Parity violating gravitational waves

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Tests of Gravity @ Case Western

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Outline

- Chern-Simons gravity
  - What & why, the extra field, stationary tests
- Gravitational waves
  - Polarization, propagation, binary mergers
- Low-frequency GW
  - Space-based detectors, SMBH mergers, parity violation
- High-frequency GW
  - Ground-based detectors, GW/GRB mergers, parity violation
- What next?

Chern-Simons gravity: What & why

- Add an extra term to the action (Jackiw & Pi 2003)

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

- Could also write as $\theta R \epsilon R$ or $K \cdot \nabla \theta$

- Standard model (chiral anomaly & lepton number)
- String theory (Green-Schwarz anomaly cancellation)
- Loop quantum gravity (Ashtekar et al 1989)

- Also consider generic parity violation (Contaldi et al 2008)

Chern-Simons gravity: The extra field

- “Canonical” CS gravity (Jackiw & Pi 2003)
  - Fix $\nabla\theta$ wrt and parallel to cosmological time

- Dynamical CS gravity (Smith et al 2008)
  - Let $\nabla\theta$ have a life of its own

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

  - Plus it can couple to fermions (Alexander & Yunes 2008)

Chern-Simons gravity: Stationary tests

- New gravitomagnetic parameter in parametrized post-Newtonian expansion (Alexander & Yunes 2007), ie spin and orbital angular momenta:

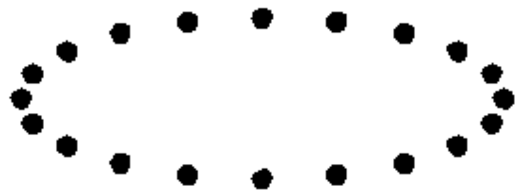
$$g_{0i} = -\frac{7}{2}V_i - \frac{1}{2}W_i + 2\dot{\theta}(\nabla \times V)_i$$

- Plus oscillating terms for finite bodies (Smith et al 2008)
- Earth orbiting satellites: $\dot{\theta} \lesssim 3000 \text{ km}$
- Double pulsar (Yunes & Spergel submitted): $\lesssim 4 \times 10^{-9} \text{ km}$

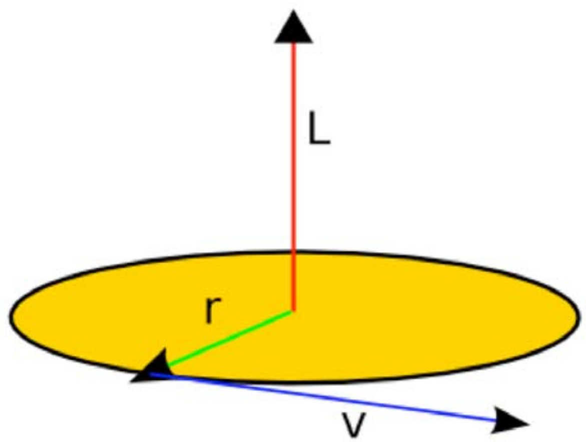
- But that's the static case … etc

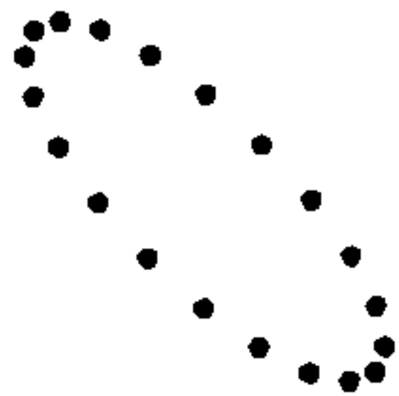
Gravitational waves: Polarization

- Linear: "plus" and "cross"



- Circular: rotation axis





Gravitational waves: Propagation

- General relativity: propagate like light, incl. cosmology
  - Perturbation $h \propto a^{-1} \exp -i[\phi(\eta) - \kappa \cdot \chi]$
  - Phase shift $i\phi'' + (\phi')^2 + \mathcal{H}' + \mathcal{H}^2 - \kappa^2 = 0$

- CS gravity: cosmological amplitude birefringence (Alexander & Martin 2005)

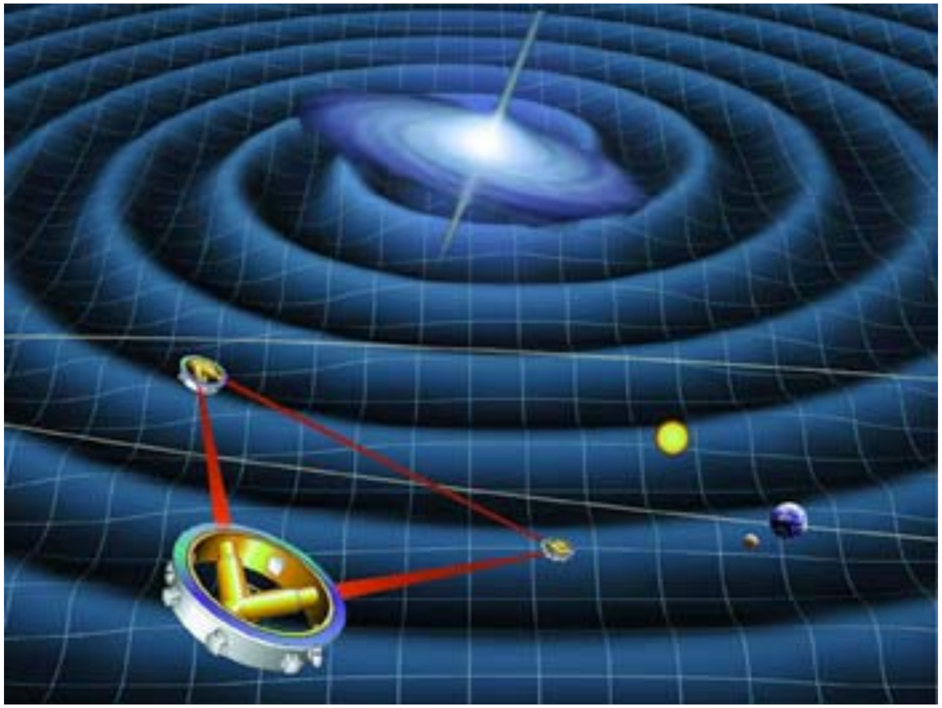
$$\phi'' = \cdots \pm \frac{\phi' \kappa}{a^2} \frac{(\theta'' - 2\mathcal{H}\theta')}{1 \mp \kappa\theta'/a^2}$$

Gravitational waves: Binary mergers

- Binary mergers are the one thing we are guaranteed to detect (hi-f in a few years, low-f later)
- Other sources
  - Stochastic GW background (Seto & Taruya 2007)
  - Effect on microwave background (Alexander & Martin 2005)
  - Pulsars, supernovae (…)
- Waveforms
  - Plus $h_+ \propto f^{-7/6}(1+\cos^2\iota)e^{i\phi}$
  - Cross $h_\times \propto f^{-7/6} 2i\cos\iota\, e^{i\phi}$
  - Observed $h = F_+ h_+ + F_\times h_\times$ (sky position & polarization angle)
  - Signal to noise ratio $\rho^2 \propto \int df |h|^2 / S_h(f)$

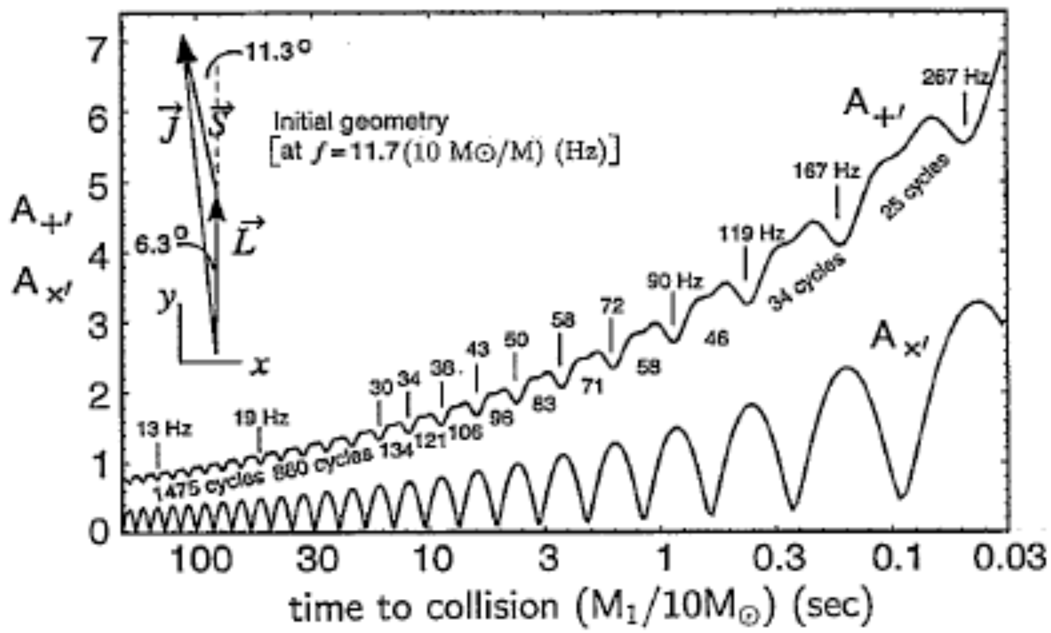
Low-frequency GW:
Space-based detectors

- Laser Interferometer Space Antenna LISA (NASA/ESA)
- To launch…um…
- 3 craft in solar orbit(s)
- Spaced 5 million km
- GWs 10^{-4} to 10^{-1} Hz
- Signals modulated by orbital tilt



Low-frequency GW: Supermassive black hole mergers

- LISA will see these things up to z = 30
- Signal-to-noise 10^3-10^4 at z = 1
- Spin-orbit precession common … (Cutler & Thorne 2002)



Apostolatos et al 1994

Low-frequency GW:
Parity violation

- LISA case solved in Alexander et al (2008):

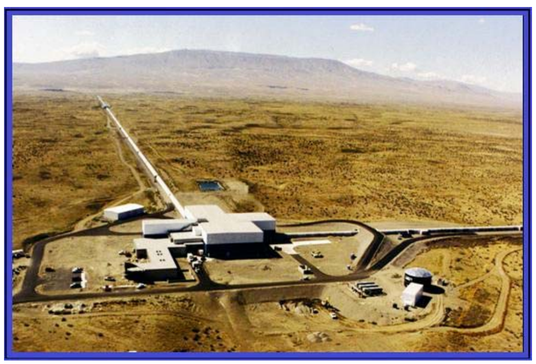
$$\langle\dot{\theta}\rangle H_0 = \int dz \left[a(z) d\theta/dz \;\&\; b(z) d^2\theta/dz^2\right]$$

- CS effectively distorts inclination angle
- Spin-orbit precession tells you how inclination should evolve in GR; know masses & spins to great accuracy so compare to GR inclination w/Fisher matrix
- End result: $\langle\dot{\theta}\rangle \lesssim 10^4$ km

High-frequency GW: Ground-based detectors

- LIGO, Virgo, … (10 to 10^4 Hz) (Abbott et al 2004-on)
  - Initial: 2005-2007, strain noise 3×10^{-23} at 150Hz
  - Enhanced: July 2009-2010?, strain noise /= 2
  - Advanced: 2014?, strain noise /= 10 or more (& lower freq.)

LIGO

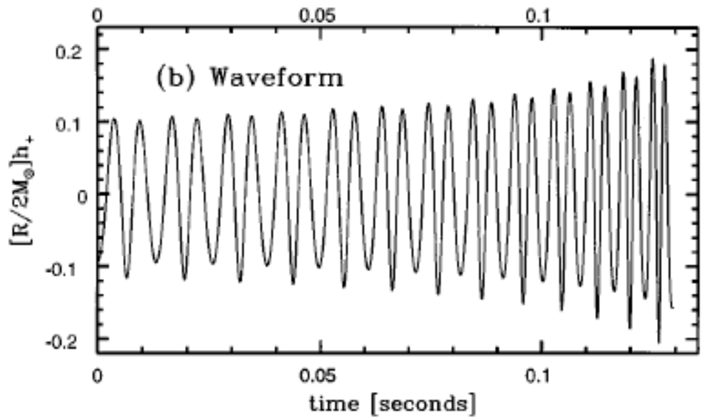


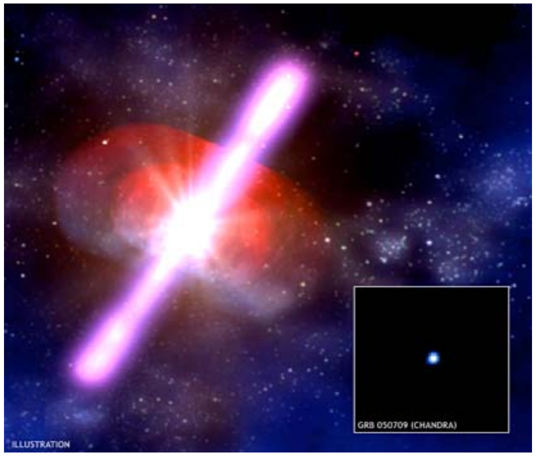
Virgo

- In concert w/photon detectors (ground or space)
  - Jodrell Bank, GRBs, RXTE, …, SkyMapper, …

High-frequency GW: GRB/GW events

- BH/NS or NS/NS … purely circular polarization





- GRB sky position enables GW distance determination
- Independent distance (host galaxy or afterglow) in many
- Advanced LIGO: Detectable to z~0.1 or more w/BH/NS

High-frequency GW: Parity violation

- Source distance in wavelengths (Alexander et al in prep)
- Weak CS high-frequency GW limit: $\delta\phi = \mp i 2\pi f z \dot{\theta}_0$
- Error in distance $\sigma_D / D = 1/\rho$

$$\rho \rightarrow \rho \left(1 \pm 2\pi z \dot{\theta}_0 I_4 / I_7\right)$$

- Result: 300 km, even w/systematics
- And less interesting polarization: full $\langle \dot{\theta} \rangle \propto \int \frac{\cdots}{1 - \kappa\theta'}$
- Pole in other polarization buys at least 10× more: 30 km

What next?

- Double pulsar result nails it for canonical CS theory
- But dynamical theory is much more interesting
- And think more experimentally
  - Tests of radiative sector are a different animal
  - Parity violation in general, not just Chern-Simons

- That was propagation, generation is another thing
  - Nonlinear effects (in propagation too)
  - Coupling to matter is barely skimmed so far