Strongly Interacting Dark Matter from Sp(4) Gauge Theory

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mostly based on [2202.05191]

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ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN
UNI GRAZ
NAWI Graz Natural Sciences
FWF Der Wissenschaftsfonds.

Quark Confinement and the Hadron Spectrum
Stavanger, August 4th 2022

Dark Matter

- Nature of Dark Matter (DM) unclear
- Only gravitational effects observed
- Hypothesis: Particle Dark Matter
  - At least one additional DM particle to SM
  - Coupling to the SM extremely weak
  - Stable over tens of billions of years

From WIMPs to SIMPs

(Strongly Interacting Massive Particles)

- WIMPs: DM as thermal relic from early universe
- Decouple below certain temperature $\rightarrow$ freeze out
- Density distribution of DM constraints theories
- Constraint given by DM depletion process

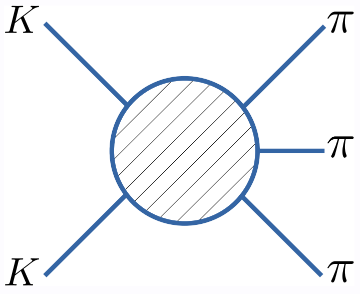
  WIMPs: $2\mathrm{DM} \rightarrow 2\mathrm{SM} \;\Rightarrow m_D \approx \mathrm{TeV}$

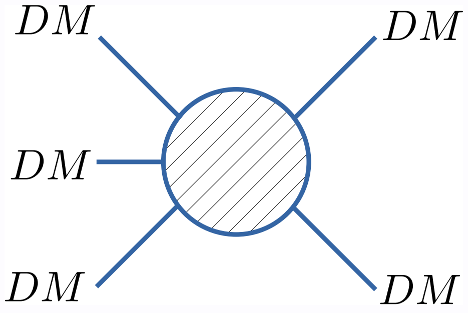
  SIMPs: $3\mathrm{DM} \rightarrow 2\mathrm{DM} \Rightarrow m_D \approx \mathcal{O}(100)\mathrm{MeV}$ **[1]**

[1] Hochberg et. al. [1402.5143] [1411.3727] [1512.07917]

$3 \to 2$ occurs in chiral effective theories!

- Spontaneous chiral symmetry breaking
  $\Rightarrow$ relatively light (pseudo-)Goldstone states
  ≥ 5 Goldstones: effective 5-point-interaction
- In QCD this describes the $2K \to 3\pi$ decay.

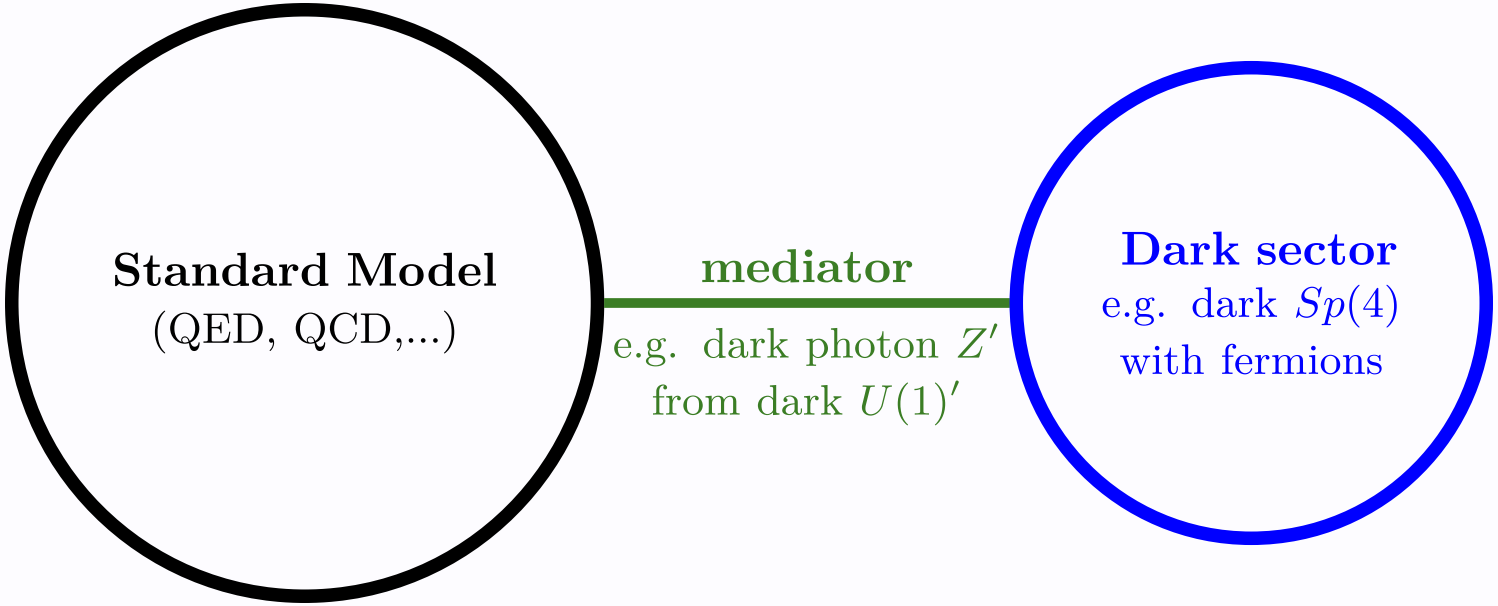




Idea **[1]**: Non-Abelian gauge theory with $3 \to 2$
Goldstones as Dark Matter candidates + mediator

[1] Hochberg et. al. [1411.3727]

Models of SIMP Dark Matter



- Strong, confining dark sector $\Rightarrow$ dark hadrons
- **Dark fermions do not carry any SM charge**
- Small coupling to the SM via Z'-γ-mixing
- DM has self-interactions

A minimal SIMP model

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Sp(4)} + \mathcal{L}_{\text{mediator}}$$

- $Sp(4)$ with $N_f = 2$ has exactly 5 Goldstones
- Dark hadrons DM candidates $\rightarrow$ non-perturbative
- Low energy effective theory (EFT) needed

- **Combine the methods with lattice field theory**
  - Derive low energy EFT for dark sector + mediator
  - Low energy constants (LECs) from lattice
  - Use EFT for astro/collider/direct detection pheno

Lagrangian of $Sp(4)_c$ with fermions

$$\mathcal{L}_{Sp(4)} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \sum_{f=u,d} \bar{\psi}_f (i \not{D} + m_f) \psi_f$$

- Higher symmetry than QCD-like theories

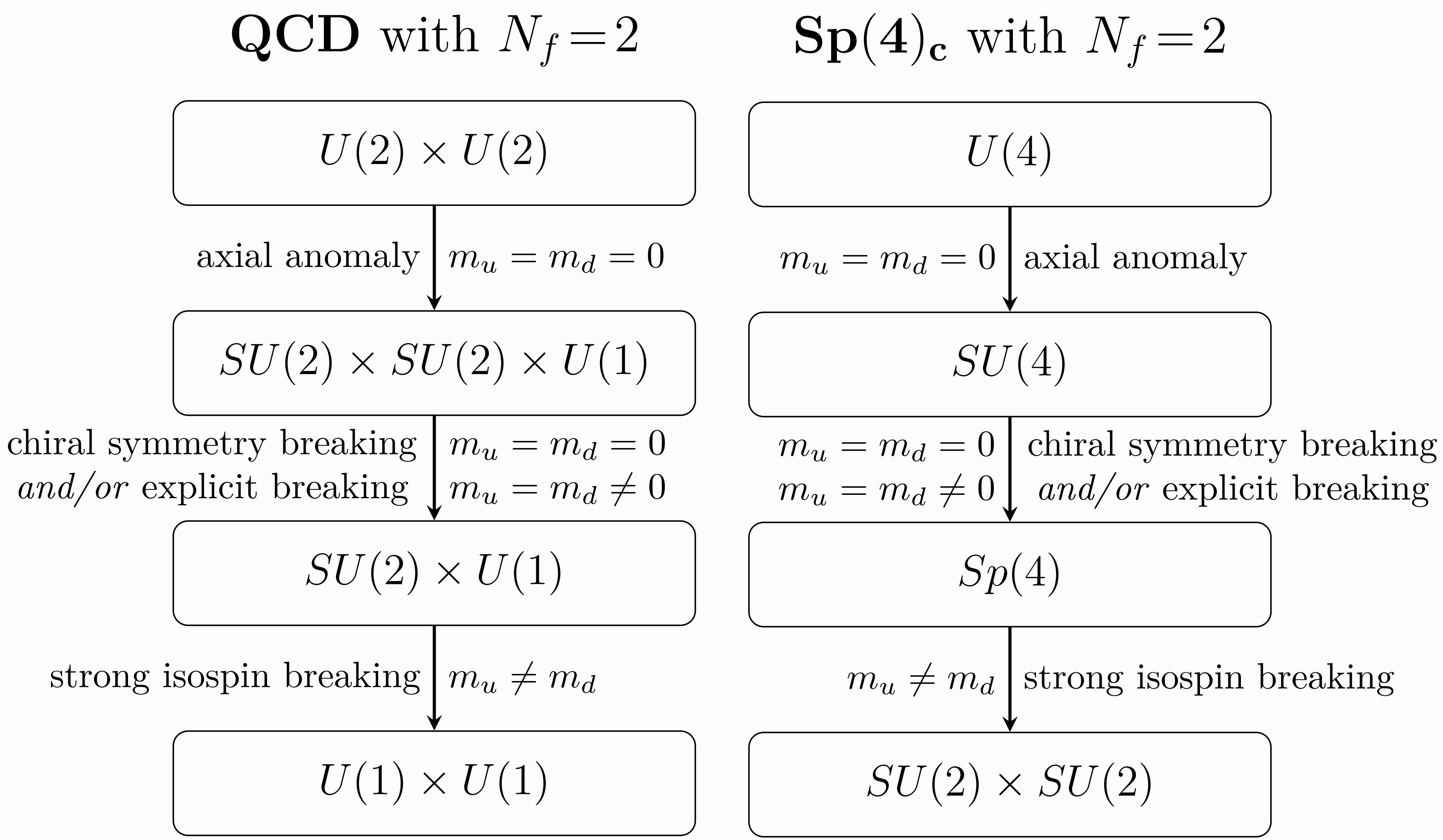
$$\Psi = \begin{pmatrix} u_L \\ d_L \\ -SCu_R^* \\ -SCd_R^* \end{pmatrix} = \begin{pmatrix} u_L \\ d_L \\ \tilde{u}_R \\ \tilde{d}_R \end{pmatrix}$$

$C \ldots$ charge conj.
$S \ldots$ colour matrix

$$\mathcal{L}_{Sp(4)} = i \bar{\Psi} \not{D} \Psi - \frac{1}{2} \left(\Psi^T SCM \Psi + h.c. \right) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

- generators τ_a in fundamental repr. : $S \tau_a S = -\tau_a^T$

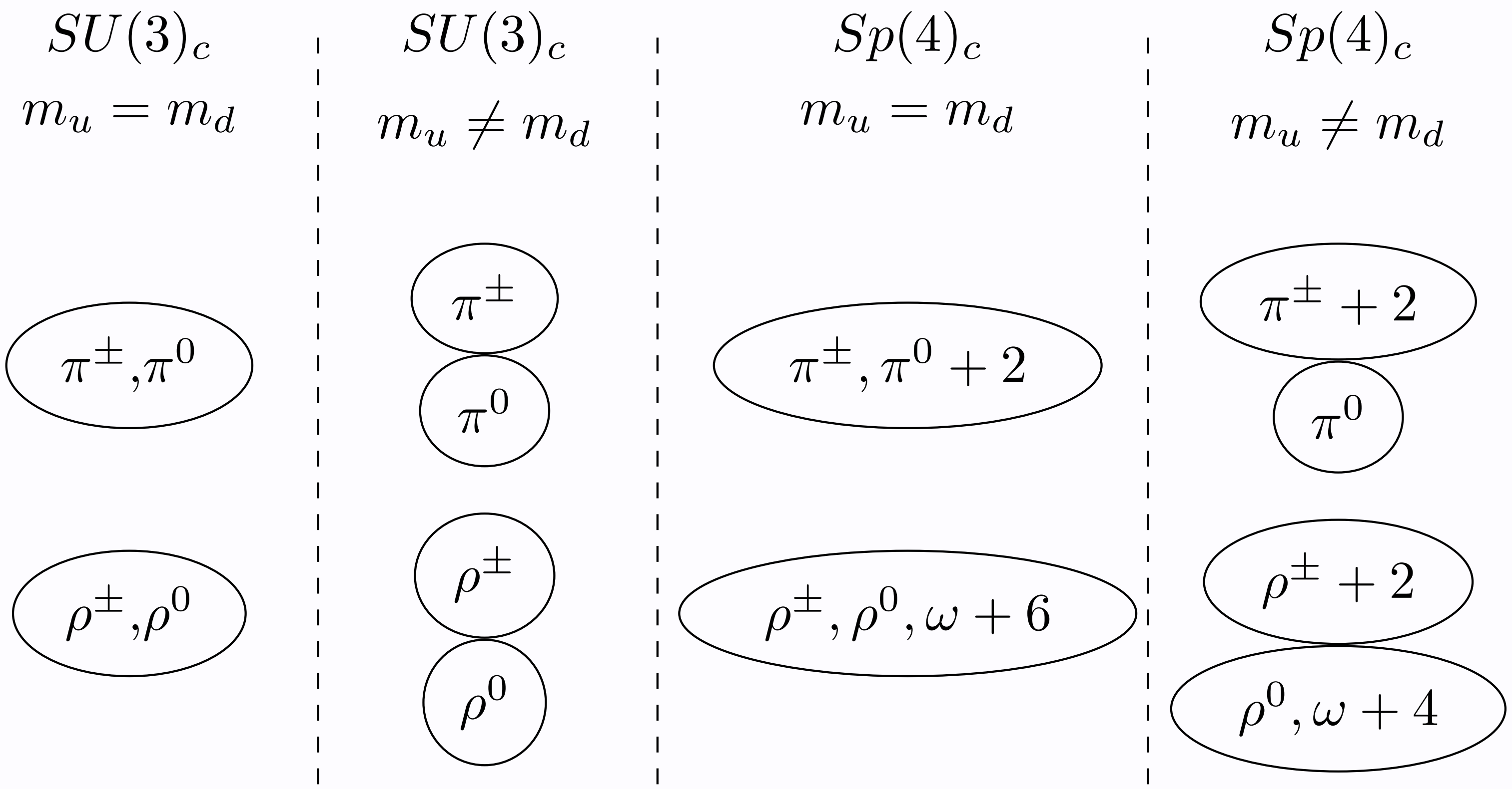
Constructing EFTs: Symmetries



see e.g. Kogut et. al. [hep-ph/0001171], von Smekal [1205.4205]

Symmetries of dark hadrons (without mediator)

- Global symmetries are enlarged compared to QCD
- New quark-quark and antiquark-antiquark states



Dark photon Z' mediator

- will break global symmetry even further
- Symmetry breaking for degenerate masses:
  a) $\mathrm{Sp}(4) \to \mathrm{SU}(2) \times \mathrm{U}(1)$
  b) $\mathrm{Sp}(4) \to \mathrm{U}(1) \times \mathrm{U}(1)$

- 5 Goldstones split into $3+2$ (a) or $1+2+2$ (b) **[1]**
- A singlet vector meson always exists **[2]**

[1] Kulkarni et. al. [2202.05191] [2] Hochberg et. al. [1512.07917]

Particle stability

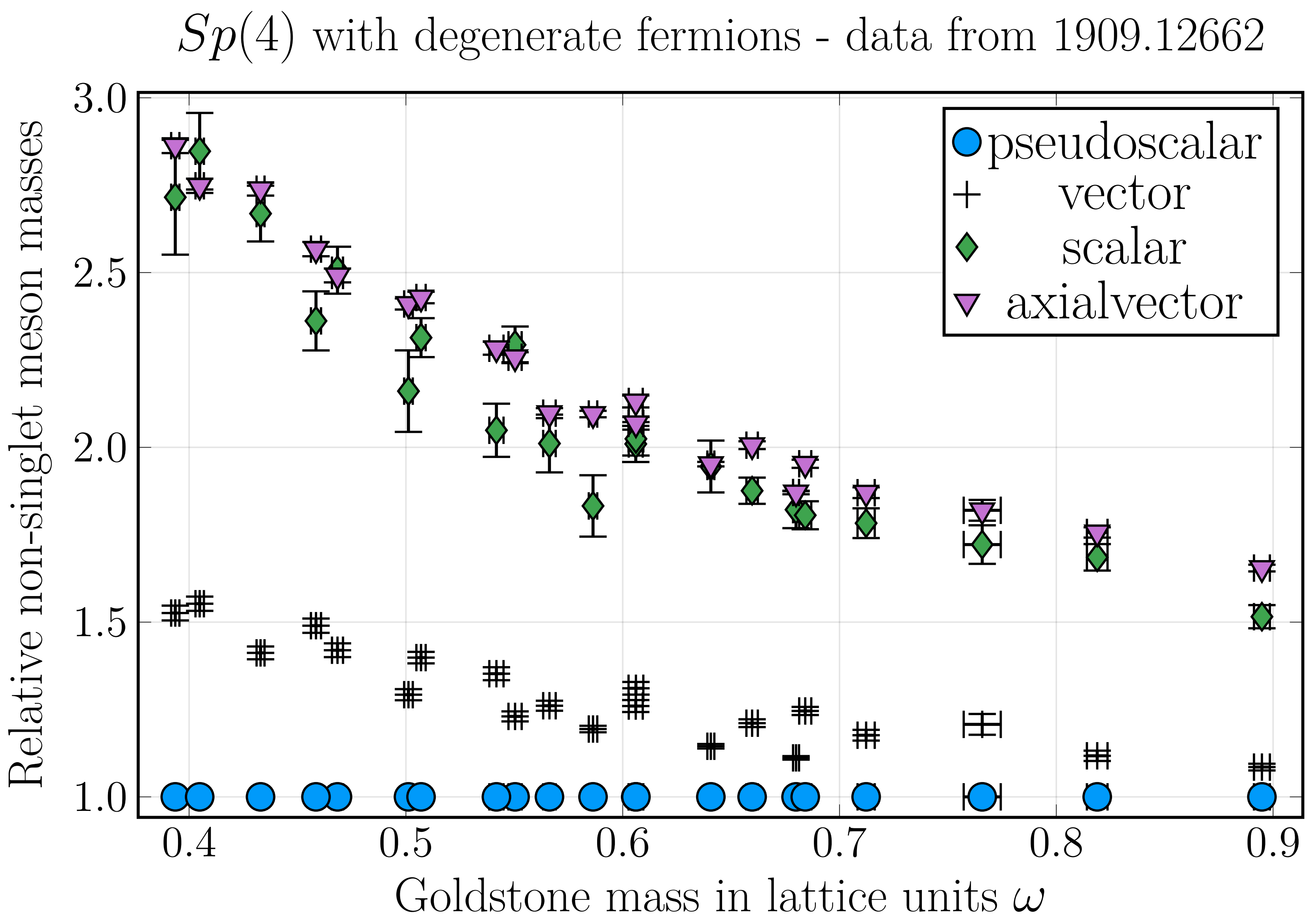
- Only multiplets are protected by symmetry
- Singlets can decay
  - $m_u = m_d$: Charge assignments without π singlets
  - $m_u \neq m_d$: Even without a Z' the π^0 is a singlet
- **For a viable DM candidate the decay of flavour singlet Goldstones needs to be suppressed**

Lattice investigations

- `HiRep` code **[1]**(Wilson action) used for study of
  - non-singlet hadronic ground state masses
  - decay constants of Goldstones π and vectors ρ
- results on Glueball spectrum available **[2]**
  $\Rightarrow$ heavier than mesonic states
- same setup useful for other symplectic groups
  lattice results for $SU(2)$ available **[3]**
- No fermionic bound states!

[1] Del Debbio et. al. [0805.2058] [2] Bennett et. al. [1712.04220] [3] Arthur et. al. [1602.06559] [1607.06654]

Hadron Spectrum from the Lattice, $m_u = m_d$

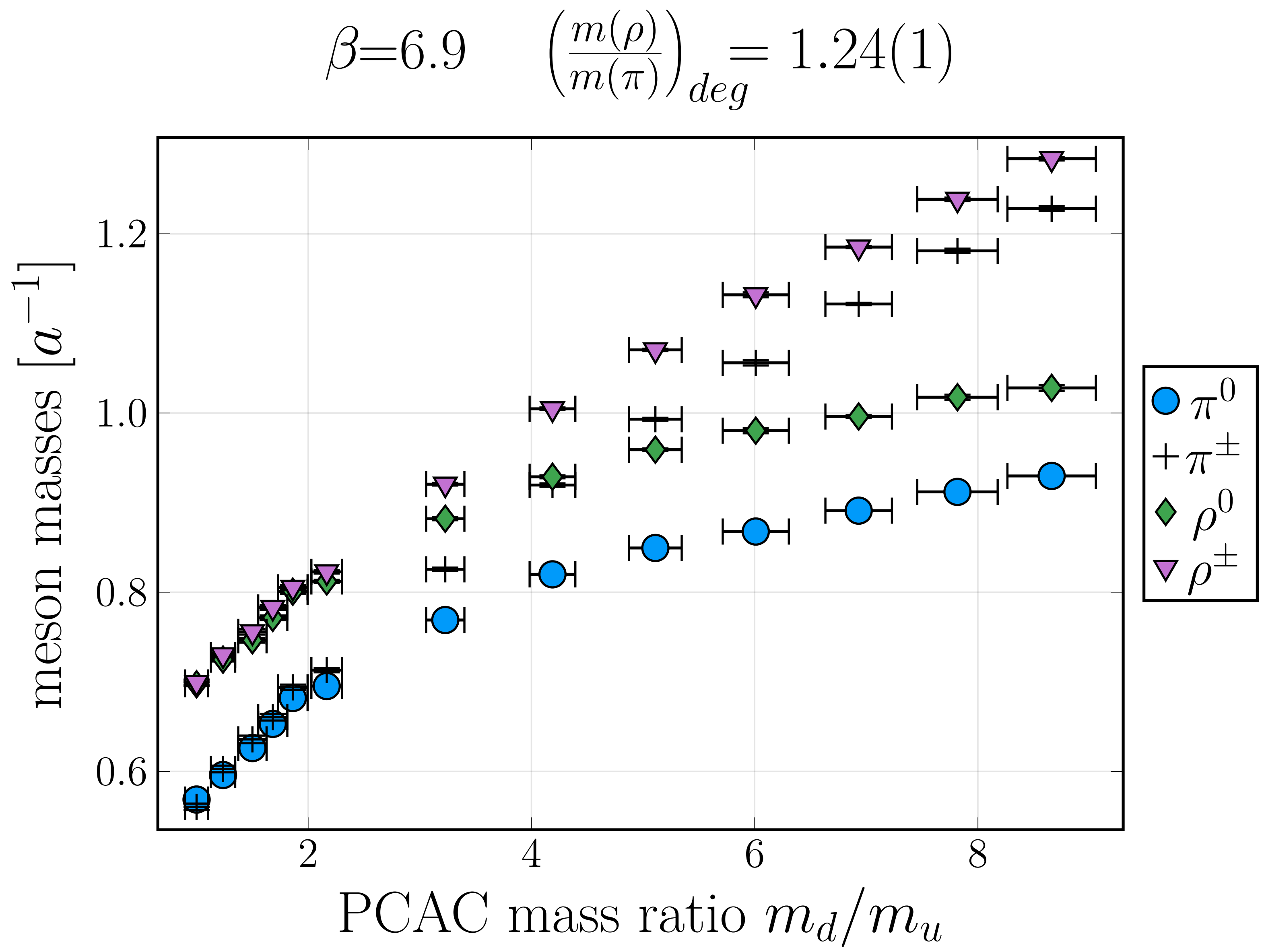


Hadron Spectrum from the Lattice, $m_u = m_d$

- (Non-singlet) scalar and axialvectors are heavy
- Glueballs are even heavier **[1]**
- **Goldstones** + **vectors** lightest nonsinglet states **[2]** (for degenerate fermions)

[1] Bennett et. al. [1712.04220] [2] Bennett et. al. [1909.12662]

Hadron Spectrum from the Lattice, $m_u \neq m_d$



Non-degenerate fermions: $Sp(4)_c$ with $N_f = 2$

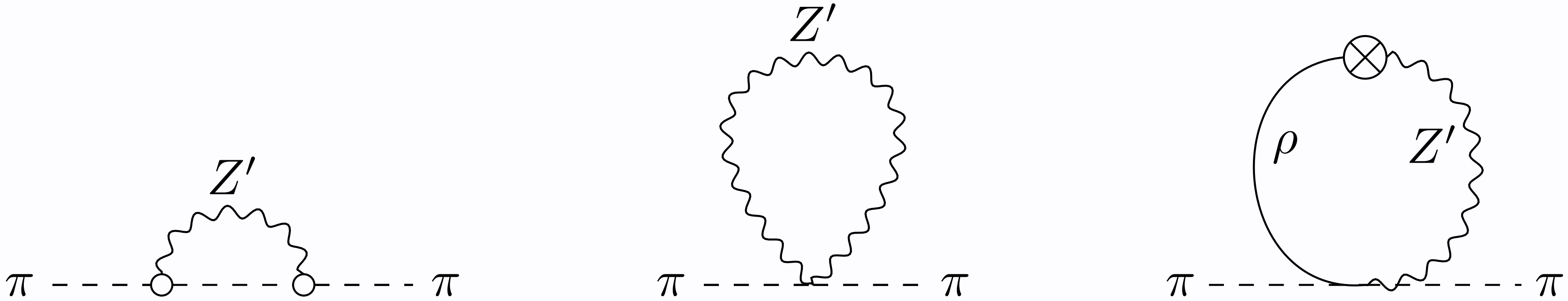
- Singlet Goldstone π^0 is the lightest state
- Unflavoured vectors lighter than flavoured ones

$$m(\rho^0) < m(\rho^\pm)$$

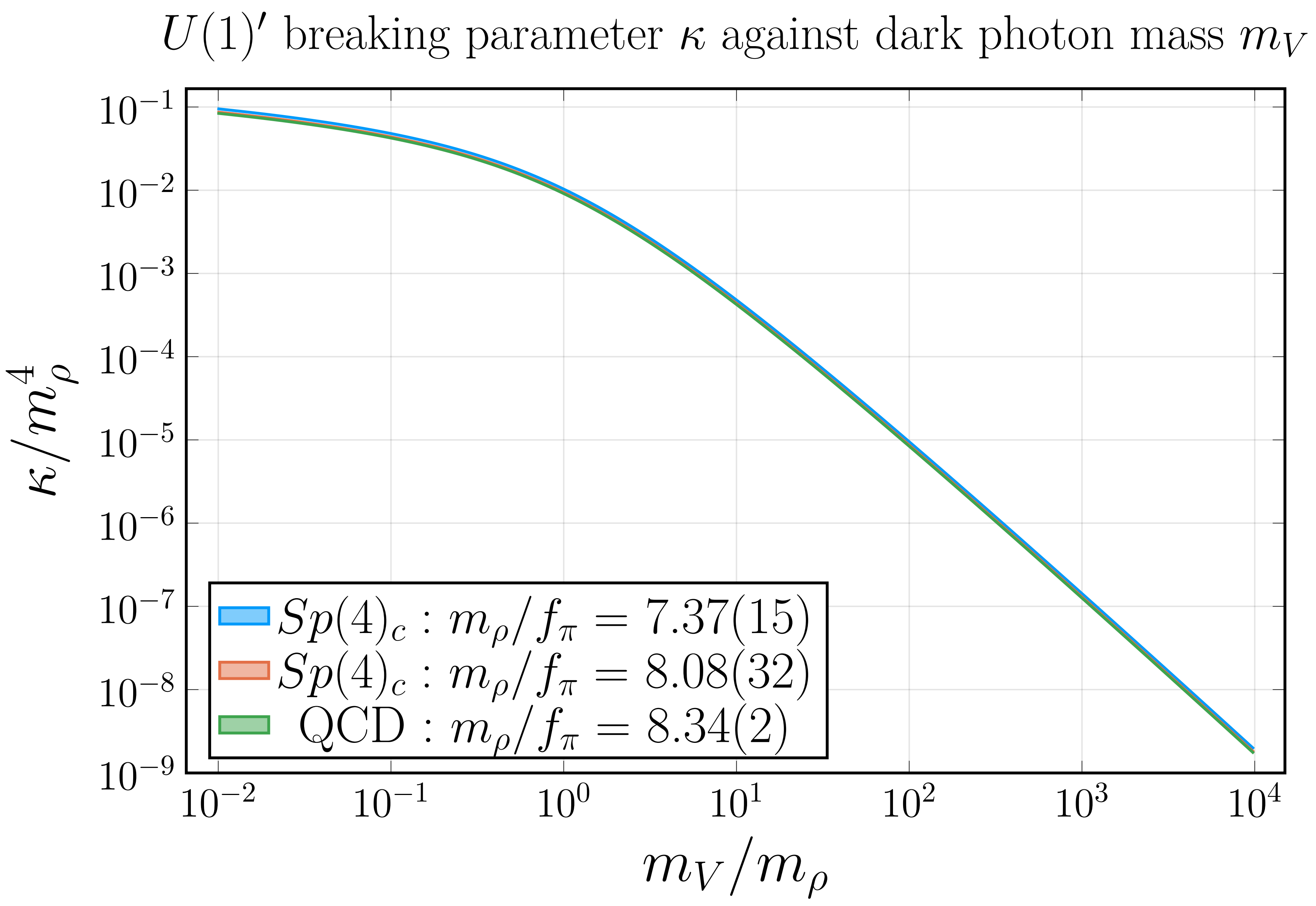
- Change in mass hierarchy at large splitting
- System resembles heavy-light quarks
- EFT for almost degenerate π's constructed **[1]**
  - m_π and f_π are the low energy constants

Further Low Energy Constants from the lattice: Z'

- Inclusion of Z' leads to different Goldstone masses
- Mass difference parametrized by one quantity κ



$$\Delta m_\pi = \frac{2\kappa e_D^2}{f_\pi^2} \qquad \kappa \approx \frac{3}{4\pi^2} \frac{f_\pi^2 m_\rho^4}{m_{Z'}^2 - m_\rho^2} \log\left(\frac{m_{Z'}^2}{m_\rho^2}\right)$$



- Similar to QCD (and possibly other gauge theories)

Conclusion

- SIMP Dark Matter is an interesting candidate model
- EFTs and meson multiplets constructed for
  - $N_f = 2$ with $m_u = m_d$ and $m_u \neq m_d$
  - Dark photon Z' mediator
- Hadron mass hierarchies and LECs from the lattice

Next steps

- singlet mesons, $2\pi \to 2\pi$ scattering, collider searches/constraints

Thank you!