GR 100 Years in Lisbon, IST 18-19 December 2015

Testing General Relativity

with present and future astrophysical observations

Berti+, Topical Review Class.Quant.Grav. 32 (2015) 24, 243001;

Gair+, Living Rev. Relativity 16 (2013), 7;

Yunes & Siemens, Living Rev. Relativity 16 (2013), 9

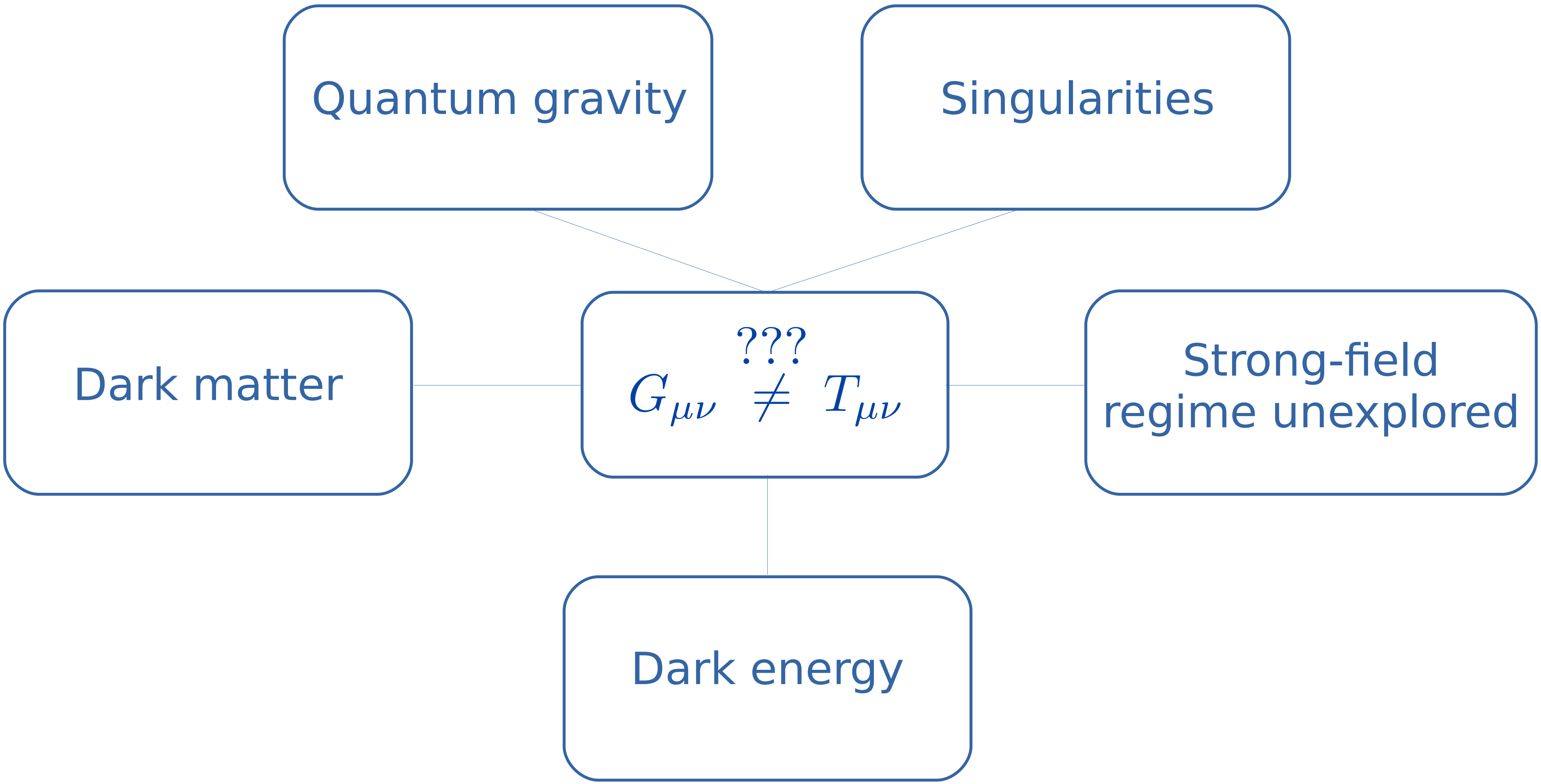
Paolo Pani

Sapienza University of Rome & Instituto Superior Técnico, Lisbon

Outline

- **Testing gravity: why bother?**
  - A compass to navigate the modified-gravity atlas
  - Approaches and tests
- **Astrophysical tests of gravity**
  - GW emission, propagation, polarization
  - Tests of compact objects, black-hole paradigm
  - Probing Dark Matter with strong gravity

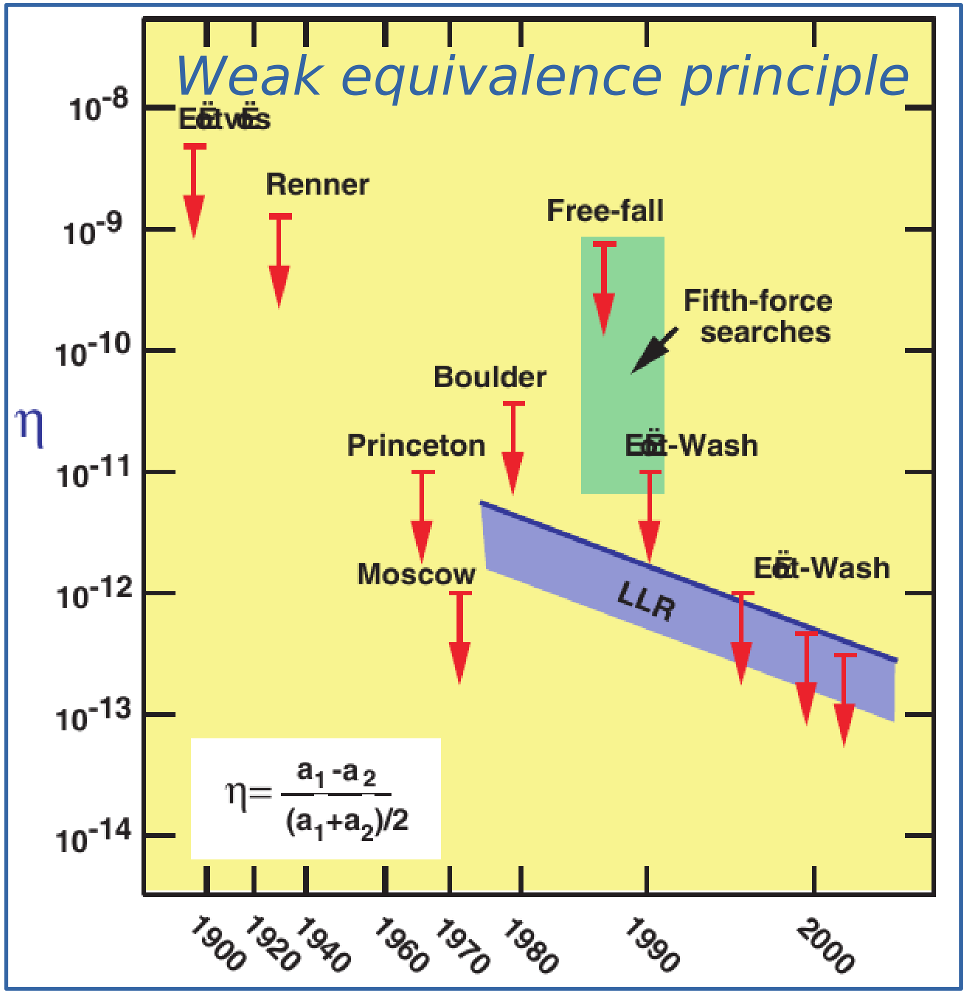
Why testing gravity?

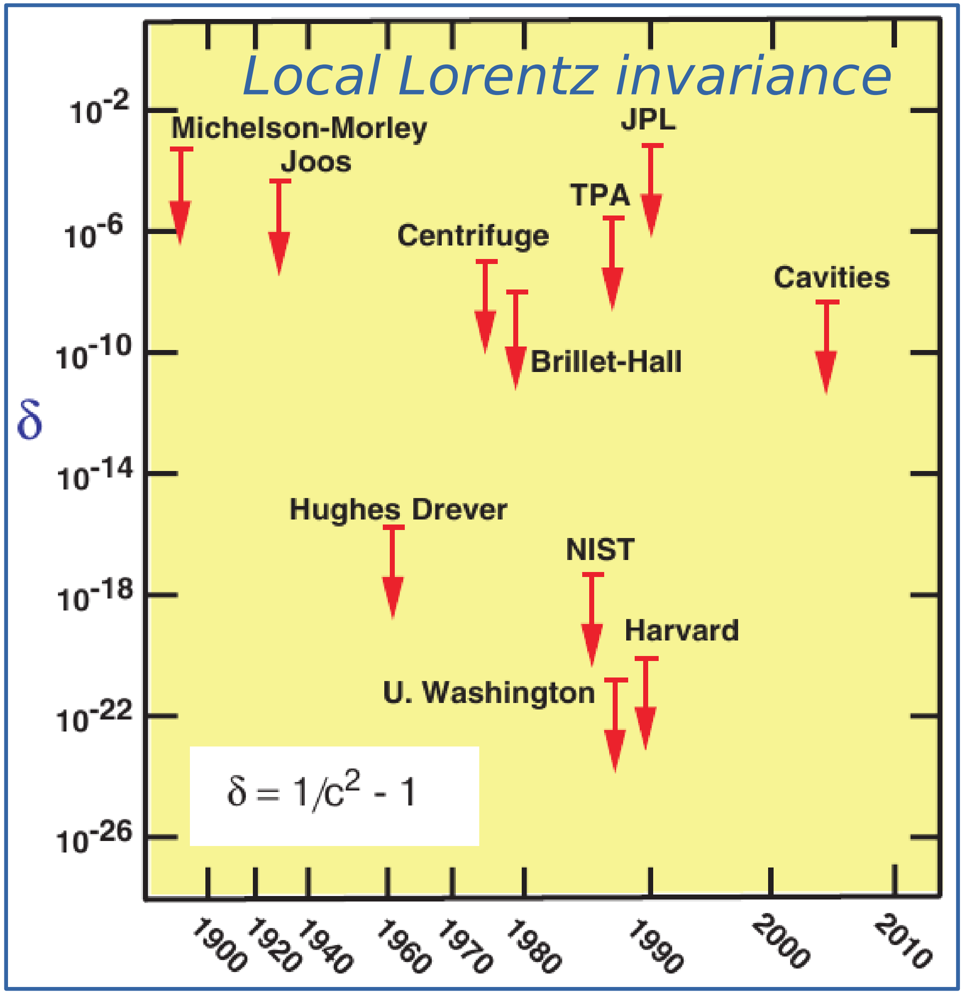


Was Einstein right?

Will, Living Reviews (2014)

"Why do you spend so much time testing GR? We know that the theory is right."
— S. Chandrasekhar to his postdoc Clifford Will





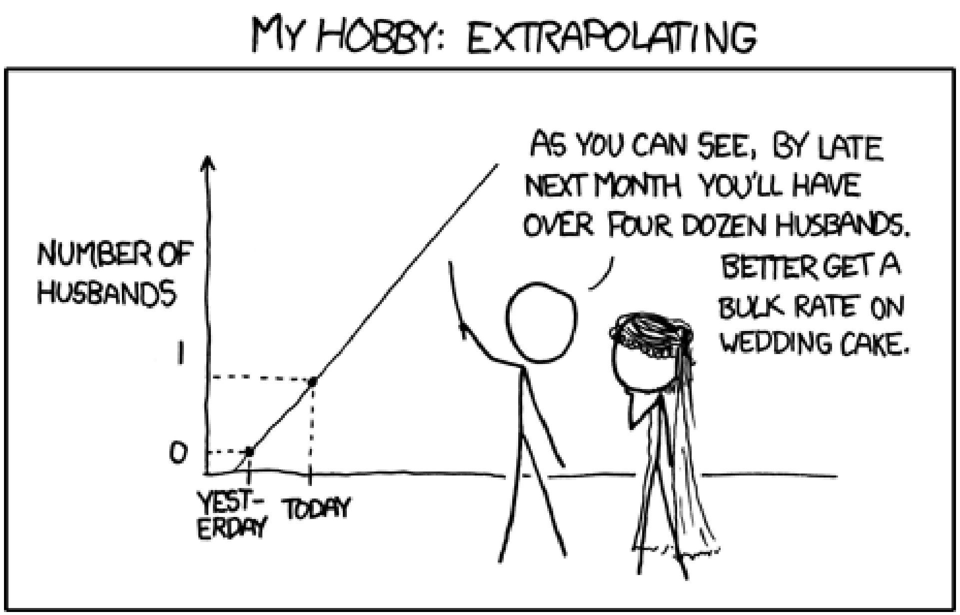
Is Einstein *still* right?

QCD
~1950s
10^{-15} meters

QED
~1920s
10^{-9} meters

Mechanics
~1700ish
10^{-3} meters

Lengthscale



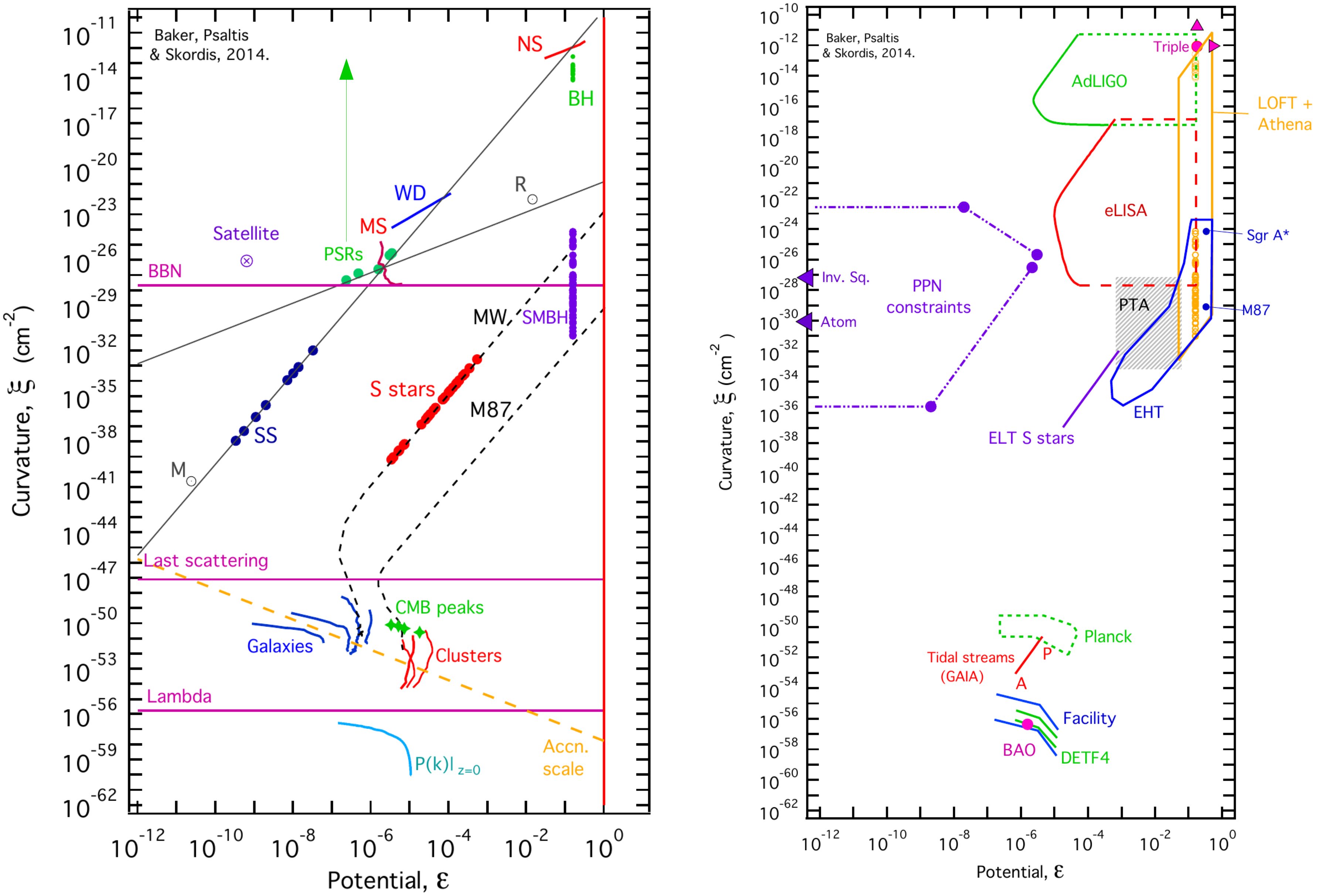
0.1-1
Compact objects
~2010s-2020s

10^{-7}
Classical tests of GR
~1920s

10^{-11}
Newton
~1700ish

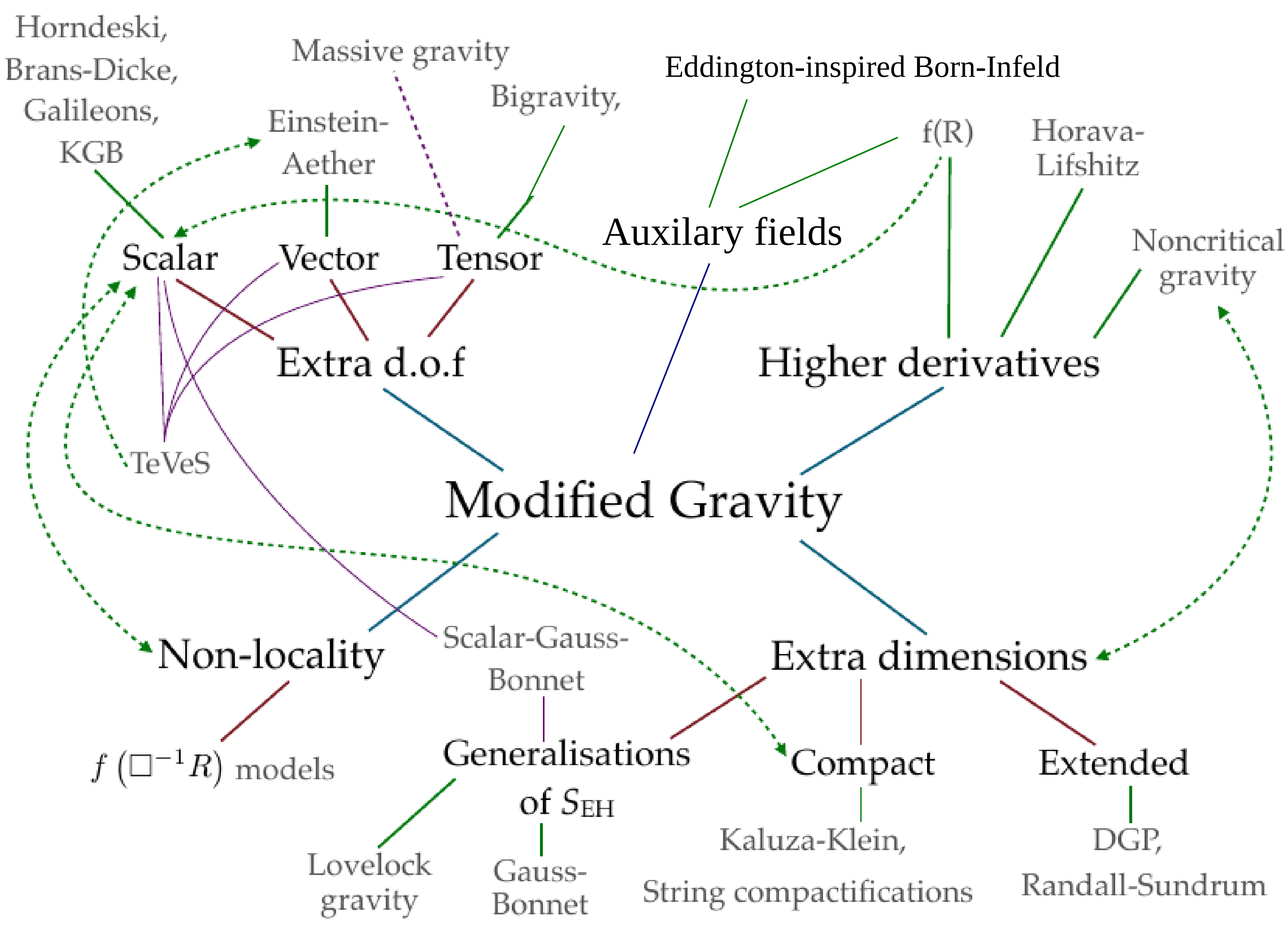
Grav. Potential
[G M/(c^2 r)]

Is Einstein *still* right?



How could Einstein be wrong?

[adapted from Clifton, Ferreira, Padilla, Skordis, Phys. Rep. 2011]



How could Einstein be wrong?

Berti+, Topical Review in CQG (2015) [1501.07274]

[Sotiriou, Lect.Notes Phys. 892 (2015) 3-24]

Lovelock's theorem:

In four spacetime dimensions the only divergence-free symmetric rank-2 tensor constructed solely from the metric $g_{\mu\nu}$ *and its derivatives up to second differential order, and preserving diffeomorphism invariance, is the Einstein tensor plus a cosmological term.*

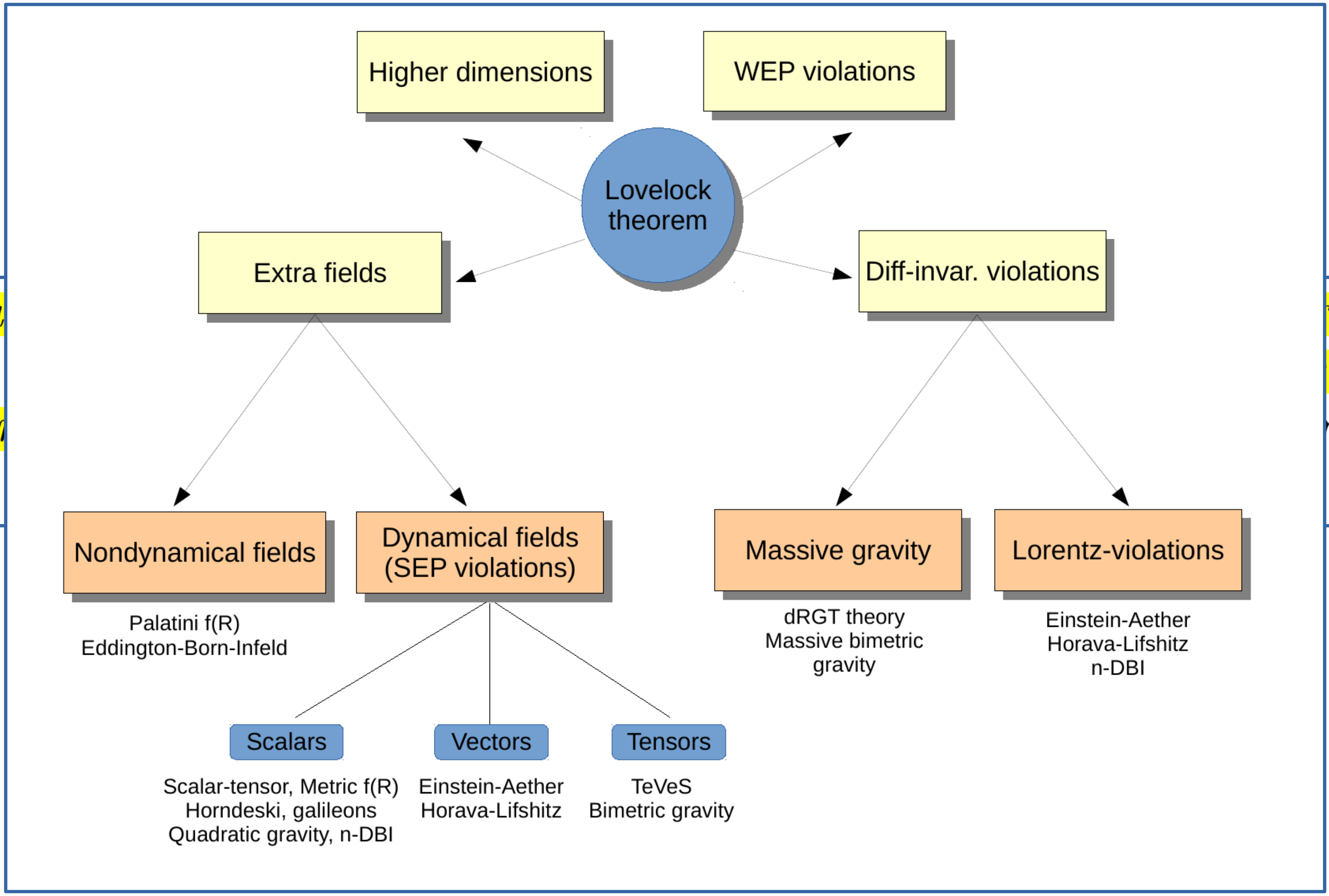
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

How could Einstein be wrong?

Berti+, Topical Review in CQG (2015) [1501.07274]

[Sotiriou, Lect.Notes Phys. 892 (2015) 3-24]

In fou … *ank-2*
tensor … *econd*
differe … *nstein*
tensor



Properties of (some) modified theories

Berti+, Topical Review in Class.Quant.Grav. 32 (2015) 24, 243001]

Theory	Field content	Strong EP	Massless graviton	Lorentz symmetry	Linear $T_{\mu\nu}$	Weak EP	Well-posed?	Weak-field constraints
Extra scalar field								
Scalar-tensor	S	✗	✓	✓	✓	✓	✓ [30]	[31–33]
Multiscalar	S	✗	✓	✓	✓	✓	✓?	[34]
Metric $f(R)$	S	✗	✓	✓	✓	✓	✓ [35, 36]	[37]
Quadratic gravity								
Gauss-Bonnet	S	✗	✓	✓	✓	✓	✓?	[38]
Chern-Simons	P	✗	✓	✓	✓	✓	✗✓? [39]	[40]
Generic	S/P	✗	✓	✓	✓	✓	?	
Horndeski	S	✗	✓	✓	✓	✓	✓?	
Lorentz-violating								
Æ-gravity	SV	✗	✓	✗	✓	✓	✓?	[41–44]
Khronometric/ Hořava-Lifshitz	S	✗	✓	✗	✓	✓	✓?	[43–46]
n-DBI	S	✗	✓	✗	✓	✓	?	none ([47])
Massive gravity								
dRGT/Bimetric	SVT	✗	✗	✓	✓	✓	?	[16]
Galileon	S	✗	✓	✓	✓	✓	✓?	[16, 48]
Nondynamical fields								
Palatini $f(R)$	–	✓	✓	✓	✗	✓	✓	none
Eddington-Born-Infeld	–	✓	✓	✓	✗	✓	?	none
Others, not covered here								
TeVeS	SVT	✗	✓	✓	✓	✓	?	[33]
$f(R)\mathcal{L}_m$	?	?	✓	✓	✓	✗	?	
$f(T)$	?	✗	✓	✗	✓	✓	?	[49]

Part II

Astrophysical tests of GR

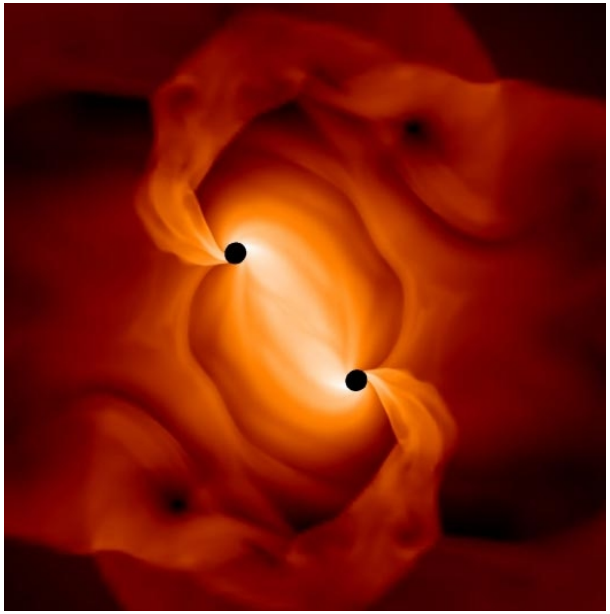
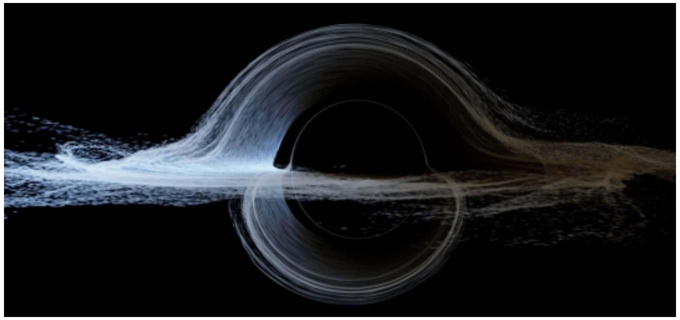
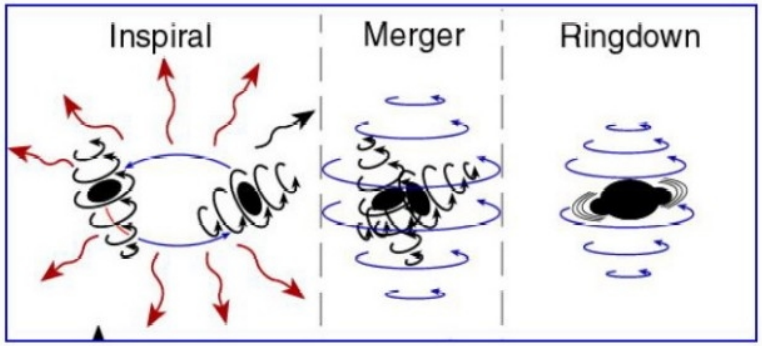
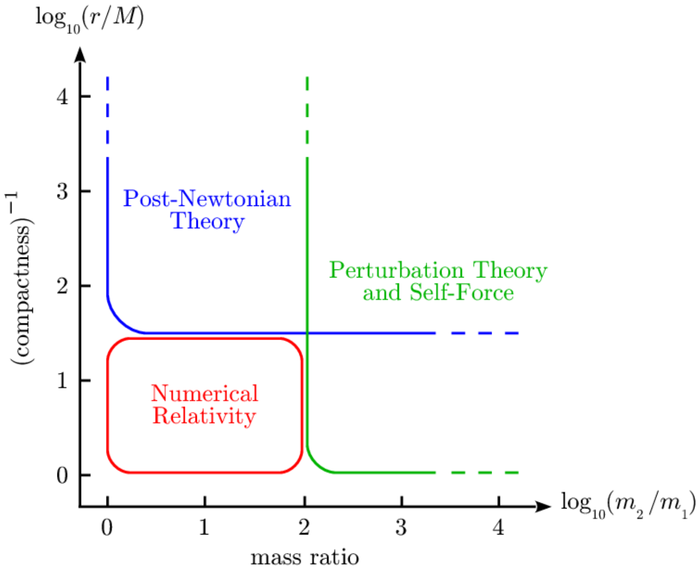


Image credit: Tanja Bode of Georgia Tech







Probes of strong-field gravity

- Gravitational waves
  - Emission
  - Propagation
  - Polarization
- Black holes
  - No-hair theorems
  - Stability
- Neutron stars
  - Degeneracy with EoS
- Exotic objects

GW detectors
(aLIGO, aVIRGO, KAGRA,..., eLISA)

Radio telescopes
(Timing, PTAs, SKA)

VLBI, VLTI, NIR
(Event Horizon Telescope, GRAVITY,...)

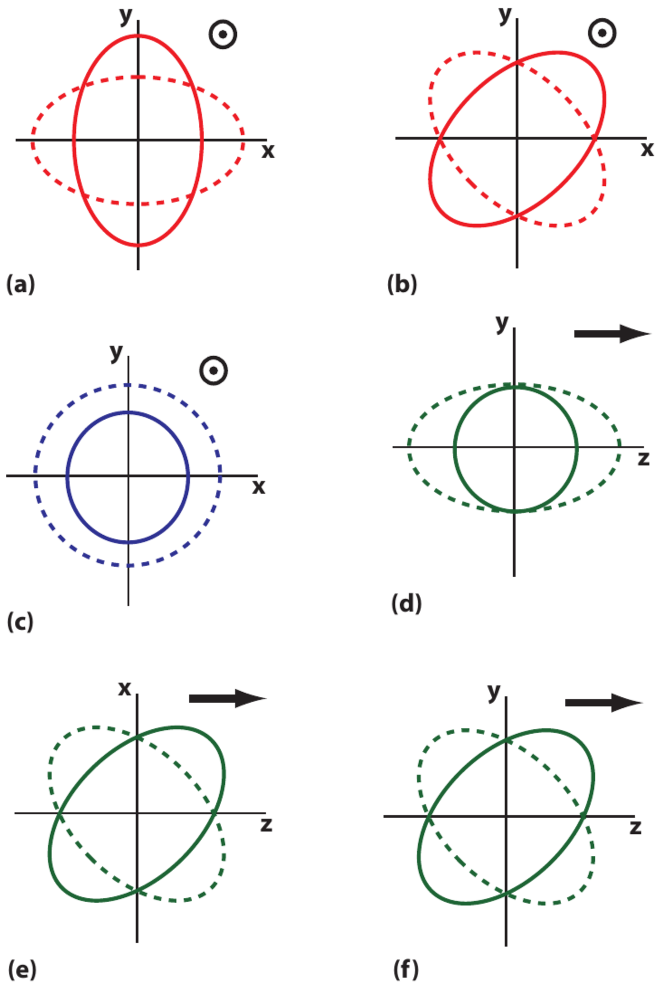
Satellites
(NICER, LOFT,...)

Tests of GW polarizations/speed

- Metric theory → 6 polarizations
- "Multipolarity" & energy loss
  - Monopole, dipole, quadrupole,....
- Propagation
  - Graviton dispersion relation
  - eLISA projected bound on the graviton mass:

$$m_g < 10^{-26}\,\mathrm{eV}$$ [Will 1997, Berti 2004]

  - GW phase VS EM phase
  - Parity violations (amplitude birefringence)



[Will, Living Review Relativity 2006-2014]

[Gair+, Living Review Relativity 2012]

Tests of the BH no-hair theorem

$$M_l + iS_l = M(ia)^l$$

In my entire scientific life [...] **the most shattering experience** has been the realization that an **exact solution** of Einstein's equations of general relativity, discovered by [...] Roy **Kerr,** provides the **absolutely exact representation of untold numbers of massive black holes that populate the universe.**

– S. Chandrasekhar

- Emission from accreting BHs (continuum fitting, K-alpha line) [Bambi+, 2011-2015]
- Quasiperiodic oscillations (QPOs) [Maselli+, 2015]
- Ringdown [Berti, Cardoso, Starinets, 2009]
- BH shadows [Cunha+ 2015, Johanssen+, 2015]
- EMRIs/IMRIs [Ryan, 1999]

BH solutions beyond GR

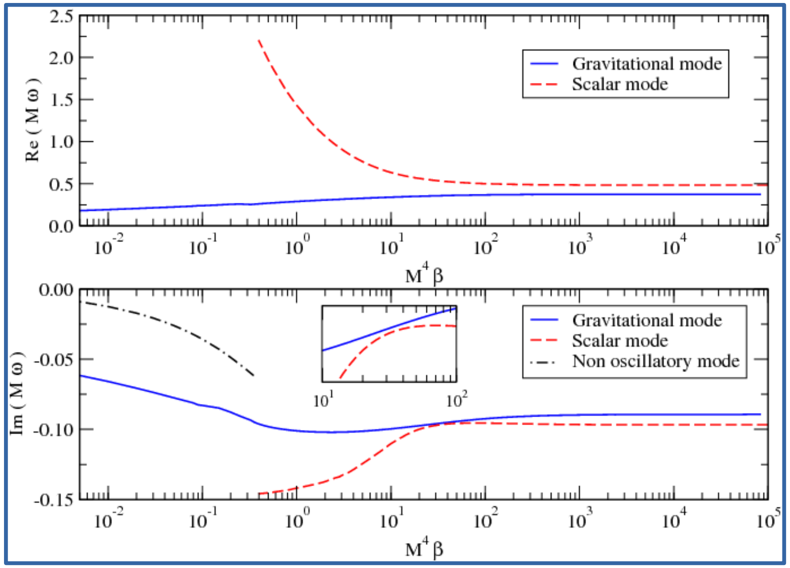
Berti+, Topical Review in Class.Quant.Grav. 32 (2015) 24, 243001]

Theory	Solutions	Stability	Geodesics	Quadrupole
Extra scalar field				
Scalar-tensor	≡GR [50–55]	[56–62]	–	–
Multiscalar/Complex scalar	⊃GR [51,63,64]	?	?	[63,64]
Metric $f(R)$	⊃GR [53,54]	[65,66]	?	?
Quadratic gravity				
Gauss-Bonnet	NR [67–69]; SR [70,71]; FR [72]	[73,74]	SR [70,75,76]; FR [72]	[71,77]
Chern-Simons	SR [78–80]; FR [81]	NR [82–85]; SR [74]	[69,86]	[80]
Generic	SR [75]	?	[75]	Eq. (3.12)
Horndeski	[87–89]	? [90,91]	?	?
Lorentz-violating				
Æ-gravity	NR [92–94]	?	[93,94]	?
Khronometric/ Hořava-Lifshitz	NR, SR [93–96]	? [97]	[93,94]	?
n-DBI	NR [98,99]	?	?	?
Massive gravity				
dRGT/Bimetric	⊃GR, NR [100–103]	[104–107]	?	?
Galileon	[108]	?	?	?
Nondynamical fields				
Palatini $f(R)$	≡GR	–	–	–
Eddington-Born-Infeld	≡GR	–	–	–

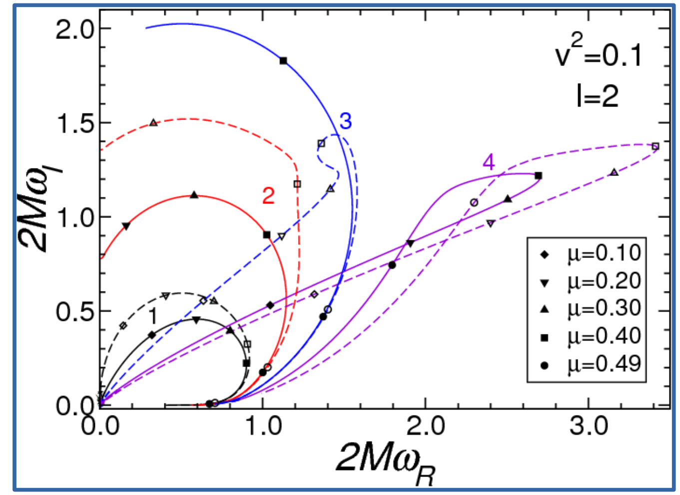
Same metric does NOT mean same dynamics!

QNM Zoo & Ringdown tests

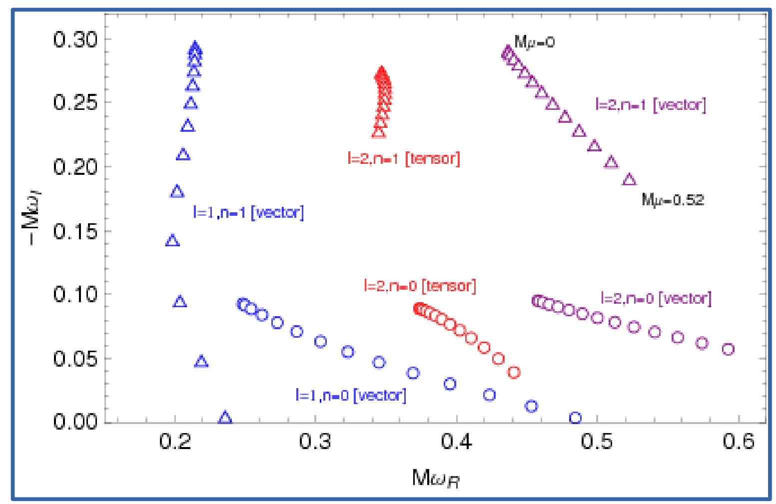
Chern-Simons



Gravastar



dRGT massive gravity



- EDGB gravity
- Boson stars
- …
- Parametrized Ringdown Approach
  - Lack of theory
  - Excitation?

[Barausse, Cardoso, Pani; 2014]

NS solutions beyond GR

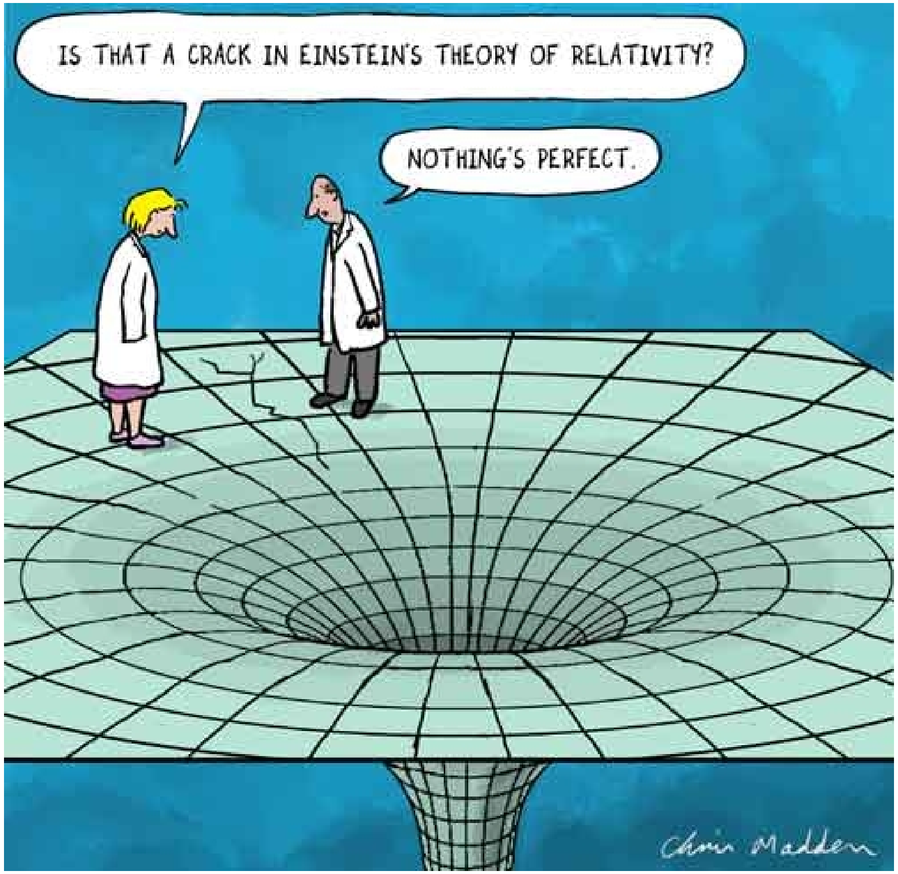
Berti+, Topical Review in Class.Quant.Grav. 32 (2015) 24, 243001]

Theory	Structure NR	Structure SR	Structure FR	Collapse	Sensitivities	Stability	Geodesics
Extra scalar field							
Scalar-Tensor	[109–114]	[112, 115, 116]	[117–119]	[120–127]	[128]	[129–139]	[118, 140]
Multiscalar	?	?	?	?	?	?	?
Metric $f(R)$	[141–153]	[154]	[155]	[156, 157]	?	[158, 159]	?
Quadratic gravity							
Gauss-Bonnet	[160]	[160]	[77]	?	?	?	?
Chern-Simons	≡ GR	[25, 40, 161–163]	?	?	[162]	?	?
Horndeski	?	?	?	?	?	?	?
Lorentz-violating							
Æ-gravity	[164, 165]	?	?	[166]	[43, 44]	[158]	?
Khronometric/ Hořava-Lifshitz	[167]	?	?	?	[43, 44]	?	?
n-DBI	?	?	?	?	?	?	?
Massive gravity							
dRGT/Bimetric	[168, 169]	?	?	?	?	?	?
Galileon	[170]	[170]	?	[171, 172]	?	?	?
Nondynamical fields							
Palatini $f(R)$	[173–177]	?	?	?	–	?	?
Eddington-Born-Infeld	[178–184]	[178, 179]	?	[179]	–	[185, 186]	?

Part III

Challenging GR

A biased overview

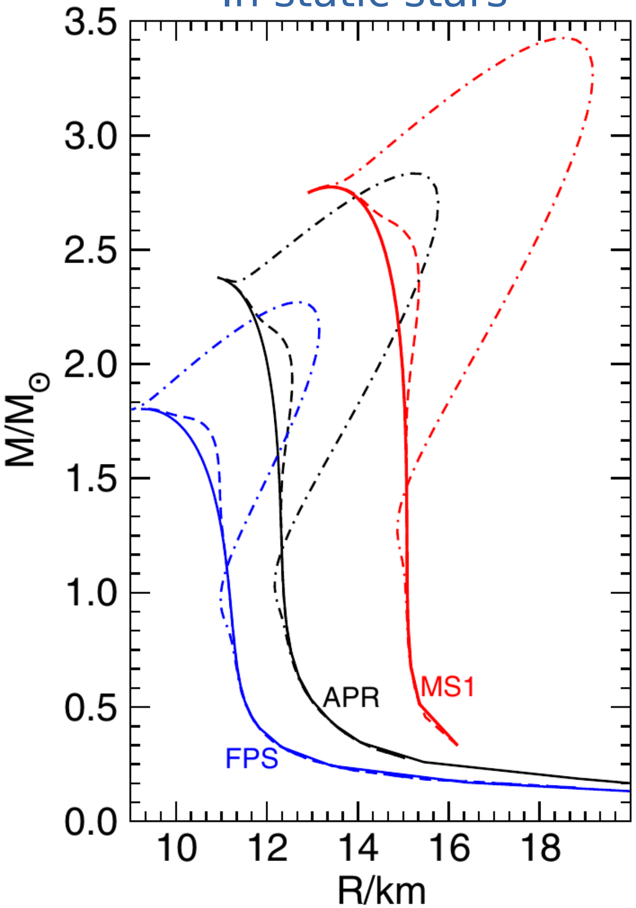


Spontaneous scalarization

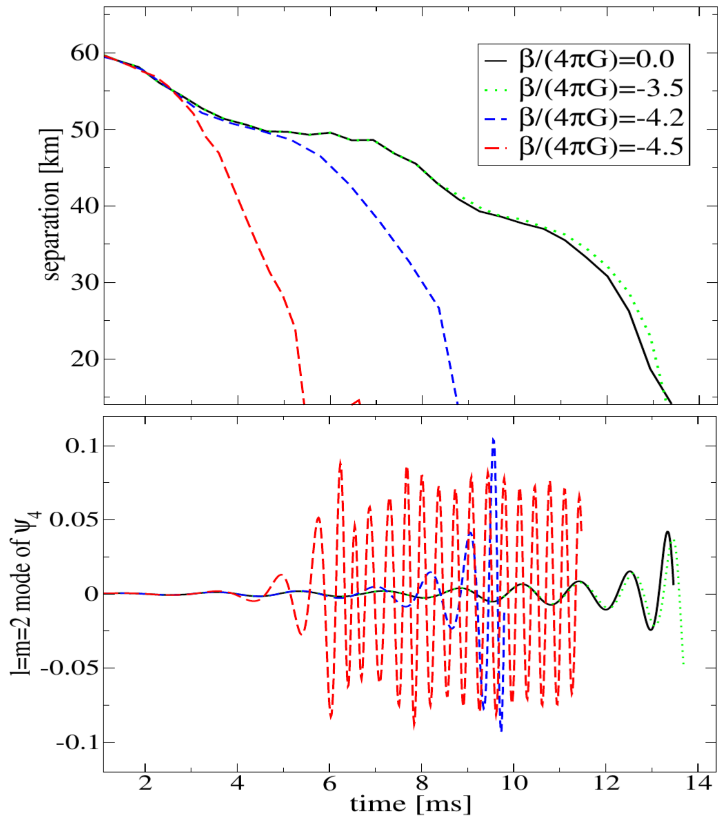
[Damour & Esposito-Farese, Phys.Rev.Lett. 70 (1993) 2220-2223]

$$S_{(E)} = \int d^4x \sqrt{-g^{(E)}} \left(\frac{R^{(E)}}{16\pi} - \frac{1}{2} g^{(E)}_{\mu\nu} \partial^\mu \Phi \partial^\nu \Phi - \frac{V(\Phi)}{16\pi} \right) + S_{\rm mat}(\Psi_m; F(\Phi) g_{\mu\nu})$$

In static stars



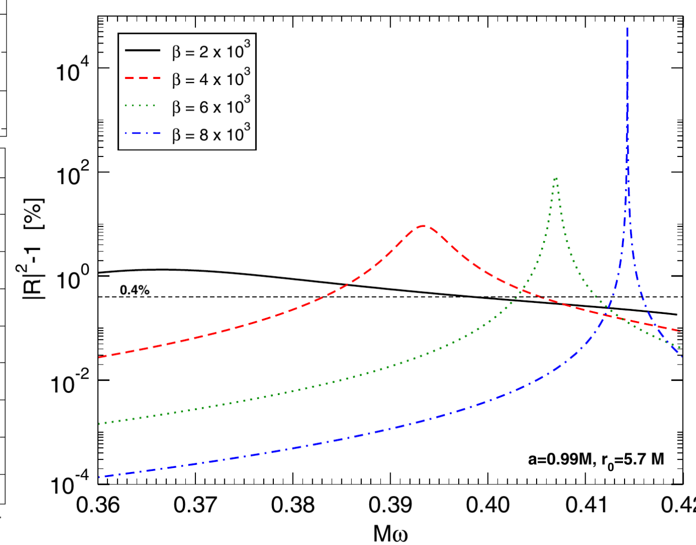
In NS-NS binaries



[Barausse, Palenzuela, Lehner, Phys.Rev. D87 (2013) 081506]

$$\Box^E \Phi = -\frac{F'(\Phi)}{F(\Phi)} T^E + \frac{V'(\Phi)}{16\pi}$$

In BHs with matter



[Cardoso, Carucci, Pani, Sotiriou, Phys.Rev.Lett. 111 (2013) 111101]

Floating orbits in ST gravity

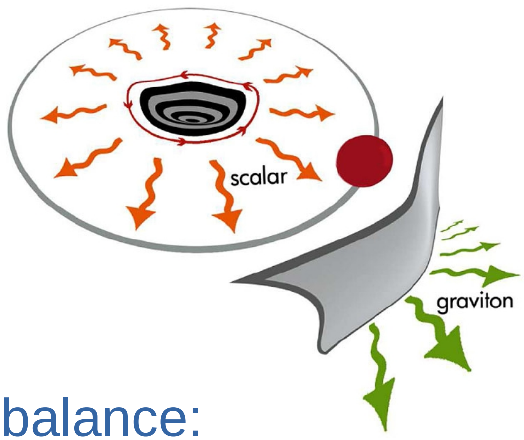
[Cardoso, Chakrabarti, Pani, Berti, Gualteri+, Phys.Rev.Lett. 107 (2011) 241101]

$$\left[\Box - \mu_s^2\right] \varphi = \alpha \mathcal{T}$$

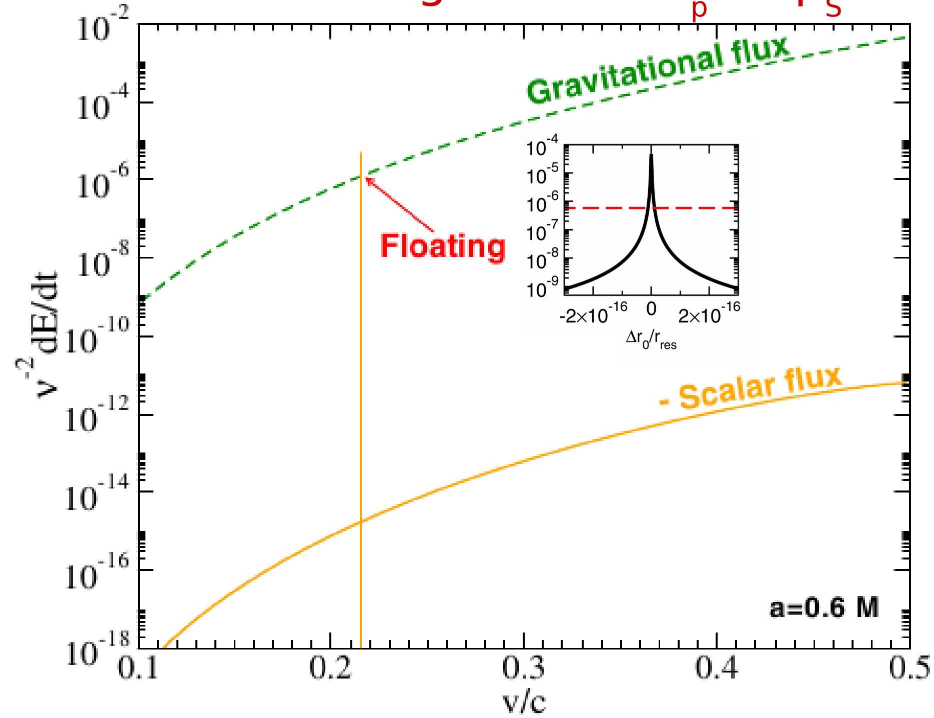
Excitation of the scalar QNMs → resonances

Superradiant energy extraction

[Brito, Cardoso, Pani, "Superradiance" (2015)]



Floating orbit at $\Omega_p \sim \mu_s$



Energy flux balance:

$$dE_p/dt = -\dot{E}_{\rm total} = -(\dot{E}_S + \dot{E}_G)$$

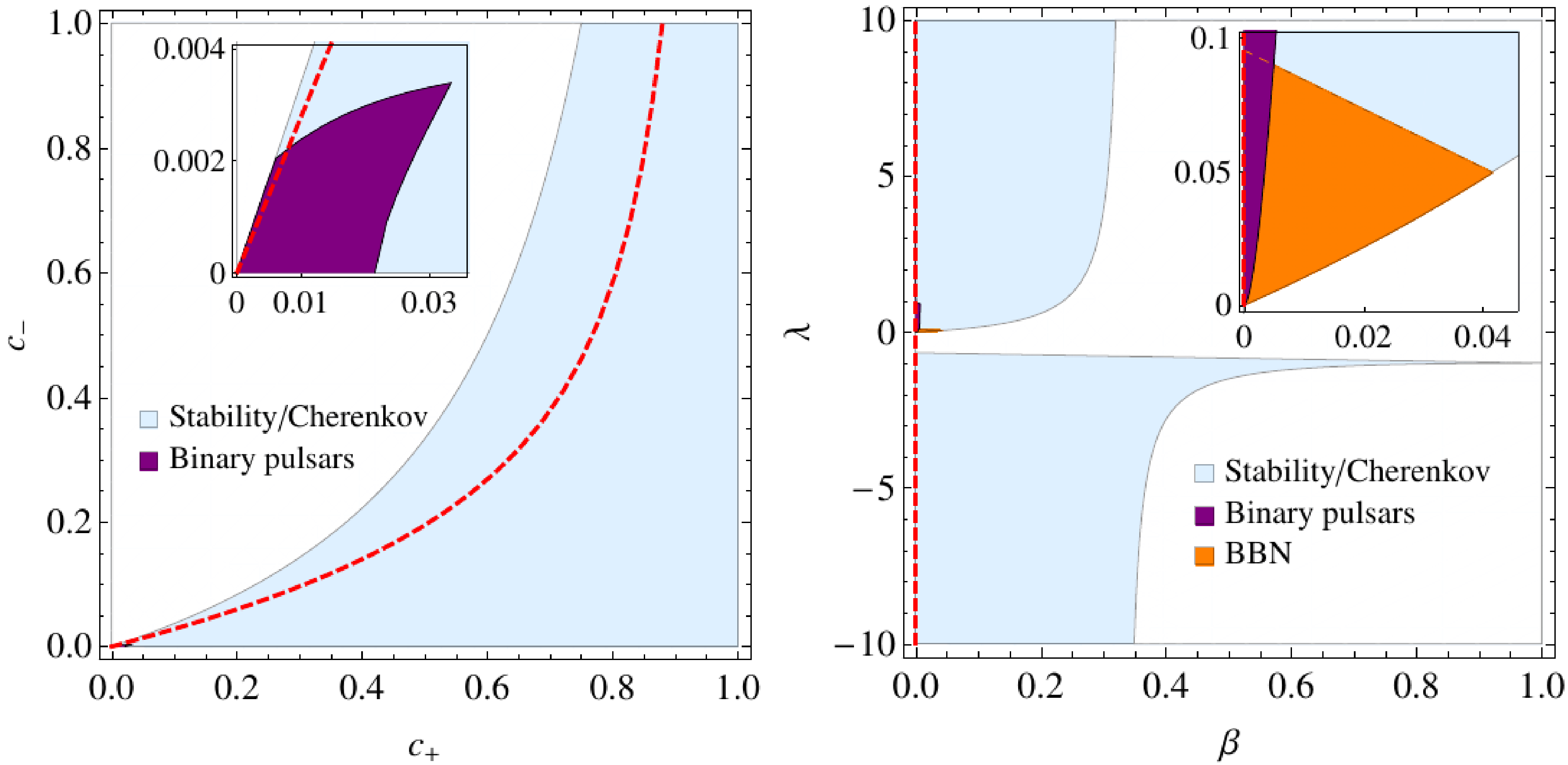
Narrow resonances → fragile?

$$\Delta\Omega \sim \frac{1}{12M} \left(\mu_s M\right)^9 \left(q - 2r_+\mu_s\right)$$

Generic effect → only needs light boson coupled to matter

Bounds on Lorentz violations

$$S_{Æ} = \frac{1}{16\pi G_{Æ}} \int \sqrt{-g} \, \left(R - M^{\alpha\beta}{}_{\mu\nu} \nabla_\alpha u^\mu \nabla_\beta u^\nu \right) \, d^4x + S_{\rm mat}\left[\Psi, \, g_{\mu\nu} \right],$$

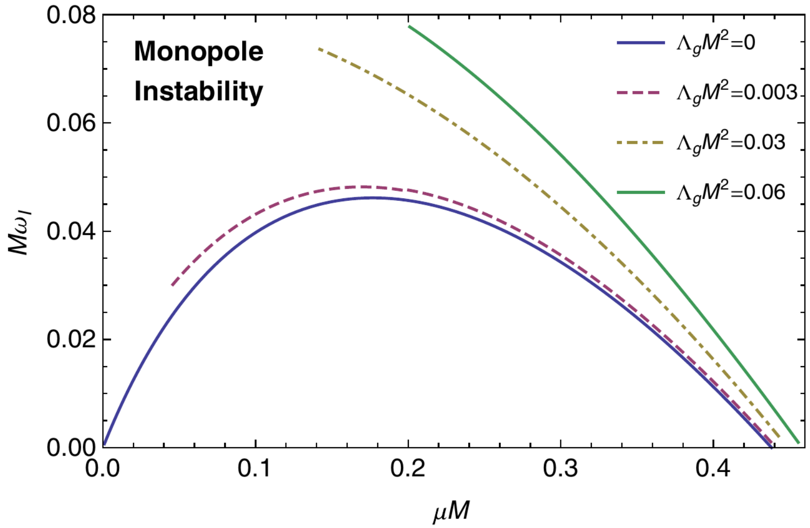


[Yagi, Blas, Yunes, Barausse, Phys.Rev.Lett. 112 (2014) 16, 161101]

Instabilities in massive gravity

$$\mathcal{L} = \sqrt{|g|}\left[m_g^2 R_g + m_f^2 \sqrt{f/g}\, R_f - 2m_v^4 V(g,f)\right]$$

[de Rham, Gabadadze, Tolley, Phys.Rev.Lett. 106 (2011) 231101]



$$\begin{cases} \bar{\Box} h_{\mu\nu} + 2\bar{R}_{\alpha\mu\beta\nu} h^{\alpha\beta} - \mu^2 h_{\mu\nu} = 0\,, \\ \mu^2 \bar{\nabla}^\mu h_{\mu\nu} = 0\,, \\ \left(\mu^2 - 2\Lambda/3\right) h = 0\,, \end{cases}$$

(Bidiagonal) Schwarzschild BHs are Gregory-Laflamme unstable!

[Babichev & Fabbri, Class.Quant.Grav. 30 (2013) 152001]
[Brito, Cardoso, Pani; Phys.Rev. D87 (2013) 12, 124024]

(Bidiagonal) Kerr BHs are superradiantly unstable

[Brito, Cardoso, Pani; Phys.Rev. D87 (2013) 12, 124024]

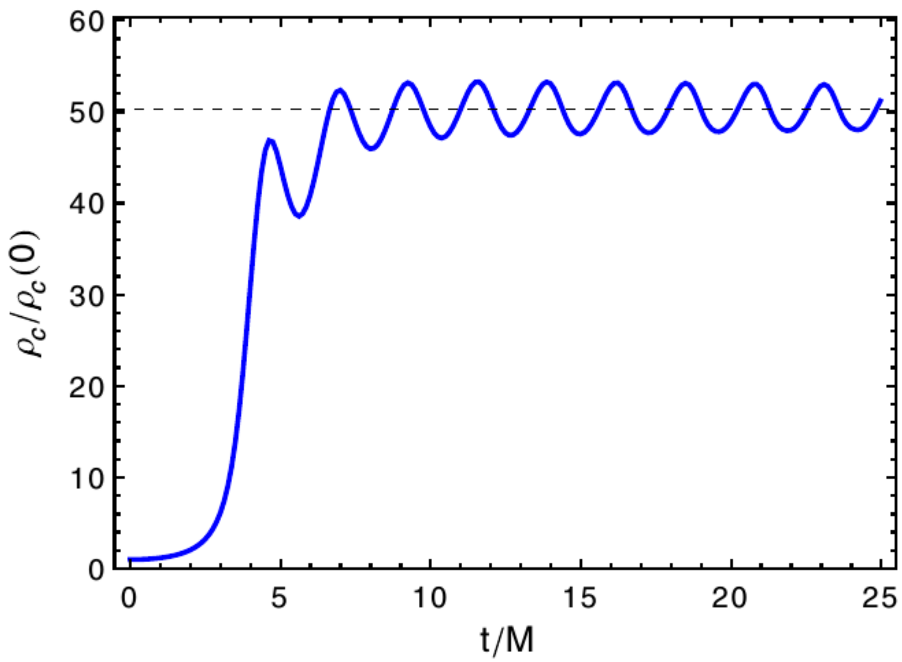
Nonbidiagonal BHs are stable

[Babichev & Fabbri, Phys.Rev. D89 (2014) 081502]
[Babichev, Brito, Pani; arXiv:1512.04058]

Singularity avoidance

$$S = \frac{2}{\kappa}\int d^4x\left(\sqrt{-|g_{ab}+\kappa R_{ab}(\Gamma)|}-\lambda\sqrt{-g}\right)+S_M\left[g,\Psi_M\right]$$

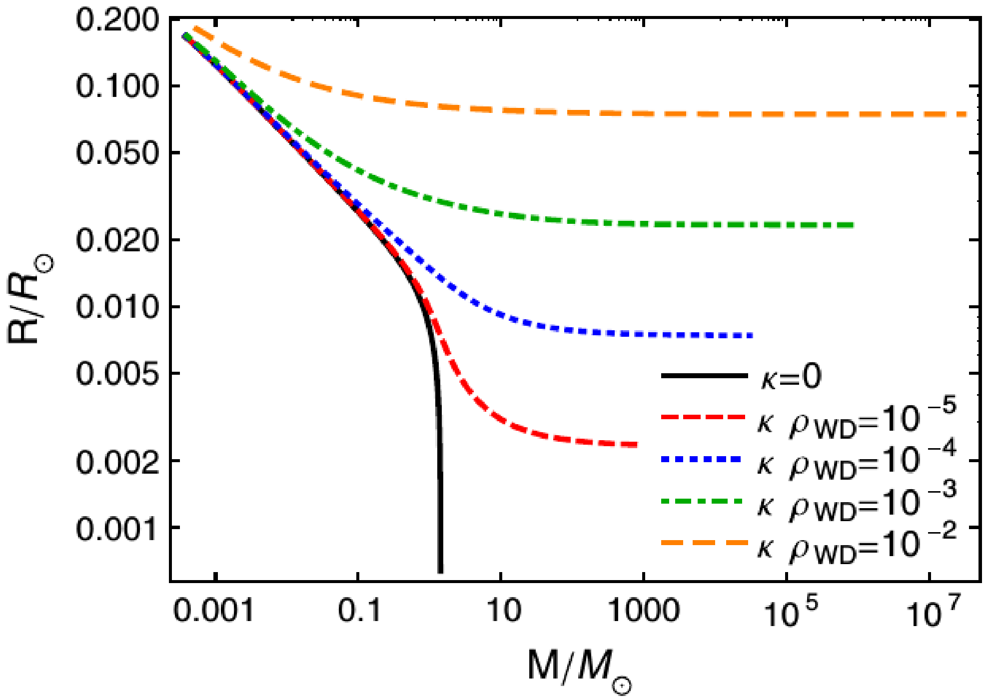
Banados & Ferreira, PRL 2010



Singularity-avoidance inside BHs

Pani, Cardoso, Delsate, PRL 2011

Pani & Sotiriou, PRL 2012



Modified mass-radius diagram for white dwarfs

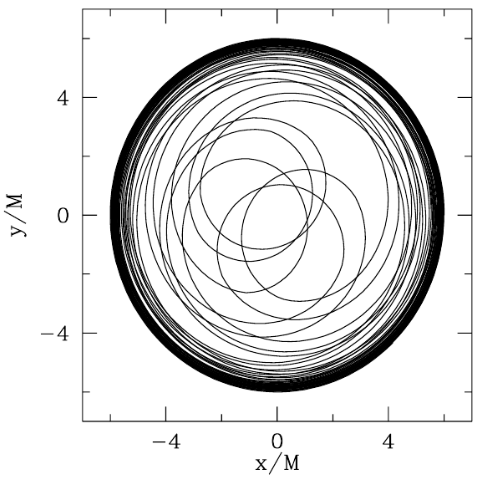
Pani, Delsate, Cardoso, PRD 2011

Testing the BH paradigm

- EMRIs around boson stars

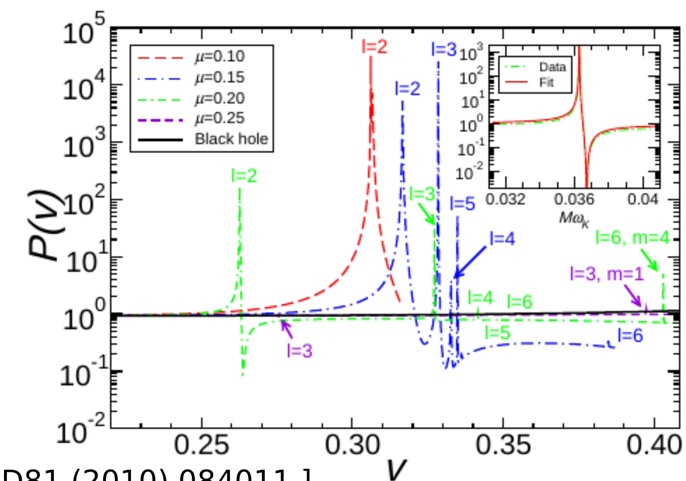
[Kesden, Gair, Kamionkowski; Phys.Rev. D71 (2005) 044015]

[Macedo, Pani, Cardoso, Crispino, Astrophys.J. 774 (2013) 48]



No horizon
Higher frequency

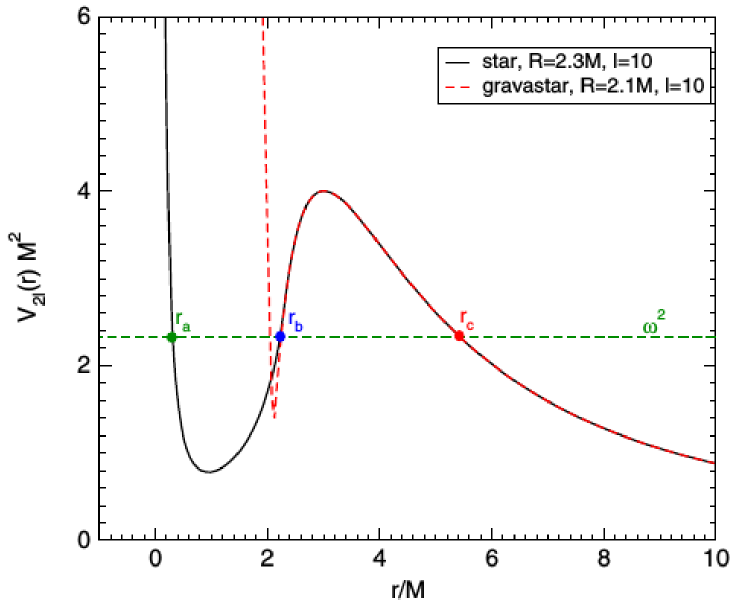
QNM
excitation



[Pani+, Phys.Rev. D81 (2010) 084011]

[Macedo+, Phys.Rev. D88 (2013) 6, 064046]

- BH mimickers unstable?



Ergoregion instability

Friedman, Commun.Math.Phys.,63,243 1978

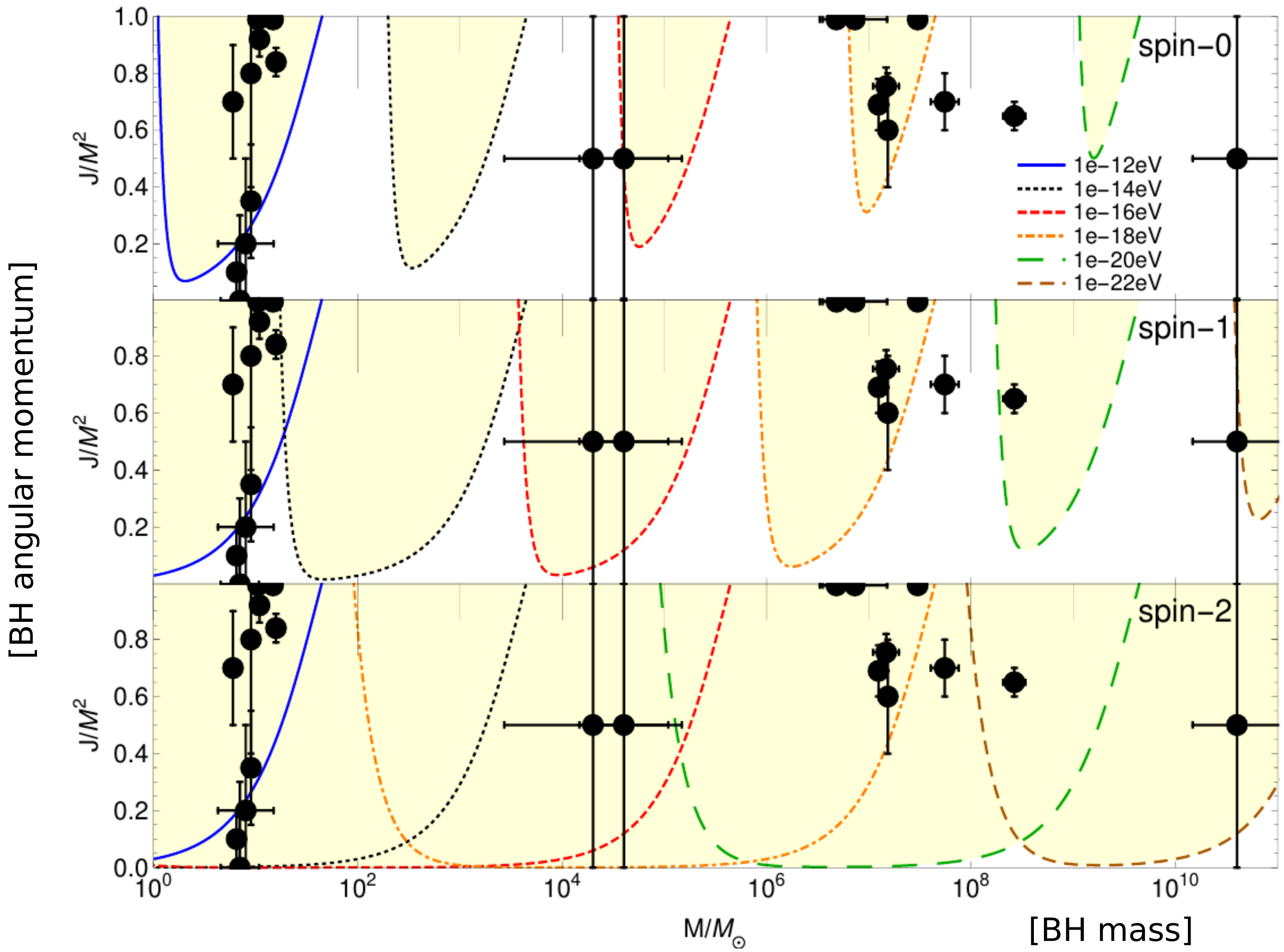
Fragmentation?

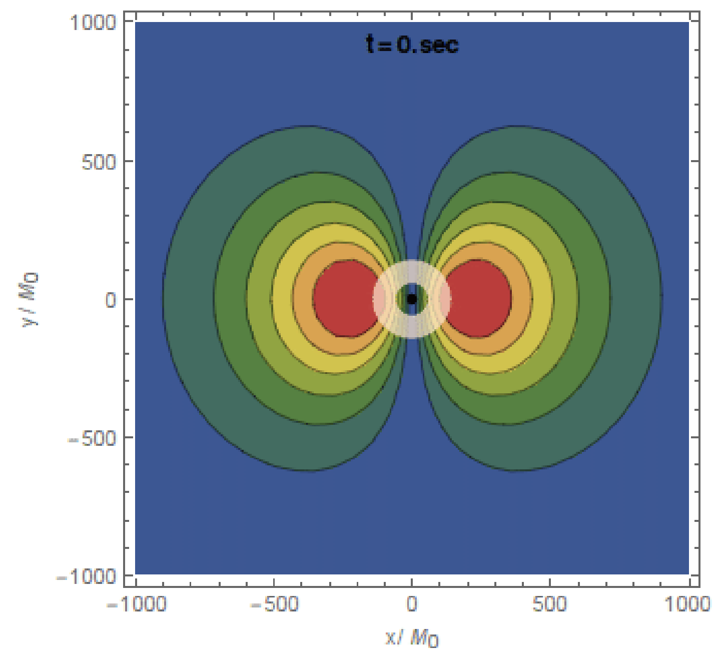
Cardoso+, Phys.Rev. D90 (2014) 044069

Light-ring → horizon

Probing DM with strong gravity

[R. Brito, V. Cardoso, P. Pani; *"Superradiance" - Springer (2015)]*





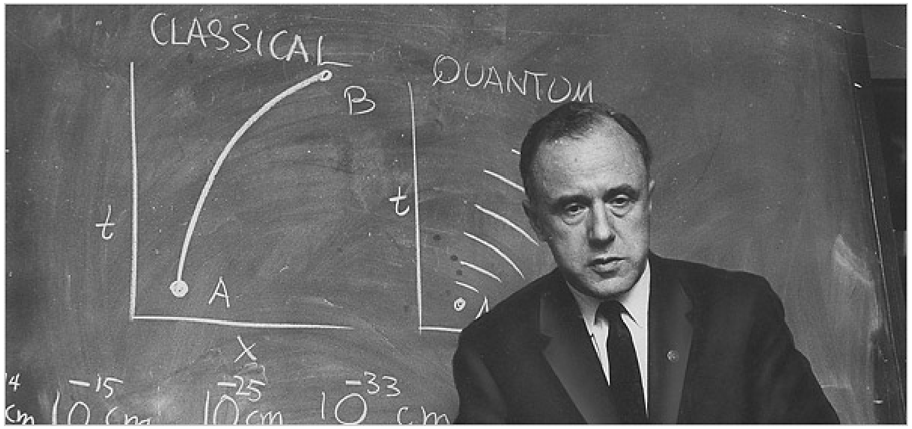
Observations of highly-spinning BHs → bounds on ultralight particles

GR, live long and prosper

- After a century, **General Relativity keeps surprising us**
- Recent conceptual, observational and technical **breakthroughs**
- Entering a new exciting area of **astrophysics@extreme gravity**

“Black holes teach us that [...] the laws of physics that we regard as ‘sacred,’ as immutable, are anything but.”

J.A. Wheeler



This work is supported by the **European Community** through the **Marie Curie IEF contracts aStronGR-2011-298297 and AstroGRAphy-2013-623439**, and by **FCT - Portugal** through projects **IF/00293/2013.**

Backup slides

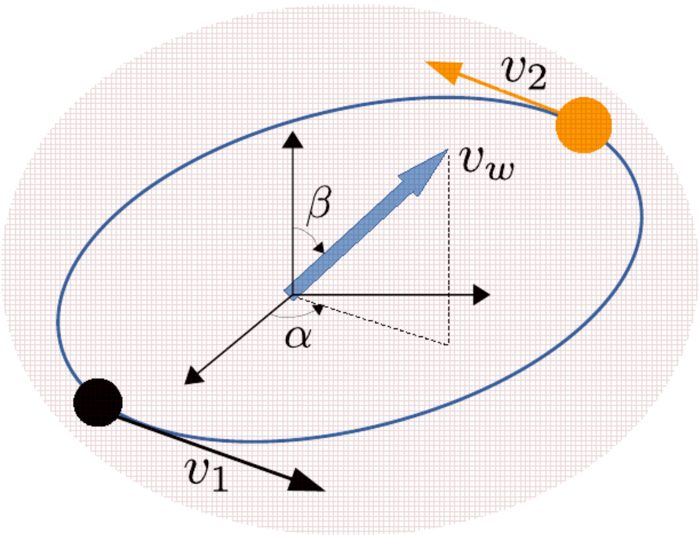
"Nothing is More Necessary than the Unnecessary"

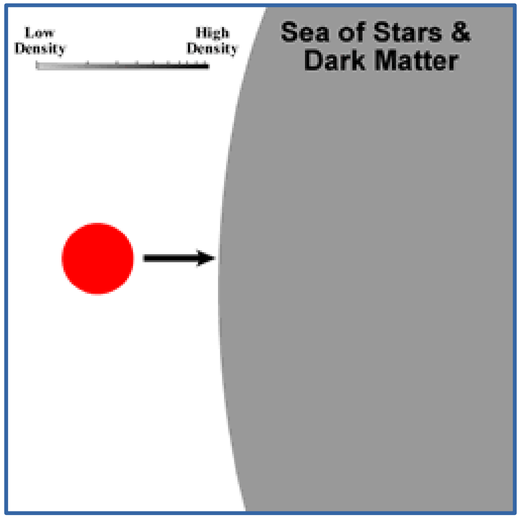
Which approach to test gravity?

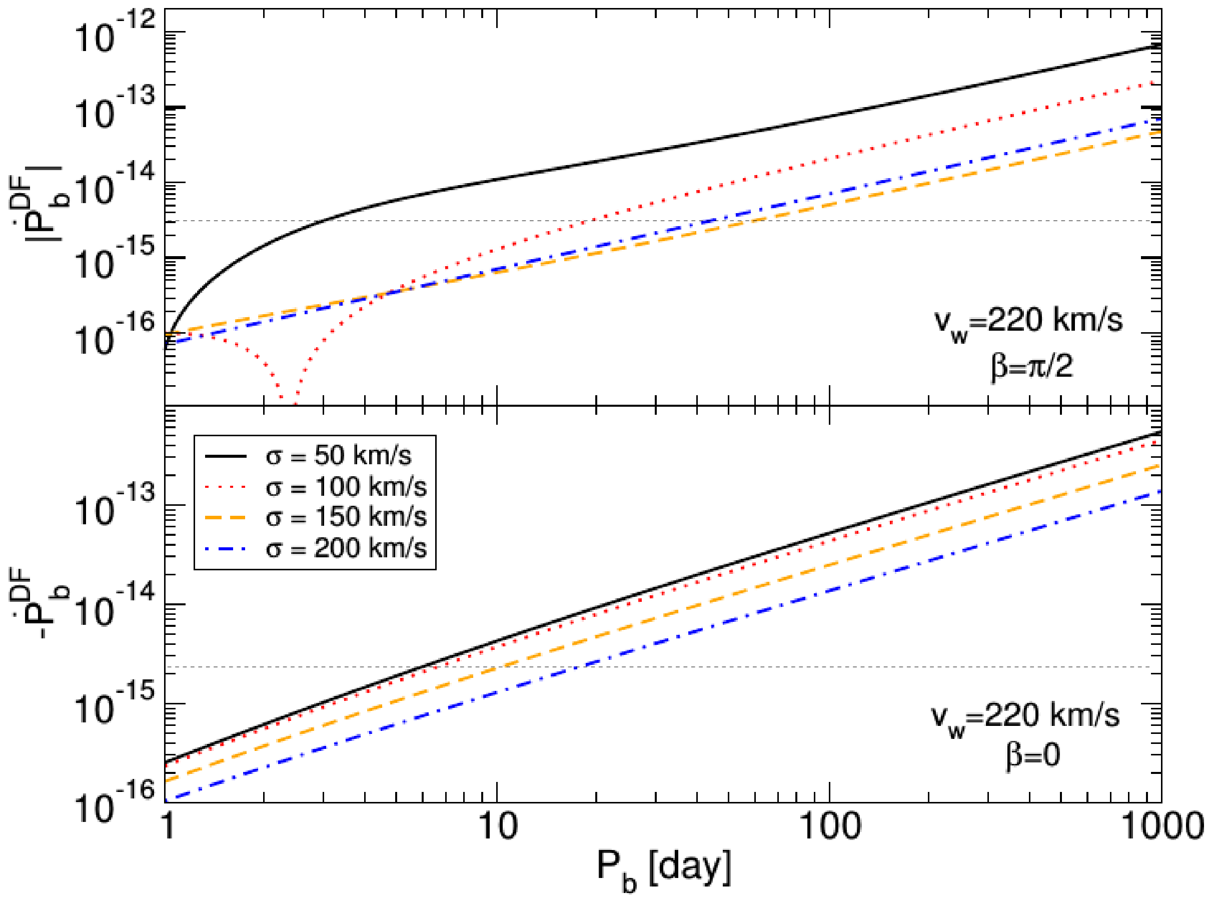
- Null experiments
- Direct approach
  - \- Inefficient
  - \- Need strong motivation
  - \+ More precise
- Smoking guns
  - \- Inefficient
  - \+ Large corrections
  - \+ New effects

- Parametrizations
  - \+ Efficient
  - \- Small corrections
  - \- Sufficiently general?
  - \- Reference quantities?

Probing DM with binary pulsars







$$\langle \dot{P}_b^{\rm DF} \rangle \sim -8\sqrt{2\pi} G^2 \frac{\mu \lambda \rho_{\rm DM} P_b}{\sigma^3}$$

Part IV
Can environmental effects spoil precision GW astrophysics?

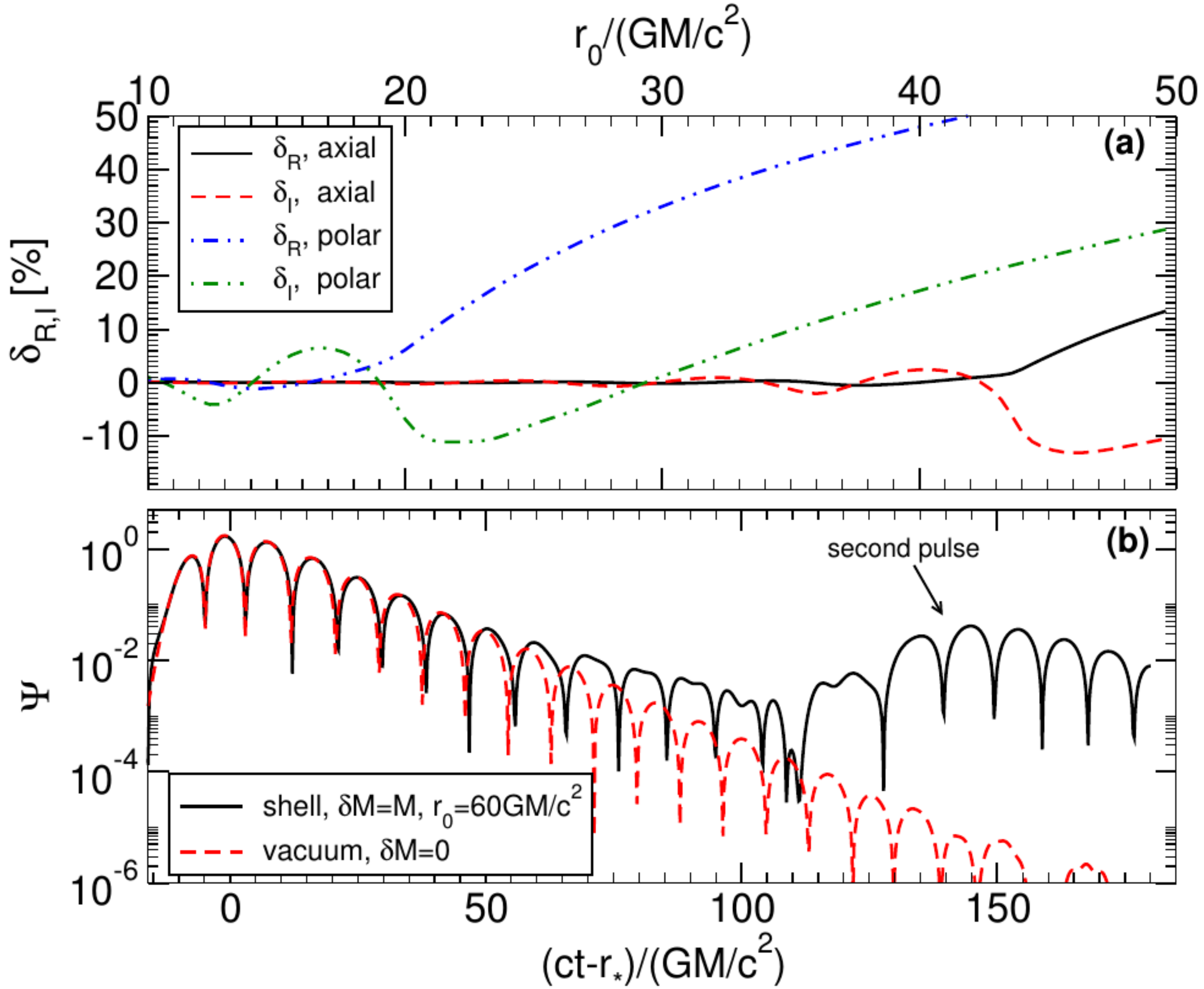
Barausse, Cardoso, Pani; Phys.Rev. D89 (2014) 10, 104059

Env. corrections to GW dephasing

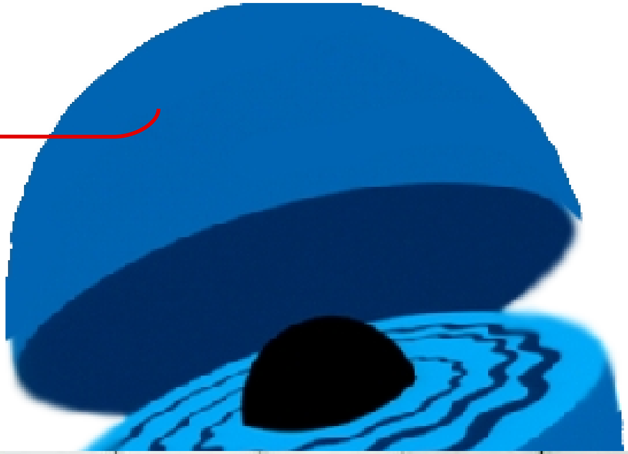
Table 1. Maximum environmental corrections to a typical EMRI's periastron shift ($\delta_{\rm per}$) and GW phase (δ_φ) over a typical eLISA's mission duration of one year. $\delta_{\rm per}$ and δ_φ are respectively the relative and absolute corrections to vacuum values. Dissipative effects such as GW radiation reaction, dynamical friction and hydrodynamic drag from accretion give negligible $\delta_{\rm per}$ and are thus not shown. We consider two BHs with masses $(10M_\odot, M = 10^6 M_\odot)$, on a quasicircular inspiral ending at the innermost stable circular orbit (ISCO) $r = 6GM/c^2$. The periastron shift is computed at $r = 10GM/c^2$. Conservative environmental reference values are $q = 10^{-3}$, $B = 10^8$ Gauss, $\rho_3^{\rm DM} = \rho_{\rm DM}/(10^3 M_\odot/{\rm pc}^3)$. We assume a Shakura-Sunyaev disk model with viscosity parameter $\alpha = 0.1$ and Eddington ratio $f_{\rm Edd} = 10^{-4}$ ($f_{\rm Edd} = 1$) for thick and thin disks, respectively. The scaling with the parameters can be found in Ref. [16], and in Ref. [21] for planetary migration.

	Correction	$\lvert\delta_{\rm per}\rvert$	$\lvert\delta_\varphi\rvert$[rads]
thin disks	planetary migration	—	10^4
	dyn. friction/accretion	—	10^2
	gravitational pull	10^{-8}	10^{-3}
	magnetic field	10^{-8}	10^{-4}
	electric charge	10^{-7}	10^{-2}
	gas accretion	10^{-8}	10^{-2}
	cosmological effects	10^{-31}	10^{-26}
thick disks	dyn. friction/accretion	—	10^{-9}
	gravitational pull	10^{-16}	10^{-11}
DM	accretion	—	$10^{-8}\rho_3^{\rm DM}$
	dynamical friction	—	$10^{-14}\rho_3^{\rm DM}$
	gravitational pull	$10^{-21}\rho_3^{\rm DM}$	$10^{-16}\rho_3^{\rm DM}$

Env. corrections to BH ringdown



QNMs are NOT ringdown modes!



$\mathcal{O}(\nu^2)$ $\mathcal{O}(\nu^3)$

AAA

$\mathcal{O}$

AAA