Quantum gravity with a LC $\gamma - \gamma$ option?

Asymptotic safety in extra dimensions at a Linear Collider

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LC workshop Hamburg

Talk based on BD & A. Eichhorn, JHEP06(2012)156, arxiv/1203.6366 [gr-qc],

October 11th 2013

HELMHOLTZ GEMEINSCHAFT

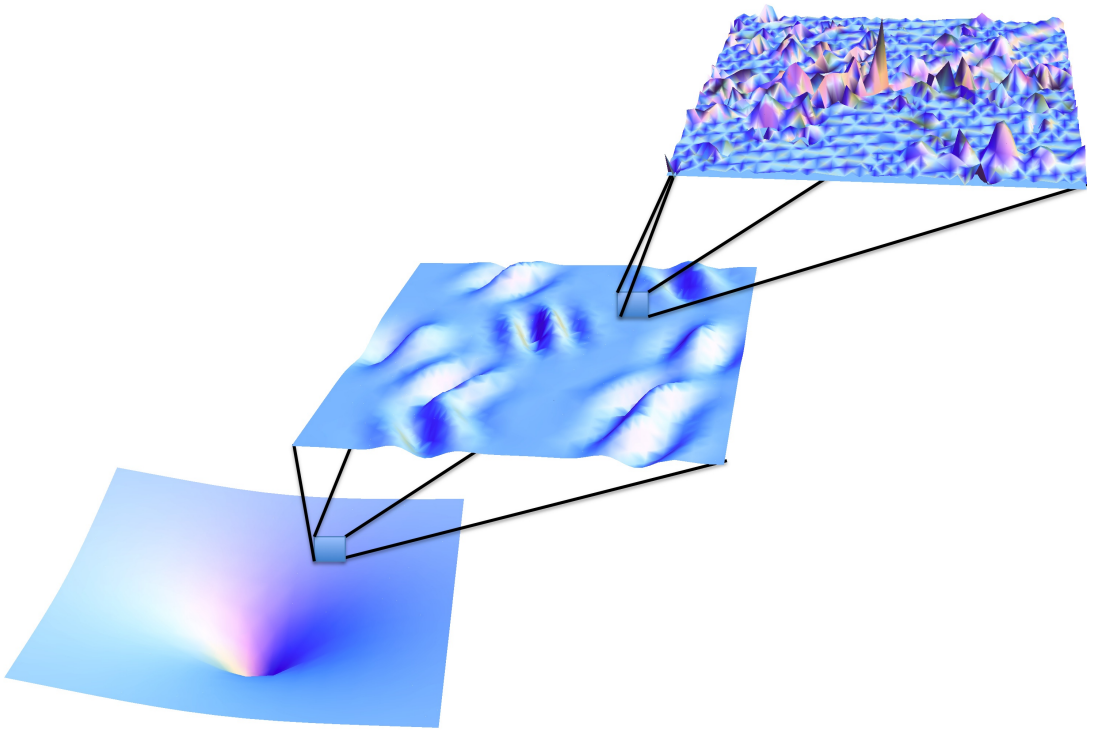
DESY

Why Quantum Gravity?

Einstein field equations

$$G_{\mu\nu} + g_{\mu\nu}\Lambda = 8\pi T_{\mu\nu}$$

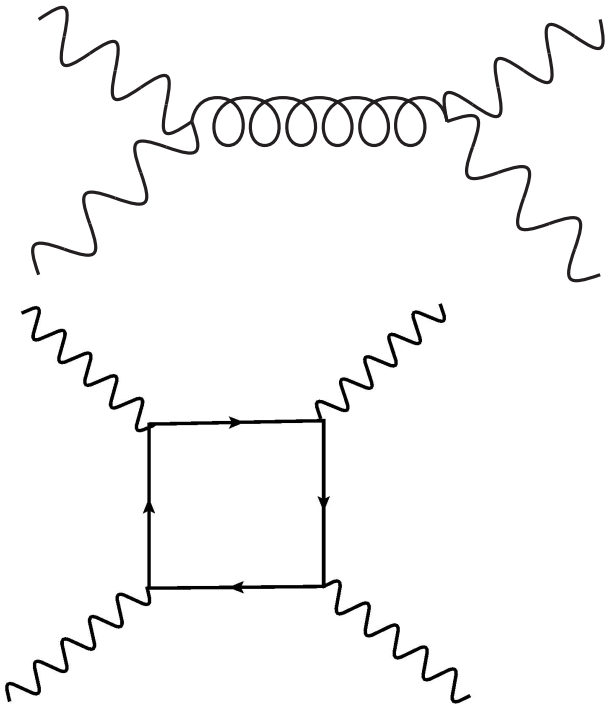
↓ classical ↓ quantized



[picture courtesy A.Eichhorn]

- QFT on curved backgrounds typically unstable (backreaction)
- QFT & GR → spacetime fluctuations at the Planck scale
- singularities in GR
- ...

γ-γ-graviton as a probe of QG?



- γ-γ: no tree-level process in SM, but tree-level via graviton!
- SM at low energies: e^+e^- loop, at higher energies W-boson loop
- high photon energies $\rightarrow$ access to this spacetime structure?

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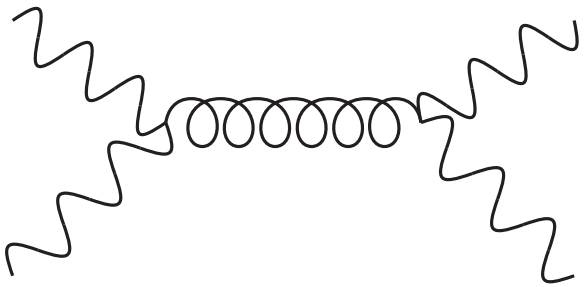

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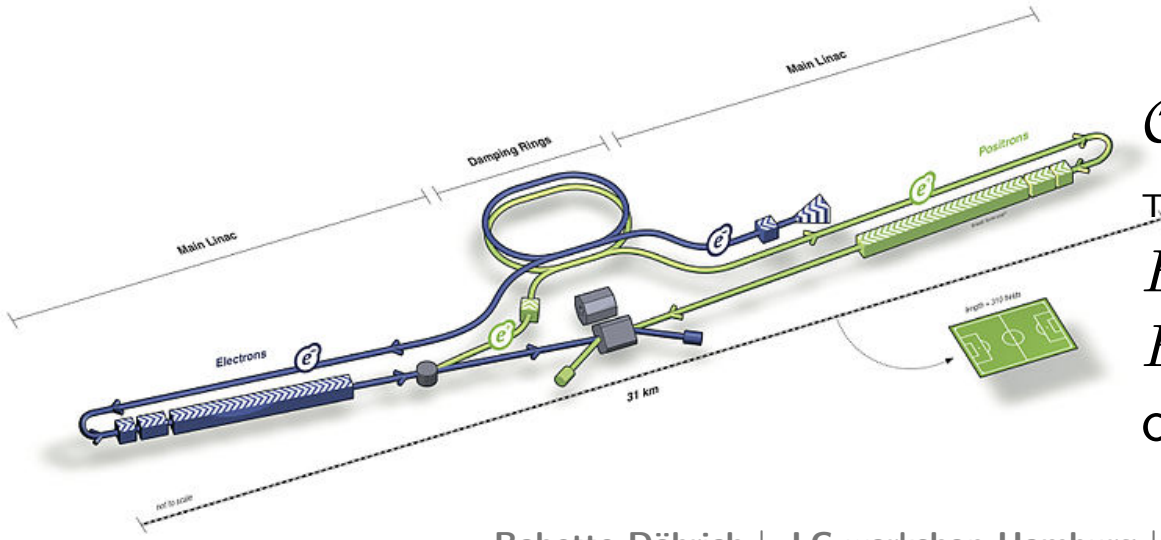
γ-γ option at a LC?



$\mathcal{O}(10)\mathrm{fb}^{-1}$ [Bechtel et al '06, Telnov '13]

$E_{\mathrm{cm}} = 1\mathrm{TeV} \rightarrow 0.4\mathrm{TeV}$,
$E_{\mathrm{cm}} = 2\mathrm{TeV} \rightarrow 0.8\mathrm{TeV}$
or lower... ?

Status of Quantum Gravity (QG)

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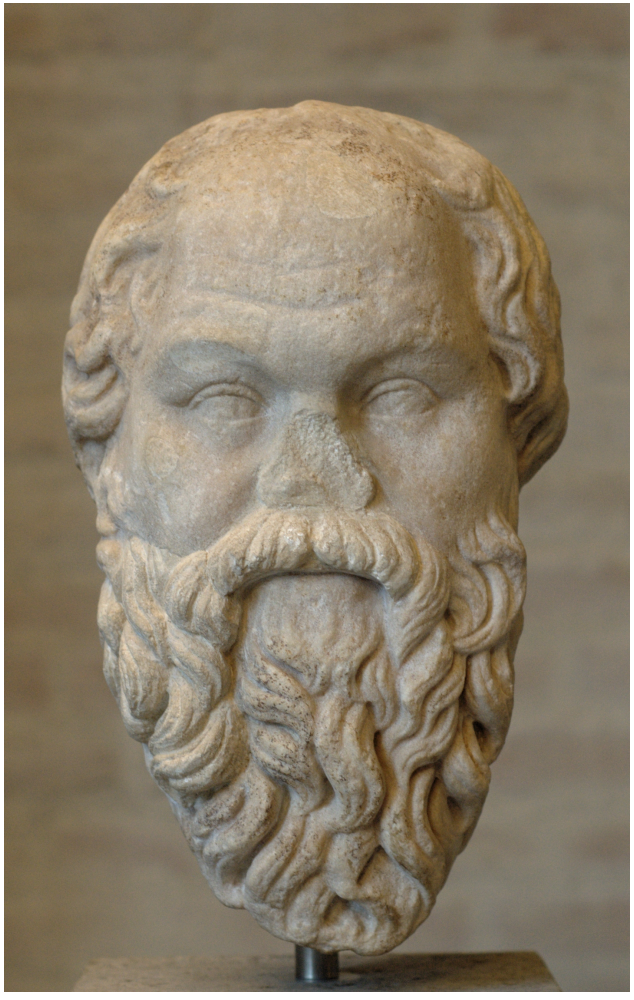

'I know that I know nothing' *Sokrates*

QG - suggestions & complications

Theory: connection gravity $\leftrightarrow$ QFT is not straightforward!

- leave the continuum? (e.g. causal sets, loop qg)
- introduce new degrees of freedom? (e.g. String, Sugra...)
- break fundamental symmetries? (care: Lorentz violation $\lightning$ spin-statistics, renormalizability?)
- ...

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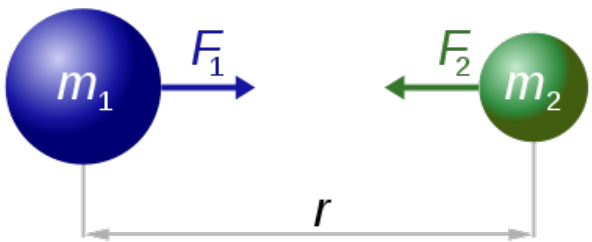
Experiment: The Planck scale is far off!

- new DOFs, e.g., in colliders?
- Lorentz symmetry? (astrophysics very sensitive)
- extra dimensions? (warning: extra dimensions per se need not necessarily teach us something about QG!)

Incomplete excursion into Extra Dimensions (ED)

- fundamental Planck scale $M_\star$
  $M_\star^{n+2} = M_{\text{Planck}}^2/(2\pi r)^n$



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

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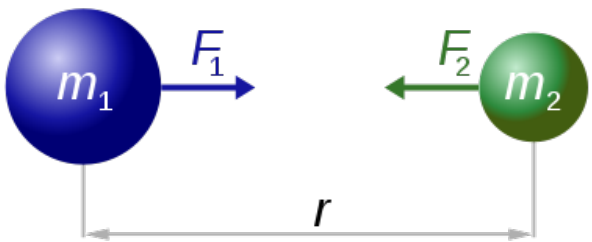

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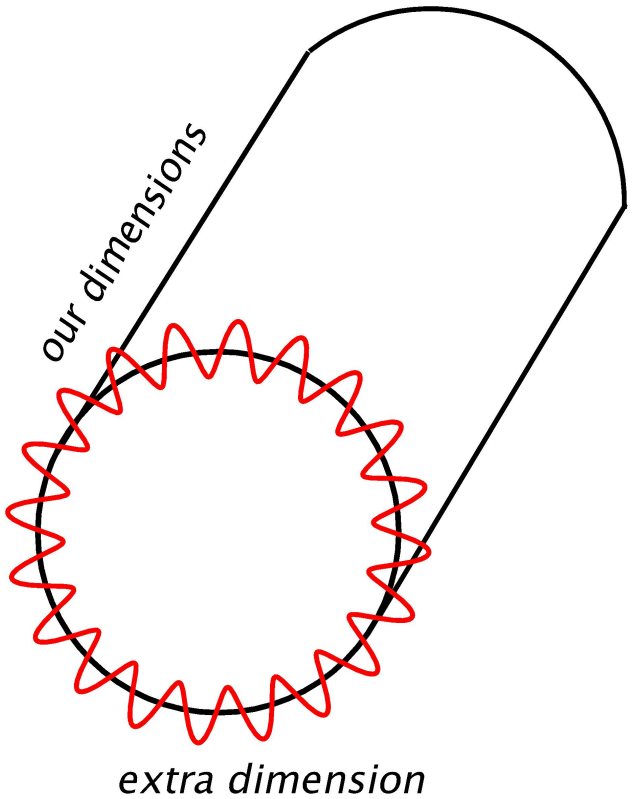

- fundamental Planck scale $M_\star$
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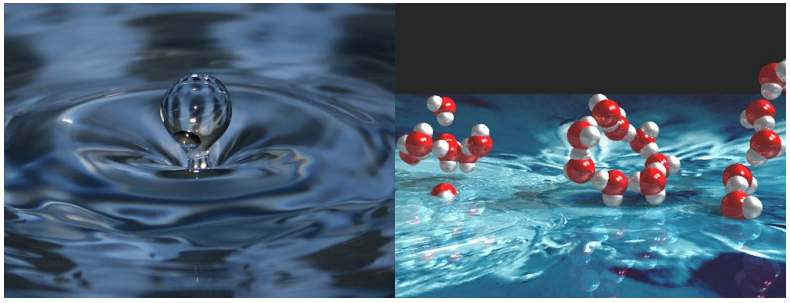
- (Particle viewpoint: ADD Arkani-Hamed et al ED at electroweak scale $\rightarrow$ hierarchy resolved)
- sum over KK vs simple graviton propagator enhances crossections!
- NB sum/integral over KK tower requires cutoff Λ for $n \geq 2$:

$$\int_0^{\infty \leftrightarrow \Lambda} dm \frac{m^{n-1} G_N}{(s - m^2)}$$

- cutoff always needed?

QG without a cutoff?



- $\int \mathcal{D}g\ e^{iS[g]}$ works as effective field theory. Can we get a fundamental theory in this (well-established) framework, valid on *all* scales?
- naive quantization fails $\rightarrow$ perturbative non-renormalizability

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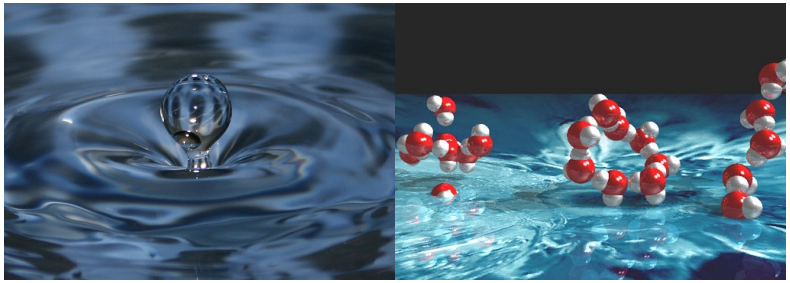
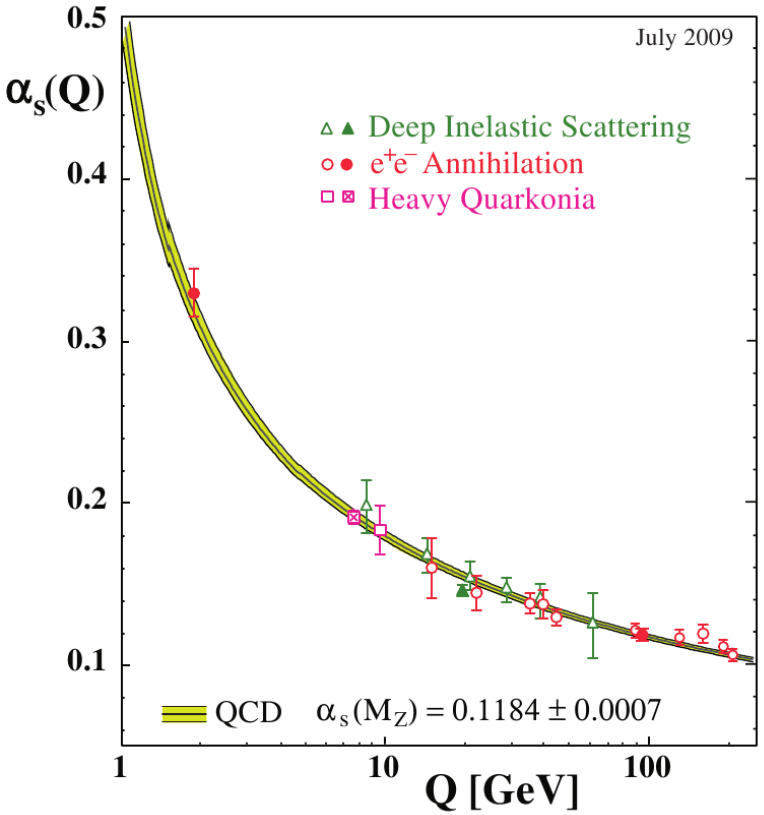
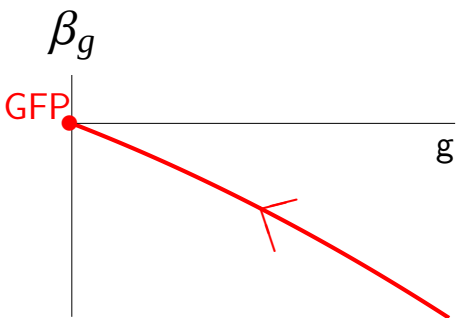




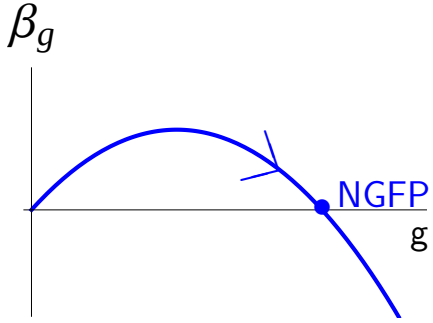
- $\int \mathcal{D}g\ e^{iS[g]}$ works as effective field theory. Can we get a fundamental theory in this (well-established) framework, valid on *all* scales?
- naive quantization fails → perturbative non-renormalizability
  - fundamental QFT → coupling finite for $k \to \infty$
  - asympotic freedom: running coupling weakens for $k \to \infty$

Asymptotic safety as a fundamental QFT



Asymptotic freedom:

non-interacting fixed point



Asymptotic safety:

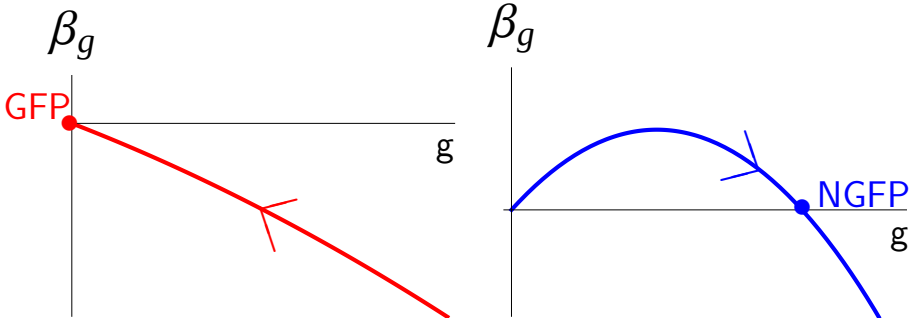
interacting fixed point

- one solution: $\exists$ nongaussian fixed point (FP) in $\beta = k\partial_k g(k)$ for dimensionless Newton coupling "asymptotic safety"

  [Weinberg'79]

- scale-free theory allows infinite momentum cutoff

Asymptotic safety as a fundamental QFT



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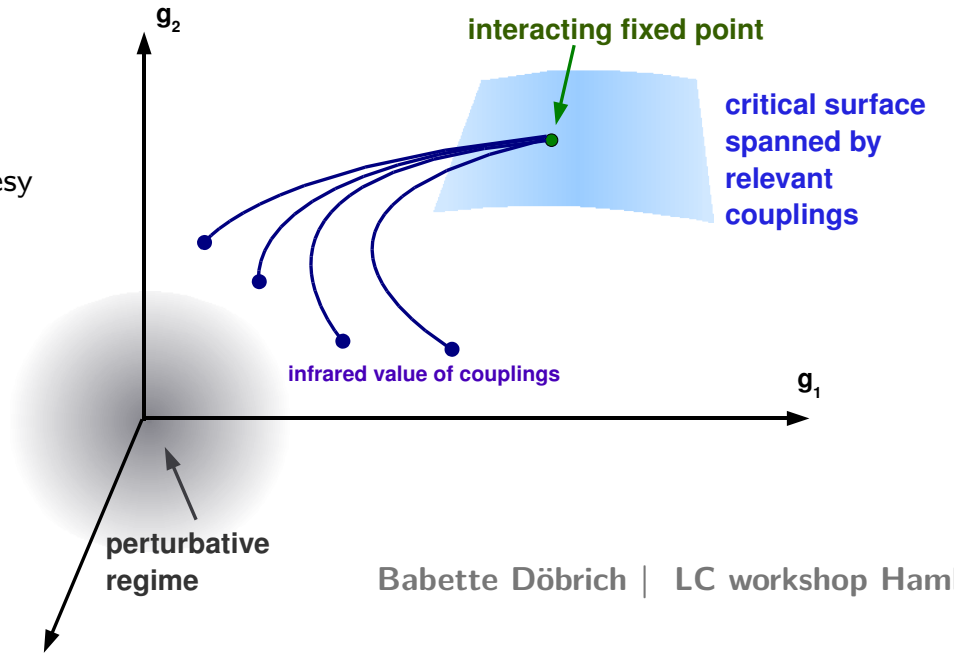
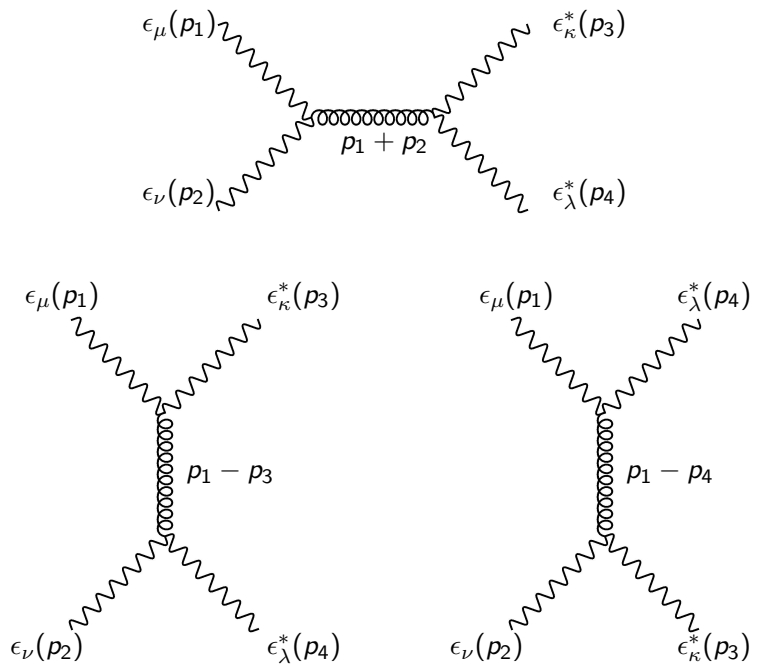
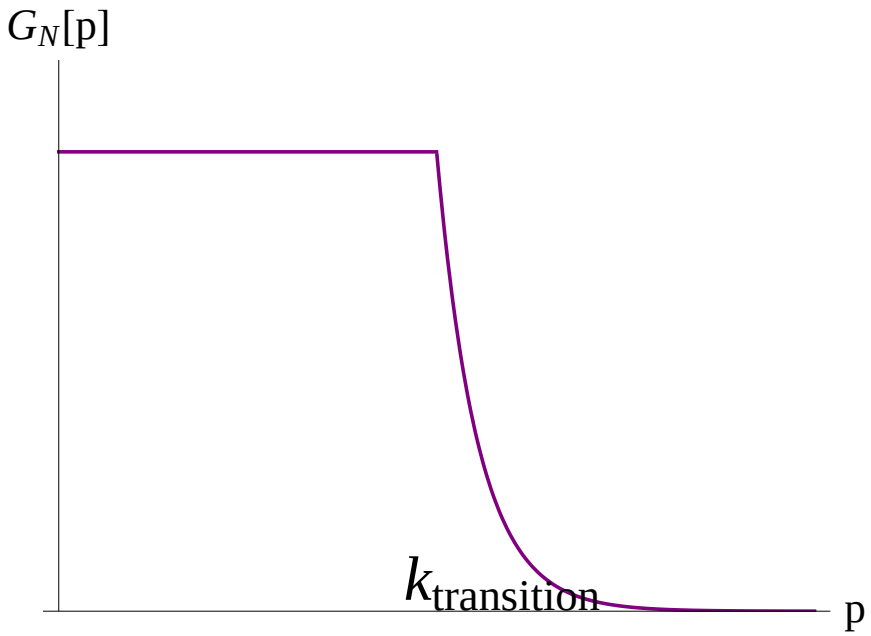
[picture courtesy A. Eichhorn]



> not proven (not perturbatively accessible), but in approx. such a FP exists [Reuter et al '12]

γ-γ-graviton in asymptotically safe QG (QEG)





Physics of asymptotic safety for $G_N(k)$

$G(k) \to$ FP for $k \to \infty$, where $G(k)$=$G_N(k)k^{d-2}$ dimensionless

$\Rightarrow G_N(k) \sim$ const for $k < k_{\text{trans}}$ and $\sim \frac{1}{k^2}$ for $k > k_{\text{trans}}$

i.e. phenomenology: the gravitational coupling $G_N(k)$ vanishes asymptotically

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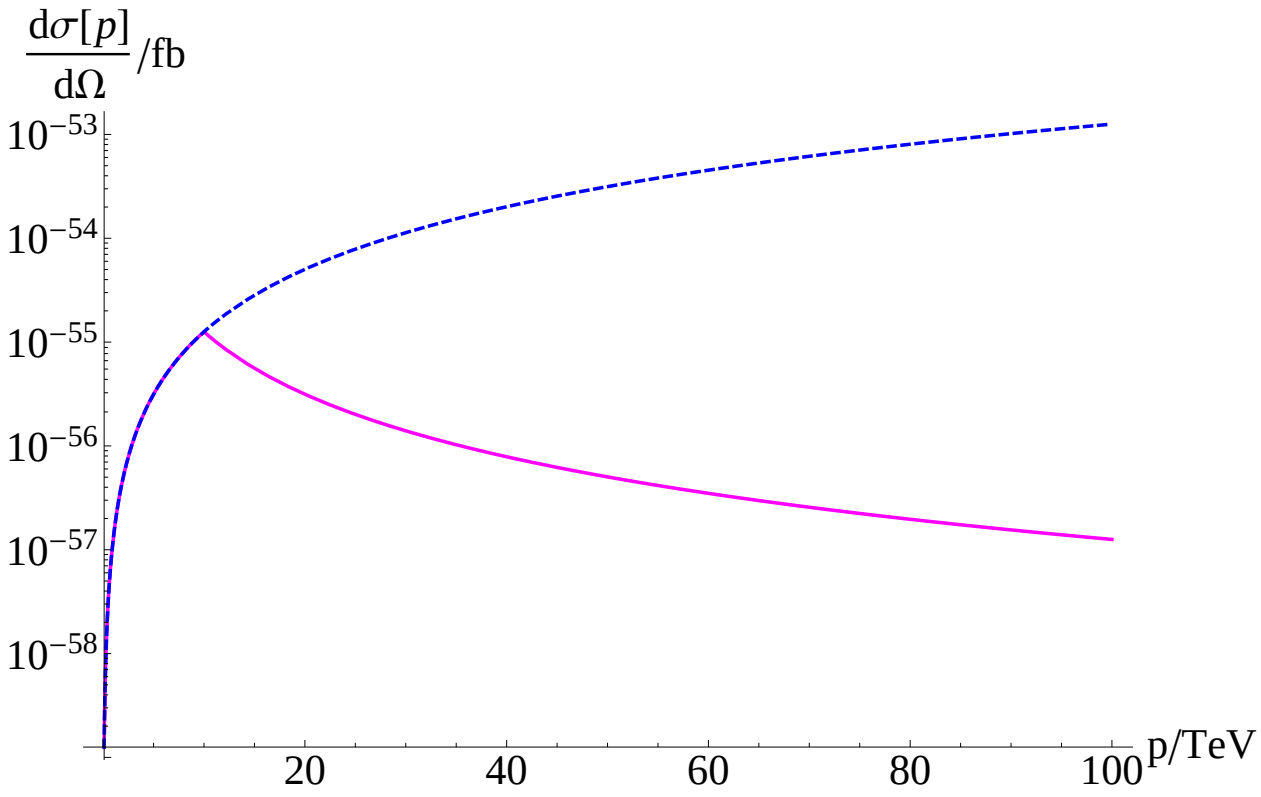
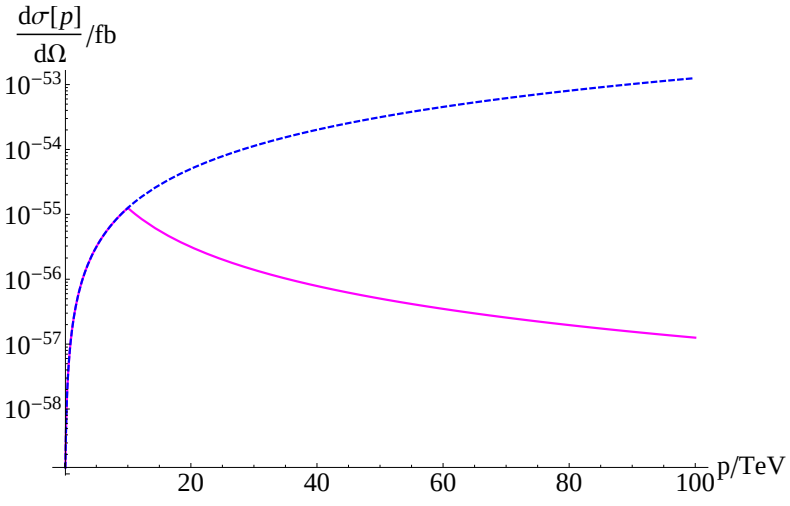


- $\gamma - \gamma$ graviton nonunitary
  [Barker et al '67] $\longrightarrow$ cutoff needed
- in asymptotic safety: $\Leftrightarrow$ $G_N(k) \sim \frac{1}{k^2}$ for $k > k_{\rm trans}$

γ-γ-graviton in asymptotically safe QG & ED

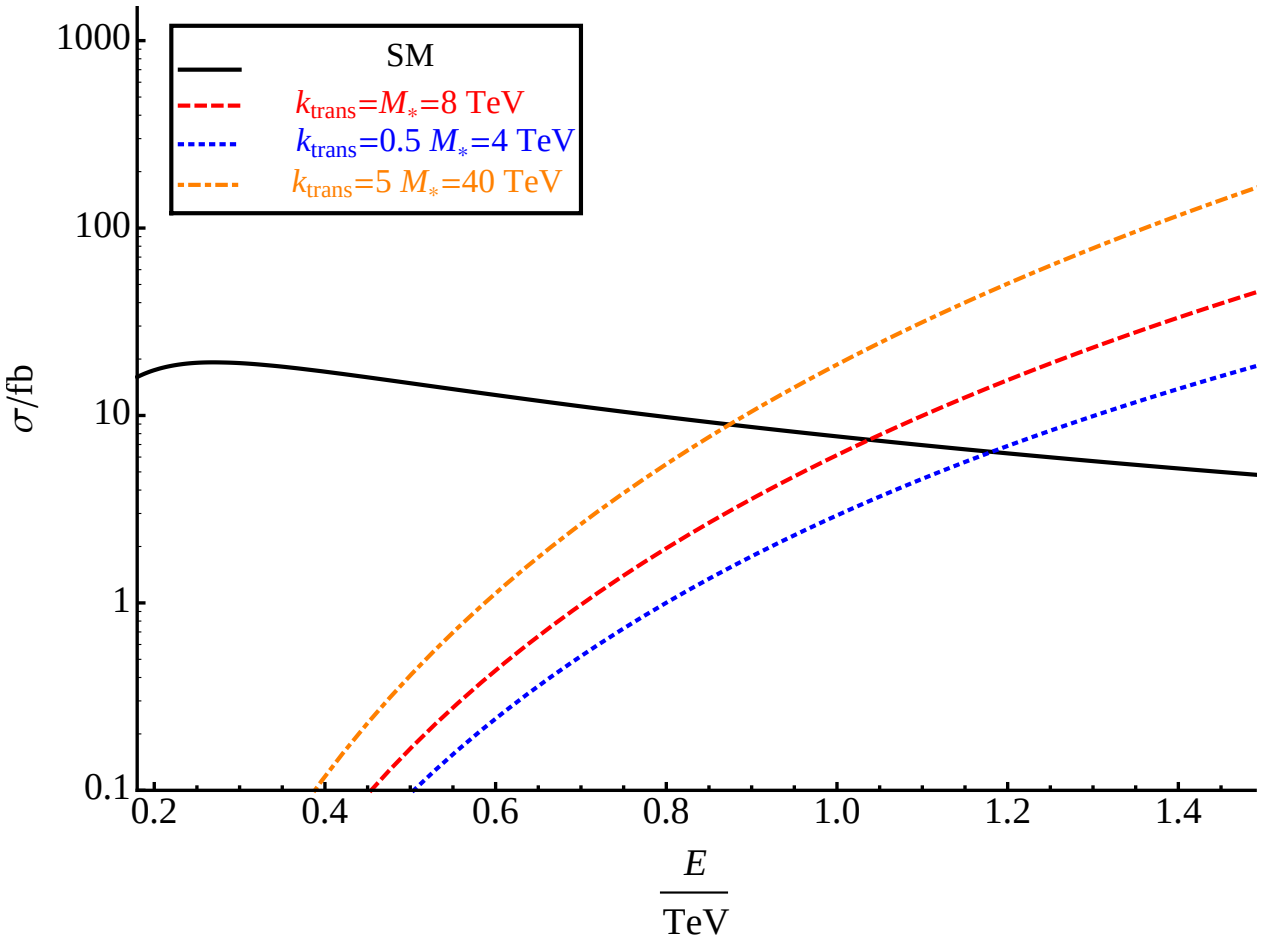


- QG viewpoint: dimensionality and topology emerge from e.g. path-integral, nontrival spacetime structure viable
- through ED, crossection increases as described above
- transition scale 'replaces' cutoff

summation over KK states in cutoff and AS:

$$\int_0^\infty dm \frac{m^{n-1} G_N(m)}{(s-m^2)} = \int_0^{k_{\rm tr}} dm \frac{m^{n-1}}{s-m^2} + k_{\rm tr}^{n+2} \int_{k_{\rm tr}}^\infty dm \frac{m^{n-1}}{m^{n+2}\,(s-m^2)}$$

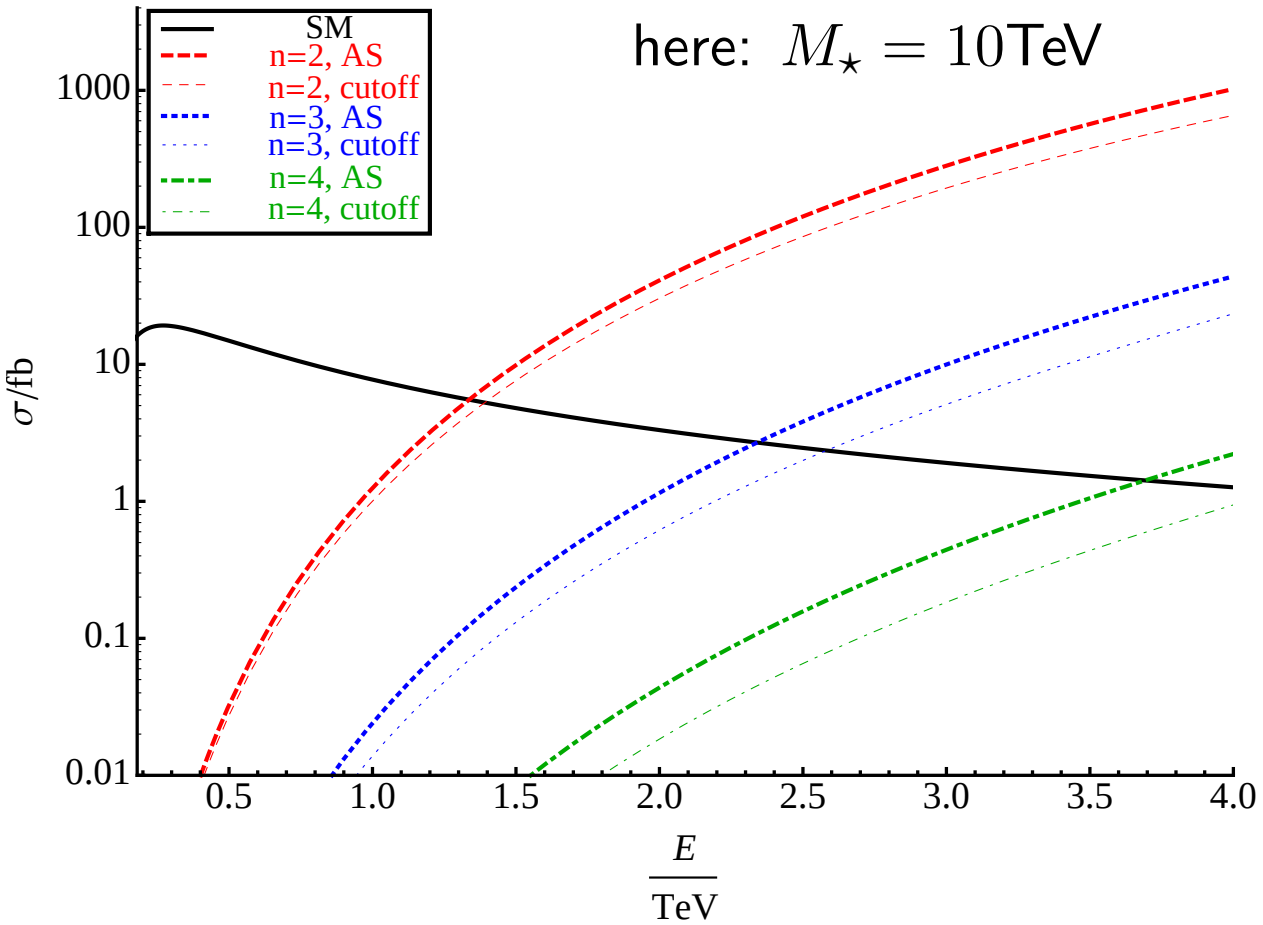
Transition scale dependence for $n = 2$



- higher transition scale more easily accessible
- if scenario realized, k_{trans} must be measured
- generally more sensitive than corresponding LHC option

[Gerwick et al '11]

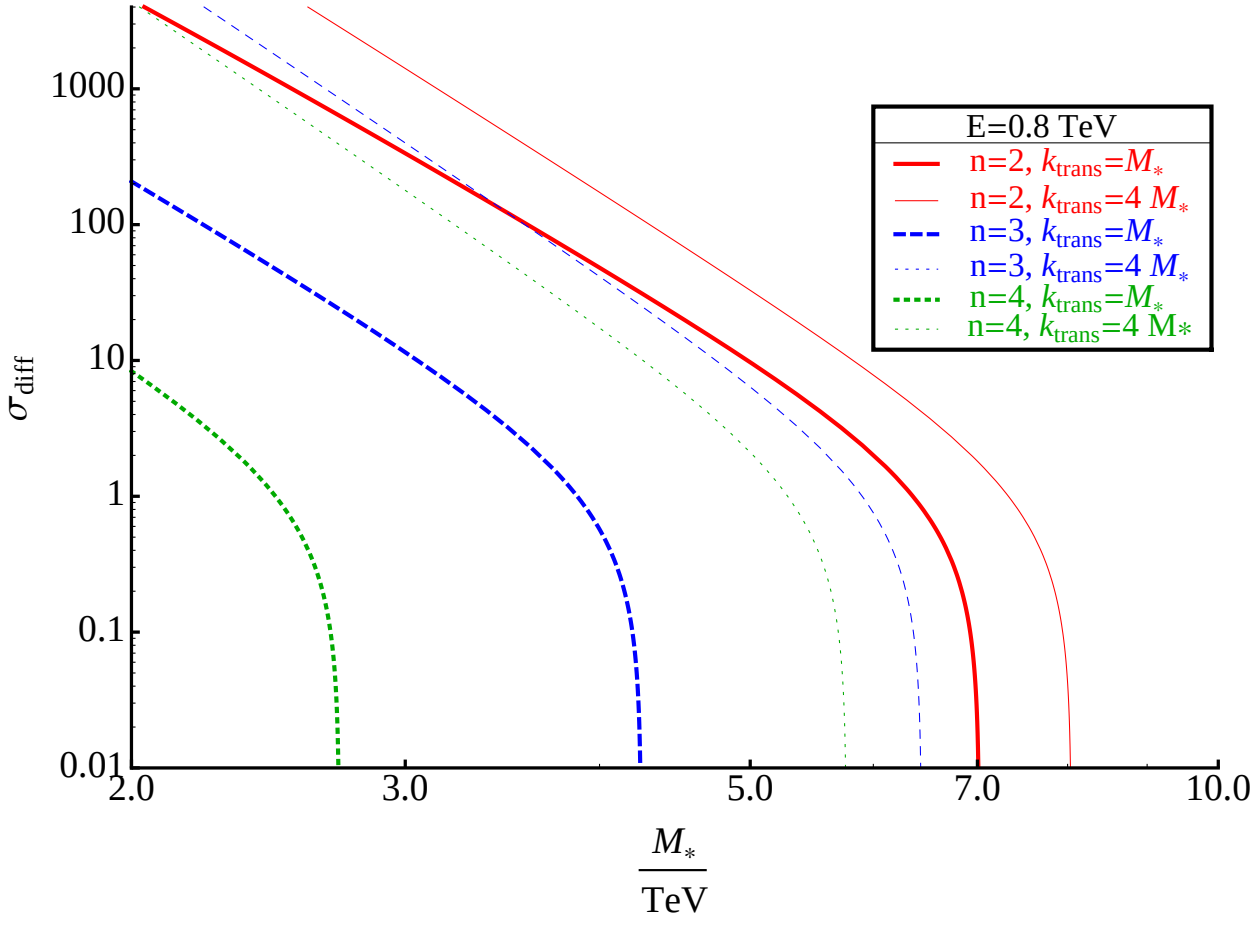
Compare with cutoff theory & dependence on n



- AS scenario & cutoff clearly **distinguish-able** → access to quantum gravity!
- distinct angular dependence (not shown)

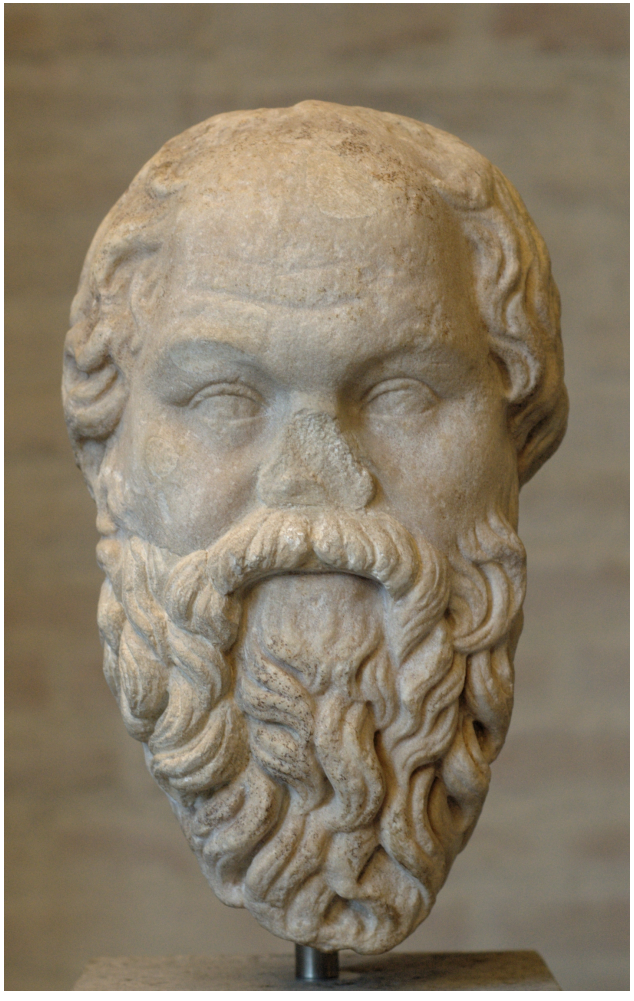
asymptotic safety: [B.D., Eichhorn'12]
cutoff: [Davoudiasl'99] [Cheung'00]

Accessibility of the fundamental Planck scale $M_\star$



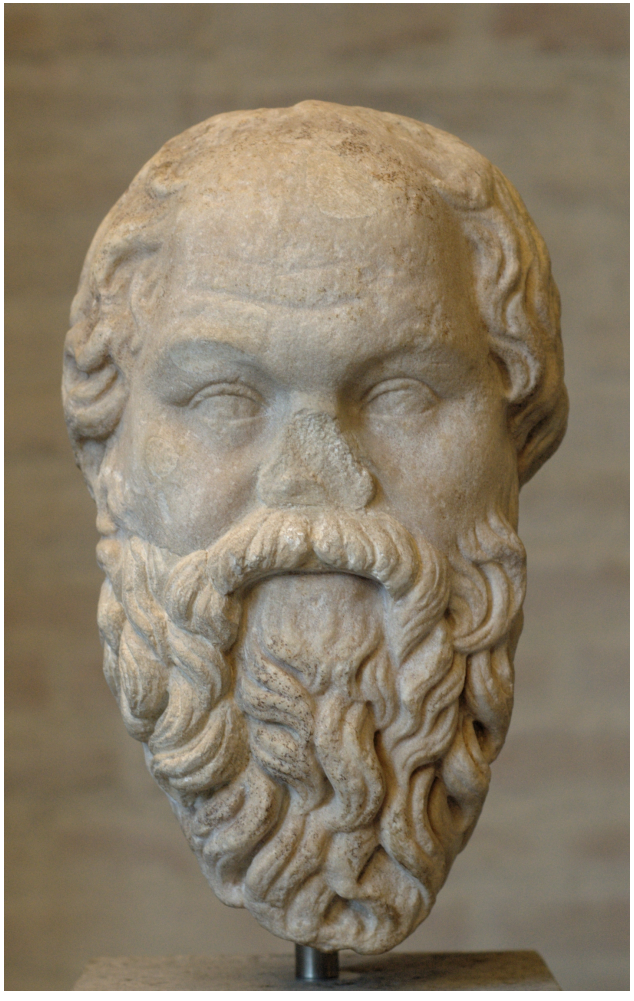
> With LC $E_{\rm cm} = 1$TeV, Planck scales up to 7 TeV accessible ($E_\gamma = 5$TeV, Planck scales up to 40TeV), whereas for LHC $E_{\rm cm} \sim M_\star$

'Result'?



'I know that I know nothing' *Sokrates*

‘Result’?



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Summary and take-away

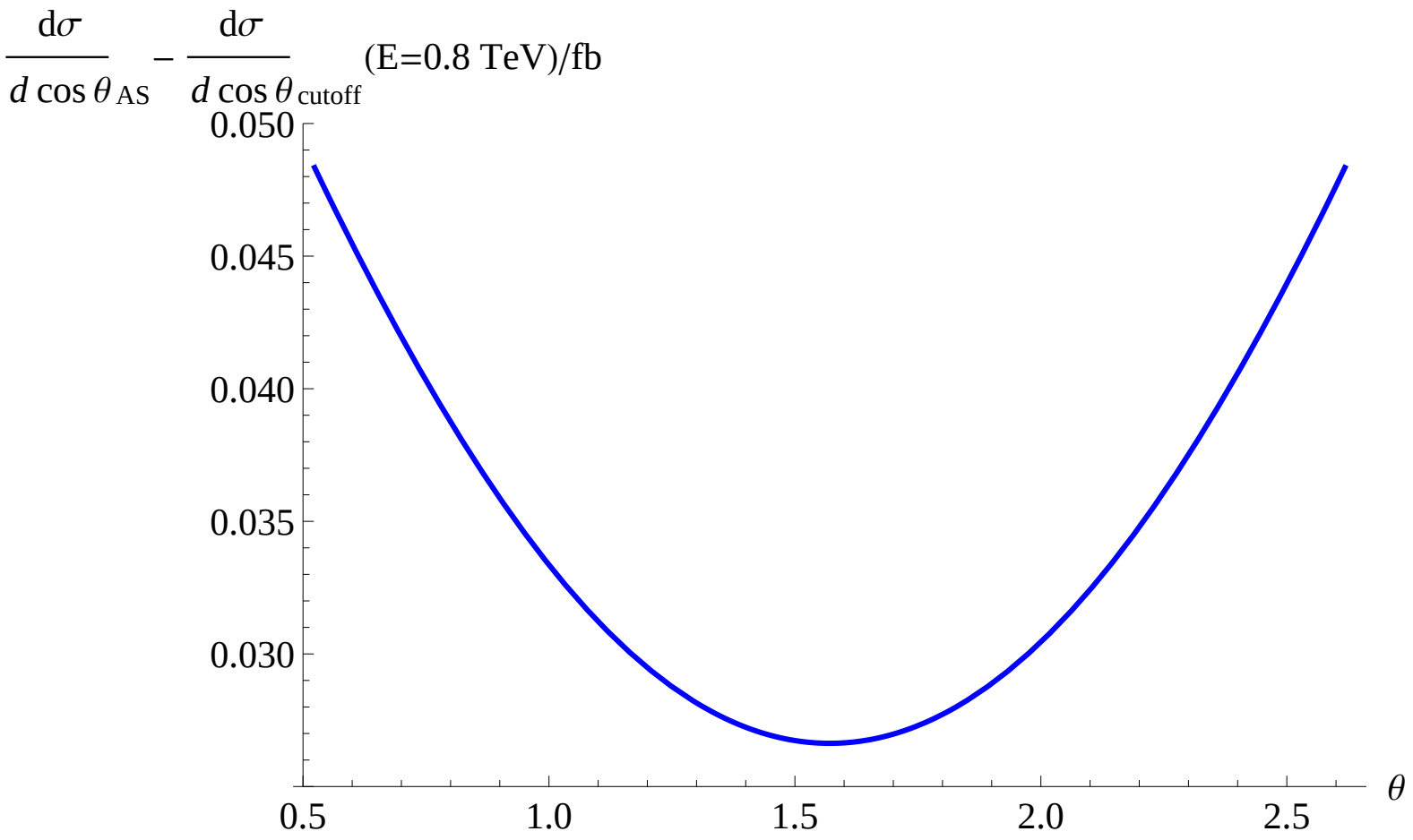
In any region of physics where very little is known, one must keep to the *experimental basis* if one is not to indulge in wild speculation that is almost certain to be wrong P. Dirac

- Experimental ideas will bring the search for QG forward
- $\gamma - \gamma$ is sensitive probe, due to missing SM tree-level (see also ALPS-II $\rightarrow$ axion et al search (ask me) ☺)
- It is emphazised that a LC with $\gamma - \gamma$ has the potential to test this and certainly many other scenarios!
- further reading: BD and Astrid Eichhorn JHEP06(2012)156 (arxiv/1203.6366 [gr-qc])

Thank you!

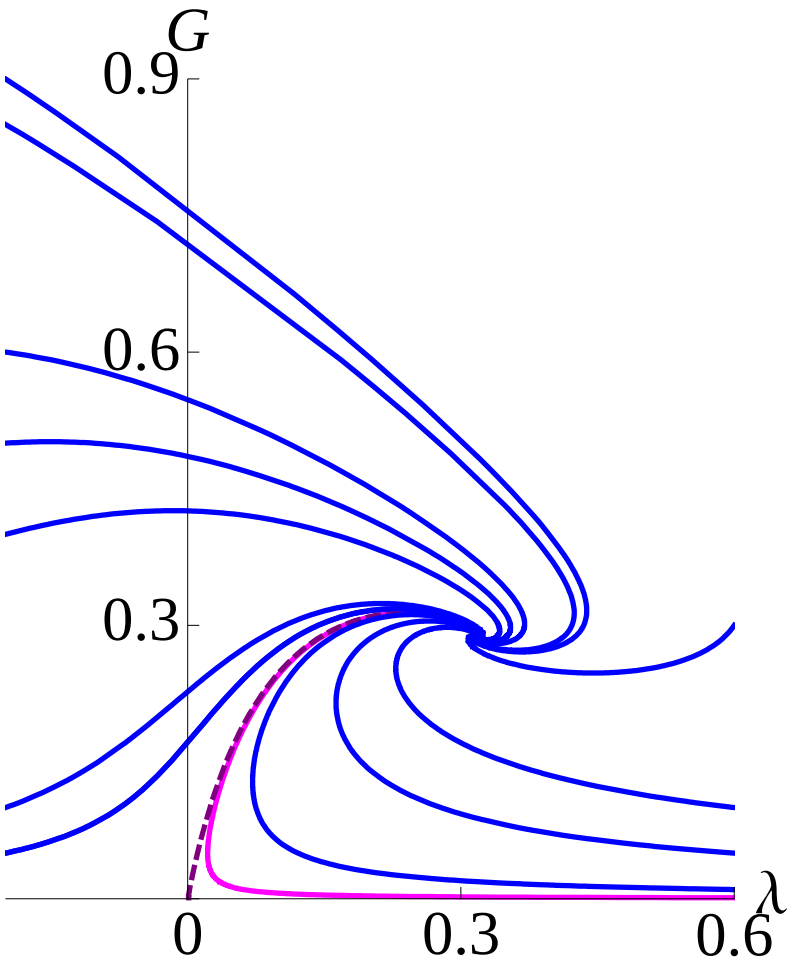
Backup

Angular dependence



> $E = 0.8$TeV and $M_\star = 10$TeV, $n = 2$

AS



> physics of scenario: Newton couling weakens at high energies
→ rich phenomenology

Exact Renormalization group equation

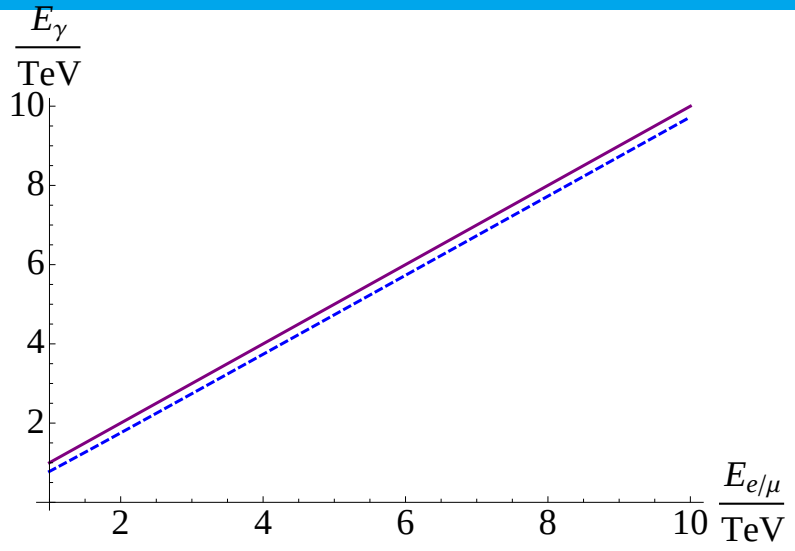
How to look for non-Gaußian fixed points

$$e^{-\Gamma_k[\phi]} = \int \mathcal{D}\varphi \; e^{-S[\varphi] - \frac{1}{2}\int_p (p)\varphi R_k(p)\phi(-p)}$$

- scale dependent action Γ_k contains effect of quantum fluctuations above momentum scale k
- R regulator
- gravity: $\Gamma_{k\to 0} = \Gamma_{\mathrm{EinsteinHilbert}}$, $\Gamma_{k\to\Lambda\to\infty} \to S$
- Wetterich Equation '93
- useful concept also e.g. to tackle triviality problem in QED & Higgs sector

$\sim$ TeV-photon beams from inverse Compton

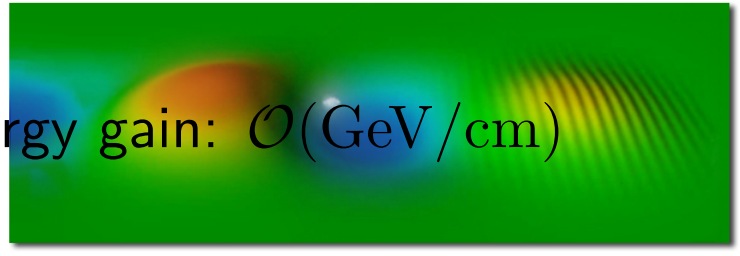
$\rightarrow$ future electron/ muon collider



$\omega_i \ll E_{\rm beam}, \omega_f$ &
$m_{e/\,\mu} \ll E_{\rm beam}$:

$$\omega_f = 4E_{\rm beam}^2 \omega_i \frac{1}{m_{e/\,\mu}^2 + 4\,E_{\rm beam}\omega_i}$$

$\rightarrow$ purely-laser based setting: staged laser wake-field acceleration?



energy gain: $\mathcal{O}(\mathrm{GeV/cm})$