(QCD-like) Strongly interacting dark matter

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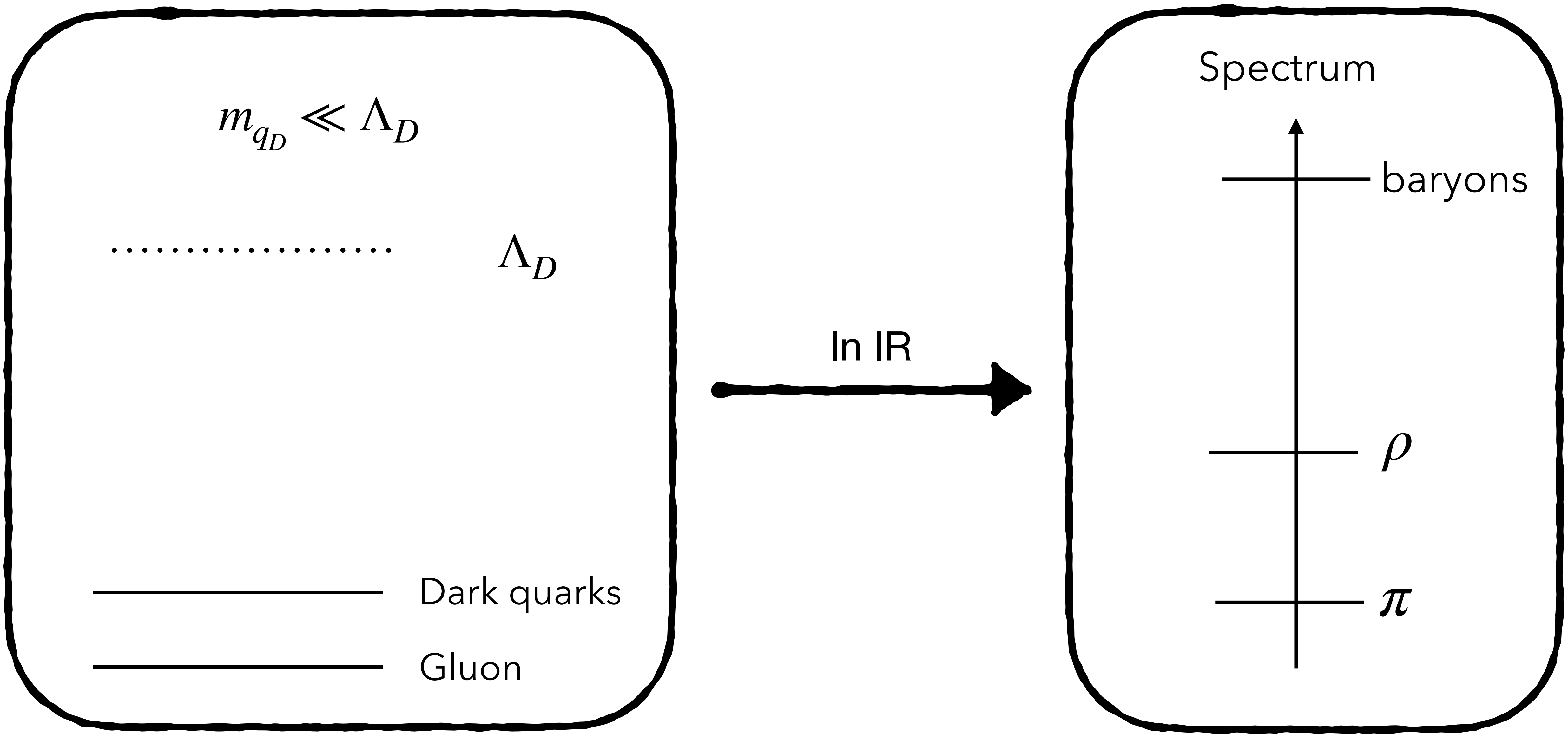
Can dark matter be composite instead of elementary?



Can dark matter be composite instead of elementary?

- Composite Higgs: dark sector (DS) scale related to SM

Nussinov Phys.Lett.B 165 (1985) 55-58, Chivakula et al, Nucl.Phys. B329 (1990) 445, Hietanen et al., arXiv:1308.4130, Cacciapaglia et al arXiv:2002.04914

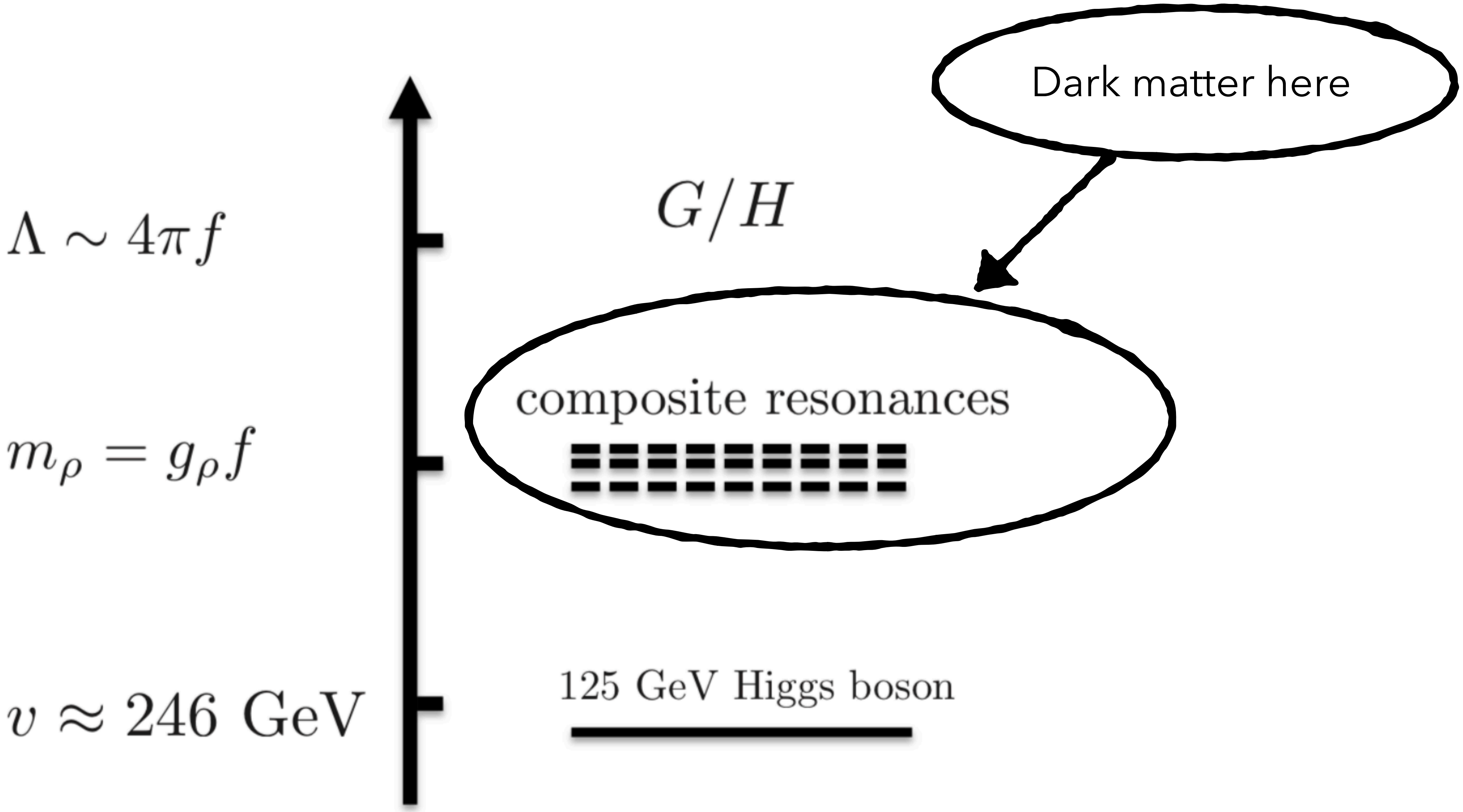


Figure from Liu et. al. arXiv:1904.00026

Strongly interacting dark matter

- Composite Higgs: dark sector (DS) scale related to SM
- This talk: no relation between DS and SM scales

Nussinov Phys.Lett.B 165 (1985) 55-58, Chivakula et al, Nucl.Phys. B329 (1990) 445, Hietanen et al., arXiv:1308.4130, Kribs et al.,arXiv:0909.2034, Buckley et al,arXiv:1209.6054 , Francis et al.,arXiv:1610.10068 , LSD, arXiv:1301.1693, Boddy et al., arXiv:1402.3629 , Detmold et al. arXiv:1406.2276 , Farrar et al arXiv:2007.10378, Kaplan et. al. arXiv:0909.0753

New previously unexplored signatures

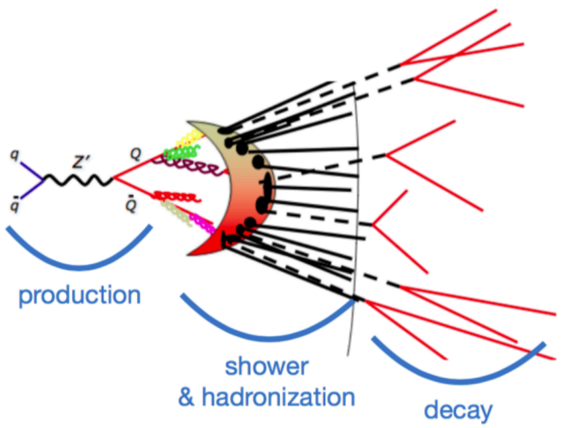
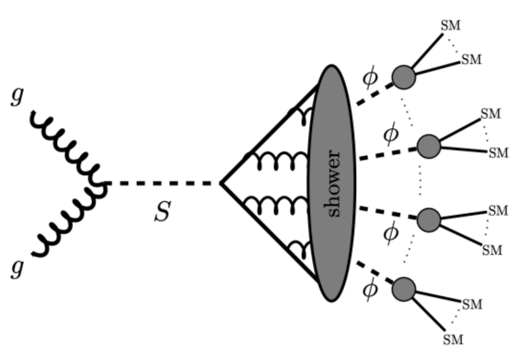
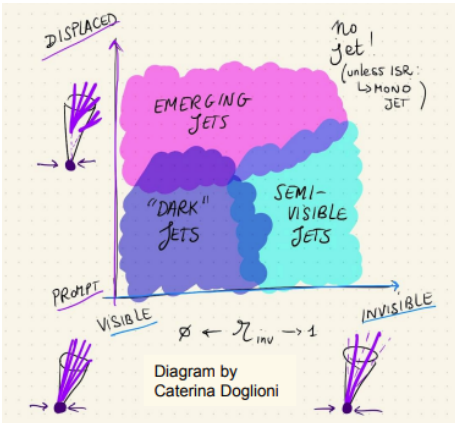


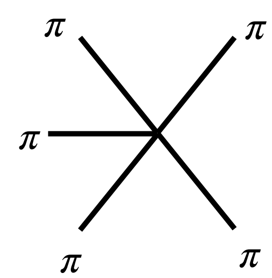
Diagram by M. Strassler

Strassler et al hep-ph/0604261
Cohen et al arXiv:1503.00009
Schwaller et al arXiv:1502.05409
LLP community report arXiv:1903.04497
Kahlhoefer et.al. arXiv:1907.04346
Hofman et al arXiv:0803.1467
Strassler arXiv:0801.0629
Knapen et al arXiv:1612.00850

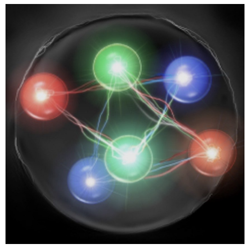


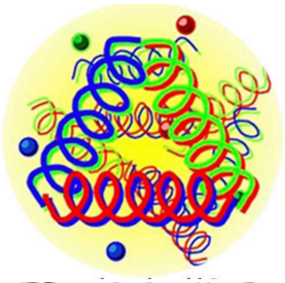


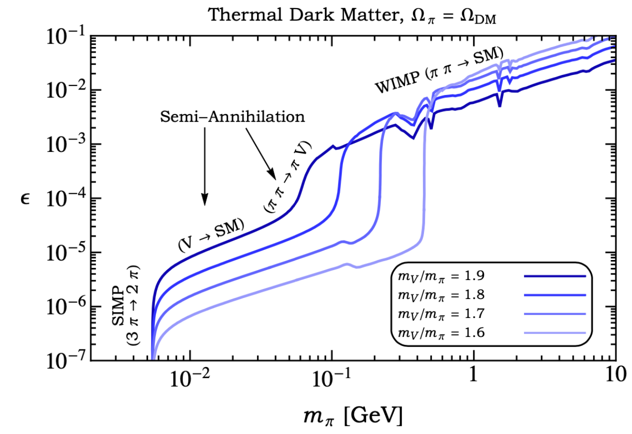
New dark matter candidates



Hochberg et al arXiv:1512.07917
Kribs et al arXiv: 1604.04627
Cline et al arXiv:2108.10314
Beriln et al arXiv:1801.05805

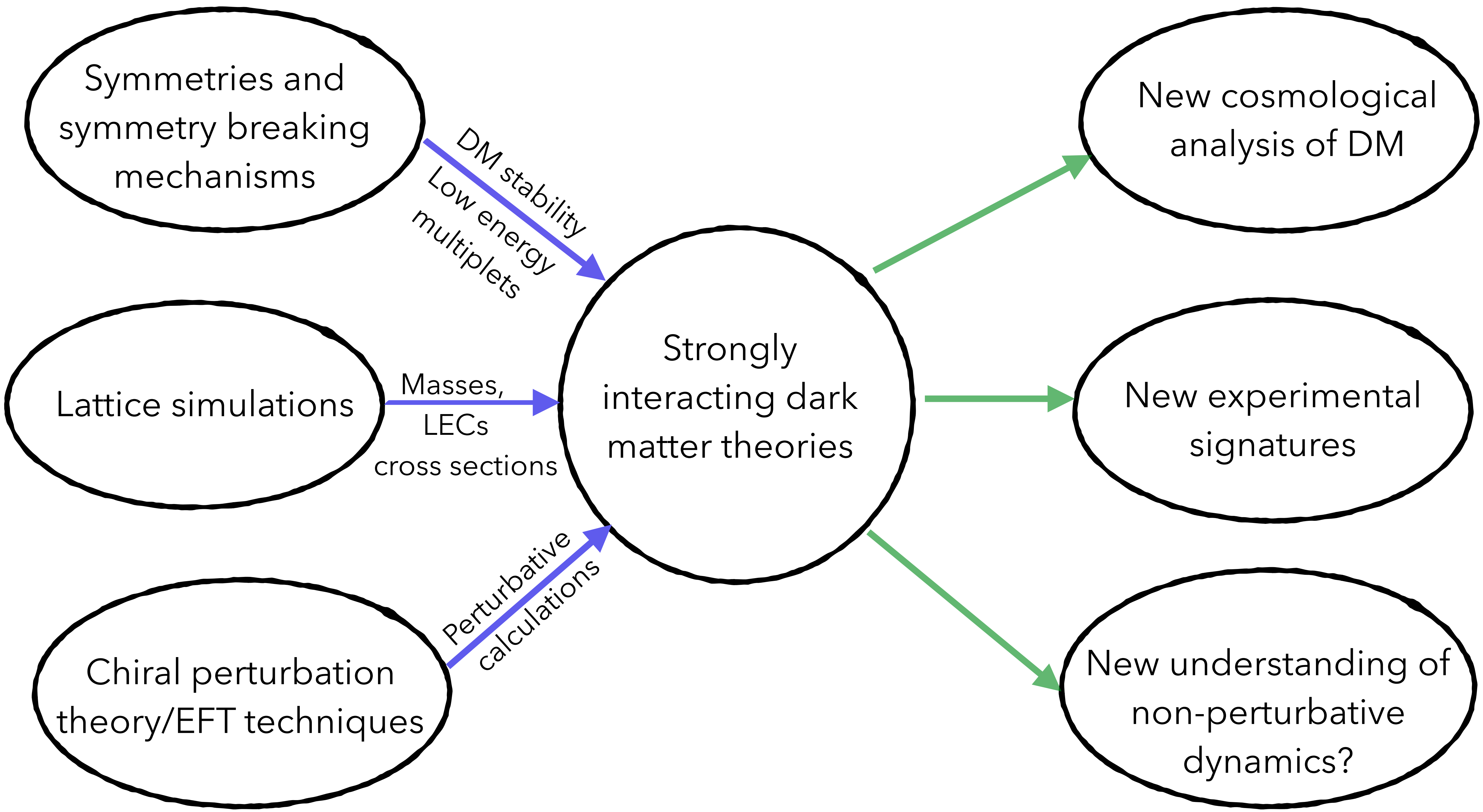






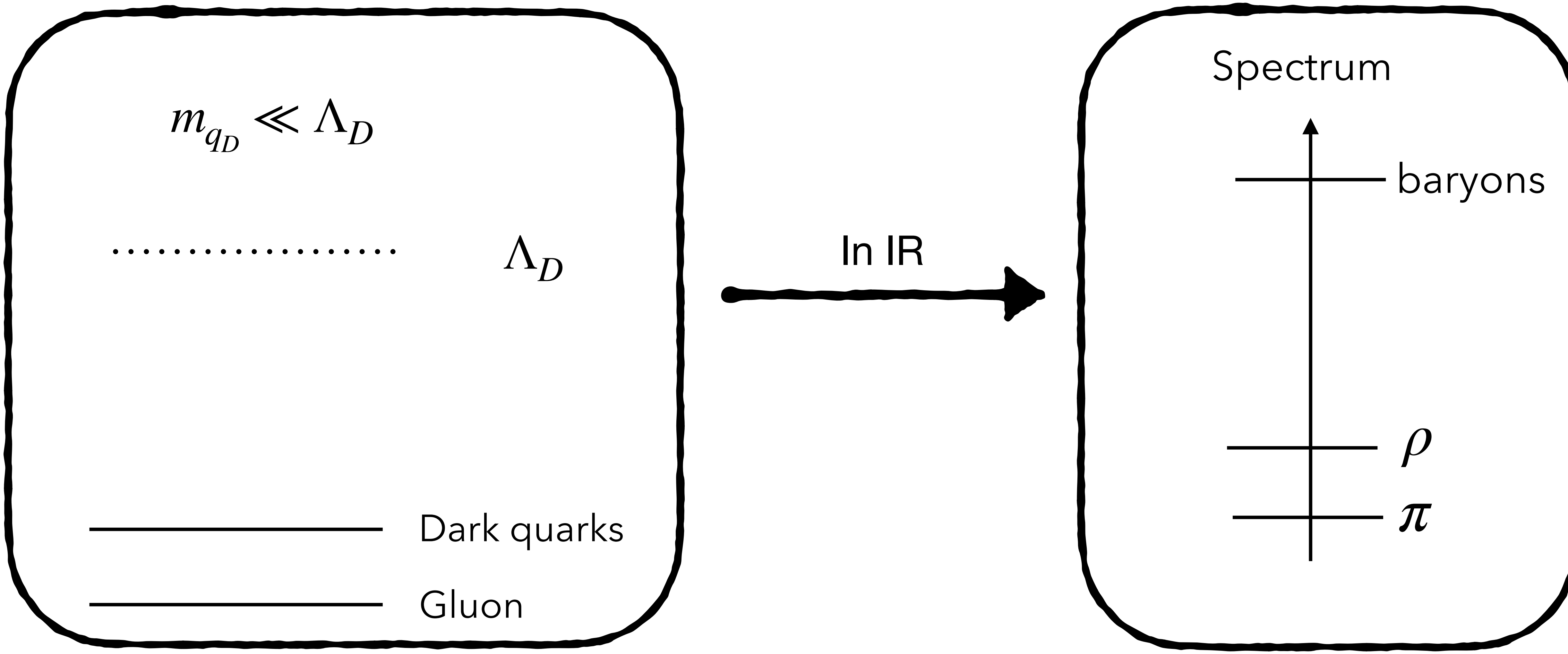
Strongly interacting theories: pathways

How to make systematic progress in the landscape of strongly interacting dark matter?



N.B. All calculations can be done on lattice, but they are expensive, perturbative analysis is pragmatic way out

Strongly interacting theories: composition

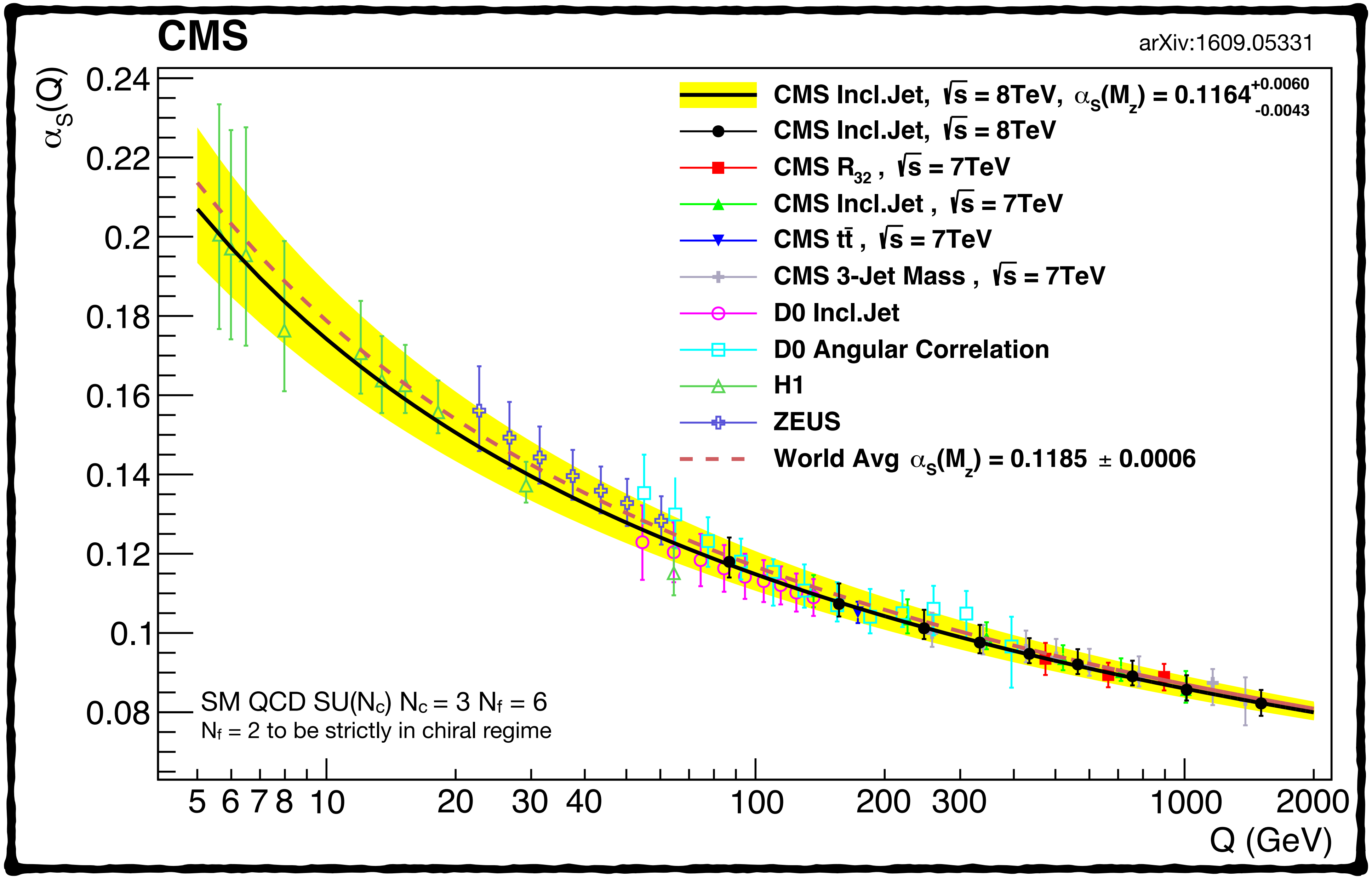


UV physics contains

- Gauge fields (gluons)
- Matter fields i.e. Dirac/Majorana fermions, Scalars (in representation N_r)
- This talk: Dirac fermions in fundamental rep

- Two discrete parameters N_{c_D}, N_{f_D}
- Two continuous parameters $m_{q_D}, \alpha_D(\mu)$ (UV)
  - $\Lambda_D, m_{\pi_D}/\Lambda_D$ or $m_{\pi_D}, m_{\pi_D}/m_{\rho_D}$ (IR)
- $N_{c_D} = 2$ and/or $N_{f_D} = 1$ special cases

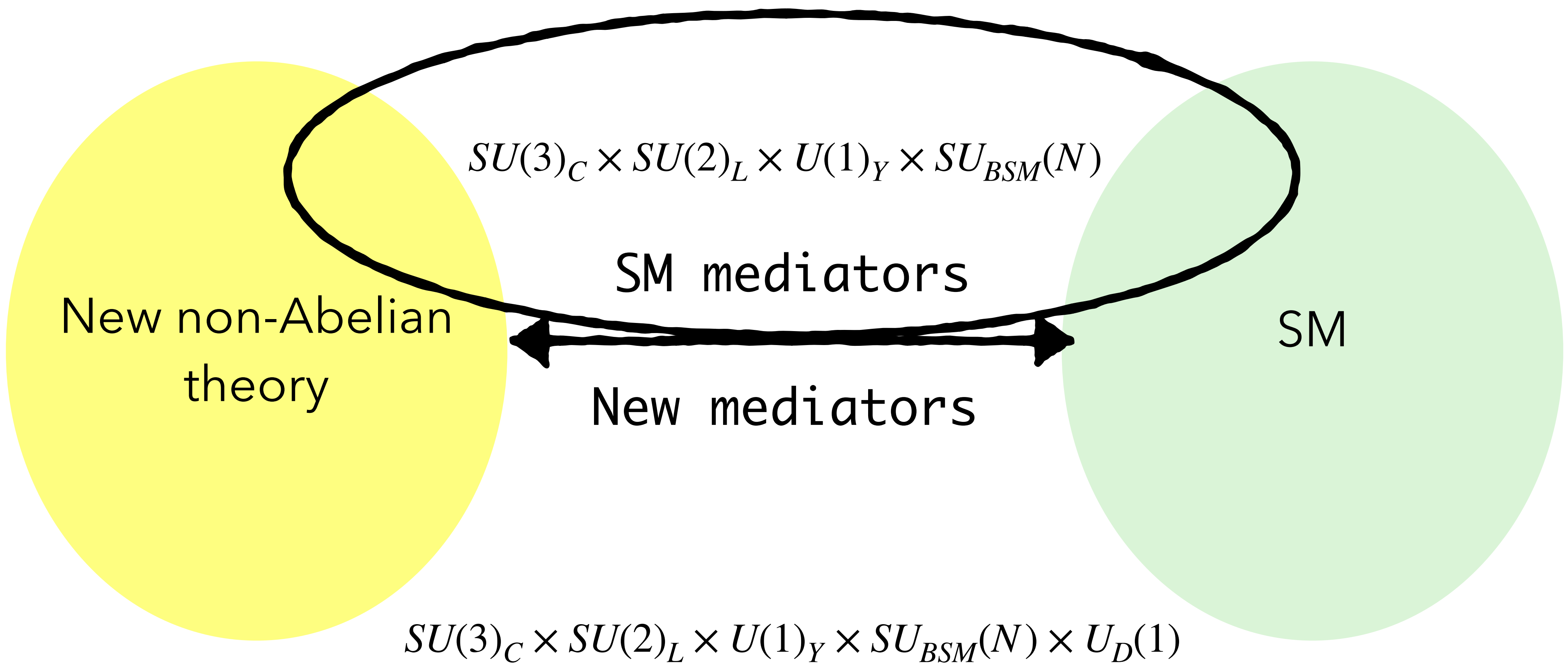
Strongly interacting theories: QCD-like



- QCD like theories: asymptotically free theories and in chirally broken phase (dark pions are Goldstones; chiral perturbation theory expected be valid)
- Choose N_{c_D}, N_{f_D} such that asymptotic freedom is achieved

New non-Abelian theory

Portal phenomenology - I

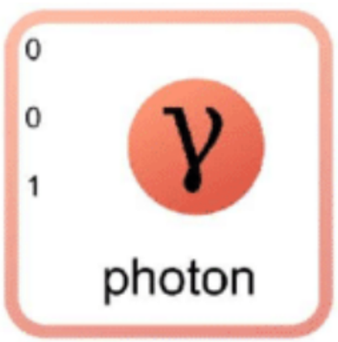


J. Butterworth, L. Corpe, **SK**., X. Kong, M. Thomas arXiv:2105.08494

SM mediators

Appelquist et al arXiv:1402.6656

Relevant if DS has SM color charges



Lowest dimensional operators:

- magnetic dipole (5)
- charge radius (6)
- polarizability (7)

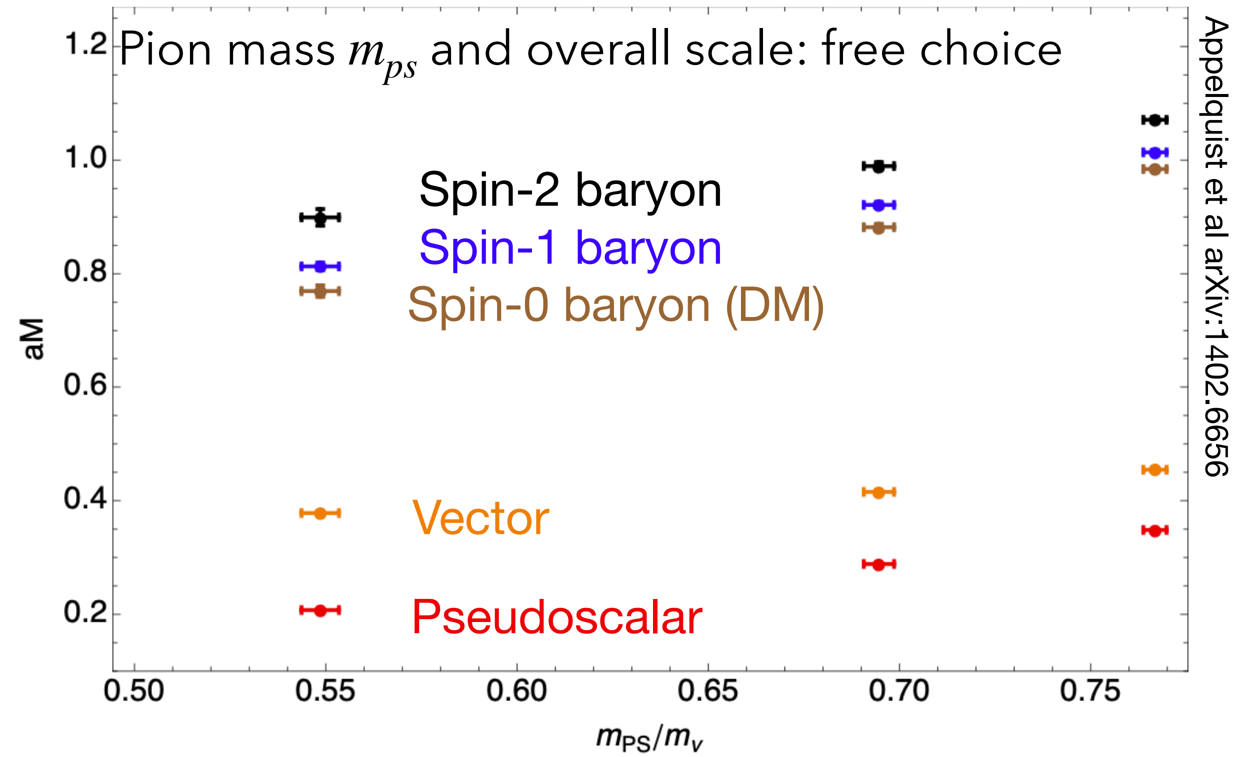
Similar considerations for W/Z mediators, suppressed by masses

Most relevant interaction if constituents have Yukawa couplings

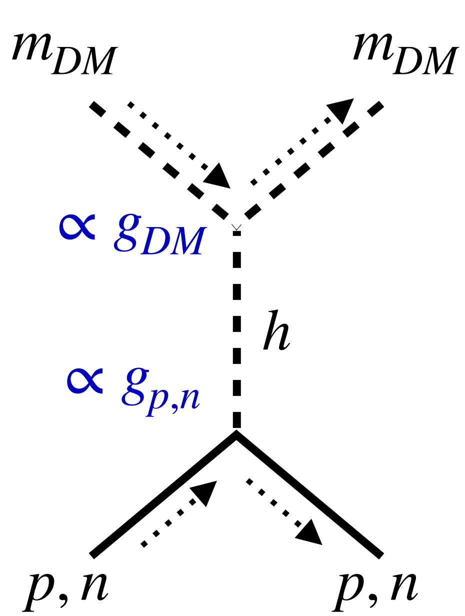
- Theory with $N_{c_D} = 4, N_{f_D} = 4$; contains scalar baryon
- Dark quarks get part of their masses from EWSB and partly vector-like

Phenomenology

- Necessary inputs for phenomenology
  - Bound state mass spectrum
  - Interaction with the SM sector
- LEP results $m_{\tilde{\tau}} > 86.6$ GeV directly applicable
  → dark proton mass > $\mathcal{O}(100)$GeV



DD phenomenology



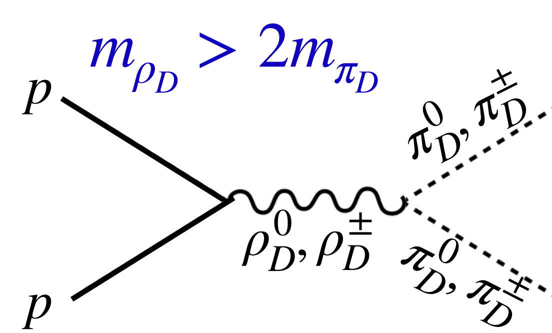
$$\mathcal{M}_{p,n} = \frac{g_{p,n}\, g_{DM}}{m_h^2}$$

$$g_{p,n} \propto f_q^{(p,n)}$$

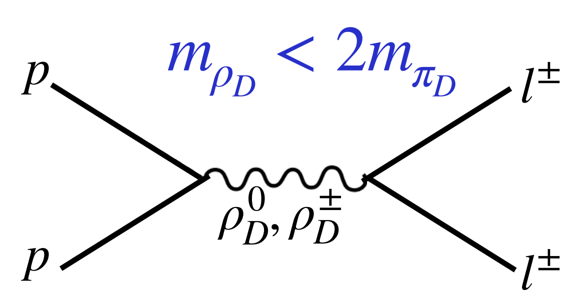
$$g_{DM} \simeq y_{eff} f_f^{DM}$$

Form factors f_q, f_f computed by lattice

LHC phenomenology

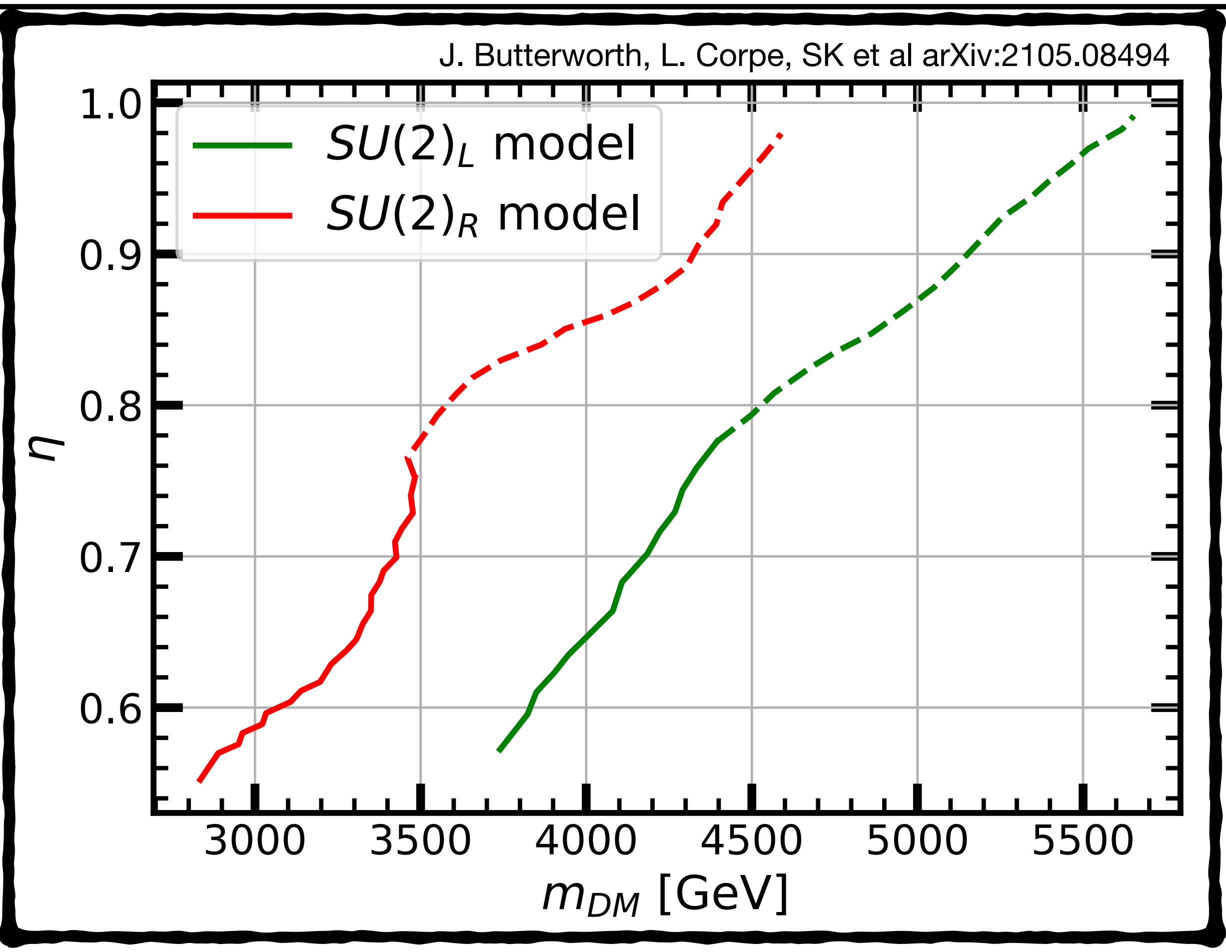


π_D decay to SM 3rd generation fermions/ Higgs → many searches



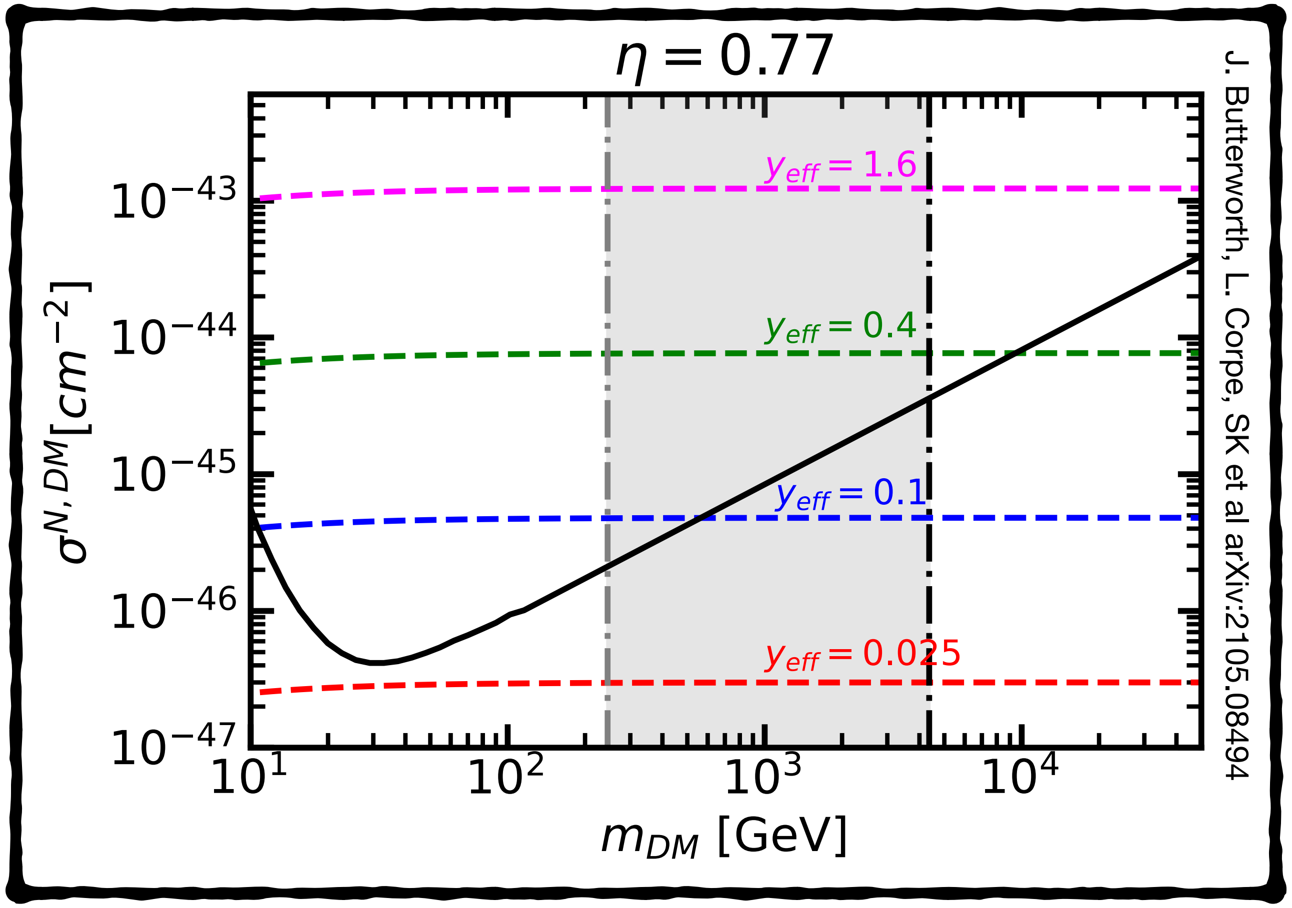
Dilepton searches

Constraints



See also Appelquist et al, arXiv:1503.04203

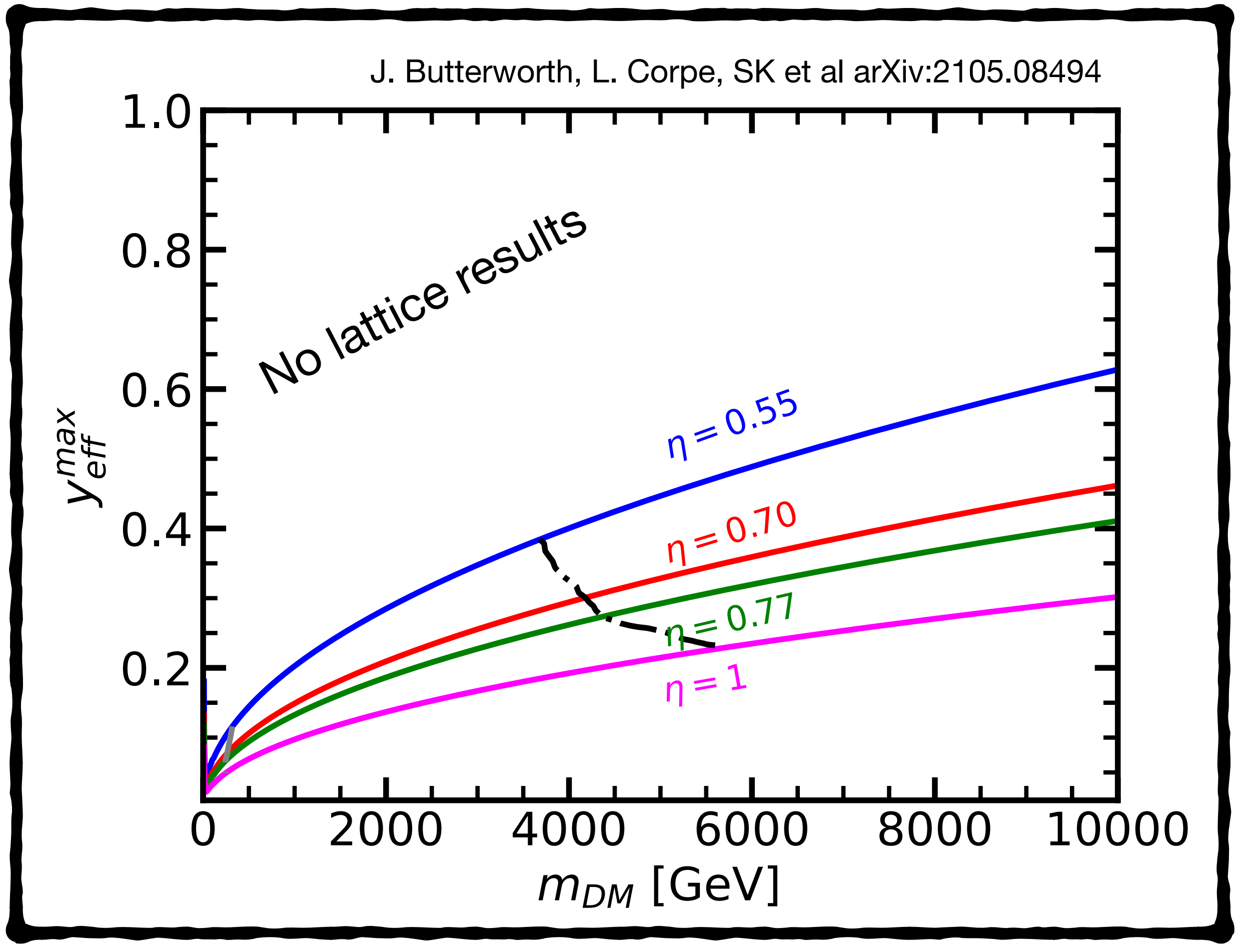
- Analysis with the help of CONTUR; constraints from SM precision measurements
- LHC exclusions together with the lattice results push the dark matter mass limits to multi-TeV mass range



- Direct detection limits push dark quark Yukawa coupling to lower values

Combined limits

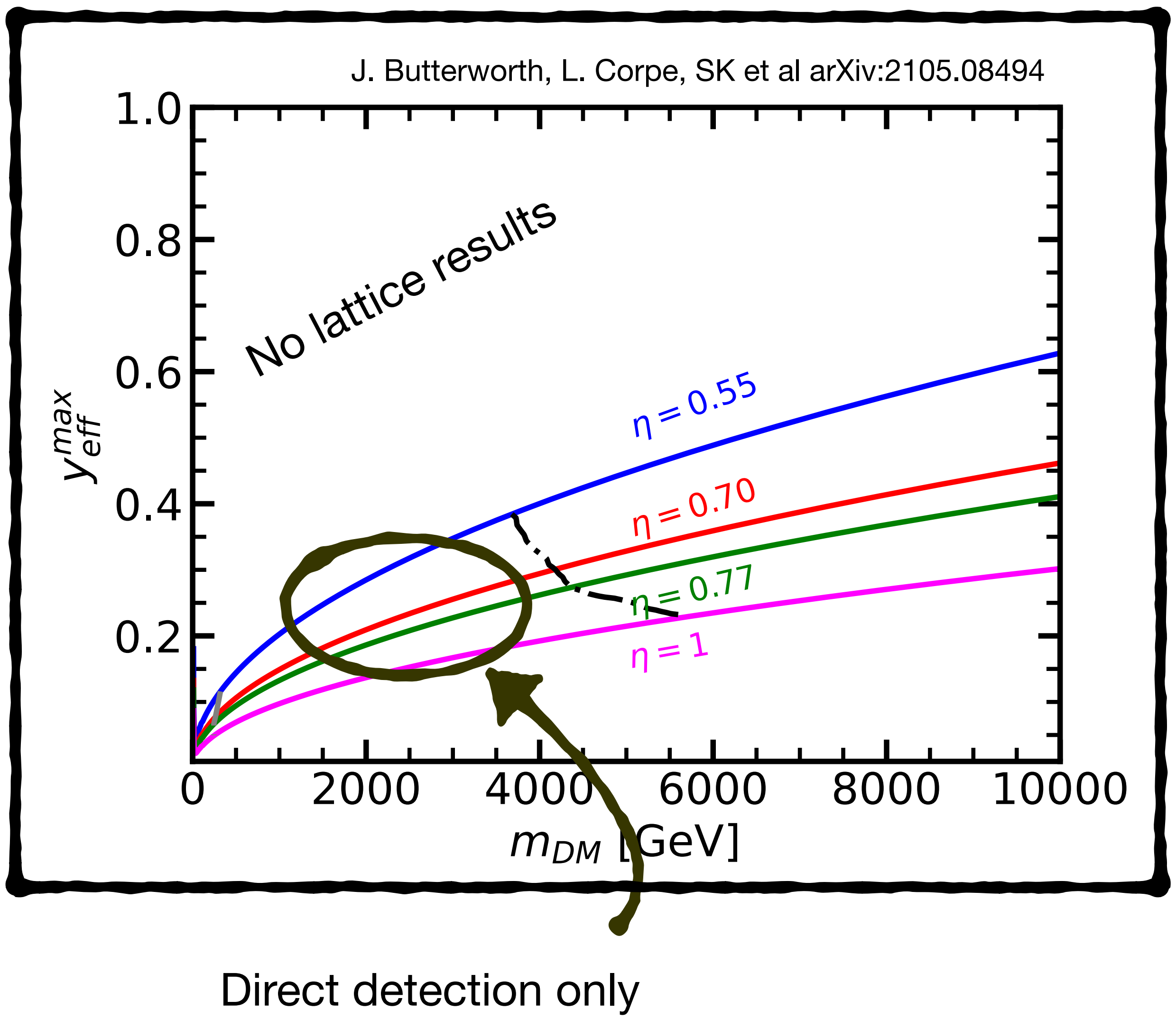
Combination of direct detection limits, LHC measurements and DY searches



Either require low values of Higgs - dark quark effective Yukawa coupling or require very heavy dark matter

Combined limits

Combination of direct detection limits, LHC measurements and DY searches



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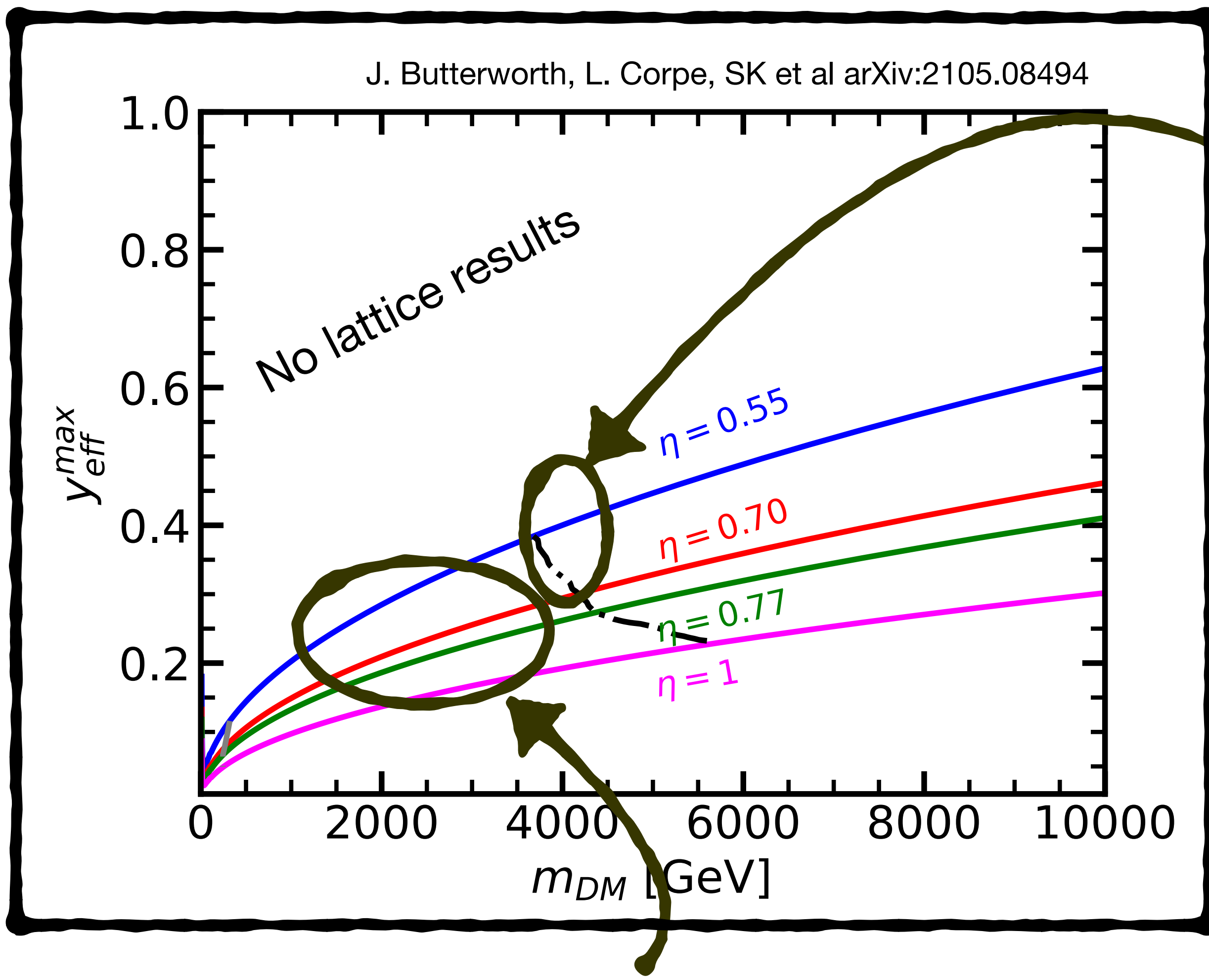


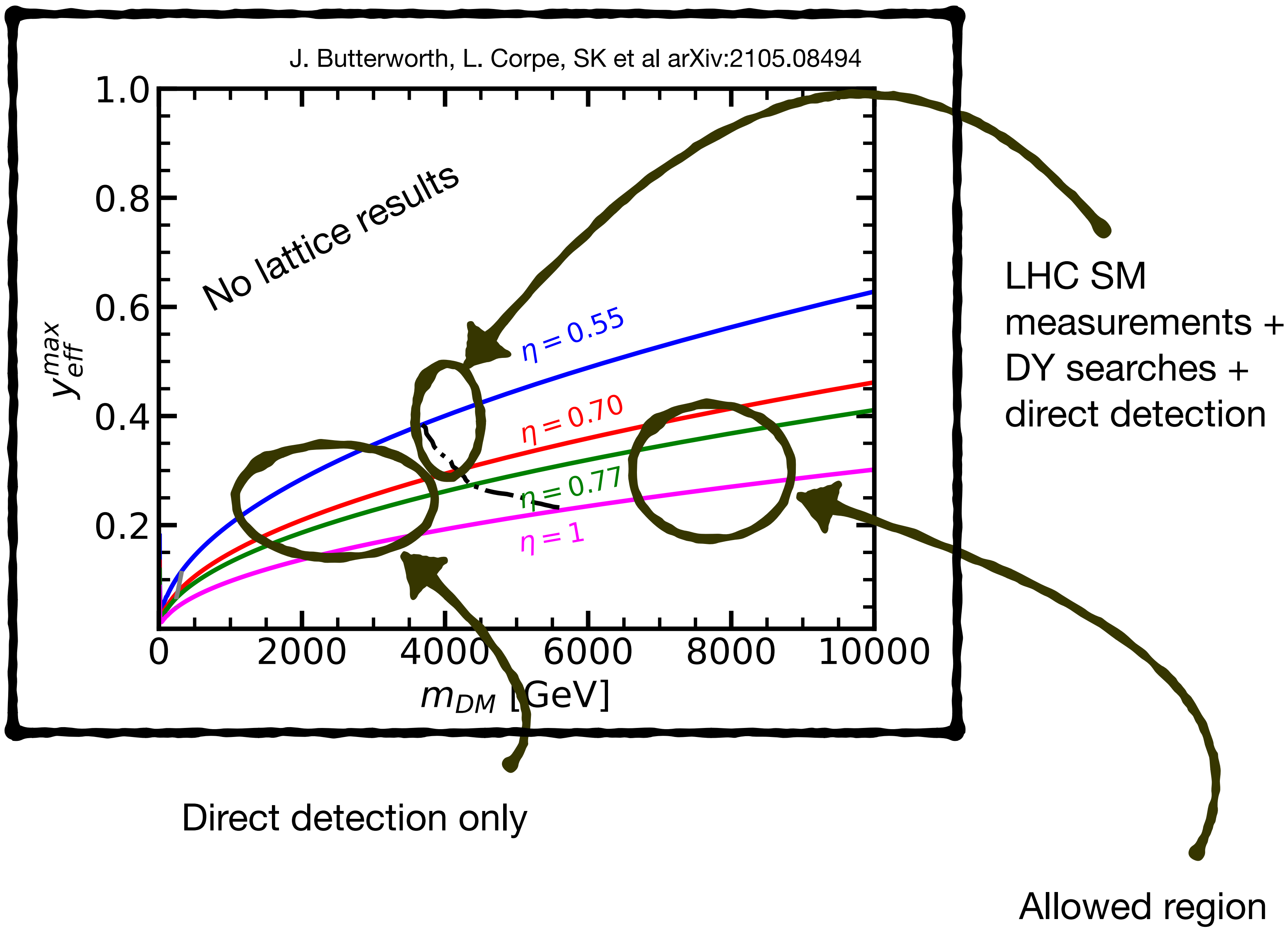
LHC SM measurements + DY searches + direct detection

Direct detection only

Either require low values of Higgs - dark quark effective Yukawa coupling or require very heavy dark matter

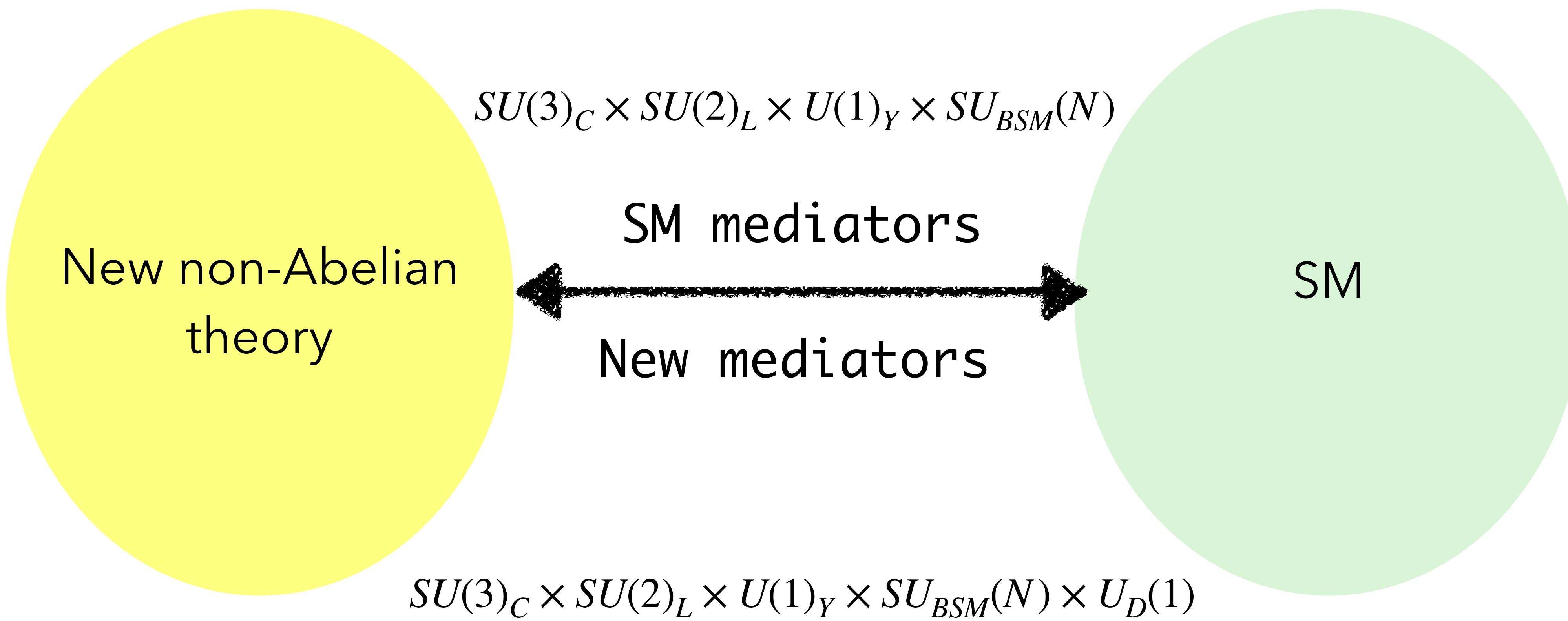
Combined limits

Combination of direct detection limits, LHC measurements and DY searches



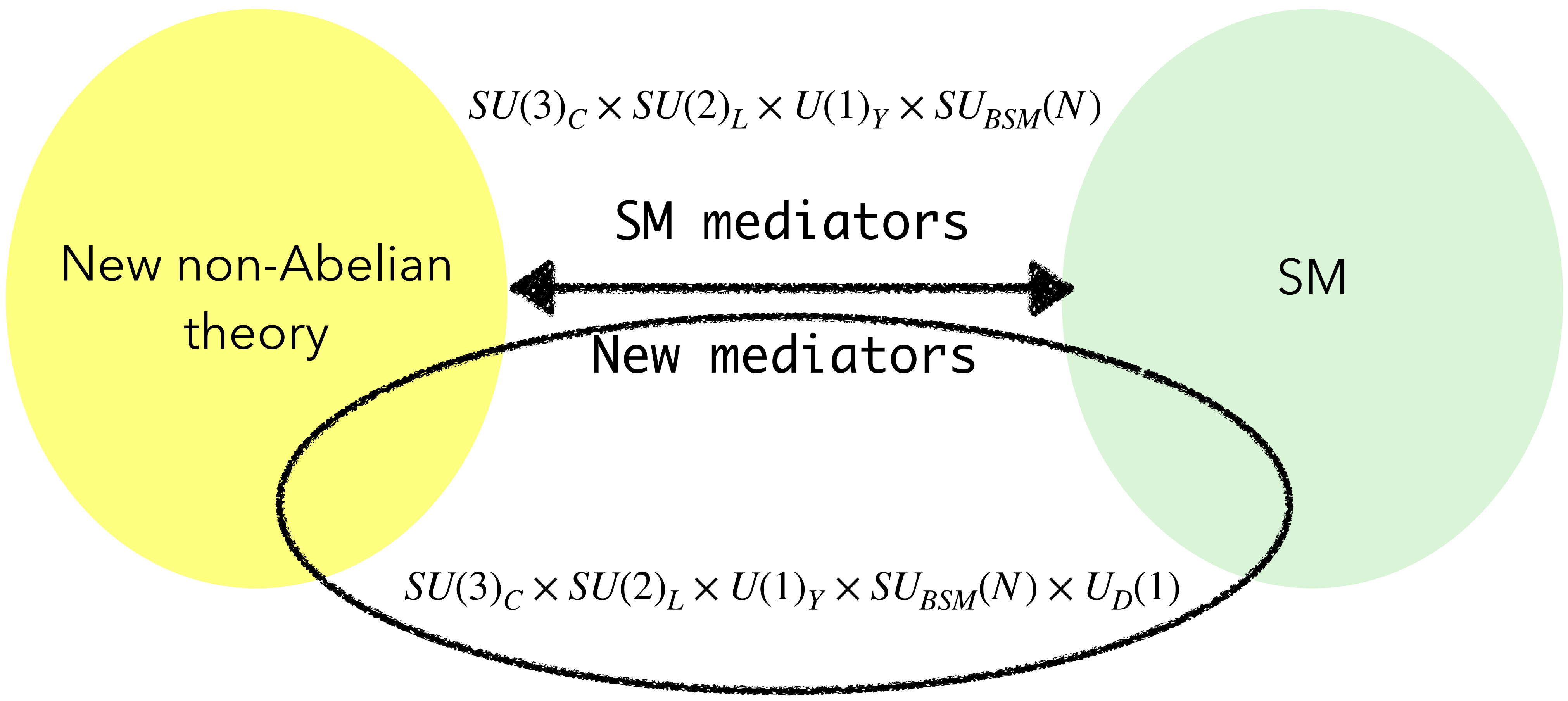
Either require low values of Higgs - dark quark effective Yukawa coupling or require very heavy dark matter

Portal phenomenology - II



Snowmass darkshowers (incl. **S.K.**, S. Mee, M. Strassler) arXiv:2202.05191

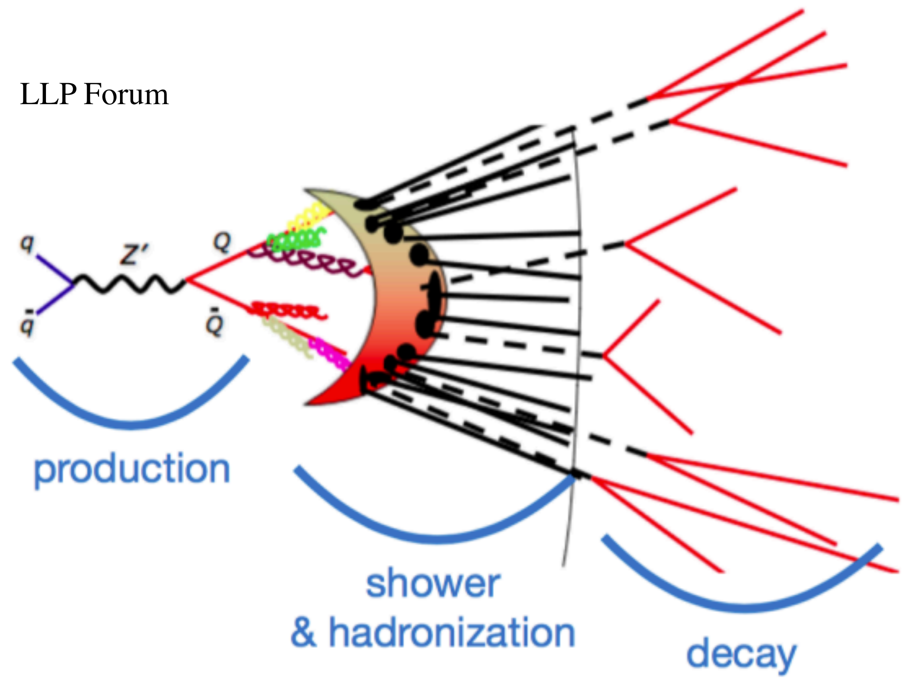
Portal phenomenology - II



Snowmass darkshowers (incl. **S.K.**, S. Mee, M. Strassler) arXiv:2202.05191

Theory setup

$$\mathcal{L}_{\text{int}} \subset -e_D Z'_\mu \sum_i \overline{q}_{Di} Q_i \gamma^\mu q_{Di} - g_q\, Z'_\mu \sum_r \overline{q}_{SM,r} \gamma^\mu q_{SM,r}$$

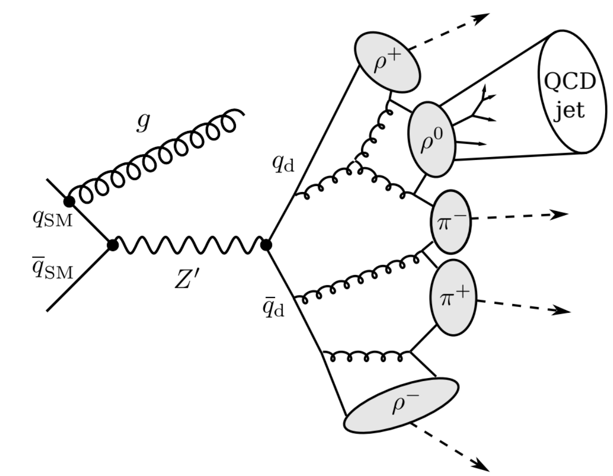


- $m_{Z'} \gtrsim 30\Lambda_D\,, m_{q_D} \ll \Lambda_D \ll \sqrt{s}$ → production of dark quarks followed by rapid parton showering and hadronization → jets
- Z' coupling leads to decay of some of the dark hadrons back to the SM; details coupling dependent

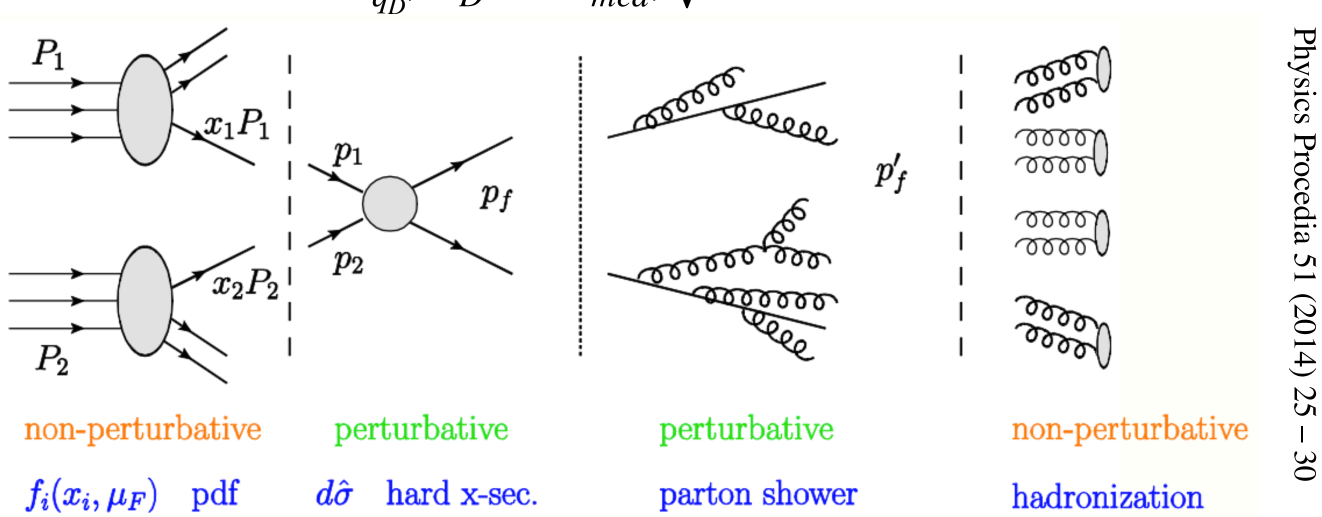
(LHC) phenomenology

- Depending on N_{c_D}, N_{f_D} a variety of DM candidates possible e.g. dark pions, dark baryon (NB: baryons could be spin 0,1/2)
- Stabilise pions with appropriate $U_D(1)$ charges → easier in even flavours than odd flavours
- Dark quark production followed by hadronization (similar to the SM at the LHC)
- Leads to new signatures, few constraints, many possibilities

Kahlhoefer et.al. arXiv:1907.04346



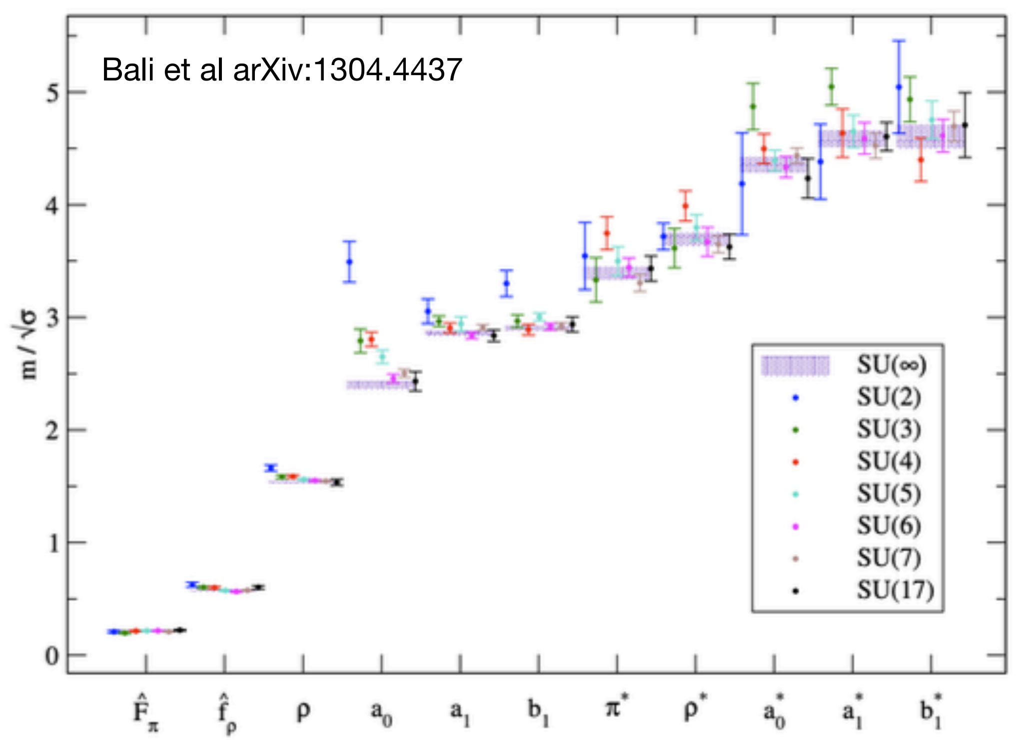
$m_{q_D}, \Lambda_D \ll m_{med}, \sqrt{s}$



α_D runs, running controlled by Λ_D

- Jet shapes and kinematics depends on consistency between UV and IR regimes
- It seems favourable to use Λ_D as external scale to define physical masses

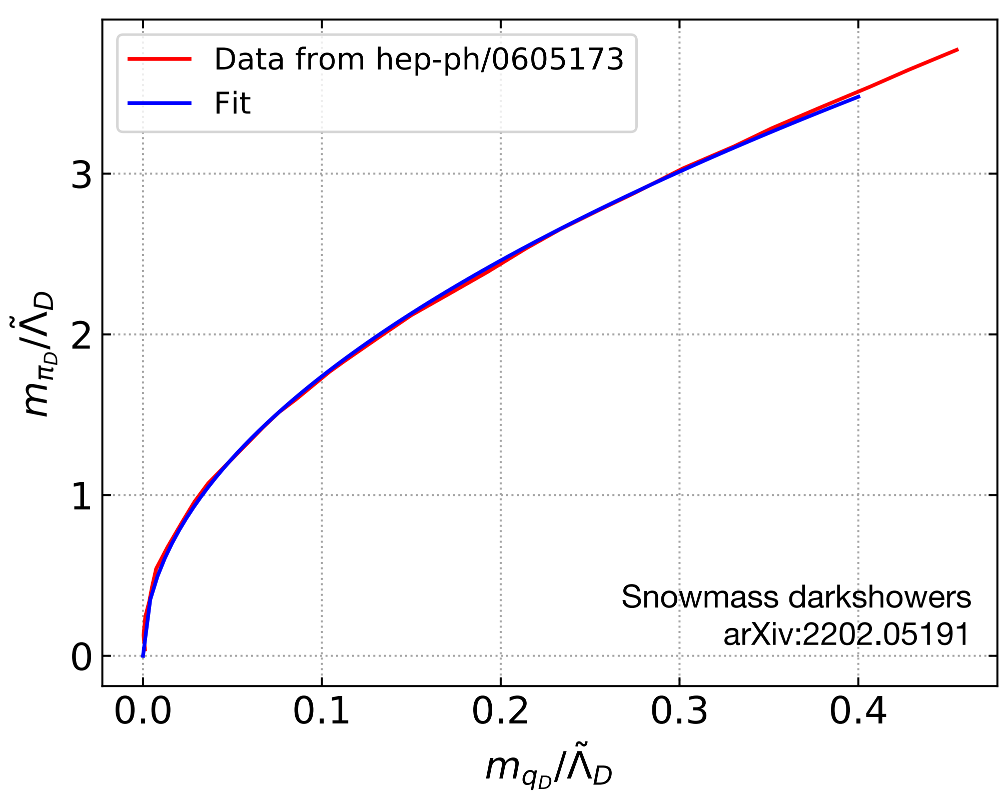
Dark meson masses

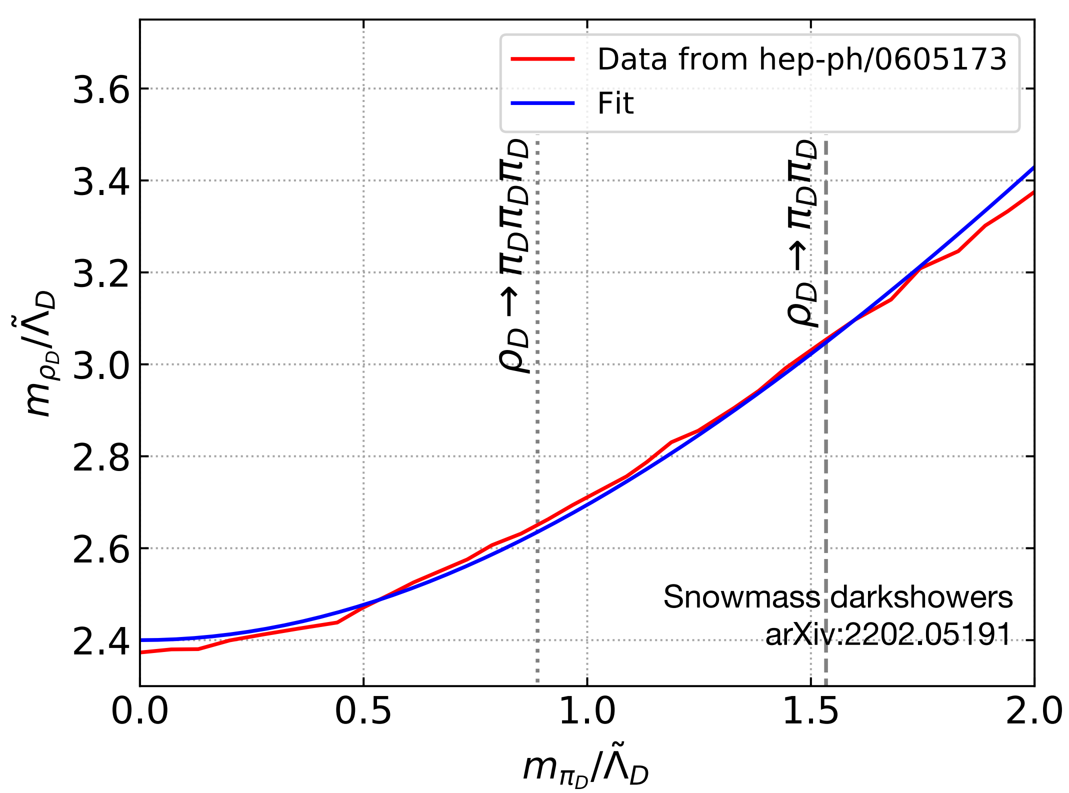


Snowmass darkshowers arXiv:2202.05191

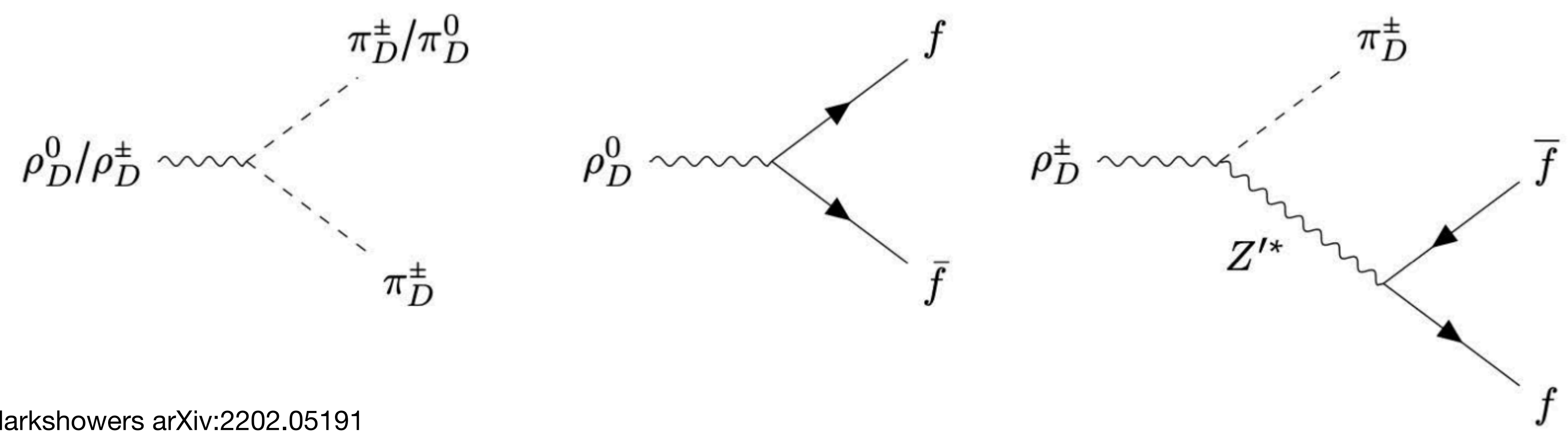
- Effects due to N_{c_D}, N_{f_D} can be ignored for now
- Dark meson mass fits from lattice results

$$\frac{m_{\pi_D}}{\tilde{\Lambda}_D} = 5.5\sqrt{\frac{m_{q_D}}{\tilde{\Lambda}_D}} \qquad \frac{m_{\rho_D}}{\tilde{\Lambda}_D} = \sqrt{5.76 + 1.5\,\frac{m_{\pi_D}^2}{\tilde{\Lambda}_D^2}}$$





Dark meson decays

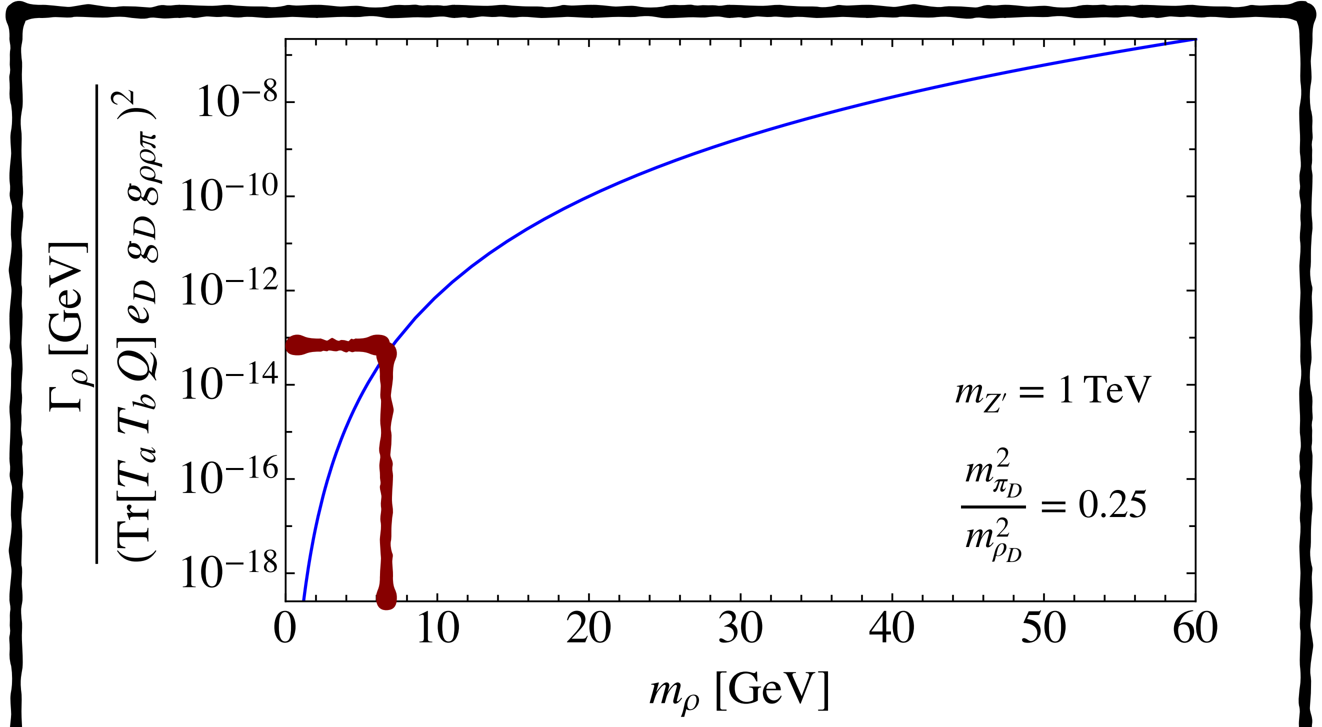


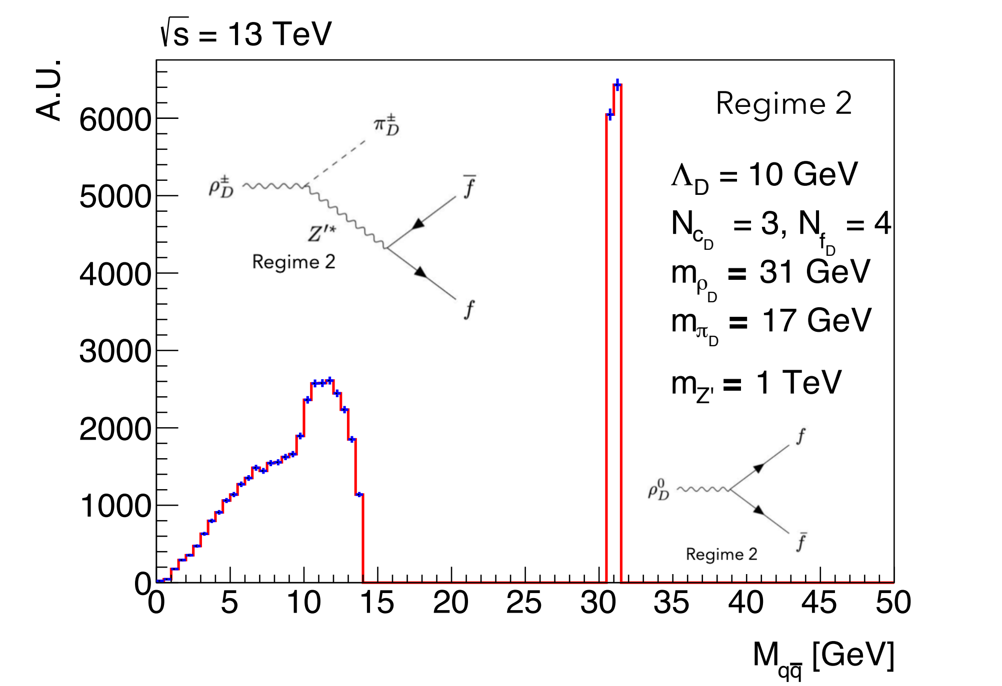
Snowmass darkshowers arXiv:2202.05191

- Off-diagonal dark rho can undergo three body decays; have been absent from much of LHC and DM phenomenology

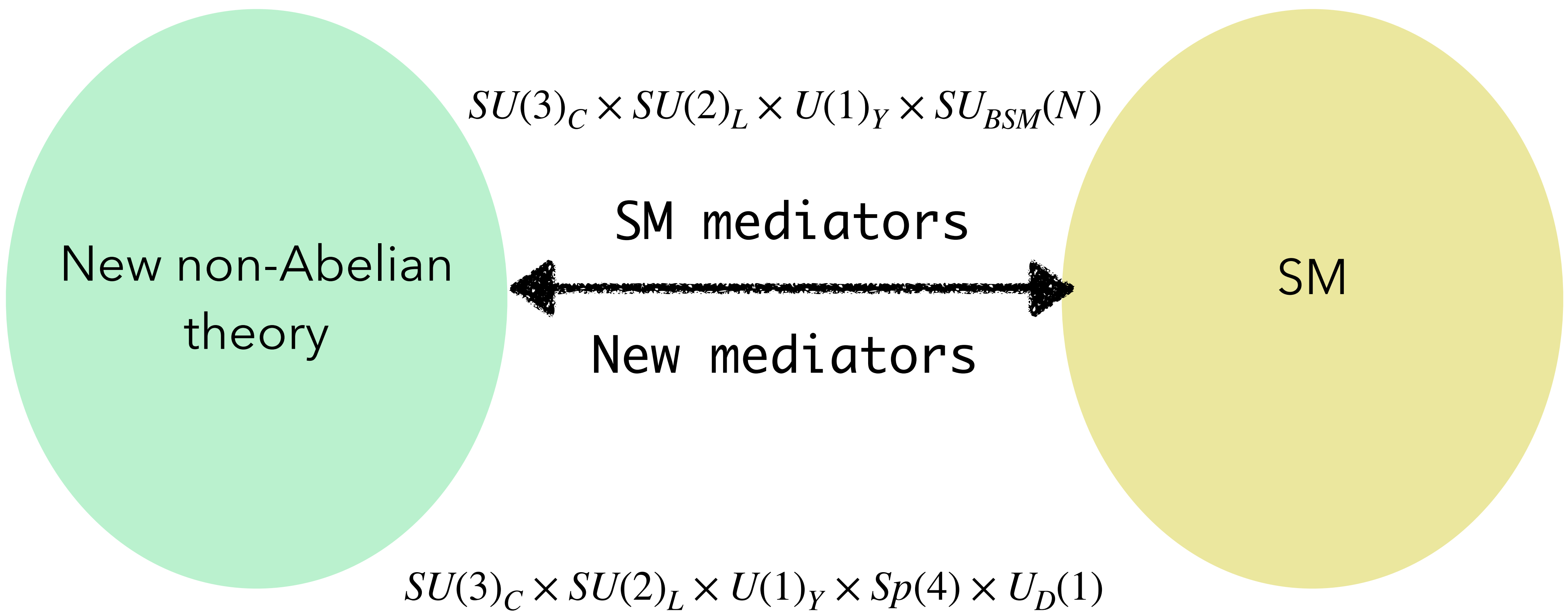
See also Beriln et al arXiv:1801.05805, Lee et al arXiv: 1504.00745

- Leads to LLPs → displaced vertices at the colliders, correlation cosmology





Beyond SU(N)



S.K., A. Maas, S. Mee, M. Nikolic, J. Pradler, F. Zierler arXiv:2202.05191

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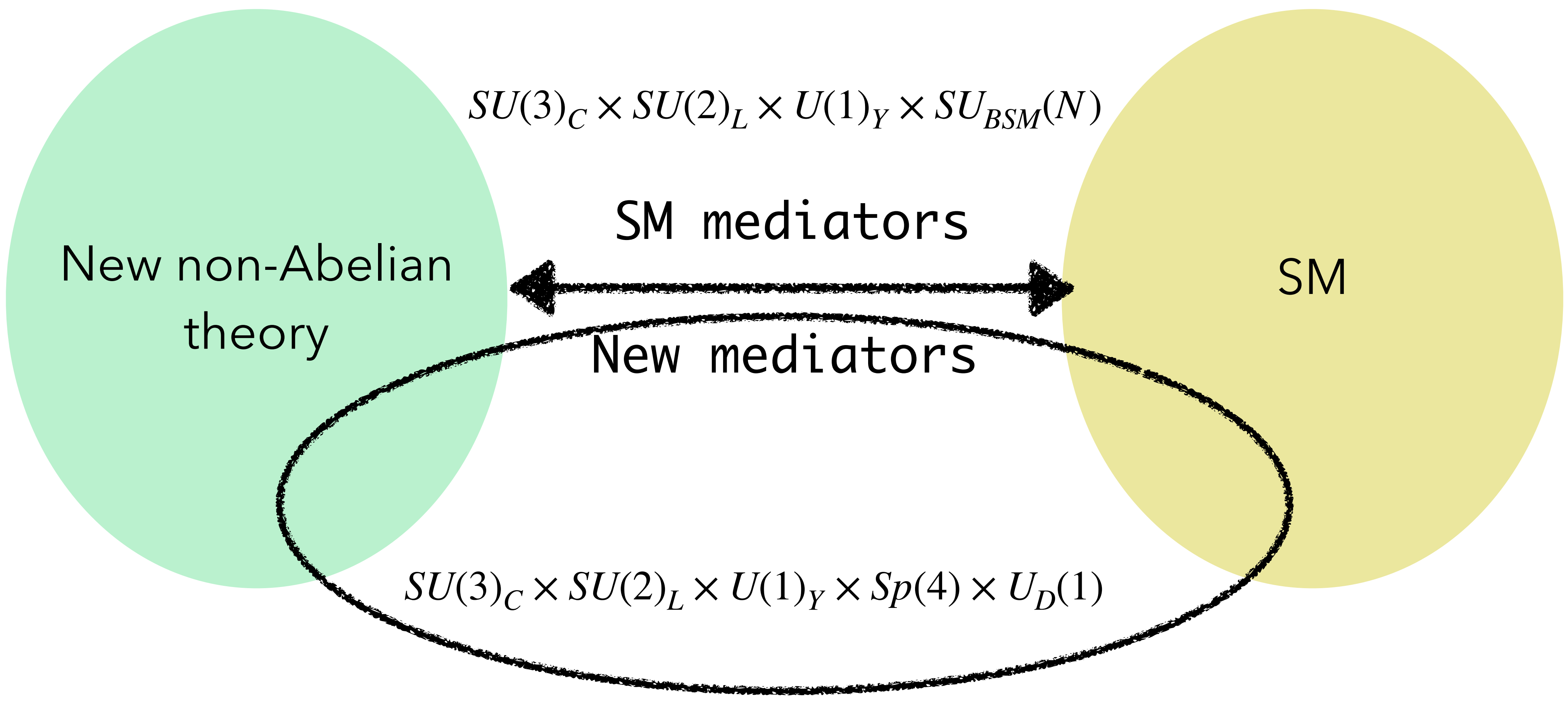

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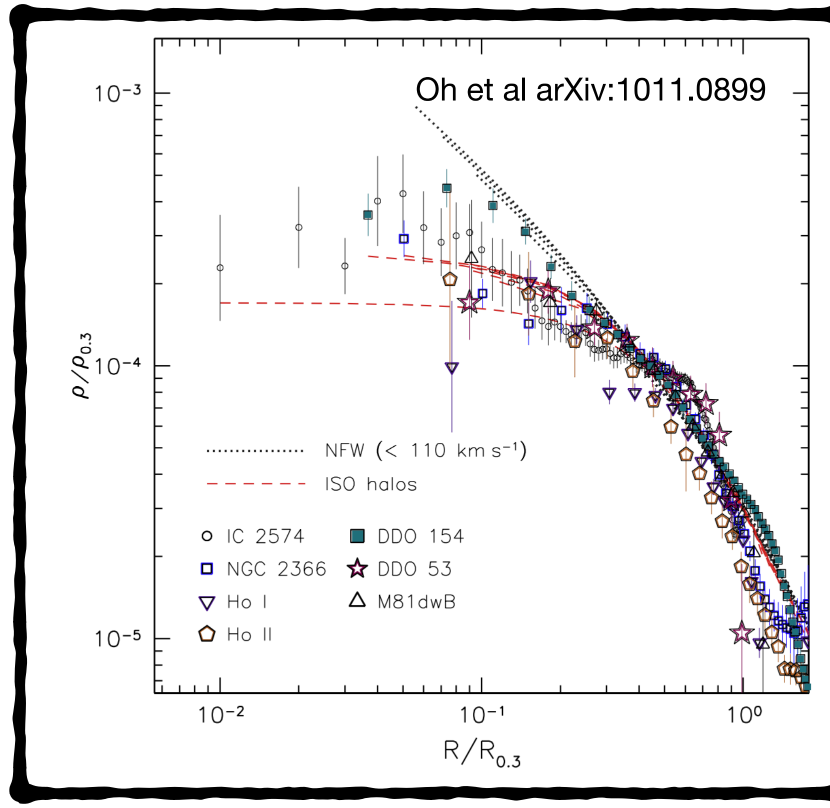
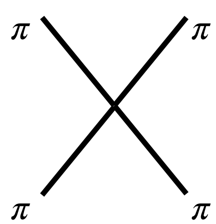
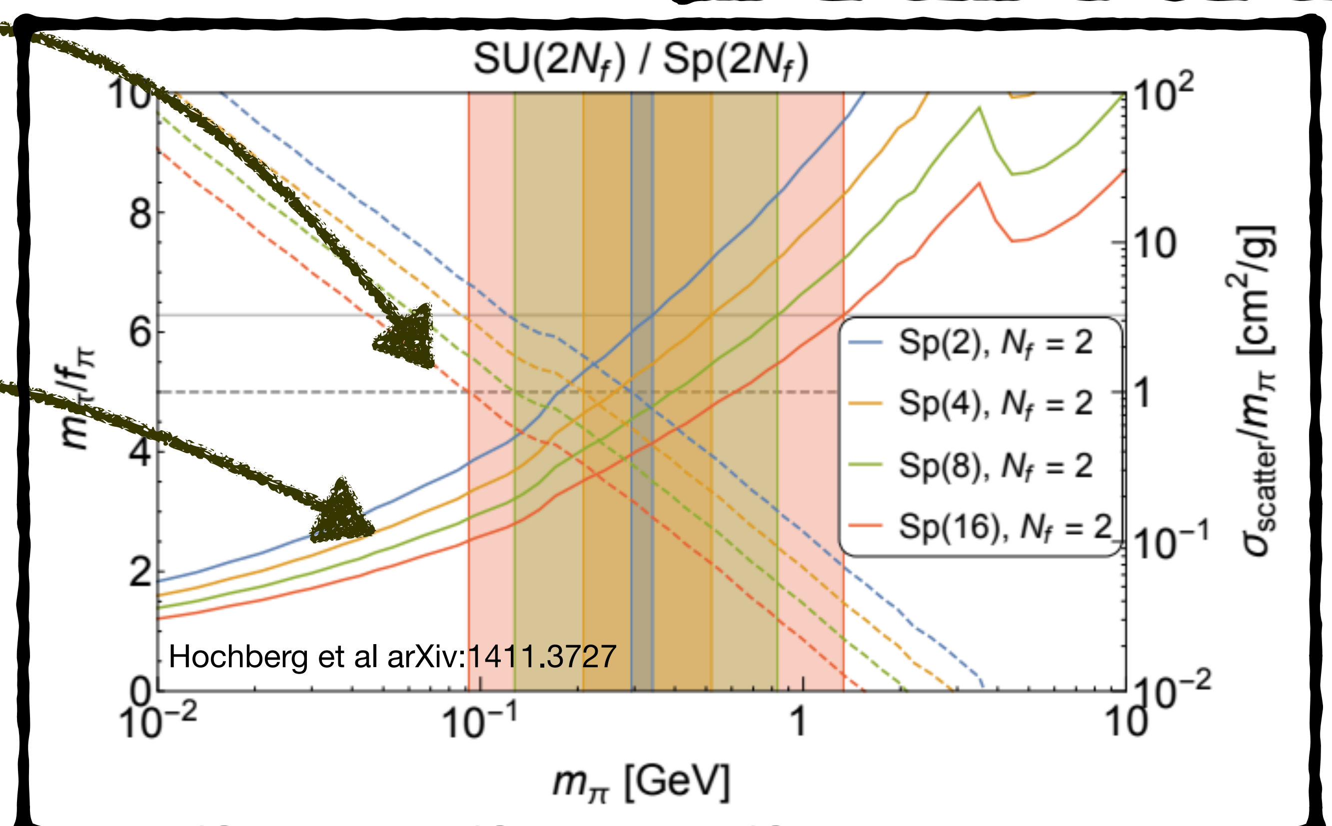
Dark pion dark matter

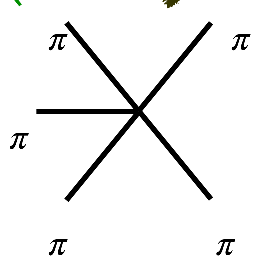
- Work in chiral regime, pions are pseudo-Goldstone bosons
- Chiral Lagrangian also contains Weiss-Zumino-Witten term
- In the SM: $K^+K^- \to \pi^+\pi^0\pi^-$ and $\pi^0 \to \gamma\gamma$







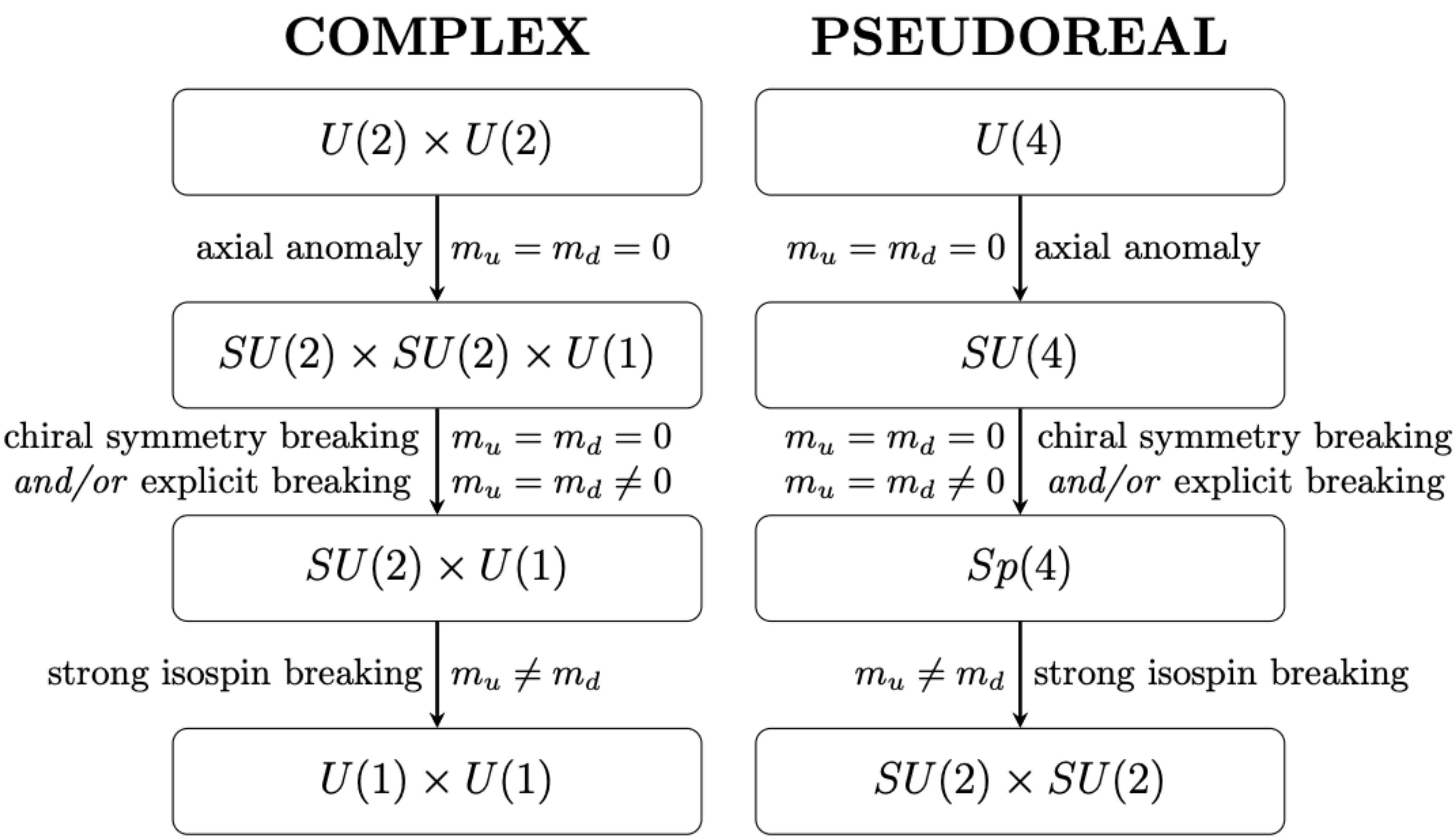
For free!



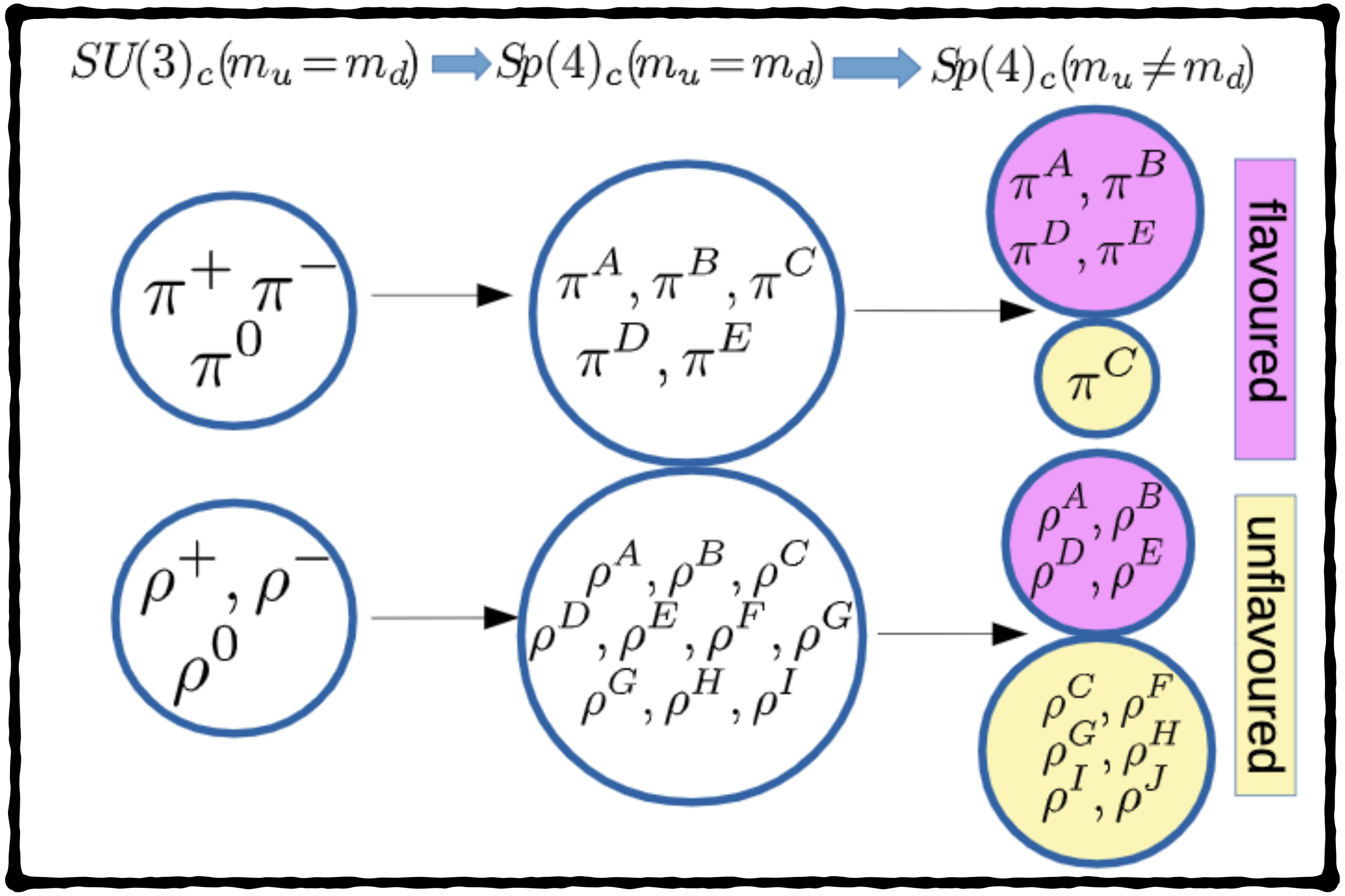
Symmetries

Any SU(N), N > 2 group $N_f = 2$

Sp(4)/symplectic group $N_f = 2$



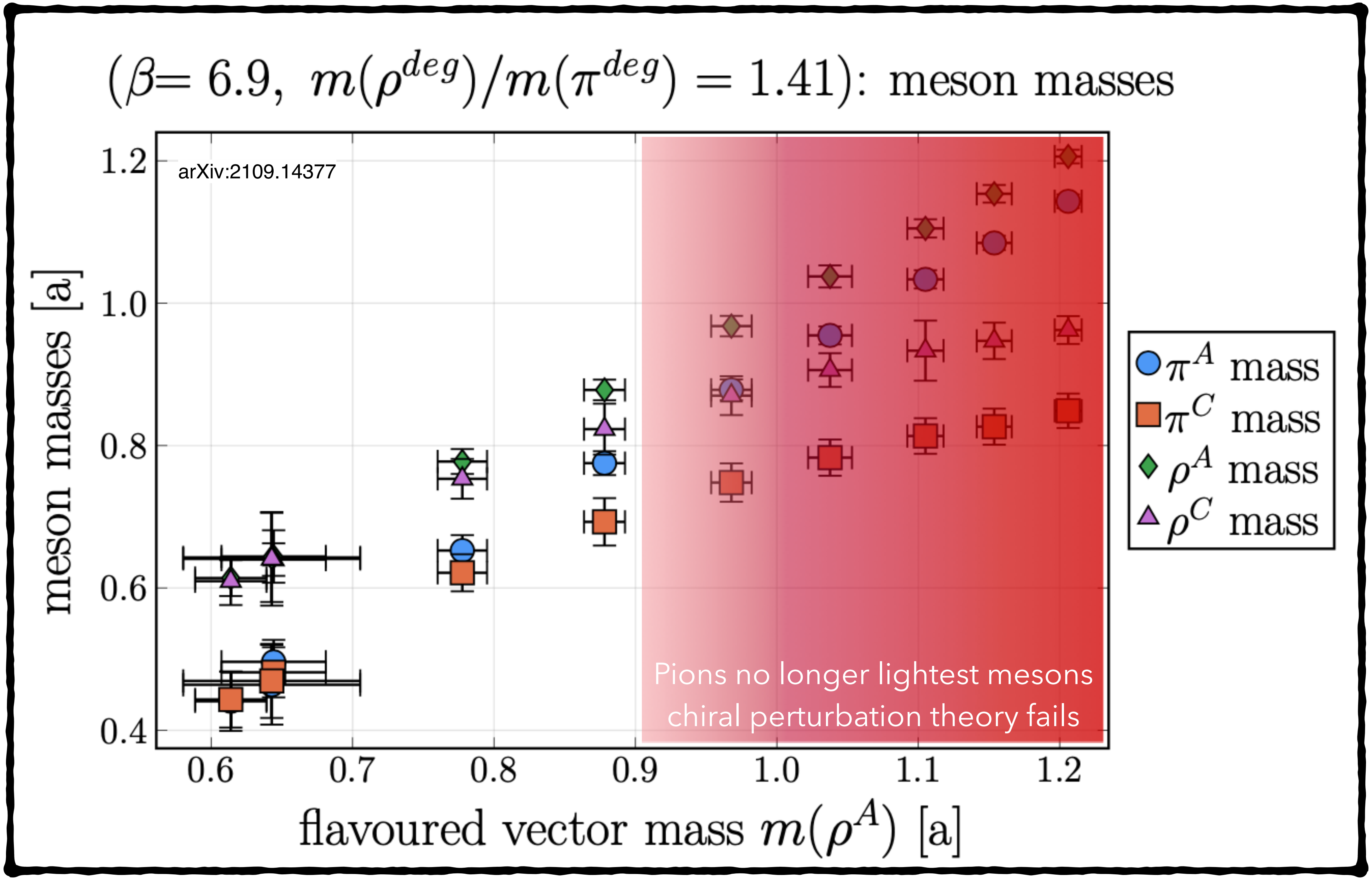
Phenomenological implications



- Theory contains 5 pions associated with broken generators of SU(4)/Sp(4)
- It contains 10 rho mesons associated with unbroken generators
- Can lead to characteristically different phenomenology in low energy
- Charging the theory under external U(1) keeps all pions stable

$$Sp(4) \to SU(2) \times U(1) \quad \begin{pmatrix} \pi^C \\ \pi^D \\ \pi^E \end{pmatrix}, \begin{pmatrix} \pi^A \\ \pi^B \end{pmatrix}$$

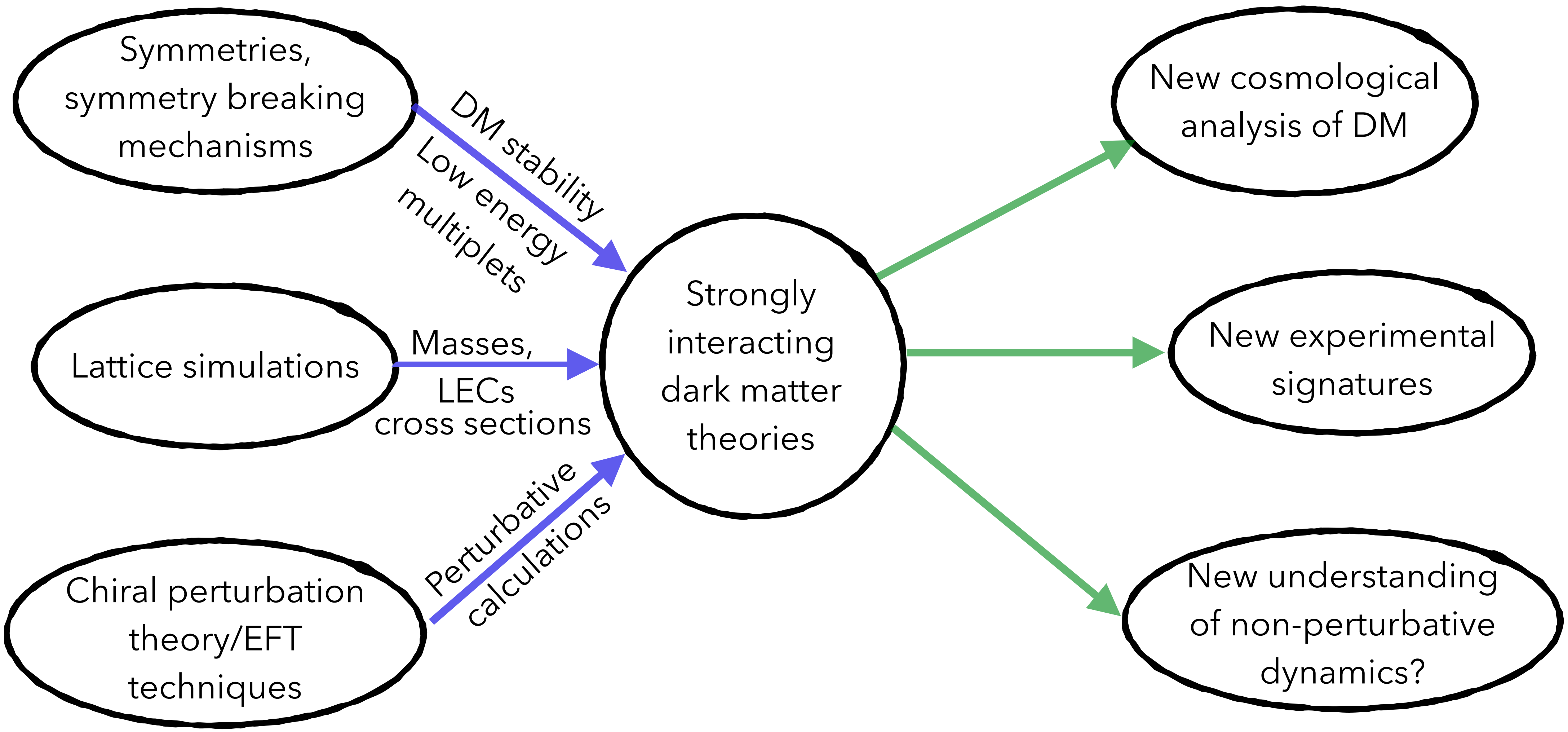
Lattice calculations $m_u \neq m_d$



- For the first time ever, lattice calculations available for non-degenerate dark quark masses

Conclusions

A systematic analysis of strongly interacting theories is possible



- Presented several examples containing dark baryon and dark pion dark matter candidates
- DM stability is ensured either via symmetries inbuilt in the theories or via careful choices of external charges
- Multiple relic density generation mechanisms can be engineered
- Portals lead to new interesting phenomenology

Thanks for listening

Questions?