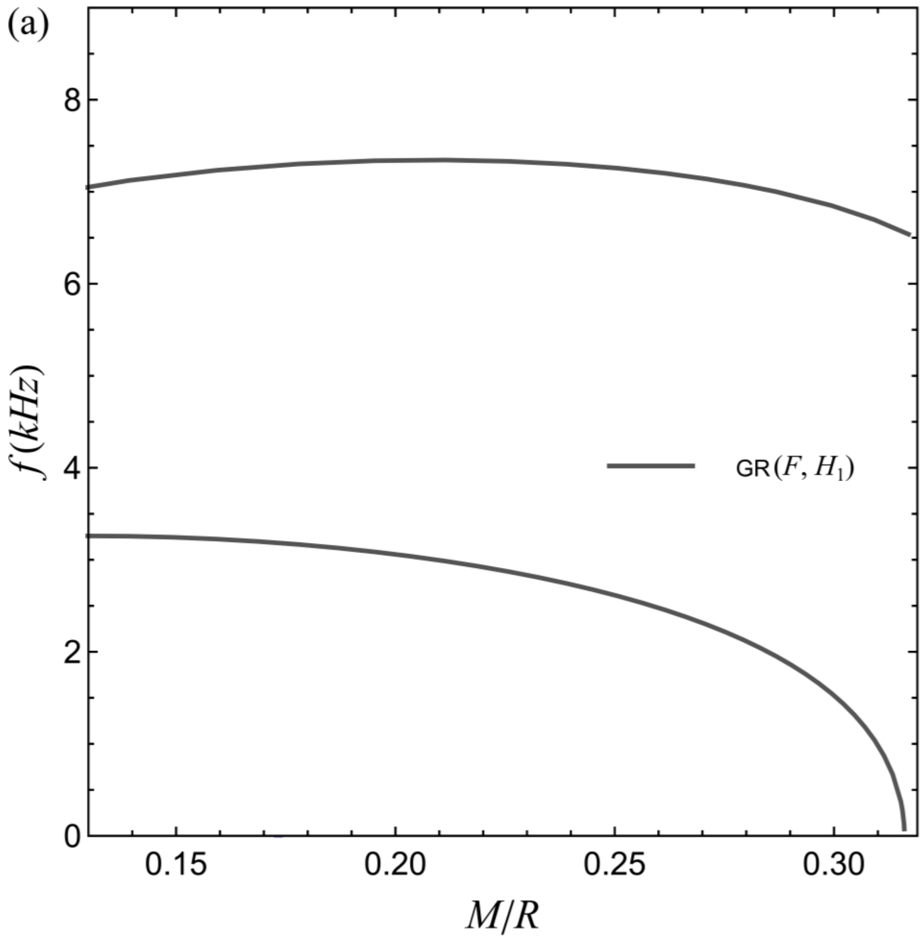
Set-up: scalar-tensor theories (STTs)

Radial perturbations

- Information about stability
- In STTs: scalar sector is dynamical even in spherical symmetry
  - General approach: no Cowling approximation (ex.: Sotani 2014)

Radial NS QNM in STTs

$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}R + S_m[\Psi_m;\ g_{\mu\nu}]$$



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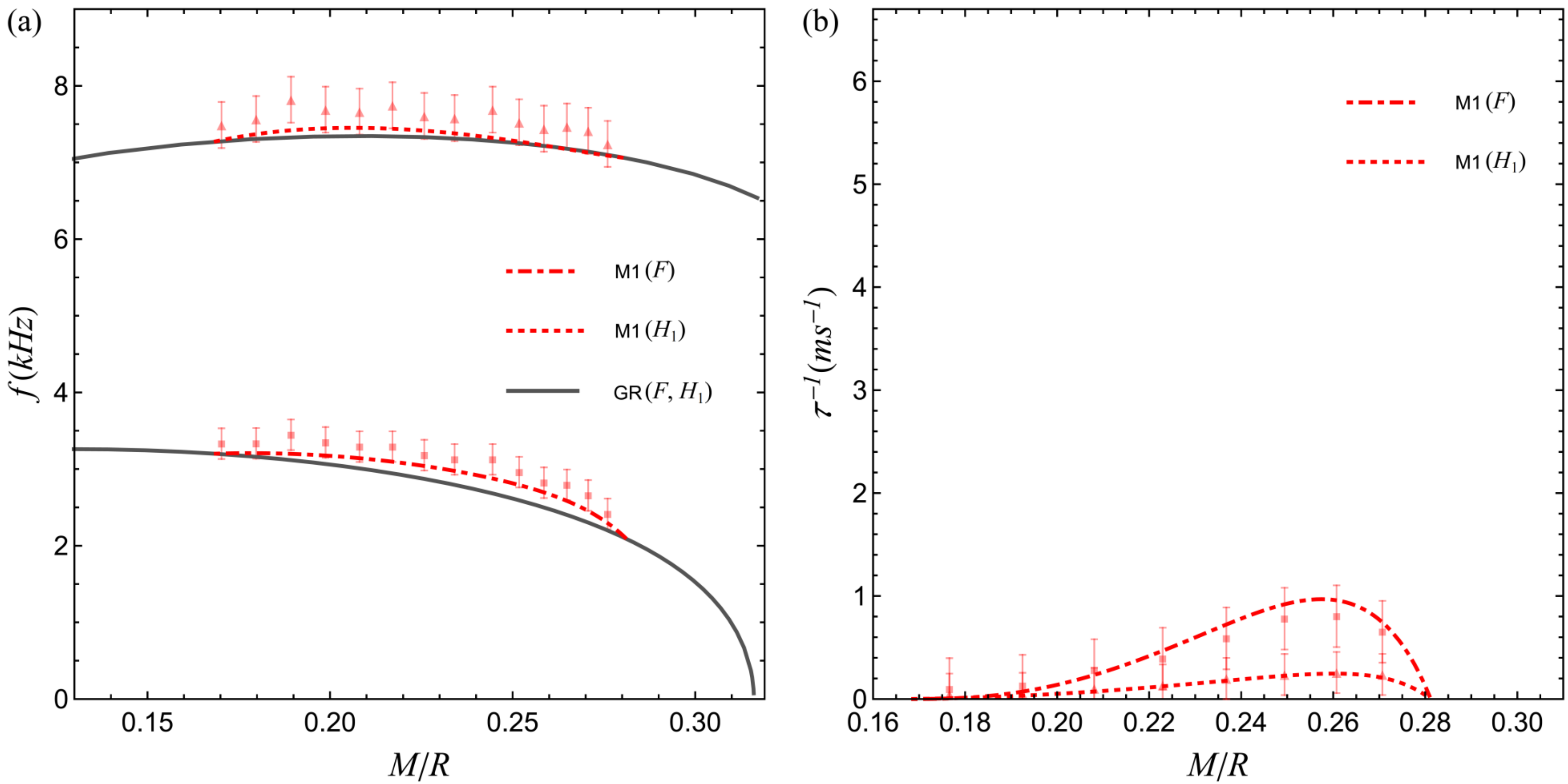

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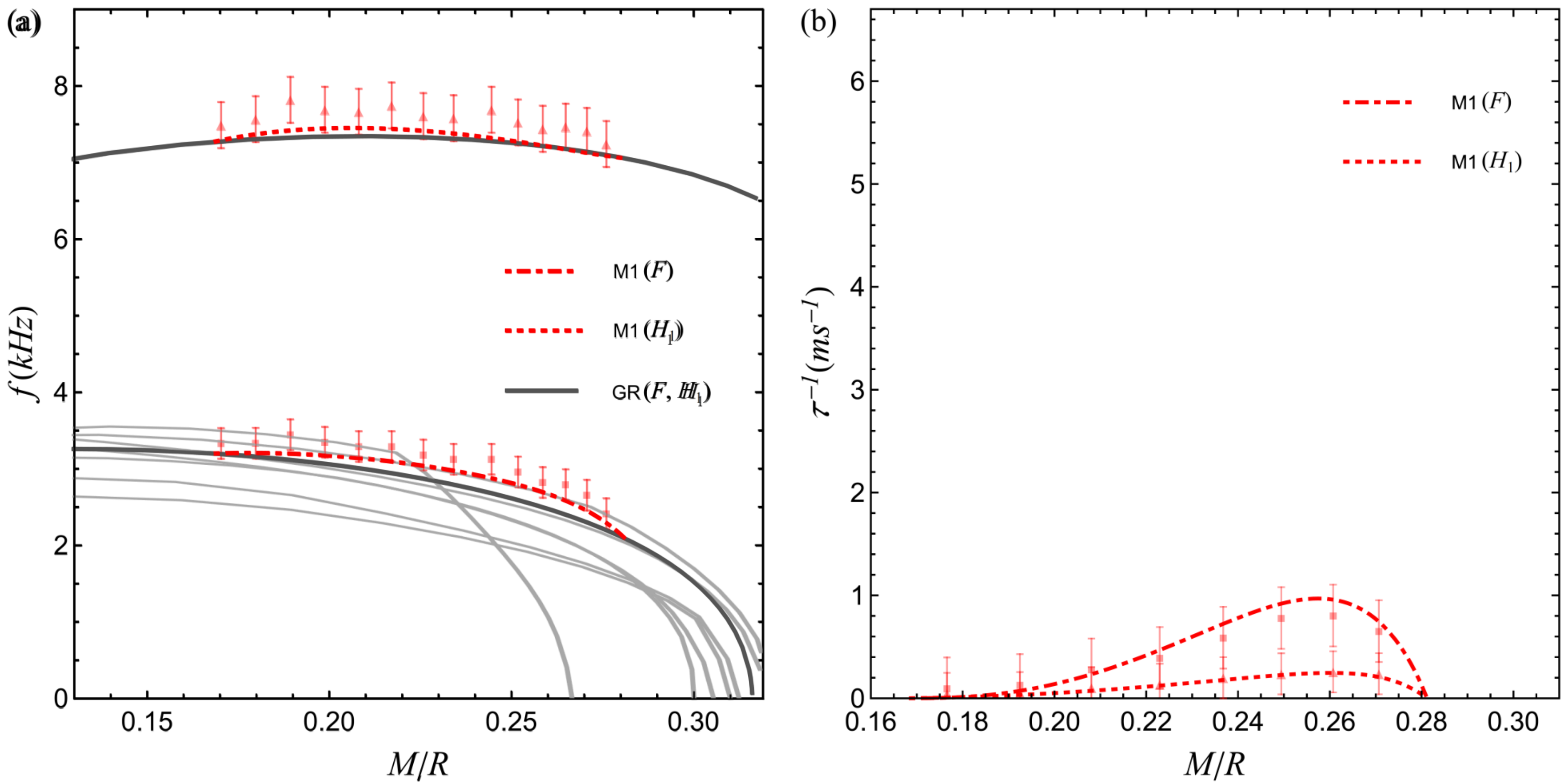

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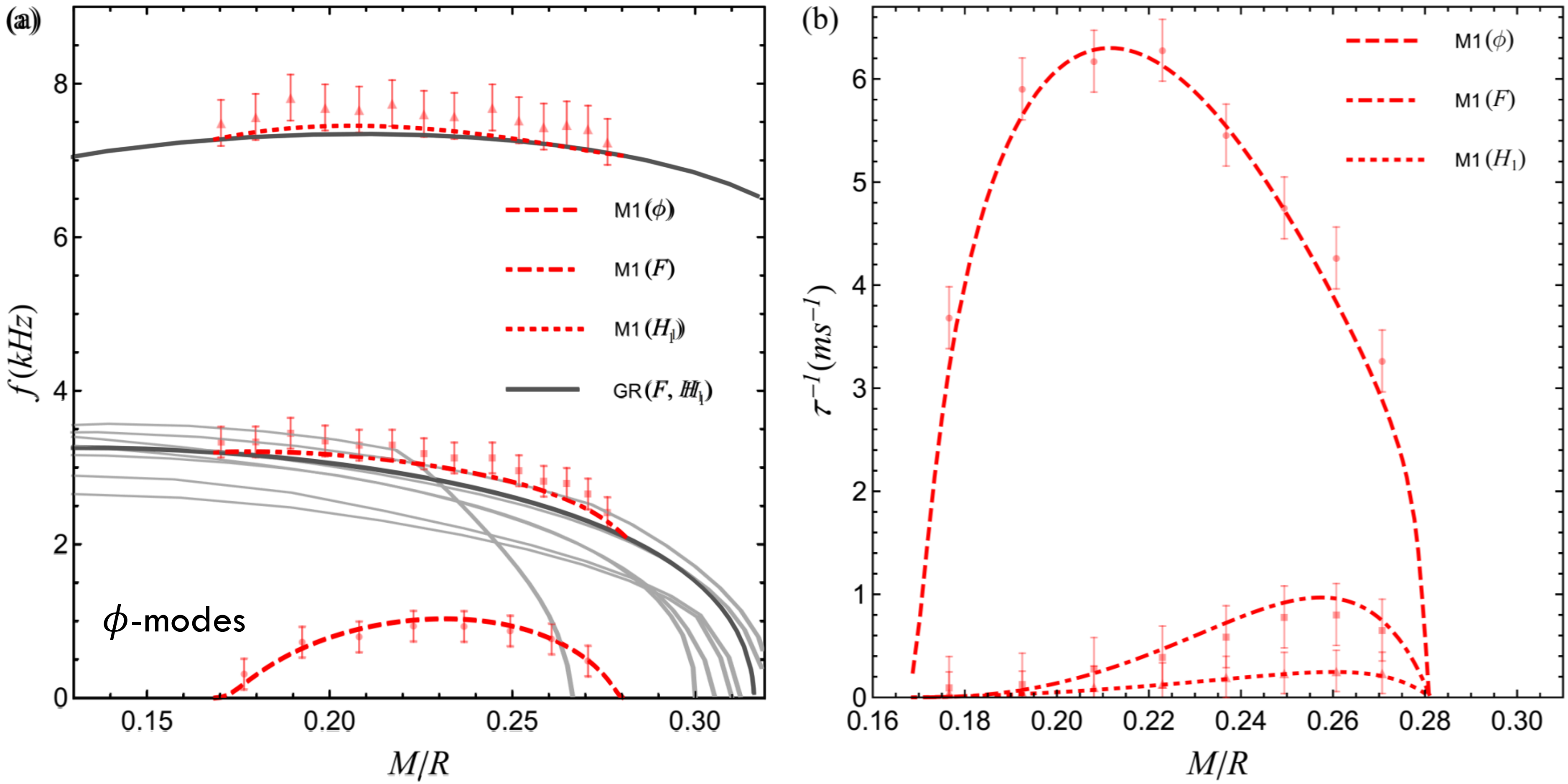
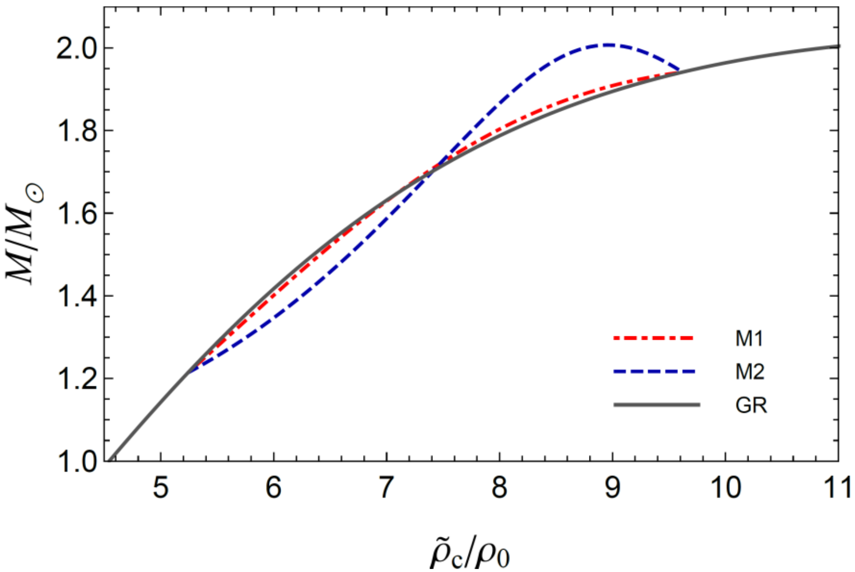
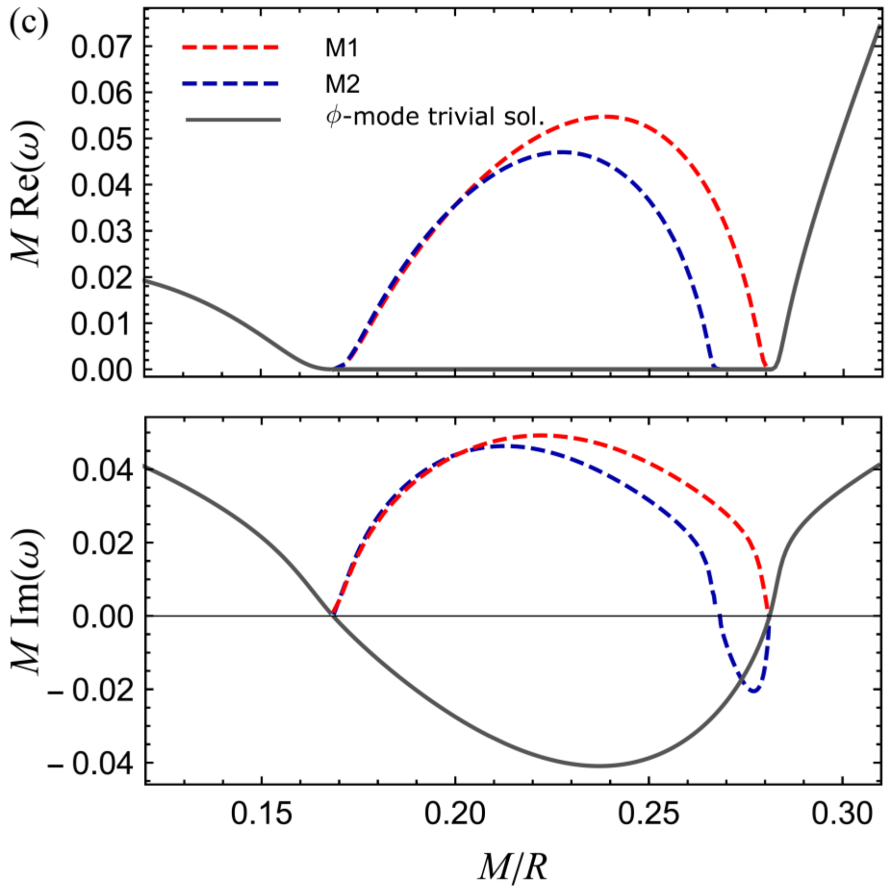


Radial NS QNM in STTs

Remarks

- Role in stability

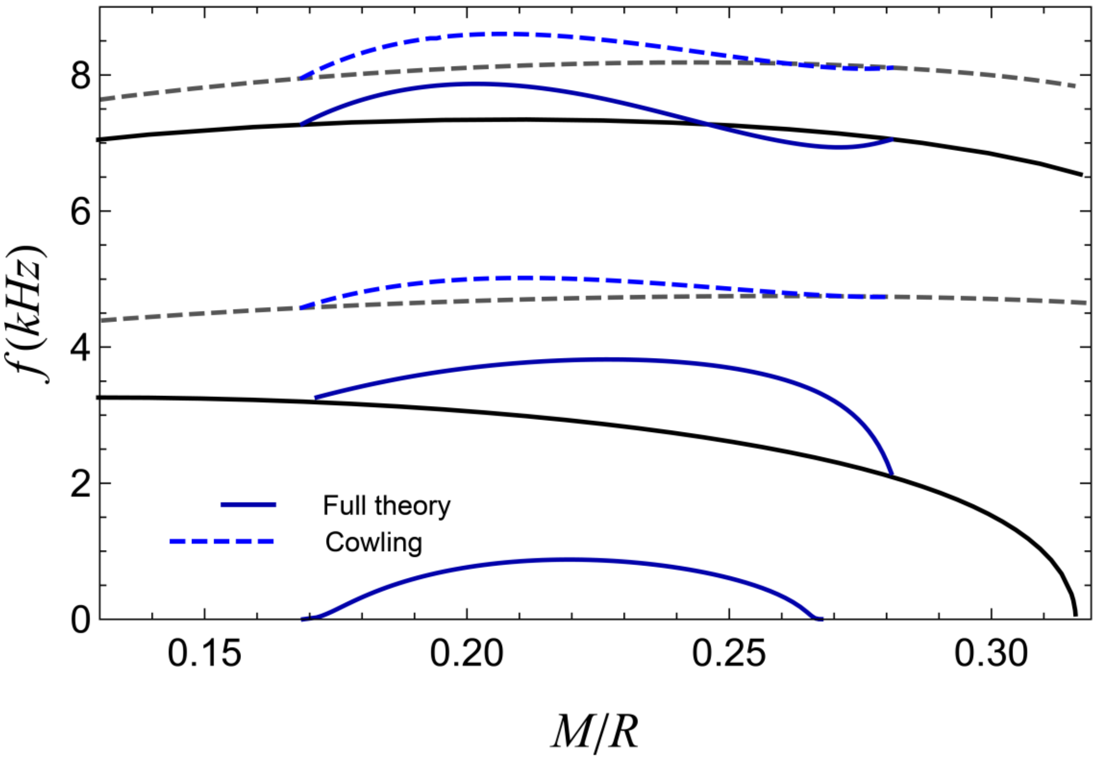




Radial NS QNM in STTs

Remarks

- Role in stability
- Unsuitability of the Cowling approximation



Radial NS QNM in STTs

Remarks

- Role in stability
- Unsuitability of the Cowling approximation
- Need for more suitable integration methods

- Perturbation variables: $\xi(t,r)$ and $\delta\phi(t,r)$
- Frequency domain calculation:

$$\xi(t,r) = \xi(r)e^{i\omega t}, \qquad \delta\phi(t,r) = \delta\phi(r)e^{i\omega t}$$

  - Boundary conditions: regularity, outgoing BC for $\delta\phi$:

$$\lim_{r\to\infty} \delta\phi(t,r) \to e^{i\omega(t-r)}$$

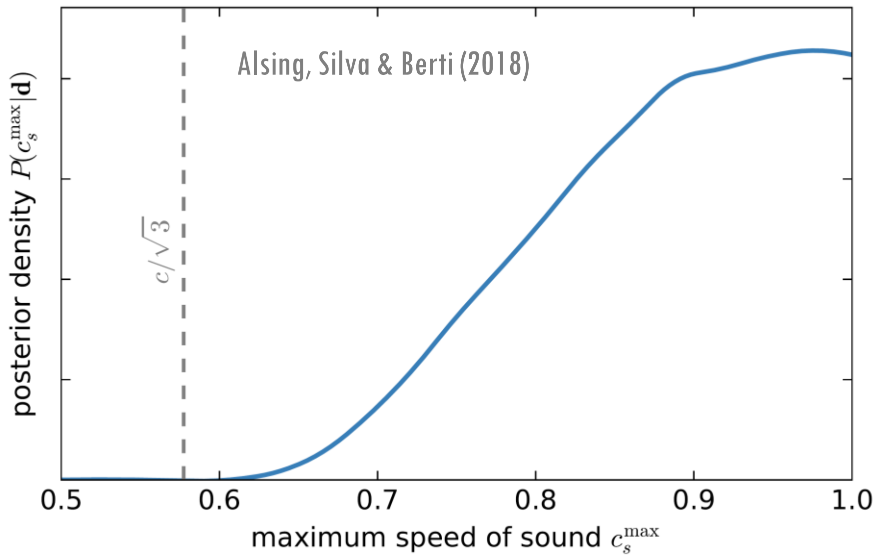
PART 2: The ‘boons’ of neutron star microphysics

Extreme properties inside NS

Extreme properties inside NS

Exceedingly large sound velocities

$$c_s^2 = \frac{dp}{d\epsilon} > \frac{1}{3}$$



Extreme properties inside NS

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$$T = 3p - \epsilon > 0$$

Extreme properties inside NS

Exceedingly large sound velocities

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Pressure-dominated phase

$$T = 3p - \epsilon > 0$$

- Is it physical?

> *"It is generally assumed [e.g. Landau & Lifshitz] that already from special theory of relativity there follows the inequality $3p \leq \epsilon$, where p is the pressure and ϵ the energy density, and ϵ includes the rest masses of the particles. The grounds advanced for this are that for the electromagnetic field $3p = \epsilon$ and for free noninteracting particles with non-vanishing rest masses $3p < \epsilon$. We shall construct below an example of a relativistically invariant theory In which $3p > \epsilon$ is possible (...)."*
>
> (Zel'dovich, 1962)

Extreme properties inside NS

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Pressure-dominated phase

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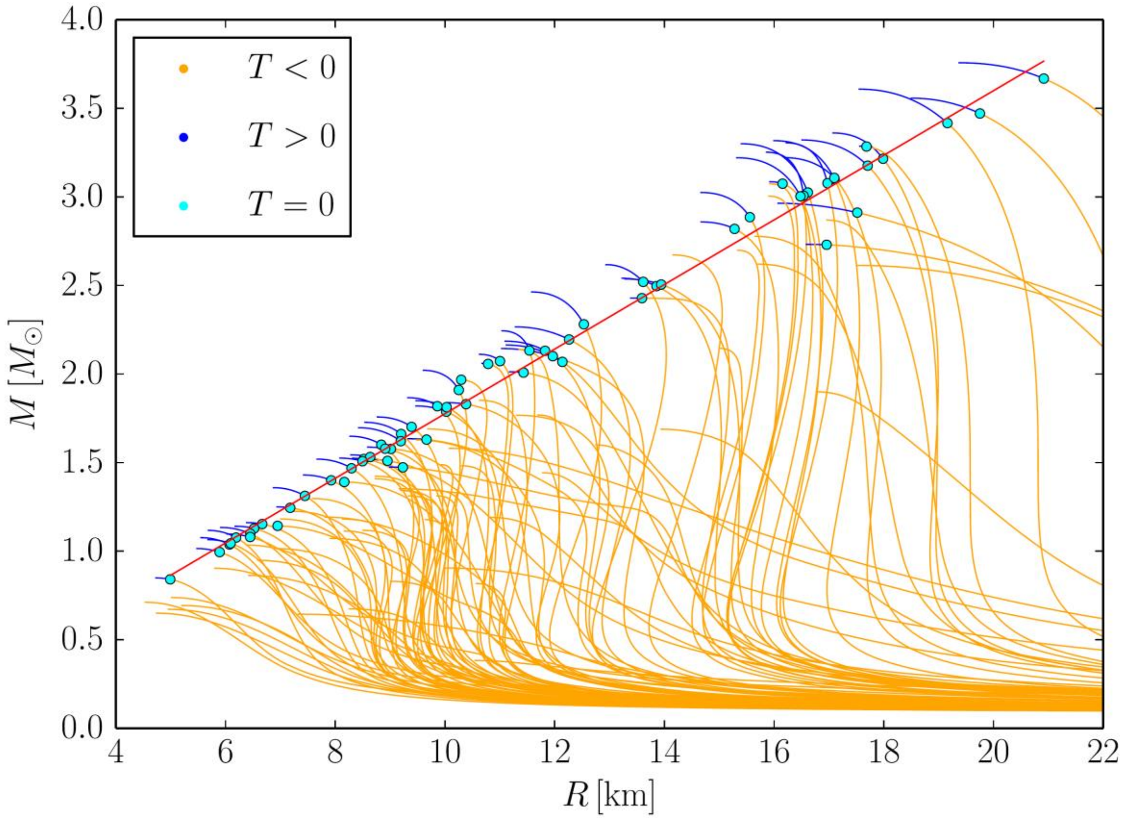
- Is it realized in Nature?

D. M. Podkowka, R. F. P. Mendes, E. Poisson, Phys. Rev. D 98, 064057 (2018)



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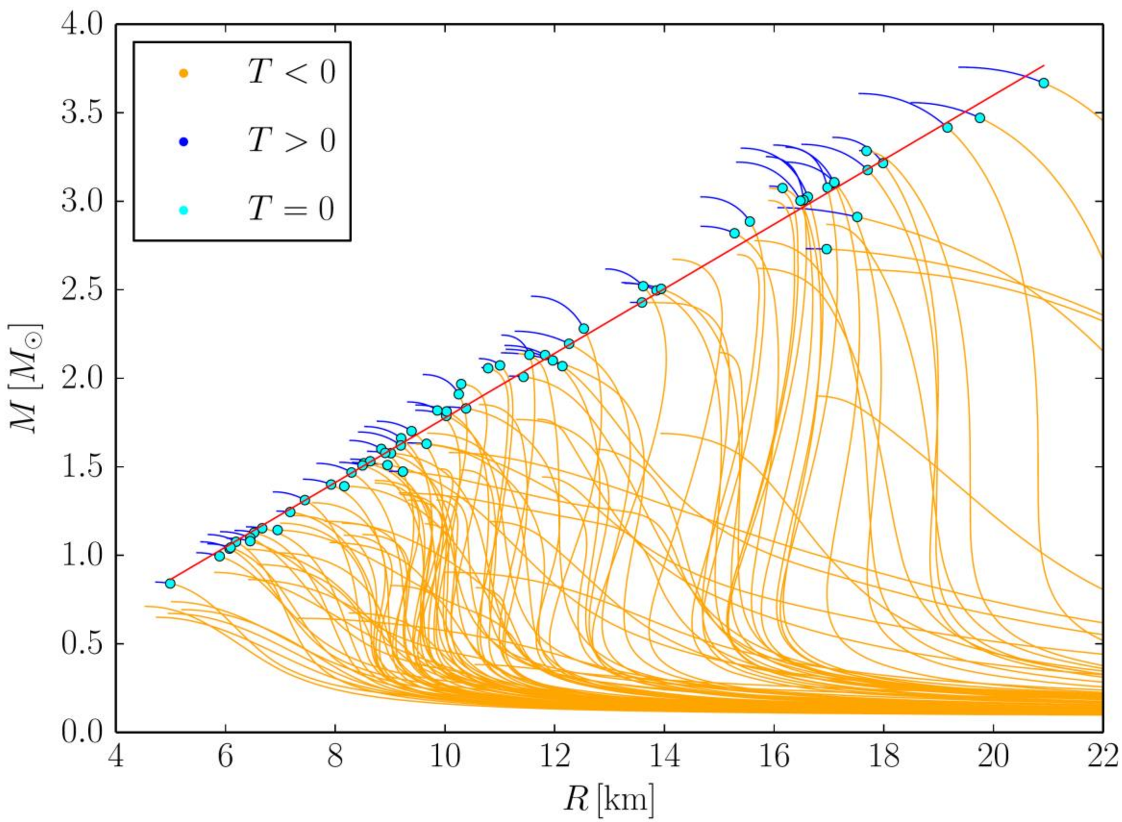
$$C = \frac{GM}{Rc^2} = 0.262^{+0.011}_{-0.017}$$

D. M. Podkowka, R. F. P. Mendes, E. Poisson, Phys. Rev. D 98, 064057 (2018)



Pressure domination: Consequences for STTs

$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\left[R - 2g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] + S_m\left[\Psi_m; a(\phi)^2 g_{\mu\nu}\right]$$

$$\nabla_\mu\nabla^\mu\phi - \frac{1}{4}\frac{dV(\phi)}{d\phi} = -4\pi\frac{d\log a(\phi)}{d\phi}T$$

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STTs of Bergmann-Wagoner type

- $V(\phi) = 0$, $a(\phi)$ nontrivial

Screened modified gravity

- $V(\phi)$, $a(\phi)$ nontrivial

Pressure domination: Consequences for STTs

$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\left[R - 2g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] + S_m\left[\Psi_m; a(\phi)^2 g_{\mu\nu}\right]$$

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Pressure domination: Consequences for STTs

$$\nabla_\mu \nabla^\mu \phi = -4\pi \frac{d \log a(\phi)}{d\phi} T$$

- Expand ($\phi_0 = \phi(\tau_0) = cte$):

$$\alpha(\phi) = \frac{d \log a(\phi)}{d\phi} = \alpha_0 + \beta_0(\phi - \phi_0) + O[(\phi - \phi_0)^2]$$

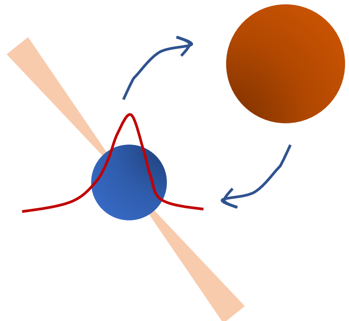
  - GR: $\alpha_0 = \beta_0 = \cdots = 0$;
  - FJBD: $\beta_0 = \cdots = 0$, $\alpha_0 \sim \frac{1}{\sqrt{\omega_{BD}}}$;
  - SNMC: $\alpha_0 = 0$, $\beta_0 = 2\xi$, $\beta_0' = 0$, $\beta''_0 = 8(1 - 12\xi)\xi^2$, …

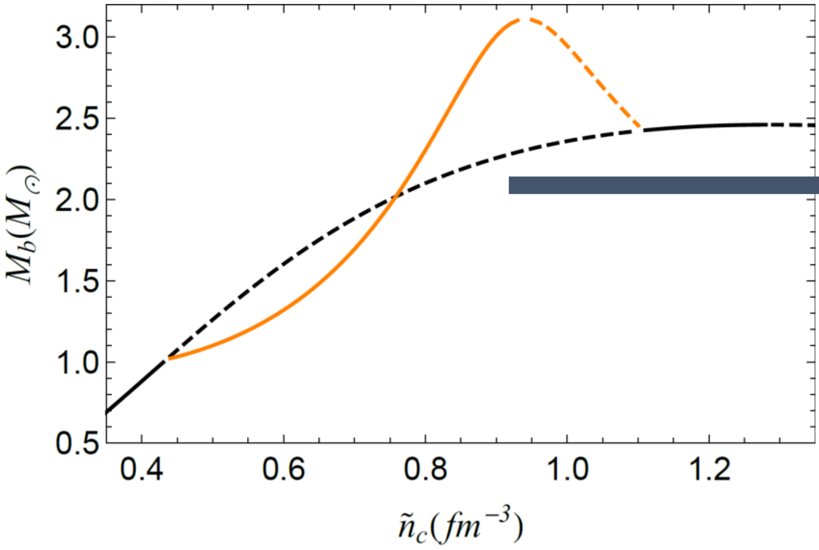
Pressure domination: Consequences for STTs

$$\alpha(\phi) = \frac{d \log a(\phi)}{d\phi} = \alpha_0 + \beta_0(\phi - \phi_0) + O[(\phi - \phi_0)^2]$$

Constrained by pulsar timing

Constrained by solar system experiments

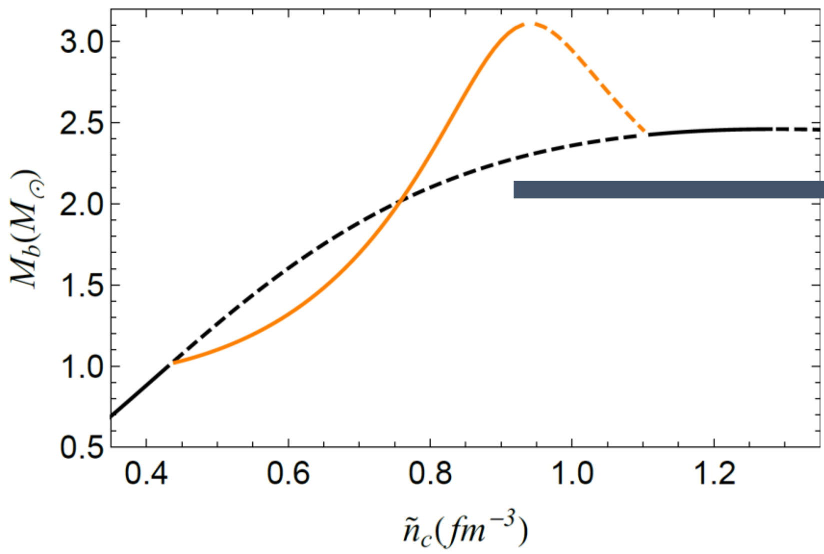




Instability of the GR solution

$$\nabla_\mu \nabla^\mu \delta\phi = -4\pi\beta_0 T\delta\phi$$

Unstable modes if
$m_{\mathrm{eff}}^2 = -4\pi\beta_0 T$
sufficiently negative



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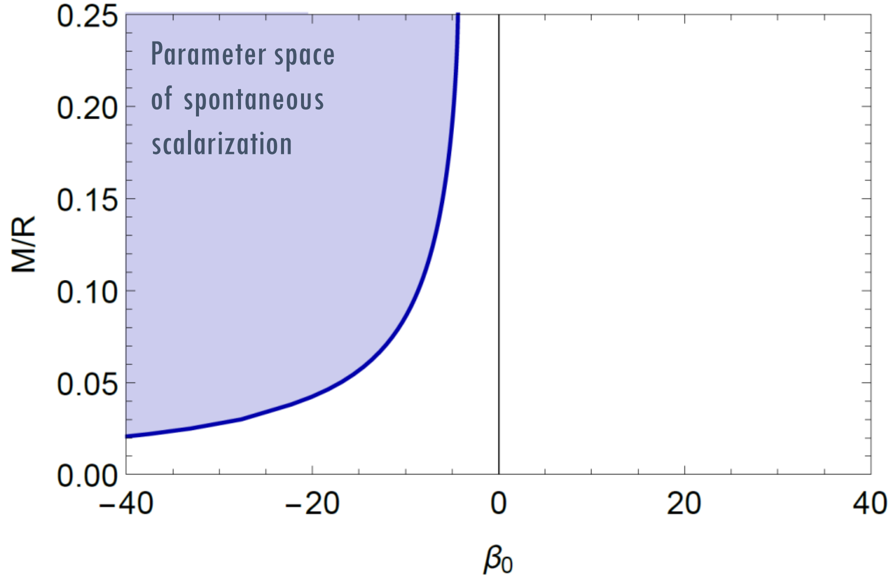

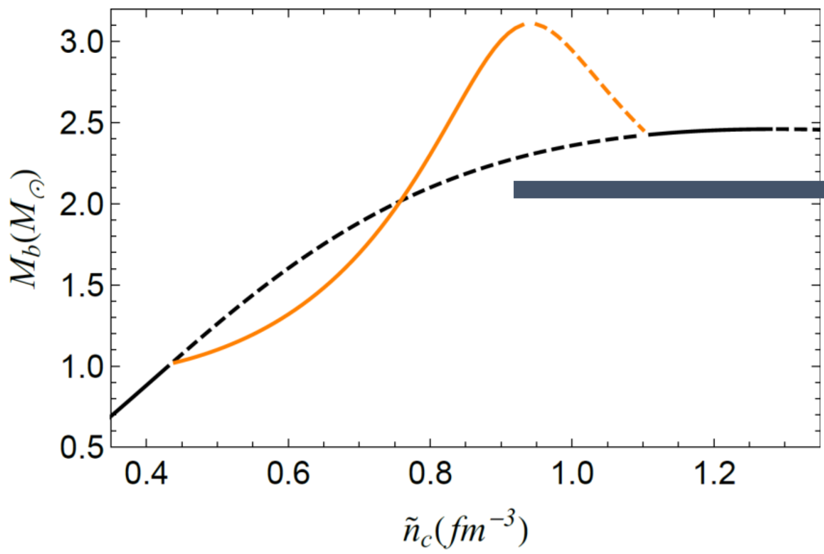

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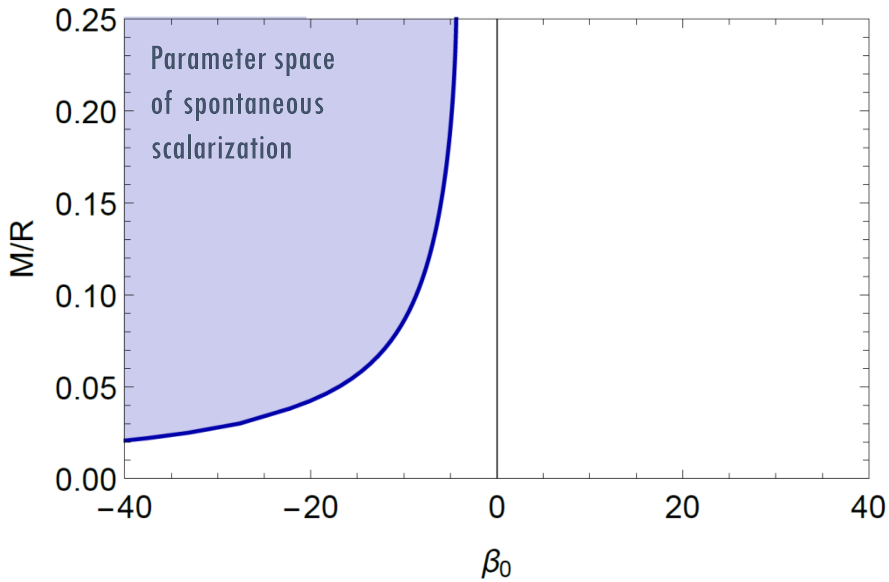

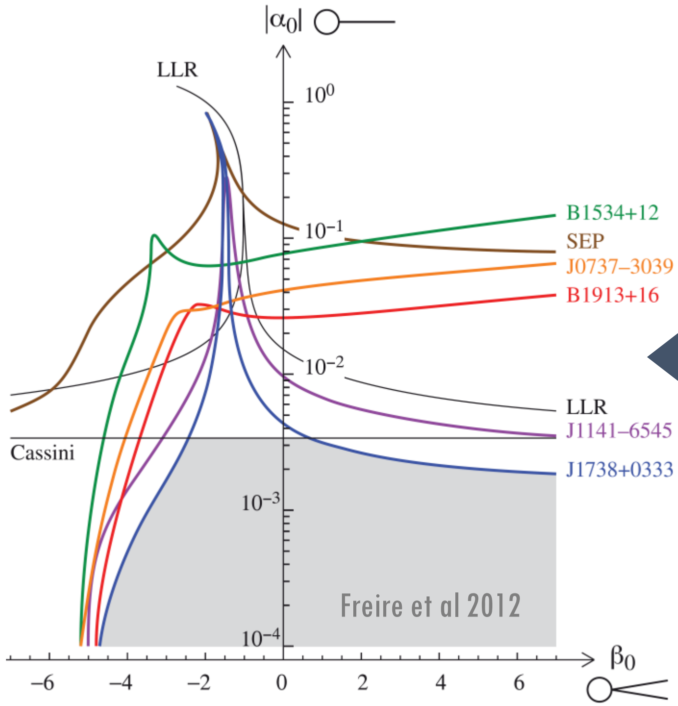

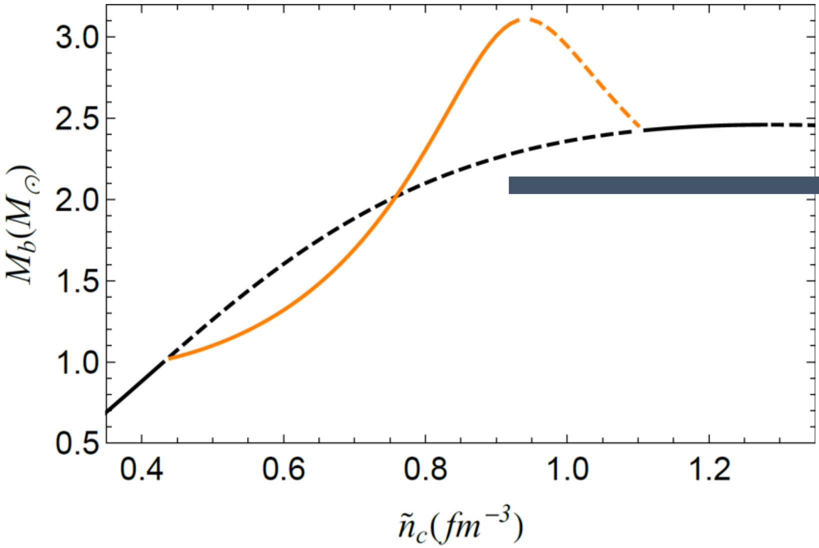

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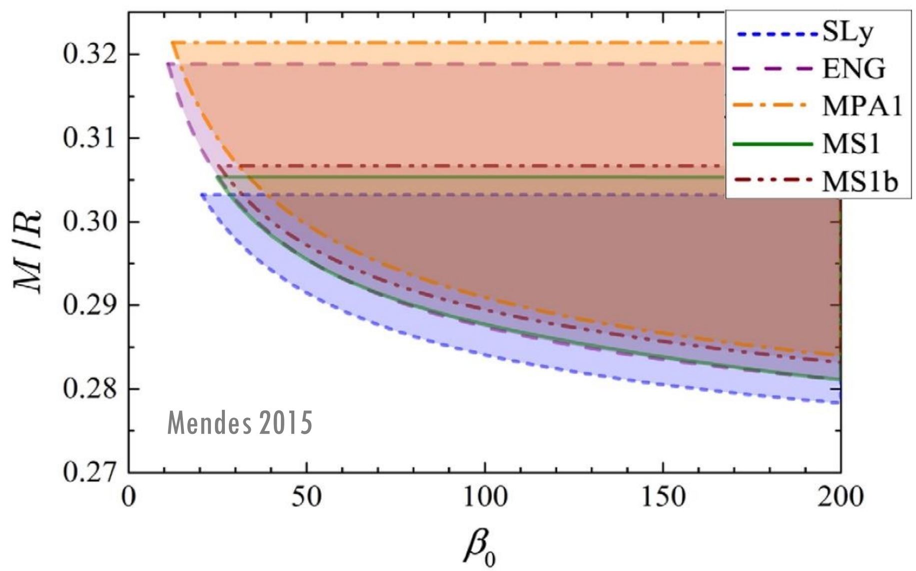
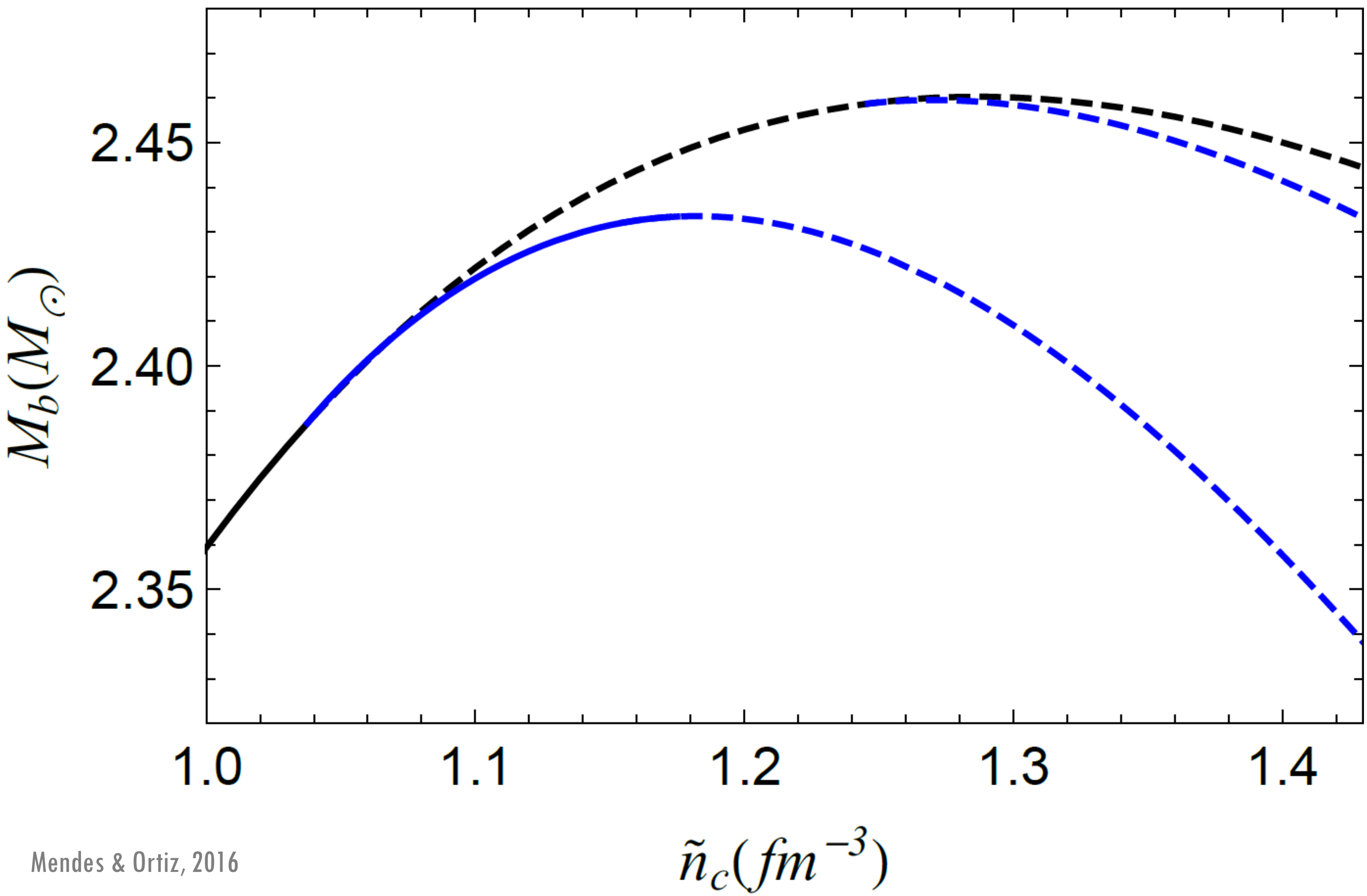


$M1$ with $\beta = 100$



Mendes & Ortiz, 2016

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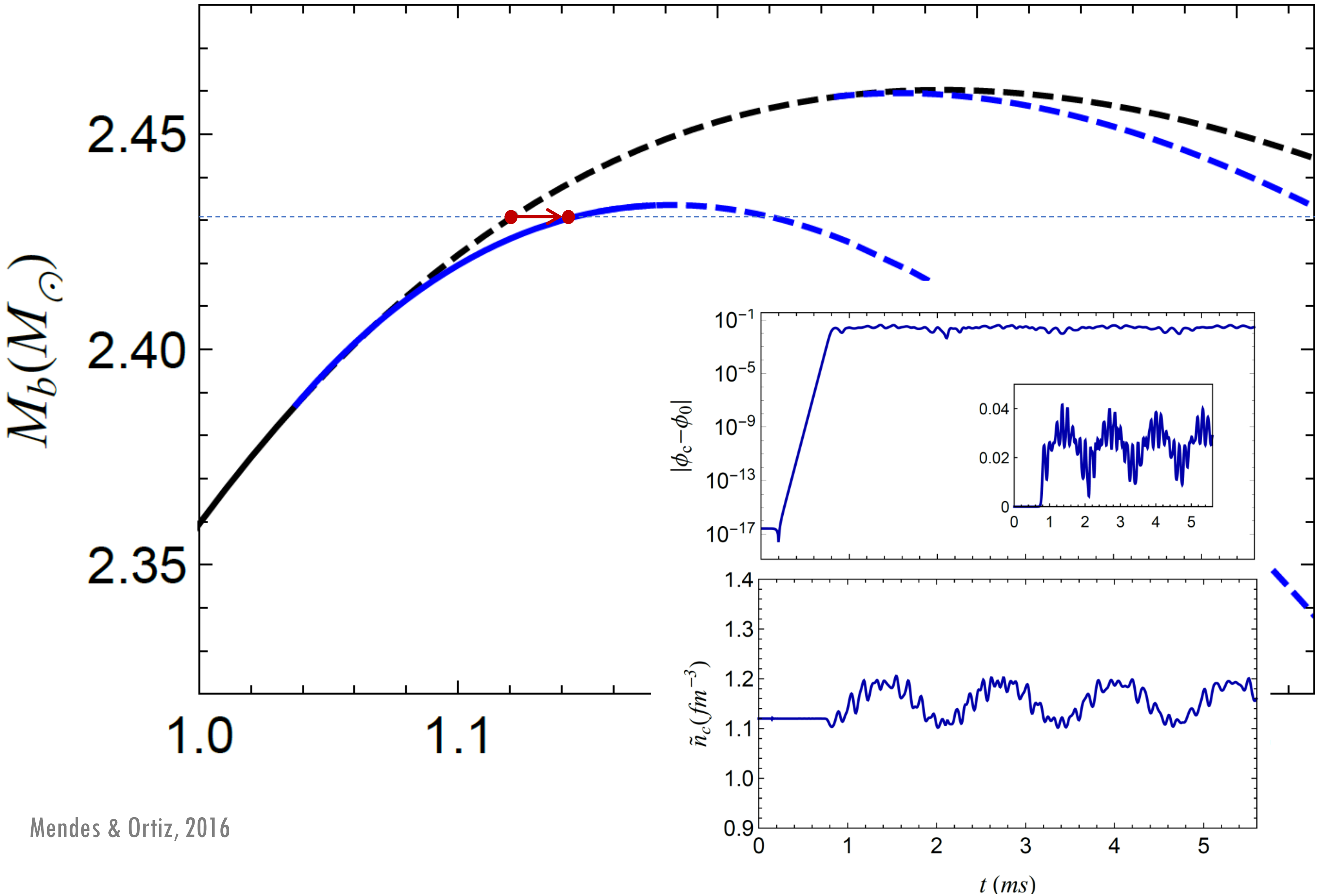

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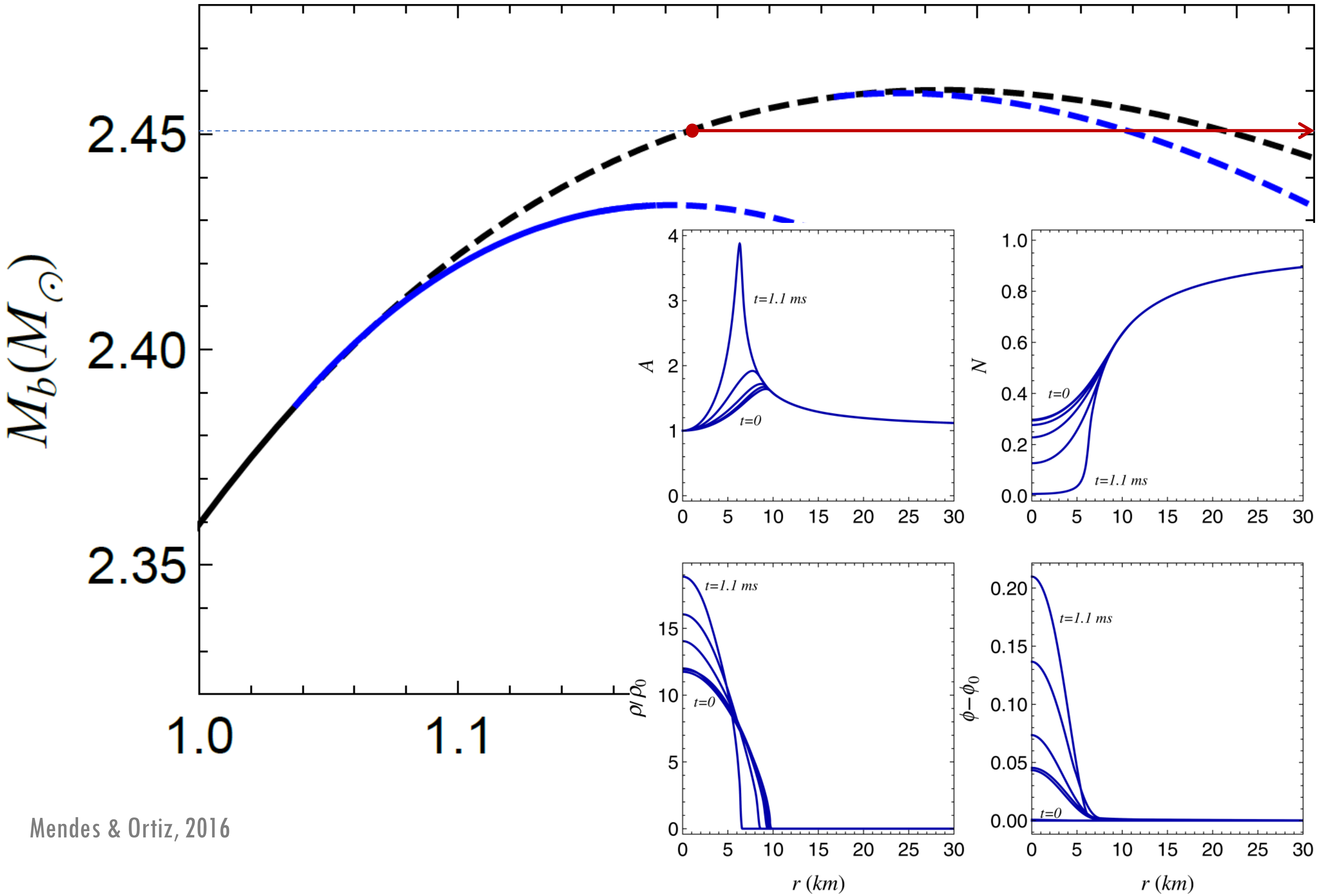

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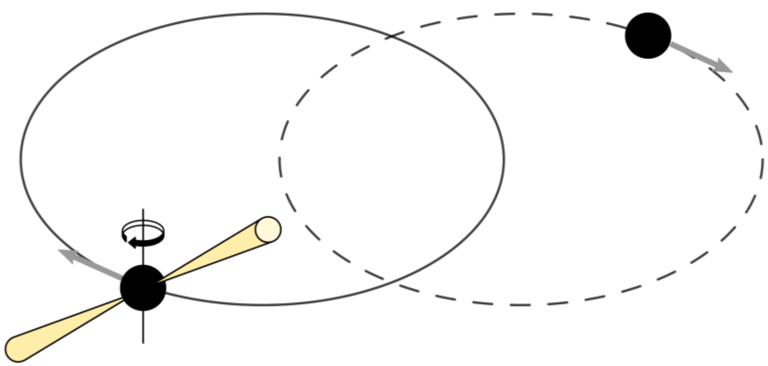

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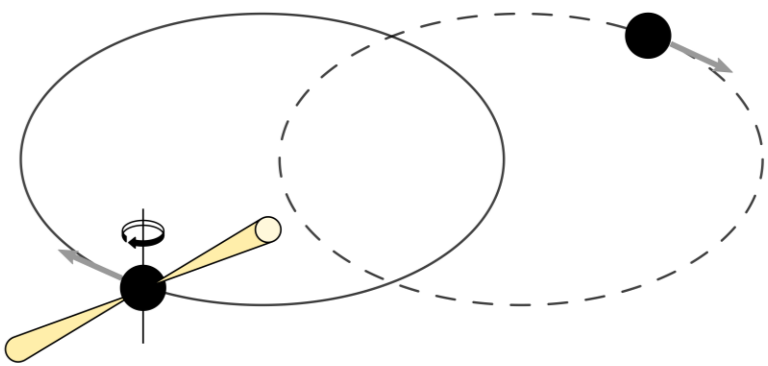

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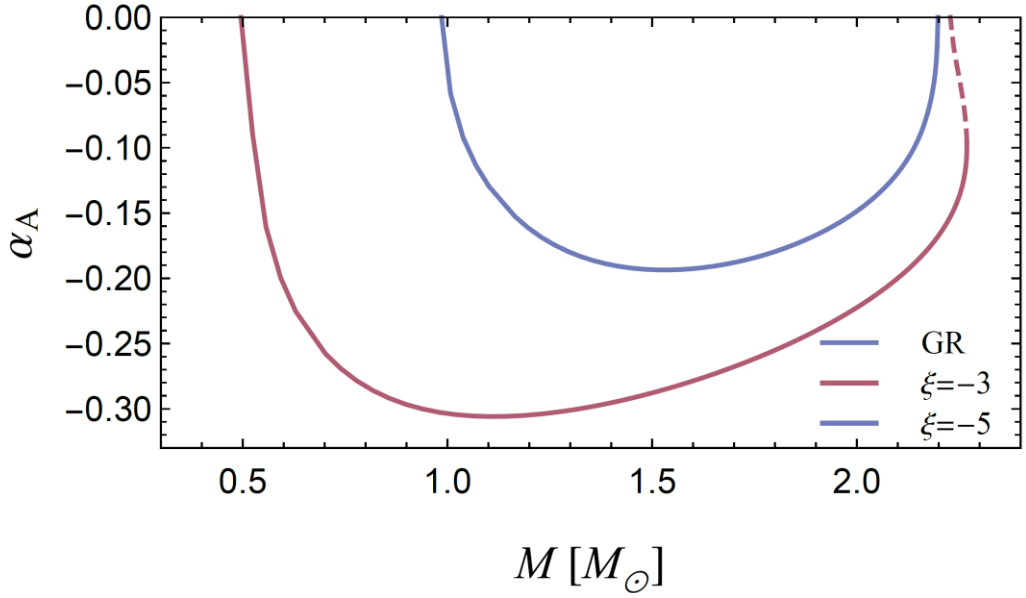

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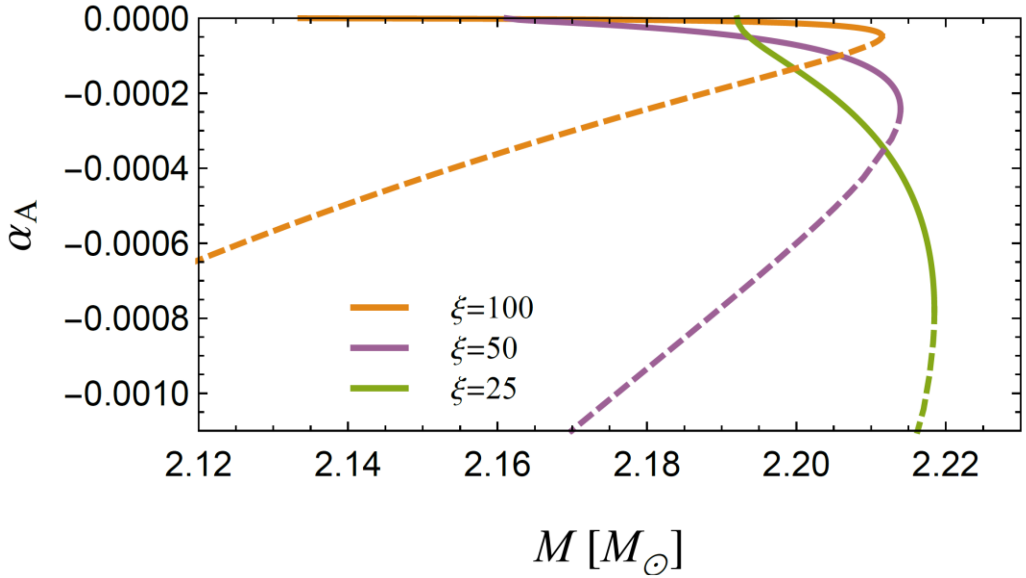

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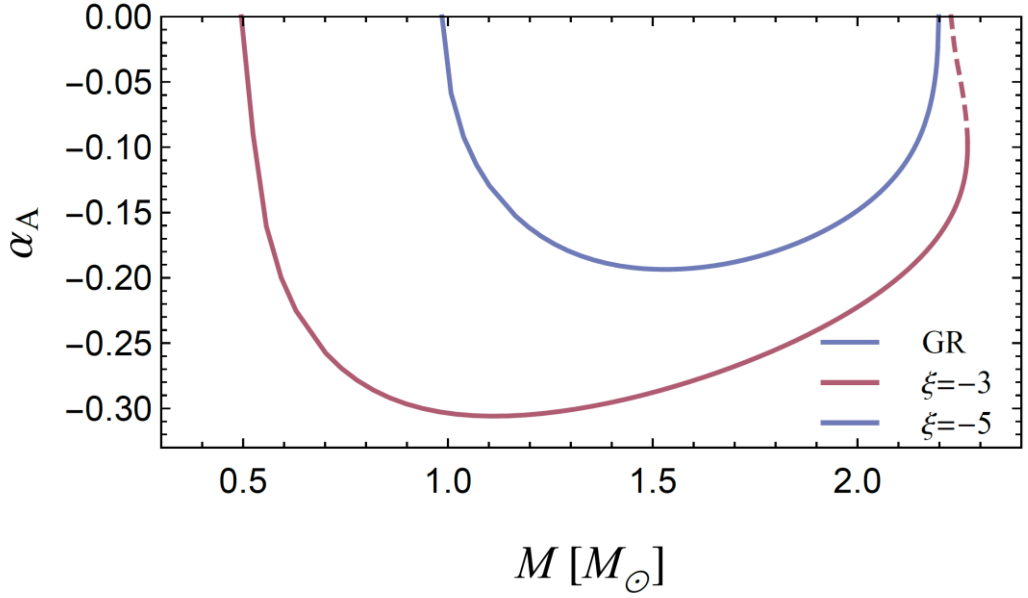

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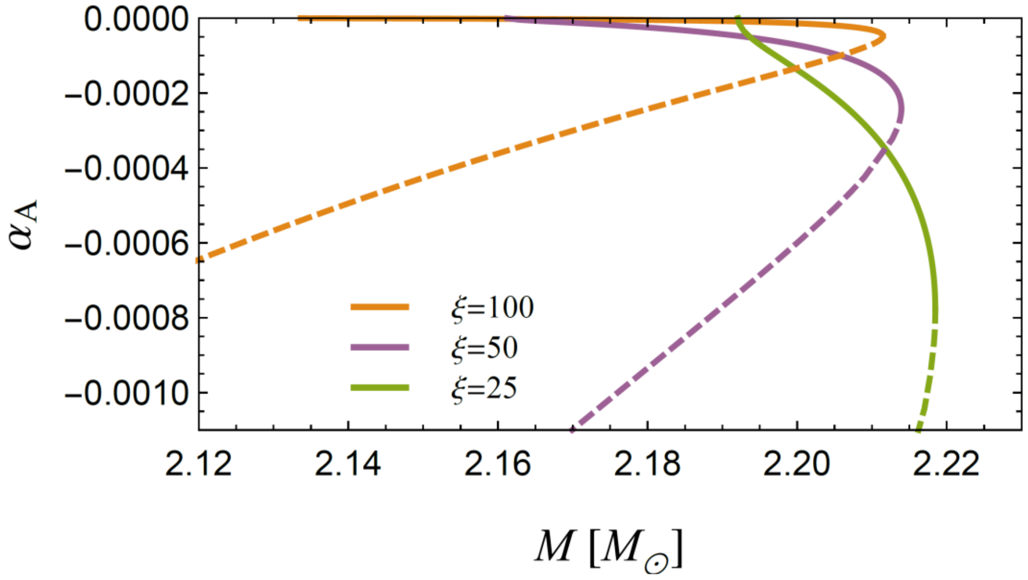
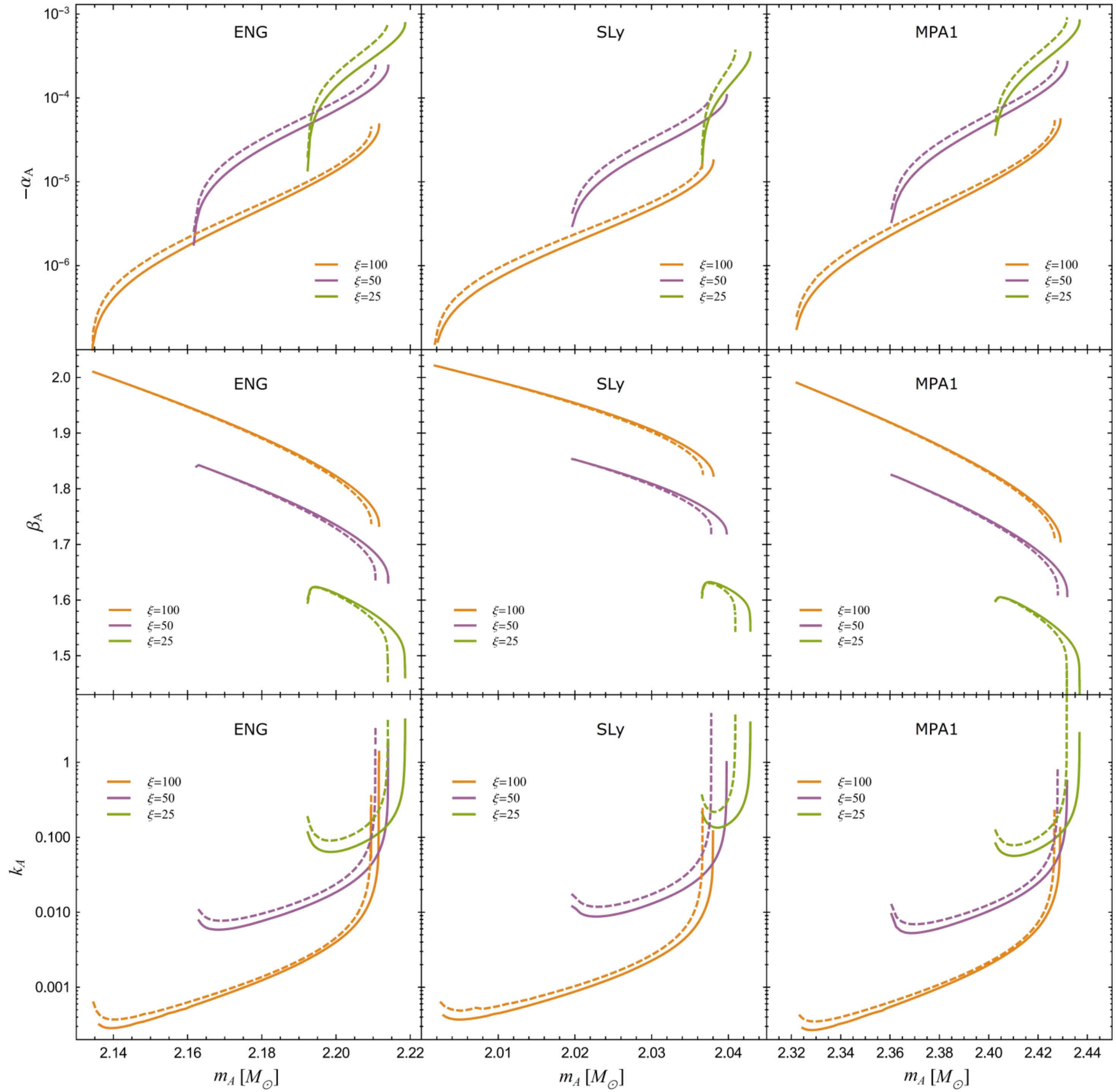


Dipole radiation ($\dot{P}_\phi^{dip}$):

- dominates by $(c/v_b)^2$
- suppressed by $(\alpha_p - \alpha_c)^2$

Mendes & Ottoni, 2019



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Pressure domination: Consequences for STTs

$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\left[R - 2g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] + S_m\left[\Psi_m; a(\phi)^2 g_{\mu\nu}\right]$$

$$\nabla_\mu\nabla^\mu\phi - \frac{1}{4}\frac{dV(\phi)}{d\phi} = -4\pi\frac{d\log a(\phi)}{d\phi}T$$

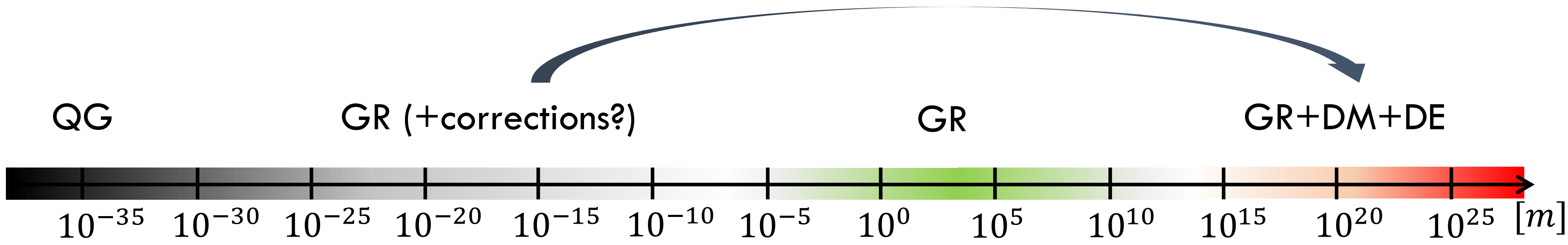
STTs of Bergmann-Wagoner type

- $V(\phi) = 0, a(\phi)$ nontrivial

Screened modified gravity

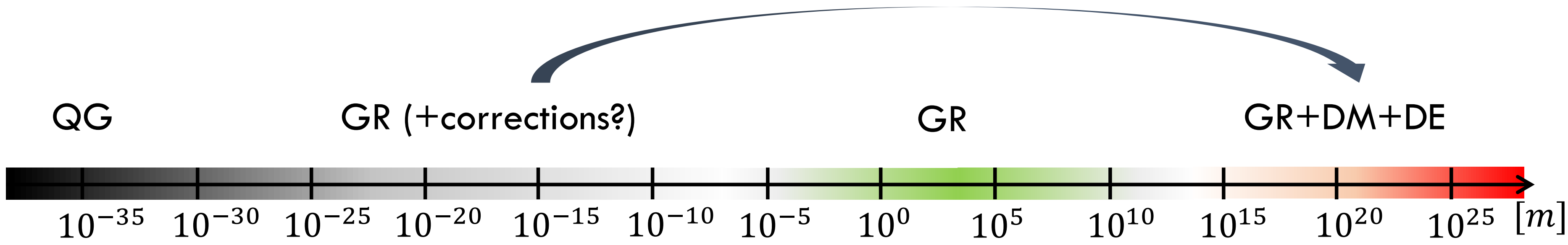
- $V(\phi), a(\phi)$ nontrivial

STTs with screening effects



<u>Screening mechanisms</u>: evade solar system tests with environmental dependence of field properties

STTs with screening effects



<u>Screening mechanisms</u>: evade solar system tests with environmental dependence of field properties

Chameleon

- m_{eff} depends on ρ_{local}
- Light in deep space; heavy near Earth

Vainshtein

- Derivative self-couplings
- Strong self-coup. near sources → weak coupling to matter

Symmetron

- VEV depends on ρ_{local}
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Unscreening in NS interior?

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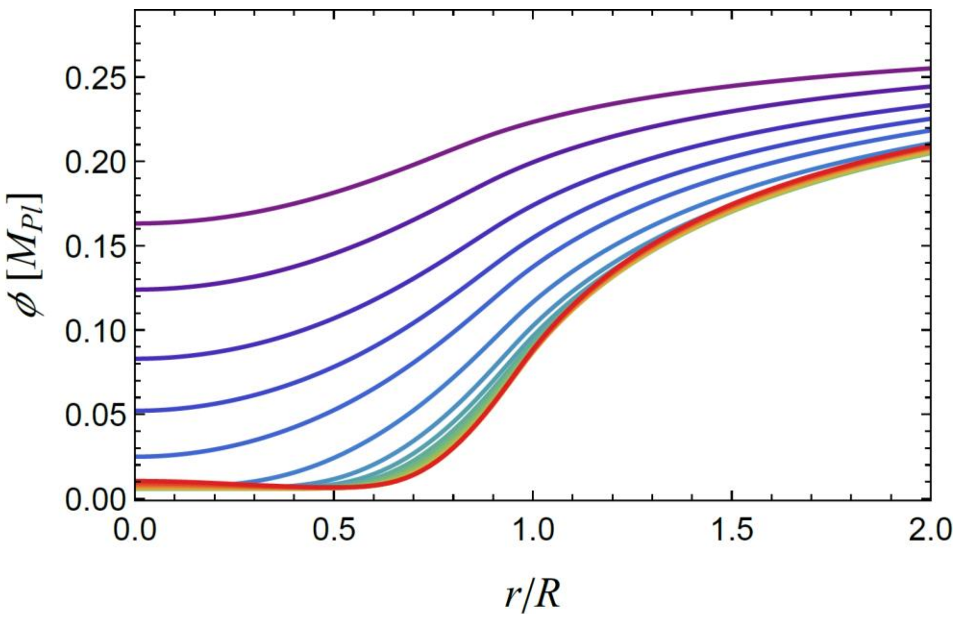
Chameleons: $V(\phi) = \mu\phi^{-1}, a(\phi) = \exp(\phi/M_c)$

H4: no pressure domination



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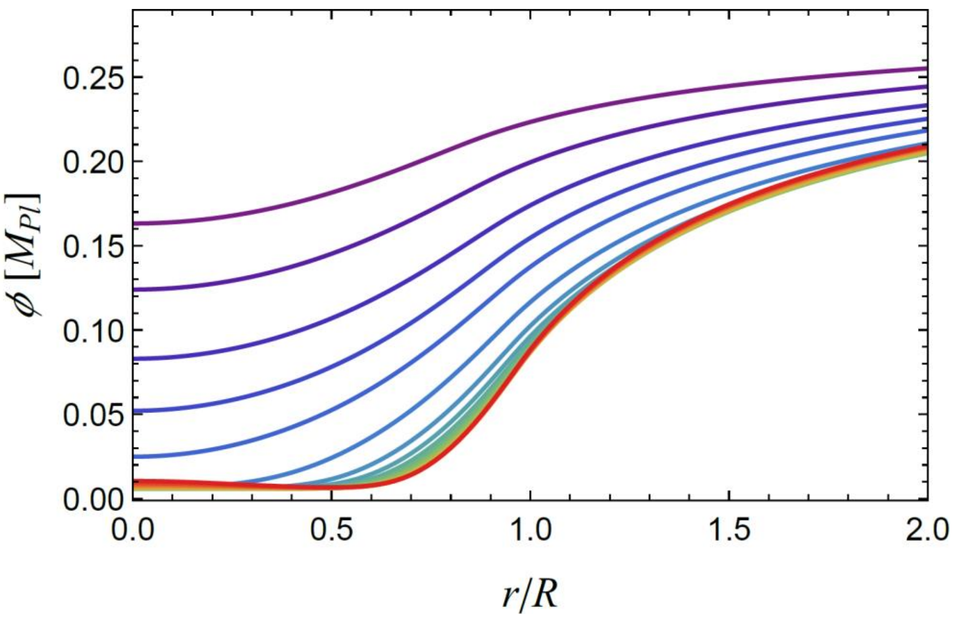

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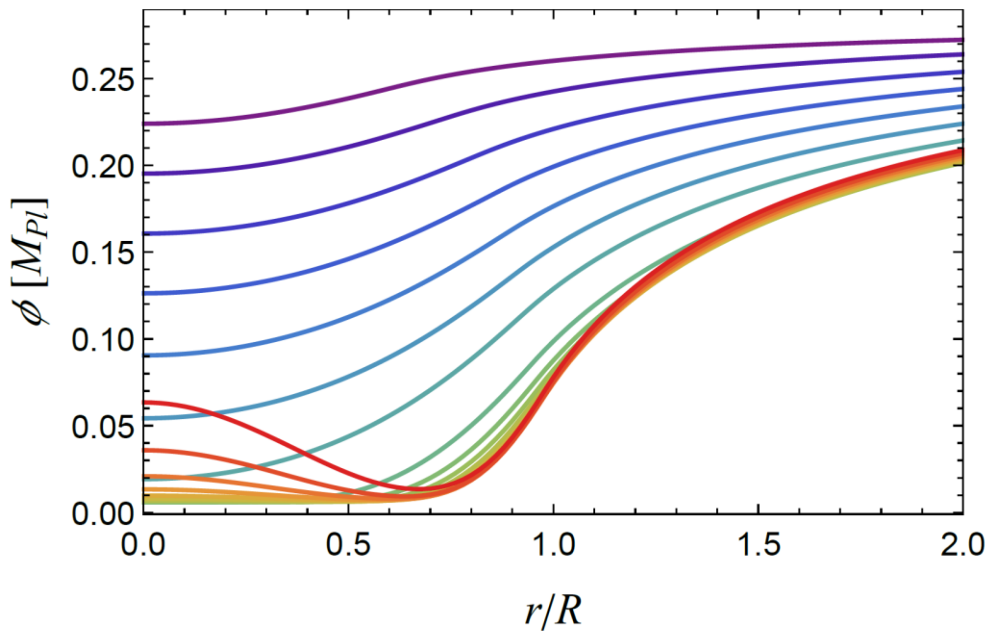

See also: Babichev & Langlois (2010)

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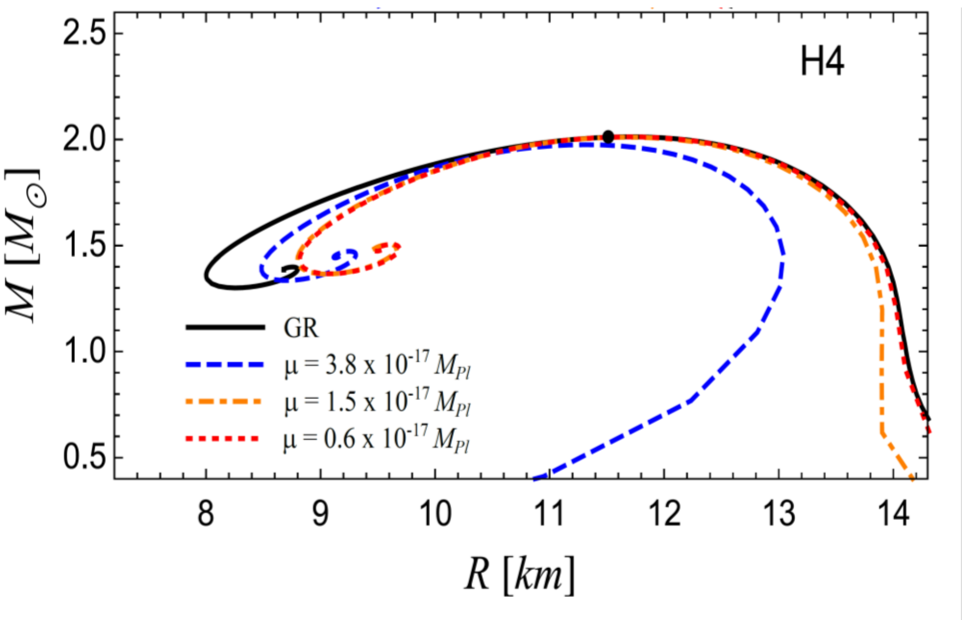

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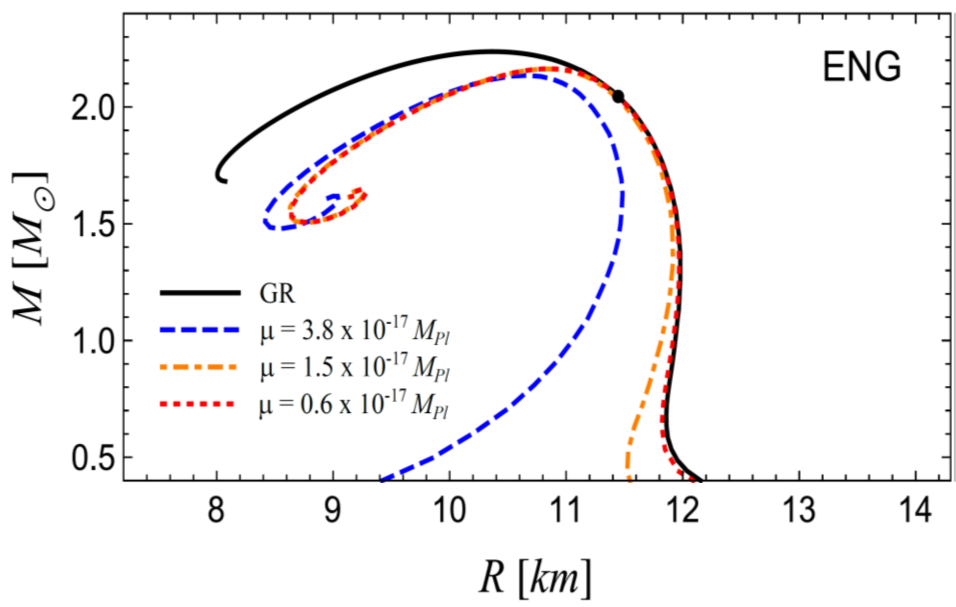

CONCLUSIONS

Nuclear physics *vs* modified gravity

THE CURSE OF NS MICROPHYSICS

How to circumvent it?

THE BOONS OF NS MICROPHYSICS

How to harness them?

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Universidade Federal Fluminense