Title: Challenges of (asymptotically safe) quantum gravity

Speakers: Marc Schiffer

Series: Quantum Gravity

Date: December 02, 2020 - 3:30 PM

URL: http://pirsa.org/20120007

Abstract: I will discuss challenges of quantum gravity, highlighting conceptual, methodological as well as phenomenological aspects. Focusing on asymptotically safe quantum gravity, I will review recent progress in addressing key theoretical challenges using continuum and lattice methods. Furthermore, I will explain how the high predictive power of the asymptotically safe fixed point for quantum gravity and matter might allow us to explain fundamental properties of our universe, for example its dimensionality. Finally, I will point out possible connections between different approaches to quantum gravity, and how these connections might help us formulating a fundamental description of nature.

# Challenges of (Asymptotically Safe) Quantum Gravity


**Marc Schiffer**, Heidelberg University

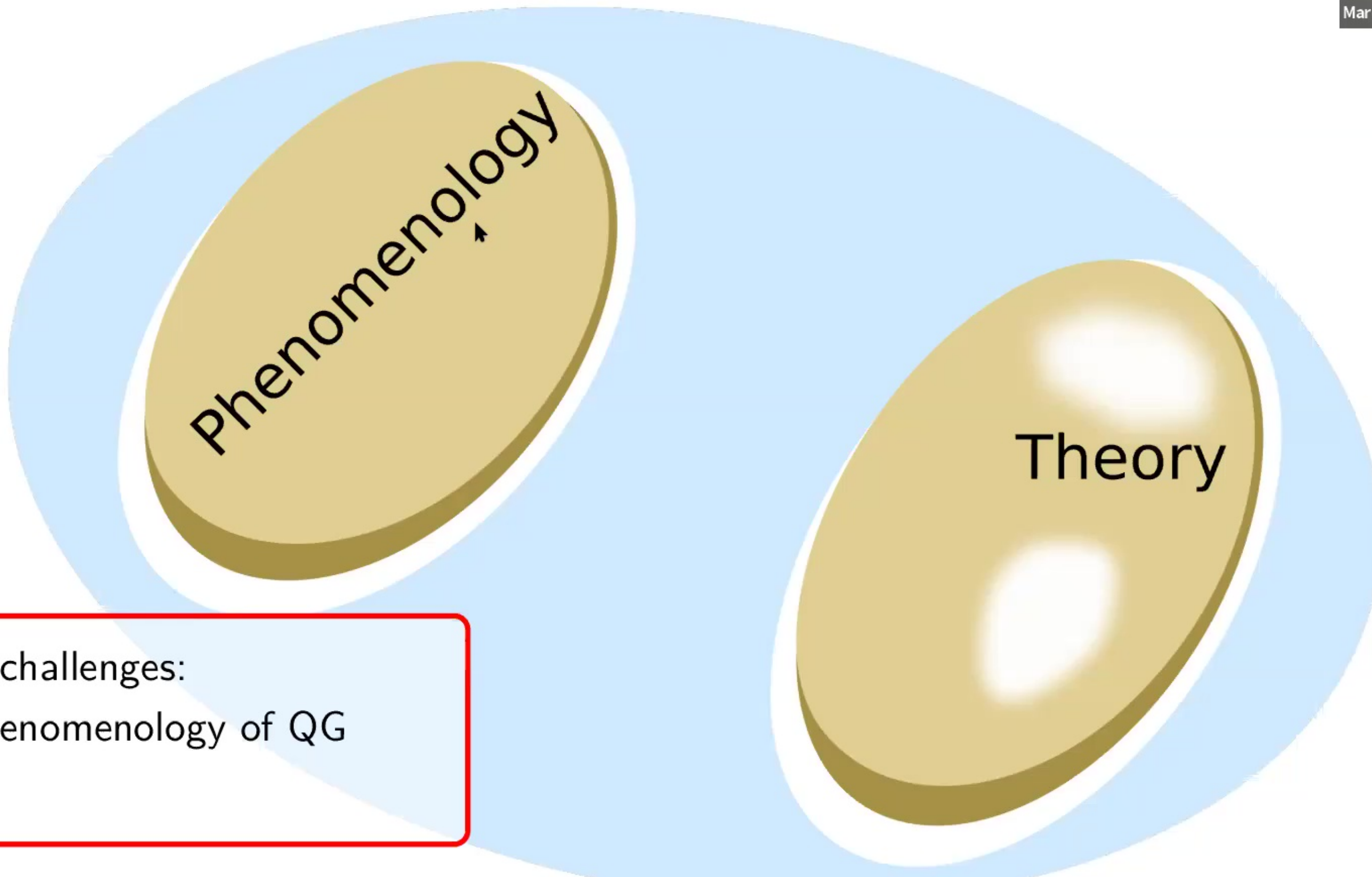
Quantum Gravity Seminar, Perimeter Institute

December 2, 2020

Studienstiftung des deutschen Volkes

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

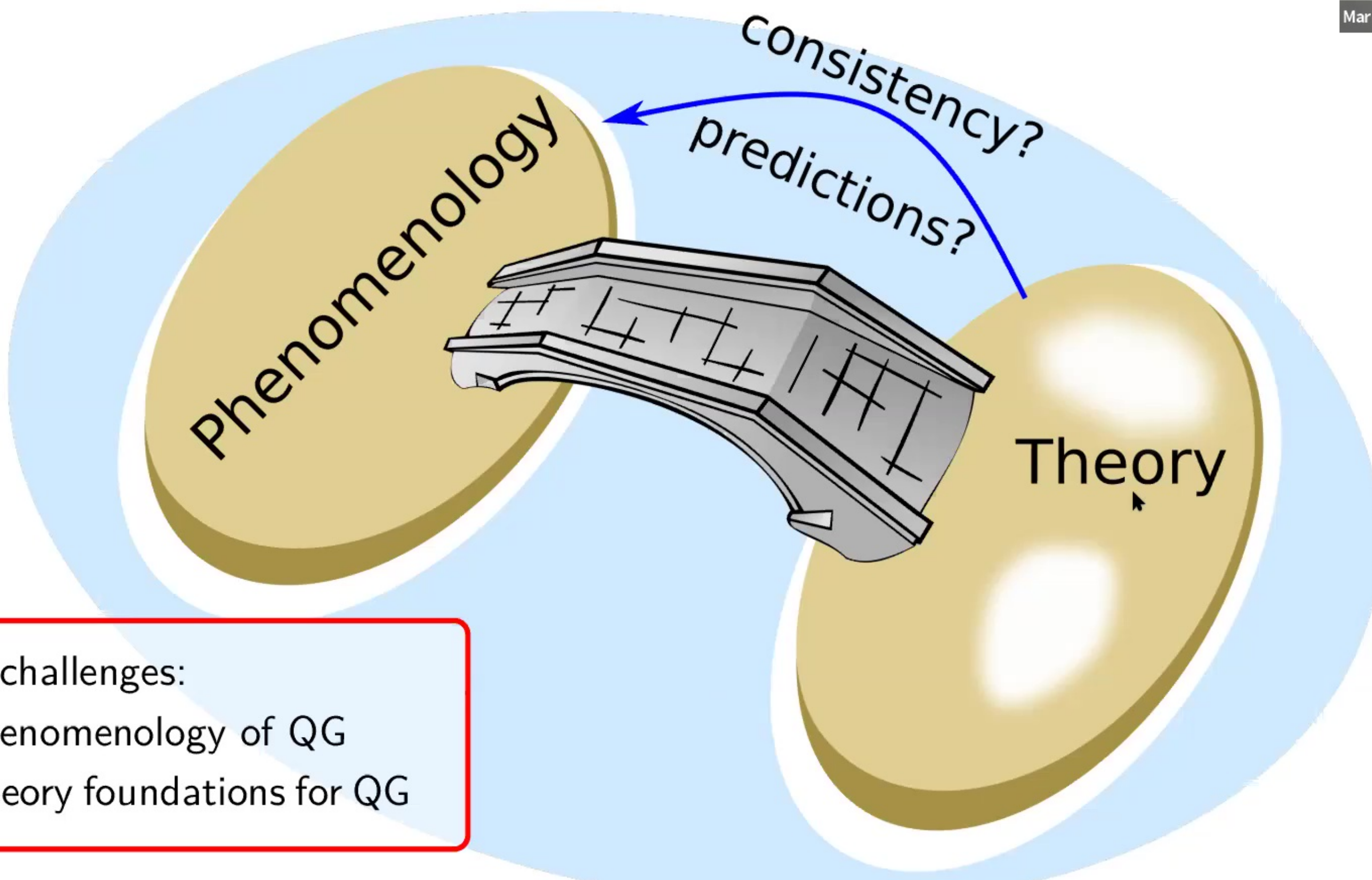
# Challenges of quantum gravity


Key challenges:

- Phenomenology of QG

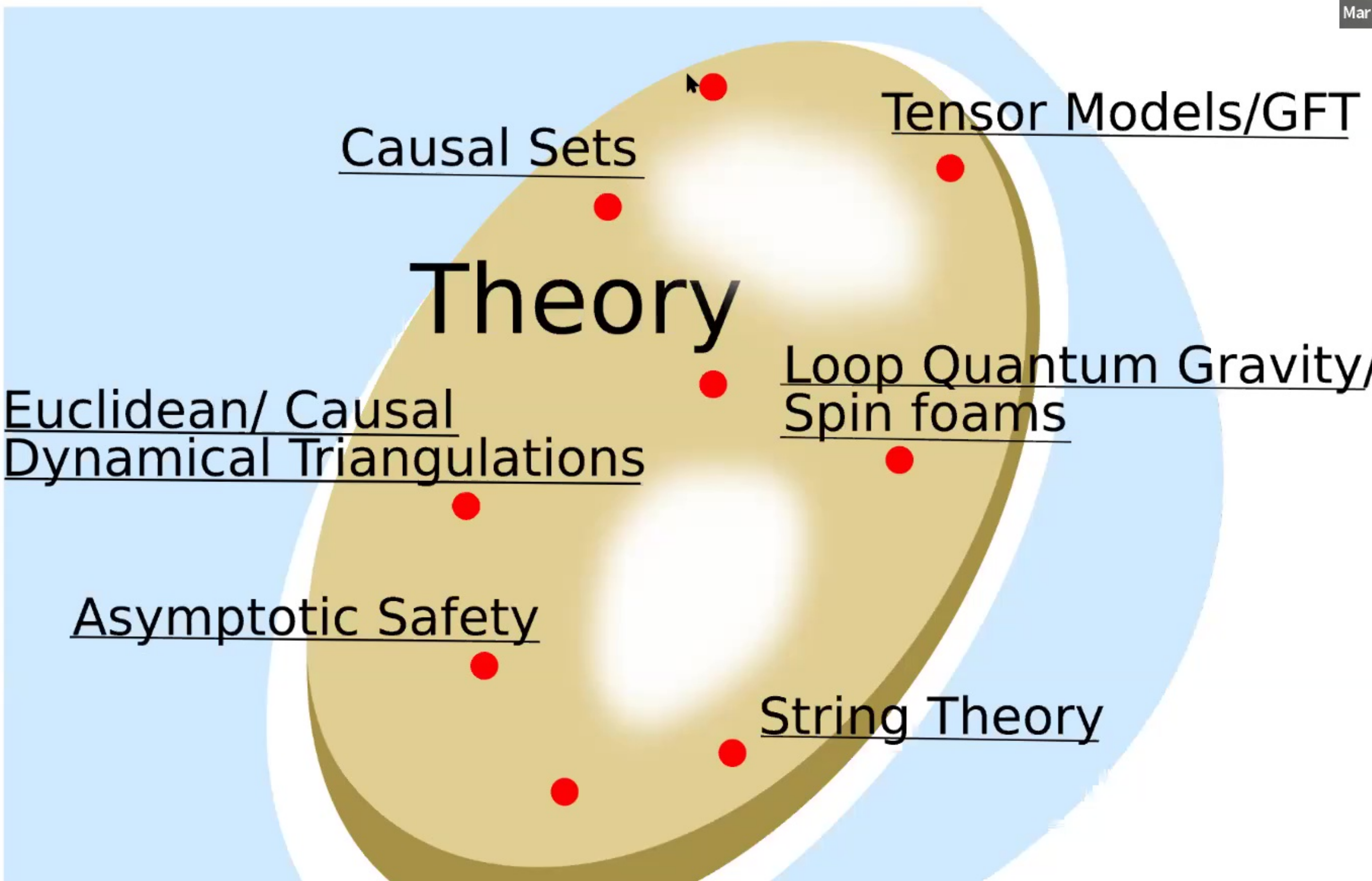
# Challenges of quantum gravity

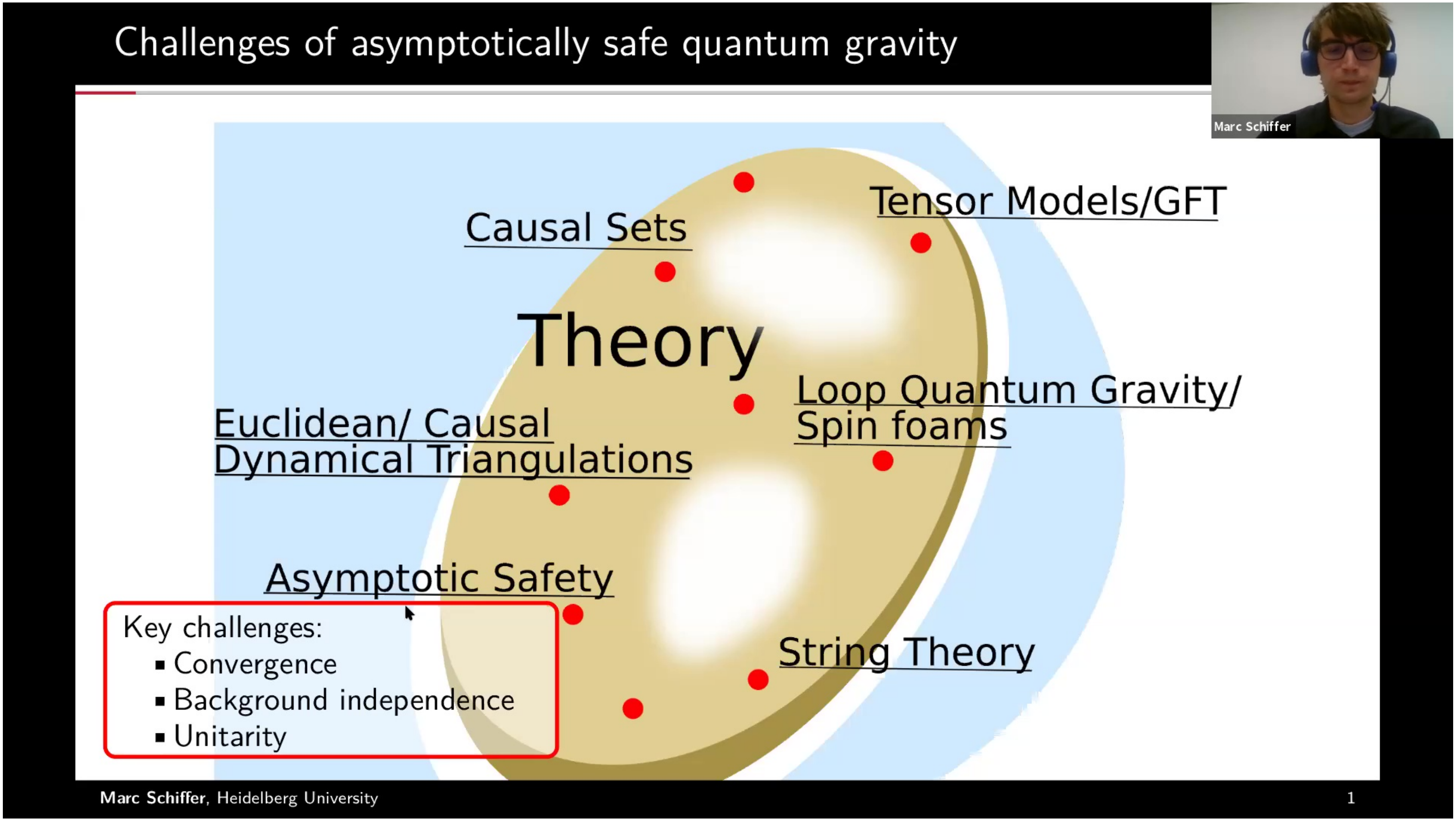




Key challenges:

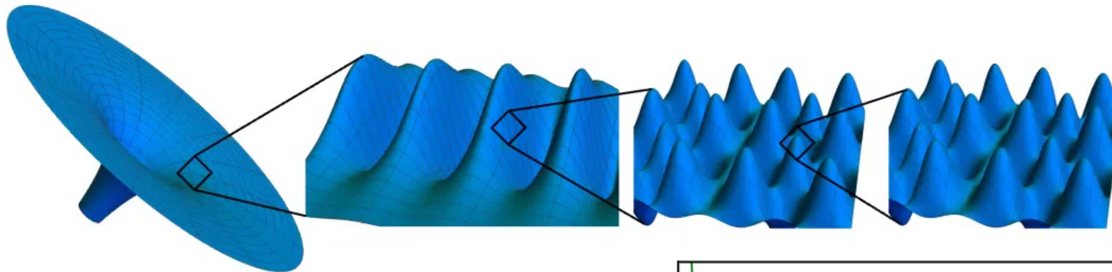
- Phenomenology of QG
- Theory foundations for QG

# Challenges of quantum gravity

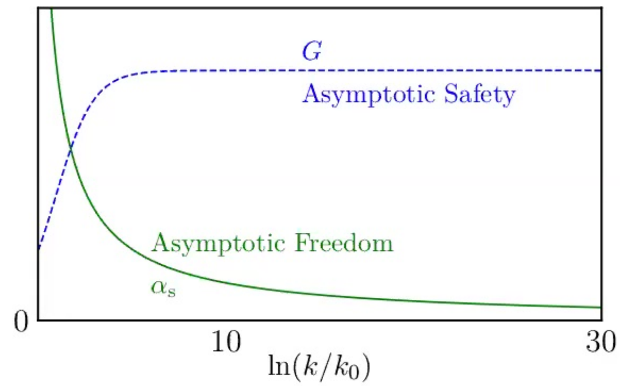




Challenges of asymptotically safe quantum gravity
Marc Schiffer
Causal Sets
Tensor Models/GFT
Theory
Loop Quantum Gravity/
Spin foams
Euclidean/ Causal
Dynamical Triangulations
Asymptotic Safety
String Theory
Key challenges:
▪ Convergence
▪ Background independence
▪ Unitarity
Marc Schiffer, Heidelberg University
1

# Asymptotically Safe Quantum Gravity

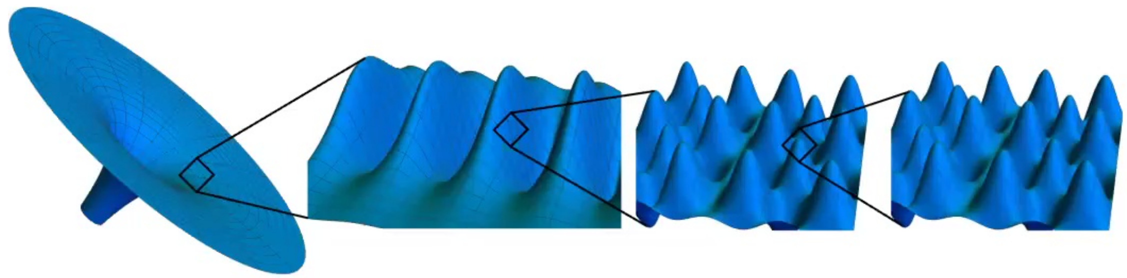
- Perturbative quantum gravity:
  loss of predictivity
- Key idea of asymptotic safety:
  Quantum realization of
  scale symmetry



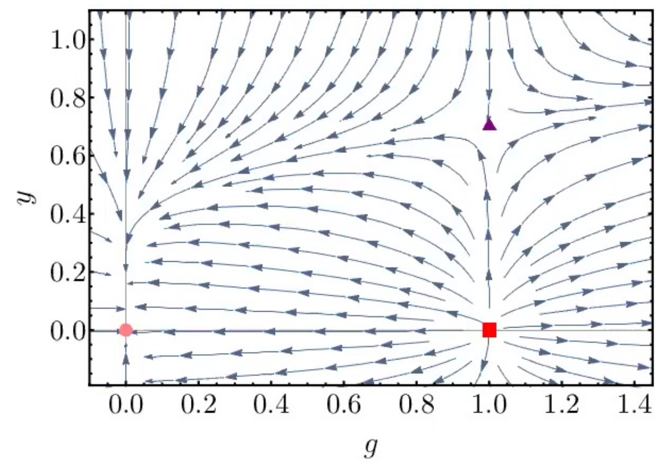

$$k\partial_k\alpha_s = -\frac{11}{2\pi}\alpha_s^2 + \mathcal{O}(\alpha_s^4)$$

$$k\partial_k G = \epsilon G - \frac{50}{3}G^2 + \mathcal{O}(G^3)$$

# Asymptotically Safe Quantum Gravity

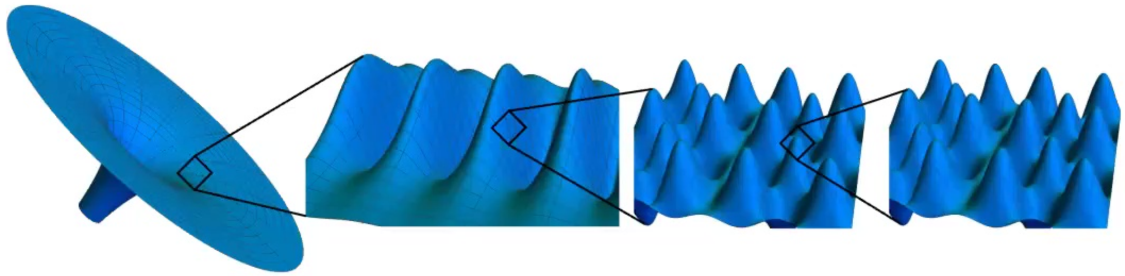
- Perturbative quantum gravity:
  loss of predictivity
- Key idea of asymptotic safety:
  Quantum realization of
  scale symmetry
  - imposes infinitely many conditions on theory space



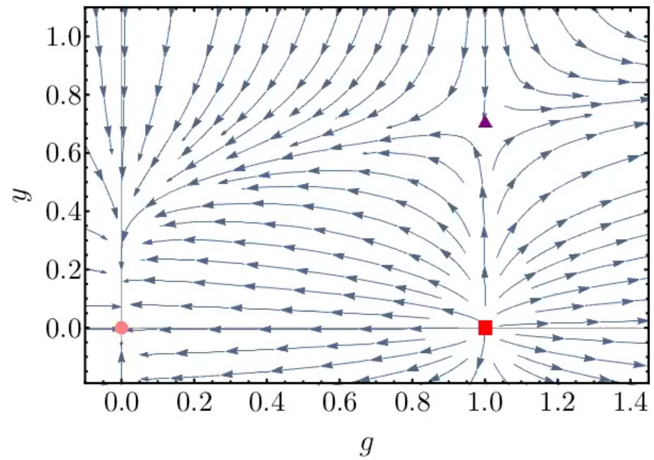

$$k\partial_k g = 2g - 2g^2$$

$$k\partial_k y = -g\,y + 2y^3$$

# Asymptotically Safe Quantum Gravity

- Perturbative quantum gravity:
  loss of predictivity
- Key idea of asymptotic safety:
  Quantum realization of
  scale symmetry
  - imposes infinitely many conditions on theory space
  - relevant directions:
    need measurement
  - irrelevant directions:
    predictions of theory




$$k\partial_k g = 2g - 2g^2$$

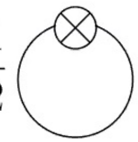
$$k\partial_k y = -g\,y + 2y^3$$

# Tool: Functional Renormalization Group


## Non-Perturbative Renormalisation Group Equation

[Wetterich, 1993], [Ellwanger, 1993], [Morris, 1994], [Reuter, 1996]

$$k\,\partial_k\Gamma_k = \frac{1}{2}\,\mathsf{STr}\left(\left(\Gamma_k^{(2)} + R_k\right)^{-1} k\,\partial_k R_k\right) = \frac{1}{2}$$



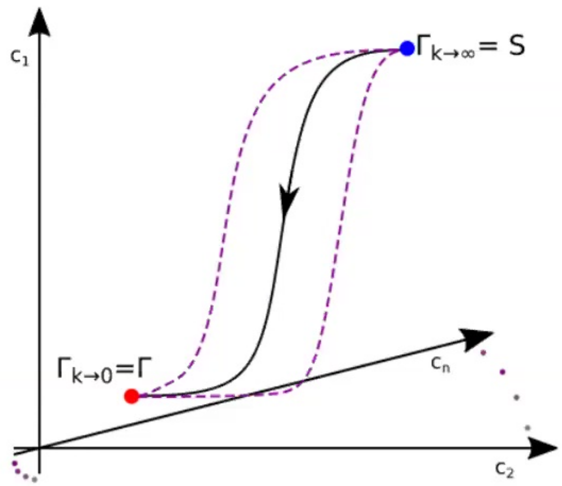
$\Gamma_k =$ scale dependent effective action

$R_k =$ IR regulator

- extract $\beta$-functions via projection
- truncation needed $\rightarrow$ not closed
- Euclidean

  Lorentzian formulation, e.g.:

  [Manrique, Rechenberger, Saueressig, 2011]

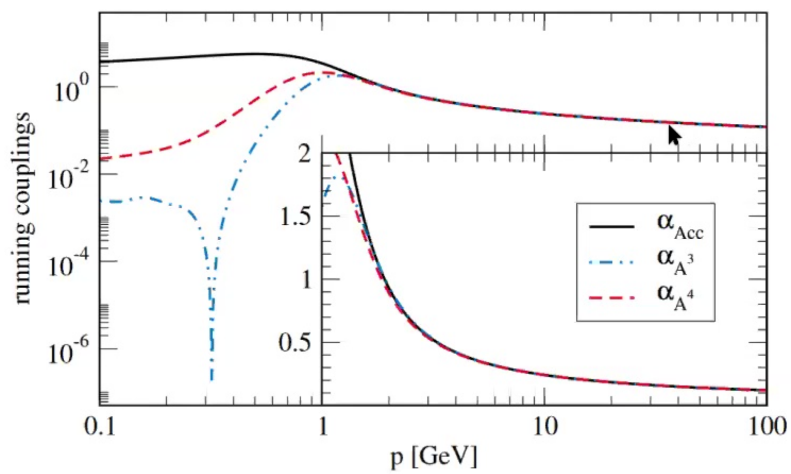


# Developments in asymptotically-safe gravity


- Evidence for fixed-point in Euclidean gravity and gravity-matter systems in $d = 4$
- Important feature:
  Indications for near-perturbative nature of fixed point
  - Symmetry identities
    [Eichhorn, Labus, Pawlowski, Reichert, 2018], [Eichhorn, Lippoldt, Pawlowski, Reichert, MS, 2018], [Eichhorn, Lippoldt, MS, 2018]
  - Non-minimal couplings
    [Eichhorn, Lippoldt, 2016], [Eichhorn, Lippoldt, MS, 2018]
  - Weak gravity bound
    [Eichhorn, Held, 2016], [Eichhorn, MS, 2019]
- Implications:
  - Predictivity
  - Guiding principle for approximations/truncations
  - Connection to perturbative methods
    [Niedermaier, 2009]

# (Effective) Universality


- QCD:
  $[\alpha_s] = 0$
  → 1-loop universality
  → perturbative regime:
  one gauge coupling

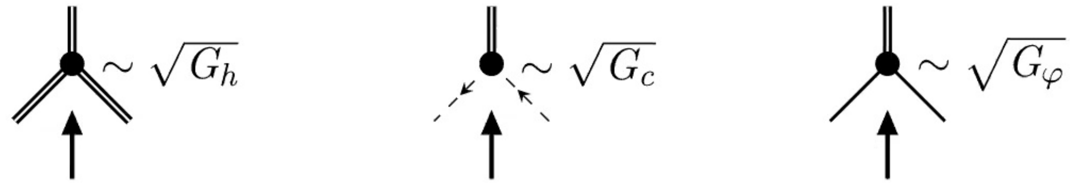



[Cyrol, Fister, Mitter, Pawlowski, Strodthoff, 2016]

- Gravity:
  $[\bar{G}_N] = -2$
  → no universality
  → gauge symmetry encoded in
  relations for vertex flows

?

# Indications for near-perturbative fixed point

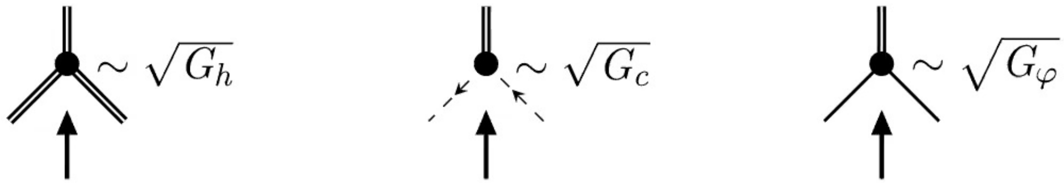




$$S = \frac{1}{16\pi G_{\mathrm{N}}} \int \mathrm{d}^4x \sqrt{g}\,(2\Lambda - R) + S_{\mathsf{gf,grav}} + S_{\mathsf{gh,grav}} + \frac{1}{2} \int \mathrm{d}^4x \sqrt{g}\, g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi$$

$$+ \int \mathrm{d}^4x \sqrt{g}\, \bar{\psi} \not{\nabla} \psi + \frac{1}{2} \int \mathrm{d}^4x \sqrt{g}\, g^{\mu\nu} g^{\rho\sigma}\, \mathrm{tr} F_{\mu\rho} F_{\nu\sigma} + S_{\mathsf{gf,gauge}} + S_{\mathsf{gh,gauge}}$$


- Gauge fixing and regulator: break diffeomorphism invariance

# Indications for near-perturbative fixed point

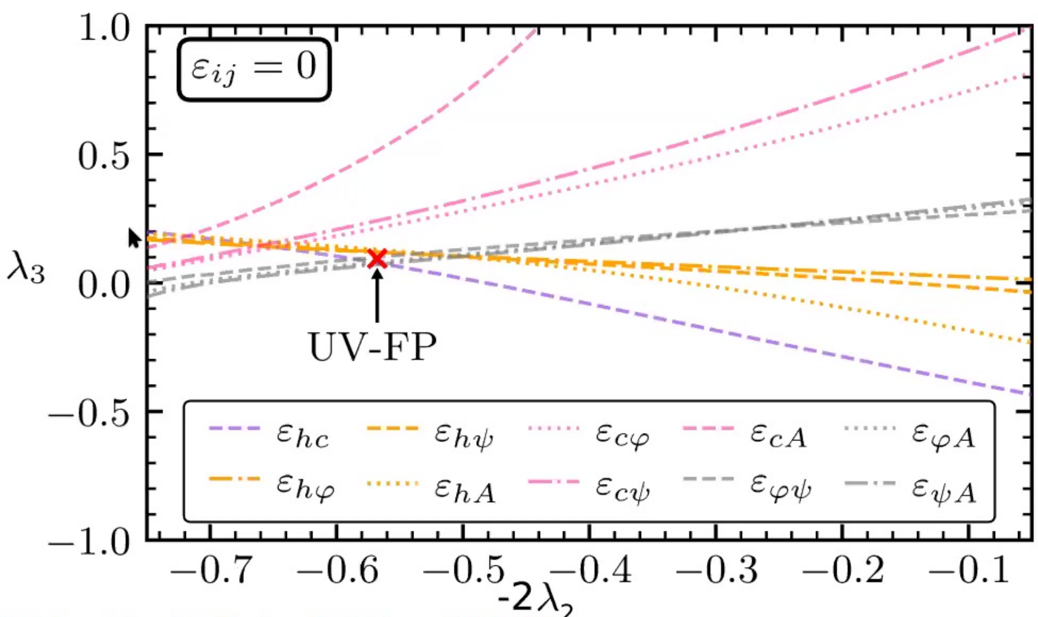

$$S = \frac{1}{16\pi G_{\mathrm{N}}} \int \mathrm{d}^4x \sqrt{g}\,(2\Lambda - R) + S_{\text{gf,grav}} + S_{\text{gh,grav}} + \frac{1}{2} \int \mathrm{d}^4x \sqrt{g} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi$$

$$+ \int \mathrm{d}^4x \sqrt{g}\, \bar{\psi} \not{\nabla} \psi + \frac{1}{2} \int \mathrm{d}^4x \sqrt{g}\, g^{\mu\nu} g^{\rho\sigma}\, \mathrm{tr} F_{\mu\rho} F_{\nu\sigma} + S_{\text{gf,gauge}} + S_{\text{gh,gauge}}$$


- Gauge fixing and regulator: break diffeomorphism invariance
- **Effective Universality**: semi-quantitative agreement of $\beta$-functions

[Eichhorn, Labus, Pawlowski, Reichert, 2018], [Eichhorn, Lippoldt, Pawlowski, Reichert, MS, 2018], [Eichhorn, Lippoldt, MS, 2018]

# How Perturbative is Quantum Gravity?




[Eichhorn, Lippoldt, Pawlowski, Reichert, MS, 2018]


- Pairwise comparison of $\beta$-functions
- $\varepsilon_{ij} \sim \left|\beta_{G_i} - \beta_{G_j}\right|$
- $\varepsilon_{ij} = 0$ lines
- Red cross: UV-FP

**Key Result**

UV-FP lies in symmetry preferred region.

**Key Result**

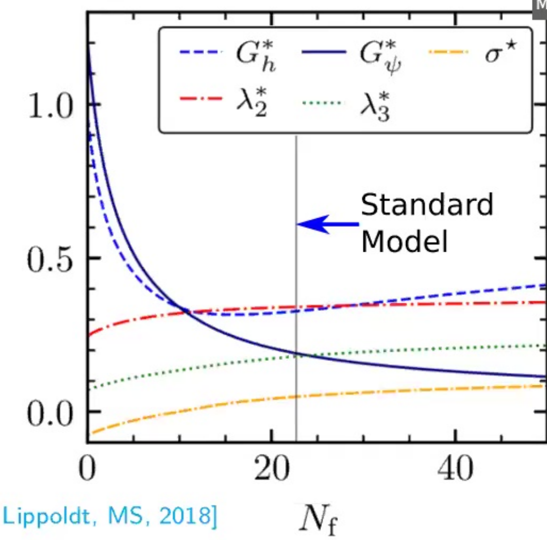
Hint for near-perturbative nature of asymptotically safe fixed point.

# Indications for small impact of induced non-minimal couplings

- At UV fixed point:
  non-minimal couplings are present
- Fermionic non-minimal coupling:

$$\sigma R^{\mu\nu}(\bar{\psi}\gamma_\mu \overleftrightarrow{\nabla}_\nu \psi)$$

- Numerical evaluation of momentum-dependent correlation functions




[Eichhorn, Lippoldt, MS, 2018]

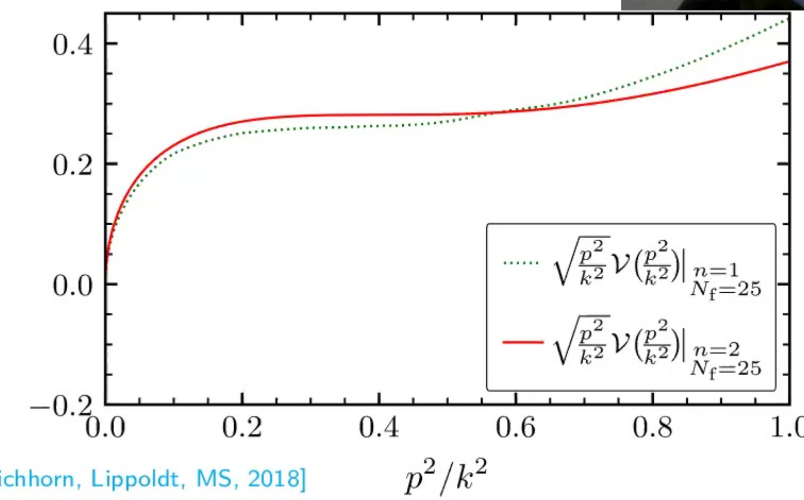
- Implications:
  - Evidence for fixed point with non-minimal coupling

# Indications for small impact of induced non-minimal couplings


- At UV fixed point:
  non-minimal couplings are present
- Fermionic non-minimal coupling:

$$\sigma R^{\mu\nu}(\bar{\psi}\gamma_\mu \overset{\leftrightarrow}{\nabla}_\nu \psi)$$

- Numerical evaluation of momentum-dependent correlation functions




[Eichhorn, Lippoldt, MS, 2018]

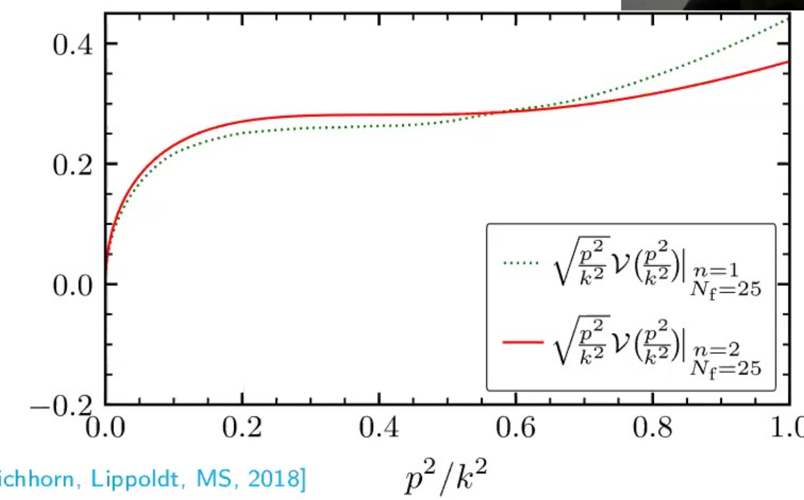
- Implications:
  - Evidence for fixed point with non-minimal coupling
  - Small impact of non-minimal coupling $\sigma$

# Indications for small impact of induced non-minimal couplings


- At UV fixed point:
  non-minimal couplings are present
- Fermionic non-minimal coupling:

$$\sigma R^{\mu\nu}(\bar{\psi}\gamma_\mu \overset{\leftrightarrow}{\nabla}_\nu \psi)$$

- Numerical evaluation of momentum-dependent correlation functions

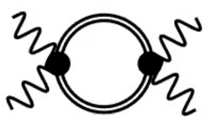


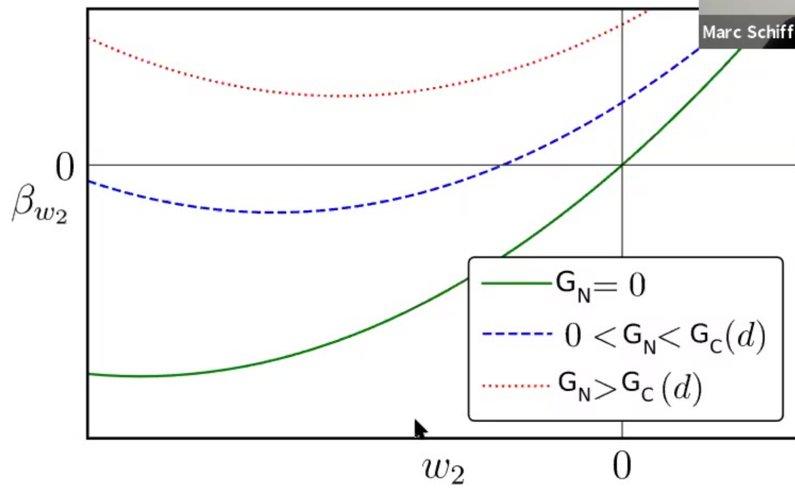

[Eichhorn, Lippoldt, MS, 2018]

- Implications:
  - Evidence for fixed point with non-minimal coupling
  - Small impact of non-minimal coupling $\sigma$
  - Indications for convergence

# Weak gravity bound


- At UV fixed point: matter self-interactions are present [Eichhorn, 2012]
- Example: Abelian gauge field
  ↳ 4-photon vertex ($w_2 F^4$) is induced



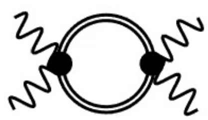


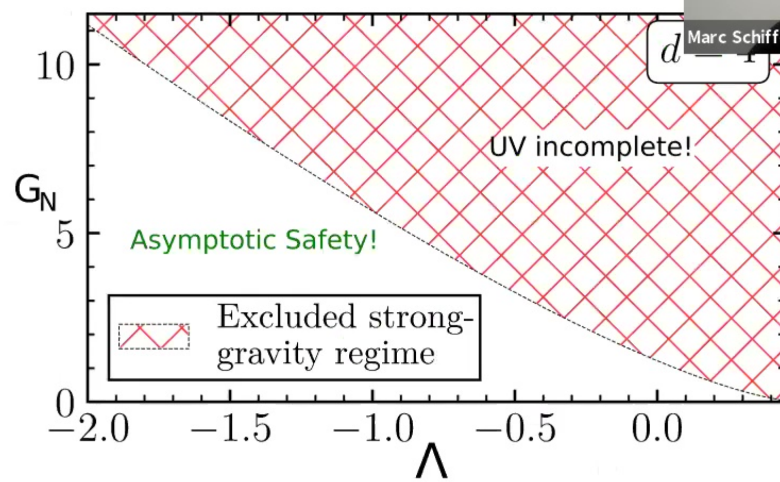

- Schematically:

$$\beta_{w_2} = B_0(G_{\rm N}) + w_2\, B_1(G_{\rm N}) + w_2^2 B_2$$

# Weak gravity bound

- At UV fixed point: matter self-interactions are present [Eichhorn, 2012]
- Example: Abelian gauge field
  ↳ 4-photon vertex $(w_2 F^4)$ is induced





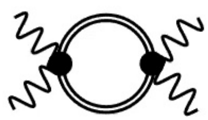


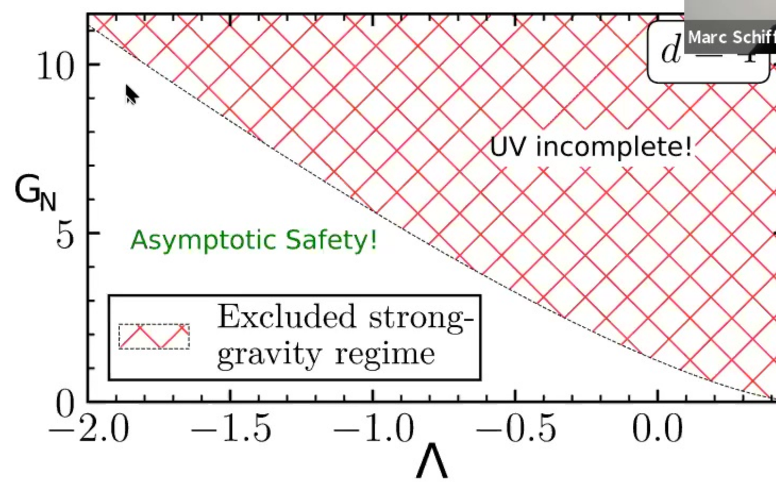
- Schematically:

$$\beta_{w_2} = B_0(G_{\rm N}) + w_2\, B_1(G_{\rm N}) + w_2^2 B_2$$

# Weak gravity bound

- At UV fixed point: matter self-interactions are present [Eichhorn, 2012]
- Example: Abelian gauge field
  ↳ 4-photon vertex $(w_2 F^4)$ is induced






- Schematically:

$$\beta_{w_2} = B_0(G_N) + w_2\, B_1(G_N) + w_2^2 B_2$$

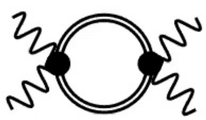
**Near-perturbative nature of quantum gravity might be necessary!**

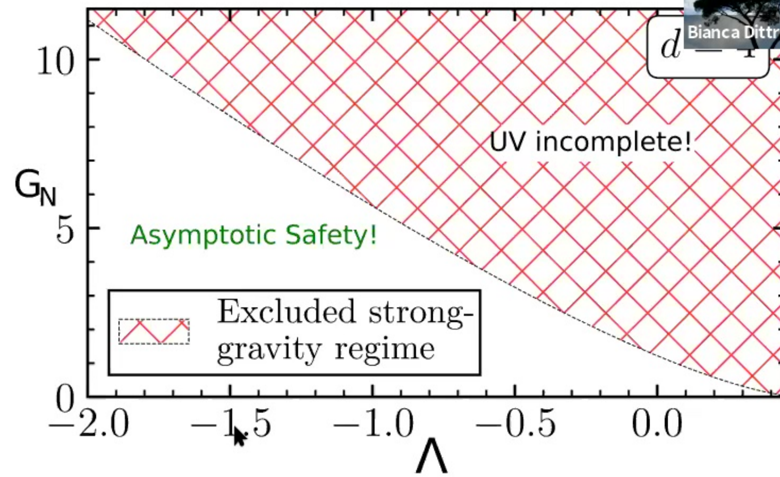
# Developments in asymptotically-safe gravity

- Important feature:
  Indications for near-perturbative nature of fixed point
  - Symmetry identities
    [Eichhorn, Labus, Pawlowski, Reichert, 2018], [Eichhorn, Lippoldt, Pawlowski, Reichert, MS, 2018], [Eichhorn, Lippoldt, MS, 2018]
  - Non-minimal couplings
    [Eichhorn, Lippoldt, 2016], [Eichhorn, Lippoldt, MS, 2018]
  - Weak gravity bound
    [Eichhorn, Held, 2016], [Eichhorn, MS, 2019]
- Implications:
  - Predictivity
  - Guiding principle for approximations/ truncations
  - Connection to perturbative methods
    [Niedermaier, 2009]

# Weak gravity bound

- At UV fixed point: matter self-interactions are present [Eichhorn, 2012]
- Example: Abelian gauge field
  ↳ 4-photon vertex ($w_2 F^4$) is induced





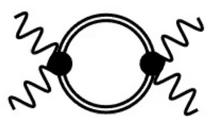

- Schematically:

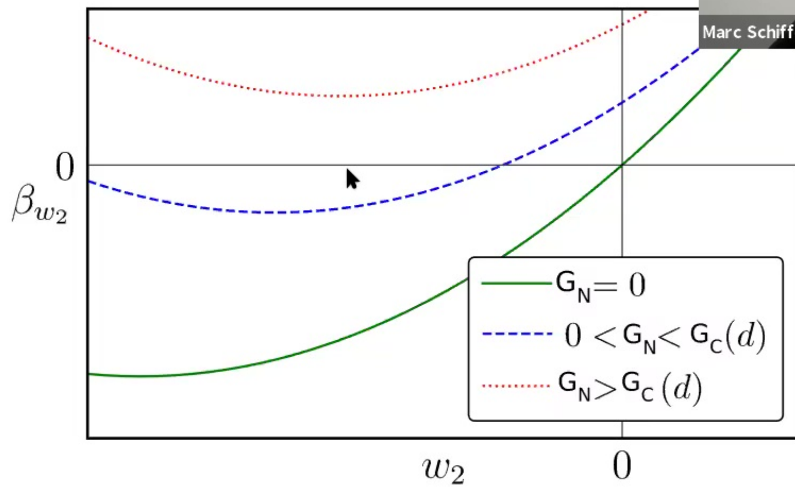
$$\beta_{w_2} = B_0(G_\mathrm{N}) + w_2\, B_1(G_\mathrm{N}) + w_2^2 B_2$$

Near-perturbative nature of quantum gravity might be necessary!

# Weak gravity bound


- At UV fixed point:
  matter self-interactions are present [Eichhorn, 2012]
- Example: Abelian gauge field
  ↳ 4-photon vertex $(w_2 F^4)$ is induced



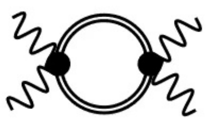


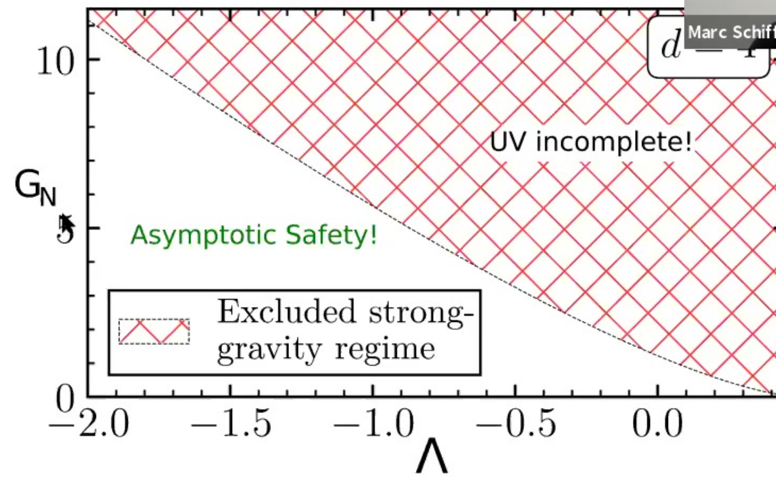

- Schematically:

$$\beta_{w_2} = B_0(G_N) + w_2\, B_1(G_N) + w_2^2 B_2$$

# Weak gravity bound


- At UV fixed point: matter self-interactions are present [Eichhorn, 2012]
- Example: Abelian gauge field
  ↳ 4-photon vertex ($w_2 F^4$) is induced

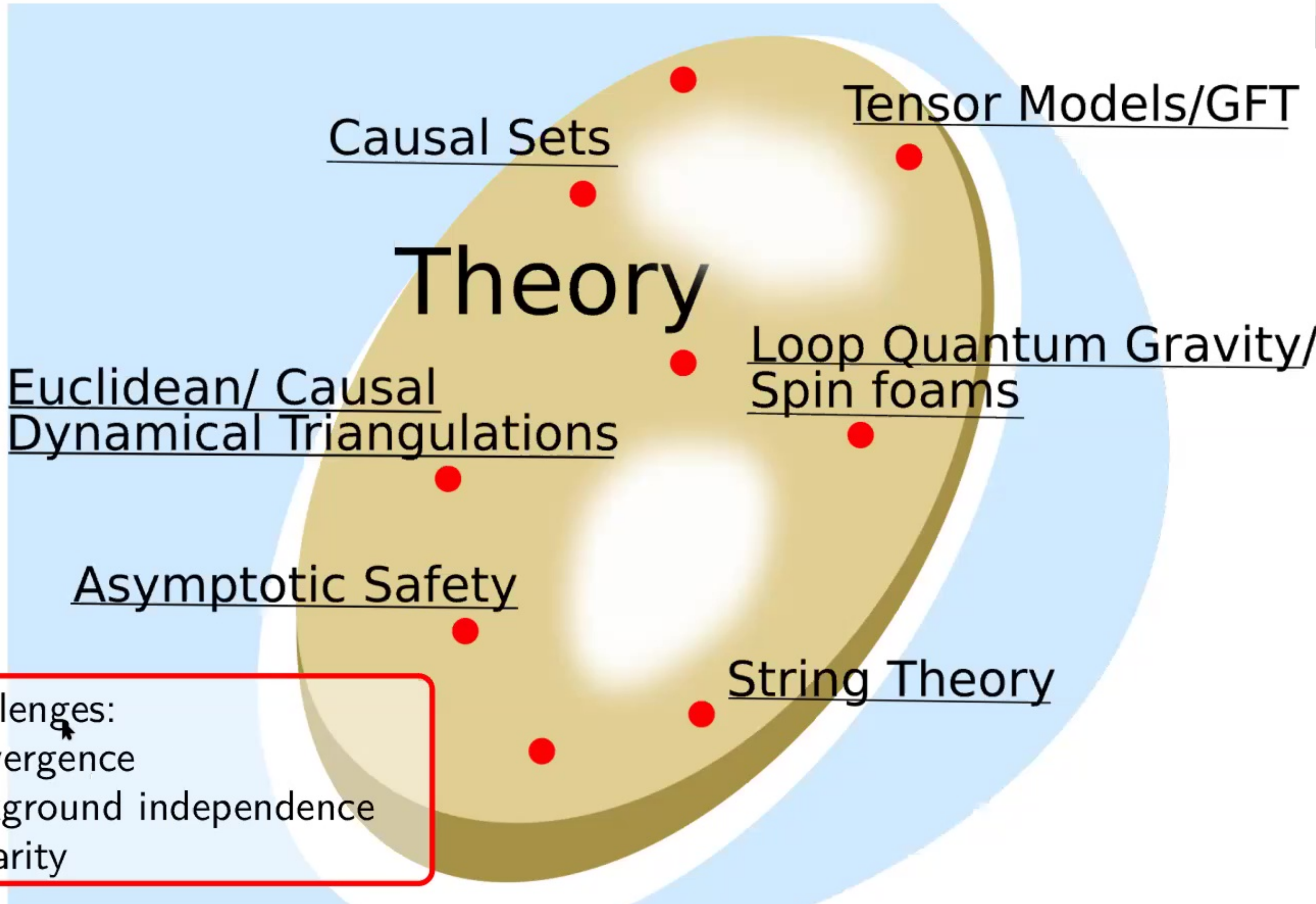





- Schematically:

$$\beta_{w_2} = B_0(G_\mathrm{N}) + w_2\, B_1(G_\mathrm{N}) + w_2^2 B_2$$

## Challenges of asymptotically safe quantum gravity




Key challenges:
- Convergence
- Background independence
- Unitarity

# Background independent evidence for AS from the lattice

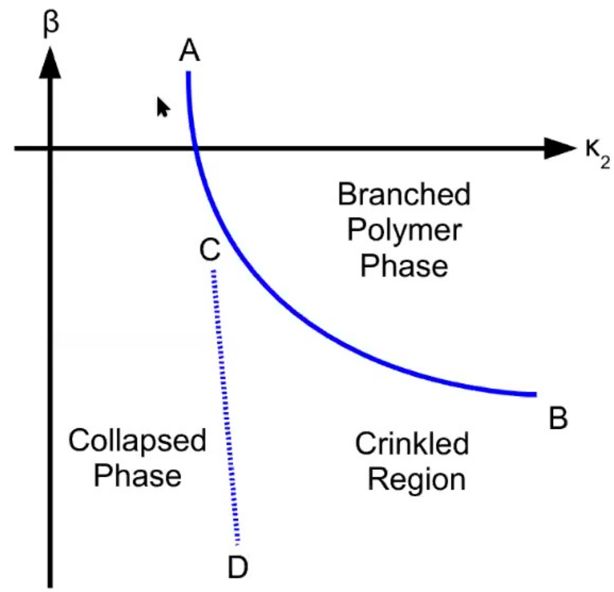

- Discretization of spacetime in terms of triangulations

$$\int \mathcal{D}g\, e^{-S[g]} \to \sum_{\mathcal{T}} \frac{1}{C_{\mathcal{T}}} \left[ \prod_{j=1}^{N_2} \mathcal{O}(t_j)^{\beta} \right] e^{-S_{\mathrm{E}}}$$

with Euclidean Einstein-Regge action

$$S_{\mathrm{E}} = -\kappa_2 N_2 + \kappa_4 N_4$$

- tune $\kappa_4$ to critical value, investigate $\beta - \kappa_2$ plane




[Ambjorn, Glaser, Goerlich, Jurkiewicz, 2013]
[Coumbe, Laiho, 2014]


# Background independent evidence for AS from the lattice

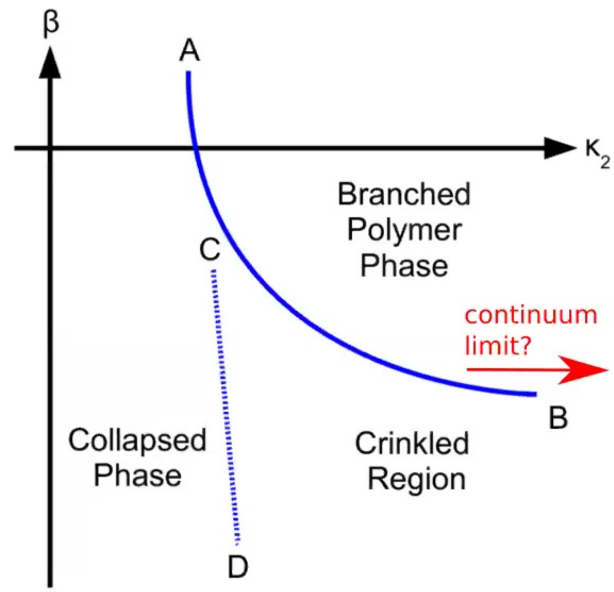
- Discretization of spacetime in terms of triangulations

$$\int \mathcal{D}g\, e^{-S[g]} \to \sum_{\mathcal{T}} \frac{1}{C_{\mathcal{T}}} \left[ \prod_{j=1}^{N_2} \mathcal{O}(t_j)^{\beta} \right] e^{-S_{\mathrm{E}}}$$

with Euclidean Einstein-Regge action

$$S_{\mathrm{E}} = -\kappa_2 N_2 + \kappa_4 N_4$$

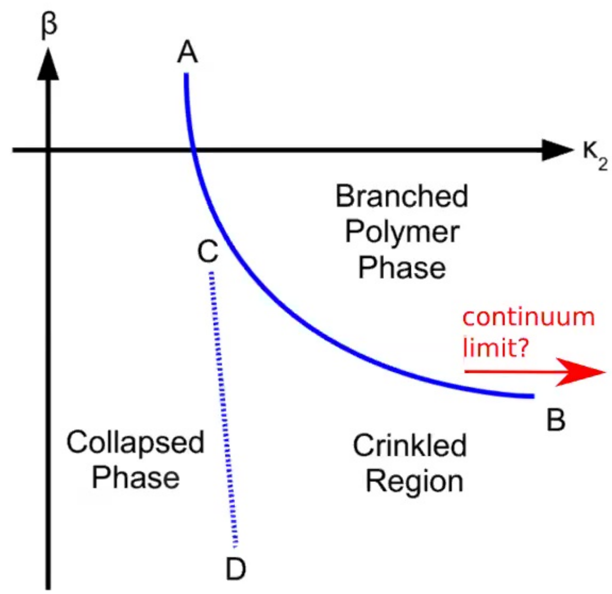
- tune $\kappa_4$ to critical value, investigate $\beta - \kappa_2$ plane




[Ambjorn, Glaser, Goerlich, Jurkiewicz, 2013]
[Coumbe, Laiho, 2014]

# Continuum limit of EDT?

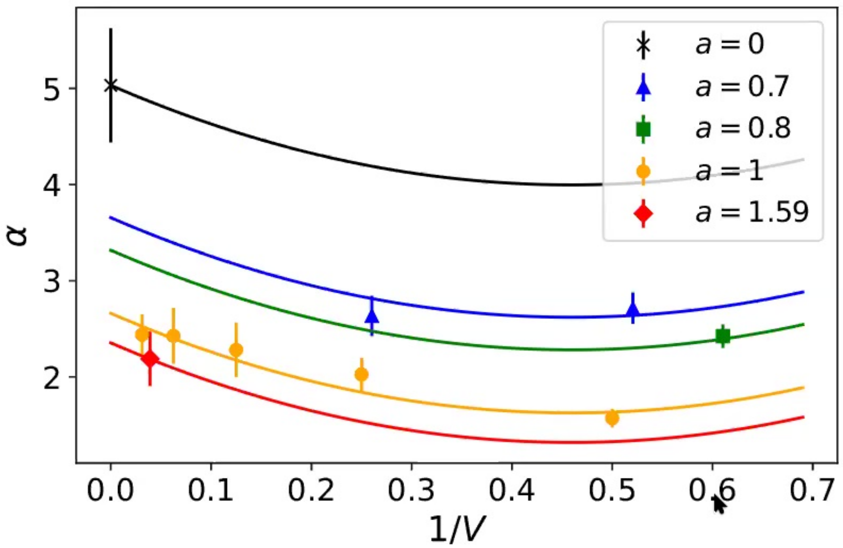

- Use matter as probe for gravity
- Study scalar fields on EDT (quenched approximation)
- Extract binding energy $E_\mathrm{b}$ and renormalized mass $m$ from one-and two-particle two-point correlators [de Bakker, Smit, 1996]
- Fit $E_\mathrm{b} = A\, m^\alpha$
- Continuum, non-relativistic limit: $E_\mathrm{b} = \frac{G\, m^5}{4}$




[Ambjorn, Glaser, Goerlich, Jurkiewicz, 2013]
[Coumbe, Laiho, 2014]

# Continuum limit of EDT?

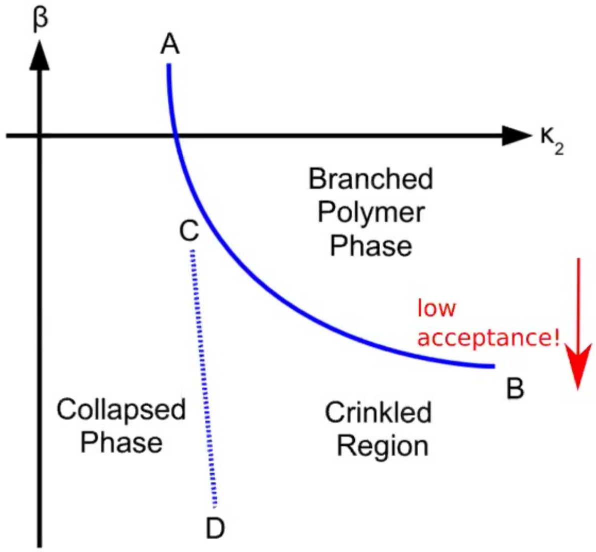

- Use matter as probe for gravity
- Study scalar fields on EDT (quenched approximation)
- Extract binding energy $E_{\mathrm{b}}$ and renormalized mass $m$ from one-and two-particle two-point correlators
  [de Bakker, Smit, 1996]
- Fit $E_{\mathrm{b}} = A\, m^{\alpha}$
- Continuum, non-relativistic limit:
  $E_{\mathrm{b}} = \frac{G\, m^5}{4}$
  EDT fit: $\alpha = 5.0 \pm 0.6$




[Dai, Laiho, MS, Unmuth-Yockey, work in progress]

# Key Challenge: Computability

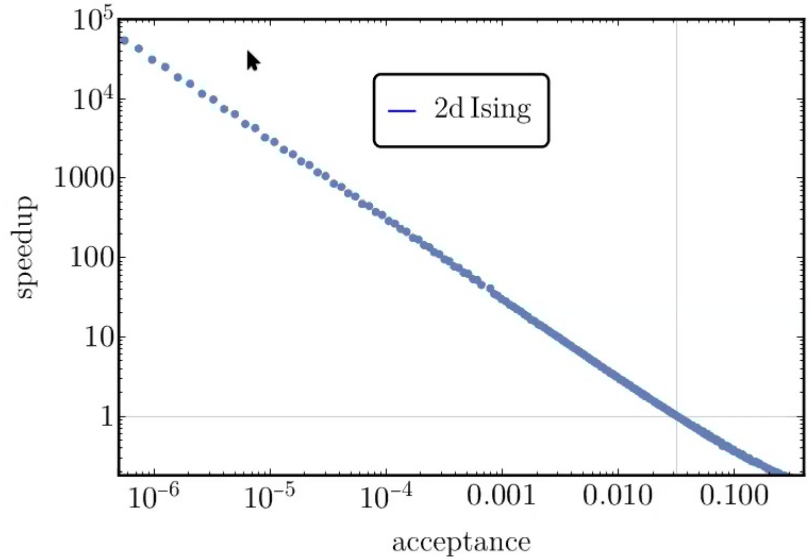

- Technical challenge:
  low acceptance rate ($\sim 10^{-6}$)
- Idea:
  Adapt rejection-free algorithm
  Used in "kinetic Monte Carlo"
  E.g., for crystal growth
  [Schulze, 2007]




[Ambjorn, Glaser, Goerlich, Jurkiewicz, 2013]
[Coumbe, Laiho, 2014]

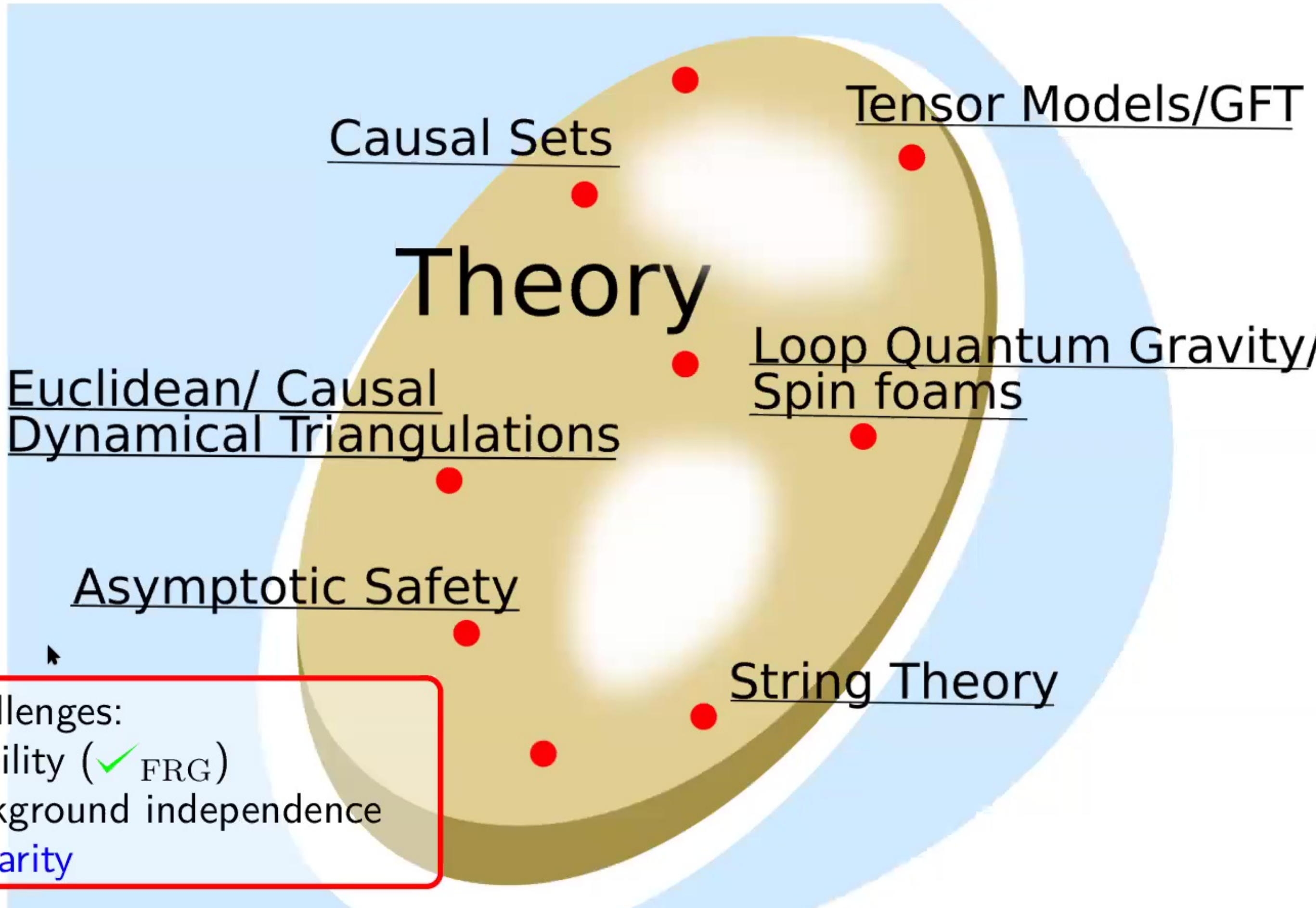
# Key Challenge: Computability


- Technical challenge:
  low acceptance rate ($\sim 10^{-6}$)
- Idea:
  Adapt rejection-free algorithm
  Used in "kinetic Monte Carlo"
  E.g., for crystal growth
  [Schulze, 2007]
- Proof-of-principle:
  $2d$ Ising model
- Implementation in EDT:
  potential gamechanger




[Freeman, MS, Trowbridge, work in progress]

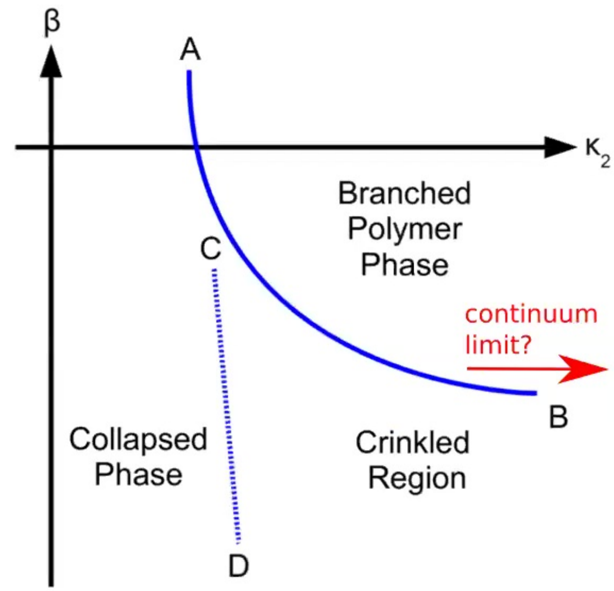
# Challenges of Quantum Gravity

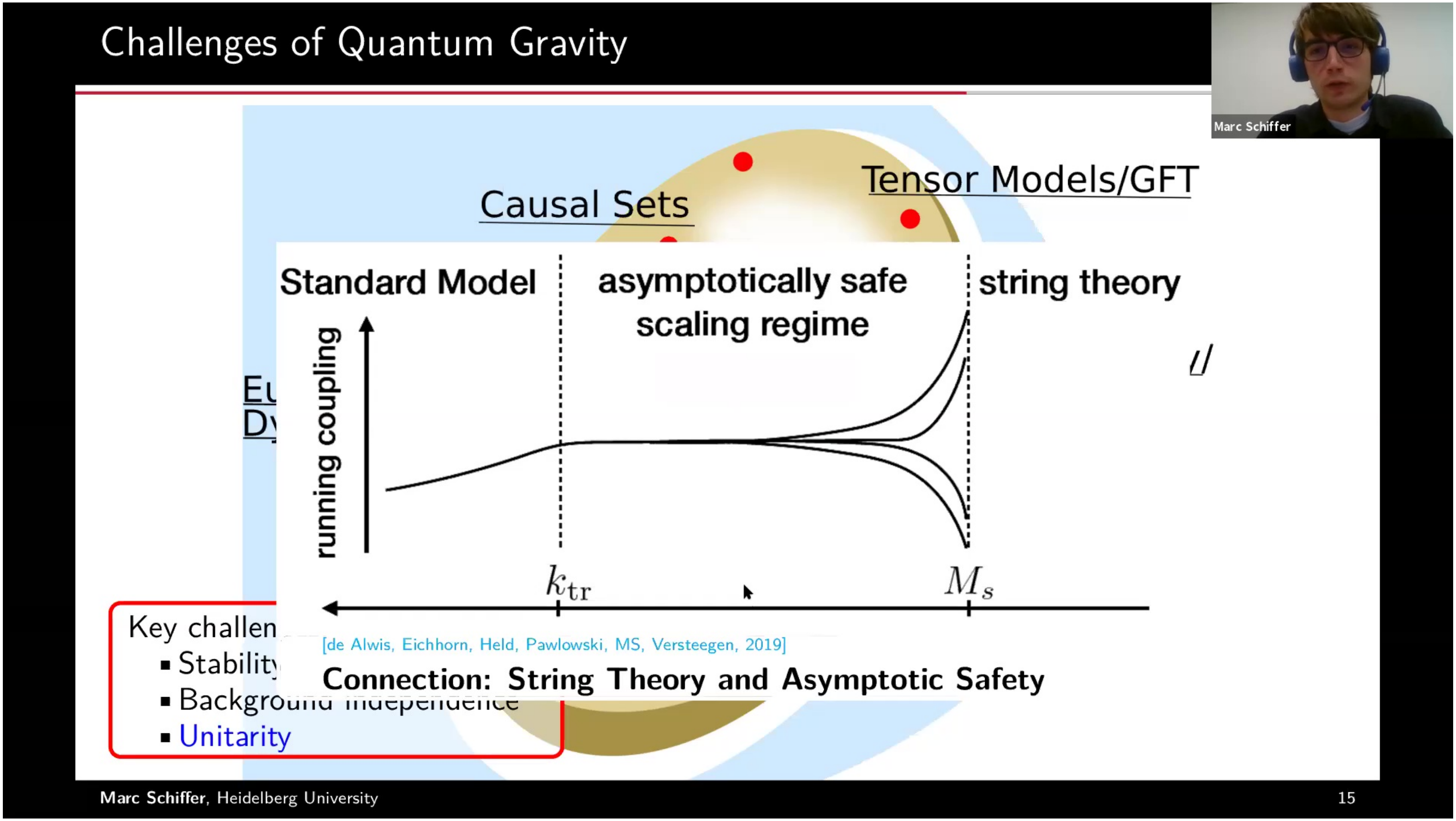

Key challenges:

- Stability (✓ FRG)
- Background independence
- Unitarity

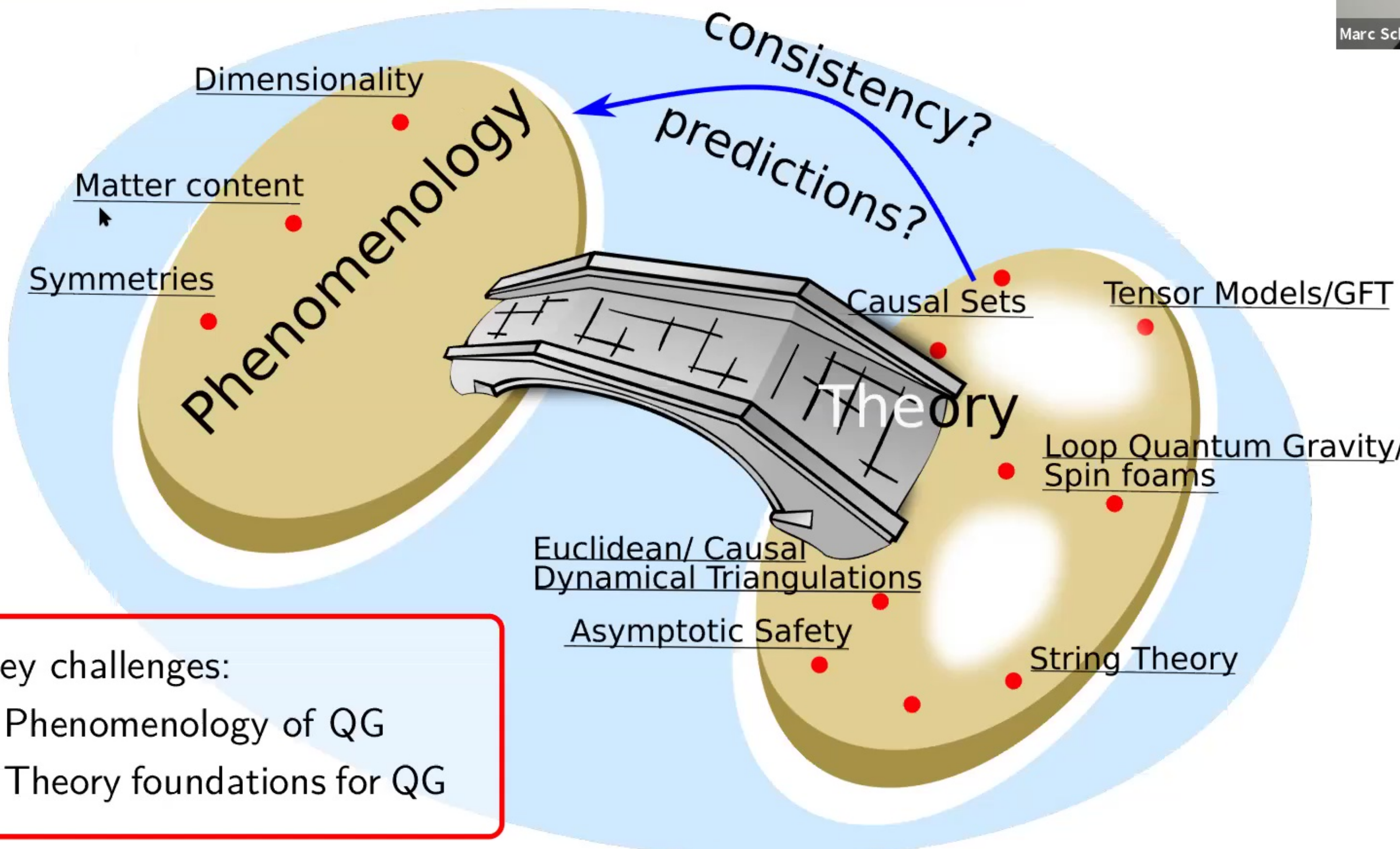
# Key Challenge: Computability


[Ambjorn, Glaser, Goerlich, Jurkiewicz, 2013]
[Coumbe, Laiho, 2014]


Challenges of Quantum Gravity
Marc Schiffer
Causal Sets
Tensor Models/GFT
Standard Model
asymptotically safe
scaling regime
string theory
running coupling
$k_{\text{tr}}$
$M_s$
[de Alwis, Eichhorn, Held, Pawlowski, MS, Versteegen, 2019]
Connection: String Theory and Asymptotic Safety
Key challen
Stability
Background independence
Unitarity
Marc Schiffer, Heidelberg University
15

# Challenges of Quantum Gravity

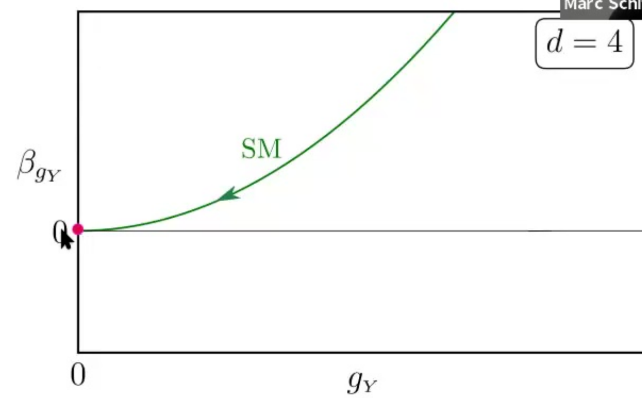

Key challenges:

- Phenomenology of QG
- Theory foundations for QG

# Why do we live in four dimensions?

- in $d = 4$:

$$\beta_{g_Y} = \qquad + \# g_Y^3 + \mathcal{O}(g_Y^5)$$

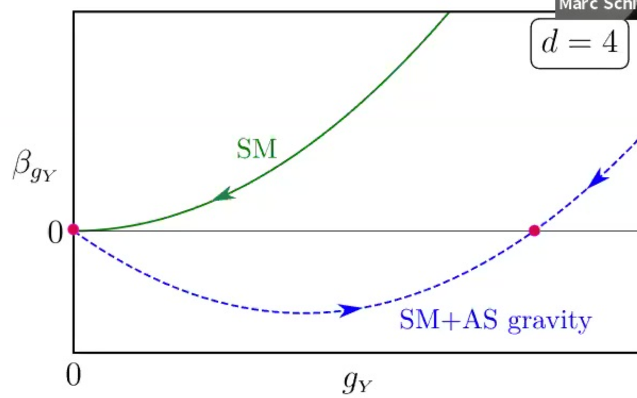



# Why do we live in four dimensions?

- in $d = 4$ with gravity: $\quad (f_g(d) \sim G_{\rm N})$

$$\beta_{g_Y} = g_Y \left( \qquad - f_g(d) \right) + \# g_Y^3 + \mathcal{O}(g_Y^5)$$

- FRG studies: $f_g \geq 0$ for $G_{\rm N} > 0$ (in $d = 4$)
  [Daum, Harst, Reuter, 2009], [Harst, Reuter, 2011], [Folkerts, Litim, Pawlowski, 2011], [Christiansen, Eichhorn, 2017], [Eichhorn, Versteegen, 2017], [Christiansen, Litim, Pawlowski, Reichert, 2017]



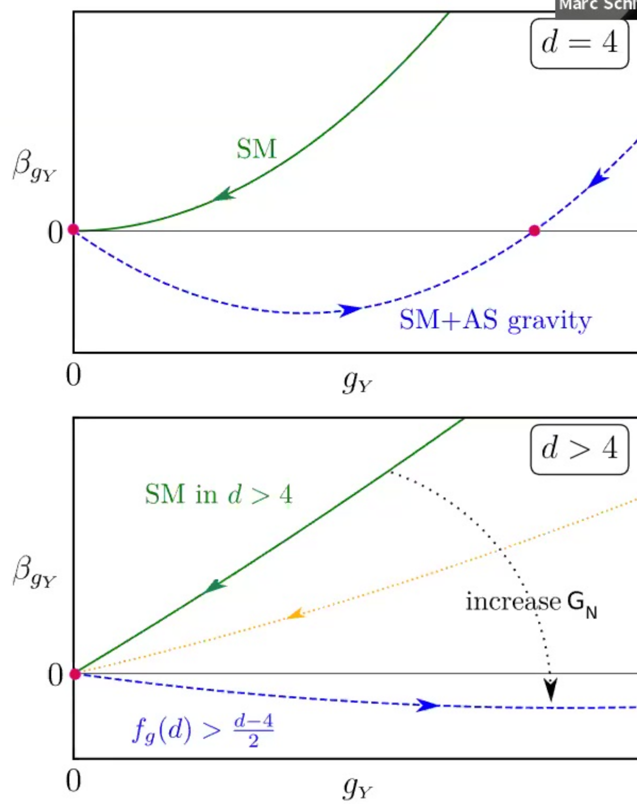

# Why do we live in four dimensions?


- $[\bar{g}_Y] = (4-d)/2$; $(f_g(d) \sim G_{\mathrm{N}})$

$$\beta_{g_Y} = g_Y \left( \frac{d-4}{2} - f_g(d) \right) + \# g_Y^3 + \mathcal{O}(g_Y^5)$$

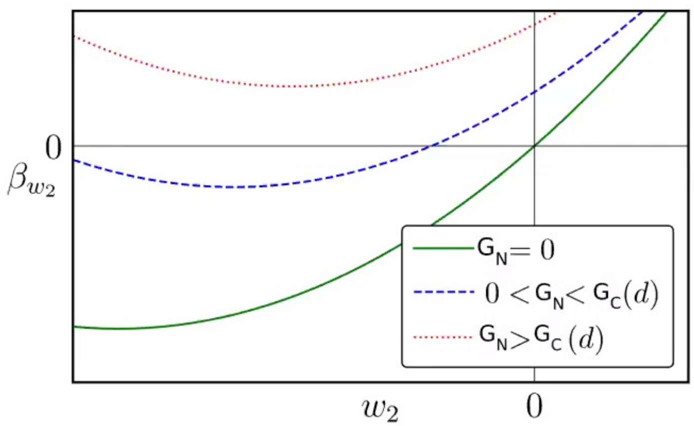
- FRG studies: $f_g \geq 0$ for $G_{\mathrm{N}} > 0$ (in $d = 4$)
  [Daum, Harst, Reuter, 2009], [Harst, Reuter, 2011], [Folkerts, Litim, Pawlowski, 2011], [Christiansen, Eichhorn, 2017], [Eichhorn, Versteegen, 2017], [Christiansen, Litim, Pawlowski, Reichert, 2017]
- Competition of $f_g(d)$ with canonical mass term.
- Necessary condition for UV completion: Effective dimensionality below four,

$$f_g(d) > \frac{d-4}{2}$$



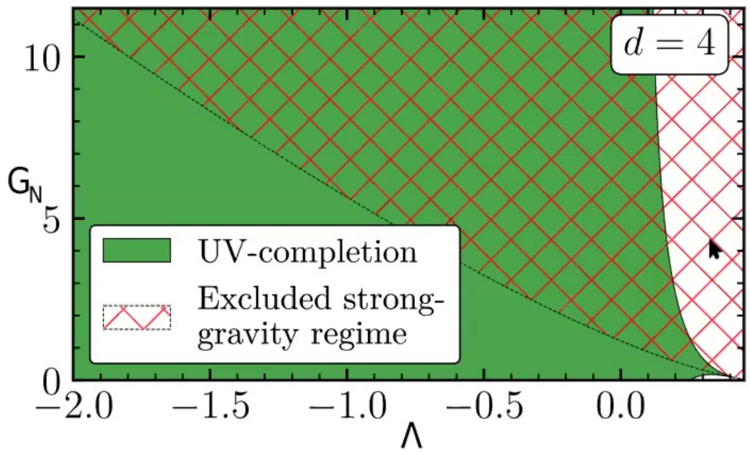
# Excluded strong gravity regime

- Evaluate $f_g = -\frac{\eta_A\big|_{\text{grav}}}{2}$ and "weak gravity bound" for $w_2 F^4$ (FRG computations)




# Excluded strong gravity regime

- Evaluate $f_g = -\frac{\eta_A\big|_{\text{grav}}}{2}$ and "weak gravity bound" for $w_2 F^4$ (FRG computations)
- Study explicitly conditions: $f_g(d) > \frac{d-4}{2}$ in weak-gravity regime

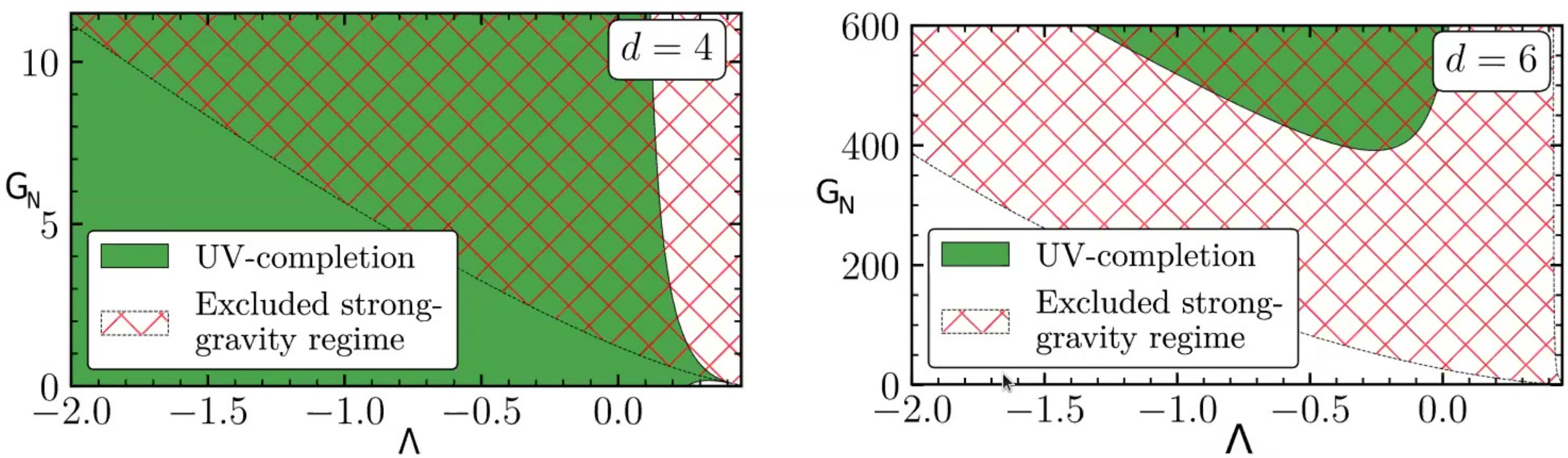



[Eichhorn, MS, 2019]

Marc Schiffer

# Excluded strong gravity regime


- Evaluate $f_g = -\frac{\eta_A\big|_{\text{grav}}}{2}$ and "weak gravity bound" for $w_2 F^4$ (FRG computations)
- Study explicitly conditions: $f_g(d) > \frac{d-4}{2}$ in weak-gravity regime

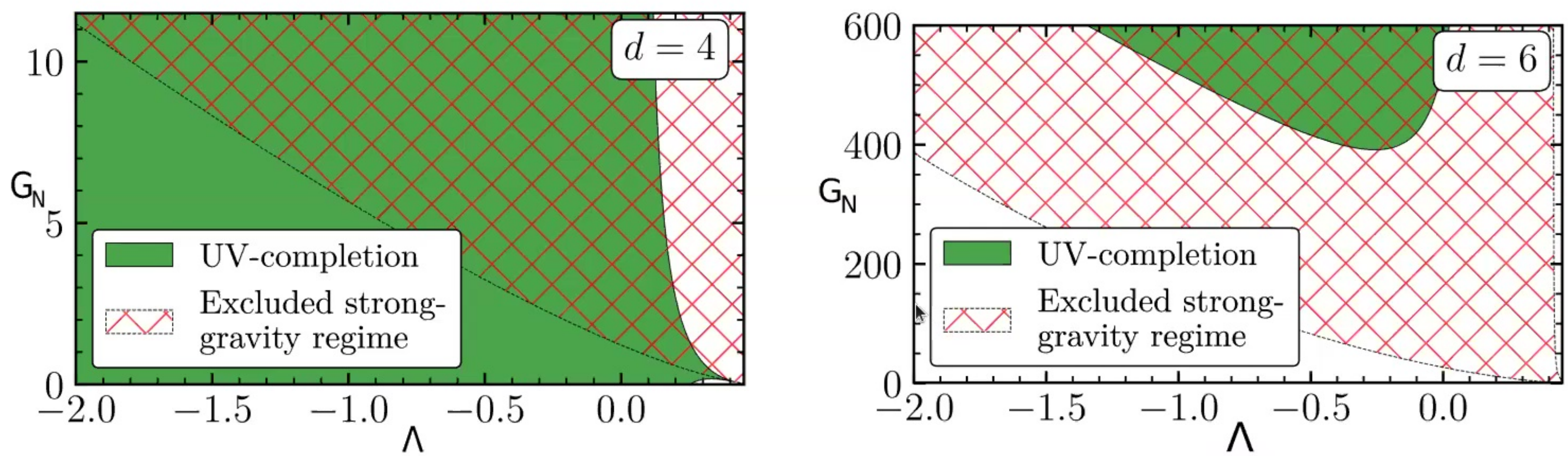



[Eichhorn, MS, 2019]

**Marc Schiffer**, Heidelberg University

# Excluded strong gravity regime


- Evaluate $f_g = -\frac{\eta_A\big|_{\text{grav}}}{2}$ and "weak gravity bound" for $w_2 F^4$ (FRG computations)
- Study explicitly conditions: $f_g(d) > \frac{d-4}{2}$ in weak-gravity regime



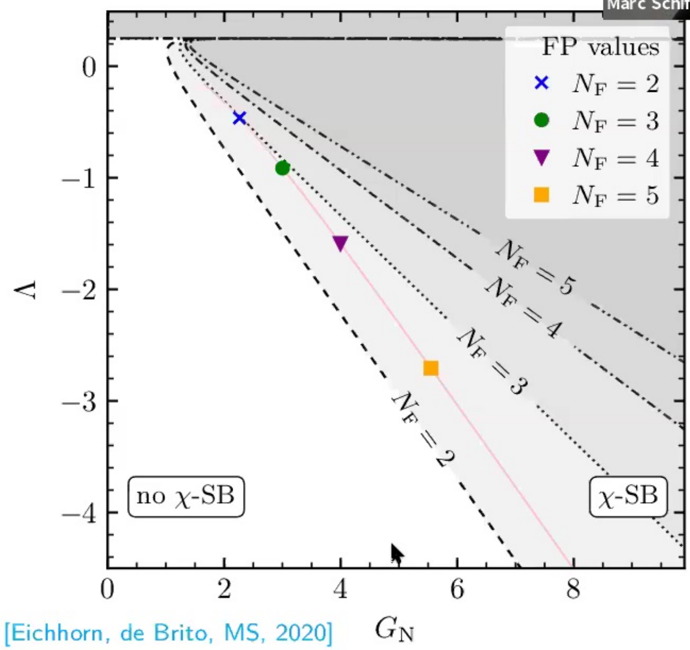

[Eichhorn, MS, 2019]

For Asymptotically safe gravity-matter models, $d = 4$ and $d = 5$ appears to be the only dimension to accommodate a UV-complete Abelian sector.

# Why is there more than one generation of fermions?

- Investigate gauge-gravity-fermion interplay
- Study fate of chiral symmetry with $e_* \sim \sqrt{f_g/N_F}$
- Analogy to QCD:
  too strong gauge coupling:
  divergences in induced fermionic-interactions

[Alkofer and von Smekal, 2001], [Gies and Wetterich, 2004]
[Braun and Gies, 2006],[Braun, 2006], [Braun and Gies, 2007]
[Haas, Braun and Pawlowski, 2011], [Braun, 2012]

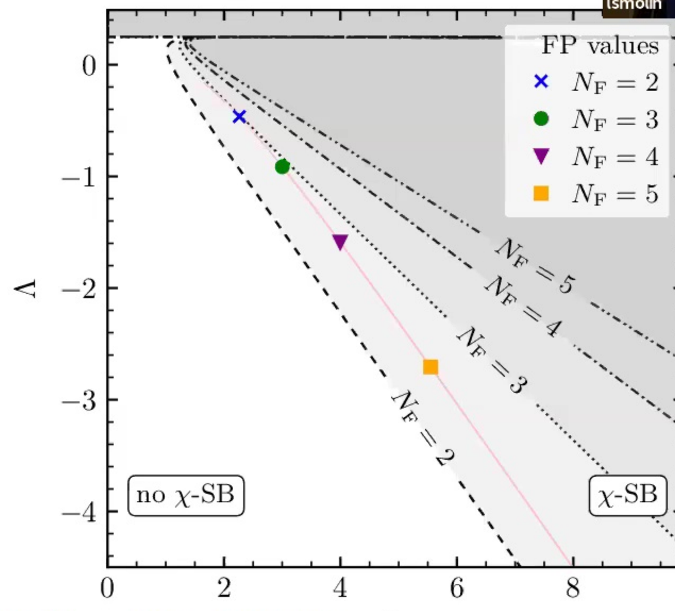



[Eichhorn, de Brito, MS, 2020]

# Why is there more than one generation of fermions?


- Investigate gauge-gravity-fermion interplay
- Study fate of chiral symmetry with $e_* \sim \sqrt{f_g/N_F}$
- Analogy to QCD:
  too strong gauge coupling:
  divergences in induced fermionic-interactions

[Alkofer and von Smekal, 2001], [Gies and Wetterich, 2004]
[Braun and Gies, 2006],[Braun, 2006], [Braun and Gies, 2007]
[Haas, Braun and Pawlowski, 2011], [Braun, 2012]




[Eichhorn, de Brito, MS, 2020]

> Interplay of quantum gravity with gauge fields and fermions might give rise to lower bound on the number of fermions.

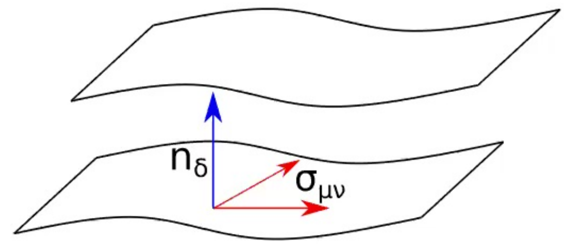
# Is Lorentz invariance a fundamental symmetry?


- Approximation of dynamics of gravity-matter system:

$$\Gamma_k = \Gamma_k^{\mathrm{EH}} + \Gamma_k^{\mathrm{Grav,\,LIV}}(a_i) + \Gamma_k^{\mathrm{Abelian,\,LI}} + \Gamma_k^{\mathrm{Abelian,\,LIV}}(\zeta)$$

- Access to foliation structure (Euclidean!):
  [B. Knorr, 2018]

$$g_{\mu\nu} = \sigma_{\mu\nu} + n_\mu n_\nu \,,$$
$$g^{\mu\nu} n_\mu \sigma_{\nu\rho} = 0 \,,$$
$$g^{\mu\nu} n_\mu n_\nu = 1$$




- Study effect of preferred frame on matter sector
  [Colladay and Kostelecky, 1998], [Jacobson and Mattingly, 2001], [Kostelecky and Mewes, 2002], [Bluhm, Bossi and Wen, 2019]

$$\Gamma_k^{\mathrm{Abelian,LIV}} = \frac{Z_A(k)}{4} \int \sqrt{g}\, \left(\zeta(k)\, k_{\mathrm{F}}^{\mu\nu\rho\sigma}\, F_{\mu\nu} F_{\rho\sigma}\right)$$

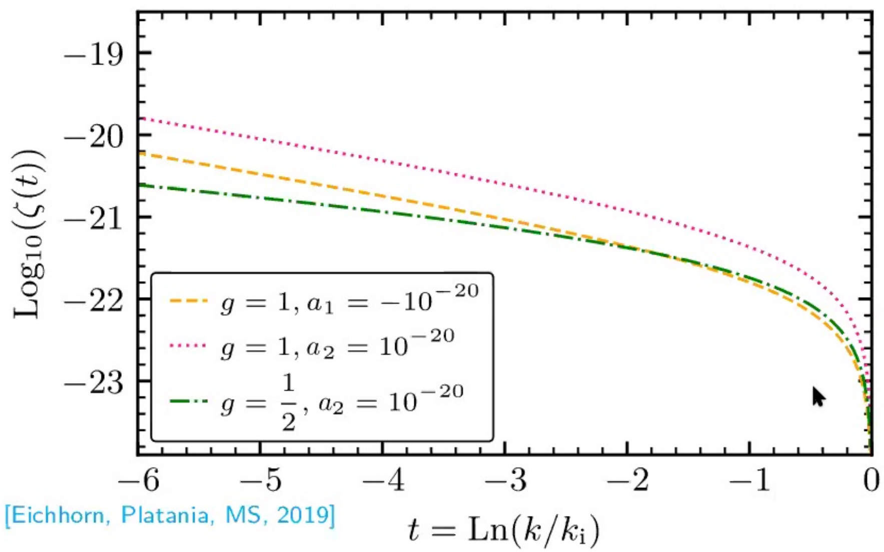
possible signatures: vacuum birefringence

# LIV percolate into matter sector


- Scale dependence of $\zeta$ (schematically), $b_i = b_i(a_i)$:

$$k\partial_k \zeta = b_0 + b_1\zeta + b_2\zeta^2 + \mathcal{O}(\zeta^3)$$

- $\zeta_* \neq 0$ in presence of preferred frame
- $\zeta(k) \sim \mathcal{O}(a_i)$ is generated




[Eichhorn, Platania, MS, 2019]

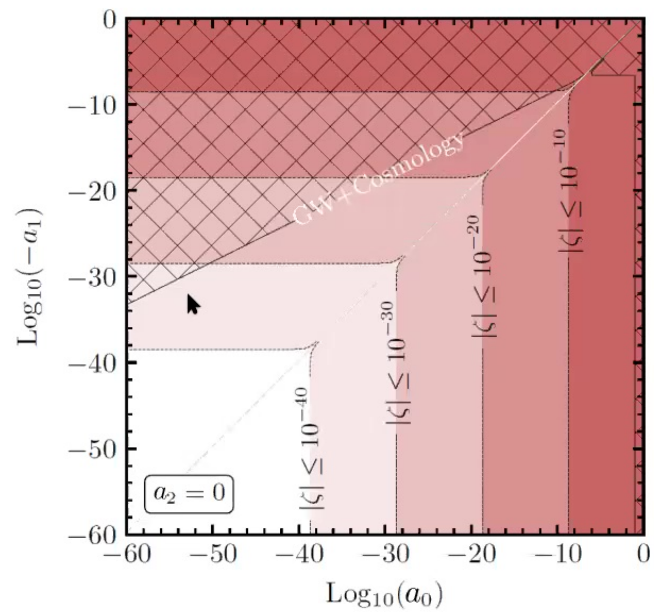
# LIV percolate into matter sector


- Scale dependence of $\zeta$ (schematically), $b_i = b_i(a_i)$:

$$k\partial_k \zeta = b_0 + b_1 \zeta + b_2 \zeta^2 + \mathcal{O}(\zeta^3)$$

- $\zeta_* \neq 0$ in presence of preferred frame
- $\zeta(k) \sim \mathcal{O}(a_i)$ is generated
- $\zeta(M_{\mathrm{Pl}}, a_i)$
- combine indirect bounds with direct constraints

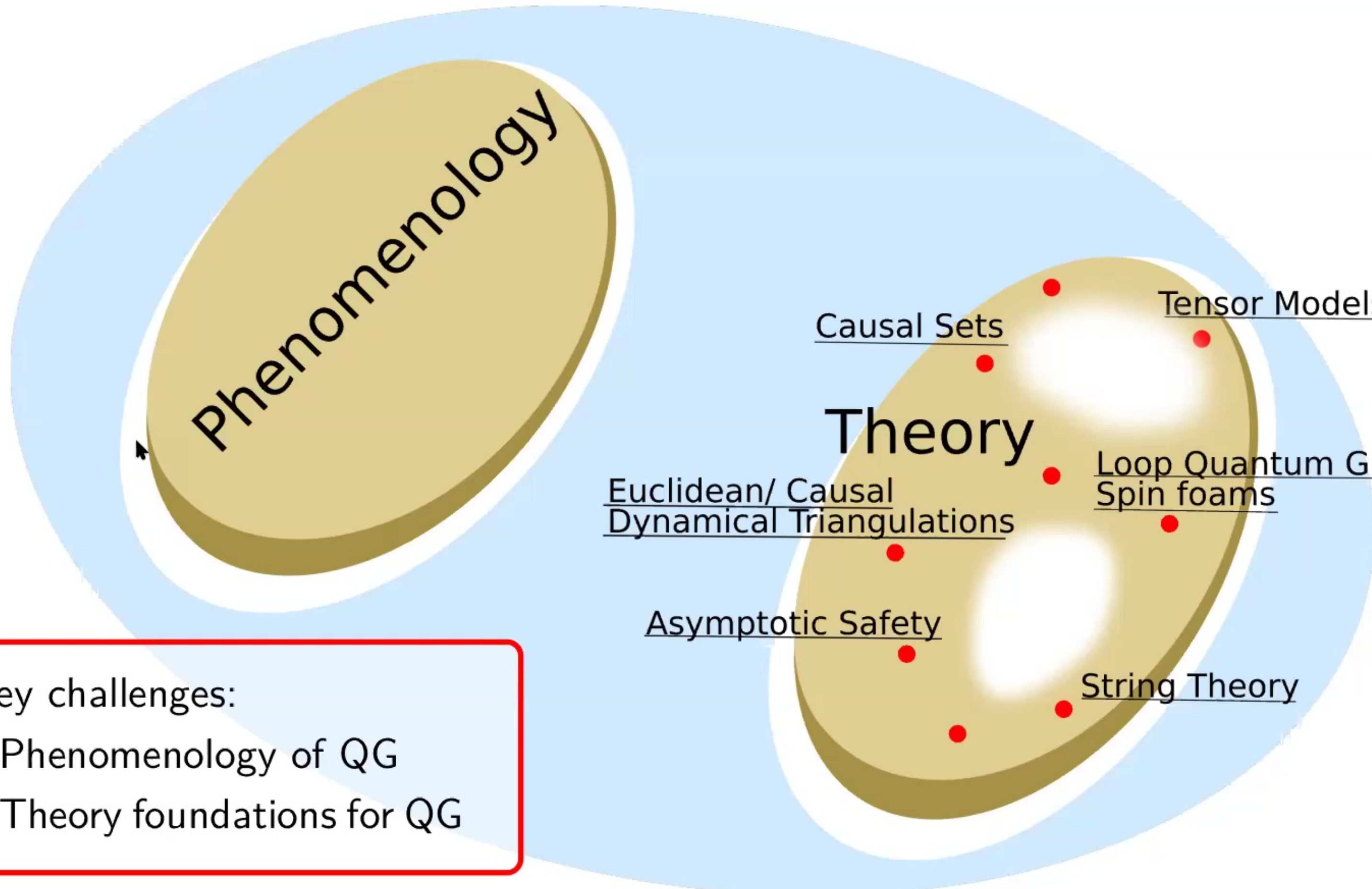
[Gümrükcüoglu, Saravani and Sotiriou, 2017]




**Key Result**

Interplay of QG and matter might pose *strong indirect* constraints on LIV in gravity!

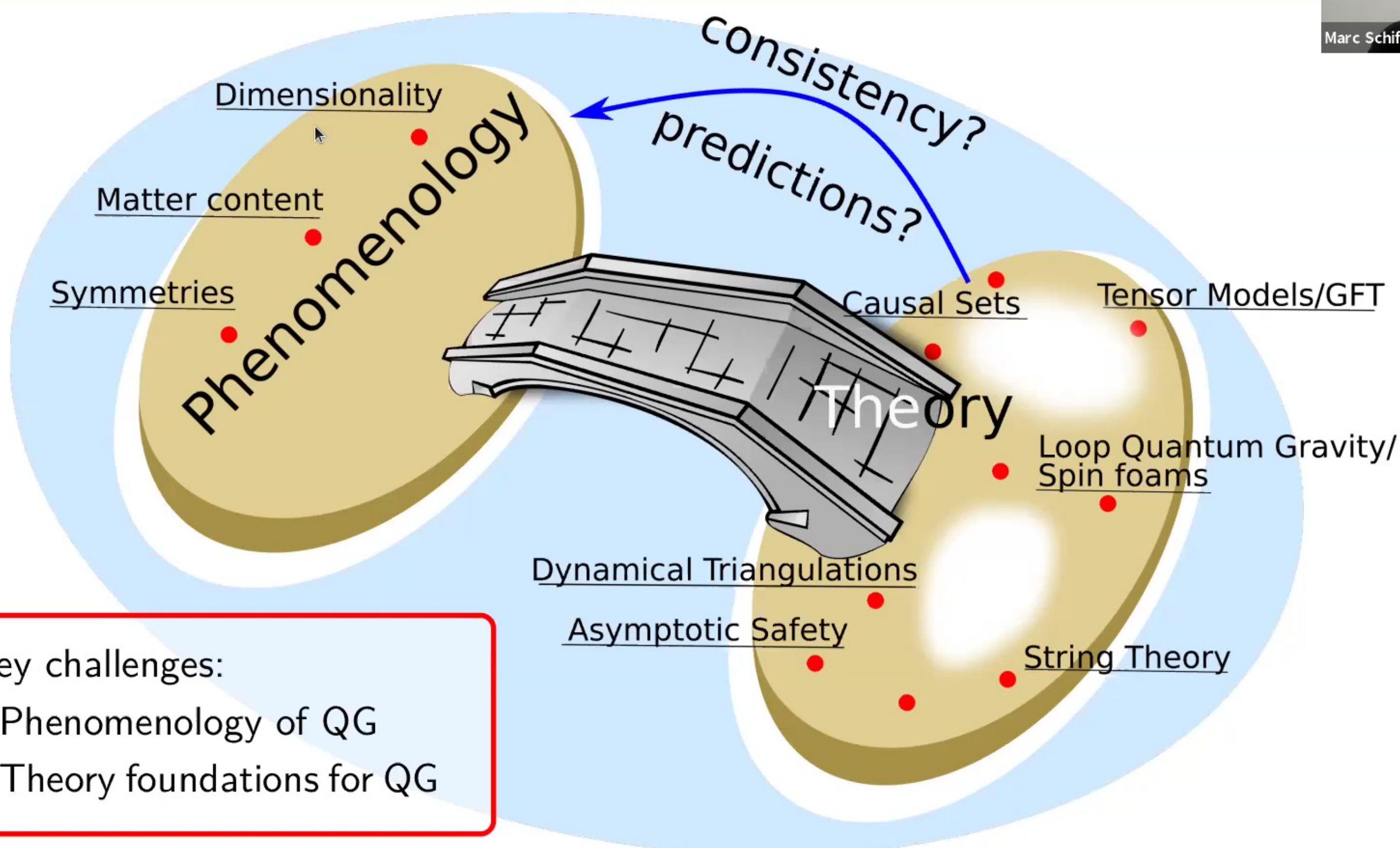
# Summary


Key challenges:

- Phenomenology of QG
- Theory foundations for QG

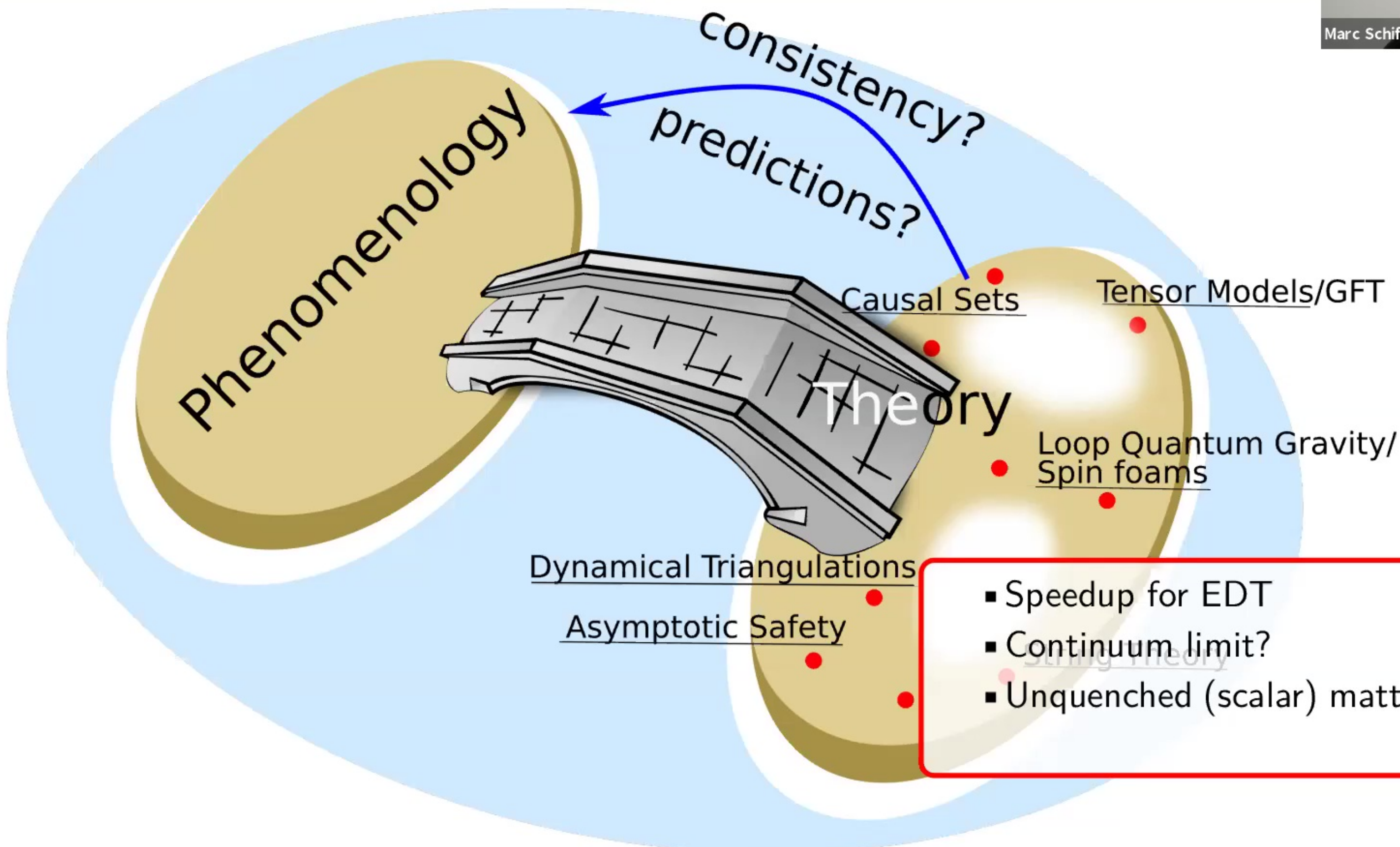
# Summary




Key challenges:

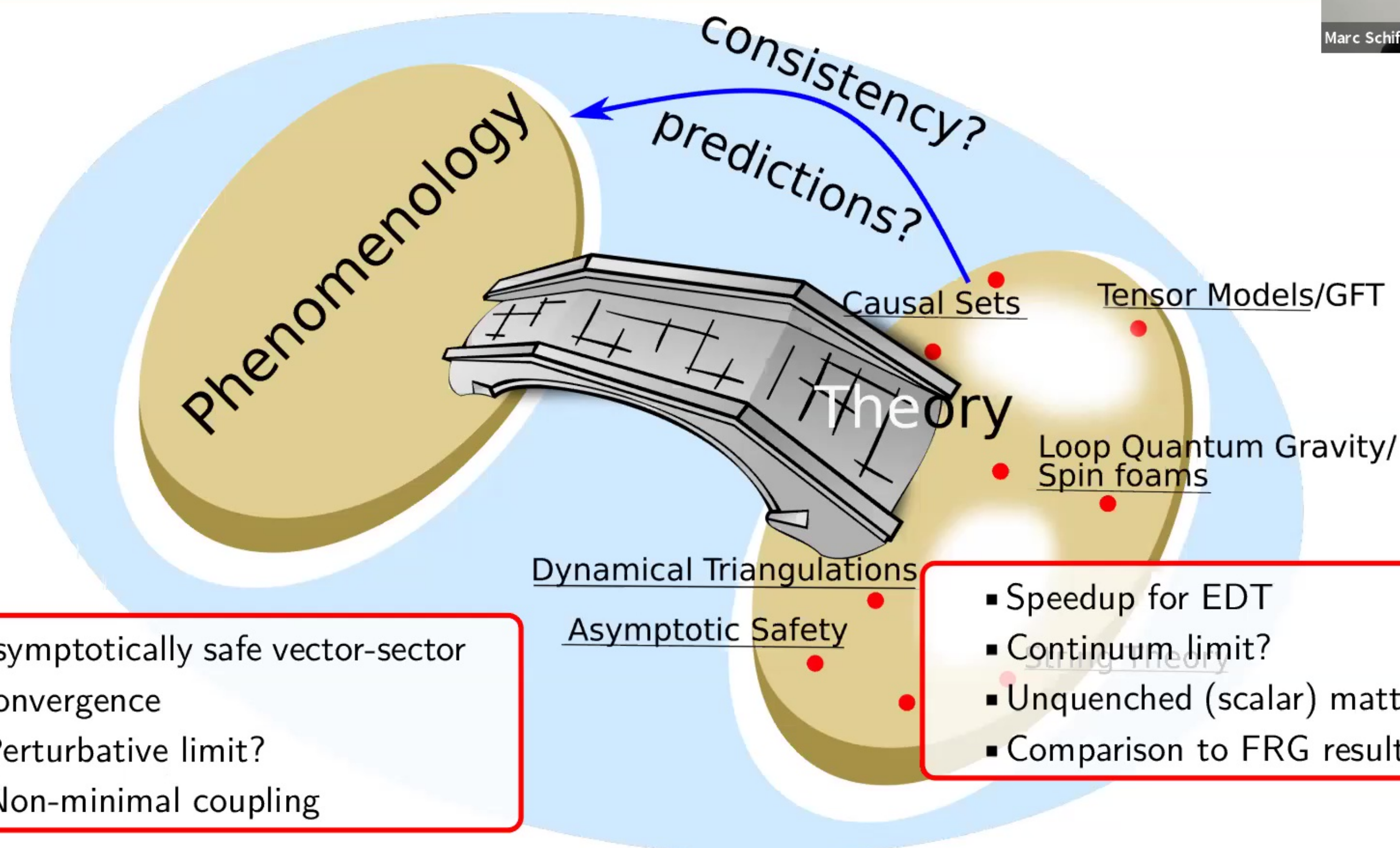
- Phenomenology of QG
- Theory foundations for QG

# Outlook



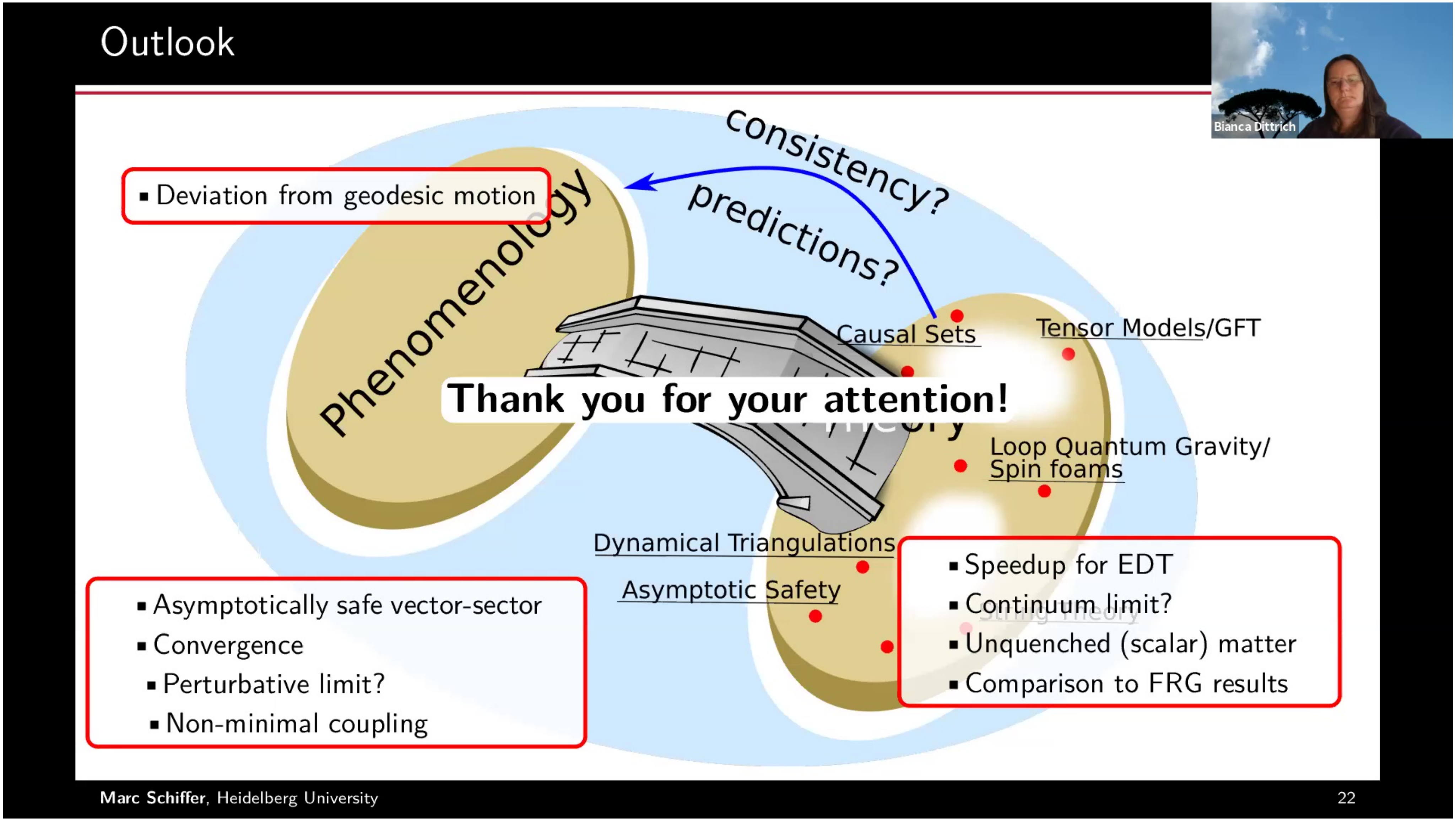

- Speedup for EDT
- Continuum limit?
- Unquenched (scalar) matter

# Outlook


- Asymptotically safe vector-sector
- Convergence
- Perturbative limit?
- Non-minimal coupling

- Speedup for EDT
- Continuum limit?
- Unquenched (scalar) matter
- Comparison to FRG results


Outlook
Bianca Dittrich
consistency?
predictions?
Phenomenology
Deviation from geodesic motion
Causal Sets
Tensor Models/GFT
Thank you for your attention!
Loop Quantum Gravity/
Spin foams
Dynamical Triangulations
Asymptotic Safety
String Theory
Speedup for EDT
Continuum limit?
Unquenched (scalar) matter
Comparison to FRG results
Asymptotically safe vector-sector
Convergence
Perturbative limit?
Non-minimal coupling
Marc Schiffer, Heidelberg University
22