Cosmology and collider implications of strongly interacting dark matter

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Based on completed and ongoing works with J. Lockyer, S. Mee, N. Hemme, E. Bernreuther, D. Stafford, F. Kahlhoefer S. Plätzer, M. Strassler

NAWI Graz Natural Sciences

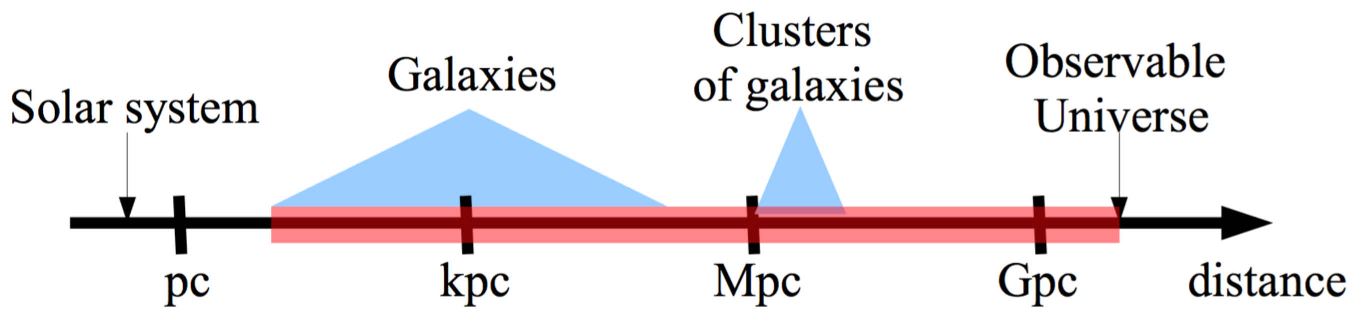
FWF Der Wissenschaftsfonds.

UNI GRAZ

Dark matter: where are we?

- Strong evidence on all scales

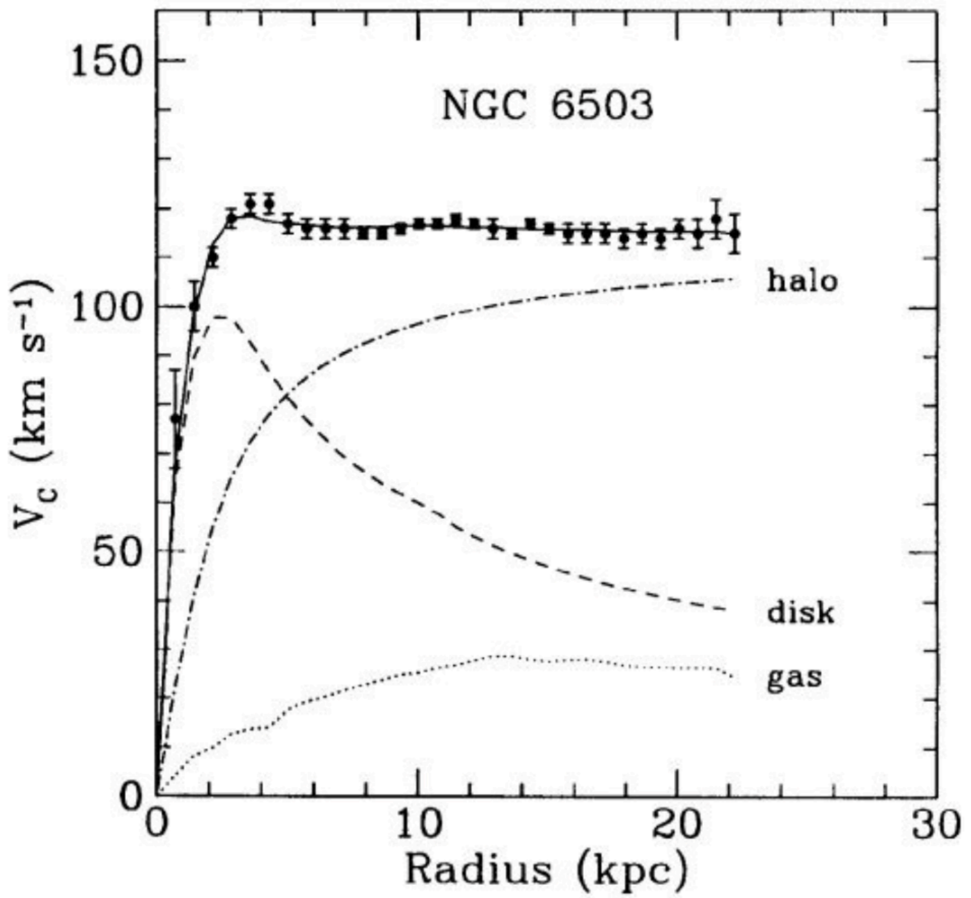
By A. Ibarra



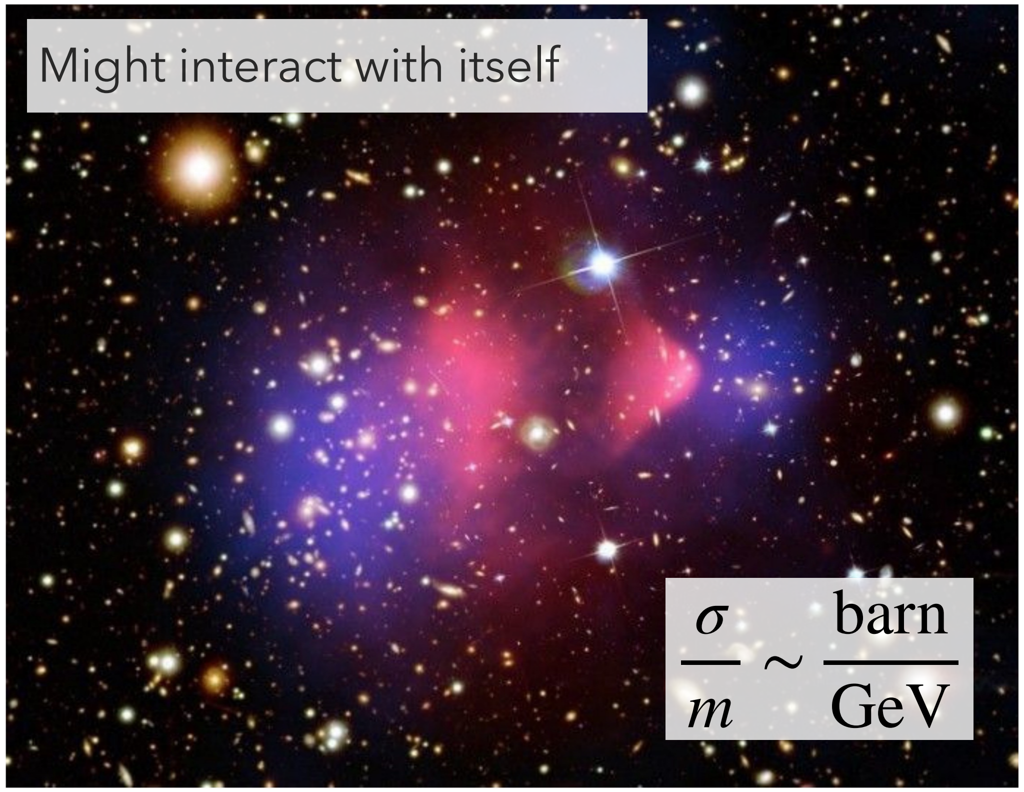
$$\Omega_{DM} h^2 \approx 0.11$$

- Four times more abundant than visible matter
- Does not directly interact with photons
- Mostly non-relativistic, charge neutral, very long lived/stable
- No such particle in the Standard Model
- No evidence at experiments so far

Diagram from here

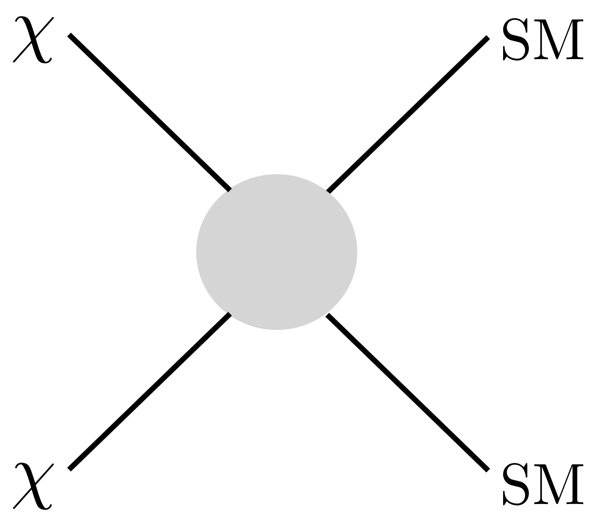


Also related to core-cusp problem see talk by. S. Rakshit



$$\frac{\sigma}{m} \sim \frac{\text{barn}}{\text{GeV}}$$

Dark matter: connecting to particle physics



$$\Omega_\chi h^2 \sim \frac{10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle} \simeq 0.1 \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m}{100\ \mathrm{GeV}}\right)^2$$

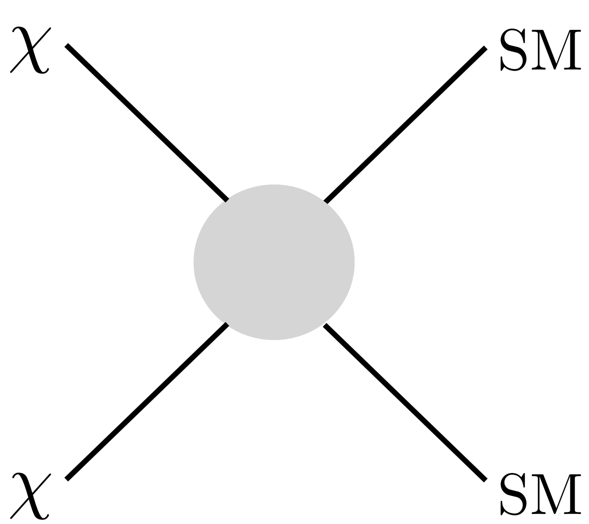
Weak scale coupling

Weak scale mass

See also talk by J. Harz

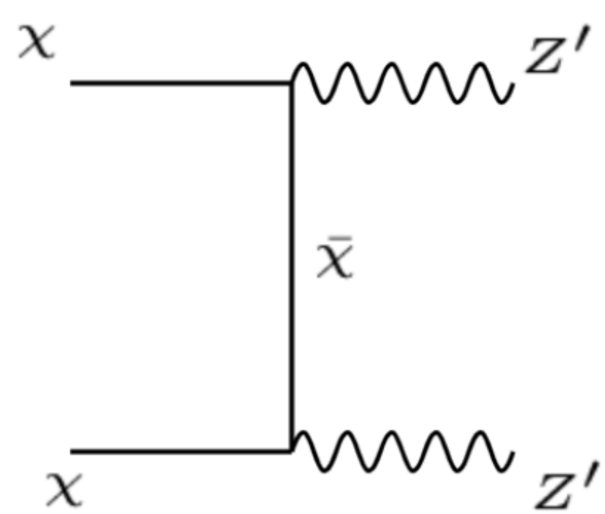
DM relic density mechanism needs a number changing interaction

Too many to add



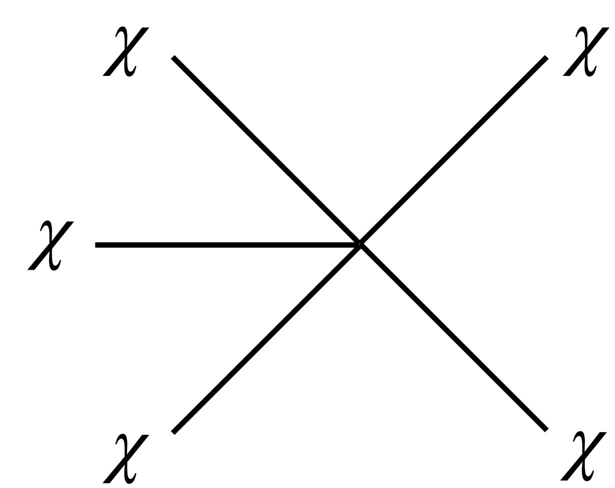
WIMP
$\mathcal{O}(100)$ GeV

D'Agnolo et al. arXiv:1505.07107
Fitzpatrick et al. arXiv:2011.01240



Light mediators
$\mathcal{O}(1) - \mathcal{O}(100)$ GeV

Hochberg et al. arXiv:1402.5143



3 →2 annihilations
$\mathcal{O}(100)$ MeV

Dark matter: connecting to particle physics

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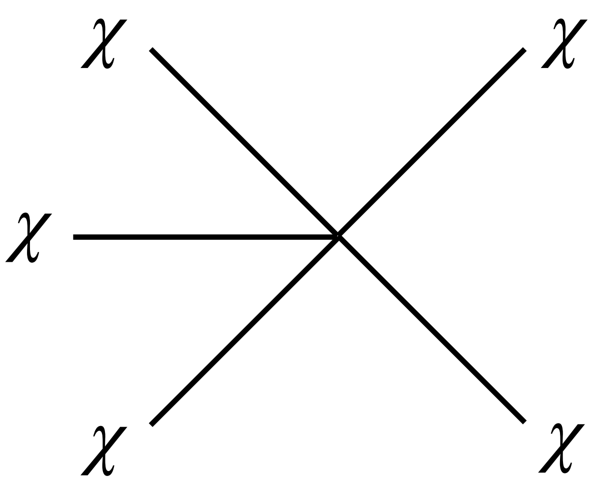


3 →2 annihilations

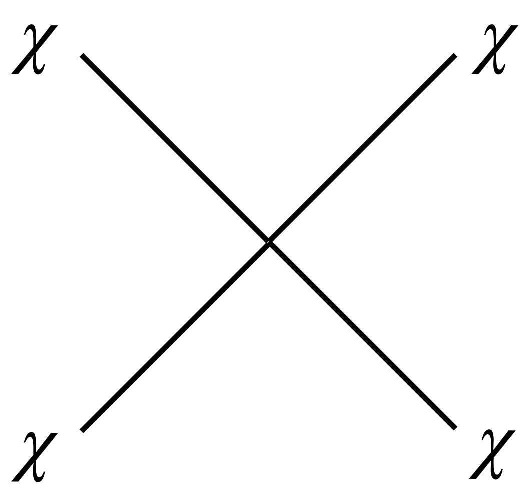
$$\Gamma_{3\to 2} \sim H$$

$$n_\chi^2 \langle \sigma v^2 \rangle_{3\to 2} \sim \frac{T_{eq}^2 m_\chi^4}{x_F^6} \times \frac{\alpha_{eff}^3}{m_\chi^5} \sim H_F \sim \frac{T_F^2}{M_{\rm Pl}}$$

$T_{eq} \sim 0.8\,\mathrm{eV}$

$x_F \sim 20$

$$m_\chi \sim \alpha_{eff} \left(T_{eq}^2 M_{\rm Pl}\right)^{1/3} < \alpha_{eff} \times \mathcal{O}(100)\,\mathrm{MeV}$$



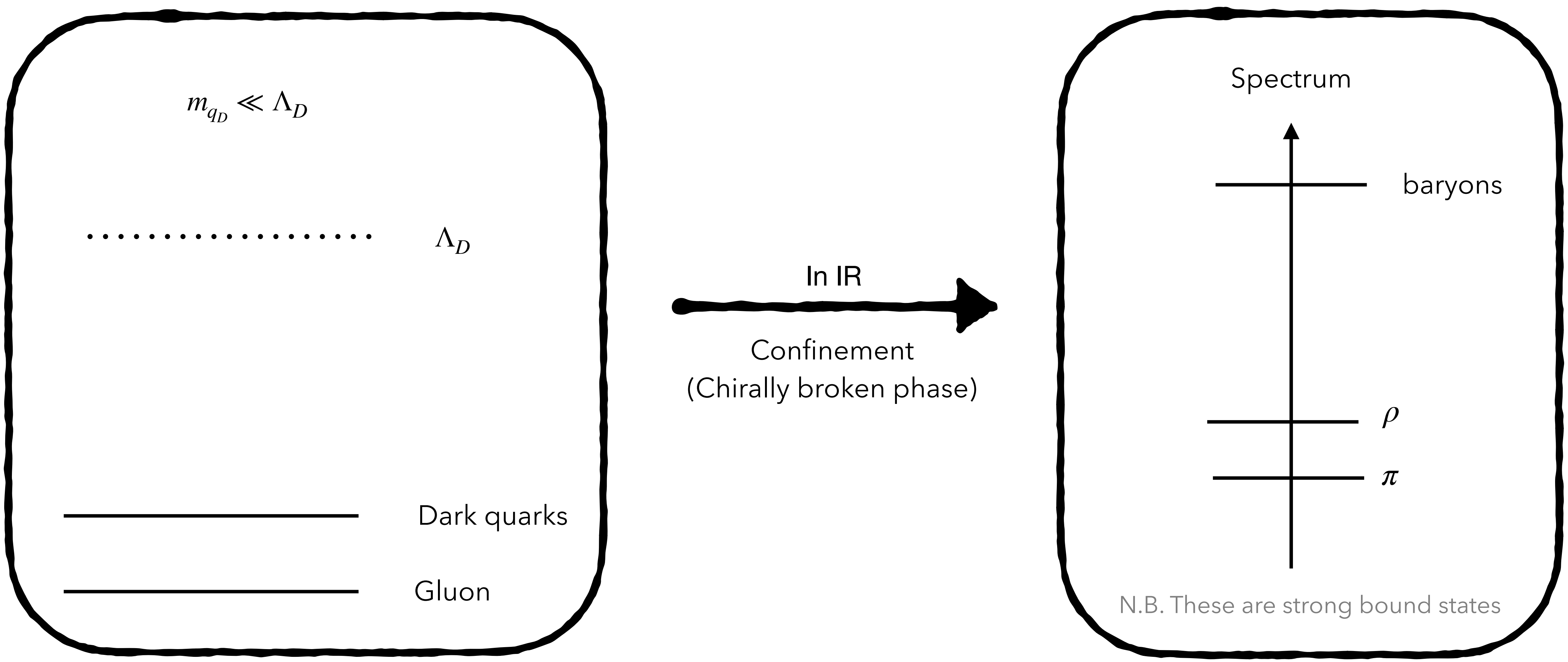
2 →2 self-interactions

$$\frac{\sigma_{\chi\chi}}{m_\chi} \sim a_{\rm int} \frac{\rm barn}{\rm GeV} \sim \frac{\alpha_{\rm eff}}{m_\chi^3}$$

$$m_\chi \geq 10 \left(\frac{a_{\rm int}}{\alpha_{\rm eff}}\right)^{1/3} \mathrm{MeV}$$

- Relic density and self-interactions require non-perturbative couplings and sub-GeV DM mass
- Very small region to reconcile both

Strongly Interacting Dark Matter



- One kind of theories where both of these may be possible are new QCD-like theories
- Also known as SIMP scenarios or (confining) Hidden Valleys or darkshowers/darkjets

Strassler hep-ph/0607160

Since PPC2022

- Yang-Mills theories ($N_f = 0$)
  - Collider simulation of glueball dark matter
  - (Deconfinement) phase transition

Batz et al. arXiv:2310.13731

Reichert et al. arXiv:2211.08877, 2109.11552,
Bennet et al arXiv:2409.19426

- QCD-like dark matter
  - FOPT in chiral regime (Columbia plot)
  - Analysis of perturbative unitarity of chiral theories
  - **New ways to generate dark matter relic density**

Bernhardt arXiv:2309.06737,
Fejos arXiv:2404.00554

Kamada arXiv:2210.01393

Bernreuther arXiv:2311.17157

- Experimental prospects
  - New darkshowers collider searches
  - **Development of Herwig event generator for simulating darkshowers**

Cazzaniga et al arXiv:2206.03909,
Beauchesne et al arXiv:2212.11523

Kulkarni et al arXiv:2408.10044

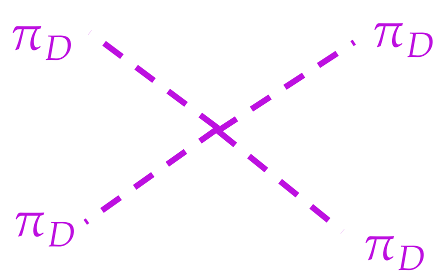
- Beyond QCD-like scenarios
  - Conformal dark matter scenarios
  - **Collider simulations of near conformal theories**

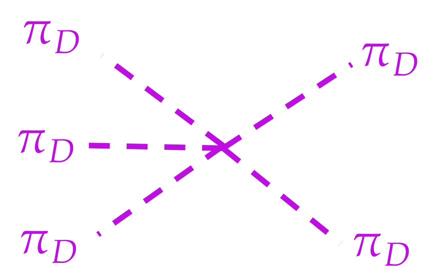
Ferrente et al. arXiv:2308.16219,
Ismail 2306.06161,
Appelquist et al arXiv:2404.07601
Lockyer, Kulkarni, Strassler (to appear)

Dark pion dark matter

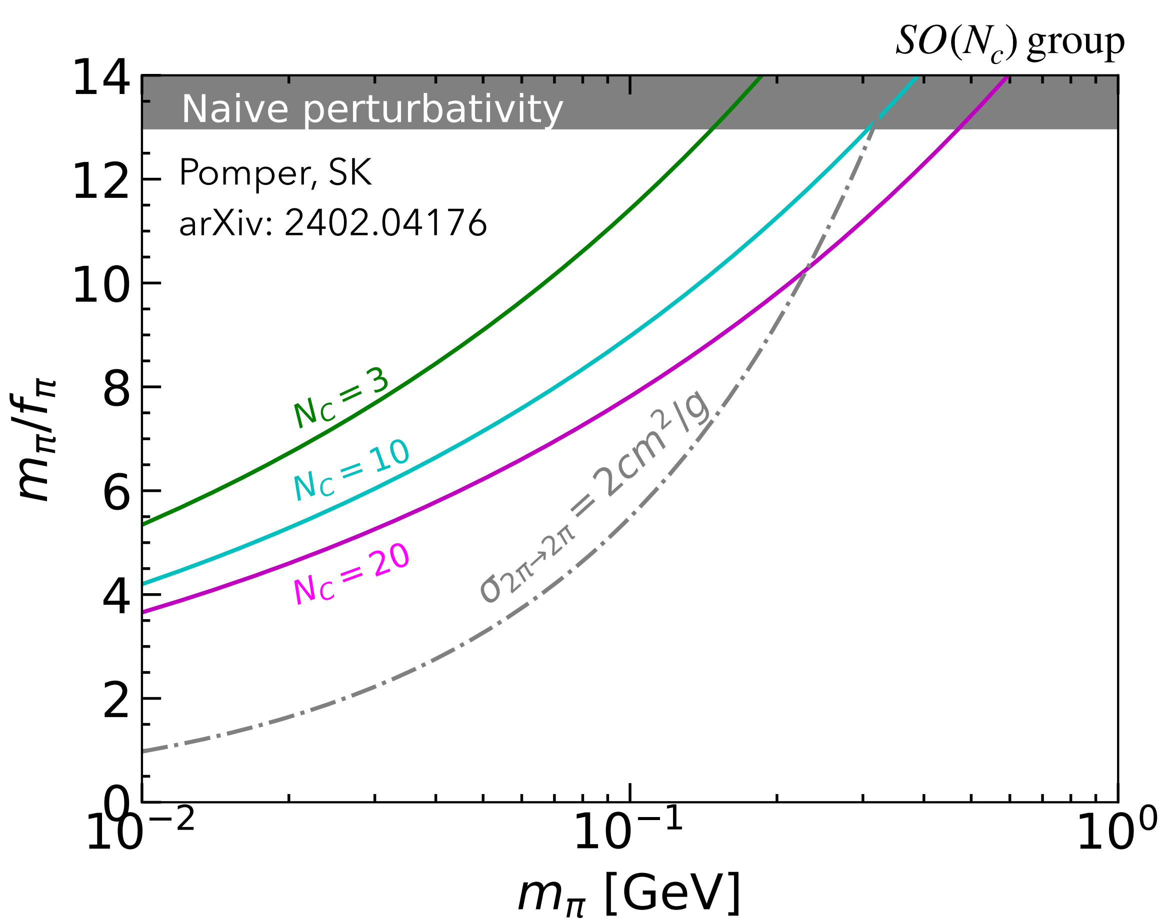
- Dark pions being the lightest states can be dark matter candidates

$\mathscr{L} = \mathscr{L}_{\text{non-anom}}$ $+ \mathscr{L}_{\text{anom}}$ → Construction a la Witten





Hochberg et al arXiv:1512.07917,
Kribs et al arXiv: 1604.04627,
Cline et al arXiv:2108.10314,
Berlin et al arXiv:1801.05805



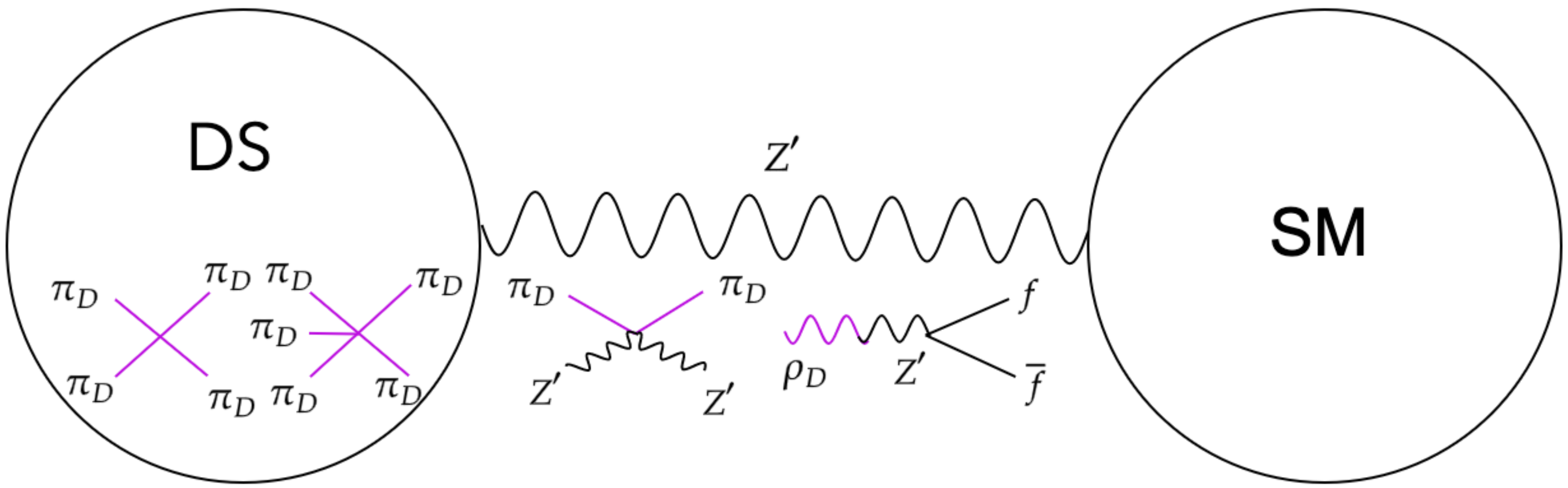
- Relic density $\quad n_{\pi_D}\langle\sigma v\rangle_{3\to 2} \sim H \implies \dfrac{m_{\pi_D}}{f_{\pi_D}} \propto m_{\pi_D}^{3/10}$

- Self-scattering $\quad \dfrac{\sigma_{\pi_D\pi_D\to\pi_D\pi_D}}{m_{\pi_D}} \propto \left(\dfrac{m_{\pi_D}}{f_{\pi_D}}\right)^4 \times \dfrac{1}{m_{\pi_D}^3}$

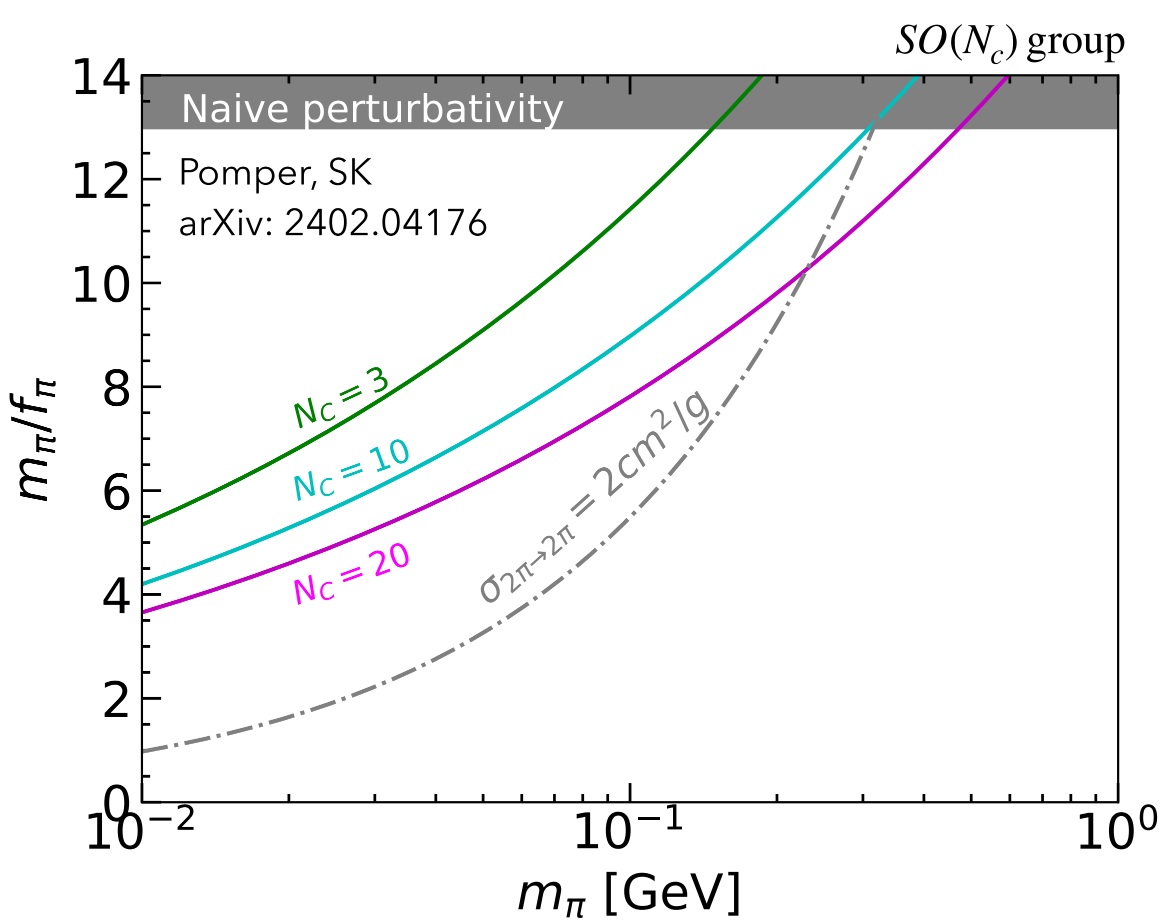
- Relic density and self-interaction preferred regions are in mutual tension

- Needs m_{π_D}/f_{π_D} near perturbative unitarity: uncomfortable for validity of underlying effective theory

Dark pion dark matter



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



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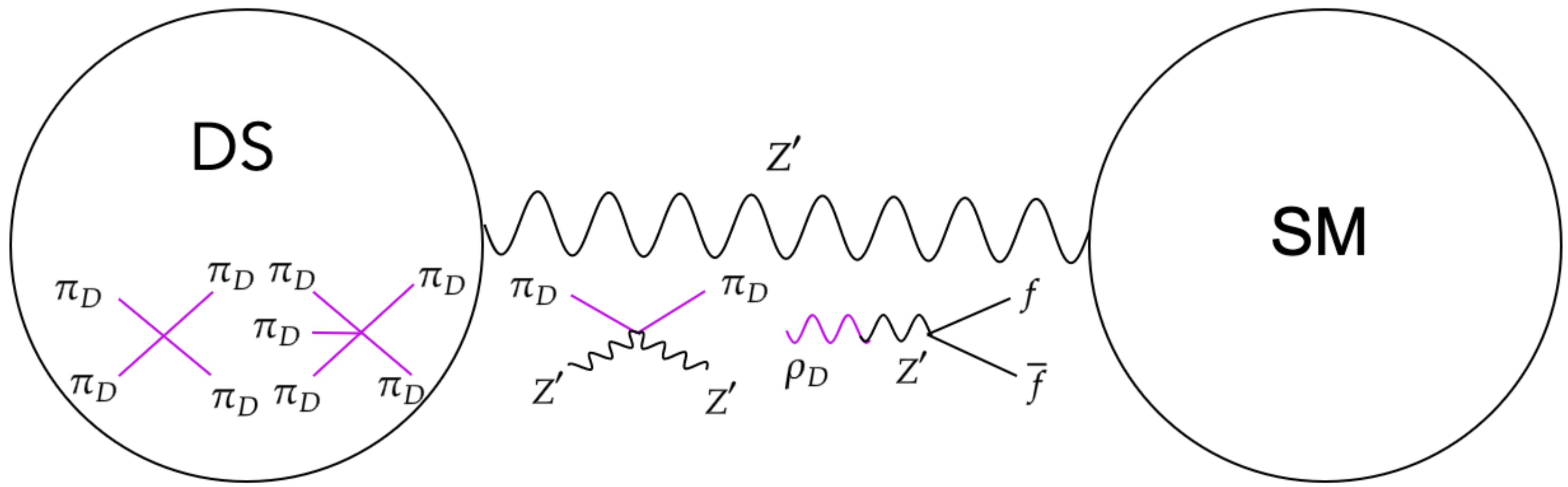
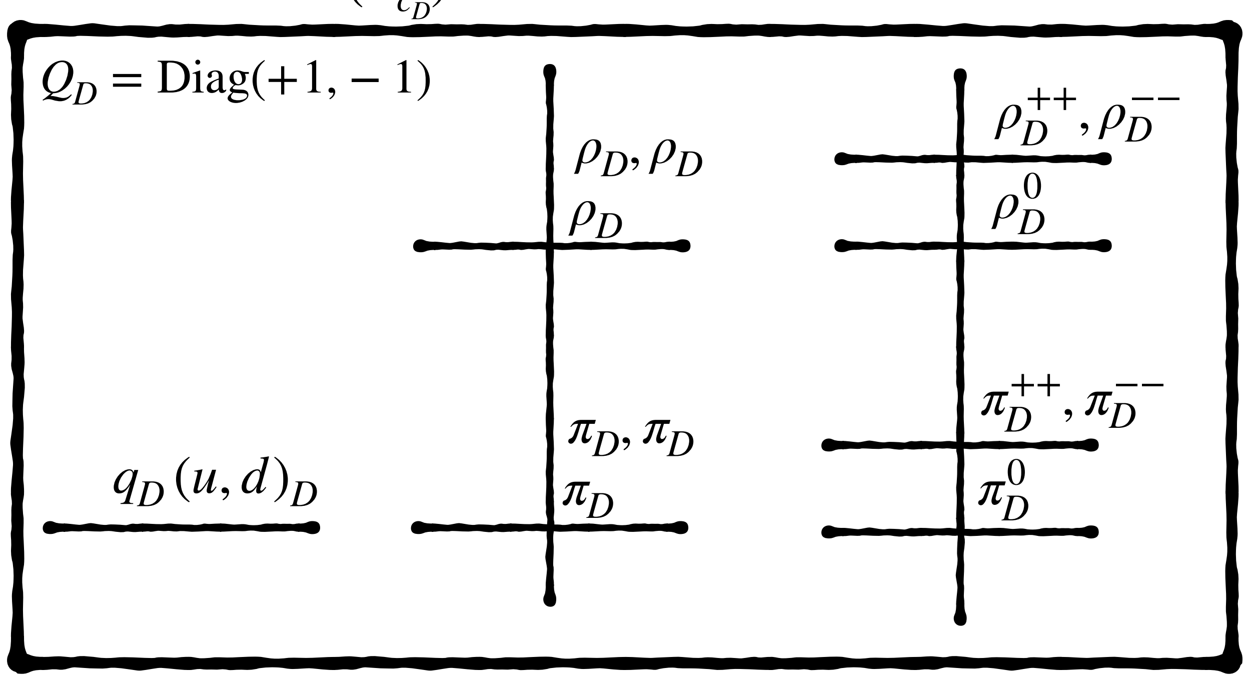
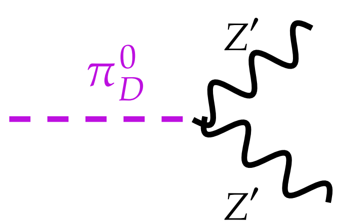
Dark pion dark matter



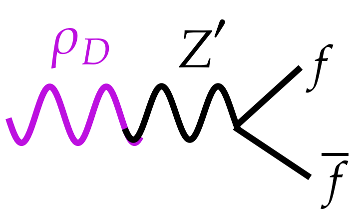
$SU(N_{c_D})$: 2 fermions in fundamental





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

$\rightarrow Q^2 \propto 1$

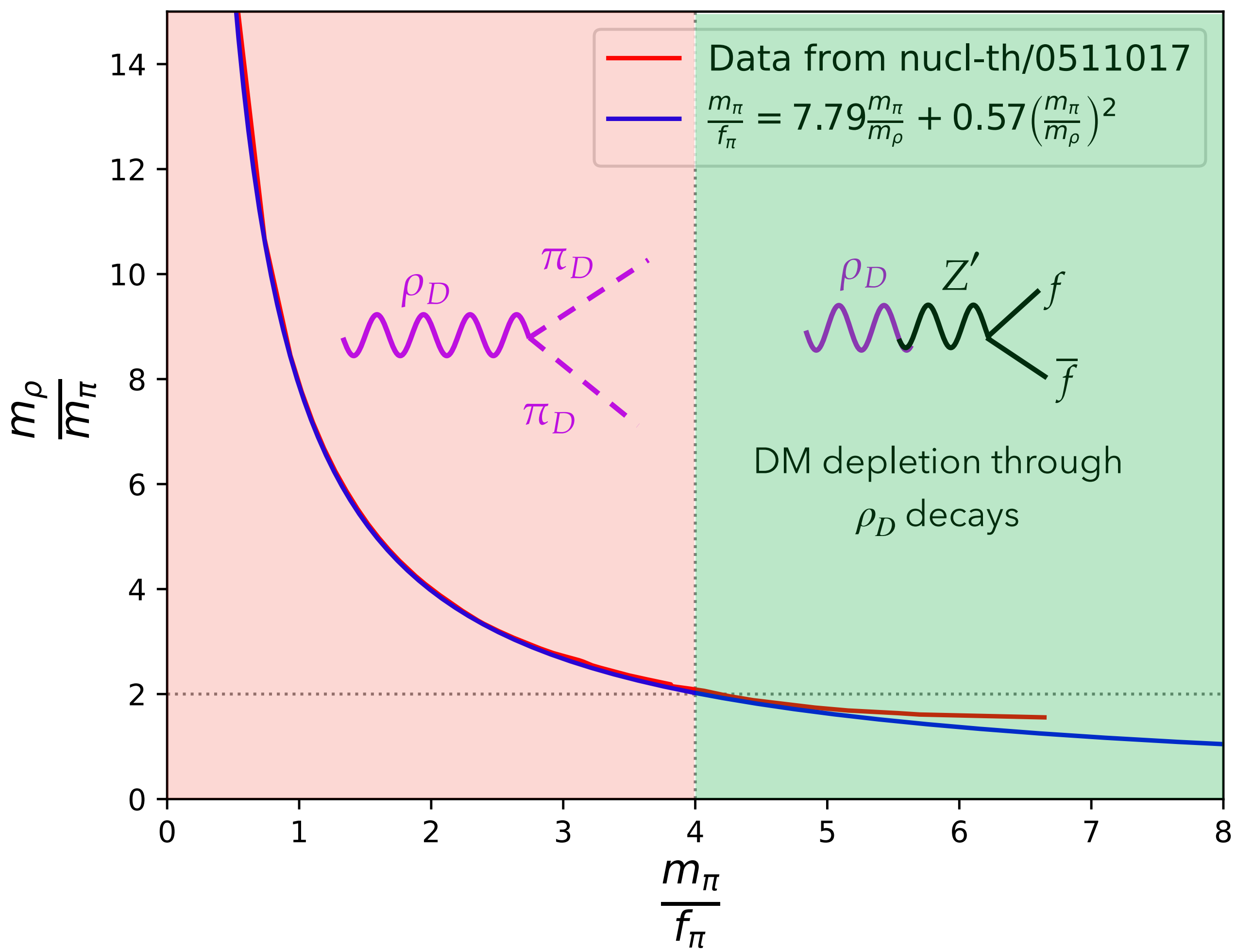


Unstable

Beyond pion only interactions

Snowmass report Kulkarni et al. arXiv:2203.09503

- Important connections through snowmass process via connections with non-perturbative analyses
  - UV and IR parameters are not uncorrelated
  - Two discrete parameters N_{c_D}, N_{f_D}
  - Two continuous parameters $m_{q_D}, \alpha_D(\mu)$ (UV)
    - $f_\pi, m_\pi/f_\pi$ or $\Lambda_D, m_{\pi_D}/\Lambda_D$ or $m_{\pi_D}, m_{\pi_D}/m_{\rho_D}$ (IR)



- Fit to non-perturbative calculations

$$\frac{m_\pi}{f_\pi} = 7.79\,\frac{m_\pi}{m_\rho} + 0.57\left(\frac{m_\pi}{m_\rho}\right)^2$$

- Need $m_\pi/f_\pi \gtrsim 4$ for interesting DM phenomenology involving vector mesons

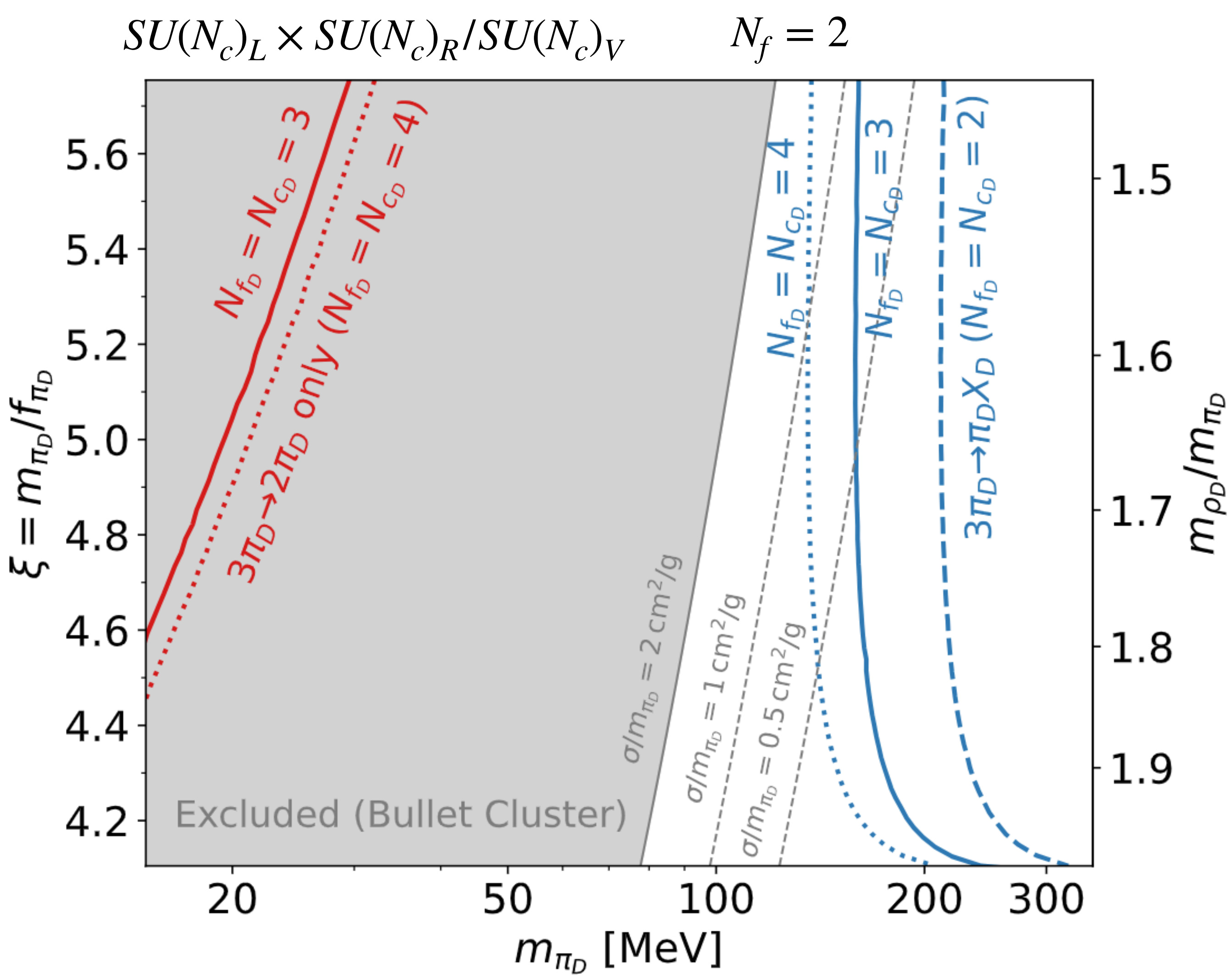
$N_{f_D} = 1$ and/or $\mathrm{N}_{\mathrm{c}_\mathrm{D}} = 2$ special cases

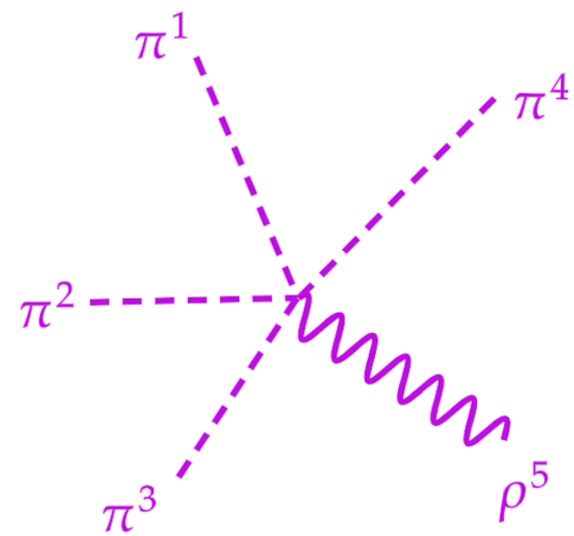
Francis et. al. arXiv:1809.09117

New relic density avenues

- Large self interactions consistent with relic density

Bernreuther, Hemme, Kahlhoefer, SK arXiv:2311.17157





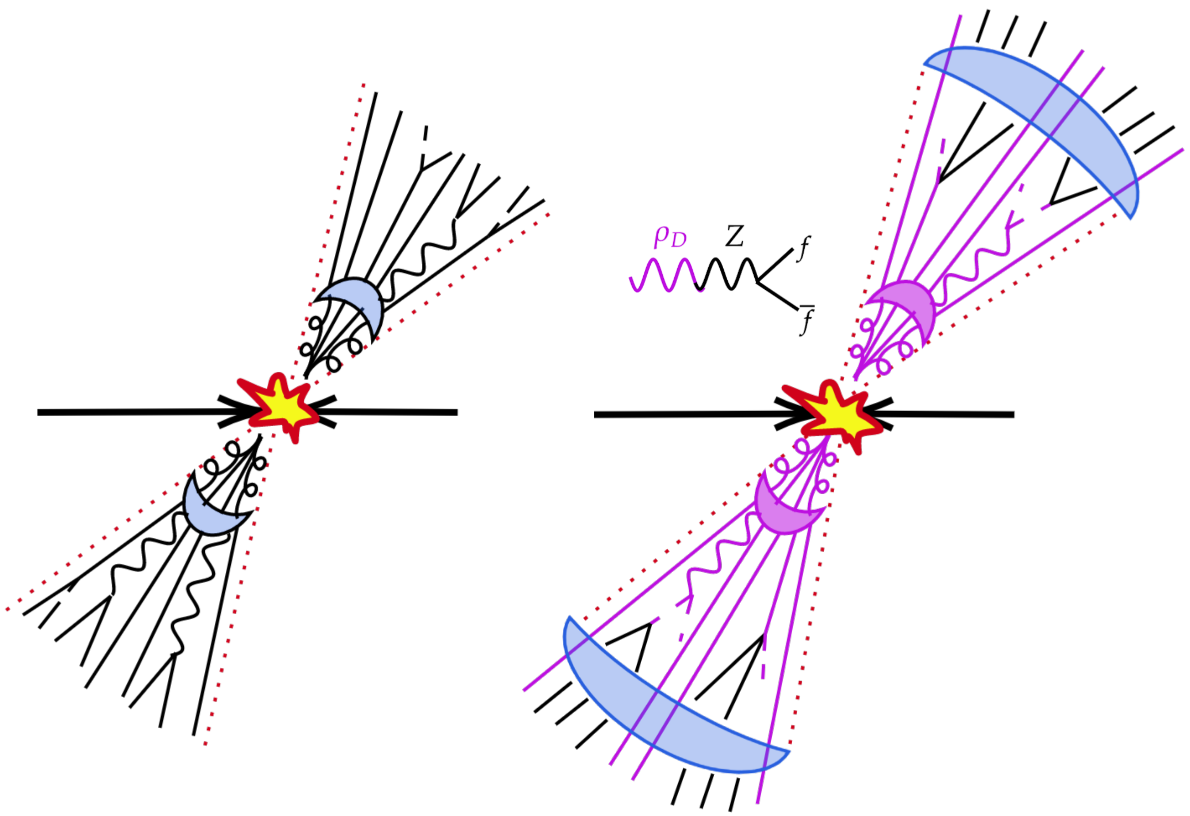
$$R \equiv \frac{\langle \sigma v^2 \rangle_{3\pi_D \to \pi_D \rho_D}}{\langle \sigma v^2 \rangle_{3\pi_D \to 2\pi_D}} = \frac{\alpha^{\text{eff}}_{3\pi_D \to \pi_D \rho_D}}{\alpha^{\text{eff}}_{3\pi_D \to 2\pi_D}}$$

$$\approx (1800 - 8500) \times \frac{1}{N_{c_D}^2 \, \xi^4} \frac{x^2}{\sqrt{1-y}}$$

- Delayed freeze out allows for larger masses thus Bullet cluster constraints can be evaded

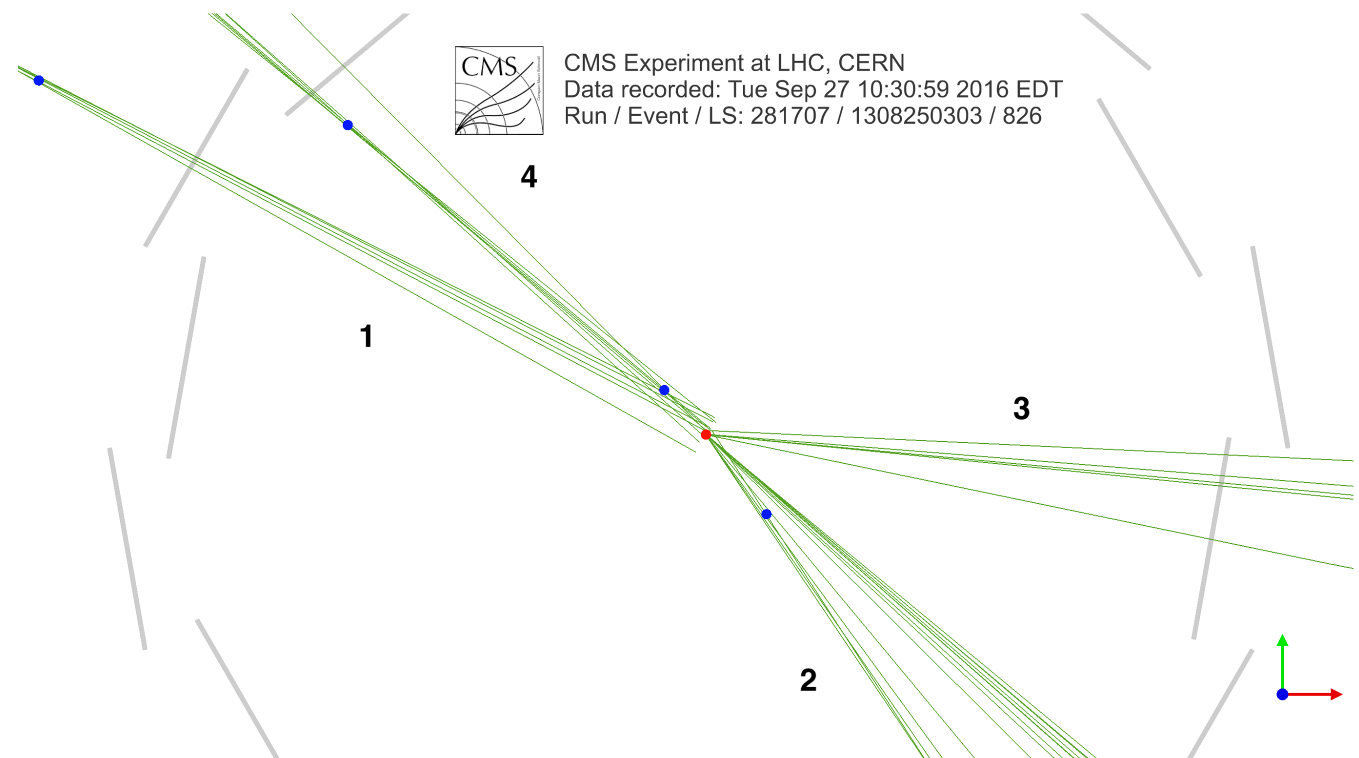
- Lead to new experimental signatures

Strassler et al hep-ph/0604261, Strassler et al arXiv:0801.0629, Hofman et al arXiv:0803.1467, Cohen et al arXiv:1503.00009, Schwaller et al arXiv:1502.05409, Knapen et al arXiv:1612.00850, Renner et al arXiv:1803.08080, Cazzaniga et al arXiv:2206.03909, Beauchesne et al arXiv:2212.11523, CMS-EXO-17-010 (2022), ATLAS-EXOT-2022-37 (2023)



- Jets containing large missing energy
- Jets containing displaced vertices
- Jets with too many or too few tracks

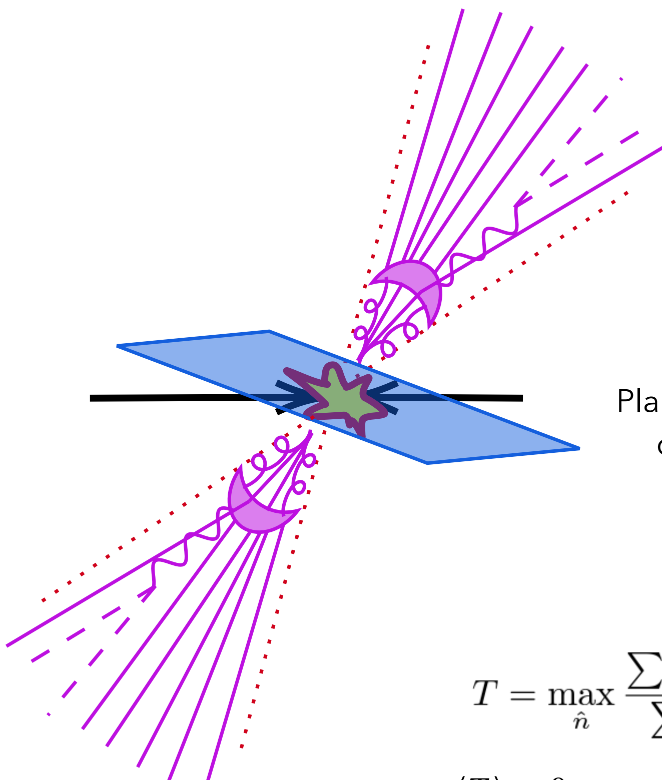
- Experimental program to look for such signatures is just beginning
- Lack of understanding between theory space and experimental signatures
- Portals to the Standard Model play an important role



arXiv:1810.10069

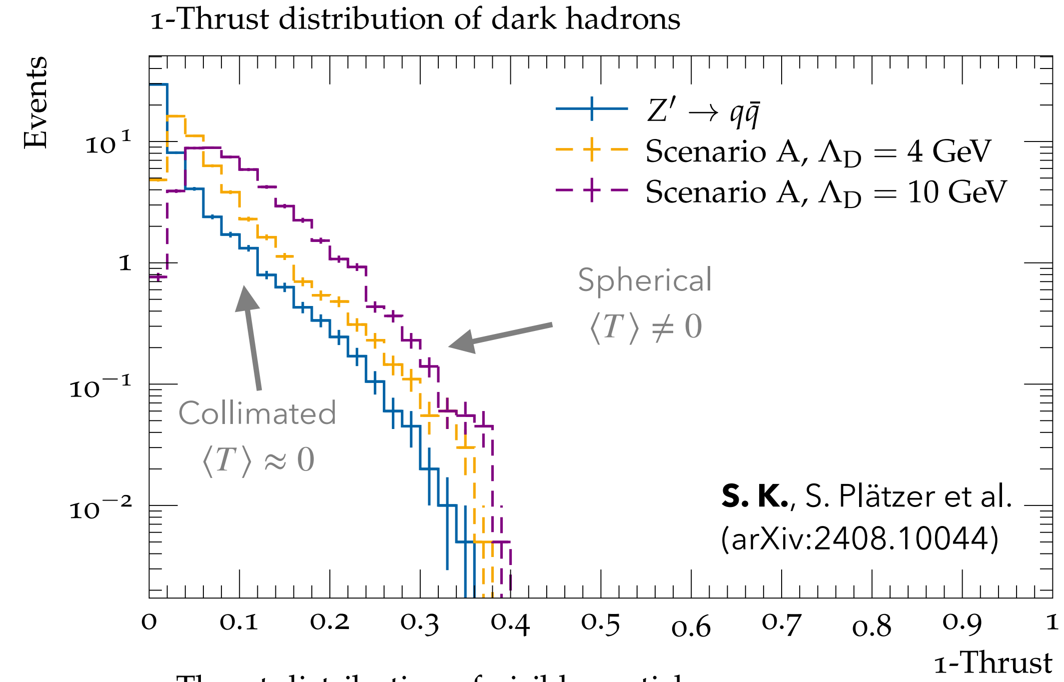
Darkshowers in Herwig7

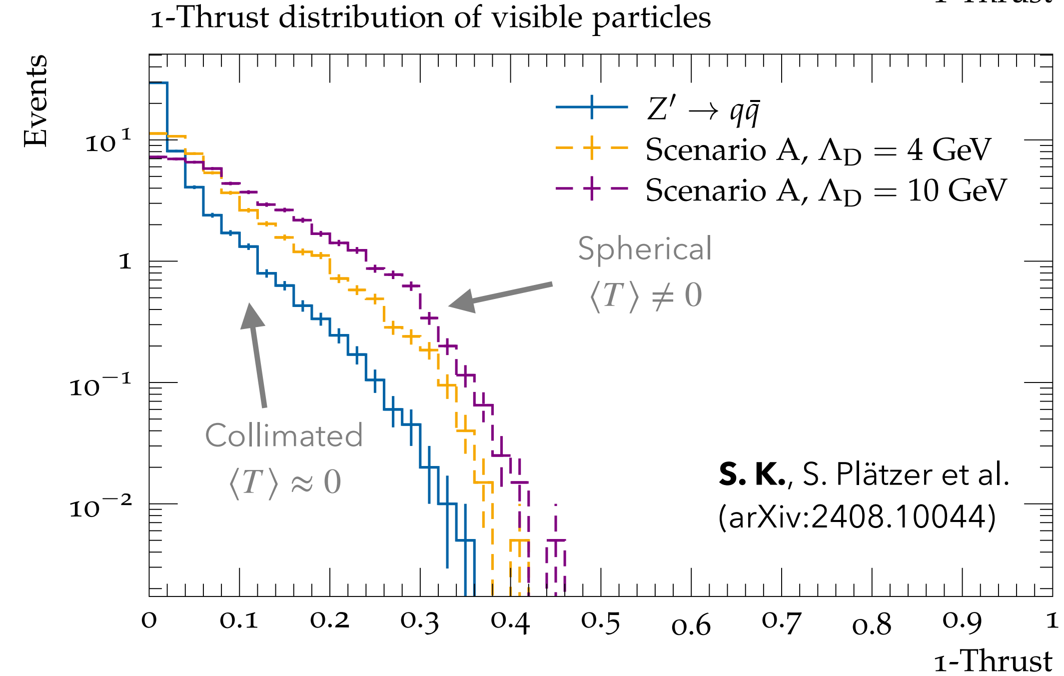
Experimental signatures are understudied



$$T = \max_{\hat{n}} \frac{\sum_i |\boldsymbol{p}_i \cdot \hat{n}|}{\sum_i |\boldsymbol{p}_i|}$$

$\langle T \rangle \approx 0 \implies$ back to back collimated radiation (jets)



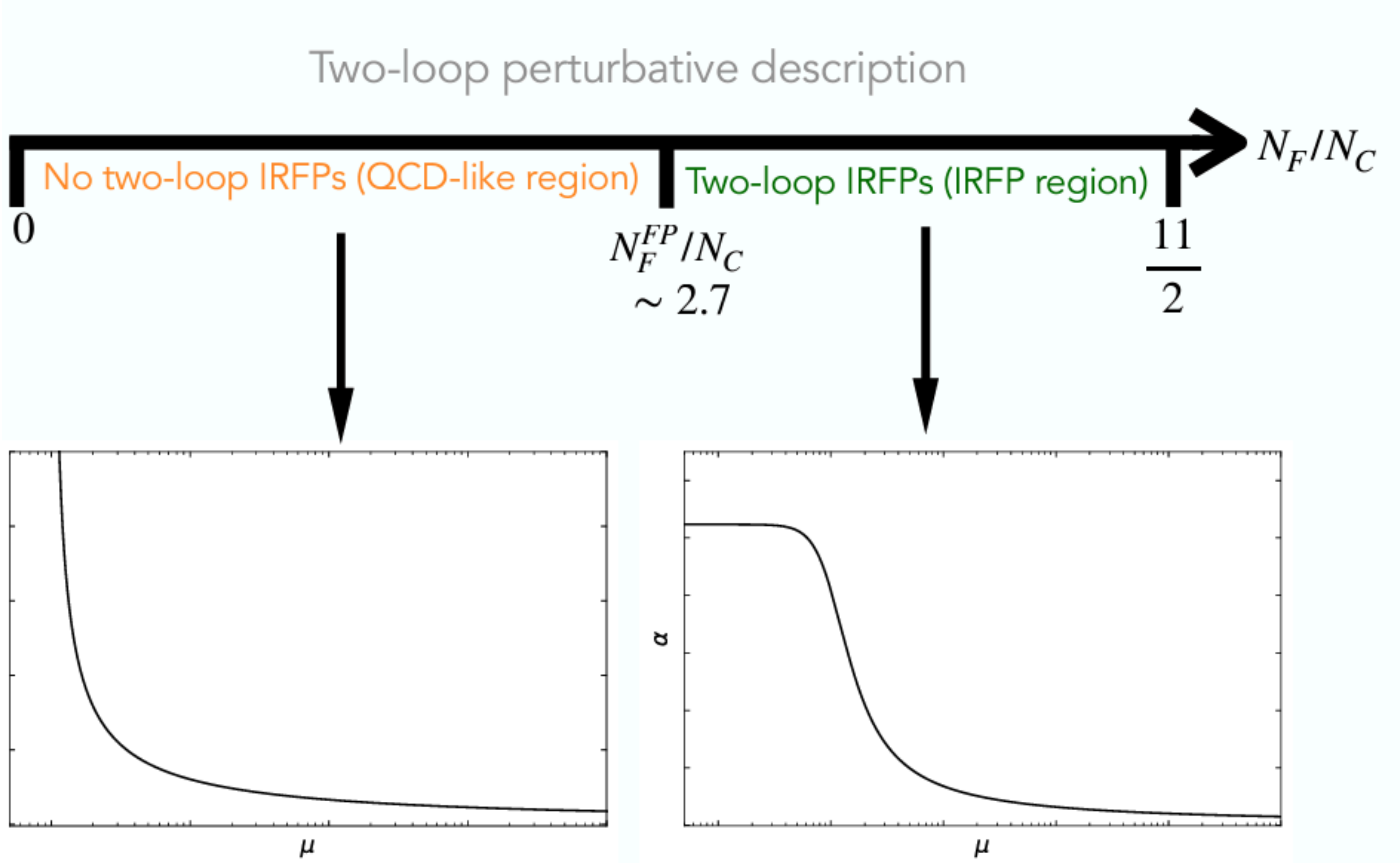


- First implementation of new strongly interacting theories in Herwig
- **First** demonstration of **change in the event shape** as a direct outcome of theory space

Beyond QCD-like theories: near conformal theories

- At larger N_f/N_c the two loop beta function of the running coupling can a non-trivial fixed point

$$\mu^2 \frac{d\alpha}{d\mu} = \beta(\alpha) = -\alpha^2(\beta_0 + \beta_1 \alpha) \qquad \alpha_* = -\frac{\beta_0}{\beta_1}; > 0 \text{ for } \frac{\mathrm{N_f}}{\mathrm{N_c}} \gtrsim 2.7$$



Beyond QCD-like theories: near conformal theories

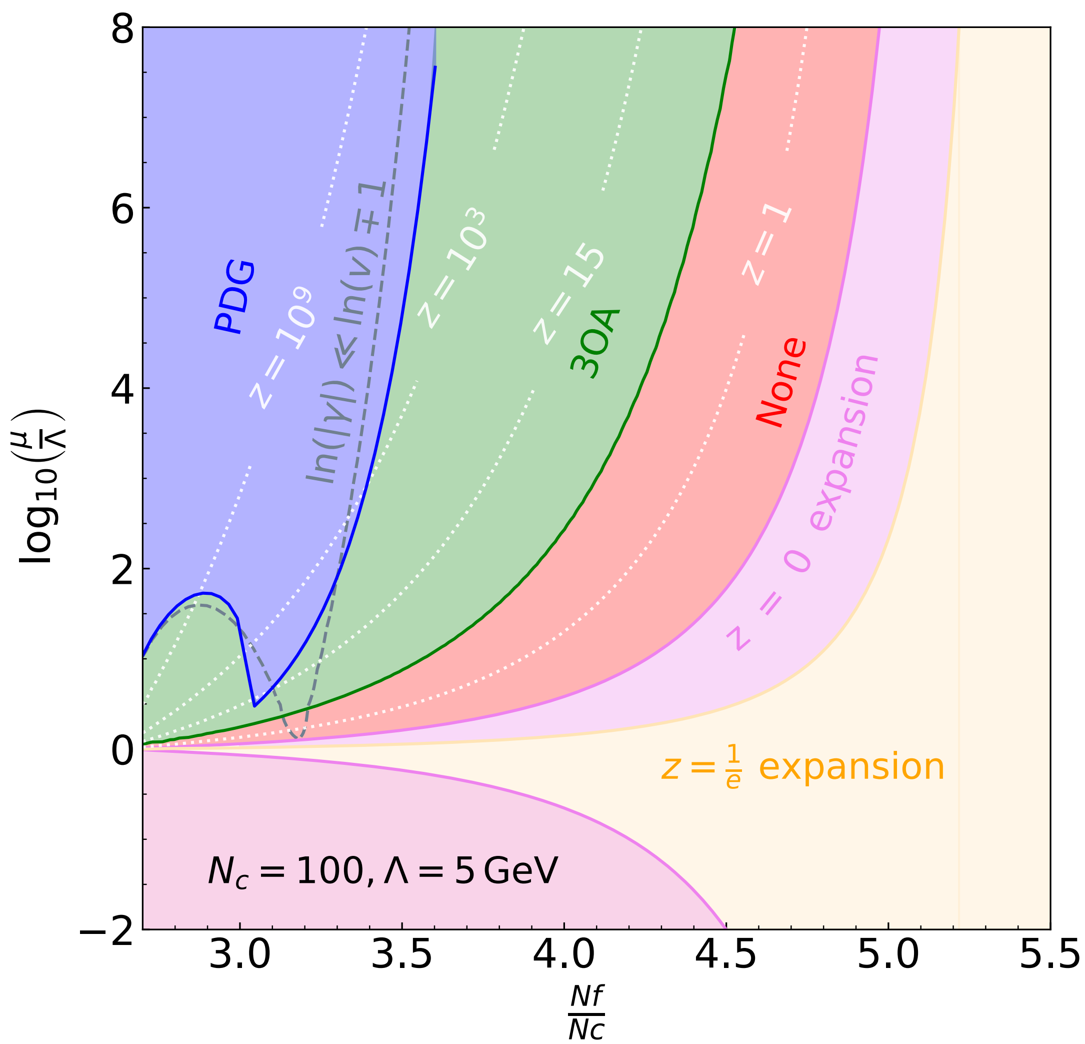
To appear with J. Lockyer, M. Strassler

- New procedure to simulate theories containing infrared fixed points defined and validated

$$\alpha = \alpha_* \left[W_{-1}(-z) + 1\right]^{-1} \quad ; \quad \alpha = \alpha_* \left[W_0(z) + 1\right]^{-1} \quad ; \quad z = \frac{1}{e}\left(\frac{\mu^2}{\Lambda^2}\right)^{\beta_0 \alpha_*}$$

QCD-like (no IRFP) IRFP-region

T. Appelquist et al. arXiv:9602385,
D. Litim et al. arXiv:1406.2337,
E. Gardi et al. arxiv:9810192



- No one solution catch all situation, need to resort to numerical interpolation

Conclusions

- Strongly interacting dark sectors are gaining well deserved attention
- Progress on multiple important fronts experimentally and theoretically
- Three important aspects in this talk
    - Generation of relic density even in absence of number violating $3\pi \to 2\pi$ interactions which also help with validity of chiral EFT
    - Development of new event generators to understand theoretical subtleties in numerical simulations and hadronization uncertainties
    - Development of collider simulations of near conformal theories leading to potentially new signatures at ongoing experiments