Dark matter: theoretical status

Suchita Kulkarni (she/her)
Junior group leader
suchita.kulkarni@uni-graz.at

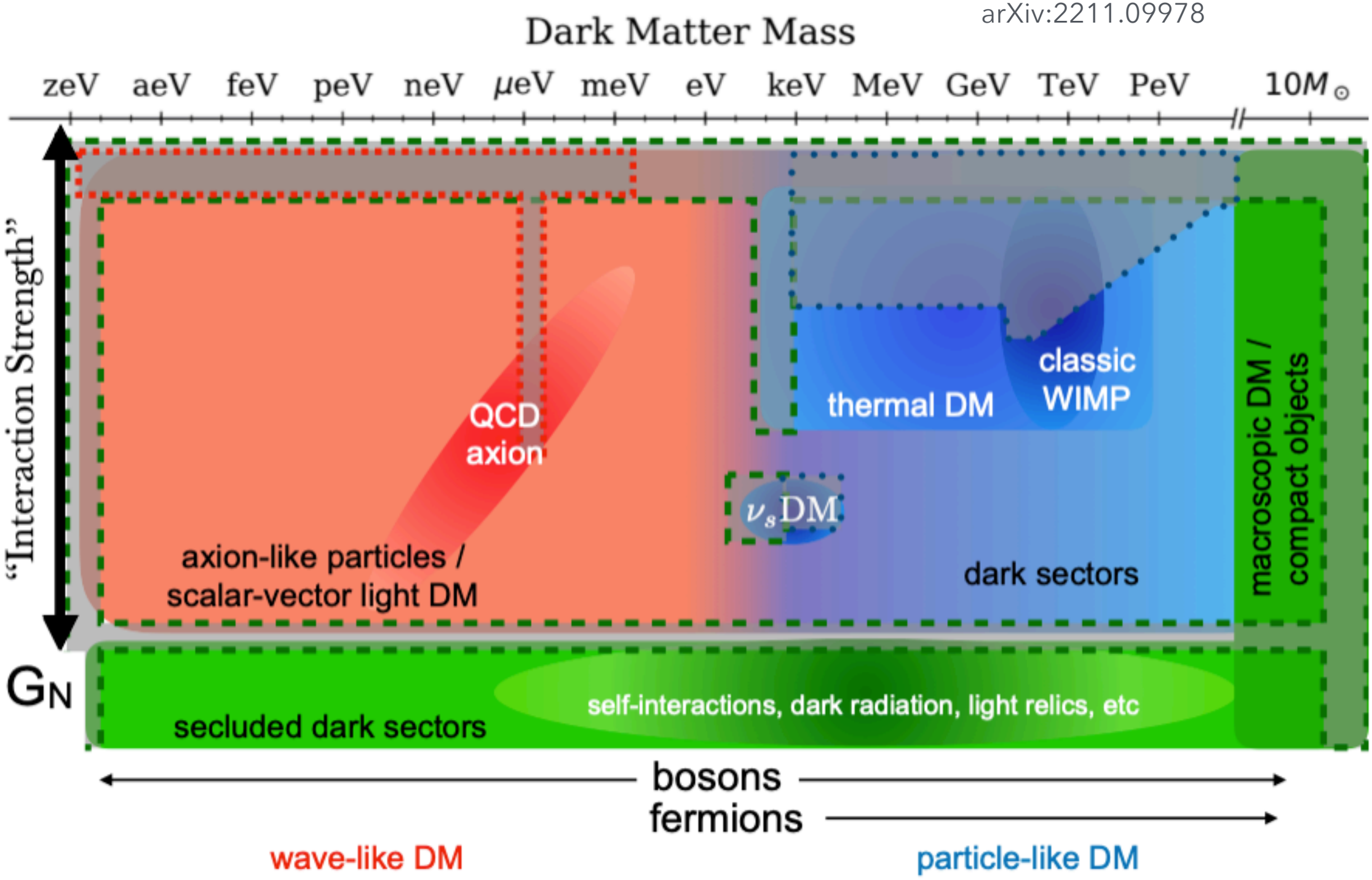
NAWI Graz
Natural Sciences

FWF
Der Wissenschaftsfonds.

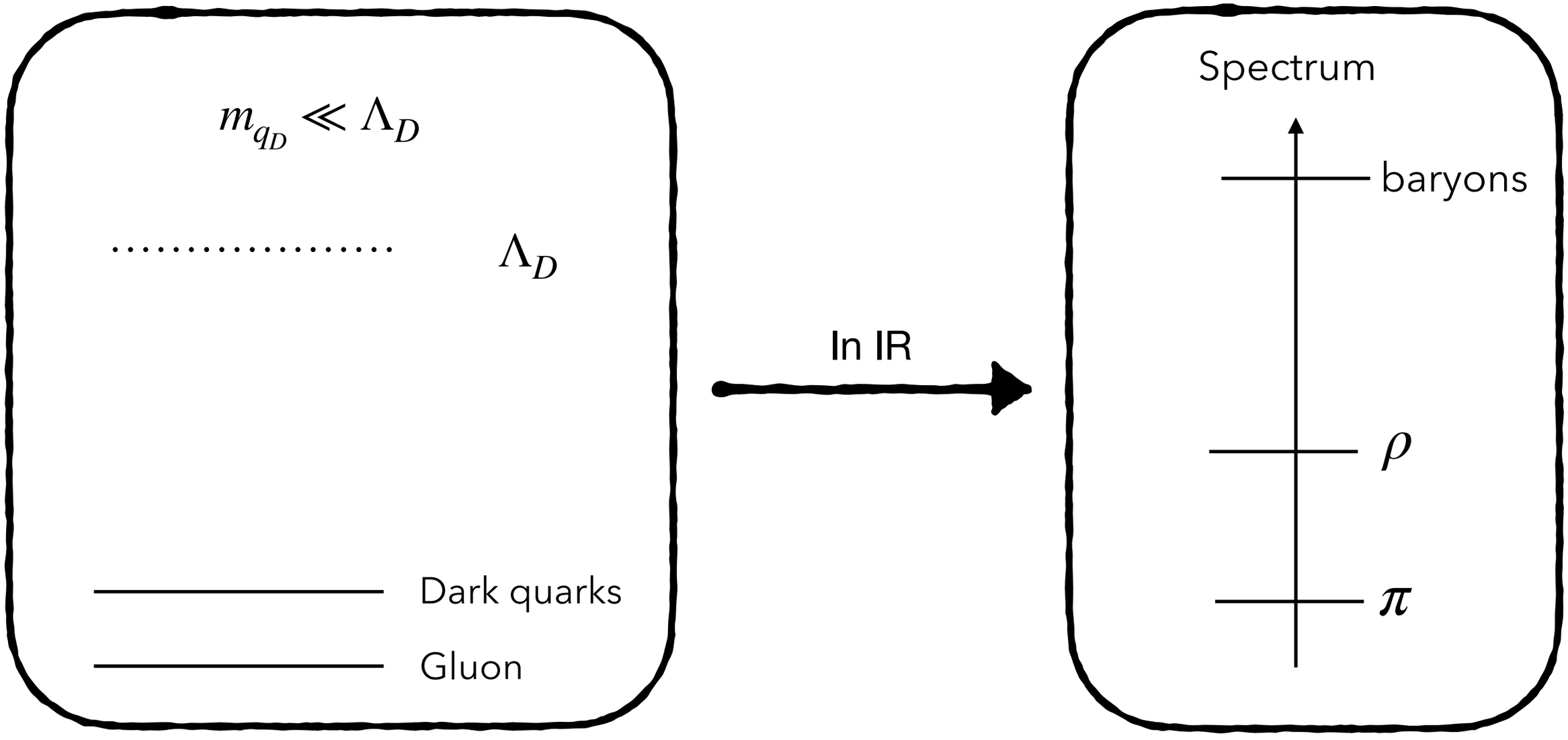
UNI GRAZ

Dark matter: where are we?

Snowmass cosmic frontier
arXiv:2211.09978



Can dark matter be composite instead of elementary?



- UV and IR dynamics are correlated with each other; learning about UV can teach us about IR and vice-versa

Can dark matter be composite instead of elementary?

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

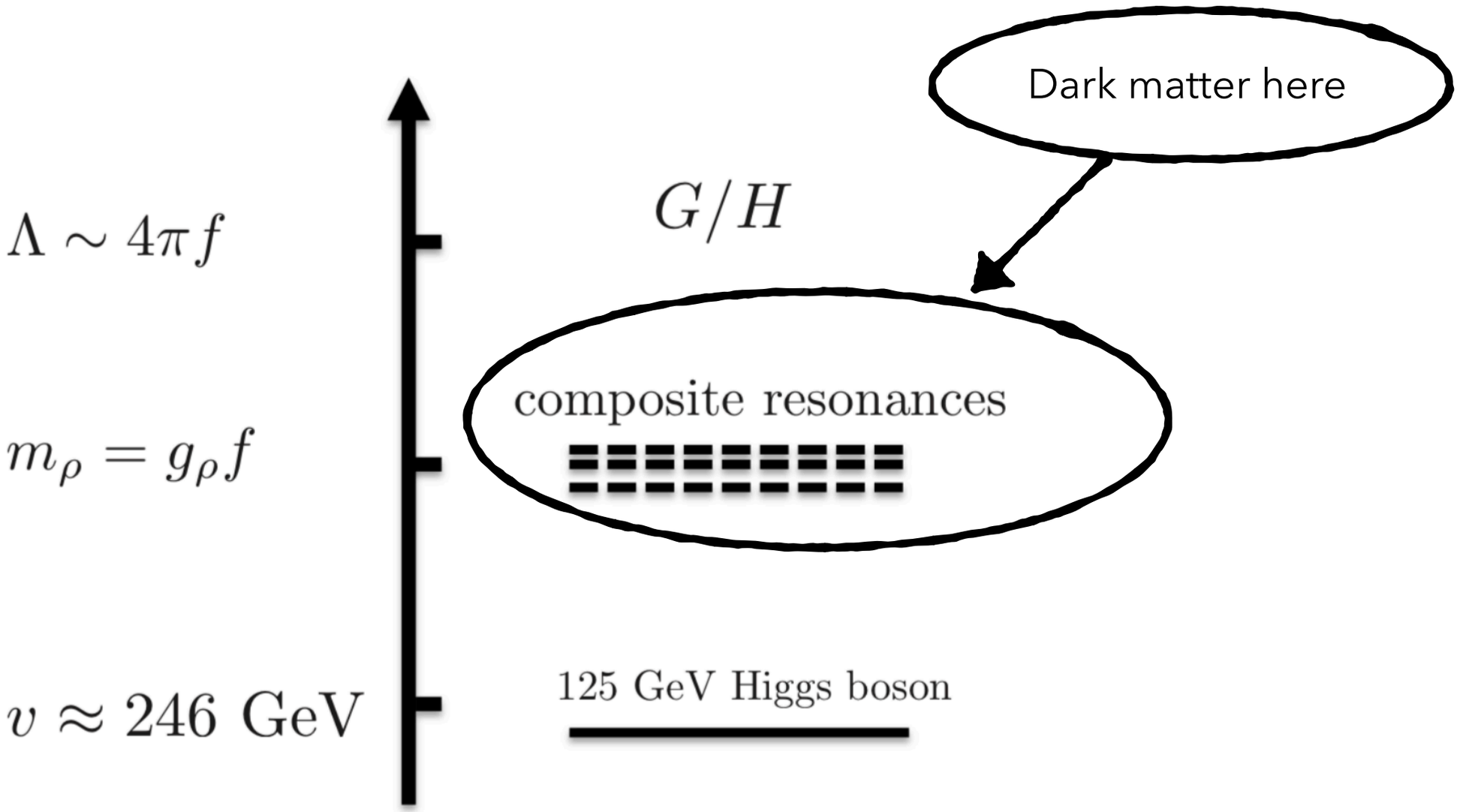


Figure from Liu et. al. arXiv:1904.00026

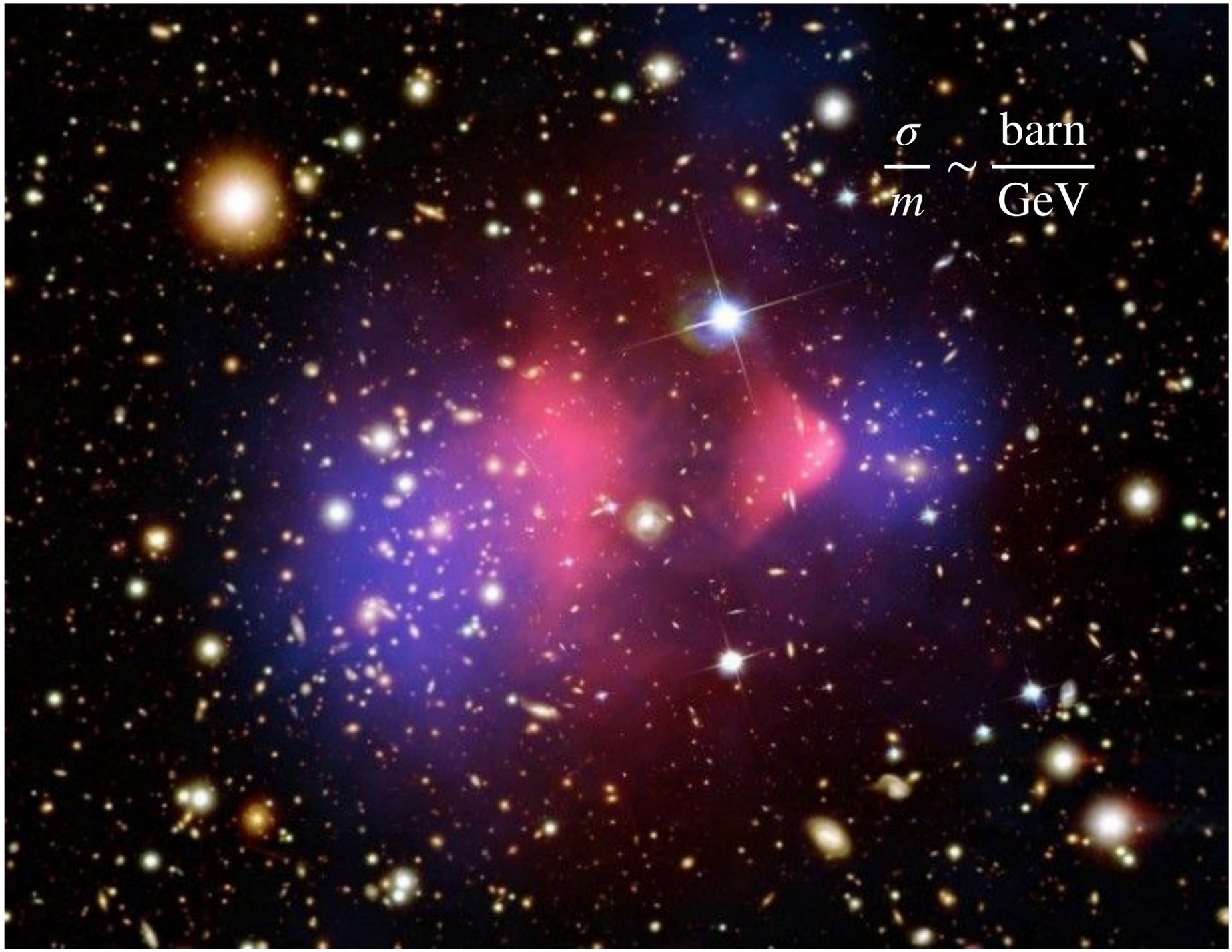
Why strongly interacting dark matter

Why not!

That’s a reason but let’s explore a bit more

Large self-interactions possible

See also review talk by J. Bagla



Large self-interactions possible

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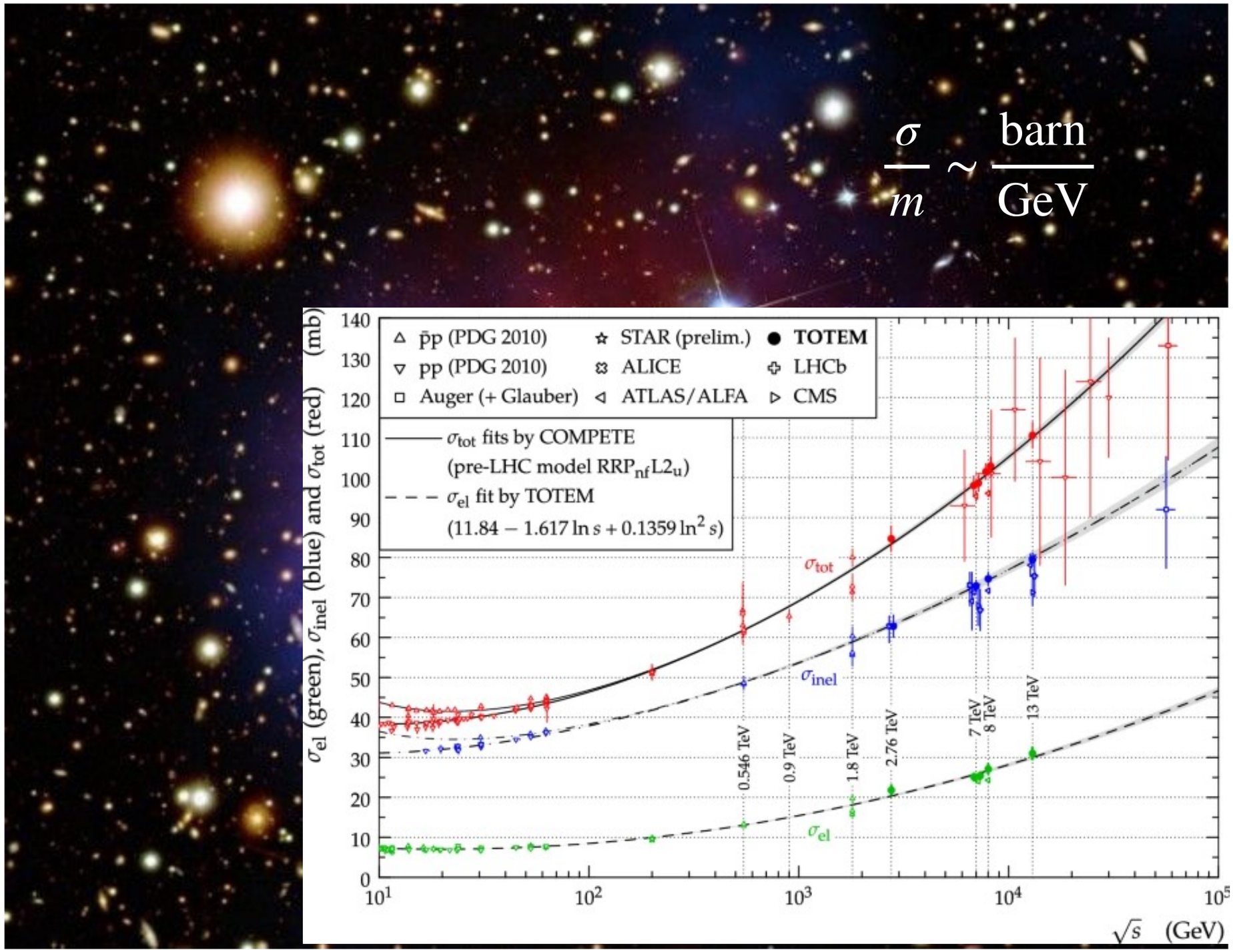
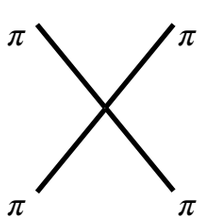
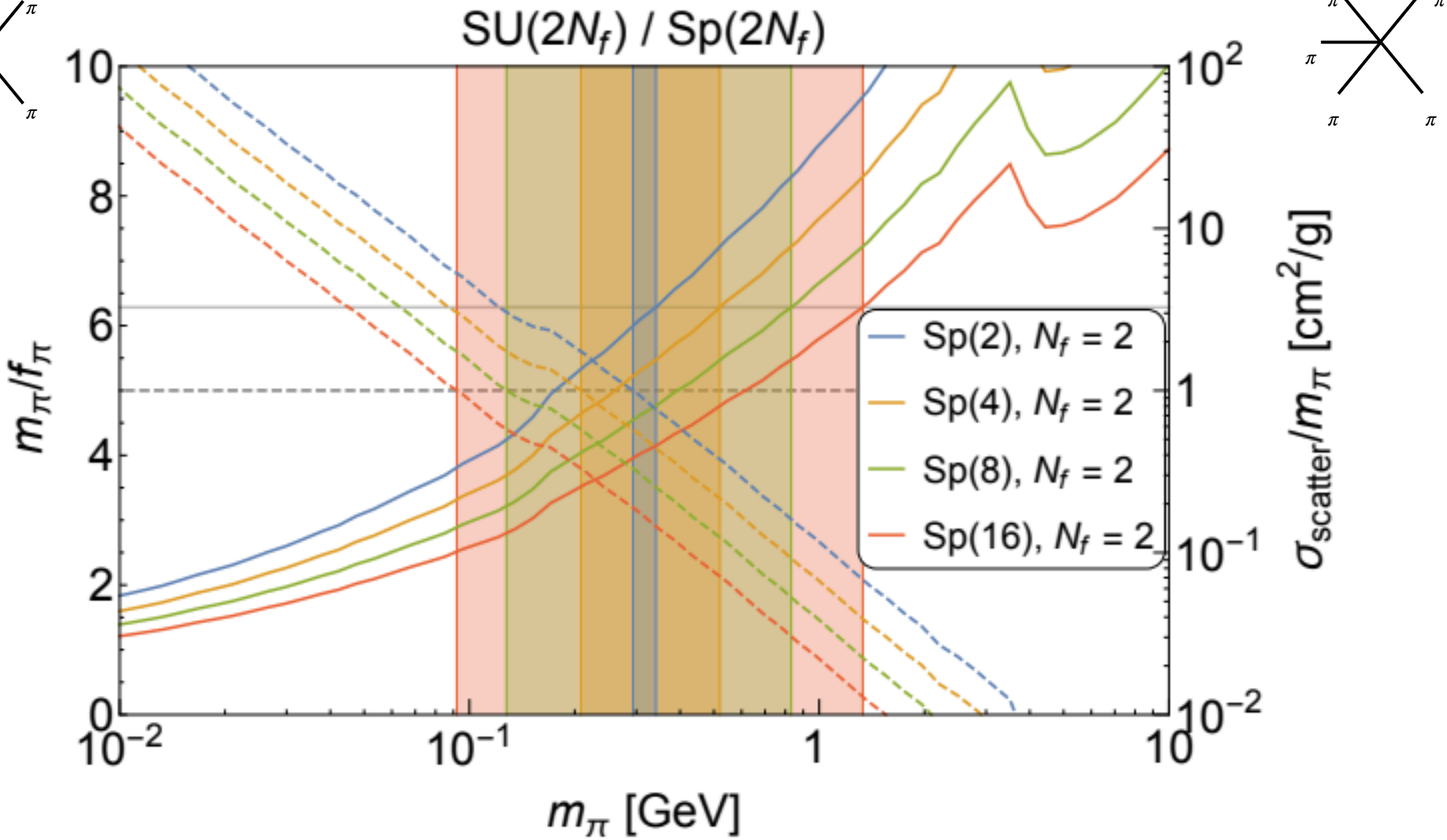


Can also generate relic

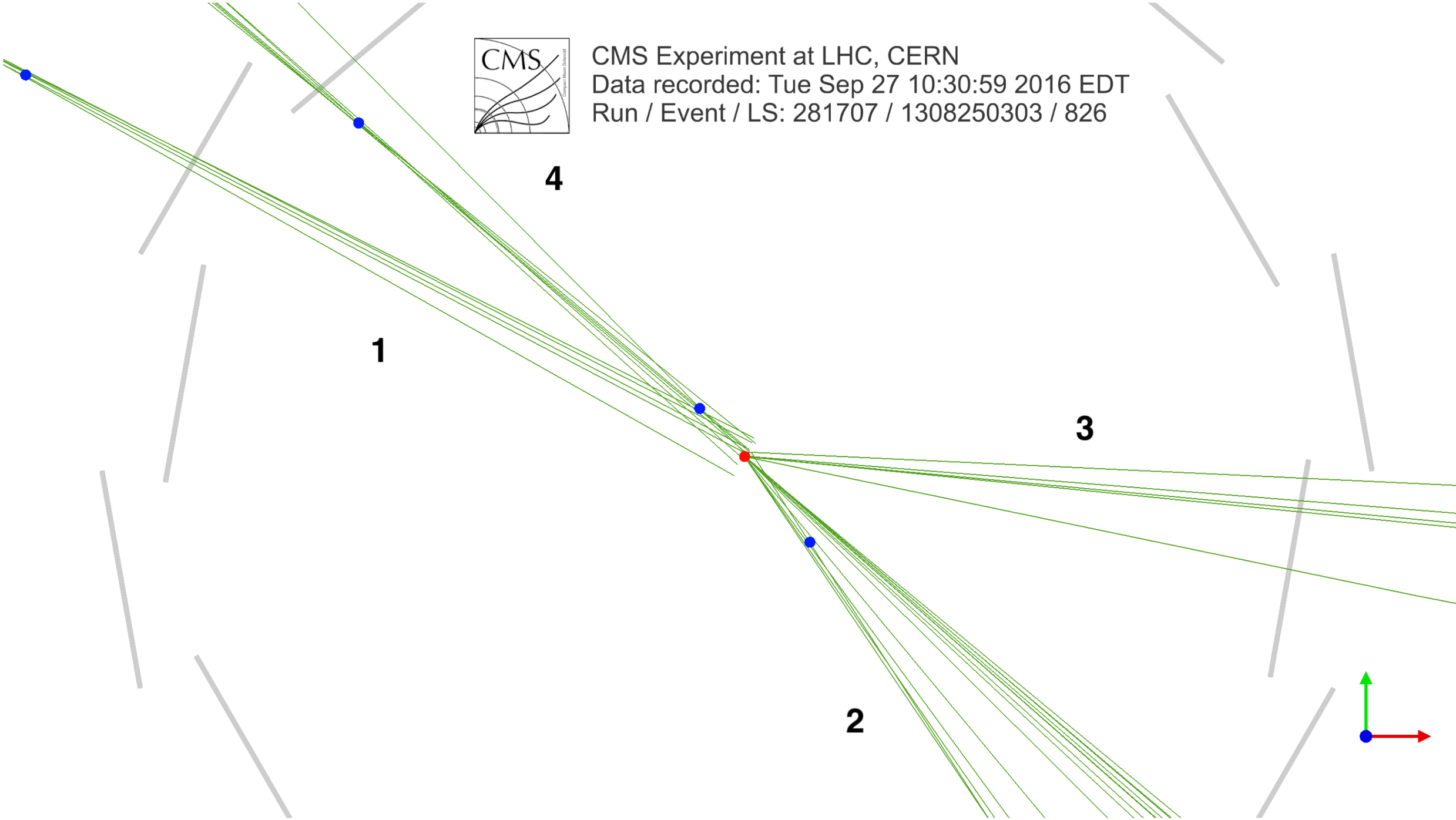
Hochberg et al arXiv:1411.3727





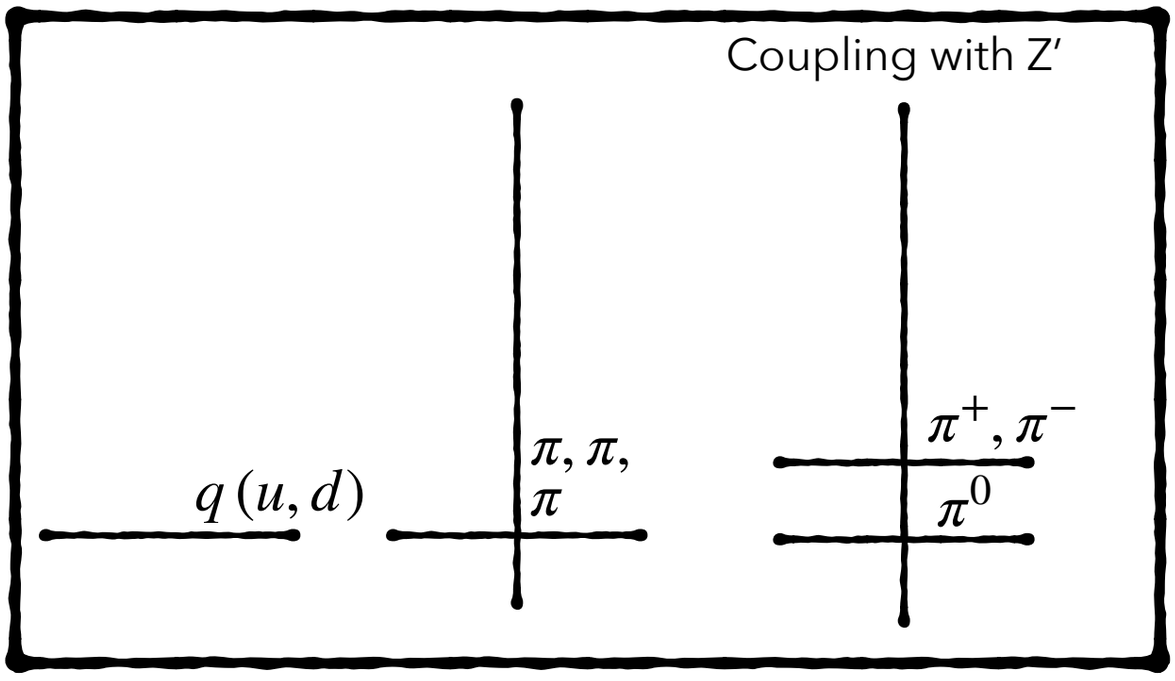
Lead to new experimental signatures

arXiv:1810.10069



Primary obstacles in theory constructions

- DM longevity needs to be ensured
  - Impose external symmetries
  - Use accidental symmetries e.g. lightest baryon (proton) is stable in the SM due to baryon number conservation
  - Engineer models to ensure stability



$\sim Tr[Q^2 T_0] = 0$

$\rightarrow Q^2 \propto 1$

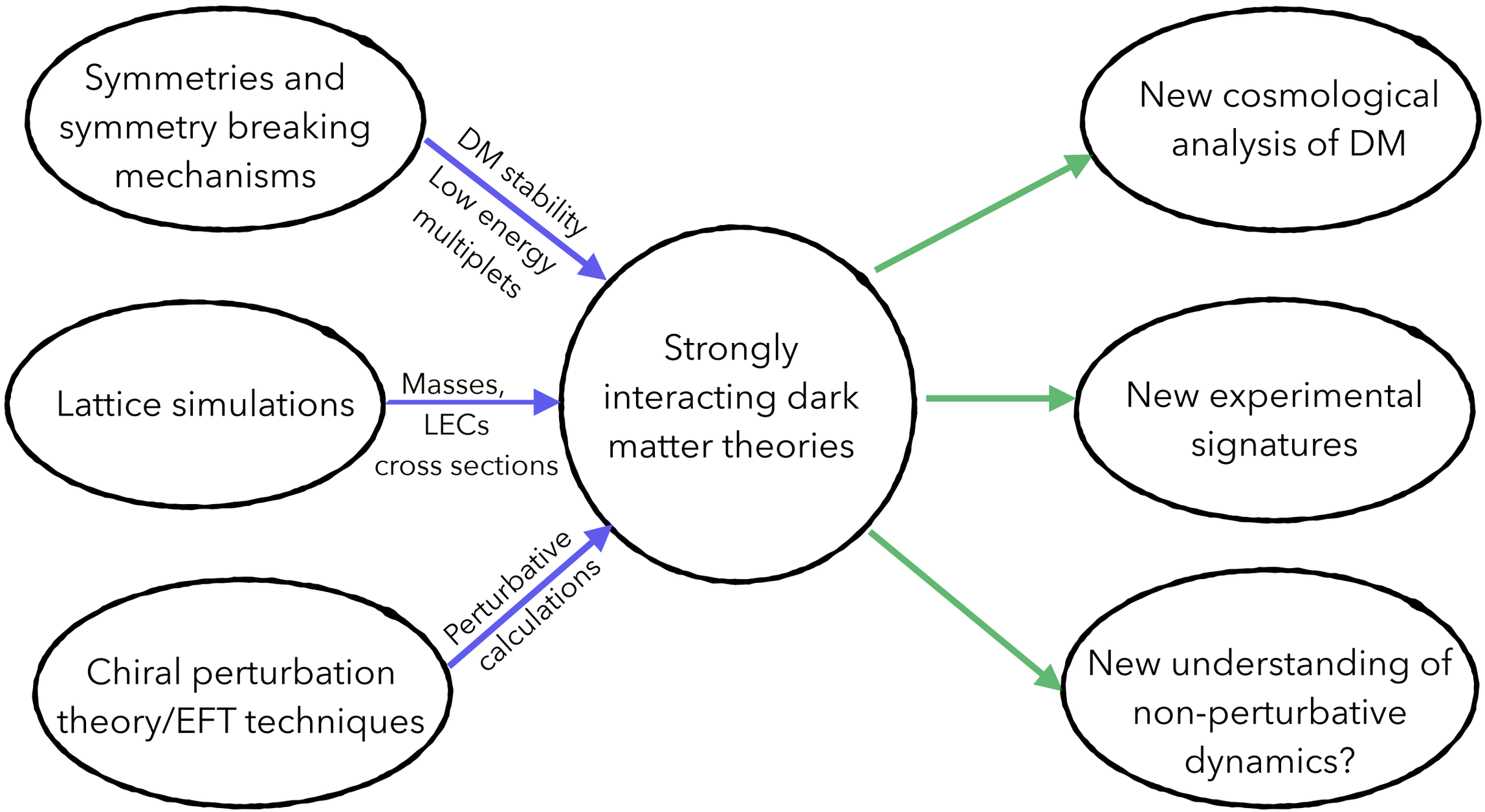
- Quantitative estimates from genuine non-perturbative physics are needed (Oida!)

Oida

German/Austrian/Bavarian expression
Literal meaning: Old one (dude/mate)
Can be used to pretty much express any emotion (see here)

Strongly interacting theories: pathways

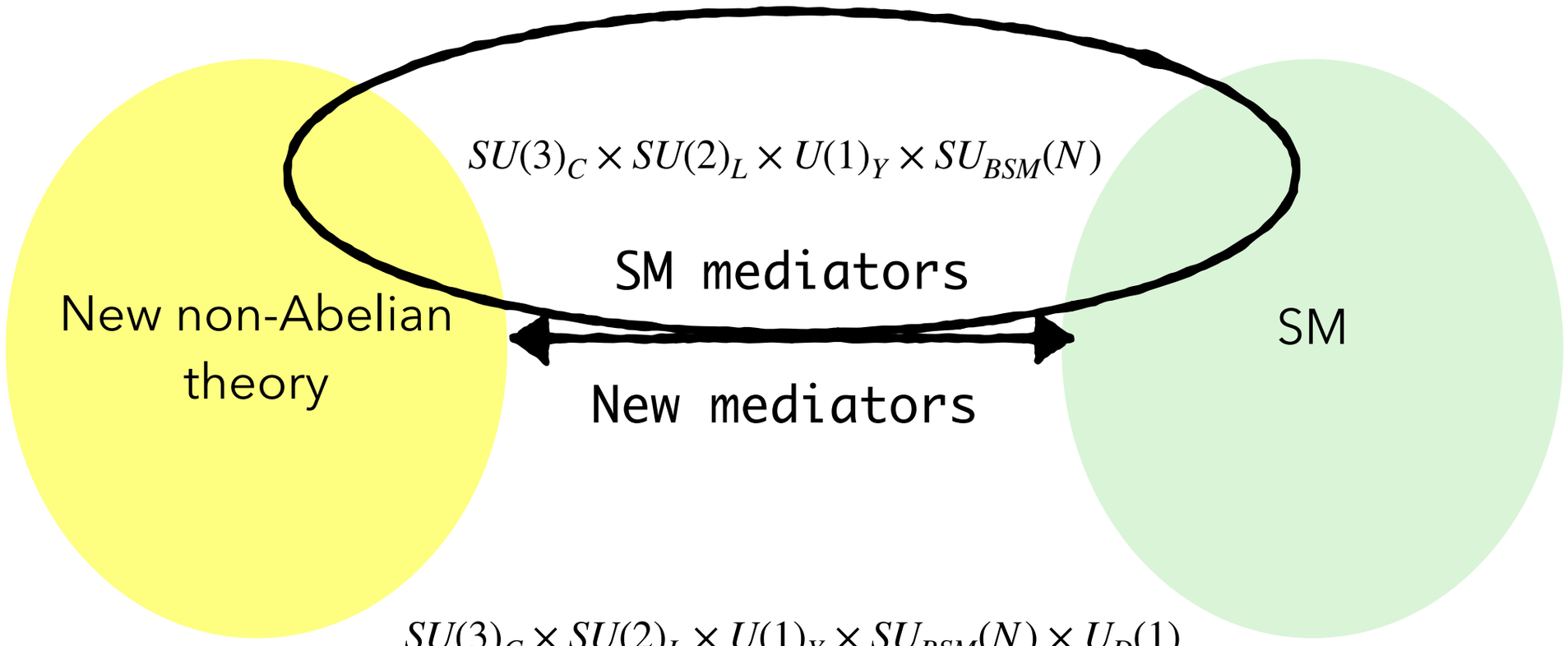
How to make systematic progress in the landscape of strongly interacting dark matter?



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

New non-Abelian theory

Portal phenomenology - I



$$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU_{BSM}(N) \times U_D(1)$$

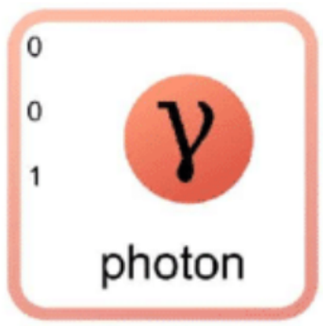
J. Butterworth, L. Corpe, **SK**., X. Kong, M. Thomas arXiv:2105.08494

SM mediators

Appelquist et al arXiv:1402.6656
Bagnasco et. al. hep-ph/9310290

Relevant if DS has SM color charges

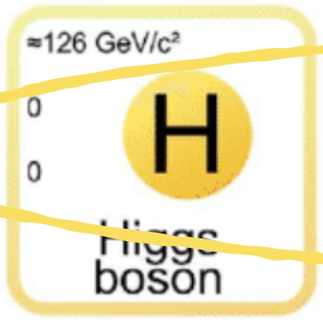
See: Chivukula et. al. hep-ph/9210274; Godbole et. al. 1506.01408; Bay and Osborne 1506.07110



Lowest dimensional operators:

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

Similar considerations for W/Z mediators, suppressed by masses

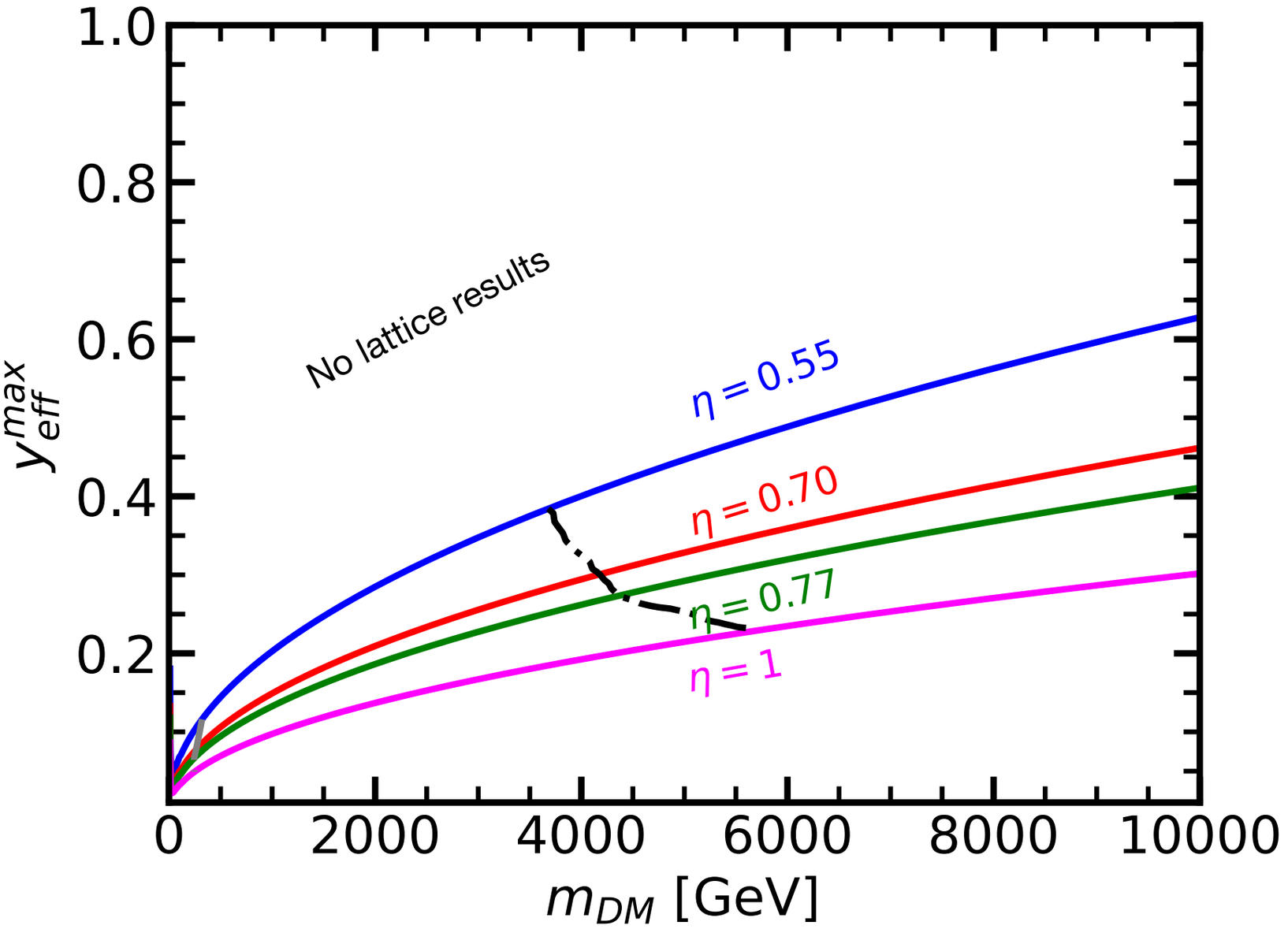


Most relevant interaction if constituents have Yukawa couplings

- Focus on Higgs mediated interactions
- 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

Higgs mediators

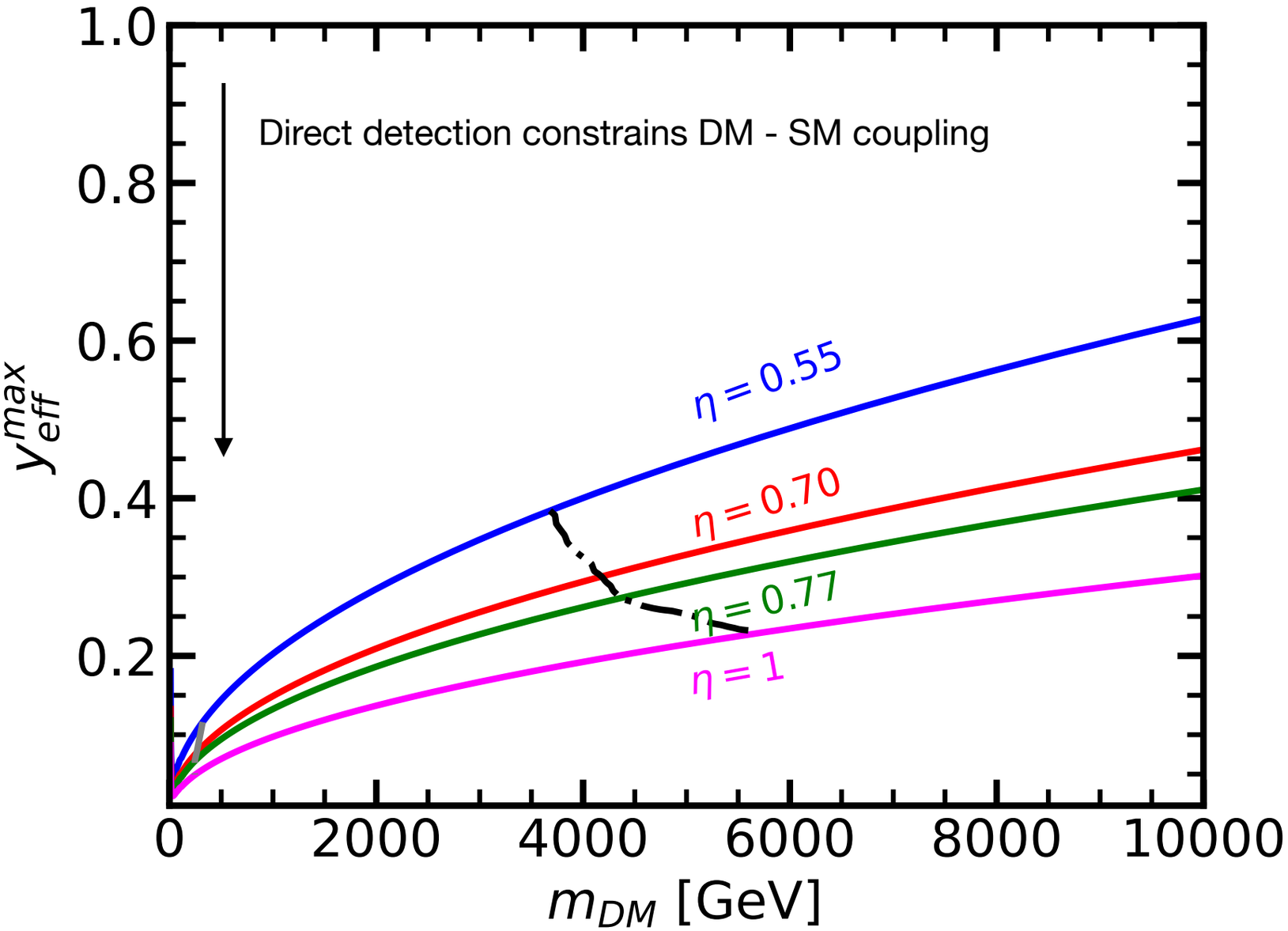
J. Butterworth, L. Corpe, **S.K.** et. al. arXiv:2105.08494

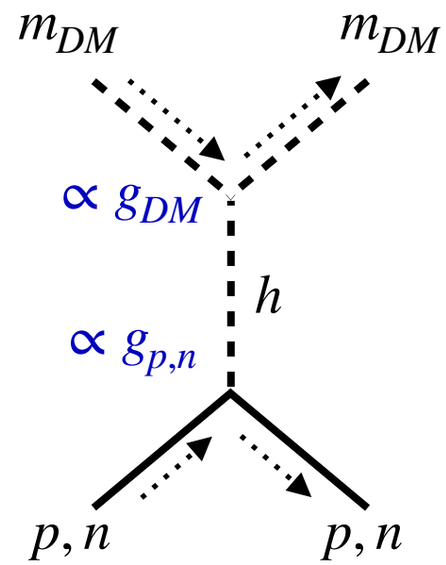


Either require low values of Higgs - dark quark effective Yukawa coupling or require very heavy dark matter

Higgs mediators

J. Butterworth, L. Corpe, **S.K.** et. al. arXiv:2105.08494





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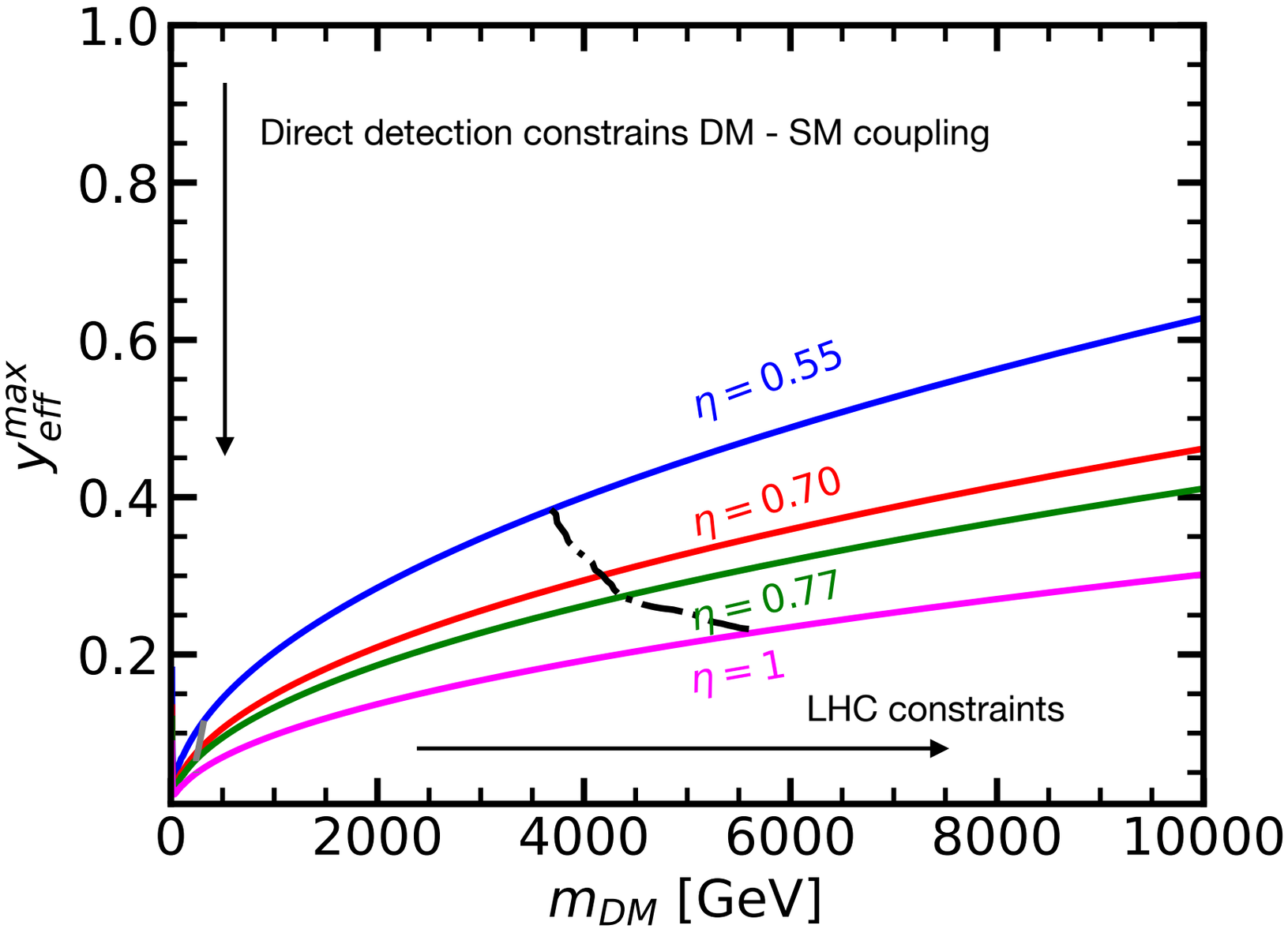
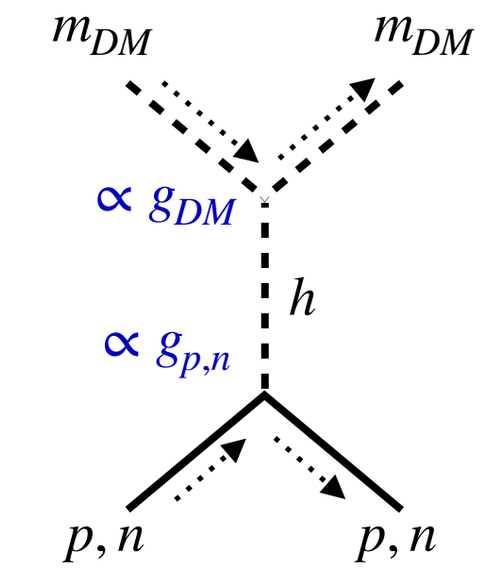
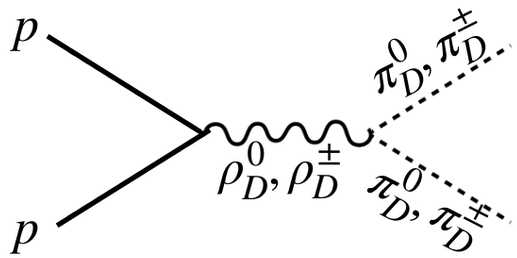


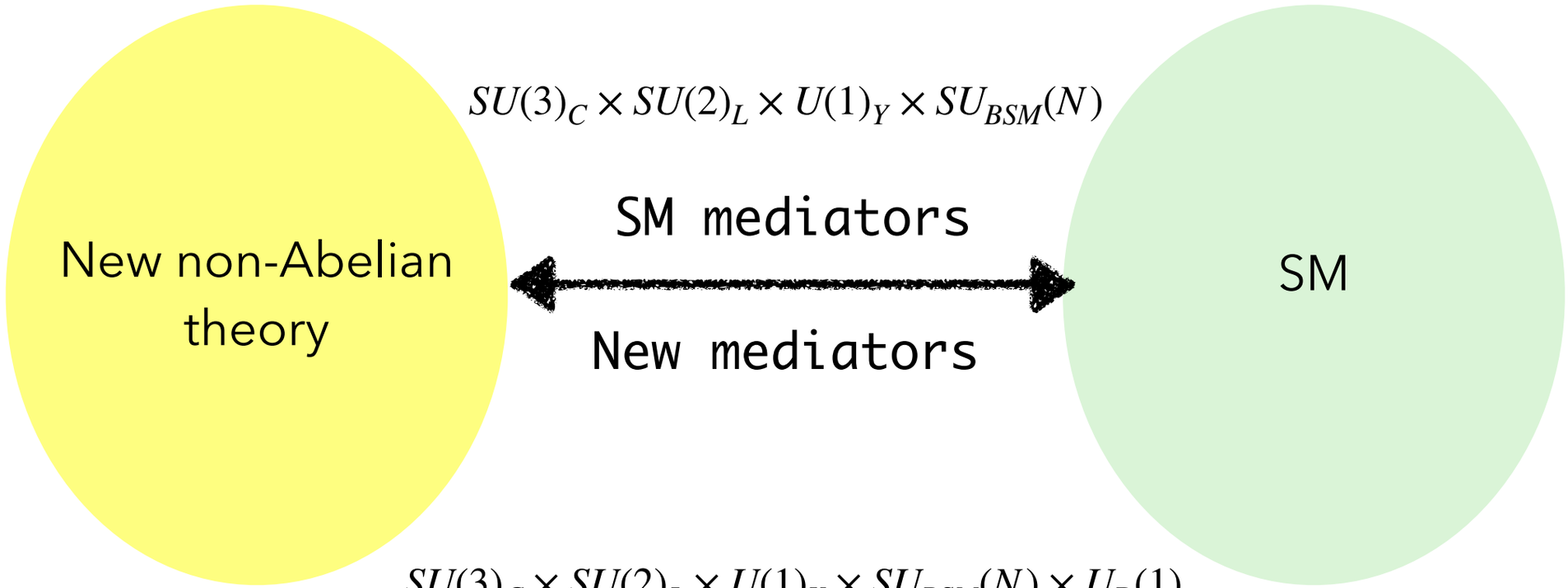




Either require low values of Higgs - dark quark effective Yukawa coupling or require very heavy dark matter

Portal phenomenology - II

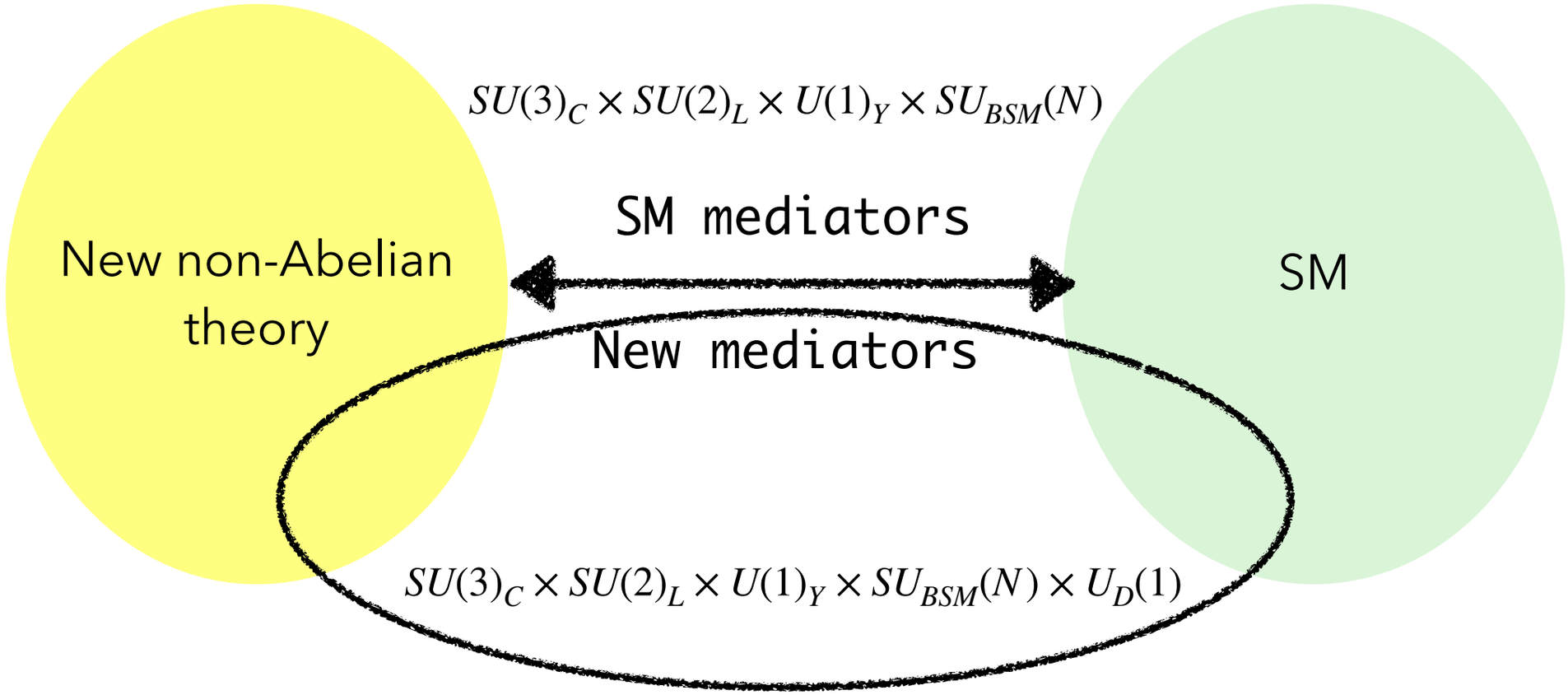
$$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU_{BSM}(N)$$



$$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU_{BSM}(N) \times U_D(1)$$

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

Portal phenomenology - II

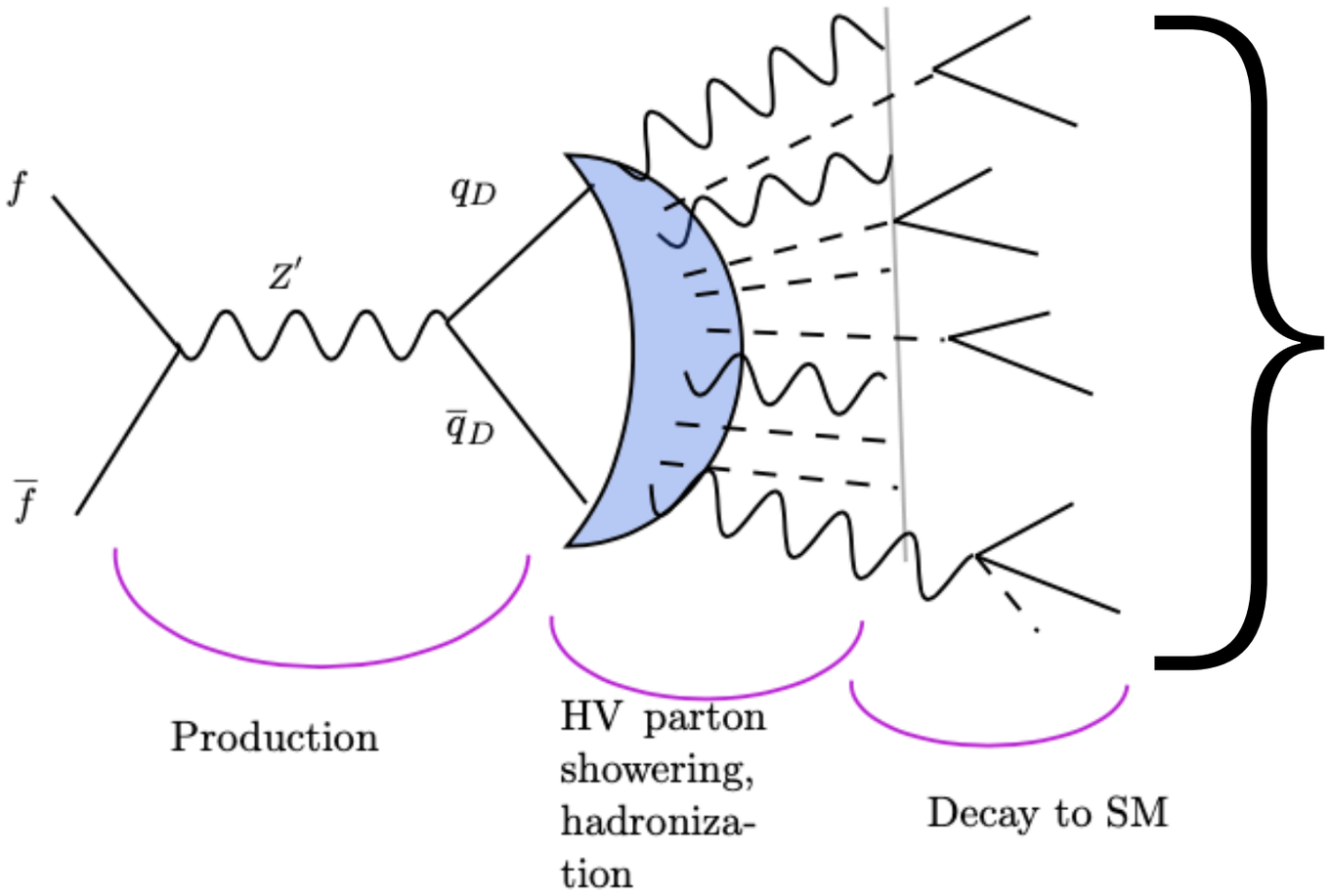


Snowmass darkshowers (incl. **S.K.**, S. Mee, M. Strassler) arXiv:2202.05191

Theory setup

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

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



- Jets with large MET inside
- Jets with displaced vertices
- Jets with too many or too few tracks

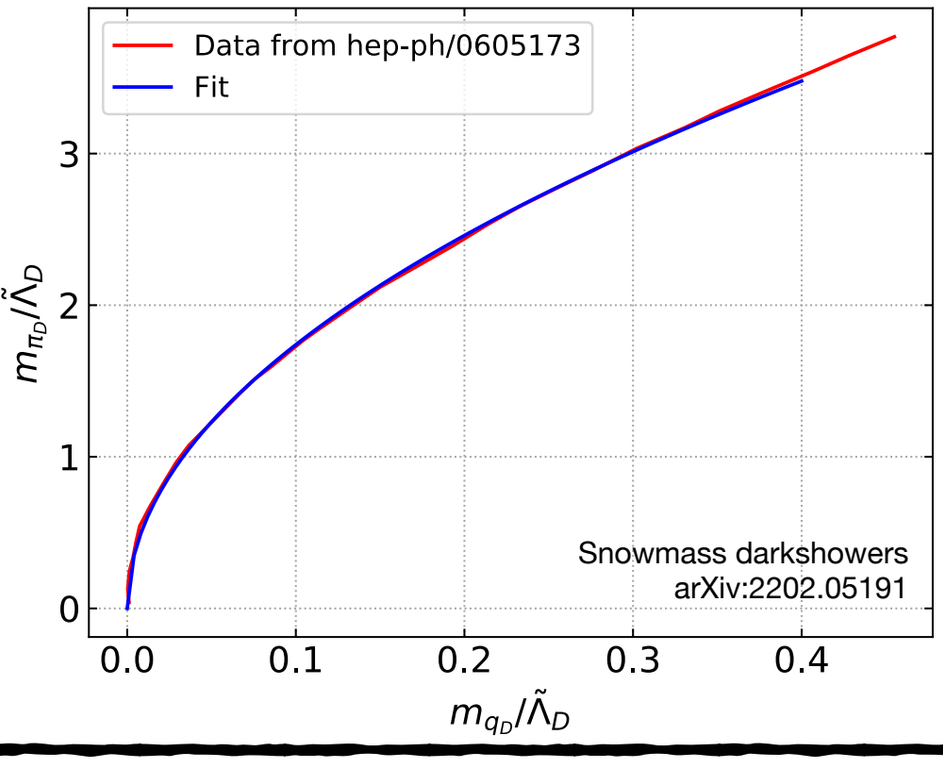
- $m_{q_D} \ll \Lambda_D \ll m_{Z'}$ → production of dark quarks followed by rapid parton showering and hadronization → jets
- Z' coupling leads to decay of some of the dark hadrons back to the SM; details coupling dependent

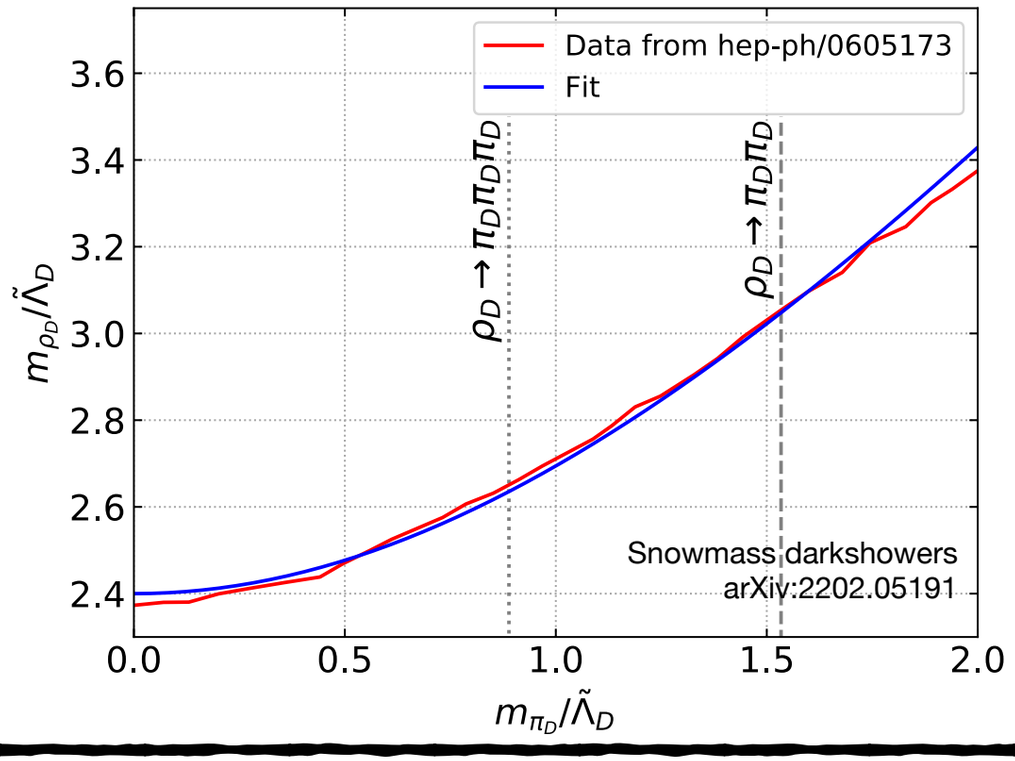
Lattice inputs

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

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





Beyond SU(N) groups

Needs "durchhiaseln”

durchhiaseln

Used in rural Austria, particular in upper Murtal region

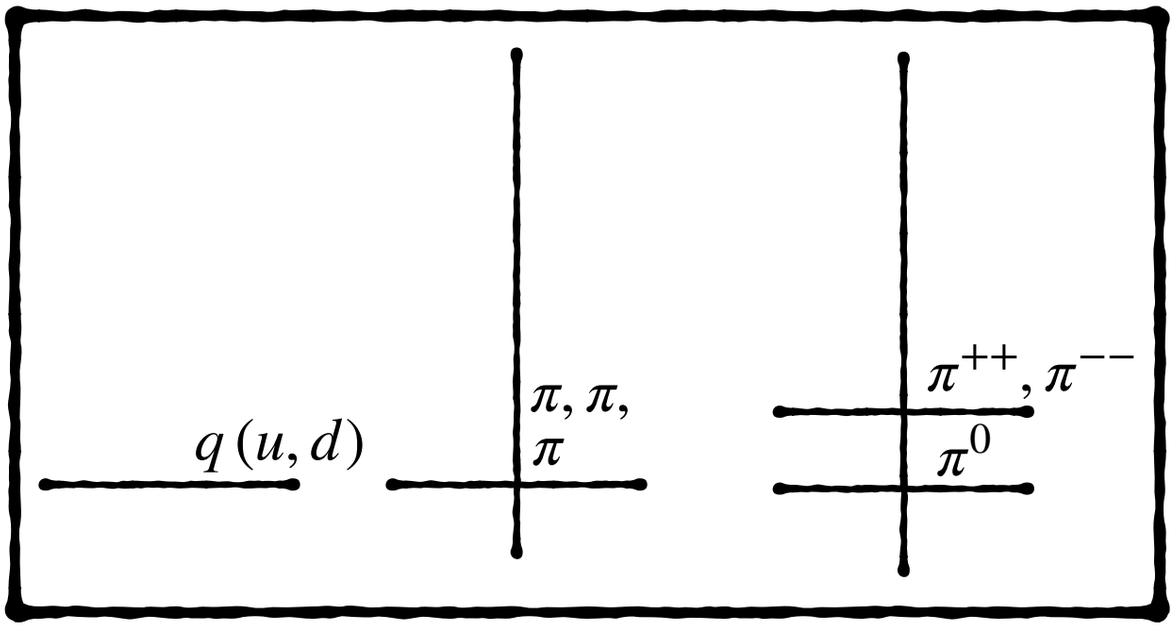
A long an tedious calculation

Number of pions can be very different - I

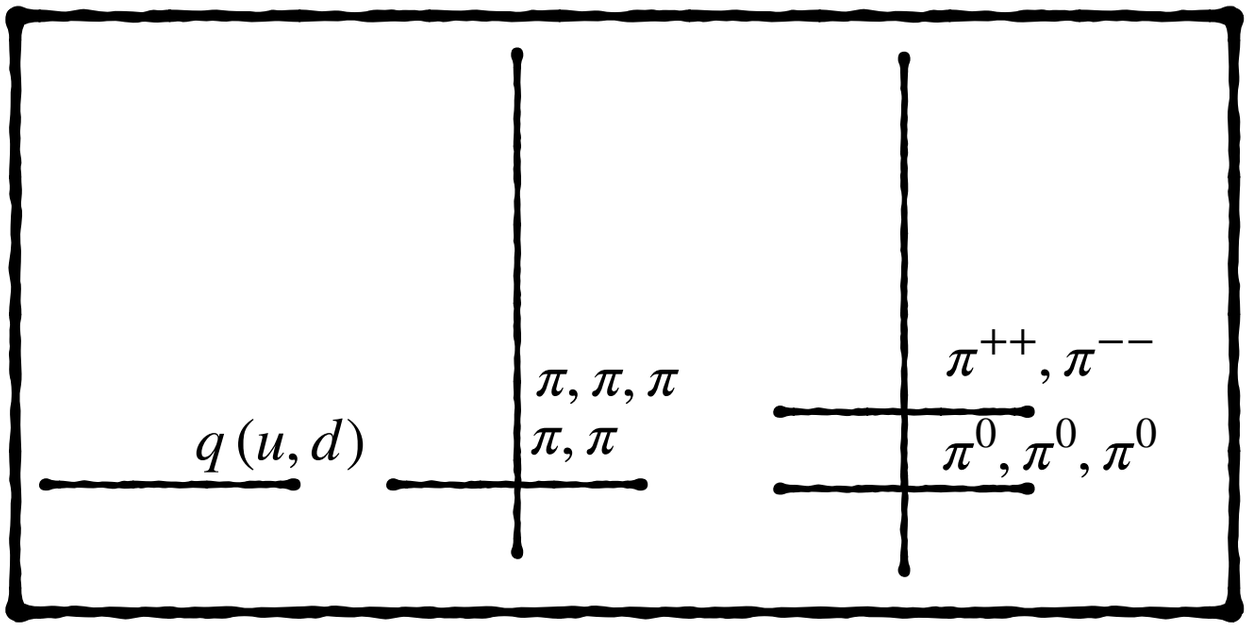
S.K., A. Maas, S. Mee, M. Nikolic, J. Pradler, F. Zierler arXiv:2202.05191

- SU(N) gauge groups: need three fermions in fundamental representation to get at least five pions
- Sp(N) gauge group: Need two fermions in fundamental representation to get five pions $SU(2N_f)/Sp(2Nf)$ coset space contains $(2N_f + 1)(N_f - 1)$ broken generators
- Coupling with Z' preserves DM stability

SU(N): 2 fermions in fundamental



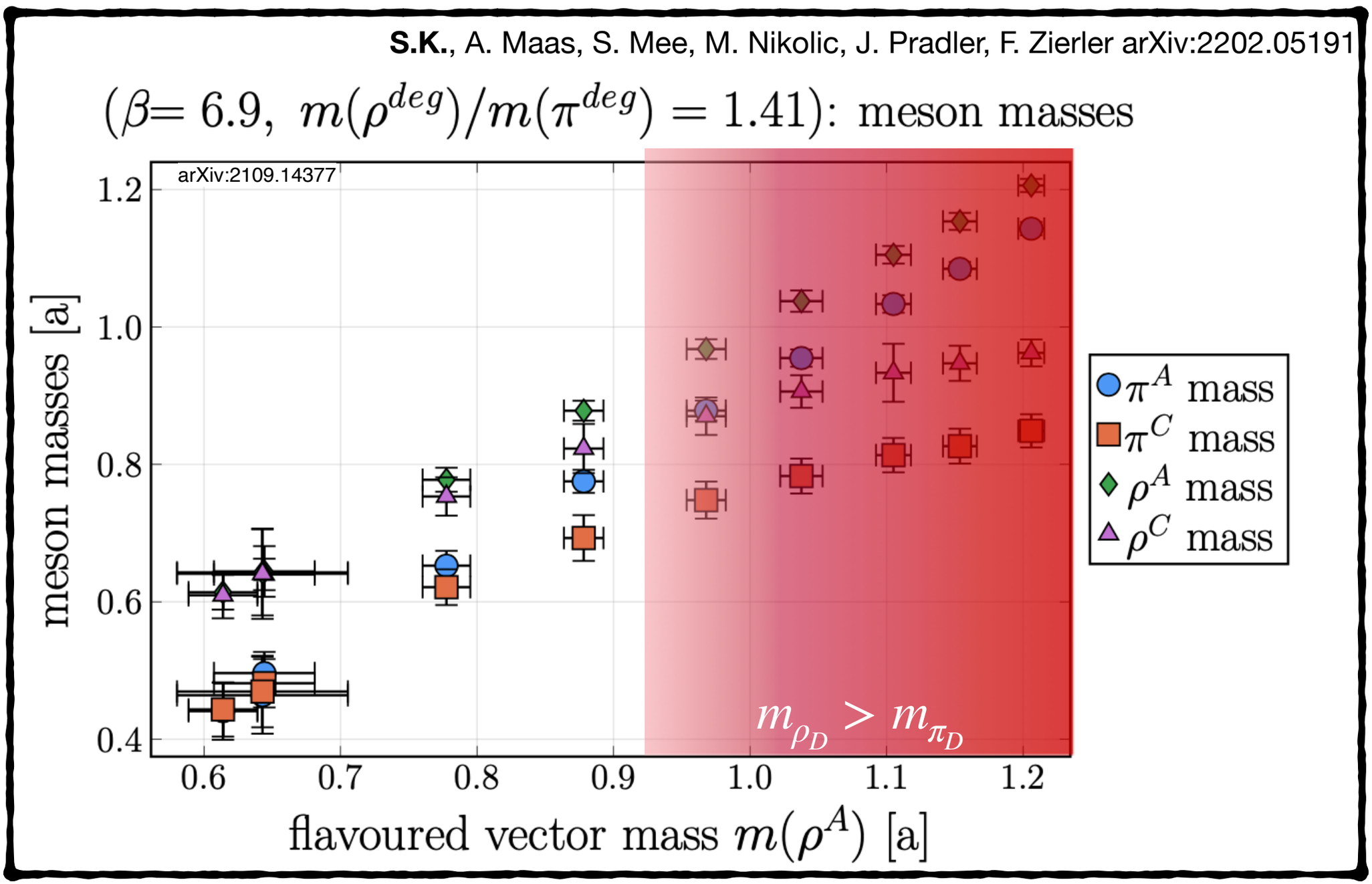
Sp(N): 2 fermions in fundamental



- Z' charged for quarks +1, -1

Lattice calculations $m_u \neq m_d$

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



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

Number of pions can be very different - II

S.K., J. Pomper (In progress)

- SU(N) gauge groups: need three fermions in fundamental representation to get at least five pions
- Sp(N) gauge group: Two fermions in adjoint representation give nine pions $SU(N_f)/SO(N_f)$ coset space contains $\frac{1}{2}(N_f+2)(N_f-1)$ broken generators
- Coupling with Z' preserves DM stability

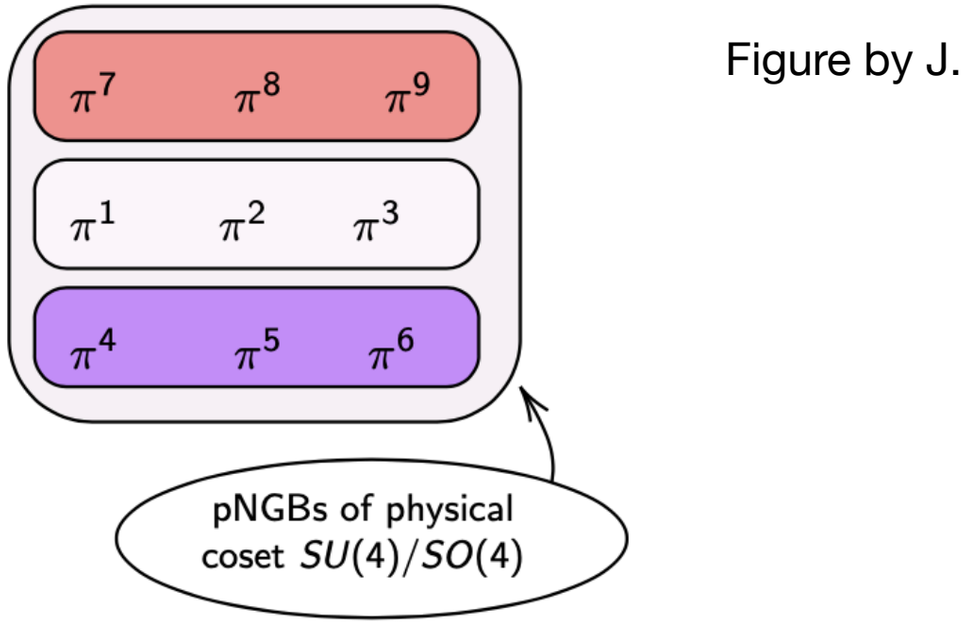


Figure by J. Pomper

Insights from UV dynamics

S.K., J. Pomper (In progress)

Witten, Nucl. Phys. B 223 (1983)

- Can not fix WZW by considering IR dynamics alone $\pi_4(SU(4)/SO(4)) \neq 0$

- WZW can be written by considering detailed UV to IR anomaly relations (if anomaly is present in IR, it must be present in the UV → anomaly equation → solution is WZW term)

Chu, Ho, and Zumino, Nuclear Physics B 475 (1996)

Wess and Zumino, Physics Letters B 37 (1971)]

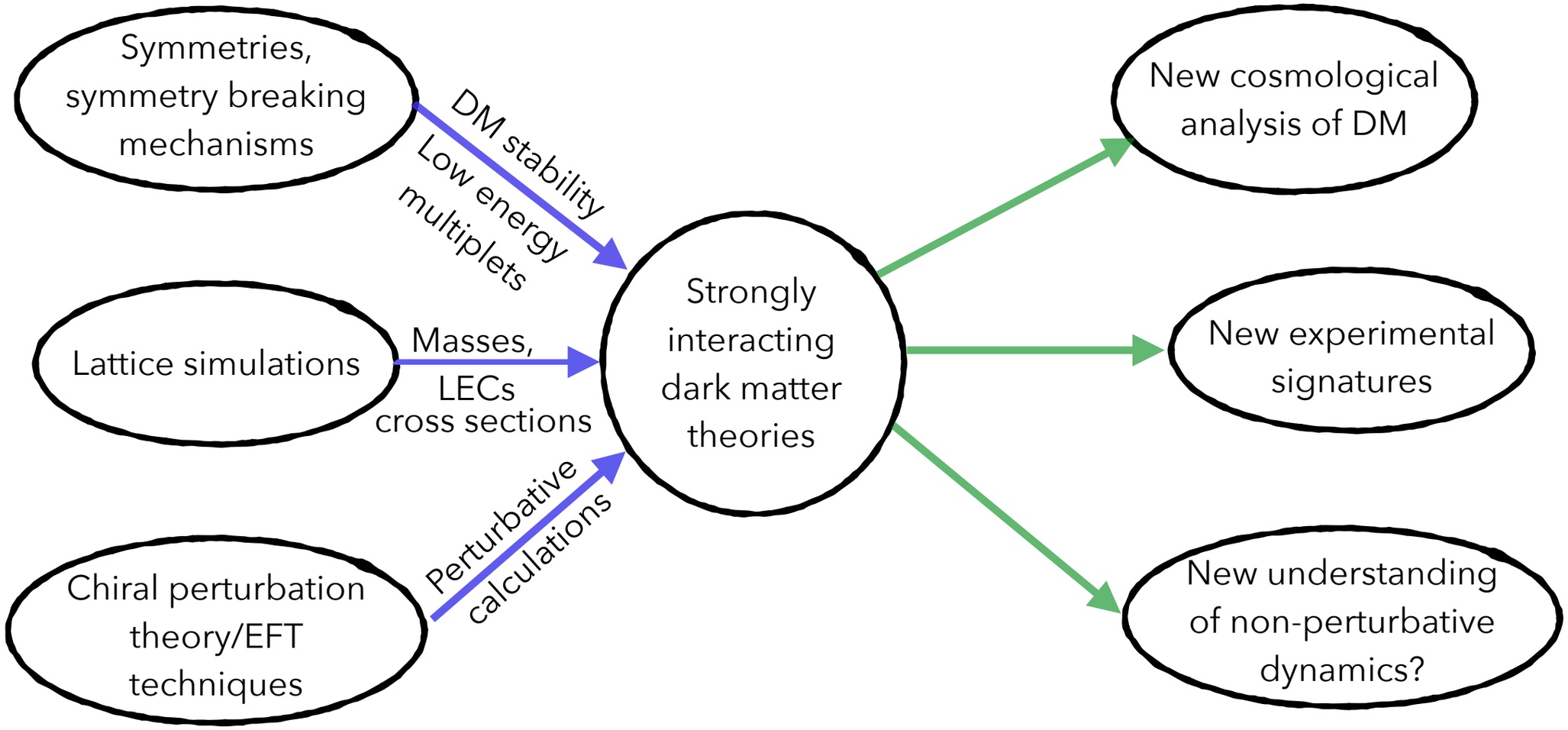
Wess-Zumino effective action

$$S_{WZ}[\xi = (\eta', \pi)] = \frac{D_C}{48\pi^2 f_\pi} \int_0^1 \mathrm{d}t \int_{S^4} \mathrm{Tr}\left\{\xi \left((U[t\xi])^{-1}\mathrm{d}U[t\xi]\right)^4\right\}$$

$$\approx \frac{D_C}{250 f_\pi \pi^2} \epsilon^{\mu\nu\sigma\rho} \int_{S^4} \mathrm{Tr}\left\{\pi\partial_\mu\pi\partial_\nu\pi\partial_\sigma\pi\partial_\rho\pi\right\}$$

Fazit
in conclusion/on the balance

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?