Title: Theoretical status of Horava gravity

Speakers: Sergey Sibiryakov

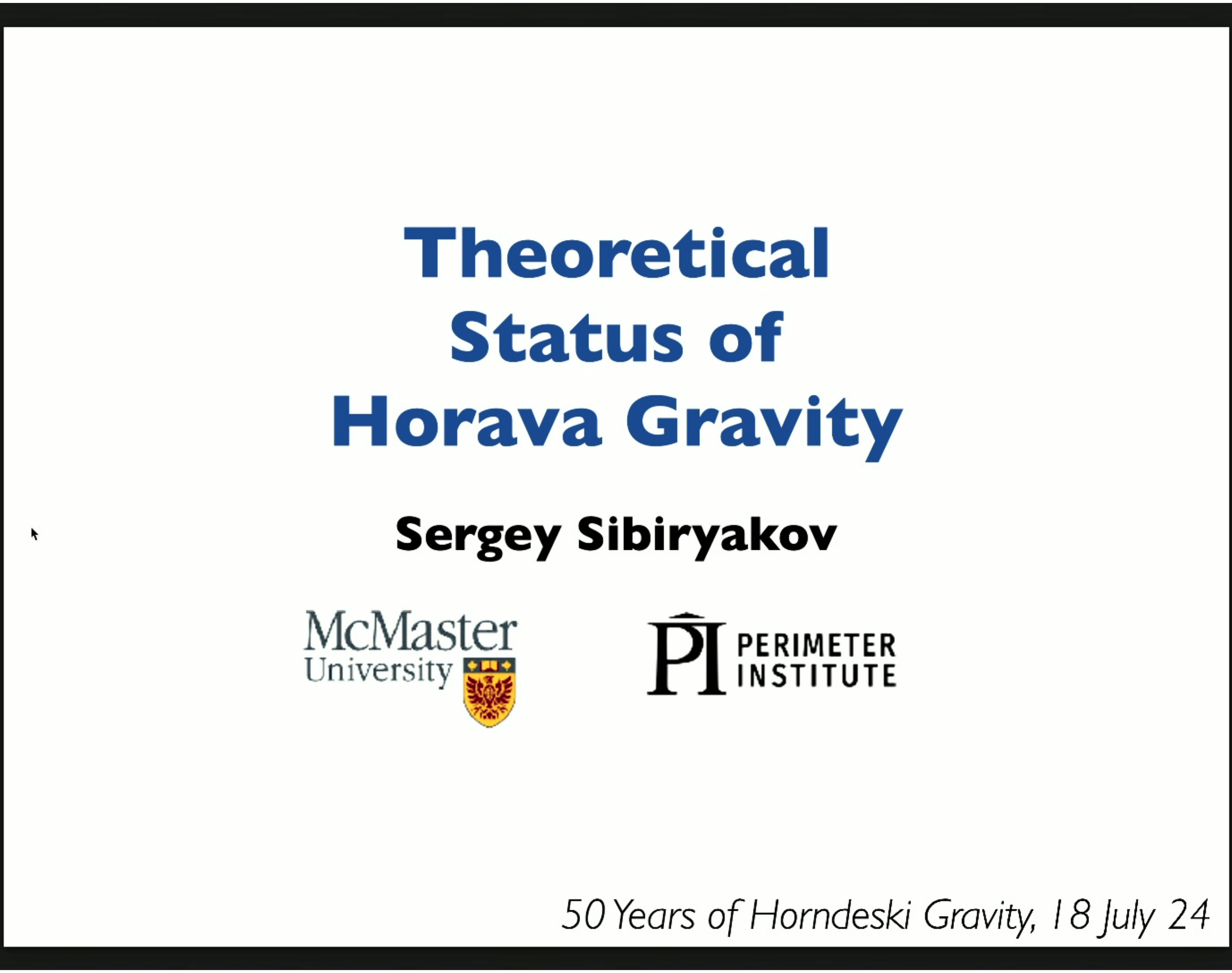
Collection/Series: 50 Years of Horndeski Gravity: Exploring Modified Gravity

Date: July 18, 2024 - 3:15 PM

URL: https://pirsa.org/24070075

Abstract:

I'll review the models of quantum gravity postulating invariance with respect to anisotropic (Lifshitz) scaling in the deep ultraviolet domain. At low energies they reduce to scalar-tensor gravity, with a timelike gradient of the scalar field breaking local Lorentz invariance. The models come in two versions differing by the dynamics in the scalar sector. The first, projectable, model has been shown to be perturbatively renormalizable and the full renormalization group (RG) flow of its marginal operators has been computed. The flow possesses a number of asymptotically free fixed points with one of them being connected by RG trajectories to the region of the parameter space where the kinetic term of the theory acquires the general relativistic form. The gravitational coupling exhibits non-monotonic behavior along the flow, vanishing both in the ultraviolet and the infrared. I'll mention the challenges facing the model in the infrared domain. The second, non-projectable, model is known to reproduce the phenomenology of general relativity in a certain region of parameters. Full proof of its renormalizability is still missing due to its complicated structure. I'll review recent progress towards constructing such proof.



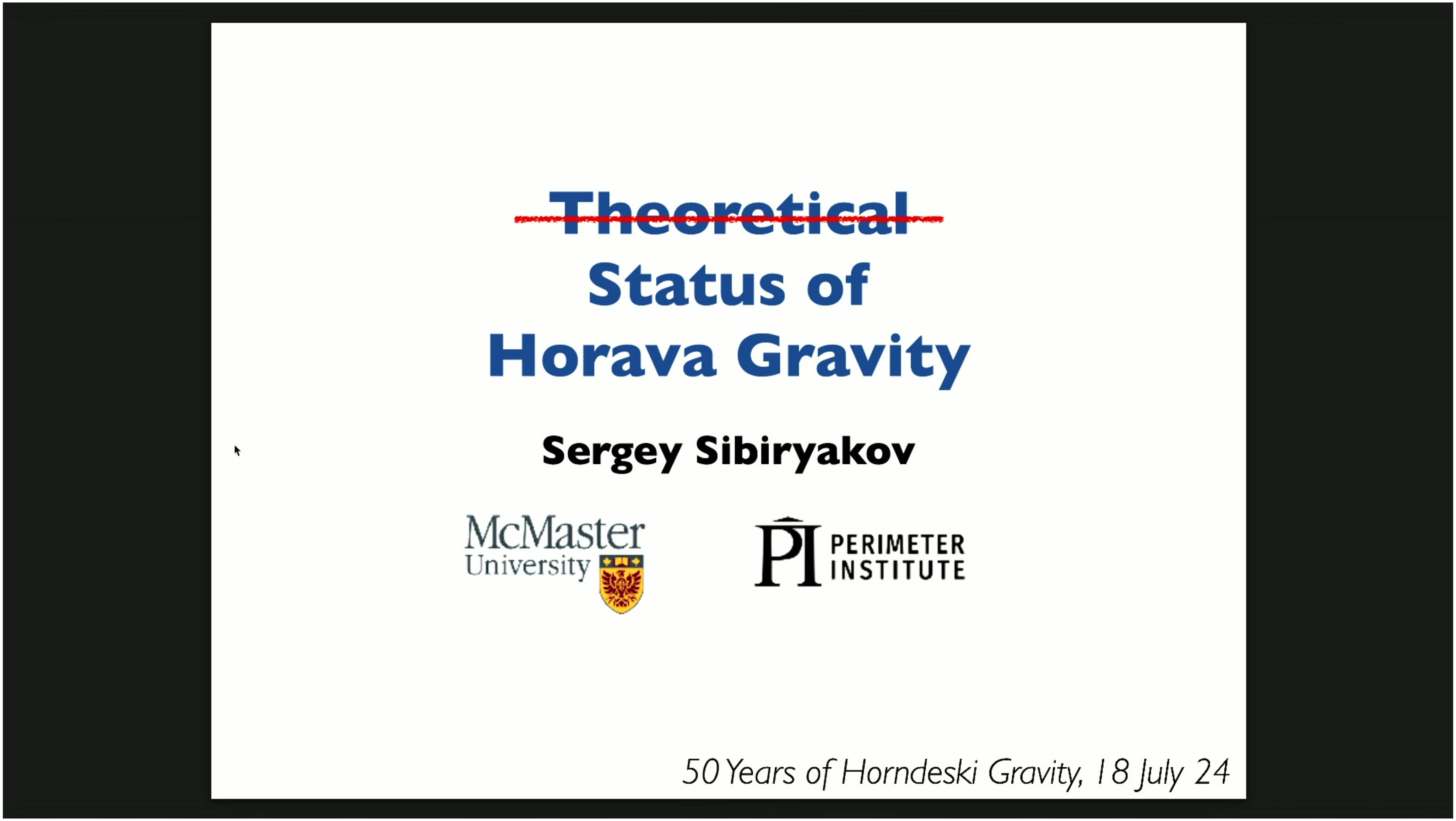
Theoretical Status of Horava Gravity

Sergey Sibiryakov

McMaster University

PERIMETER INSTITUTE

50 Years of Horndeski Gravity, 18 July 24



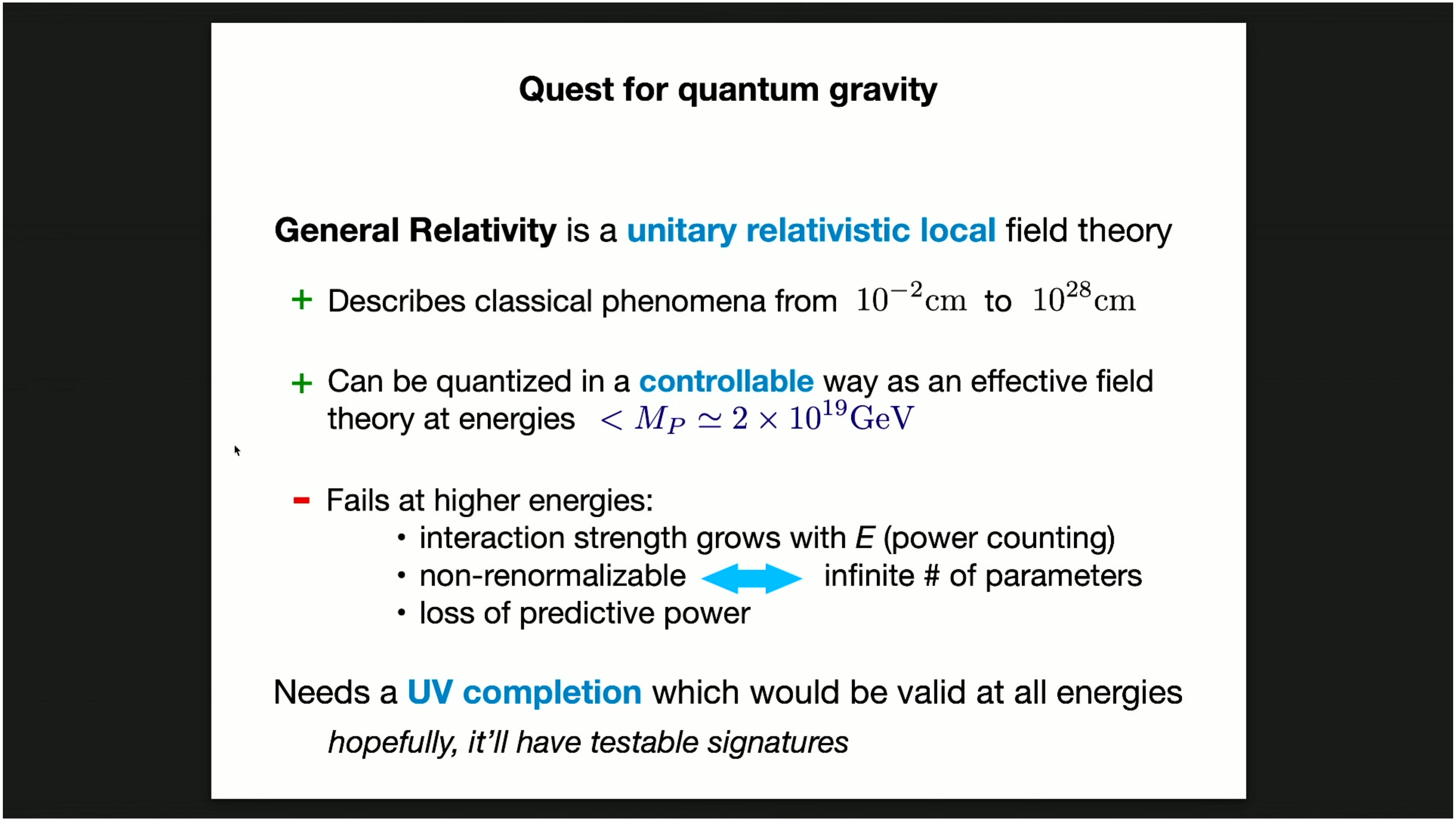
~~Theoretical~~ Status of Horava Gravity

Sergey Sibiryakov

McMaster University

PERIMETER INSTITUTE

50 Years of Horndeski Gravity, 18 July 24



Quest for quantum gravity

General Relativity is a **unitary relativistic local** field theory

- \+ Describes classical phenomena from $10^{-2}\mathrm{cm}$ to $10^{28}\mathrm{cm}$
- \+ Can be quantized in a **controllable** way as an effective field theory at energies $< M_P \simeq 2 \times 10^{19}\mathrm{GeV}$
- − Fails at higher energies:
  - interaction strength grows with *E* (power counting)
  - non-renormalizable ⟷ infinite # of parameters
  - loss of predictive power

Needs a **UV completion** which would be valid at all energies

hopefully, it'll have testable signatures

Quest for quantum gravity

$R_{\mu\nu}^2$-gravity

General Relativity is a ~~unitary~~ **relativistic local** field theory

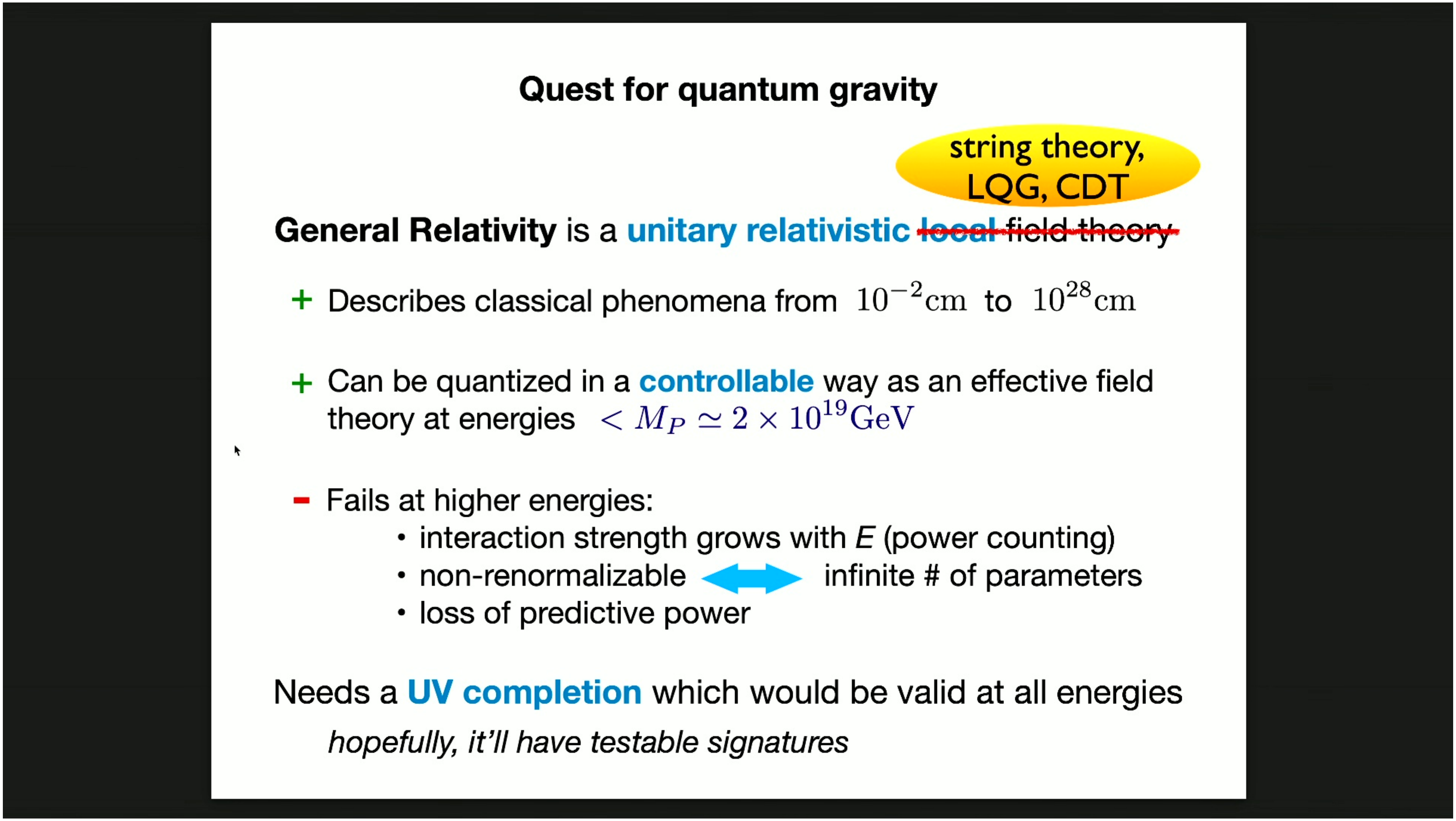
+ Describes classical phenomena from $10^{-2}\mathrm{cm}$ to $10^{28}\mathrm{cm}$

+ Can be quantized in a **controllable** way as an effective field theory at energies $< M_P \simeq 2 \times 10^{19}\mathrm{GeV}$

− Fails at higher energies:
  - interaction strength grows with *E* (power counting)
  - non-renormalizable ↔ infinite # of parameters
  - loss of predictive power

Needs a **UV completion** which would be valid at all energies

hopefully, it'll have testable signatures



Quest for quantum gravity

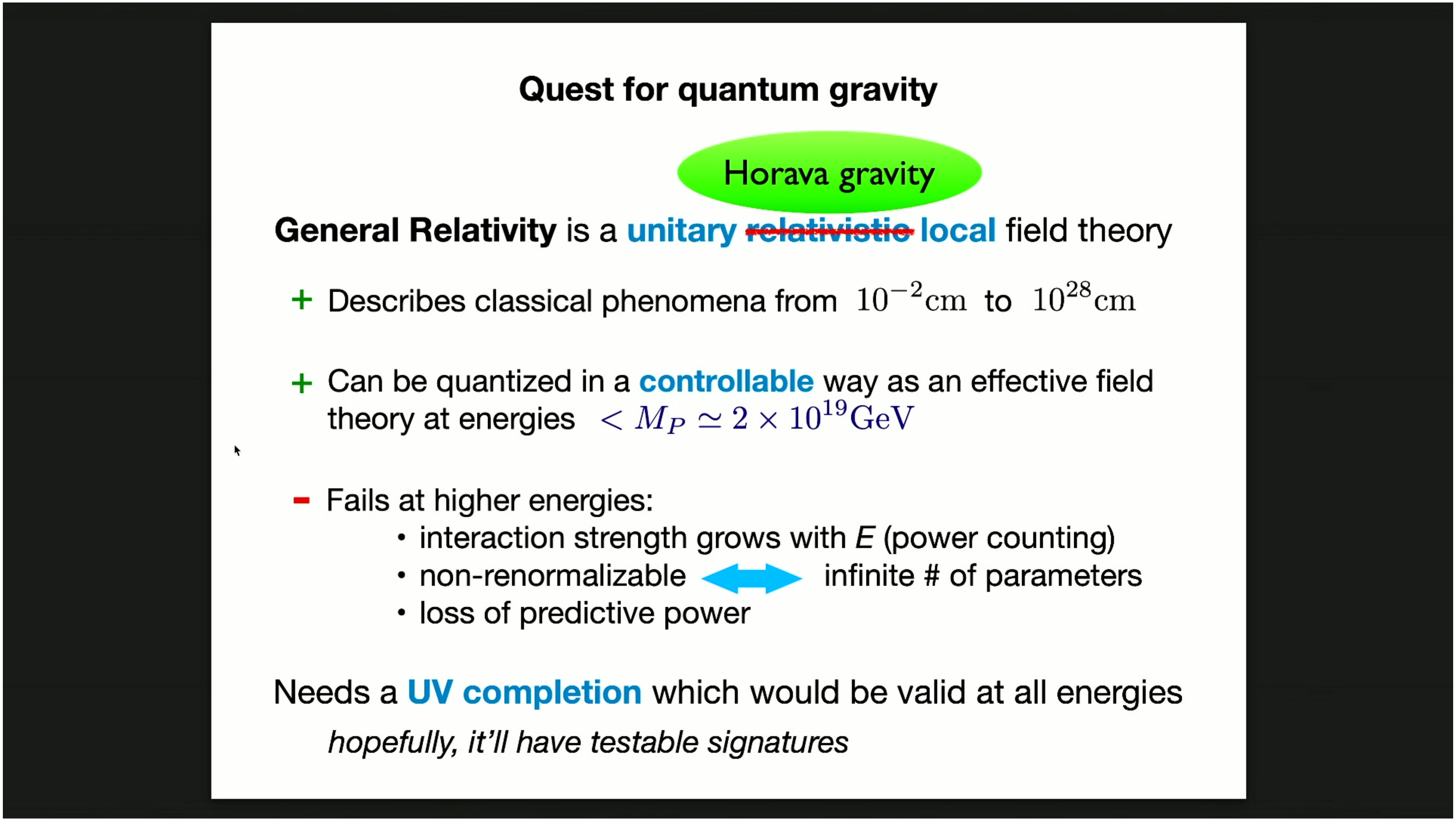
string theory,
LQG, CDT

General Relativity is a **unitary relativistic** ~~local field theory~~

- \+ Describes classical phenomena from $10^{-2}\mathrm{cm}$ to $10^{28}\mathrm{cm}$
- \+ Can be quantized in a **controllable** way as an effective field theory at energies $< M_P \simeq 2 \times 10^{19}\mathrm{GeV}$
- − Fails at higher energies:
  - interaction strength grows with *E* (power counting)
  - non-renormalizable ↔ infinite # of parameters
  - loss of predictive power

Needs a **UV completion** which would be valid at all energies

hopefully, it'll have testable signatures



Quest for quantum gravity

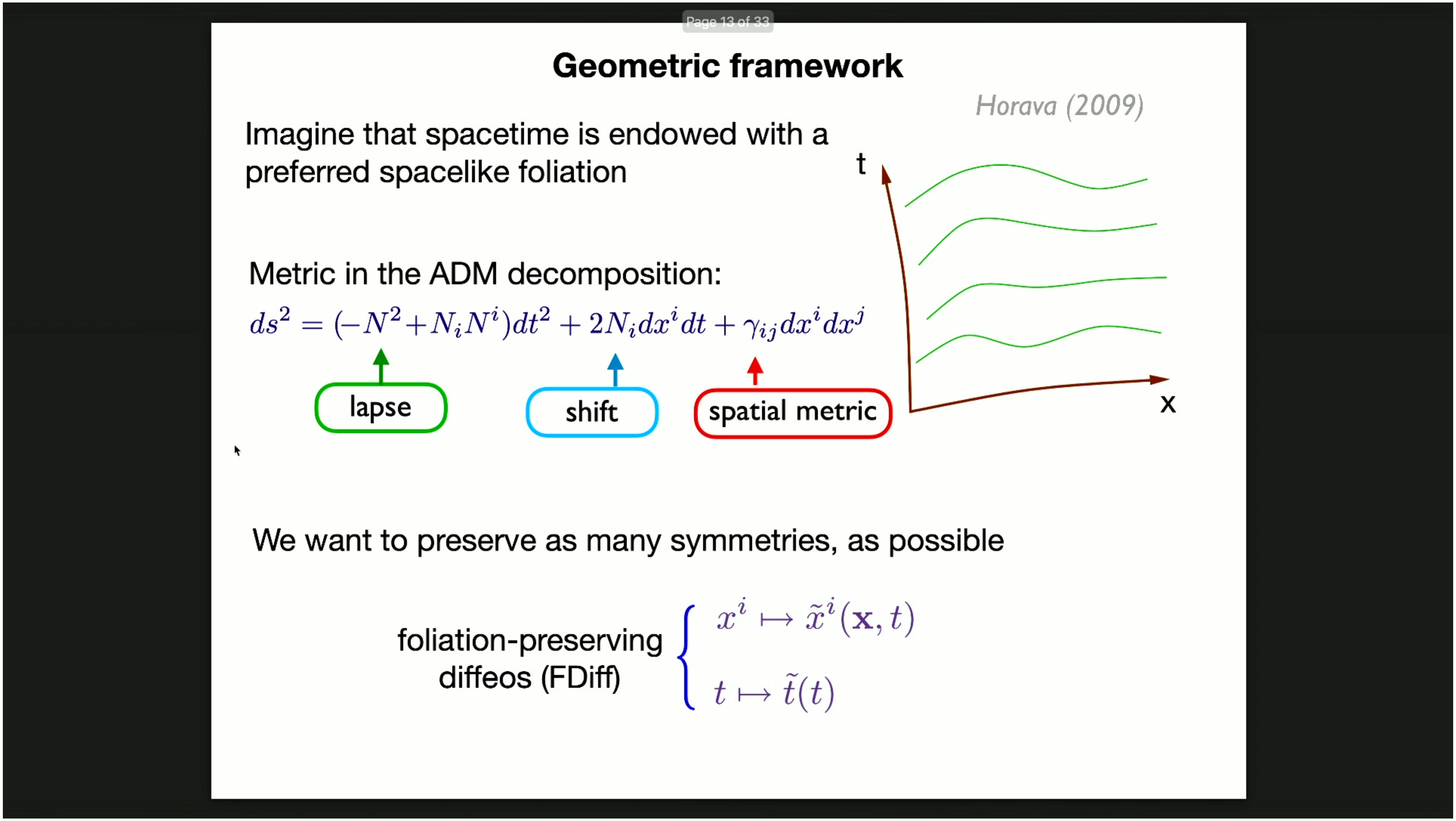
Horava gravity

General Relativity is a **unitary** ~~**relativistic**~~ **local** field theory

- \+ Describes classical phenomena from 10^{-2}cm to 10^{28}cm
- \+ Can be quantized in a **controllable** way as an effective field theory at energies $< M_P \simeq 2 \times 10^{19}\text{GeV}$
- – Fails at higher energies:
  - interaction strength grows with *E* (power counting)
  - non-renormalizable ↔ infinite # of parameters
  - loss of predictive power

Needs a **UV completion** which would be valid at all energies

hopefully, it'll have testable signatures



Geometric framework

Horava (2009)

Imagine that spacetime is endowed with a preferred spacelike foliation

Metric in the ADM decomposition:

$$ds^2 = (-N^2 + N_i N^i)dt^2 + 2N_i dx^i dt + \gamma_{ij} dx^i dx^j$$

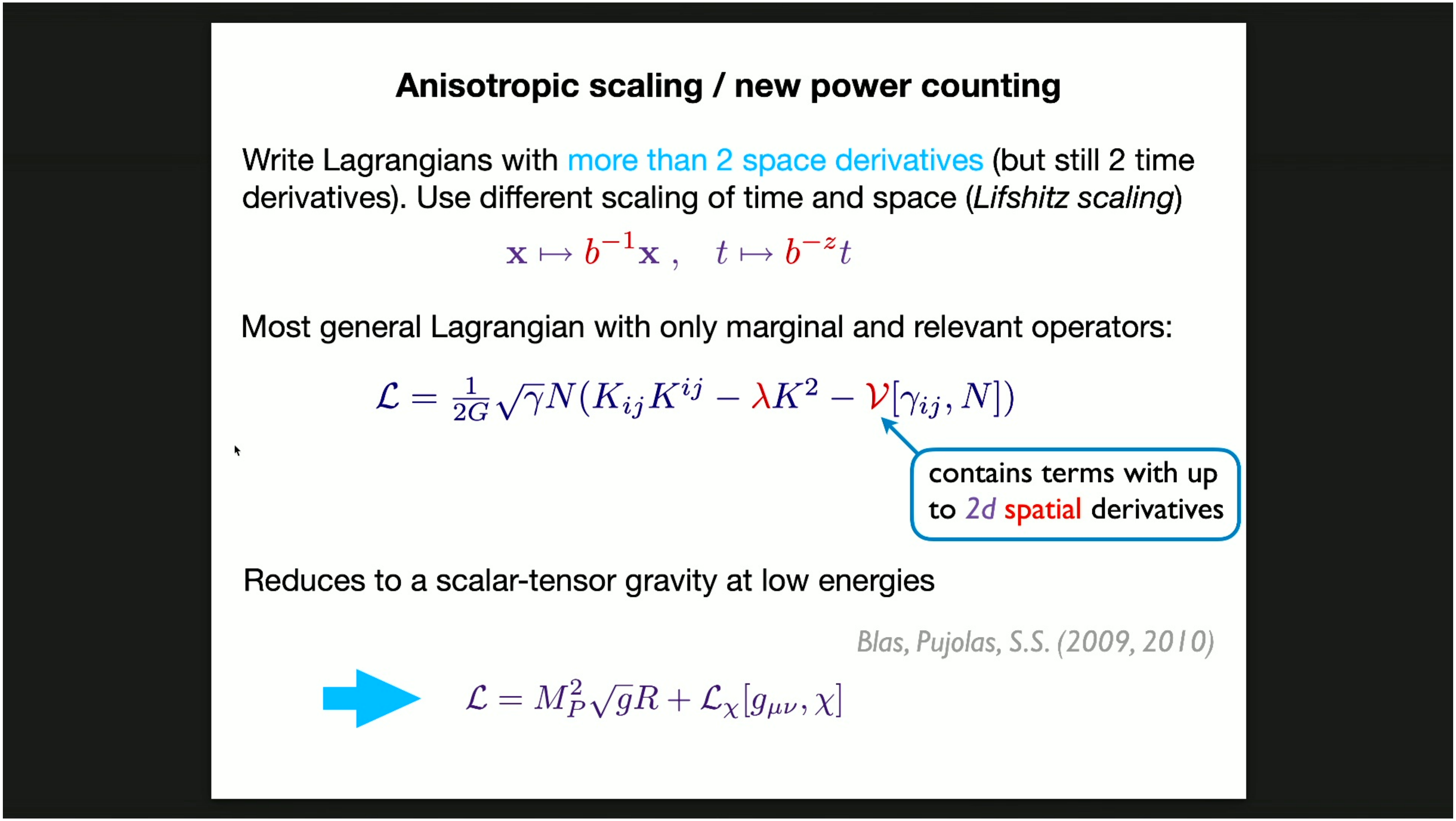
lapse

shift

spatial metric

We want to preserve as many symmetries, as possible

foliation-preserving diffeos (FDiff) $\begin{cases} x^i \mapsto \tilde{x}^i(\mathbf{x}, t) \\ t \mapsto \tilde{t}(t) \end{cases}$



Anisotropic scaling / new power counting

Write Lagrangians with more than 2 space derivatives (but still 2 time derivatives). Use different scaling of time and space (*Lifshitz scaling*)

$$\mathbf{x} \mapsto b^{-1}\mathbf{x}\,, \quad t \mapsto b^{-z}t$$

Most general Lagrangian with only marginal and relevant operators:

$$\mathcal{L} = \frac{1}{2G}\sqrt{\gamma}N(K_{ij}K^{ij} - \lambda K^2 - \mathcal{V}[\gamma_{ij}, N])$$

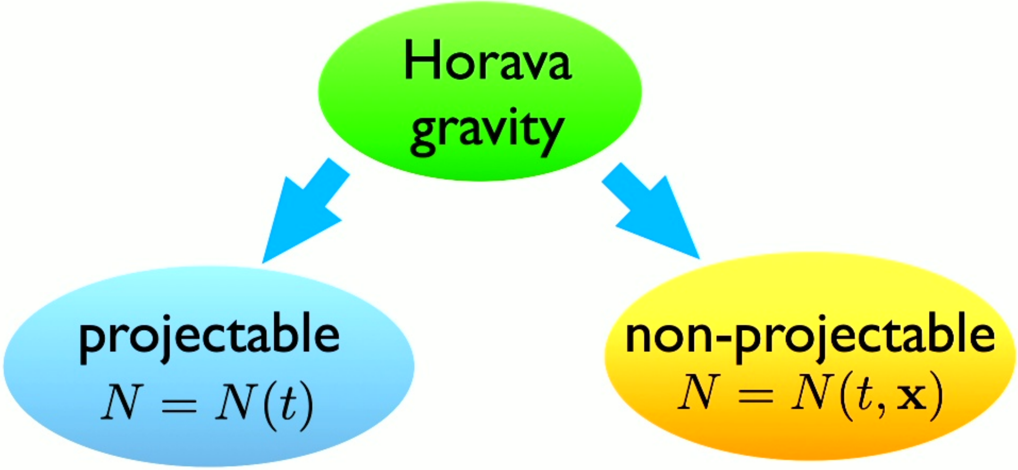
contains terms with up to $2d$ spatial derivatives

Reduces to a scalar-tensor gravity at low energies

Blas, Pujolas, S.S. (2009, 2010)

$$\mathcal{L} = M_P^2\sqrt{g}R + \mathcal{L}_\chi[g_{\mu\nu}, \chi]$$

Two flavours of HG



Horava gravity

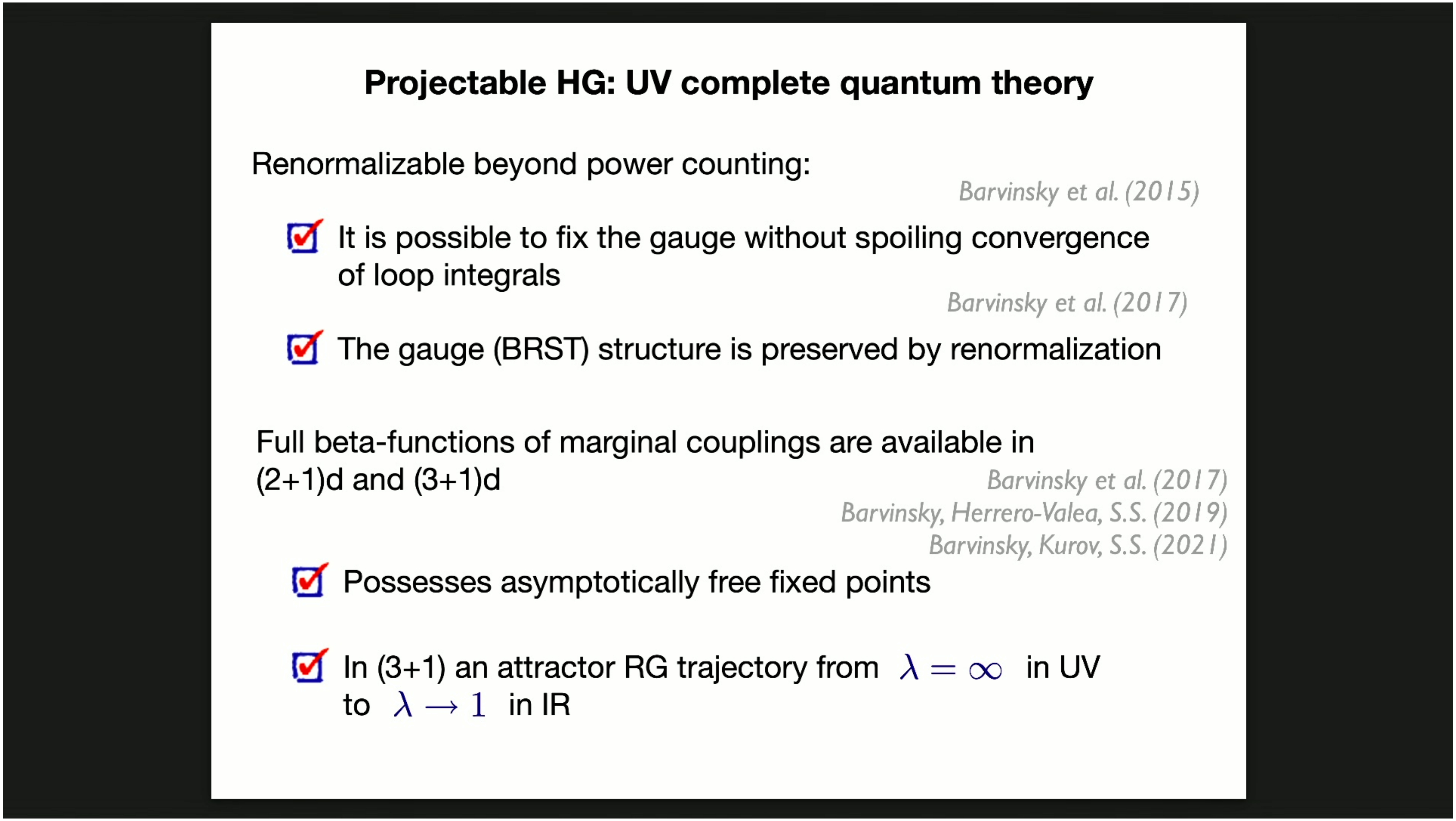
projectable

$N = N(t)$

non-projectable

$N = N(t, \mathbf{x})$

theory	AAA	A
pheno	BB	A



Projectable HG: UV complete quantum theory

Renormalizable beyond power counting:

Barvinsky et al. (2015)

- ☑ It is possible to fix the gauge without spoiling convergence of loop integrals

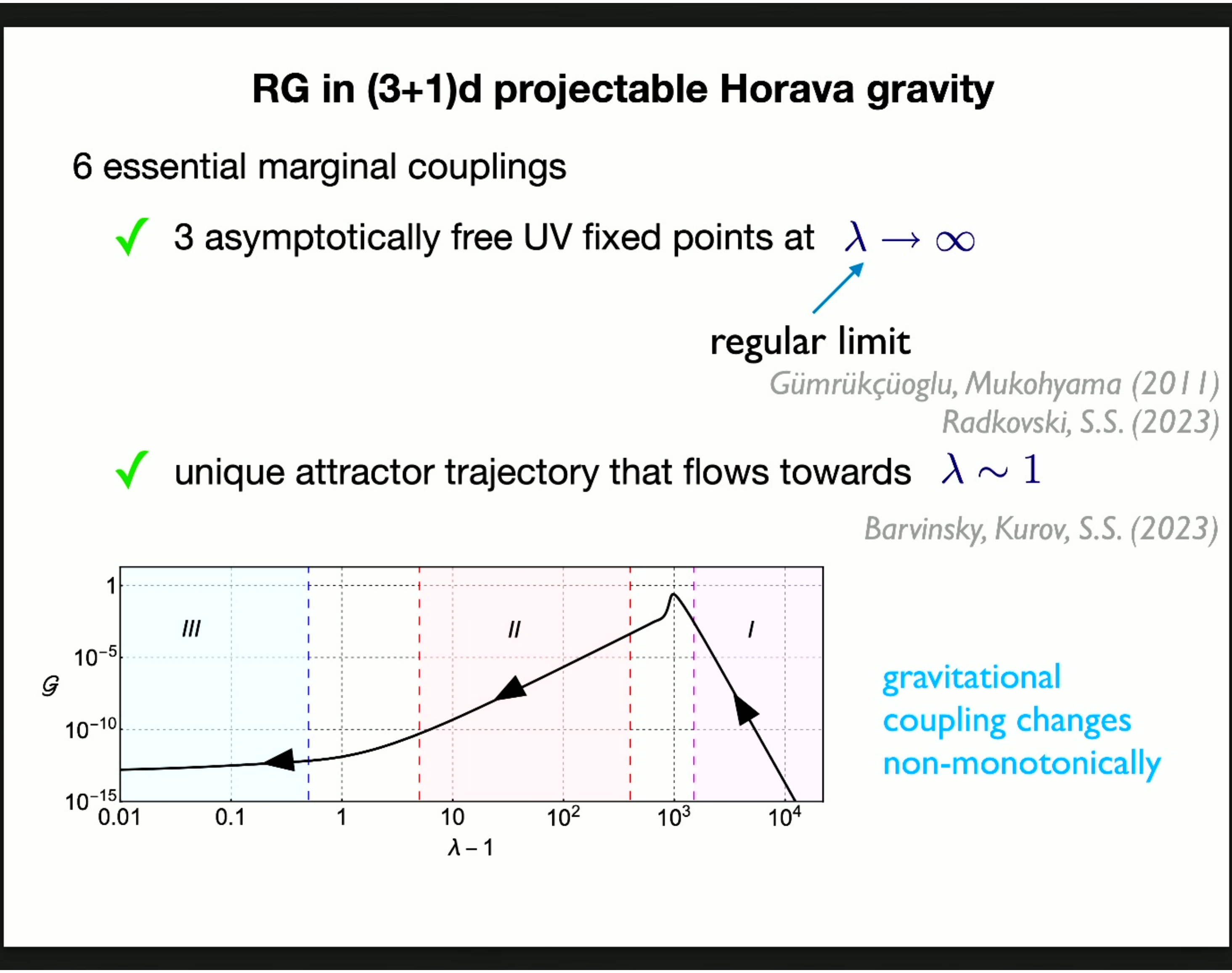
Barvinsky et al. (2017)

- ☑ The gauge (BRST) structure is preserved by renormalization

Full beta-functions of marginal couplings are available in (2+1)d and (3+1)d

Barvinsky et al. (2017)
Barvinsky, Herrero-Valea, S.S. (2019)
Barvinsky, Kurov, S.S. (2021)

- ☑ Possesses asymptotically free fixed points
- ☑ In (3+1) an attractor RG trajectory from $\lambda = \infty$ in UV to $\lambda \to 1$ in IR



RG in (3+1)d projectable Horava gravity

6 essential marginal couplings

- ✓ 3 asymptotically free UV fixed points at $\lambda \to \infty$

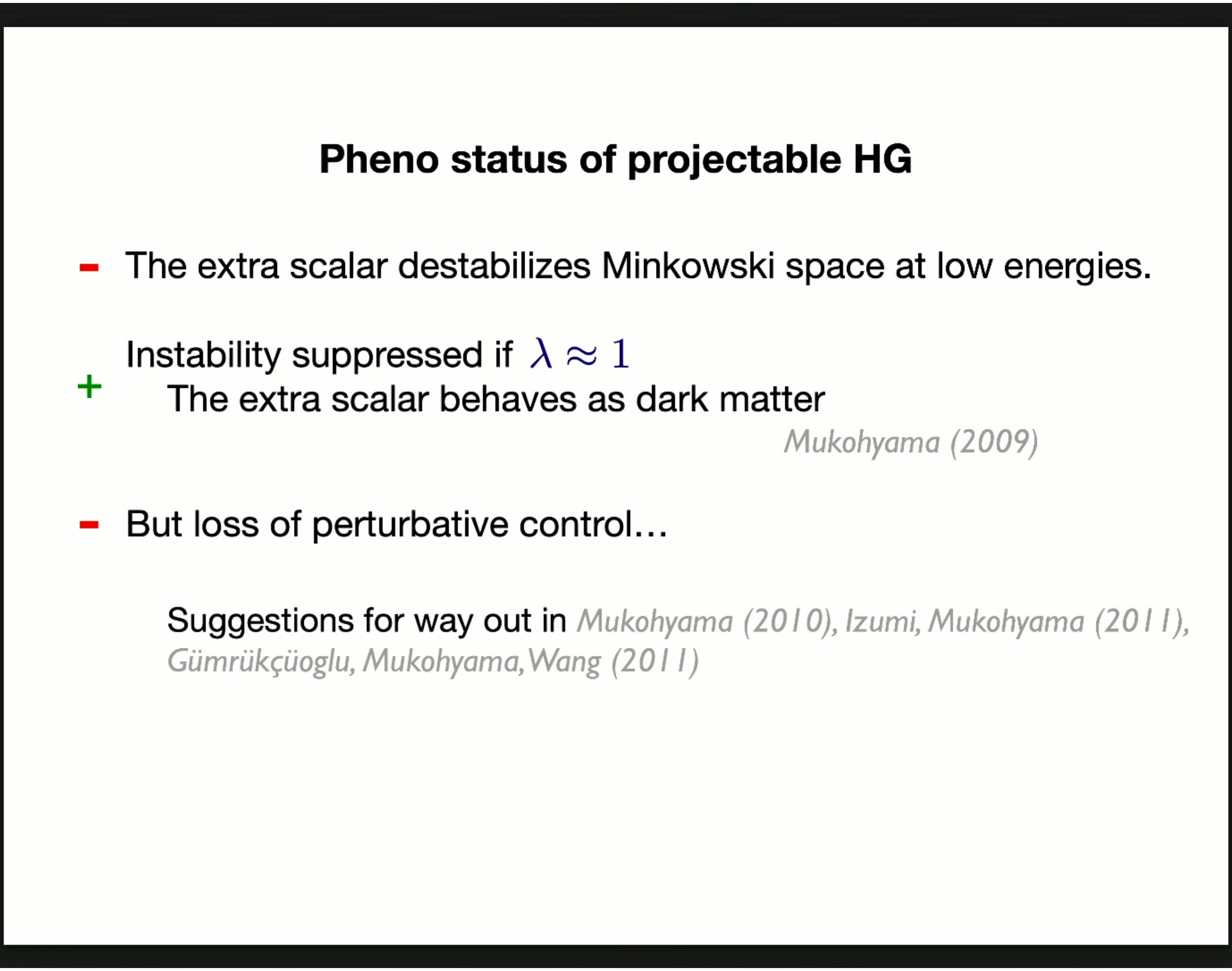
regular limit

Gümrükçüoglu, Mukohyama (2011)
Radkovski, S.S. (2023)

- ✓ unique attractor trajectory that flows towards $\lambda \sim 1$

Barvinsky, Kurov, S.S. (2023)

gravitational coupling changes non-monotonically



Pheno status of projectable HG

– The extra scalar destabilizes Minkowski space at low energies.

\+ Instability suppressed if $\lambda \approx 1$
The extra scalar behaves as dark matter

Mukohyama (2009)

– But loss of perturbative control…

Suggestions for way out in *Mukohyama (2010), Izumi, Mukohyama (2011), Gümrükçüoglu, Mukohyama, Wang (2011)*

What about Non-projectable HG?

Is it renormalizable?

- ⚡ We don't know: divergences may be non-local
- ✓ Non-localities cancel at one loop!

Bellorin, Borquez, Droguett (2022)

- ✎ Can work at higher loops if canonical structure associated to 2nd class constraints is preserved

Is it phenomenologically viable?

Yes … with fine-tuning to recover Lorentz invariance

Blas, Pujolas, S.S., (2009, 2010, 2011)
Gümrükçüoglu, Saravani, Sotiriou (2017)

Low energy limit of NP HG

khrono-metric Lagrangian:

$\lambda' = \lambda - 1$

$$\mathcal{L} = -\frac{1}{2}M_P^2\sqrt{-g}\big(R + \alpha a_\mu a^\mu + \beta \nabla_\mu u_\nu \nabla^\nu u^\mu + \lambda' \vartheta^2\big)$$

$a_\mu = u^\nu \nabla_\nu u_\mu$

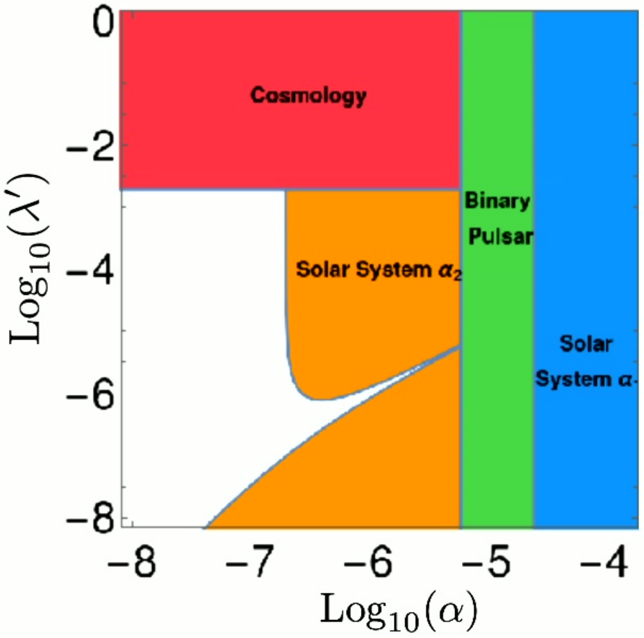
$\vartheta = \nabla_\nu u^\nu$

$$u_\mu = \frac{\partial_\mu \chi}{\sqrt{(\partial\chi)^2}}$$

similar to Einstein-aether

Jacobson, Mattingly (2000)

GW170817: $|\beta| \lesssim 10^{-15}$



Low energy limit of NP HG

khrono-metric Lagrangian:

$\lambda' = \lambda - 1$

$$\mathcal{L} = -\frac{1}{2} M_P^2 \sqrt{-g}\left(R + \alpha a_\mu a^\mu + \beta \nabla_\mu u_\nu \nabla^\nu u^\mu + \lambda' \vartheta^2\right)$$

$a_\mu = u^\nu \nabla_\nu u_\mu$

$\vartheta = \nabla_\nu u^\nu$

$$u_\mu = \frac{\partial_\mu \chi}{\sqrt{(\partial\chi)^2}}$$

similar to Einstein-aether

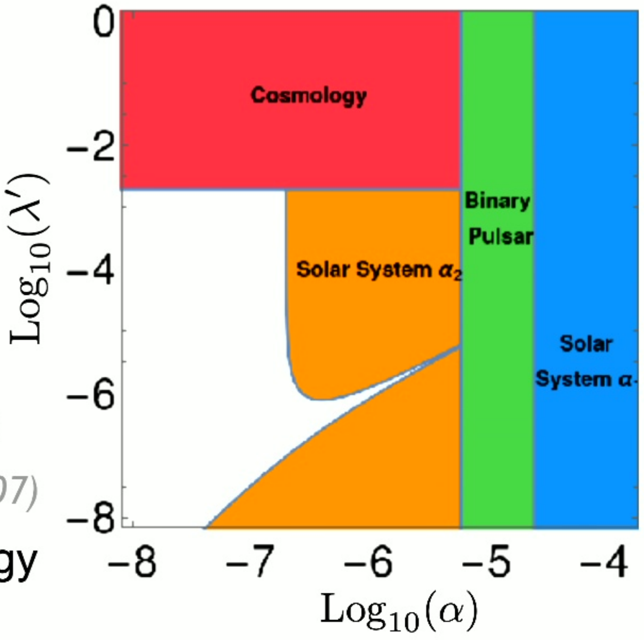
Jacobson, Mattingly (2000)

GW170817: $|\beta| \lesssim 10^{-15}$

NB. Reduces to cuscuton in the limit

$\alpha = \beta = 0$ *Afshordi et al. (2007)*

→ constraints only from cosmology



Summary

- ☑ Horava gravity provides a class of renormalizable quantum gravity theories

- ☑ Full RG flow available in the **projectable** version (2+1) and (3+1)d. Asymptotically free

- ☑ Progress towards renormalizability of the **non-projectable** version

- ☑ Viability penomenology constrained by the data