An example: Using short GRBs to limit Birefringence in Chern-Simons-modified gravity

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Yunes, ROS, Owen, Alexander: [arXiv:1005.3310]

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Workshop on Gravitational wave tests of alternative gravity

Outline

- Part I: Parity violation and Chern-Simons gravity
- Part II: Theorists perspective
  - Birefringence in Chern-Simons gravity
  - Short GRB test
  - Matters of concern
    - Theory: Propagation resonance; generation effects
    - Data analysis: Finite opening angle; accurate binary parameters (modified Fisher)
- Part III: Discussion: Data analysis decisions
  - Models to deliverables?
  - Open floor

Parity violation in GR

Why parity violation?

- Often violated (e.g., through anomalies in QM)

- Expected in many modified-gravity theories

  (effective theories; string theory; loop quantum gravity)

- Parity violation = generic deviation from GR

How to do it?

- Phenomenologically:

$$\epsilon^{abcd} R_{ab} R_{cd} \qquad\qquad \epsilon^{abcd} R_{abcd}$$

$$\epsilon^{\cdots} R_{\ldots} R_{..}{}^{\cdot\cdot} = R_{\ldots} (*R)^{\cdots}$$

- From theory: CS term follows naturally from theories above

CS gravity

Modified action

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left(R + \frac{1}{4}\theta\,\mathbf{R}\,{}^*\mathbf{R} + (\nabla\theta)^2 + V(\theta)\right)$$

Field equations

$$\mathbf{G} + \mathbf{C} = 8\pi\mathbf{T},$$

$$C^{\alpha\beta} = (\nabla_\gamma\theta)\,\epsilon^{\gamma\delta\rho(\alpha}\nabla_\rho R^{\beta)}{}_\delta + (\nabla_\gamma\nabla_\delta\theta)\;{}^*R^{\delta(\alpha\beta)\gamma}\,,$$

$$\Box\theta + \frac{dV}{d\theta} = -\frac{1}{4}\mathbf{R}{}^*\mathbf{R}.$$

Scalar propagation [this paper]

Assume slow, cosmological-scale variation

Birefringence

Phenomenologically: Propagation asymmetry

$$\begin{pmatrix} h_{R,k}(t) \\ h_{L,k}(t) \end{pmatrix} = e^{-i\omega t} \begin{pmatrix} u+v & 0 \\ 0 & u-v \end{pmatrix} \begin{pmatrix} h_{R,k}(0) \\ h_{L,k}(0) \end{pmatrix}.$$

Birefringence in CS

Phenomenologically: Propagation asymmetry

$$\begin{pmatrix} h_{R,k}(t) \\ h_{L,k}(t) \end{pmatrix} = e^{-i\omega t} \begin{pmatrix} u+v & 0 \\ 0 & u-v \end{pmatrix} \begin{pmatrix} h_{R,k}(0) \\ h_{L,k}(0) \end{pmatrix}.$$

Form in CS gravity:

$$\begin{aligned} v &= \pi a_0 f_0 \left(\frac{\dot\theta_0}{a_0} - \frac{\dot\theta_s}{a_s} \right) \\ &= \pi f \delta(\dot\theta/a) \\ &\approx \pi f D \frac{\delta(\dot\theta/a)}{\delta D} \end{aligned}$$

Linear limit

$$Z = a^2 - \kappa\theta'$$

$$[h_k'' + k^2 h_k] + \frac{Z_k'}{Z_k} h_k' = 0$$

$$h_\kappa(\eta) = \sqrt{\frac{Z(\eta_s)}{Z(\eta)}} e^{\pm i\kappa\eta}.$$

$$v = \frac{1}{2} \frac{a(\eta)}{a(\eta_s)} \left[\sqrt{\frac{Z_R(\eta_s)}{Z_R(\eta)}} - \sqrt{\frac{Z_L(\eta_s)}{Z_L(\eta)}} \right].$$

Example: face-on, low-mass inspirals?

Simplest source: $|h(f)| \sim f^{-7/3}$, circular, optimally oriented

Optimally matched SNR:

$$\frac{\rho^2}{\rho^2_{GR}} = 1 + 2\langle v \rangle$$

$$= 1 + 2\langle f \rangle D\pi \frac{\delta(\dot{\theta}/a)}{\delta D}$$

$$< f > \equiv \frac{\int f^{-4/3}/S_h}{\int f^{-7/3}/S_h}$$

Expected variation *slow*:

$$\frac{\delta(\dot{\theta}/a)}{\delta D} \equiv H_o \dot{\theta} q \qquad q \simeq O(1)$$

Assume: ***known*** **binary, distance, & GR-consistent**:

$$\frac{|\delta\rho|}{\rho} \leq O(1) \rightarrow |\dot{\theta}| \leq \frac{1}{(\rho_{GR} D)\langle f \rangle \pi H_o q}$$

$$\leq \frac{1}{\rho_{det} D_h \langle f \rangle \pi H_o q}$$

(1) Constraint *independent* of distance

(2) Calibration error smallest for *faintest* source

Short GRB constraint

Constraint:

$$|\dot{\theta}| \leq O(1000\mathrm{km})(D_h/300\mathrm{Mpc})^{-1}$$

mod sky position

Concerns:

- Physical issues
  - Resonant propagation
  - Opening angle of burst
  - Host associations
  - Variation in θ field (direction; time)
  - Strong-field generation effects in CS?
  - Physical signal model (higher harmonics, etc)
- Practical issues:
  - Calibration error [10%*8=0.8~O(1)]
  - Big changes to analysis?
    - Overlap with standard GR templates?
    - Rejection/vetoing if amplification strong?
    - Long coherent match times?
  - Consistent mass, misalignment, ‘v’ measurement?
  - Disentangle CS generation, propagation? [CS-Fisher?]

For short/nonresonant analysis, less problematic: good GR overlap

Short GRB constraint: Issues

Resonant propagation:

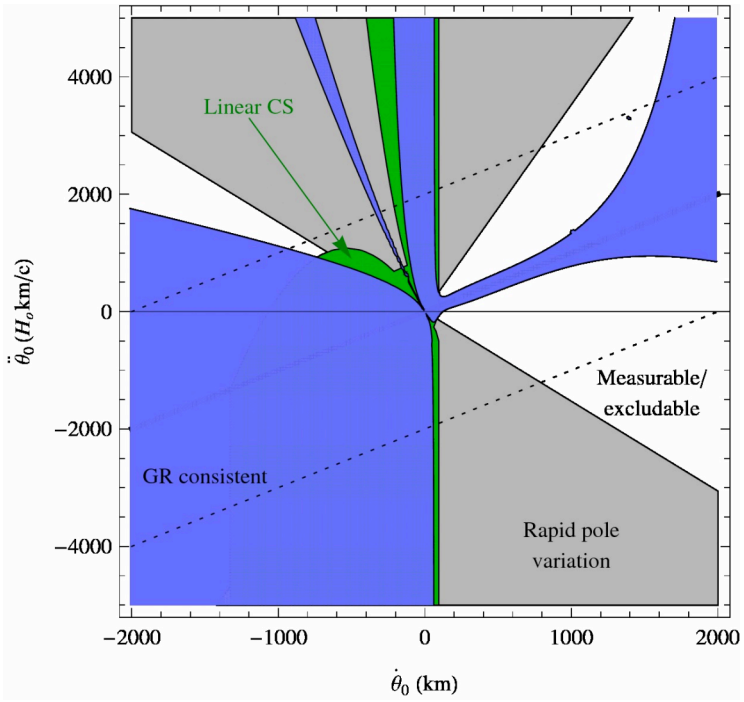
- One frequency ***strongly*** resonant at each time [=evolving pole in propagator]

$$h_\kappa(\eta) = \sqrt{\frac{Z(\eta_s)}{Z(\eta)}} e^{\pm i\kappa\eta} \,.$$

$$Z = a^2 - k\theta'$$

- Worst case:
  - Cosmological expansion limits resonance
  - *Small* frequency range stretched over ~ 1 yr
  - Most amplification in other frequencies
- Duration-limited case:
  - Data-taking time limits resonance
  - ~ identical to above

- Constraints more complicated



Short GRB constraint: Issues

Misalignment of orbit axis with LOS:

- Can happen
  - EM emission opening angle wide?
  - Source model (e.g., strong BH spins, tidal disruption engine)

- Not circularly polarized?

- Implications:

  single source constraint

  - Constrain correlated parameter (~ v - cos(inc))
  - **Polarization** measurements partially break ambiguity

  multiple-source constraint

  Disentangle

Short GRB constraint: Issues

Simultaneous constraints

Templated follow-up model (?) with:

- Binary masses
- Amplification & orbit inclination
- Spin (BH-NS)
- CS generation effects
- Any other modified-gravity parameters

single-event : unpleasant joint likelihood

: weakly separable Fisher (strong vs weak phase/amp changes)

multi-event : separate uncertainties

modified-GR : common effect required

source-specific

Short GRB constraint: Summary

Constraint:

$$|\dot{\theta}| \leq O(1000\mathrm{km})(D_h/300\mathrm{Mpc})^{-1}$$ mod sky position

Concerns:

- Physical issues
  - Resonant propagation -> more complicated but solved
  - Opening angle of burst -> if narrow,ok; if wide, complicated
  - Host associations --> only problem if null event (suppression); focus on amplifications?
  - Variation in θ field (direction; time) --> map field vs direction; needs many events
  - Strong-field generation effects in CS? --> hard; in progress
- Practical issues:
  - Calibration error [10%*8=0.8~O(1)]
  - Big changes to analysis?
    - Overlap with standard GR templates?
    - Rejection/vetoing if amplification strong?
    - Long coherent match times?
  - Consistent mass, misalignment, 'v' measurement?
  - Disentangle CS generation, propagation? [CS-Fisher?]

For short/<u>nonresonant</u> analysis, less problematic: good GR overlap

Discussion

- How would you limit weak parity violation?
  - Single event?
  - Stacking/ joint likelihood from multiple sources?
    - Bias towards left or right handed?

- What about limiting
  - Strong violation
    - all sources one handed? All sources one-handed in a certain band?
    - How important is network topology (=direct polarization limits)?
  - Resonant propagation? [generically]