Lorentz and CPT Violation in Astrophysics and Cosmology

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Lorentz-violating Vacuum Birefringence & Its Astrophysical Consequences

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TPCSF

Outline

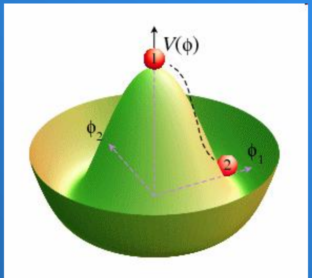
- Quantum gravity & Lorentz violation
- Modified Maxwell eqs & light propagation
- Phenomena & Observations
  - Peak doubling (@ Fermi era)
  - De-polarization (e.g., Cygnus X-1 BH)
- Summary

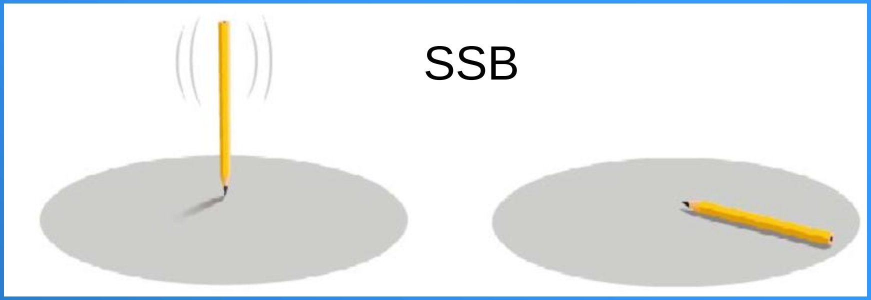
How about Lorentz symmetry breaking?

- Symmetries are the most important ingredients in modern physics
- However, it is not symmetry, but symmetry breaking, that makes our world vivid
- Nature Mother doesn't respect symmetries
  - Parity, CP, Vacuum, etc

Peccei's talk

- Eh, so how about Lorentz symmetry?





broken beauty

Quantum spacetime induced LV?

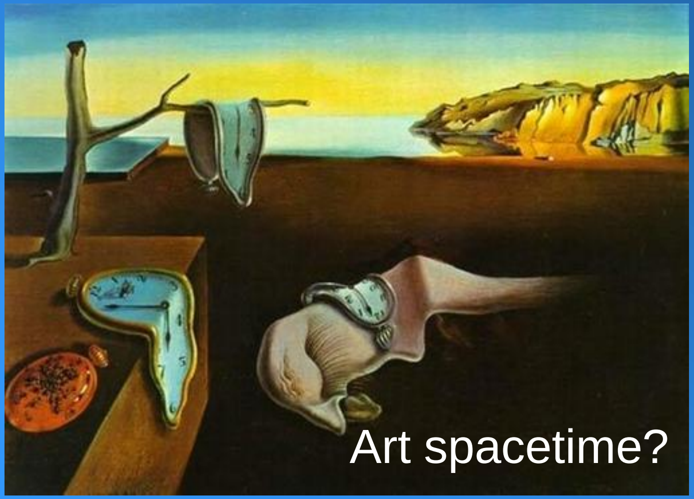
- Standard model (particles) + General relativity (gravity)?

  —— things are not easy…

- Quantum gravity & Lorentz violation

  Lehnert's & Ma & Anselmi's talks

  - String theory, loop quantum gravity, foamy spacetime, standard model extension, doubly special relativity, Horava-Lifshitz gravity, etc



- Astrophysics: Dai & Wu & Ma & Qu & Bi & Anselmi & Yuan & Li's talks
- Cosmology: Cai & Vikman & Zhang & Li & Brandenberger & Evslin's talks

For reviews, see e.g., Mattingly, 2005; Liberati & Maccione, 2009; Shao & Ma, 2010

Vacuum birefringence

- an analogy with birefringence within some anisotropic medium, where left-handed and right-handed polarization modes of light travel with different phase velocity and group velocity.
- can arise from many parity-violating theories
  - Chern-Simons terms Carroll et al. 1990; Alighieri et al. 2011
  - loop quantum gravity Gambini & Pullin 1999; Gleiser & Kozameh 2001
  - effective field theories Colladay & Kostelecky 1998; Myers & Pospelov 2003

Wu's talk

- energy-independent, energy-dependent, direction-independent, direction-dependent
- can also serve to distinguish parity-violating theories from those of even parity
  - foamy spacetime Amelino-Camelia et al. 1998
  - doubly special relativity Amelino-Camelia 2002

Example: Photons in loop quantum gravity

- modified Maxwell eqs

  Gambini & Pullin, 1999

$$\partial_t \vec{E} = \nabla \times \vec{B} + 2\chi l_{\rm Pl} \nabla^2 \vec{B},$$

$$\partial_t \vec{B} = -\nabla \times \vec{E} - 2\chi l_{\rm Pl} \nabla^2 \vec{E},$$

$$1.6 \times 10^{-35}\ \mathrm{m}$$

- dispersion relation

$$\Omega_\pm = |\vec{k}| \mp 2\chi l_{\rm Pl} |\vec{k}|^2$$

- energy(helicity)-dependent velocity

  Shao & Ma, 2011

$$v_\pm^{\rm p} \equiv \frac{\Omega_\pm}{|\vec{k}|} = 1 \mp 2\chi l_{\rm Pl}|\vec{k}|, \qquad v_\pm^{\rm g} \equiv \frac{\partial \Omega_\pm}{\partial |\vec{k}|} = 1 \mp 4\chi l_{\rm Pl}|\vec{k}|$$

- 5-d EFT

$$\mathcal{L} = \mathcal{L}_0 + \delta\mathcal{L} = -F^{\mu\nu}F_{\mu\nu}/4 + \xi l_{\rm Pl} n^\mu n_\rho F_{\mu\nu} (n \cdot \partial) \tilde{F}^{\rho\nu}$$

  Myers & Pospelov, 2003

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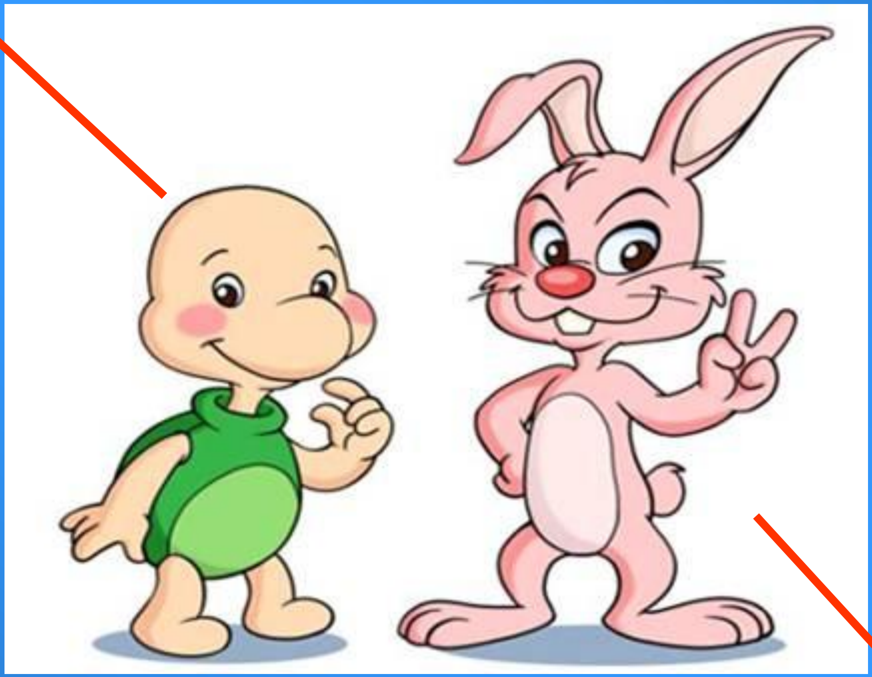
Tortoise and the Hare (龟兔赛跑)

Left-handed polarization



Right-handed polarization

Light propagation

- wave-package Gleiser & Kozameh, 2001; Shao & Ma, 2011

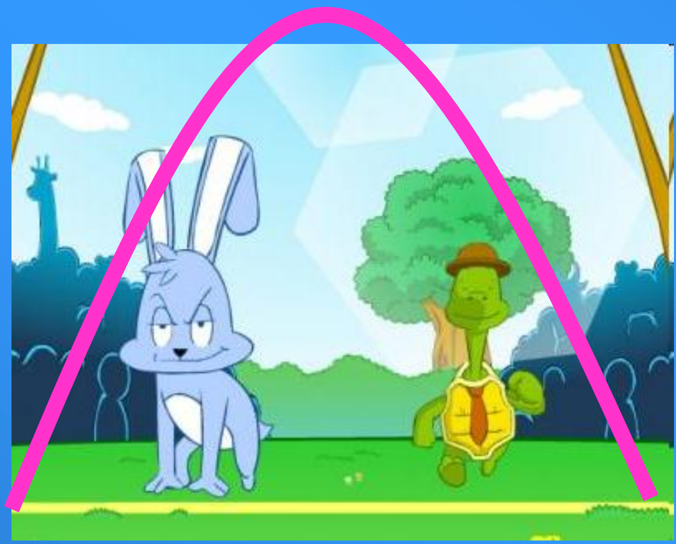
$$\vec{E}_\pm = \mathrm{Re}\left\{ \mathcal{A}\exp\left[i(\Omega_0 t - k_\pm z)\right]\exp\left[-\frac{(z-v^{\mathrm{g}}_\pm t)^2}{\Delta^2}\right]\hat{\mathrm{e}}_\pm\right\}$$

- linear polarized light from astrophysics $\hat{\mathrm{e}}_\pm \equiv \hat{\mathrm{e}}_1 \pm i\hat{\mathrm{e}}_2$
  - e.g., synchrotron radiation in a region penetrated with well ordered magnetic field
    - neutron stars (NSs)
    - active galactic nuclei (AGNs)
    - gamma-ray bursts (GRBs)

$$\varpi_L = \frac{p+1}{p+7/3}$$

- peak doubling Gambini & Pullin, 1999; Shao & Ma, 2011
- de-polarization Gleiser & Kozameh, 2001; Shao & Ma, 2011

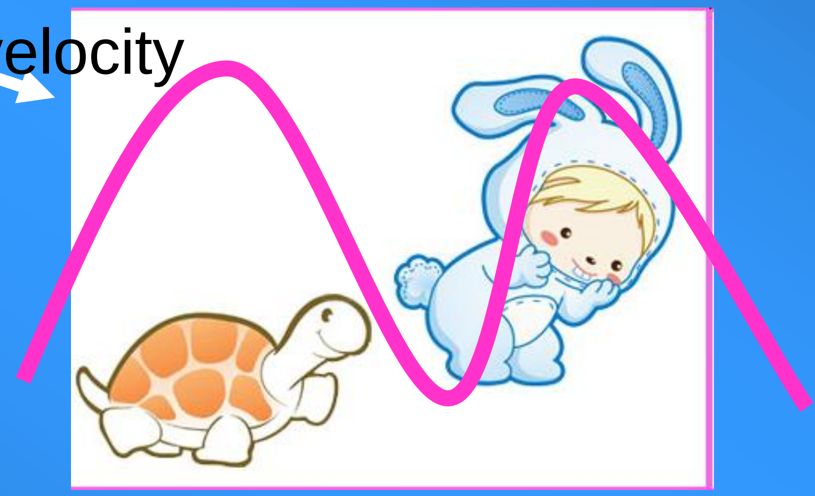
Peak doubling



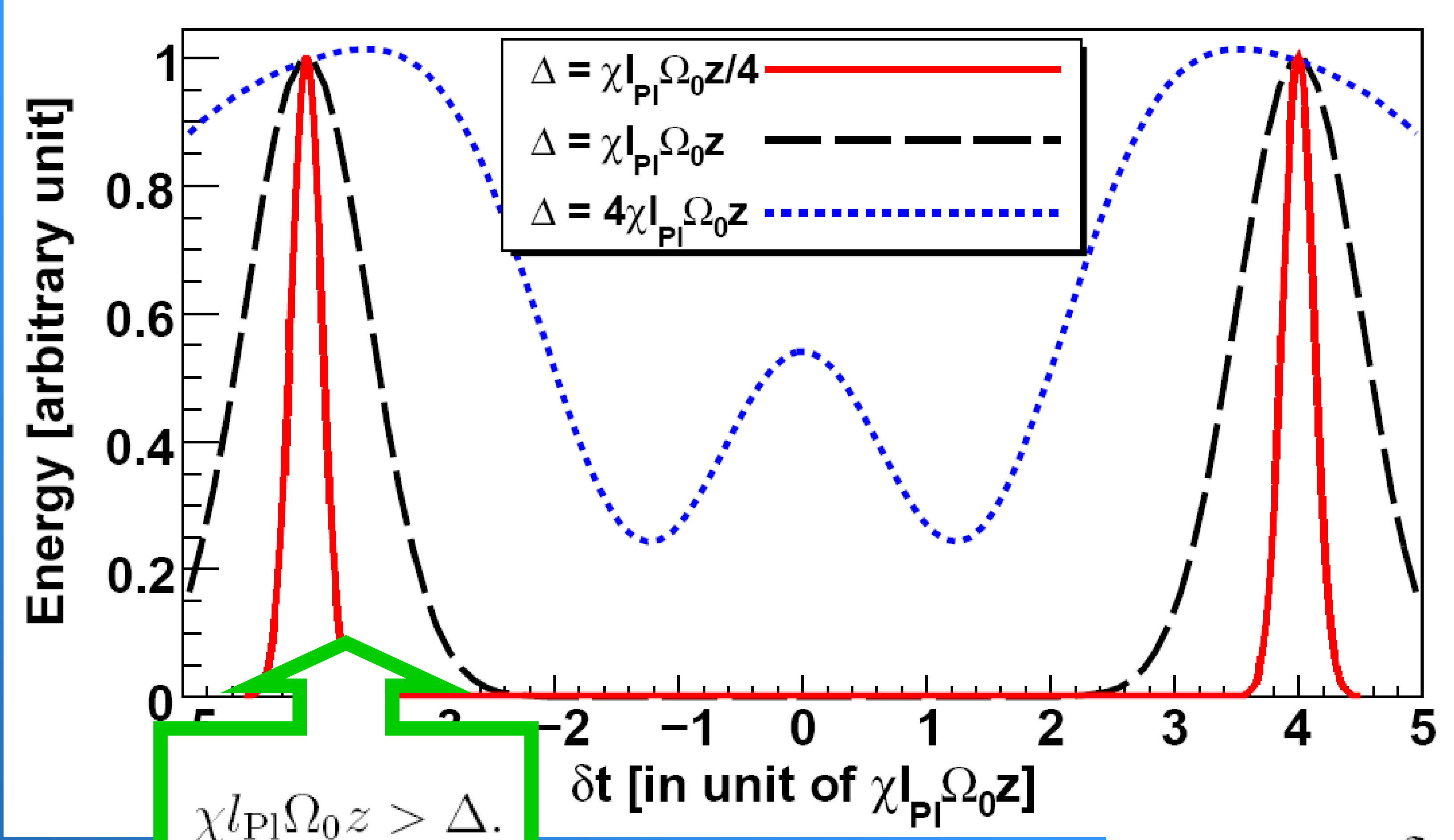
start at the same time @ source

difference in the group velocity

arrive in sequence @ earth



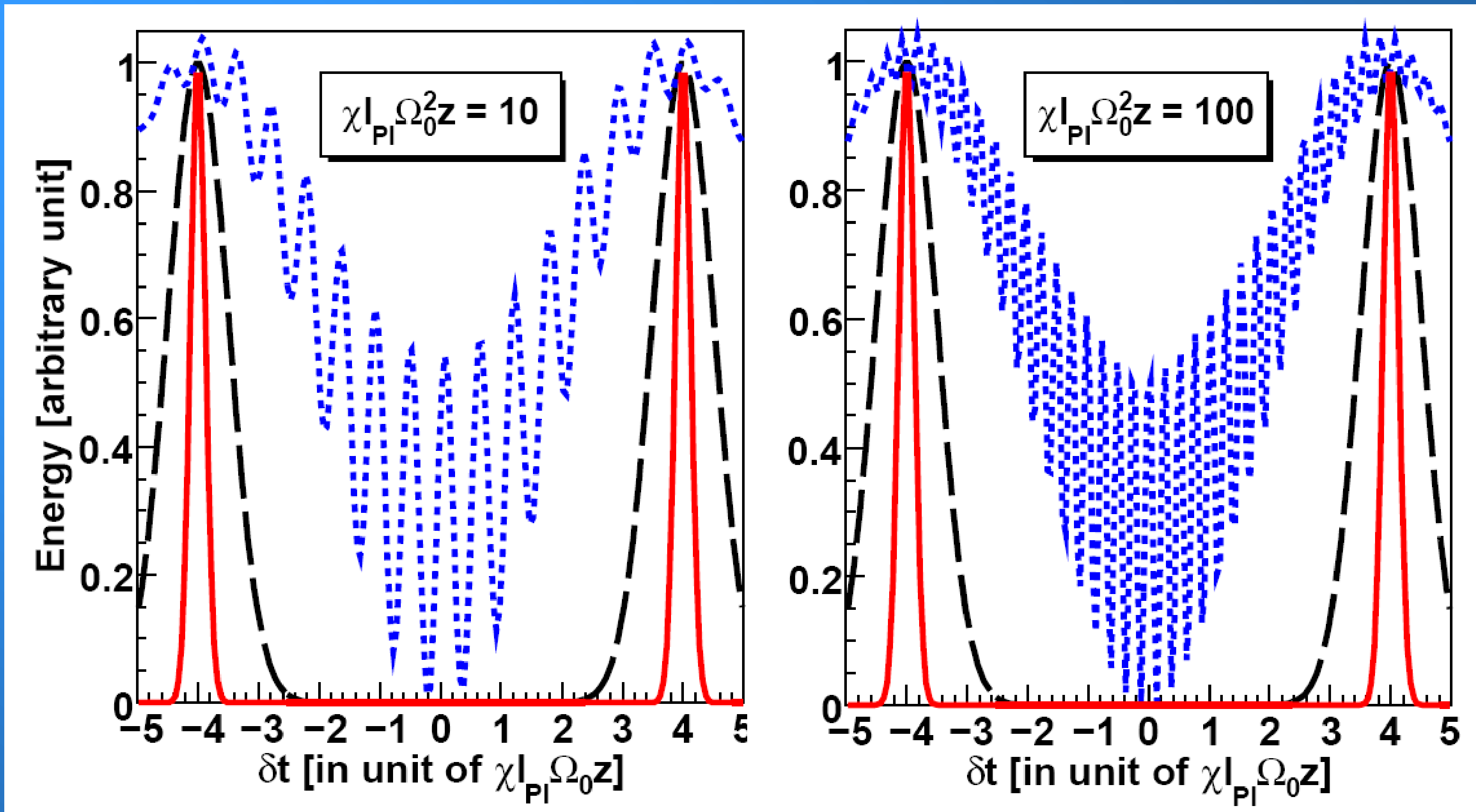
Peak doubling



$\chi l_{\rm Pl}\Omega_0 z > \Delta.$

$z = t + \delta t$

Shao & Ma, 2011



Shao & Ma, 2011

$$\chi l_{\rm Pl}\Omega_0^2 z \simeq 4.8\left(\frac{\chi}{10^{-14}}\right)\left(\frac{l_{\rm Pl}}{10^{-28}\ {\rm eV}^{-1}}\right)\left(\frac{\Omega_0}{100\ {\rm keV}}\right)^2\left(\frac{z}{10^{10}\ {\rm l.y.}}\right)$$

Peak doubling: BATSE vs Fermi

Dai & Wu's talks

- re-proposal at Fermi era
  - a fictitious BATSE GRB: 10^-5 s if LV parameter is of order O(1) Gambini & Pullin, 1999
  - a fictitious Fermi GRB: Shao & Ma 2011

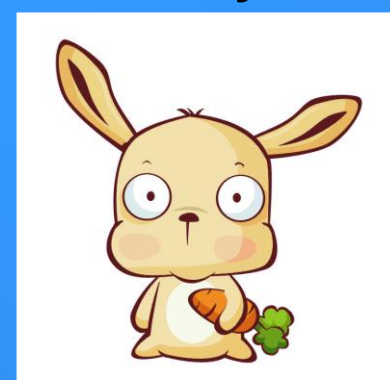
$$8\chi l_{\rm Pl}\Omega_0 z \sim 10^2\chi\left(\frac{l_{\rm Pl}}{10^{-28}\ {\rm eV}^{-1}}\right)\left(\frac{\Omega_0}{300\ {\rm GeV}}\right)\left(\frac{z}{10^{10}\ {\rm l.y.}}\right)\ {\rm s.}$$

De-polarization

coherent @ source

different in the phase velocity

de-coherent when arriving @ earth



De-polarization

- Stocks parameter

Shao & Ma, 2011

$$S_0 \equiv I \equiv a_1^2 + a_2^2 = 2(\mathcal{A}_+^2 + \mathcal{A}_-^2),$$
$$S_1 \equiv Q \equiv a_1^2 - a_2^2 = 4\mathcal{A}_+\mathcal{A}_- \cos[4\chi l_{\rm Pl}\Omega_0^2 z],$$
$$S_2 \equiv U \equiv 2a_1 a_2 \cos[\delta_2 - \delta_1] = 4\mathcal{A}_+\mathcal{A}_- \sin[4\chi l_{\rm Pl}\Omega_0^2 z]$$
$$S_3 \equiv V \equiv 2a_1 a_2 \sin[\delta_2 - \delta_1] = 2(\mathcal{A}_+^2 - \mathcal{A}_-^2).$$

$$\mathcal{S}_0 = \mathcal{I} = 2\sqrt{2\pi}|\mathcal{A}|^2\Delta,$$
$$\mathcal{S}_1 = \mathcal{Q} = 2\sqrt{2\pi}|\mathcal{A}|^2\Delta \exp\left[-\frac{32\chi^2 l_{\rm Pl}^2\Omega_0^2 z^2}{\Delta^2}\right]\cos[4\chi l_{\rm Pl}\Omega_0^2 z]$$
$$\mathcal{S}_2 = \mathcal{U} = 2\sqrt{2\pi}|\mathcal{A}|^2\Delta \exp\left[-\frac{32\chi^2 l_{\rm Pl}^2\Omega_0^2 z^2}{\Delta^2}\right]\sin[4\chi l_{\rm Pl}\Omega_0^2 z]$$
$$\mathcal{S}_3 = \mathcal{V} = 0.$$

- degrees of polarization

Shao & Ma, 2011

$$\pi \equiv \frac{\sqrt{Q^2 + U^2 + V^2}}{I} = 1.$$

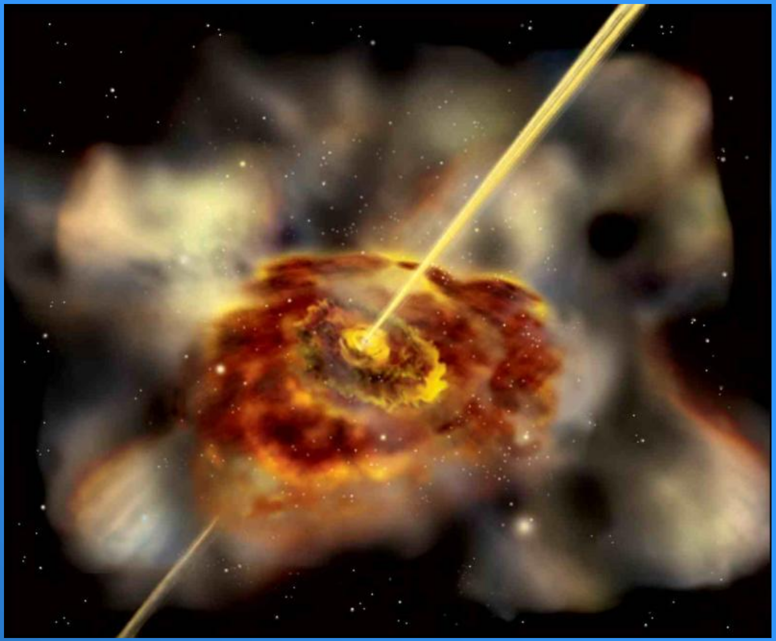
$$\ldots_L \equiv \frac{\sqrt{Q^2 + U^2}}{I} = \frac{2\mathcal{A}_+\mathcal{A}_-}{\mathcal{A}_+^2 + \mathcal{A}_-^2} = \cosh^{-1}\left[\frac{16\chi l_{\rm Pl}\Omega_0 z \delta t}{\Delta^2}\right]$$

$$\varpi \equiv \frac{\sqrt{\mathcal{Q}^2 + \ldots}}{\mathcal{I}} \ldots \Omega_0^2 z^2 \ldots \Delta^2 \ldots$$

$$\chi l_{\rm Pl}\Omega_0 z > \Delta.$$

$$\varpi_L \equiv \frac{\sqrt{\mathcal{Q}^2 + \mathcal{U}^2}}{\mathcal{I}} = \exp\left[-\frac{32\chi^2 l_{\rm Pl}^2\Omega_0^2 z^2}{\Delta^2}\right]$$

AGNs, GRBs, Crab Pulsar, etc



Active Galactic Nucleus

Gamma-ray Burst

Crab Pulsar

Observational constraints

Source	Observation Site	Distance	Energy	ϖ_L	$\lvert\chi\rvert_{\rm upper}$ [a]
3C 256	Mayall	$\mathcal{Z} \simeq 1.82$	$3000 - 4000$ Å	$16.4 \pm 2.2\%$	5×10^{-5}
GRB 020813	LRIS	$\mathcal{Z} \simeq 1.3$	$3500 - 8800$ Å	$1.8 - 2.4\%$	1×10^{-7}
GRB 021004	ESO-VLT	$\mathcal{Z} \simeq 2.3$	$3500 - 8600$ Å	$\lesssim 2\%$	5×10^{-8}
GRB 021206	RHESSI	$\mathcal{Z} \sim 0.1$	$0.15 - 2.0$ MeV	$80 \pm 20\%$	1×10^{-15}
Crab pulsar	SPI	~ 2 kpc	$0.1 - 1$ MeV	$46 \pm 10\%$	2×10^{-10}
GRB 041219A	SPI	$\mathcal{Z} \sim 0.3$	$100 - 350$ keV	$63^{+31}_{-30}\%$, $96^{+39}_{-40}\%$	1×10^{-14}

- ✓ 3C 256 — Gleiser & Kozameh, 2001
- ✓ GRB0 20813 & GRB 021004 — Fan et al. 2006
- ✓ GRB 021206 [refuted] — Jacobson et al. 2004
- ✓ Crab Pulsar — Maccione et al. 2008
- ✓ GRB041219A [estimated distance] — Stecker 2011

Previous constraints on de-polarization

$$|2\chi l_{\rm Pl}(\Omega_{0h}^2 - \Omega_{0l}^2)z| \lesssim \pi$$

- spectra $$N(\Omega_0) \propto \Omega_0^{-\Gamma} \mathrm{e}^{-\Omega_0/E_0}$$

$$\langle \varpi_L \rangle \equiv \frac{\int_{E_1}^{E_2} N(\Omega_0)\varpi_L(\Omega_0)\mathrm{d}\Omega_0}{\int_{E_1}^{E_2} N(\Omega_0)\mathrm{d}\Omega_0},$$

Cygnus X-1 black hole

Polarized Gamma-Ray Emission from the Galactic Black Hole Cygnus X-1

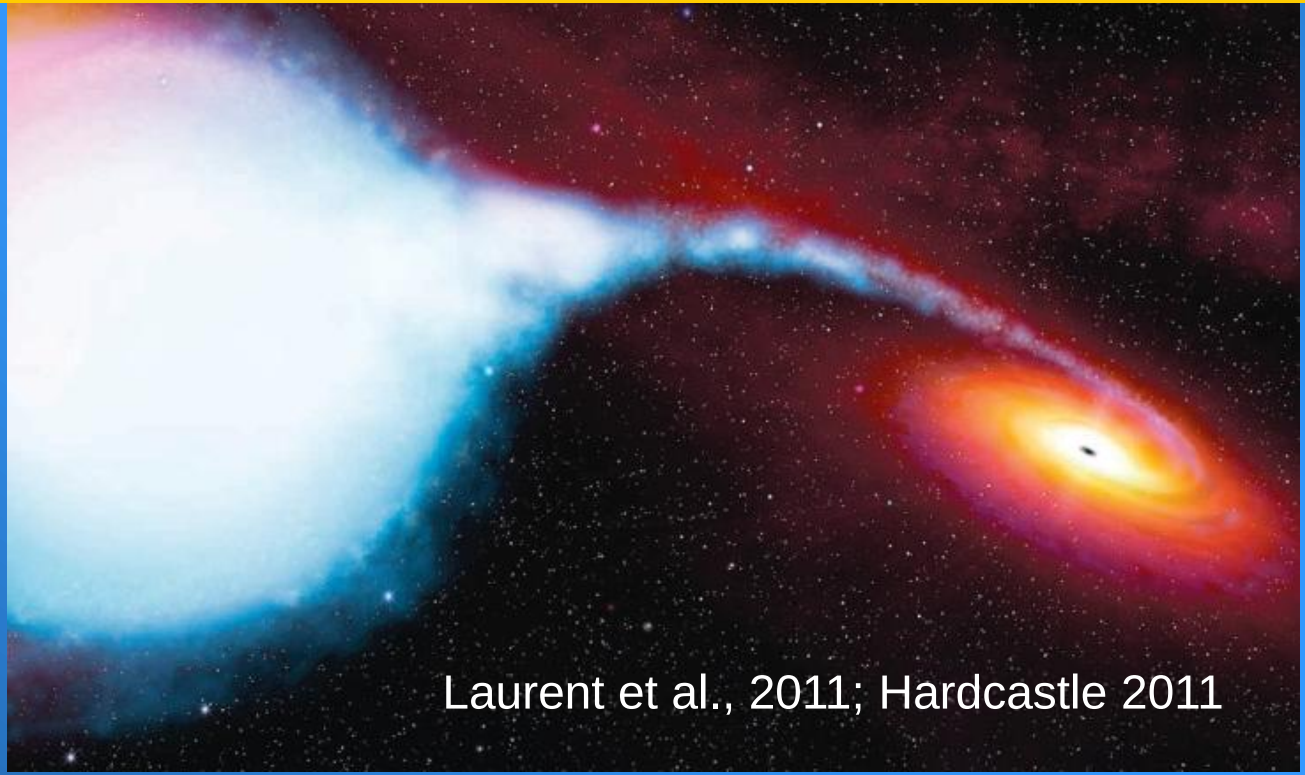
P. Laurent, *et al.*

Science **332**, 438 (2011);

DOI: 10.1126/science.1200848

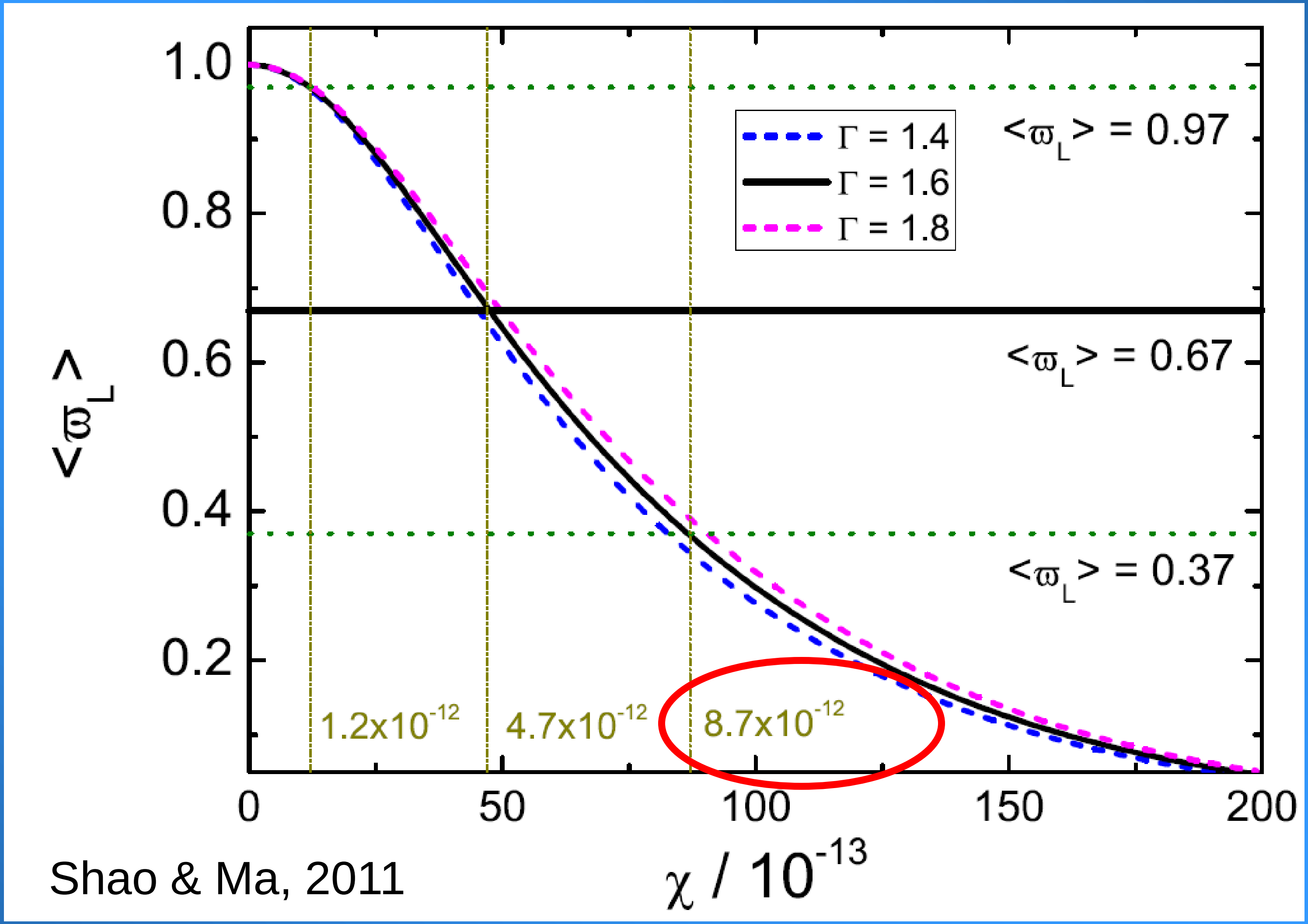
distance ~ 2.1 kpc; 400 eV -- 2MeV;

Gamma-ray polarization : 67 +/- 30%



Laurent et al., 2011; Hardcastle 2011

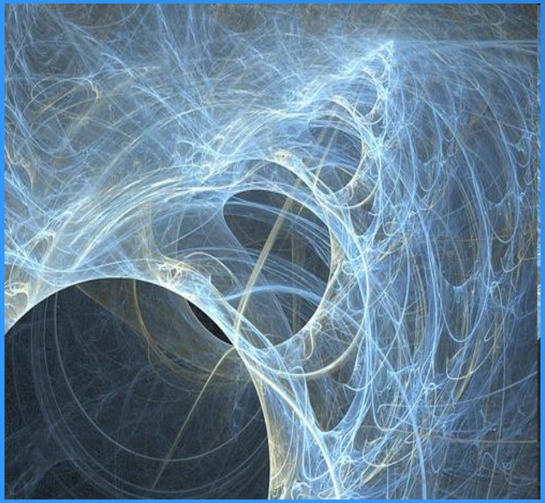
Cygnus X-1 black hole



Summary

- standard model + gravity = quantum gravity?
- Lorentz violation: an valuably observational window

  (@ cutting-edge)
- many astrophysical consequences
  - (example) vacuum birefringence
    - peak doubling
    - de-polarization
- LV Future (observational-oriented)
  - confirm: big news in physical society
  - non-confirm: challenge for some quantum gravitational theories



Spacetime in Fuzziness is also of Beauty

Reflection of BoYa Tower @ Peking University