Title: Strong Binary Pulsar Constraints on Lorentz Violation in Gravity

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Abstract: Binary pulsars are excellent laboratories to test the building blocks of Einstein's theory of General
Relativity. One of these is Lorentz symmetry which states that physical phenomena appear the same for all inertially moving observers. We study the e ect of violations of Lorentz symmetry in the orbital evolution of binary pulsars and that it induces a much more rapid decay of the binary's orbital period due to the emission of dipolar radiation. The absence of such behavior in recent observations allows us to place the most stringent constraints on Lorentz violation in gravity, thus verifying one of the cornerstones of Einstein's theory much more accurately than any previous gravitational observation.

Outline

- Lorentz violation in gravity: why and how

  Einstein aether theory and khronometric theory (= low-energy Horava gravity)

- Lorentz violation implies violations of the strong equivalence principle:

  The motion of neutron stars (the “sensitivities” and dipolar gravitational-wave emission)

- Constraints from binaries containing pulsar

Lorentz violation in gravity: why?

- LV may give better UV behavior (Horava), QG completions generally lead to LV
- LV allows MOND-like (Bekenstein, Blanchet & Marsat) or DE-like (eg Afshordi) 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, 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) that's quadratic in derivatives is given (up to total derivatives) by

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

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

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

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

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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 $\sim M^4_{\mathrm{Planck}}/(MM_\star)^2 \ \sim 10^{-14}(M_\odot/M)^2$

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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) ….

$$c_\pm = c_1 \pm c_3$$

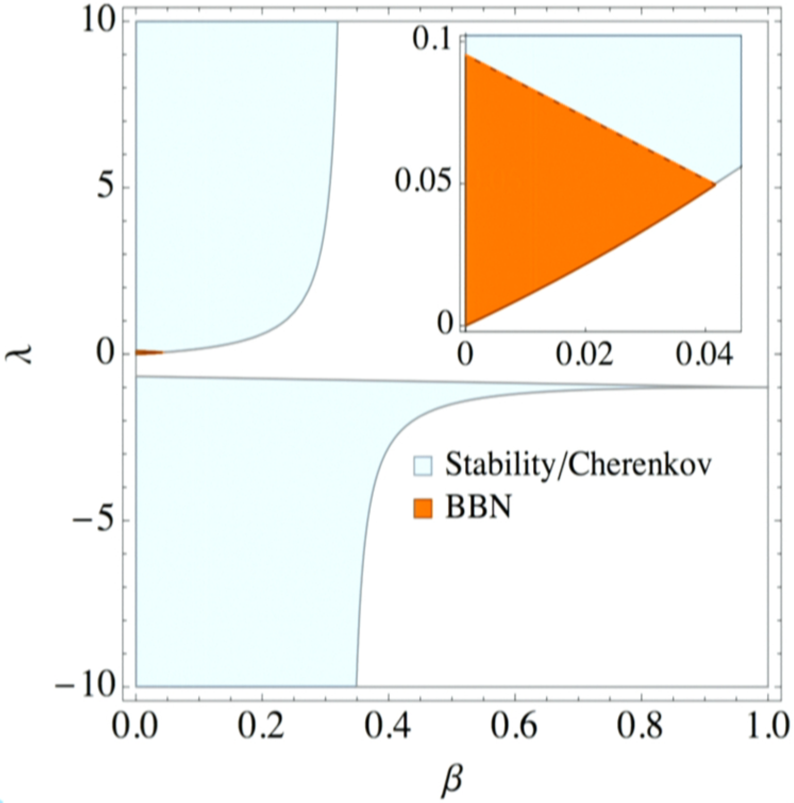
… and from 3 to 2 (khronometric theory) $\lambda = \mu/\xi - 1\,, \quad \beta = (\xi - 1)/\xi$

- c_+, c_- and λ, β enter at PN order > 1 (they are "stronger-field")

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 stability, propagation speeds need to be real (no tachyonic instability)
- Propagation speed must be larger than speed of light to avoid gravitational Cherenkov radiation

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

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

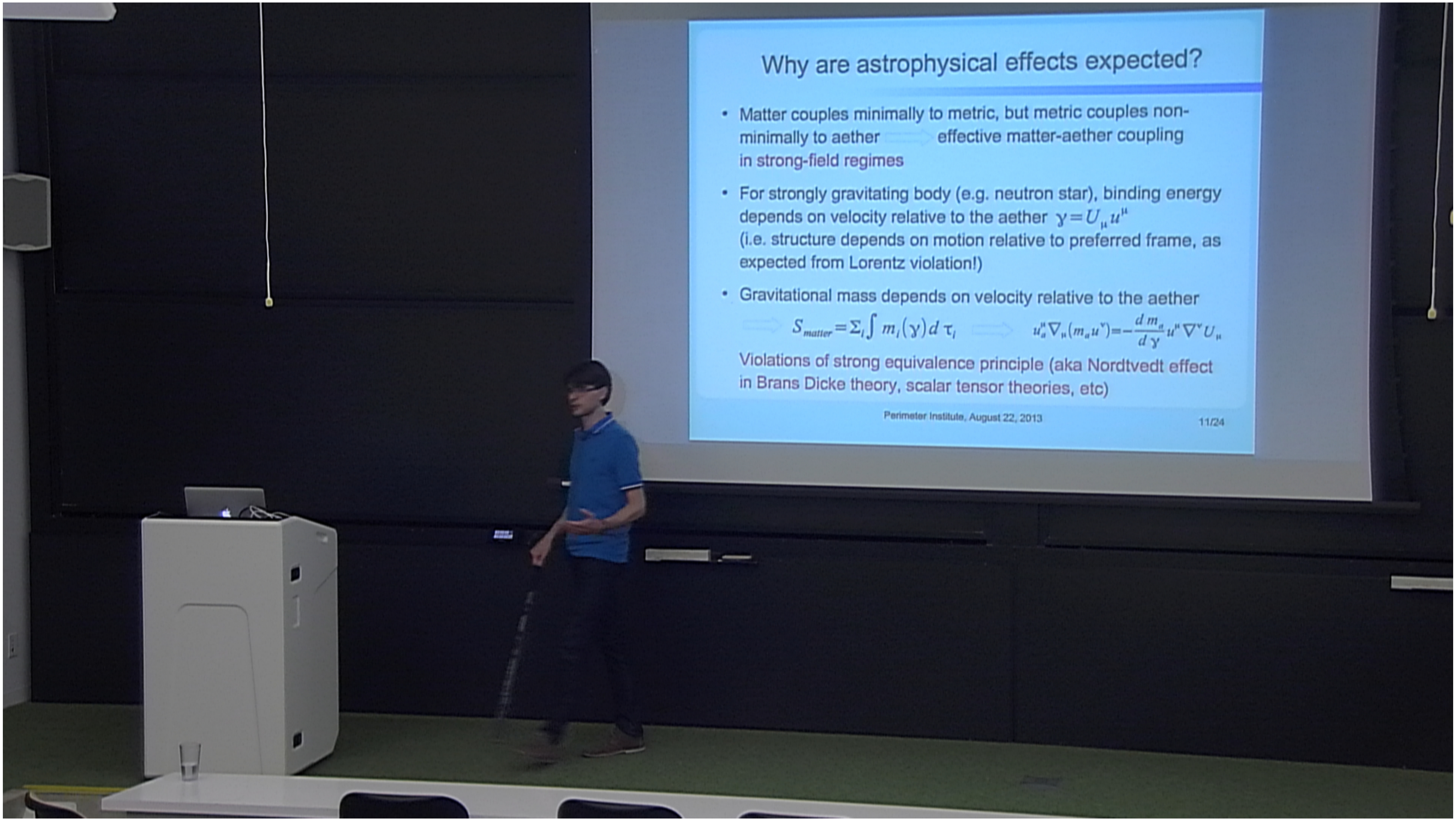
- No constraints from CMB in khronometric theory yet

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

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

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



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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,

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

- 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, Yunes, EB 2013)

- As binary's binding energy decreases, period decreases

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

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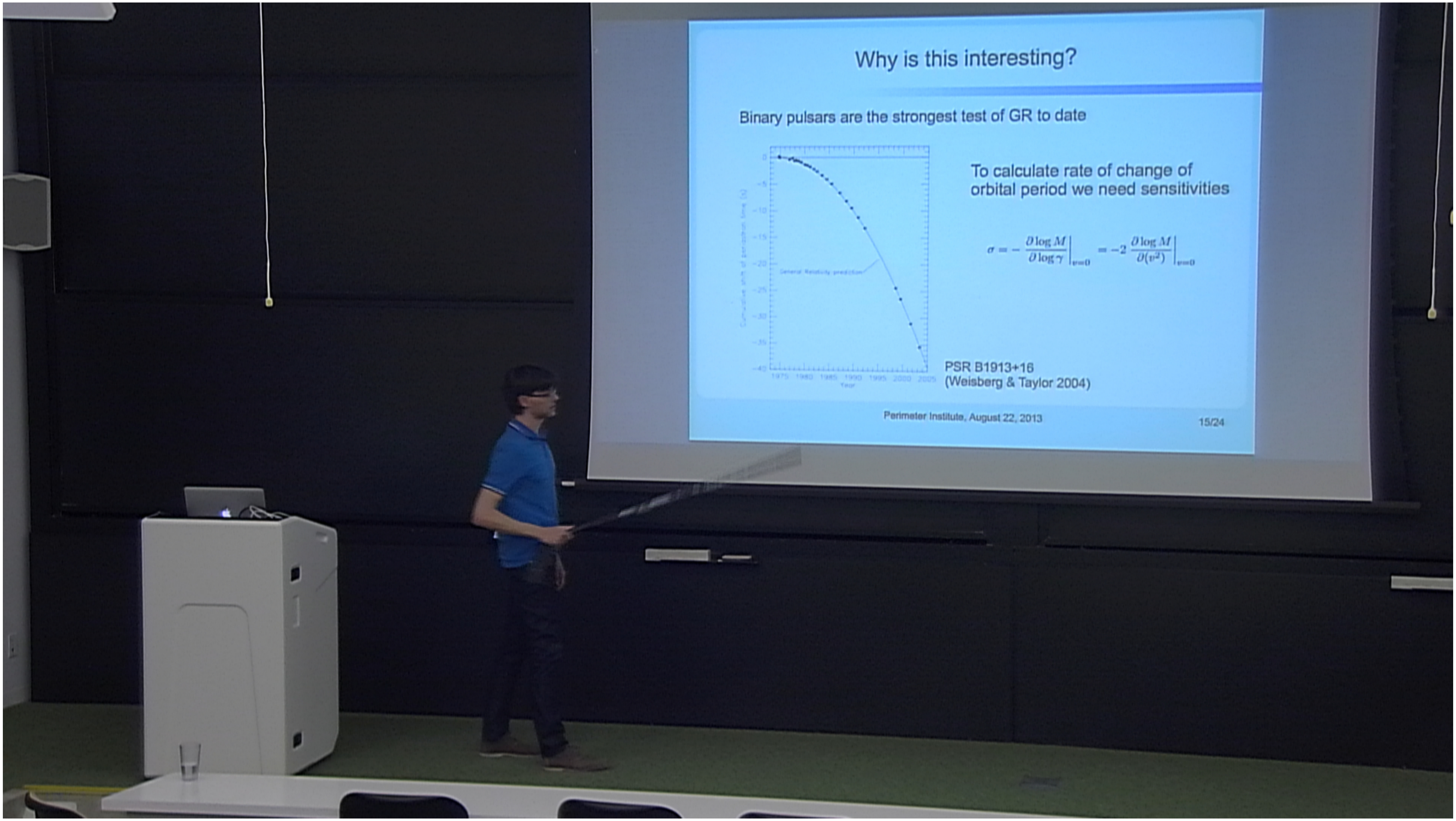

Why is this interesting?
Binary pulsars are the strongest test of GR to date
To calculate rate of change of orbital period we need sensitivities
$\sigma = -\frac{\partial \log M}{\partial \log \gamma}\Big|_{v=0} = -2\frac{\partial \log M}{\partial (v^2)}\Big|_{v=0}$
General Relativity prediction
PSR B1913+16
(Weisberg & Taylor 2004)
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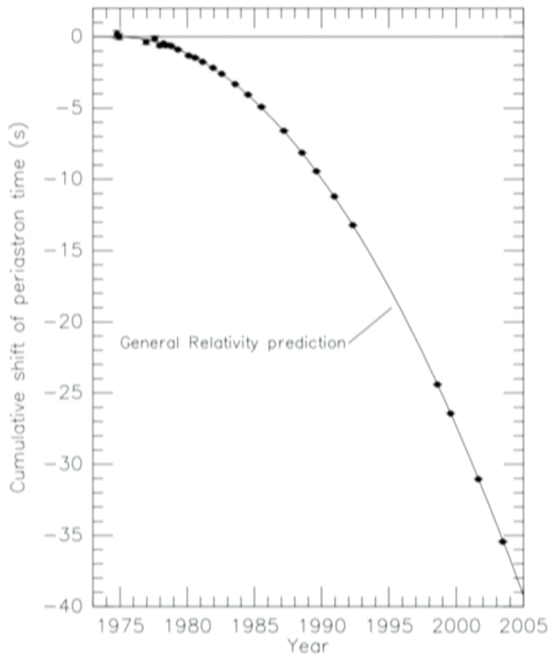

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A strong-field derivation of the sensitivities

- Consider stationary configuration descriving NS and aether moving with small velocity *v* against it, i.e. asymptotically

$$ds^2 = \left[\left(1-\frac{2M_*}{r}\right)dt^2 - \left(1+\frac{2M_*}{r}\right)dr^2 \right.$$
$$-r^2 d\theta^2 - r^2\sin^2\theta d\phi^2$$
$$-2v(B^- + B^+ + 4)\frac{M_*}{r}\cos\theta dt dr$$
$$\left. +v(7+2B^-)M_*\sin\theta dt d\theta\right] \times \left[1+\mathcal{O}\left(v,\frac{1}{r}\right)\right]$$

$$U_\mu dx^\mu = \left\{\left(1-\frac{M_*}{r}\right)dt\right.$$
$$+v\left[1-(1+B^- + B^+ + C^- + C^+)\frac{M_*}{r}\right]\cos\theta dr$$
$$\left. -vr\left[1-(3+2B^- + 2C^-)\frac{M_*}{2r}\right]\sin\theta d\theta\right\}$$
$$\times\left[1+\mathcal{O}\left(v,\frac{1}{r}\right)\right],$$

- All fields are time-independent, so $M = -\int_\Sigma d^3x(\mathcal{L}_g + \mathcal{L}_U + \mathcal{L}_m)$

$$\mathcal{L}_g = \sqrt{-g}g^{\mu\nu}(\Gamma^\alpha_{\mu\lambda}\Gamma^\lambda_{\nu\alpha} - \Gamma^\lambda_{\mu\nu}\Gamma^\alpha_{\lambda\alpha}) \qquad \mathcal{L}_U = -\frac{1}{16\pi G}\sqrt{-g}M^{\alpha\beta}{}_{\mu\nu}\nabla_\alpha U^\mu \nabla_\beta U^\nu$$

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$$U_\mu dx^\mu = \Bigg\{\left(1 - \frac{M_*}{r}\right)dt + v\left[1 - (1 + B^- + B^+ + C^- + C^+)\frac{M_*}{r}\right]\cos\theta dr - vr\left[1 - (3 + 2B^- + 2C^-)\frac{M_*}{2r}\right]\sin\theta d\theta\Bigg\} \times \left[1 + \mathcal{O}\left(v, \frac{1}{r}\right)\right],$$

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A strong-field derivation of the sensitivities

- Taking difference between configurations with *v* and *v*+*δv*, bulk terms disappear (because we are on shell).
- Surface terms from metric vanish because of boundary conditions, and those from matter vanish because no matter at spatial infinity

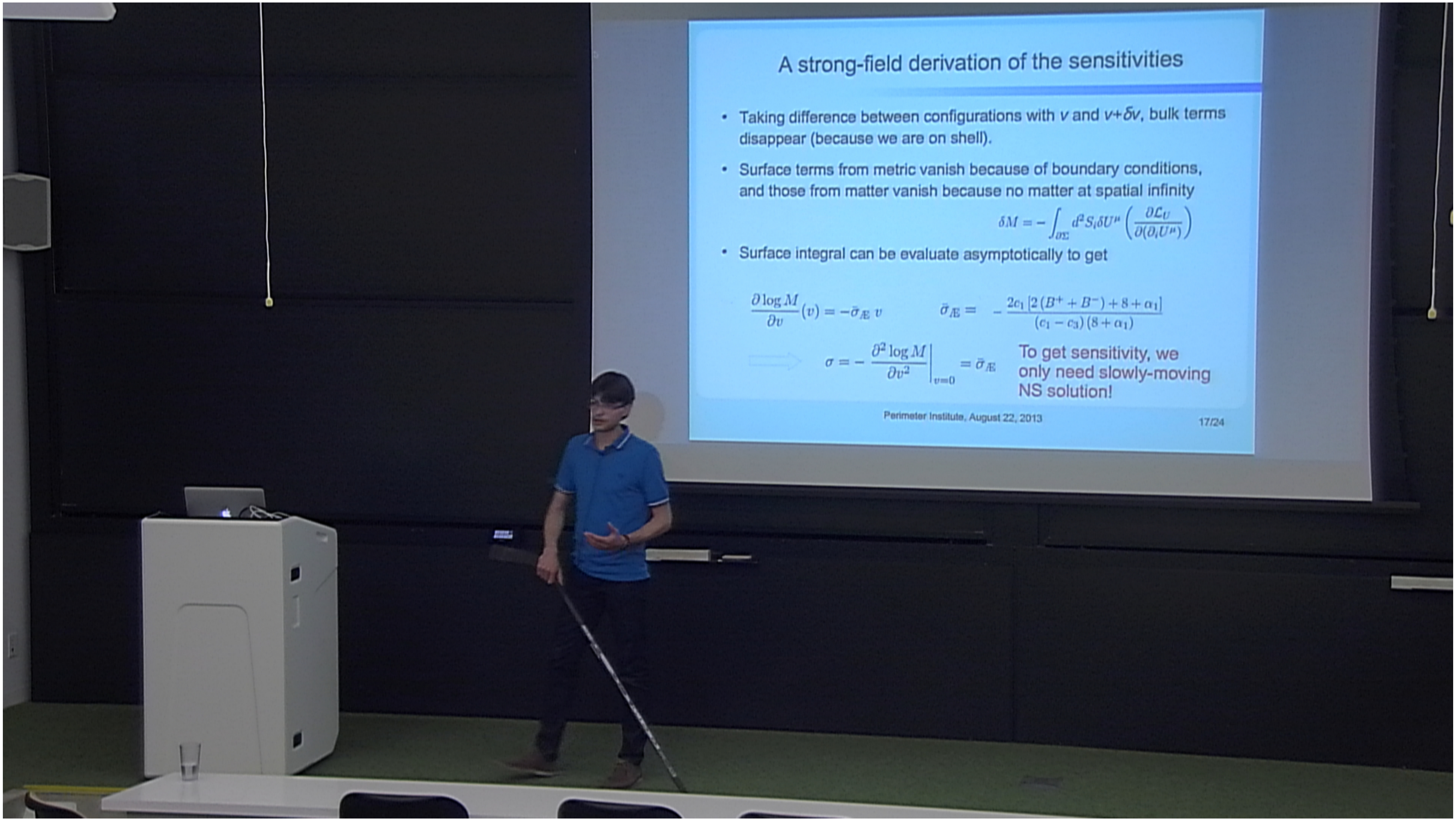
$$\delta M = -\int_{\partial\Sigma} d^2 S_i \delta U^\mu \left(\frac{\partial \mathcal{L}_U}{\partial(\partial_i U^\mu)} \right)$$

- Surface integral can be evaluate asymptotically to get

$$\frac{\partial \log M}{\partial v}(v) = -\bar{\sigma}_{Æ}\, v \qquad \bar{\sigma}_{Æ} = -\frac{2c_1\left[2\left(B^+ + B^-\right) + 8 + \alpha_1\right]}{(c_1 - c_3)\,(8 + \alpha_1)}$$

$$\Rightarrow \quad \sigma = -\left.\frac{\partial^2 \log M}{\partial v^2}\right|_{v=0} = \bar{\sigma}_{Æ}$$

To get sensitivity, we only need slowly-moving NS solution!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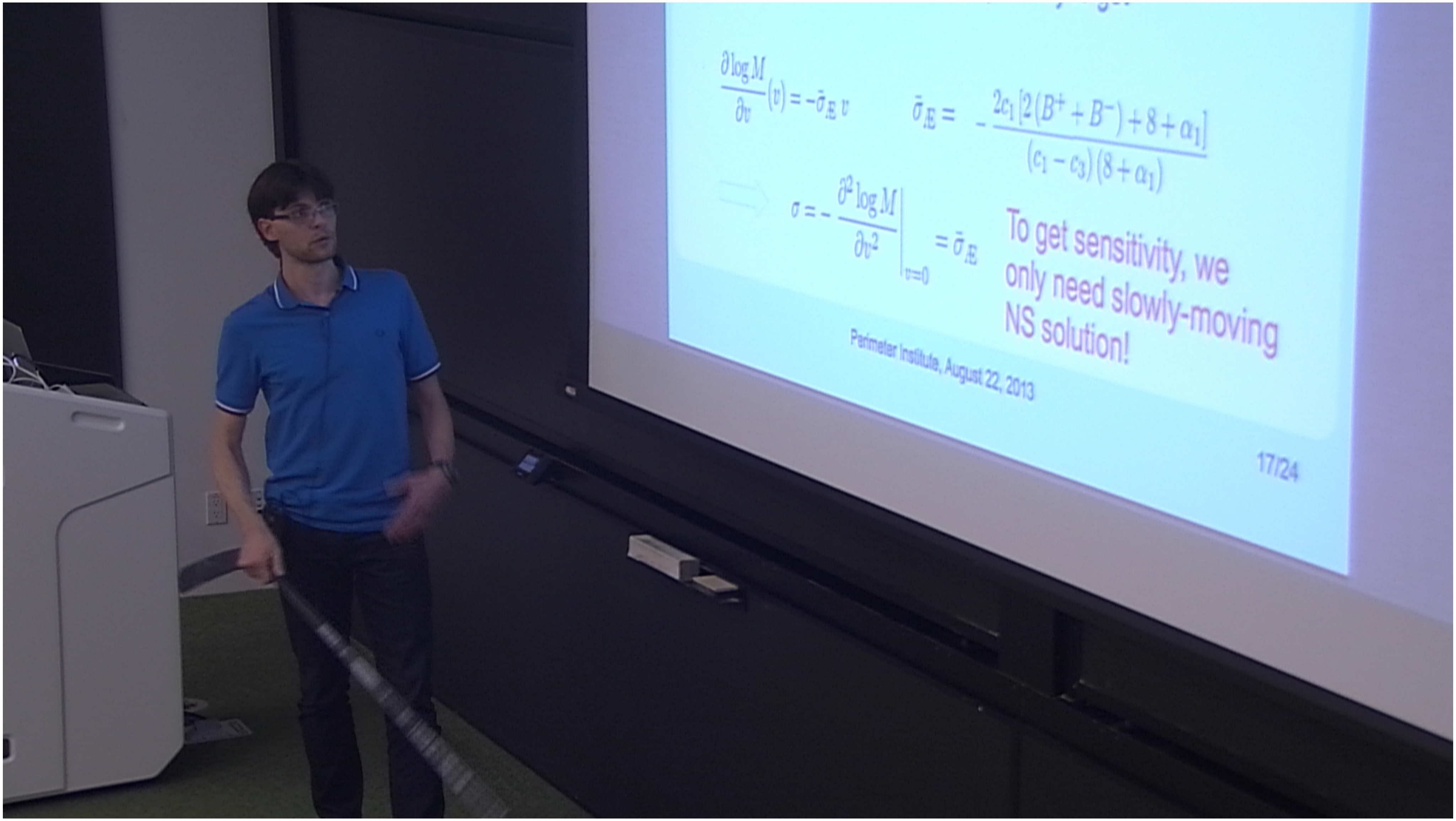
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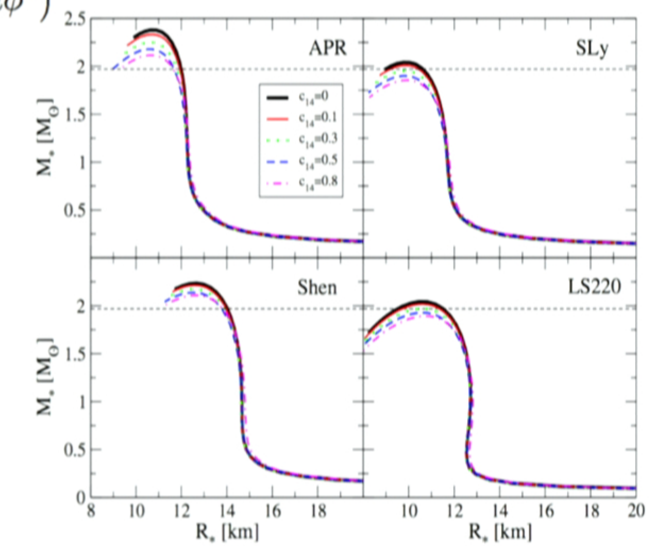
Neutron stars at order $O(v)^0$

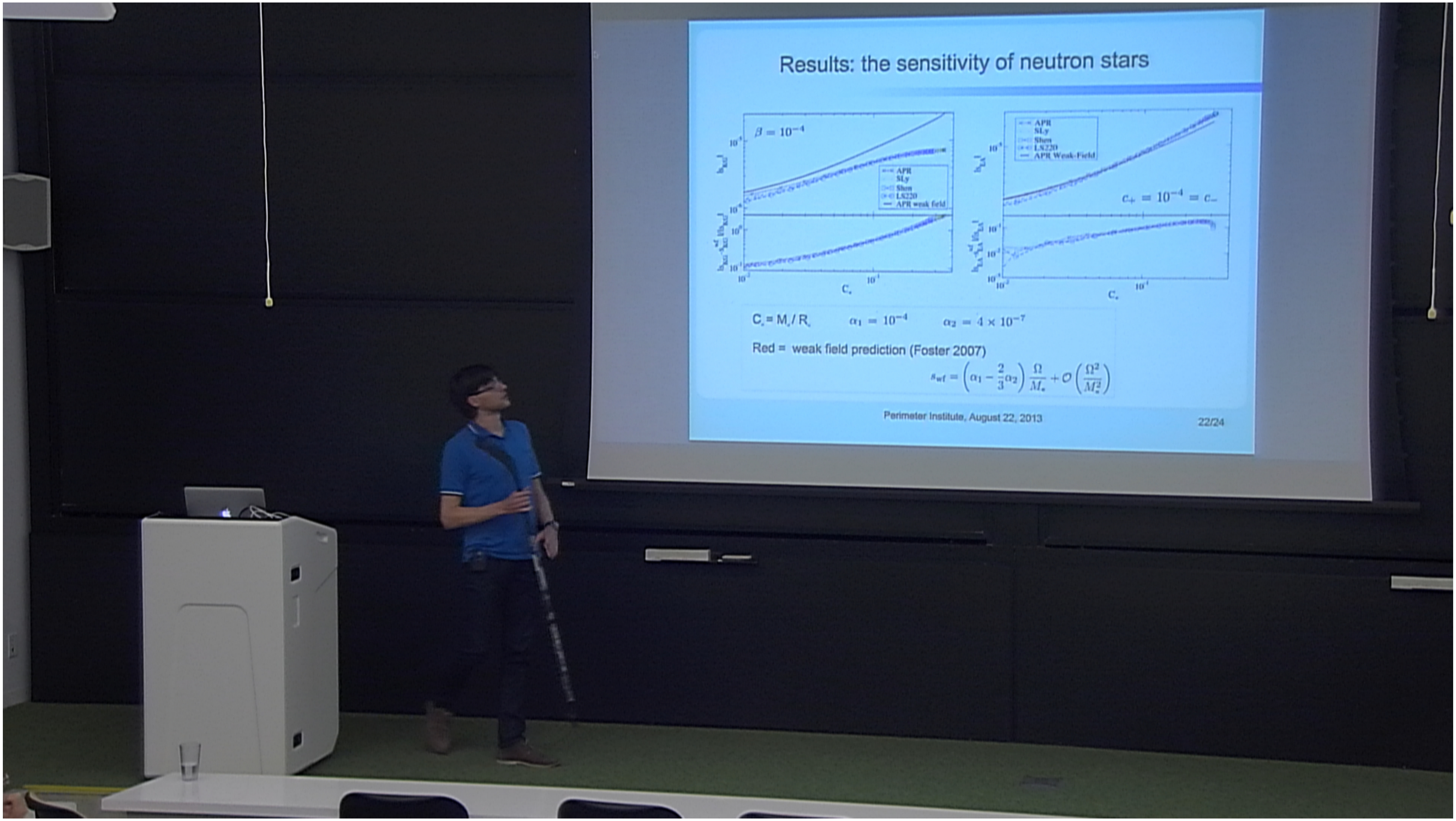
- Static spherically symmetric, asymptotically flat solutions, same in AE and khronometric theory
- Aether and fluid are at rest

$$ds^2 = e^{\nu(r)}dt^2 - e^{\mu(r)}dr^2 - r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)$$

$$\boldsymbol{U} = \boldsymbol{u} = e^{\nu(r)/2}dt$$

- Solutions found by imposing
  - regularity at center
  - junction condition at surface (i.e. no jumps in potentials whose derivatives enter field eqs)
  - asymptotic flatness
- Various EOS





Results: the sensitivity of neutron stars
$\beta = 10^{-4}$
APR
SLy
Shen
LS220
APR weak field
C_*
APR
SLy
Shen
LS220
APR Weak-Field
$c_+ = 10^{-4} = c_-$
C_*
$C_* = M_*/R_*$ $\alpha_1 = 10^{-4}$ $\alpha_2 = 4 \times 10^{-7}$
Red = weak field prediction (Foster 2007)
$s_{wf} = \left(\alpha_1 - \frac{2}{3}\alpha_2\right)\frac{\Omega}{M_*} + \mathcal{O}\left(\frac{\Omega^2}{M_*^2}\right)$
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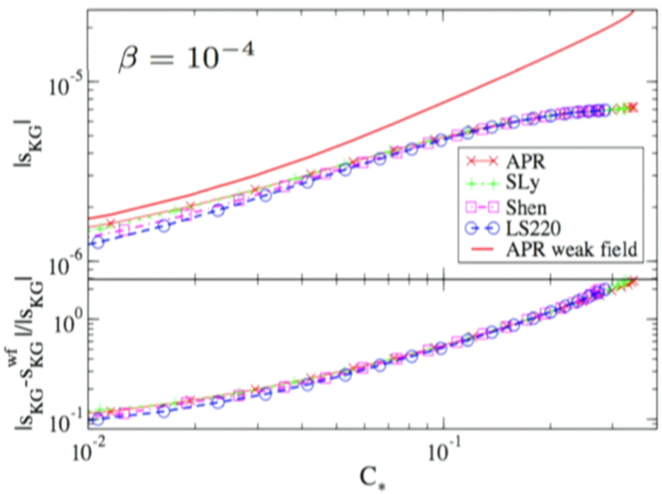
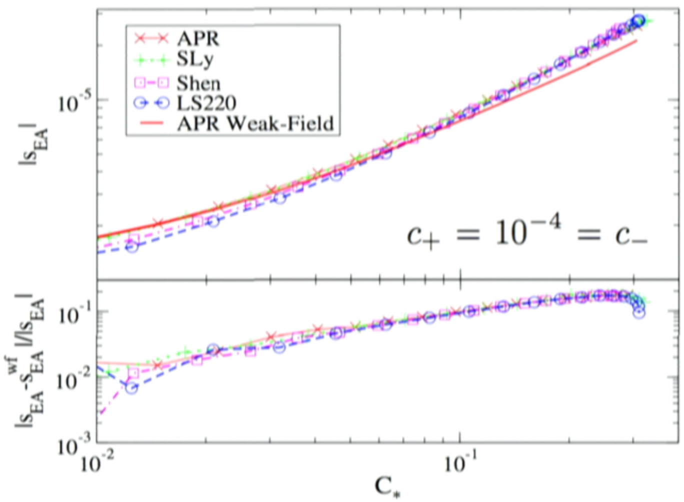


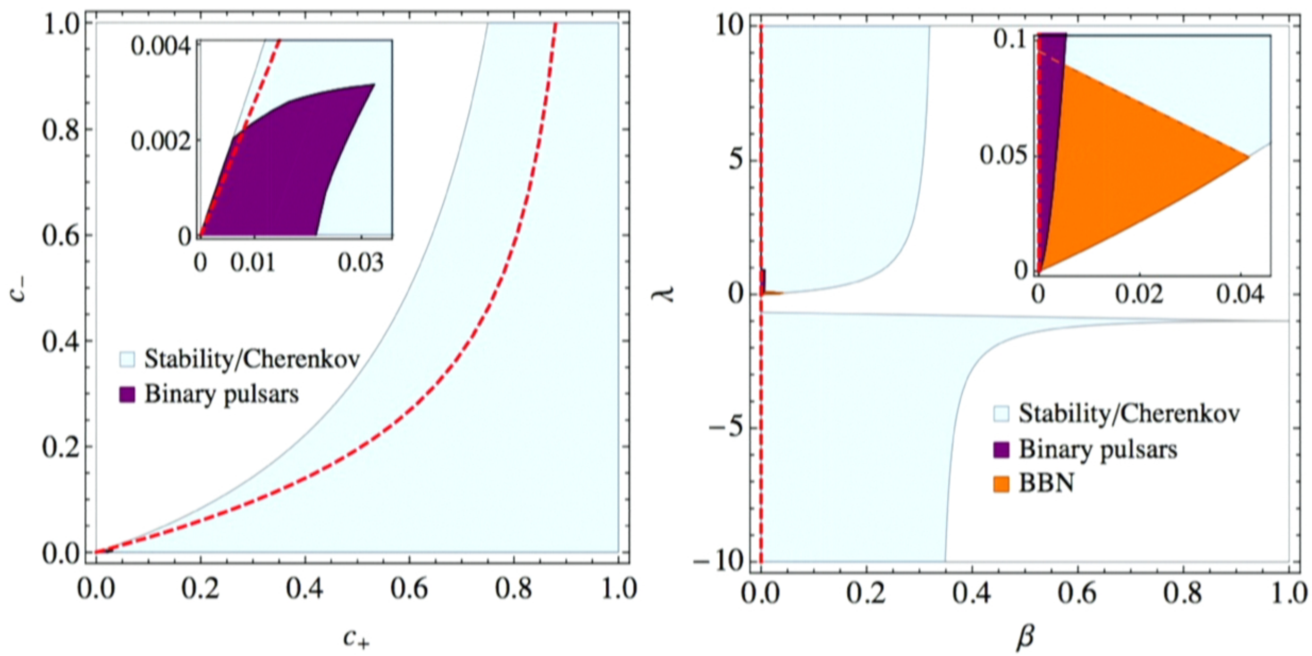


$C_* = M_* / R_*$ $\alpha_1 = 10^{-4}$ $\alpha_2 = 4 \times 10^{-7}$

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



- Red = weak field prediction for $\alpha_1 = \alpha_2 = 0$ (by requiring exactly same fluxes as GR)
- Combined constraints from 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)

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Conclusions

- Lorentz violations in gravity generically introduces violations of strong equivalence principle and thus dipole emission
- Placing precise constraints with binary pulsars requires exact calculation of sensitivities (weak field approximation inadequate)
- Sensitivities can be obtained exactly from slowly moving, strong-field neutron star solutions
- Resulting constraints are strong-field and ~ order of magnitude stronger than previous ones