Composite Dark Matter from Sp(2N) gauge theories

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`mostly based on 2202.05191, 2304.07191, 2311.18549`

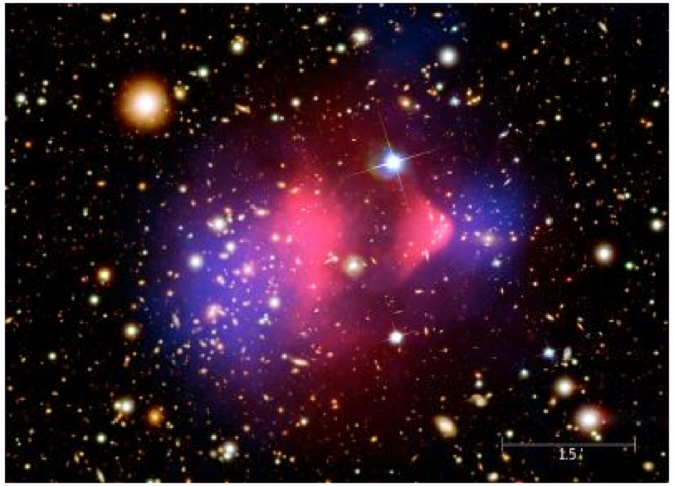
slides available at: fzierler.github.io/talks/

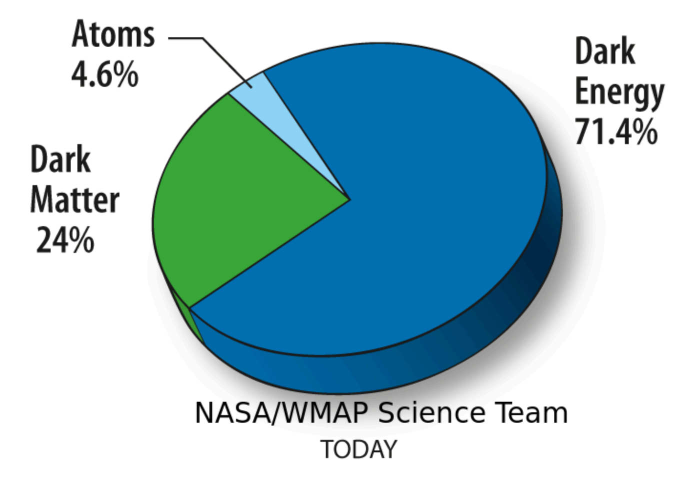
Outline

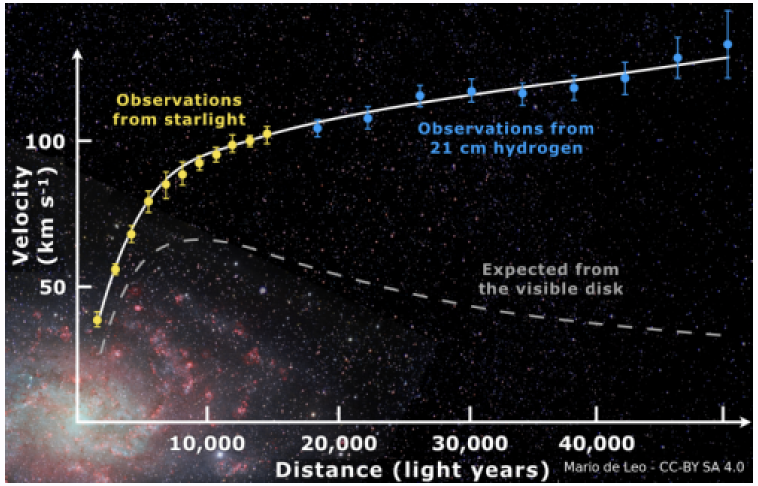
- Composite, self-interacting Dark Matter models
  - Strongly Interacting Massive Particles (SIMPs)
  - A specific model: $Sp(4)$ with two Dirac fermions
- Lattice Field Theory and numerical results
  - Meson spectroscopy
  - Goldstone scattering
  - Conclusions for Phenomenology and model building

Dark Matter - Why?

- Strong observational evidence at many scales! [1]
- Modified Gravity [2] is a potential alternative
- New particles beyond the Standard Model (BSM) promising!



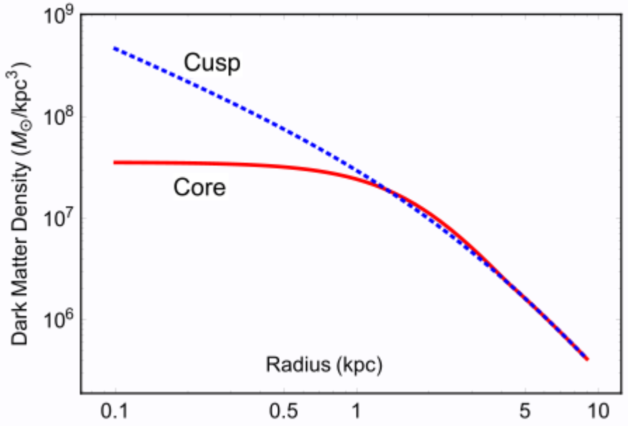


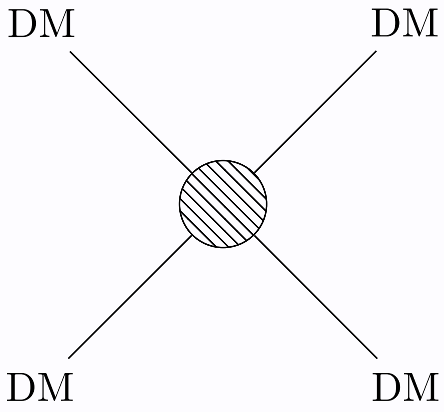


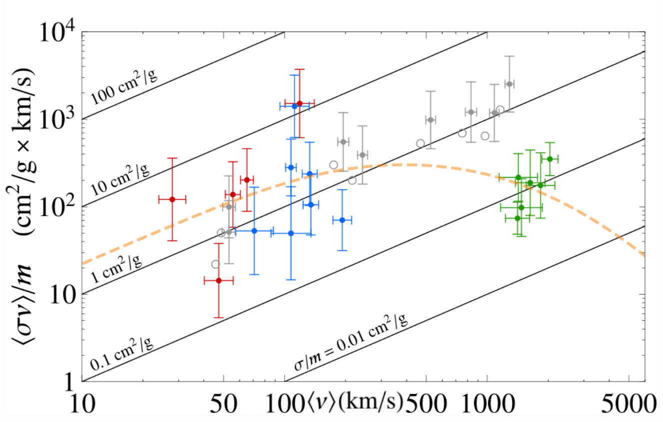
[1] see e.g. Bullock,Boylan-Kolchin [1707.04256], Tulin, Yu [1705.02358]

Dark Matter properties

- DM self-interaction phenomenologically allowed[1] and potentially relevant for small-scale structure problems
  - non-vanishing scattering cross-sections $\sigma_{2\mathrm{DM}\to 2\mathrm{DM}}$
  - velocity dependence of $\sigma_{2\mathrm{DM}\to 2\mathrm{DM}}$ preferred



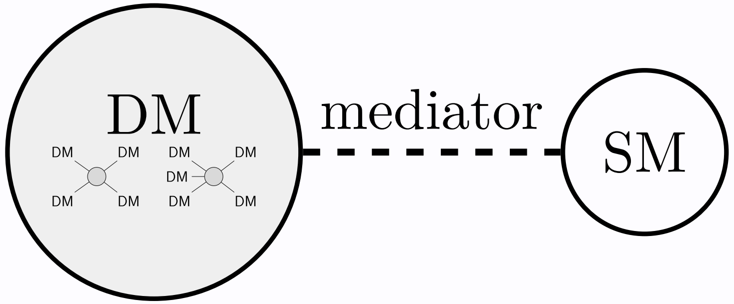




QCD-like Dark Matter can those provide self-interactions!

Strongly Interacting Gauge Theories in DM Models

- With fermions: Global symmetries make DM stable
- With mediator: Dark sector coupled to SM



$$\mathcal{L}_{\rm DM} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}_f (i\not{D} + m_f)\psi_f$$

- Non-vanishing self-scattering cross-section arise

$$\langle v\sigma_{\pi\pi\to\pi\pi}\rangle \neq 0$$

- Relic density driven by strong processes

Dark meson scattering: Determine DM relic density

- Any model must predict the current density of DM correctly
  - number density n can be calculated using Boltzmann equations

$$\partial_t n + 3Hn = f(\langle v\sigma_{\text{number changing}}\rangle)$$

- Cross-sections $\langle \sigma v \rangle$ are input for Boltzmann equations
  - describe non-equilibrium dynamics
  - H is the Hubble rate

Strongly Interacting Massive Particles (SIMPs)

- Depletion via $3\mathrm{DM} \to 2\mathrm{DM}$ [1], i.e. $3\pi \to 2\pi$
  - same as $KK \to 3\pi$ in QCD [2]
  - Dark matter depletion process: ***freeze-out***
- LO ChiPT matches relic density at

$$m_\pi \approx \mathcal{O}(100)\mathrm{MeV} - \mathcal{O}(1)\mathrm{GeV}$$

- Other mass scales than QCD are relevant!
  - g^2 and m_f are free parameters

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Dark Matter with 3DM → 2DM depletion and self-interactions
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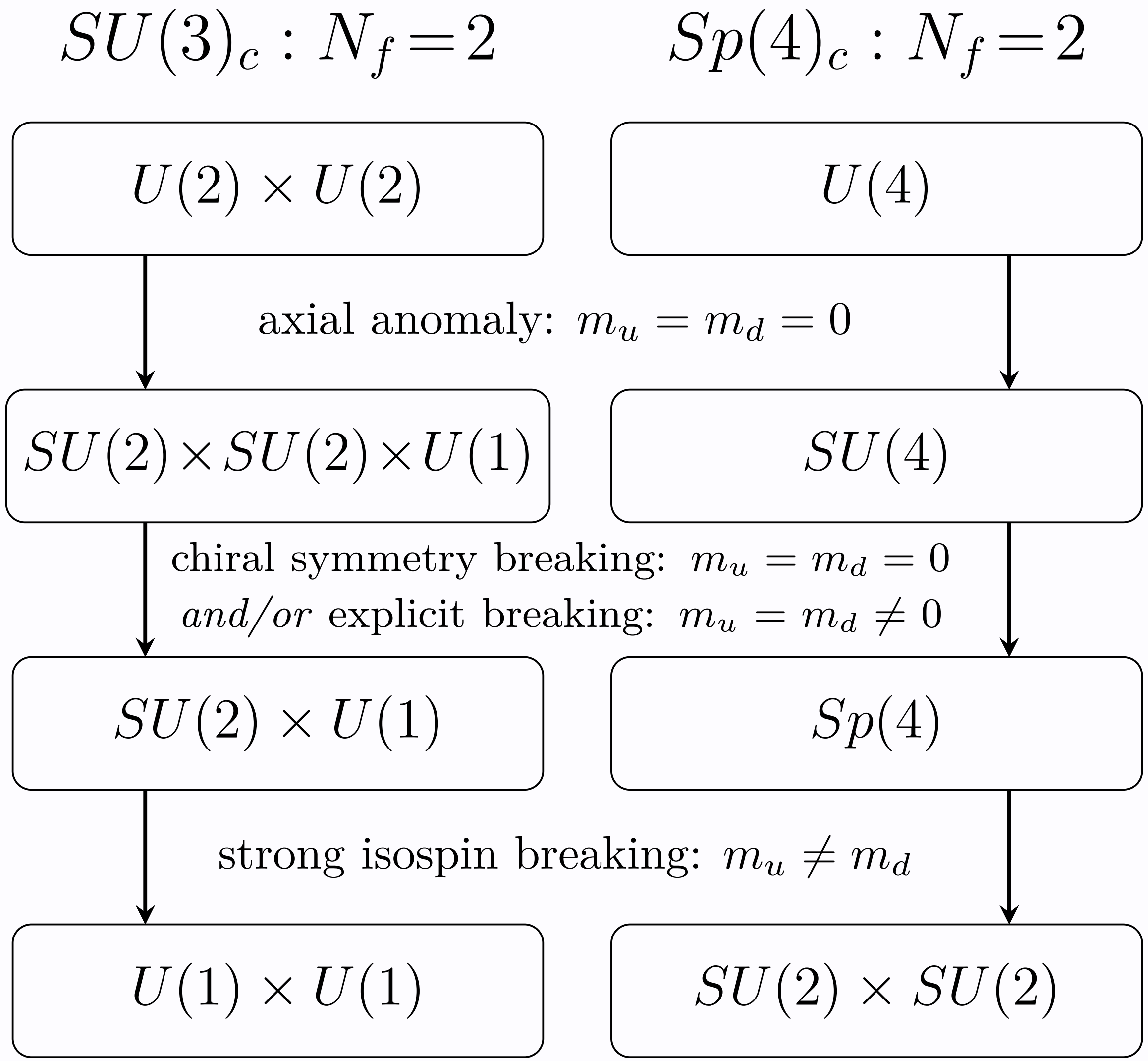
Other relevant channels

- decay to Standard Model: $2\pi \to SM$ [1]
- involvement of vector mesons: $\pi\pi \to \pi\rho$, $3\pi \to \pi\rho$ [2]
- influence of light singlets: $\eta'\eta' \to \pi\pi, \pi\pi \to \eta'\pi, \dots$ [3]
- resonances and multi-hadron states: $2\pi \to 2\pi$, $2n\pi \to 2\pi$ [4]

- The relevance depends on the spectrum
- lattice investigations inform EFT construction

[1] Kosower (Phys.Lett.B. 1984)

[2] Hochberg et. al. [1411.3727] [1512.07917]



SIMPs from $Sp(4)$ gauge theory

- Pseudo-real representation: [1]
  - $\Rightarrow$ more pseudo-Goldstones
  - $\Rightarrow$ no fermionic bound states
- $N_f = 2$: exactly 5 Goldstones
  - Allows $3\mathrm{DM} \to 2\mathrm{DM}$ [2]

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Sp(4) with two fermions is
a minimal SIMP DM realisation
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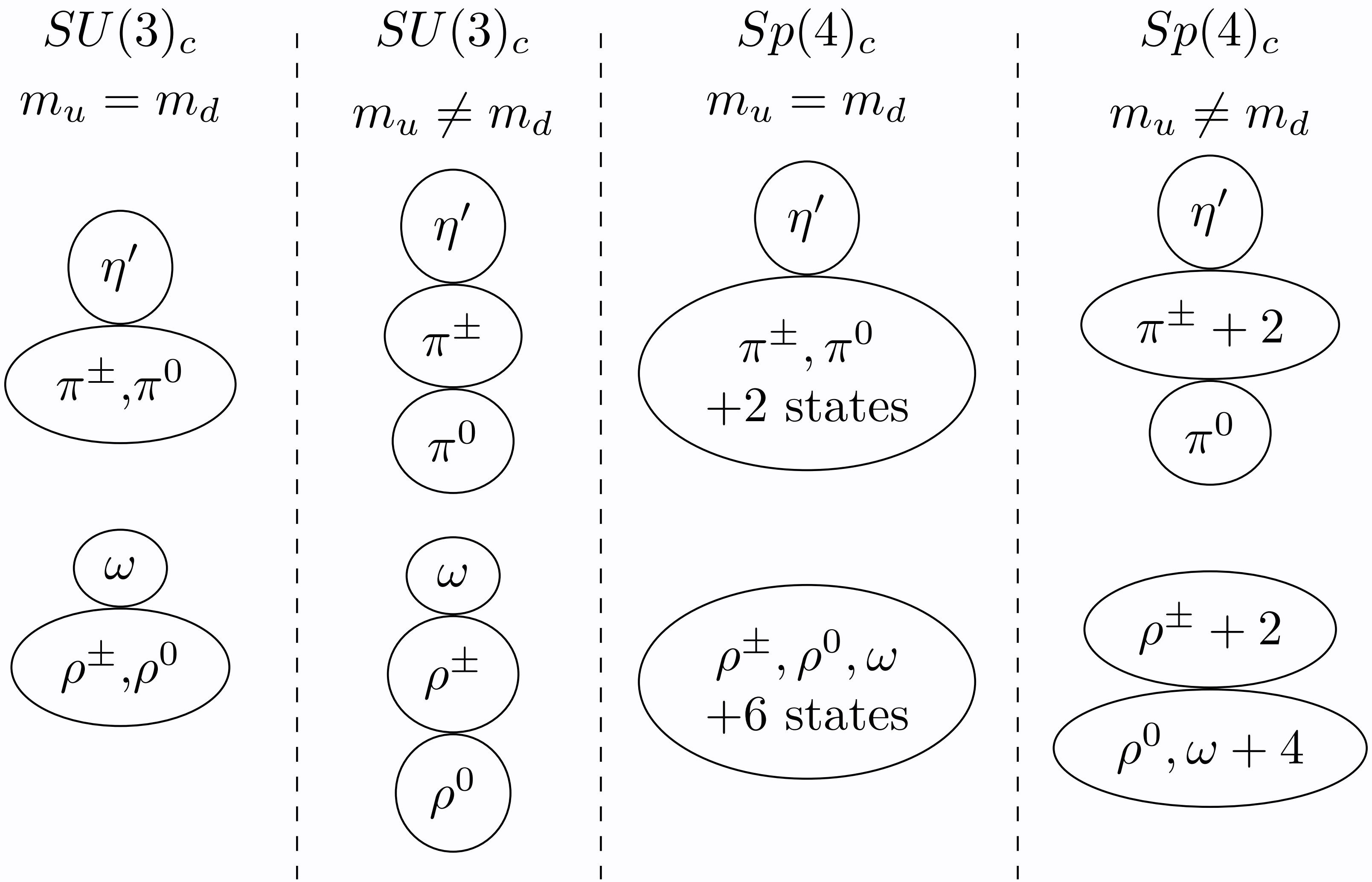
Meson multiplets of $Sp(4)_c$ with $N_f = 2$



The same patterns persist for other channels.

BSM wishlist from the lattice

- Masses and decay constants of dark hadrons
- Scattering of dark pions: $2\pi \to 2\pi$ and $3\pi \to 2\pi$
- Applicability of χPT and related EFTs

- Composite Higgs studies can be repurposed
  - Composite Higgs model usually allow SIMP DM

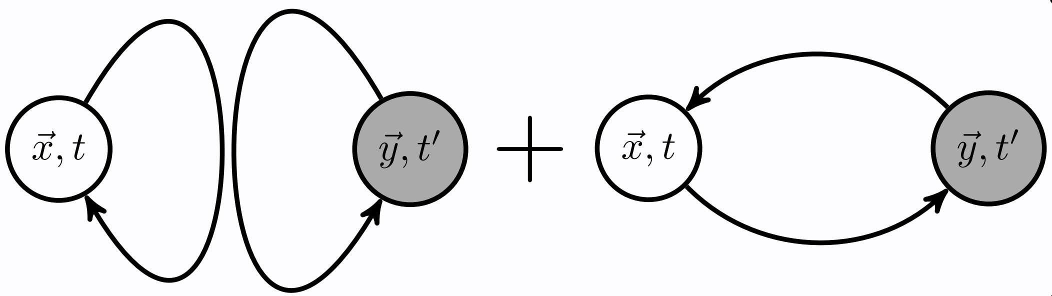
Lattice Investigations:

Quantitative Insights

Calculating the meson correlator

- Evaluate diagrams in terms of fermion propagator D^{-1}

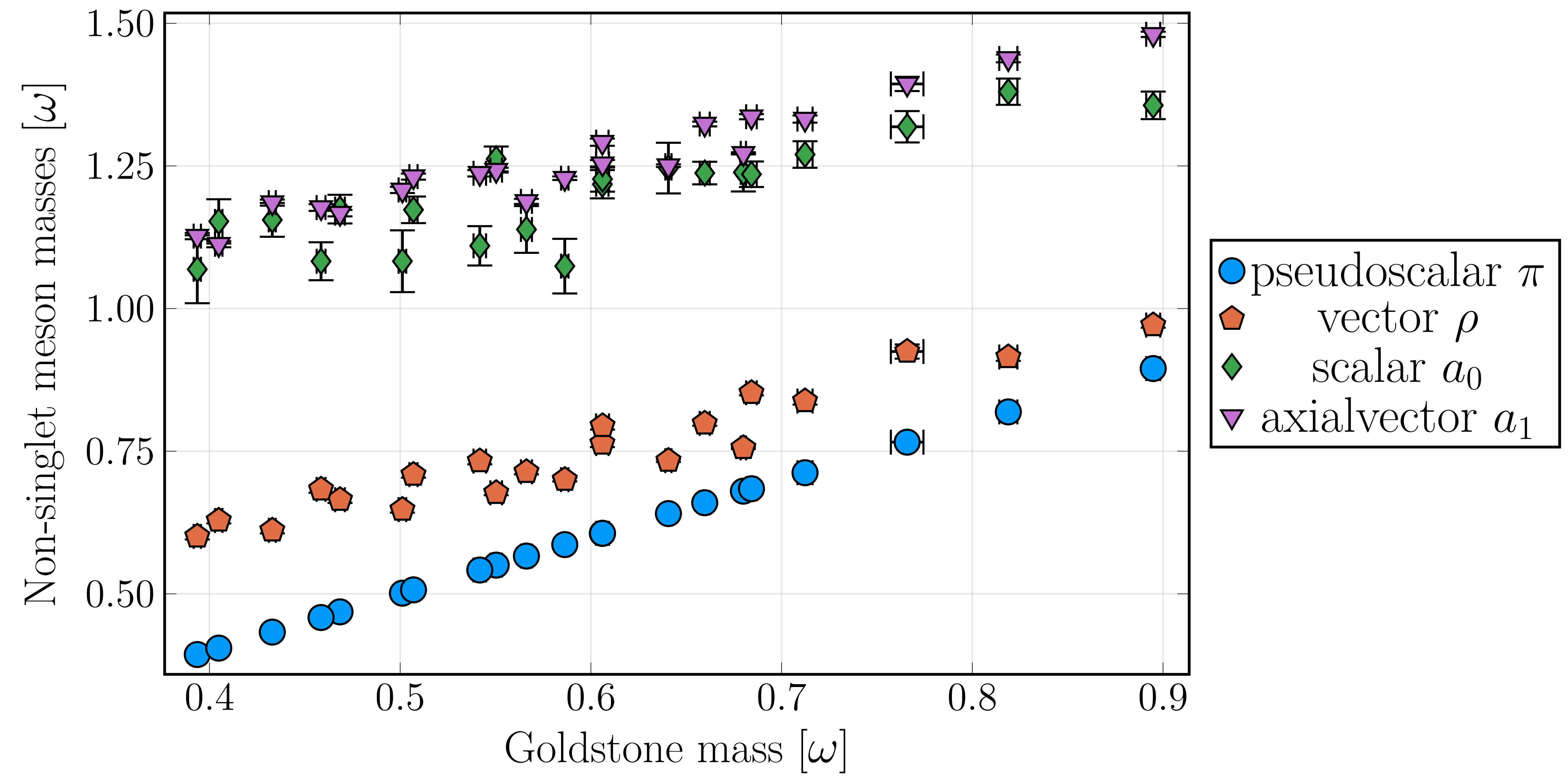
$$C(t-t') = \sum_{\vec{x},\vec{y}} \Big(\quad \Big) + \underbrace{\text{const.}}_{=|\langle 0|O|0\rangle|^2}$$



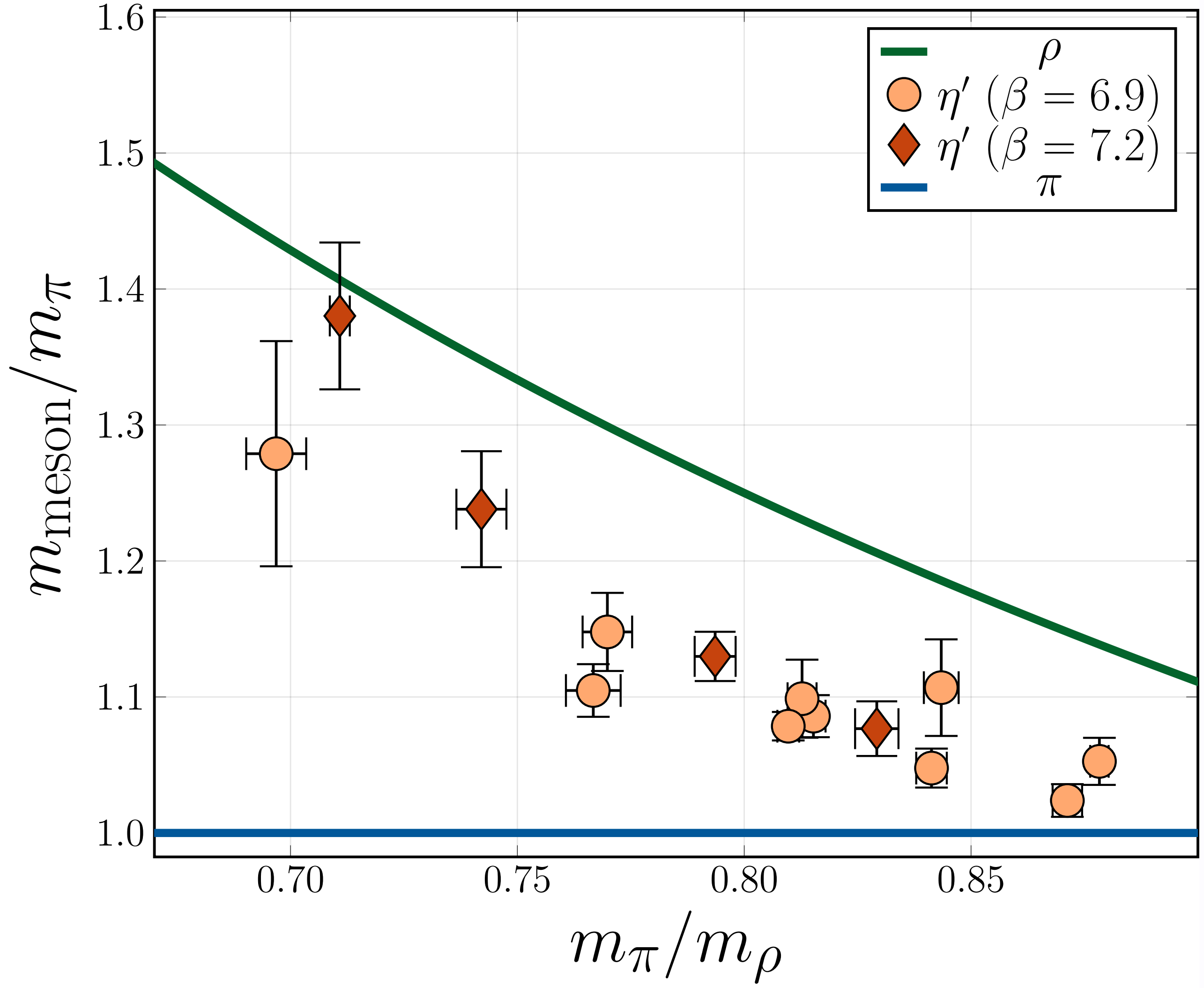
- Disconnected diagram (left) particularly challenging
  - only appears for singlets (gluonic propagation)
- Constant term arises for singlets
  - vacuum term for σ, fixed topological charge for η'

Non-singlet spectrum

Bennett et. al. [1909.12662]



The pseudoscalar and vector mesons are the lightest non-singlets.



The pseudoscalar singlet η' is surprisingly light!

- Phenomenologically relevant:
  - $m_\rho > m_{\eta'}$ different from QCD
  - relevant low-energy dof
  - η' relevant for $\pi\pi$ scattering
  - more accessible channels for decays into SM

Interesting! Is this surprising?

Bennett et. al. [2304.07191]

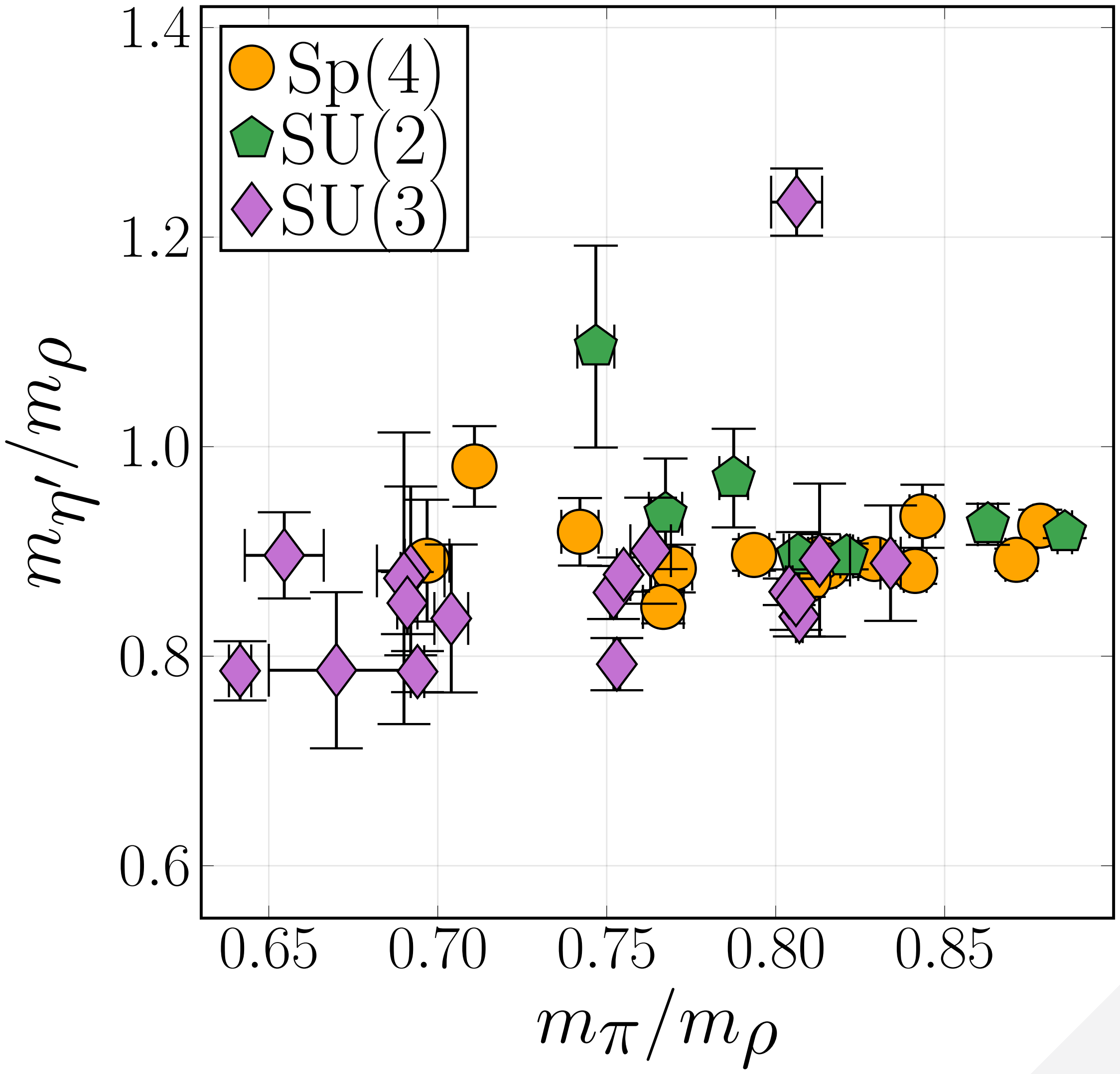
Consider different theories:

- Large N_c: $m_{\eta'} - m_\pi \propto N_f / N_c$
  - $N_f = 2$ could be "small"
  - $N_c = 4$ could be "large"

SU(2) and SU(3) comparison:

- Similarities:generic $N_f = 2$ feature?
- QCD: strong N_f dependence
- Differences may arise $m_\pi / m_\rho \to 0$

mass driven by flavour content!



Consequences for Dark Matter models

- Mass hierarchies: limit χPT validity
  - inclusion of other states than π required, e.g. η' and ρ
- Light unprotected state η': decay into SM allowed
  - could be turned off at large N

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Are these fermion masses phenomenologically relevant?
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Dark Matter Scattering on the Lattice

- Pions are in the 5-dimensional representations
- A two pion scattering is in one of three irreps

$$5 \times 5 = 14 \oplus 10 \oplus 1$$

- Corresponds to the usual QCD channels
  - $14 \Leftrightarrow$ isospin $I = 2$ in QCD, e.g. $\pi^+\pi^+$
  - $10 \Leftrightarrow$ isospin $I = 1$ in QCD, e.g. $\pi\pi \to \rho$
  - $0 \Leftrightarrow$ isospin $I = 0$ in QCD, e.g. $\pi\pi \to \sigma / f_0$

Scattering information from the lattice

- Scattering phase shift $\delta_0(p)$ from finite volume energy

$$\tan(\delta_0(q)) = \frac{\pi^{\frac{3}{2}} q}{\mathcal{Z}_{00}^{\vec{0}}(1, q^2)}, \quad q = p^* \frac{L}{2\pi}$$

$$\cosh\left(\frac{E_{\pi\pi}}{2}\right) = \cosh(m_{\pi\pi}) + 2\sin\left(\frac{p^*}{2}\right)^2$$

- Low-velocity behaviour: Scattering length

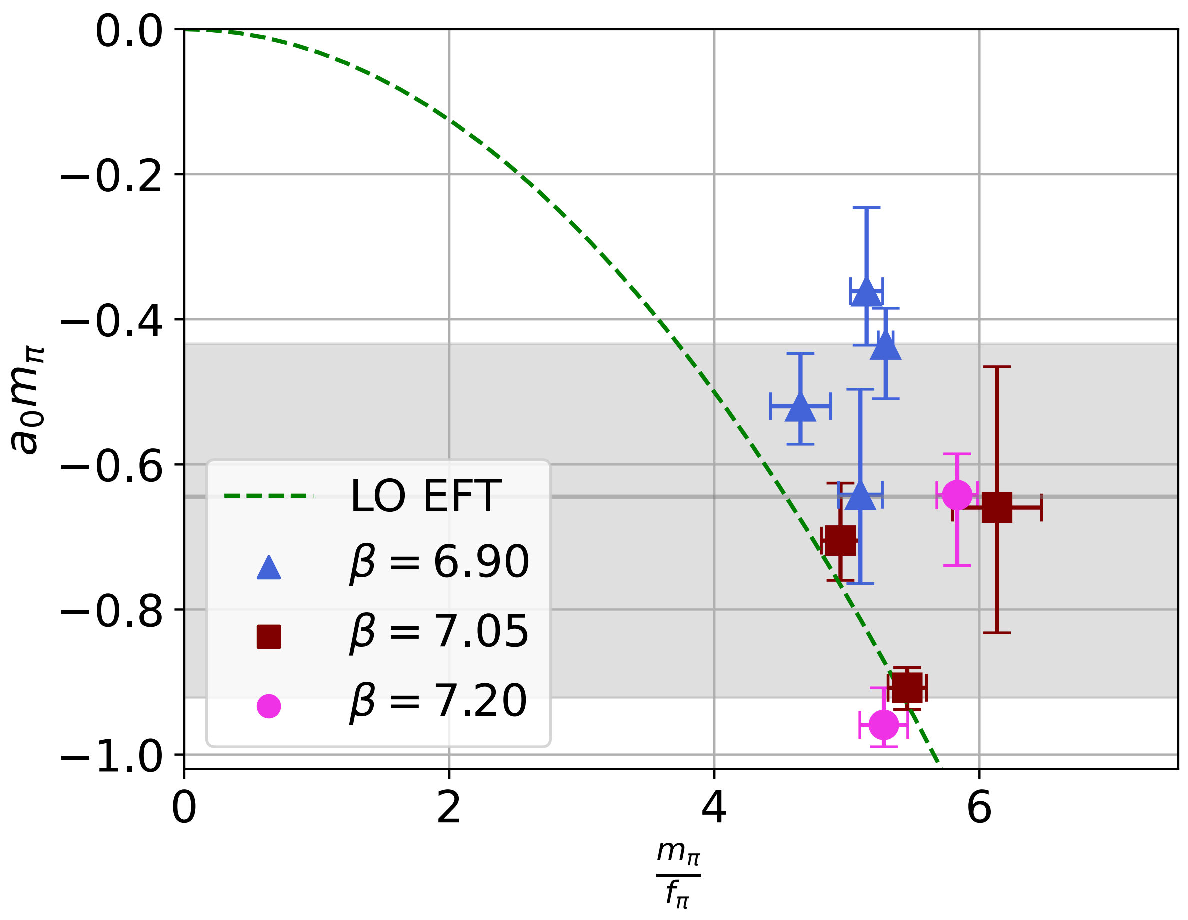
$\Rightarrow$ relation between $\pi\pi$ energy $E_{\pi\pi}$ and m_π on a lattice [1]

$$\frac{\delta E_{\pi\pi}}{m_\pi} = \frac{4\pi m_\pi a_0}{(m_\pi L)^3}\left(1 + c_1 \frac{m_\pi a_0}{m_\pi L} + c_2 \left(\frac{m_\pi a_0}{m_\pi L}\right)^2\right)$$

[1] Dengler et.al. [2311.18549]

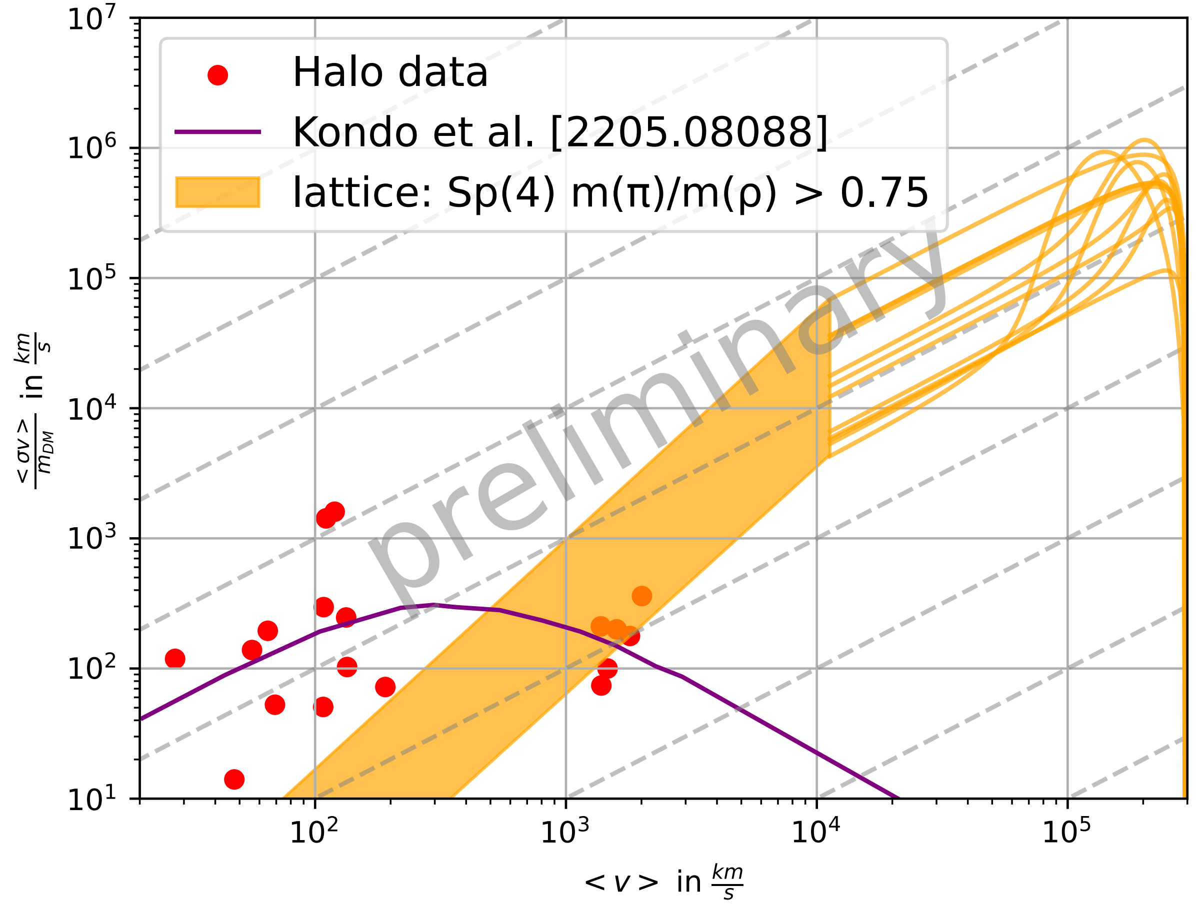
see also Arthur et. al. [1412.4771] for SU(2)

Blum et.al. [2301.09286] for SU(3)



First investigation of isospin-2 scattering

- repulsive $\pi\pi$ interaction
- few lattice energy levels available $\Rightarrow$ systematics
- finite volume effects present
- roughly matches ChiPT



First investigation of isospin-2 scattering

- phase shift $\delta(p)$ gives velocity dependence $\langle \sigma v \rangle$
- No velocity dependence in isospin-2 channel
- Overall scale chosen to match low velocity behaviour

Summary

- Full light hadron spectrum of two-flavour $Sp(4)$
  - surprisingly light η'
  - input for EFTs: masses and decay constants
  - first determination of isospin-2 $\pi\pi$ scattering

Outlook

- Full scattering analysis of $2\pi \to 2\pi$ and $3\pi \to 2\pi$
  - velocity dependence from strong resonances?
- Better understanding of singlets and scattering states
- Singlet spectroscopy closer to the chiral limit