NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Toward Quantum Gravity Phenomenology

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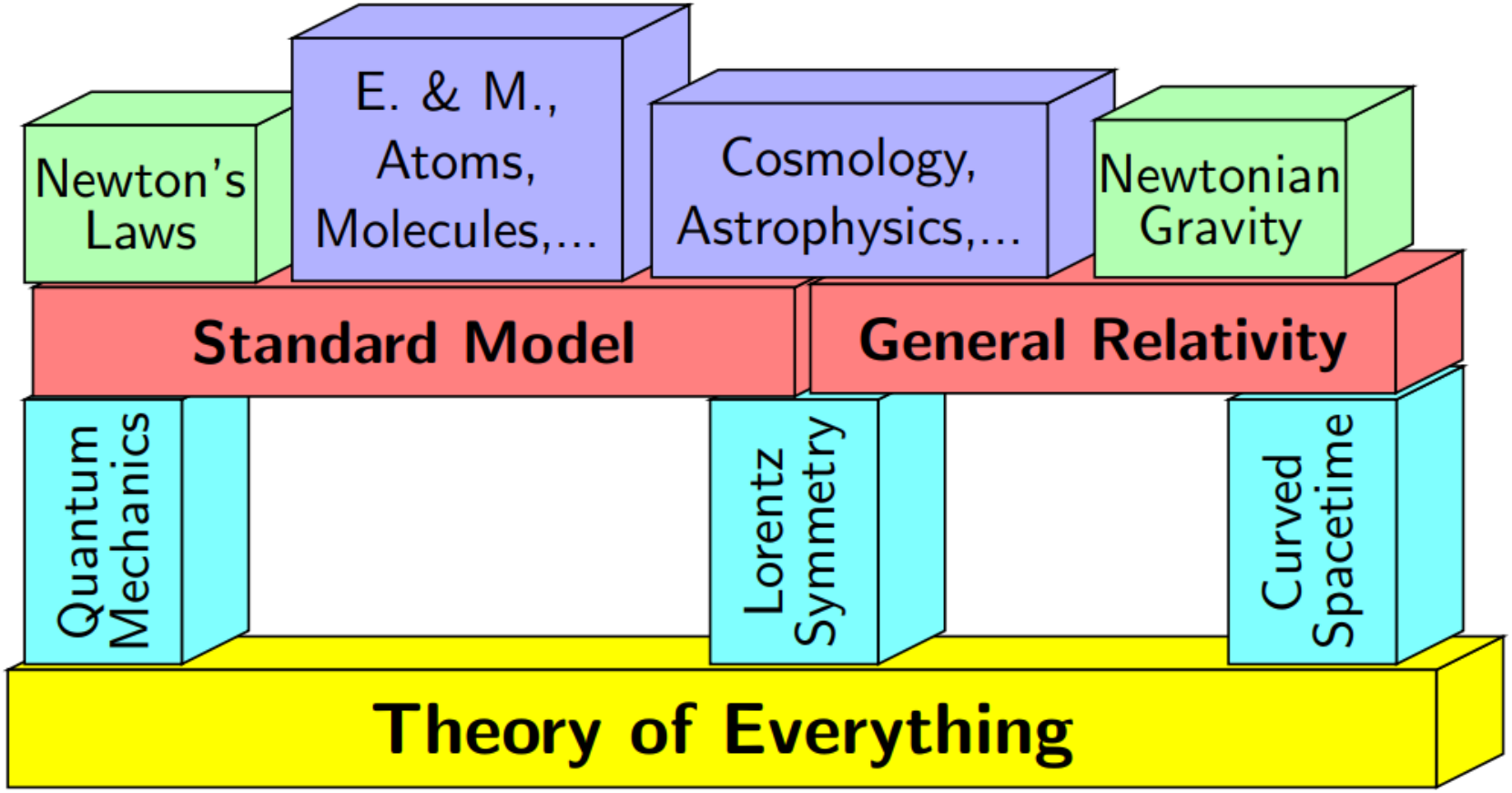
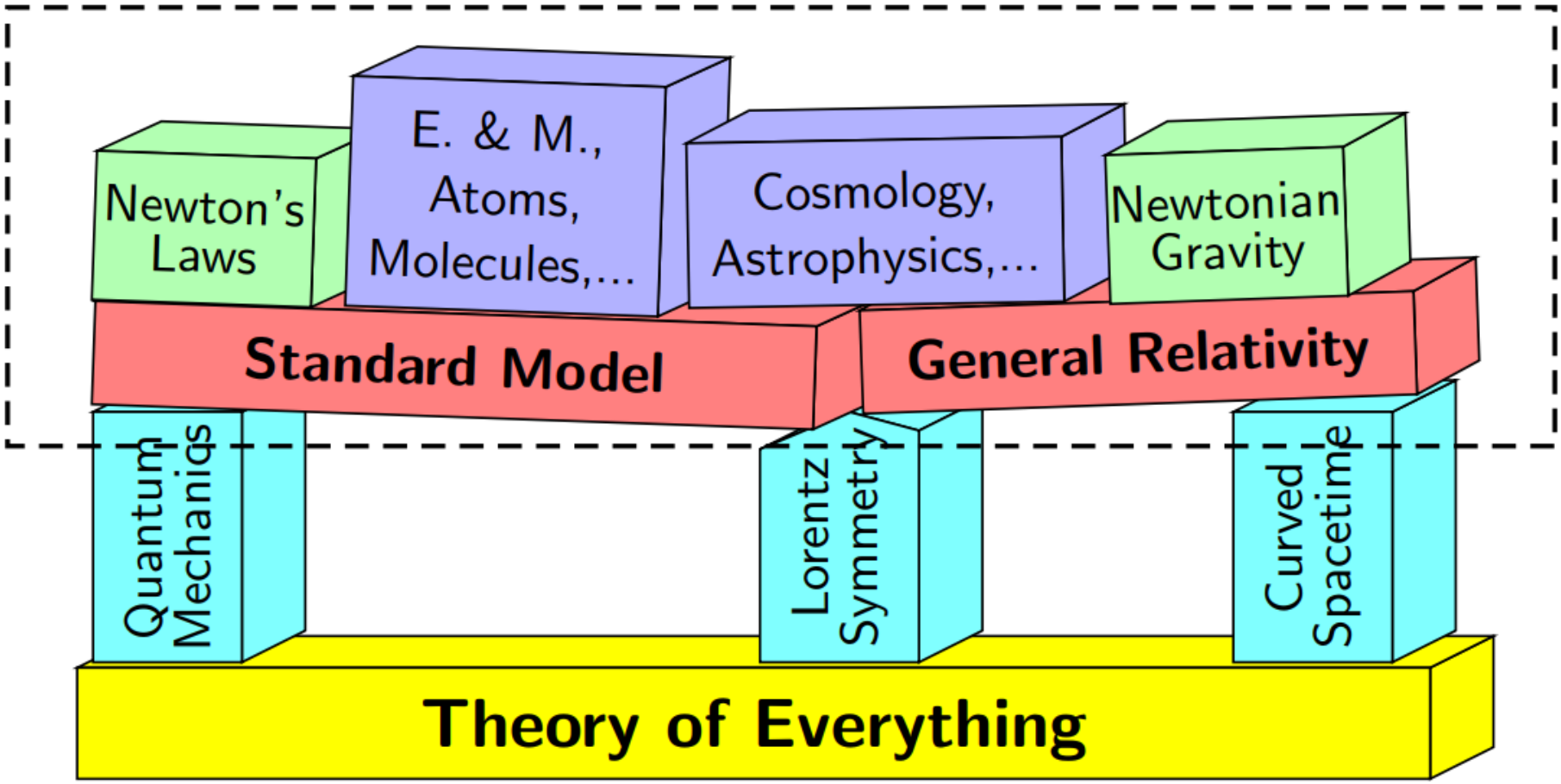
May 25, 2018

Singularities in General Relativity and their Quantum Fate, Warsaw

What I am going to tell you

1. Frameworks for Lorentz violation phenomenology
   - Modified Dispersion Relation
   - The Standard Model Extension
2. Ultraviolet Lorentz violation: Hořava-Lifshitz
3. Modified dispersion relation: Rainbow framework
4. Effective field theory: Standard Model Extension


Newton's Laws
E. & M., Atoms, Molecules,...
Cosmology, Astrophysics,...
Newtonian Gravity
Standard Model
General Relativity
Quantum Mechanics
Lorentz Symmetry
Curved Spacetime
Theory of Everything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1. Frameworks for Lorentz violation phenomenology

Modified Dispersion Relations

Straight to phenomenology

$$p^2 = E^2 \longrightarrow p^2 = E^2\left[1 + f(E)\right]$$

$$f(E) \approx \chi_n \left(\frac{E}{E_c}\right)^n$$

Define an *effective* photon mass: $E^2 - p^2 \equiv m^2$

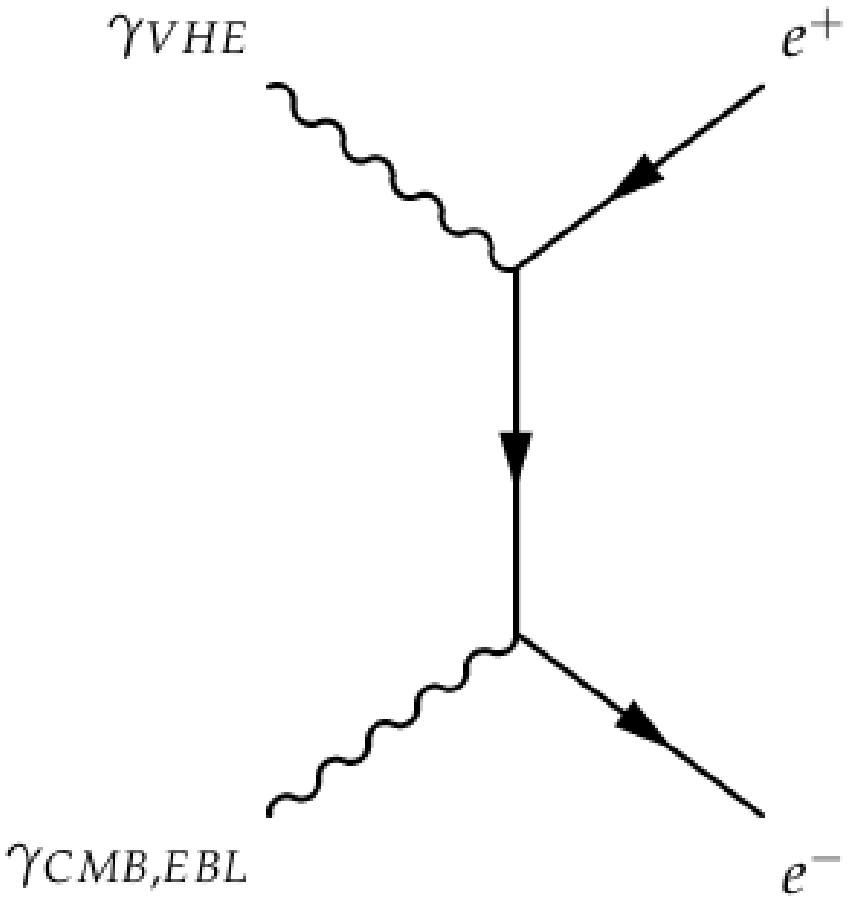
Rainbow framework

$$ds^2 = -f_1^{-2}(E)dt^2 + f_2^{-2}(E)a^2(t)\gamma_{ij}dx^i dx^j$$

Straight to Phenomenology

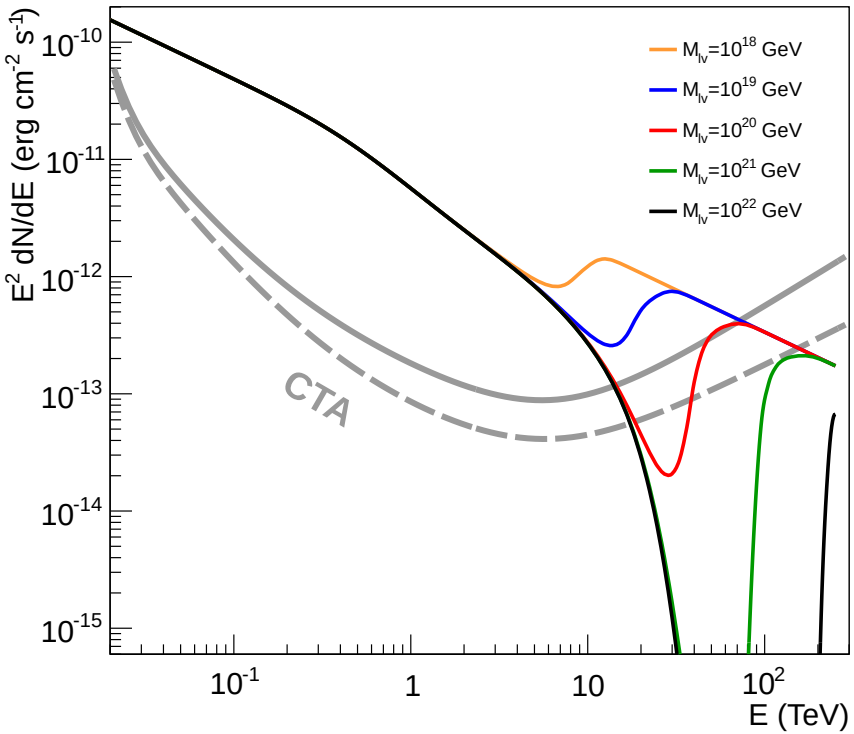
Absorption by the CMB and EBL:

$$x_{\gamma\gamma}^{-1} = \frac{1}{8E_\gamma^2\beta_\gamma}\int_{\epsilon_{min}}^{\infty} d\epsilon \frac{n(\epsilon)}{\epsilon^2}\int_{s_{min}}^{s_{max}(\epsilon,E_\gamma)} ds\left(s - m_\gamma^2 c^4\right)\sigma(s)$$



Straight to Phenomenology

Cherenkov Telescope Array



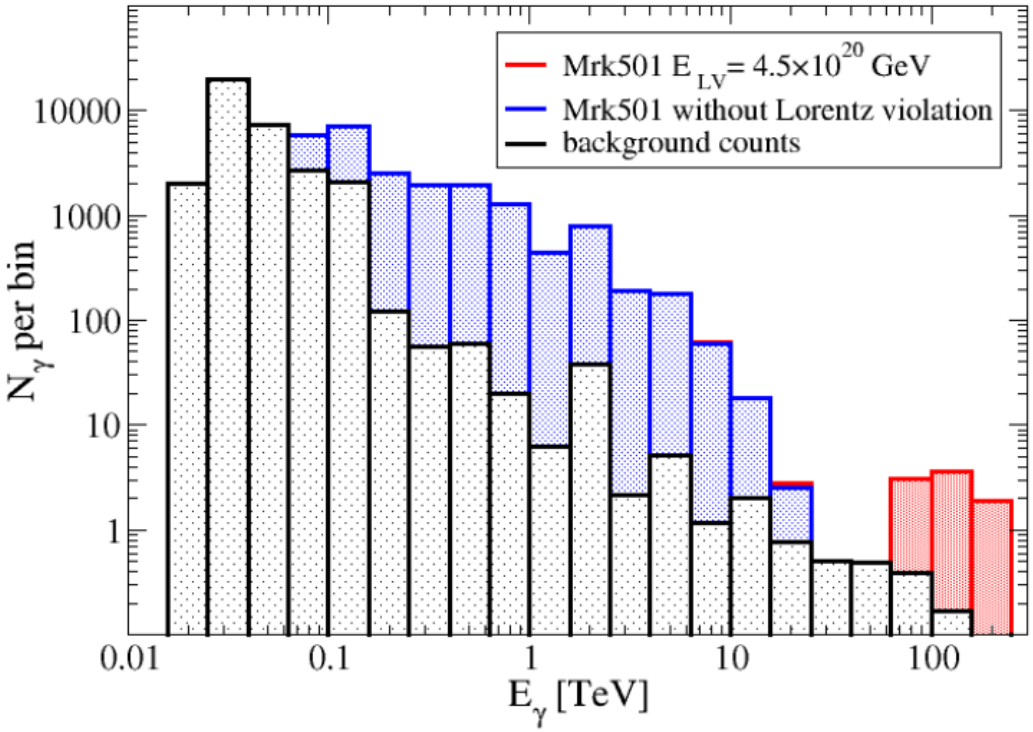


Figure 1: M.Fairbairn, NAN, J.Ellis, 2014

Energy scale of Lorentz violation: How do we find E_{LV}?

$$\Delta t = \frac{D_L}{c}\left(\frac{E}{E_{LV,n}}\right)^n$$

Limits on $E_{LV,n}$: $7.62 \cdot 10^{16}$ GeV ($n = 1$), $1.69 \cdot 10^9$ GeV ($n = 2$)

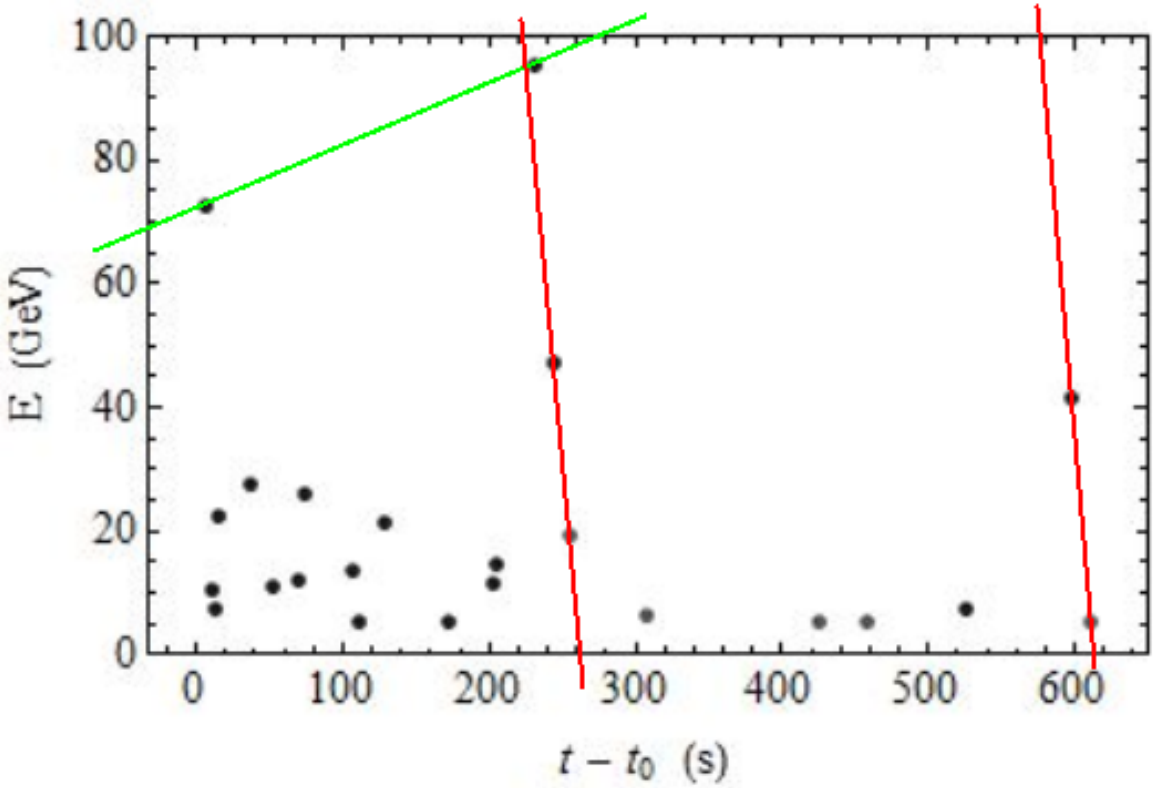


Figure 2: G.Amelino-Camelia, F.Fiore, D.Guetta, S.Puccetti, 2014

Energy scale of Lorentz violation: How do we find E_{LV}?

Rainbow approach

Spacetime metric is modified to include energy dependent functions, leading to a modified dispersion relation:

$$-E^2 f_1^2(E) + p^2 f_2^2(E) = m_0$$

demanding plane-wave solutions to free field theories $\Longrightarrow$:

$$\eta^{\mu\nu} = \mathrm{diag}(f_1^2, f_2^2, f_2^2, f_2^2)$$

Now we can identify:

$$f_1(E) = \sqrt{1 - \left(\frac{E}{E_{Pl}}\right)^n}, \quad f_2(E) = 1$$

Energy scale of Lorentz violation: How do we find E_{LV}?

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G(E)\rho}{3f_1^2(E)} - \frac{K}{a^2}\left[\frac{f_2(E)}{f_1(E)}\right]^2 + \frac{\Lambda(E)}{3f_1^2(E)}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G(E)(\rho + 3p)}{3f_1^2(E)} + \frac{\Lambda(E)}{3f_1^2(E)}$$

$$\dot{\rho} = 3\frac{\dot{a}}{a}(\rho + p)$$

Energy scale of Lorentz violation: How do we find E_{LV}?

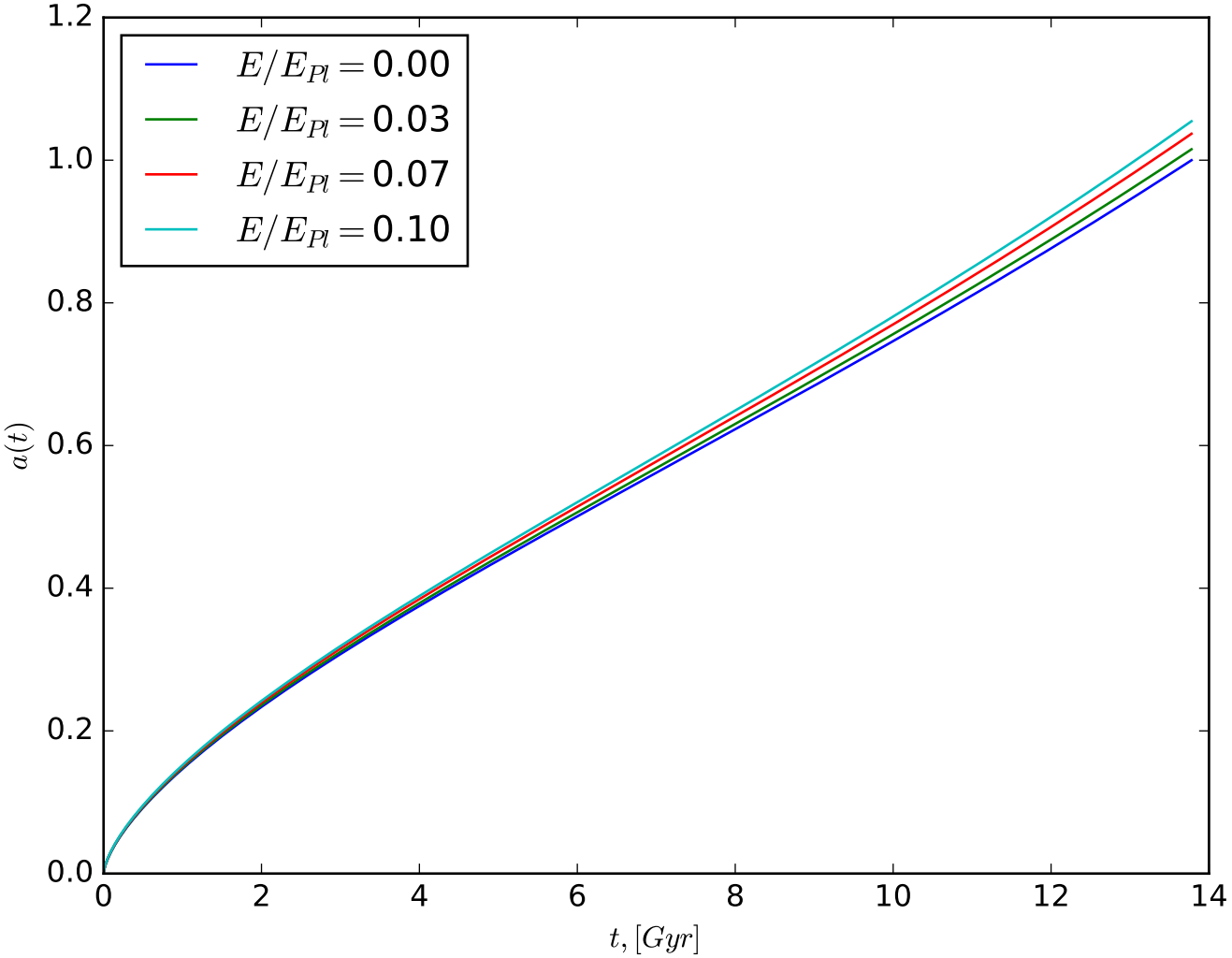


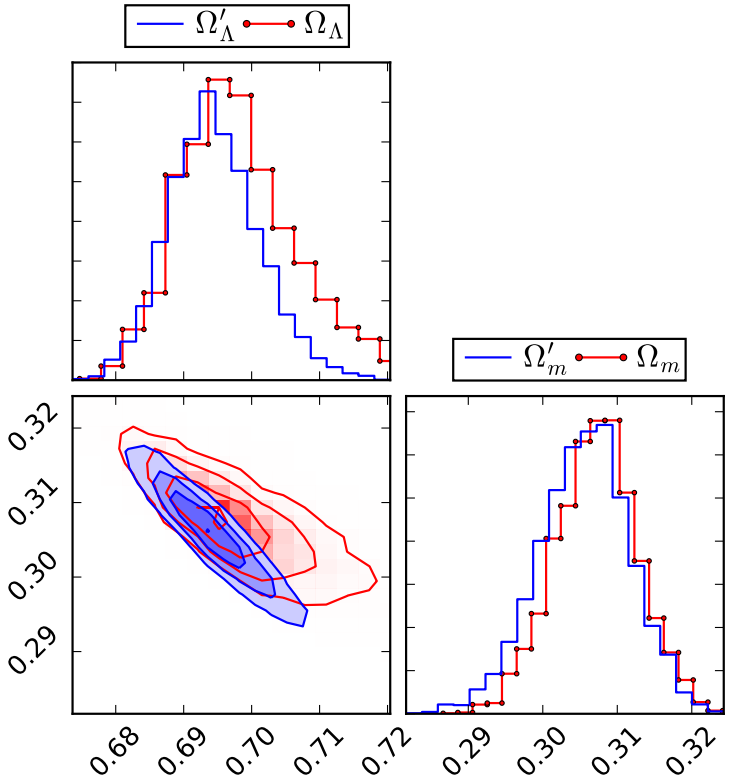
Figure 3: NAN, M.P.Dąbrowski, 2018

Energy scale of Lorentz violation: How do we find E_{LV}?

Value of E_{LV}

We get *lower* bound on E_{LV} (NAN, M.P. Dąbrowski, 2017):

$$E_{LV} > \frac{E}{E_{Pl}} \sim 10^{16} \text{ GeV} \ , 1\sigma$$



What about quantisation?

Prescription:

- Spatial derivatives $\mathcal{O} > 2$, time derivatives $\mathcal{O} = 2$
- Requires explicit breaking of Lorentz symmetry in the UV
- **All** experiments consistent with Lorentz symmetry
- No a priori reason to have it in the far UV

2. Hořava-Lifshitz gravity

What is HL?

Introduce an anisotropic (Lifshitz) scaling:

$$t \to b^{-z} t, \quad x^i \to b^{-1} x^i$$

For Lorentz invariance: $z = 1$

For power-counting renormalisability: $z \geq 4$

Usually assumed to be broken down to: $t \to \xi_0(t), \quad x^i \to x^i(t, x^k)$

Hořava-Lifshitz structure

- Symmetry group: Diff[M,$\mathcal{F}$]
- Preferred foliation on constant time slices, breaking Lorentz invariance
- Spacetime diffeomorphism symmetry $\longrightarrow$ time-dependent diffeomorphism symmetry + reparametrisation of global time coordinate

Hořava-Lifshitz gravity

Incomplete list of work done:

Binary pulsars	Yagi, Blas, et al. 2014
Energy scale of Lorentz violation	Liberati, Maccione & Sotiriou, 2012
Gravitational waves	Ynes, Yagi, Pretorius, 2016
Chiral primordial GW's	Takahashi, Soda, 2009
Cosmological perturbations	Kobayashi, Urakawa & Yamaguchi, 2010
Dark energy	Blas, Sibiryakov, 2011
Dark matter	Blas, Ivanov & Sibiryakov 2012
CMB	Wang, Wu, et al. 2013
Black holes	Shu, Kin, et al. 2014

Time for HL cosmology

$$\mathrm{d}s^2 = -\,N^2\,\mathrm{d}t^2 + g_{ij}\left(\mathrm{d}x^i + N^i\,\mathrm{d}t\right)\left(\mathrm{d}x^j + N^j\,\mathrm{d}t\right)$$

- Lapse function
- Shift vectors

Most general action:

$$S = \int \mathrm{d}^3x\,\mathrm{d}t N\sqrt{g}\left[K^{ij}K_{ij} - \lambda K^2 + \mathcal{V}(g_{ij})\right]$$

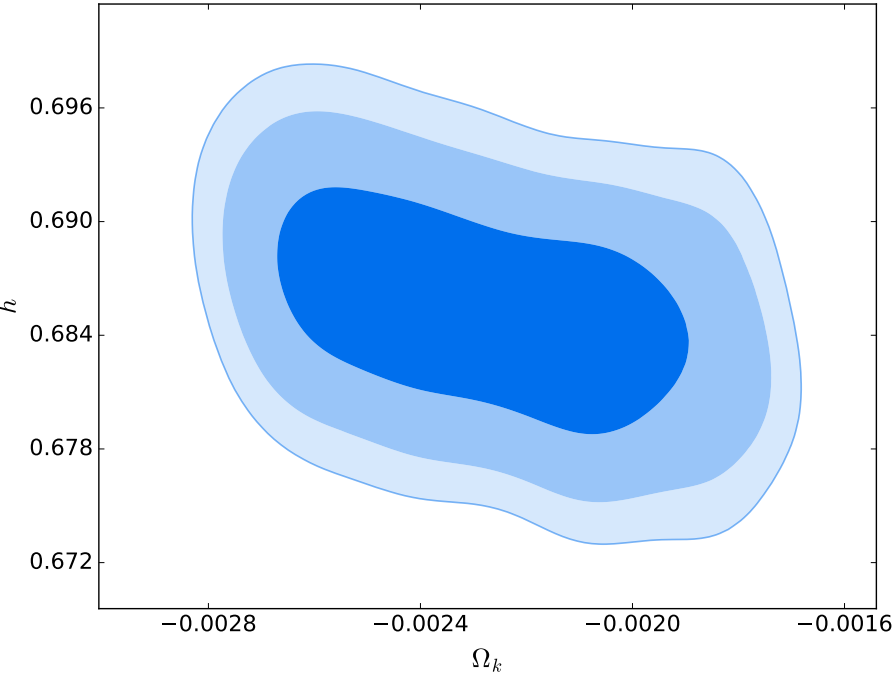
Setup for observational constraints

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\kappa^2}{6(3\lambda-1)}\left[\rho_m + \rho_r\right] + \frac{\kappa^2}{6(3\lambda-1)}\left[\frac{3\kappa^2\mu^2K^2}{8(3\lambda-1)a^4} + \frac{3\kappa^2\mu^2\Lambda^2}{8(3\lambda-1)}\right] - \frac{\kappa^4\mu^2\Lambda K}{8(3\lambda-1)^2a^2}$$

- λ dimensionless running Lagrange multiplier. Three fixed IR points, $(3, 1, \infty)$
- To flow towards GR need $\lambda = 1$.
- IR correspondence leads to:

$$G = \frac{\kappa^2}{32\pi c}, \quad c = \frac{\kappa^4\mu^2\Lambda}{8(3\lambda-1)^2}$$

What you can get



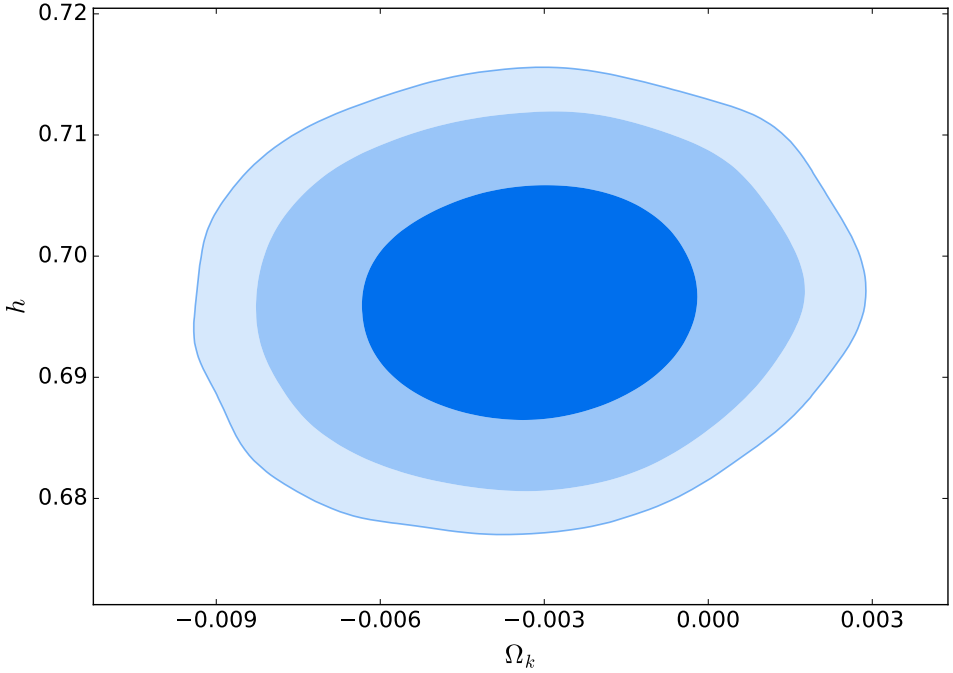


Figure 4: NAN, E.Czuchry 1803.03615

Any more smoking guns?

- Scalar gravitational wave modes
- Effective number of neutrino species, ΔN_ν

3. Standard Model Extension (SME)

Standard Model Extension - SME

Effective field theory representation of the Standard Model + more.

<u>Contains:</u>

- Standard model of particle physics
- General relativity
- ALL operators breaking Lorentz and CPT symmetry

$$\mathcal{L}_{\text{SME}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{EH} + \mathcal{L}_{\text{LV}}$$

- Gauge invariant, power-counting renormalisable, microcausal, positive energy etc.

Standard Model Extension - SME

Example: The photon sector.

$$\mathcal{L}^{mSME}_{\text{photon}} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\mathcal{L}_{\text{photon}}} \underbrace{-\frac{1}{4}\left(k_F\right)_{\mu\nu\lambda\kappa} F^{\mu\nu}F^{\lambda\kappa}}_{\mathcal{L}^{\text{CPT-even}}_{\text{photon}}} \underbrace{+\frac{1}{2}\left(k_{AF}\right)^{\kappa}\epsilon_{\kappa\lambda\mu\nu}A^{\lambda}F^{\mu\nu}}_{\mathcal{L}^{\text{CPT-odd}}_{\text{photon}}}$$

- CPT conserving. 19 Lorentz violating d.o.f
- CPT violating $\Longrightarrow$ Birefringence

Standard Model Extension

Zero-torsion limit $\Longrightarrow$ Riemannian spacetime

$$S_{\text{gravity}} = \int \mathrm{d}^4x\sqrt{-g}\left[(1-u)R - 2\Lambda + s^{\mu\nu}R^{(T)}_{\mu\nu} + t^{\mu\nu\alpha\beta}W_{\mu\nu\alpha\beta}\right]$$

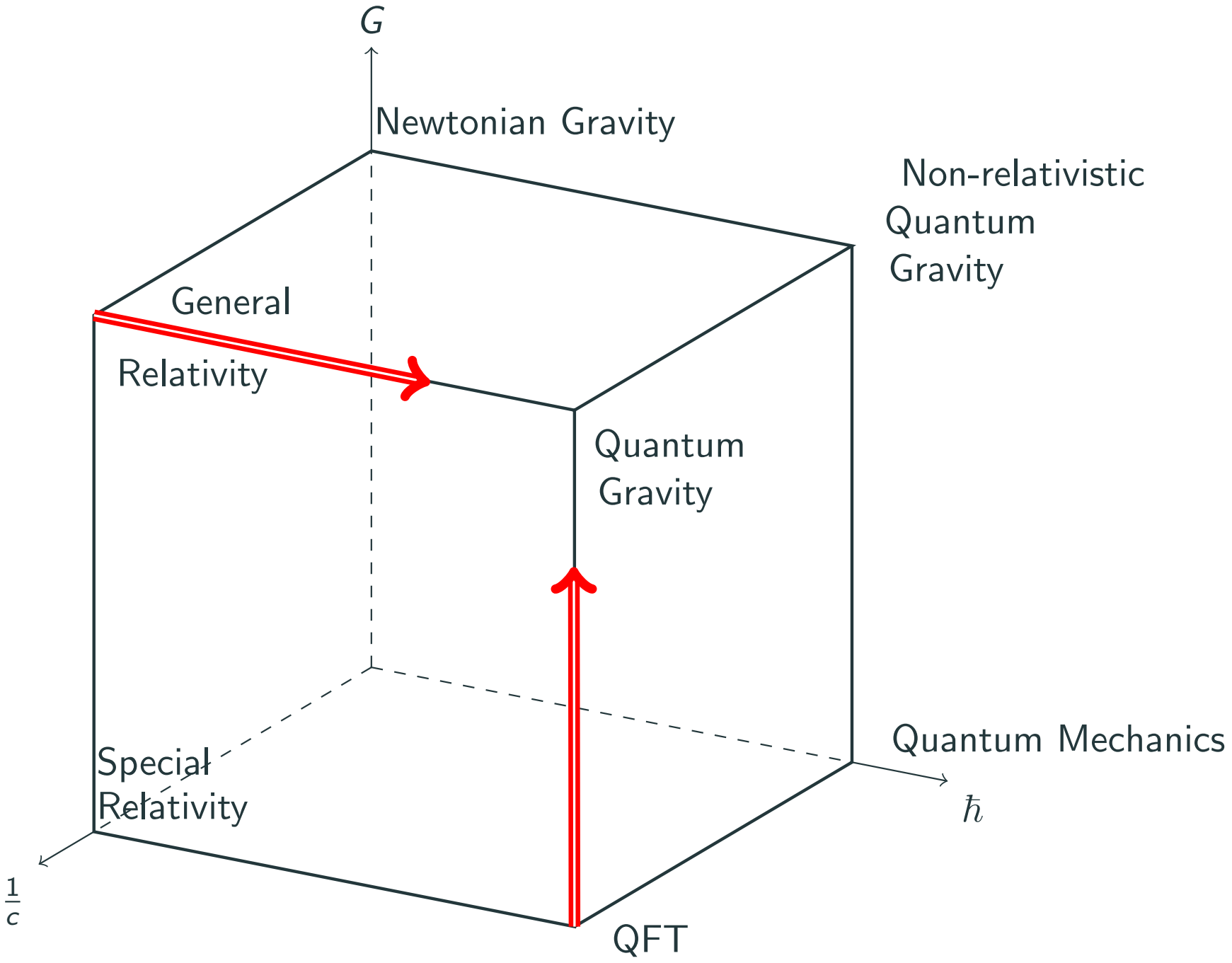
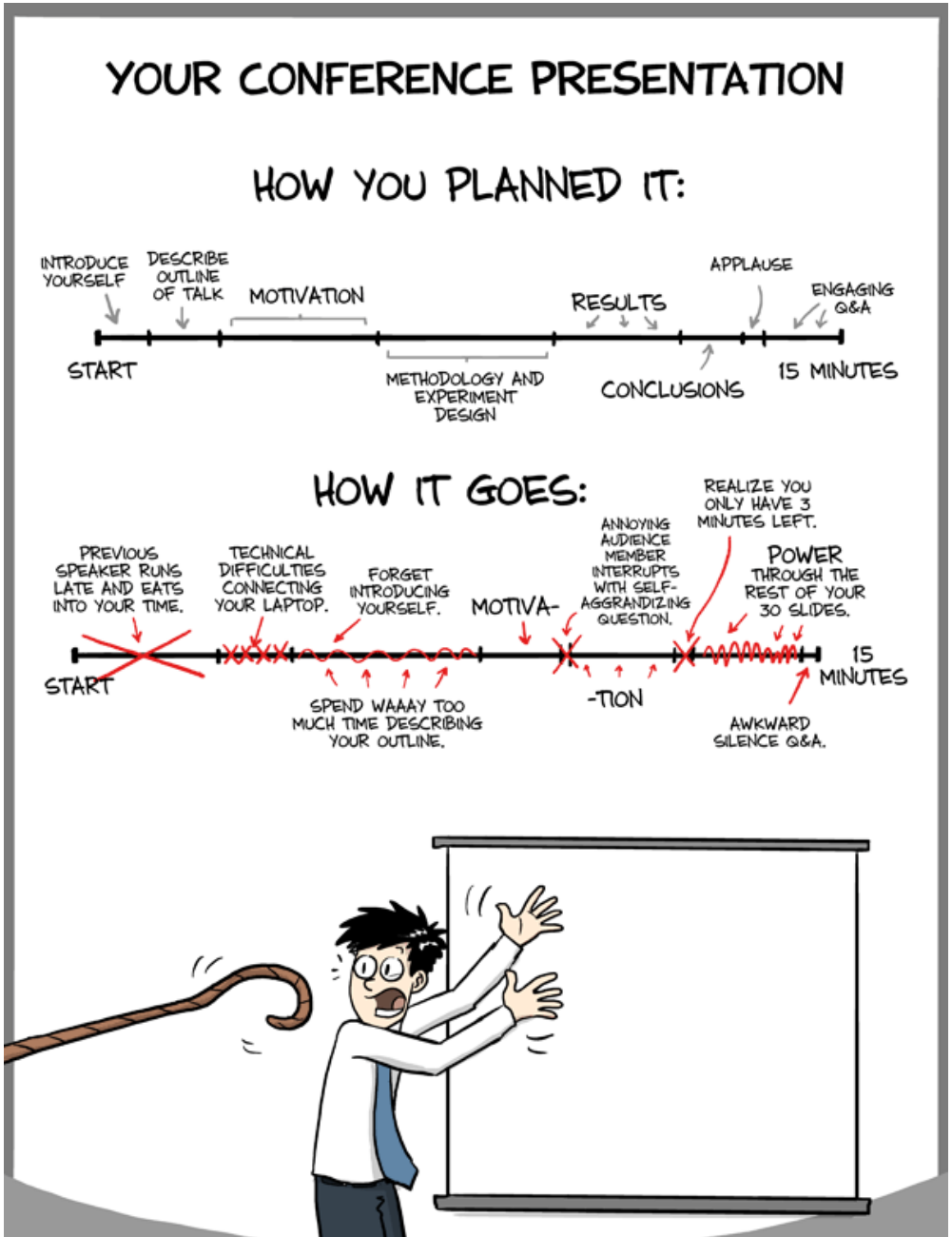
- Unobservable!

$$S_{\text{gravity}} = \int \mathrm{d}^4x\sqrt{-g}\,t^{\mu\nu\alpha\beta}W_{\mu\nu\alpha\beta}$$

Standard Model Extension

system	coefficients
gravitational Čerenkov radiation	$\bar{s}^{(4)}_{\mu\nu}$, $\bar{s}^{(6)}_{\mu\nu\alpha_1\alpha_2}$, $\bar{s}^{(8)}_{\mu\nu\alpha_1\alpha_2\alpha_3\alpha_4}$, $\bar{s}^{(10)*}_{\mu\nu\alpha_1\alpha_2\alpha_3\alpha_4\alpha_5\alpha_6}$
superconducting gravimeters	$(\bar{a}_{\rm eff})_\mu$, $\bar{c}_{\mu\nu}$, $\bar{s}^{(4)}_{\mu\nu}$
short-range gravity devices	$(\bar{k}_{\rm eff})_{jklm}$ $(\bar{a}_{\rm eff})_\mu$
gravitational-wave interferometers	$\bar{s}^{(4)}_{\mu\nu}$, $\bar{s}^{(6)}_{\mu\nu\alpha_1\alpha_2}$, $q^{(5)\,\mu\rho\alpha\nu\beta\sigma\gamma}$, $k^{(6)\,\mu\alpha\nu\beta\rho\gamma\sigma\delta}$
lunar laser ranging	$\bar{s}^{(4)}_{\mu\nu}$
binary-pulsar observations	$\bar{s}^{(4)}_{\mu\nu}$
planetary ephemerides	$(\bar{a}_{\rm eff})_\mu$, $\bar{s}^{(4)}_{\mu\nu}$
gravity probe B	$\bar{s}^{(4)}_{\mu\nu}$
bound kinetic energy WEP	$(\bar{a}_{\rm eff})_\mu$, $\bar{c}_{\mu\nu}$
atom interferometers	$(\bar{a}_{\rm eff})_\mu$, $\bar{c}_{\mu\nu}$, $\bar{s}^{(4)}_{\mu\nu}$
comagnetometry	$(\bar{a}_{\rm eff})_\mu$, $\bar{s}^{(4)}_{\mu\nu}$
perihelion precession	$(\bar{a}_{\rm eff})_\mu$, $\bar{c}_{\mu\nu}$
equivalence-principle pendulum	$(\bar{a}_{\rm eff})_\mu$
Solar-spin precession	$\bar{s}^{(4)}_{\mu\nu}$

Figure 5: Kostelecky, 2013


G
Newtonian Gravity
Non-relativistic
Quantum
Gravity
General
Relativity
Quantum
Gravity
Quantum Mechanics
Special
Relativity
$\hbar$
$\frac{1}{c}$
QFT

Thank you for your attention