Strongly Interacting Dark Matter from Sp(4) Gauge Theory

S. Kulkarni, A. Maas, S. Mee
M. Nikolic, J. Pradler, **F. Zierler**

mostly based on [2202.05191]

universität wien
HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK
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

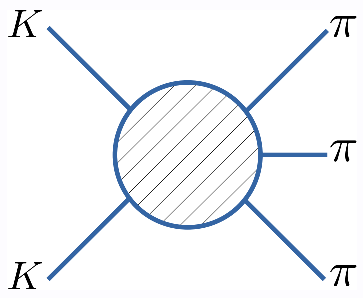
  WIMPs: $2\mathrm{DM} \rightarrow 2\mathrm{SM} \;\Rightarrow m_D \approx \mathrm{TeV}$

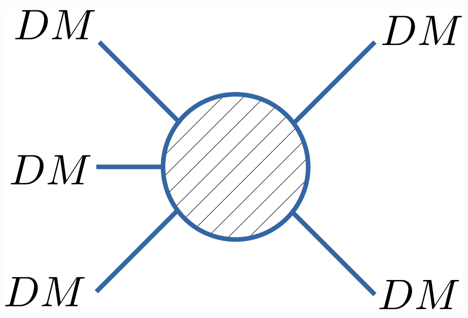
  SIMPs: $3\mathrm{DM} \rightarrow 2\mathrm{DM} \Rightarrow m_D \approx \mathcal{O}(100)\mathrm{MeV}$ **[1]**

[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.

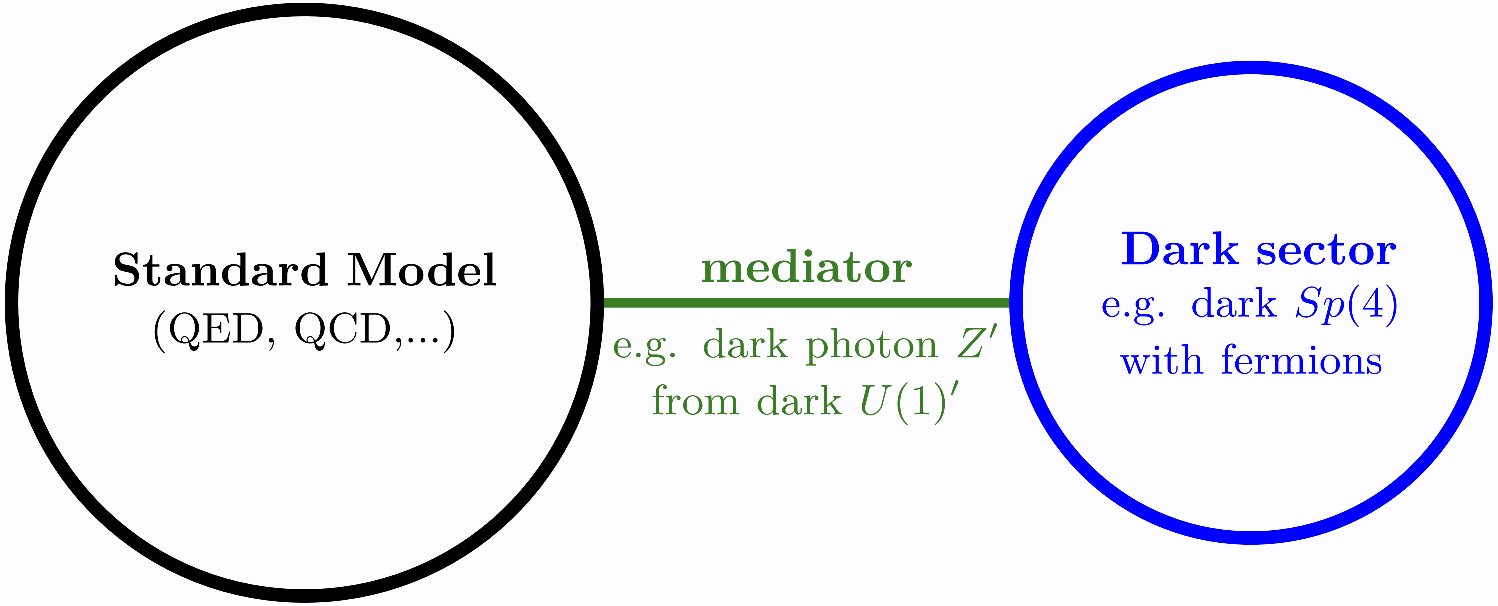




Idea **[1]**: Non-Abelian gauge theory with $3 \to 2$
Goldstones as Dark Matter candidates + mediator

[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 $\to$ 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

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

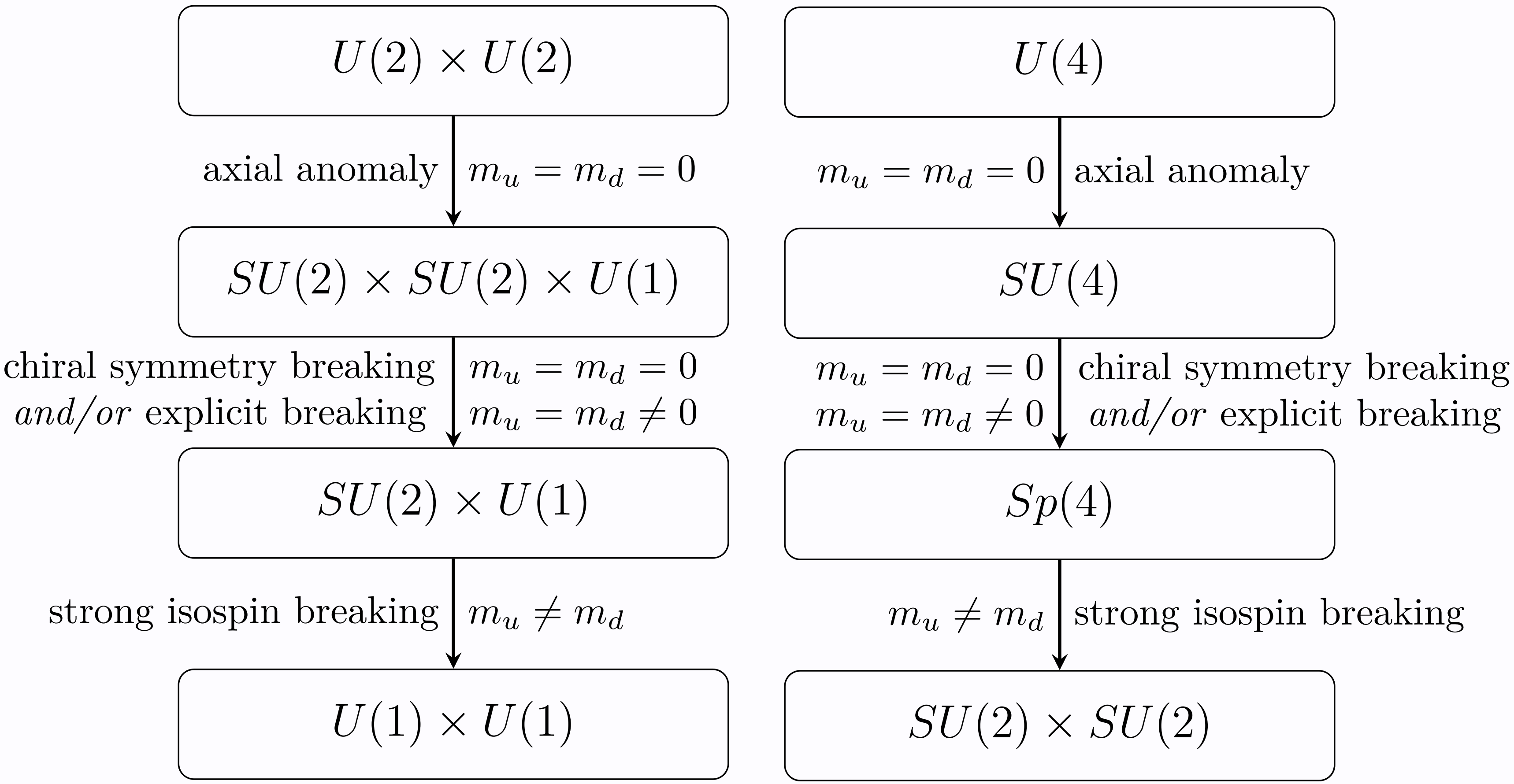
$C \ldots$ charge conj.
$S \ldots$ colour matrix

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

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

Constructing EFTs: Symmetries

$\mathbf{QCD}$ with $N_f = 2$ | $\mathbf{Sp(4)_c}$ with $N_f = 2$



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

$SU(3)_c$, $m_u = m_d$	$SU(3)_c$, $m_u \neq m_d$	$Sp(4)_c$, $m_u = m_d$	$Sp(4)_c$, $m_u \neq m_d$
$\pi^{\pm}, \pi^0$	$\pi^{\pm}$; π^0	$\pi^{\pm}, \pi^0 + 2$	$\pi^{\pm} + 2$; π^0
$\rho^{\pm}, \rho^0$	$\rho^{\pm}$; ρ^0	$\rho^{\pm}, \rho^0, \omega + 6$	$\rho^{\pm} + 2$; $\rho^0, \omega + 4$

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

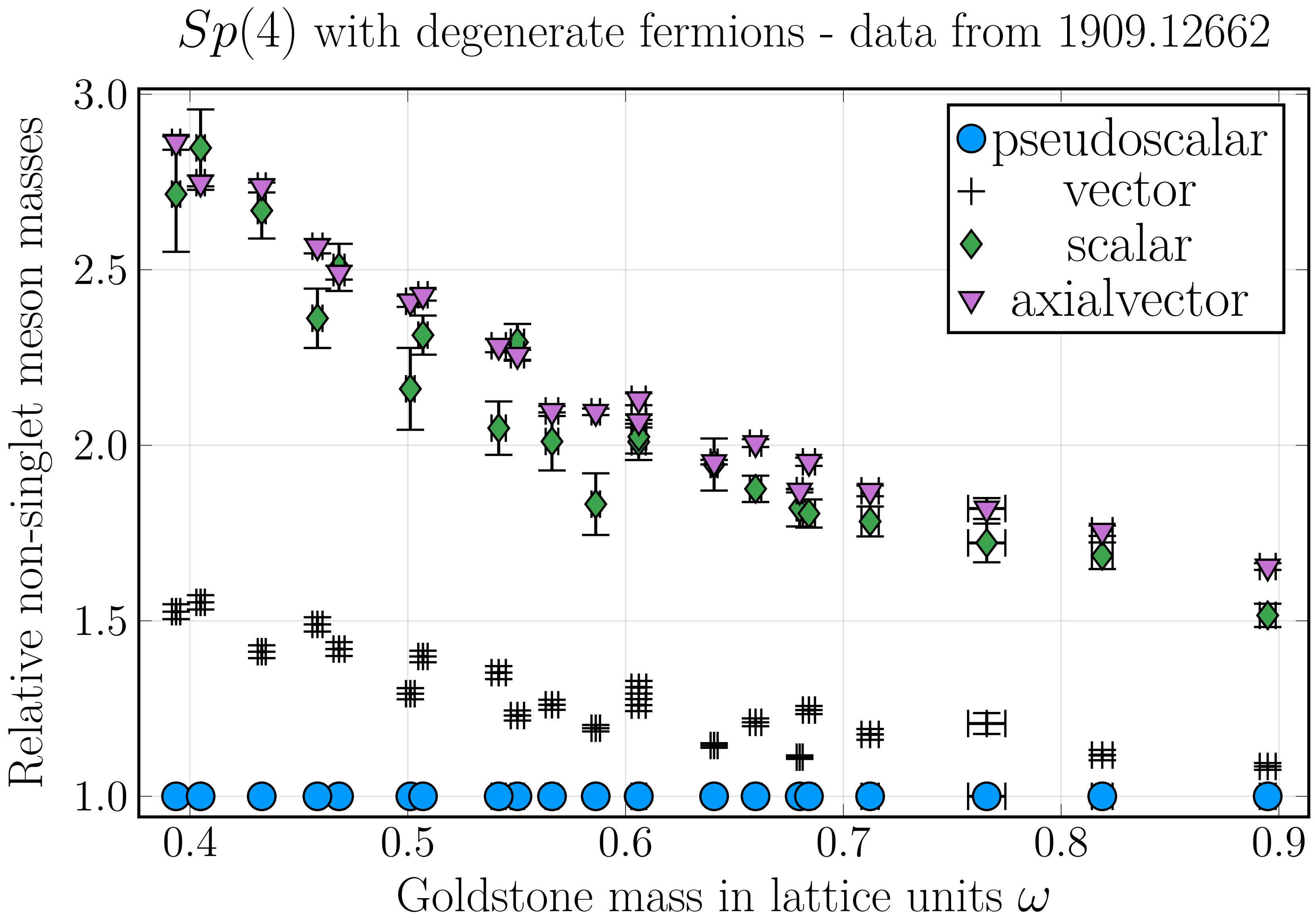
- Only multiplets are protected by symmetry
- Singlets can decay
  - $m_u = m_d$: Charge assignments without π singlets
  - $m_u \neq m_d$: Even without a Z' the π^0 is a singlet
- **For a viable DM candidate the decay of flavour singlet Goldstones needs to be suppressed**

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, $m_u = m_d$

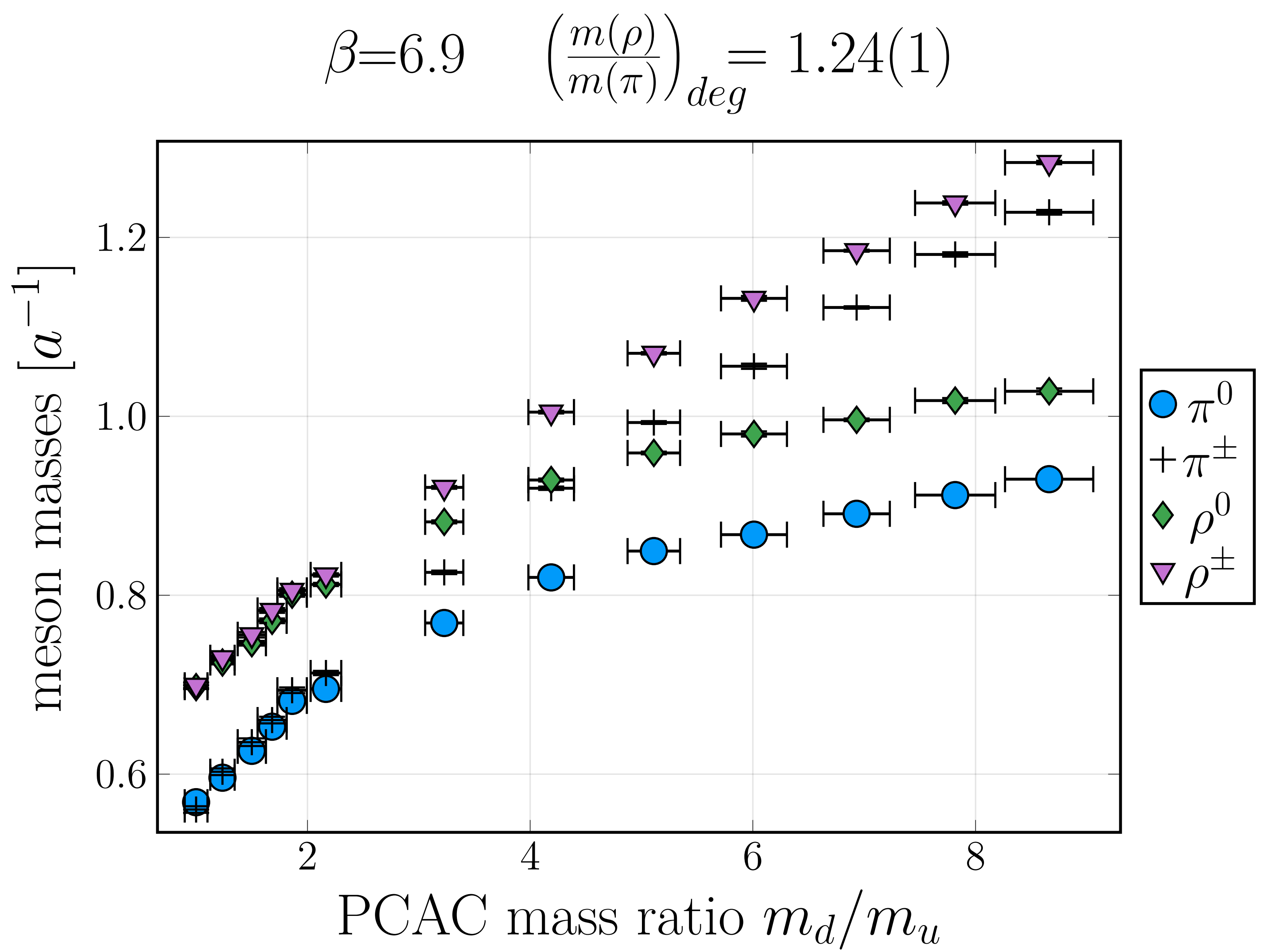


Hadron Spectrum from the Lattice, $m_u = m_d$

- (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 $N_f = 2$

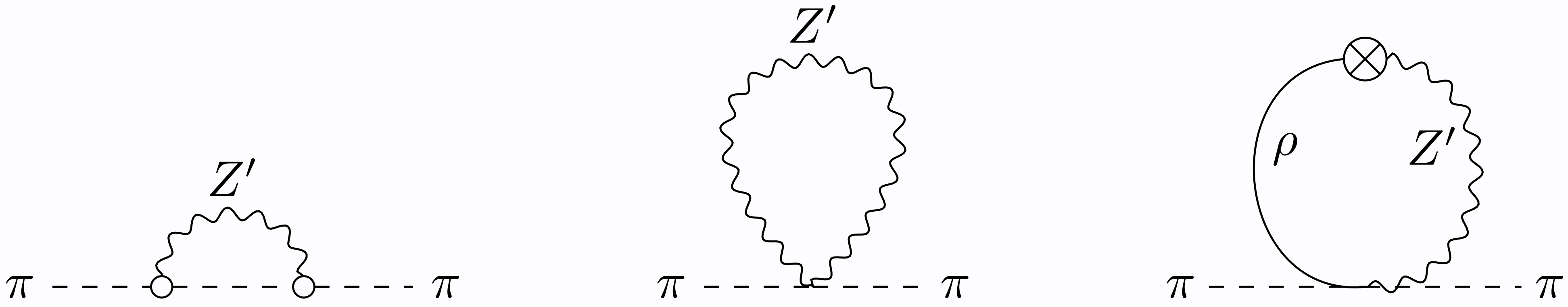
- Singlet Goldstone π^0 is the lightest state
- Unflavoured vectors lighter than flavoured ones

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

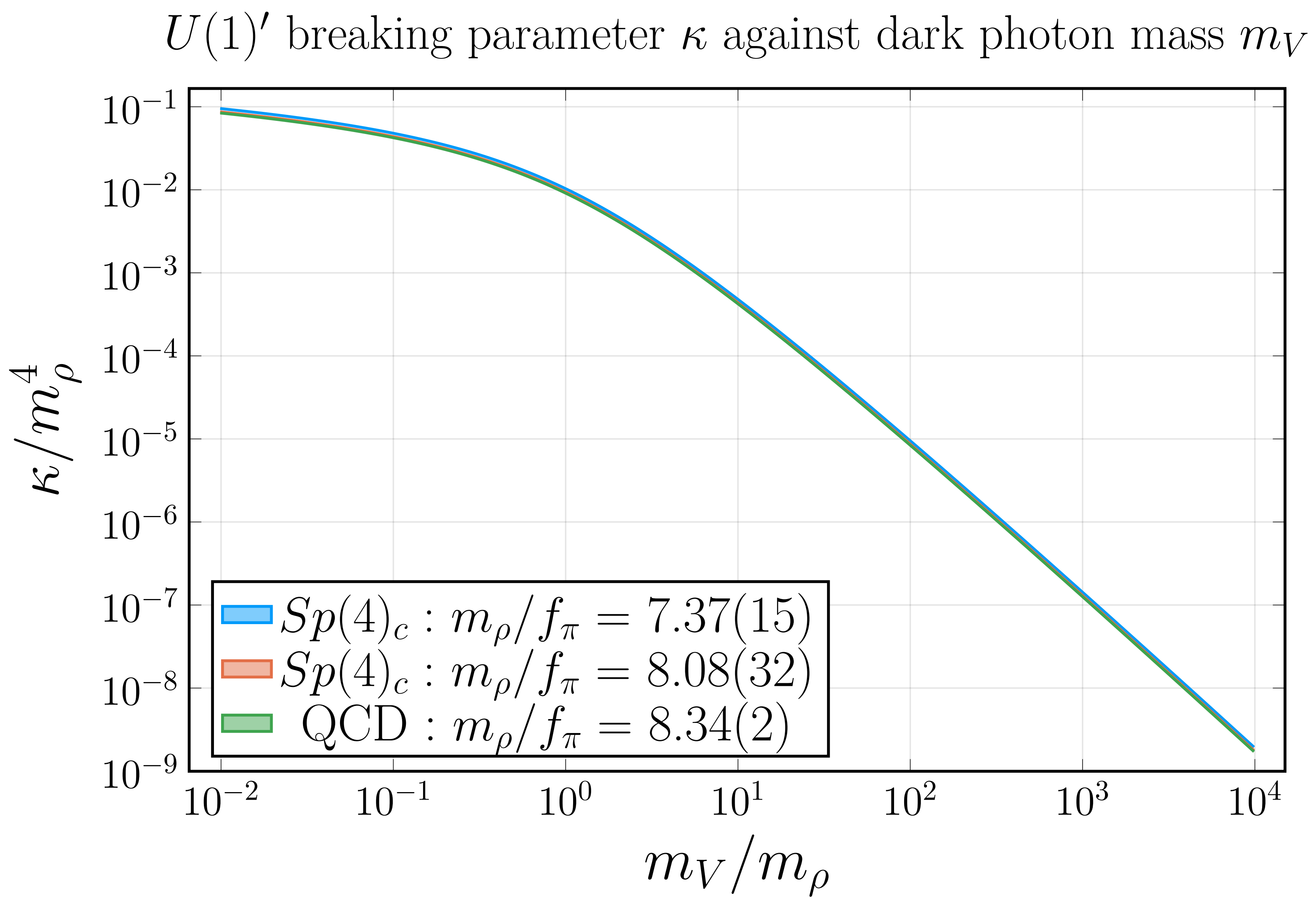
- Change in mass hierarchy at large splitting
- System resembles heavy-light quarks
- EFT for almost degenerate π's constructed **[1]**
    - m_π and f_π are the low energy constants

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

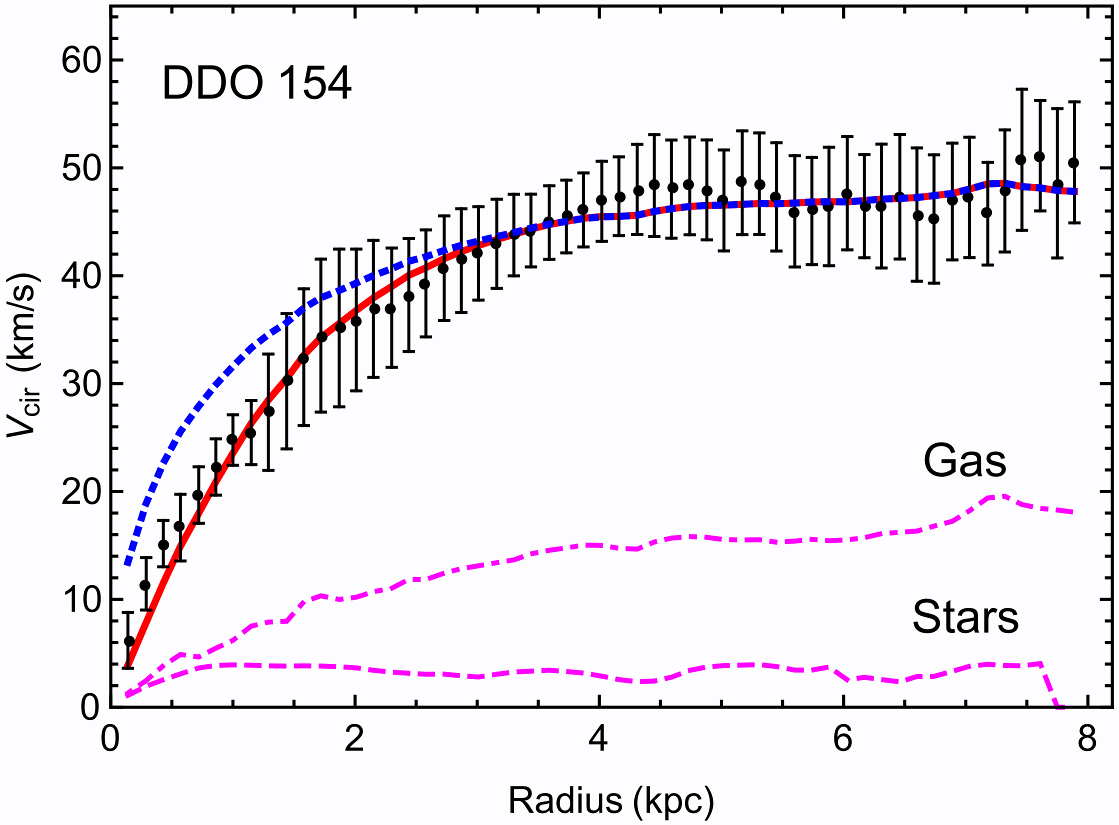
Next steps

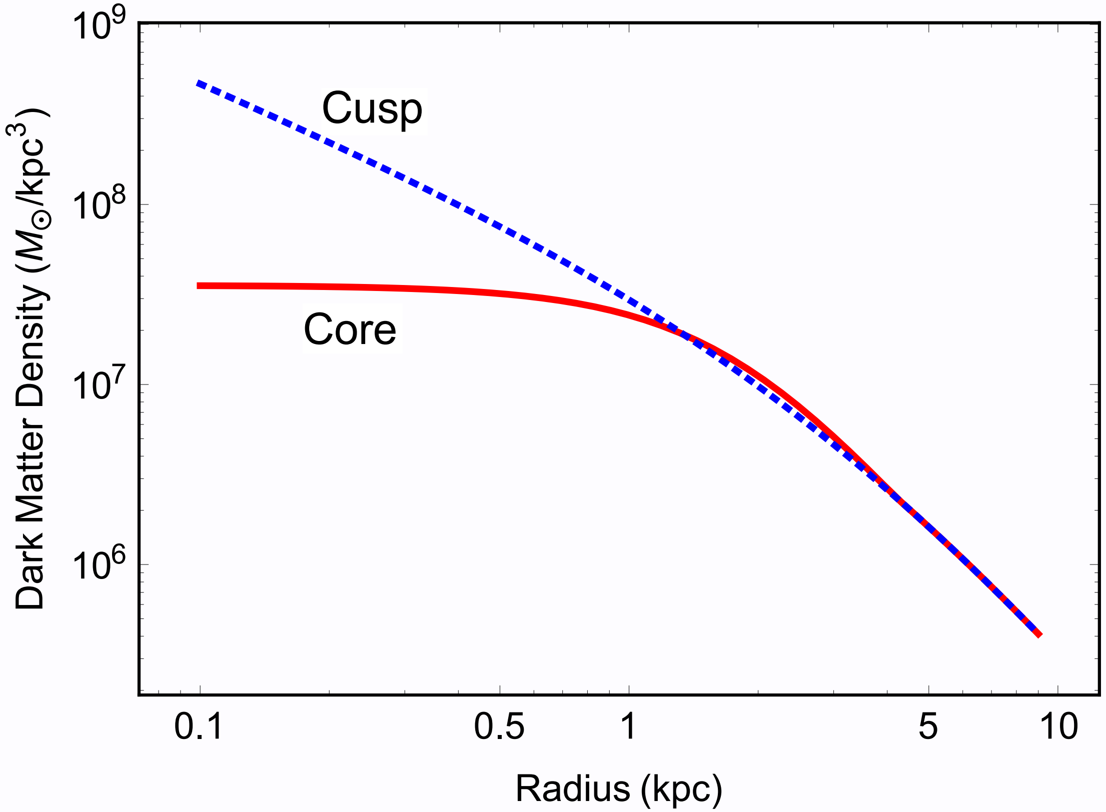
- singlet mesons, $2\pi \to 2\pi$ scattering, collider searches/constraints

Thank you!

Backup slides

Core-vs-cusp problem





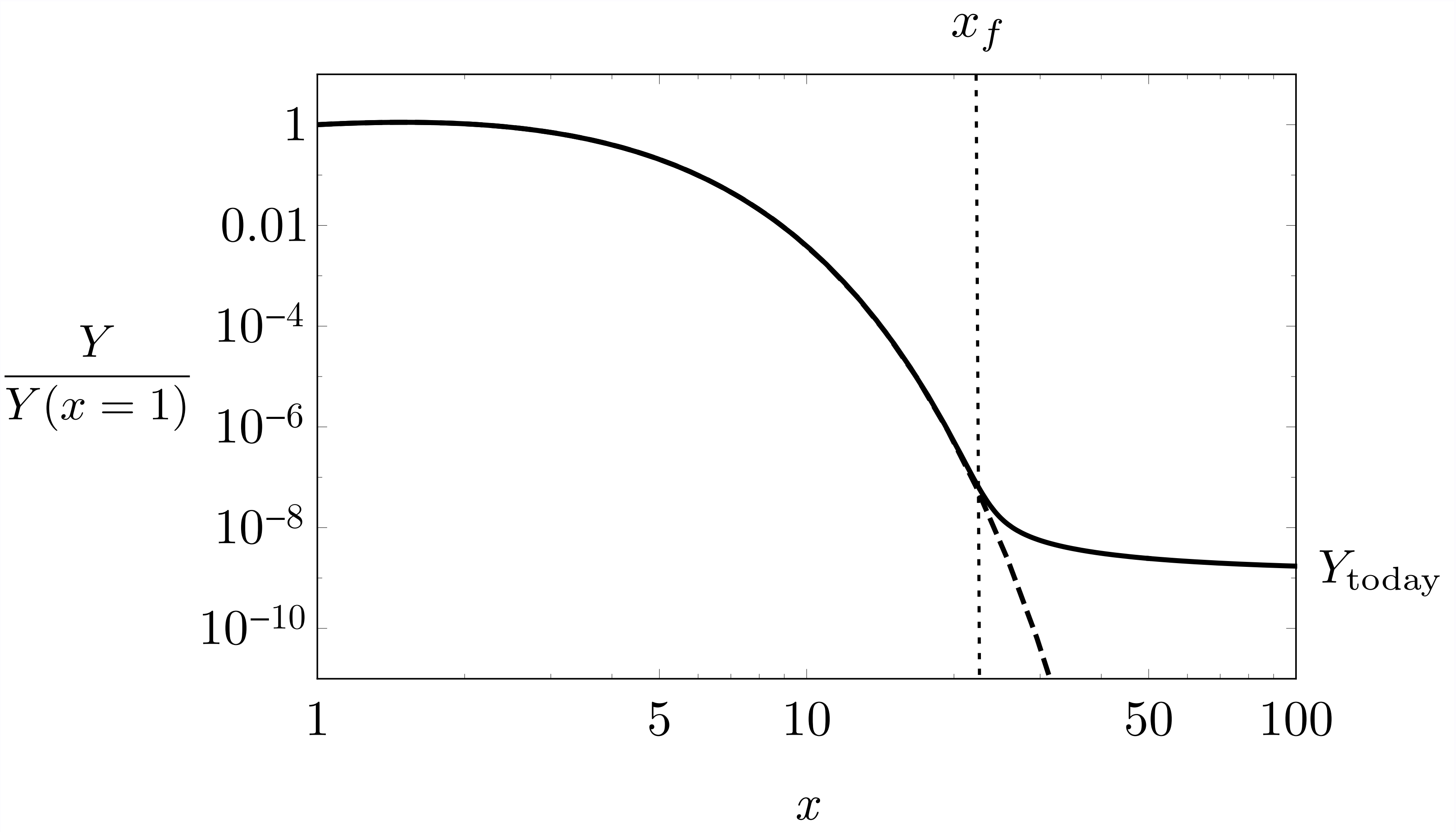
taken from: Tulin and Yu 1705.02358v2

Thermal Dark Matter - Freeze out

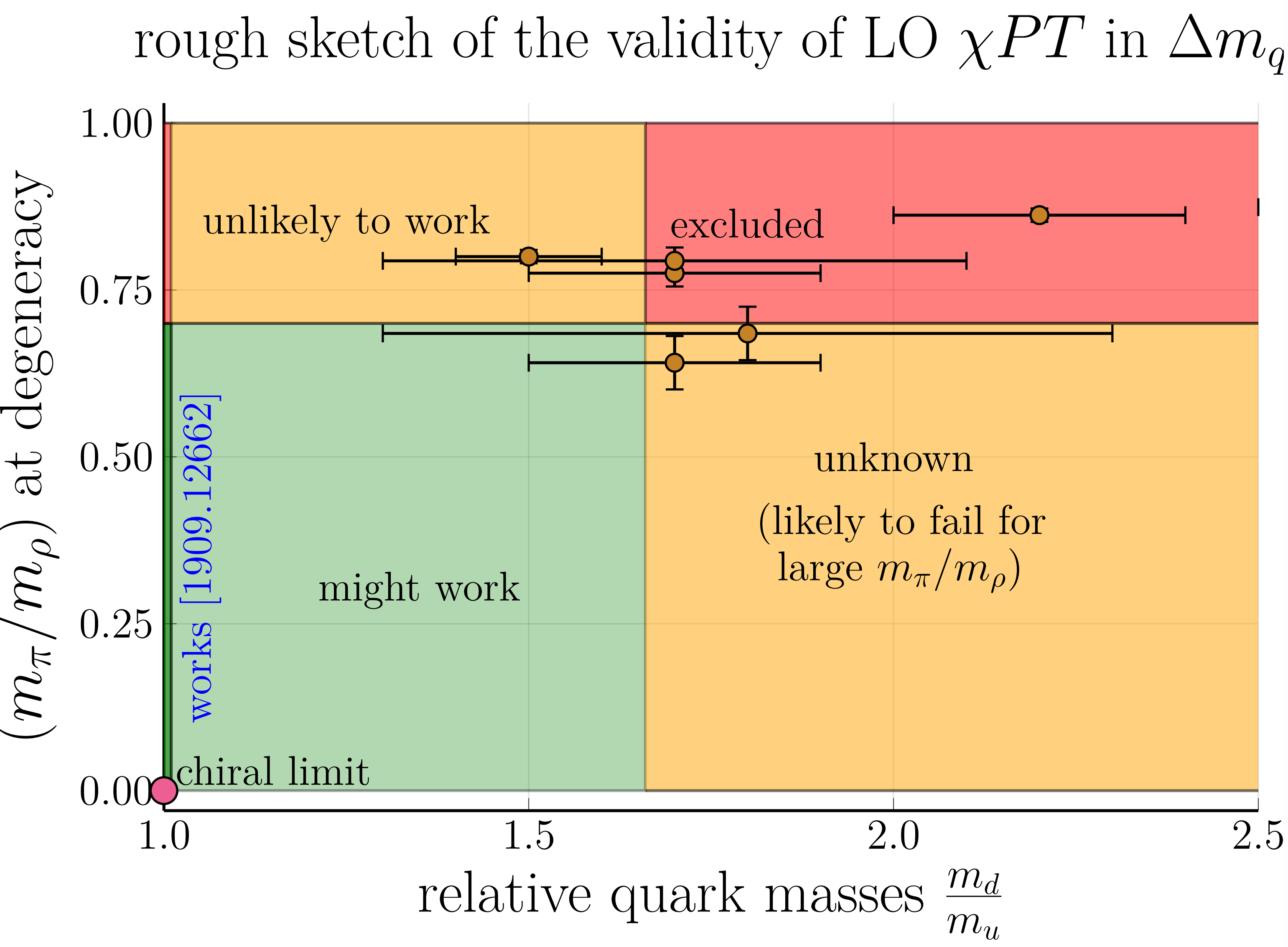
- Early universe: Thermal and chemical equilibrium
- DM depletion process, e.g. $\chi\chi_{DM} \leftrightarrow \psi\psi_{SM}$
  - Universe cools: $\psi\psi \rightarrow \chi\chi$ kinematically forbidden
  - *Dark Matter number decreases* through $\chi\chi \rightarrow \psi\psi$
  - Universe expands: χ annihilation stops

- DM eventually thermally decoupled: **freeze out**

Freeze-out process

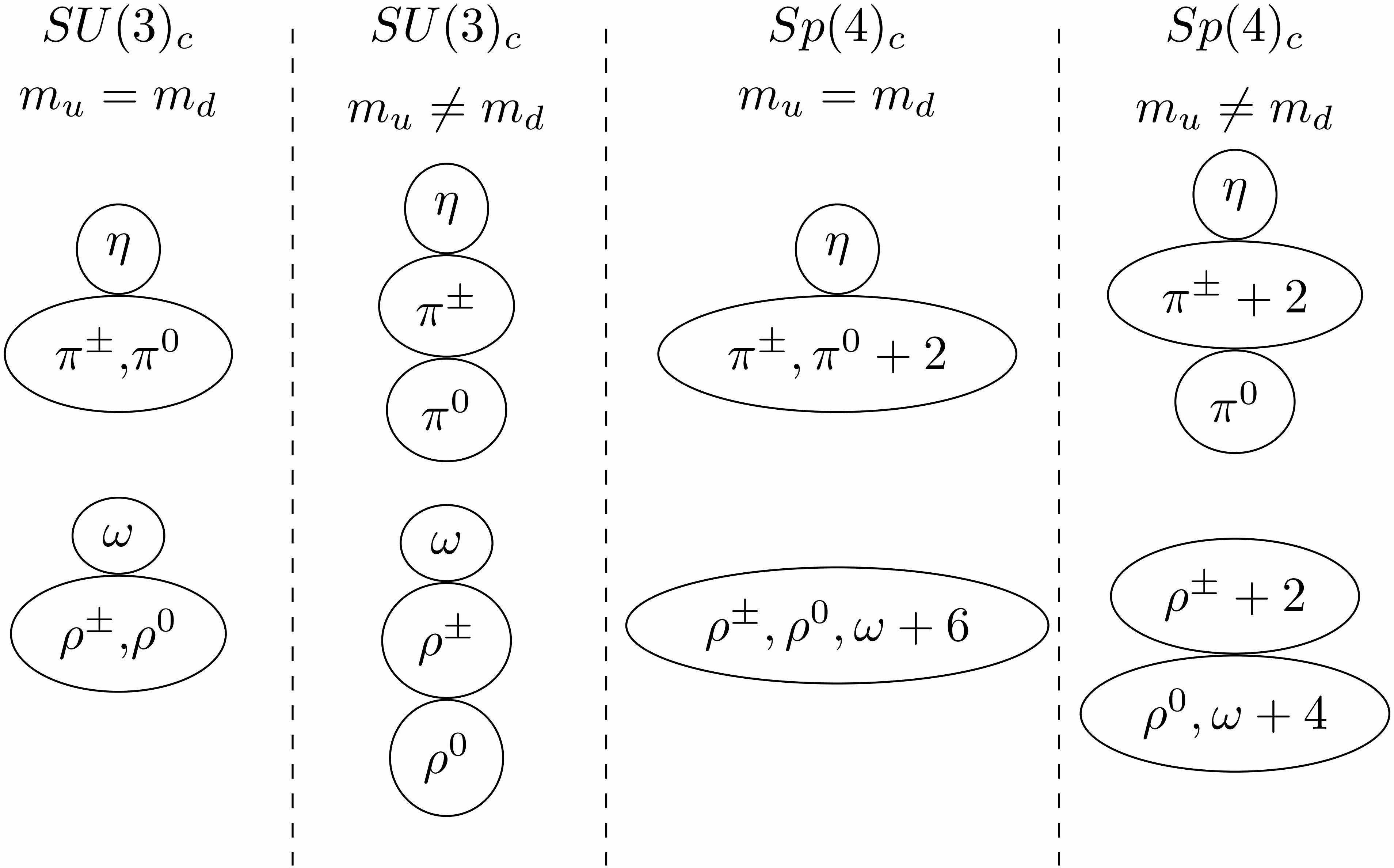


- Y ... DM number density, $x = m_{DM}/T$



- data points: breakdown of LO χPT in Δm on the lattice
- $\frac{m_d}{m_u} = 1 + \Delta m$
- $\frac{m_\pi}{m_\rho}$ fixed at degeneracy

Pseudoscalar (PS) and vector (V) multiplets



Meson Spectroscopy

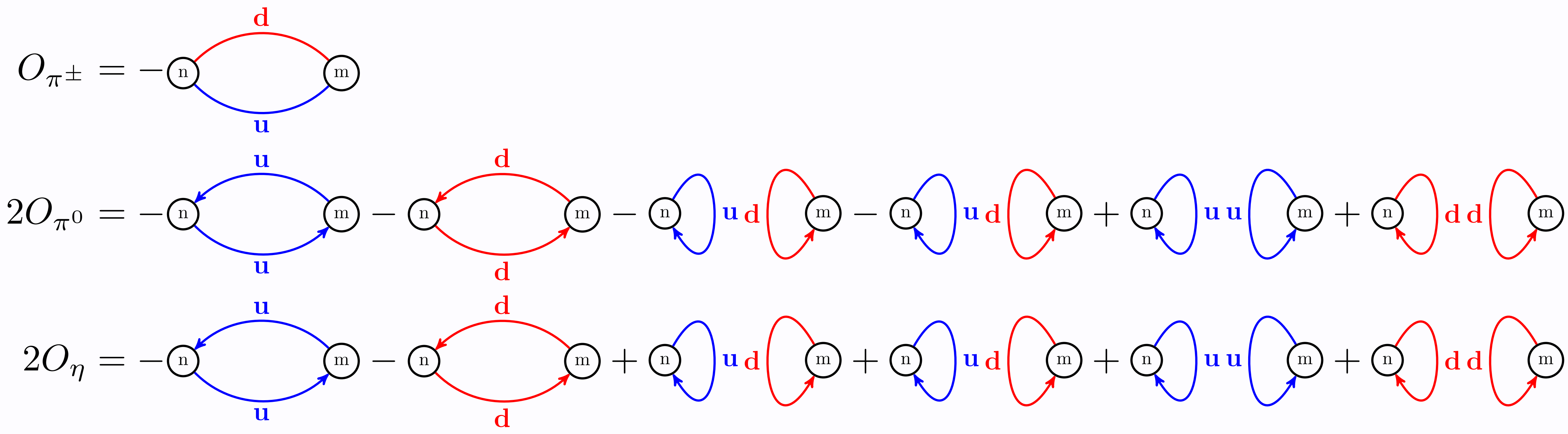
- Obtain 2-point function of Operator $\mathcal{O}(x)$

$$\mathcal{O}_{\pi^+} = \bar{u}\gamma_5 d$$
$$\mathcal{O}_{\pi^-} = \bar{d}\gamma_5 u$$
$$\mathcal{O}_{\pi^0} = \left(\bar{u}\gamma_5 u - \bar{d}\gamma_5 d\right)/\sqrt{2}$$
$$\mathcal{O}_{\eta} = \left(\bar{u}\gamma_5 u + \bar{d}\gamma_5 d\right)/\sqrt{2}$$

- For scalars replace $\gamma_5 \to \mathbb{I}$, for vectors $\gamma_5 \to \gamma_i$

$$\langle O(\vec{x},t)\bar{O}(0)\rangle = \sum_n \langle 0|\hat{O}|n\rangle\langle n|\hat{O}^\dagger|0\rangle e^{-tE_n}$$

Diagrammatical representation



- Quark lines "come back" $\Rightarrow$ **disconnected** diagrams
- Cancellation for π^0 in symmetric limit

Always present for singlet mesons!

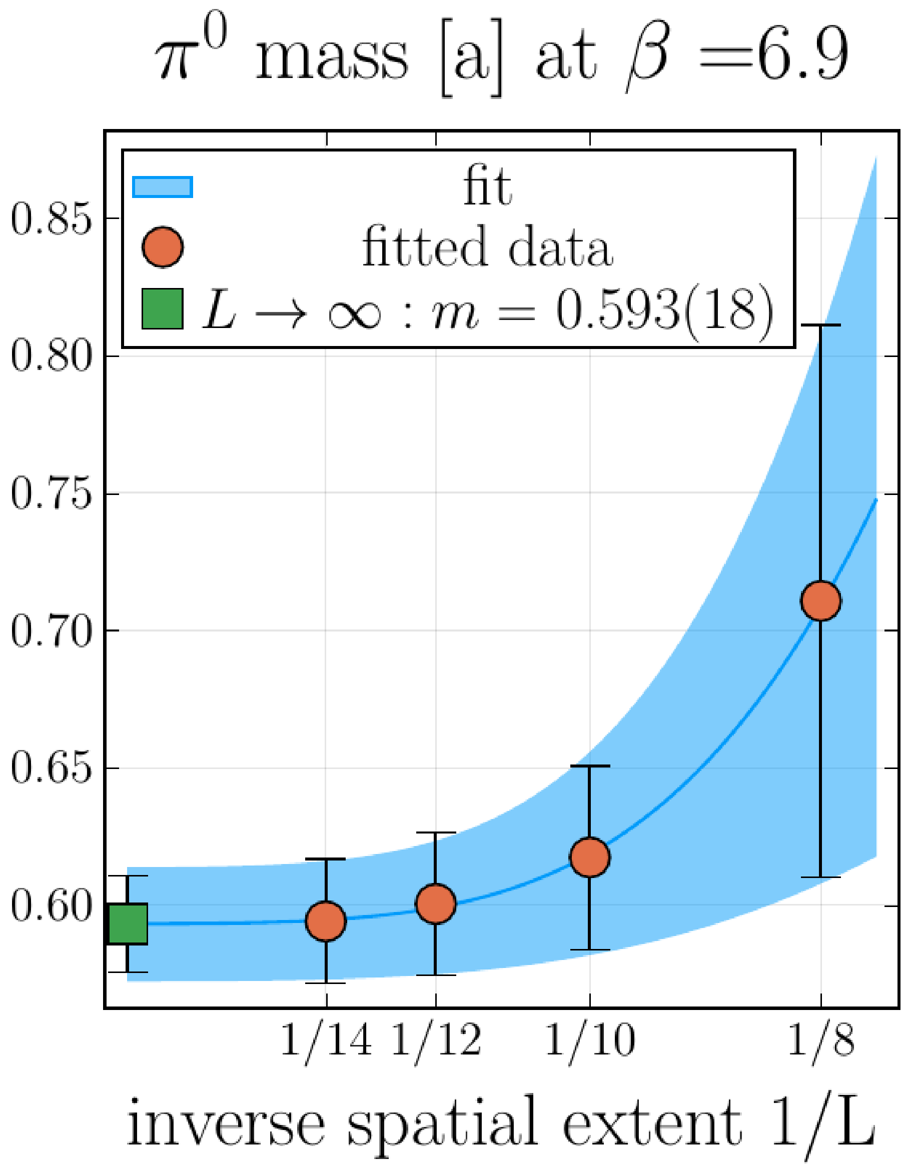
Goldstone bosons and parity

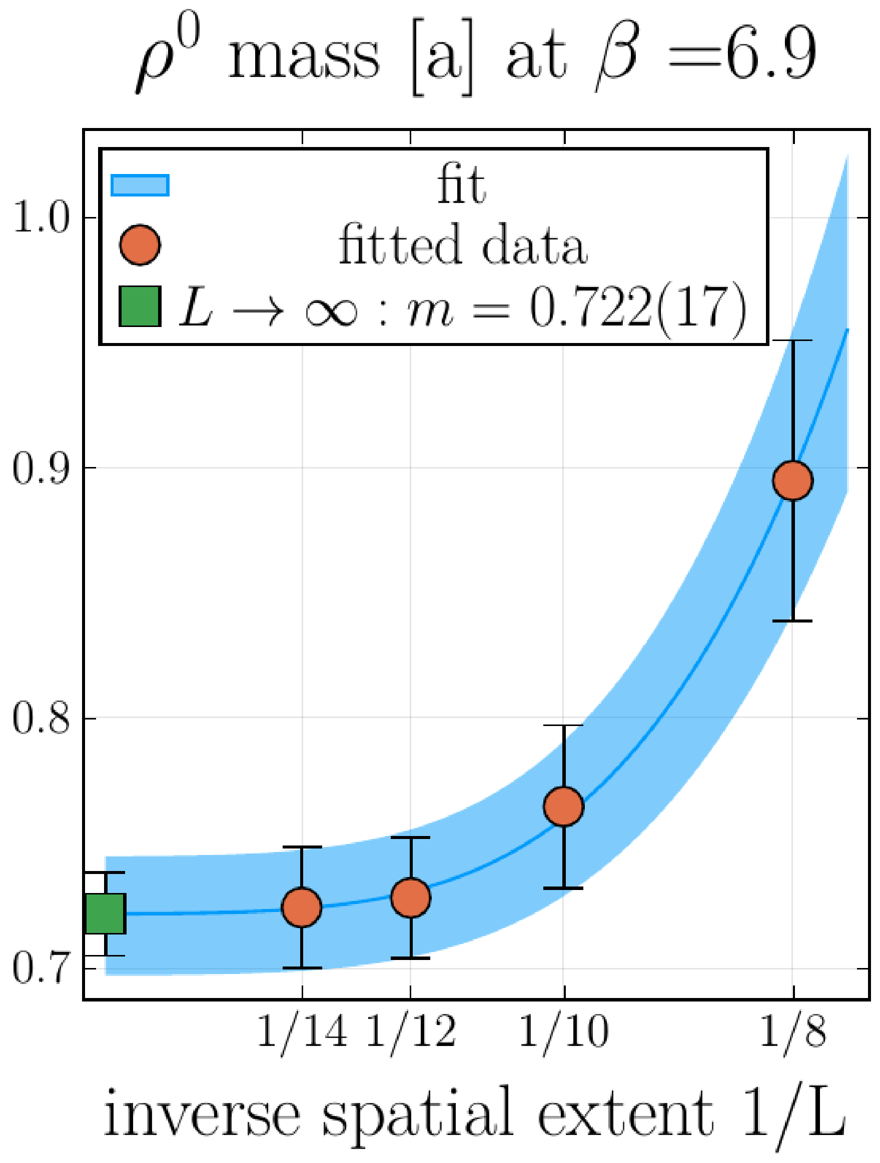
$$P : \psi(x,t) \to \gamma_0 \psi(-x,t)$$

$$D : \psi(x,t) \to \pm i\gamma_0 \psi(-x,t)$$

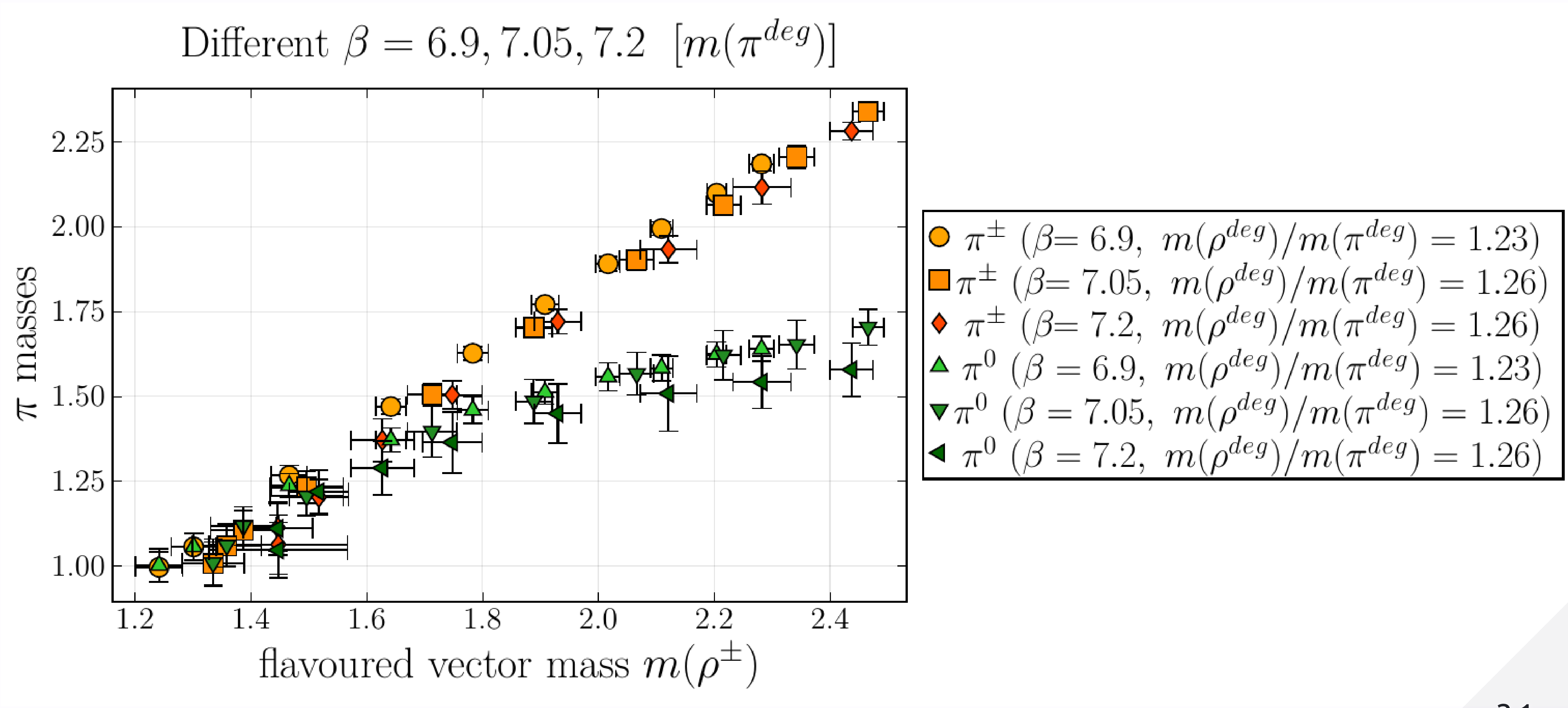
name	operator	J^P	J^D
π^-	$\bar{u}\gamma_5 d$	0^-	0^-
π^+	$\bar{d}\gamma_5 u$	0^-	0^-
π^0	$\bar{u}\gamma_5 u - \bar{d}\gamma_5 d$	0^-	0^-
π_{qq}	$u^T SC\gamma_5 d$	0^+	0^-
$\pi_{\bar{q}\bar{q}}$	$\bar{u}SC\gamma_5 \bar{d}^T$	0^+	0^-

Finite Volume: Meson masses

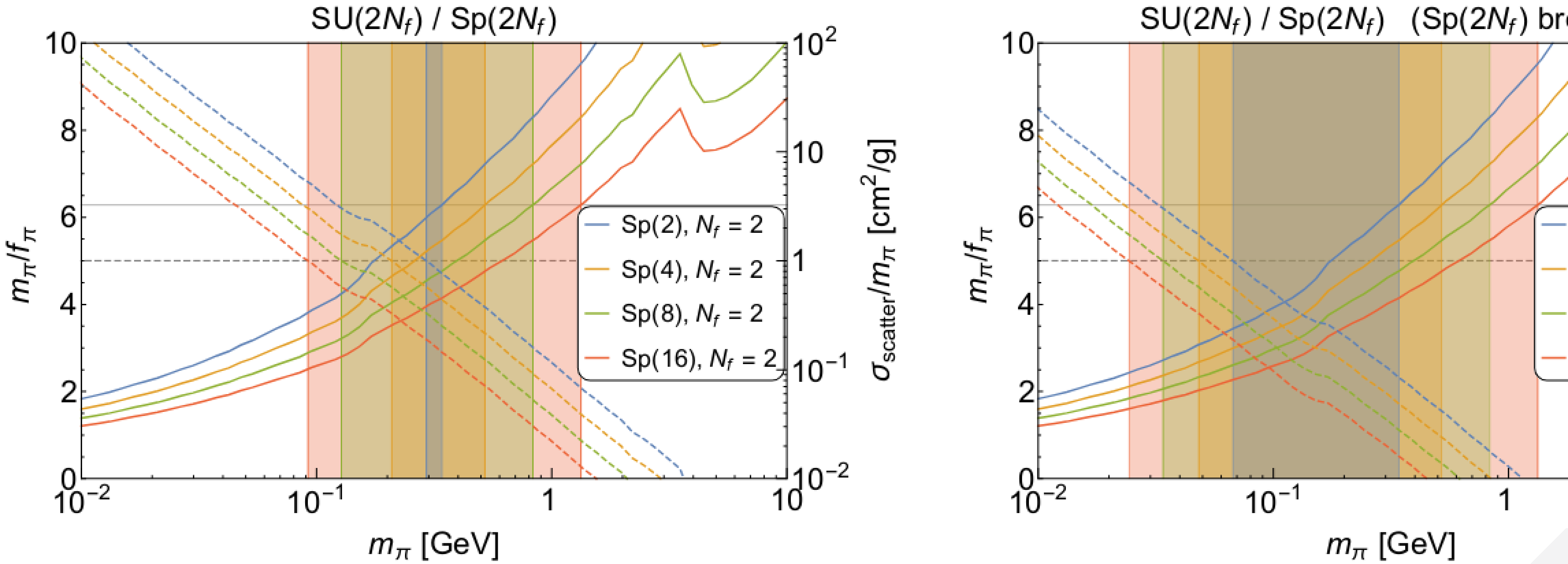




Spacing effects: Goldstone masses



Effects of varying N_c and $Sp(2N_f)$ breaking



taken from [1411.3727]