GPhys Day, July 6, 2015

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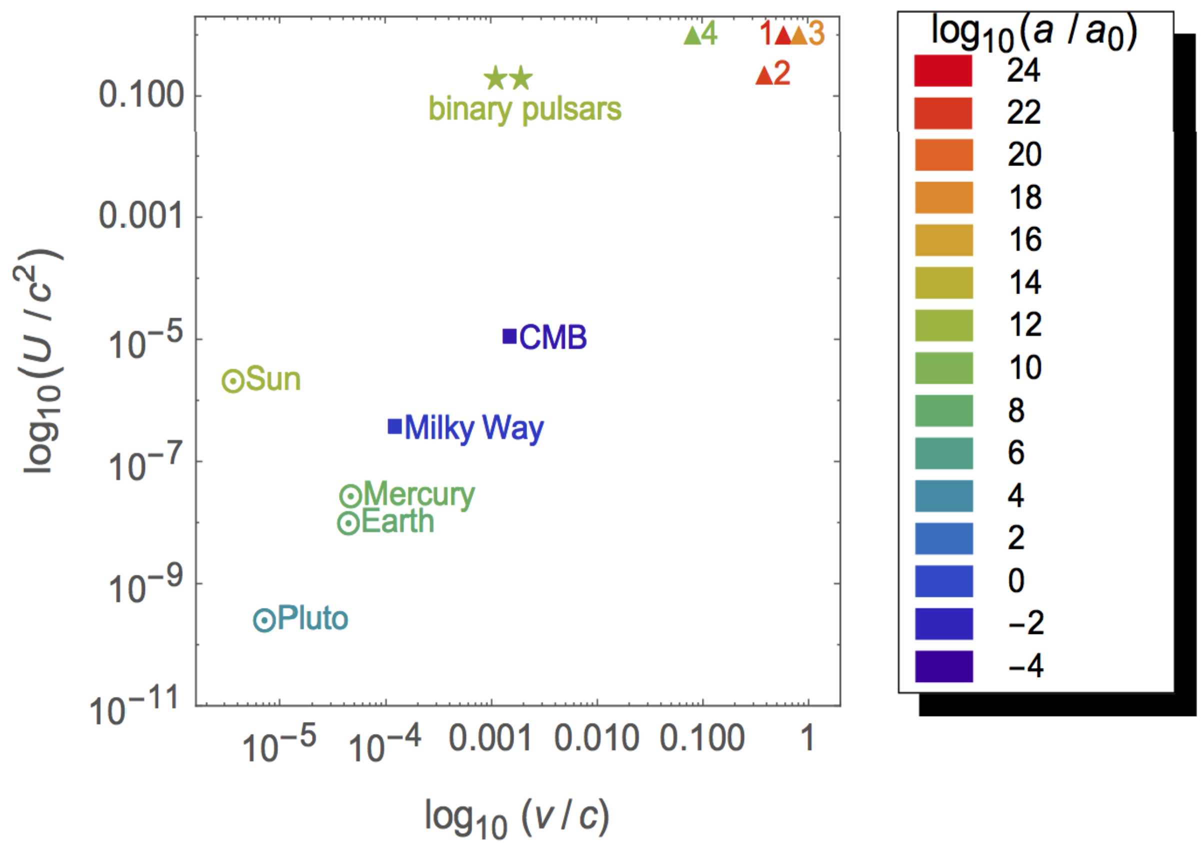
Why bother about strong-field gravity?
The example of Lorentz-violating gravity theories

PCIG11-GA-2012-321608

Dark Matter/Energy or Dark Gravity?



1=BH-BH systems with aLIGO/aVirgo/KAGRA

2=NS-NS systems with aLIGO/aVirgo/KAGRA,

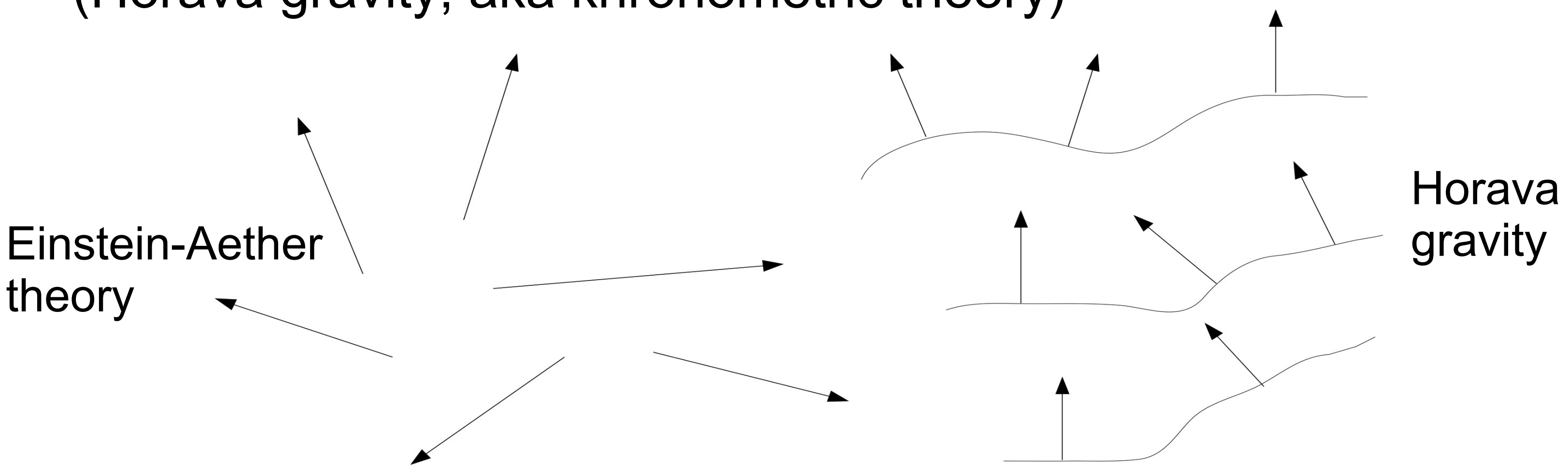
3=BH-BH with eLISA,

4=BH- BH with PTAs

Evidence for Dark Sector from accelerations lower than $a_0 \sim 10^{-10} m/s^2$

Lorentz-violating gravity

Break explicitly boost invariance by choosing time direction at each point of spacetime (Einstein-Aether theory) or a preferred foliation (Horava gravity, aka khronometric theory)

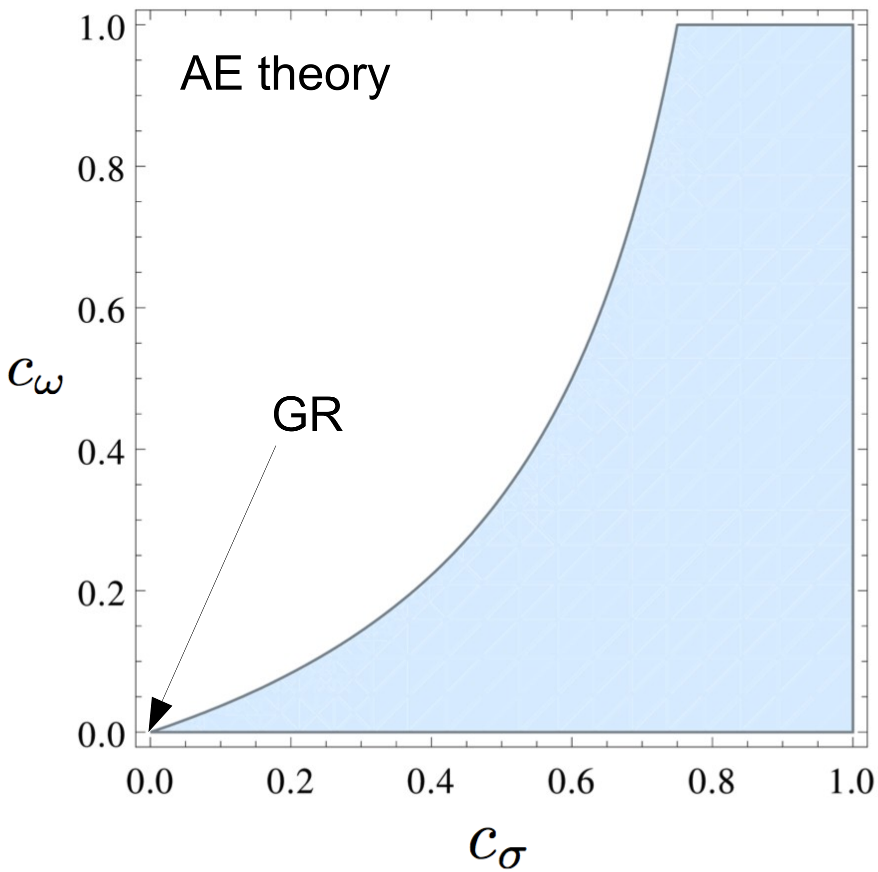


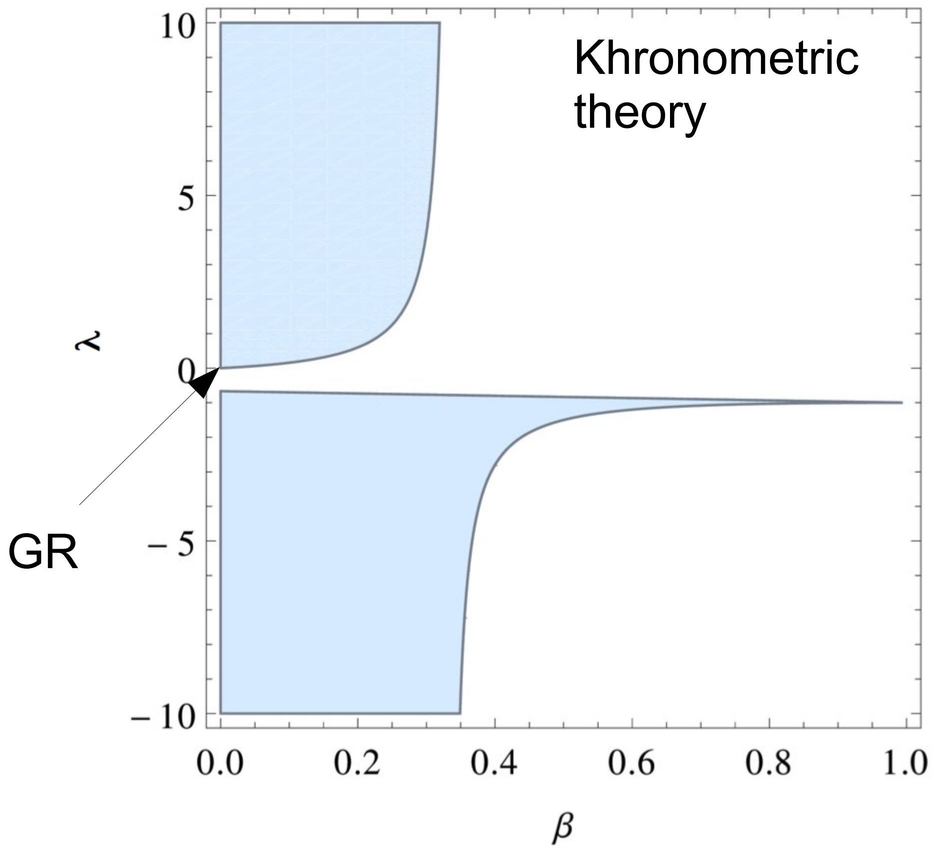
- Pro's: better UV behavior (power-counting renormalizability); provides natural way to obtain acceleration-dependent phenomenology
- Con's: No direct coupling of vector field to matter, but percolation of Lorentz violations from gravity to matter

Experimental and theoretical constraints

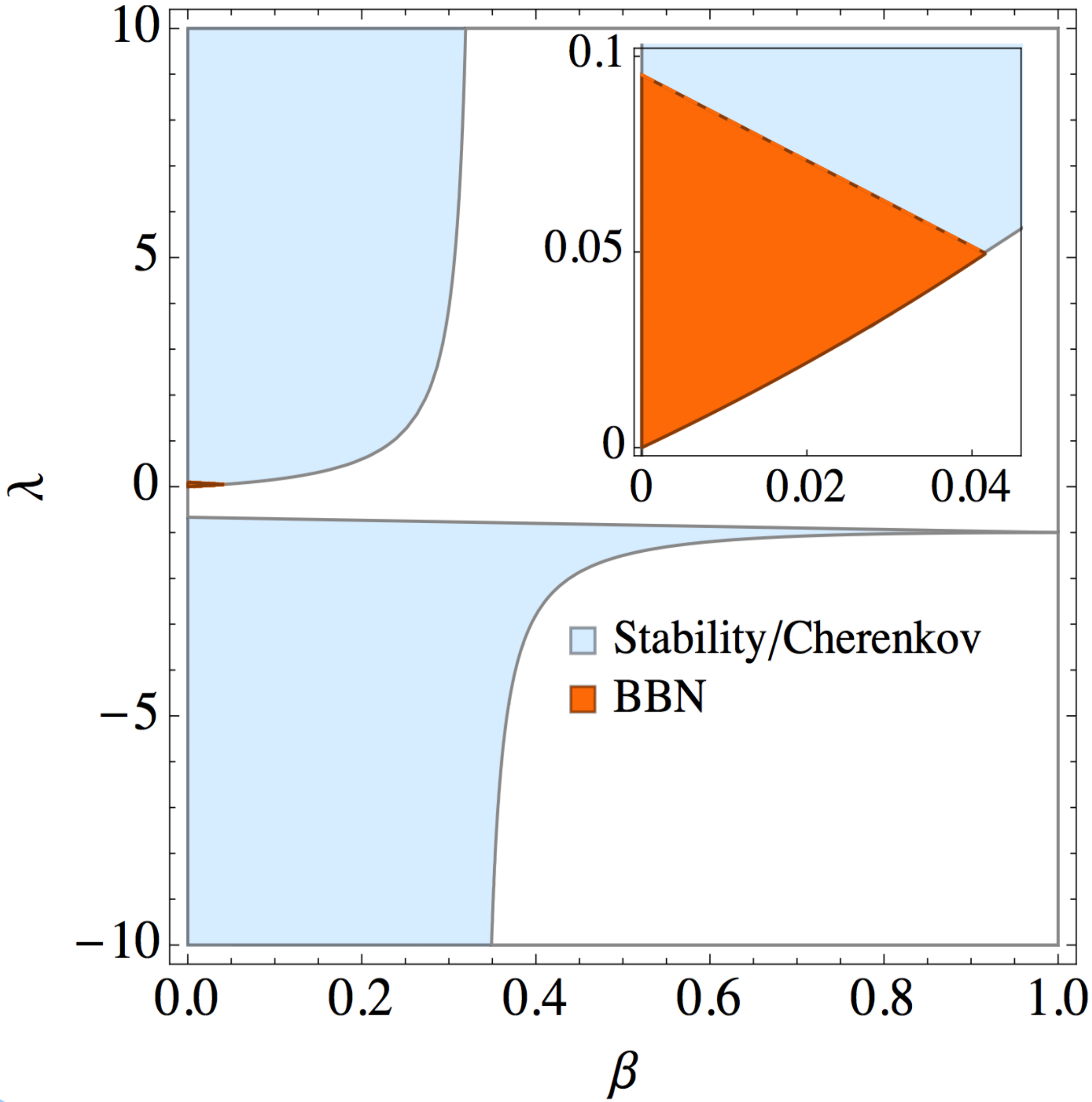
- Solar system (i.e. 1PN) constraints: can be matched as well as in GR
- AE theory has propagating spin-0, spin-1 and spin-2 gravitational modes; khronometric theory has spin-0, spin-2 modes
- For classical/quantum stability (i.e. no gradient instabilities and no ghosts), real propagation speeds and positive energies are required
- Propagation speed must be larger than speed of light to avoid gravitational Cherenkov radiation
- Well posedness proved in flat space and in spherical symmetry

Stability+Solar System+Cherenkov constraints





How about cosmological constraints?



- Weak for AE theory
- For khronometric theory,

$$\frac{G_N}{G_C} = \frac{2+\beta+3\lambda}{2(1-\beta)}$$

and BBN requires

$$|G_N/G_C - 1| < 1/8$$

- No constraints from CMB in khronometric theory yet

Why are astrophysical effects expected?

- Matter couples minimally to metric, but metric couples non-minimally to aether $\Rightarrow$ effective matter-aether coupling in strong-field regimes

- For strongly gravitating body (e.g. neutron star), binding energy depends on velocity relative to the aether $\gamma = U_\mu u^\mu$
(i.e. structure depends on motion relative to preferred frame, as expected from Lorentz violation!)

- Gravitational mass depends on velocity relative to the aether

$$\Rightarrow \quad S_{matter} = \Sigma_i \int m_i(\gamma)\, d\tau_i \quad \Rightarrow \quad u_a^\mu \nabla_\mu (m_a u^\nu) = -\frac{d m_a}{d\gamma} u^\mu \nabla^\nu U_\mu$$

Violations of strong equivalence principle (aka Nordtvedt effect in Brans Dicke theory, scalar tensor theories, etc)

Why are astrophysical effects expected?

Whenever strong equivalence principle (SEP) is violated, dipolar gravitational-wave emission may be produced

- In GR, dipolar emission not present because of SEP + conservation of linear momentum

$$M_1 \equiv \int \rho\, x_i\, d^3x \qquad h \sim \frac{G}{c^3}\frac{d}{dt}\frac{M_1}{r} \sim \frac{G}{c^3}\frac{P}{r}$$

not a wave!

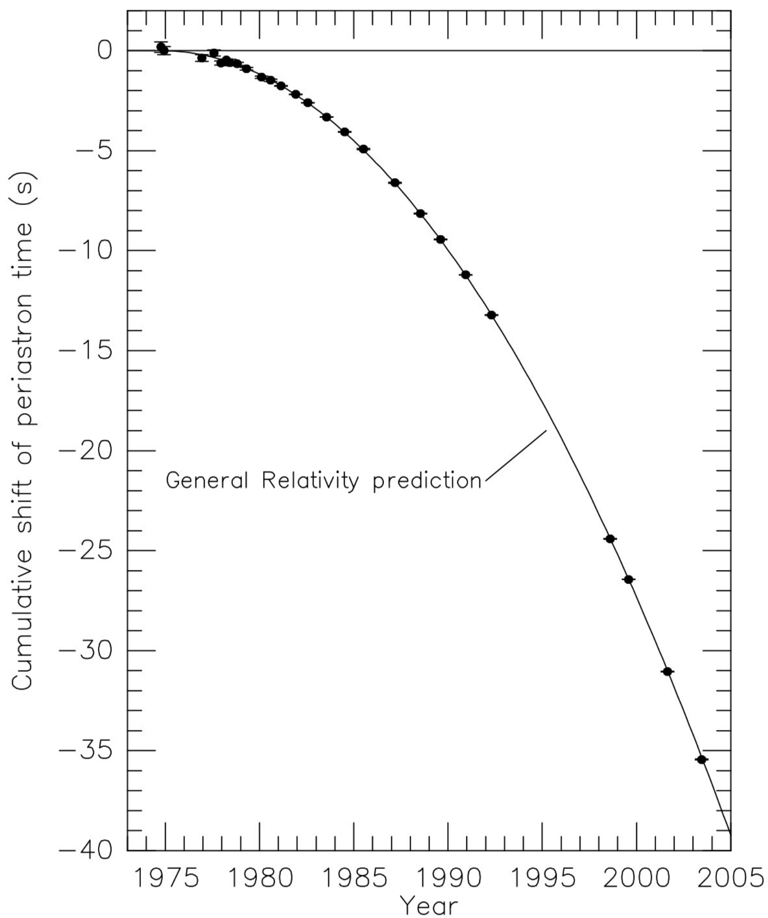
- If SEP is violated,

$$h \sim \frac{1}{R}\frac{d}{dt}\left[m_1(\gamma)x_1 + m_2(\gamma)x_2\right] \propto \left(\frac{d\log m_1}{d\log\gamma} - \frac{d\log m_2}{d\log\gamma}\right)$$

- Dipolar mode might be observable directly by interferometers, or indirectly via its backreaction on a binary's evolution

Why is this interesting?

Binary pulsars are the strongest test of GR to date!



PSR B1913+16
(Weisberg & Taylor 2004)

To calculate rate of change of orbital period we need sensitivities

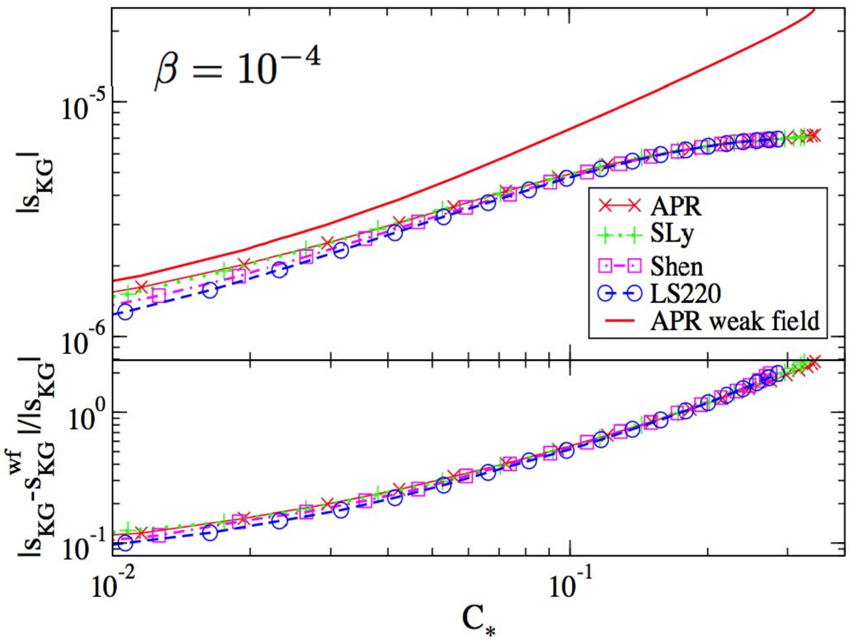
$$\sigma = -\left.\frac{\partial \log M}{\partial \log \gamma}\right|_{v=0} = -2\left.\frac{\partial \log M}{\partial (v^2)}\right|_{v=0}$$

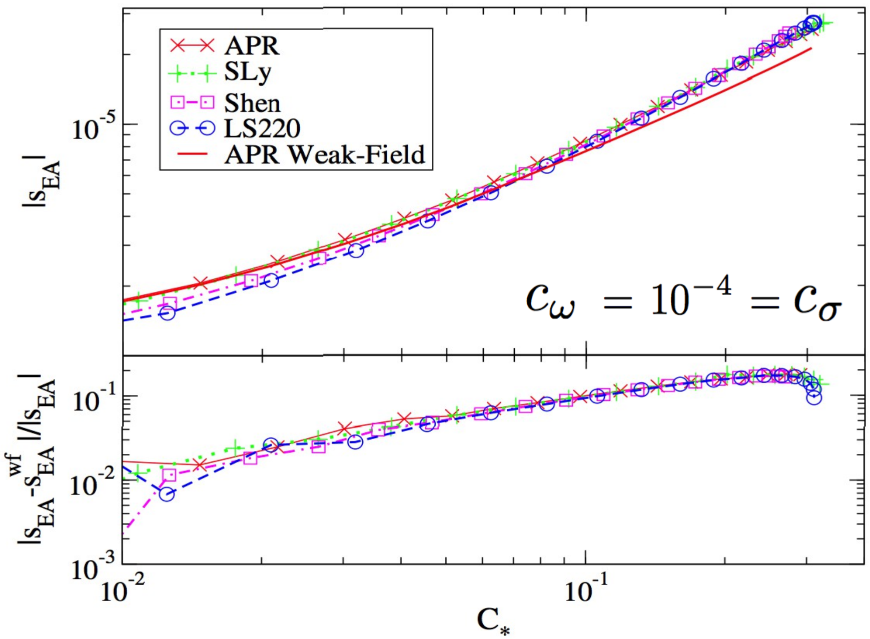
The sensitivity of neutron stars

(Yagi, Blas, Yunes, EB 2013; Yagi, Blas, EB, Yunes 2013)

Calculation is non trivial!

Requires solving numerically for stars in motion relative to aether, to first order in velocity (thanks to Gauss theorem)





$\alpha_1 = 10^{-4}$

$\alpha_2 = 4 \times 10^{-7}$

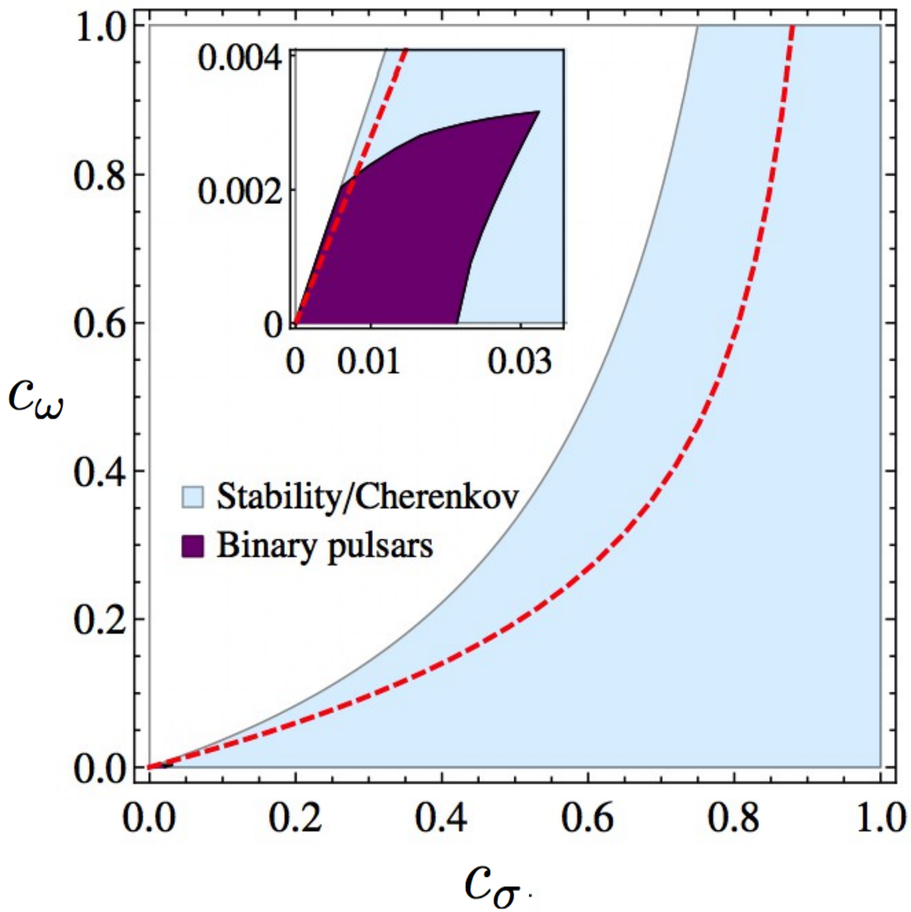
$C_* = M_* / R_*$

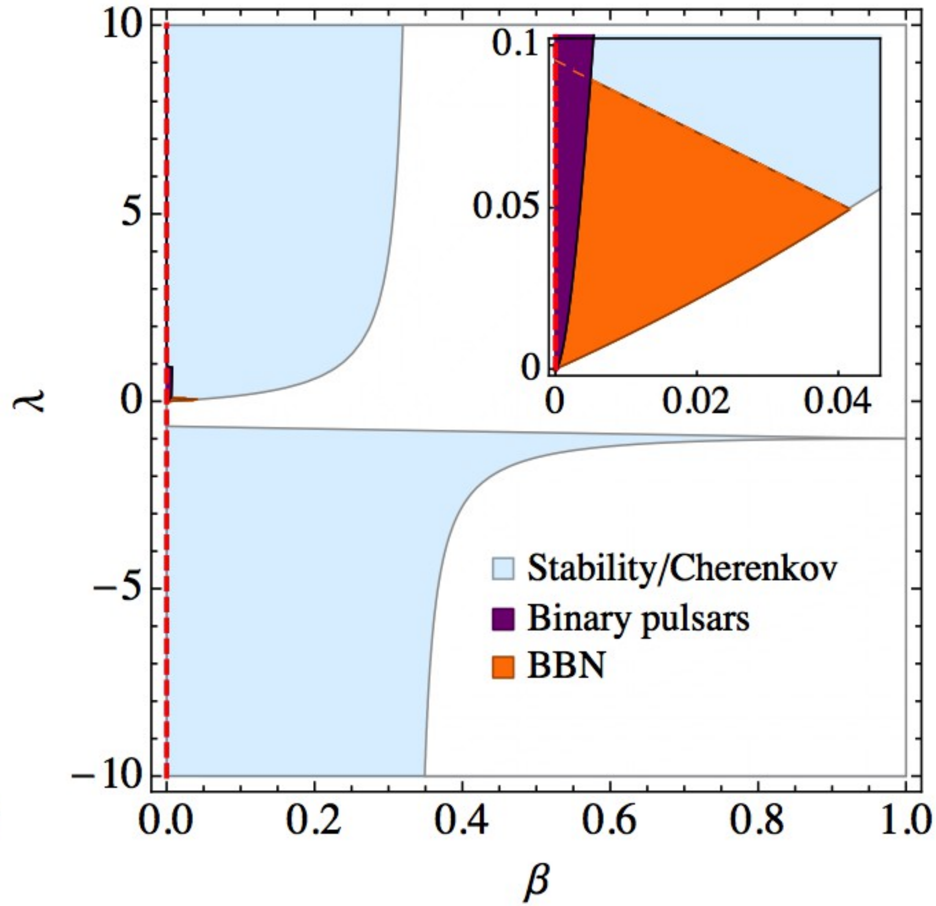
Red = weak field prediction (Foster 2007)

$$s_{\rm wf} = \left(\alpha_1 - \frac{2}{3}\alpha_2\right)\frac{\Omega}{M_*} + \mathcal{O}\left(\frac{\Omega^2}{M_*^2}\right)$$

Constraints on Lorentz violation in gravity

(Yagi, Blas, Yunes, EB 2013; Yagi, Blas, EB, Yunes 2013)





- Red = weak field prediction for $\alpha_1 = \alpha_2 = 0$ (by requiring exactly same fluxes as GR)
- Combined constraints from almost-circular WD-pulsar and pulsar-pulsar systems (PSR J1141-6545, PSR J0348+0432, PSR J0737-3039, PSR J1738+0333)
- Includes observational uncertainties (masses, spins, eccentricity, EOS)

Are BHs possible in LV gravity?

- BHs in GR defined in terms of spacetime causal structure

  eg in static spherical spacetime, horizon lies where light cones "tilt inwards" (cf Eddington Finkelstein coordinates).

- In GR, matter (photons) and gravitons have same speed c
- In LV gravity, photon, spin-2, spin-1 and spin-0 gravitons have different propagation speeds $\Rightarrow$ different propagation cones $\Rightarrow$ multiple horizons
- If higher-order terms included in the action, non-linear dispersion relations for gravitons $\omega^2 = k^2 + \alpha k^4 + \ldots$ $\Rightarrow$ infinite speed in the UV limit $\Rightarrow$ do BHs exist at all?

A universal horizon for signals of infinite speed

(Blas and Sibiryakov 2011; EB, Jacobson & Sotiriou 2011)

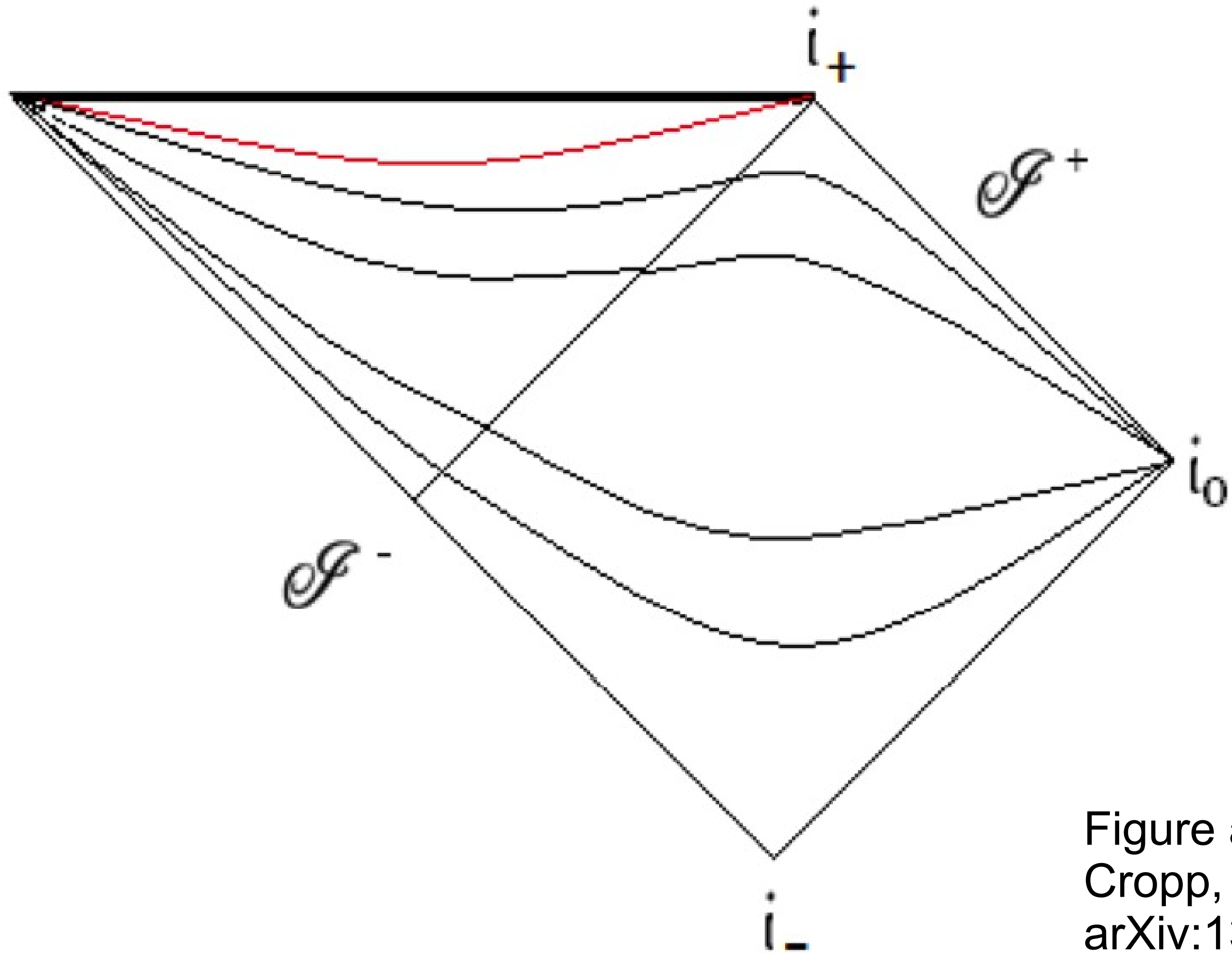


Figure adapted from Cropp, Liberati and Mohd, arXiv:1312.0405

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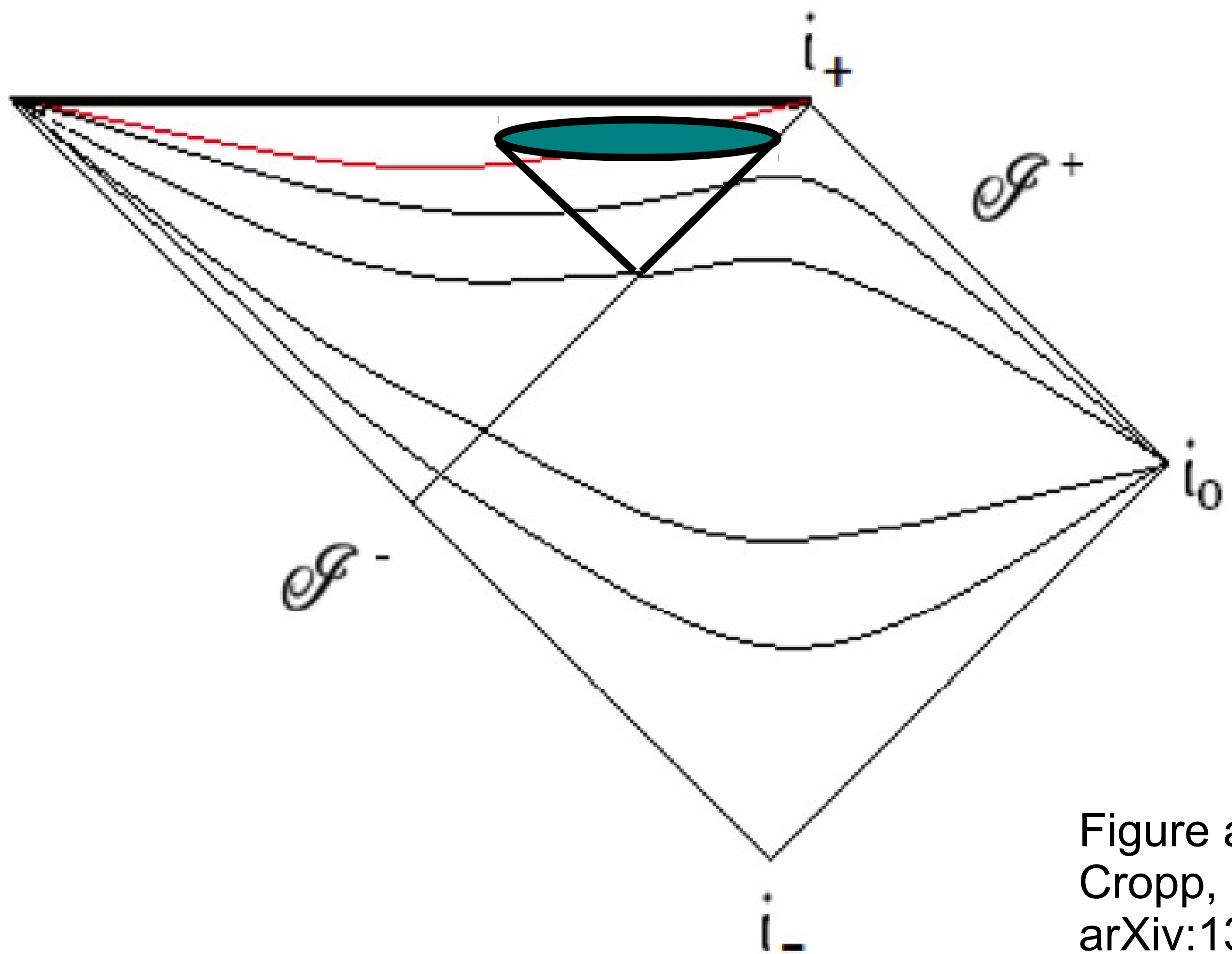

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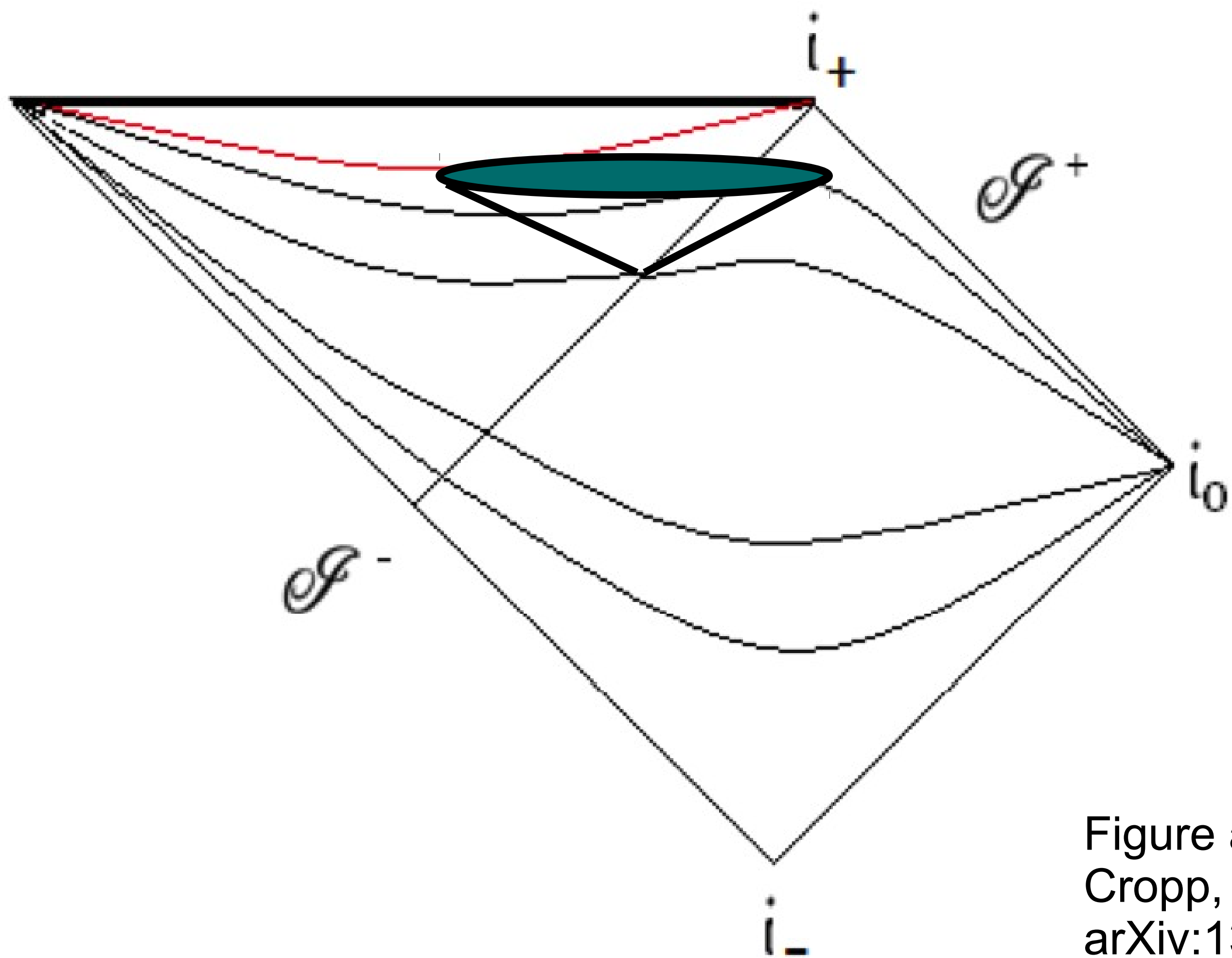

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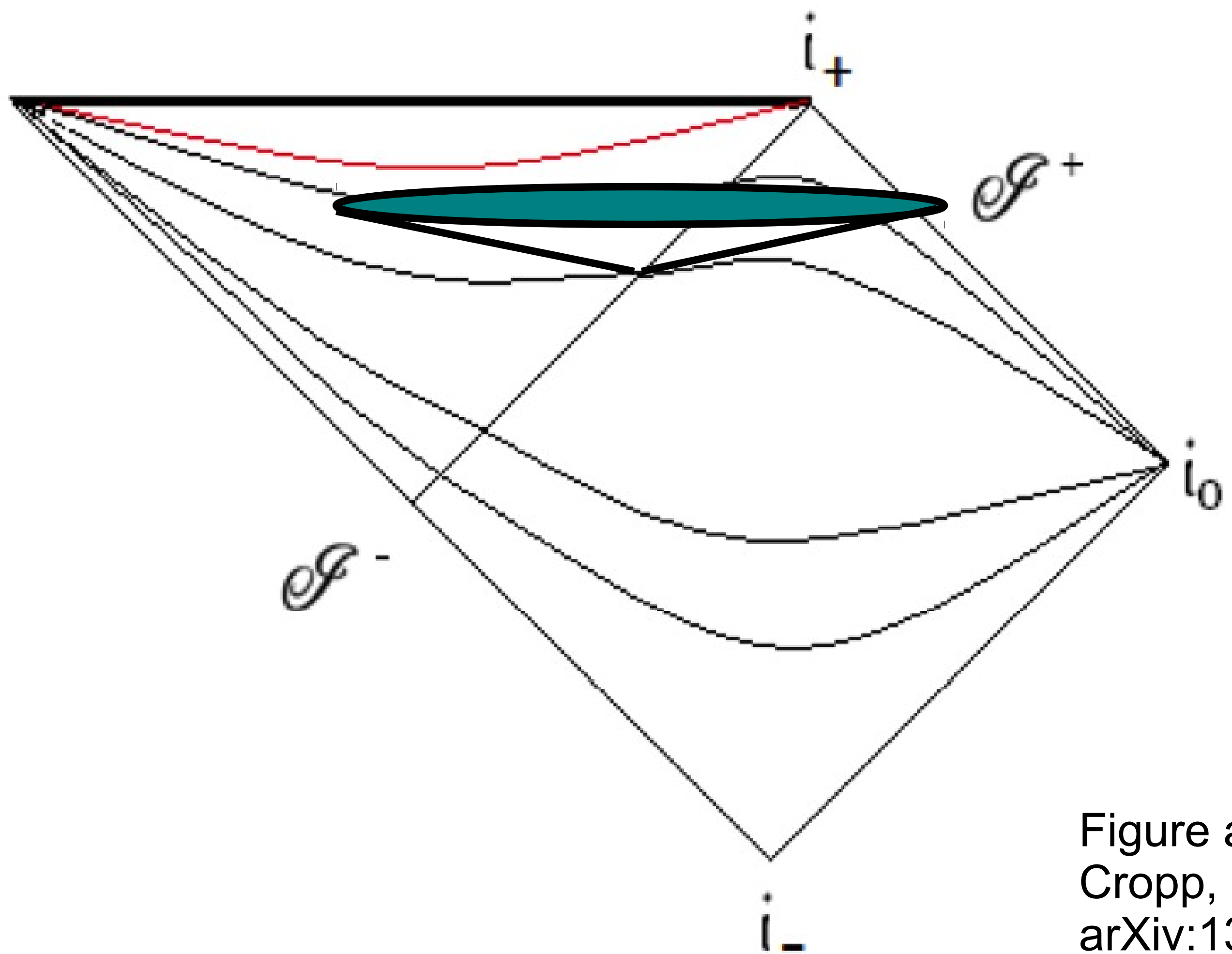

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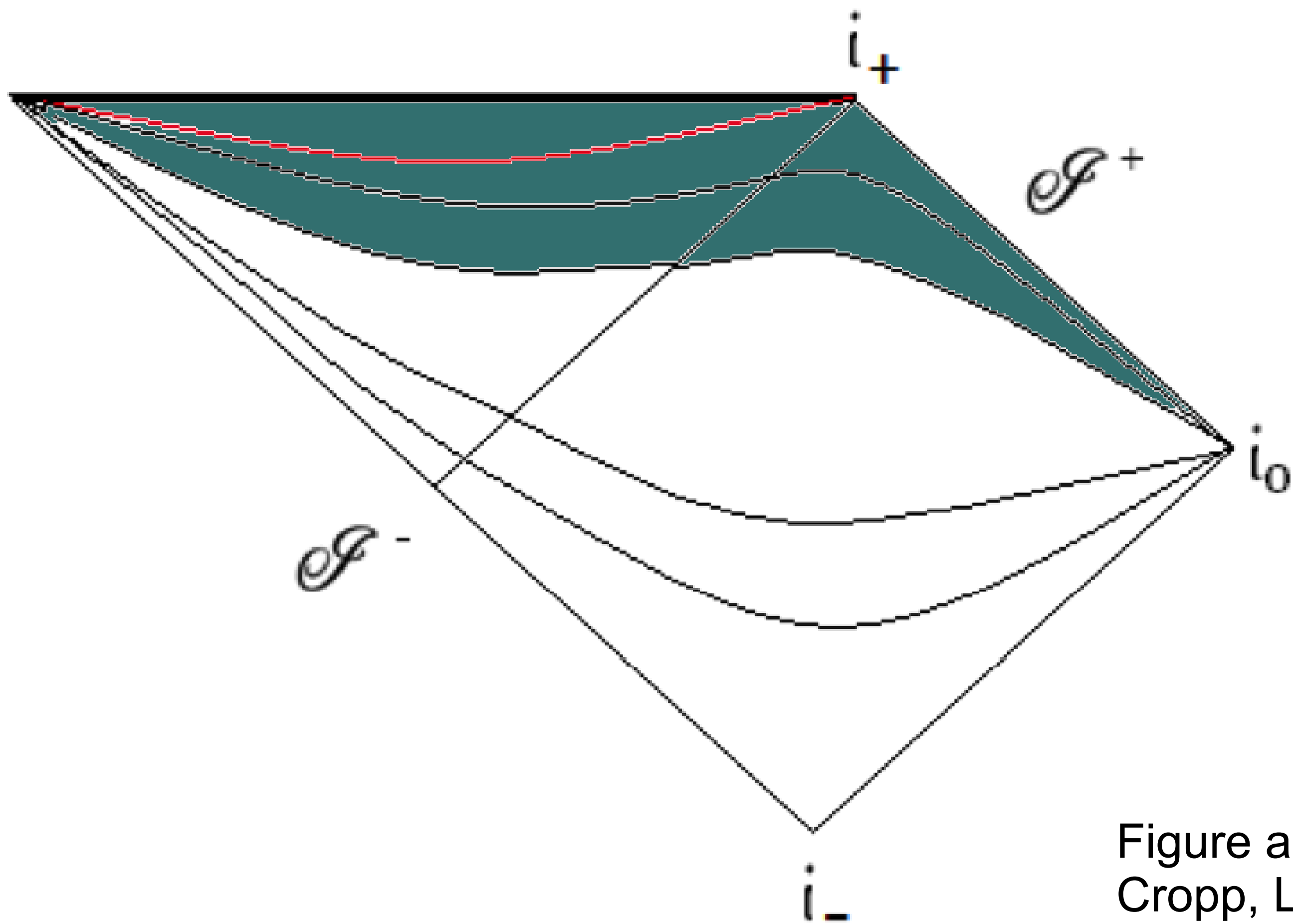

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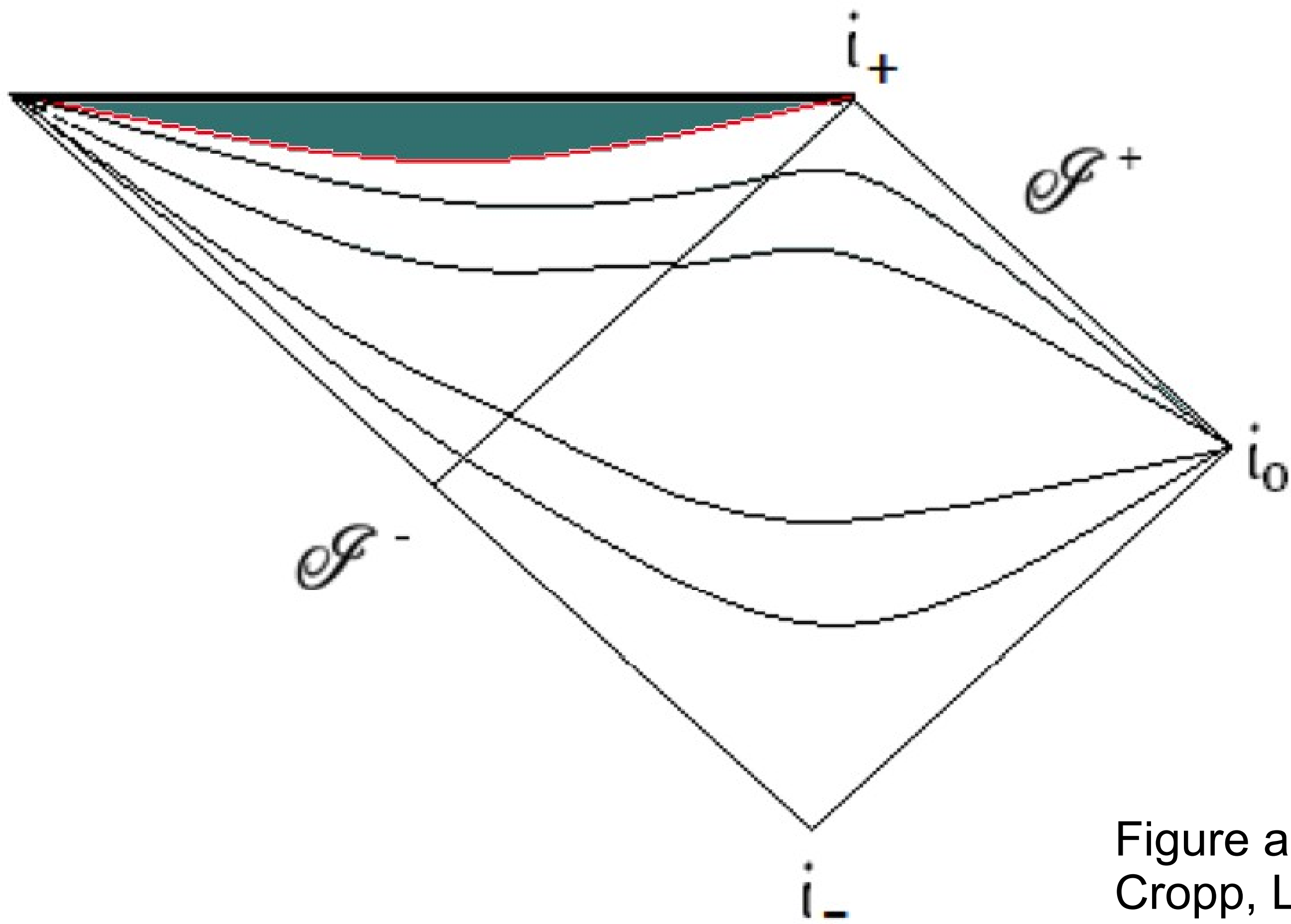

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Modified gravity as substitute for Dark Matter?

- Unorthodox way to explain Dark Matter phenomenology at galactic scales (galaxy rotation curves, Tully-Fisher & Faber-Jackson relations) is to modify Newtonian dynamics (MOND: Milgrom 1983) below acceleration $a_0 \sim \sqrt{\Lambda}$

$$\vec{\nabla} \cdot \left[\mu \left(\frac{|\vec{\nabla}\Phi|}{a_0} \right) \vec{\nabla}\Phi \right] = 4\pi G\rho \cdot$$

$$a \gg a_0 : \mu \sim 1$$

$$a \ll a_0 : \mu(x) \sim x$$

- Advantages: naturally explains appearance of universal scale $a_0 \sim \sqrt{\Lambda}$ (no feedback)
- Open problems: predictions for larger scale cosmology need relativistic extension

A MOND Relativistic extension via Lorentz violations

(Blanchet & Marsat 2011, Bonetti & EB 2015)

1 PN rotation curves for a galaxy accreting matter from its surroundings

$$v_\varphi^{0\mathrm{PN}} = \sqrt[4]{GMa_0} \qquad r_0 = \sqrt{\frac{GM}{a_0}}$$

$$\begin{aligned}
v^2_{\varphi,1\mathrm{PN}} &= \sqrt{G_N M(t) a_0} \\
&+ \frac{1}{c^2}\Bigg\{-\frac{a_0(2+\beta+3\lambda)^2}{144(\beta+\lambda)}\frac{\dot{M}^2}{M(t)^2}\left[4(r_0^3-r^3)+3r^3\ln\left(\frac{r}{r_0}\right)\right] \\
&- \frac{\dot{M}^2}{36r(\beta+\lambda)M(t)}\sqrt{\frac{a_0 G_N}{M(t)}}\Bigg[(2+\beta+3\lambda)\times \\
&\times\left(4r^3+14r_0^3-3r^3\ln\left(\frac{r}{r_0}\right)\right)+18(2\beta-2)r_0^3\Bigg]\Bigg\} \\
&+ \mathcal{O}(\beta+\lambda)^0+\mathcal{O}(\alpha_1,\alpha_2)+\mathcal{O}_{\mathrm{finite}}(\dot{M},\Lambda_{\mathrm{obs}})+O(4)\,.
\end{aligned}$$

Strong coupling problem at 1PN if β+λ is small (Bonetti & EB, 2015)

How to avoid strong coupling

Choose realistic galaxy masses and accretion rate and impose 1PN terms do not dominate over Newtonian terms

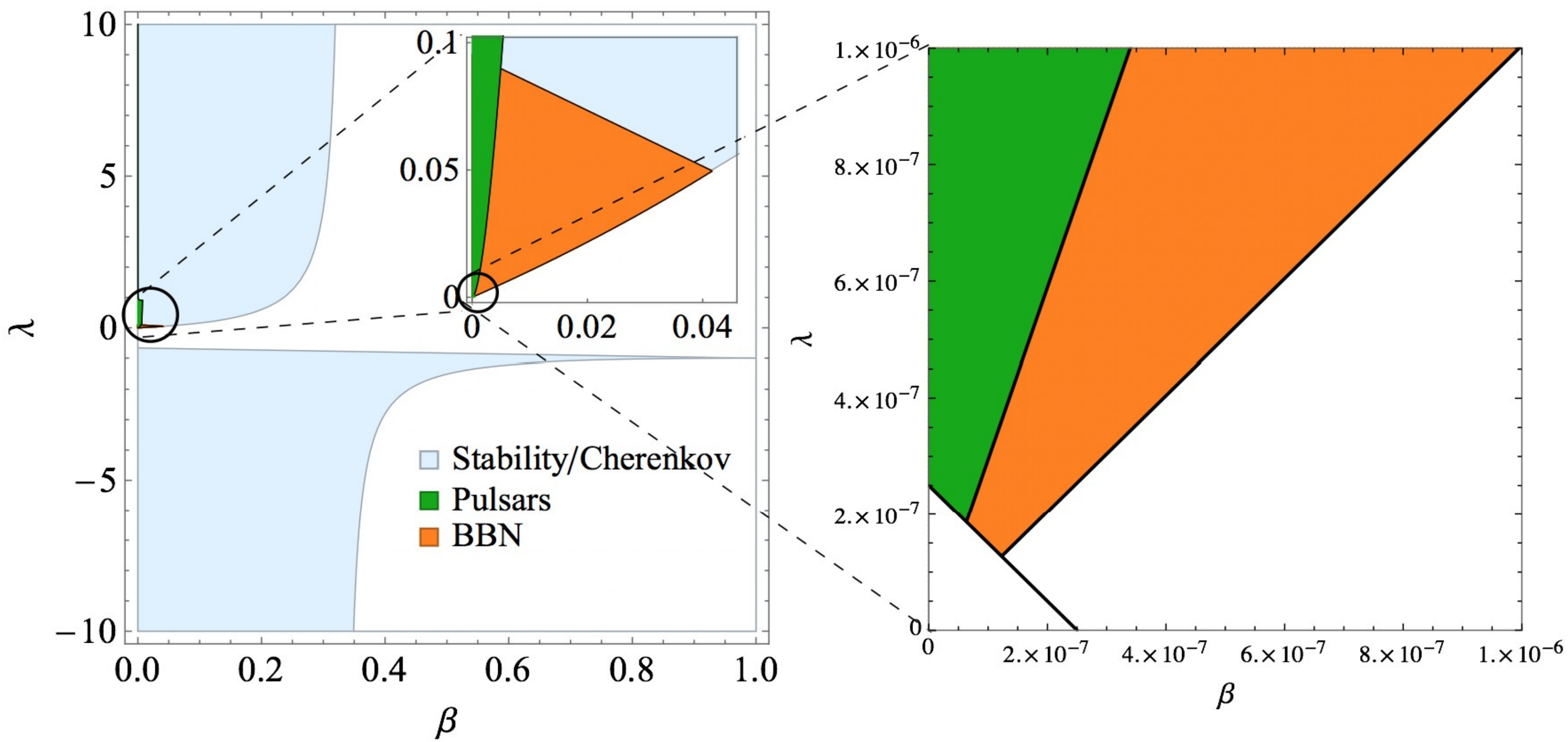

Figure from Bonetti & EB 2015

How to modify GR?

Lovelock's theorem

In a 4-dimensional spacetime, the only divergence-free symmetric rank-2 tensor constructed only 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, i.e. $G_{\mu\nu} + \Lambda\, g_{\mu\nu}$

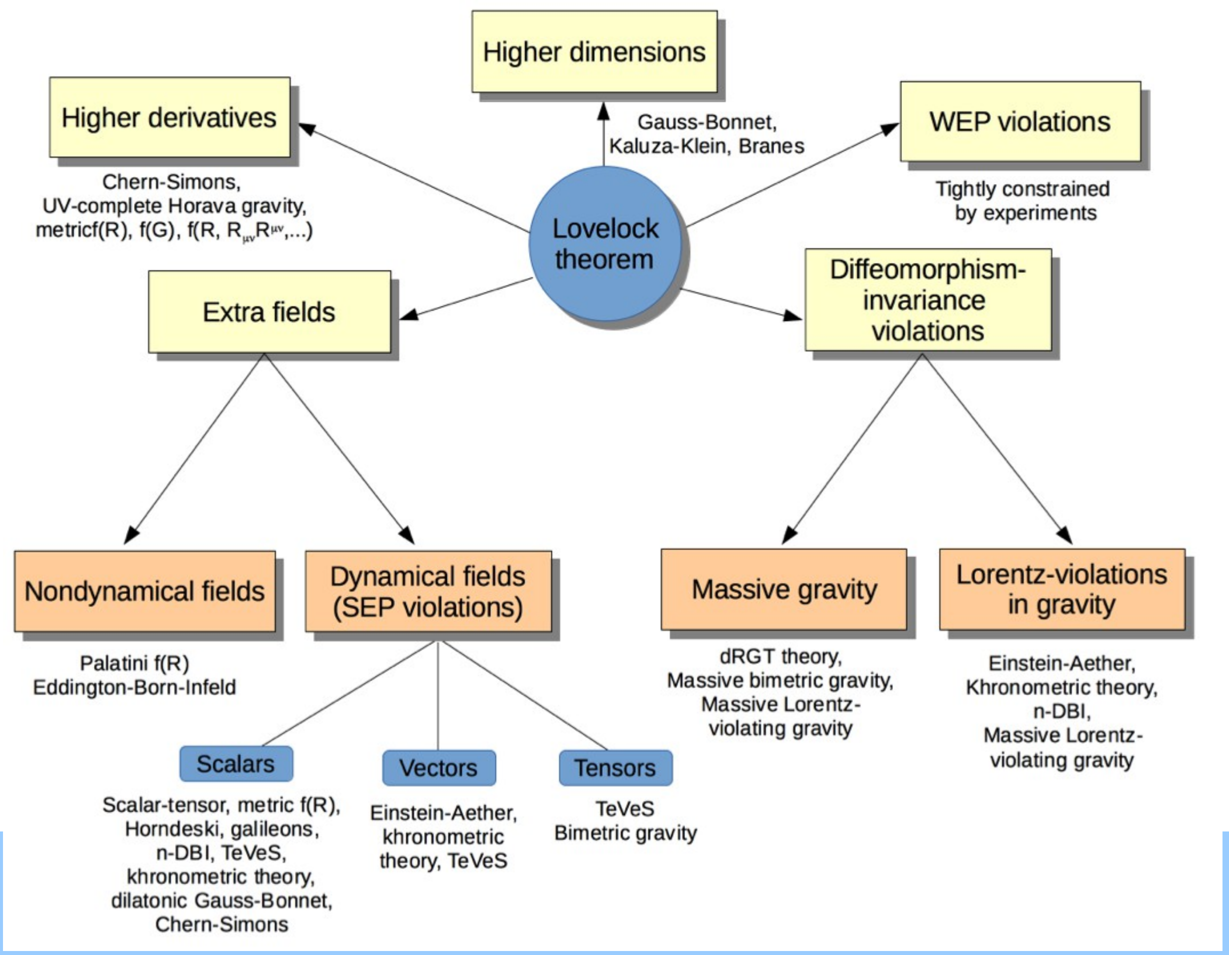

Figure from
Berti, EB et al 2015

There is more to life than cosmology!

Theory's properties

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]

Table 1. Catalog of several theories of gravity and their relation with the assumptions of Lovelock's theorem. Each theory violates at least one assumption (see also Figure 2.1), and can be seen as a proxy for testing a specific principle underlying GR. See text for details of the entries. Key to abbreviations: S: scalar; P: pseudoscalar; V: vector; T: tensor; ?: unknown; ✓?: not explored in detail or not rigorously proven, but there exist arguments to expect ✓. The occurrence of ✗✓? means that there exist arguments in favor of well-posedness within the EFT formulation, and against well-posedness for the full theory. Weak-field constraints (as opposed to strong-field constraints, which are the main topic of this review) refer to Solar System and binary pulsar tests. Entries below the last horizontal line are not covered in this review.

Table from Berti, EB et al 2015

There is more to life than cosmology!

BH properties

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	–	–	–

Table 2. Catalogue of BH properties in several theories of gravity. The column "Solutions" refers to asymptotically-flat, regular solutions. Legend: ST="Scalar-Tensor," ≡GR="Same solutions as in GR," ⊃GR="GR solutions are also solutions of the theory," NR="Non rotating," SR="Slowly rotating," FR="Fast rotating/Generic rotation," ?=unknown or uncertain.

Table from Berti, EB et al 2015

There is more to life than cosmology!

NS properties

Theory	Structure			Collapse	Sensitivities	Stability	Geodesics
	NR	SR	FR				
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	$\equiv$ 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]	?

Table 3. Catalog of NS properties in several theories of gravity. Symbols and abbreviations are the same as in Table 2.

Table from Berti, EB et al 2015

Conclusions

- Lorentz violations in gravity generically introduces violations of strong equivalence principle and thus dipole emission
- Placing precise constraints with binary pulsars requires exact values of sensitivities (non-trivial calculation)
- Resulting constraints are strong-field and ~ order of magnitude stronger than previous ones
- BH solutions very similar to GR in the "exterior", but causal structure is very different in the "interior" (universal horizon acts as boundary for perturbations with infinite speed)
- Dark-Matter phenomenology without Dark Matter on galactic scales
- Same blueprint may be followed with other promising gravity theories