Title: Was Einstein Right Handed?

Date: Nov 25, 2009 02:00 PM

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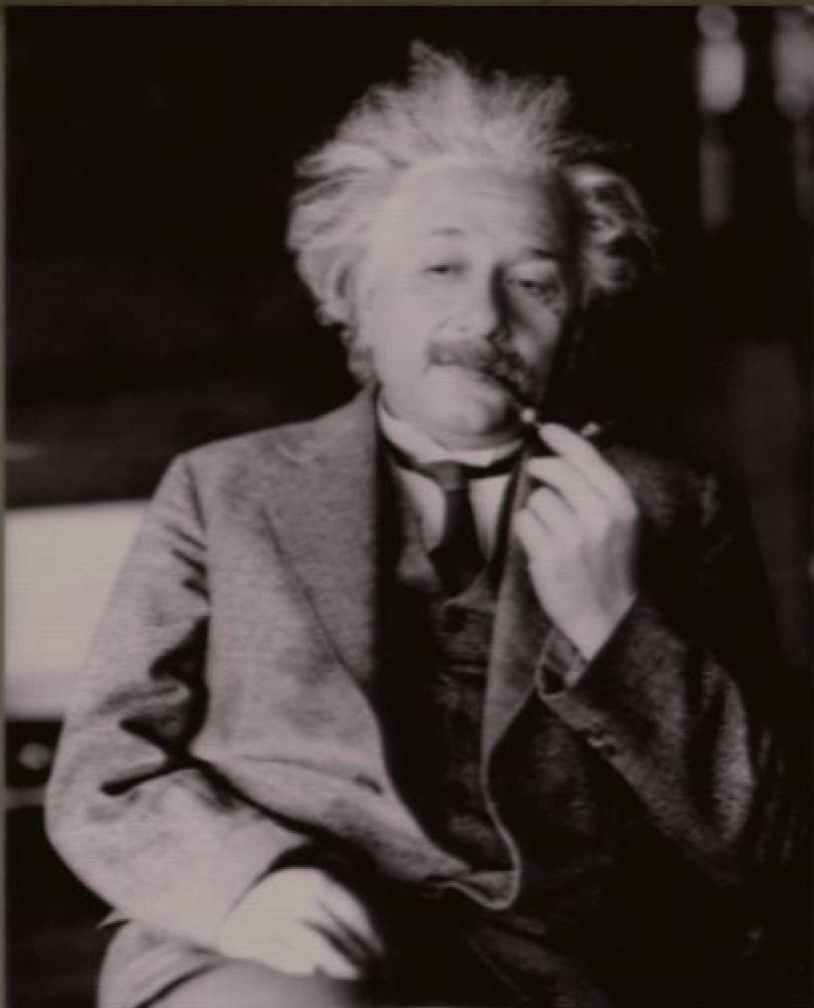
Abstract: Of all four forces only the weak interaction has experimentally exhibited parity violation. At the same time observations suggest that general relativity may require modification to account for dark matter and dark energy. Could it be that this modification involves gravitational parity violation? Many of the dominant approaches to quantum gravity, such as string theory and loop quantum gravity, point to an effective parity violating extension to general relativity known as Chern-Simons General Relativity (CSGR). In this colloquium I will discuss the uniqueness and phenomenological implications of parity violation in CSGR. In particular, I will discuss how CSGR can work together with inflation to generate the cosmic baryon asymmetry in a most economical fashion, through gravitational waves; and its predictions for upcoming CMB polarization experiments. I will also discuss current predictions of CSGR on binary pulsars, neutron stars and prospects for the LISA/LIGO gravitational wave detectors. While we focus on a specific theory for concreteness, some of the results presented in this colloquium can be seen as model independent.

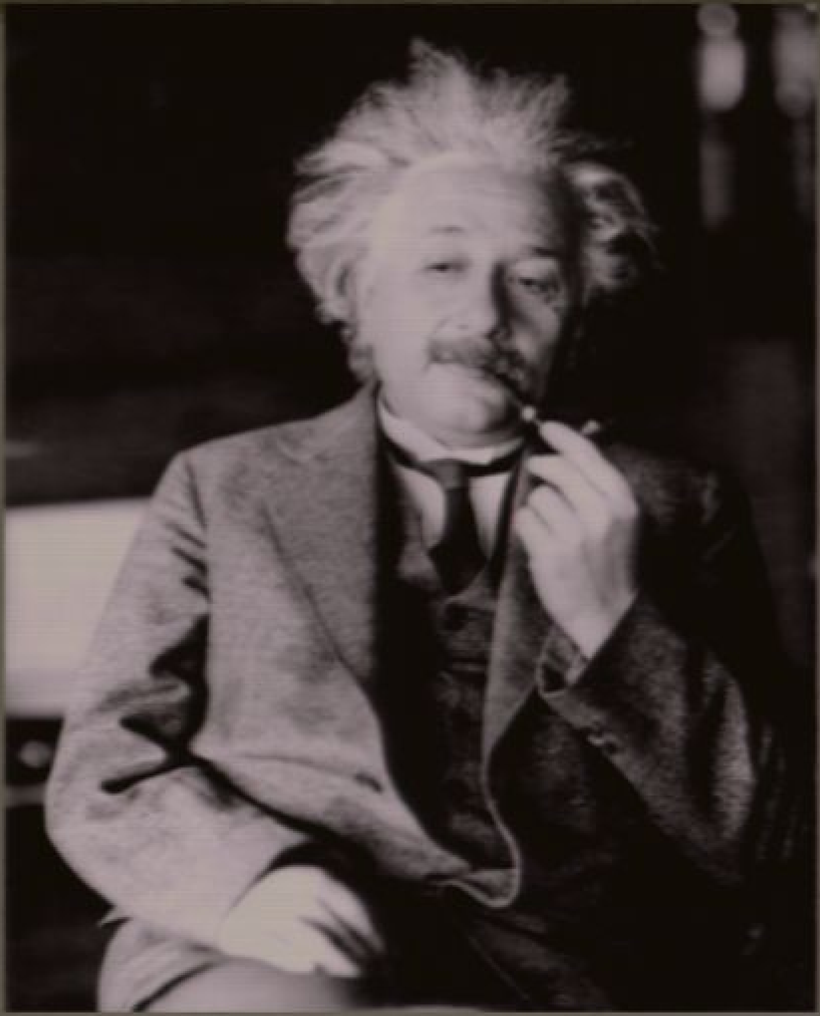
WAS EINSTEIN LEFT-HANDED?

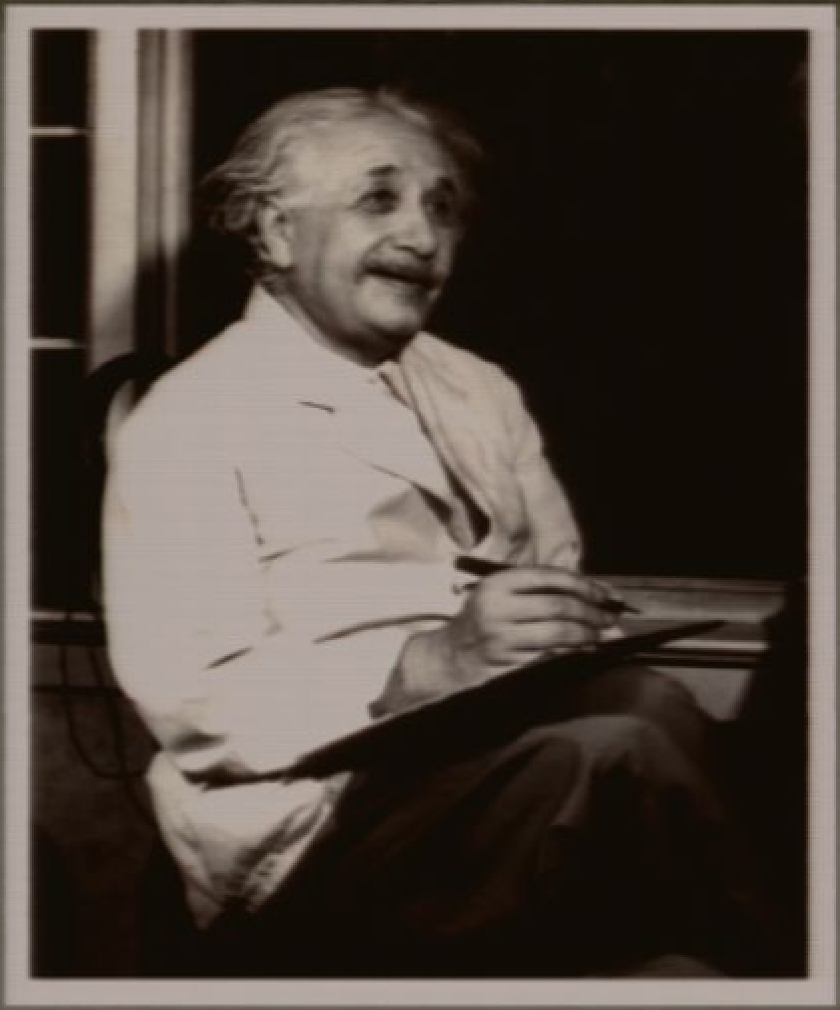
Stephon Alexander
Haverford College
&
The Institute for Gravitation and the Cosmos
Penn State

Perimeter Institute
Colloquium



Left-handed !!





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Right-handed?

Before we look at Einstein, let's look at Maxwell!

$$S \sim \int (E^2 + B^2)$$

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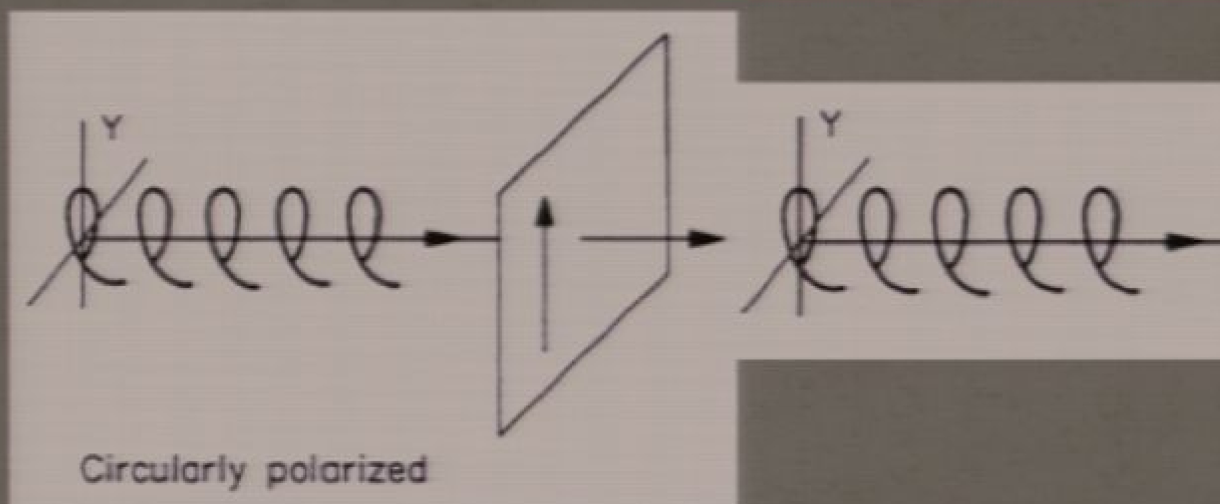
P[B] = −B but P[S] = + S !!

$\boxed{\text{Maxwell is ambidextrous}}$



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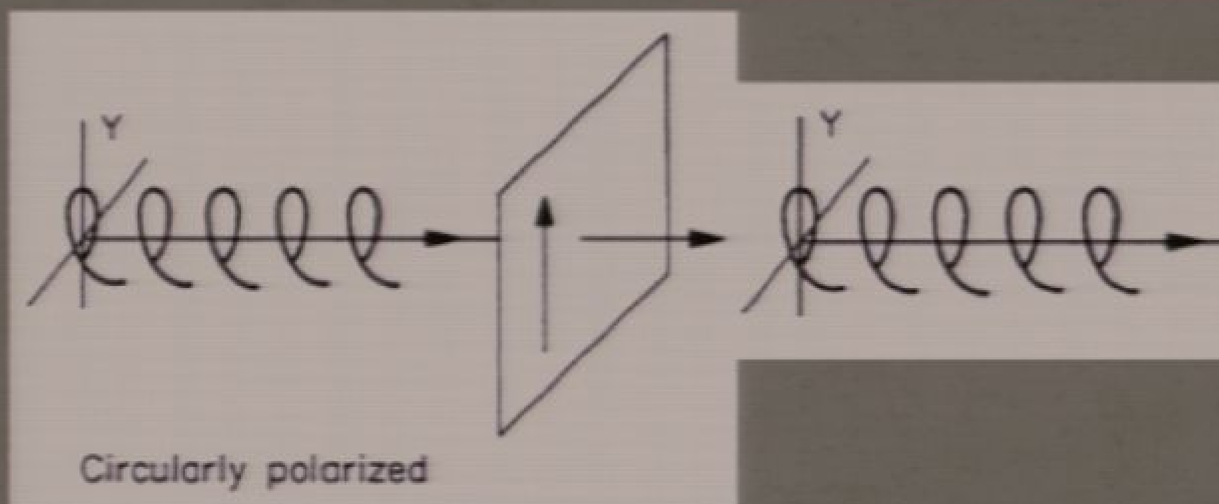

A right-polarized EM wave stays right-polarized under reflection

Obviously, since

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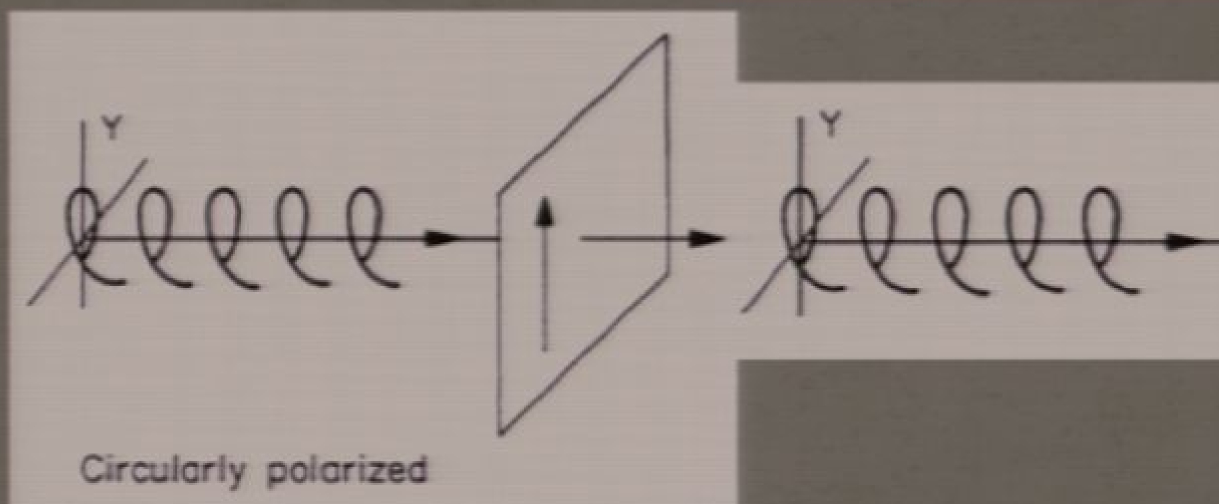

A right-polarized EM wave stays right-polarized under reflection

Obviously, since $\vec{E} \cdot \vec{B} = 0$

The Einstein equations are also parity invariant!

$$S \sim \int (R + \mathcal{L}_M) \;\rightarrow\; G_{ab} \sim T_{ab}$$

Due to symmetries of Riemann Tensor

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But what happens if we add this term to the action?

IMPORTANT FACTS:

- Chern-Simon's General Relavitivty is motivated by
- The standard-model (Adler, Bell, Jackiw; Salam, Isham, Duff, Deser)
- String Theory (Green Schwarz, S.A, Gates)
- Loop Quantum Gravity (Smolin; Nesti Peracci, S.A, Perez, Friedel, Mercuri)

- The Only modified Gravity theory known to have specific signatures of parity violation and circular polarization of GW generation/propigation
- LET'S EXPLORE...

Part I: The Action

$^*RR \sim e^{....} R....R....$ is the Pontryagin density.

$$R^{\beta}{}_{\alpha}{}^{\gamma\delta}\left(\frac{1}{2}\epsilon_{\sigma\tau\gamma\delta}R^{\alpha}{}_{\beta}{}^{\sigma\tau}\right)$$

Dual of Riemann tensor

- $$S \propto \int R + \theta\, {}^{\star}RR + (\nabla\theta)^2 + V[\theta]$$
- θ is either
  - a fixed, externally prescribed par.
  - a dynamical field that evolves.

Non-Dynamical Framework

Dynamical Framework

[Jackiw & Pi, PRD 68 (2003);, SA, Peskin, Sheikh-Jabbari

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Road Map

- Chern-Simons Basics:
  - Action
  - Field Equations
  - Stringy Realization
- Cosmology: Baryogenesis
- Chern-Simons Observables:
  - Solutions
  - Frame-Dragging
  - Gravitational Waves
- Chern-Simons Tests:
  - Solar System
  - Binary Pulsar
  - LISA

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Basics: Field Equations

$$\boxed{G_{ab} + C_{ab} = \kappa\, T_{ab}}$$

- "C-tensor": $C^{\cdot\cdot} \sim (\nabla.\theta)\,\epsilon^{\cdot\cdot\cdot\cdot}\,\nabla.R^{\cdot}_{\cdot} + (\nabla.\nabla.\theta)\,\epsilon^{\cdot\cdot\cdot\cdot}\,R^{\cdot\cdot}_{\cdot\cdot}$

$$C^{\mu\nu} = \frac{1}{2}\left[(\partial_\sigma\theta)\underbrace{\left(\epsilon^{\sigma\mu\alpha\beta}\nabla_\alpha R^\nu_\beta + \epsilon^{\sigma\nu\alpha\beta}\nabla_\alpha R^\mu_\beta\right)}_{\text{Derivatives of Ricci tensor}} + \nabla_\tau(\partial_\sigma\theta)\underbrace{\left(\tilde{R}^{\tau\mu\sigma\nu} + \tilde{R}^{\tau\nu\sigma\mu}\right)}_{\text{Dual of Riemann Tensor}}\right]$$

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- In non-dyn framework

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- In non-dyn framework ${}^*RR = 0 \longrightarrow$ Pontryagin Constraint
- Theta evolution preserves SEP: $\nabla^{\cdot} T_{\cdot\cdot} = 0$
- But does this modification change any GR results?

Basics: Stringy Realization

- 10D string-action for Heterotic String $S \propto \int R + H_{(3)}^2$

$$*dB = d\vartheta$$

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Derivatives of Ricci tensor — Dual of Riemann Tensor

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Compactification to 4D leads to $(*dB = d\vartheta)$

$$
\begin{aligned}
S &\sim \int d^6y \int d^4x \, (dB_{(2)} + w_{(3)})^2 \\
&\sim \int d^4x \, [dB \wedge *dB + *dB \wedge w + \cdots] \\
&\sim \int d^4x \boxed{[(\partial\vartheta)^2 - \vartheta \, R^* R]}
\end{aligned}
$$

[S.A & S.J Gates Jr. (2006)]

Part II: Chern-Simons Gravity and Leptogenesis

SA, Peskin, S Jabbari PRL 05, S. Weinberg 08, Lyth et. al 06

On largest scales we see no anti-galaxies(matter)

$$\frac{n_B}{n_\gamma} = (6.5 \pm 0.4) \times 10^{-10}$$

Nucleosynthesis and WMAP measure

Baryon/Lepton violation

CP Violation

The must happen out of equilibrium

A QUICK DETOUR....

$$S = \int d^4x \sqrt{-g} \left(-\frac{1}{16\pi G} R + \frac{\ell}{12} \theta R \tilde{R} \right)$$

Action

$$R\tilde{R} = \frac{4i}{a^3} \left[\left(\partial_z^2 h_R \, \partial_z \partial_t h_L + a^2 \partial_t^2 h_R \, \partial_t \partial_z h_L + \frac{1}{2} \partial_t a^2 \partial_t h_R \, \partial_t \partial_z h_L \right) - (L \leftrightarrow R) \right]$$

$$\Box h_L = -2i \frac{\Theta}{a} \dot{h}'_L \, , \qquad \Box h_R = +2i \frac{\Theta}{a} \dot{h}'_R$$

Birefringent Gravity Waves (Circular Dichrohism)

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Birefringent Gravity Waves (Circular Dichrohism)

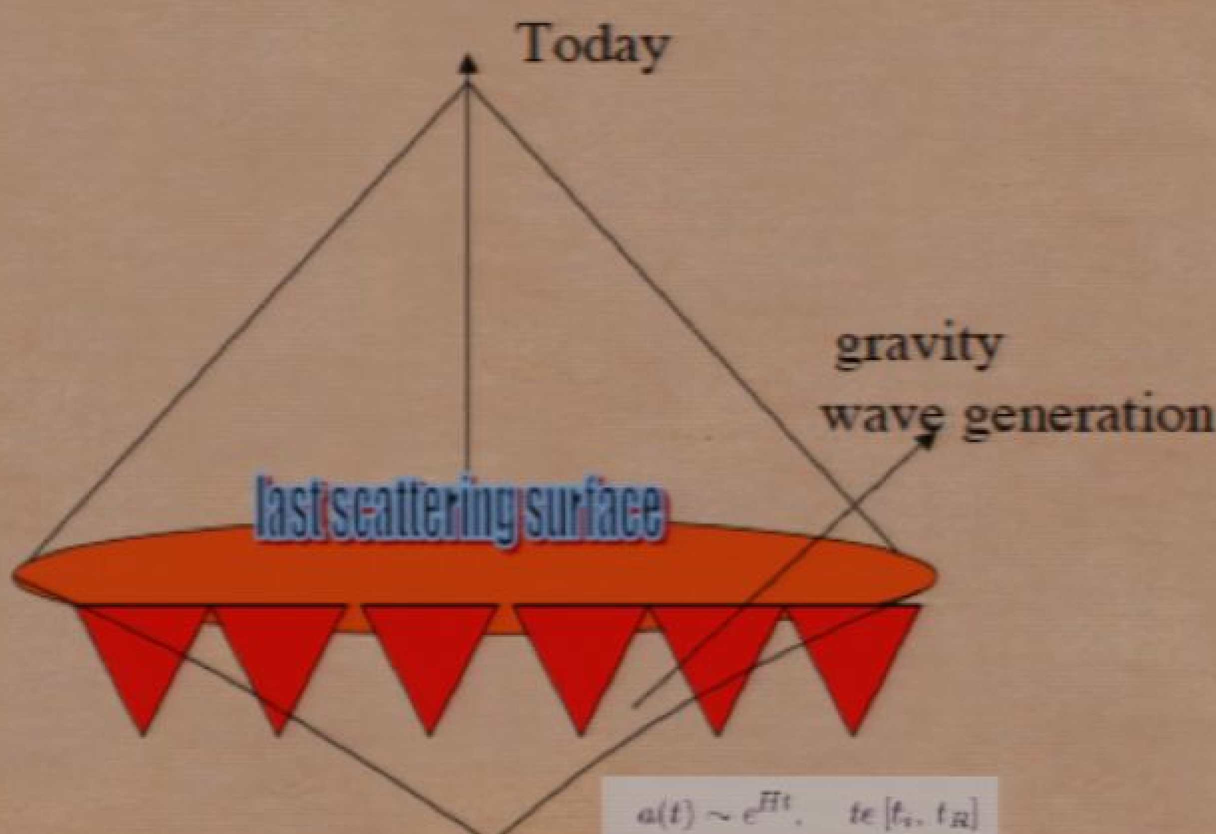
Question: Can nature make use of primordial gravitational waves?

- Scalar perturbations source the gravitational potential for structure formation.
- But we still need asymmetry in matter over anti matter (otherwise we'll have anti-galaxies).

We argue that birefringent gravity waves source matter asymmetry, giving them a physical role in the early universe.

Inflation Basics

Inflation is an epoch wherein
The scale factor has positive acceleration

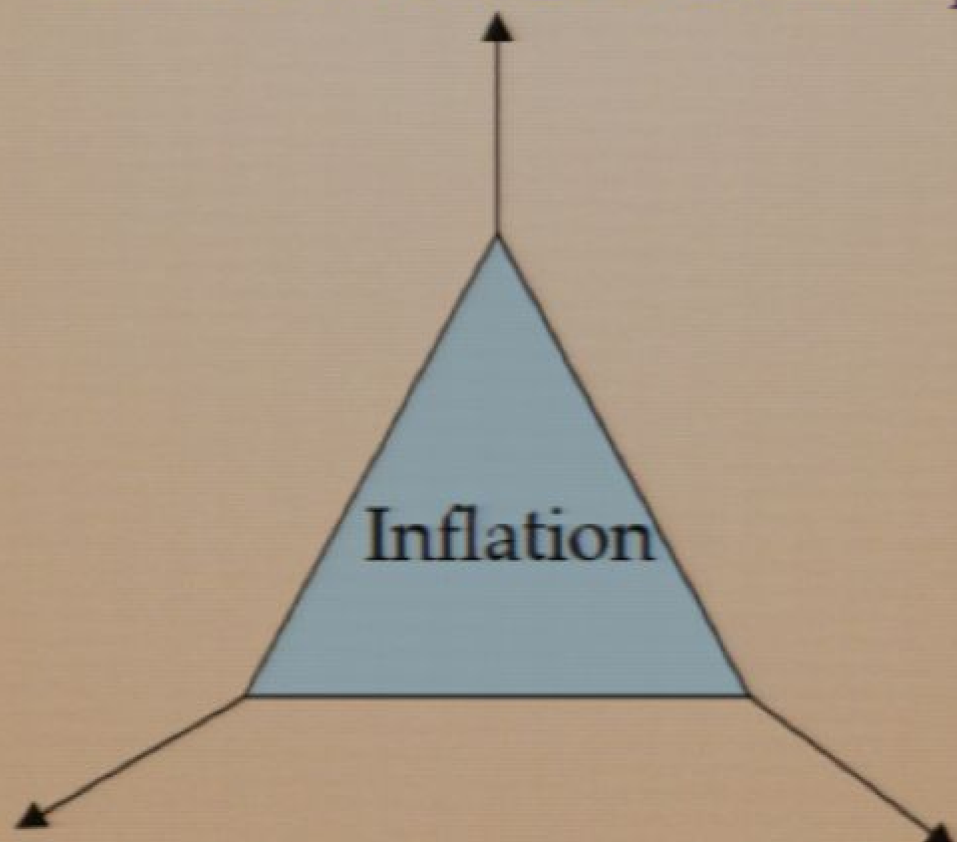


$a(t) \sim e^{Ht}, \quad t \in [t_i, t_R]$

The Mechanism

(CP)

Inflaton sourced GW production:
CP Violation in Inflaton's phase



(EQ)

Rapid Expansion:
out of equilibrium

(B)

Gravitational Anomaly
-> lepton production

Gravity Waves and Chirality

Left and Right handed
GWs can 'stir' leptons
Out of the empty vacuum

Inflation amplifies this
Process

OPPORTUNITY:
CMB Polarization may
Detect this event.

We Need one Important Ingredient

Lepton Number Violation

Gravitational Chiral Anomaly

In the interaction the global lepton current is classically conserved

$$\partial_\mu J_{\mu 5} = \partial_\mu \bar{\Psi} \gamma_\mu \gamma_5 \Psi = 0$$

One Loop Graviton Quantum correction ...

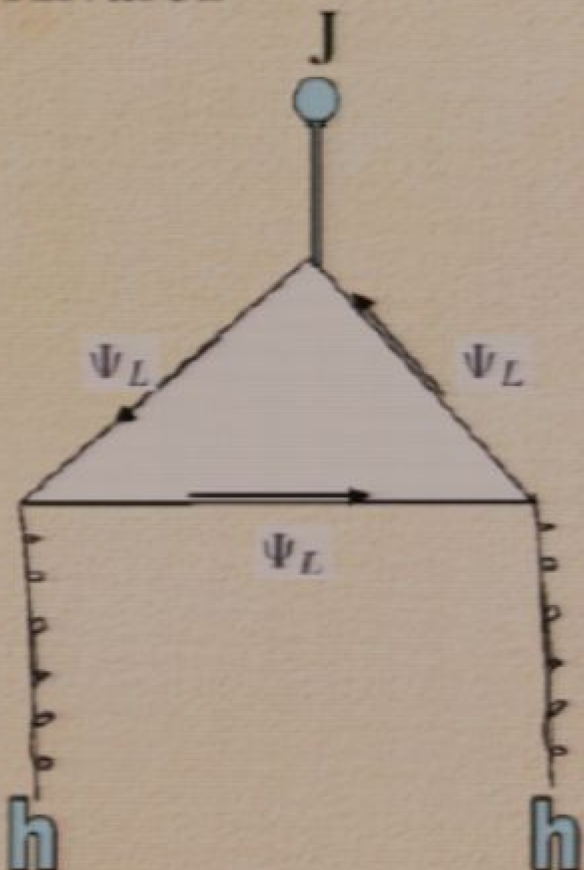
$$\partial_\mu J_l^\mu = \frac{1}{16\pi^2} R\tilde{R} \quad J_l^\mu = \bar{l}_i \gamma^\mu l_i + \bar{\nu}_i \gamma^\mu \nu_i$$

Chiral-Current Anomaly

Duff, Deser, Isham 88; Alvarez-Gaume, Witten 90

Alvarez-Gaume, Nelson, '85

Cardoso, Ovrut, '91



Hence the quantum expectation value:

$$< R\tilde{R} >= \frac{16}{a} \int \frac{d^3k}{2\pi^3} \frac{H^2}{2k^3 M_{Pl}^2} (k\eta)^2 . k^4 \Theta$$

We pick up only the leading behavior for $k\eta >> 1$
Which corresponds to UV Sub-Horizon modes

A reminder: The above expression is non-zero because of the effect of inflation in producing CP asymmetry out of equilibrium.

WE ARE FINALLY READY TO COMPUTE LEPTON NUMBER :)

DO WE GET ENOUGH?

SEMI-FINAL RESULT

- We arrive at the final result for the baryon to entropy ratio. We can find μ for a range of Hubble that is acceptable by CMB constraints.

$$\frac{n}{s} \sim 1 \times 10^{-5} \cdot \left(\frac{H}{M_{\rm Pl}}\right)^{-1/2} \left(\frac{\mu}{M_{\rm Pl}}\right)^{5}$$

$$10^{-30} \lesssim H/M_{\rm Pl} < 10^{-4}$$

The range is $3 \times 10^{14} < \mu \lesssim 10^{17}$

Which is the scale of the right handed neutrino! From this we can get

$$\Rightarrow \frac{n}{s} \sim 10^{-10}$$

Caveat: Still some fine tuning

CMB Polarization

- Lue, Wang and Kamionkowski showed that birefringent GW lead to parity violtating cross-correlations.

$$C_l^{XX'} \equiv \langle a^{X}_{(lm)} (a^{X'}_{(lm)})^* \rangle$$

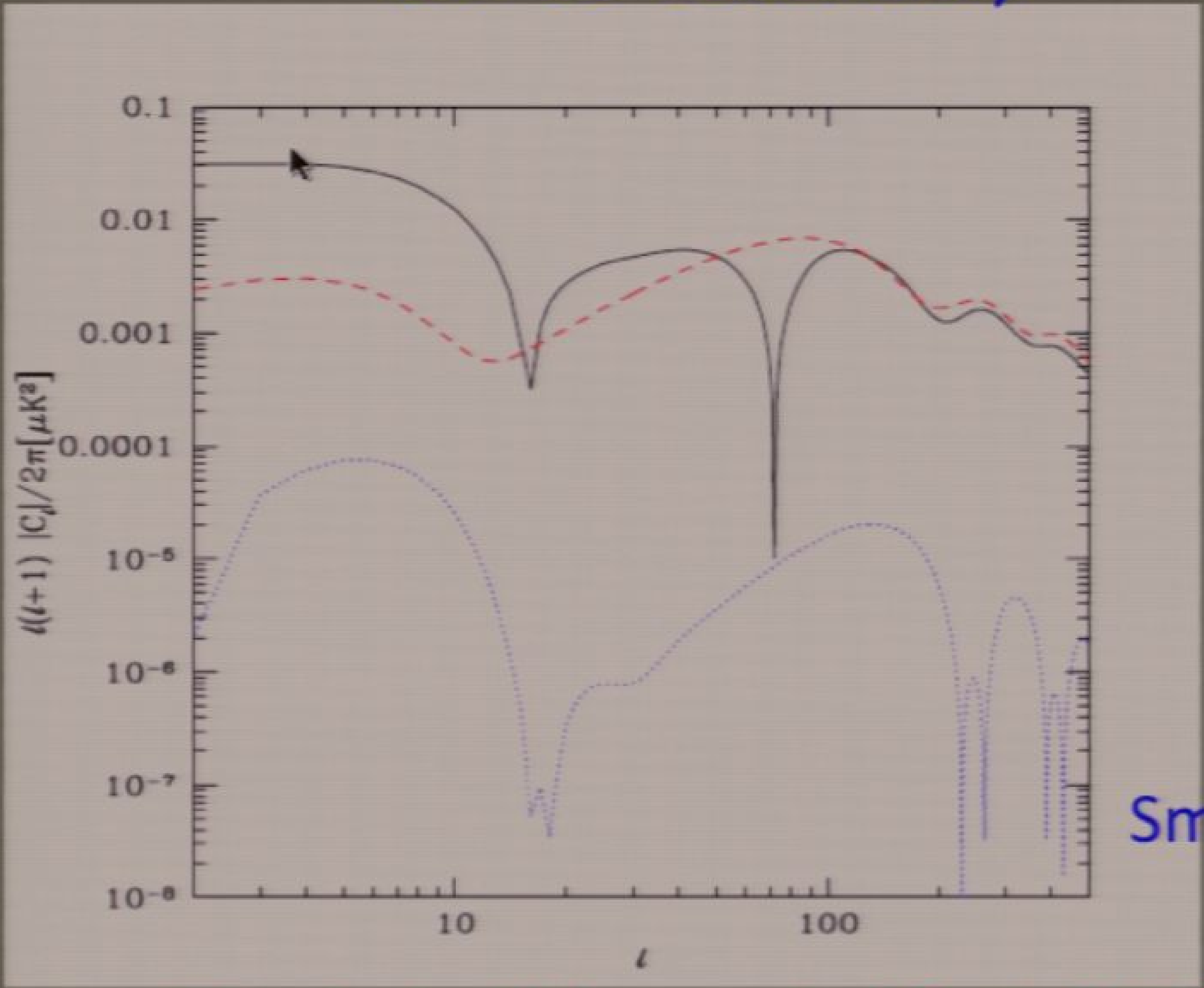
$$\mathrm{X} = \{\mathrm{T}, \mathrm{G}, \mathrm{C}\}$$

$$C_l^{TC} = 2(2l+1)^{-1} A_l^T(k) A_l^C(k)$$

$$a^T_{(lm)} = \begin{cases} (\delta_{m,2} + \delta_{m,-2}) A_l^T(k) & \text{even l} \quad (+), \\ -i(\delta_{m,2} - \delta_{m,-2}) A_l^T(k) & \text{odd l} \quad (\times), \end{cases}$$

$$a^C_{(lm)} = \begin{cases} (\delta_{m,2} + \delta_{m,-2}) A_l^C(k) & \text{even l} \quad (\times), \\ -i(\delta_{m,2} - \delta_{m,-2}) A_l^C(k) & \text{odd l} \quad (+), \end{cases}$$

TB > BB Generically



Black: TB
Red: BB
Blue: EB

Contaldi, Majueijo Smolin(PRL '08)

This signal will be searched for in BICEP & PLANCK sattellite data (Keating, Miller Shimon; Partridge (private Communication)

Part III: Testing Chern-Simons Gravity in our solar system

$$\delta h_{0i} \sim 2\dot{f}\,(\nabla \times V)_i$$

LEADS TO FRAME DRAGGING OF GYROSCOPES

CHERN SIMONS PREDICTS A COMPLETELY NEW PPN PARAMETER

$$\boxed{\delta h_{0i} \sim 2\dot{f}\,(\nabla \times V)_i}$$

LEADS TO FRAME DRAGGING OF GYROSCOPES

Introducing Gravitomagnetism

Start with a perturbed metric: $g_{\mu\nu} = \underbrace{\eta_{\mu\nu}}_{\text{Flat}} + \underbrace{h_{\mu\nu}}_{\text{Small perturbation}}$

Define the vector potential: $A_\mu \equiv -\frac{1}{4}\left(h_{0\mu} - \frac{1}{2}\eta_{0\mu}h\right)$

Define the mass current density: $J_\mu \equiv -T_{\mu 0} = (-\rho, \vec{J}\,)$

density x velocity

$$\Box A_\mu = -4\pi G J_\mu$$

$$\vec{a} = -\vec{E} - 4\vec{v} \times \vec{B}$$

acceleration velocity

$$\vec{E} = \vec{\nabla} A_0 - \partial_t \vec{A}$$

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$$\vec{\nabla} \times \vec{B} - \frac{\partial E}{\partial t} - \frac{1}{m_{cs}} \Box \vec{B} = 4\pi G \vec{J}$$

Standard GR

Mass Current Density

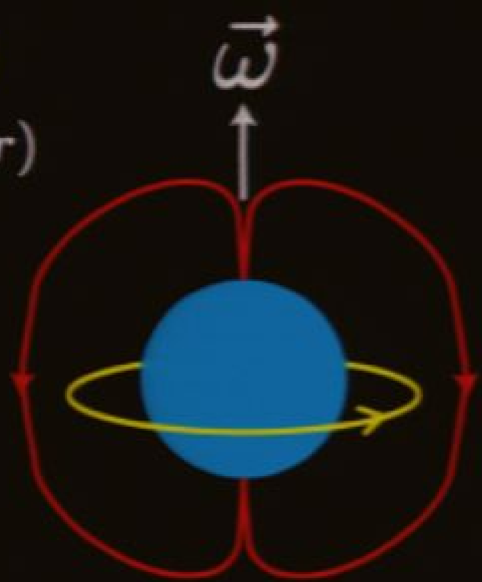
New parity-violating term!

$$m_{cs} \equiv \frac{-3}{8\pi G \ell \dot{\theta}}$$

Solving the modified Ampère's Law and imposing continuity of the vector potential yields

$$\vec{B} = \vec{B}_{GR} + \vec{B}_{CS}$$

- $\vec{B}_{CS}$ is ocsillatory: $B_{CS} \propto y_{1,2}(m_{cs} r)$
- While $\vec{B}_{GR}$ is purely poloidal, $\vec{B}_{CS}$ has poloidal and toroidal components. Toroidal fields violate parity.



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Flat — Small perturbation

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acceleration — velocity

$$\vec{E} = \vec{\nabla} A_0 - \partial_t \vec{A}$$

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$$\vec{\nabla} \times \vec{B} - \frac{\partial E}{\partial t} - \frac{1}{m_{cs}} \Box \vec{B} = 4\pi G \vec{J}$$

Standard GR

Mass Current Density

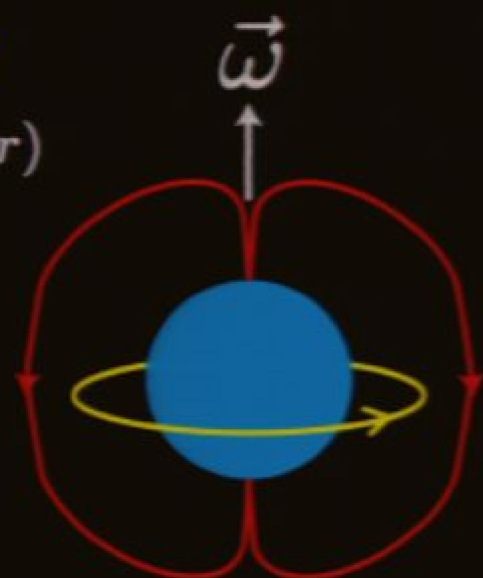
New parity-violating term!

$$m_{cs} \equiv \frac{-3}{8\pi G \ell \dot{\theta}}$$

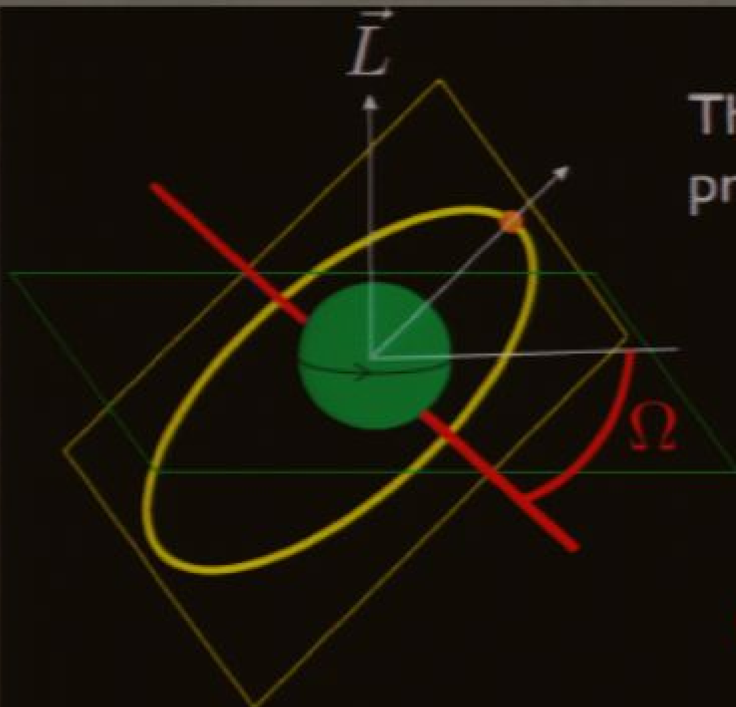
Solving the modified Ampère's Law and imposing continuity of the vector potential yields

$$\vec{B} = \vec{B}_{GR} + \vec{B}_{CS}$$

- $\vec{B}_{CS}$ is ocsillatory: $B_{CS} \propto y_{1,2}(m_{cs} r)$
- While $\vec{B}_{GR}$ is purely poloidal, $\vec{B}_{CS}$ has poloidal and toroidal components. Toroidal fields violate parity.



Modified Precession



The gravitomagnetic field causes a precession of the line of nodes.

$$\dot{\Omega}_{GR} = \frac{2GL}{a^3(1-e^2)^{3/2}}$$

$\dot{\Omega} \simeq 31$ mas yr^{-1} for $a = 12,200$km

$$\left(\vec{B} = \vec{B}_{GR} + \vec{B}_{CS}\right) \Rightarrow \left(\dot{\Omega} = \dot{\Omega}_{GR} + \dot{\Omega}_{CS}\right)$$

Kamionkowski, Erickcek, Smith PRD 08,
S.A. , Yunes 08 PRL

Observables: Frame-dragging

Generically, stationary, spinning solutions are CS modified in the gravitomagnetic sector only!

$$g_{ti} = g_{ti}^{(GR)} + g_{ti}^{(CS)}$$

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distance to source

source radius

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[Smith et. al, RD 77 (2008), Sa.A, Yunes PRL (2008)]

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- Focus on the propagation of GWs: $g_{ab} = \underbrace{g_{ab}^{FRW}}_{\text{background}} + \underbrace{\frac{\overbrace{\boxed{\mathcal{A}_{ab}}}^{\text{Amp}}}{a} e^{-i\overbrace{\phi}^{\text{phase}}}}_{\text{GW}}$

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$\longrightarrow$ Amplitude Birefringence

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$$\boxed{\frac{h_R}{h_L} \sim \frac{h_R^{GR}}{h_L^{GR}} \exp\left[\kappa \int (\partial\theta)\, dz\right]}$$

Tests: Solar System

Most Solar System tests passed (Schw. still a sol.)

Kerr is not a solution!

LAGEOS (or GP B) can search for frame-dragging effects:

- LAGEOS (I&II) are laser-ranged satellites, whose orbit can be mapped accurately.
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redshift

[SA, Finn & Yunes, PRD 78 (2008)]

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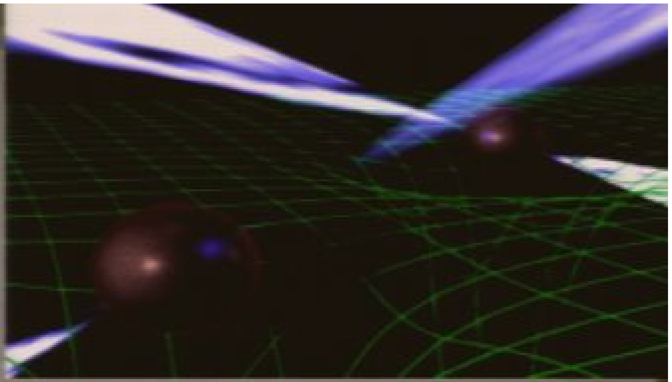
[S.A & Yunes, PRL 99 (2007), Kamionkowski, Smith et. al, PRD 77 (2008)]

First test of local, non-dynamical CS effects for canonical CS field

Tests: Binary Pulsar



Binary pulsars sensitive to precession.

CS correction larger for binary pulsar because:

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Recent improvement from CS neutron stars
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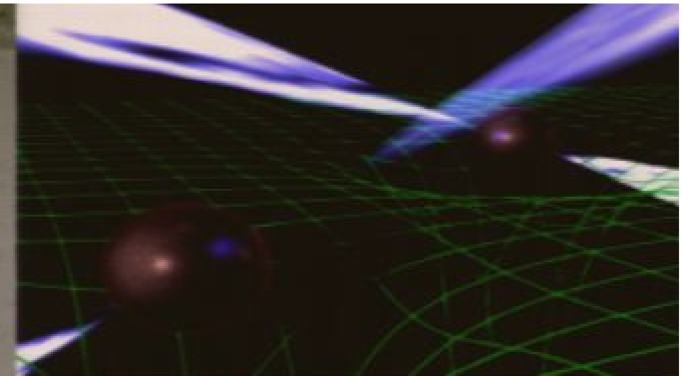

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Satellite altitude

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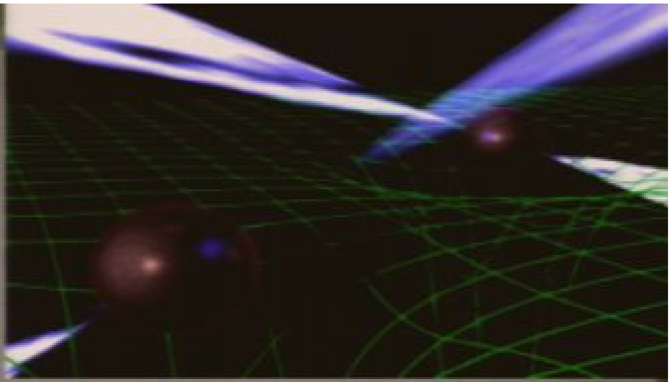

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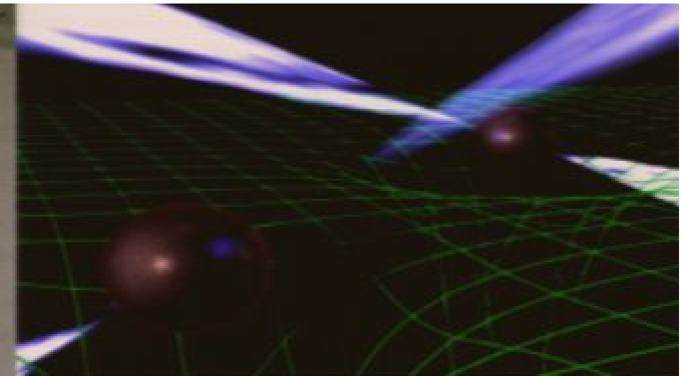

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Binary Pulsar test improves Solar System one by at least eleven orders of magnitude!!

Recent improvement from CS neutron stars

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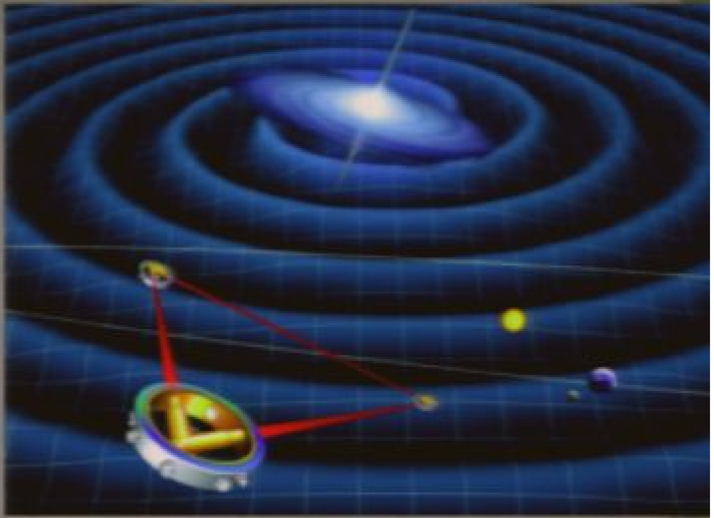
Tests: LISA

LISA is capable of detecting GWs from EMRIs far away.



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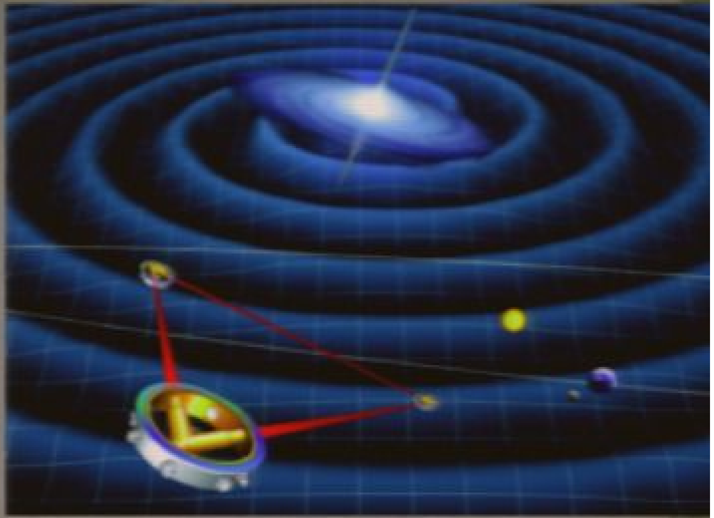

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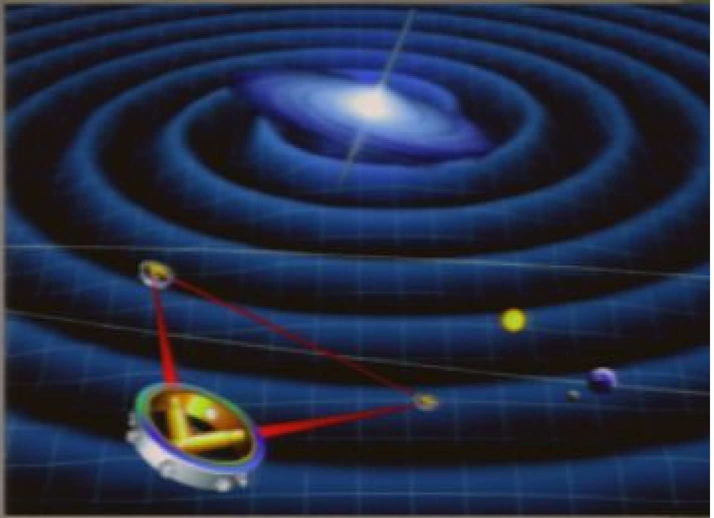

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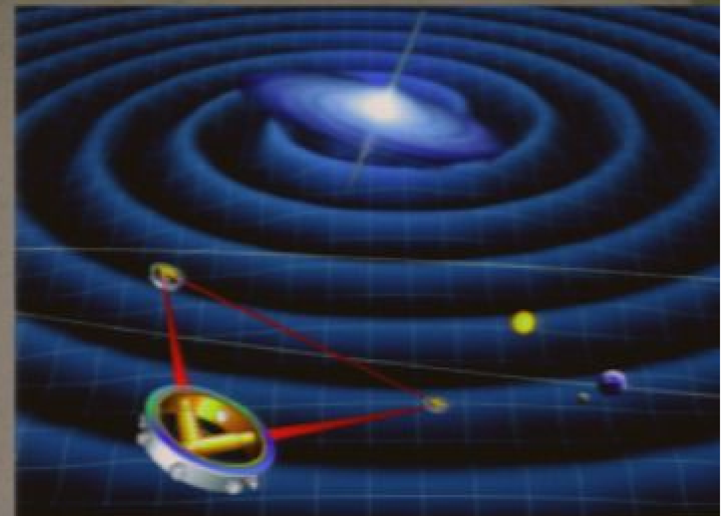

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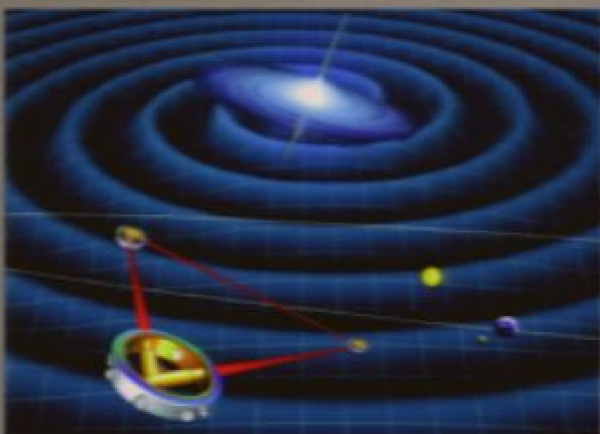
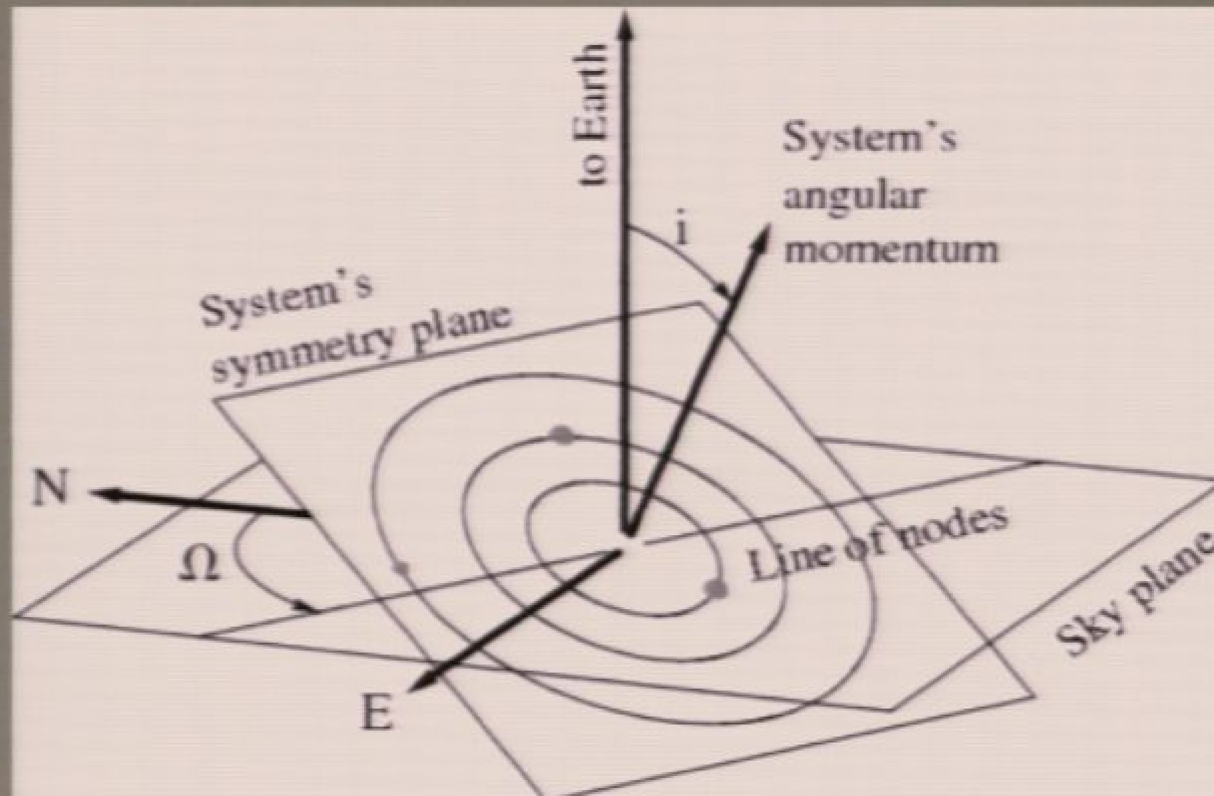
LISA could be a probe into effective quantum gravity!

LISA SPACE SATTELITE TEST CONT'D





$$\frac{h_{\rm R}}{h_{\rm L}} = \frac{h_{\rm R}^{GR}}{h_{\rm L}^{GR}} \exp\left[\frac{2k_0(t)\xi(z)}{H_0}\right] \sim \cos\iota + \frac{k_0(t)\xi(z)}{H_0}\,\sin^2\iota$$

where we have defined the redshift-dependent CS form-factor $\xi(z)$ via

$$\xi(z) = \frac{H_0^2}{2}\int_0^z dz\,(1+z)^{5/2}\left[\frac{7}{2}\frac{d\theta}{dz} + (1+z)\,\frac{d^2\theta}{dz^2}\right]$$

UPCOMING WORK

- We must understand how GWs behave in dynamical CS, thus, define the following program:

  - I. Find a CS modified relevant background.
  - II. Calculate the modified Quadrupole formula.
  - III. Study EMRIs in this background.
  - IV. Study Binary BH mergers in full generality.
    - (Program being carried out at Princeton by Pretorius and Yunes)

- So far, completed (I), a/M<<1 & $\xi/M^4 \ll 1$

$$ds^2 \sim ds^2_{\text{Kerr}} + \frac{5}{8}\frac{\xi\, a}{r^4}\left(1 + \frac{12}{7}\frac{M}{r} + \frac{27}{10}\frac{M^2}{r^2}\right)\sin^2\theta dt d\phi,$$

$$\vartheta \sim \frac{5}{8}\sqrt{\xi}\frac{a}{M}\frac{\cos(\theta)}{r^2}\left(1 + \frac{2M}{r} + \frac{18M^2}{5r^2}\right)$$

- CS gravity is an effective theory of quantum gravity that encodes gravitational parity violation.
- CS affects: frame-dragging and gravitational waves (circular-dichrohism)
- Frame-dragging tests (Solar Sys., Bin. Pul.) have strongly constrained the non-dynamical model.
- Gravitational waves could constraint the dynamical framework.