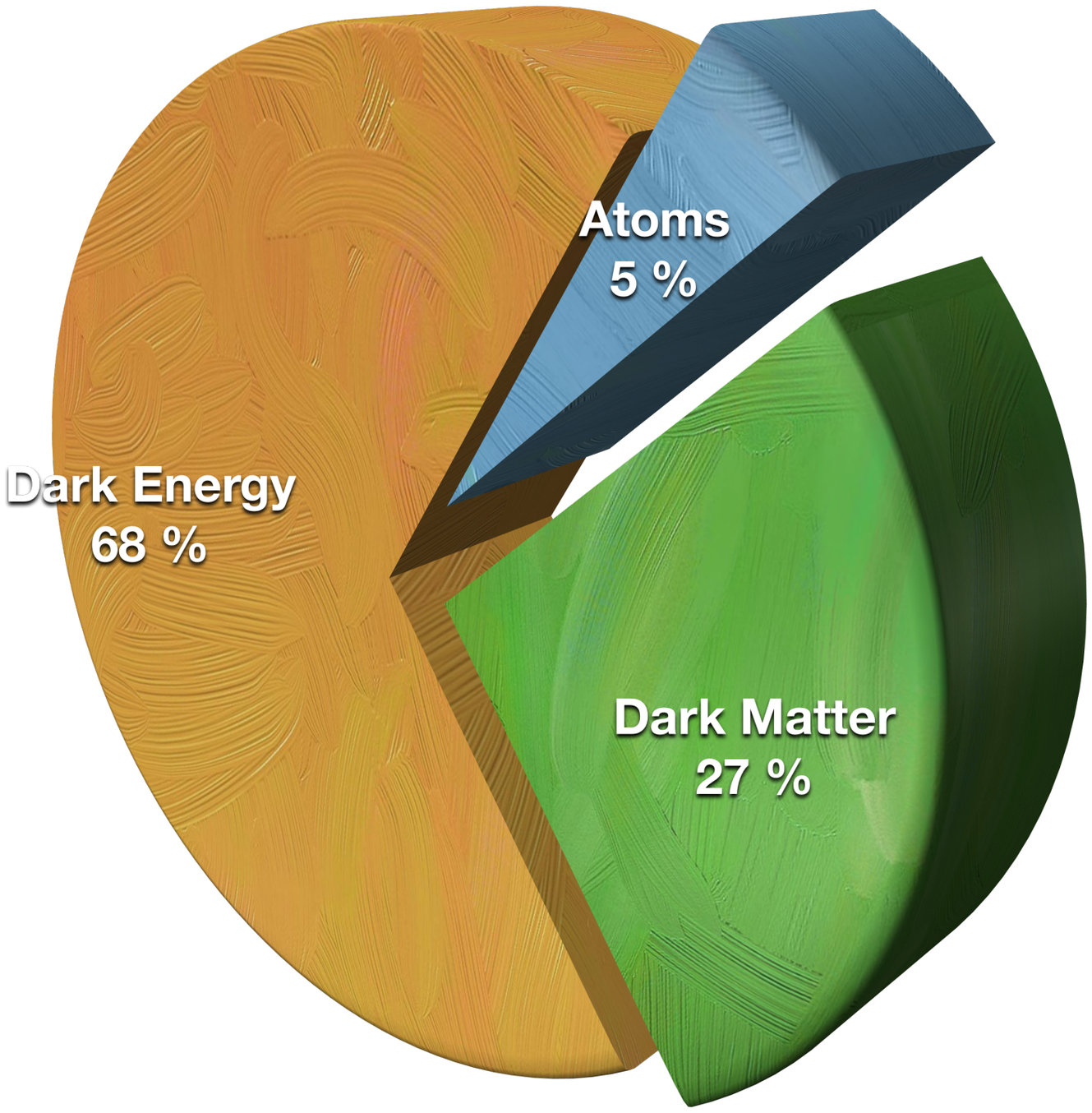
Fundamental Composite Dynamics

Francesco Sannino

SYDDANSKUNIVERSITET.DK

CP³ Origins
Cosmology & Particle Physics

Much ado for 5%



95% is unknown!

Richer than 5%? Likely

Minimal Composite Dynamics

Minimal Composite Dynamics

Minimal = 4D minimal matter and simplest gauge-groups

Minimal Composite Dynamics

Minimal = 4D minimal matter and simplest gauge-groups

- SU(**2**) or SU(**3**) New Gauge Group
- At most 2 New Dirac Flavours
- Either Fund., Symmetric or Adj matter rep.

Minimal Composite Dynamics

Minimal = 4D minimal matter and simplest gauge-groups

- SU(**2**) or SU(**3**) New Gauge Group
- At most 2 New Dirac Flavours
- Either Fund., Symmetric or Adj matter rep.

What is the dynamics and spectrum of these theories ?

Bright side

Composite Higgs dynamics

$$DH^{\dagger}DH - V(H) + \overline{\Psi}_L H \psi_R$$

Composite Higgs dynamics

$$DH^{\dagger}DH - V(H) + \overline{\Psi}_L H \psi_R$$

$$m_W^2 WW$$

Composite Higgs dynamics

$$DH^{\dagger}DH - V(H) + \overline{\Psi}_L H \psi_R$$

$$m_W^2 WW$$

$$m_\psi \overline{\psi}_L \psi_R$$

Composite Higgs dynamics

$$DH^{\dagger}DH - V(H) + \overline{\Psi}_L H \psi_R$$

$$m_W^2 WW$$

$$m_\psi \overline{\psi}_L \psi_R$$

TC/Fund Comp Dyn

Composite Higgs dynamics

$$DH^{\dagger}DH - V(H) + \overline{\Psi}_L H \psi_R$$

$$m_W^2 WW$$

$$m_\psi \overline{\psi}_L \psi_R$$

TC/Fund Comp Dyn

Extended TC (ETC)

Composite Higgs dynamics

$$DH^{\dagger}DH - V(H) + \overline{\Psi}_L H \psi_R$$

$$m_W^2 WW \qquad\qquad m_\psi \overline{\psi}_L \psi_R$$

TC/Fund Comp Dyn $\longleftrightarrow$ Extended TC (ETC)

Minimal Technicolor

Higgs is the lightest scalar excitation of the condensate

Minimal Technicolor

Higgs is the lightest scalar excitation of the condensate

Inside the box

- Break EW
- Theories available/unexplored
- Vacuum stable
- Natural

Minimal Technicolor

Higgs is the lightest scalar excitation of the condensate

Inside the box

- Break EW
- Theories available/unexplored
- Vacuum stable
- Natural

Outside the box

- Fermion masses vs FCNC
- Electroweak precision data
- Light Higgs

Minimal Technicolor

Higgs is the lightest scalar excitation of the condensate

Inside the box

- Break EW
- Theories available/unexplored
- Vacuum stable
- Natural

Outside the box

- Fermion masses vs FCNC
- Electroweak precision data
- Light Higgs

TC can be conformal if ETC is strong

Minimal Technicolor

Higgs is the lightest scalar excitation of the condensate

Inside the box

- Break EW
- Theories available/unexplored
- Vacuum stable
- Natural

Outside the box

- Fermion masses vs FCNC
- Electroweak precision data
- Light Higgs

TC can be conformal if ETC is strong

If ETC scales differ for each generation, walking is not needed..

Composite Goldstone Higgs

D.B. Kaplan & H. Georgi, 84

Higgs is a composite pseudo goldstone

Composite Goldstone Higgs

D.B. Kaplan & H. Georgi, 84

Higgs is a composite pseudo goldstone

Inside the box

- Higgs is massless
- Gauge boson couplings
- Technicolor limit

Composite Goldstone Higgs

D.B. Kaplan & H. Georgi, 84

Higgs is a composite pseudo goldstone

Inside the box

- Higgs is massless
- Gauge boson couplings
- Technicolor limit

Outside the box

- Underlying theory
- Higgs mass
- Fermion masses/couplings
- EW vacuum alignment

Composite Goldstone Higgs

D.B. Kaplan & H. Georgi, 84

Higgs is a composite pseudo goldstone

Inside the box

- Higgs is massless
- Gauge boson couplings
- Technicolor limit

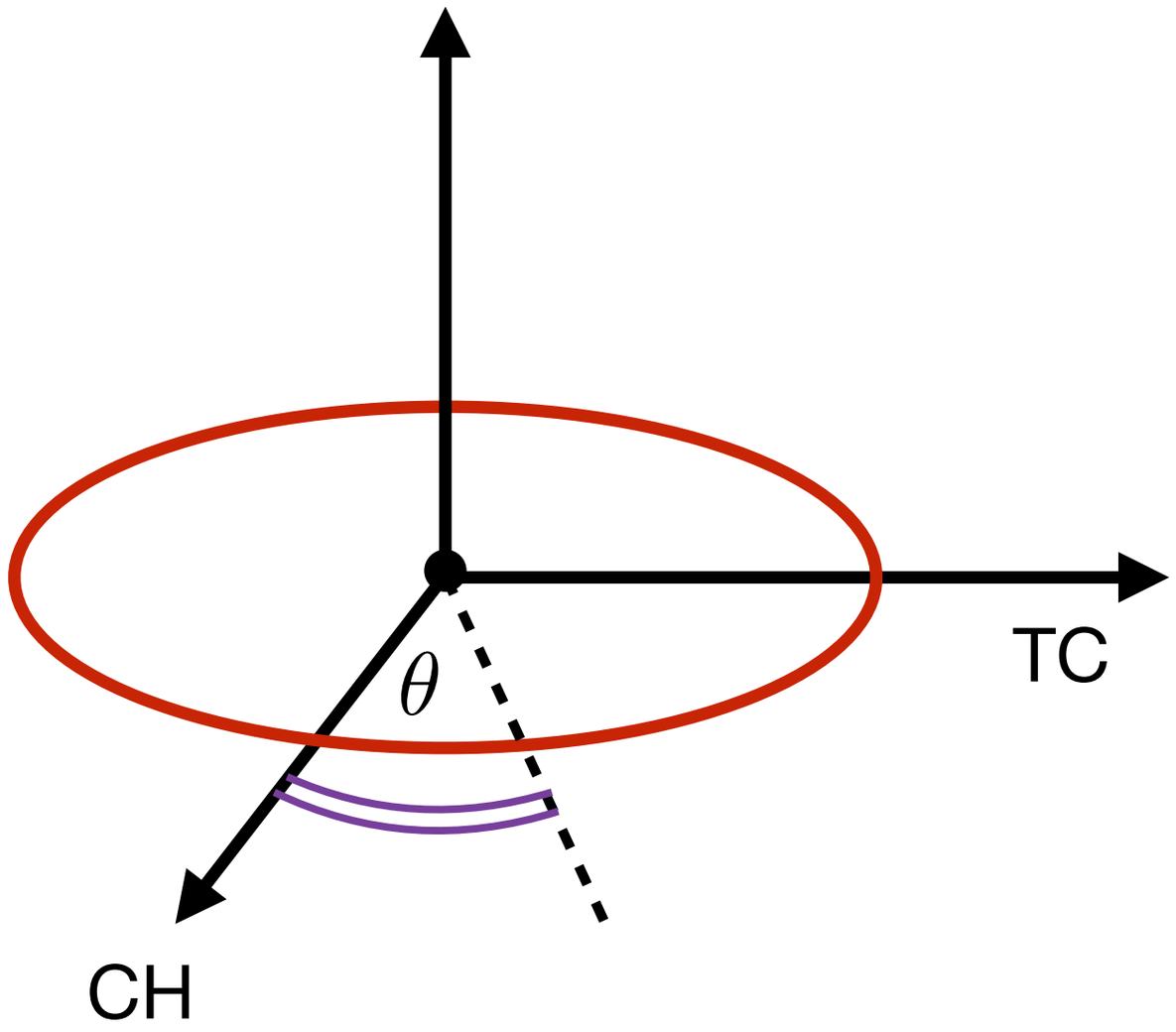
Work in 4 dimensions

Outside the box

- Underlying theory
- Higgs mass
- Fermion masses/couplings
- EW vacuum alignment

Fundamental Composite Dynamics

- Unified TC and CH framework
- Fund 4D underlying theory
- Spectrum via lattice



(Mostly) Effective Theories

Appelquist, Sannino, 98, 99

Ryttov, Sannino, 2008

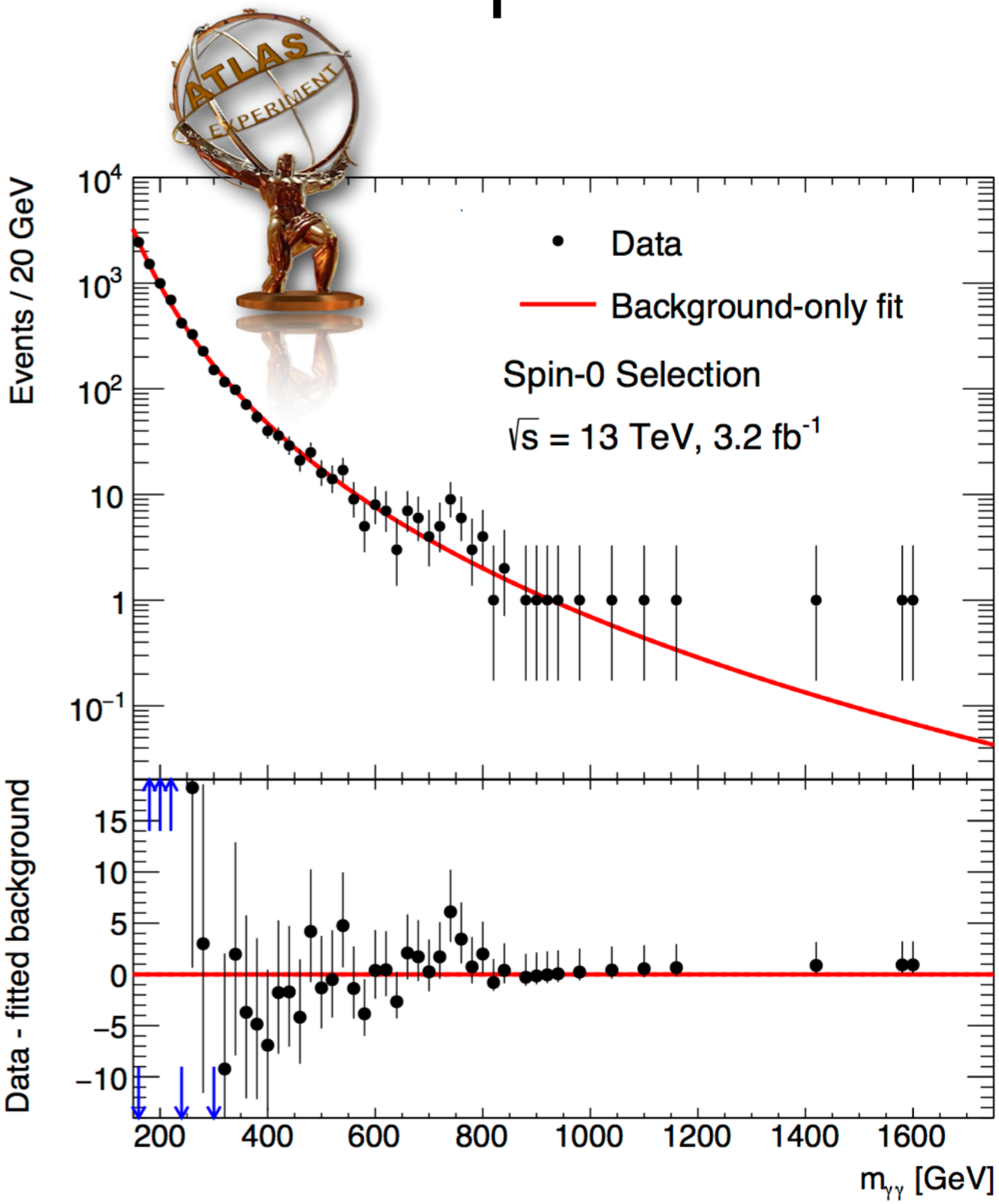
Katz, Nelson Walker, 2005

Gripaios, Pomarol, Riva, Serra, 2009

Galloway, Evans, Luty, Tacchi, 2010

Cacciapaglia and Sannino 1402.0233 JHEP

Diphoton Gold Rush



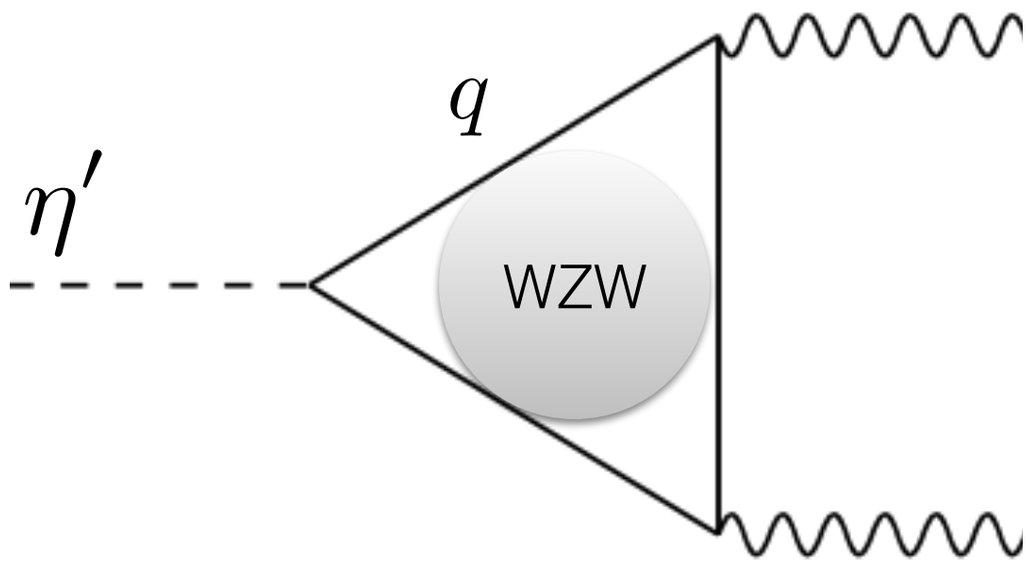
Diphoton explained minimally and naturally

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

Diphoton explained minimally and naturally

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

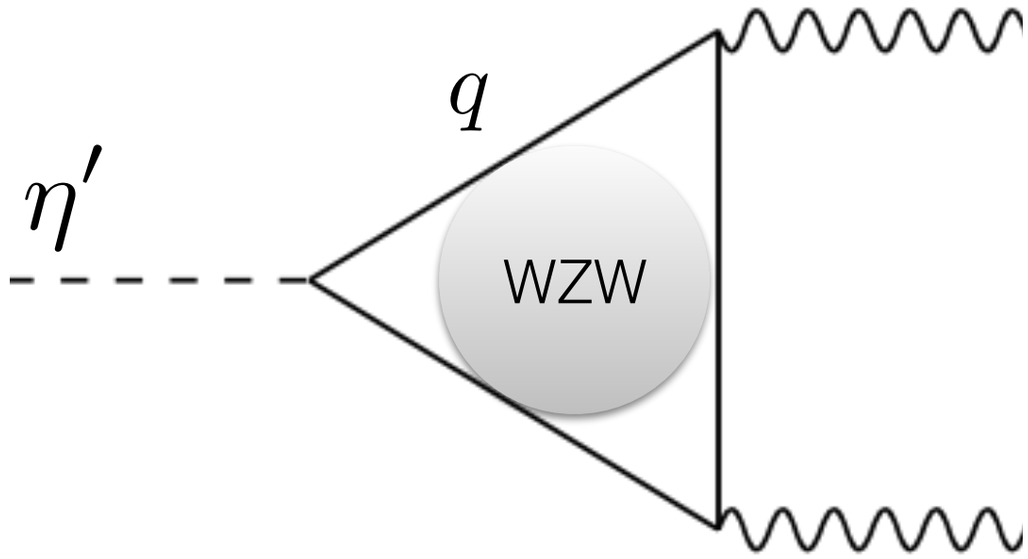
QCD axial anomaly template



Diphoton explained minimally and naturally

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

QCD axial anomaly template

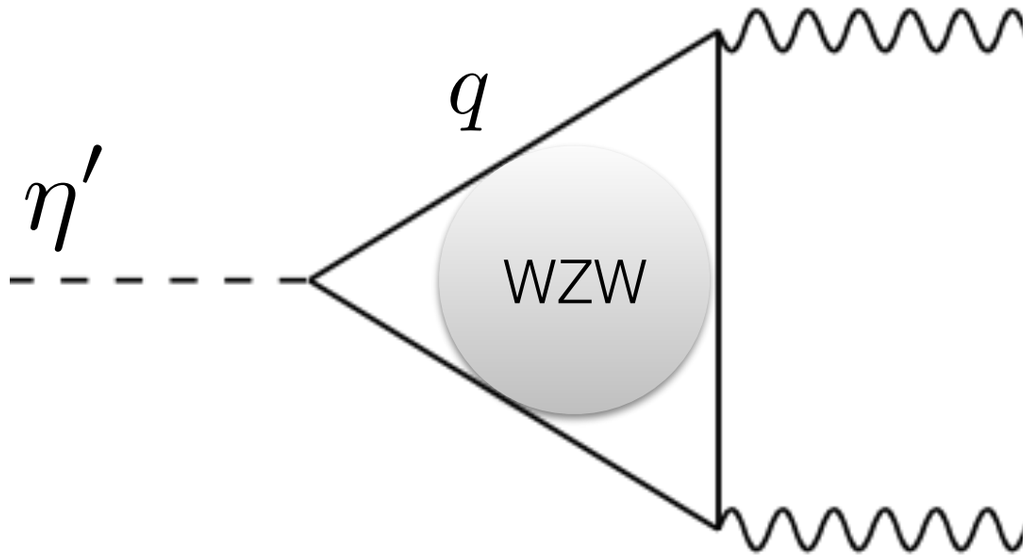


Related to the topological susceptibility

Diphoton explained minimally and naturally

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

QCD axial anomaly template



Related to the topological susceptibility

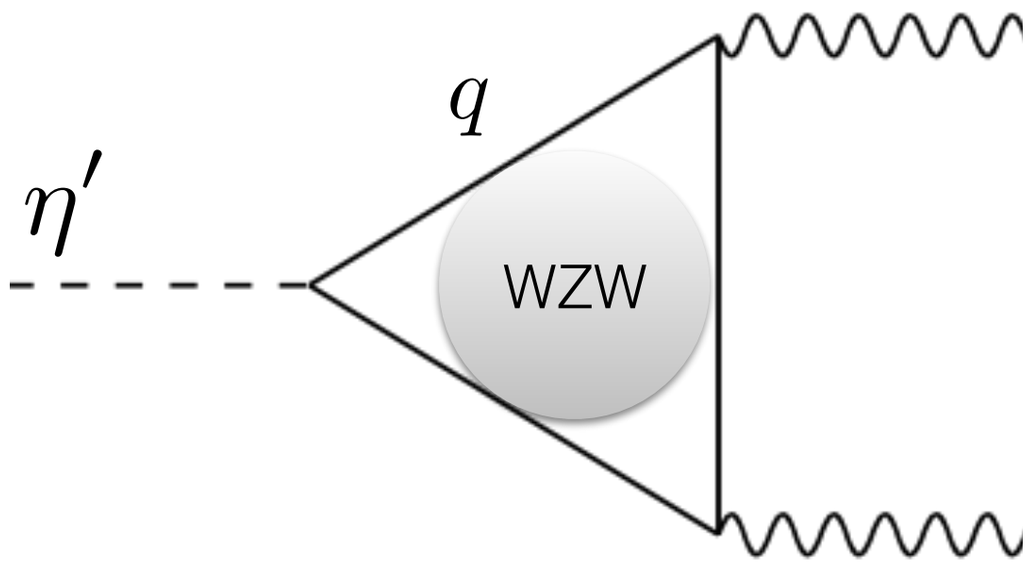
Generalization to non-fund. representations and multiple QCDs

Di Vecchia and Sannino, 1310.0954

Diphoton explained minimally and naturally

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

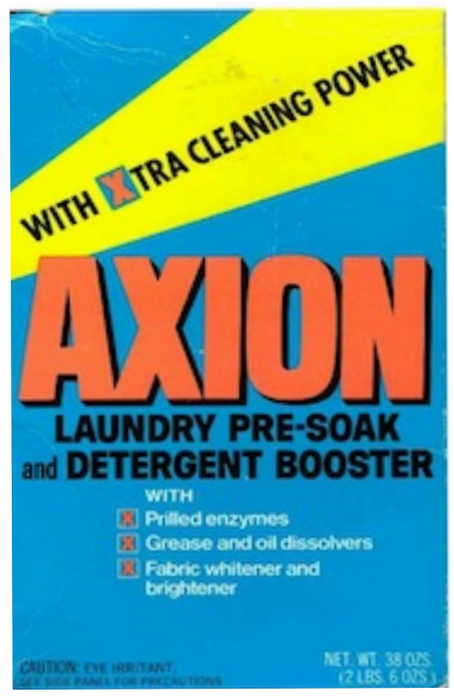
QCD axial anomaly template



Related to the topological susceptibility

Generalization to non-fund. representations and multiple QCDs

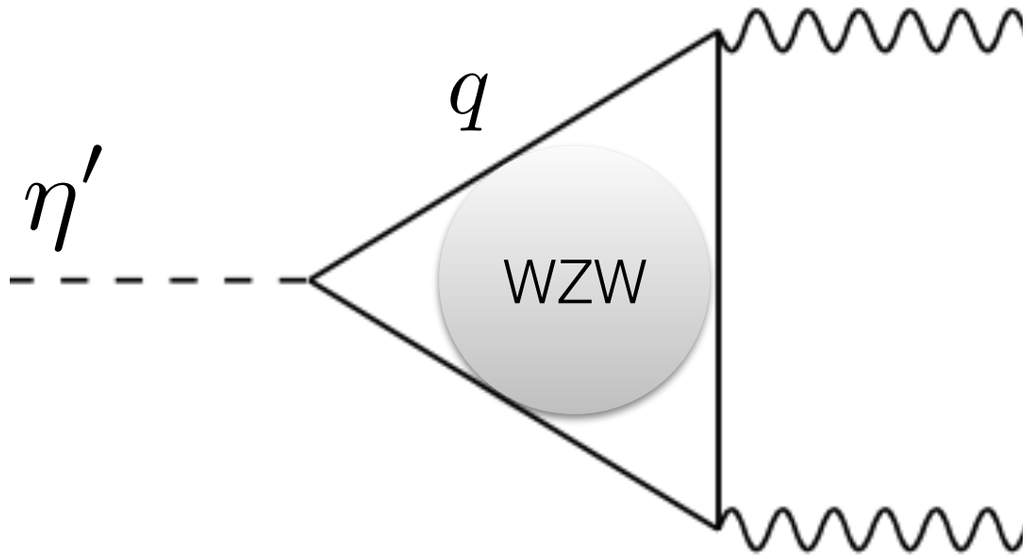
Di Vecchia and Sannino, 1310.0954



Diphoton explained minimally and naturally

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

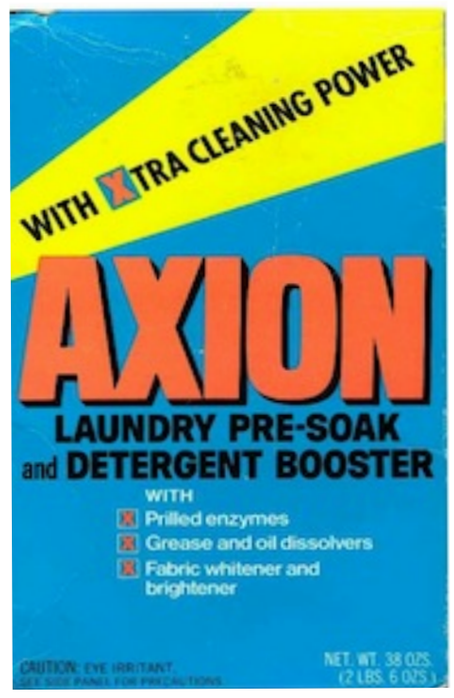
QCD axial anomaly template



Related to the topological susceptibility

Generalization to non-fund. representations and multiple QCDs

Di Vecchia and Sannino, 1310.0954



(QCD axion might be replaced by new colored gapped dynamics,
Hsu & Sannino hep-ph\0408319 in PLB, Wilczek and Moore 1601.02937)

Minimal Composite Dynamics

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

Minimal Composite Dynamics

$$SU(2) \times SU(2) \to SU(2)$$

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

Minimal Composite Dynamics

$$SU(2) \times SU(2) \to SU(2)$$

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

- Techni-eta prime
- Calculable gauged WZW terms
- Natural mass scale
- Littlest matter required
- No Landau poles

Minimal Composite Dynamics

$$SU(2) \times SU(2) \to SU(2)$$

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

- Techni-eta prime
- Calculable gauged WZW terms
- Natural mass scale
- Littlest matter required
- No Landau poles

Hierarch problem is addressed

Minimal Composite Dynamics

$$SU(2) \times SU(2) \to SU(2)$$

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

- Techni-eta prime
- Calculable gauged WZW terms
- Natural mass scale
- Littlest matter required
- No Landau poles

$$Q_L \equiv (U_L, D_L) \quad U_R,\, D_R$$

$$Y(Q_L) = \frac{y}{2} \quad Y(U_R/D_R) = \frac{y \pm 1}{2}$$

Hierarch problem is addressed

Minimal Composite Dynamics

$$SU(2) \times SU(2) \to SU(2)$$

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

- Techni-eta prime
- Calculable gauged WZW terms
- Natural mass scale
- Littlest matter required
- No Landau poles

Hierarch problem is addressed

$$Q_L \equiv (U_L, D_L) \quad U_R,\, D_R$$

$$Y(Q_L) = \frac{y}{2} \quad Y(U_R/D_R) = \frac{y \pm 1}{2}$$

$$\mathcal{U} = e^{i\Phi/F_T} = \exp\left[\frac{i}{F_T}(a + \boldsymbol{\tau}\cdot\boldsymbol{\Pi})\right]$$

$$F_T = 246 \text{ GeV}$$

Minimal Composite Dynamics

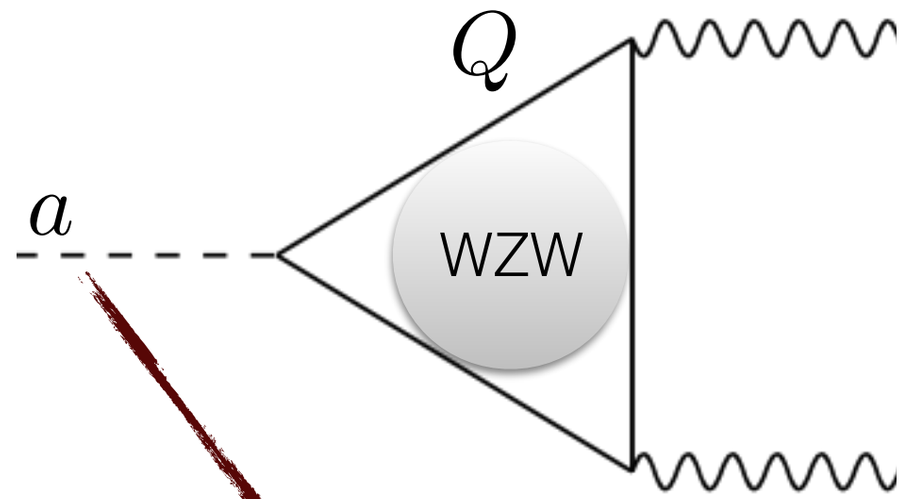
$$SU(2) \times SU(2) \to SU(2)$$

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

- Techni-eta prime
- Calculable gauged WZW terms
- Natural mass scale
- Littlest matter required
- No Landau poles

Hierarch problem is addressed

Techni-QCD axial anomaly



$$Q_L \equiv (U_L, D_L) \qquad U_R,\ D_R$$

$$Y(Q_L) = \frac{y}{2} \qquad Y(U_R/D_R) = \frac{y \pm 1}{2}$$

$$\mathcal{U} = e^{i\Phi/F_T} = \exp\left[\frac{i}{F_T}(a + \boldsymbol{\tau}\cdot\boldsymbol{\Pi})\right]$$

$$F_T = 246\ \text{GeV}$$

Production

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

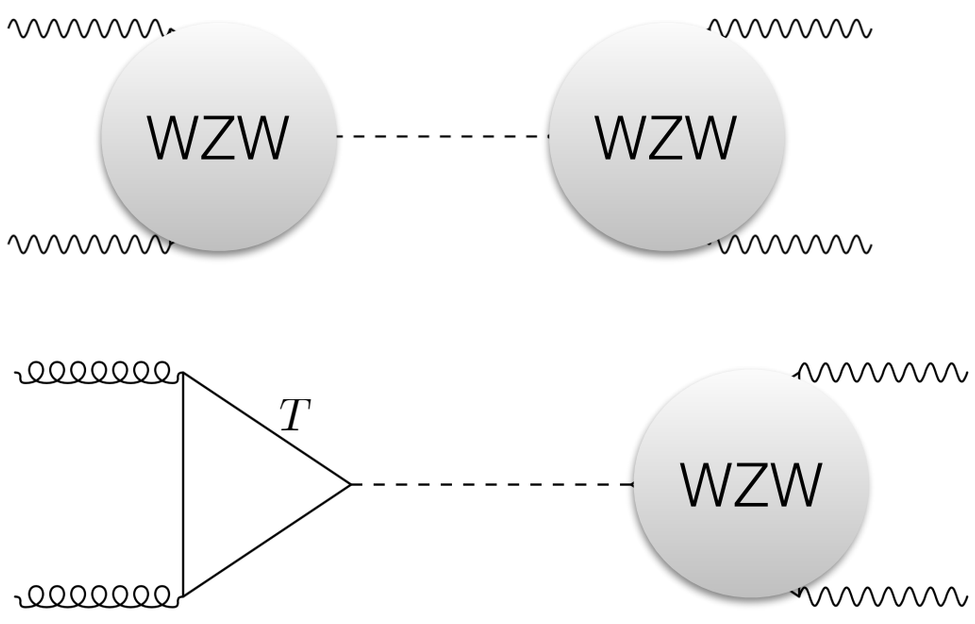
Talk by Emiliano Molinaro this afternoon

Production

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

Narrow width

- photon fusion
- top prime induced gluon fusion



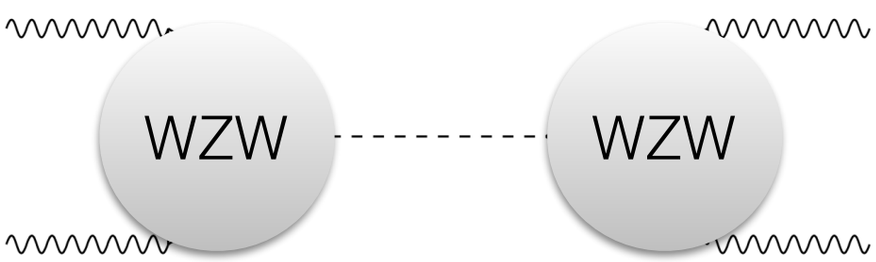
Talk by Emiliano Molinaro this afternoon

Production

Molinaro, Vignaroli, Sannino.1512.05334,1602.07574

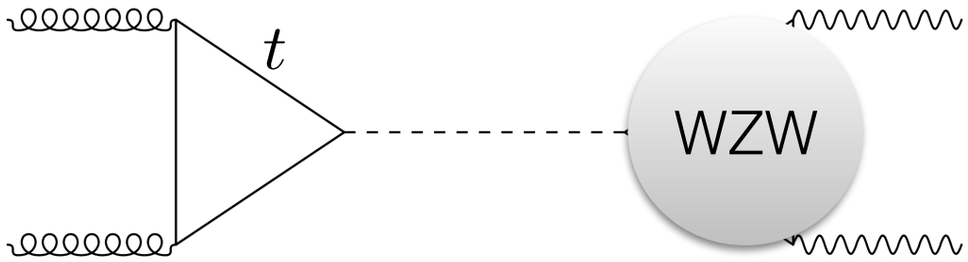
Narrow width

- photon fusion
- top prime induced gluon fusion



ATLAS width ~ 40 GeV

- Coupling with top via mass operator



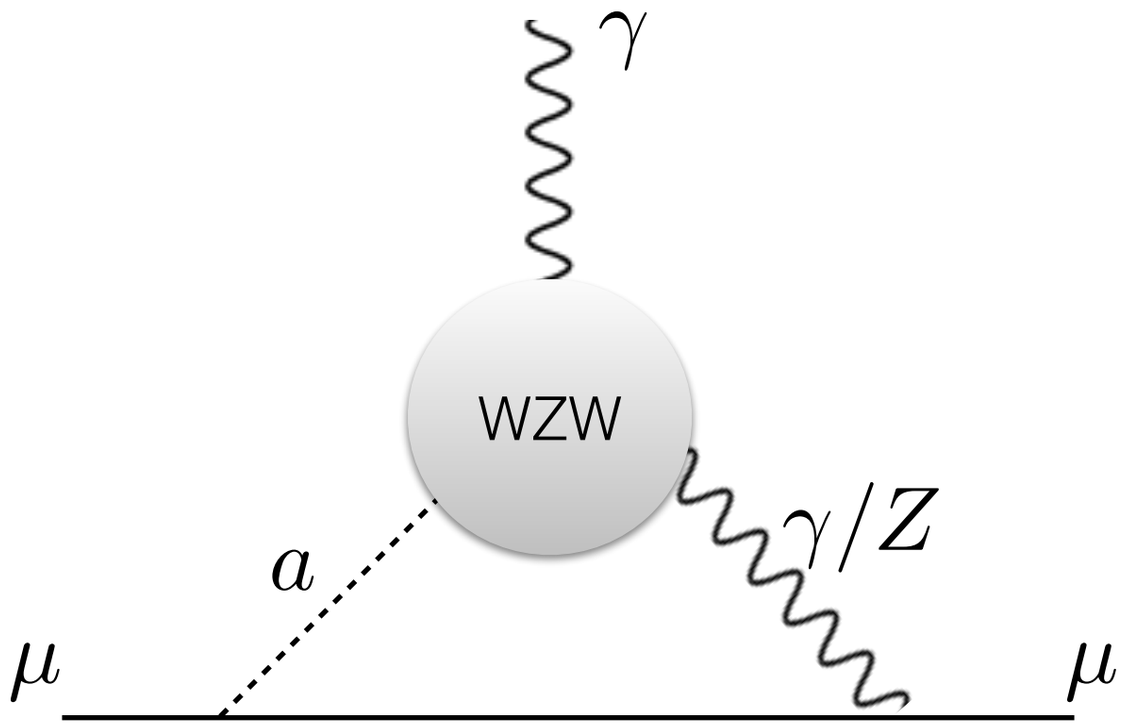
Talk by Emiliano Molinaro this afternoon

g - 2

about 3.2 sigma deviations (BNL) 2006

Naive dimensional analysis

Deog Ki Hong, Du Hwan Kim 1602.06628

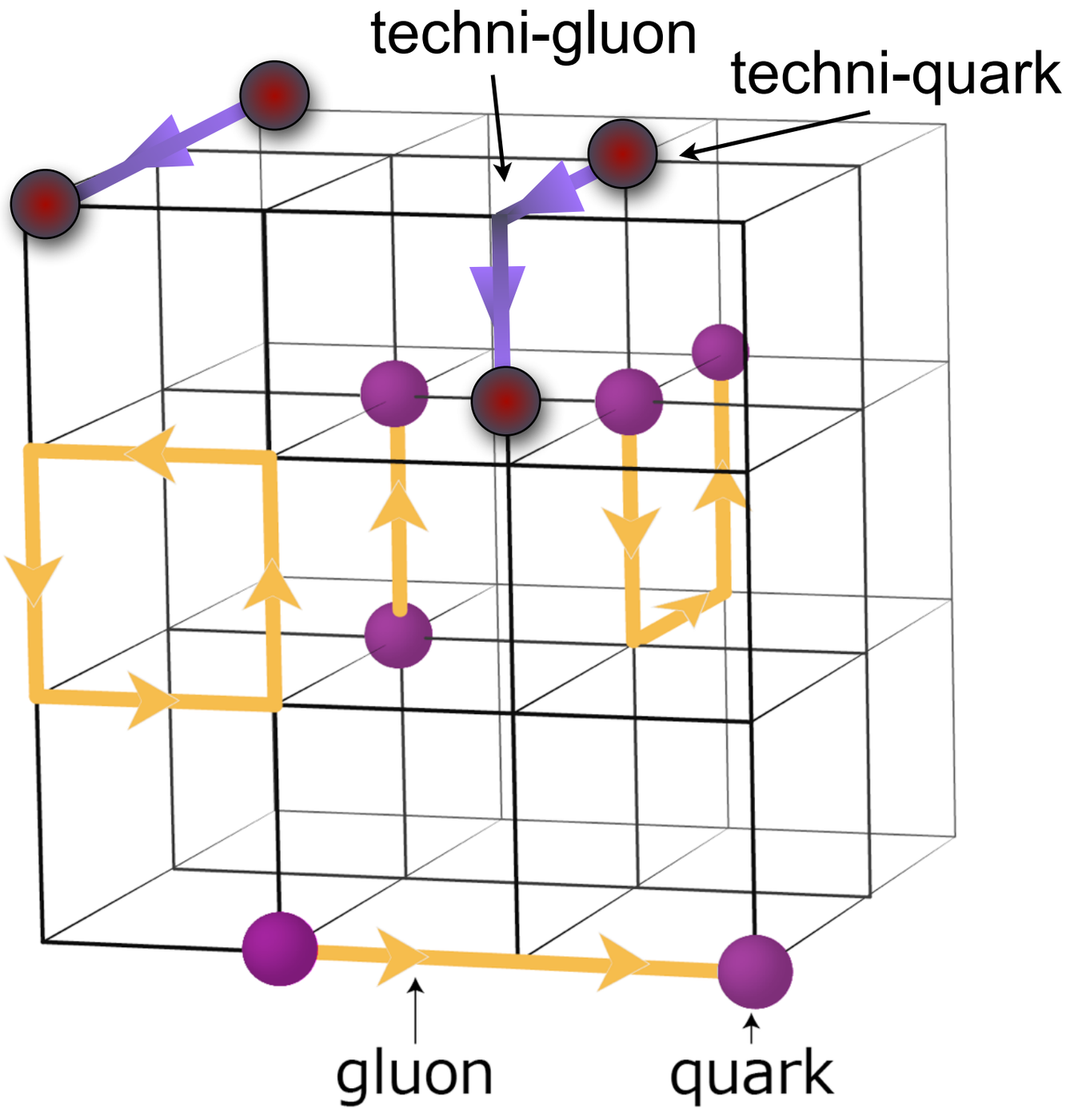


What will LHC see next?

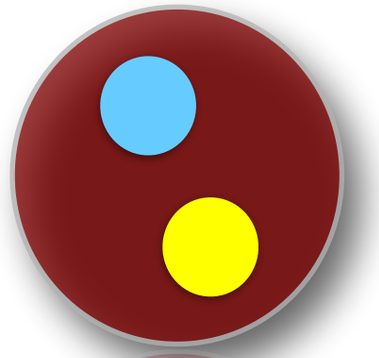
What will LHC see next?

- Related TC-eta processes
- Spin-1 resonances in Drell-Yan (2 - 4) TeV
- Diboson resonances (2-4) TeV
- New lepton/color states needed to fix anomalies and top mass
- Direct tests of Minimal TC via diphotons
- ….

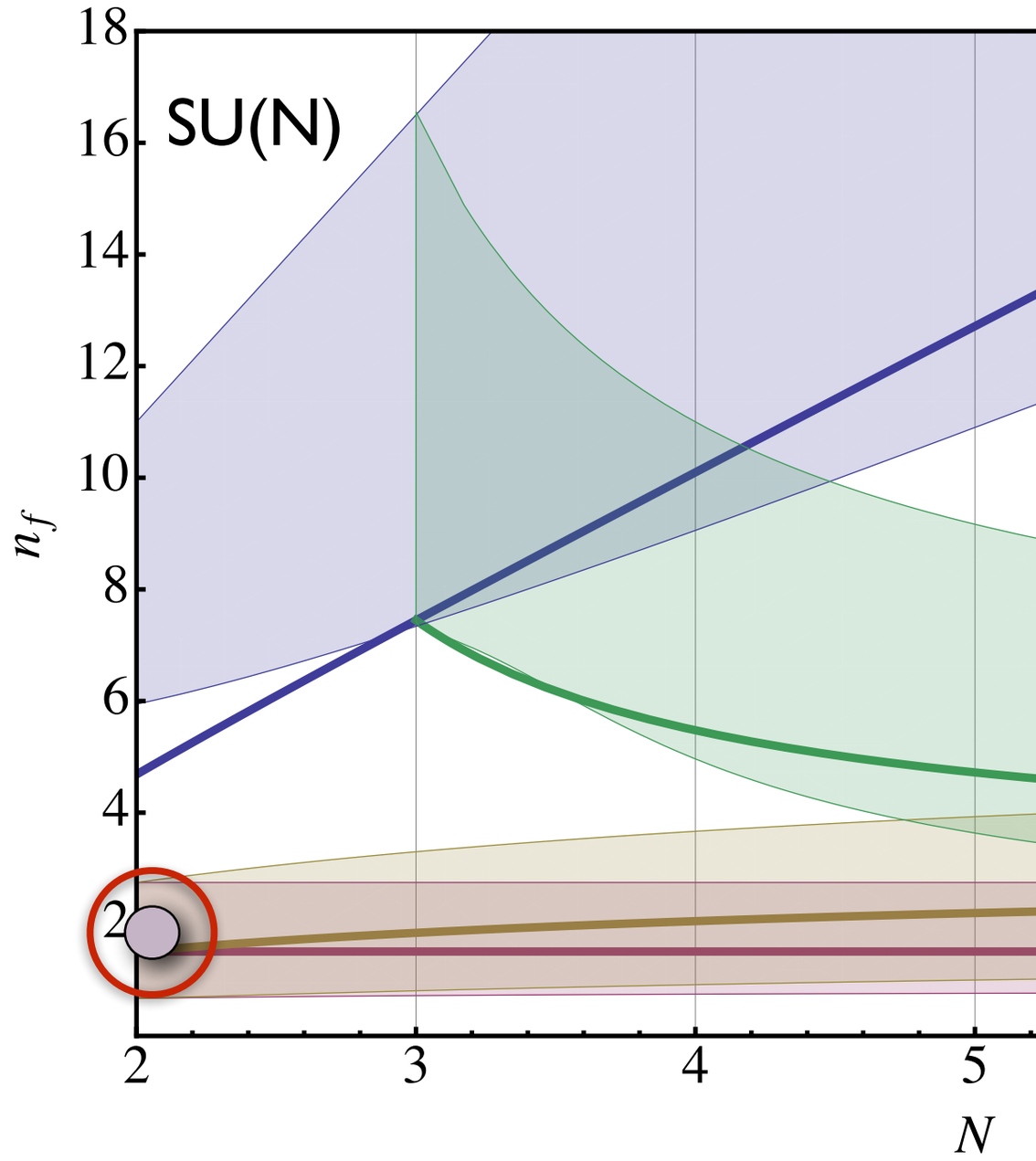
Composite Dynamics on the Lattice



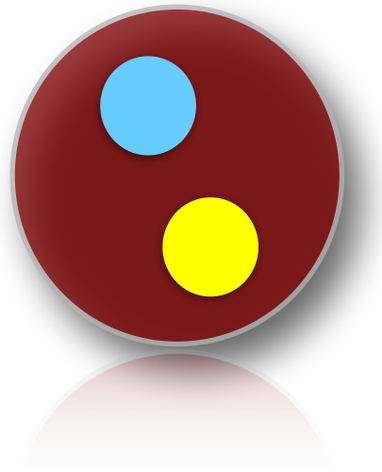
SU(2) = Sp(2) with 2 Flavors



Minimal Fund. Template

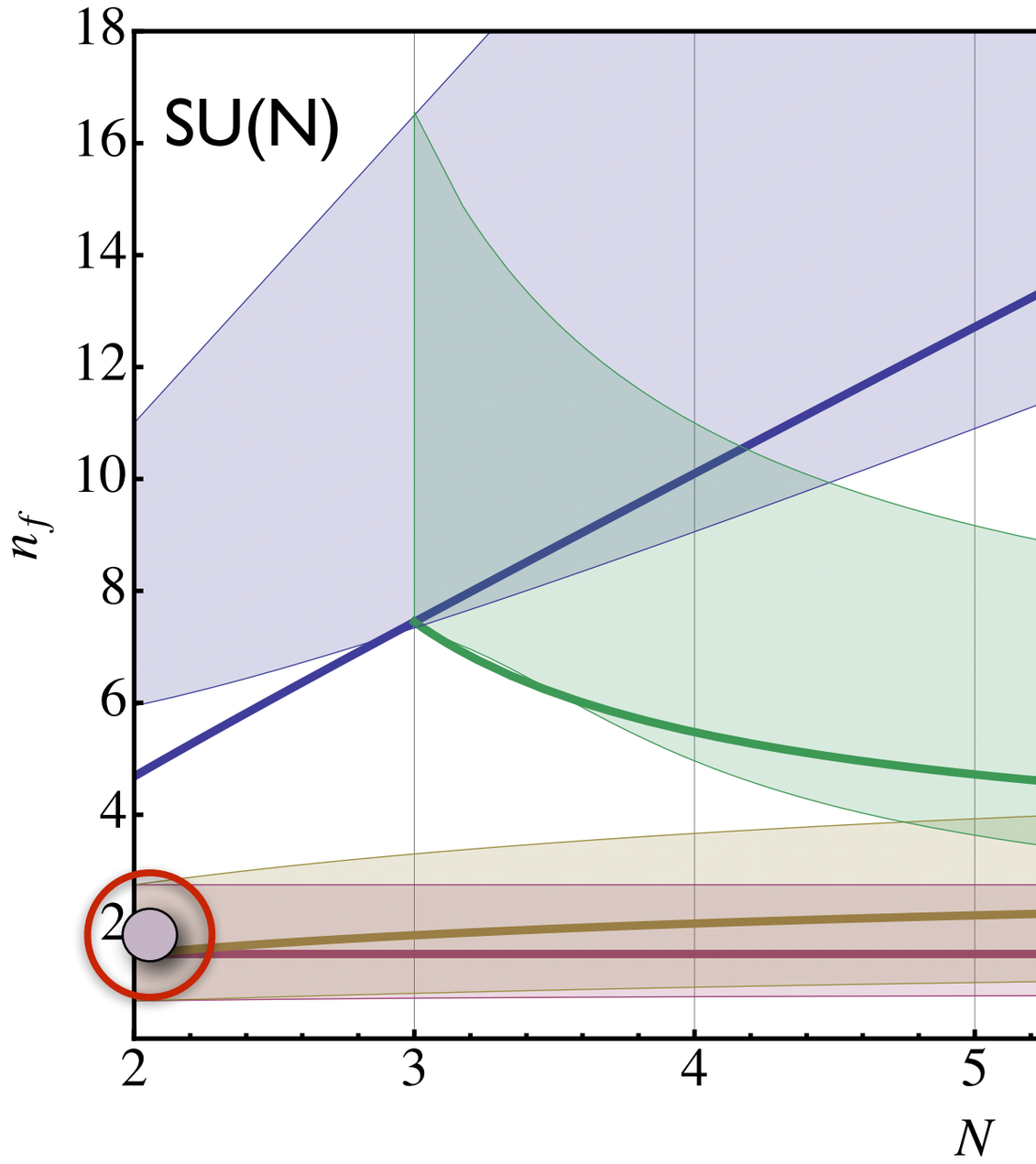


SU(2) = Sp(2) with 2 Flavors

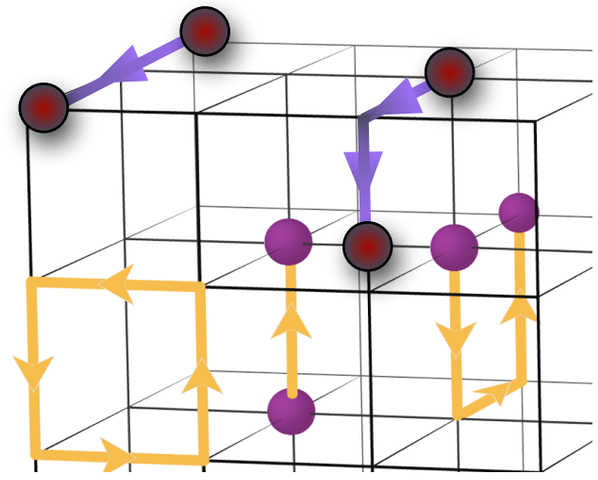


Minimal Fund. Template

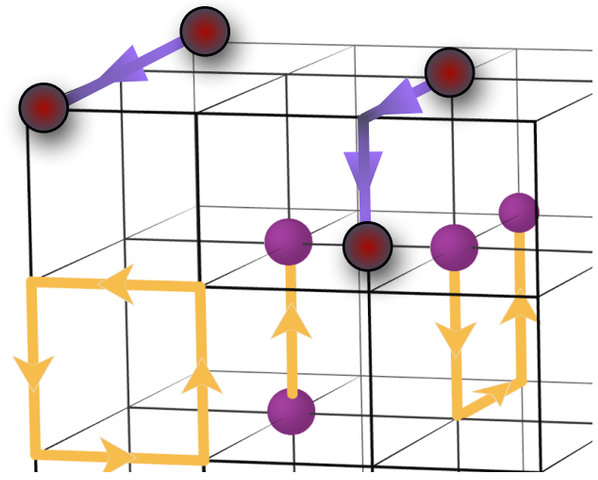
- Unified TC & Comp. Goldstone Higgs
- TC Meson DM
- Stealth DM
- Dark Nuclei
- SIMPlest Miracle
- …



SU(**2**) + 2 Dirac Flavors



SU(**2**) + 2 Dirac Flavors



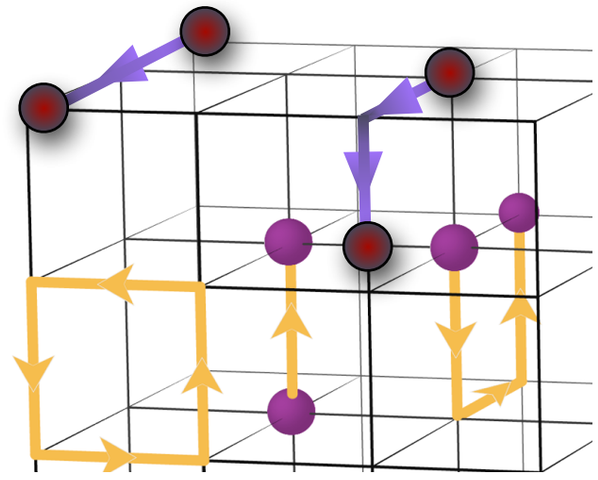
- SU(4) global symmetry breaks to Sp(4)
- 5 Goldstone bosons
- Goldstone form factors

Lewis, Pica, Sannino, 1109.3513

Hietanen, Lewis, Pica, Sannino, 1308.4130

Hietanen, Lewis, Pica, Sannino, 1404.2794

SU(**2**) + 2 Dirac Flavors



- SU(4) global symmetry breaks to Sp(4)
- 5 Goldstone bosons
- Goldstone form factors

Lewis, Pica, Sannino, 1109.3513

Hietanen, Lewis, Pica, Sannino, 1308.4130

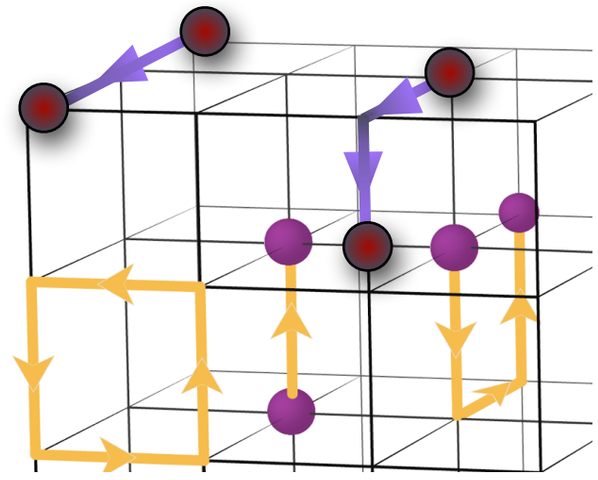
Hietanen, Lewis, Pica, Sannino, 1404.2794

Lattice predictions for TC & CH Spin-One states

$$m_V = \frac{3.2(5)}{\sin\theta}\ \mathrm{TeV} \qquad\qquad m_A = \frac{3.6(9)}{\sin\theta}\ \mathrm{TeV}$$

Arthur, Drach, Hansen, Hietanen, Pica, Sannino, 1602.06559

SU(**2**) + 2 Dirac Flavors



- SU(4) global symmetry breaks to Sp(4)
- 5 Goldstone bosons
- Goldstone form factors

Lewis, Pica, Sannino, 1109.3513

Hietanen, Lewis, Pica, Sannino, 1308.4130

Hietanen, Lewis, Pica, Sannino, 1404.2794

Lattice predictions for TC & CH Spin-One states

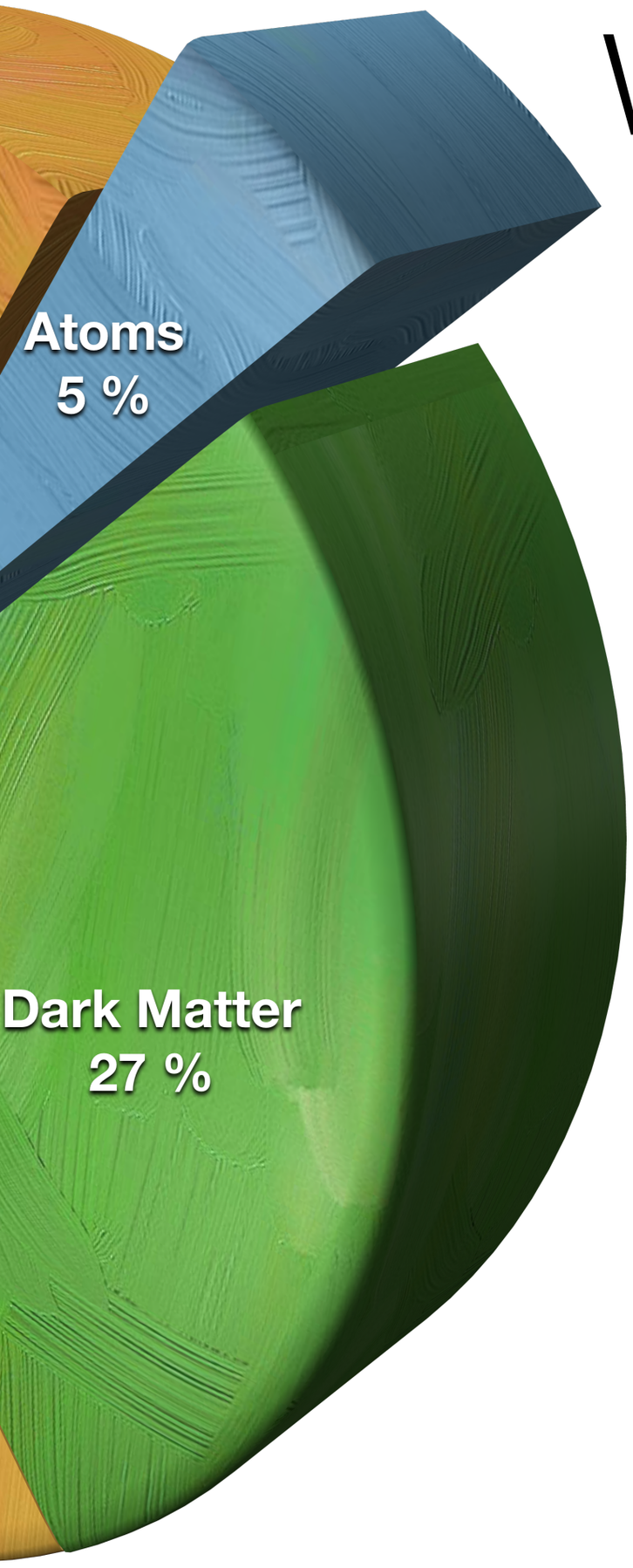
$$m_V = \frac{3.2(5)}{\sin\theta}\ \mathrm{TeV} \qquad m_A = \frac{3.6(9)}{\sin\theta}\ \mathrm{TeV}$$

Arthur, Drach, Hansen, Hietanen, Pica, Sannino, 1602.06559

In progress:

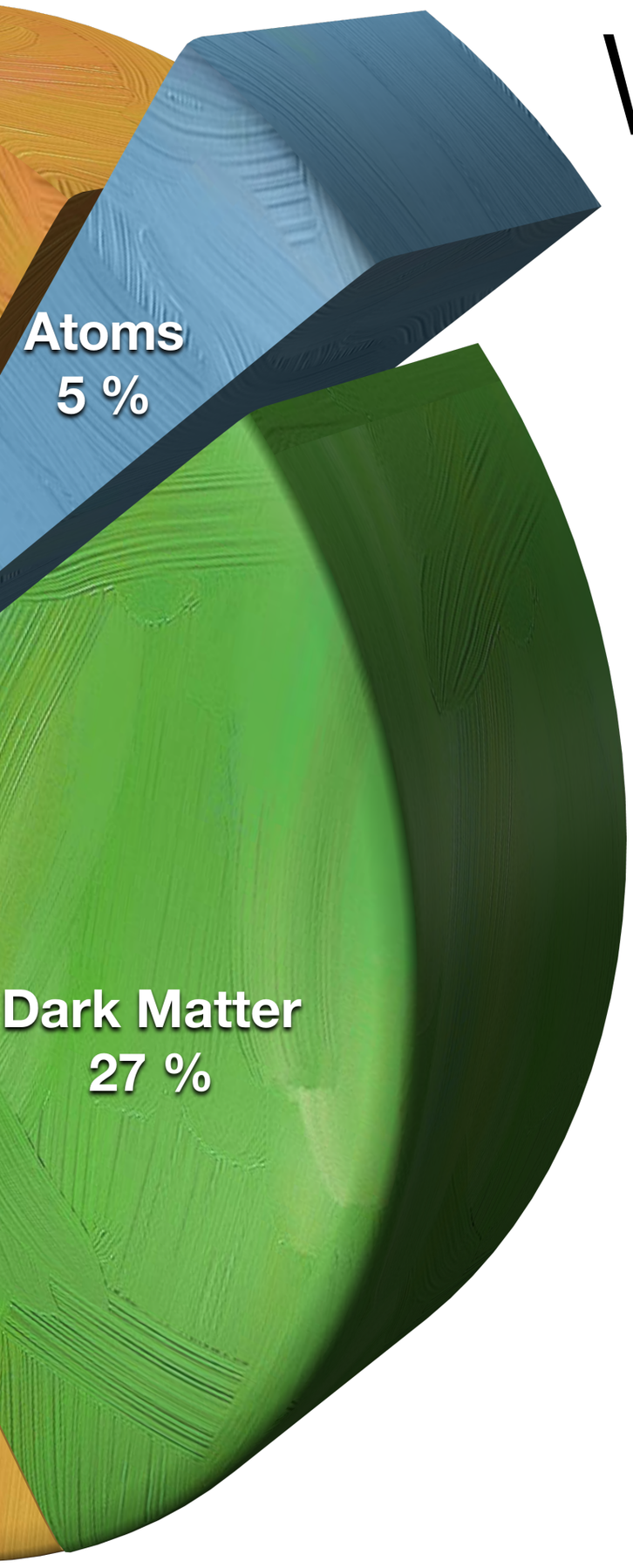
- Scalar spectrum
- Scattering amplitudes

Dark side



What makes dark matter ?

Atoms: 3 forces and many fund. particles

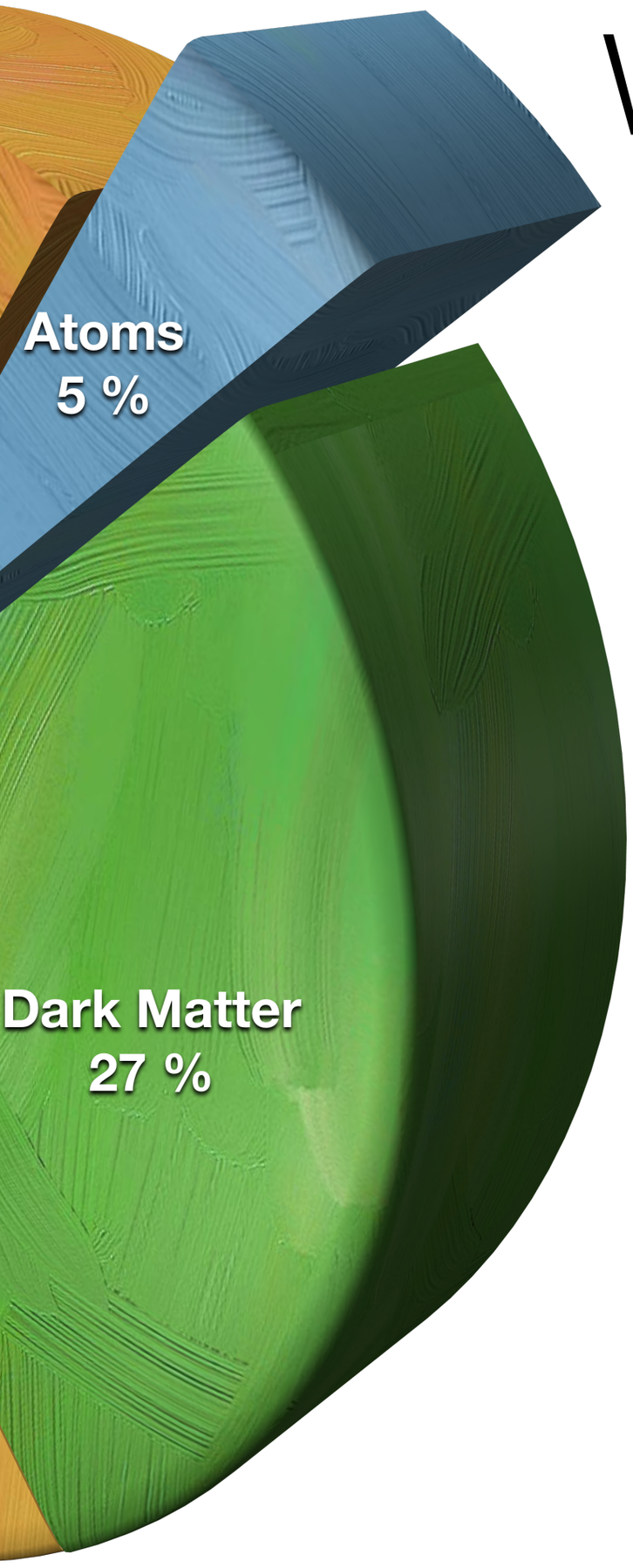


What makes dark matter ?

Atoms: 3 forces and many fund. particles

DM oversimplification

DM Particle



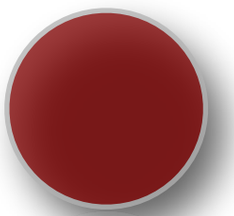
What makes dark matter ?

Atoms: 3 forces and many fund. particles

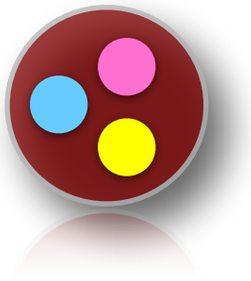
DM oversimplification

DM Particle

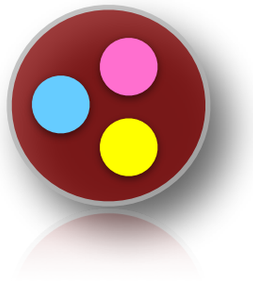
Elementary



Composite



Composite Dark Matter



Composite Dark Matter

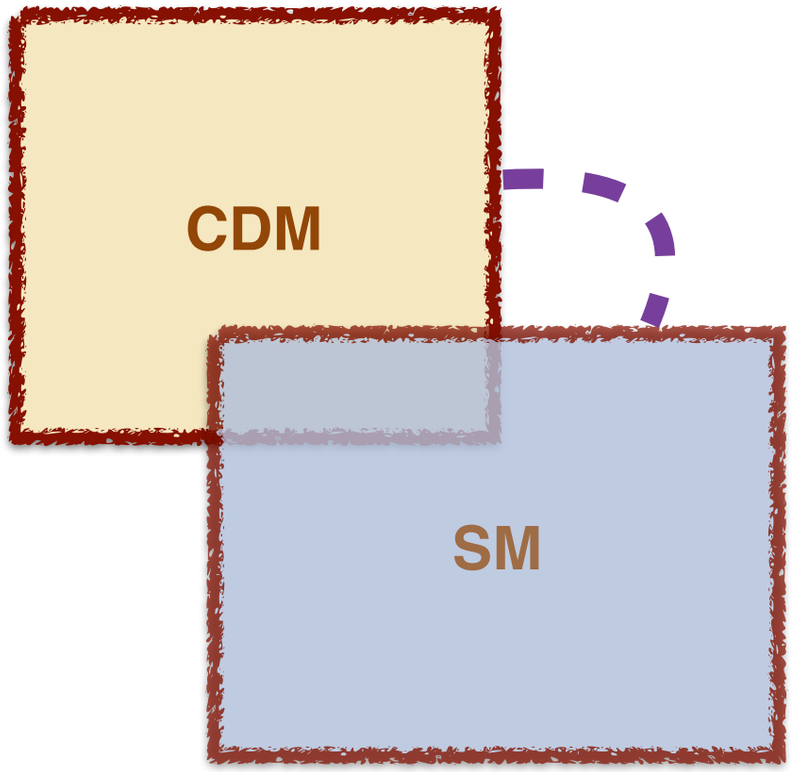
Building Blocks

Composite Dark Matter

Building Blocks

SM charged

Type I



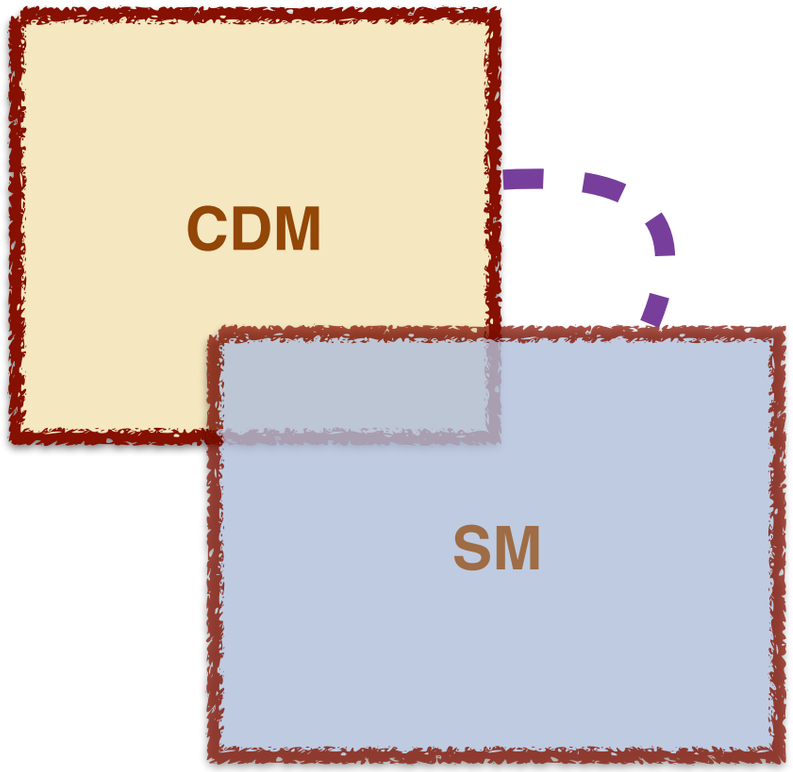
Composite Dark Matter

Building Blocks

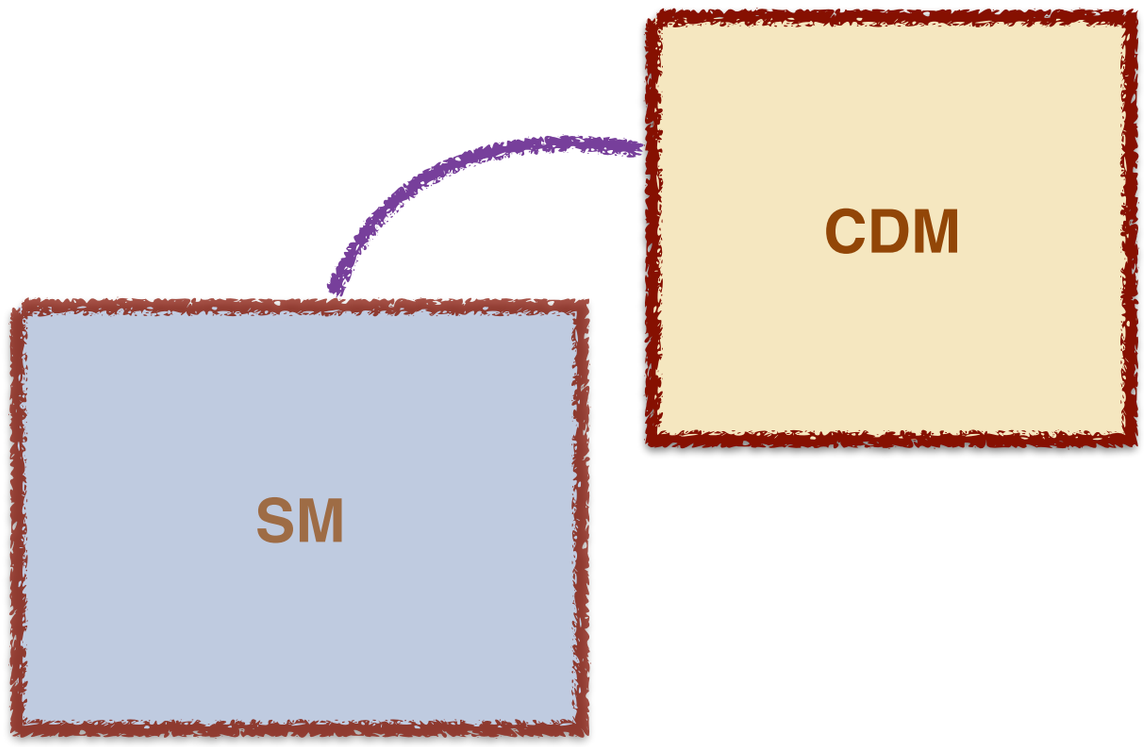
SM charged

SM singlets

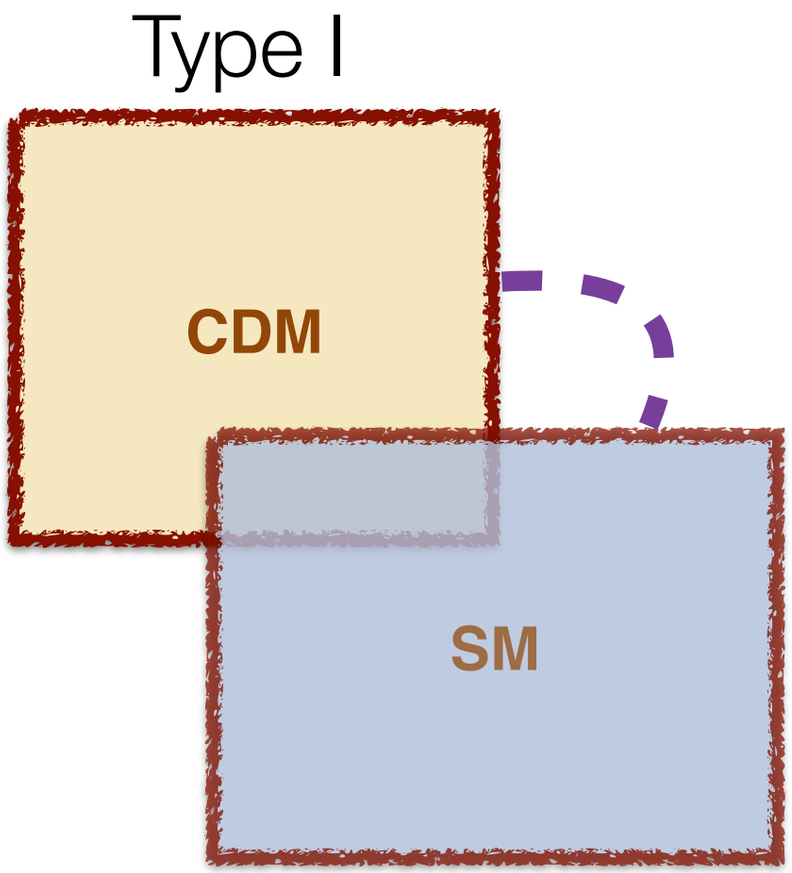
Type I



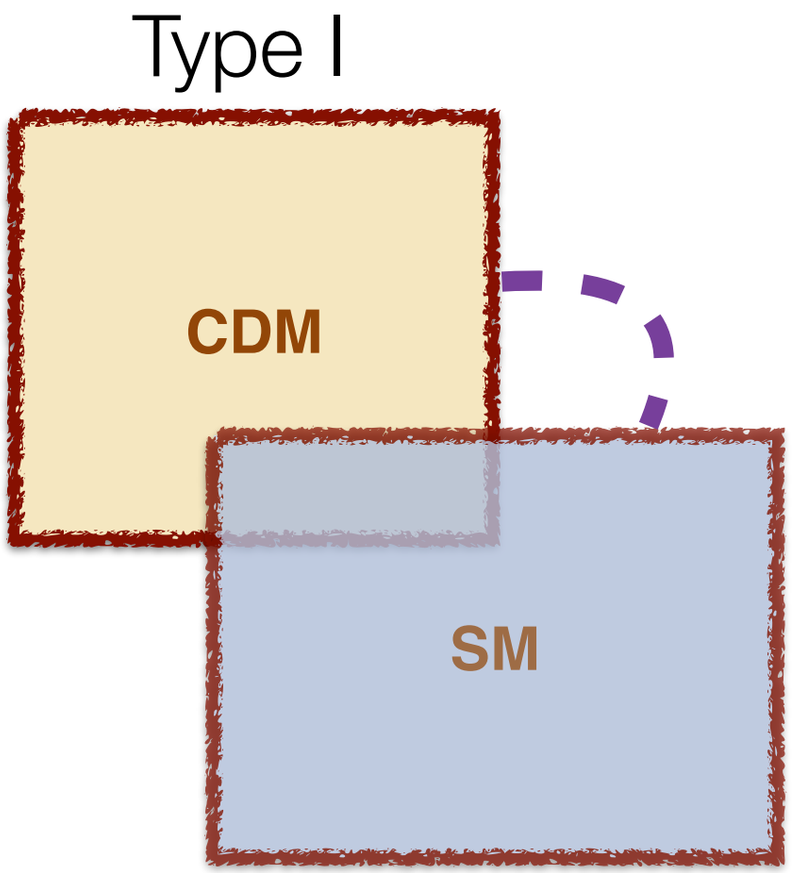
Type II



CDM Type I



CDM Type I



- TC Baryon[1]
- TC Meson[2]
- Millicharged Comp. DM[3]
- Stealth DM[4]
- Solitons/Little Higgs[5]
- ….

[1]Nussinov 85 & Barr, Chivukula, Farhi 90

[2]Gudnason, Kouvaris, Sannino ph-0603014, 0608055

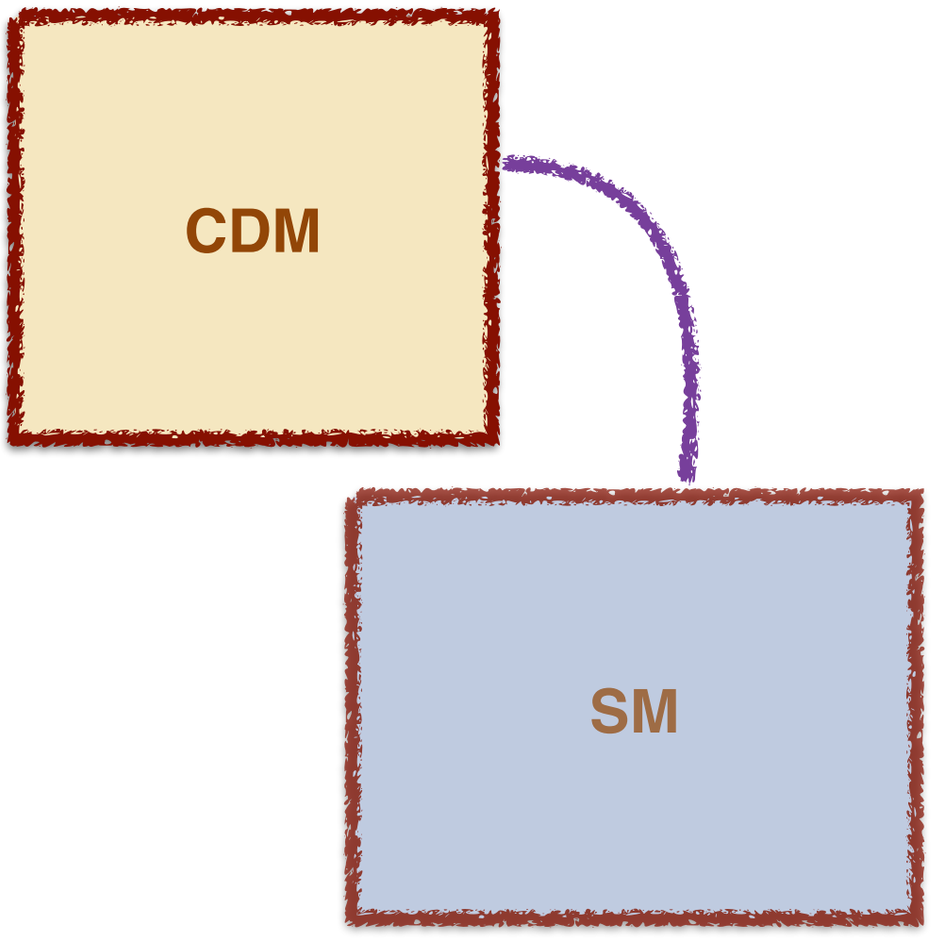
[3]Kouvaris 1304.7476

[4]Appelquist et al. 1503.04203

[5]Gillioz, 1103.5990

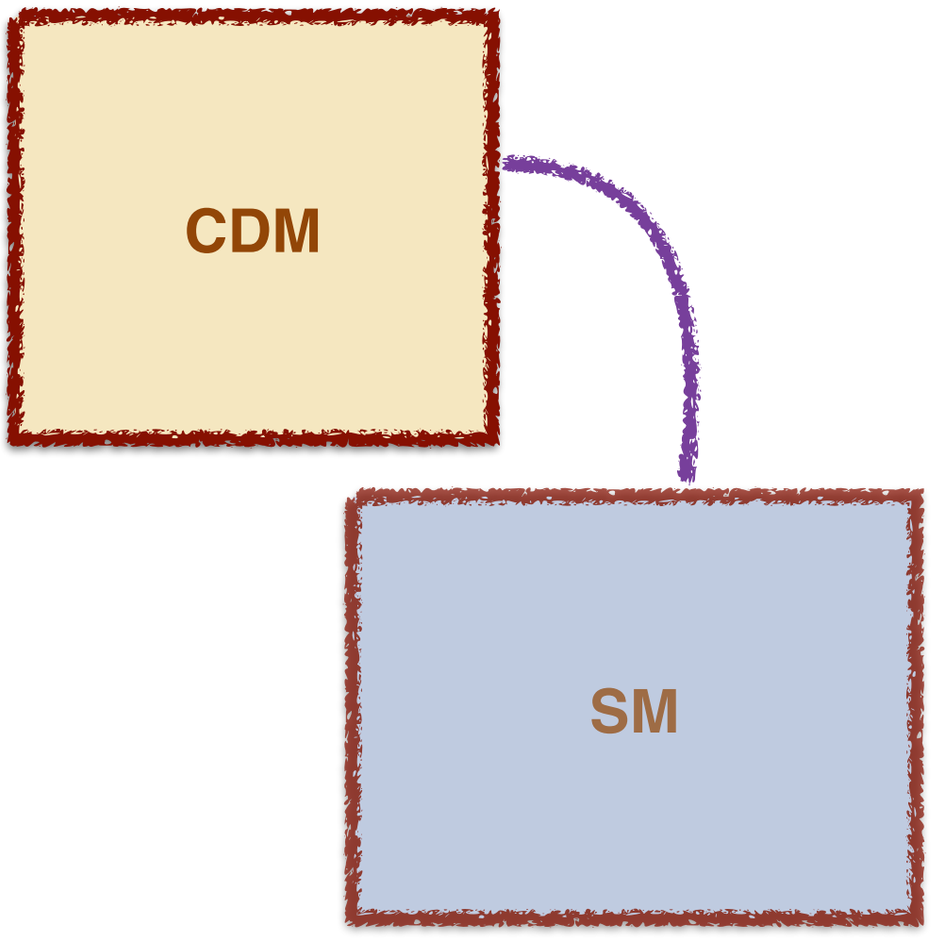
CDM Type II

Type II



CDM Type II

Type II



- Dark Nuclei[1]
- SIMPlest Miracle[2,3]
- Solitonic
- ….

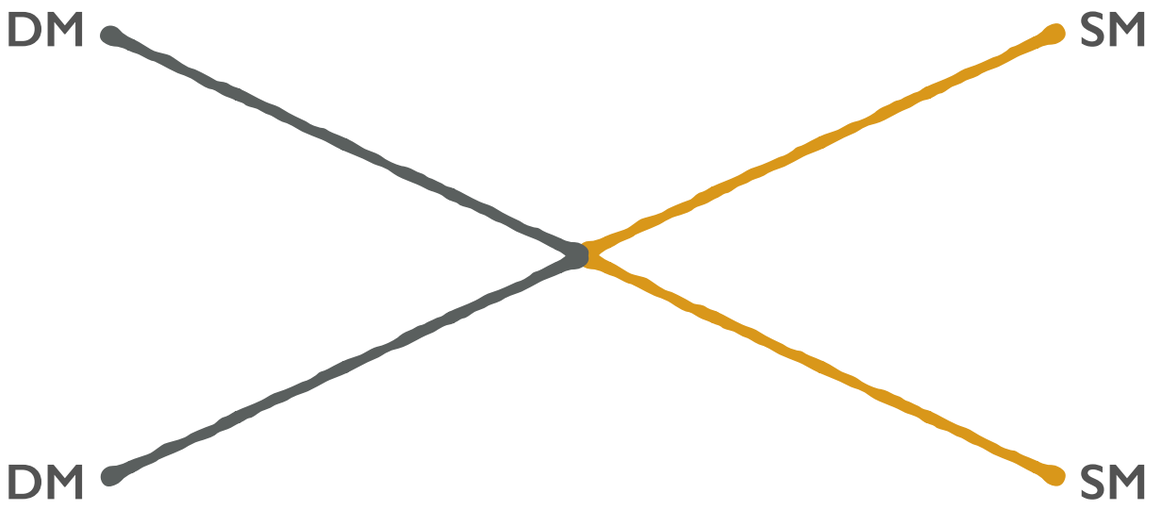
[1]Detmold, McCullough, Pochinsky 1406.2276

[2]Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727

[3]Hansen, Langaeble, Sannino, 1507.01590

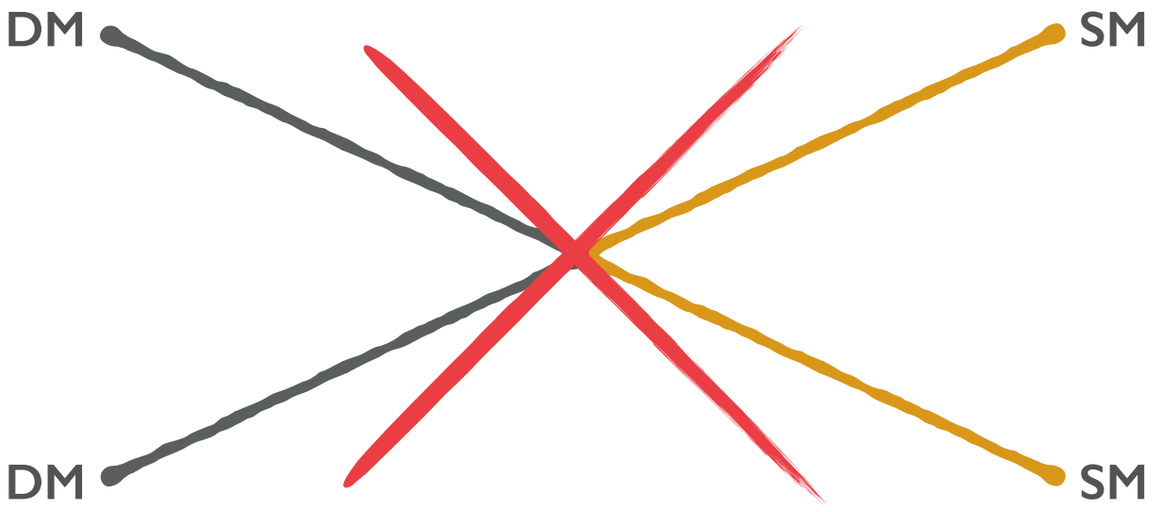
(Not) the SIMPlest miracle

The SIMP Mechanism



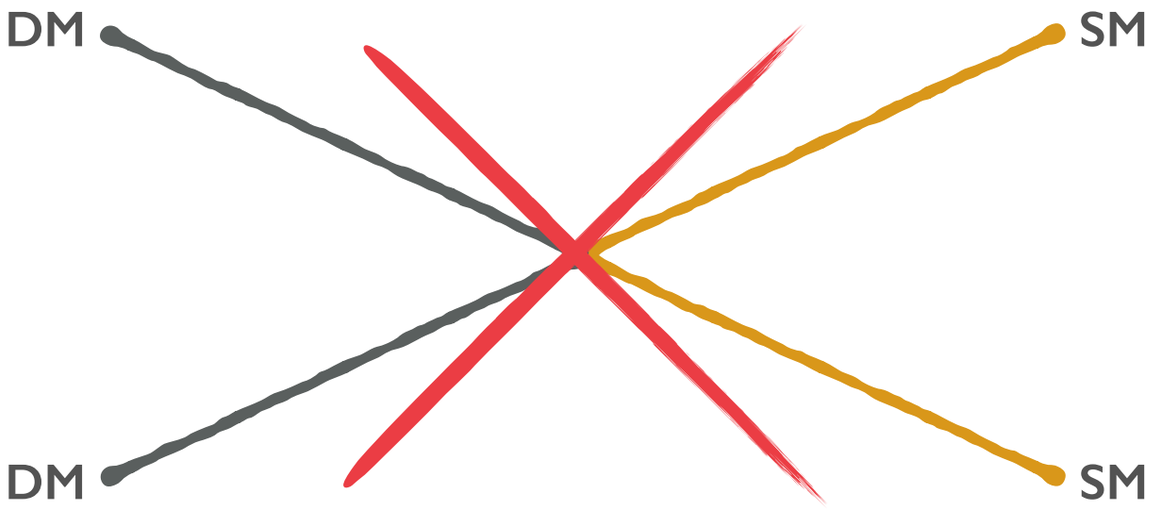
2 → 2 annihilation

The SIMP Mechanism

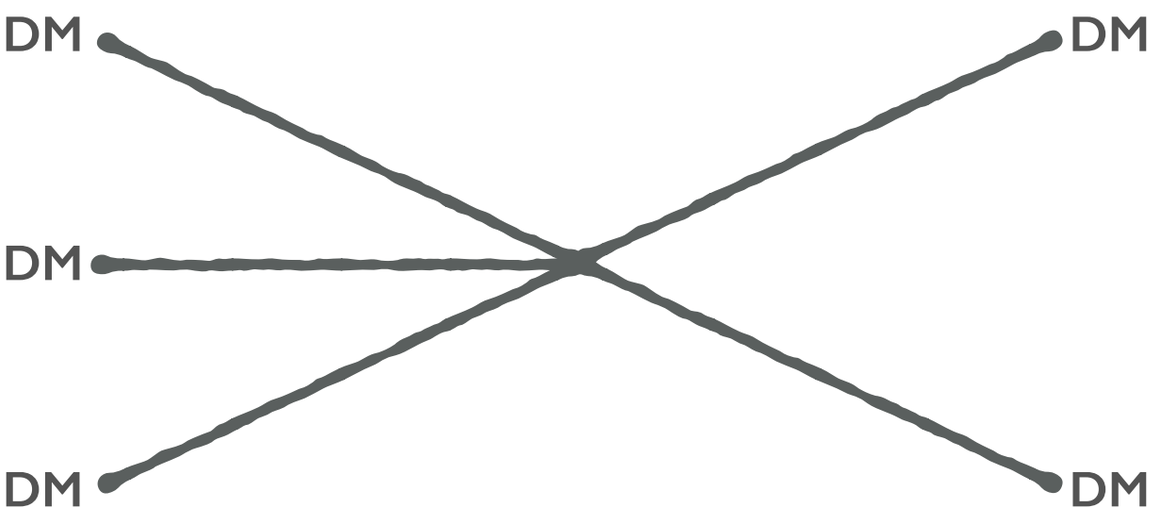


$2 \rightarrow 2$ annihilation

The SIMP Mechanism

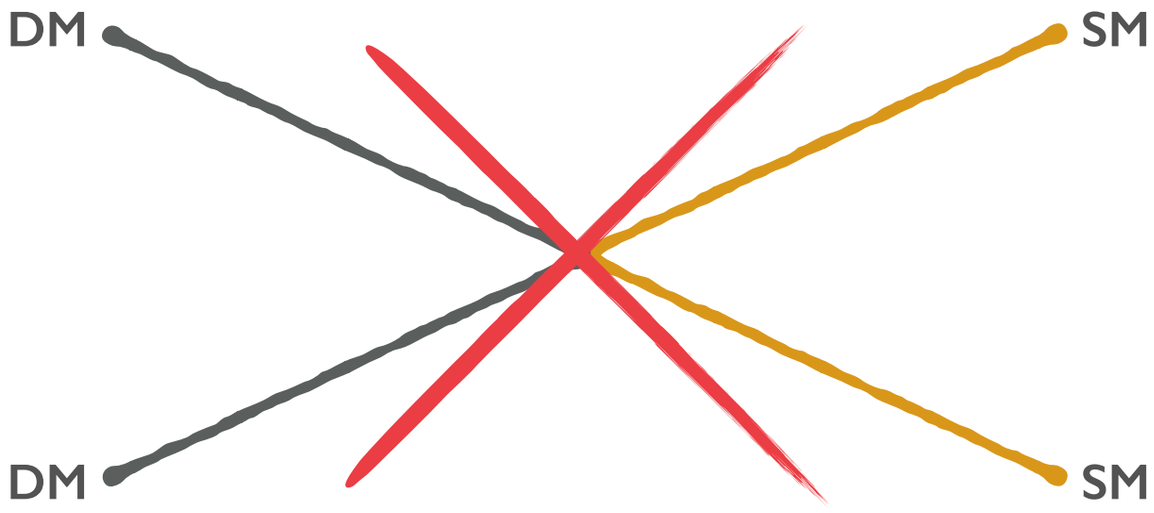


2 → 2 annihilation

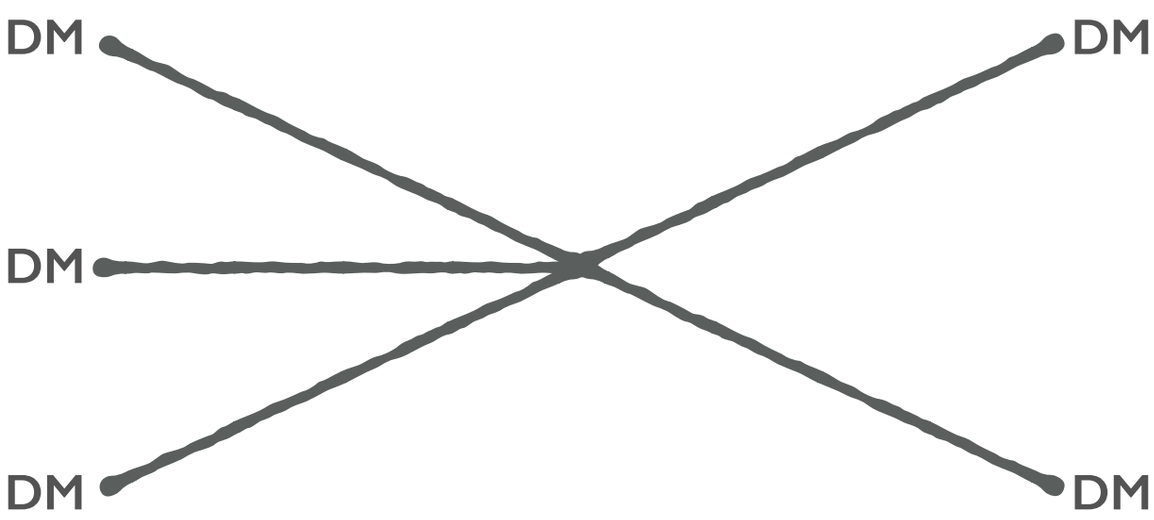


3 → 2 annihilation

The SIMP Mechanism



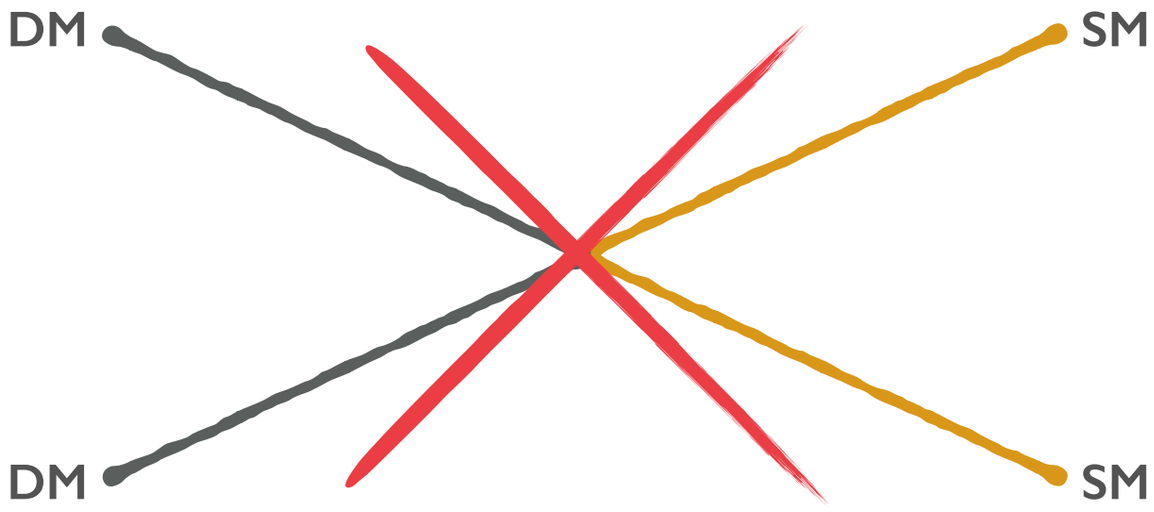
$2 \to 2$ annihilation



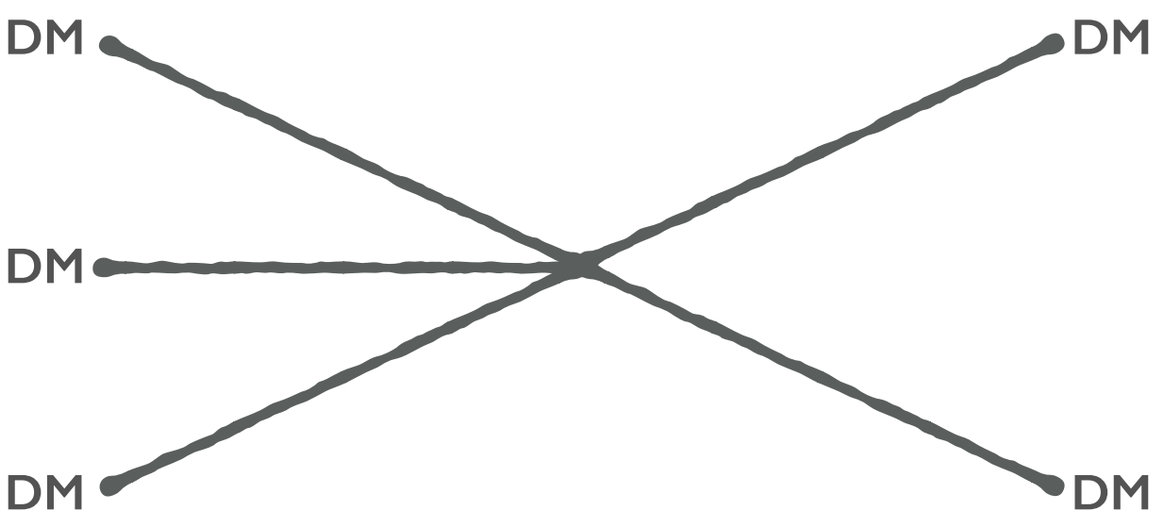
$3 \to 2$ annihilation

Relevant DM - DM # changing operators

The SIMP Mechanism



2 → 2 annihilation



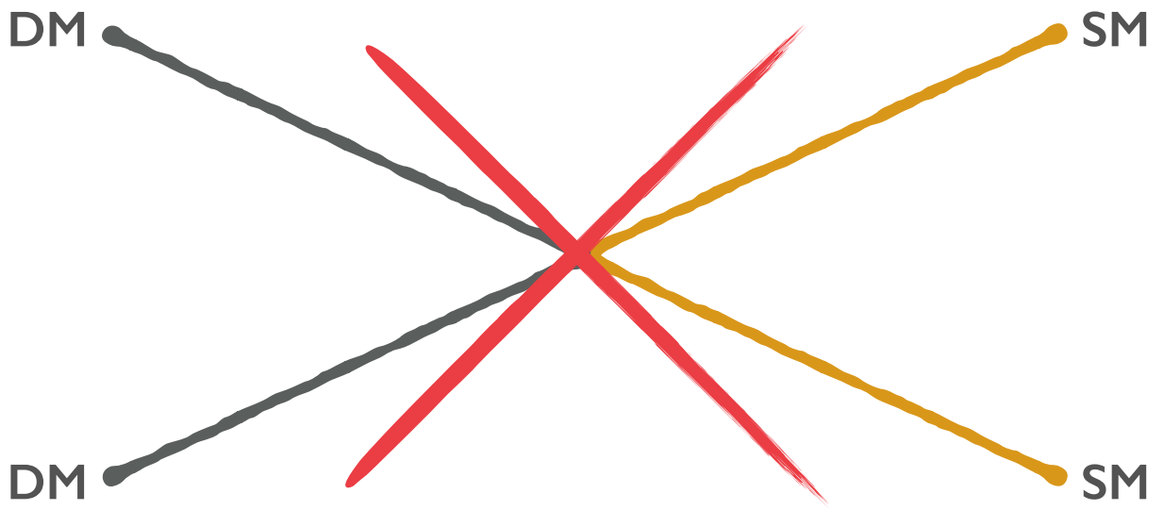
3 → 2 annihilation

Relevant DM - DM # changing operators

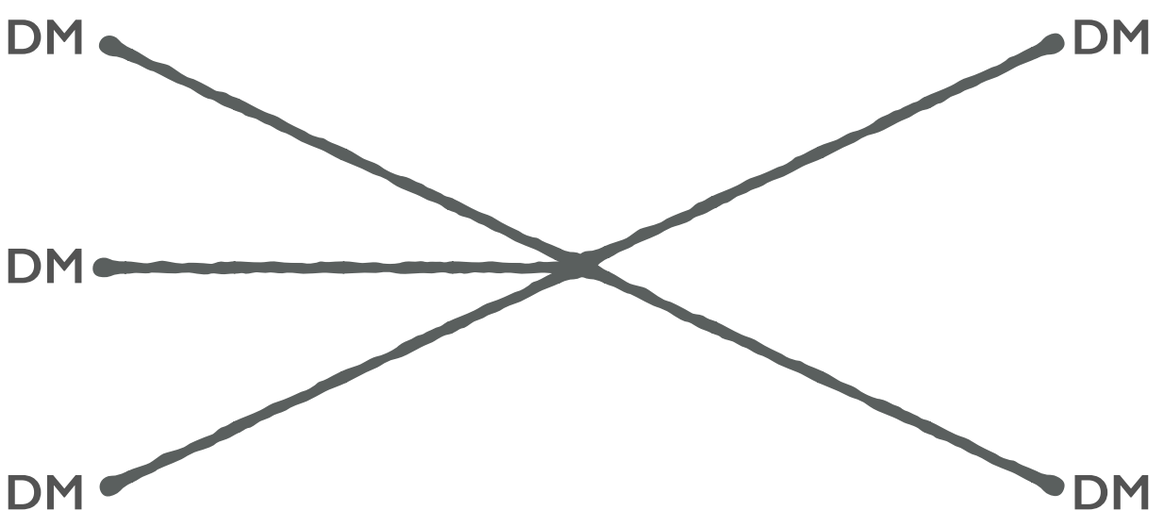
Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727,PRL

Hansen, Langaeble, Sannino, 1507.01590, PRD

The SIMP Mechanism



2 → 2 annihilation



3 → 2 annihilation

Relevant DM - DM # changing operators

Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727,PRL

Hansen, Langaeble, Sannino, 1507.01590, PRD

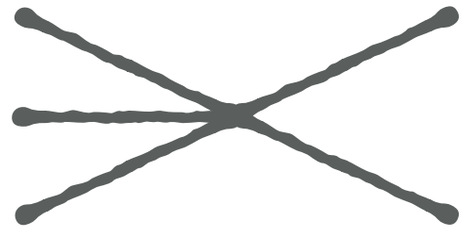
Original idea

E. Carlson et al: Astrophys.J. 398 (1992) 43-52

A. de Laix et al: Astrophys.J. 452 (1995) 495

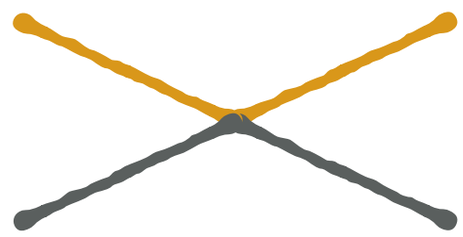
Relevant processes

- The 3 → 2 process constrains DM via Boltzmann equation/ relic-density.

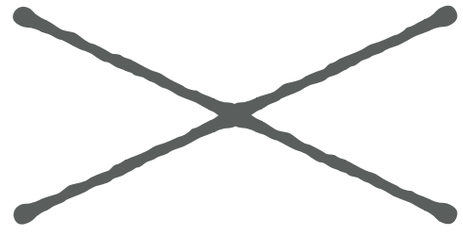


$$\dot{n} + 3Hn = -(n^3 - n^2 n_{eq})\langle \sigma v^2 \rangle_{3\to 2}$$

- @ Freeze-out, thermal equilibrium with SM via e.g. 2 → 2 scattering between DM - SM



- The 2 → 2 scattering among DM constrained by observations



Dark SU(**2**) + 2 Dirac Flavors

Dark SU(**2**) + 2 Dirac Flavors

- SU(4) global symmetry breaks to Sp(4)
- 5 Goldstone bosons

ChPT based on SU(4) to Sp(4)

$$u = \exp\left(\frac{i\alpha}{\sqrt{2}f} X^a \phi^a\right)$$

$$u_a = i(u^\dagger \partial_a u - u \partial_a u^\dagger)$$

Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727,PRL

ChPT based on SU(4) to Sp(4)

$$u = \exp\left(\frac{i\alpha}{\sqrt{2}f} X^a \phi^a\right) \qquad u_a = i(u^\dagger \partial_a u - u \partial_a u^\dagger)$$

The topological WZW term leads to a 5-point interaction

$$\mathcal{L}^{(4)}_{WZW} = \frac{N_c}{240\pi^2} \int_0^1 d\alpha \int d^4x \; \epsilon^{abcde} \langle u_a u_b u_c u_d u_e \rangle$$

Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727,PRL

ChPT based on SU(4) to Sp(4)

$$u = \exp\left(\frac{i\alpha}{\sqrt{2}f} X^a \phi^a\right) \qquad u_a = i(u^\dagger \partial_a u - u \partial_a u^\dagger)$$

The topological WZW term leads to a 5-point interaction

$$\mathcal{L}^{(4)}_{WZW} = \frac{N_c}{240\pi^2} \int_0^1 d\alpha \int d^4x \; \epsilon^{abcde} \langle u_a u_b u_c u_d u_e \rangle$$

(Inconsistent) 2 → 2 analysis to lowest non-vanishing order

$$\mathcal{L}^{(2)} = \frac{f^2}{4} \langle u^\mu u_\mu + \chi_+ \rangle$$

Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727,PRL

Consistent ChPT SIMP corrections

2 → 2 evaluated at the same 3 → 2 order

P*hysical* values for the mass and decay constant.

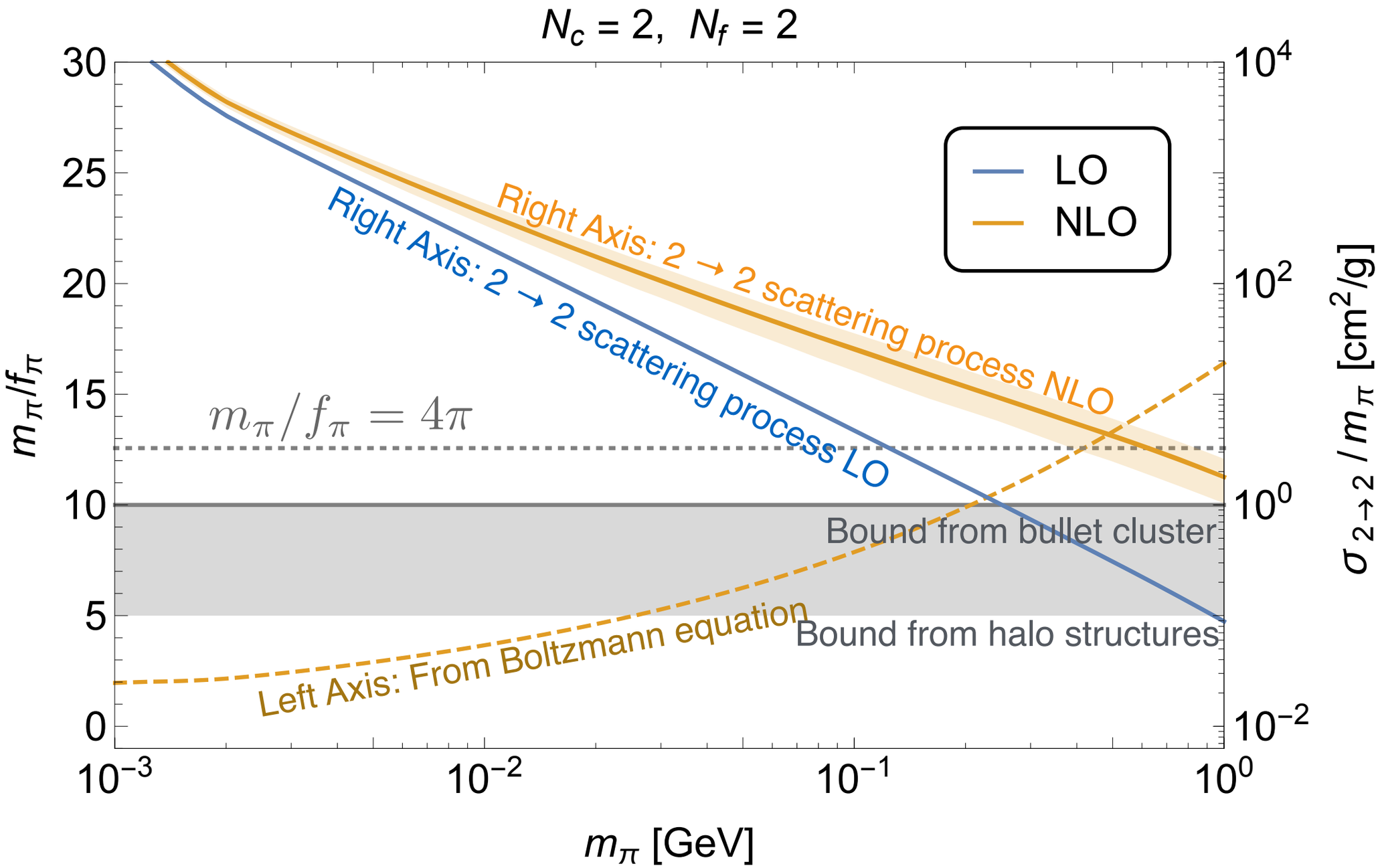
$$f_\pi = f\left[1 + \frac{m^2}{f^2}(a_f L + b_f)\right] \qquad m_\pi^2 = m^2\left[1 + \frac{m^2}{f^2}(a_m L + b_m)\right]$$

DM relic density relates mass and decay constant

DM 2 → 2 scattering process (constrained)

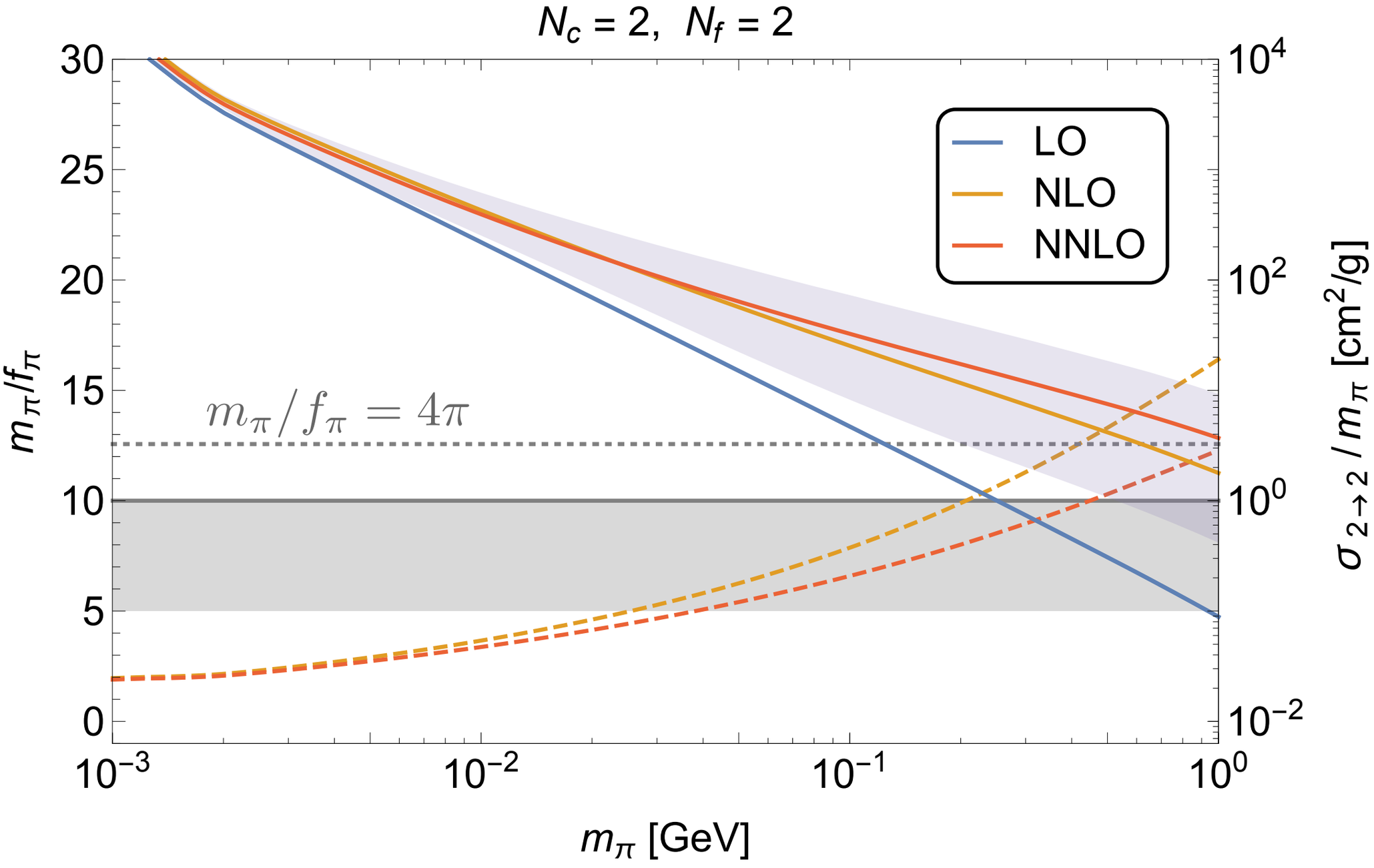
Hansen, Langaeble, Sannino, 1507.01590, PRD

ChPT SU(2) with 2 Dirac Flavours



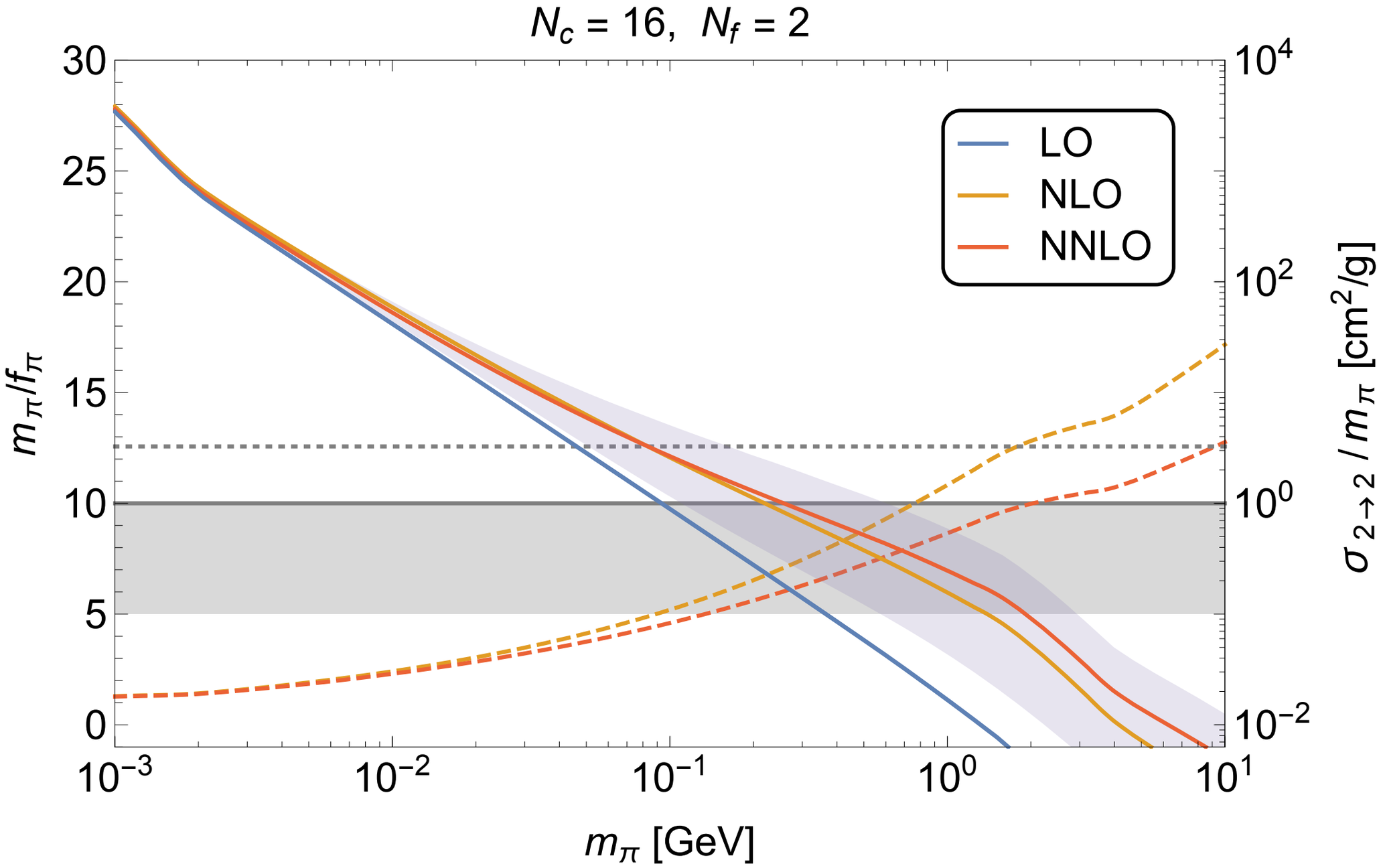
Hansen, Langaeble, Sannino Phys.Rev. D92 (2015) 075036 (arXiv:1507.01590)

ChPT SU(2) with 2 Dirac Flavours



Hansen, Langaeble, Sannino Phys.Rev. D92 (2015) 075036 (arXiv:1507.01590)

ChPT Sp(**16**) with 2 Dirac Flavours



Hansen, Langaeble, Sannino Phys.Rev. D92 (2015) 075036 (arXiv:1507.01590)

(Not) the SIMPlest Miracle

- Consistent (N)NLO corrections challenge the minimal model

- Large (dark) pion masses vs decay constant needed

- Lattice results 1602.06559: compressed dark spin-one resonance spectrum for large dark quark masses

- Large number of dark colors help

Summary

Bright

- Minimal underlying composite template for TC and CH
- Lattice predictions for composite spin-one resonances
- TC-eta prime is a natural/testable candidate for the 750 GeV state

Molinaro, Vignaroli, Sannino. 1512.05334, 1602.07574

Di Vecchia, Veneziano, (1980)

Dark

- Presented several more or less natural composite realisations of DM
- Introduced the SIMP paradigm and its underlying template theory
- (N)NLO ChPT for SIMPlest miracle makes it less miraculous
- (N)NLO must be taken into account when SIMPs is coupled to SM fields

Charting strong dynamics is key to concrete composite extensions of the SM

Backup slides

Composite theory space

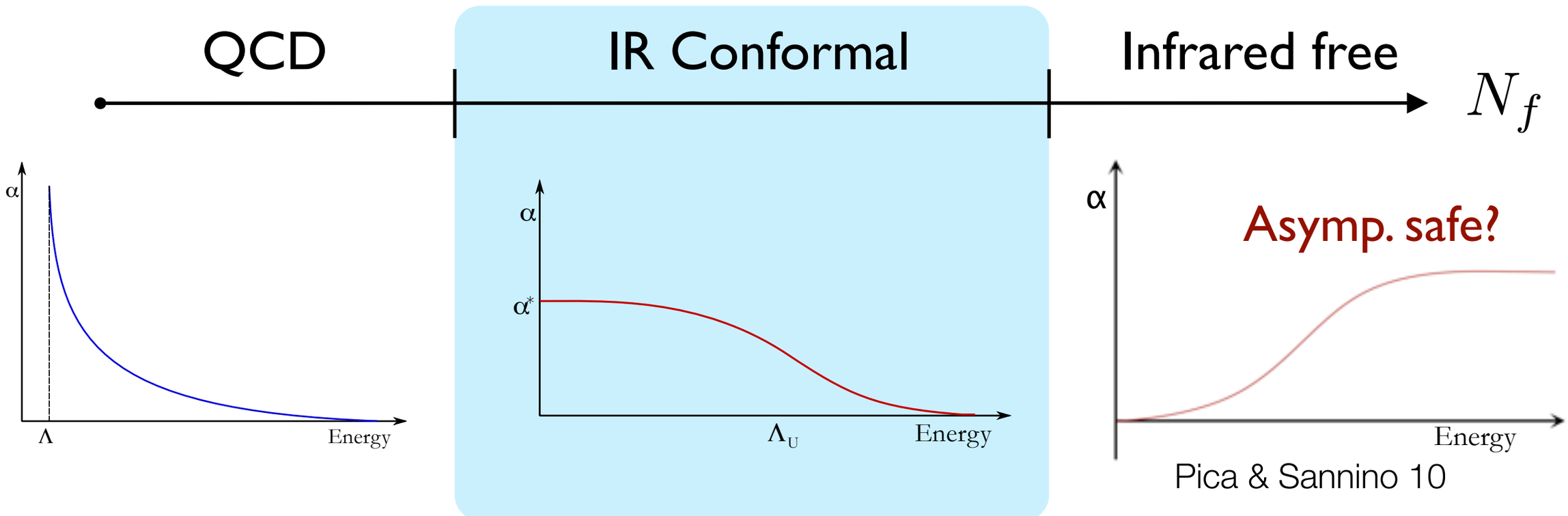
Knobs

Gauge Group: SU, SO, SP, Exceptional

Matter Representation

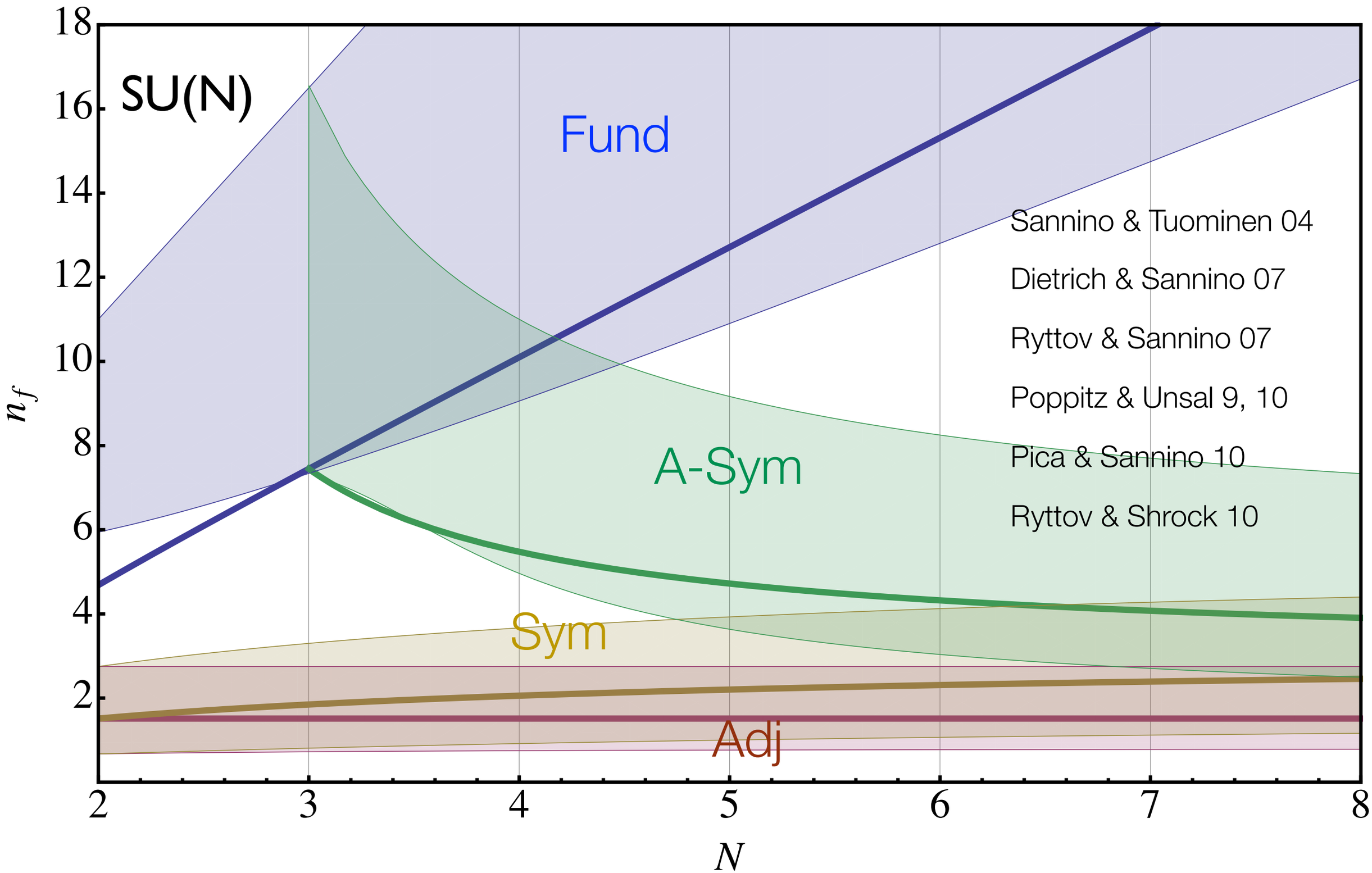
# of Flavours per Representation

4 Fermi interactions / ETC

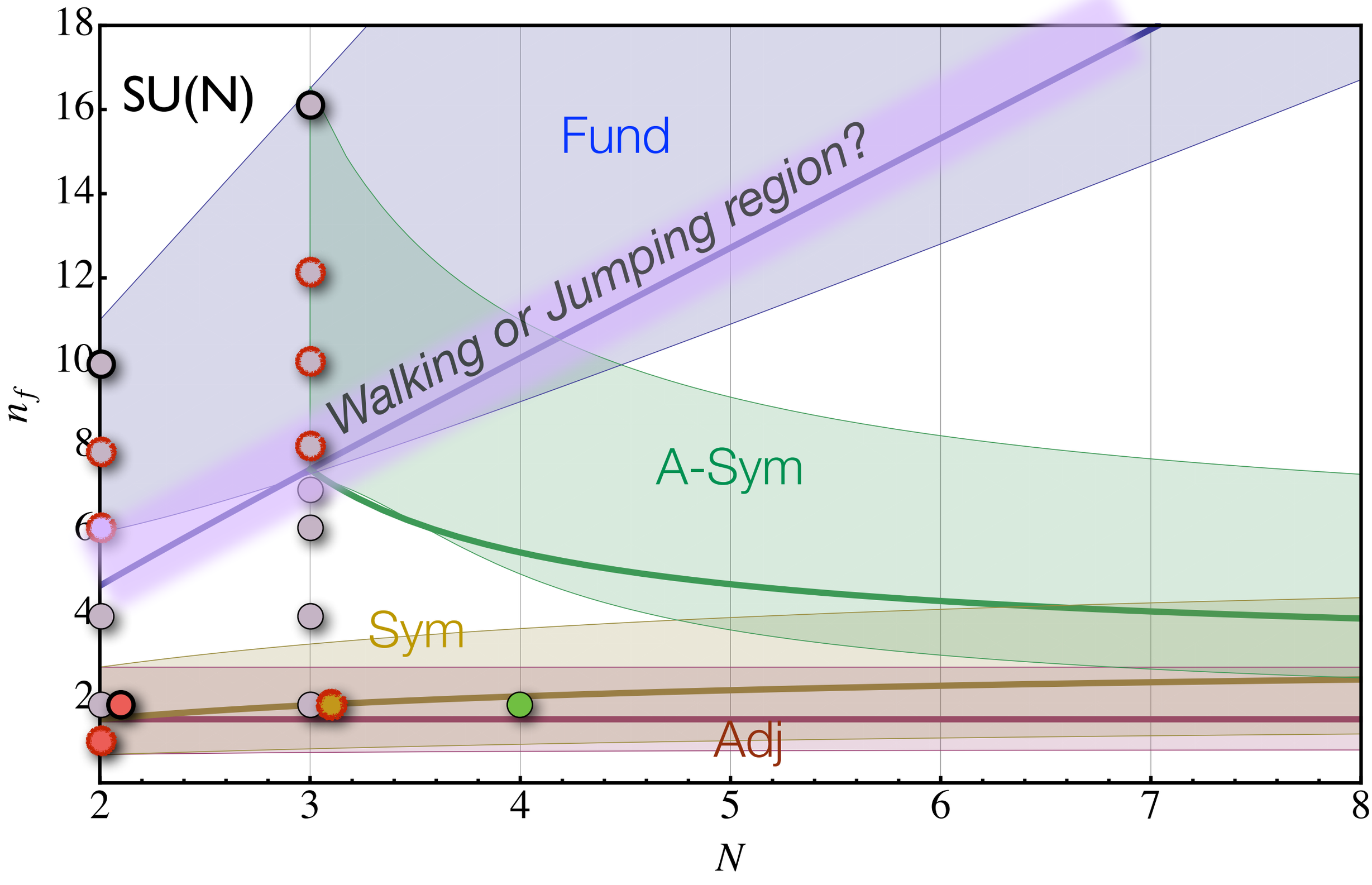


Pica & Sannino 10

SU(N) Phase Diagram



Lattice SU(N) Phase Diagram

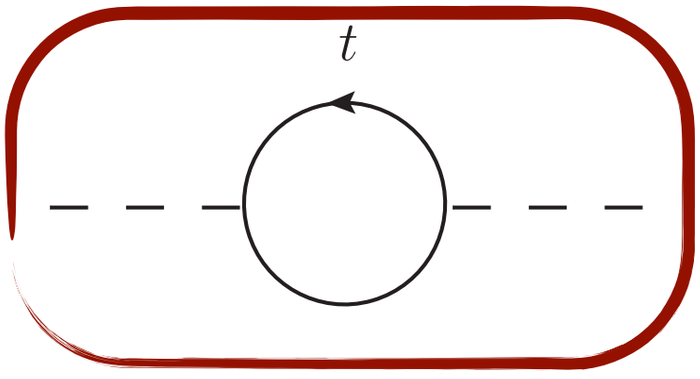


TC Higgs

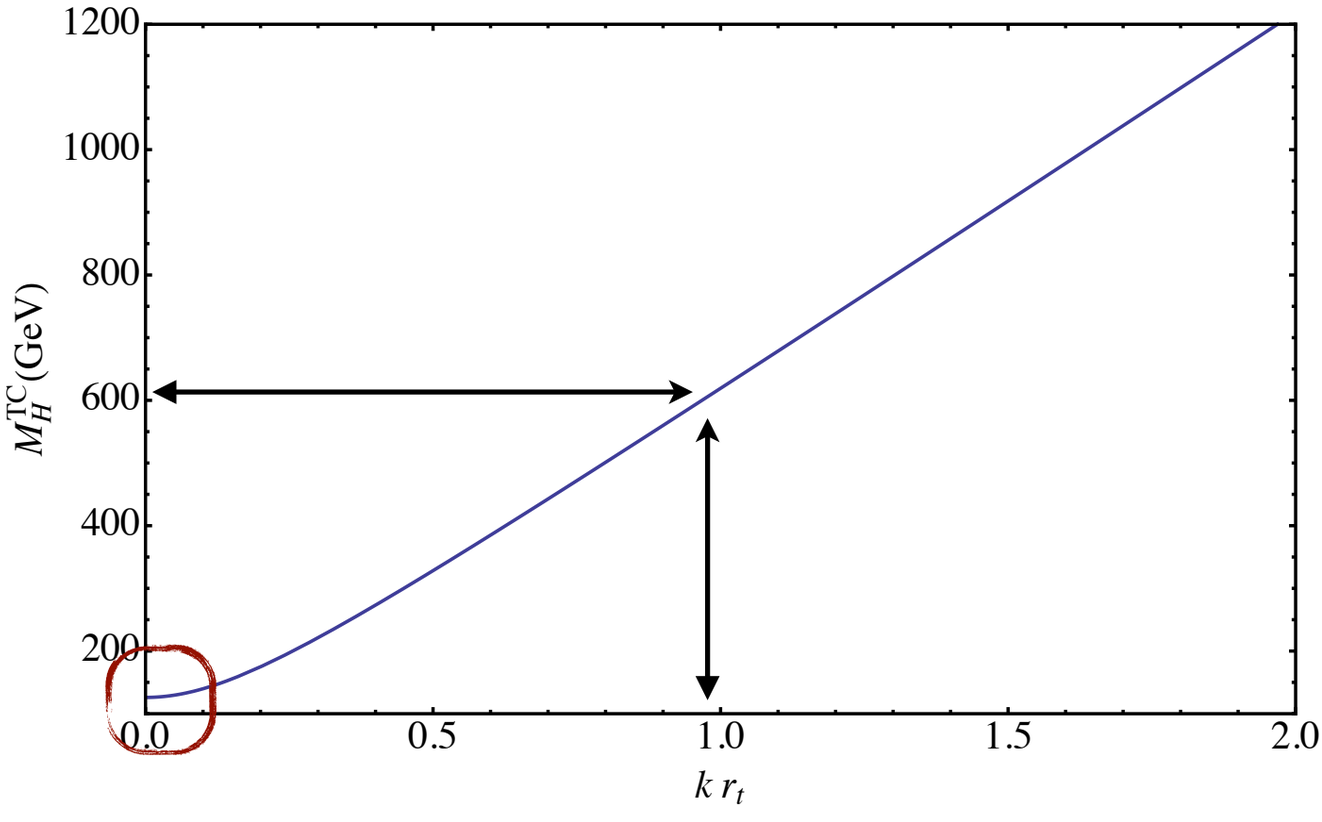
TC - Higgs is the lightest spin-0 scalar made of TC-fermions

$$H \sim c_1 \bar{Q}Q + c_2 \bar{Q}Q\bar{Q}Q + \cdots$$

Top corrections



$$(M_H^{\rm TC})^2 \simeq M_H^2 + 12\ \kappa^2 r_t^2 m_t^2$$



Foadi, Frandsen, Sannino, 1211.1083 PRD

Cacciapaglia, Sannino 1402.0233 JHEP

TC Higgs can be heavy

Minimal Composite Dynamics

2 Dirac flavours in a given underlying rep.

Complex: SU(2)xSU(2)xU(1) -> SU(2)xU(1)

QCD with 2 Dirac flavours

Pseudoreal: SU(4) -> Sp(4)

SU(2) gauge with 2 fund. Dirac flavours

Real: SU(4) -> SO(4)

SU(2) gauge with 2 adj. Dirac flavours