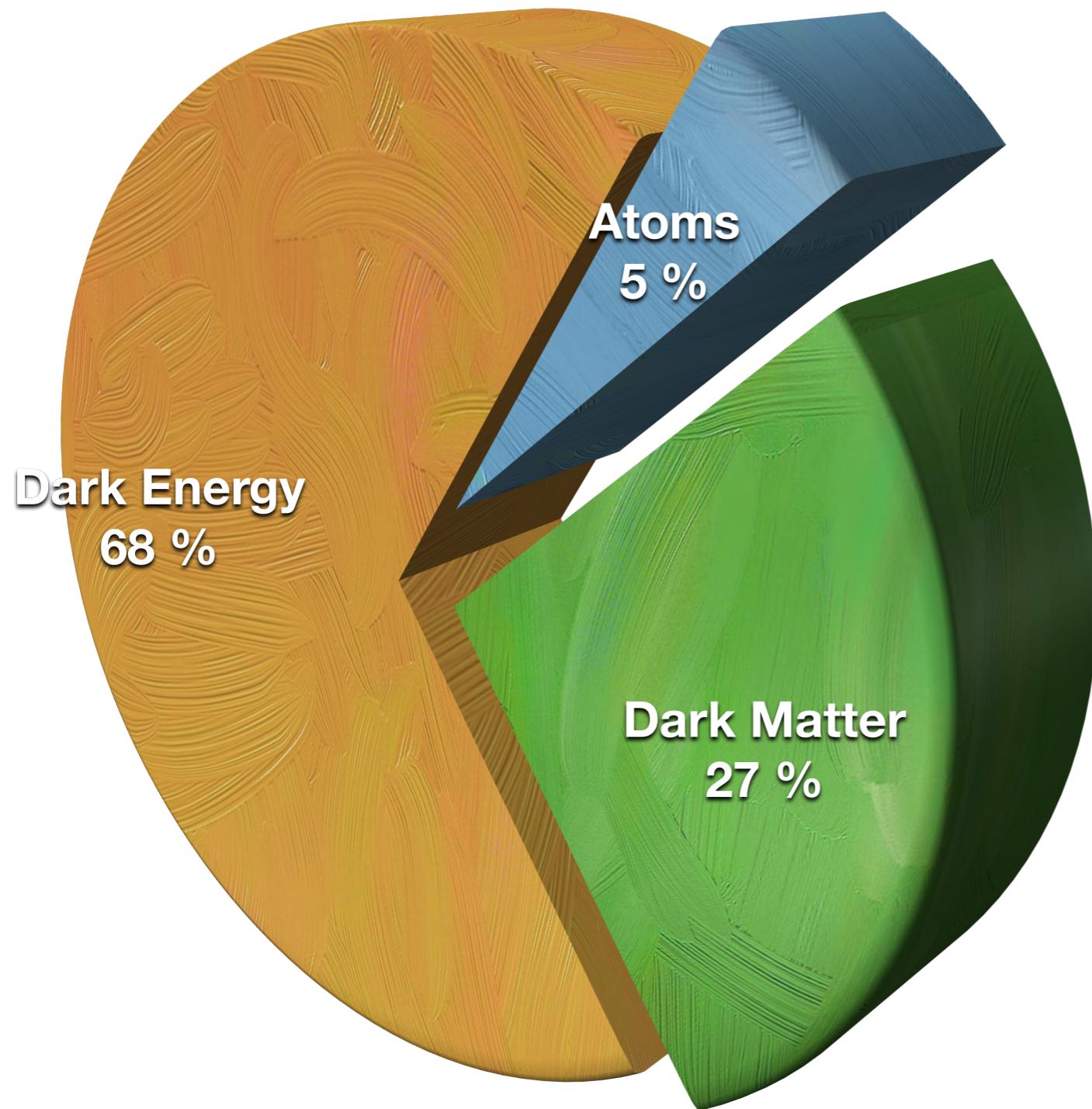


Fundamental Composite Dynamics

Francesco Sannino

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

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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
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What is the dynamics and spectrum of these theories ?

Bright side

Composite Higgs dynamics

$$D H^\dagger D H - V(H) + \bar{\Psi}_L H \psi_R$$

Composite Higgs dynamics

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



$$m_W^2 WW$$

Composite Higgs dynamics

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

The diagram illustrates the decomposition of the composite Higgs Lagrangian into its constituent parts. At the top, the full Lagrangian term $DH^\dagger DH - V(H) + \bar{\Psi}_L H \psi_R$ is shown. The first term, $DH^\dagger DH - V(H)$, is highlighted with a red box and has an arrow pointing down to the term $m_W^2 WW$. The second term, $\bar{\Psi}_L H \psi_R$, is highlighted with a blue box and has an arrow pointing down to the term $m_\psi \bar{\Psi}_L \psi_R$.

Composite Higgs dynamics

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



$$m_W^2 WW$$



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

TC/Fund Comp Dyn

Composite Higgs dynamics

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



$$m_W^2 WW$$

$$m_\psi \bar{\Psi}_L \Psi_R$$

TC/Fund Comp Dyn

Extended TC (ETC)

Composite Higgs dynamics

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



$$m_W^2 WW$$

$$m_\psi \bar{\Psi}_L \Psi_R$$

TC/Fund Comp Dyn

Extended TC (ETC)

Minimal Technicolor

Higgs is the lightest scalar excitation of the condensate

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Inside the box

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

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Outside the box

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

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TC can be conformal if ETC is strong

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- ◆ 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

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D.B. Kaplan & H. Georgi, 84

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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
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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

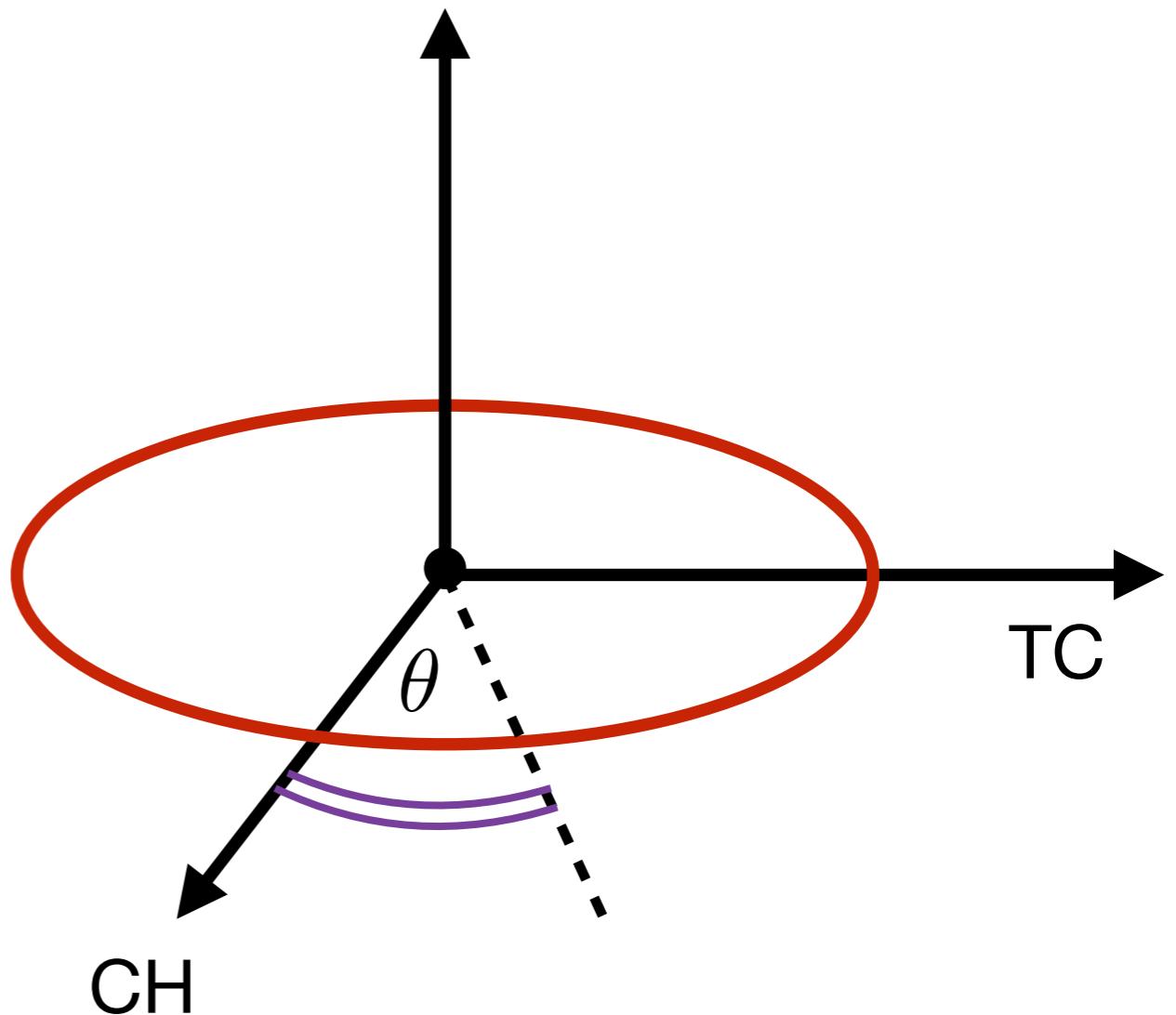
Appelquist, Sannino, 98, 99

Ryttov, Sannino, 2008

Katz, Nelson Walker, 2005

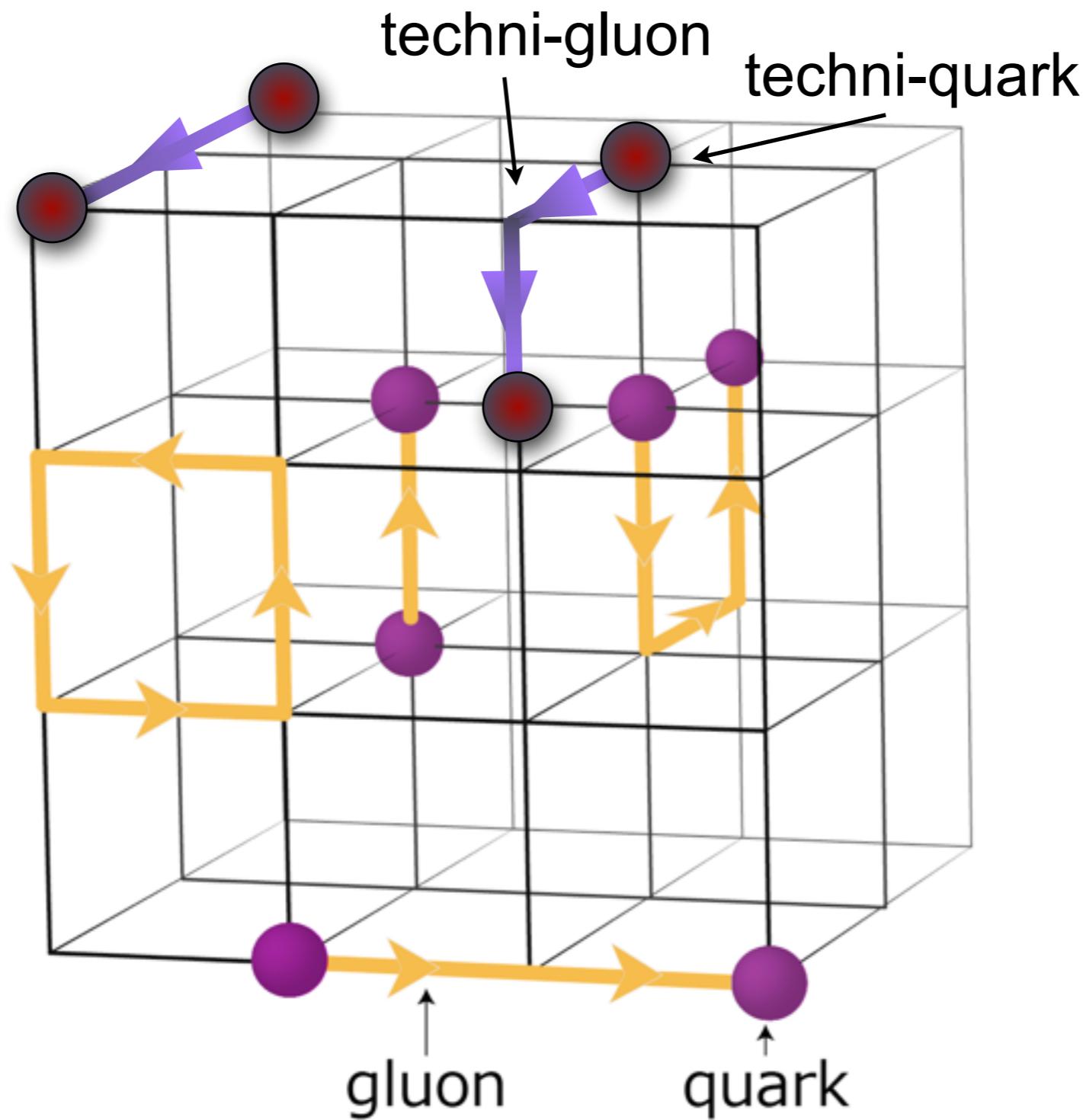
Gripaios, Pomarol, Riva, Serra, 2009

Galloway, Evans, Luty, Tacchi, 2010

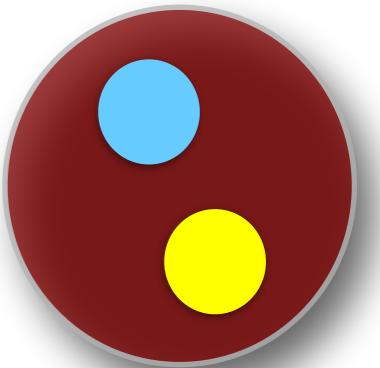


Cacciapaglia and Sannino 1402.0233 JHEP

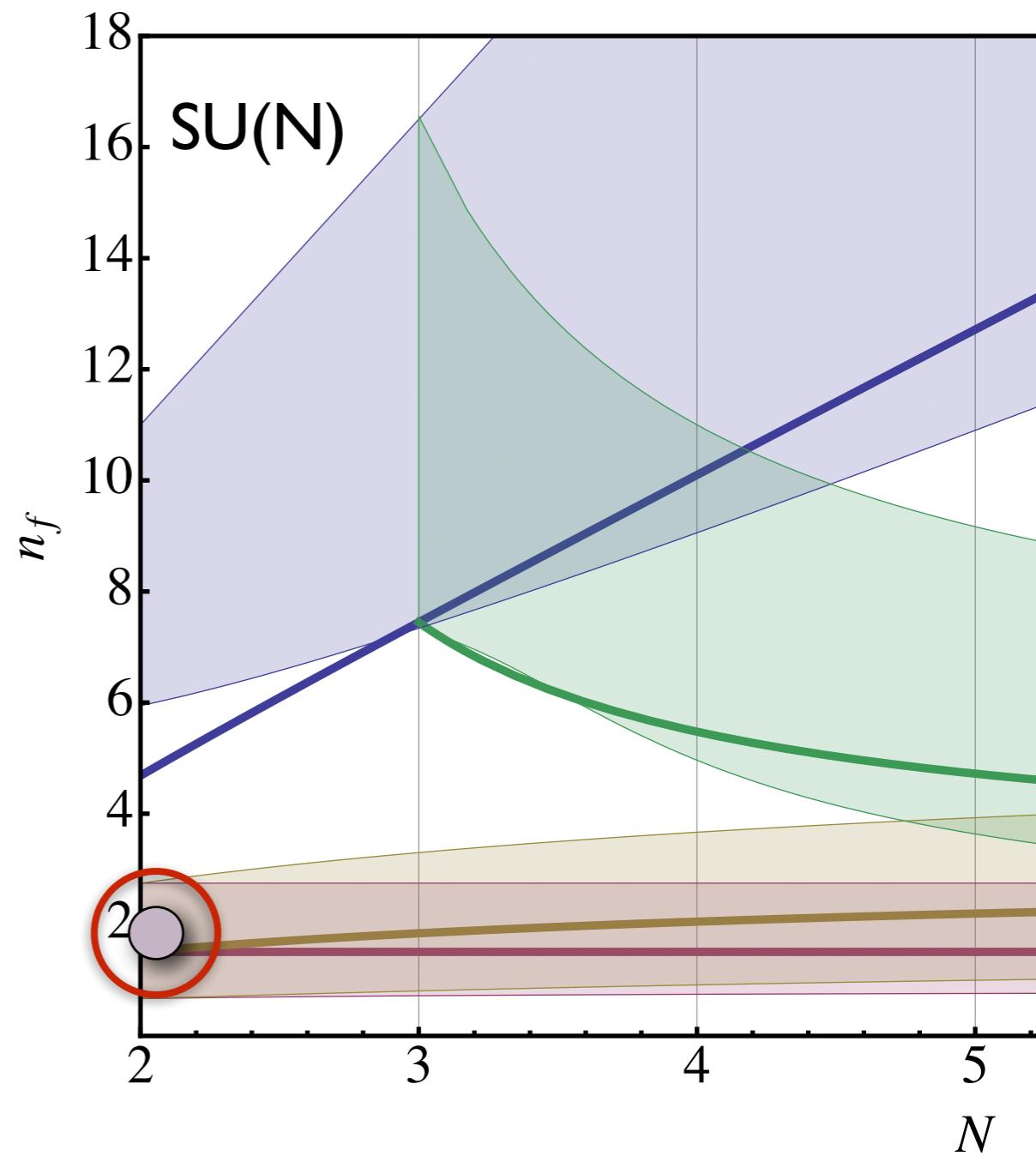
Composite Dynamics on the Lattice



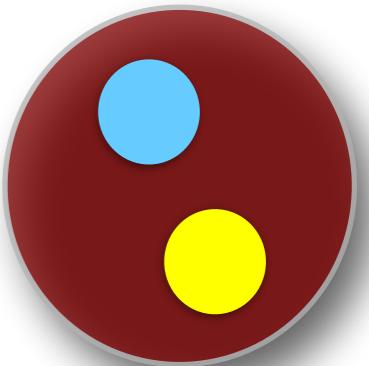
$SU(2) = Sp(2)$ with 2 Flavors



Minimal Fund. Template

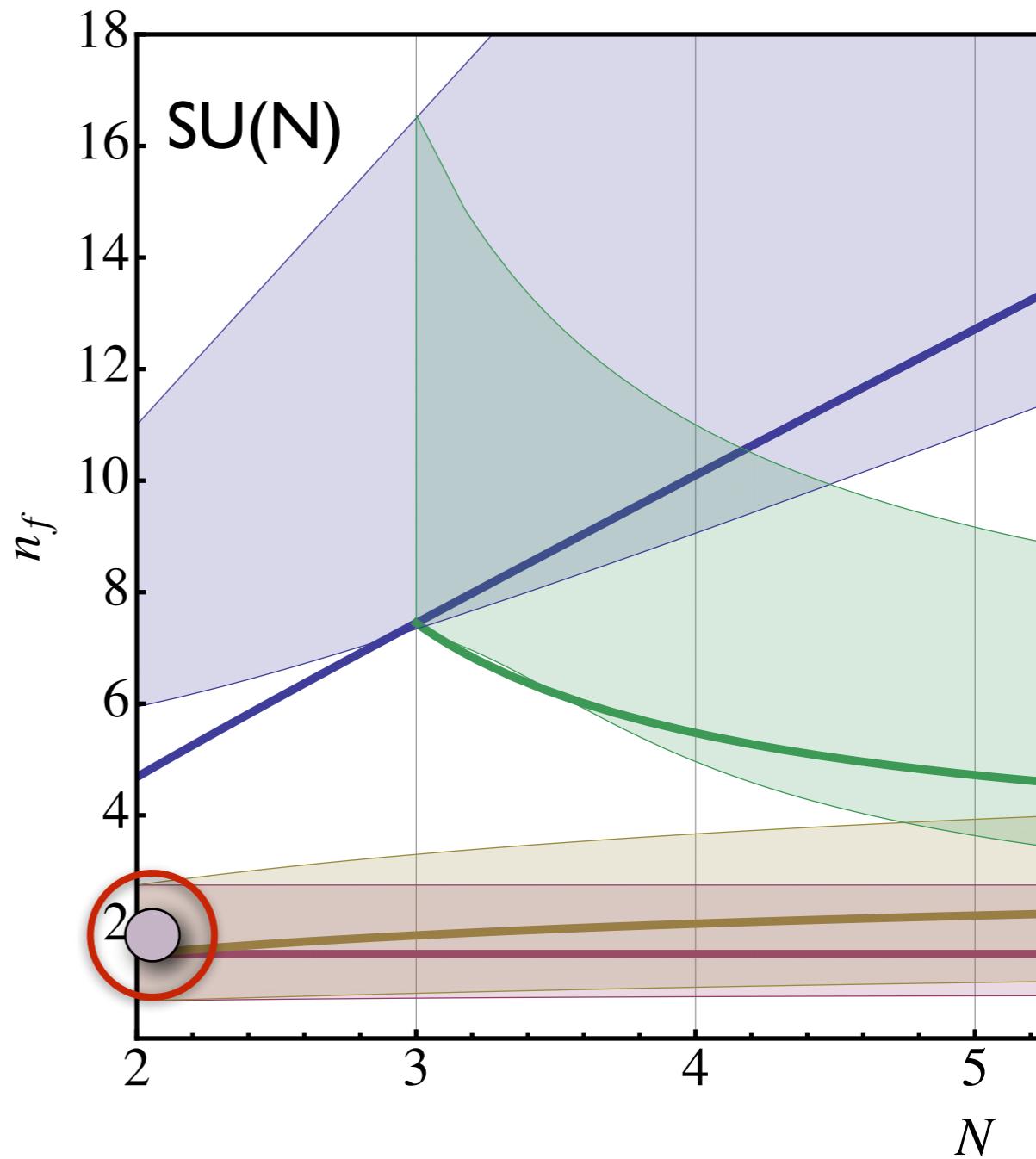


$SU(2) = Sp(2)$ with 2 Flavors

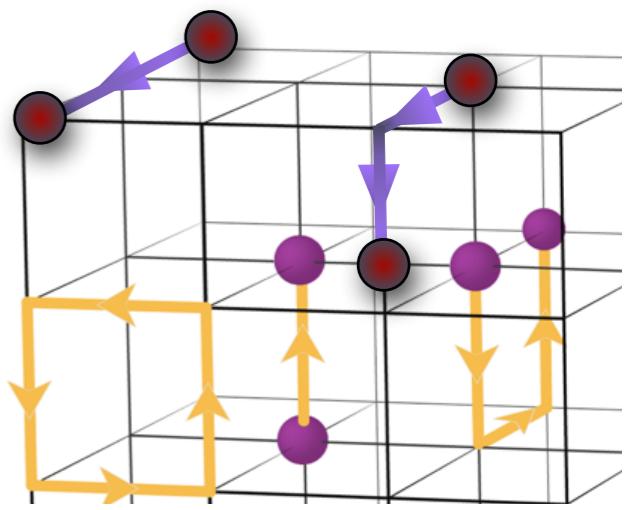


Minimal Fund. Template

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



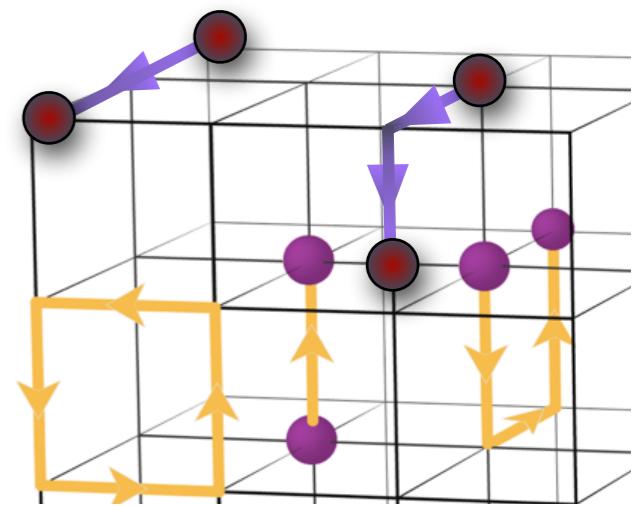
$SU(2)$ + 2 Dirac Flavors



$SU(2) + 2$ Dirac Flavors

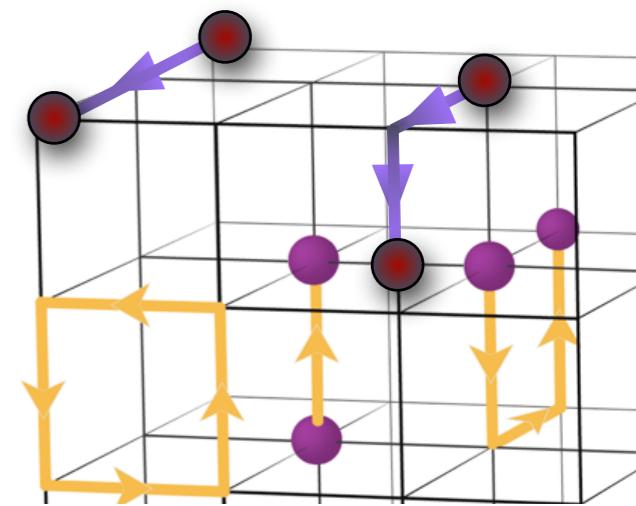
- ◆ $SU(4)$ global symmetry breaks to $Sp(4)$
- ◆ 5 Goldstone bosons
- ◆ Goldstone form factors

Lewis, Pica, Sannino, 1109.3513
Hietanen, Lewis, Pica, Sannino, 1308.4130
Hietanen, Lewis, Pica, Sannino, 1404.2794



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Lattice predictions for TC & CH Spin-One states

$$m_V = \frac{3.2(5)}{\sin \theta} \text{ TeV}$$

$$m_A = \frac{3.6(9)}{\sin \theta} \text{ TeV}$$

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

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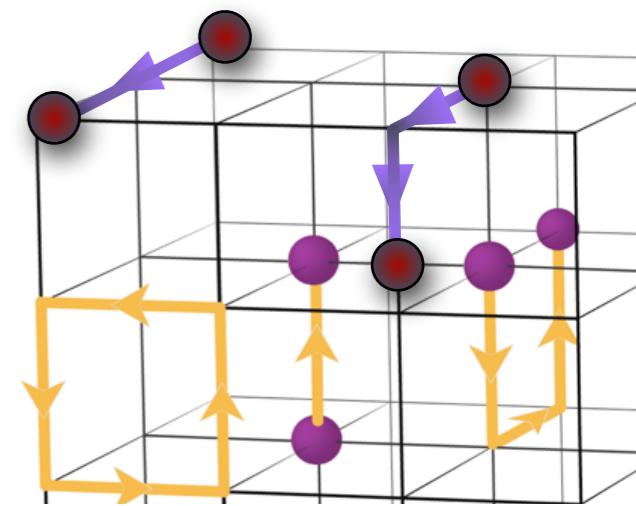
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Hietanen, Lewis, Pica, Sannino, 1308.4130

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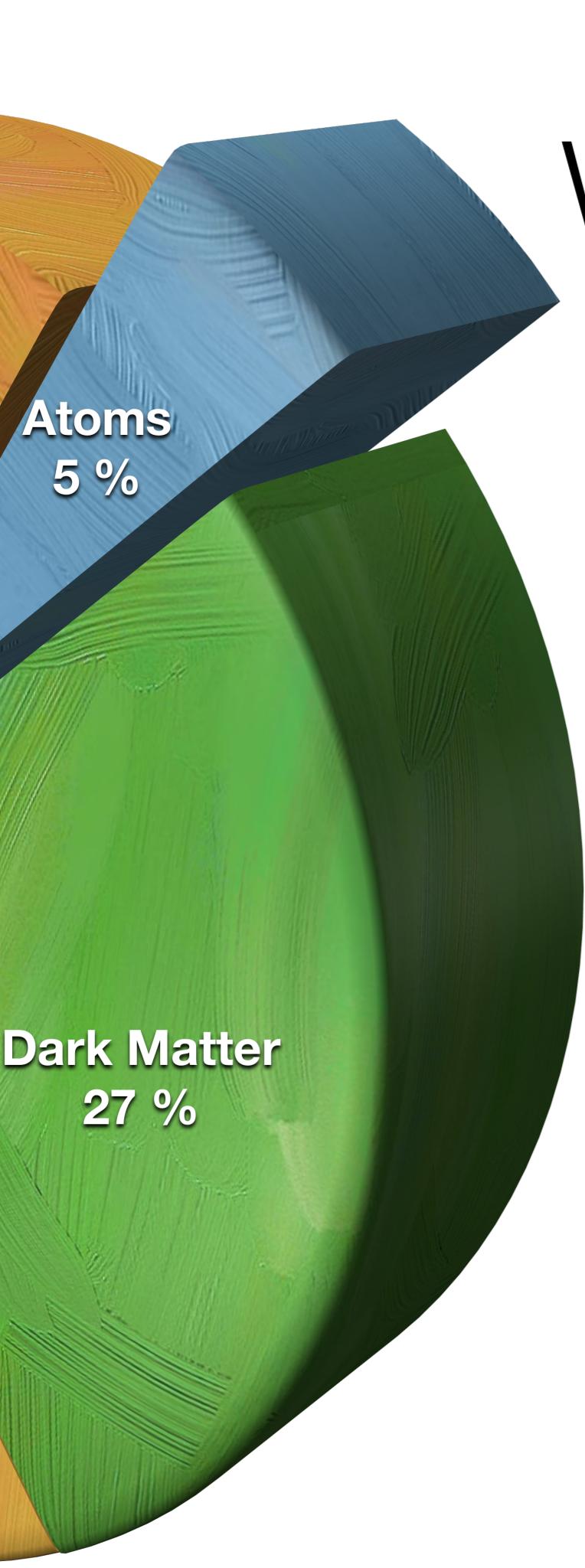
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Arthur, Drach, Hansen, Hietanen, Pica, Sannino, 1602.06559

In progress:

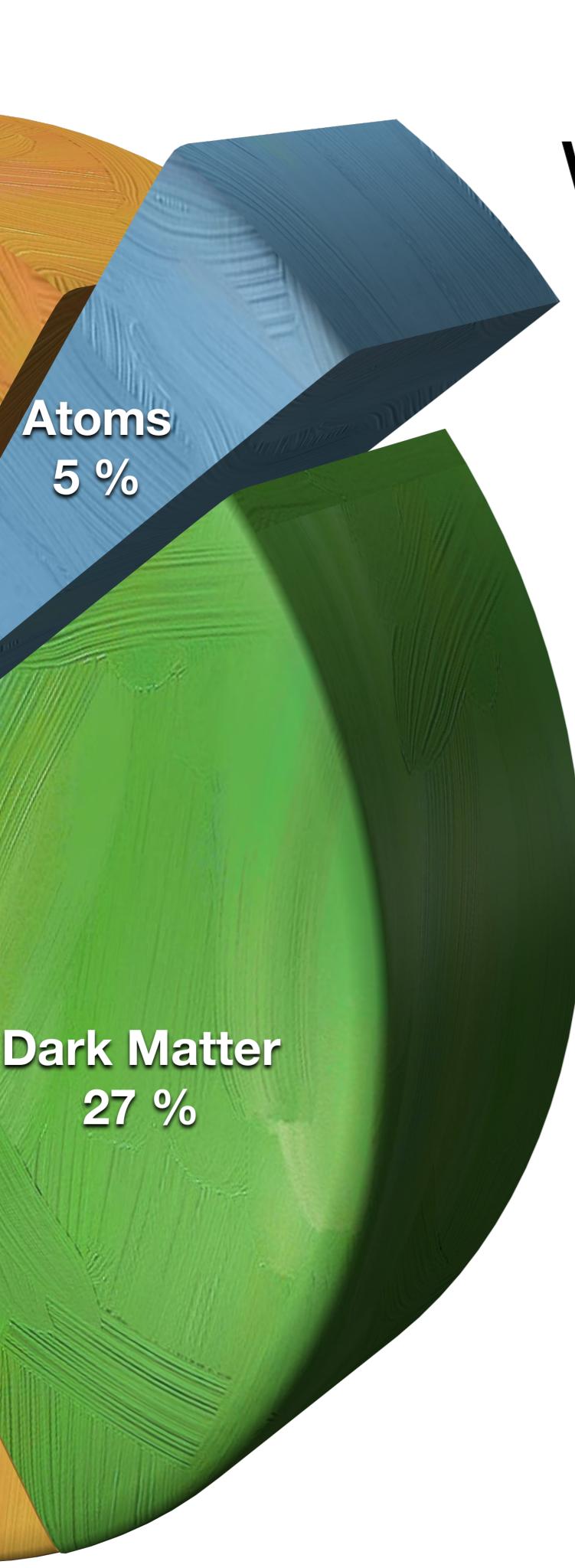
- ◆ Scalar spectrum
- ◆ Scattering amplitudes

Dark side



What makes dark matter ?

Atoms: 3 forces and many fund. particles



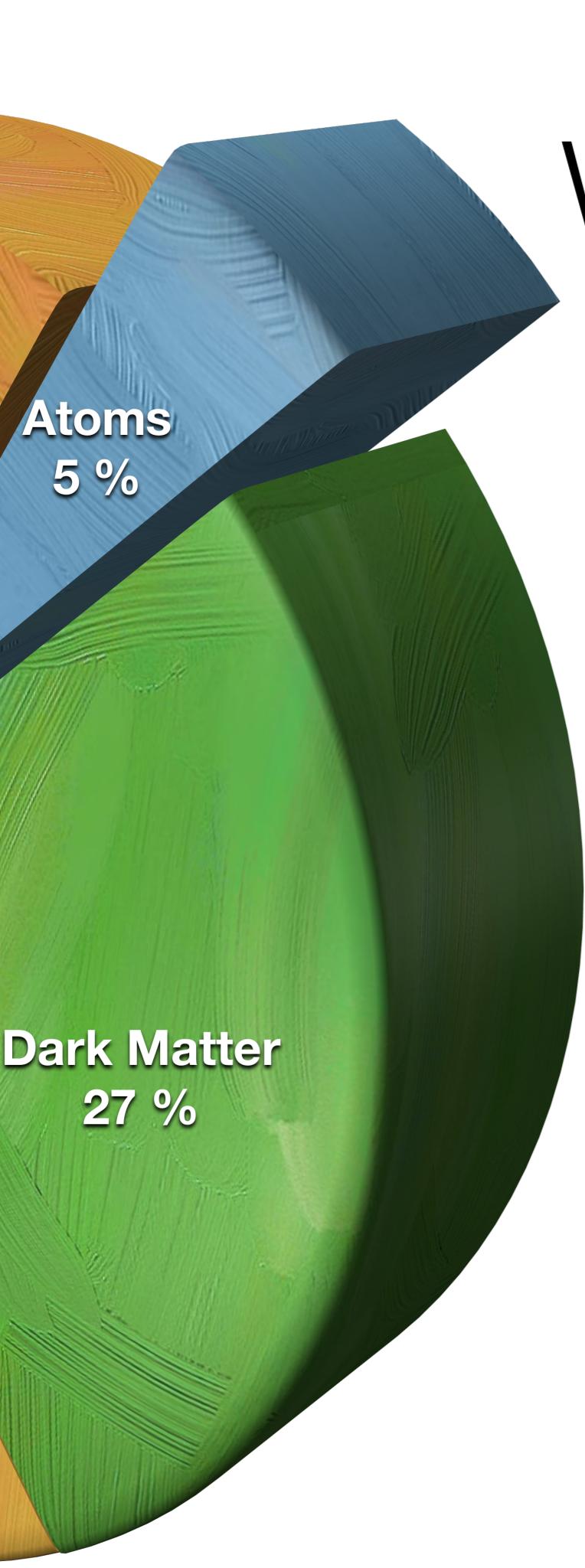
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DM oversimplification

DM Particle

???



What makes dark matter ?

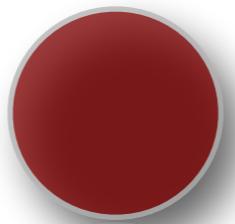
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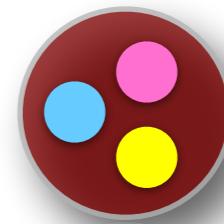
DM Particle

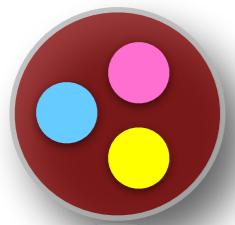
???

Elementary

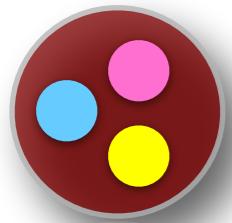


Composite



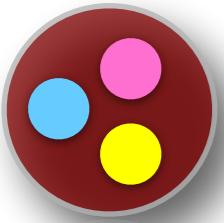


Composite Dark Matter



Composite Dark Matter

Building Blocks

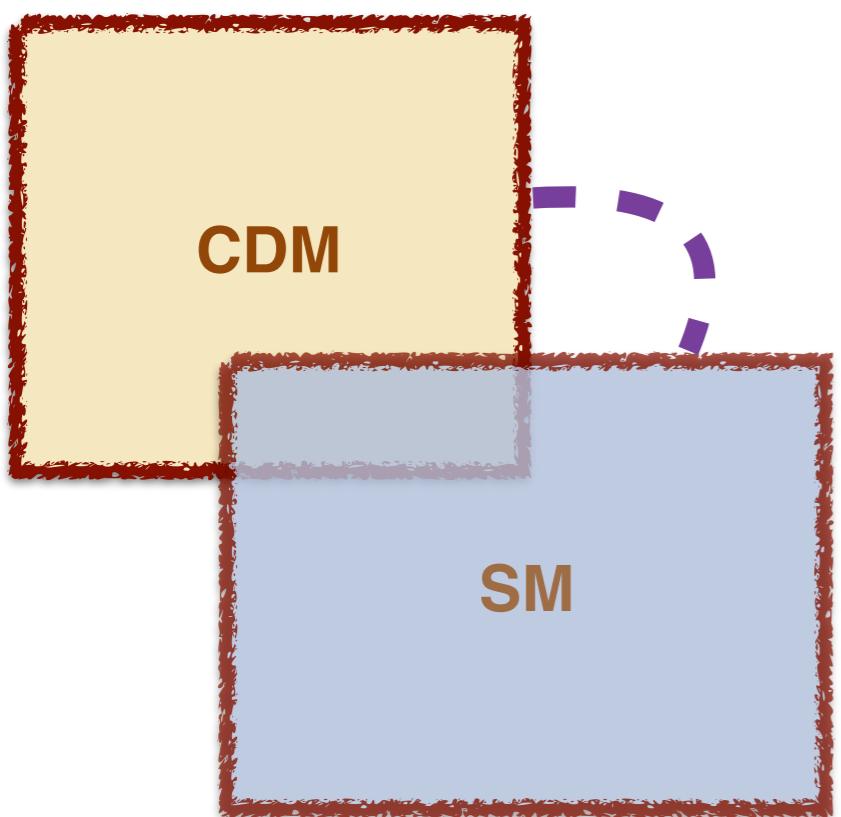


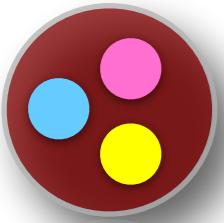
Composite Dark Matter

Building Blocks

SM charged

Type I





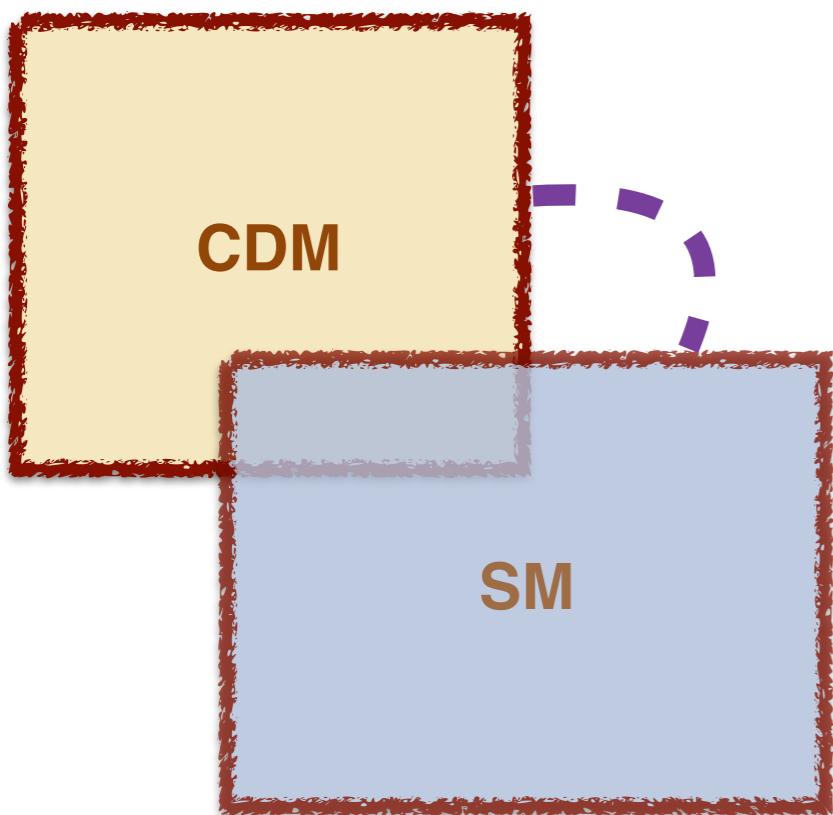
Composite Dark Matter

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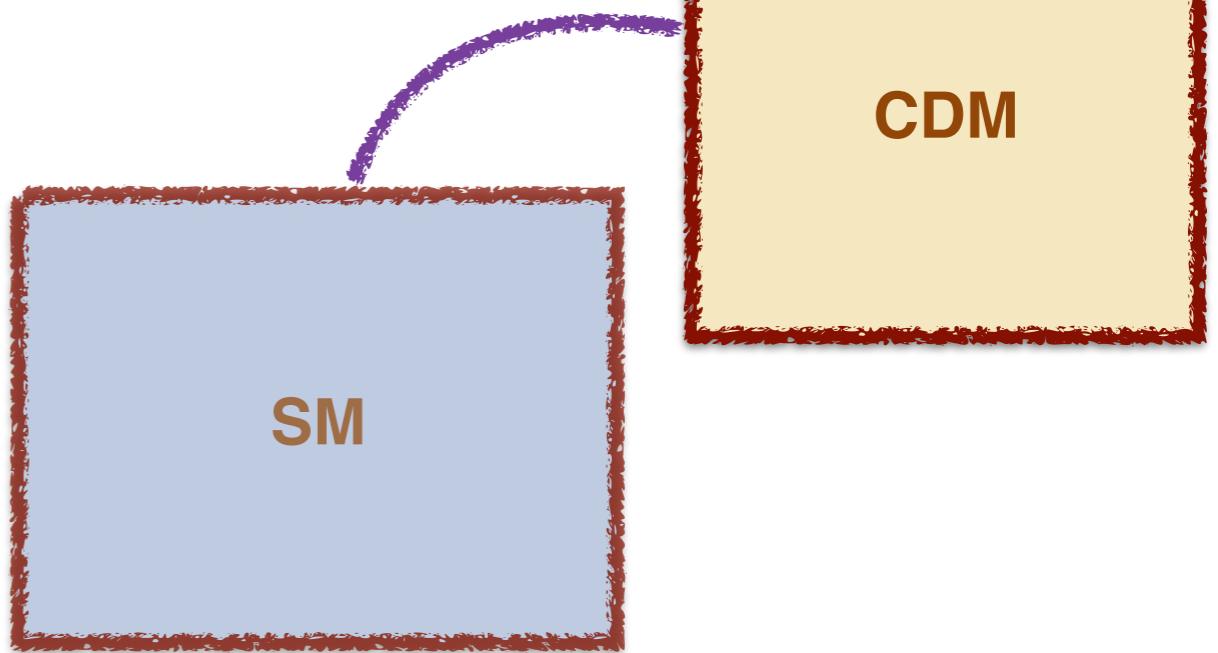
SM charged

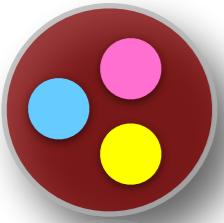
SM singlets

Type I

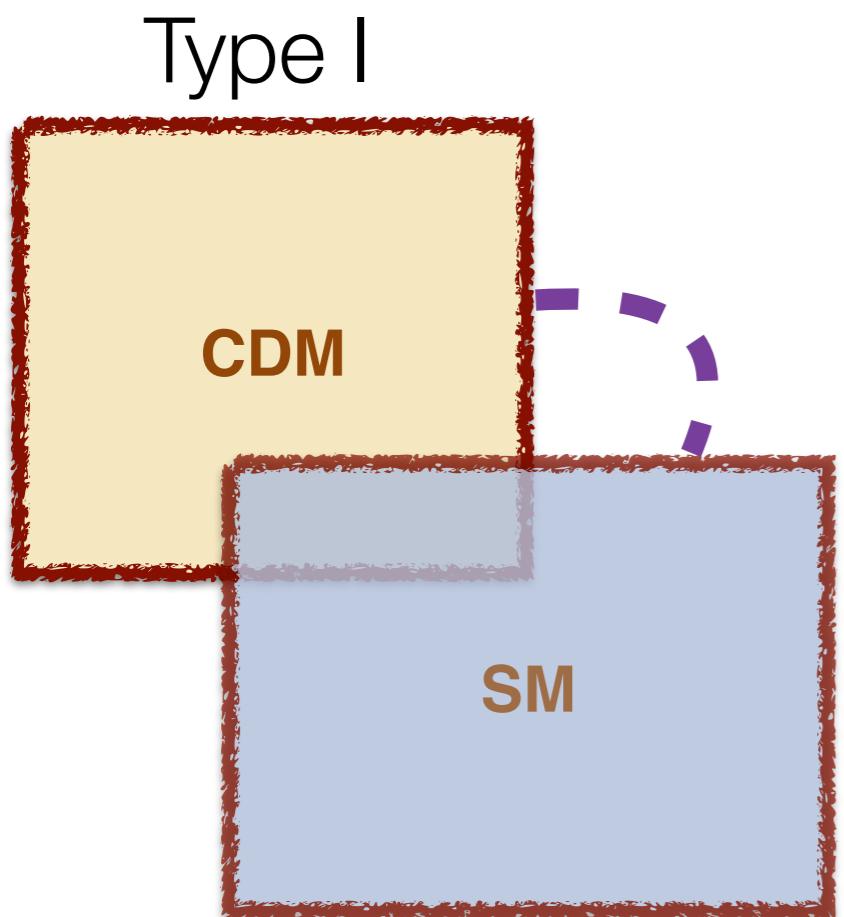


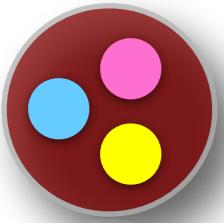
Type II



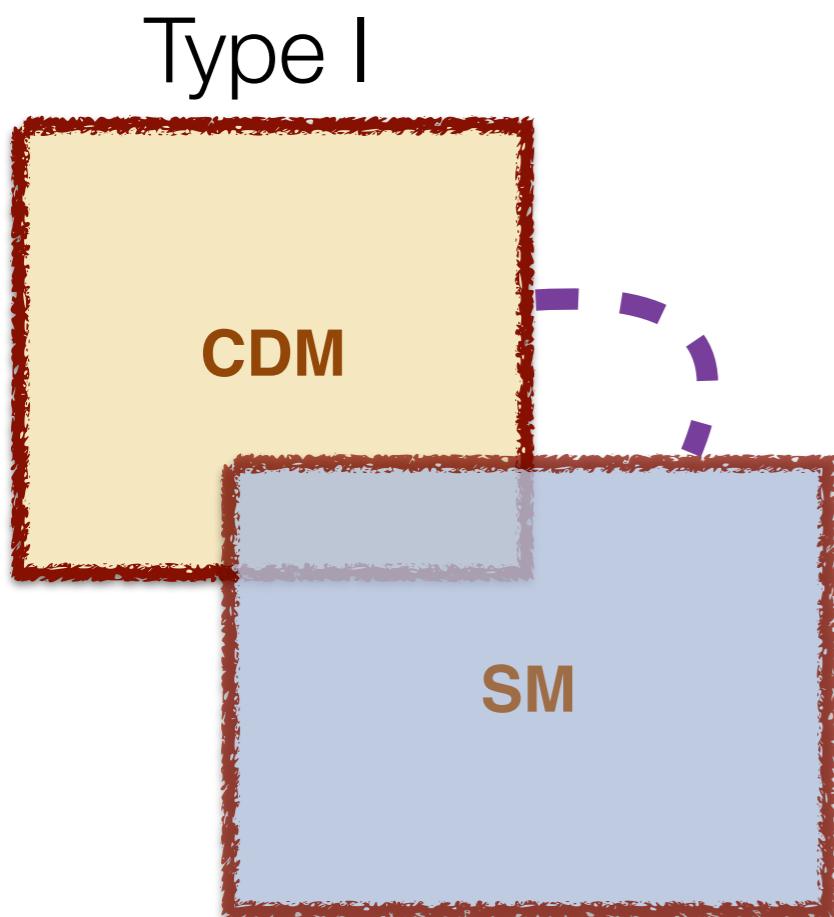


CDM Type I





CDM Type I



- TC Baryon¹
- TC Meson²
- Millicharged Comp. DM³
- Stealth DM⁴
- Solitons/Little Higgs⁵
-

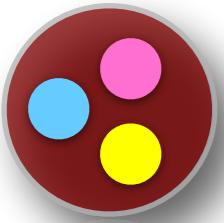
¹Nussinov 85 & Barr, Chivukula, Farhi 90

²Gudnason, Kouvaris, Sannino ph-0603014, 0608055

³Kouvaris 1304.7476

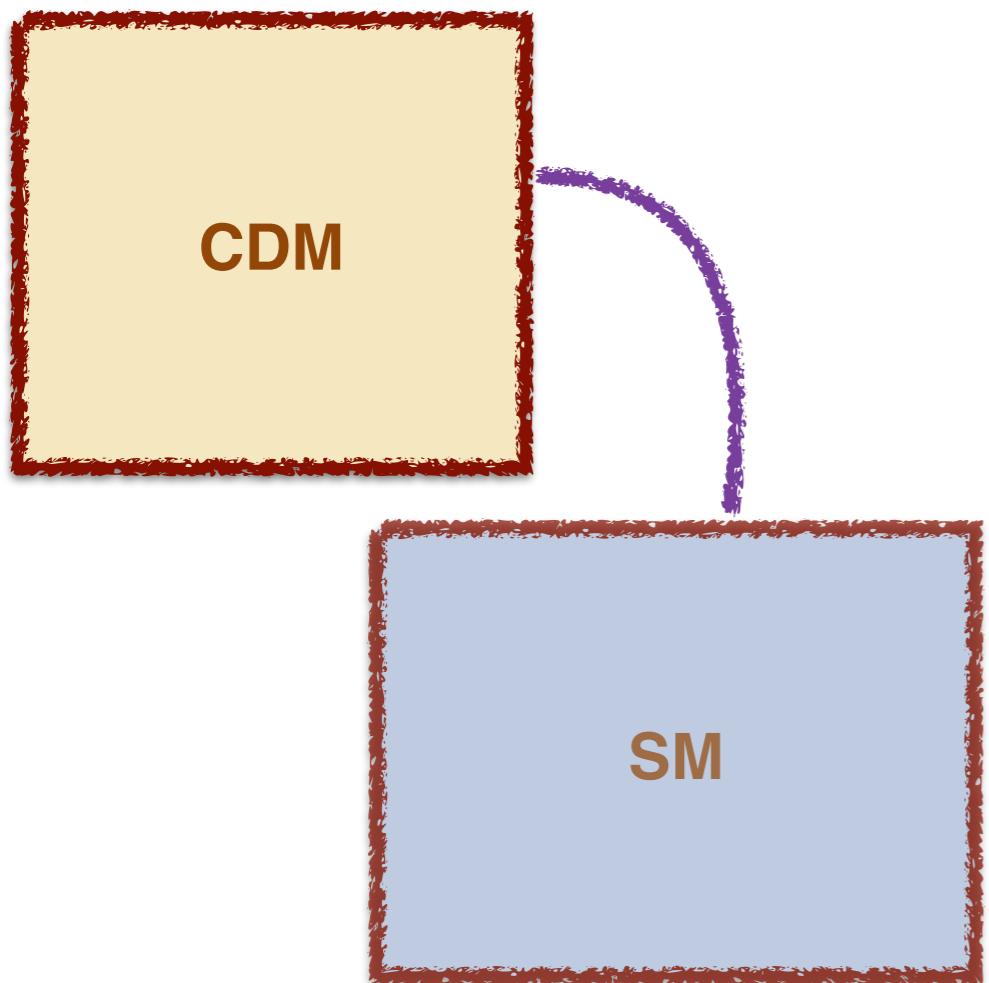
⁴Appelquist et al. 1503.04203

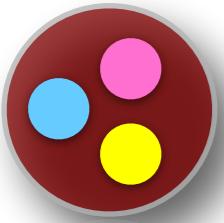
⁵Gillioz, 1103.5990



CDM Type II

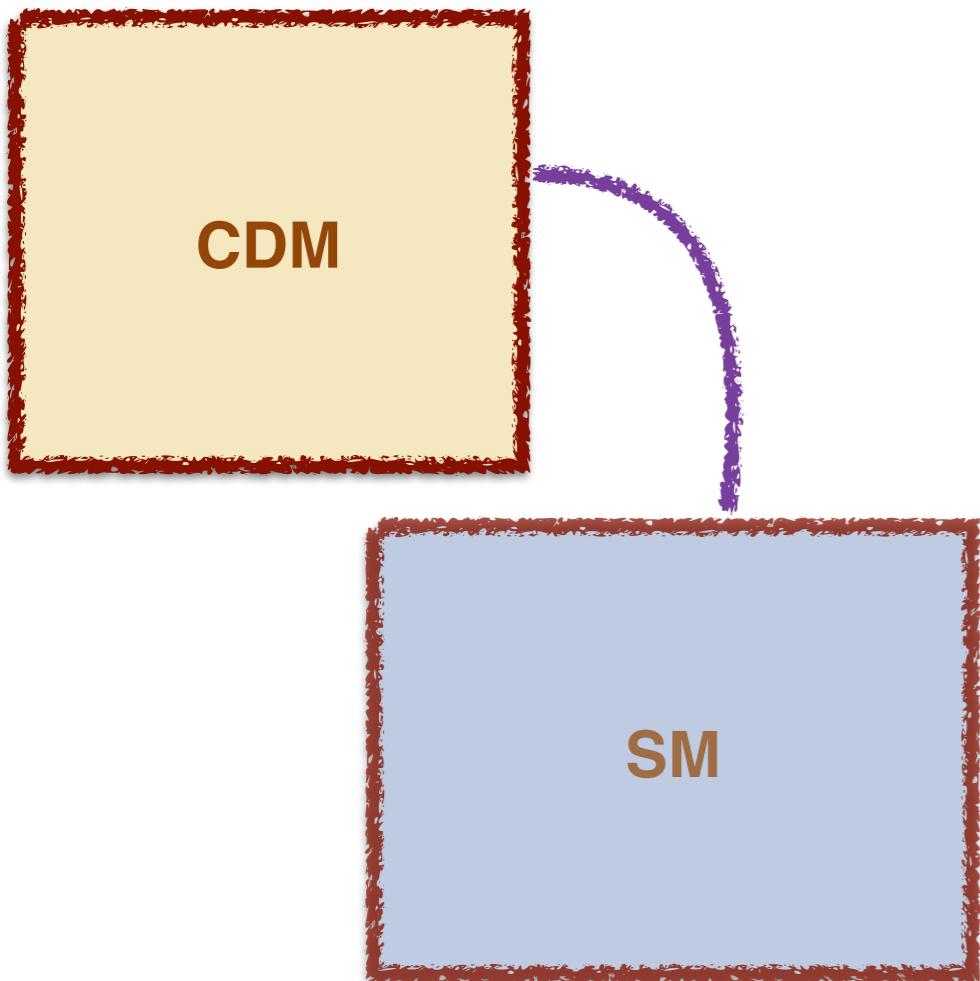
Type II





CDM Type II

Type II



- Dark Nuclei¹
- SIMPlest Miracle^{2,3}
- Solitonic
-

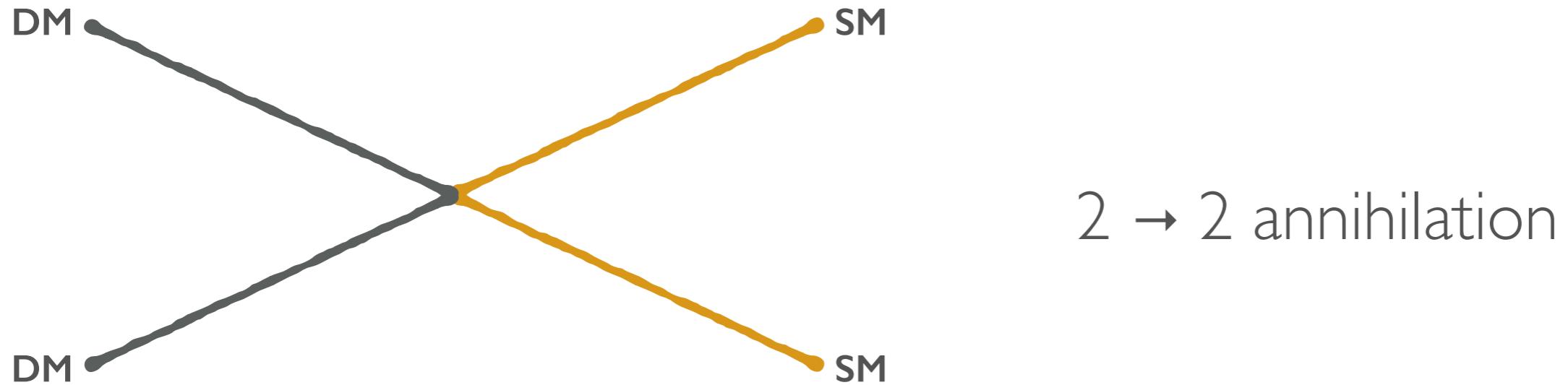
¹Detmold, McCullough, Pochinsky 1406.2276

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

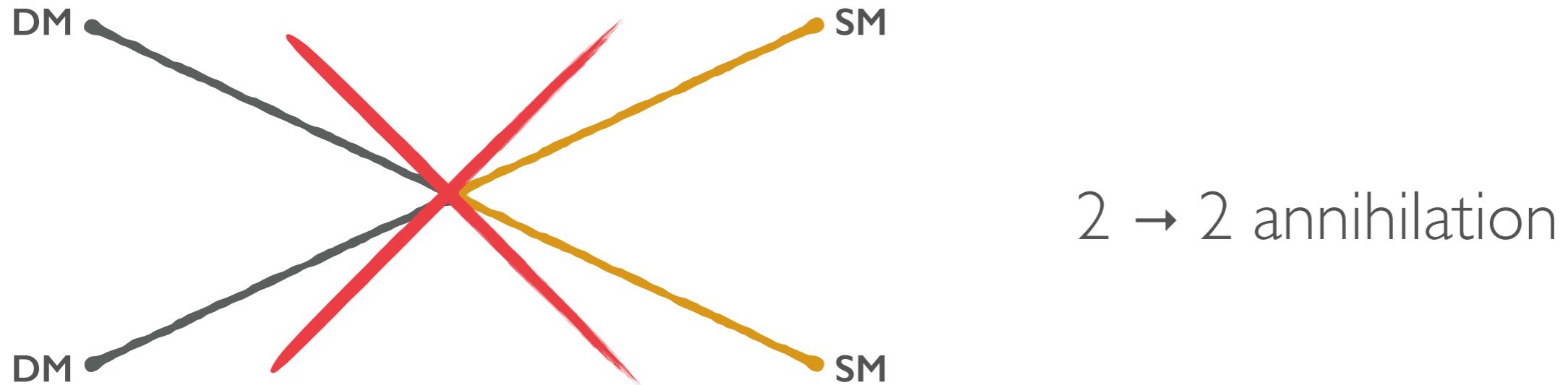
³Hansen, Langaeble, Sannino, 1507.01590

(Not) the SIMPlest miracle

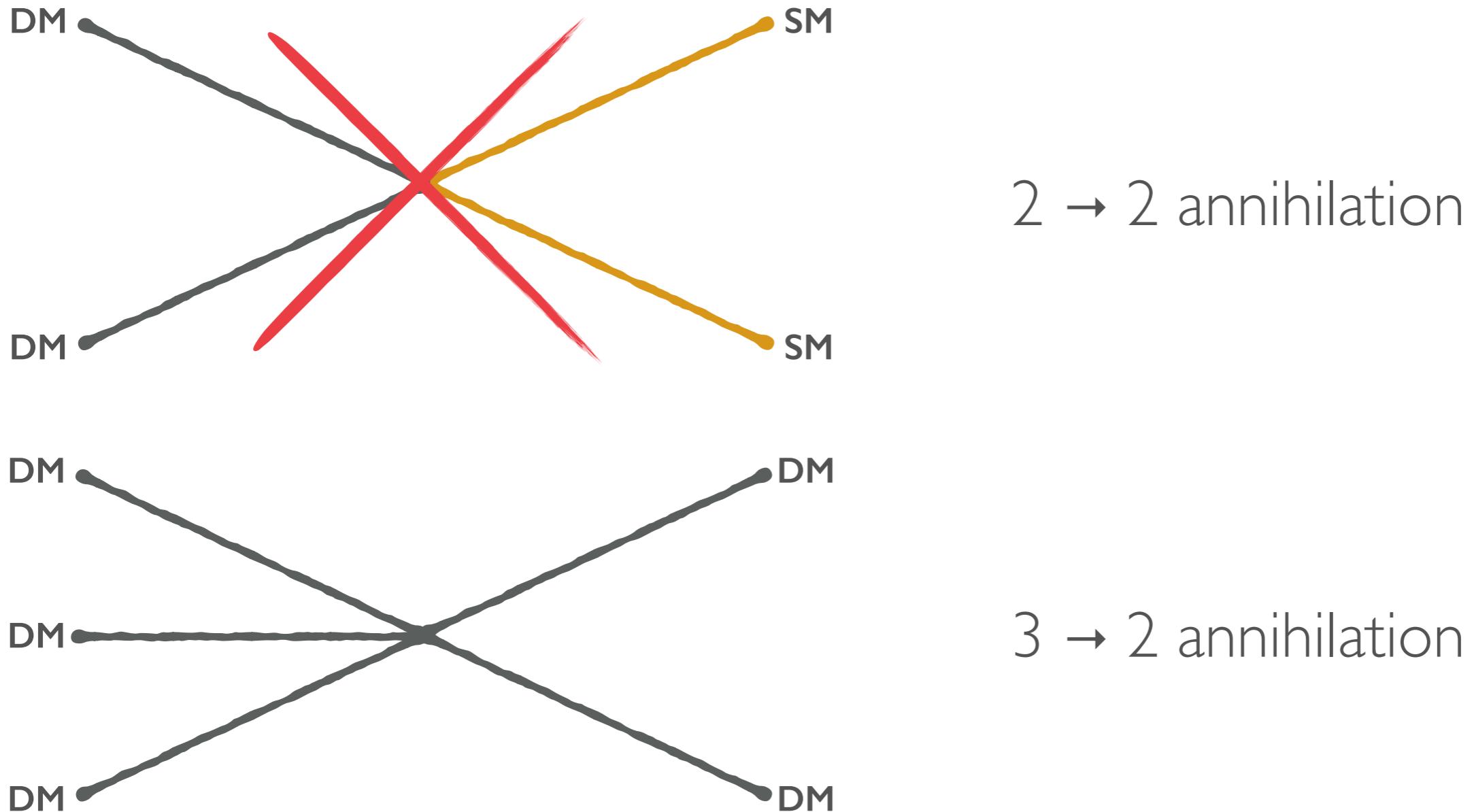
The SIMP Mechanism



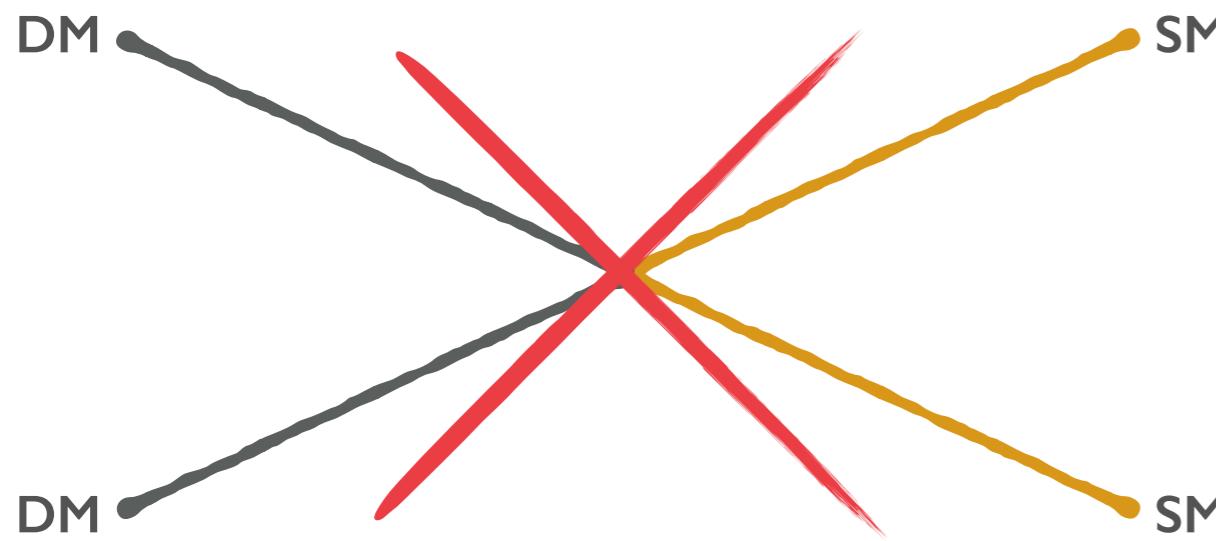
The SIMP Mechanism



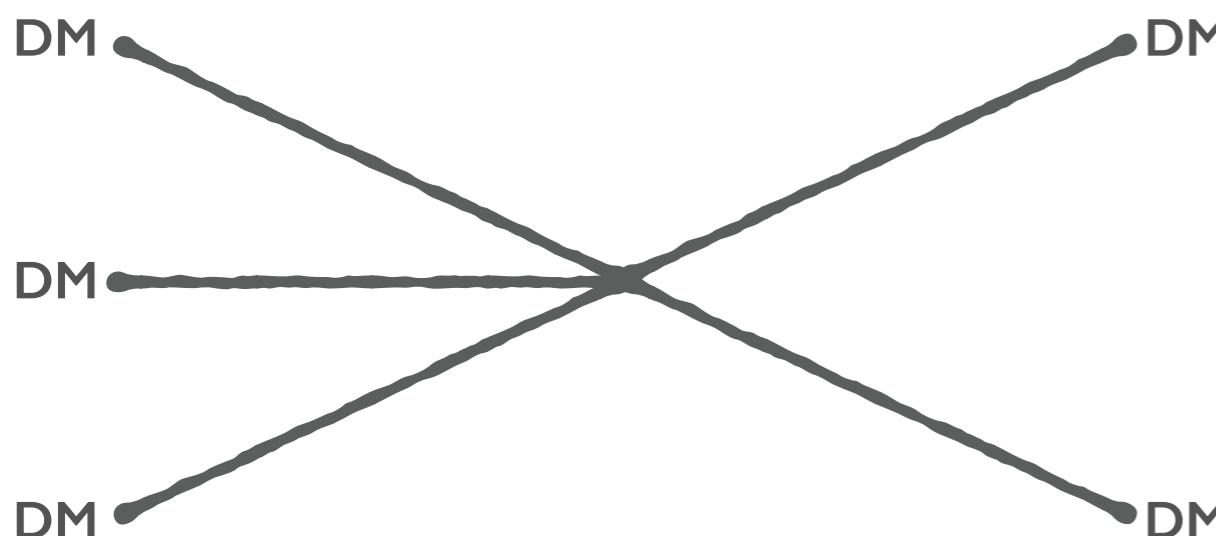
The SIMP Mechanism



The SIMP Mechanism



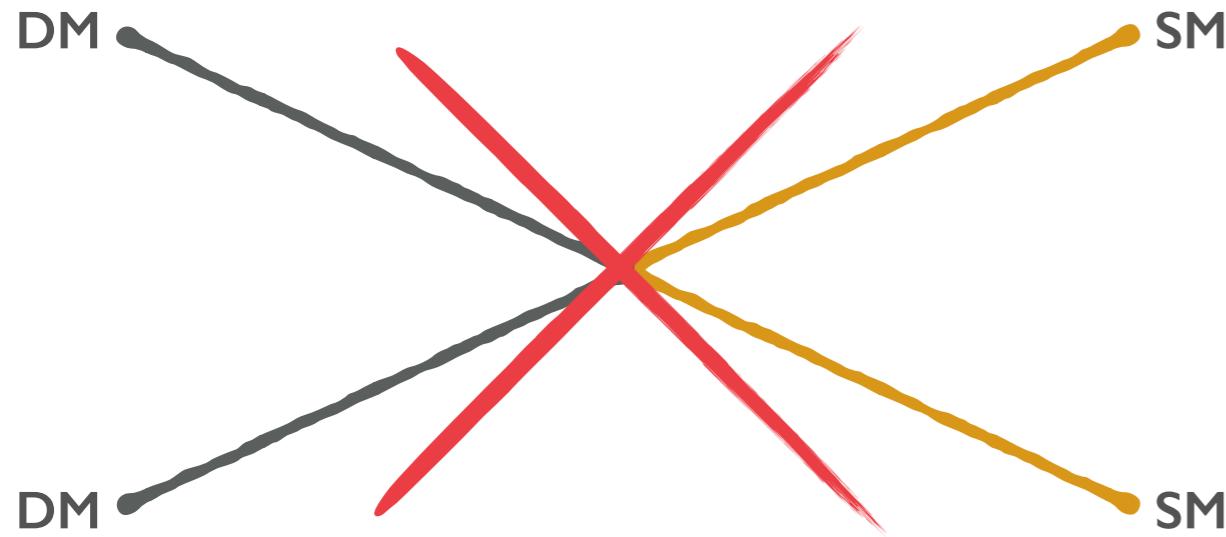
2 → 2 annihilation



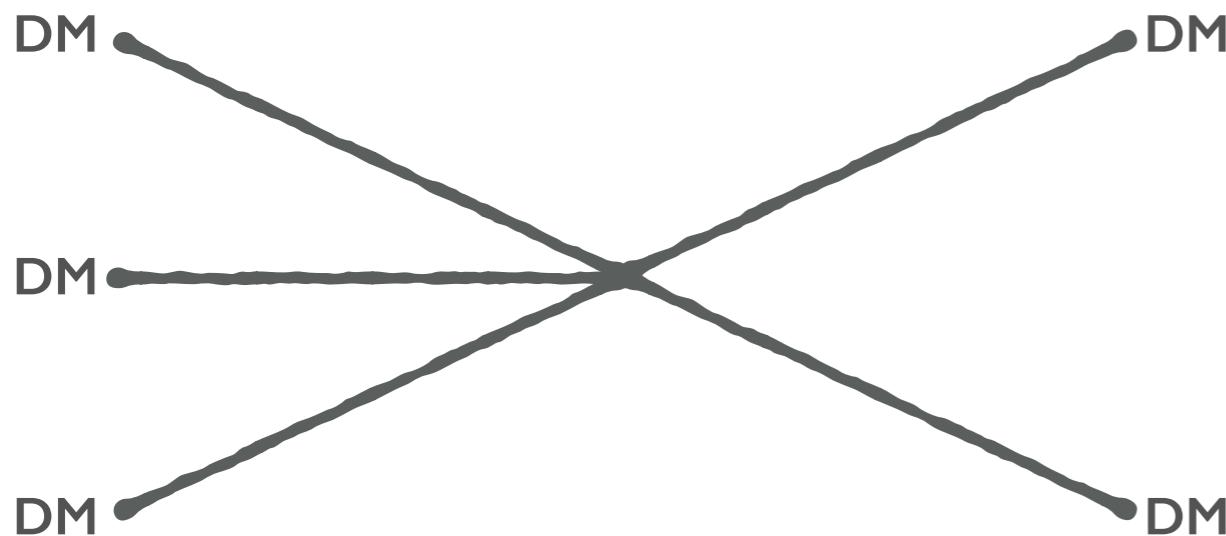
3 → 2 annihilation

Relevant DM - DM # changing operators

The SIMP Mechanism



$2 \rightarrow 2$ annihilation



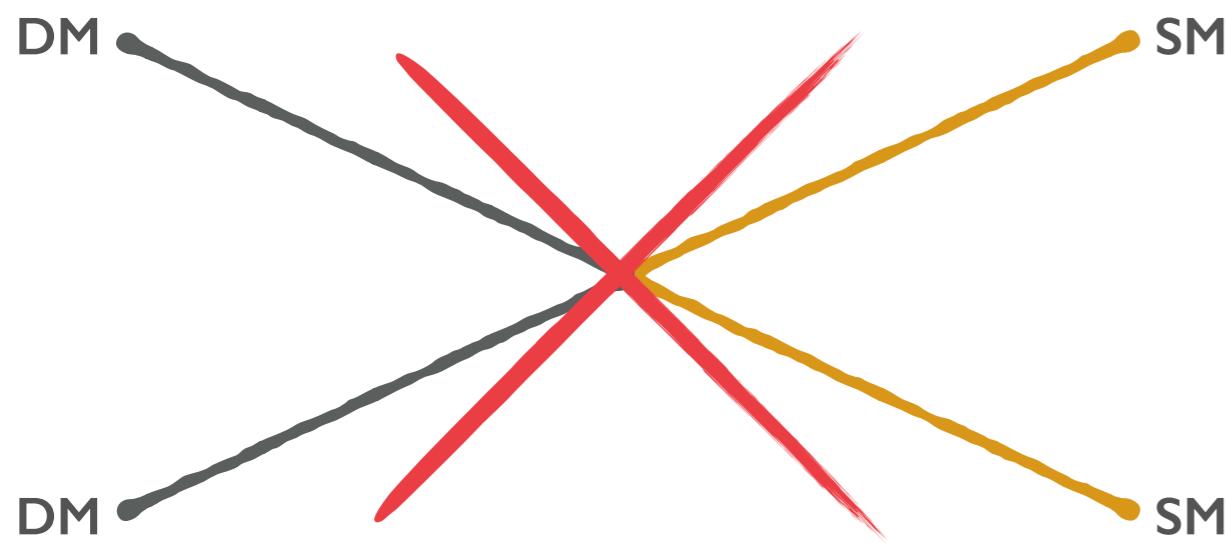
$3 \rightarrow 2$ annihilation

Relevant DM - DM # changing operators

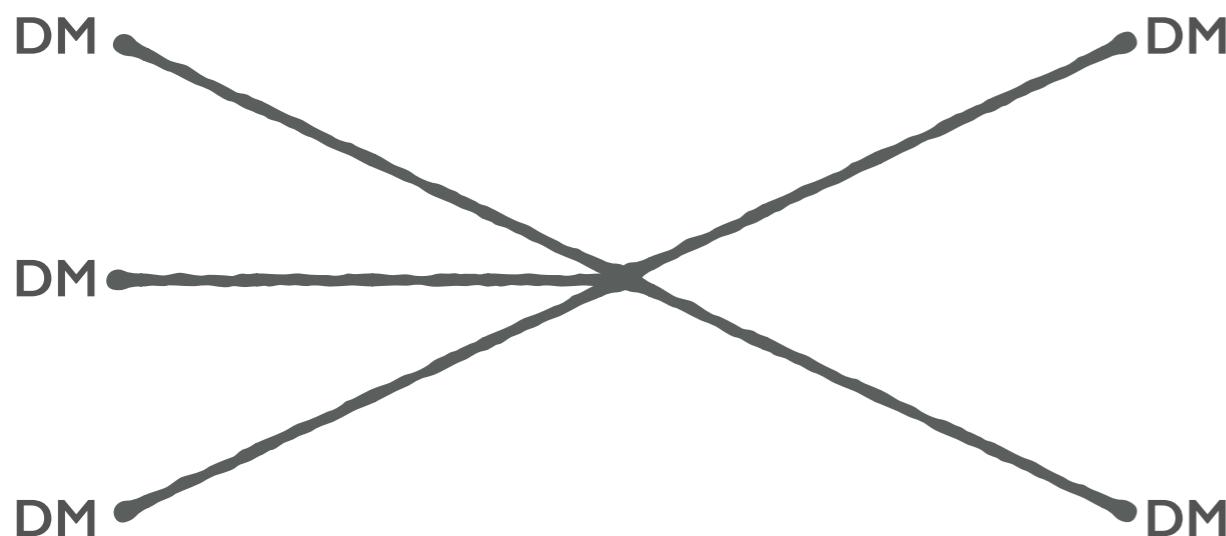
Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727, PRL

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

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Original idea

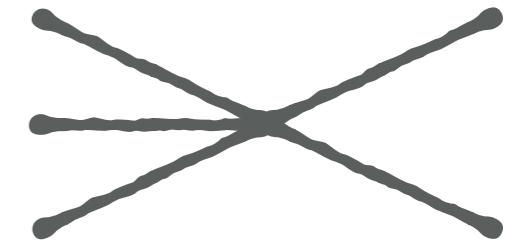
E. Carlson et al: *Astrophys.J.* 398 (1992) 43-52

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

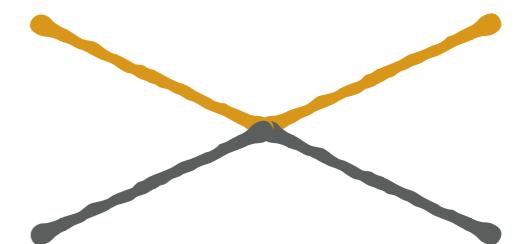
Relevant processes

- The $3 \rightarrow 2$ process constrains DM via Boltzmann equation/relic-density.

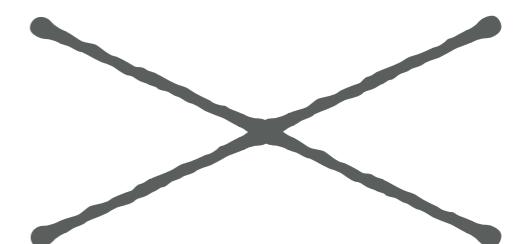
$$\dot{n} + 3Hn = -(n^3 - n^2 n_{eq}) \langle \sigma v^2 \rangle_{3 \rightarrow 2}$$



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



- The $2 \rightarrow 2$ 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)

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

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

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

The topological WZW term leads to a 5-point interaction

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

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(Inconsistent) $2 \rightarrow 2$ analysis to lowest non-vanishing order

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

Consistent ChPT SIMP corrections

$2 \rightarrow 2$ evaluated at the same $3 \rightarrow 2$ order

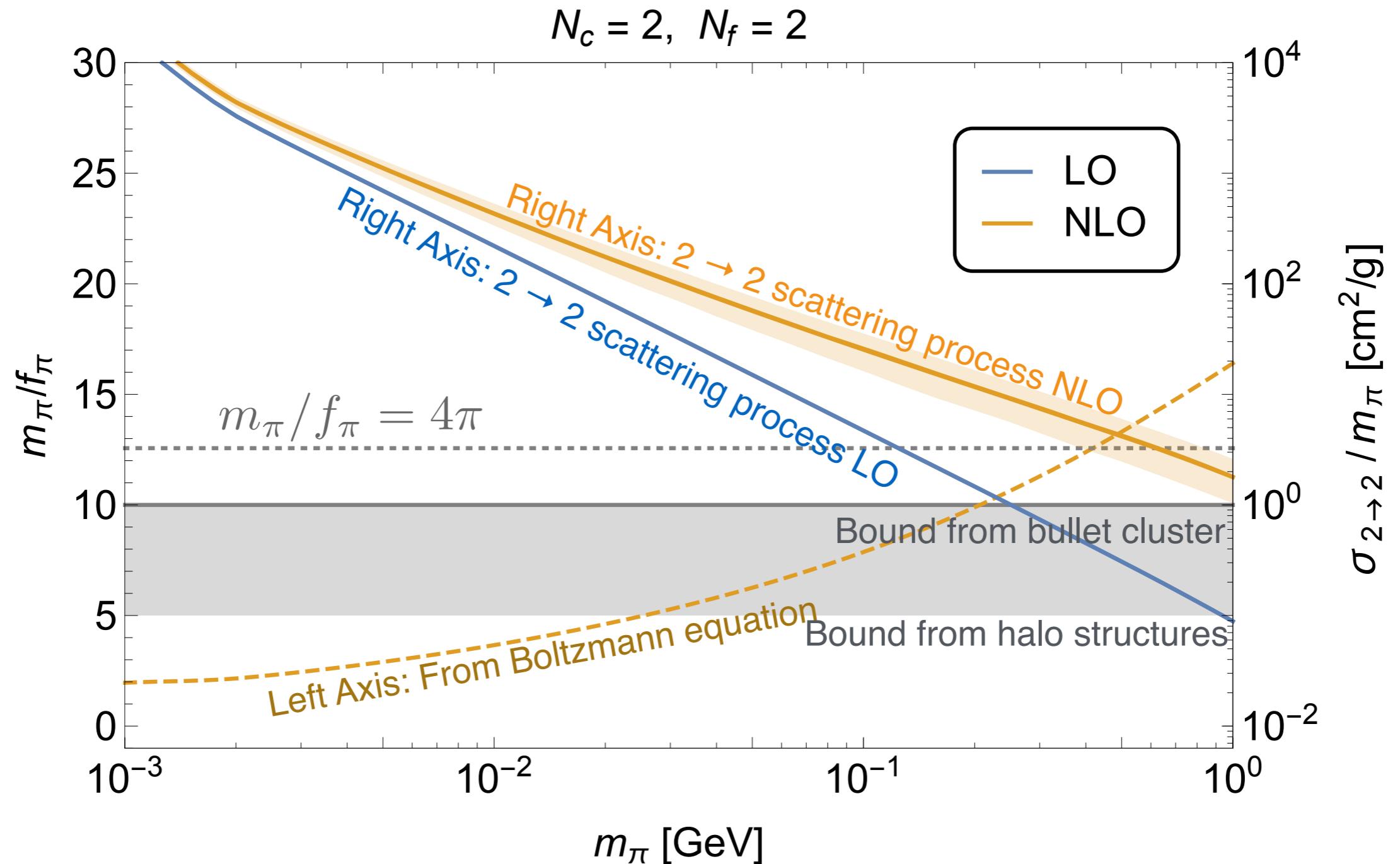
Physical values for the mass and decay constant.

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

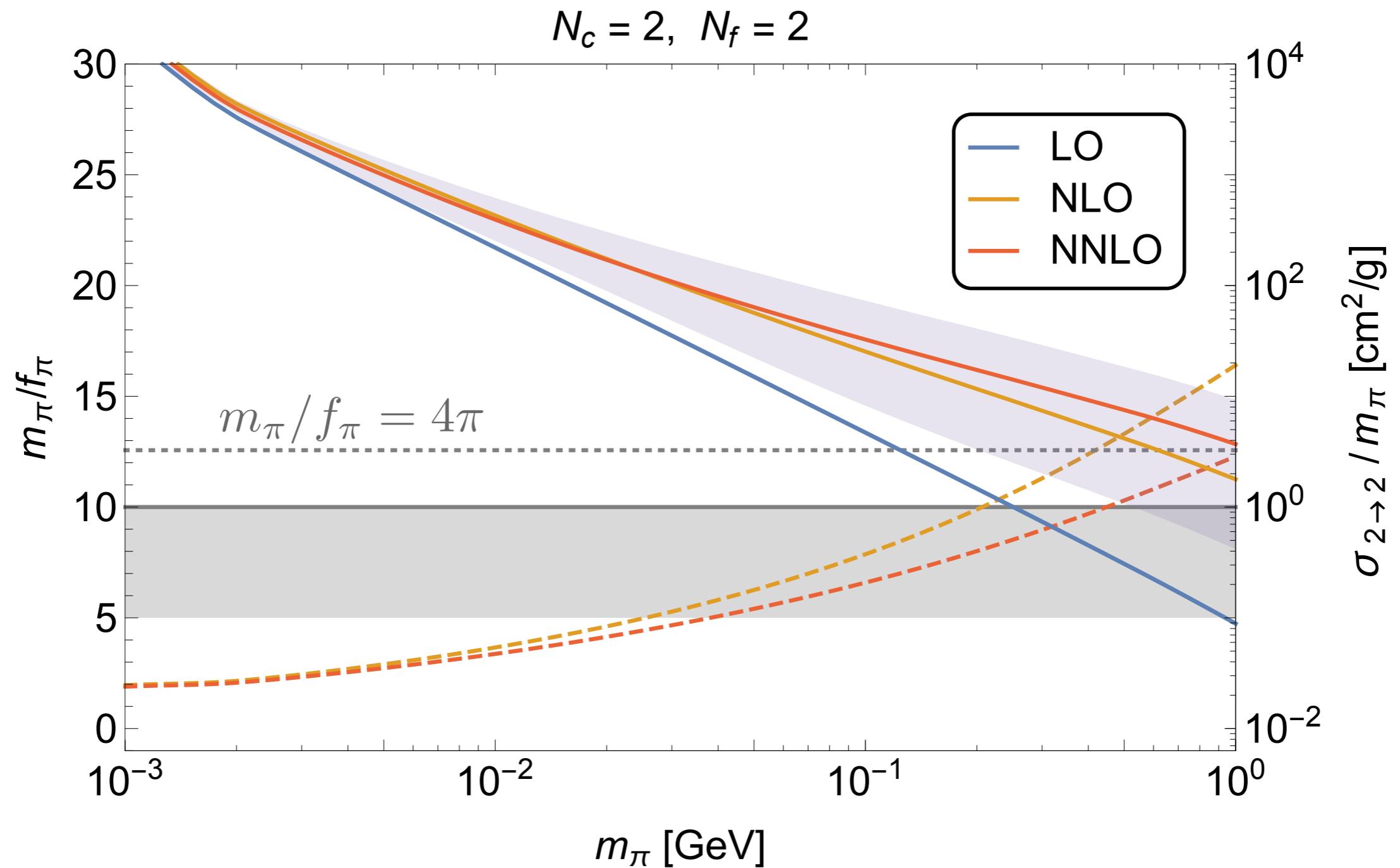
DM relic density relates mass and decay constant

DM $2 \rightarrow 2$ scattering process (constrained)

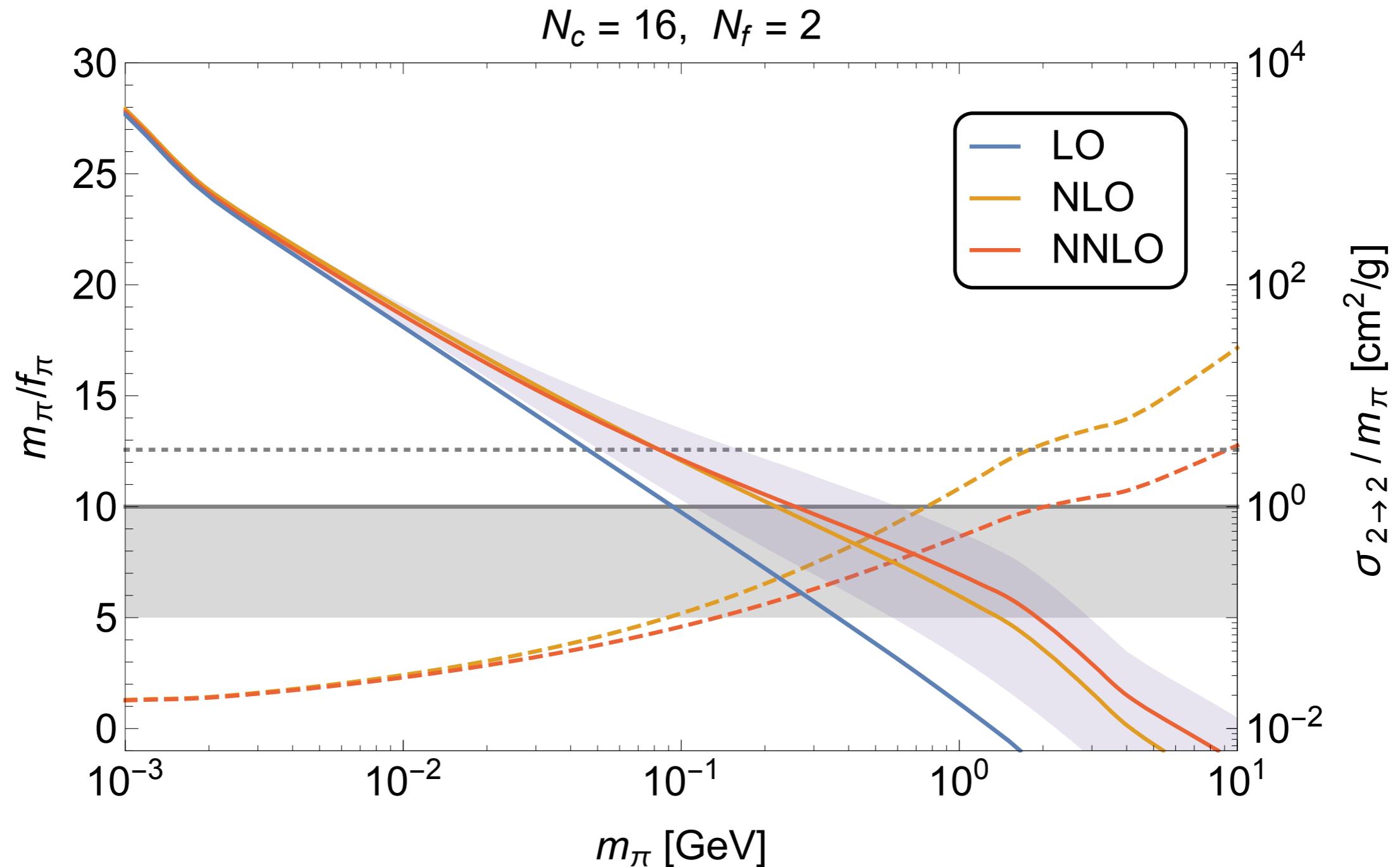
ChPT SU(2) with 2 Dirac Flavours



ChPT SU(2) with 2 Dirac Flavours



ChPT Sp(16) with 2 Dirac Flavours



(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 (nonminimal) 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

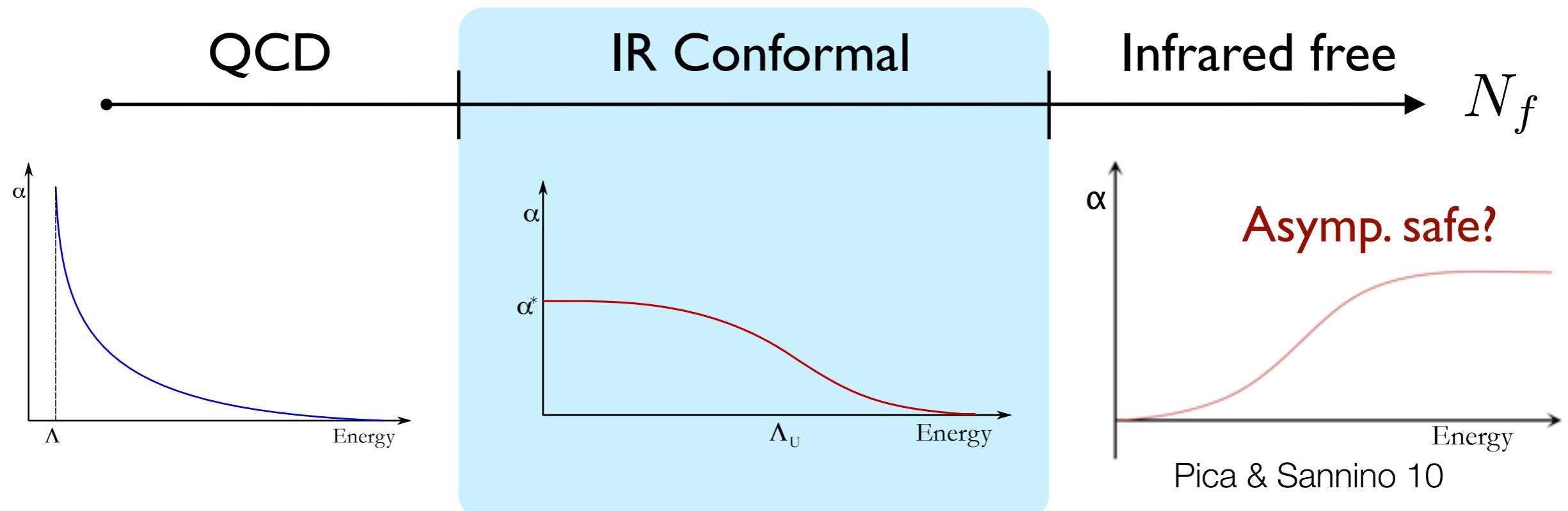


Gauge Group: SU, SO, SP, Exceptional

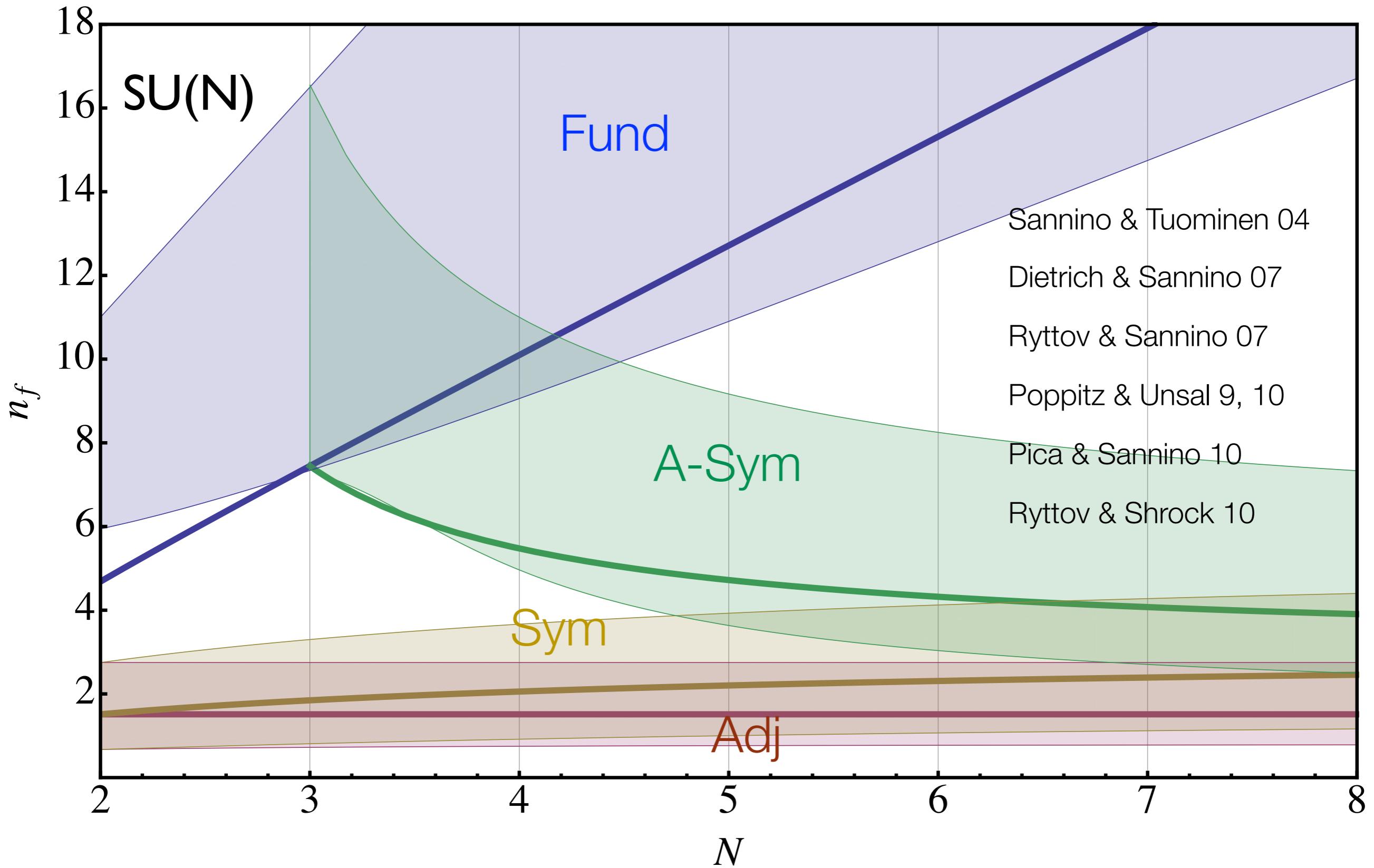
Matter Representation

of Flavours per Representation

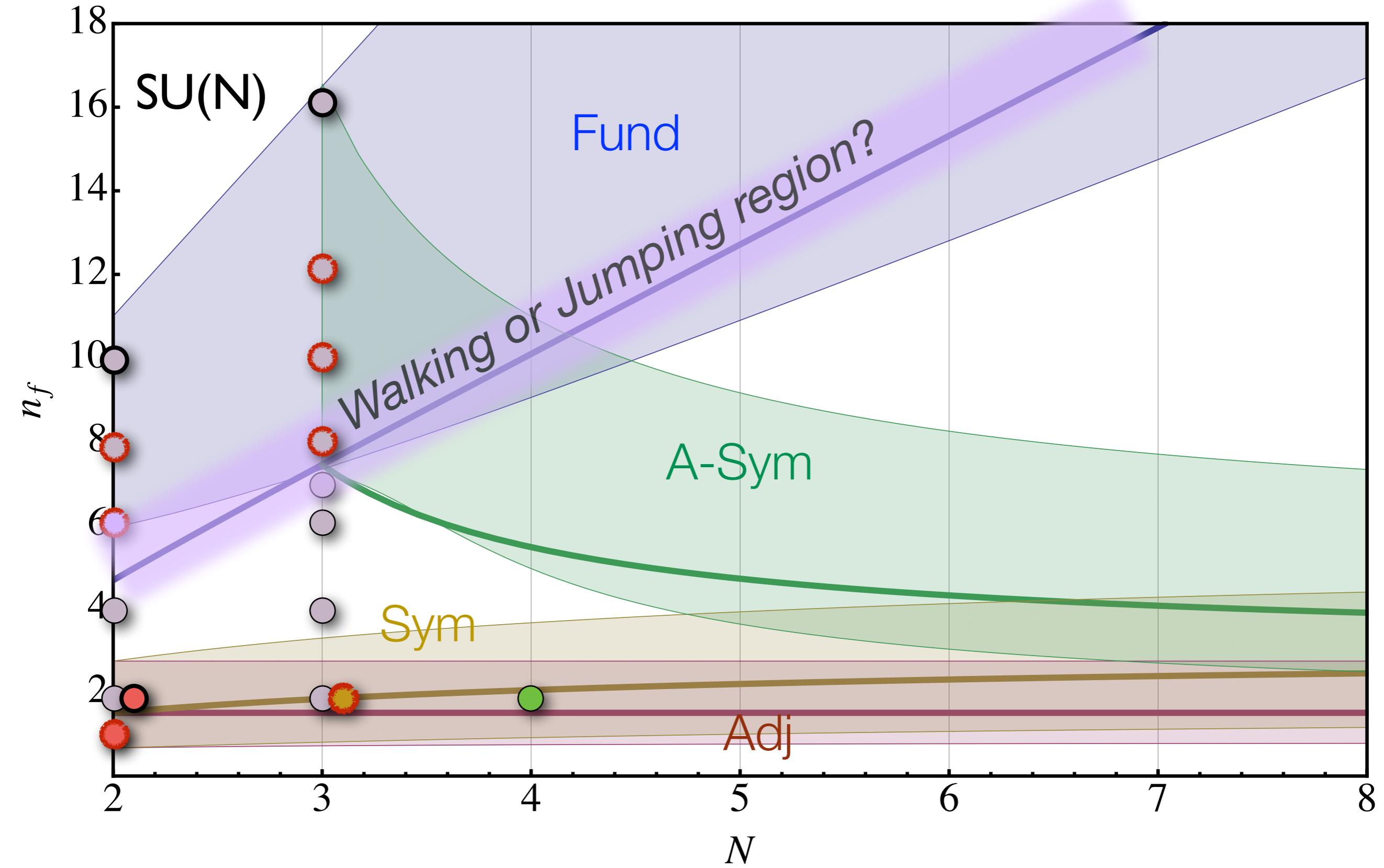
4 Fermi interactions / ETC



SU(N) Phase Diagram



Lattice SU(N) Phase Diagram

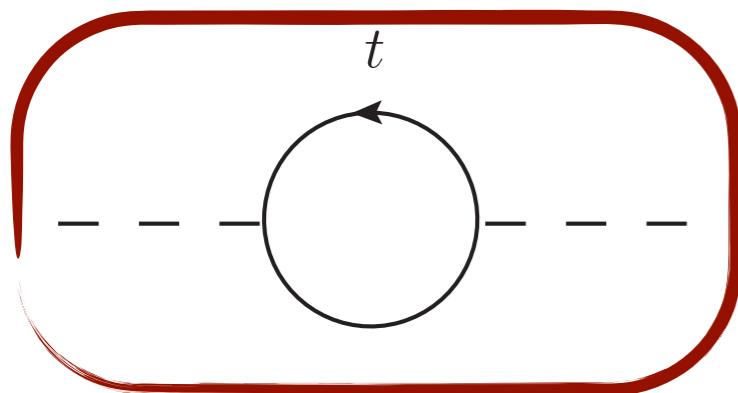


TC Higgs

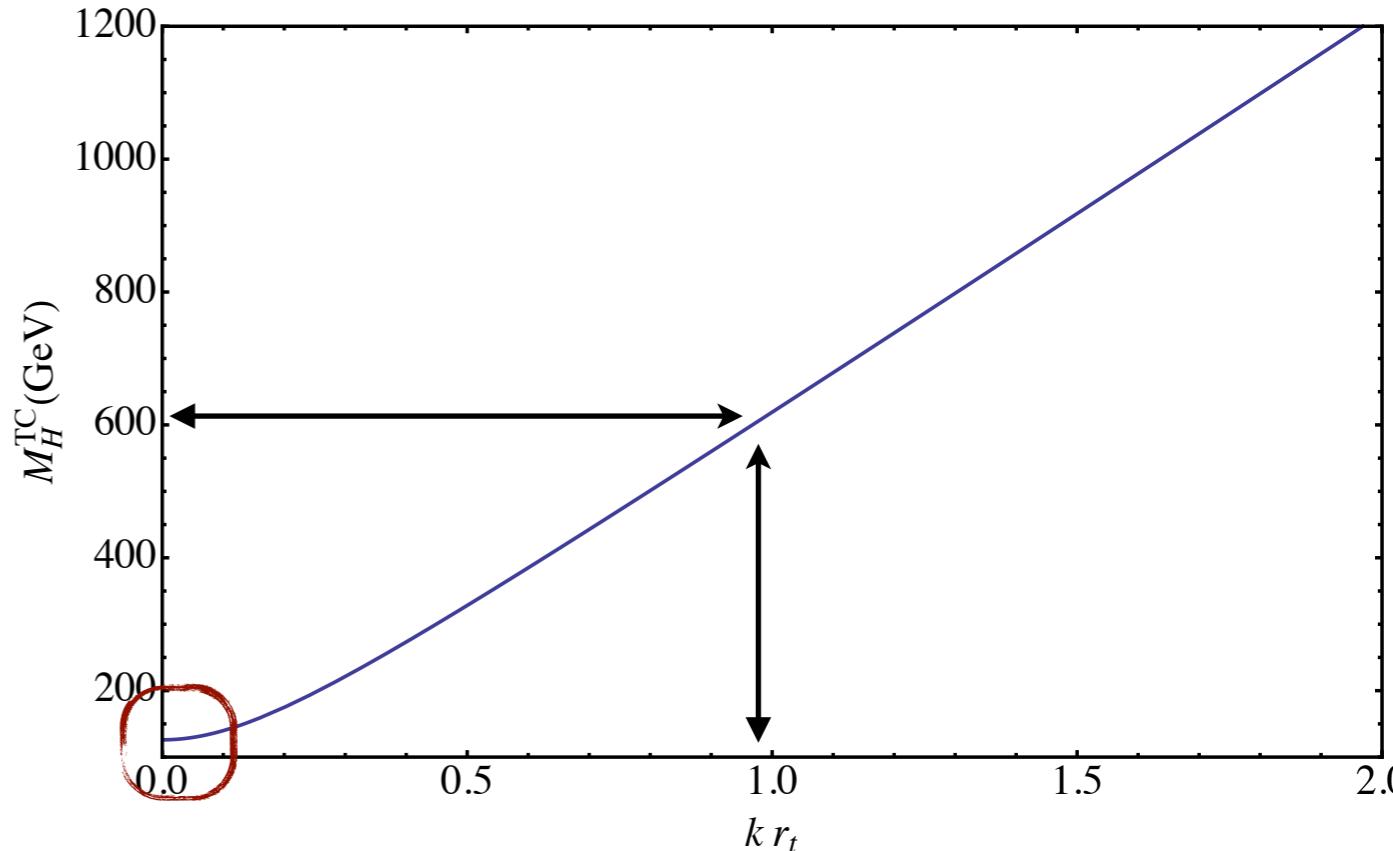
TC - Higgs is the lightest spin-0 scalar made of TC-fermions

$$H \sim c_1 \bar{Q}Q + c_2 \bar{Q}QQ\bar{Q}Q + \dots$$

Top corrections



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



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: $SU(2) \times SU(2) \times U(1) \rightarrow SU(2) \times U(1)$

QCD with 2 Dirac flavours

Pseudoreal: $SU(4) \rightarrow Sp(4)$

$SU(2)$ gauge with 2 fund. Dirac flavours

Real: $SU(4) \rightarrow SO(4)$

$SU(2)$ gauge with 2 adj. Dirac flavours