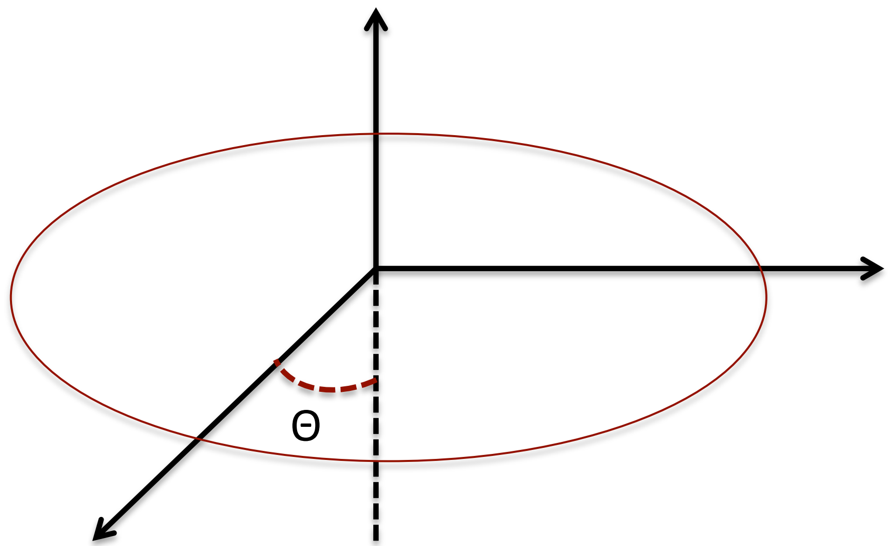
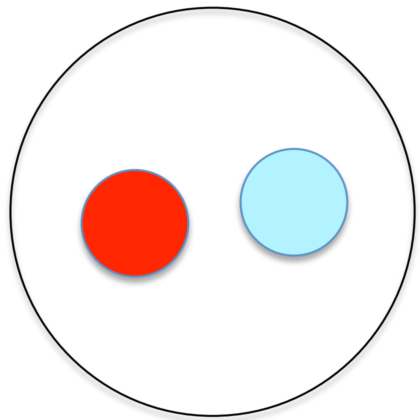
Dark Matter in Composite Models

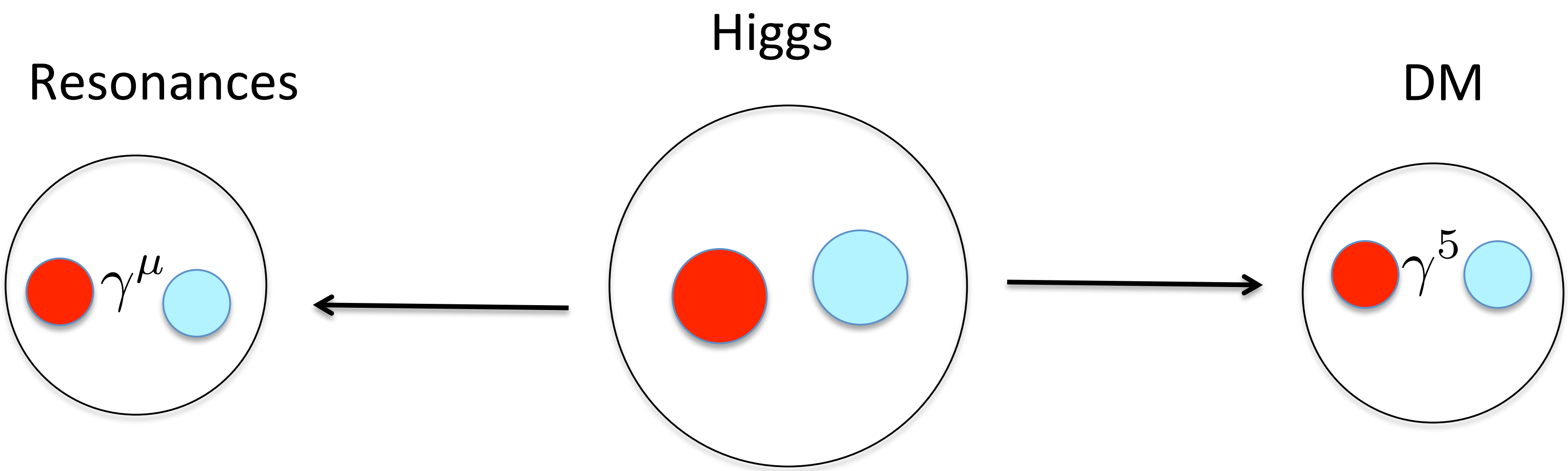


Mads Toudal Frandsen

Motivation



Motivation



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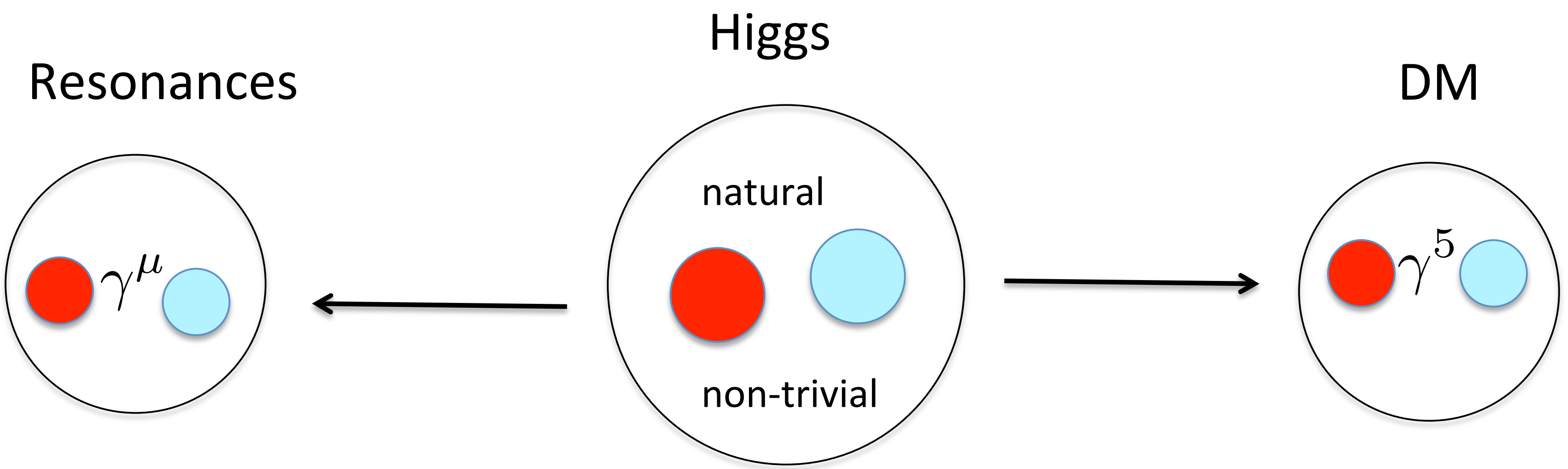
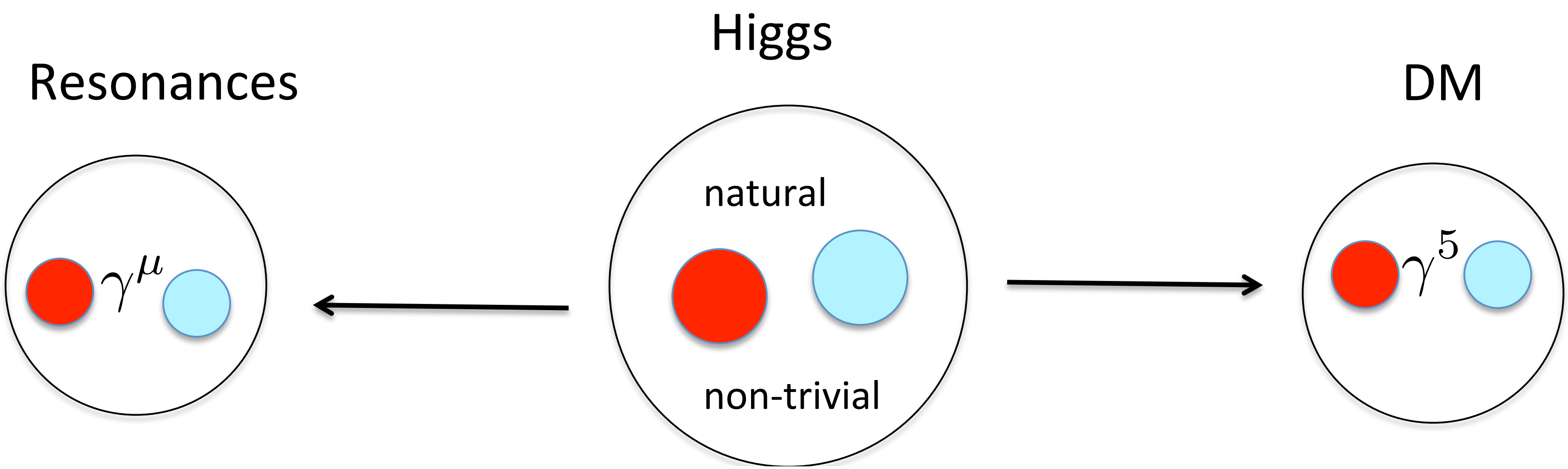


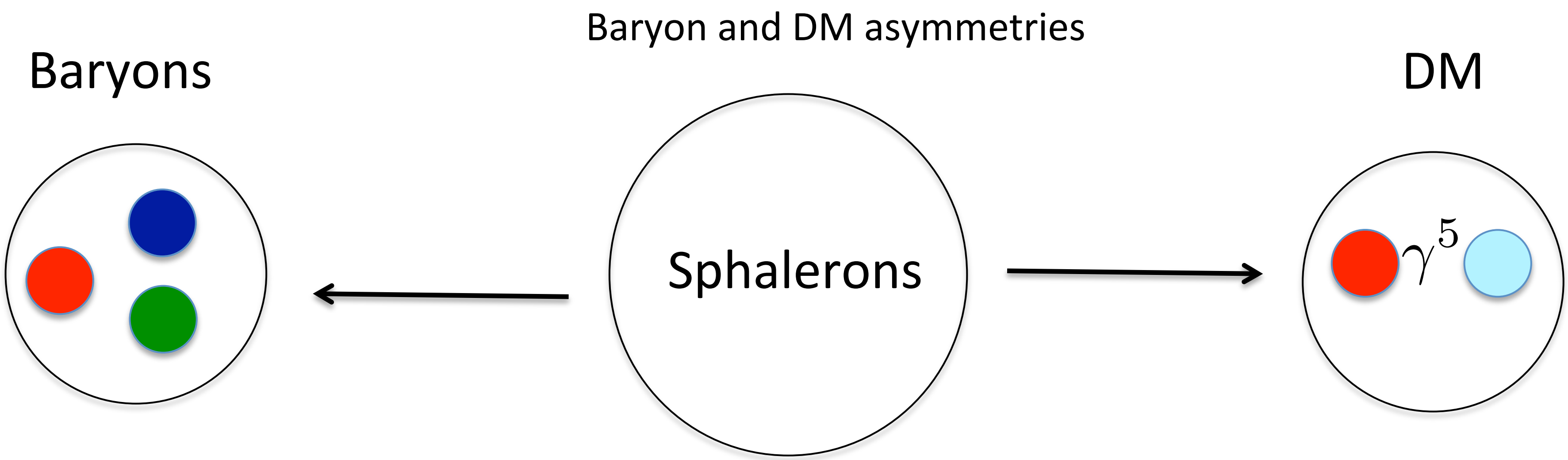
(Weinberg; Susskind & Dimopoulos; Eichten & Lane; 't Hooft; Kaplan & Georgi; Nussinov)

Motivation



	$SU(2)_{TC}$	$SU(2)_W$	$U(1)_Y$
(U_L, D_L)	$\square$	$\square$	0
$\widetilde{U}_L$	$\square$	1	$-1/2$
$\widetilde{D}_L$	$\square$	1	$+1/2$

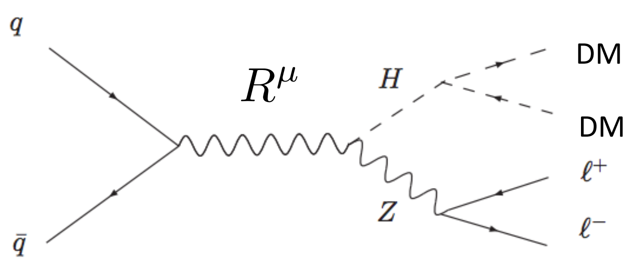
Motivation

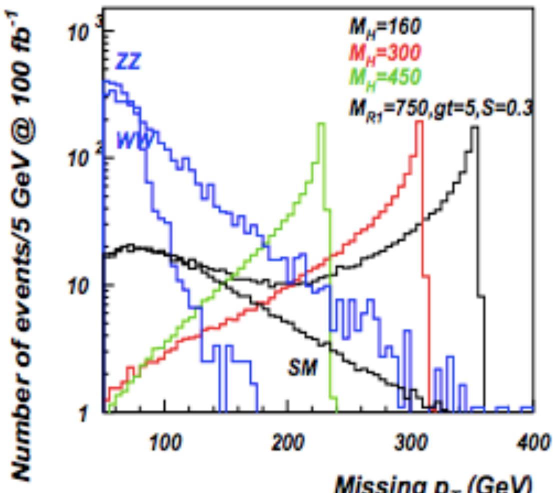


(Barr, Chivukula & Farhi)

Composite DM Probes

- Resonances in e.g LHC missing E_T searches (U. Haisch talk ZPW19)





(Foadi, MTF, Sannino '08)

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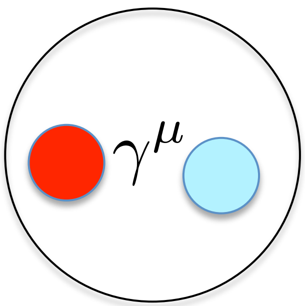
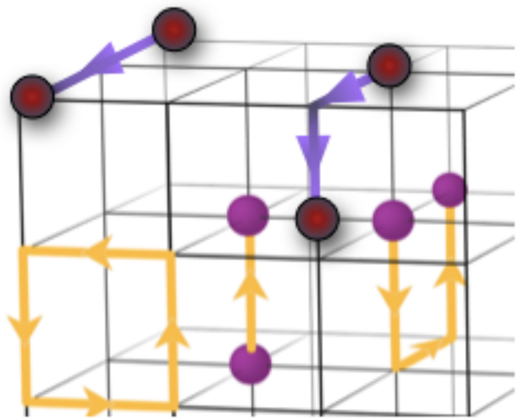
Composite DM Probes

- lattice predictions, low mass DM (F. Petricca talk ZPW19)

m_R=2.5 (0.5) TeV,

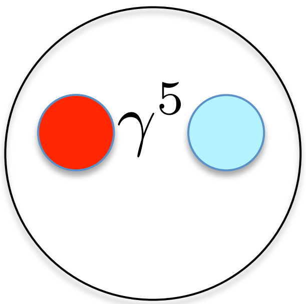


SU(2) MWT model



(Arthur, Drach, Hansen, Hietanen, Lewis, Pica & Sannino ’14)

DM pNGB,



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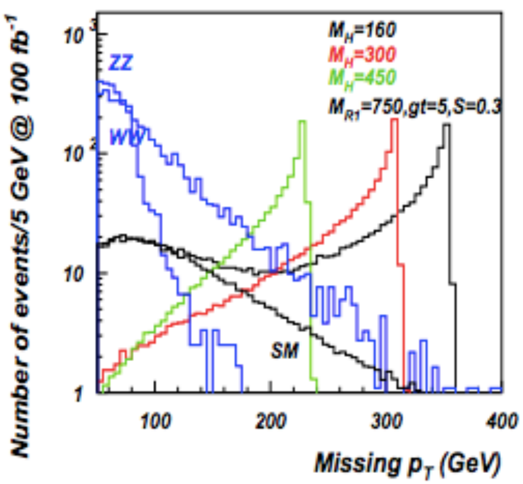
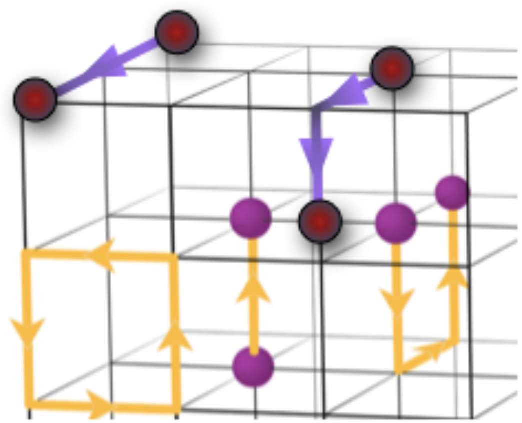


SU(2) MWT model

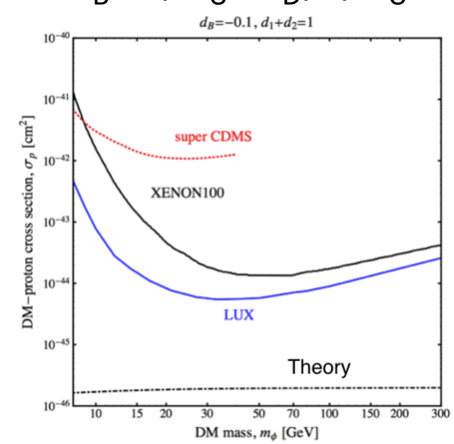


(Arthur, Drach, Hansen, Hietanen, Lewis, Pica & Sannino '14)

DM pNGB, $\Lambda=m_R$

$$ie\frac{d_B}{\Lambda^2}\Pi^*_{UD}\overleftrightarrow{\partial_\mu}\Pi_{UD}\partial_\nu F^{\mu\nu}$$

$d_B = (m_U-m_D)/(m_U+m_D)$



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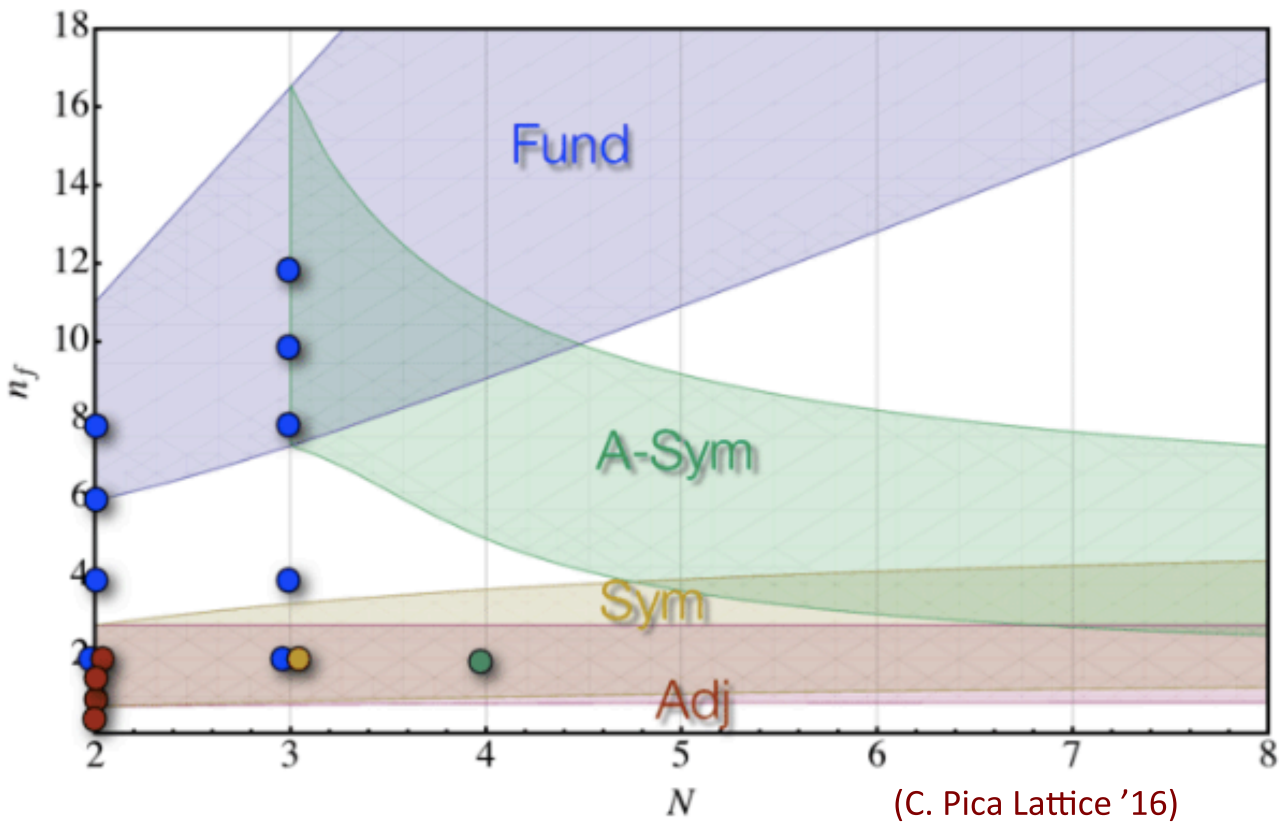
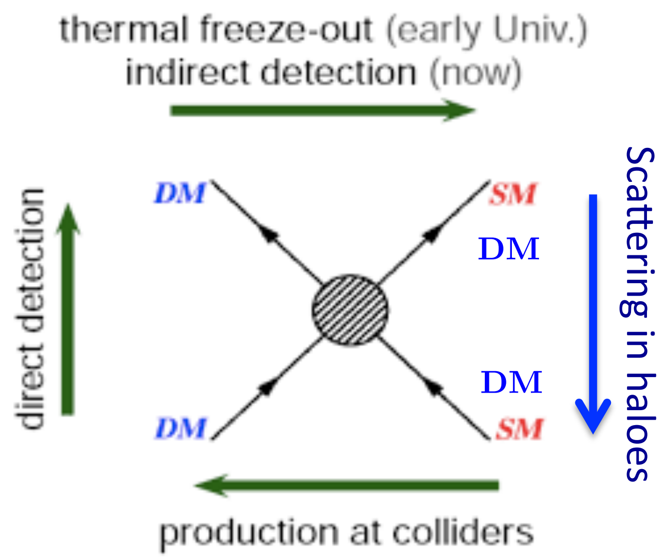


(C. Pica Lattice '16)

Composite DM Probes

- Large (in some cases) self-interactions in clusters and galaxies

(J. Read talk ZPW19)



Composite DM Probes

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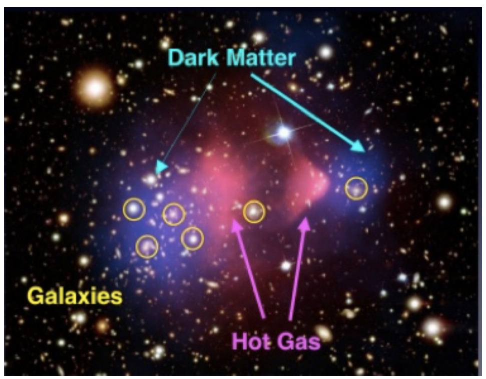
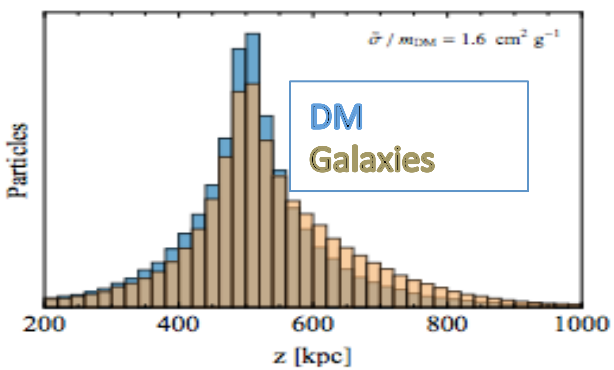
(J. Read talk ZPW19)



Bullet Cluster

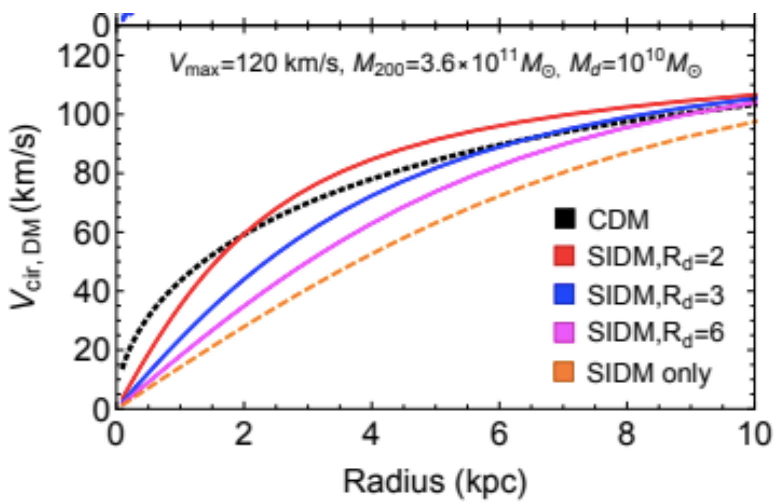


(Kahlhoefer, Schmidt-Hoberg, M.T. F & Sarkar '13)

Composite DM Probes

- Large (in some cases) self-interactions in clusters and galaxies

(J. Read talk ZPW19)

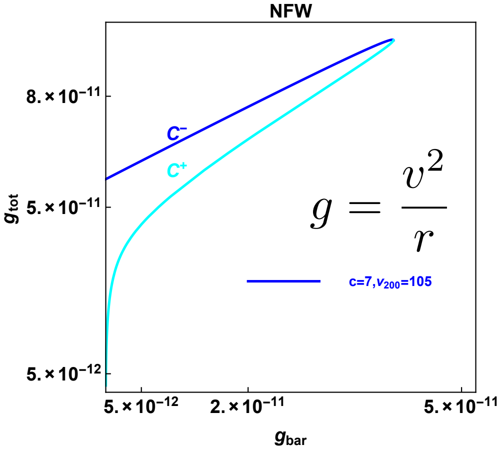


(Kamada, Kaplinghat Pace & Yu '16)

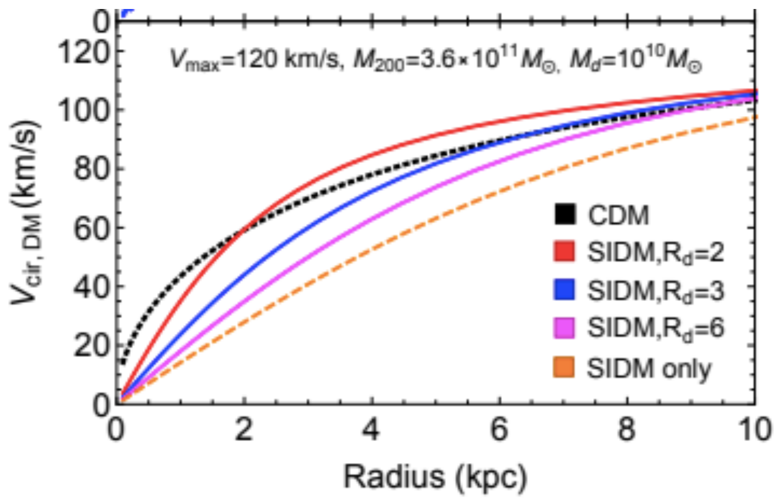
Composite DM Probes

- Large (in some cases) self-interactions in clusters and galaxies

(J. Read talk ZPW19)



(MTF & Petersen ’18)



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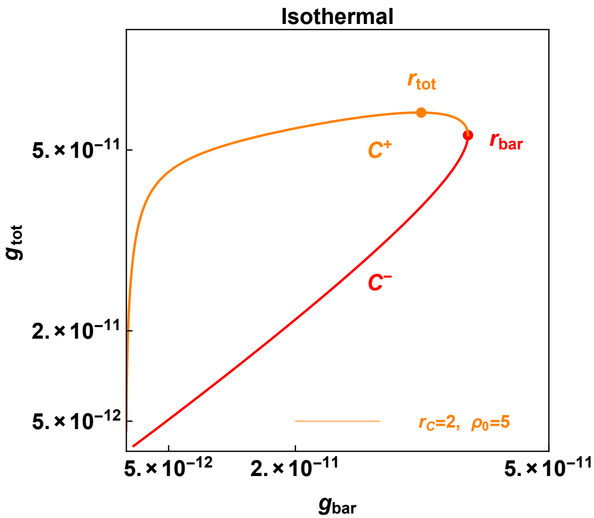

(MTF & Petersen ’18)

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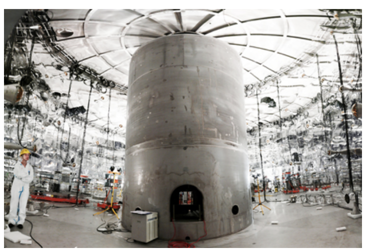
Composite DM Probes

- Non-standard signatures from asymmetry:
  decaying DM, no annihilation signals, possible low scale 0νββ

low scale 0νββ



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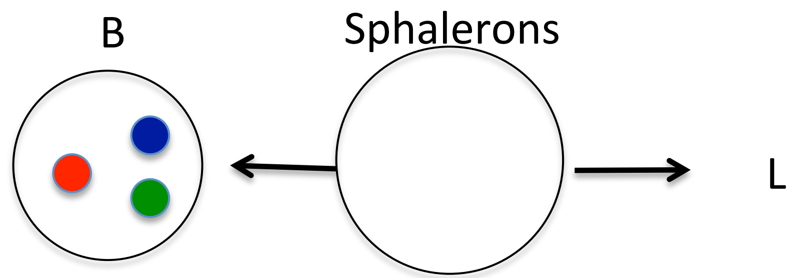

$\mu_\ell + \mu_H = 0$. & $3\,(3\,\mu_q + \mu_\ell) = 0$ $\longrightarrow$ B=0

(Harvey & Turner)

Composite DM Brobes

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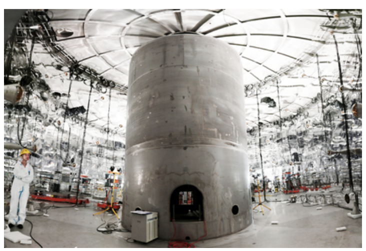
  decaying DM, no annihilation signals, possible low scale 0νββ

low scale 0νββ



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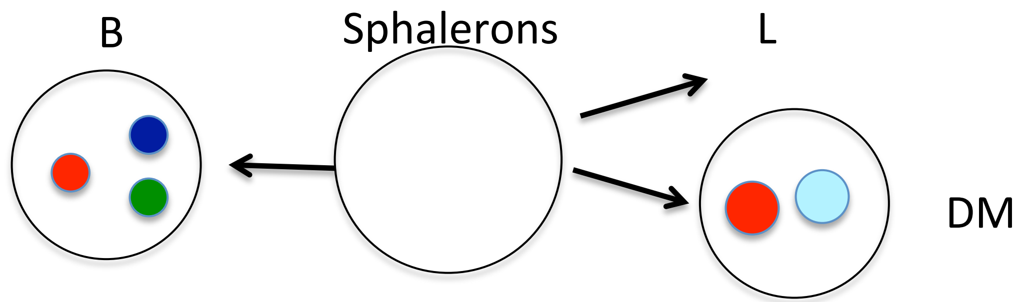


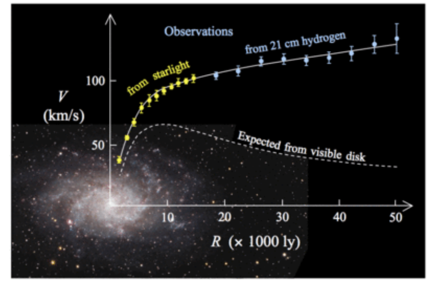
$\mu_\ell + \mu_H = 0$ & $3\,(3\,\mu_q + \mu_\ell) + n_F \mu_F = 0,$ ⟶ B≠0, DM≠0

(MTF, Hagedorn, Huang, Molinaro & Päs ’18)

The missing mass problem

Galactic scales

(Freeman ’70, Bosma ’78, Rubin et al ’78)

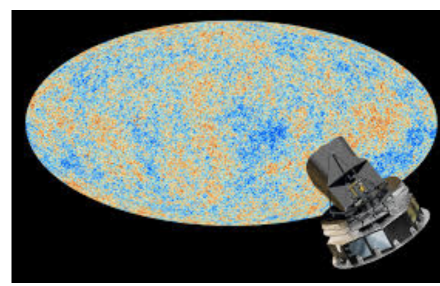


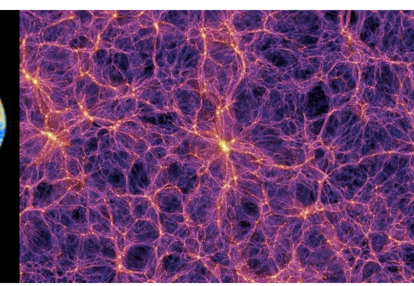
Cluster Scales

(Zwicky ’33, Clowe et al ’06)

Cosmological scales

(Davis et al ’82, Peebles ’82)





Universality vs Diversity

NFW scaling of radial DM density profiles from dwarf galaxies to galaxy clusters
DM only cosmological N-body simulations. No baryons

(Navarro, Frenk & White '95)

MOND/RAR: Total acceleration in circular motion correlates with that from baryons
At galactic scales

(Tully & Fisher '77; McGaugh '11)

Cusp/Core
Flat or cored DM profiles in dwarf and Low Surface Brightness galaxies

(Moore '94; Flores & Primack '94)

Missing Sattelites & Too-big-to-fail
Too many sattelites that are too dense and massive are predicted

(Moore, Quinn, Governato, Stadel & Lake '99; Klypin, Kravtsov, Valenzuela & Prada '99; Boylan-Kolchin, Bullock, Kaplinghat '11)

Universality vs Diversity

Baryonic physics
Discrepancies arise from comparing to DM-only simulations

(J. Read talk ZPW19)

Adiabatic contraction

Supernova feedback

AGN

DM (self-) interactions
Small scales are high DM density and DM interaction rates

Velocity dependence

Long rage, short range

Gravity

Discrepancies arise assuming Newtonian gravity

With or without DM

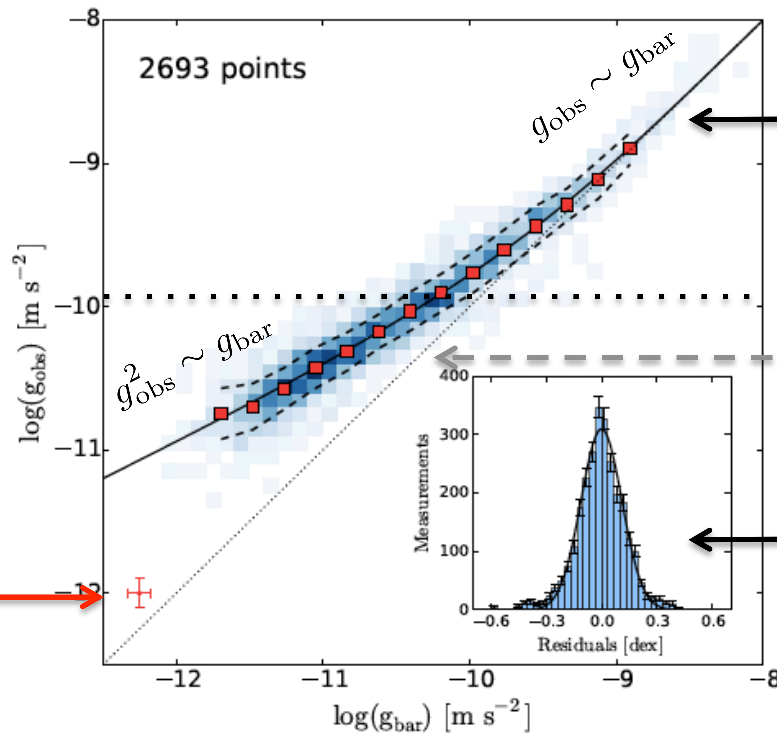
Modified NewtonianDynamics

Modified Gravity

SPARC Radial Acceleration Relation

(McGaugh, Lelli & Schombert ’16)

g2-space curve



MOND (modified inertia) fit curve

$$g_{\rm obs} = \frac{g_{\rm bar}}{1 - e^{-\sqrt{\frac{g_{\rm bar}}{g_0}}}}$$

Newtonian, no missing mass

Fit residuals

Typical error

MOND

$$\mu(\frac{g_M}{g_0})g_M = g_{\rm bar}$$

MOND modified inertia

(Milgrom '83, '93)

Inverse interpolation function *ν* gives *exact* MOND modified inertia acceleration

$$g_{\rm M} = \nu(\frac{g_{\rm bar}}{g_0})g_{\rm bar}$$

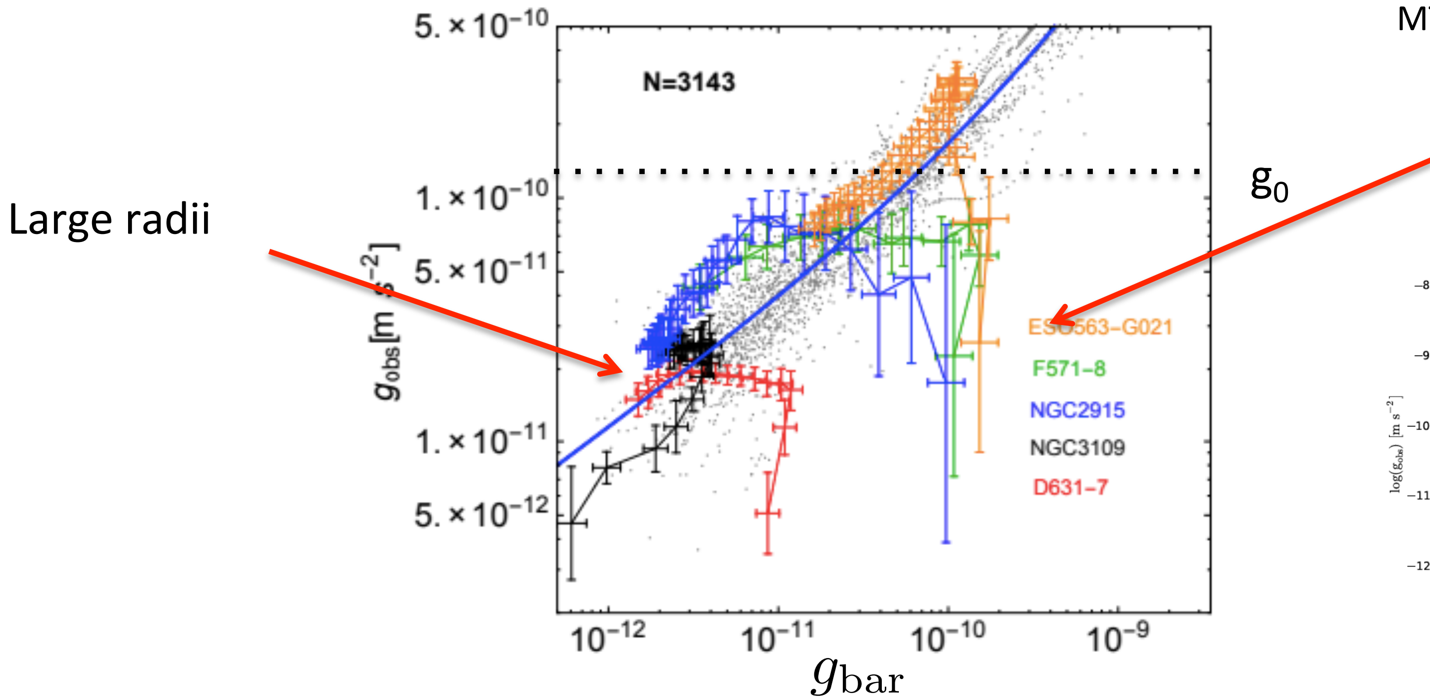
Or *simplest* approximation for MOND modified gravity

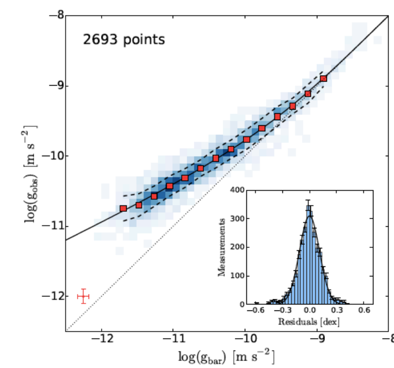
Example inverse interpolation function: (Famaey and McGaugh '11)

$$g_M = \frac{g_{\rm bar}}{1 - e^{-\sqrt{\frac{g_{\rm bar}}{g_0}}}} \qquad \nu(\frac{g_{\rm bar}}{g_0}) = \frac{1}{1 - e^{-\sqrt{\frac{g_{\rm bar}}{g_0}}}}$$

SPARC Individual galaxies highlighted

(J. Petersen and MTF '17
MTF and J. Petersen '18)

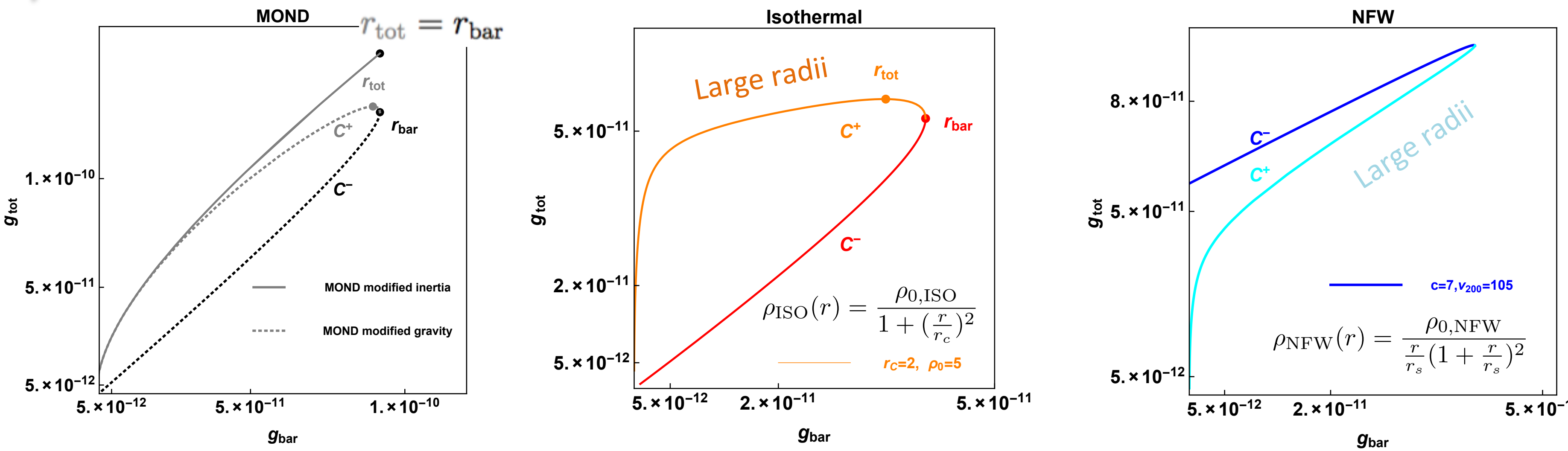




Grey dots are all data points from SPARC in g2-space

Individual galaxies don't follow Radial Acceleration Relation at smaller radii

MOND and DM geometry in g2-space



Geometric Classification

Mond Modified Inertia

MOND Modified Gravity

DM Pseudo-Isothermal

DM Navarro-Frenk-White

Models	Reference radii	Curve segments	Curve Area[a]
MOND-MI	$r_{tot} = r_{bar}$	$\mathcal{C}^+ = \mathcal{C}^-$	$\mathcal{A}(\mathcal{C}) = 0$
MOND-MG	$r_{tot} > r_{bar}$	$\mathcal{C}^+ > \mathcal{C}^-$	$\mathcal{A}(\mathcal{C}) > 0$
DM-ISO	$r_{tot} > r_{bar}$	$\mathcal{C}^+ > \mathcal{C}^-$	$\mathcal{A}(\mathcal{C}) > 0$
DM-NFW	$r_{tot} < r_{bar}$	$\mathcal{C}^+ < \mathcal{C}^-$	Curves open

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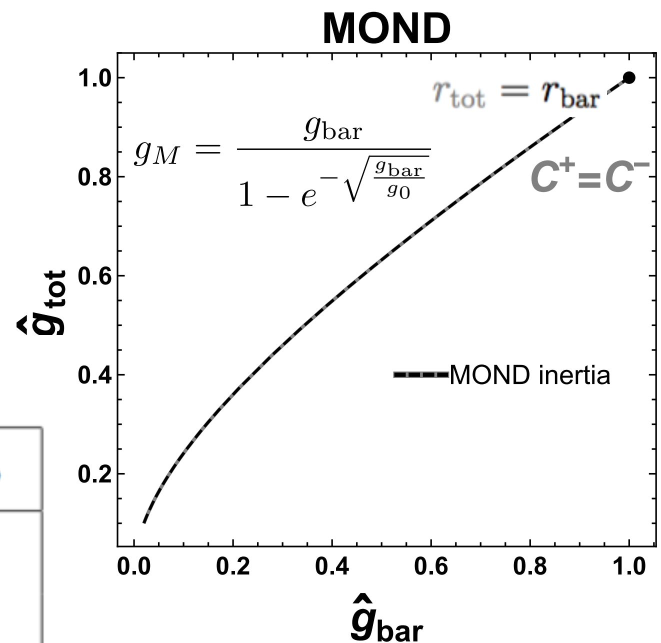
MOND models in ĝ2-space

$$\hat{g}(r)_{\rm bar,tot} = \frac{g(r)_{\rm bar,tot}}{g(r_{\rm bar})_{\rm bar,tot}}$$

(MTF and J. Petersen '18)

MOND modified Inertia consequences:

$r_{tot} = r_{bar}$ and $C^+ = C^-$ so $\hat{g}(r_{\rm tot})_{\rm bar,tot} = 1$



SPARC data for $\hat{g}(r_{\rm tot})_{\rm bar,tot}$

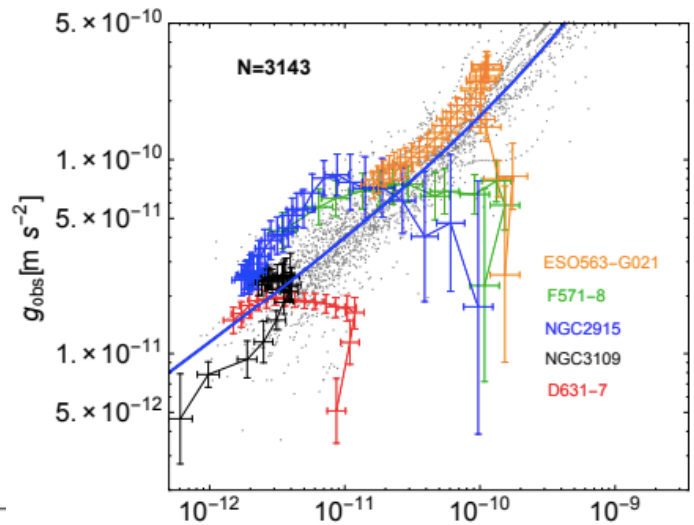
Data selection	Points	$\langle \hat{g}_{\rm obs} \pm \delta\hat{g}_{\rm obs} \rangle$	$\langle \hat{g}_{\rm bar} \pm \delta\hat{g}_{\rm bar} \rangle$
$r_j = r_{\rm obs}$	152	1.39 ± 0.12	0.83 ± 0.01
$r_j = r_{\rm obs}, \frac{\delta v_{\rm obs}}{v_{\rm obs}} < 0.1$	146	1.12 ± 0.02	0.91 ± 0.01
$r_{j,\rm bar} \in \Delta r_{\rm obs,bar}$	~ 400	1.23 ± 0.04	0.89 ± 0.01

(For data points $g_{tot} = g_{obs}$, $r_{tot} = r_{obs}$)

MOND models in ĝ2-space

$$\hat{g}(r)_{\mathrm{bar,tot}} = \frac{g(r)_{\mathrm{bar,tot}}}{g(r_{\mathrm{bar}})_{\mathrm{bar,tot}}}$$

(MTF and J. Petersen '18)



MOND modified Inertia consequences:

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SPARC data for $\hat{g}(r_{\mathrm{tot}})_{\mathrm{bar,tot}}$

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(For data points $g_{tot} = g_{obs}$, $r_{tot} = r_{obs}$)

Particle DM

- Assumption: (All) the missing mass is particle DM

- Strategies:
- **Generalize the SM baryonic relic (neutron)**
- Generalize the SM neutrino relic
- Something different

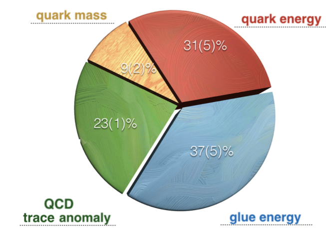
Baryonic relic density

- Proton stability (longevity) due to a **U(1) symmetry**

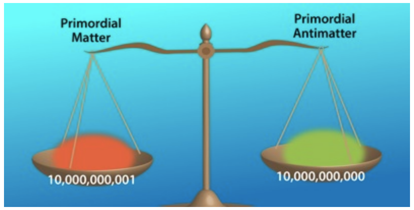
2 flavor massless QCD

$$SU(2)_L \times SU(2)_R \times U(1)_B \\ \rightarrow SU(2)_V \times U(1)_B$$

- Proton mass from **strong dynamics** (and Higgs)



- Proton relic density from some **asymmetry**



- **Neutron** lightest table baryon for zero current quark masses.
  Self-interactions from strong dynamics

New Composite Dynamics

- 4d Gauge-Yukawa model with fermions and strong interactions
- May also (partially) break EW symmetry $\langle Q^I Q^J \rangle \sim f^3 E_Q^{IJ}$

$$\mathcal{L} = \mathcal{L}_{\rm SD} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SD+SM}$$

CD breaks EW:
e.g TC, CH

$$\mathcal{O}_{\rm CD} \sim QQ$$

$$\mathcal{L} = \mathcal{L}_{\rm SD} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SD+SM}$$

CD induces EW breaking:
e.g. PCH,

$$\mathcal{O}_{\rm CD+SM} \sim QHQ$$
$$\mathcal{O}_{\rm CD+SM} \sim QQH^\dagger H$$

$$\mathcal{L} = \mathcal{L}_{\rm SD} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SD+SM}$$

SM breaks EW:
e.g. SIDM

$$\mathcal{O}_{\rm SM} \sim H^\dagger H$$

(Spergel & Steinhardt)

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- 4d Gauge-Yukawa model with fermions and strong interactions
- May also (partially) break EW symmetry $\langle Q^I Q^J \rangle \sim f^3 E_Q^{IJ}$

$$\mathcal{L} = \mathcal{L}_{\rm CD} + \mathcal{L}_{\rm CD+SM} + \mathcal{L}_{\rm SM}$$

CD breaks EW: $\mathcal{O}_{\rm CD} \sim QQ$
e.g TC, CH

$$\mathcal{L} = \mathcal{L}_{\rm CD} + \mathcal{L}_{\rm CD+SM} + \mathcal{L}_{\rm SM}$$

CD induces EW breaking: $\mathcal{O}_{\rm CD+SM} \sim QHQ$
e.g. PCH, $\mathcal{O}_{\rm CD+SM} \sim QQH^\dagger H$

$$\mathcal{L} = \mathcal{L}_{\rm CD} + \mathcal{L}_{\rm CD+SM} + \mathcal{L}_{\rm SM}$$

SM breaks EW: $\mathcal{O}_{\rm SM} \sim H^\dagger H$
e.g. SIDM

(Spergel & Steinhardt)

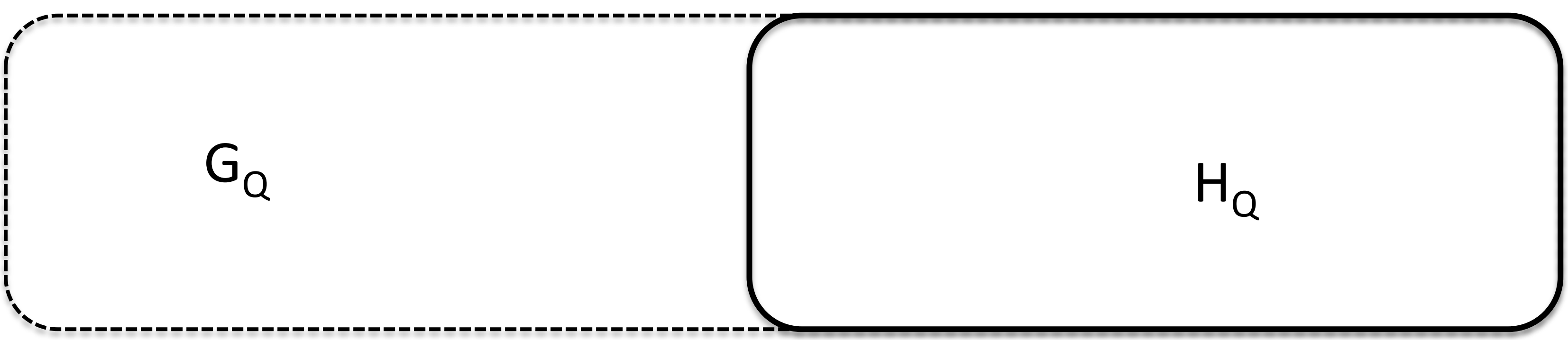
New Composite Dynamics

UV: $\mathcal{L}_{UV} = \bar{Q}\gamma^{\mu} D_{\mu} Q + \mathcal{L}_{SM-Higgs} + \delta\mathcal{L}$

IR: $\langle Q^I Q^J \rangle \sim f^3 E_Q^{IJ}$

$$G_Q \supset SU(2) \times SU(2) \times U(1) \quad \rightarrow \quad H_Q \supset SU(2) \times U(1)$$

SM custodial symmetry DM symmetry



New Composite Dynamics

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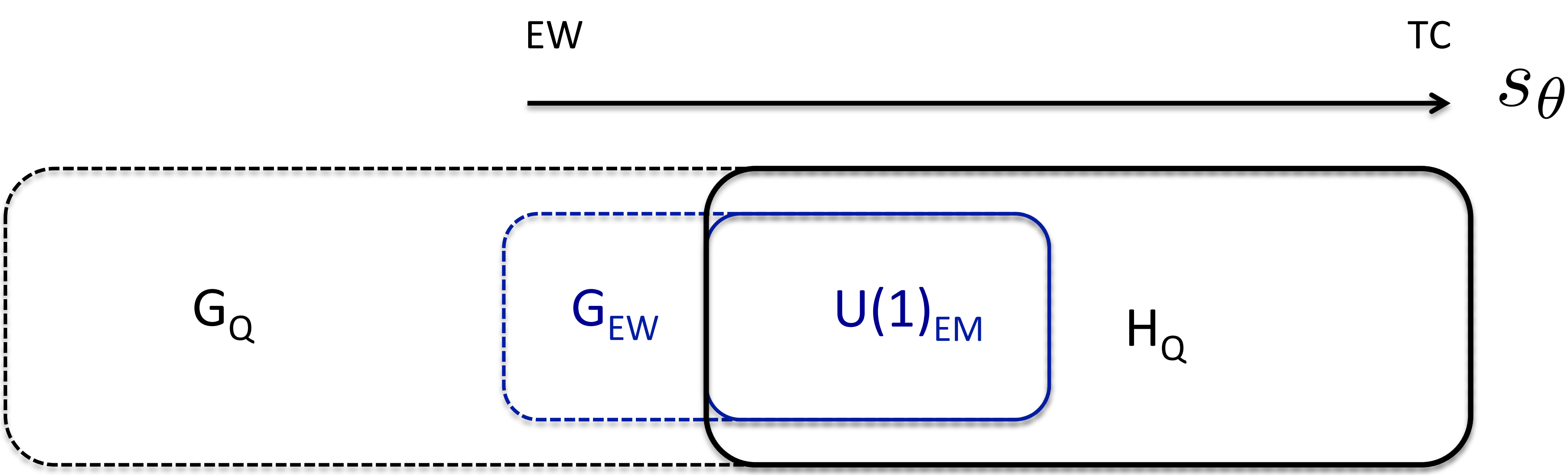

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Framework: Composite Dynamics

UV: $\mathcal{L}_{UV} = \bar{Q}\gamma^\mu D_\mu Q + \mathcal{L}_{SM-Higgs} + \delta\mathcal{L}$

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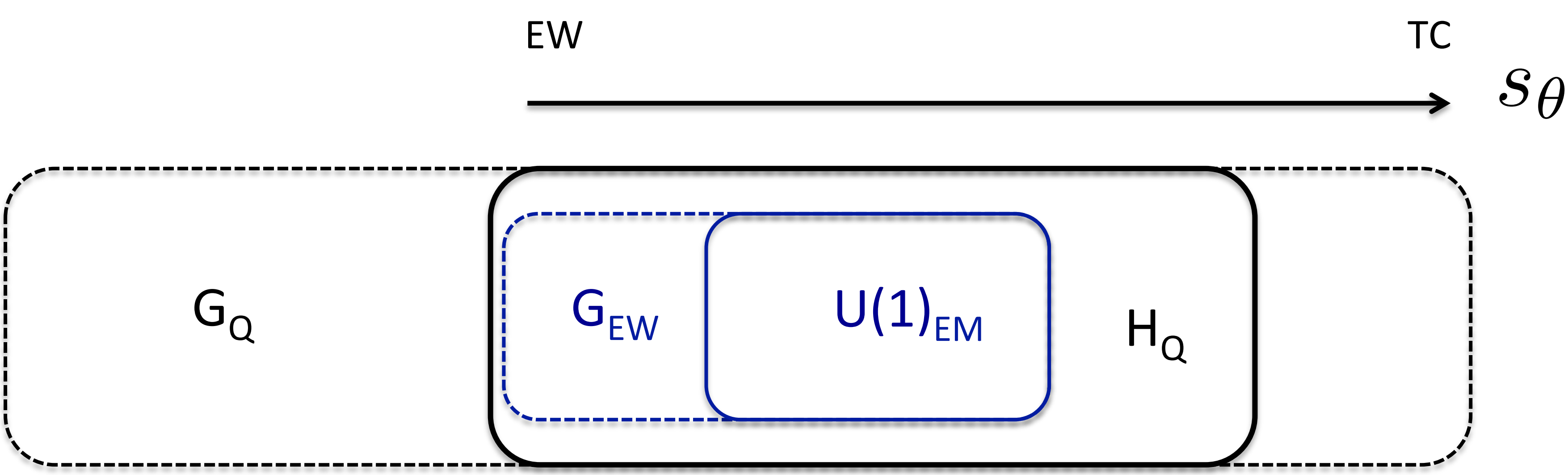


Framework: Composite Dynamics

UV: $\mathcal{L}_{UV} = \bar{Q}\gamma^{\mu} D_{\mu} Q + \mathcal{L}_{SM-Higgs} + \delta\mathcal{L}$

IR: $\langle Q^I Q^J \rangle \sim f^3 E_Q^{IJ}$

$$G_Q \supset SU(2) \times SU(2) \times U(1) \quad \rightarrow \quad H_Q \supset SU(2) \times U(1)$$

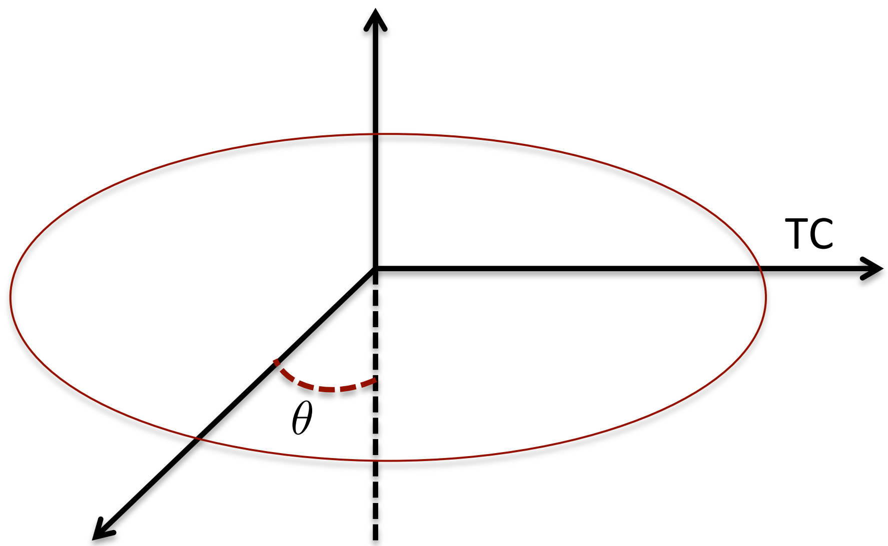
SM custodial symmetry DM symmetry

Example: $G_Q = SU(4) \quad \rightarrow \quad H_Q = Sp(4)$

	$\mathrm{SU(2)_{TC}}$	$\mathrm{SU(2)_W}$	$\mathrm{U(1)}_Y$
(U_L, D_L)	$\square$	$\square$	0
$\widetilde{U}_{\mathrm{L}}$	$\square$	1	$-1/2$
$\widetilde{D}_{\mathrm{L}}$	$\square$	1	$+1/2$

$$Q = \begin{pmatrix} U_{\mathrm{L}} \\ D_{\mathrm{L}} \\ \widetilde{U}_{\mathrm{L}} \\ \widetilde{D}_{\mathrm{L}} \end{pmatrix}$$

Framework: Composite Dynamics



$\langle U_L \tilde{U}_L + D_L \tilde{D}_L \rangle$

Θ=π/2:
EW broken
TC Higgs radial excitation

U(1) TB broken only by EW anomaly

$\partial_\mu J^\mu \sim W^{\mu\nu} \widetilde{W}_{\mu\nu}$

$\langle U_L D_L + \tilde{U}_L \tilde{D}_L \rangle$

EW

Θ=0:
EW Unbroken
Higgs exact Goldstone

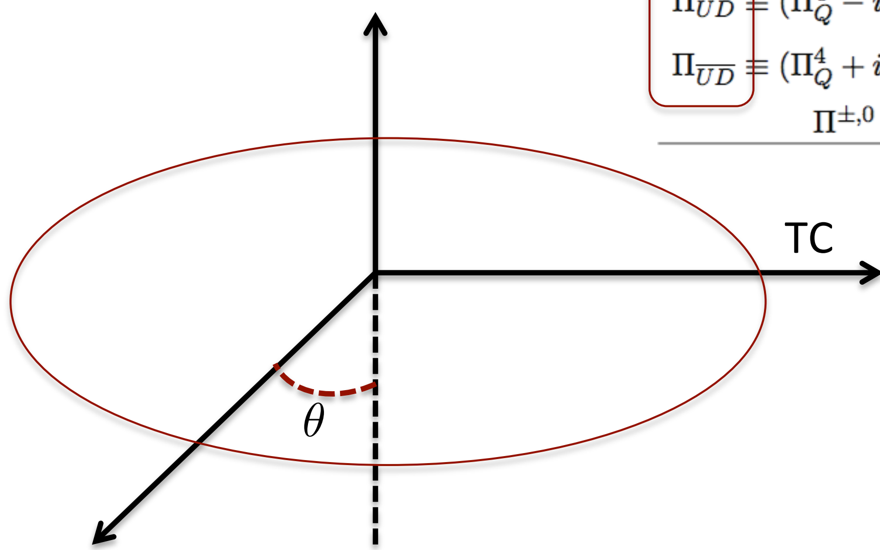
U(1) TB broken by vacuum

CH

0<Θ<π/2:
EW Broken
Higgs pseudo Goldstone

U(1) TB broken by vacuum

Framework: Composite Dynamics



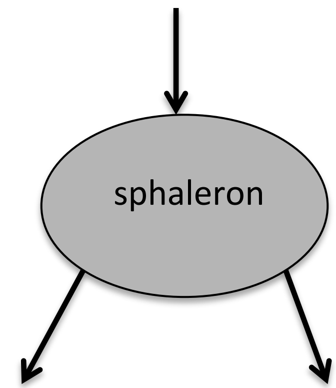
Composites	$U(1)_{TB}$	$U(1)_{EM}$	Θ
$\Pi_{UD} \equiv (\Pi^4_Q - i\Pi^5_Q)/\sqrt{2} \sim U^T C D$	$\frac{1}{\sqrt{2}}$	0	$\pi/2$
$\Pi_{\overline{UD}} \equiv (\Pi^4_Q + i\Pi^5_Q)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	$\pi/2$
$\Pi^{\pm,0} \equiv \Pi^{1,2,3}$	0	$\pm 1, 0$	$\pi/2$

$$\mathcal{L}_{\rm kin} \supset -\frac{g^2}{2} s_\theta^2 W^+_\mu W^{-\,\nu} \Pi_{UD} \bar{\Pi}_{UD}$$

$$\langle \sigma v \rangle \sim 2 \cdot 10^{-24} {\rm cm}^3/{\rm s} \frac{s_\theta^4 m^2_{\Pi_{UD}}}{m_W^2}$$

Initial asymmetry

$$\partial_\mu J^\mu \sim W^{\mu\nu} \widetilde{W}_{\mu\nu}$$



Baryon asymmetry Π_{UD} asymmetry

Technicolor limit

- Technibaryon stable due to (anomalous) **U(1) TB symmetry**
- mass from new **TC strong dynamics** (and Higgs)
- relic density from **sphaleron asymmetry transfer?**
- Self-interactions from TC strong dynamics
- **Technineutron** (pNGB)of some kind DM candidate

Technicolor limit

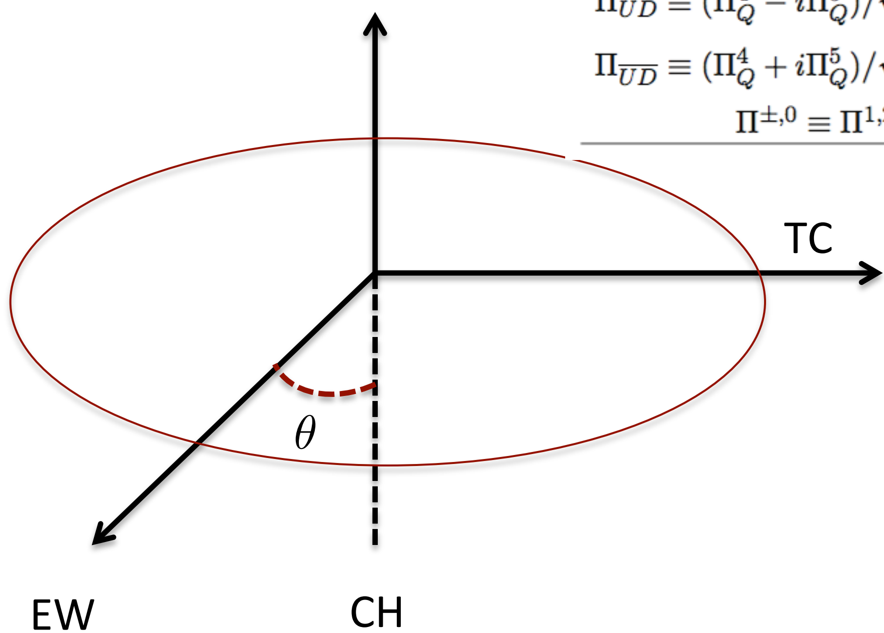
- Technibaryon stability due to (anomalous) **U(1) TB symmetry**
- mass from new **TC strong dynamics** (and Higgs)
- relic density from **sphaleron asymmetry transfer?**
- Self-interactions from TC strong dynamics
- **Technineutron** of some kind DM candidate

Extremely compelling, apparently wrong limit

Observed Higgs properties not obviously consistent with a TC Higgs

Framework: Composite Dynamics

Composites	$U(1)_{TB}$	$U(1)_{EM}$	Θ
$\Pi_{UD} \equiv (\Pi^4_Q - i\Pi^5_Q)/\sqrt{2} \sim U^T C D$	$\frac{1}{\sqrt{2}}$	0	$\pi/2$
$\Pi_{\overline{UD}} \equiv (\Pi^4_Q + i\Pi^5_Q)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	$\pi/2$
$\Pi^{\pm,0} \equiv \Pi^{1,2,3}$	0	$\pm 1, 0$	$\pi/2$



Composites	$U(1)_{TB}$	$U(1)_{EM}$	Θ
$h \equiv \Pi^4_Q \sim \bar{U}U + \bar{D}D$	–	0	0
$\eta \equiv \Pi^5_Q \sim \mathrm{Im}\, U^T C D$	–	0	0
$\Pi^{\pm,0} \equiv \Pi^{1,2,3}$	0	$\pm 1, 0$	0

No underlying stabilizing symmetry for the CH range of parameters

(Galloway, Evans, Luty & Tacchi '10; Ferretti & Karateev '13; Cacciapaglia & Sannino'14; Alanne, Buarque Franzosi & MTF '17)

Inert extensions

(Luty & Okui ‘04; Dietrich, Sannino & Tuominen ’06; Ryttov & Sannino ’08; Luty ’09)

	$SU(2)_{TC}$	$SU(2)_W$	$U(1)_Y$
(U_L, D_L)	$\square$	$\square$	0
$\widetilde{U}_L$	$\square$	1	$-1/2$
$\widetilde{D}_L$	$\square$	1	$+1/2$
λ_L	Adj	1	0
$\widetilde{\lambda}_L$	Adj	1	0

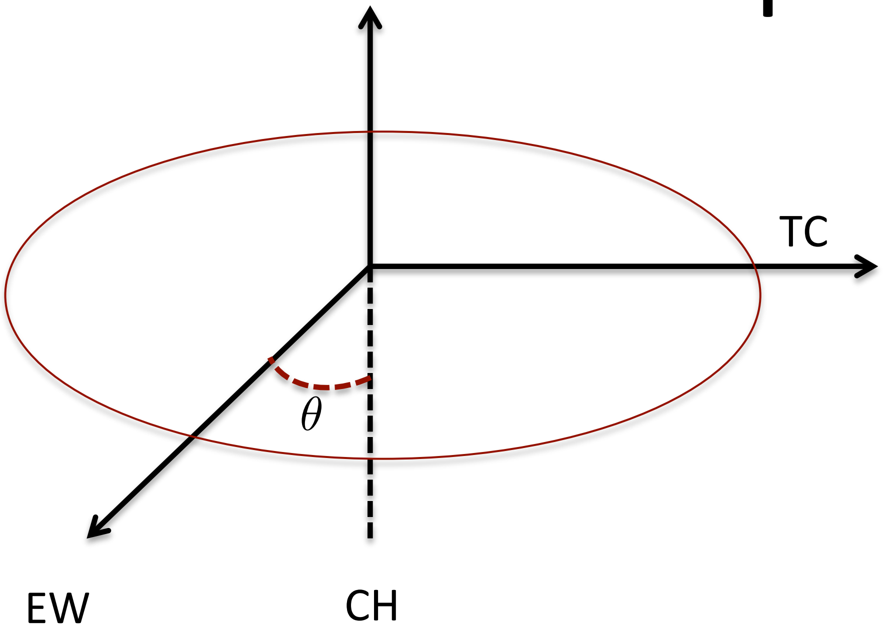
$$Q = \begin{pmatrix} U_L \\ D_L \\ \widetilde{U}_L \\ \widetilde{D}_L \end{pmatrix} \quad SU(4)$$

$$\Lambda = \begin{pmatrix} \lambda_L \\ \tilde{\lambda}_L \end{pmatrix} \quad SU(2)$$

(M.T.F, Sarkar Schmidt-Hoberg ‘11; Ryttov & Sannino ’08; Alanne, Buarque Franzosi, MTF & Rosenlyst ’18)

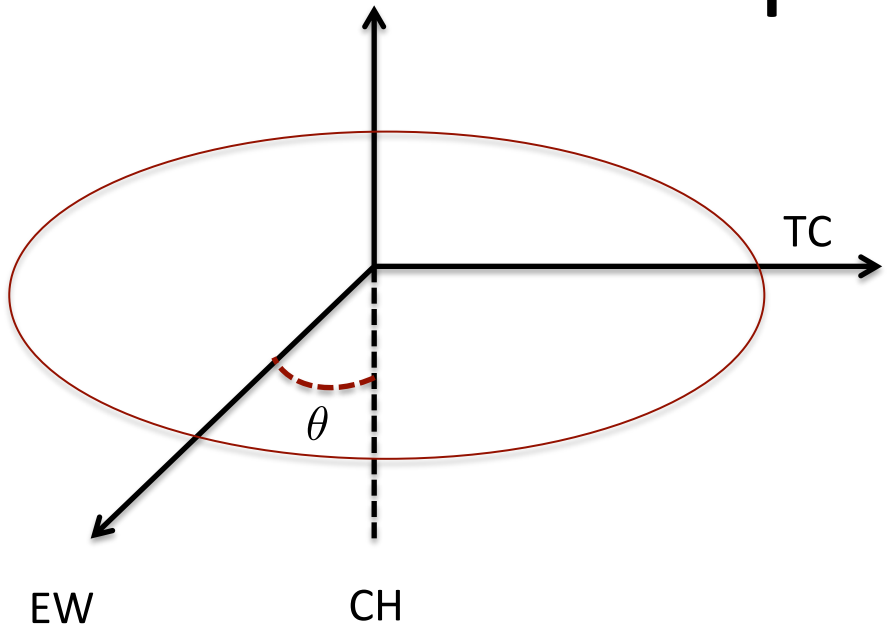
Global symmetry breaking pattern: SU(4) x SU(2) x U(1) -> Sp(4) x $U(1)_{DM}$ x Z_2

Framework: Composite Dynamics



Composites	$U(1)_{TB}$	$U(1)_{\Lambda}$	Z_2
$\Pi_{UD} \equiv (\Pi_Q^4 - i\Pi_Q^5)/\sqrt{2} \sim U^T C D$	$\frac{1}{\sqrt{2}}$	0	0
$\Pi_{\overline{UD}} \equiv (\Pi_Q^4 + i\Pi_Q^5)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	0
$\Phi \sim \Lambda^T C \Lambda$	0	1	0
$\bar{\Phi} \sim \bar{\Lambda} C \bar{\Lambda}^T$	0	-1	0
$\Theta \sim i(\bar{U}\gamma^5 U + \bar{D}\gamma^5 D - (1/2)\bar{\Lambda}\gamma^5\Lambda)$	0	0	0

Framework: Composite Dynamics



Composites	$\mathrm{U}(1)_{\mathrm{TB}}$	$\mathrm{U}(1)_\Lambda$	Z_2
$\Pi_{UD} \equiv (\Pi_Q^4 - i\Pi_Q^5)/\sqrt{2} \sim U^T C D$	$\frac{1}{\sqrt{2}}$	0	0
$\Pi_{\overline{UD}} \equiv (\Pi_Q^4 + i\Pi_Q^5)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	0
$\Phi \sim \Lambda^T C \Lambda$	0	1	0
$\bar{\Phi} \sim \bar{\Lambda} C \bar{\Lambda}^T$	0	-1	0
$\Theta \sim i(\bar{U}\gamma^5 U + \bar{D}\gamma^5 D - (1/2)\bar{\Lambda}\gamma^5\Lambda)$	0	0	0

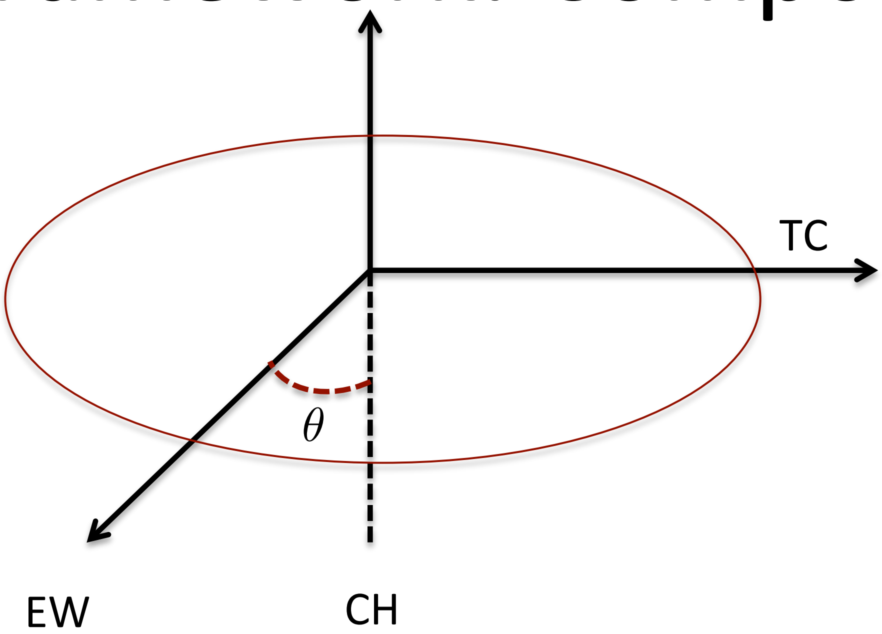
$$\mathcal{L}_{\rm kin} = \frac{f^2}{8}\mathrm{Tr}[D_\mu \Sigma_Q^\dagger D^\mu \Sigma_Q] + \frac{f_\Lambda^2}{8}\mathrm{Tr}[\partial_\mu \Sigma_\Lambda^\dagger \partial^\mu \Sigma_\Lambda],$$

$$+ \frac{c_1}{4\pi}\mathrm{Tr}[D_\mu \Sigma_Q^\dagger D^\mu \Sigma_Q]\mathrm{Tr}[\partial_\mu \Sigma_\Lambda^\dagger \partial^\mu \Sigma_\Lambda]$$

$$\langle \sigma v \rangle \simeq 2 \cdot 10^{-25}\mathrm{cm}^3/\mathrm{s}\,\frac{c_1^2 m_\Phi^4}{f_\Lambda^4}\frac{s_\theta^4 m_\Phi^2}{m_W^2}$$

'WIMP' from strong interactions

Framework: Composite Dynamics



Composites	$U(1)_{TB}$	$U(1)_\Lambda$	Z_2
$\Pi_{UD} \equiv (\Pi^4_Q - i\Pi^5_Q)/\sqrt{2} \sim U^T C D$	$\frac{1}{\sqrt{2}}$	0	0
$\Pi_{\overline{UD}} \equiv (\Pi^4_Q + i\Pi^5_Q)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	0
$\Phi \sim \Lambda^T C \Lambda$	0	1	0
$\bar{\Phi} \sim \bar{\Lambda} C \bar{\Lambda}^T$	0	−1	0
$\Theta \sim i(\bar{U}\gamma^5 U + \bar{D}\gamma^5 D - (1/2)\bar{\Lambda}\gamma^5\Lambda)$	0	0	0

$$\mathcal{L}_{\rm kin} = \frac{f^2}{8}\mathrm{Tr}[D_\mu \Sigma_Q^\dagger D^\mu \Sigma_Q] + \frac{f_\Lambda^2}{8}\mathrm{Tr}[\partial_\mu \Sigma_\Lambda^\dagger \partial^\mu \Sigma_\Lambda],$$

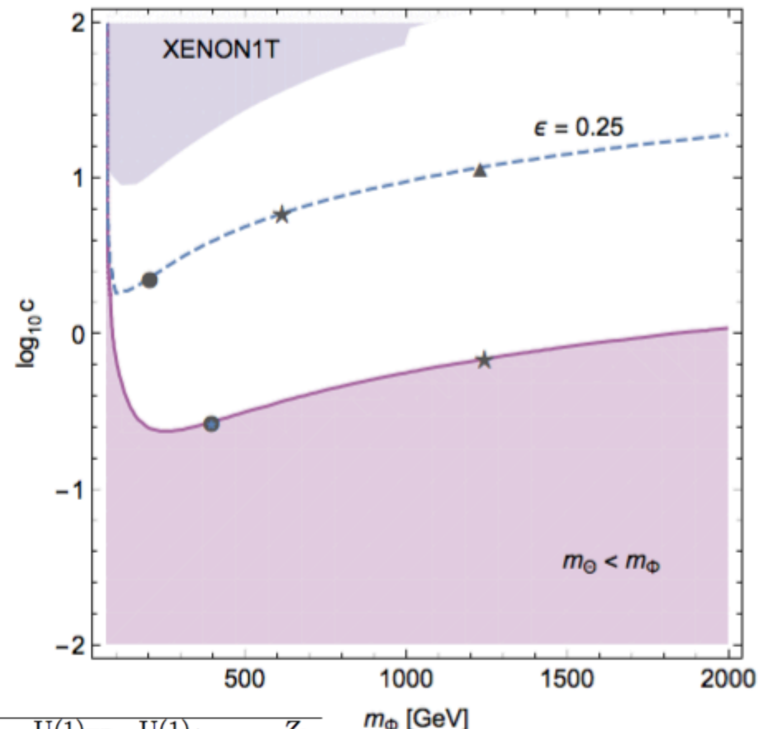
$$+ \frac{c_1}{4\pi}\mathrm{Tr}[D_\mu \Sigma_Q^\dagger D^\mu \Sigma_Q]\mathrm{Tr}[\partial_\mu \Sigma_\Lambda^\dagger \partial^\mu \Sigma_\Lambda]$$

Composites	$U(1)_{TB}$	$U(1)_\Lambda$	Z_2
$h \equiv \Pi^4_Q \sim \bar{U}U + \bar{D}D$	–	0	0
$\eta \equiv \Pi^5_Q \sim \mathrm{Im}\, U^T C D$	–	0	0
$\Phi \sim \Lambda^T C \Lambda$	–	1	0
$\bar{\Phi} \sim \bar{\Lambda} C \bar{\Lambda}^T$	–	−1	0
$\Theta \sim i(\bar{U}\gamma^5 U + \bar{D}\gamma^5 D - (1/2)\bar{\Lambda}\gamma^5\Lambda)$	–	0	0

$$\langle \sigma v \rangle \simeq 2 \cdot 10^{-25} \mathrm{cm}^3/\mathrm{s} \frac{c_1^2 m_\Phi^4}{f_\Lambda^4} \frac{s_\theta^4 m_\Phi^2}{m_W^2}$$

’WIMP’ from strong interactions in TC and CH limits

Constraints



$\epsilon = m_\Phi / f$

Increasing $f=f_\Lambda$

Composites	$U(1)_{TB}$	$U(1)_\Lambda$	Z_2
$h \equiv \Pi_Q^4 \sim \bar{U}U + \bar{D}D$	–	0	0
$\eta \equiv \Pi_Q^5 \sim \mathrm{Im}\, U^T C D$	–	0	0
$\Phi \sim \Lambda^T C \Lambda$	–	1	0
$\bar{\Phi} \sim \bar{\Lambda} C \bar{\Lambda}^T$	–	−1	0
$\Theta \sim i(\bar{U}\gamma^5 U + \bar{D}\gamma^5 D - (1/2)\bar{\Lambda}\gamma^5\Lambda)$	–	0	0

pNGB spectrum
From vacuum angle

$$m_\Phi^2 = -16\pi c_\Lambda f_\Lambda m$$

$$m_\eta^2 = m_h^2 / s_\theta^2$$

$$m_\Theta^2 = \frac{8}{9} m_\eta^2 c_\theta^2 + \frac{1}{9} m_\Phi^2$$

CP³ Origins
Cosmology & Particle Physics

SDU

Summary

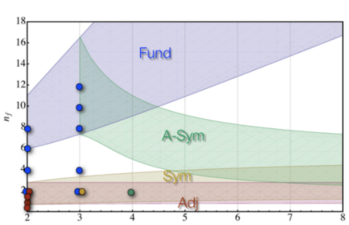
- Composite Dynamics compelling framework for DM and EW

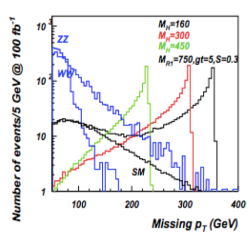
U(1) stabilizing symmetries, dynamical symmetry breaking, naturalness, non-triviality, predictability (lattice)

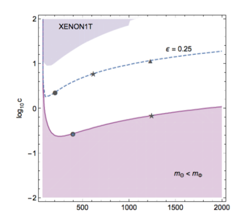
- Vast space of models from 4d gauge-fermion-Yukawa theories

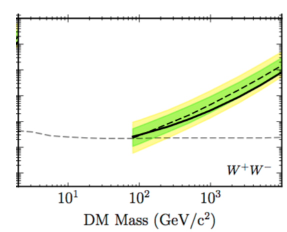
CH limit yields pNGB Higgs with properties tunably close to the SM Higgs. Correlated with DM turning WIMPy (in studied model)

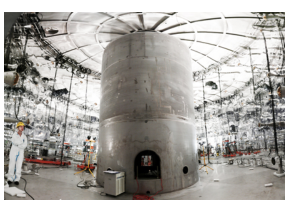
- Lattice and diverse experiments test underlying models











Model example

(Alanne, Buarque Franzosi, MTF & Rosenlyst '18)

Composites	$\mathrm{U}(1)_{\mathrm{TB}}$	$\mathrm{U}(1)_{\Lambda}$	Z_2
$h \equiv \Pi_Q^4 \sim \bar{U}U + \bar{D}D$	–	0	0
$\eta \equiv \Pi_Q^5 \sim \mathrm{Im}\, U^T C D$	–	0	0
$\Phi \sim \Lambda^T C \Lambda$	–	1	0
$\bar{\Phi} \sim \bar{\Lambda} C \bar{\Lambda}^T$	–	−1	0
$\Theta \sim i(\bar{U}\gamma^5 U + \bar{D}\gamma^5 D - (1/2)\bar{\Lambda}\gamma^5\Lambda)$	–	0	0

EW breaking sector   Inert strong sector

$$\mathcal{L}_{\text{kin}} = \frac{f^2}{8}\mathrm{Tr}[D_\mu \Sigma_Q^\dagger D^\mu \Sigma_Q] + \frac{f_\Lambda^2}{8}\mathrm{Tr}[\partial_\mu \Sigma_\Lambda^\dagger \partial^\mu \Sigma_\Lambda], + \frac{c_1}{4\pi}\mathrm{Tr}[D_\mu \Sigma_Q^\dagger D^\mu \Sigma_Q]\mathrm{Tr}[\partial_\mu \Sigma_\Lambda^\dagger \partial^\mu \Sigma_\Lambda]$$

$$\langle \sigma v \rangle \simeq 2 \cdot 10^{-25}\mathrm{cm}^3/\mathrm{s}\frac{c_1^2 m_\Phi^4}{f_\Lambda^4}\frac{s_\theta^4 m_\Phi^2}{m_W^2}$$

annihilation cross-section   'WIMP' from strong interactions

Model example

(Alanne, Buarque Franzosi, MTF & Rosenlyst '18)

		$U(1)_{TB}$	$U(1)_\Lambda$	Z_2	
	$h \equiv \Pi_Q^4 \sim \bar{U}U + \bar{D}D$	$-$	0	0	EW unbroken s_θ=0
	$\eta \equiv \Pi_Q^5 \sim \mathrm{Im}\, U^T C D$	$-$	0	0	
DM candidate	$\Phi \equiv (\Pi_\Lambda^1 - i\Pi_\Lambda^2)/\sqrt{2} \sim \Lambda^T C \Lambda$	$-$	1	0	
	$\bar{\Phi} \equiv (\Pi_\Lambda^1 + i\Pi_\Lambda^2)/\sqrt{2} \sim \bar{\Lambda} C \bar{\Lambda}^T$	$-$	-1	0	
	$\Theta \sim i(\bar{U}\gamma^5 U + \bar{D}\gamma^5 D - (1/2)\bar{\Lambda}\gamma^5\Lambda)$	$-$	0	0	
ADM candidate (Sannino & Ryttov '08)	$\Pi_{UD} \equiv (\Pi_Q^4 - i\Pi_Q^5)/\sqrt{2} \sim U^T C D$	$\frac{1}{\sqrt{2}}$	0	0	TC limit c_θ=0
	$\Pi_{\overline{UD}} \equiv (\Pi_Q^4 + i\Pi_Q^5)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	0	
DM candidate (MTF, Sarkar & Schmidt-Hoberg '11)	Φ	0	1	0	
	$\bar{\Phi}$	0	-1	0	
	Θ	0	0	0	

Effective Lagrangian

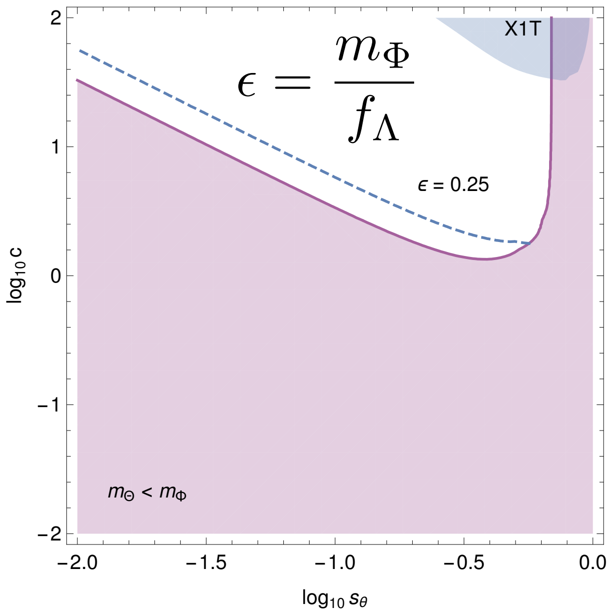
$$\mathcal{L}_{\rm kin} = \frac{f^2}{8}\mathrm{Tr}[D_\mu \Sigma_Q^\dagger D^\mu \Sigma_Q] + \frac{f_\Lambda^2}{8}\mathrm{Tr}[\partial_\mu \Sigma_\Lambda^\dagger \partial^\mu \Sigma_\Lambda],$$
$$+\frac{c_1}{4\pi}\mathrm{Tr}[D_\mu \Sigma_Q^\dagger D^\mu \Sigma_Q]\mathrm{Tr}[\partial_\mu \Sigma_\Lambda^\dagger \partial^\mu \Sigma_\Lambda] \quad + \ldots$$

annihilation cross-section

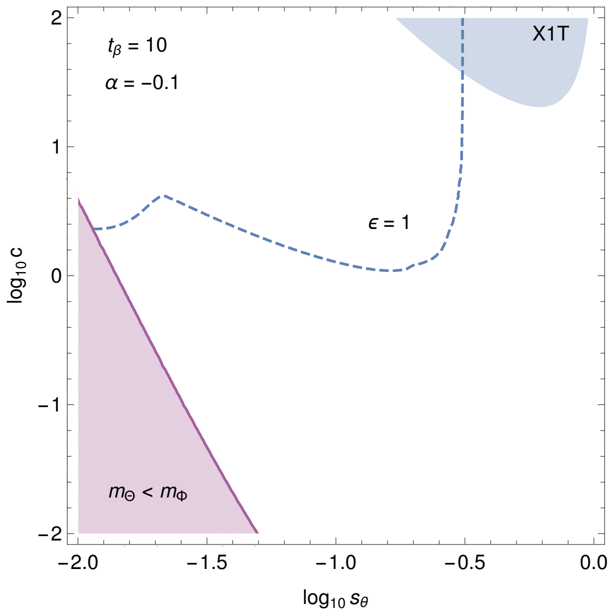
$$\langle \sigma v \rangle \simeq 2 \cdot 10^{-25}\mathrm{cm}^3/\mathrm{s}\, \frac{c_1^2 m_\Phi^4}{f_\Lambda^4}\, \frac{s_\theta^4 m_\Phi^2}{m_W^2}$$

Thermal relic density & constraints

Fermion partial compositeness



Partially composite Higgs



Framework: Composite Dynamics

	$SU(2)_{TC}$	$SU(2)_W$	$U(1)_Y$
(U_L, D_L)	$\square$	$\square$	0
$\widetilde{U}_L$	$\square$	1	$-1/2$
$\widetilde{D}_L$	$\square$	1	$+1/2$

$$Q = \begin{pmatrix} U_L \\ D_L \\ \widetilde{U}_L \\ \widetilde{D}_L \end{pmatrix}$$

$$U(1) : Q \rightarrow e^{-\alpha} Q$$

Framework 2: Composite Higgs

- pNGB Higgs properties tunably close to the SM Higgs

Framework: Composite Dynamics

- 4d Gauge-Yukawa model with strongly interacting fermions
- Technicolor and Composite Higgs models simply different vacuum alignment limits
- Vacuum alignment determined by interactions external to the strong dynamics

Framework 2: Composite Higgs

- Technibaryon stability (longevity) due to a U(1) symmetry ?
- Technibaryon mass from new strong dynamics (and Higgs)
- Technibaryon relic density origin?
- Self-interactions from new strong dynamics

- pNGB Higgs properties tunably close to the SM Higgs

Baryonic relic density

- Proton stability (longevity) due to a U(1) symmetry
- Proton mass from strong dynamics (and Higgs)
- Proton relic density from some asymmetry
- Proton self-interactions from strong dynamics

Composite Higgs

- Technibaryon stability (longevity) due to a U(1) symmetry ?
- Technibaryon mass from new strong dynamics (and Higgs)
- Technibaryon relic density origin?
- Self-interactions from new strong dynamics

- pNGB Higgs properies tunably close to the SM Higgs

Model example

(Alanne, Buarque Franzosi, MTF & Rosenlyst '18)

		$SU(2)_{TC}$	$SU(2)_W$	$U(1)_Y$
SU(4)	(U_L, D_L)	$\square$	$\square$	0
	$\widetilde{U}_L$	$\square$	1	$-1/2$
	$\widetilde{D}_L$	$\square$	1	$+1/2$
SU(2)	λ_L	Adj	1	0
	$\widetilde{\lambda}_L$	Adj	1	0

(TC: Appelquist, Da Silva, Sannino & Duan '99, '00
CH: Galloway, Evans, Luty & Tacchi '10; Ferretti & Karateev '13; Cacciapaglia & Sannino'14)

(TC: Sannino & Ryttov '08; MTF, Sarkar & Schmidt-Hoberg '11)

Global symmetry breaking pattern: SU(4) x SU(2) x U(1) -> Sp(4) x $U(1)_{DM}$ x Z_2
Technicolor limit:

$$\langle QQ \rangle \sim f^3 E_Q, \langle \Lambda\Lambda \rangle \sim f_\Lambda^3 E_\Lambda$$

Model example

(Alanne, Buarque Franzosi, MTF & Rosenlyst '18)

	$\mathrm{U}(1)_{\mathrm{TB}}$	$\mathrm{U}(1)_{\Lambda}$	Z_2
$h \equiv \Pi_Q^4 \sim \bar{U}U + \bar{D}D$	$-$	0	0
$\eta \equiv \Pi_Q^5 \sim \mathrm{Im}\, U^T CD$	$-$	0	0
$\Phi \equiv (\Pi_\Lambda^1 - i\Pi_\Lambda^2)/\sqrt{2} \sim \Lambda^T C \Lambda$	$-$	1	0
$\bar{\Phi} \equiv (\Pi_\Lambda^1 + i\Pi_\Lambda^2)/\sqrt{2} \sim \bar{\Lambda} C \bar{\Lambda}^T$	$-$	-1	0
$\Theta \sim i(\bar{U}\gamma^5 U + \bar{D}\gamma^5 D - (1/2)\bar{\Lambda}\gamma^5\Lambda)$	$-$	0	0
$\Pi_{UD} \equiv (\Pi_Q^4 - i\Pi_Q^5)/\sqrt{2} \sim U^T CD$	$\frac{1}{\sqrt{2}}$	0	0
$\Pi_{\overline{UD}} \equiv (\Pi_Q^4 + i\Pi_Q^5)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	0
Φ	0	1	0
$\bar{\Phi}$	0	-1	0
Θ	0	0	0

EW unbroken $s_\theta=0$

TC limit $c_\theta=0$

Vacuum alignment in Q-sector $\langle QQ \rangle \sim f^3 E_Q, \langle \Lambda\Lambda \rangle \sim f_\Lambda^3 E_\Lambda$ $\quad E_Q = c_\theta E_Q^- + s_\theta E_Q^B.$

$$E_Q^\pm = \begin{pmatrix} \mathrm{i}\sigma_2 & 0 \\ 0 & \pm\mathrm{i}\sigma_2 \end{pmatrix}, \quad E_Q^B = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, \quad E_\Lambda = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

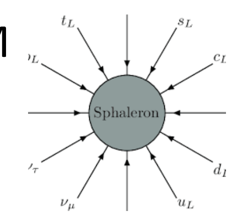
Model example

(Alanne, Buarque Franzosi, MTF & Rosenlyst ‘18)

		$U(1)_{TB}$	$U(1)_{\Lambda}$	Z_2	
	$h \equiv \Pi^4_Q \sim \bar{U}U + \bar{D}D$	$-$	0	0	EW unbroken s_θ=0
	$\eta \equiv \Pi^5_Q \sim \mathrm{Im}\, U^T C D$	$-$	0	0	
DM candidate	$\Phi \equiv (\Pi^1_\Lambda - i\Pi^2_\Lambda)/\sqrt{2} \sim \Lambda^T C \Lambda$	$-$	1	0	
	$\bar{\Phi} \equiv (\Pi^1_\Lambda + i\Pi^2_\Lambda)/\sqrt{2} \sim \bar{\Lambda} C \bar{\Lambda}^T$	$-$	-1	0	
	$\Theta \sim i(\bar{U}\gamma^5 U + \bar{D}\gamma^5 D - (1/2)\bar{\Lambda}\gamma^5\Lambda)$	$-$	0	0	
ADM candidate (Sannino & Ryttov ’08)	$\Pi_{UD} \equiv (\Pi^4_Q - i\Pi^5_Q)/\sqrt{2} \sim U^T C D$	$\frac{1}{\sqrt{2}}$	0	0	TC limit c_θ=0
	$\Pi_{\overline{UD}} \equiv (\Pi^4_Q + i\Pi^5_Q)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	0	
DM candidate (MTF, Sarkar & Schmidt-Hoberg ’11)	Φ	0	1	0	
	$\bar{\Phi}$	0	-1	0	
	Θ	0	0	0	

TC limit: $U(1)_{TB}$ current is preserved by condensates but EW anomalous -> ADM

$$\partial_\mu J^\mu_{TB} = \frac{1}{2\sqrt{2}} \frac{g^2}{32\pi^2} \epsilon_{\mu\nu\rho\sigma} W^{\mu\nu} W^{\rho\sigma} \,, \quad \text{and} \quad J^\mu_{TB} = \frac{1}{2\sqrt{2}} \left(\bar{U}\gamma^\mu U + \bar{D}\gamma^\mu D \right)$$



(TC: Sannino & Ryttov ’08; MTF, Sarkar & Schmidt-Hoberg ’11)

Model example

(Alanne, Buarque Franzosi, MTF & Rosenlyst '18)

		$\mathrm{U(1)_{TB}}$	$\mathrm{U(1)_\Lambda}$	Z_2	
	$h \equiv \Pi_Q^4 \sim \bar{U}U + \bar{D}D$	$-$	0	0	EW unbroken s_θ=0
	$\eta \equiv \Pi_Q^5 \sim \mathrm{Im}\, U^T C D$	$-$	0	0	
DM candidate	$\Phi \equiv (\Pi_\Lambda^1 - i\Pi_\Lambda^2)/\sqrt{2} \sim \Lambda^T C \Lambda$	$-$	1	0	
DM candidate	$\bar\Phi \equiv (\Pi_\Lambda^1 + i\Pi_\Lambda^2)/\sqrt{2} \sim \bar\Lambda C \bar\Lambda^T$	$-$	-1	0	
	$\Theta \sim i(\bar{U}\gamma^5 U + \bar{D}\gamma^5 D - (1/2)\bar\Lambda\gamma^5\Lambda)$	$-$	0	0	
ADM candidate (Sannino & Ryttov '08)	$\Pi_{UD} \equiv (\Pi_Q^4 - i\Pi_Q^5)/\sqrt{2} \sim U^T C D$	$\frac{1}{\sqrt{2}}$	0	0	TC limit c_θ=0
ADM candidate (Sannino & Ryttov '08)	$\Pi_{\overline{UD}} \equiv (\Pi_Q^4 + i\Pi_Q^5)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	0	
DM candidate (MTF, Sarkar & Schmidt-Hoberg '11)	Φ	0	1	0	
DM candidate (MTF, Sarkar & Schmidt-Hoberg '11)	$\bar\Phi$	0	-1	0	
	Θ	0	0	0	

Effective Lagrangian

$$\mathcal{L}_{\rm kin} = \frac{f^2}{8}\mathrm{Tr}[D_\mu \Sigma_Q^\dagger D^\mu \Sigma_Q] + \frac{f_\Lambda^2}{8}\mathrm{Tr}[\partial_\mu \Sigma_\Lambda^\dagger \partial^\mu \Sigma_\Lambda],$$

$$\Sigma_Q = \exp\left[2\sqrt{2}\, i\left(\frac{\Pi_Q}{f} - \frac{1}{3}\frac{\Theta}{f_\Theta}\mathbb{1}_4\right)\right] E_Q$$

$$\Sigma_\Lambda = \exp\left[2\sqrt{2}\, i\left(\frac{\Pi_\Lambda}{f_\Lambda} + \frac{1}{6}\frac{\Theta}{f_\Theta}\mathbb{1}_2\right)\right] E_\Lambda,$$

Model example

(Alanne, Buarque Franzosi, MTF & Rosenlyst '18)

	$U(1)_{TB}$	$U(1)_{\Lambda}$	Z_2
$h \equiv \Pi_Q^4 \sim \bar{U}U + \bar{D}D$	–	0	0
$\eta \equiv \Pi_Q^5 \sim \mathrm{Im}\, U^T C D$	–	0	0
$\Phi \equiv (\Pi_\Lambda^1 - i\Pi_\Lambda^2)/\sqrt{2} \sim \Lambda^T C \Lambda$	–	1	0
$\bar{\Phi} \equiv (\Pi_\Lambda^1 + i\Pi_\Lambda^2)/\sqrt{2} \sim \bar{\Lambda} C \bar{\Lambda}^T$	–	−1	0
$\Theta \sim i(\bar{U}\gamma^5 U + \bar{D}\gamma^5 D - (1/2)\bar{\Lambda}\gamma^5\Lambda)$	–	0	0
$\Pi_{UD} \equiv (\Pi_Q^4 - i\Pi_Q^5)/\sqrt{2} \sim U^T C D$	$\frac{1}{\sqrt{2}}$	0	0
$\Pi_{\overline{UD}} \equiv (\Pi_Q^4 + i\Pi_Q^5)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	0
Φ	0	1	0
$\bar{\Phi}$	0	−1	0
Θ	0	0	0

DM candidate

EW unbroken $s_\theta=0$

ADM candidate
(Sannino & Ryttov '08)

DM candidate
(MTF, Sarkar & Schmidt-Hoberg '11)

TC limit $c_\theta=0$

Effective Lagrangian

$$\mathcal{L}_{\rm kin} = \frac{f^2}{8}\mathrm{Tr}[D_\mu \Sigma_Q^\dagger D^\mu \Sigma_Q] + \frac{f_\Lambda^2}{8}\mathrm{Tr}[\partial_\mu \Sigma_\Lambda^\dagger \partial^\mu \Sigma_\Lambda],$$

Π_{UD} annihilation cross-section

$$\mathcal{L}_{\rm kin} \supset -\frac{g^2}{2} s_\theta^2 W_\mu^+ W^{-\nu} \Pi_{UD} \bar{\Pi}_{UD}$$

$$\langle \sigma v \rangle \simeq 2 \cdot 10^{-24} \mathrm{cm}^3/\mathrm{s} \frac{s_\theta^4 m_{\Pi_{UD}}^2}{m_W^2}$$

Model example

(Alanne, Buarque Franzosi, MTF & Rosenlyst '18)

		$U(1)_{TB}$	$U(1)_\Lambda$	Z_2	
	$h \equiv \Pi_Q^4 \sim \bar{U}U + \bar{D}D$	–	0	0	EW unbroken s_θ=0
	$\eta \equiv \Pi_Q^5 \sim \mathrm{Im}\, U^T C D$	–	0	0	
DM candidate	$\Phi \equiv (\Pi_\Lambda^1 - i\Pi_\Lambda^2)/\sqrt{2} \sim \Lambda^T C \Lambda$	–	1	0	
	$\bar{\Phi} \equiv (\Pi_\Lambda^1 + i\Pi_\Lambda^2)/\sqrt{2} \sim \bar{\Lambda} C \bar{\Lambda}^T$	–	−1	0	
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	Θ	0	0	0	

Effective Lagrangian

$$\mathcal{L}_{\rm kin} = \frac{f^2}{8}\mathrm{Tr}[D_\mu \Sigma_Q^\dagger D^\mu \Sigma_Q] + \frac{f_\Lambda^2}{8}\mathrm{Tr}[\partial_\mu \Sigma_\Lambda^\dagger \partial^\mu \Sigma_\Lambda],$$

Π_{UD} annihilation cross-section

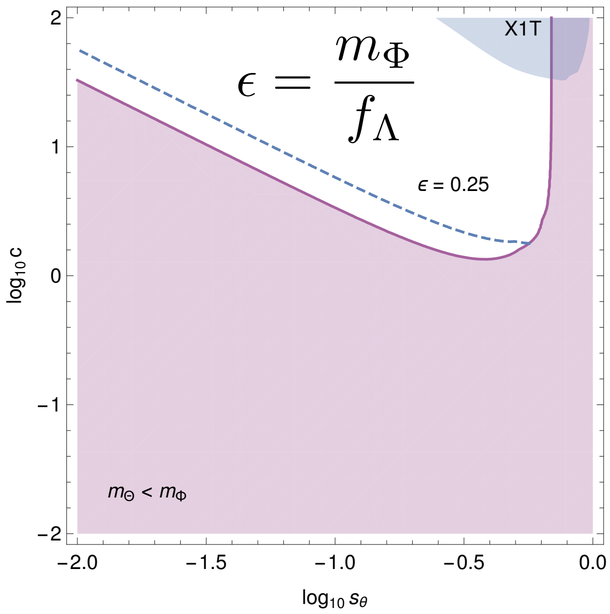
$$\mathcal{L}_{\rm kin} \supset -\frac{g^2}{2} s_\theta^2 W_\mu^+ W^{-\nu} \Pi_{UD} \bar{\Pi}_{UD}$$

Correct size for EW scale mass and s_θ= 0.1 →

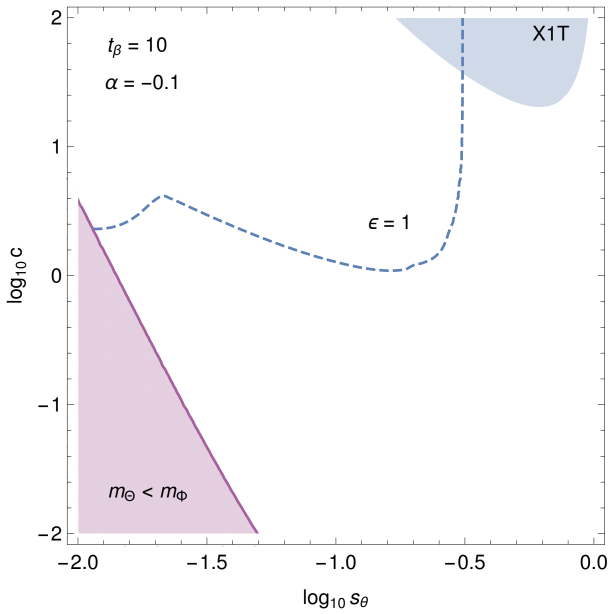
$$\langle \sigma v \rangle \simeq 2 \cdot 10^{-24} \mathrm{cm}^3/\mathrm{s}\, \frac{s_\theta^4 m_{\Pi_{UD}}^2}{m_W^2}$$

Thermal relic density & constraints

Fermion partial compositeness



Partially composite Higgs



Summary II

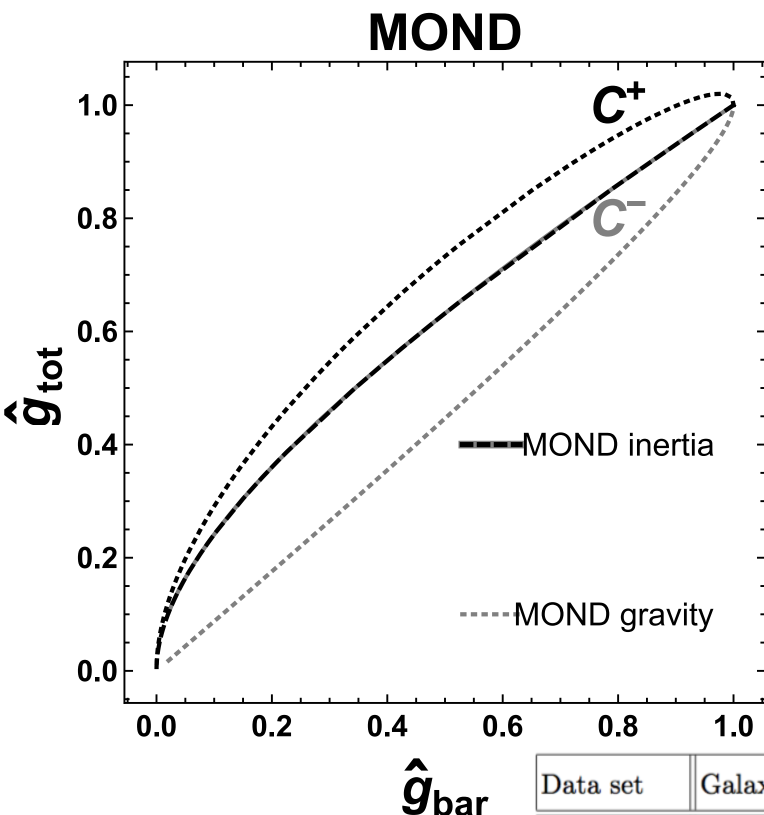
- Composite Dynamics well motivated framework for EWSB & DM
- Nature has been somewhat tough on TC so CH is next best thing
- Simple ADM scenario of TC is not easily transferred to CH
- But U(1) symmetric DM candidates exist

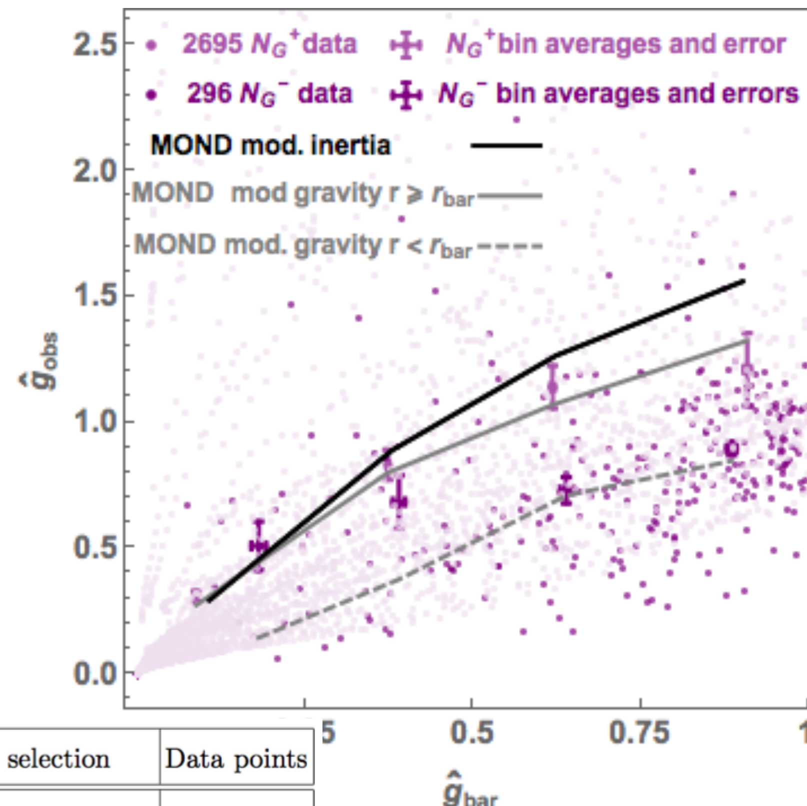
(Ma & Cacciapaglia ’15;
Cai, Cacciapaglia, Zhang ’18)

SPARC data in ĝ2-space

(MTF and J. Petersen '18)

All SPARC data after quality criteria organized wrt r_{bar}





Data set	Galaxy selection	Data selection	Data points
N_G^+	all (152)	$r_j > r_{\rm bar}$	2695
N_G^-	all (152)	$r_j \leq r_{\rm bar}$	296

Comparison to SPARC data

(MTF and J. Petersen '18)

(NB: For data g_{tot}-> g_{obs})

$g_{obs,bar}$ in terms of measusred quantities:

$$g_{\rm obs}(r_j) = \frac{v_{\rm obs}^2(r_j)}{r_j}, \quad g_{\rm bar}(r_j) = \frac{\left(v_{\rm gas}^2(r_j) + \Upsilon_{\rm disk} v_{\rm disk}^2(r_j) + \Upsilon_{\rm bul} v_{\rm bul}^2(r_j)\right)}{r_j}$$

Comparison to SPARC data

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g_{obs} uncertainties: random $\boldsymbol{\delta v_{obs}}$, Inclination angle $\boldsymbol{\delta i}$, Galaxy distance $\boldsymbol{\delta D}$

$$\delta g_{\rm obs}(r_j) = g_{\rm obs}(r_j)\sqrt{\left[\frac{2\delta v_{\rm obs}(r_j)}{v_{\rm obs}(r_j)}\right]^2 + \left[\frac{2\delta i}{\tan(i)}\right]^2 + \left[\frac{\delta D}{D}\right]^2}$$

g_{bar} uncertainties: $\boldsymbol{\delta v_{gas}}$, disk and bulge mass to light ratios $\boldsymbol{\delta Y_{disk,bulge}}$

$$\delta g_{\rm bar}(r_j) = \frac{\sqrt{(2v_{\rm gas}(r_j))^2\delta v^2_{\rm gas} + v^4_{\rm disk}(r_j)\delta\Upsilon^2_{\rm disk} + v^4_{\rm bulge}(r_j)\delta\Upsilon^2_{\rm bulge}}}{r_j}$$

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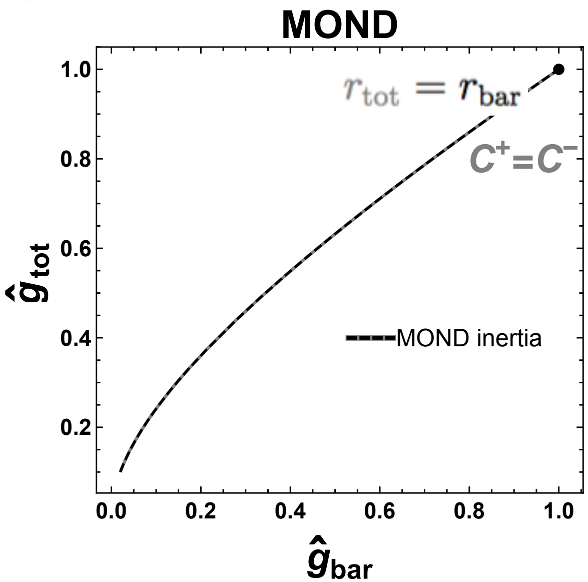
$$\delta g_{\rm bar}(r_j) = \frac{\sqrt{(2v_{\rm gas}(r_j))^2 \delta v_{\rm gas}^2 + v_{\rm disk}^4(r_j)\delta\Upsilon_{\rm disk}^2 + v_{\rm bulge}^4(r_j)\delta\Upsilon_{\rm bulge}^2}}{r_j}$$

Galaxy specific uncertainties $\boldsymbol{\delta i, \delta D, \delta Y_{disk,bulge}}$ dominate the RAR scatter

(Li, Lelli, Mcgaugh & Schombert ’18)

Also these will depend on radius

MOND geometry in g2-space



Geometric Classification

MOND Modified Inertia

Models	Reference radii	Curve segments	Curve Area
MOND-MI	$r_{\rm tot} = r_{\rm bar}$	$\mathcal{C}^+ = \mathcal{C}^-$	$\mathcal{A}(\mathcal{C}) = 0$

MOND models in ĝ2-space

(MTF and J. Petersen '18)

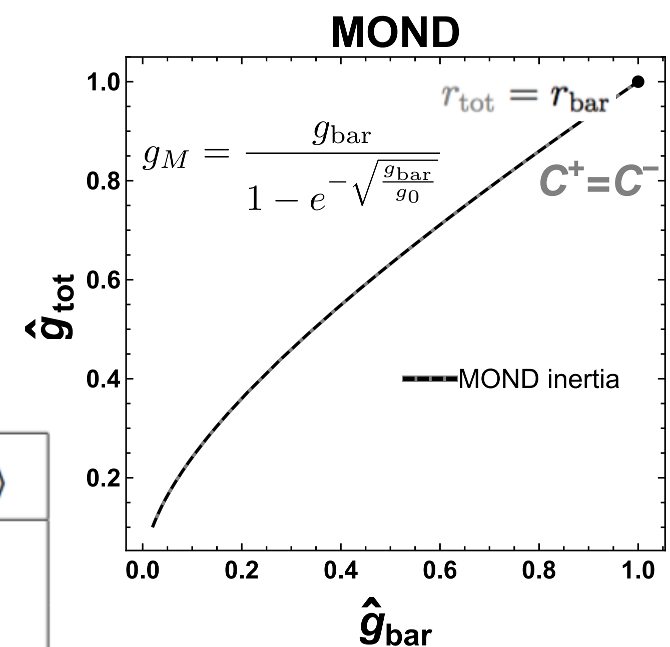
MOND modified Inertia consequences:

$r_{tot} = r_{bar}$ and $C^+ = C^-$ so $\hat{g}(r_{tot})_{bar,tot} = 1$

Ruled out independent of model > 5σ

SPARC data analysis for $\hat{g}(r_{tot})_{bar,tot}$

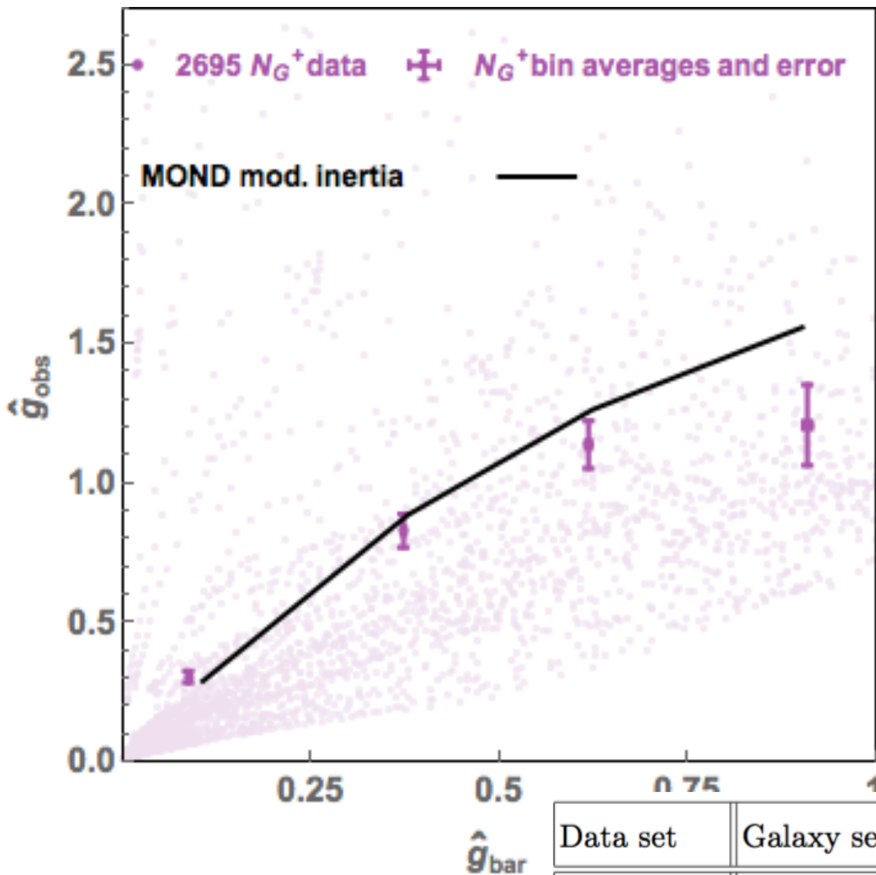
Data selection	points	$\langle \hat{g}_{obs} \pm \delta\hat{g}_{obs} \rangle$	$\langle \hat{g}_{bar} \pm \delta\hat{g}_{bar} \rangle$
$r_j = r_{obs}$	152	1.39 ± 0.12	0.83 ± 0.01
$r_j = r_{obs},\ \frac{\delta v_{obs}}{v_{obs}} < 0.1$	146	1.12 ± 0.02	0.91 ± 0.01



(NB: For data points $g_{tot} \to g_{obs}$, $r_{tot} \to r_{obs}$)

SPARC data in ĝ2-space

(MTF and J. Petersen ’18)



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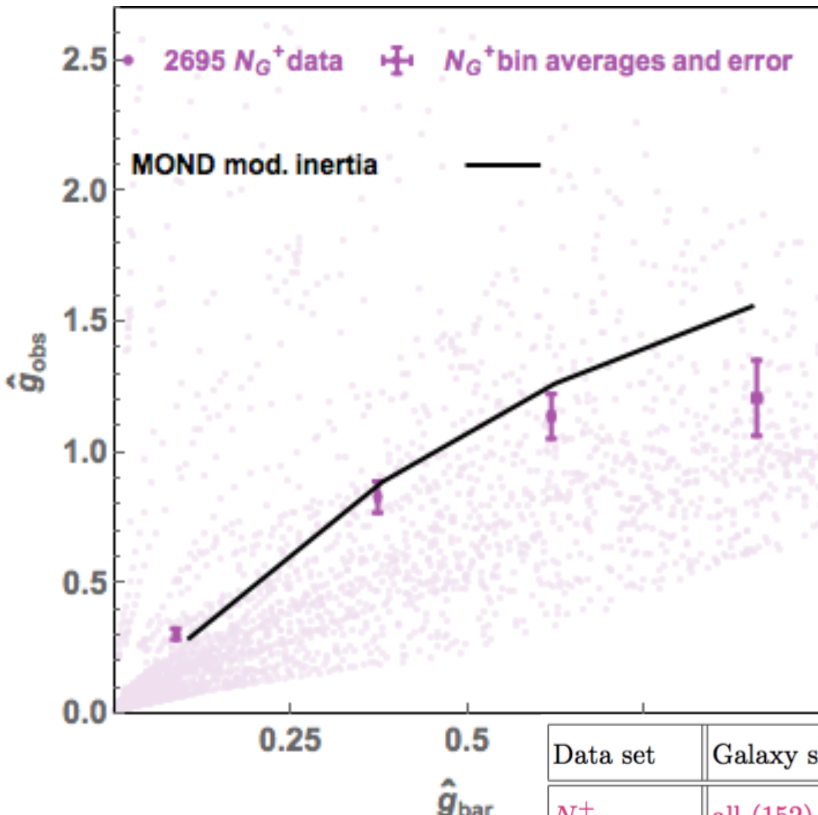
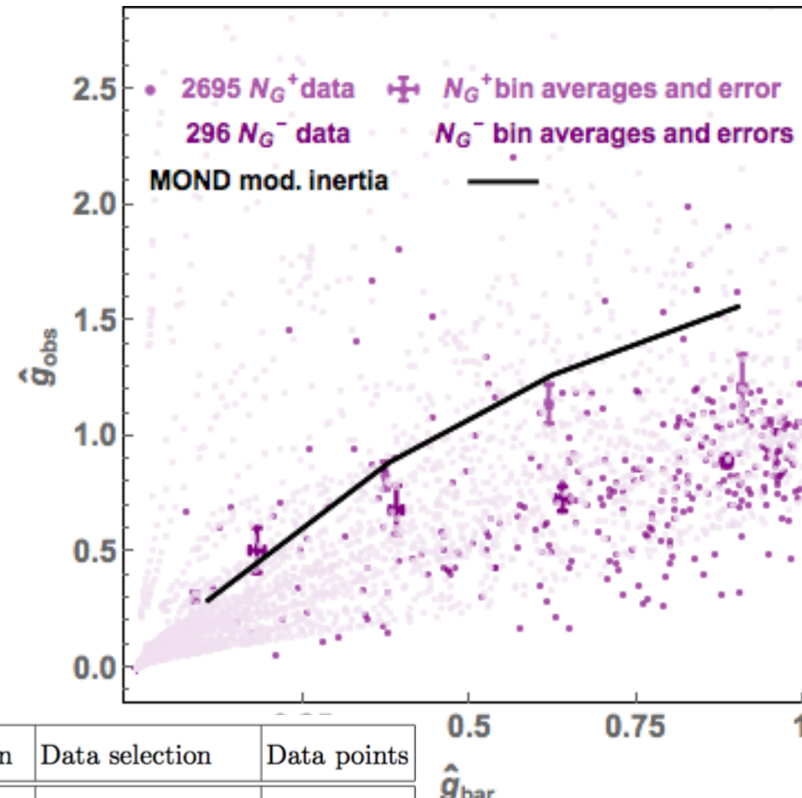
SPARC data in ĝ2-space

(MTF and J. Petersen '18)

All SPARC data after quality criteria organized wrt r_{bar}





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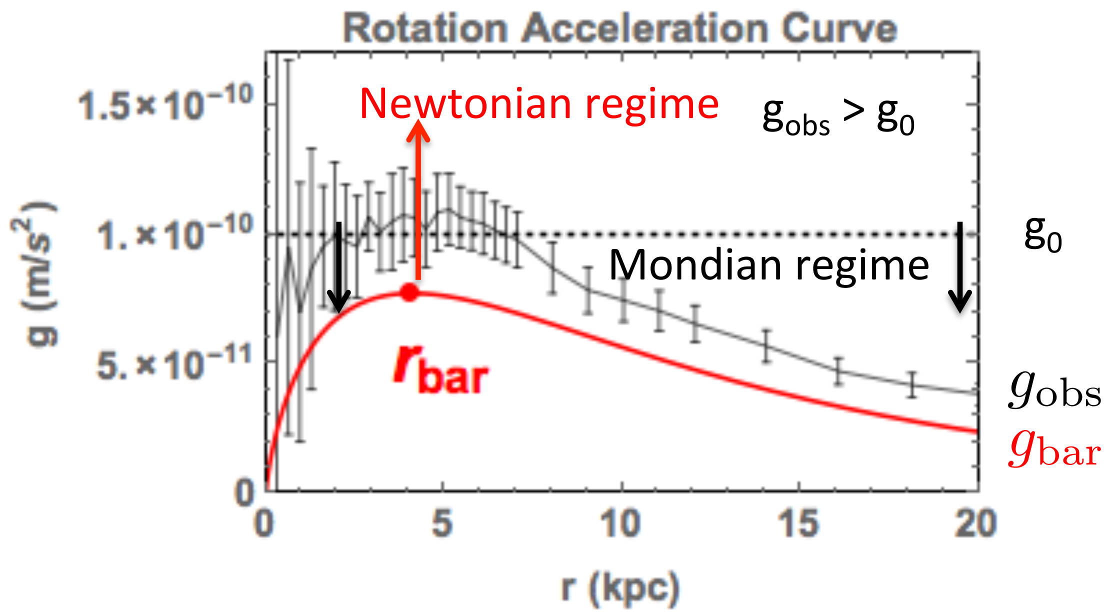
Rotation acceleration curves

Baryonic and total/observed accelerations

MONDian acceleration relation

$$\mu(\frac{g_M}{g_0})g_M = g_{\rm bar}$$

$$\mu(x) = \begin{cases} \mu(x) \simeq 1 & x \gg 1 \\ \mu(x) \simeq x & x \ll 1 \end{cases}$$



Newtonian regime $g_{obs} > g_0$

$$g_{\rm obs} \sim g_{\rm bar}$$

Mondian regime $g_{obs} < g_0$

$$g_{\rm obs}^2 \sim g_{\rm bar}$$

$g_0 \sim 10^{-10}$ m/s^2 is transition acc. scale

r_{bar} is radii of maximum baryonic acc.

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Framework: Composite Dynamics

UV $\mathcal{L}_{UV} = \bar{Q}\gamma^{\mu} D_{\mu} Q + \mathcal{L}_{SM-Higgs} + \delta\mathcal{L}$ $\quad G_Q \in SU(2) \times SU(2) \times U(1)$

SM Higgs custodial symmetry DM symmetry

IR $\langle Q^I Q^J \rangle \sim f^3 E_Q^{IJ}$ $\quad H_Q \in SU(2) \times U(1)$

Example

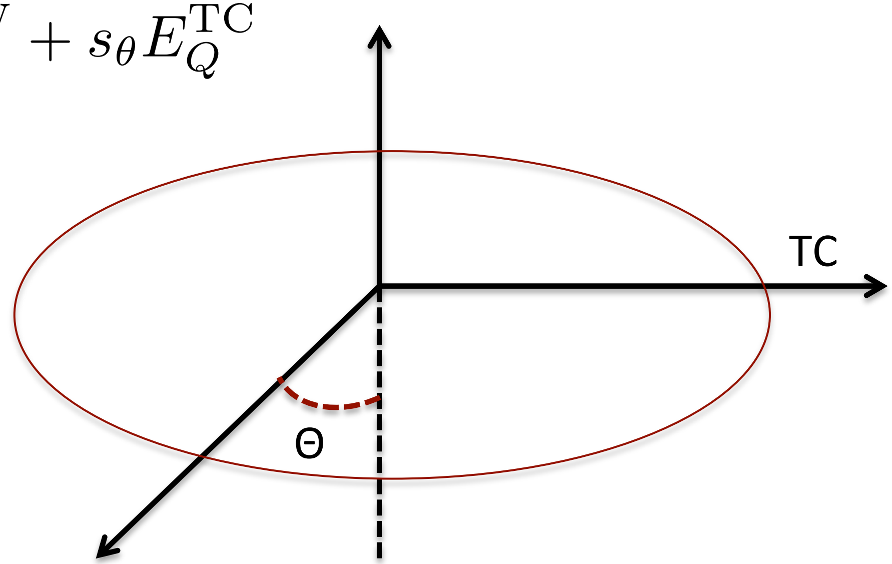
	$SU(2)_{TC}$	$SU(2)_W$	$U(1)_Y$
(U_L, D_L)	$\square$	$\square$	0
$\widetilde{U}_L$	$\square$	1	$-1/2$
$\widetilde{D}_L$	$\square$	1	$+1/2$

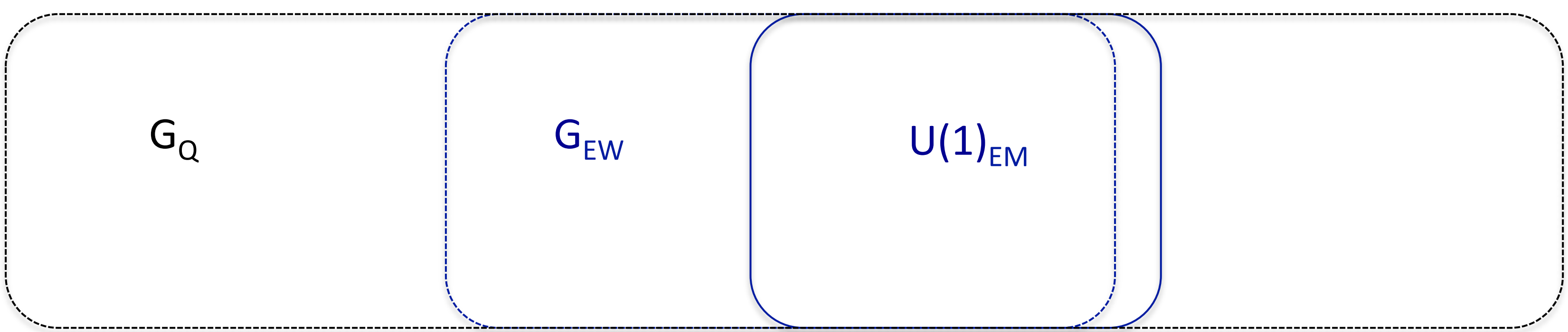
$$Q = \begin{pmatrix} U_L \\ D_L \\ \widetilde{U}_L \\ \widetilde{D}_L \end{pmatrix}$$

$$U(1) : Q \to e^{-\alpha} Q$$

Framework: Composite Dynamics

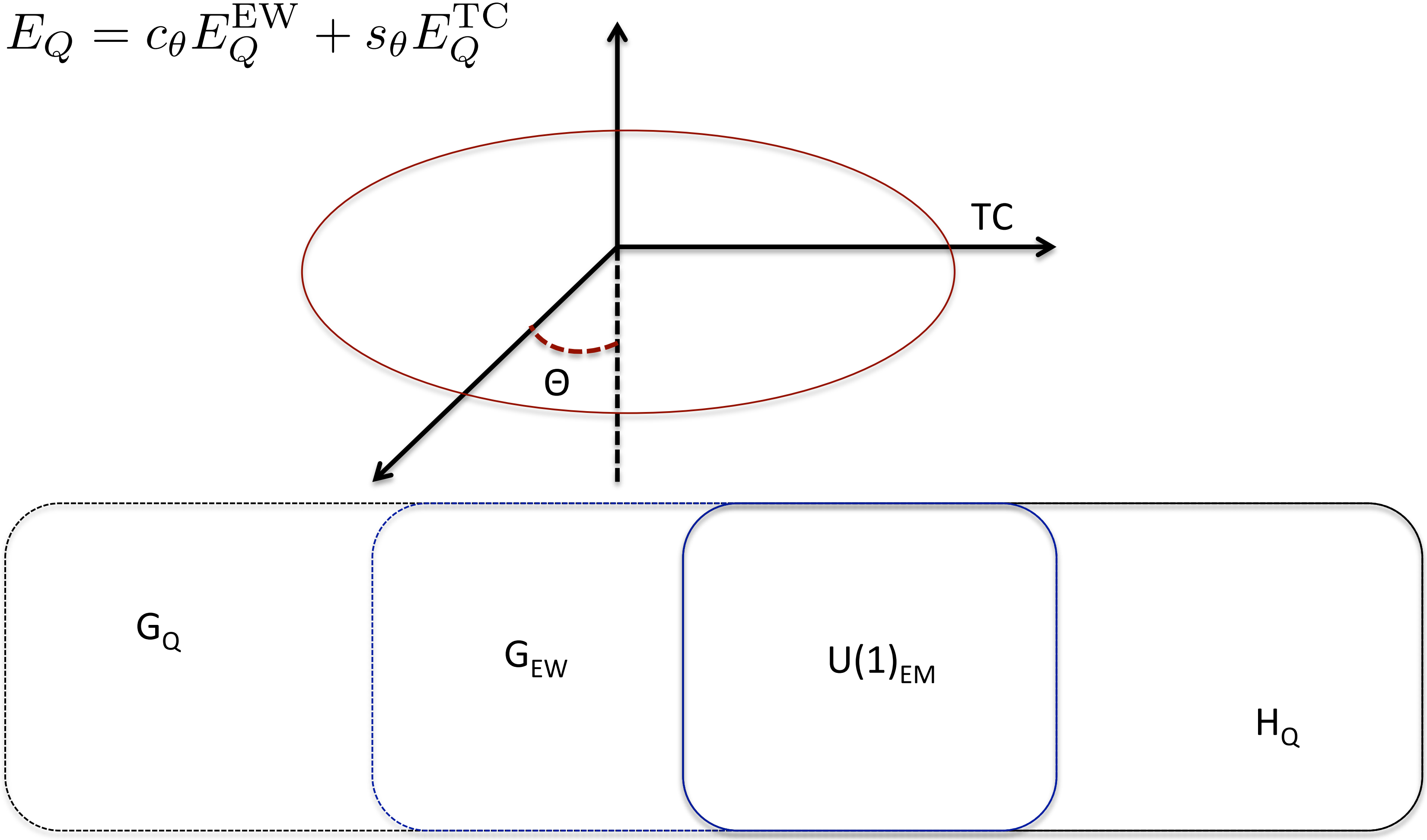
$$E_Q = c_\theta E_Q^{\rm EW} + s_\theta E_Q^{\rm TC}$$





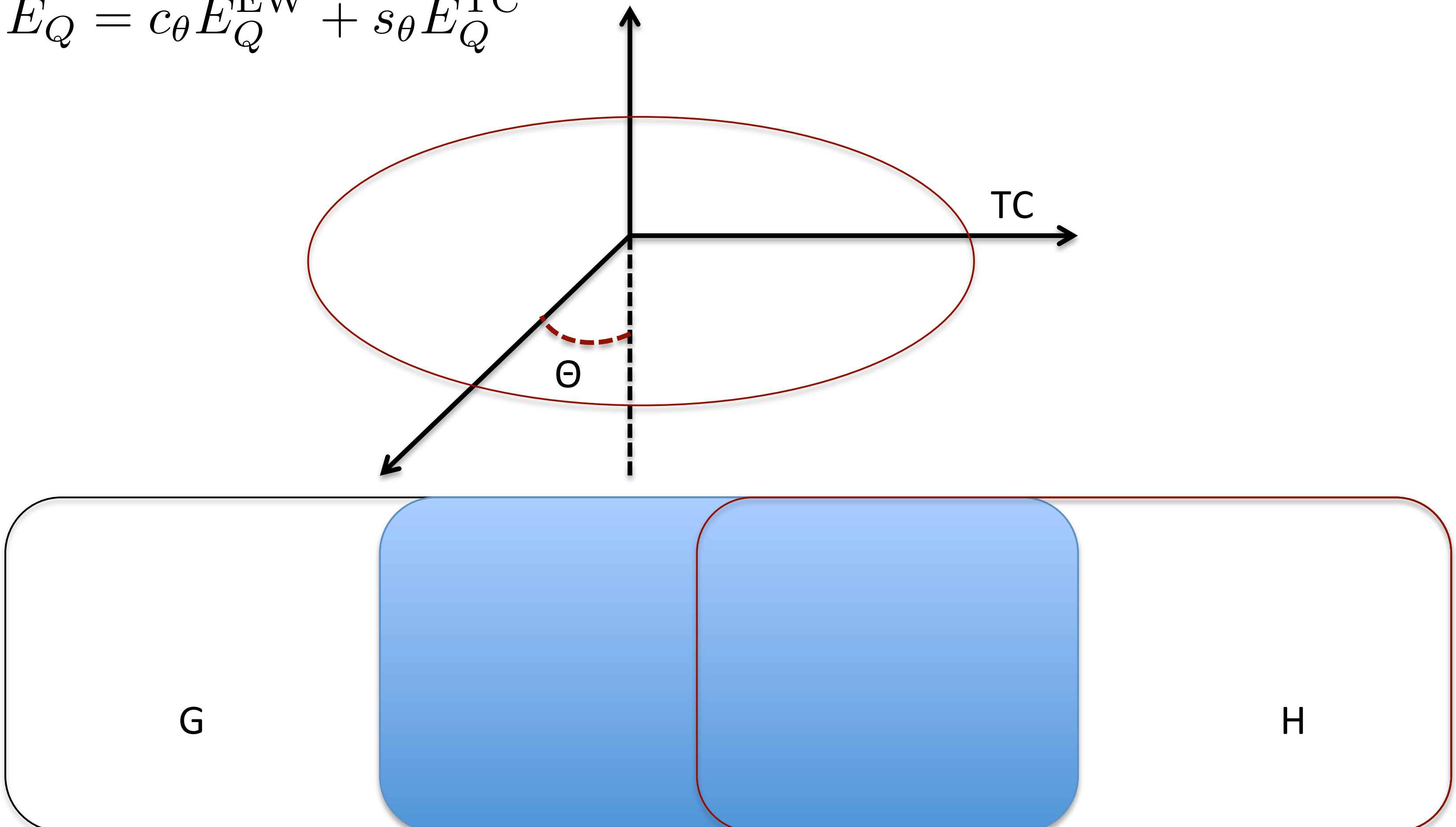
Framework: Composite Dynamics

$$E_Q = c_\theta E_Q^{\mathrm{EW}} + s_\theta E_Q^{\mathrm{TC}}$$

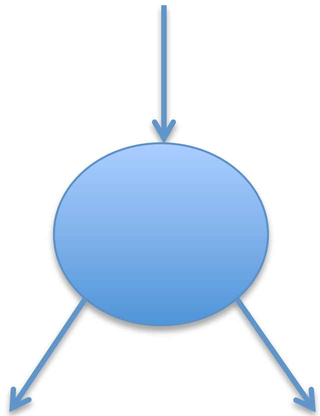


Framework: Composite Dynamics

$$E_Q = c_\theta E_Q^{\rm EW} + s_\theta E_Q^{\rm TC}$$

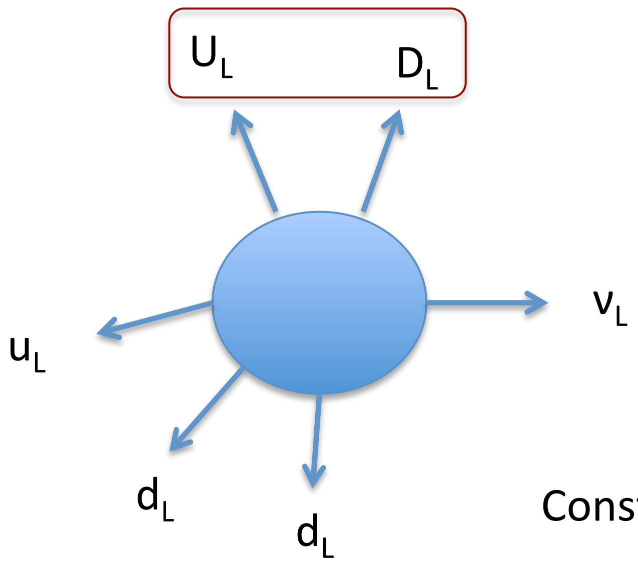


Framework: Composite Dynamics



Composites	$U(1)_{TB}$	$U(1)_{EM}$	Θ
$\Pi_{UD} \equiv (\Pi_Q^4 - i\Pi_Q^5)/\sqrt{2} \sim U^T C D$	$\frac{1}{\sqrt{2}}$	0	$\pi/2$
$\Pi_{\overline{UD}} \equiv (\Pi_Q^4 + i\Pi_Q^5)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	$\pi/2$
$\Pi^{\pm,0} \equiv \Pi^{1,2,3}$	0	$\pm 1, 0$	$\pi/2$

Framework: Composite Dynamics

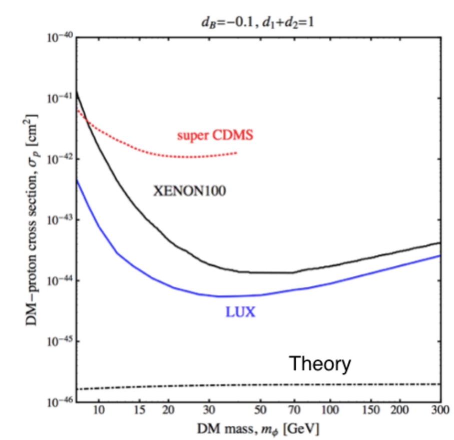


Composites	$U(1)_{TB}$	$U(1)_{EM}$	Θ
$\Pi_{UD} \equiv (\Pi^4_Q - i\Pi^5_Q)/\sqrt{2} \sim U^T C D$	$\frac{1}{\sqrt{2}}$	0	$\pi/2$
$\Pi_{\overline{UD}} \equiv (\Pi^4_Q + i\Pi^5_Q)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	$\pi/2$
$\Pi^{\pm,0} \equiv \Pi^{1,2,3}$	0	$\pm 1, 0$	$\pi/2$

Constrained by T-parameter

$$ie\frac{d_B}{\Lambda^2}\Pi^*_{UD}\overleftrightarrow{\partial_\mu}\Pi_{UD}\partial_\nu F^{\mu\nu}$$

Measured by Lattice (VMD)



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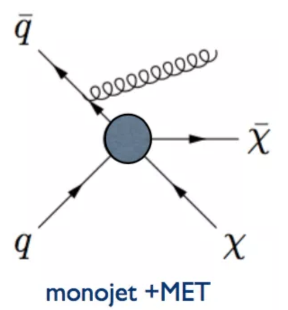
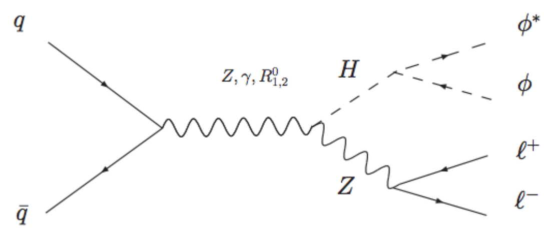
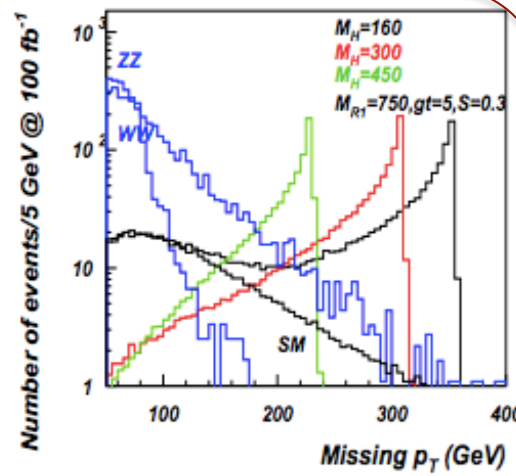
Composite DM Possible Features

- Resonances in collider searches ,
  e.g missing E_T searches

(U. Haisch talk ZPW19)





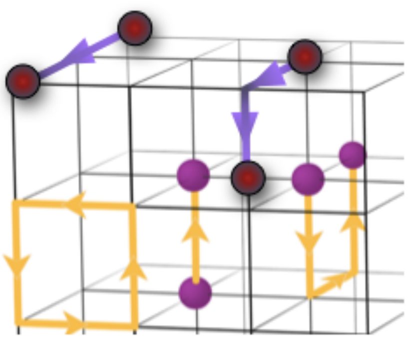


(Foadi, MTF, Sannino '08)

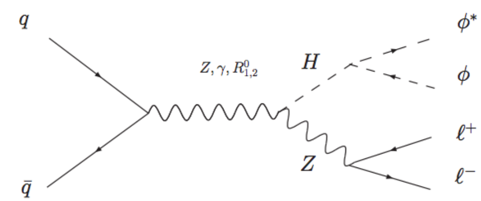
Composite DM Features

- lattice predictions and low mass DM, e.g. for direct detection, LHC (F. Petricca talk ZPW19)

SU(2) MWT model
m_{R1}=2.5 (0.5) TeV,
$\Lambda=m_{R1}$, $d_B = (m_U-m_D)/(m_U+m_D)$



(Arthur, Drach, Hansen, Hietanen, Lewis, Pica & Sannino ’14)



$$ie\frac{d_B}{\Lambda^2}\Pi^*_{UD}\overleftrightarrow{\partial_\mu}\Pi_{UD}\partial_\nu F^{\mu\nu}$$