Slow Force Carriers
&
a Standard Model reference frame

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In this talk:

A new kind of physics could be hidden within the Standard Model: slow force carriers

New regime of Lorentz breaking: Standard Model + a reference frame that you can hit

Where are the missing IR pieces of nature?

Option 1	Dark physics follows the same structures we have observed so far: new fields within Lorentz and gauge invariant theory.
Option 2	Dark physics indicates a mismatch between nature and symmetry: new exotic excitations with Lorentz-breaking spectrum. Dark because they break the symmetry.

Breaking of Lorentz symmetry

Gravity:		Reference frame has gravitational properties; defined by clock field (aether/khronon).	(e.g. Jacobson2004, Blas2010)
Standard Model:	Historically	Reference frame is a passive, ethereal medium; background effect: only change dispersion relations.	(e.g. Colladay1998)
	This talk	Is there room for a material reference frame with more active SM properties?	

Symmetry point of view

Lorentz symmetry $\xrightarrow{\text{therefore}}$ gauge symmetry

+ (spin=1, m=0) (little group) $\varepsilon_\mu(q) \to \varepsilon_\mu(q) + q_\mu$

Dynamical view of gauge theory

Hamiltonian for gapless spin1 + local conservation law

$$\cancel{\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}} \qquad H = \int d^3x \left(\frac{1}{2}\vec{E}^2 + \frac{1}{2}(\vec{\nabla}\wedge\vec{A})^2\right) \qquad A_0 = 0 \quad \{\vec{A}(\vec{x}), \vec{E}(\vec{y})\} = \delta^3(\vec{x}-\vec{y})$$

No dependence on the longitudinal part of A,
The longitudinal mode has speed=0

Local conservation law

$$\frac{d}{dt}\vec{\nabla}\cdot\vec{E} = \{\vec{\nabla}\cdot\vec{E}, H\} = 0$$

Unphysical, gauge transformations

$$\delta_\lambda F = \lambda(\vec{x})\{F, \vec{\nabla}\cdot\vec{E}\} \qquad \delta_\lambda \vec{A} = \vec{\nabla}\lambda$$

Slow departures from gauge theory

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Dynamically weak departure from gauge invariance:

- Keep Hamiltonian almost unchanged;
- Add no new fields or fundamental energy scales;

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give the longitudinal mode a low speed

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$$H = \int d^3x \left(\frac{1}{2}\vec{E}^2 + \frac{1}{2}(\vec{\nabla}\wedge\vec{A})^2 + \frac{c_L^2}{2}(\vec{\nabla}\cdot\vec{A})^2 \right) \qquad c_L \ll 1$$

(gauge theory limit: $c_L \to 0$)

Slow massless photon

$$\frac{d}{dt}\vec{E} = \vec{\nabla}\wedge(\vec{\nabla}\wedge\vec{A}) + c_L^2\vec{\nabla}(\vec{\nabla}\cdot\vec{A}) \qquad \frac{d}{dt}\vec{A} = \vec{E}$$

$$\vec{A} = \vec{A}_T + \vec{A}_L\,,\ \vec{E} = \vec{E}_T + \vec{E}_L$$

usual photons

$$\frac{d^2}{dt^2}\vec{A}_T = \vec{\nabla}\wedge(\vec{\nabla}\wedge\vec{A}_T)$$

slow longitudinal gapless mode

$$\frac{d^2}{dt^2}\vec{A}_L = c_L^2\vec{\nabla}^2\vec{A}_L \xrightarrow{c_L \to 0} \frac{d}{dt}\vec{\nabla}\cdot\vec{E} = 0$$

$$\omega^2 = c_L^2\vec{k}^2$$

Higher-form Galilean symmetry: mass is protected

$$A_i \to A_i + c_i + b_{ij}x^j$$

$$\frac{d}{dt}\int d^3x\,(c_i x^i + b_{ij}x^i x^j)\left(\vec{\nabla}\cdot\vec{E} - J^0\right) = 0 \longrightarrow m = 0$$

Decoupling by low speed

Limit of $c_L \to 0$ gives QED.

gauge-invariant dressing ~ resummation of slow modes

$$\vec{A}_L = \vec{\nabla}\phi \qquad \Psi(x) = e^{-ie\phi(x)}\psi(x)$$

$$\bar{\psi}\left(i\gamma^0\partial_t - i\vec{\gamma}\cdot\vec{\nabla} - \boxed{e\vec{\gamma}\cdot\vec{A}_L} - m\right)\psi = \bar{\Psi}\left(i\gamma^0\partial_t - \boxed{\gamma^0\partial_t\phi} - i\vec{\gamma}\cdot\vec{\nabla} - m\right)\Psi$$

$$\boxed{\partial_t\phi(\vec{k},t) = -c_L\hat{k}\cdot\vec{A}_L(\vec{k},t)}$$

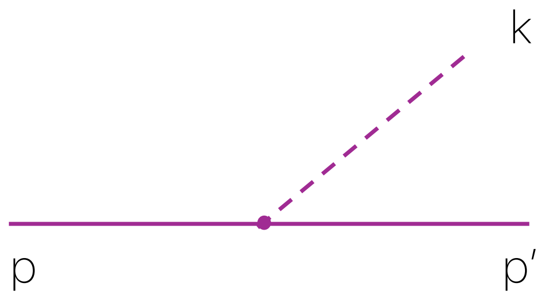
$\longrightarrow$ the coupling to gauge invariant fields is speed-suppressed!!

$$\mathcal{L} = \frac{1}{2}\dot{\vec{A}}^2 - \frac{1}{2}(\vec{\nabla}\wedge\vec{A})^2 - \frac{c_L^2}{2}(\vec{\nabla}\cdot\vec{A})^2 + \bar{\Psi}\left(i\gamma^0\partial_t - i\vec{\gamma}\cdot\vec{\nabla} - e\vec{\gamma}\cdot\vec{A}_T - \boxed{e\gamma^0\partial_t\phi} - m\right)\Psi$$

Cherenkov Radiation $\longrightarrow$ Hard Recoils

Very slow, gapless mode, couples to matter:

$$\begin{pmatrix} \sqrt{p^2+m^2} \\ \vec{p} \end{pmatrix} = \begin{pmatrix} \sqrt{p'^2+m^2} + c_L k \\ \vec{p}\,' + \vec{k} \end{pmatrix}$$



$$\vec{p}\,' \simeq \vec{p} - 2p\cos\theta\,\hat{k}$$ $\longrightarrow$ Large momentum transfer!

For a fermion:

$$\Gamma = \frac{1}{2E_p}\int \frac{d^3p'\,d^3k}{(2\pi)^6}\frac{1}{2E_{p'}2c_L|\vec{k}|}\frac{1}{4}\sum_{spin}|\hat{k}\cdot\vec{J}(p,p')|^2(2\pi)^4\delta^4(p-p'-k)$$

$$\Gamma = 4\alpha c_L\left(E_p - \frac{p^2}{3E_p}\right) + O(c_L^2)$$ $\longrightarrow$ Rare event!

A new regime: SM + reference frame

What happens if, e.g., $c_L \lesssim 10^{-40}$?

- Modes do not propagate
- SM interactions look perfect
- Very rare, but visible recoils!

$\downarrow$

Slow modes become momentum stored in the rest frame.

$\downarrow$

The reference frame becomes a material that you can hit!

Experimental bounds

$g-2$	$c_L \lesssim 10^{-7}$
Cosmic rays power loss	$c_L \lesssim 10^{-23}$
Recoils: Collider beams	$c_L \lesssim 10^{-29}$
Recoils: Pulsar spin-down rate	$c_L \lesssim 10^{-40}$
Recoils: Earth heat balance	$c_L \lesssim 10^{-45}$
Recoils: cosmic ray nuclei	$c_L \lesssim 10^{-48}$
Recoils: DM detection (Xe)	$c_L \lesssim 10^{-60}$

→ Ordinary observables & effects

→ Rare, Hard recoils against the reference frame!

Coming next: Cosmic Recoil Background?

So…

slow force carriers

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reference frame

New IR physics within gauge theory, new effects, new ways to test SM:

New connection between gauge redundancy and soft modes/IR divergences

a whole quantum reference frame!

opportunities for new physics, especially in gravity and cosmology

is relativity fundamental?