Cosmological vs astrophysical tests of gravity: the Lorentz violating case

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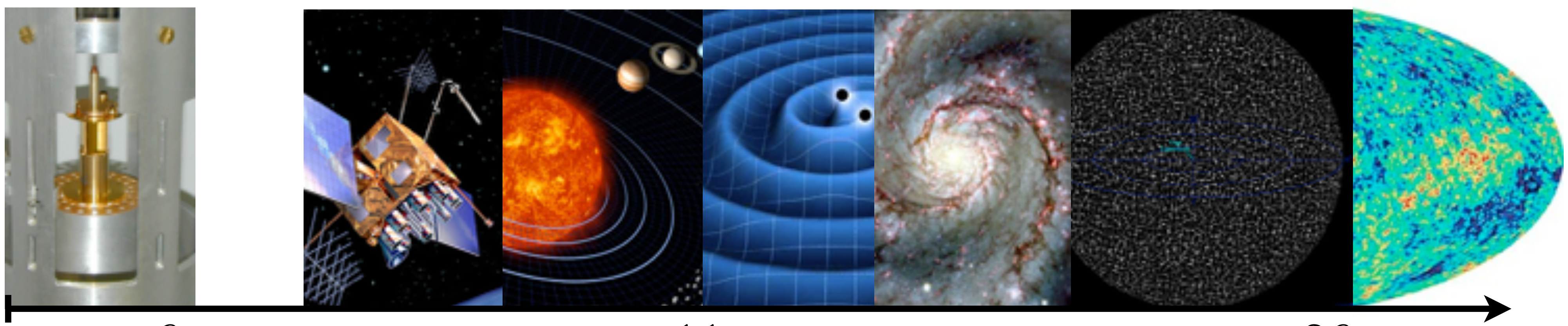
w/ B. Audren, E. Barausse, M. Ivanov, J. Lesgourgues, S. Sibiryakov, K. Yagi, N. Yunes

1412.4828 [gr-qc] (review article w/ E. Lim)

Modified/Testing gravity program

two main reasons

✓ because we can/must (data driven)



10^{-6} 10^{11} 10^{26} m

what are we learning from data?

GR is great, but we can quantify this and test its principles: *Minimal, Lorentz invariant, Unitary, Massless, Metric, EFT, Local, 4D,…*

✓ because we need to (theory driven)

GR is *not* a complete theory and the CC *bone* is still in our throats

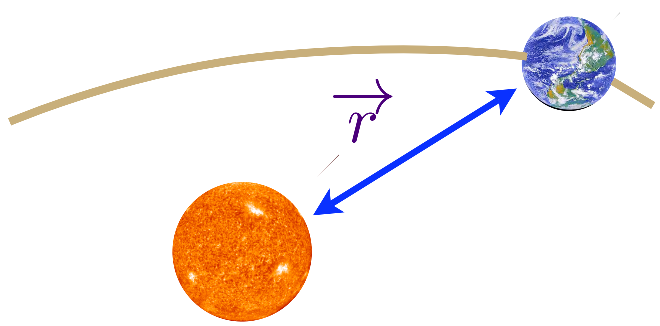
How to do it?

two approaches

✓ phenomenological:

modify the GR predictions for certain scales

canonical example: PPN parameters



$v \ll c \qquad \phi_N \ll 1$ virialized system

$g_{\mu\nu}(\beta, \gamma, \alpha_{1,2}, \ldots)$ 10 parameters, some with physical interpretation

✓ fundamental:

modify the GR Lagrangian given certain criteria

$$\mathcal{L} = M_P^2 R + \Lambda^4 F(\phi, g_{\mu\nu})$$

How to do it?

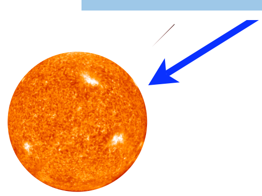
two approaches

✓ phenomenological:

modify the GR predictions for certain scales

canonical example: PPN parameters

model independent: generic effects



$g_{\mu\nu}(\beta, \gamma, \alpha_{1,2}, \ldots)$ 10 parameters, some with physical interpretation

✓ fundamental:

modify the GR Lagrangian given certain criteria

physical interpretation of the constraints, unforeseen effects and connection between observations

Lorentz violation case

benefits of abandoning LI in gravity:

- ✓ quantum gravity (Hořava gravity, CDT,…)
- ✓ new ideas for black holes
- ✓ natural dark energy candidate
- ✓ Higgs mechanism for massive gravitons
- ✓ test a fundamental property of GR @ all scales

Lorentz invariance (LI) is a key ingredient of
Particle Physics, Gravity, Dark Sector

is LI necessary? which are the bounds on deviations?
how do different observations compare?

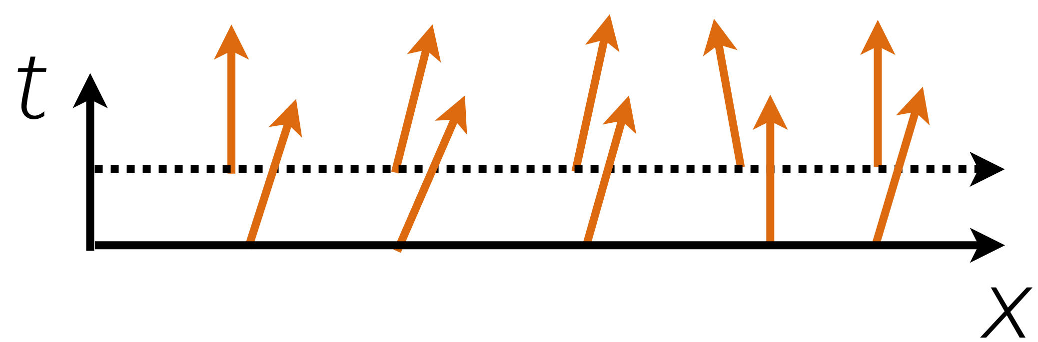
LV theories: the preferred frame case

Space-time filled by a preferred **time** direction associated to a time-like unit vector u_μ

Generic:
Einstein-æther

Jacobson, Mattingly 01

$$u_\mu u^\mu = 1$$

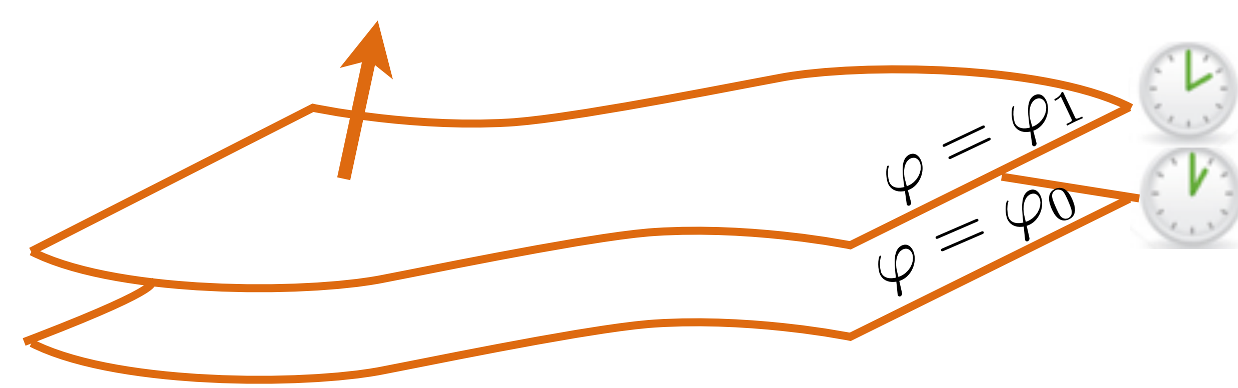


Scalar-vector

Hypersurface orthogonal:
Khronometric

DB, Pujolas, Sibiryakov 09

$$u_\mu \equiv \frac{\partial_\mu \varphi}{\sqrt{\partial_\alpha \varphi \partial^\alpha \varphi}}$$



Scalar: khronon $\chi\rho\acute{o}\nu o\varsigma$

Lagrangian

Ingredients: $u_\mu \;,\; g_{\mu\nu}$

Khronometric $u_\mu \equiv \dfrac{\partial_\mu \varphi}{\sqrt{\partial_\alpha \varphi \partial^\alpha \varphi}}$

DB, Pujolas, Sibiryakov 09
Horava 09

$$\mathcal{L}_{\chi GR} = \mathcal{L}_{EH} + M_P^2 \sqrt{-g}\left(\lambda \left(\nabla^\mu u_\mu\right)^2 + \alpha \left(u^\nu \nabla_\nu u_\mu\right)^2 + \beta \nabla_\mu u_\nu \nabla^\nu u^\mu\right)$$

- **massless** spin 2 graviton: $\omega^2 = c_t^2\, \mathrm{k}^2 \,,\qquad c_t^2 = \dfrac{1}{1-\beta}$
- massless **scalar** $\varphi = t + \chi$: $\omega^2 = c_\chi^2\, \mathrm{k}^2 \,,\qquad c_\chi^2 = \dfrac{\beta + \lambda}{\alpha}$

Stable Minkowski & no gravitational Cherenkov:

$$0 < \alpha < 2 \quad , \quad c_t^2 \geq 1,\; c_\chi^2 \geq 1$$

Einstein-æther: extra term $\gamma \nabla_\mu u_\nu \nabla^\mu u^\nu$

Jacobson, Mattingly 01

- extra **vector** $u_\mu u^\mu = 1$

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DB, Pujolas, Sibiryakov 09
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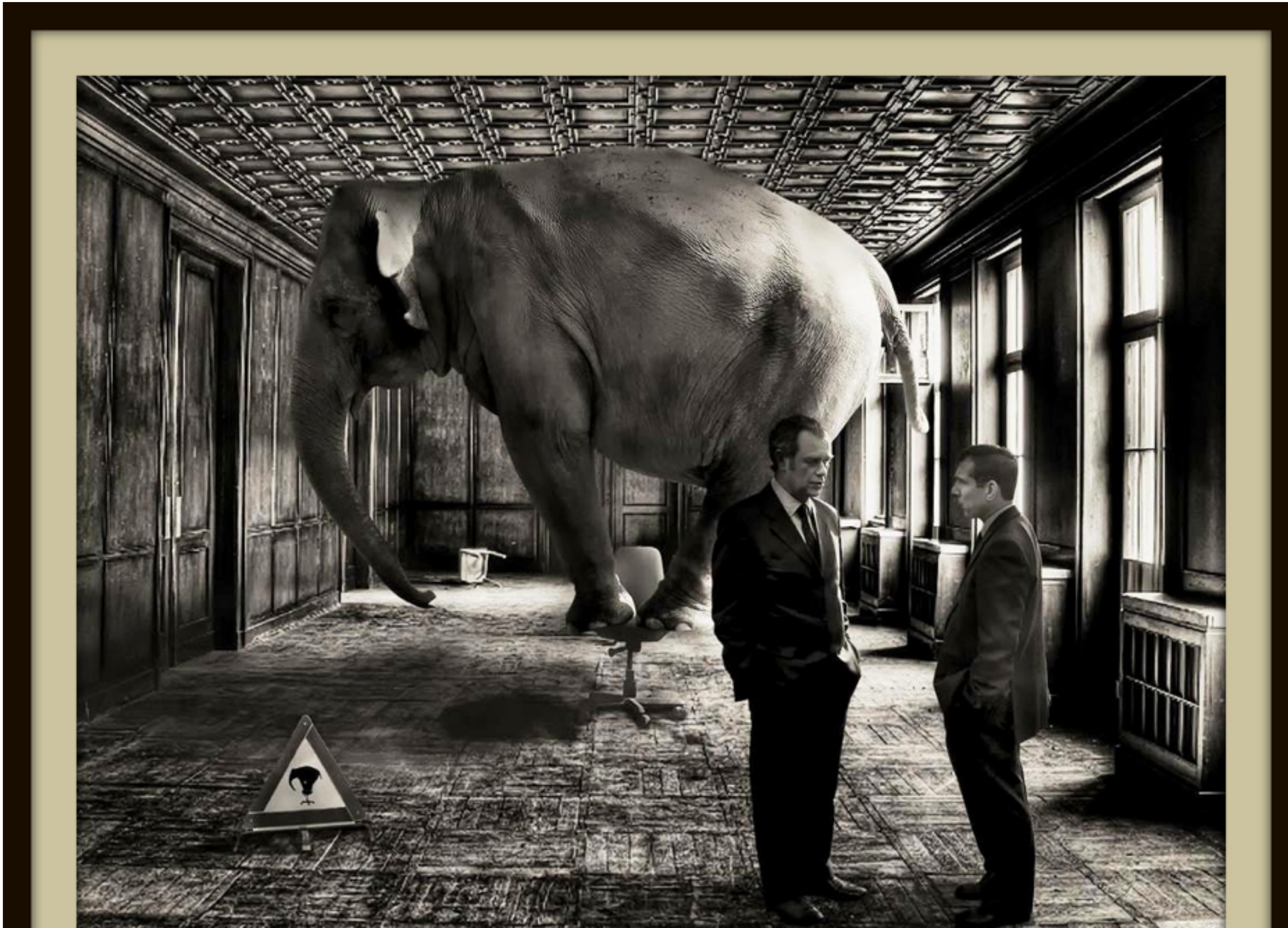
Jacobson, Mattingly 01

- extra **vector** $u_\mu u^\mu = 1$

+ higher derivatives: $\dfrac{1}{{M_\star}^{d-4}} O_{d>4}(u_\mu, g_{\mu\nu}, \nabla_\mu)$

Matter Lagrangian



Matter Lagrangian

Ingredients: u_μ , $g_{\mu\nu}$ + SM Fields + DM + DE

$$\mathcal{L}_m = \mathcal{L}_{LI}(\mathrm{SM}, \mathrm{DM}, \mathrm{DE}, g_{\mu\nu}) + \kappa_{SM}\ \mathcal{L}_{LV}(\mathrm{SM}, g_{\mu\nu}, u_\mu)$$
$$+\kappa_{DM}\ \mathcal{L}_{LV}(\mathrm{DM}, g_{\mu\nu}, u_\mu) + \kappa_{DE}\ \mathcal{L}_{LV}(\mathrm{DE}, g_{\mu\nu}, u_\mu)$$

SM: e.g. $\bar{\psi}\, u^\mu u^\nu \gamma_\mu \partial_\nu \psi$ ➤ $\omega_\psi^2 = m_\psi^2 + c_\psi^2 \mathrm{k}^2$

$|1 - c_{p,n}/c_\gamma| < 10^{-22}$ dynamical explanation? review by Liberati 13

Kostelecky, Liberati, Mattingly, ... in the following $\kappa_{SM} = 0$

DM, DE: κ_{DM}, κ_{DE}? to be answered by cosmology

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Tests of LV in gravity

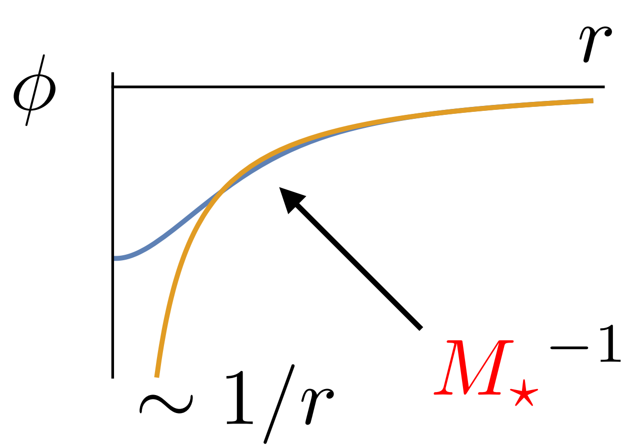
$M_\star$ $\qquad\qquad$ $\alpha,\ \beta,\ \gamma, \lambda$

New massless extra degree of freedom,
modification of the graviton
and preferred frame

10^{-6} $\qquad$ 10^{11} $\qquad$ 10^{26} $\quad m$

UV modifications

Solar system, GWs, astro, cosmology,…



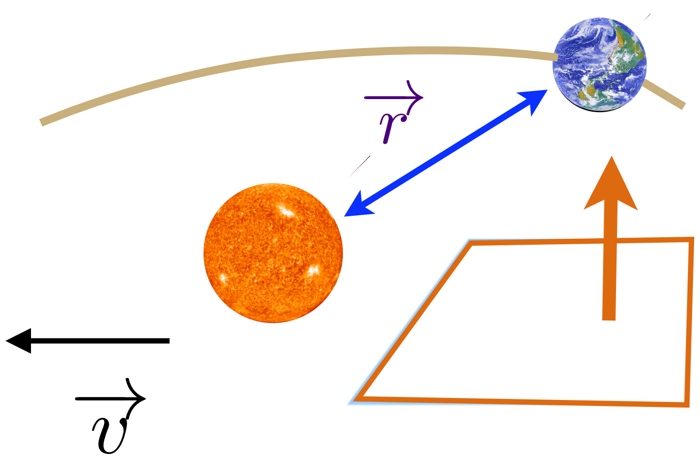
$$\Delta\left(1 + c_1 \frac{\Delta}{M_\star^2} + \ldots\right)\phi = \frac{\tau^{00}}{2M_P^2}$$

$M_\star{}^{-1} < \mu m \sim (0.1\ \mathrm{eV})^{-1}$

Solar System Constraints (Kh)

Solar system (PN gravity)

DB, Pujolas, Sibiryakov 10



$$h_{00} = -2G_N \frac{M}{r}\left(1 - \frac{(\alpha_1^{PPN} - \alpha_2^{PPN})v^2}{2} - \frac{\alpha_2^{PPN}}{2}\frac{(x^i v^i)^2}{r^2}\right)$$

$$h_{0i} = \frac{\alpha_1^{PPN}}{2} G_N \frac{m}{r} v^i$$

$$\alpha_1^{PPN} = -4(\alpha - 2\beta) \qquad G_N \equiv \frac{1}{8\pi M_P^2 (1 - \alpha/2)}$$

$$\alpha_2^{PPN} = \frac{(\alpha - 2\beta)(\alpha - \lambda - 3\beta)}{2(\lambda + \beta)}$$

Will 05

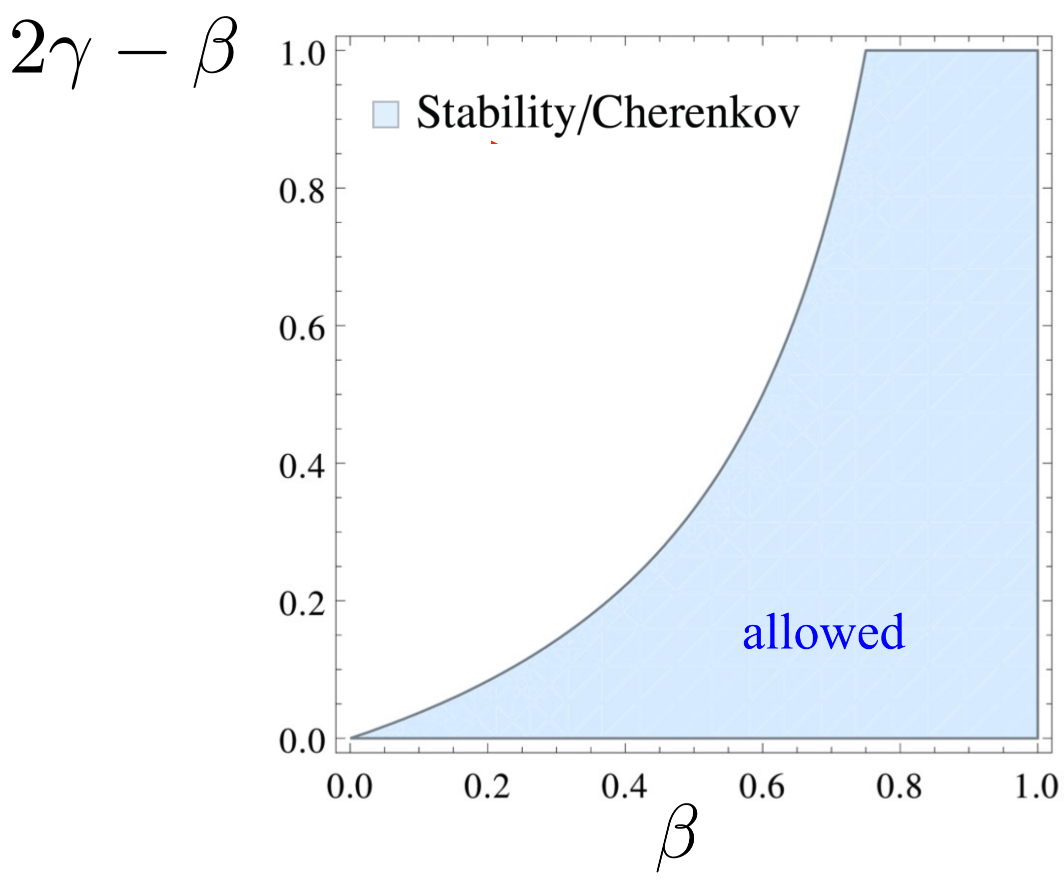
With respect to CMB frame $\vec{v} \sim 10^{-2}$ $\begin{cases} \alpha_1^{PPN} \lesssim 10^{-4} \\ \alpha_2^{PPN} \lesssim 10^{-7} \end{cases}$

$\alpha = 2\beta$ identical to GR in the Solar System!

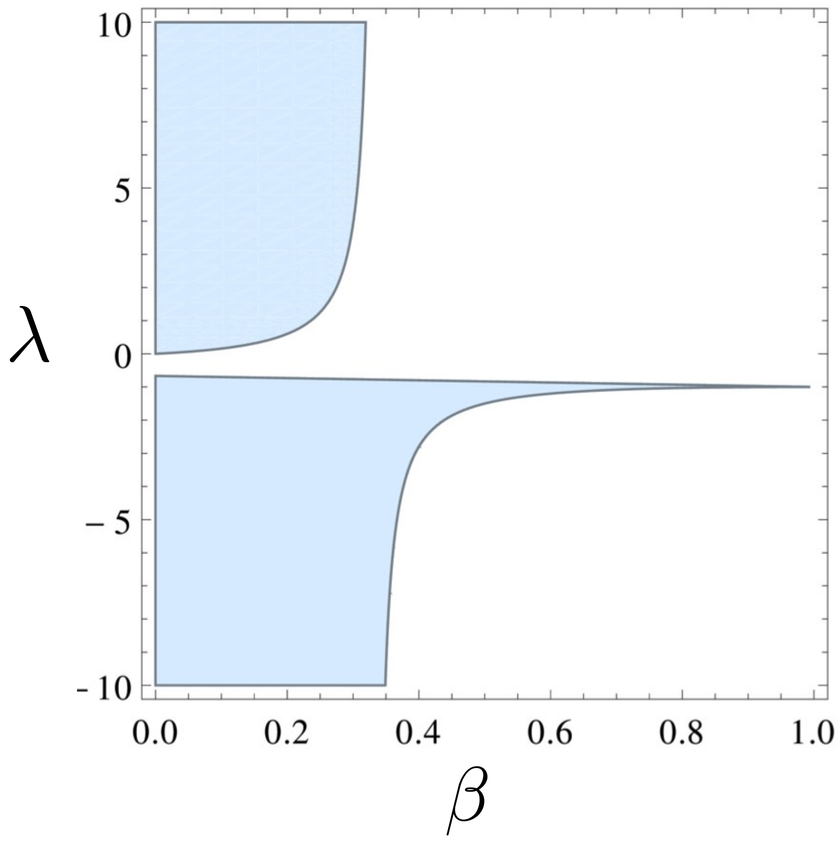
Weak field constraints summary

Solar System constraints leave 2 free parameters

Einstein-æther



Khronometric



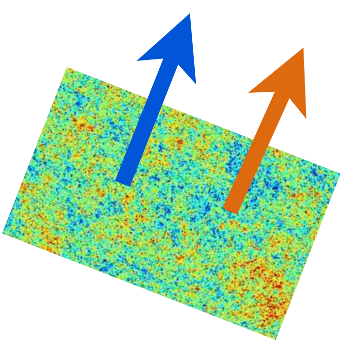
Constraints from late time cosmology

$$\mathcal{L}_{\chi GR} = \mathcal{L}_{EH} + M_P^2\sqrt{-g}\left(\lambda\left(\nabla^\mu u_\mu\right)^2 + \alpha\left(u^\nu\nabla_\nu u_\mu\right)^2 + \beta\nabla_\mu u_\nu\nabla^\nu u^\mu\right)$$

$$\mathcal{L}_m = \mathcal{L}_{LI}(\mathrm{SM}, \mathrm{DM}, \Lambda, g_{\mu\nu}) + \cancel{\kappa_{SM}\,\mathcal{L}_{LV}(\mathrm{SM}, g_{\mu\nu}, u_\mu)}$$
$$+\cancel{\kappa_{DM}\,\mathcal{L}_{LV}(\mathrm{DM}, g_{\mu\nu}, u_\mu)} + \cancel{\kappa_{DE}\,\mathcal{L}_{LV}(\mathrm{DE}, g_{\mu\nu}, u_\mu)}$$

LV effects from the coupling to $u_\mu = \bar{u}_\mu + \delta u_\mu$:

(i) background $\bar{u}_\mu$ modifies Friedmann equation



$$\mathcal{H}^2 = \frac{8\pi}{3}G_c\rho_m\,; \qquad \frac{G_c}{G_N} = \frac{2-\alpha}{2+\beta+3\lambda}$$

BBN
$|G_N/G_c - 1| \lesssim 0.1$

(ii) new interaction from δu_μ

different clustering properties and extra ingredients!

Growth of DM perturbations and shear

Kobayashi, Urakawa, Yamaguchi 10

$$\mathrm{d}s^2 = a(t)^2\left[(1+2\phi)\mathrm{d}t^2 - \delta_{ij}(1-2\psi)\mathrm{d}x^i\mathrm{d}x^j\right] \quad ; \quad \delta \equiv \frac{\rho}{\bar{\rho}} - 1$$

- Faster Jeans instability: DM dom, subhorizon

$$\frac{k^2\phi}{a^2} = \frac{3H^2(1+\beta/2+3\lambda/2)}{2(1-\alpha/2)}\delta = \frac{3G_N}{2G_c}H^2\delta \quad ; \quad \delta'' + 2H\delta' = -\frac{k^2\phi}{a^2}$$

$$\boxed{\delta \sim t^{\frac{1}{6}\left(-1+\sqrt{1+24\frac{G_N}{G_c}}\right)}}$$

$$\alpha = 2\beta \quad \Rightarrow \quad \frac{G_N}{G_c} - 1 = \frac{3(\beta+\lambda)}{2} + O(2) > 0$$

- Anisotropic stress

Audren, DB, Lesgourgues, Sibiryakov 13

$$\boxed{\phi - \psi = O(\beta)F(\dot{\chi})}$$

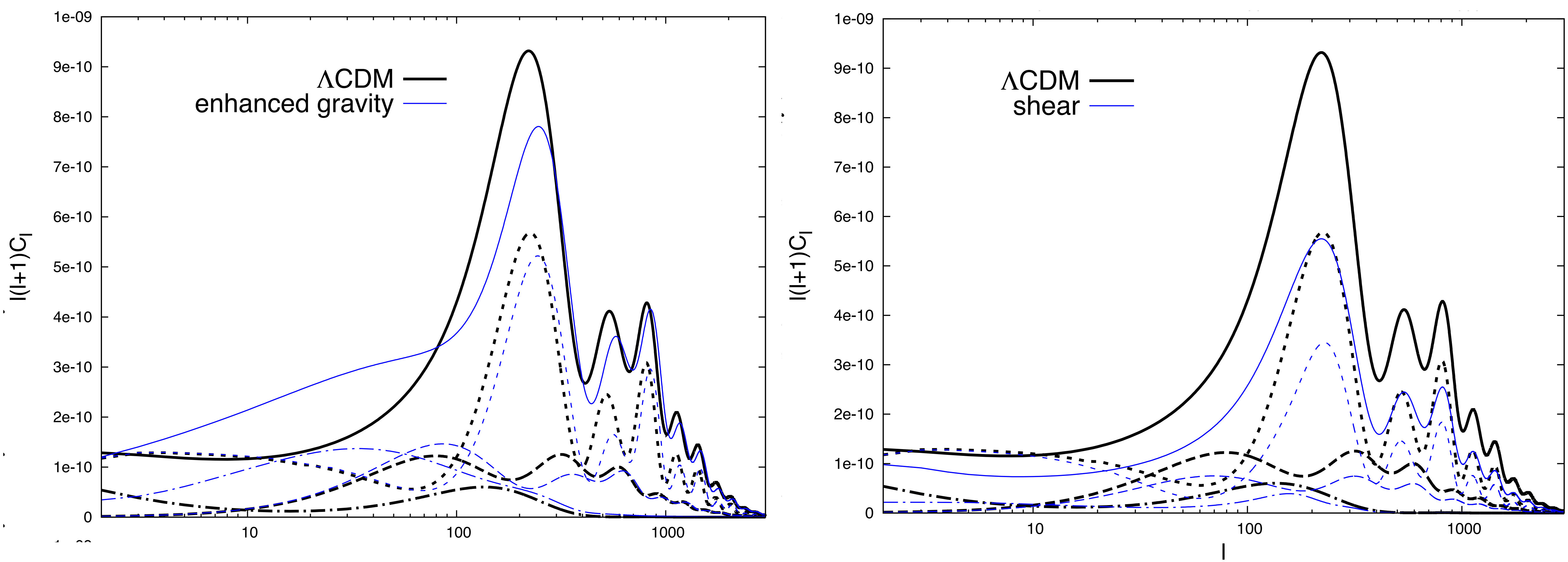
Effects on CMB

Audren, DB, Lesgourgues, Sibiryakov 13

$$\ddot{\delta}_\gamma + k^2 c_s^2 \delta_\gamma \supset -\left(\frac{4k^2}{3}\psi\right) \Leftarrow k^2\psi \sim \frac{G_N}{G_c}\delta_\gamma \Rightarrow c_s^{eff}$$

$$\frac{4}{3}\frac{k^4}{\mathcal{H}^2}(\phi-\psi) \Leftarrow \phi - \psi = O(\beta)\,F(\dot{\chi})$$

Shift of the peaks, change of zero point of oscillation and amplitude



http://class-code.net

Cosmological Constraints

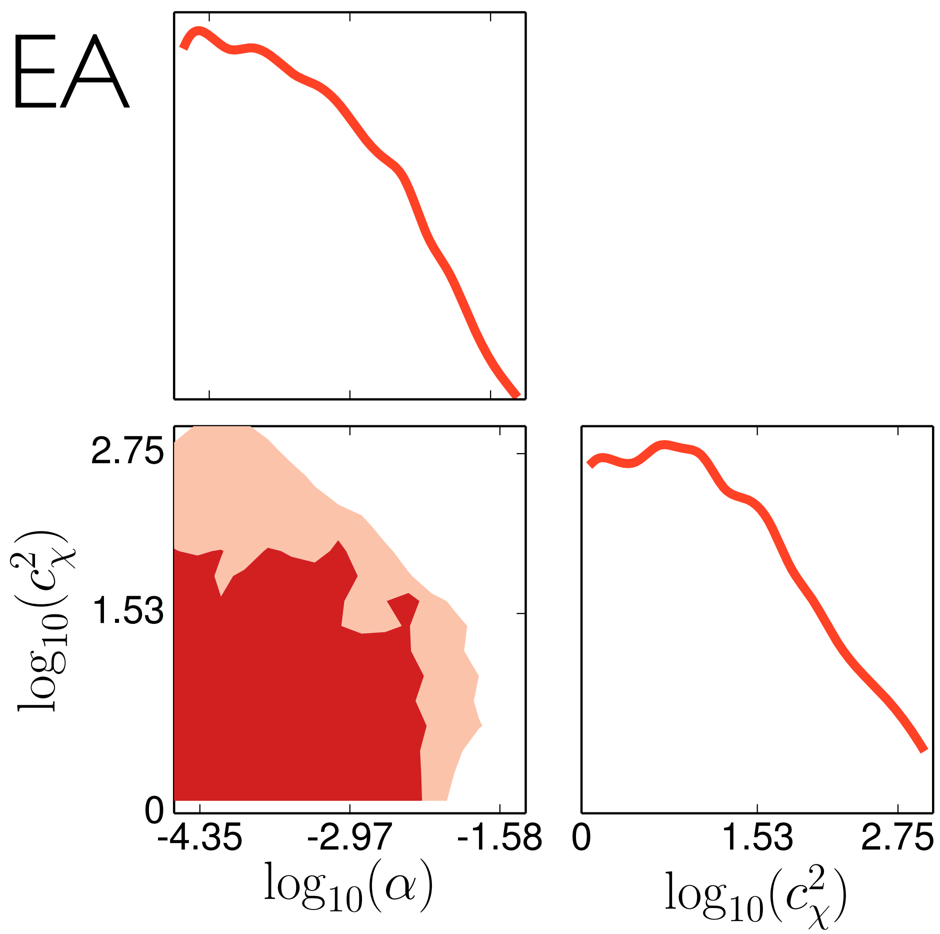
Planck13, SPT, WiggleZ
http://montepython.net/

Audren, DB, Ivanov, Lesgourgues, Sibiryakov 14

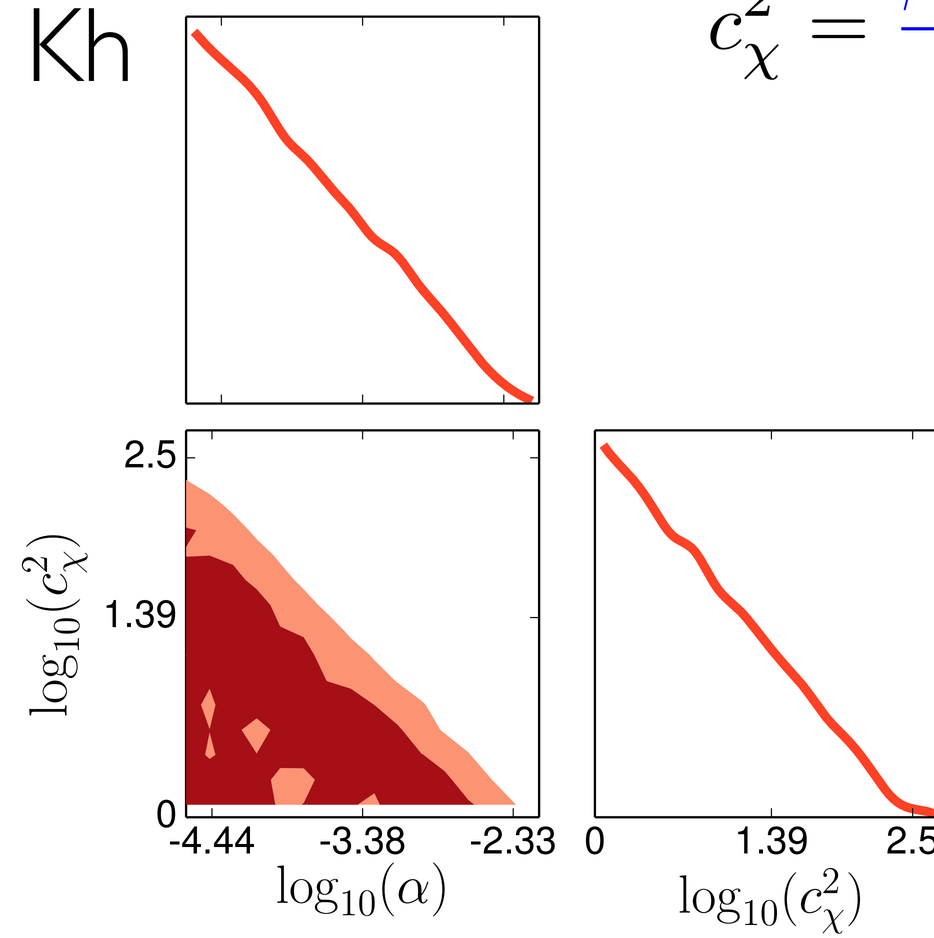
$$\alpha = 2\beta$$

$$c_\chi^2 = \frac{\beta + \lambda}{\alpha}$$

EA



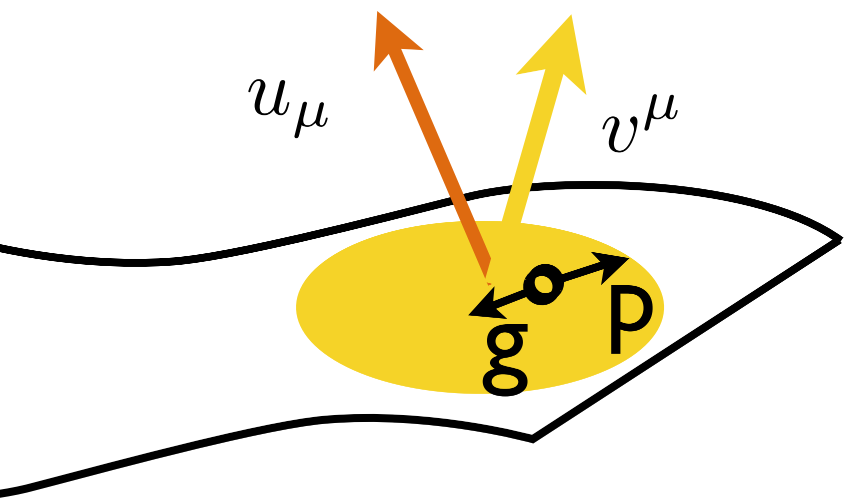
Kh



$\alpha < 10^{-2}$ $\quad c_\chi^2 < 400$ $\quad \alpha < 10^{-3}$ $\quad c_\chi^2 < 90$

Cosmological tests break the degeneracies
left by PPN analysis!

Constraints from binaries



Matter is not modified

Gravitation modified:
coupling gravitons and u_μ

Violation of **strong equivalence principle (SEP)**
(Nordtvedt effect)

$$T_{\mu\nu} = T^m_{\mu\nu} + T^g_{\mu\nu} + T^u_{\mu\nu}$$

produces $g_{\mu\nu}, \quad u^\mu$

Far away: point-particle description with extra coupling

$$S_{pp} = -\tilde{m} \int \mathrm{d}s \quad \Rightarrow \quad S_{pp} = -\tilde{m} \int \mathrm{d}s \, f(u_\mu v^\mu)$$

the **orbital** equations depend on $u_\mu v^\mu$

(analogous to the scalar-tensor case Damour Esposito-Farese 92)

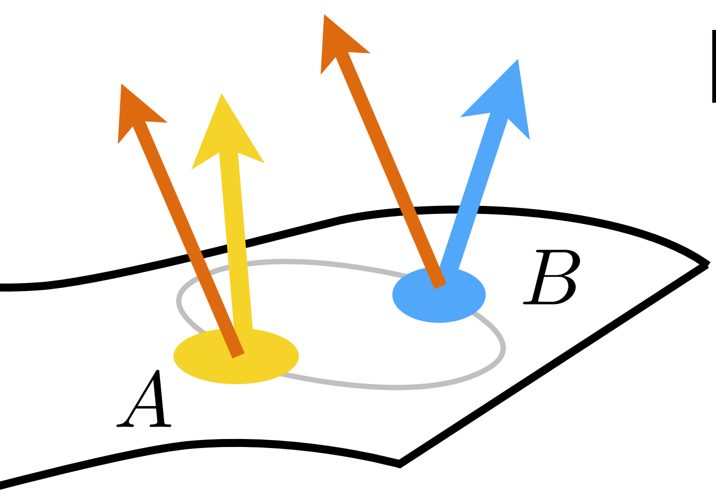
Orbital effects: PN analysis

$$S_{pp} = -\tilde{m}\int \mathrm{d}s\, f(u_\mu v^\mu)$$

Slowly moving $\quad |u^\mu v_\mu - 1| \ll 1$

$$S_{pp} = -\tilde{m}\int ds\, [(1+\sigma(1-u_\mu v^\mu) + O(u_\mu v^\mu - 1)^2]$$

sensitivity: encapsulates the strong-field effects



Newtonian limit of N-particles

$$\dot{v}^i_A = \sum_{B\neq A} \frac{-\mathcal{G}_{AB} m_B}{r^3_{AB}} r^i_{AB}$$

$m_A \equiv \tilde{m}_A(1+\sigma_A)$ active masses

$\mathcal{G}_{AB} \equiv \dfrac{G_N}{(1+\sigma_A)(1+\sigma_B)}$ strong field G_N

Expected dipolar emission

If strong equivalence principle is violated
dipolar radiation expected in binaries
(similar phenomenon in scalar-tensor)

$$h \sim \frac{G}{c^3}\frac{d}{dt}\frac{\Sigma_i}{r} \sim \frac{G}{c^3}\frac{P_i}{r} + O(1/c^4)\, GR \quad , \quad \Sigma_i \equiv \int d^3x \tilde{\rho} x^i$$

$$P^i = \tilde{m}_1 v_1^i + \tilde{m}_2 v_2^i$$

$$\dot{v}_A^i = \sum_{B \neq A} \frac{-\mathcal{G}_{AB} m_B}{r_{AB}^3} r_{AB}^i$$

Equivalence principle violated: P^i not conserved!

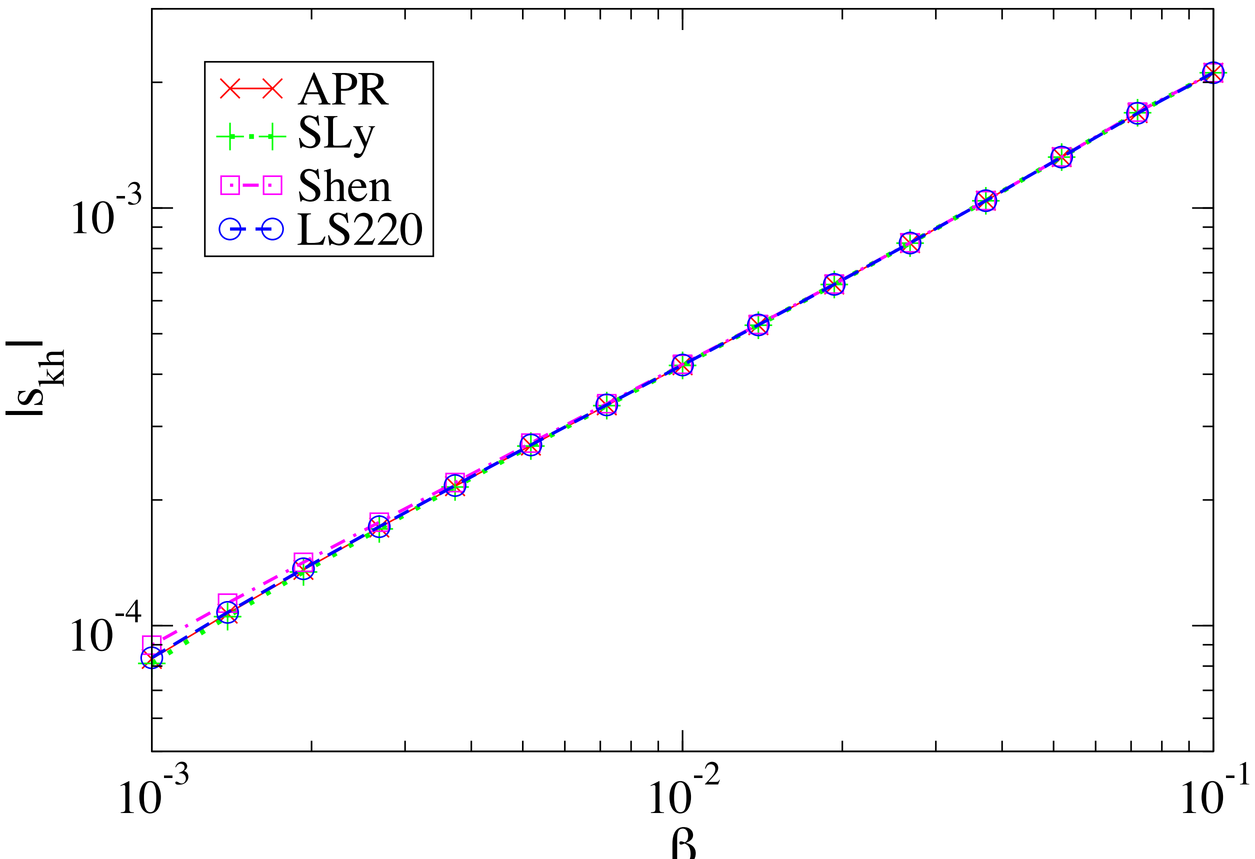
$$\dot{h} \sim \frac{G}{c^3}\frac{\dot{P}}{r} + O(1/c^4)\, \dot{GR}$$

More efficient emission: faster damping of orbits!
(quadrupolar terms are also modified)

Sensitivities for slowly moving case

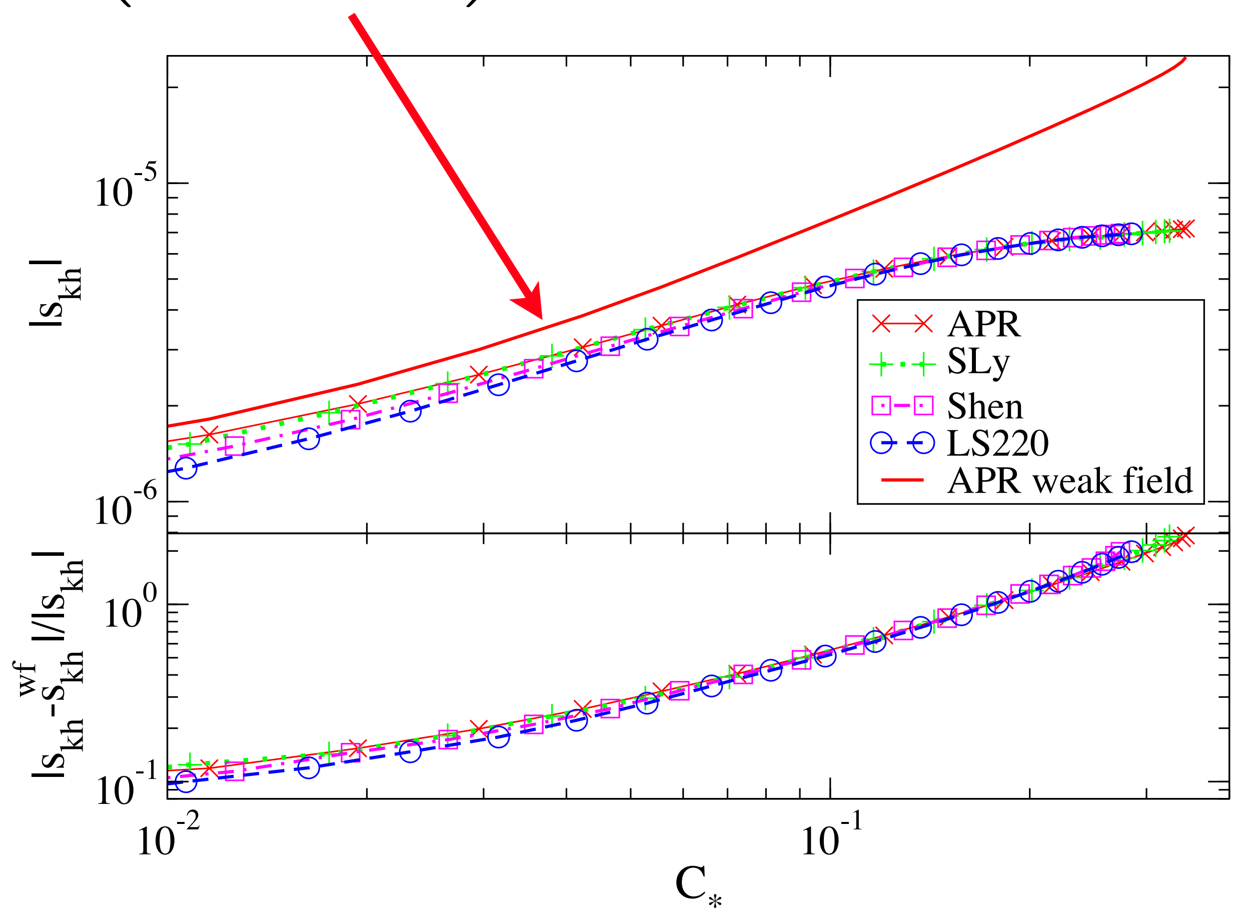
Yagi, DB, Yunes, Barausse 13

Weak field result $s = \left(\alpha_1 - \frac{2}{3}\alpha_2\right) C_* + O(C_*^2)$ Foster 07



$m = 1.4 M_\odot$

$\alpha_1 = \alpha_2 = 0$

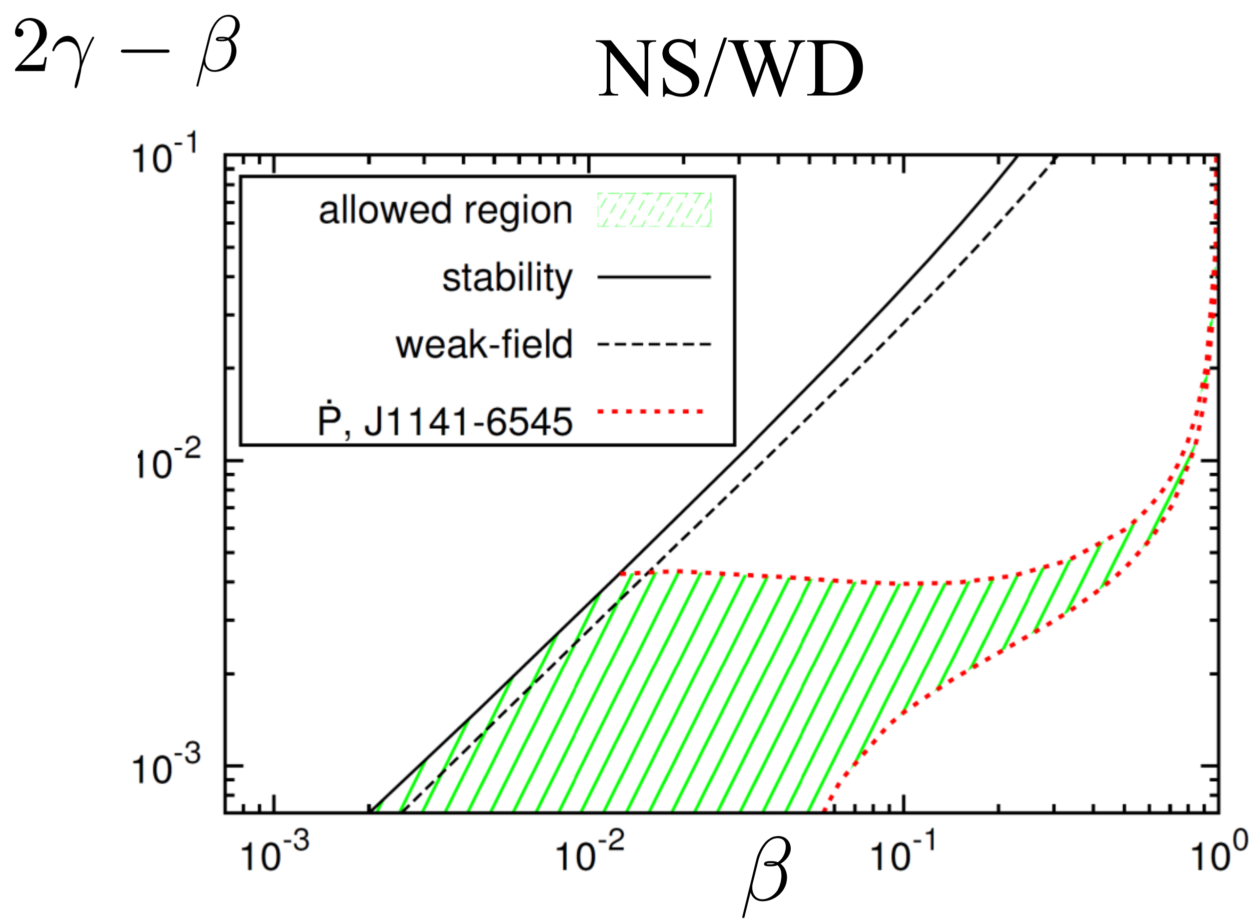


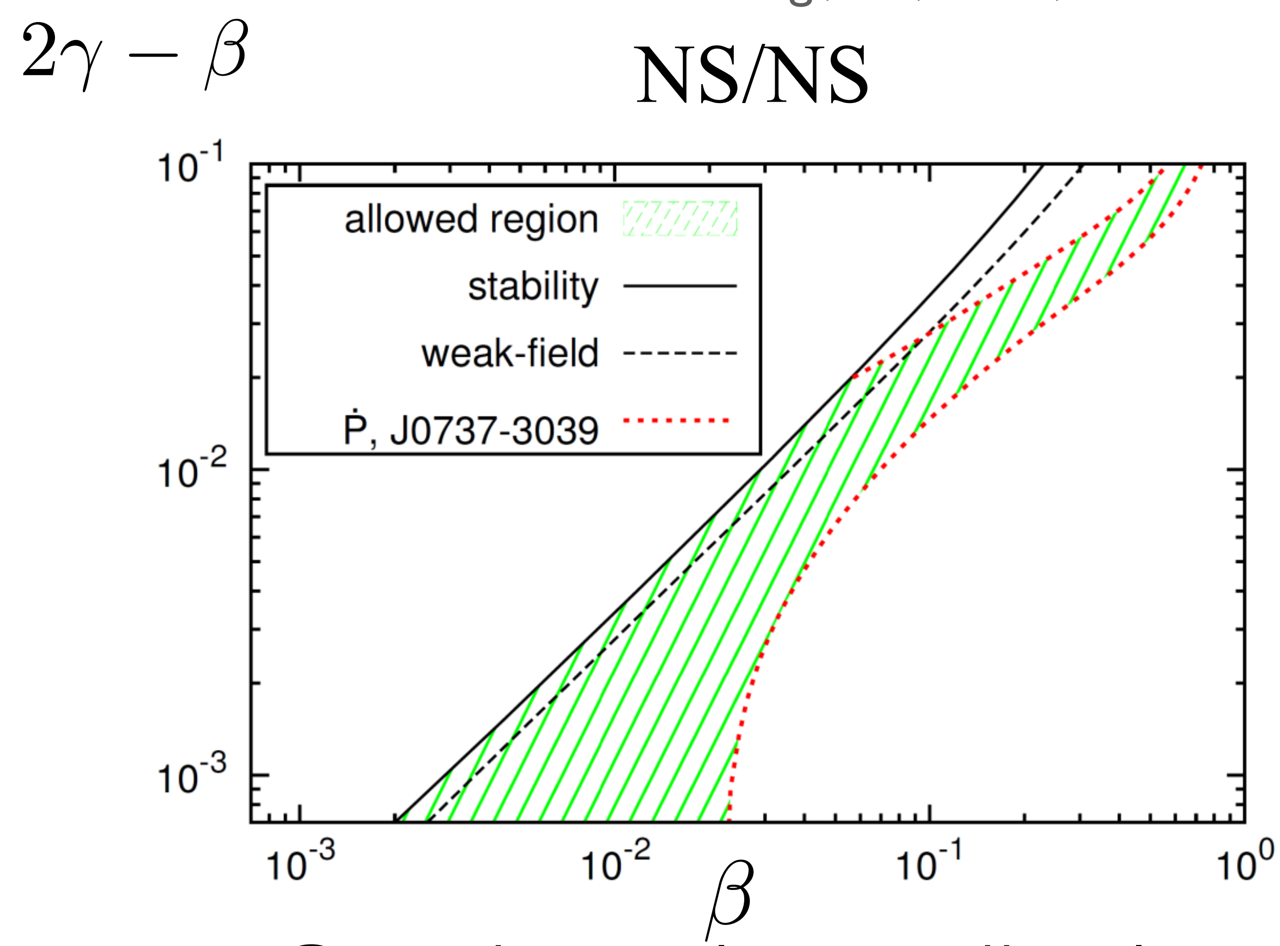
$C_* \equiv G_N m / R$

$\beta = 10^{-4}$

Constraints from damping of binaries (EA)

Yagi, DB, Yunes, Barausse 13





Mostly dipolar

Quadrupolar + dipolar

$$\frac{\dot{P}_b}{P_b} = -\frac{3}{2}\frac{\dot{E}}{E} = -\frac{192\pi}{5}\left(\frac{2\pi G_N m}{P_b}\right)^{5/3}\left(\frac{\mu}{m}\right)\frac{1}{P_b}\langle\mathcal{A}\rangle$$

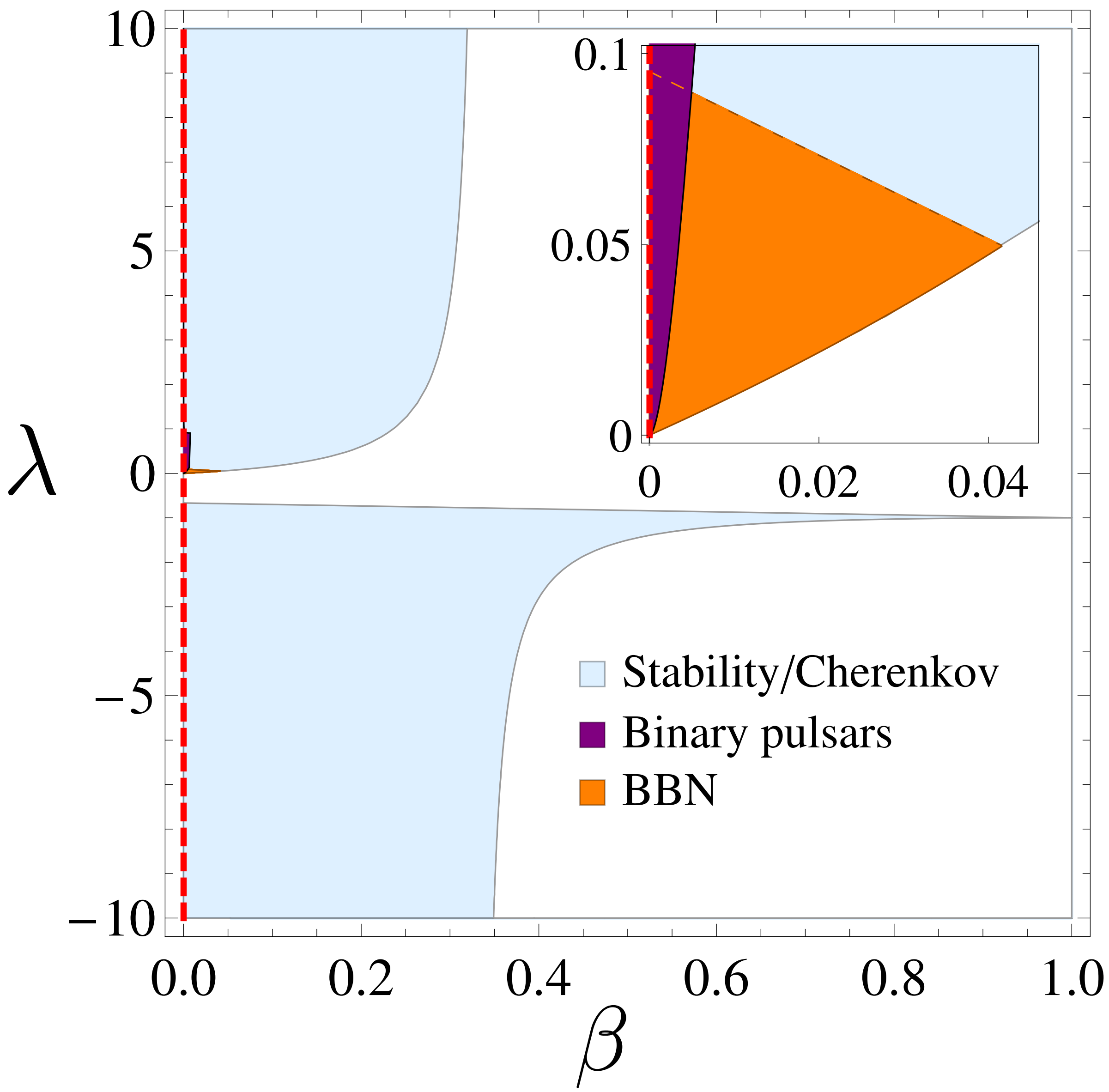
$$\langle\mathcal{A}\rangle \equiv (s_1 - s_2)^2\left(\frac{P_b}{2\pi G_N m}\right)^{2/3}\mathcal{C}$$

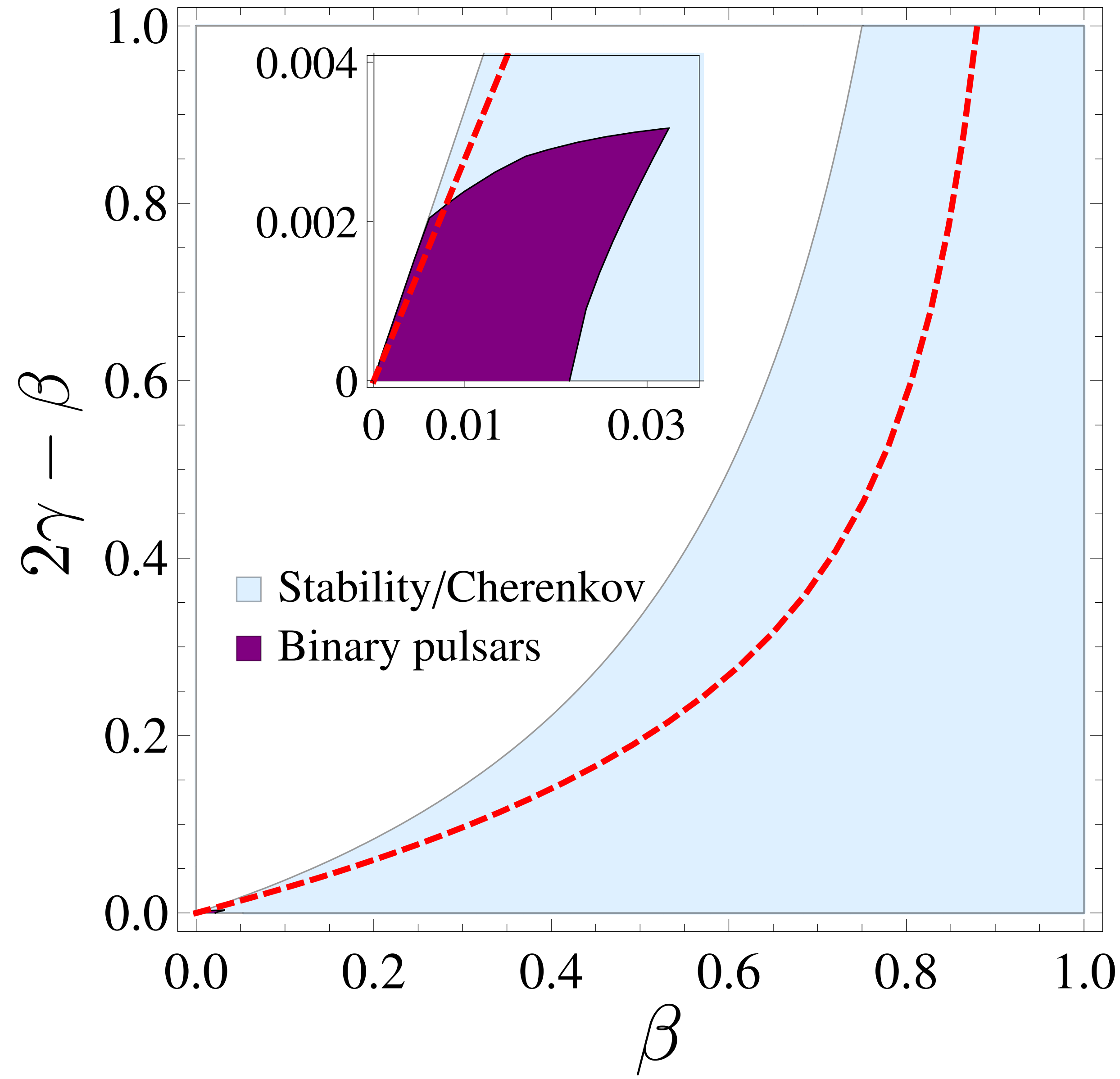
$$+\left[(1-s_1)(1-s_2)\right]^{2/3}\left(\mathcal{A}_1 + \mathcal{S}\mathcal{A}_2 + \mathcal{S}^2\mathcal{A}_3\right)$$

Constraints from binaries

(Solar system constraints imposed)

Yagi, DB, Yunes, Barausse 13





Combined constraints from PSR J1141-6545,
PSR J0348+0432, PSR J0737-3039, J1738+0333

Conclusions

- Exploring Lorentz violation yields a rich phenomenology with strong theoretical motivations (effective or fundamental)
- Lorentz violation modifies gravity at every scale (extra massless d.o.f. $\varphi = t + \chi$ and modified graviton)
- Tests in the gravitational sector (long distance)

  Solar system tests: $\alpha_1^{PPN} \lesssim 10^{-4}$ $\alpha_2^{PPN} \lesssim 10^{-7}$ ➡ $\alpha = 2\beta$
- Cosmological constraints (background and perturbations): growth rate + anisotropic stress
- Effects on the CMB and matter power spectrum

  $\beta,\ \lambda \lesssim O(.01)$ $\kappa_{DM} \lesssim O(.01)$
- SEP violated: modified orbits and dipolar GWs emission in **binary** systems (sensitivities) $\beta,\ \lambda \lesssim O(.01)$