Astrophysical consequences of Lorentz violations in gravity

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Outline

- Lorentz violation in gravity: motivation, phenomenology & experimental constraints
- Lorentz violation implies violations of the strong equivalence principle:

  The motion of neutron stars (the "sensitivities" and dipolar gravitational-wave emission) and constraints from pulsars. Based on

  Yagi, Blas, Yunes, EB arXiv:1307.6219, PRL in press;
  Yagi, Blas, EB, Yunes arXiv:1311.7144, PRD in press

- Black hole solutions and universal horizons. Based on

  EB, Jacobson & Sotiriou PRD 83, 124043 (2011);
  EB and Sotiriou CQG 30 244010 (2013)

Lorentz violation in gravity: why?

- LV may give better UV behavior (Horava), quantum-gravity completions generally lead to LV
- LV allows MOND-like (Bekenstein, Blanchet & Marsat) or dark-energy-like phenomenology
- Strong constraints in matter sector, weaker ones in gravity sector (caveat: constraints expected to percolate from gravity to matter sector)
- Solar system/isolated & binary pulsar experiments historically used to constrains LV in weak field (1 PN) regimes (“preferred-frame parameters”: Nordvedt, Kramer, Wex, Freire, Shao, Damour, Esposito Farese...), but surprises may happen in stronger-field regimes

Einstein-aether theory

- We want to specify a (local) preferred time "direction"
  → timelike aether field U_μ with unit norm
- Most generic action (in 4D) quadratic in derivatives is given (up to total derivatives) by

$$S_{æ} = \frac{1}{16\pi G_{æ}} \int d^4x \sqrt{-g} \left(-R - M^{\alpha\beta}{}_{\mu\nu} \nabla_\alpha U^\mu \nabla_\beta U^\nu\right)$$

$$M^{\alpha\beta}{}_{\mu\nu} = c_1 g^{\alpha\beta} g_{\mu\nu} + c_2 \delta^\alpha_\mu \delta^\beta_\nu + c_3 \delta^\alpha_\nu \delta^\beta_\mu + c_4 U^\alpha U^\beta g_{\mu\nu}$$

- To satisfy weak equivalence principle, matter fields couple minimally to metric (and not directly to aether)

$$S = S_{æ} + S_{\mathrm{matter}}(\psi, g_{\mu\nu})$$

Khronometric gravity

- To specify a global time, U must be hypersurface orthogonal ("khronometric" theory)

$$U_\mu = \frac{\partial_\mu T}{\sqrt{g^{\mu\nu}\partial_\mu T \partial_\nu T}} \qquad S_{æ} = \frac{1}{16\pi G_{æ}} \int d^4x \sqrt{-g}\, \left(-R - M^{\alpha\beta}{}_{\mu\nu} \nabla_\alpha U^\mu \nabla_\beta U^\nu\right)$$

- Because U is timelike, T can be used to as time coordinate

$$U_\alpha = \delta^T_\alpha (g^{TT})^{-1/2} = N \delta^T_\alpha \qquad a_i = \partial_i \ln N$$

$$S_K = \frac{1}{16\pi G_K} \int dT d^3x\, N \sqrt{h}\, (K_{ij}K^{ij} - \mu K^2 \;+ \xi\, {}^{(3)}R + \eta a_i a^i)$$

- 3 free parameters vs 4 of AE theory (because aether is hypersurface orthogonal)

Khronometric vs Horava gravity

$$S_H = \frac{1}{16\pi G_K} \int dT d^3x\, N\sqrt{h} \left(L_2 + \frac{1}{M_\star^2} L_4 + \frac{1}{M_\star^4} L_6 \right)$$

$$L_2 = K_{ij}K^{ij} - \mu K^2 + \xi^{(3)}R + \eta a_i a^i,$$

- L_4 and L_6 contain 4th- and 6th-order terms in the spatial derivatives
- Lower bound on M* depends on details of percolation of Lorentz violations from gravity to matter: from Lorentz violations in gravity alone, $M_\star \gtrsim 10^{-3}\ \mathrm{eV}$, but precise bounds depend on percolation
- Theory remains perturbative at all scales if $M_\star \lesssim 10^{16}\ \mathrm{GeV}$
- Terms crucial in the UV, but unimportant astrophysically, ie error scales as $\sim M_{\rm Planck}^4/(MM_\star)^2 \sim 10^{-14}(M_\odot/M)^2$

Constraints on the coupling constants: the Parametrized Post-Newtonian expansion

- At 1PN, theories = to GR except for preferred-frame parameters α_1 and α_2 which are zero in GR but not in LV gravity
- Solar system & pulsar experiments require $|\alpha_1| \lesssim 10^{-5}$ $|\alpha_2| \lesssim 10^{-9}$

Imposing $\alpha_1 = \alpha_2 = 0$ reduces couplings from 4 to 2 (AE theory): c_+, c_- …

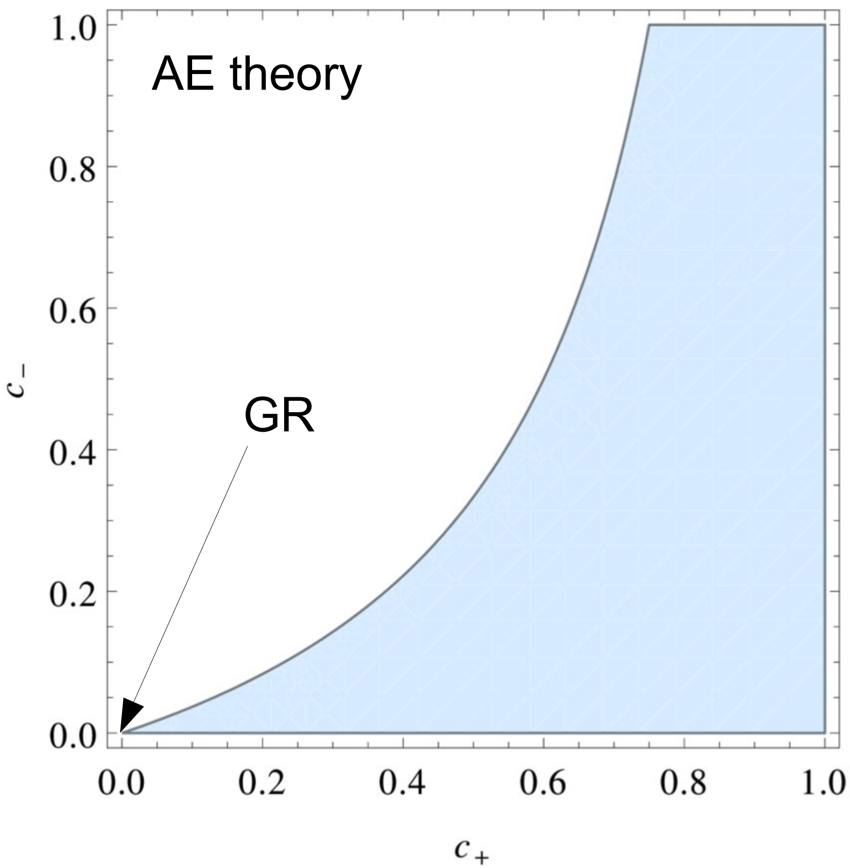
… and from 3 to 2 (khronometric theory): λ , β

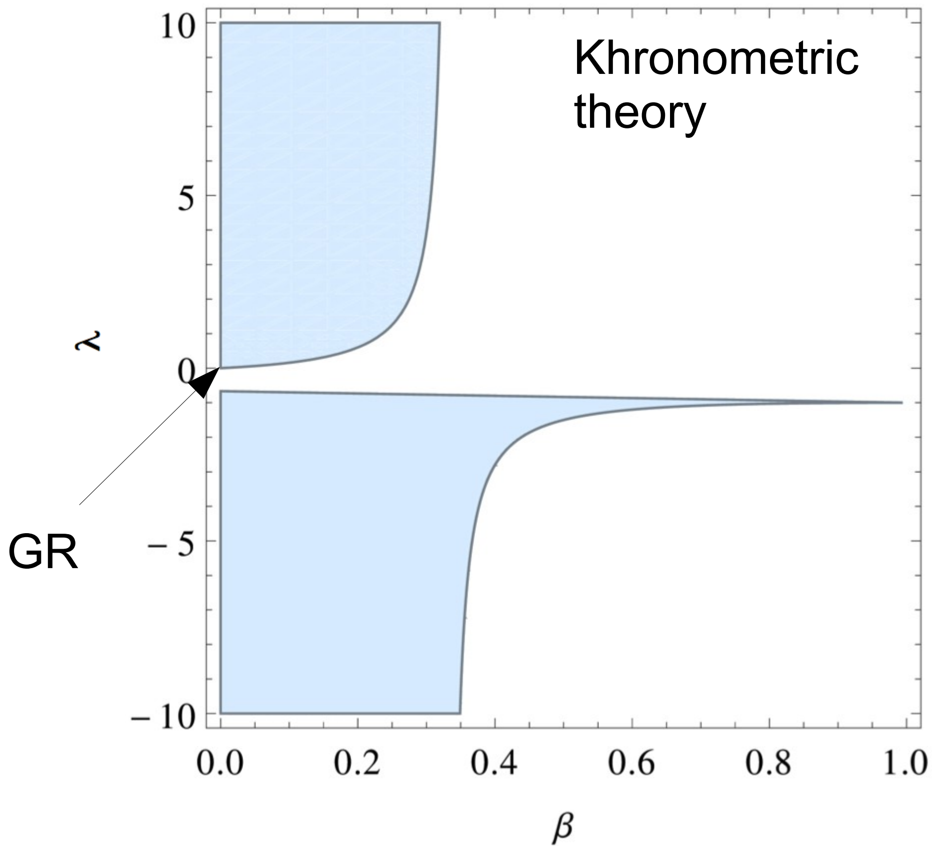
- c_+, c_- and λ , β enter at PN order > 1 (they are “strong-field couplings”)

Constraints on the coupling constants: stability

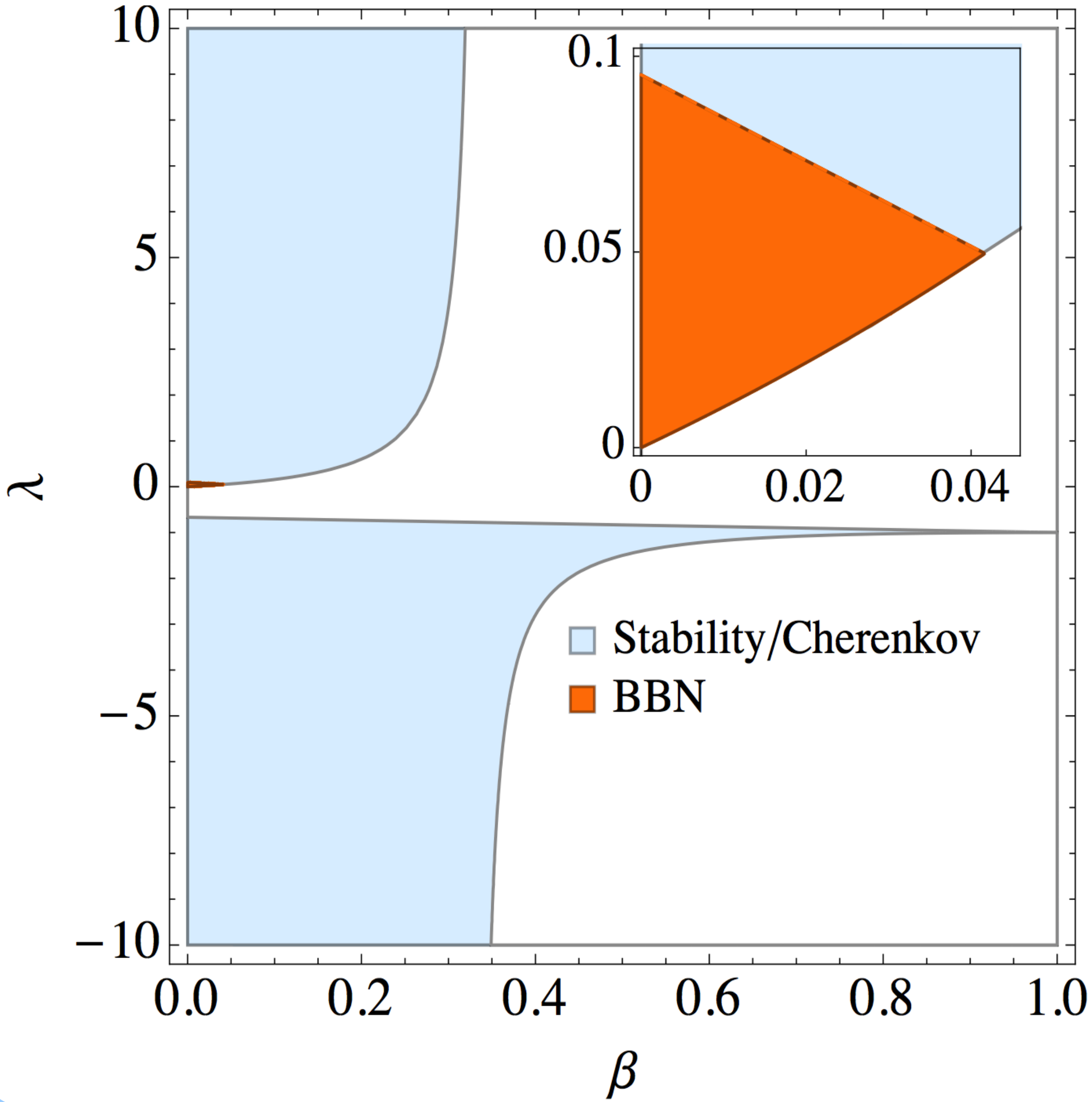
- AE theory has propagating spin-0, spin-1 and spin-2 gravitational modes
- Khronometric theory has spin-0, spin-2 modes
- For classical/quantum stability, real propagation speeds and positive energies
- Propagation speed must be larger than speed of light to avoid gravitational Cherenkov radiation
- Well posedness proved in flat space and in spherical symmetry

Stability+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 ⟶ 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

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

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

A PN analysis: the violation of the SEP

$$S_A = -\int d\tau\, \tilde{m}_A[\gamma] = -\tilde{m}_A \int d\tau\, \left\{1 + \sigma_A (1-\gamma_A) + \frac{1}{2}\sigma'_A (1-\gamma_A)^2 + \mathcal{O}\left[(1-\gamma_A)^3\right]\right\}$$

$$\gamma = U^\mu u_\mu \qquad \sigma_A \equiv -\left.\frac{d\ln\tilde{m}_A[\gamma_A]}{d\ln\gamma_A}\right|_{\gamma_A=1} \qquad \sigma'_A \equiv \sigma_A + \sigma_A^2 + \left.\frac{d^2\ln\tilde{m}_A[\gamma_A]}{d\ln\gamma_A^2}\right|_{\gamma_A=1}$$

body's “sensitivities”

Define “active” gravitational mass $m_A = (1+\sigma_A)\tilde{m}_A$

and “strong-field” gravitational constant $\mathcal{G}_{AB} = \dfrac{G_N}{(1+\sigma_A)(1+\sigma_B)}$

Modified Newton's law:

$$\dot{v}_A^i = \sum_{B\neq A} \frac{-G_N \tilde{m}_B}{(1+\sigma_A) r_{AB}^3} r_{AB}^i \equiv \sum_{B\neq A} \frac{-\mathcal{G}_{AB} m_B}{r_{AB}^3} r_{AB}^i$$

Foster 2007

A PN analysis: the dissipative dynamics

- GWs carry energy away from binaries

$$S=(s_1 m_2 + s_2 m_1)/M$$
$$M = m_1 + m_2$$
$$\mu = \frac{m_1 m_2}{M}, \quad s_A = \sigma_A/(1+\sigma_A)$$

$$\dot{\mathcal{E}} = -\frac{32}{5} G_N (G_N M)^{4/3} \mu^2 \left(\frac{P_b}{2\pi}\right)^{-10/3} \langle \mathcal{A} \rangle$$

$$\langle \mathcal{A} \rangle = \frac{1}{(1+\sigma_1)^{4/3}(1+\sigma_2)^{4/3}} \left[\mathcal{A}_1 + \mathcal{S}\mathcal{A}_2 + \mathcal{S}^2 \mathcal{A}_3 \right.$$ → Quadrupole

$$\left. + \frac{5}{32}(s_1 - s_2)^2 \mathcal{C} (1+\sigma_1)^{2/3}(1+\sigma_2)^{2/3} \left(\frac{P_b}{2\pi G_N M}\right)^{2/3} \right]$$ → Dipole

$\mathcal{A}_1, \mathcal{A}_2, \mathcal{A}_3$ are functions of the coupling constants (c_+, c_-) or (β, λ);

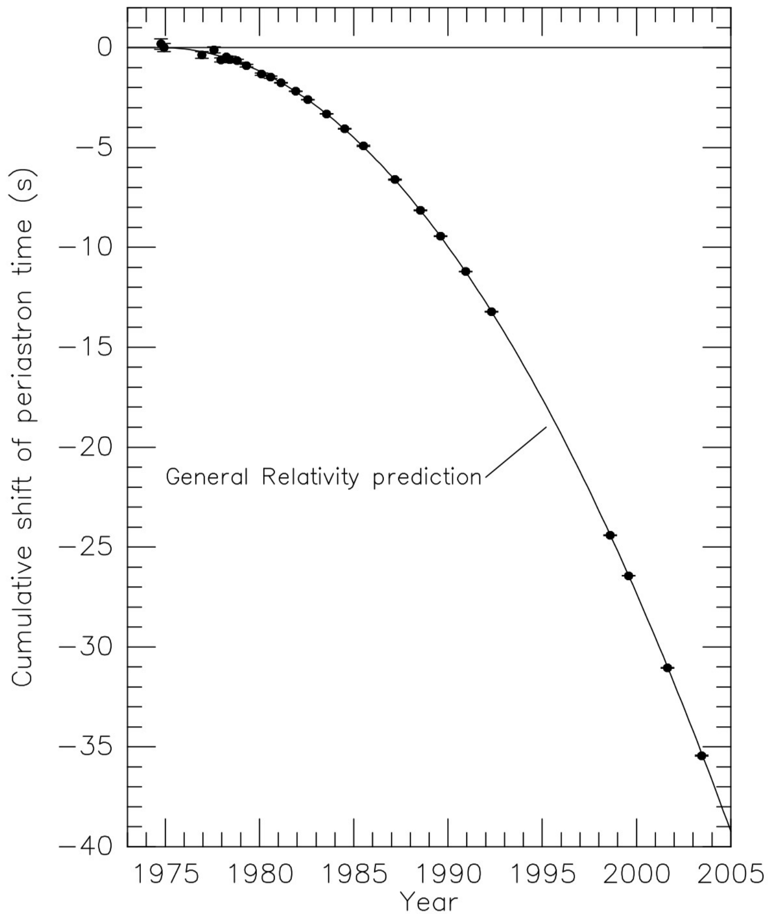
in GR $\mathcal{A} = 1$ (Foster 2007, Yagi, Blas, EB, Yunes 2013, Yagi, Blas, Yunes, EB 2013)

- As binary's binding energy decreases, period decreases

$$\frac{\dot{P}_b}{P_b} = -\frac{3}{2}\frac{\dot{E}}{E} = \frac{3}{2}\frac{\dot{\mathcal{E}}}{E}$$

Why is this interesting?

Binary pulsars are the strongest test of GR to date



To calculate rate of change of orbital period we need sensitivities

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

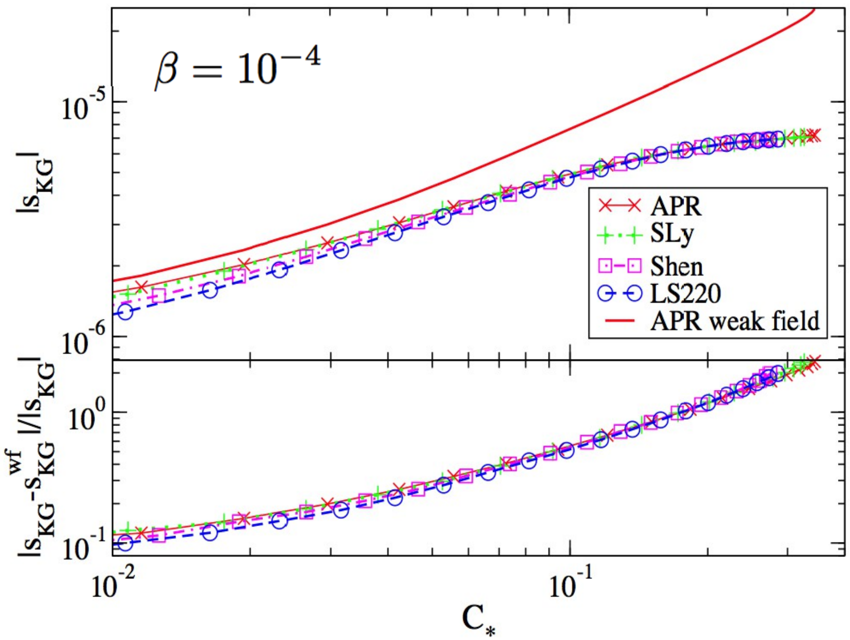
PSR B1913+16
(Weisberg & Taylor 2004)

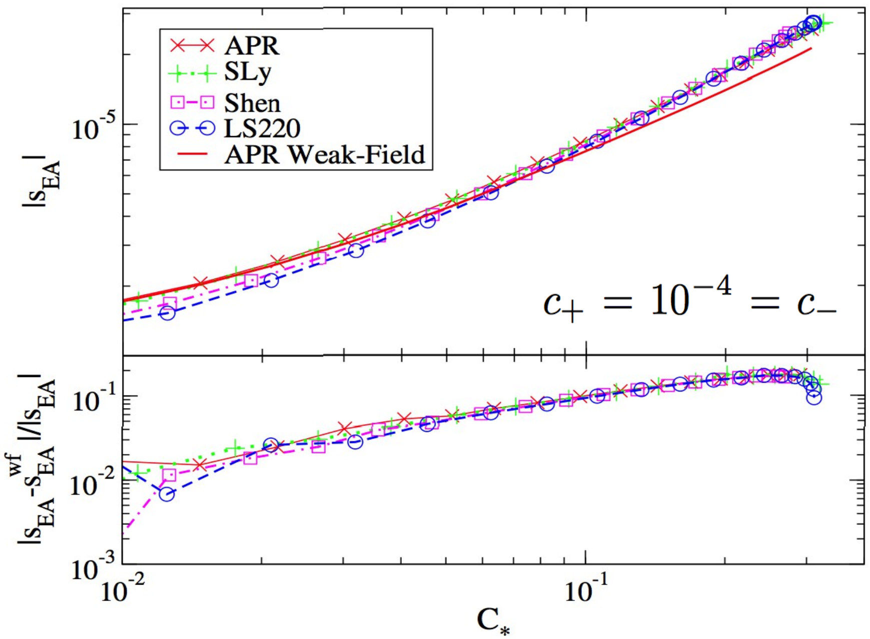
The sensitivity of neutron stars

(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)





$\alpha_1 = 10^{-4}$

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

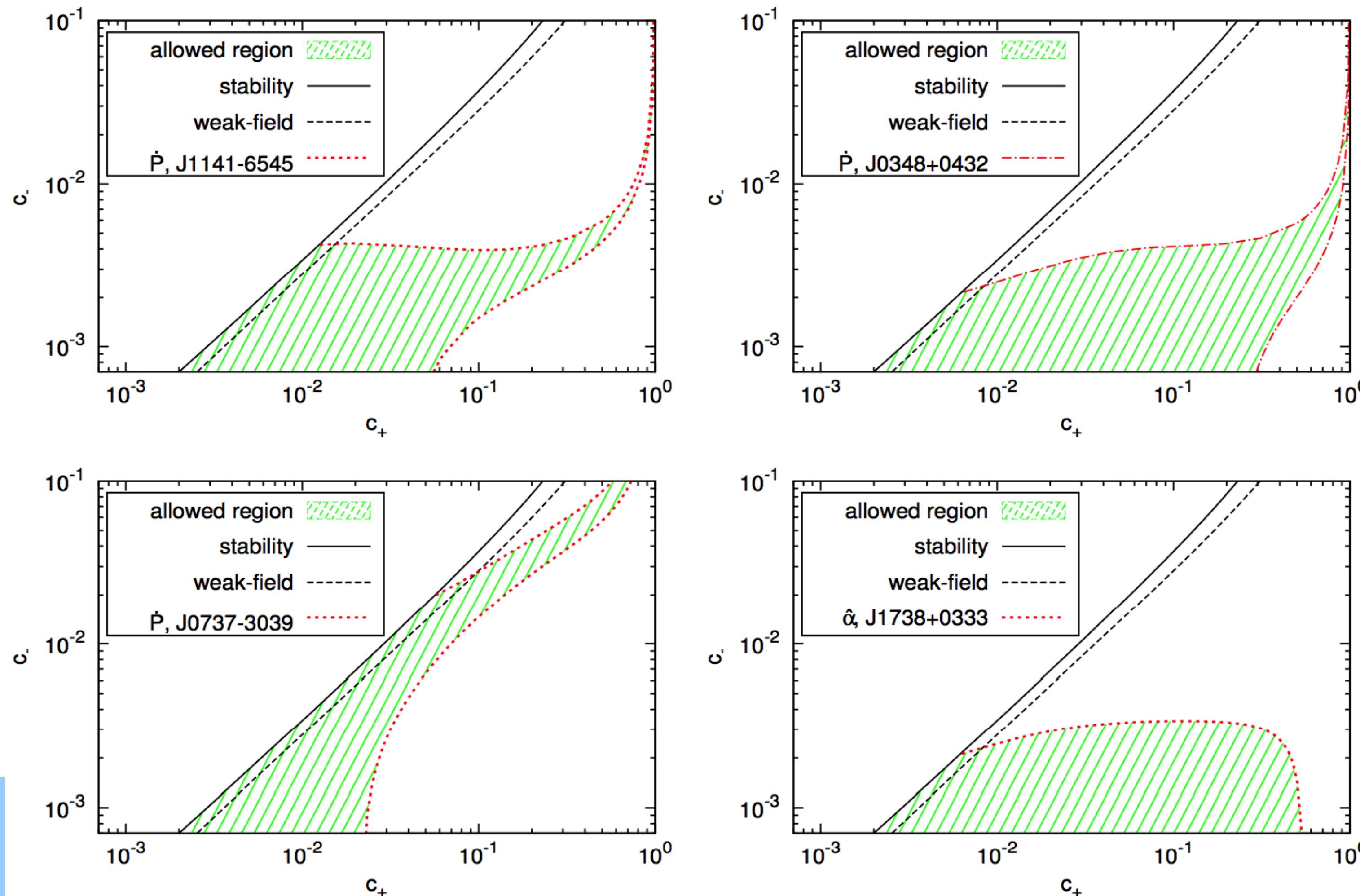
$C_* = M_* / R_*$

Red = weak field prediction (Foster 2007)

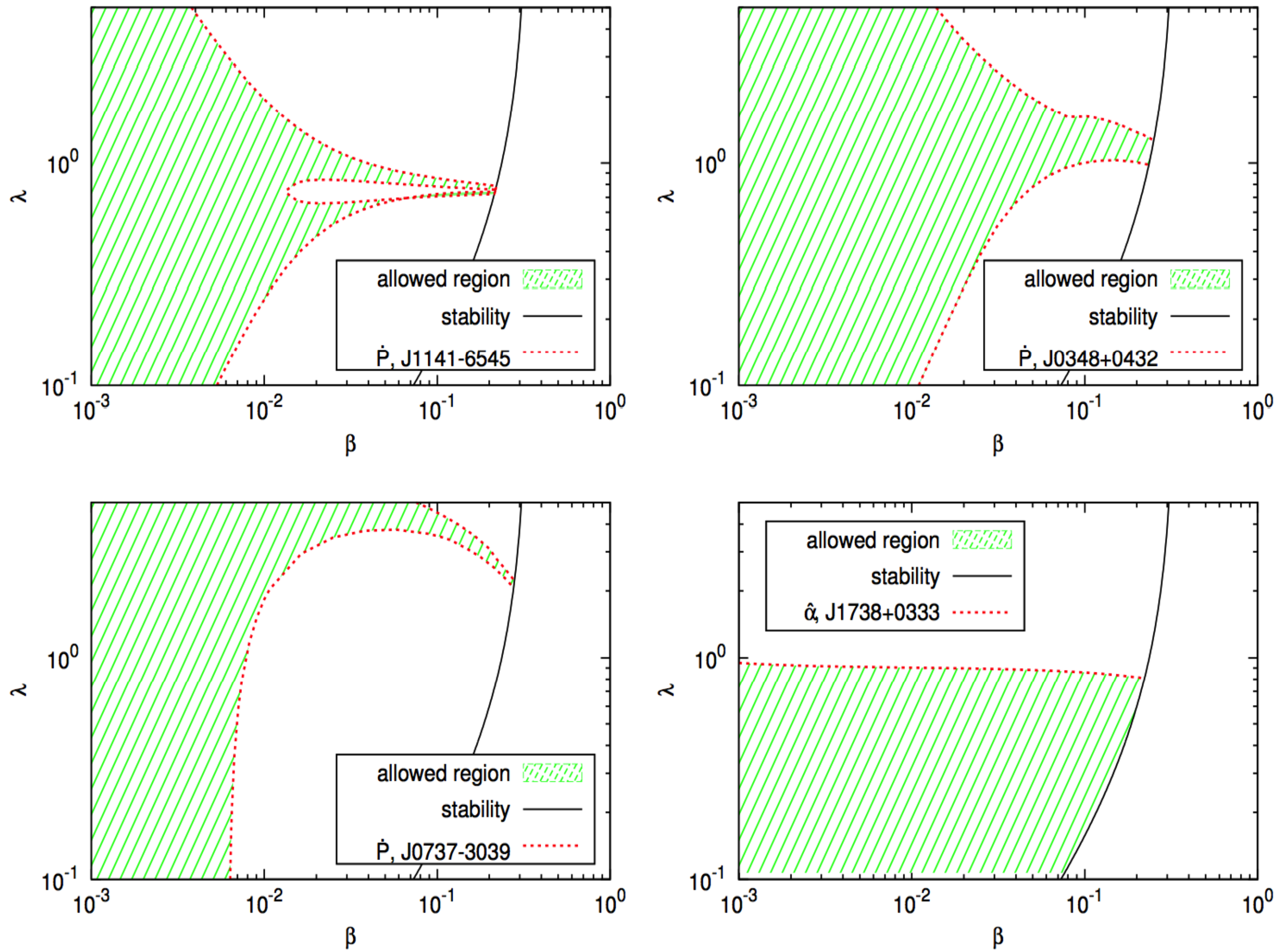
$$s_{\rm wf} = \left(\alpha_1 - \frac{2}{3}\alpha_2\right)\frac{\Omega}{M_*} + \mathcal{O}\left(\frac{\Omega^2}{M_*^2}\right)$$

Constraints from binary pulsars

We choose pulsar-pulsar and pulsar-WD binaries with small eccentricities (PSR J1141-6545, PSR J0348+0432, PSR J0737-3039, PSR J1738+0333), and impose that difference from GR is < data uncertainties

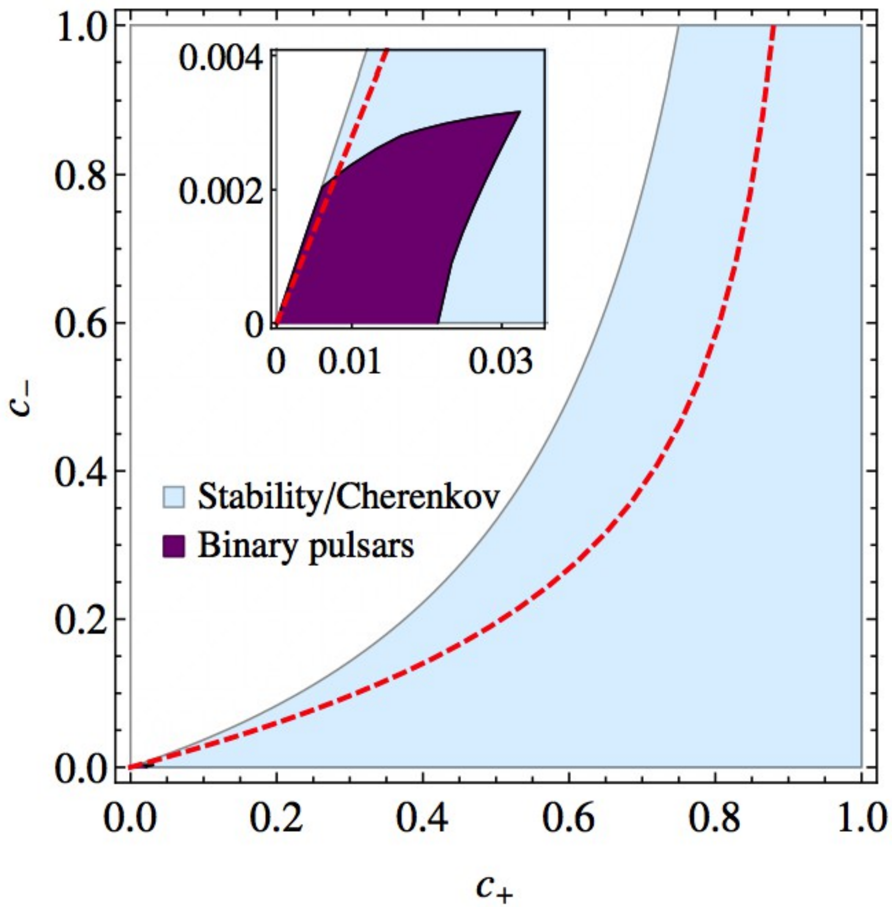


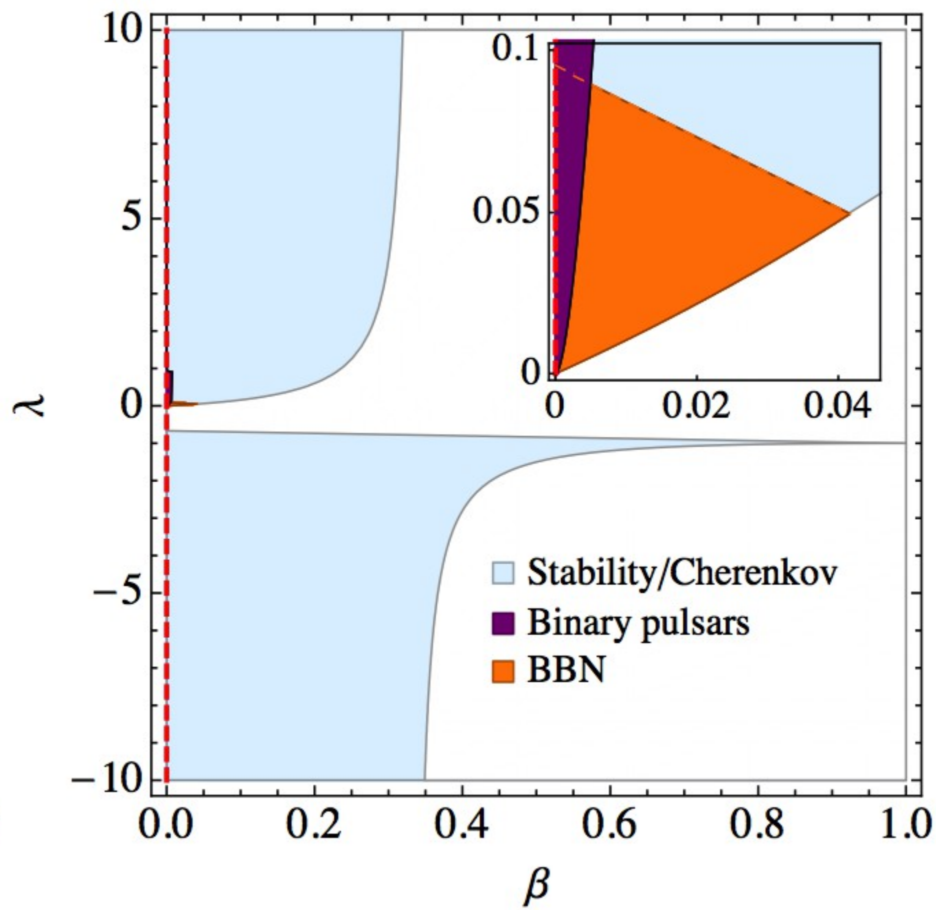
Constraints from binary pulsars



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 → different propagation cones → multiple horizons
- If higher-order terms included in the action, non-linear dispersion relations for gravitons $\omega^2 = k^2 + \alpha k^4 + \ldots$ → infinite speed in the UV limit → do BHs exist at all?

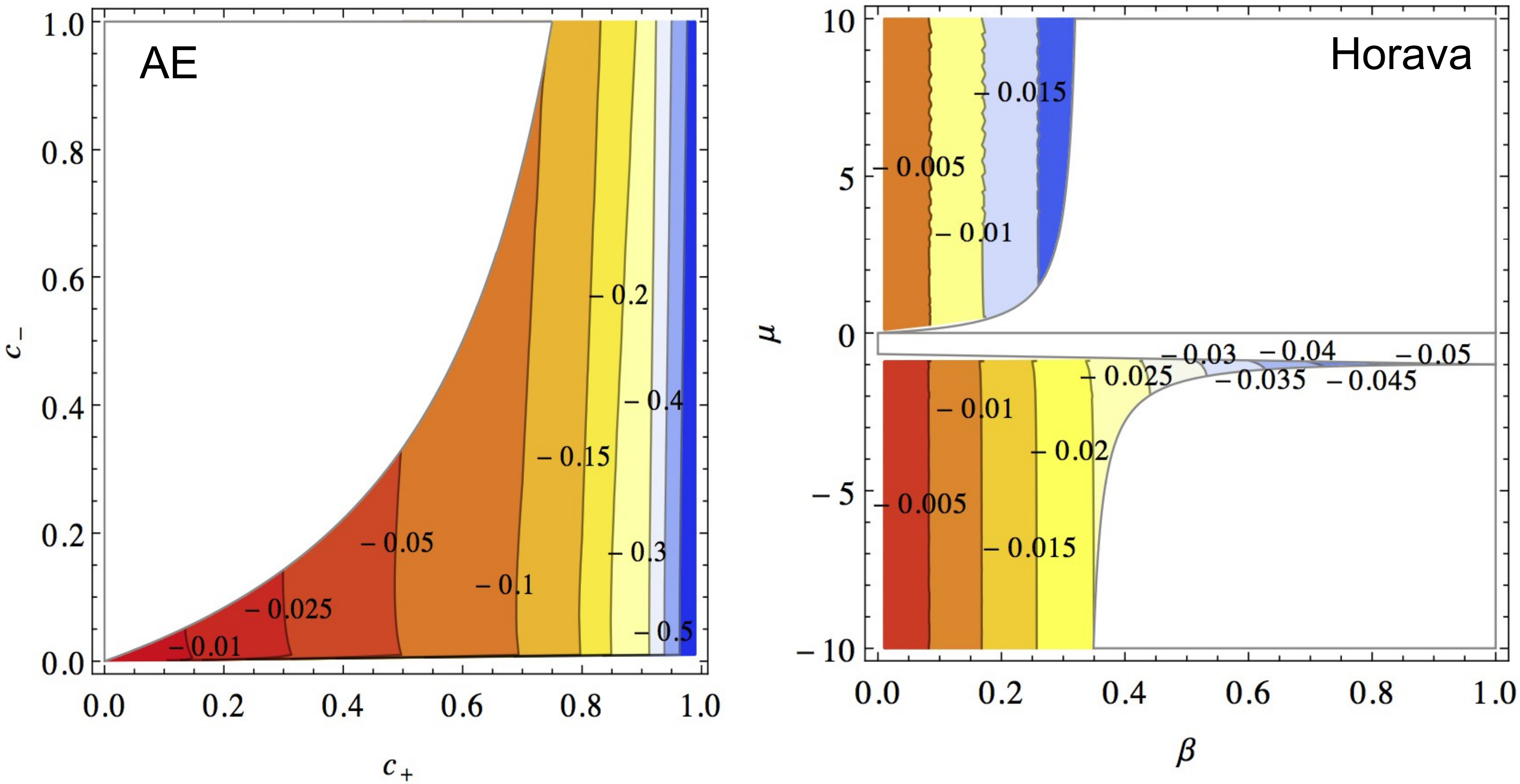
Spherical BHs in infrared LV gravity

(EB, Jacobson & Sotiriou 2011)

- Once fixed mass, one-parameter family of solutions characterized by aether charge A_2
- For $A_2 \neq A_2^{reg}$ naked curvature singularity at spin-0 horizon, but gravitational collapse picks regular solution $A_2 \neq A_2^{reg}$ (Garfinkle, Eling & Jacobson 2007)
- Impose regularity at spin-0 horizon by solving field eqs perturbatively, and pick asymptotically flat solution by shooting method (asymptotic flatness does not follow from field eqs, unlike in GR)
- UV corrections due to higher curvature terms small away from central singularity $\sim M_{\rm Planck}^4/(M M_\star)^2 \lesssim 10^{-14}(M_\odot/M)^2$

BH exterior structure

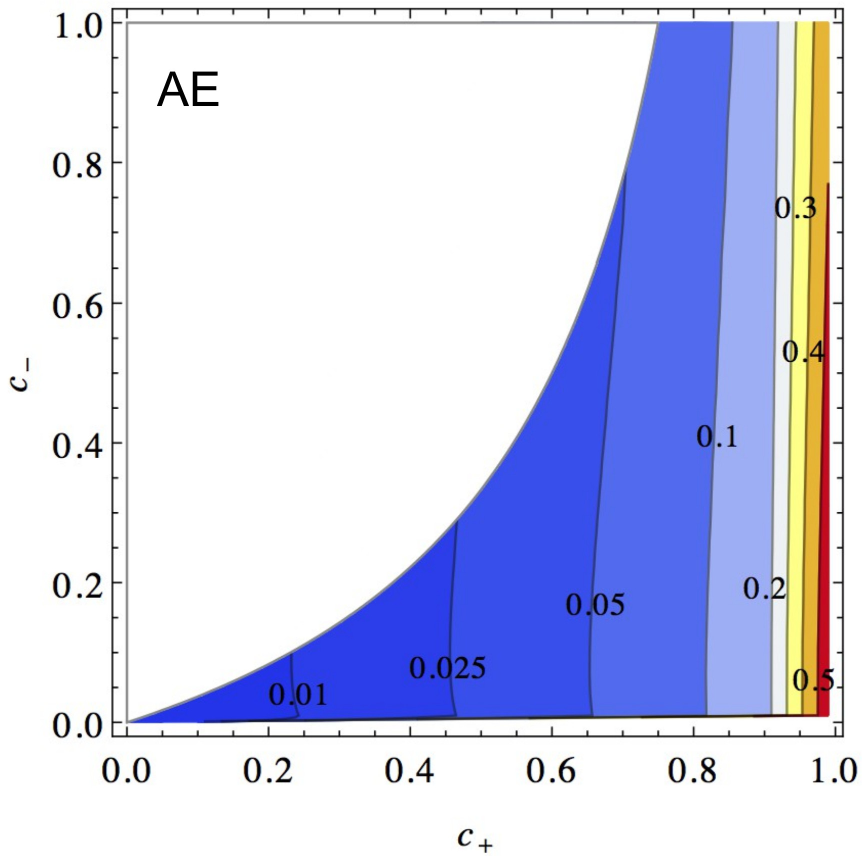
- Because of Cherenkov bound, spin-0 horizon is inside matter horizon (“metric horizon”)
- Outside metric horizons, BHs similar to Schwarzschild

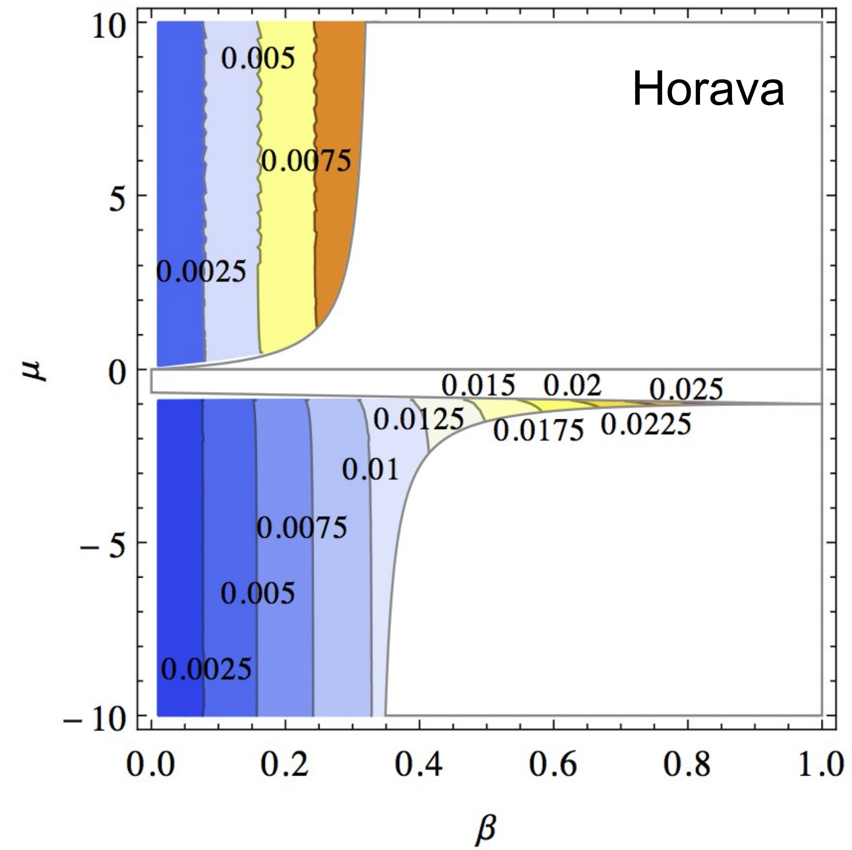


$$\frac{\Delta\left(\Omega_{ISCO} r_g\right)}{\Omega_{ISCO} r_g}$$

$$f(r) = 1 - \frac{r_g}{r} + \ldots$$

BH exterior structure





$$\frac{\Delta\left(b_{ph}/r_g\right)}{b_{ph}/r_g} = \frac{\Delta\left(\Omega_{ph} r_g\right)}{\Omega r_g}$$

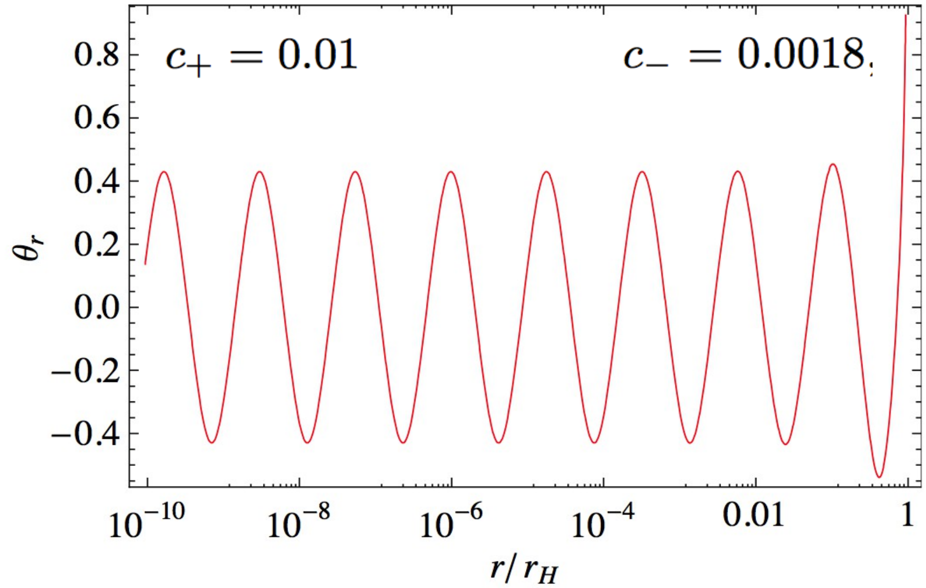
Measurable with GWs?

BH interior structure

Metric qualitatively similar to Schwarzschild (curvature singularity at $r=0$), aether oscillates

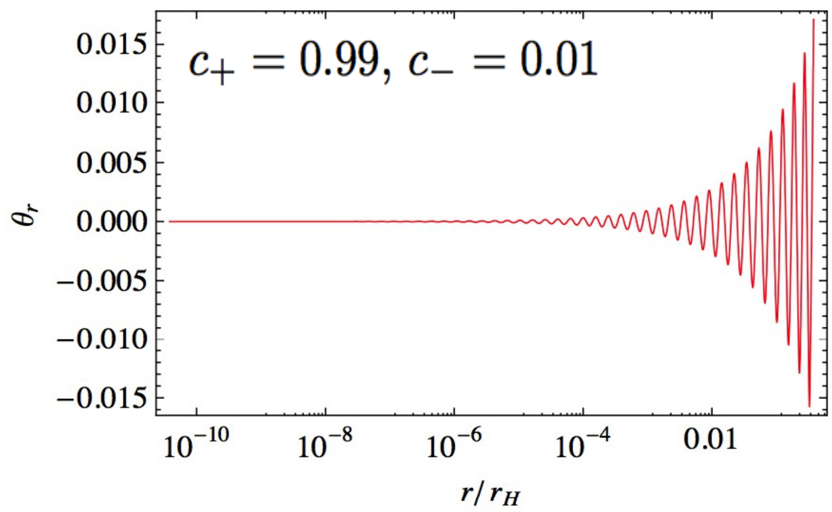
$$\theta_r = \mathrm{arccosh}\gamma_r$$

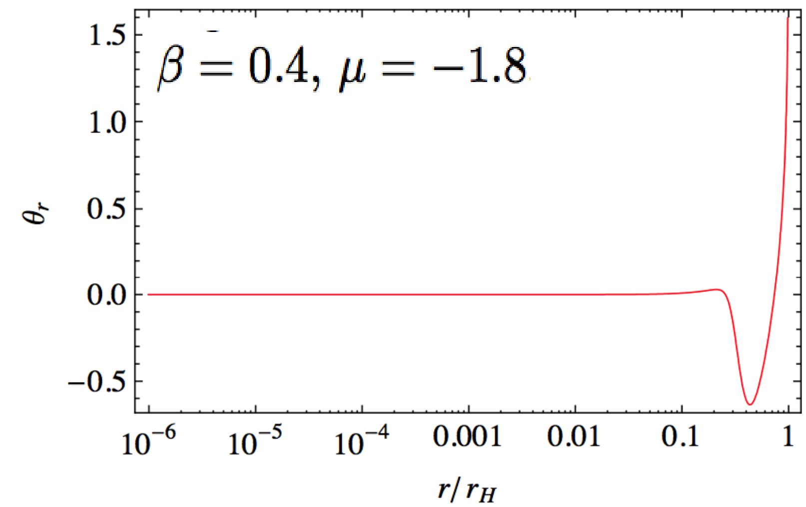
$$\gamma_r \equiv u^{\alpha}_{\mathrm{obs}} u_{\alpha} = -\frac{u^r}{\sqrt{g^{rr}}}$$

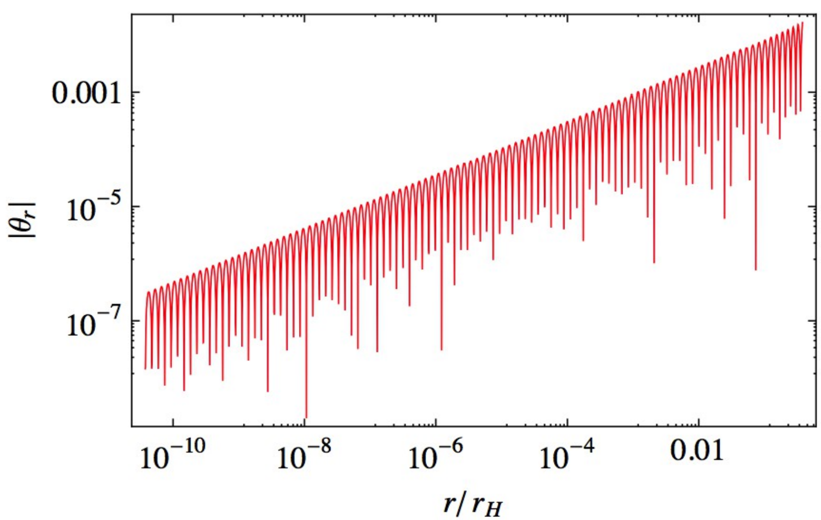


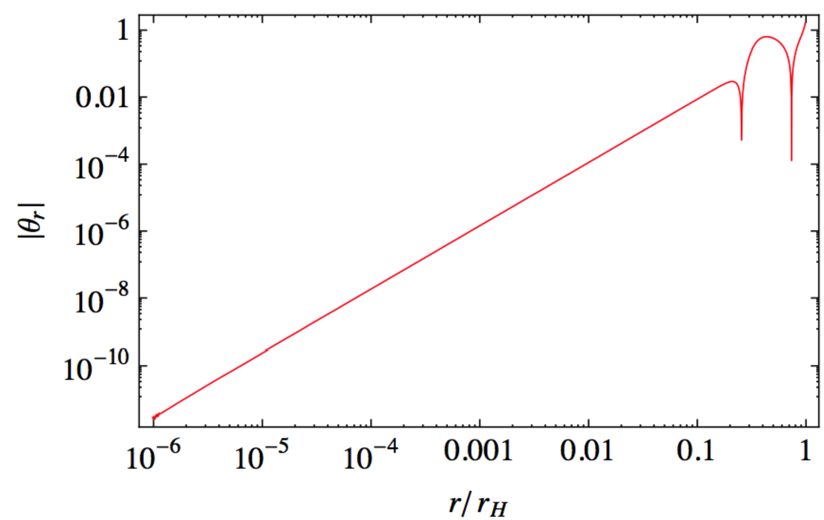
γ_r is aether's Lorentz factor relative to observer orthogonal to (spacelike) hypersurface *r = const*

BH interior structure



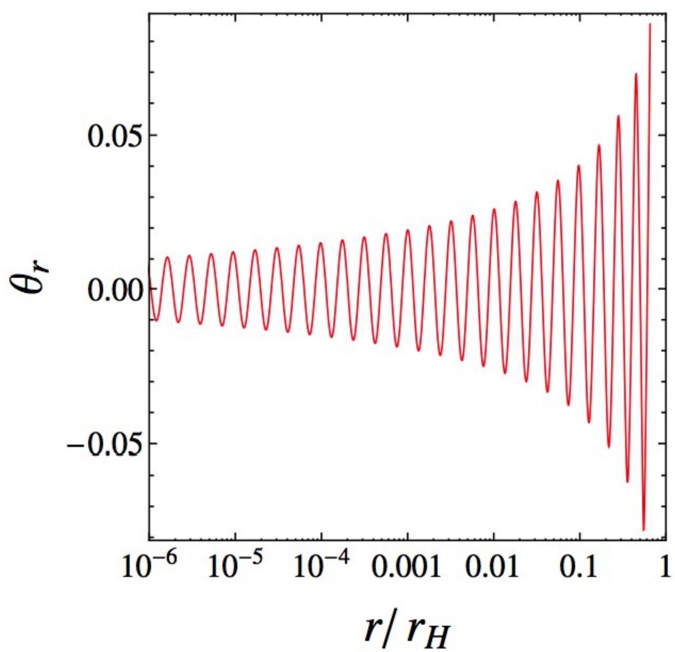


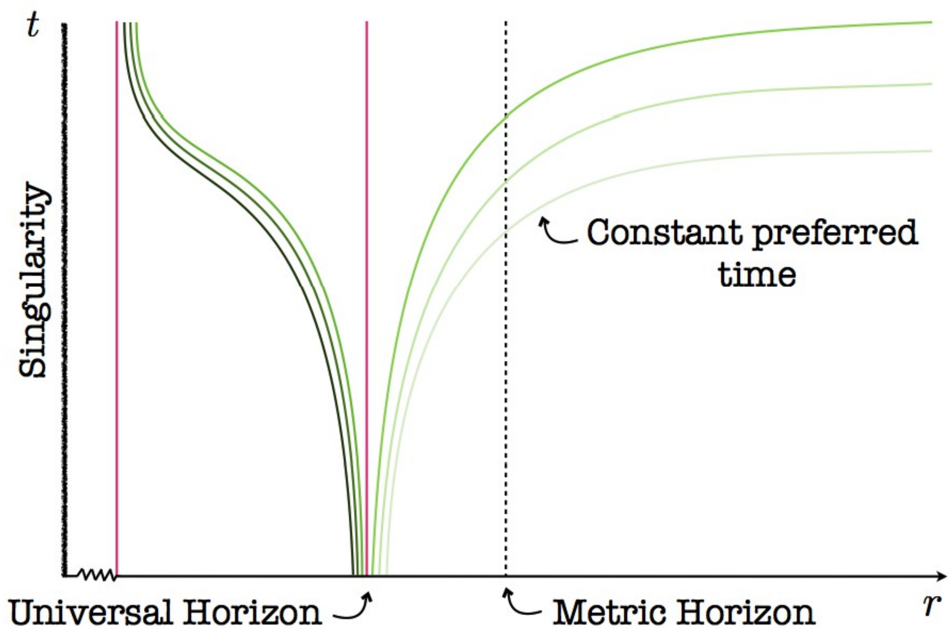




Implications for causal structure in BH interior

$\theta_r = 0$ ⇨ aether orthogonal to (spacelike) hypersurface $r = r_u = const$





Any signal $r < r_u$ can only propagate inwards, whatever its speed, because future=inwards ⇨ $r = r_u$ is a Universal Horizon

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

A universal horizon for signals of infinite speed

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

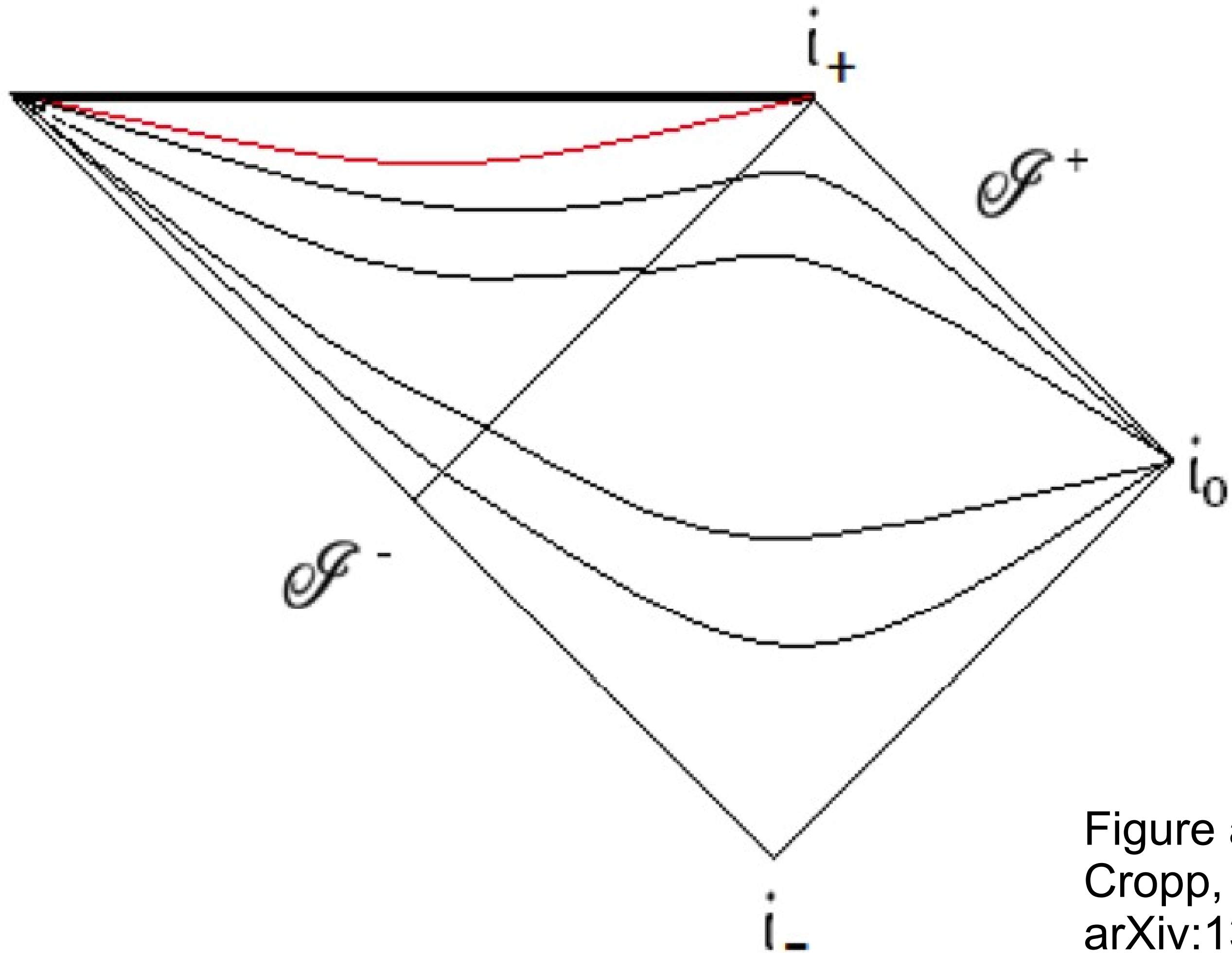


Figure adapted from
Cropp, Liberati and Mohd,
arXiv:1312.0405

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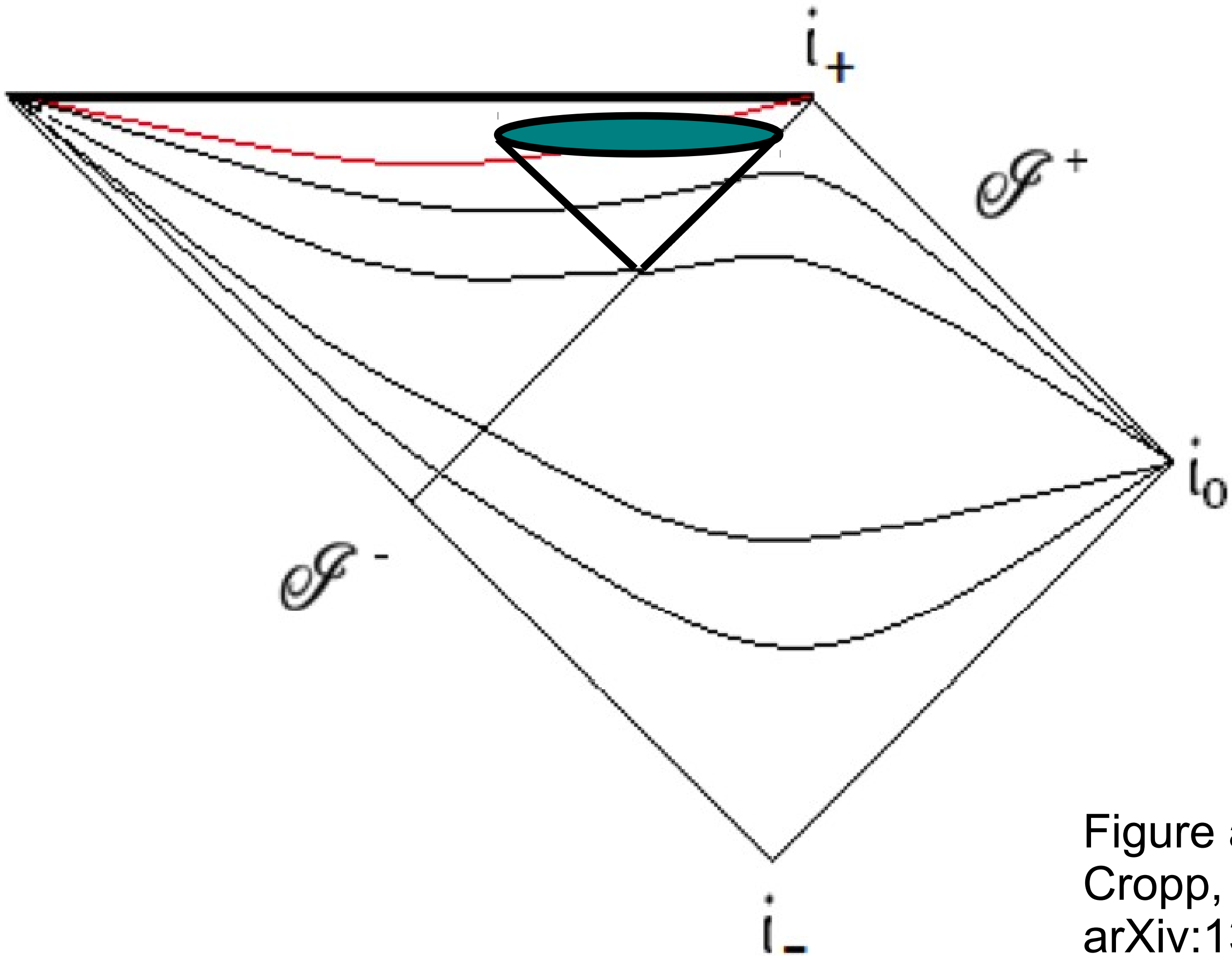

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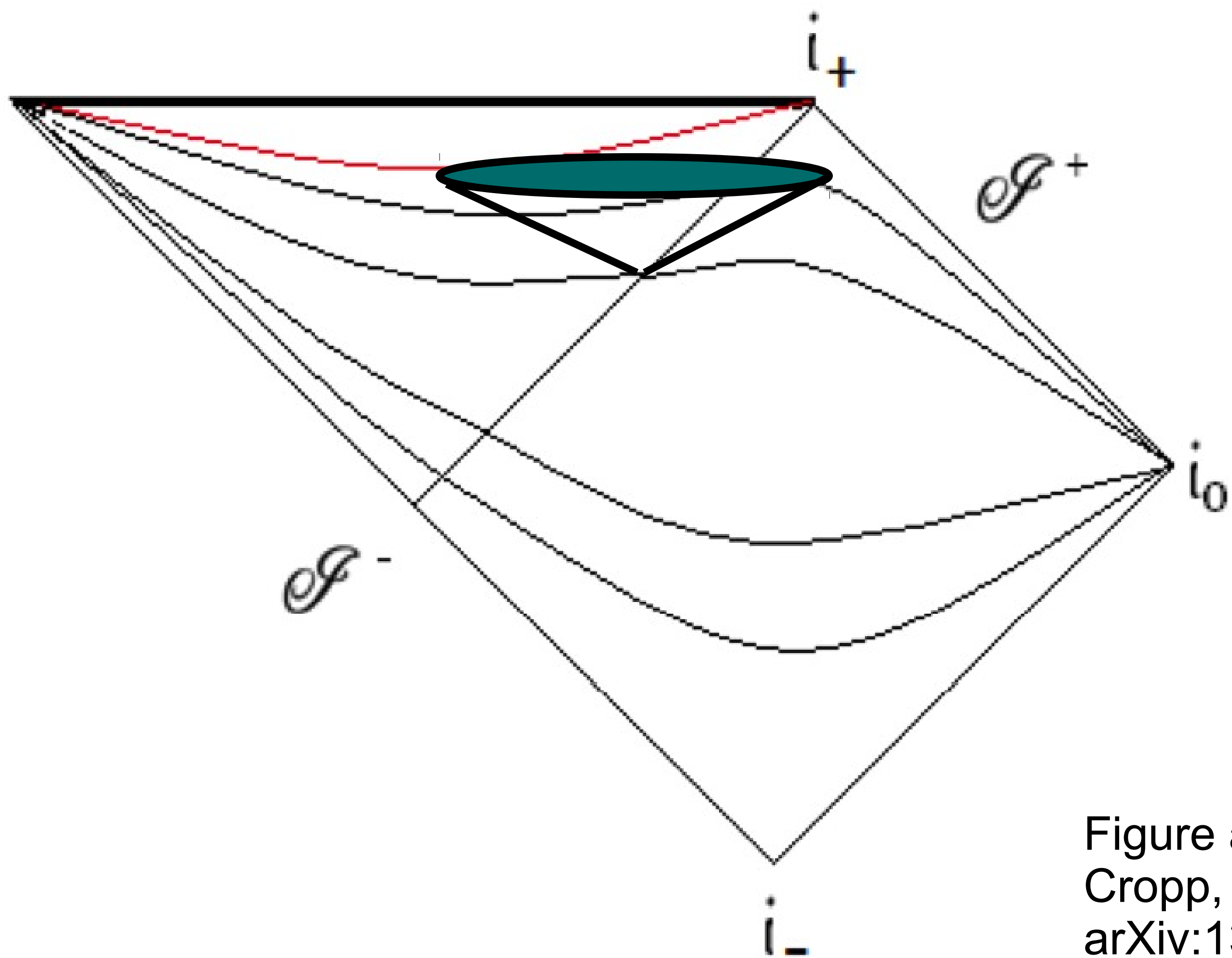

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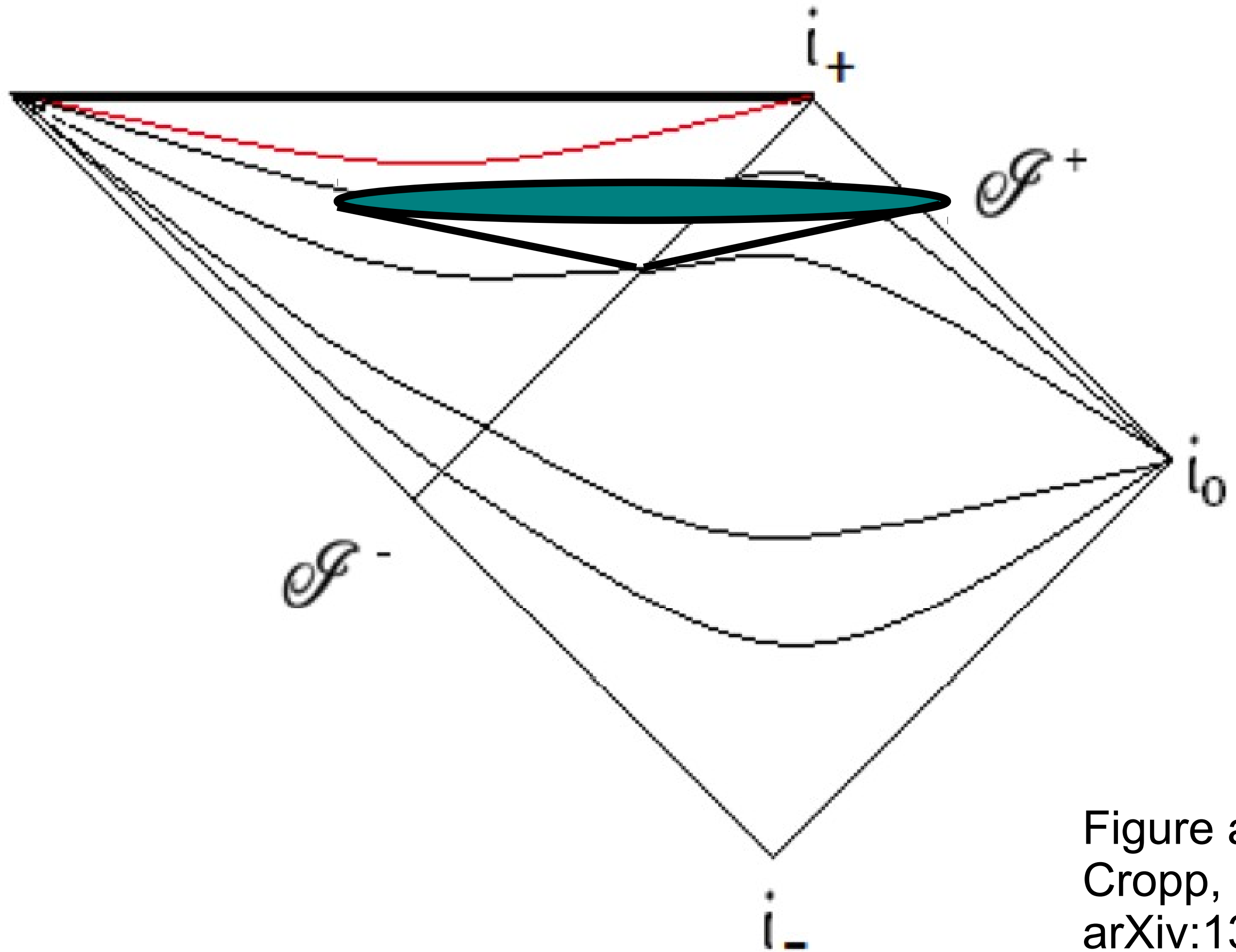

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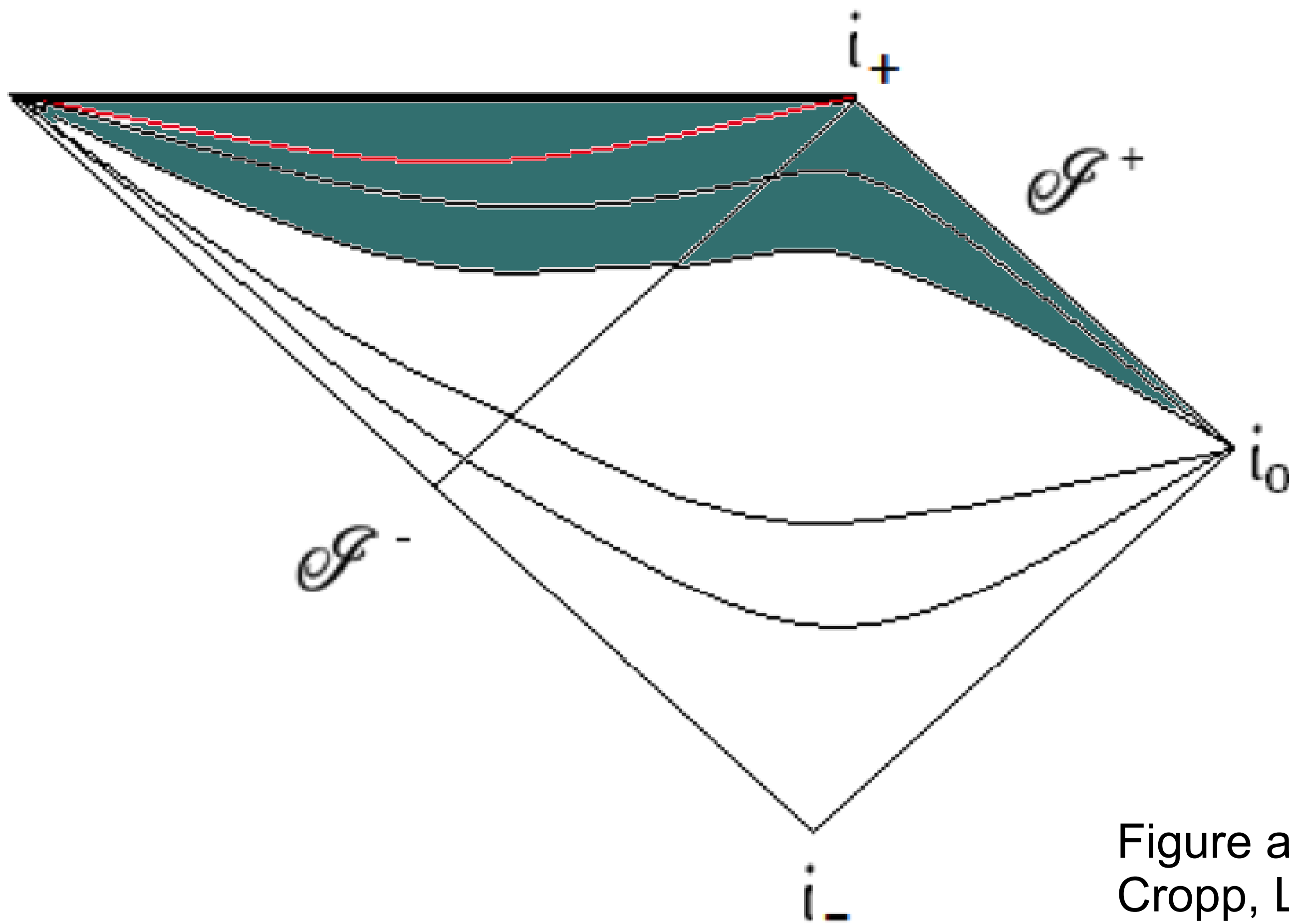

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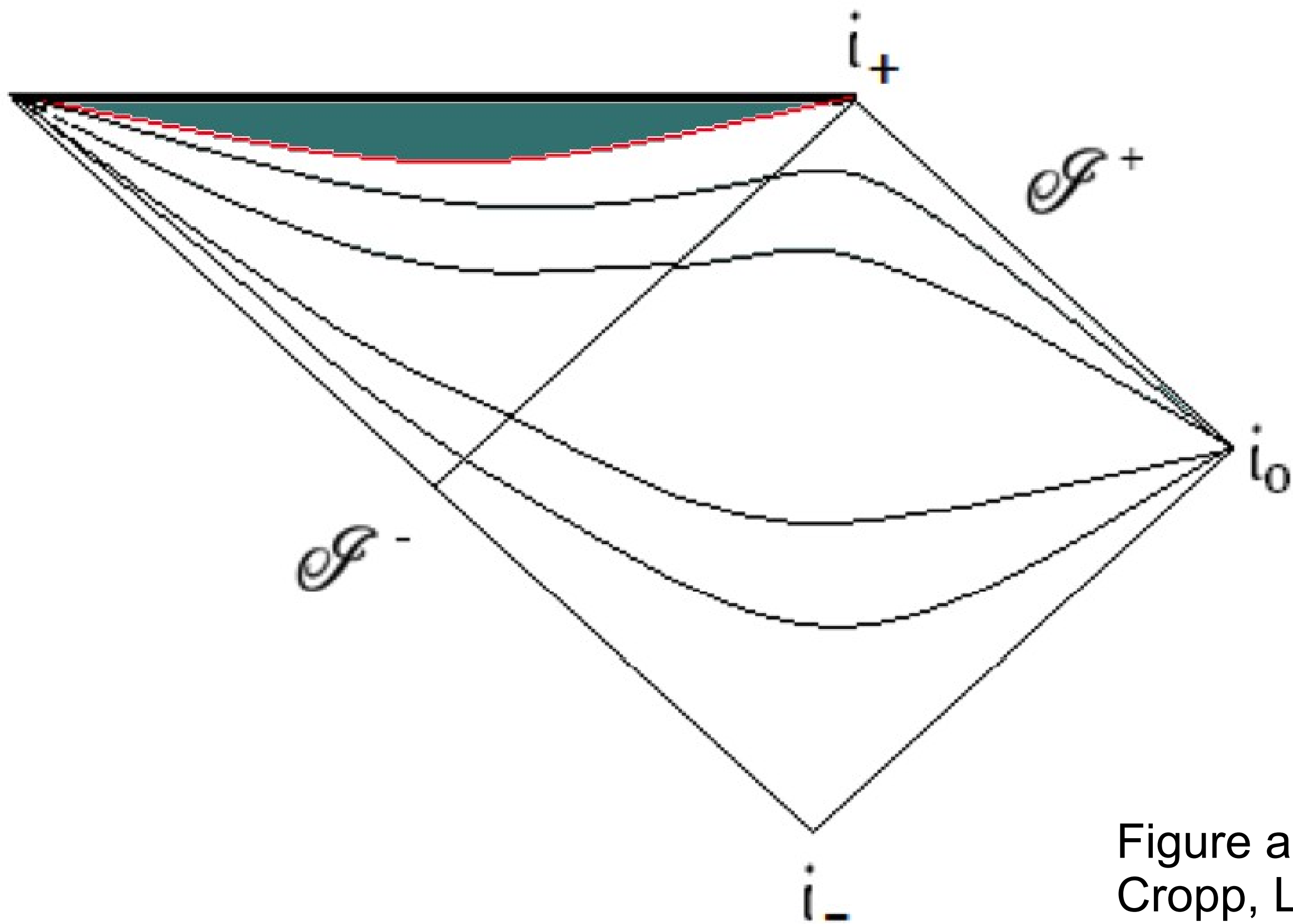

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Further developments about Universal Horizons

- Universal horizon seems to exists also in slowly rotating BHs (at least in Horava gravity, Barausse and Sotiriou 2013) and is robust to UV corrections to the action
- Universal horizons satisfy first law of BH thermodynamics (Berglund, Bhattacharyya, Mattingly 2012, 2013; Mohd 2013), and evidence that Hawking radiation is associated to it (Cropp, Liberati and Mohd 2013)
- Confirmation that universal horizons form in gravitational collapse (Saravani, Afshordi, Mann 2013)
- Universal horizon linearly stable, but clues of non-linear instability (Blas and Sibiryakov 2011)

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)