Dark matter as bound states in asymptotically safe quantum gravity

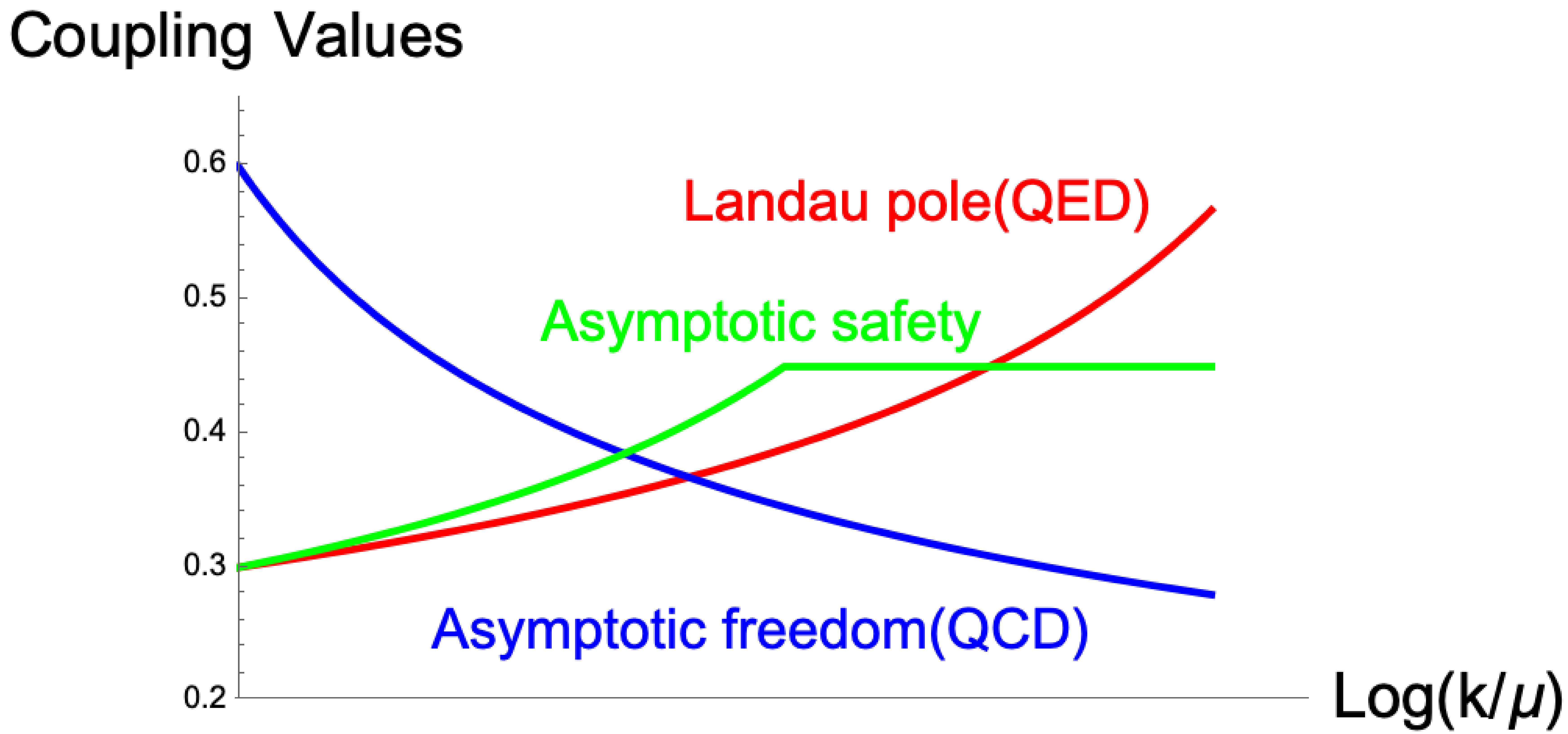
Abhishek Chikkaballi
National Center for Nuclear Research (NCBJ)
Warsaw, Poland
In collaboration with
Gustavo Pazzini de Brito, Astrid Eichhorn, Mads T. Frandsen, Martin Jorgensen, Arthur F. Vieira

Dark Matter 2025

02 June 2025

Santander, Spain

Asymptotic safety



UV complete theory: all the couplings approach a UV fixed point

$\Longrightarrow$ The theory can be extrapolated to infinitely large energy scales

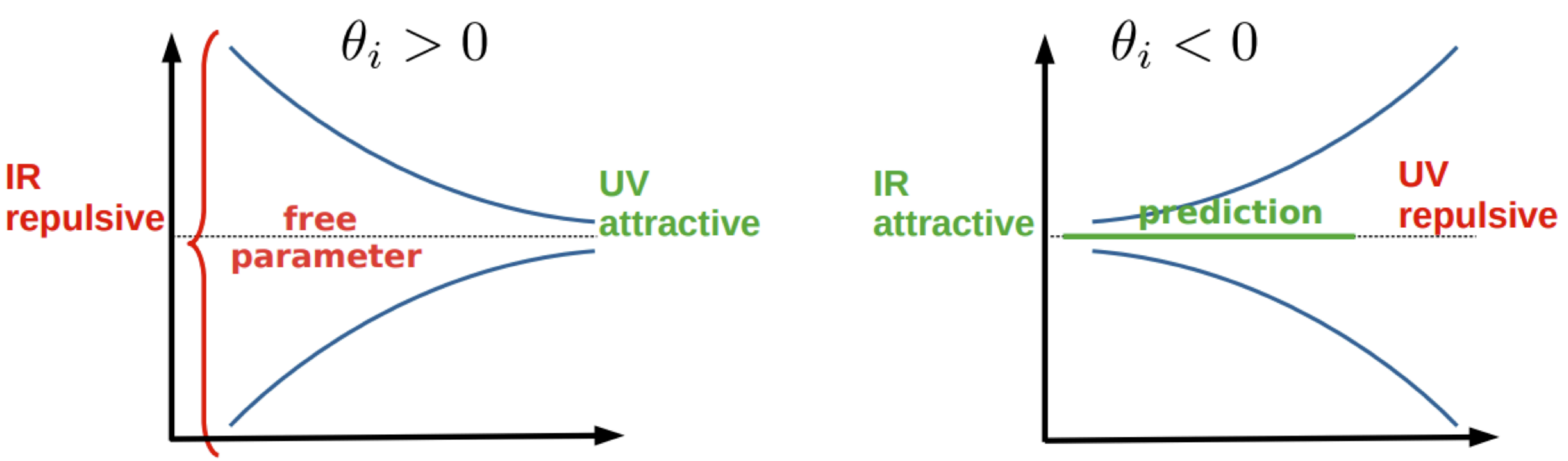
Predictions and free parameters

- Fixed point: where all the couplings stay constant with the changing scale

$$\beta_i(\{g_j\}) = 0$$

- Linearized flow near the fixed point

$$\text{Stability matrix: Stability matrix: } M_{ij} \equiv \left.\frac{\partial \beta_i}{\partial g_j}\right|_{\{g_i^*\}} \longrightarrow \{\theta_i\}\text{Critical exponents}$$



Relevant couplings are free parameters of the theory

Irrelevant couplings provide predictions

Asymptotically Safe Gravity

- Gravity as a QFT
  - Non-renormalizable —> but a consistent EFT to compute corrections below M_{Pl}
  - Infinitely tower of counter terms
  - Lacks predectivity i.e infinite number of experiments to fix the initial condition

- Asymptotically Safe Gravity:
  - Quantum scale invariance
  - Finite free parameters ➡ predictivity

Christiansen, Eichhorn '17, Christiansen et al. '17, Shaposhnikov, Wetterich '09, Dona, Eichhorn, Percacci '13, Meibohm, Pawlowski, Reichert '15, Knorr, Ripken, Saueressig '19, Eichhorn, Held, Pawlowski '16, Wetterich, Yamada '16, Hamada, Yamada '17, Pawlowski et al. '18, Eichhorn, Versteegen '17, Eichhorn, Held '17-'18, Pastor-Gutiérrez, Pawlowski, Reichert '22,Falls, Ohta, Percacci '20, Benedetti, Caravelli '12, ...

Example:

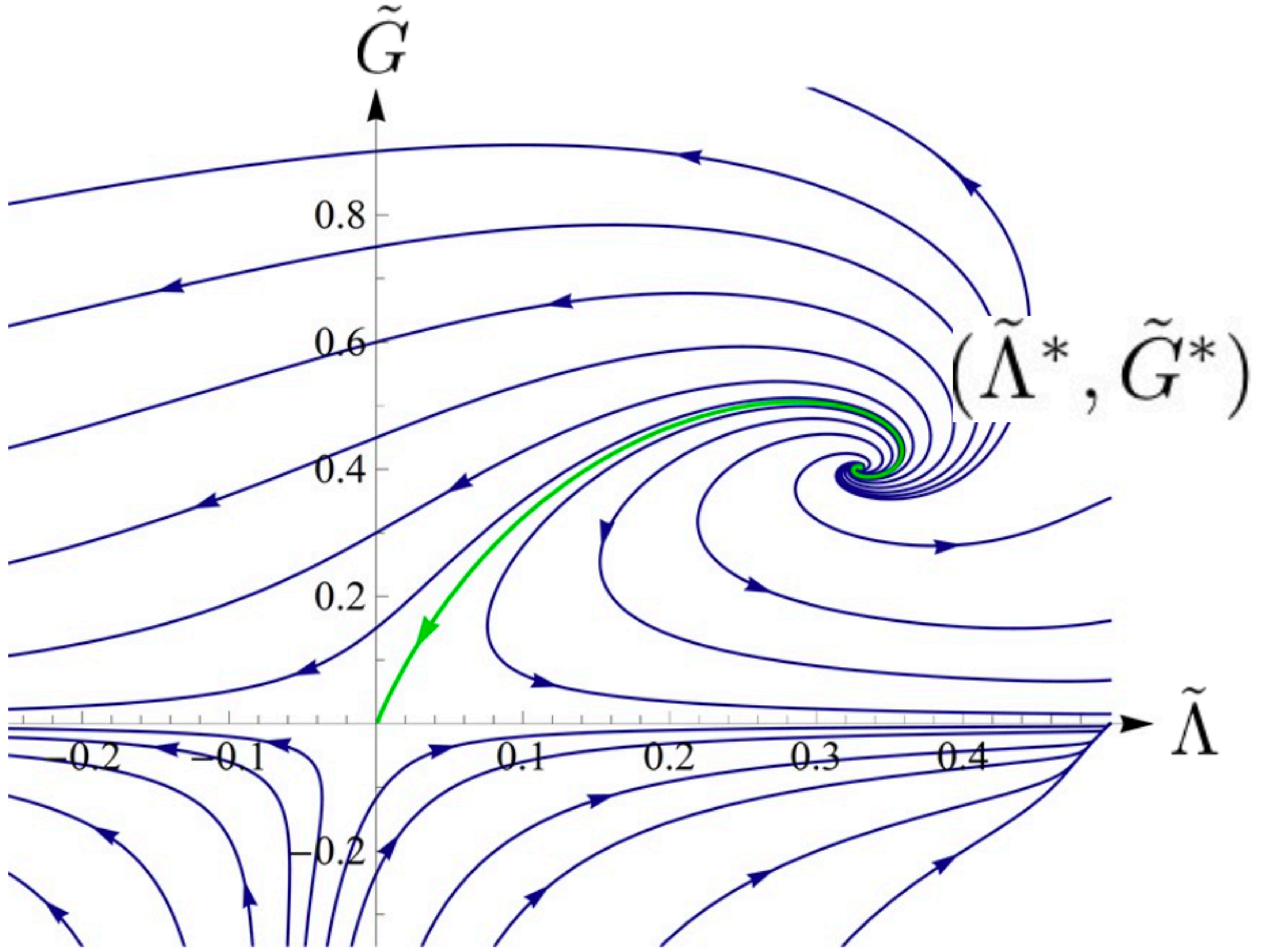
Reuter '96

$$\Gamma_k = \frac{1}{16\,\pi\,G}\int d^4x\,\sqrt{g}(\Lambda - R)$$

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

$$\frac{d\tilde{G}_N}{dt} = \beta_G\,(G,\Lambda) \qquad \frac{d\tilde{\Lambda}}{dt} = \beta_\Lambda\,(G,\Lambda)$$

Further evidence for ASG from various truncations



Reuter, Saueressig, hep-th/0110054

Gravity affects matter

- Modifications to RGEs above M_{Pl}

$$\beta_g = \beta_g^{SM+NP} - f_g(\tilde{G}^*, \tilde{\Lambda}^*)\, g$$

Example: $$f_g = G \frac{1-4\Lambda}{4\pi(1-2\Lambda)^2}$$

Eichhorn et. al. '16

- Universal

- $f_g > 0$ but large theoretical uncertainties

Potential consequences

- Avoid Landau pole

  e.g. Eichhorn, Versteegen '17

- Reduce Standard Model free parameters

  e.g. Eichhorn, Held '17, Shaposhnikov, Wetterich '09

- Predict New Physics couplings

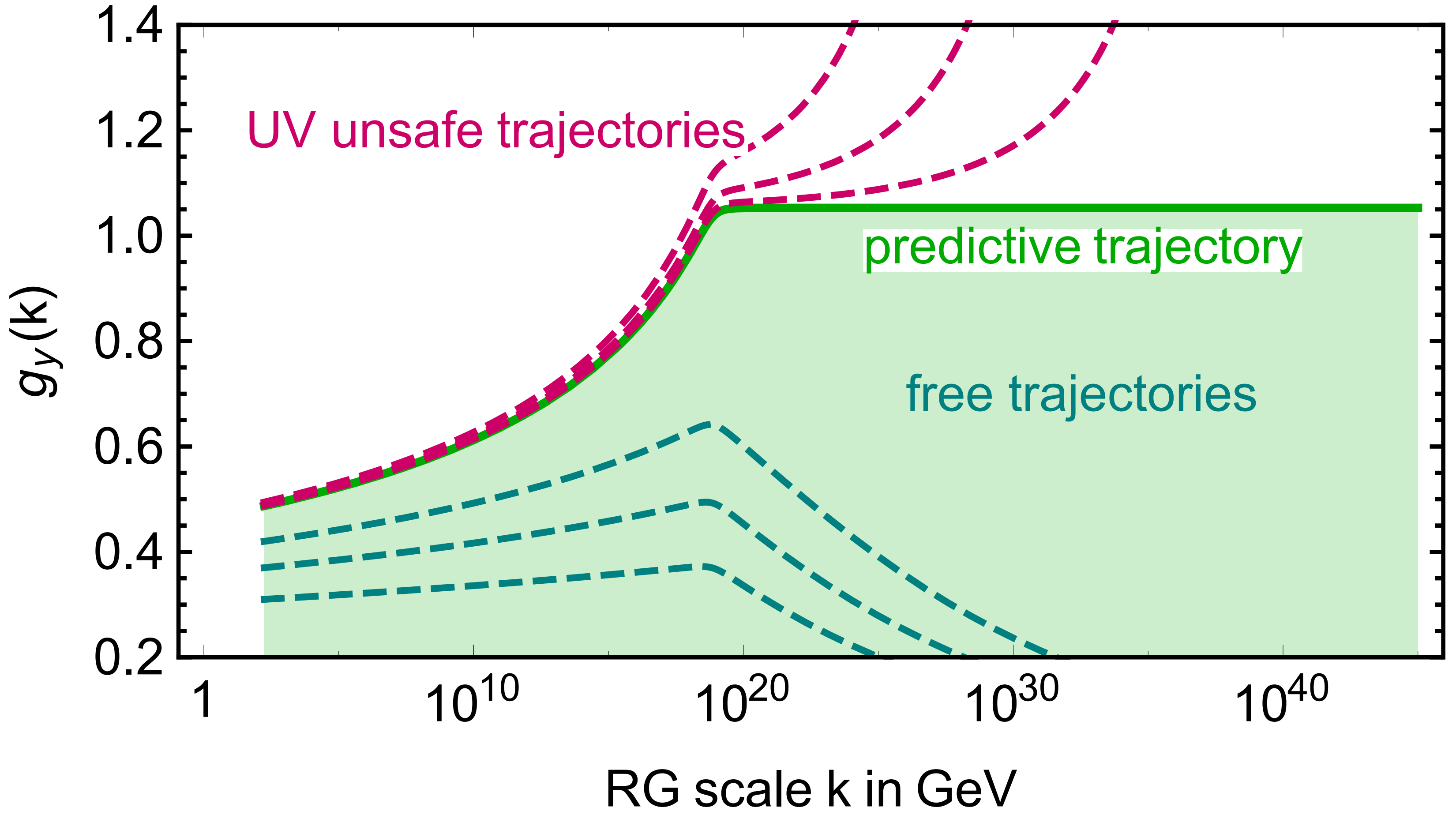
  e.g. AC, Kowalska, Sessolo '21-'22, Brito, Eichhorn et al '23

- Address problem of naturalness

  e.g. Wetterich, Yamada '16, AC, Kowalska, Sessolo '22

Example: $$\beta_{g_Y} = \frac{g_Y^3}{16\pi^2}\frac{41}{6} - f_g g_Y$$

Eichhorn, Versteegen '17



Limitation of other DM models in Asymptotically Safe Gravity

- Predicted top quark mass is too small

  de Brito, Eichhorn, Frandsen, Rosenlyst, Vieira ‘23

- Unstable potential

  Eichhorn, Pauly ‘21

- Strongly constrained parameter space

  Reichert, Smirnov ’19

Chiral symmetry breaking

$$SU(N_c)_L \times SU(N_c)_R \to SU(N_c)_V$$

- Strong interactions could induce chiral symmetry breaking and bound state formation

$$\int_x \sqrt{g}\bar{\psi}\gamma^\mu \nabla_\mu \psi + \sqrt{g}\left[\frac{\bar{\lambda}_+}{2}(\mathcal{V}+\mathcal{A}) + \frac{\bar{\lambda}_-}{2}(\mathcal{V}-\mathcal{A})\right]$$

  - Diverging 4-fermion couplings

$$\mathcal{V} \pm \mathcal{A} = \left(\bar{\psi}\gamma_\mu\psi\right)^2 \mp \left(\bar{\psi}\gamma_\mu\gamma_5\psi\right)^2$$

  - Dim-6 couplings → set to zero at the UV scale

- But may be generated during the RG flow through other strong interactions

  - **Strong Gravity** → $m \sim M_{Pl}$ Weak gravity bound

    Eichhorn, Gies '11, Gies, Martini '18

  - Large Abelian gauge coupling

    Britto, Eichhorn, Shourya '23

  - Non-abelian gauge coupling

Example: QCD strong interactions

Composite dark matter

- Dark SU(3) analogous to QCD
- Λ_{dQCD} is a free parameter
- Confined states

$$m_{Nd} \approx 3.8\Lambda_{dQCD}$$

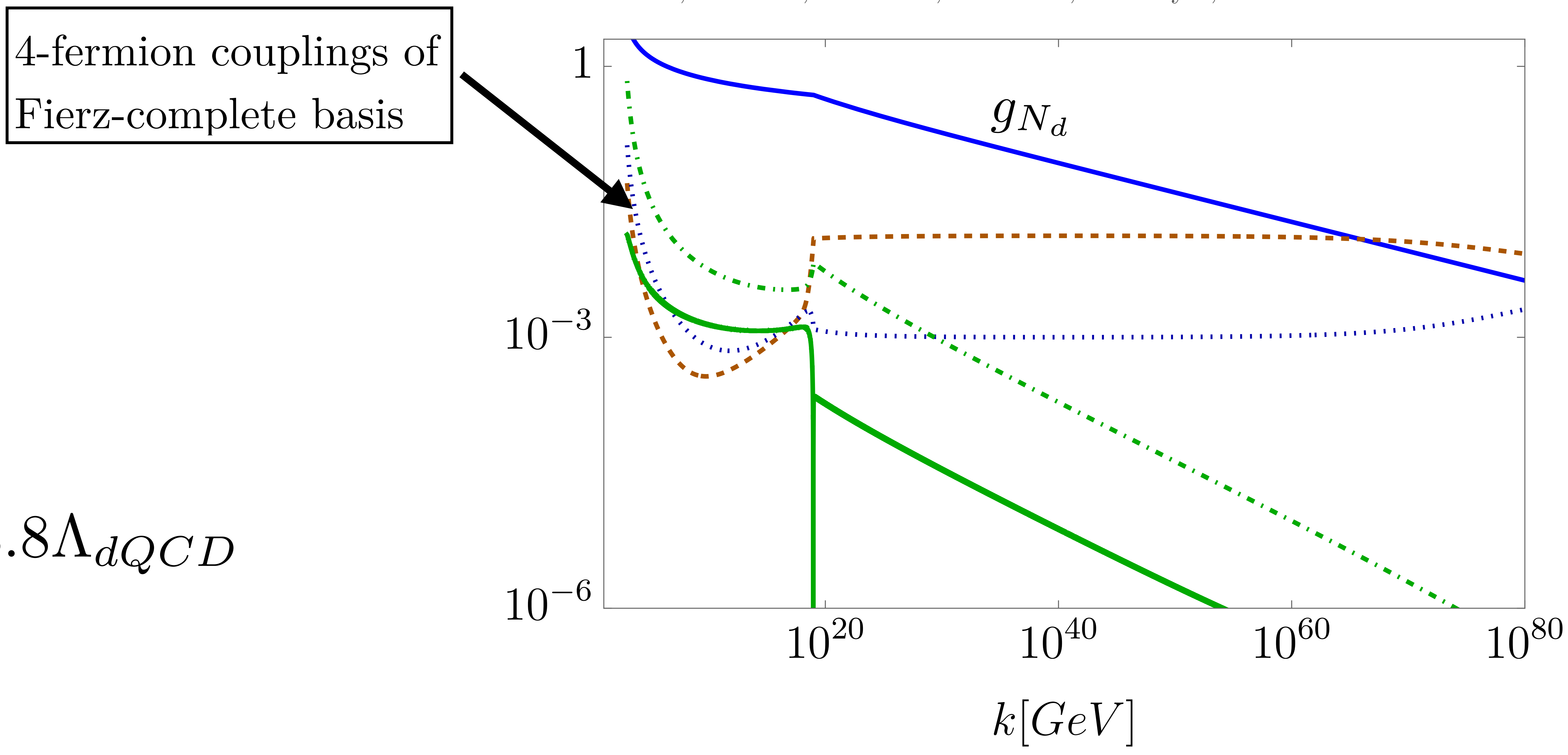
  - Lightest baryon is the dark matter
  - Pions (pseudo-NGBs) →

freeze-in portal

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}X^{\mu\nu} + i\bar{\psi}\left(\partial^\mu - ig_X Q_X \tilde{X}^\mu\right)\gamma_\mu\psi + m\bar{\psi}\psi$$

Soft breaking of χ-symmetry

AC, de Brito, Eichhorn, Frandsen, Rosenlyst, Vieira

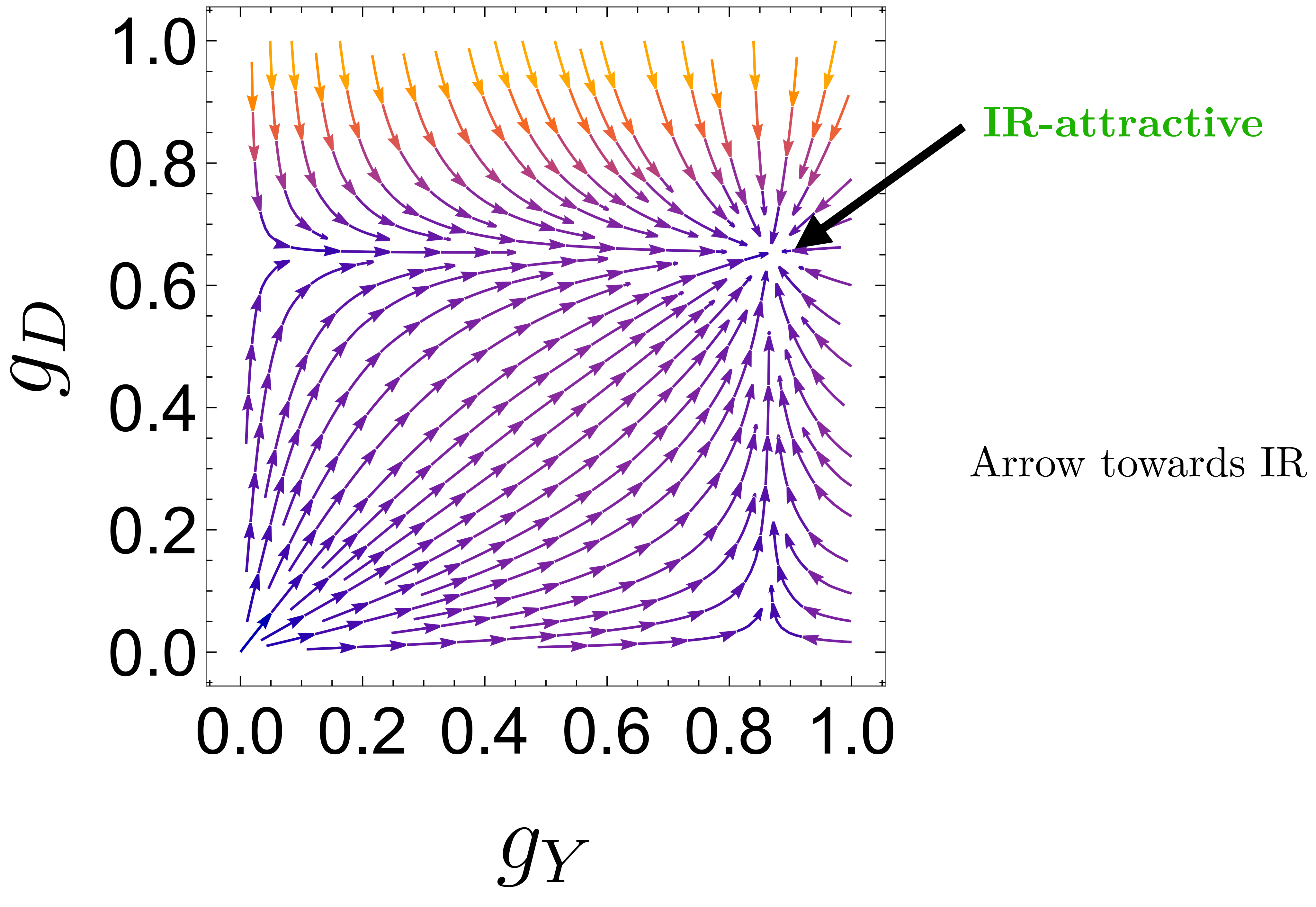


- Mediates self-interactions
- Massless pions $\implies$ Long range self-interactions
- Soft-breaking of chiral symmetry

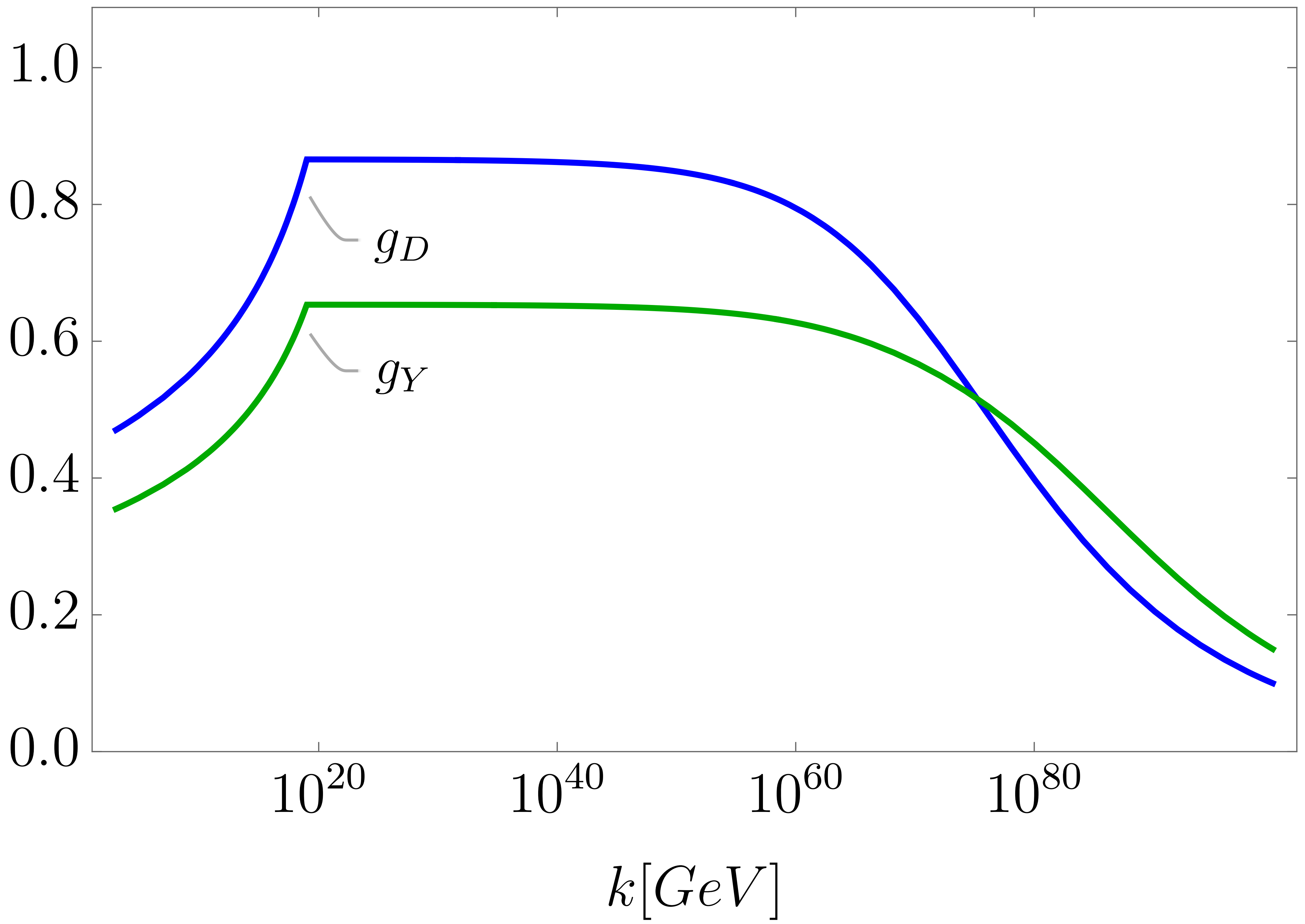
Abelian gauge sector

$$\beta_{g_Y} = \frac{g_Y^3}{16\pi^2}\frac{41}{6} - f_g g_Y$$
$$\beta_{g_D} = \frac{g_D}{16\pi^2}\left(\frac{41}{6}g_D g_\epsilon + 12 g_D^2\right) - f_g g_D$$
$$\beta_{g_\epsilon} = \frac{g_\epsilon}{16\pi^2}\left(\frac{41}{3}g_Y^2 + \frac{41}{6}g_\epsilon^2 + 12 g_D^2\right) - f_g g_\epsilon$$

AC, de Brito, Eichhorn, Frandsen, Rosenlyst, Vieira



AC, de Brito, Eichhorn, Frandsen, Rosenlyst, Vieira



Matching the experimental value of $g_Y(t_{EW})$ fixes the $g_Y(t_{M_{Pl}})$

$\Longrightarrow$ determines g_D

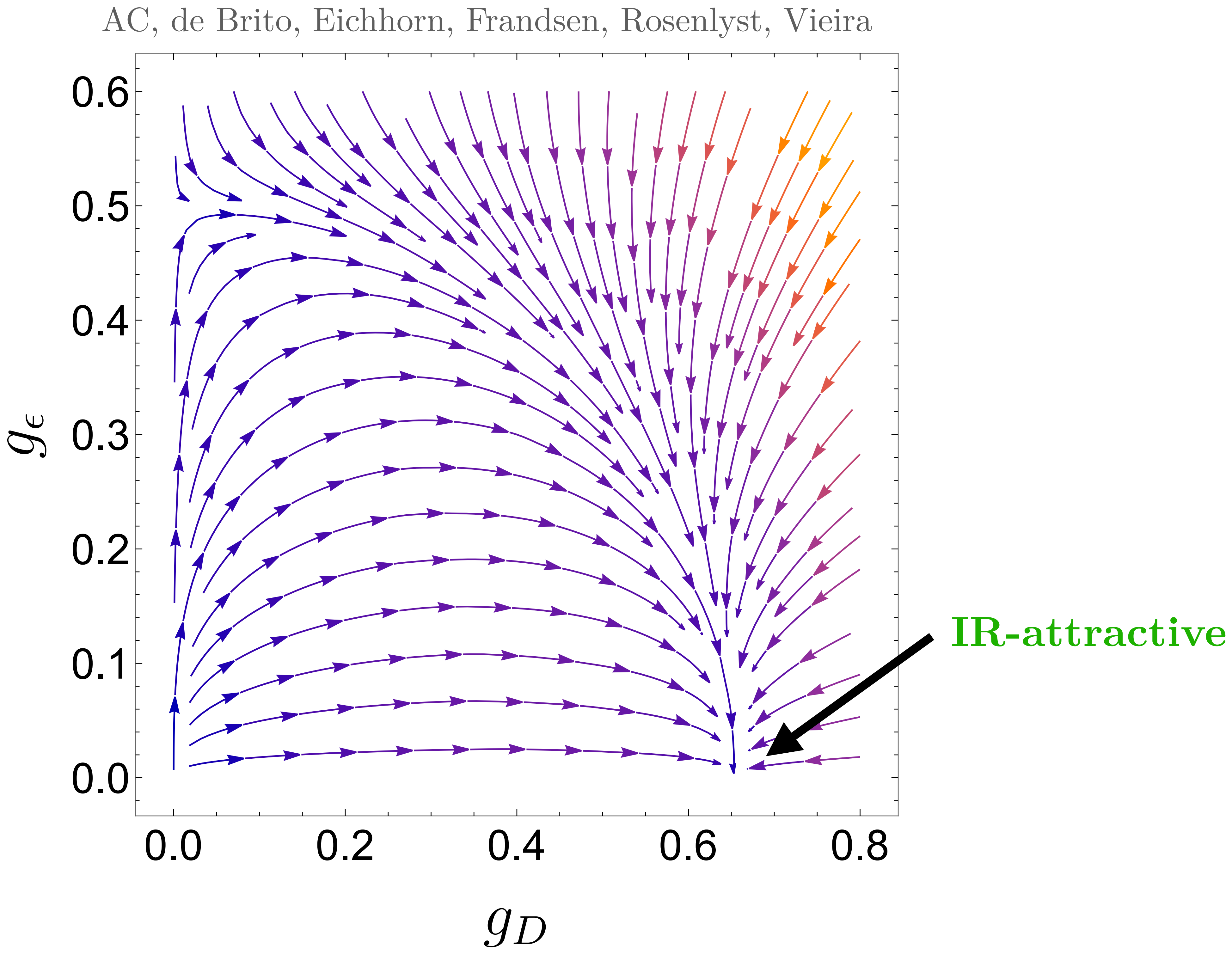
- Upper bound on the couplings
- Prediction of dark gauge coupling

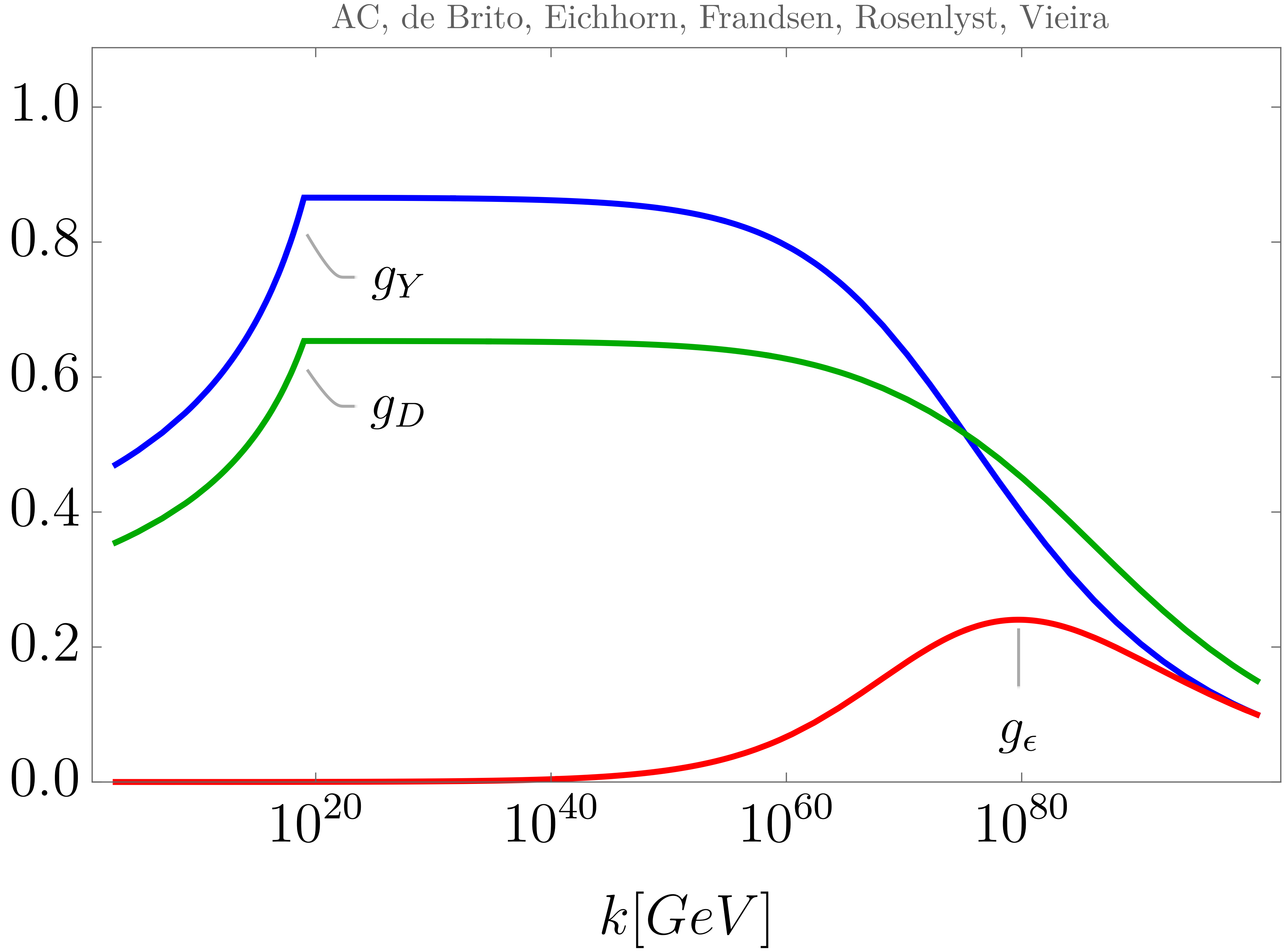
Abelian gauge sector

$$\beta_{g_Y} = \frac{g_Y^3}{16\pi^2}\frac{41}{6} - f_g g_Y$$

$$\beta_{g_D} = \frac{g_D}{16\pi^2}\left(\frac{41}{6}g_D g_\epsilon + 12 g_D^2\right) - f_g g_D$$

$$\beta_{g_\epsilon} = \frac{g_\epsilon}{16\pi^2}\left(\frac{41}{3}g_Y^2 + \frac{41}{6}g_\epsilon^2 + 12 g_D^2\right) - f_g g_\epsilon$$





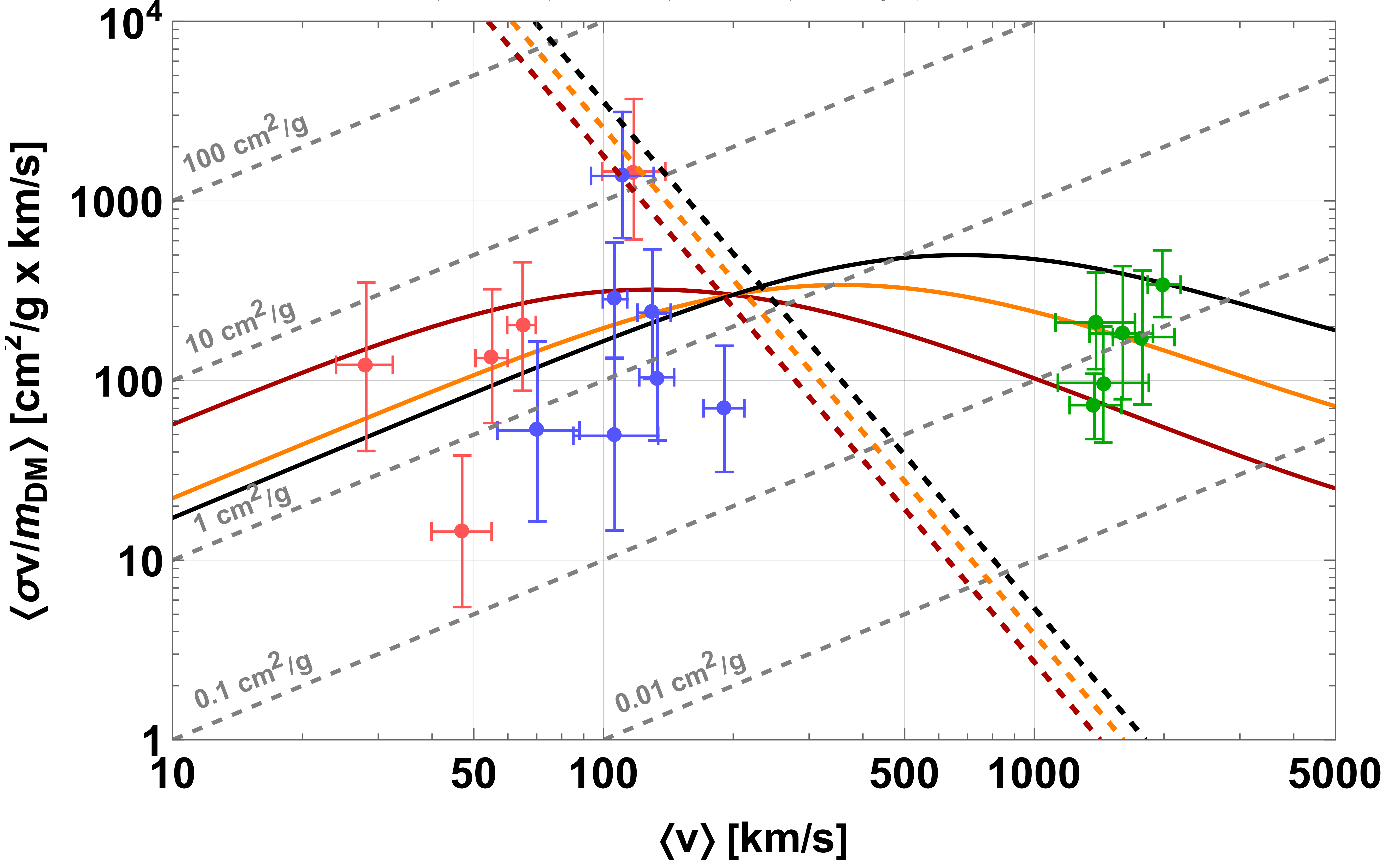
g_ϵ has IR-attractive fixed point at 0

$\Longrightarrow g_\epsilon$ driven to tiny value

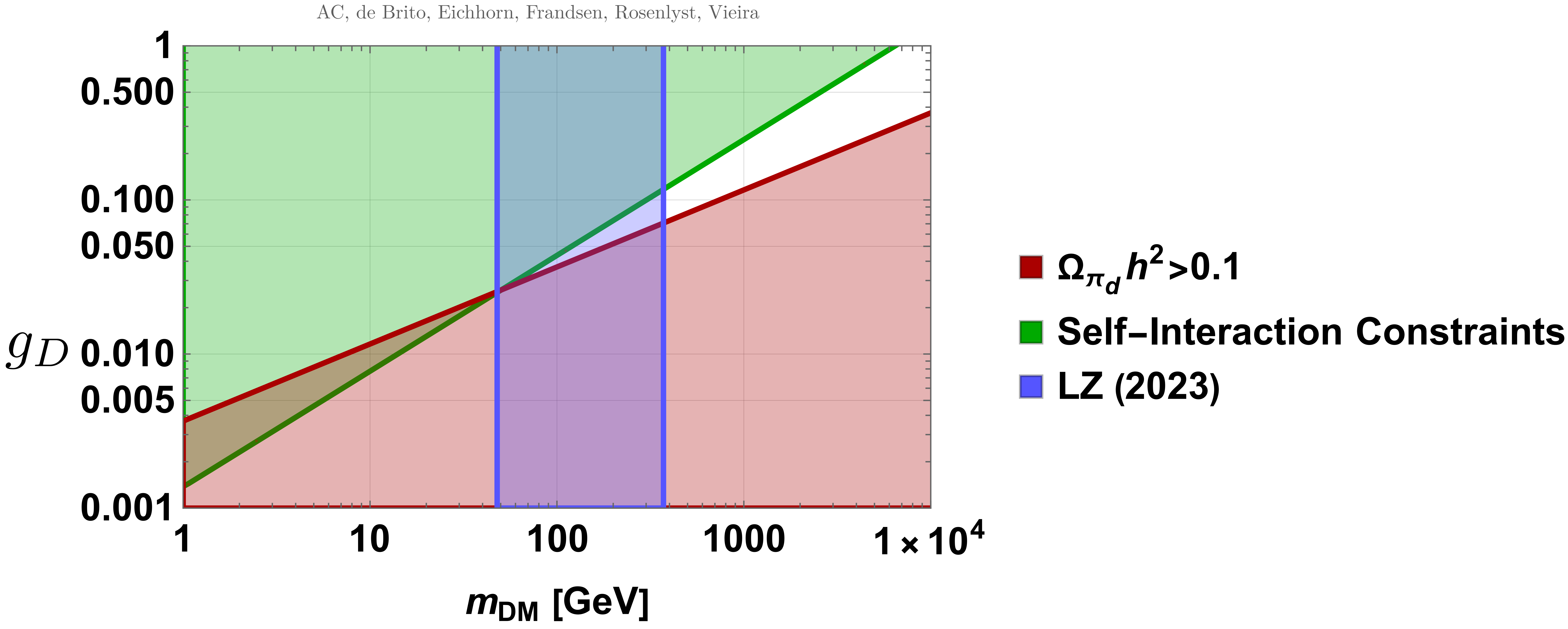
Phenomenology

- Strong self-interaction ameliorated the issues of TBTF and core-cusp
- However, merging galaxy clusters observations prefer weaker self-interactions
- Self-interactions: through pion exchange and dark photon exchange (Rutherford scattering)

AC, de Brito, Eichhorn, Frandsen, Rosenlyst, Vieira



Phenomenology



Conclusion

- ✦ Asymptotic Safety provides a predictive framework
  - ✦ Sets upper bound on dark gauge interaction (g_D)
- ✦ Composite dark matter is more viable within the theoretical landscape of Asymptotically Safe Gravity (ASG).
- ✦ ASG could induce IR-attractive Gaussian fixed point in g_ϵ

  $\Longrightarrow$Naturally suppressed kinetic-mixing

Thank you

Backup

Beta functions

$$
\begin{aligned}
\beta_{\lambda_+} = {}& 2\lambda_+ + \frac{9g_D^4}{32\pi^2} + \frac{9g_{N_d}^4(N_d^2+4)}{512\pi^2 N_d^2} - \frac{9g_D^2 g_{N_d}^2}{32\pi^2 N_d} + \frac{5}{8}G_{(3,0)}^2 - \frac{3g_D^2\lambda_+}{4\pi^2} + \frac{3g_{N_d}^2\lambda_+}{8\pi^2 N_d} \\
&+ \frac{\lambda_+\lambda_-}{4\pi^2} + \frac{N_d N_{q_d}\lambda_+\lambda_-}{4\pi^2} + \frac{3\lambda_+^2}{8\pi^2} + \frac{5g_D^2}{16\pi}G_{(2,0)} - \frac{5g_{N_d}^2}{32\pi N_d}G_{(2,0)} + \frac{5g_D^2}{16\pi}G_{(1,0)} \\
&- \frac{5g_{N_d}^2}{32\pi N_d}G_{(1,0)} - \frac{3g_D^2}{160\pi}G_{(0,2)} + \frac{3g_{N_d}^2}{320\pi N_d}G_{(0,2)} + \frac{3g_D^2}{160\pi}G_{(0,1)} - \frac{3g_{N_d}^2}{320\pi N_d}G_{(0,1)} \\
&- f_\lambda\lambda_+ + \frac{\lambda_+\lambda_{\rm VA}}{4\pi^2}(N_{\rm d} + N_{q_d}) - \frac{N_{q_d}\lambda_-\lambda_\sigma}{8\pi^2} - \frac{\lambda_{\rm VA}\lambda_\sigma}{8\pi^2} - \frac{\lambda_\sigma^2}{32\pi^2}\,,
\end{aligned}
$$

$$
\begin{aligned}
\beta_{\lambda_-} = {}& 2\lambda_- - \frac{9g_D^4}{32\pi^2} - \frac{9g_{N_d}^4(3N_{\rm d}^2+4)}{512\pi^2 N_{\rm d}^2} + \frac{9g_D^2 g_{N_d}^2}{32\pi^2 N_{\rm d}} - \frac{5}{8}G_{(3,0)}^2 + \frac{3g_D^2\lambda_-}{4\pi^2} - \frac{3g_{N_d}^2\lambda_-}{8\pi^2 N_{\rm d}} \\
&- \frac{\lambda_-^2}{8\pi^2} + \frac{N_{\rm d} N_{q_d}\lambda_-^2}{8\pi^2} + \frac{5g_D^2}{16\pi}G_{(2,0)} - \frac{5g_{N_d}^2}{32\pi N_{\rm d}}G_{(2,0)} + \frac{5g_D^2}{16\pi}G_{(1,0)} - \frac{5g_{N_d}^2}{32\pi N_{\rm d}}G_{(1,0)} \\
&- \frac{3g_D^2}{160\pi}G_{(0,2)} + \frac{3g_{N_d}^2}{160\pi N_{\rm d}}G_{(0,2)} + \frac{3g_D^2}{160\pi}G_{(0,1)} - \frac{3g_{N_d}^2}{320\pi N_{\rm d}}G_{(0,1)} + \frac{N_{\rm d}N_{q_d}}{8\pi^2}\lambda_+^2 \\
&- f_\lambda\lambda_- + \frac{3g_{N_d}^2}{8\pi^2}\lambda_{\rm VA} + \frac{\lambda_-\lambda_{\rm VA}}{4\pi^2}(N_{\rm d} + N_{q_d}) - \frac{\lambda_{\rm VA}^2}{4\pi^2} - \frac{N_{q_d}\lambda_+\lambda_\sigma}{8\pi^2}\,.
\end{aligned}
$$

$$
\begin{aligned}
\beta_{g_1} &= -f_g g_1 + \frac{41}{96\pi^2}g_1^3\,, \\
\beta_{g_D} &= -f_g g_D + \frac{41}{96\pi^2}g_D^2 g_\epsilon + \frac{N_{q_d}N_d}{42\pi^2}g_D^3\,, \\
\beta_{g_\epsilon} &= -f_g g_\epsilon + \frac{41}{48\pi^2}g_1^2 g_\epsilon + \frac{41}{96\pi^2}g_\epsilon^2 + \frac{N_{q_d}N_d}{12\pi^2}g_D^2 g_\epsilon\,, \\
\beta_{g_{N_d}} &= -f_g g_{N_d} + \frac{g_{N_d}^3}{48\pi^2}(2N_{q_d} - 11N_d)
\end{aligned}
$$