The Scale of Dark QCD

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Lattice Meets Experiment 2013

arXiv: 1306.4676

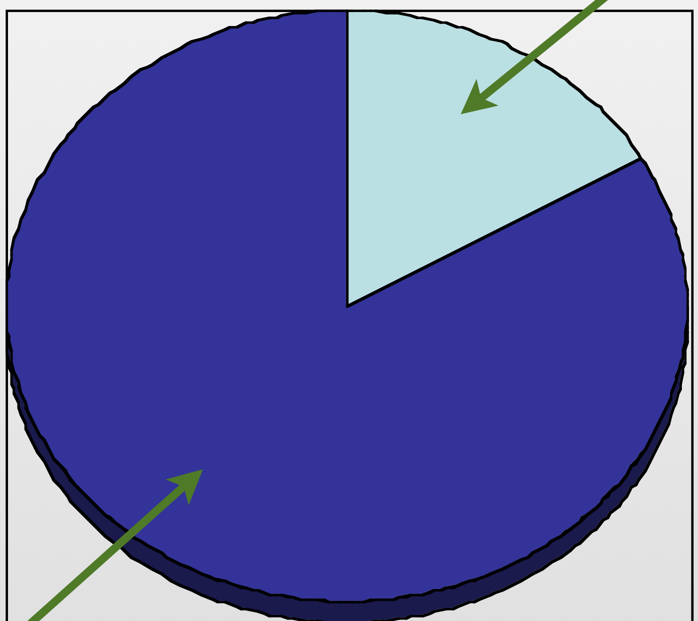
with **Pedro Schwaller** →

at CERN

Dec. 5, 2013

Dark Matter Energy Density

Ordinary Matter
15.5%



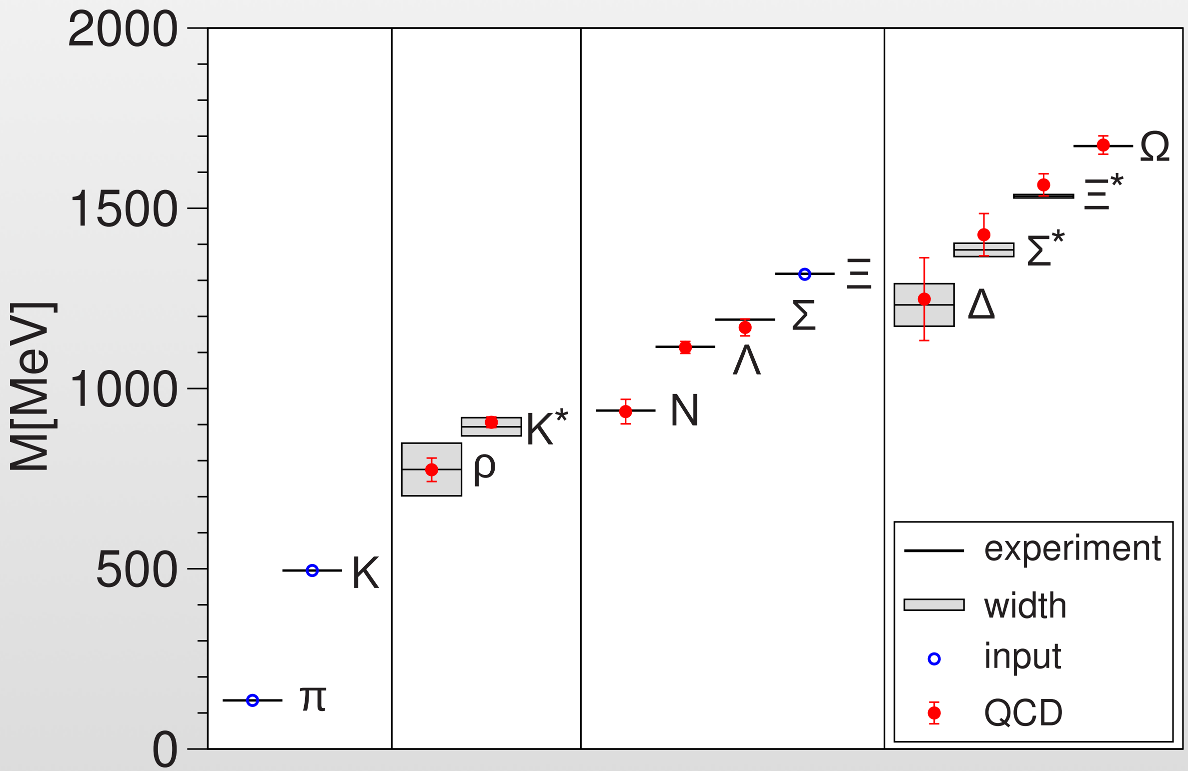
Dark Matter 84.5%

From Planck 2013

Ordinary Matter

The ordinary matter has its mass from protons and neutrons

Durr, et.al., Science 322, 1224 (2008)



90% of the mass of ordinary matter emerges from QCD

Introduction of Dark QCD

A simple-minded conjecture:

Dark QCD

dark quarks, dark pions,
dark baryons, dark axions
...

The dark matter has its mass from a "dark QCD"

Is it new?

TECHNOCOSMOLOGY – COULD A TECHNIBARYON EXCESS PROVIDE A "NATURAL" MISSING MASS CANDIDATE?

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Received 7 October 1985

asymmetric dark matter

TECHNICOLOR COSMOLOGY

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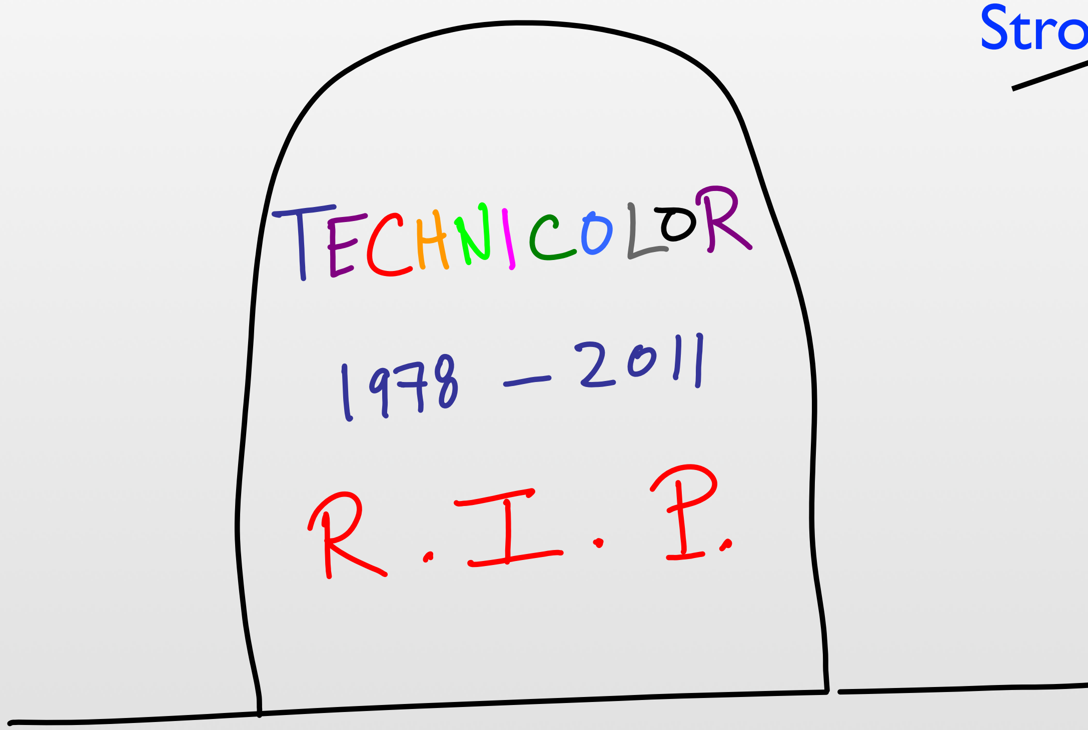
Received 16 June 1989

WIMP

The Discovery of Higgs Boson

~~Strong dynamics~~



Nima Arkani-Hamed, talk at SavasFest, May 2012

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.6 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\tau}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta$ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 275-430 GeV	$m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-200 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 271-520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e, μ (SS)	1 b	Yes	14.3	sgluon 800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

10^{-1} 1 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

we’ve seen this
for a while

time to add this?

some talk given by someone in the audience

The dynamics in the dark sector may have nothing to do with the electroweak symmetry breaking !!!

We need to study dark matter for its own purpose

One Number to Explain

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm Baryon}} = \frac{m_{\rm DM} n_{\rm DM}}{m_{\rm p} n_p} \approx 5 \sim 6$$

Most popular models: “WIMP miracle”

$$\Omega_{\rm DM} = \frac{s_0}{\rho_c} \left(\frac{45}{\pi g_*} \right)^{1/2} \frac{x_f}{m_{\rm pl}} \frac{1}{\langle \sigma v \rangle} \qquad \langle \sigma v \rangle \approx 1 \text{ pb} \approx \frac{\pi \alpha^2}{8 m_{\rm DM}^2}$$

for $m_{\rm DM} = 100$ GeV

This could be just one option:

dark matter is related to the electroweak scale

Two Options in dark QCD

- Thermal dark matter (not necessarily weakly-interaction)

$$\langle \sigma v \rangle \approx 1 \text{ pb} \qquad \langle \sigma v \rangle \approx \frac{g_\chi^4}{4\pi m_{\rm DM}^2} \approx \frac{(4\pi)^2}{4\pi m_{\rm DM}^2}$$

- Asymmetric dark matter

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm Baryon}} = \frac{m_{\rm DM} n_{\rm DM}}{m_{\rm p} n_p} \approx 5 \sim 6$$

Two conditions:

(1): $n_{\rm DM} \sim n_p$

(2): $m_{\rm DM} \sim m_p$

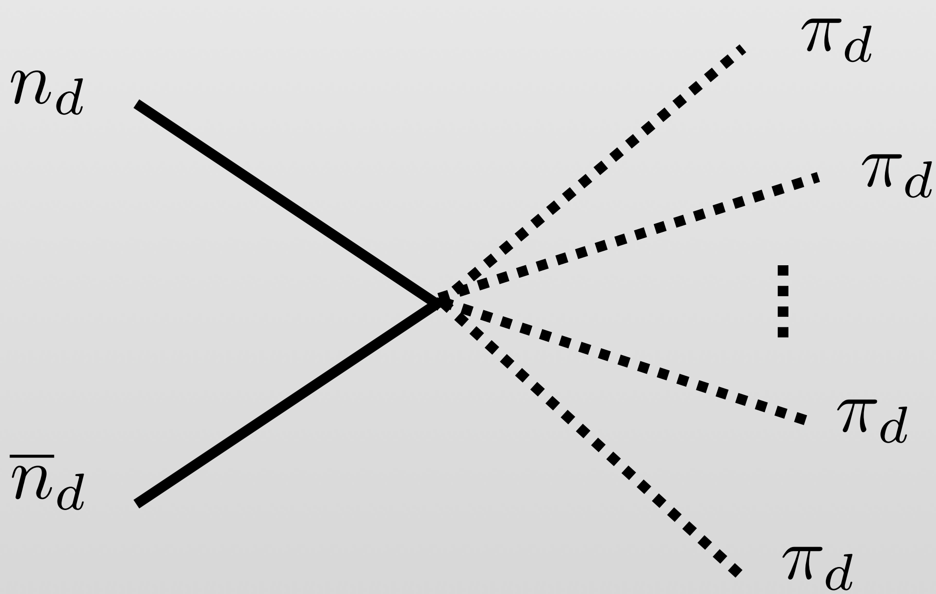
Thermal Dark Baryon

- For simplicity, we just use $SU(N_d = 3)$ as dark QCD gauge group. With two flavors of dark quarks, the "dark neutron" could be the dark matter candidate

It is a Dirac dark fermion:

general study for Dirac DM:
Harnik and Kribs: 0810:5557

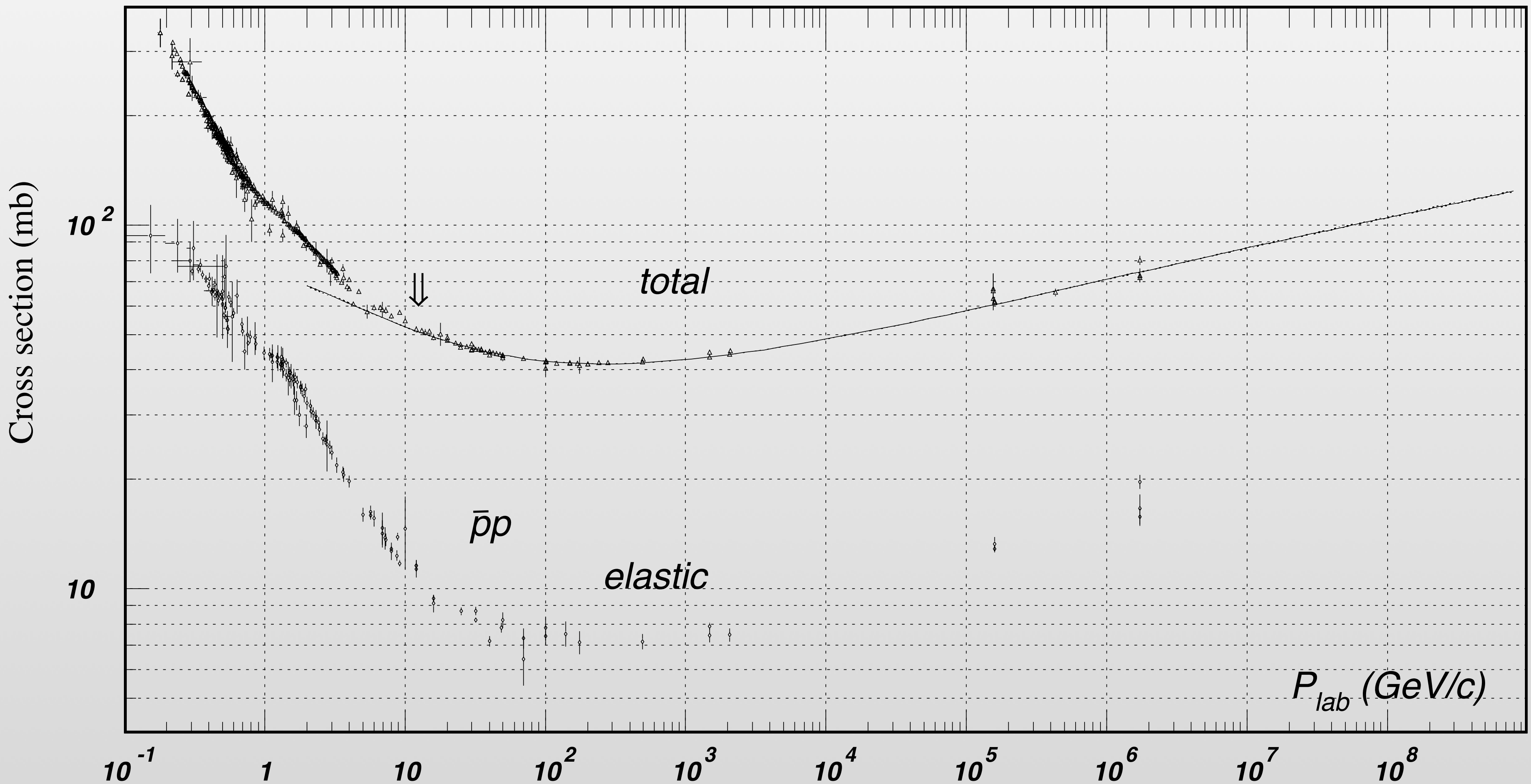
It is not p-wave suppressed; however:



π_d then decays to SM particles

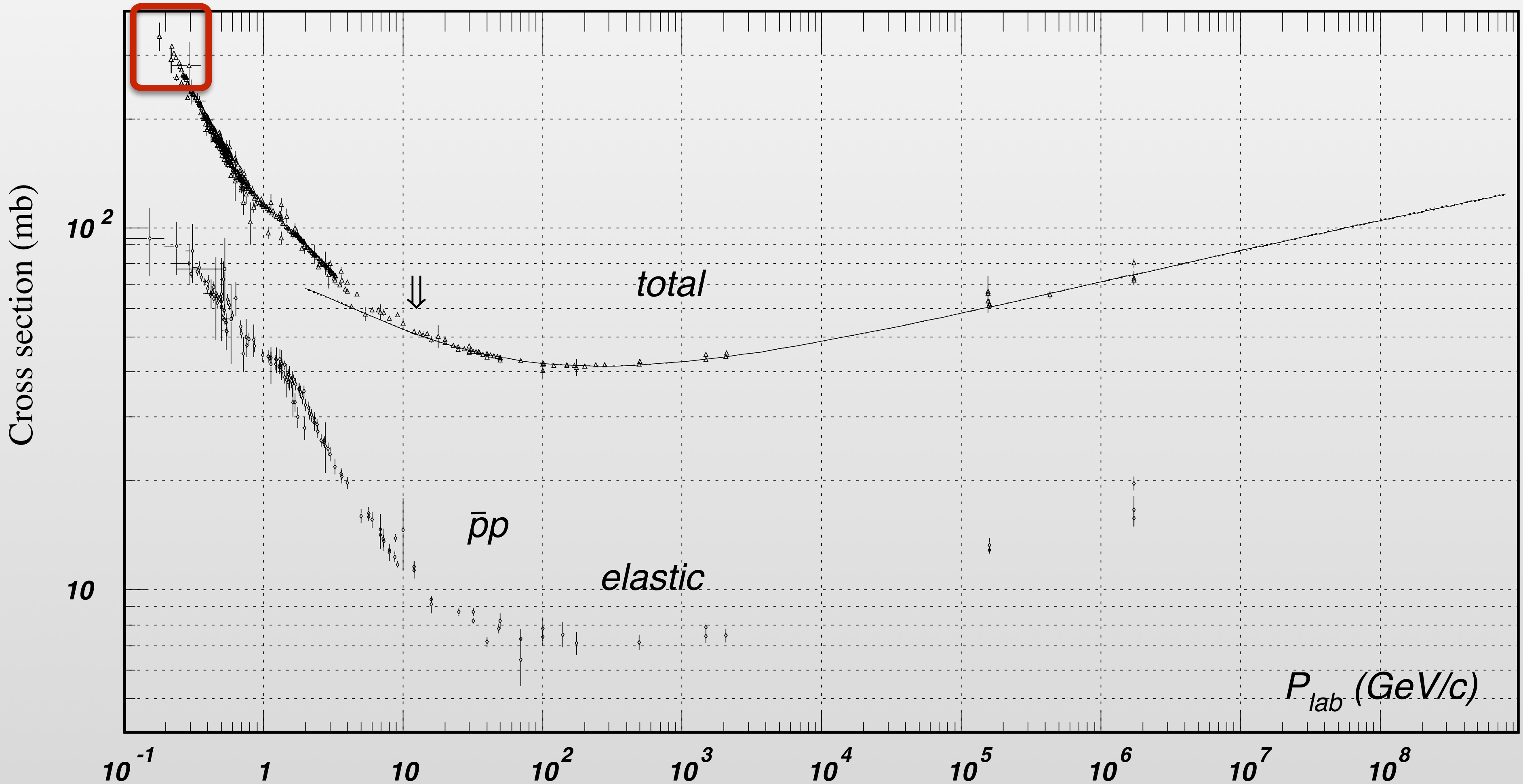
Thermal Dark Baryon

- Fortunately, we have experimental data from our QCD sector



Thermal Dark Baryon

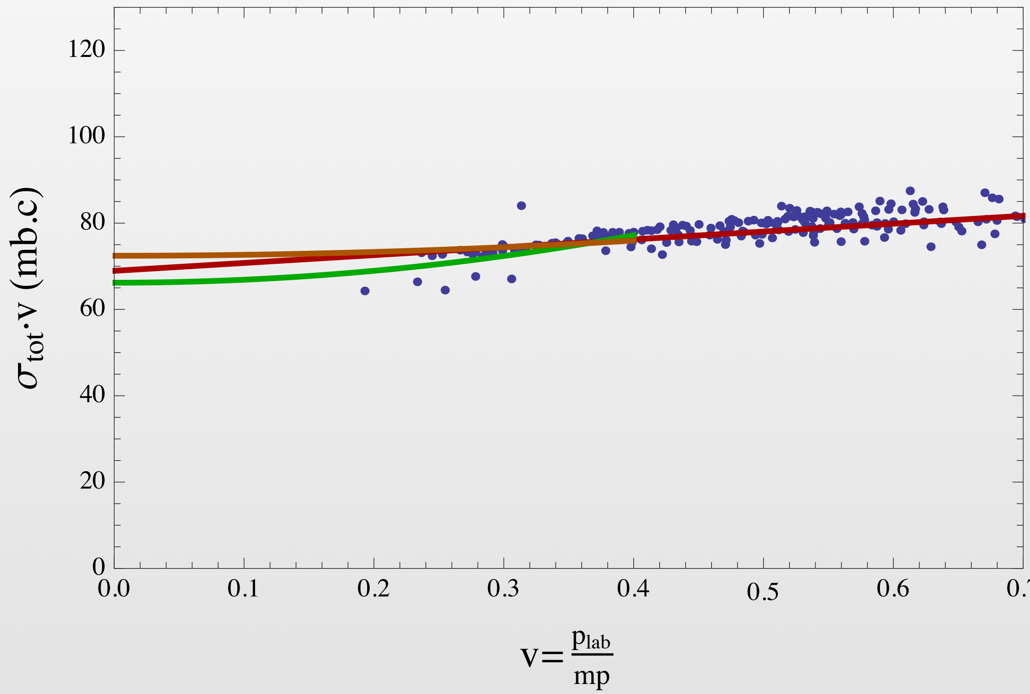
- Fortunately, we have experimental data from our QCD sector



Thermal Dark Baryon

- Use polynomial to fit the data

YB, Draper, Lu, in progress

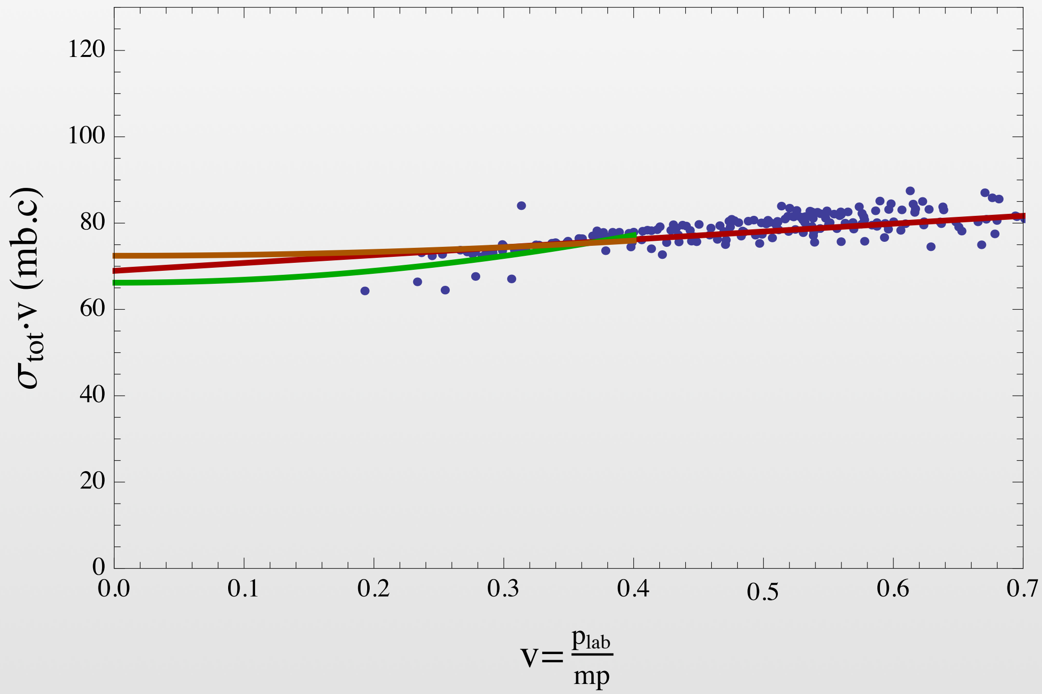


$$(\sigma \cdot v)_{n_d \bar{n}_d} = (\sigma \cdot v)_{p\bar{p}} \frac{m_p^2}{m_{\text{dark neutron}}^2}$$

Thermal Dark Baryon

- Use polynomial to fit the data

YB, Draper, Lu, in progress



$$(\sigma \cdot v)_{n_d \bar{n}_d} = (\sigma \cdot v)_{p\bar{p}} \frac{m_p^2}{m_{\text{dark neutron}}^2}$$

relic abundance calculation $\longrightarrow$ $m_{\text{dark neutron}} \approx 150\ \text{TeV}$

Thermal Dark Baryon

- Too high for the current hadron colliders
- Direct detection can still probe the thermal dark neutron

a) Tree-level coupling to Z boson

b) Dimension-5 operator:

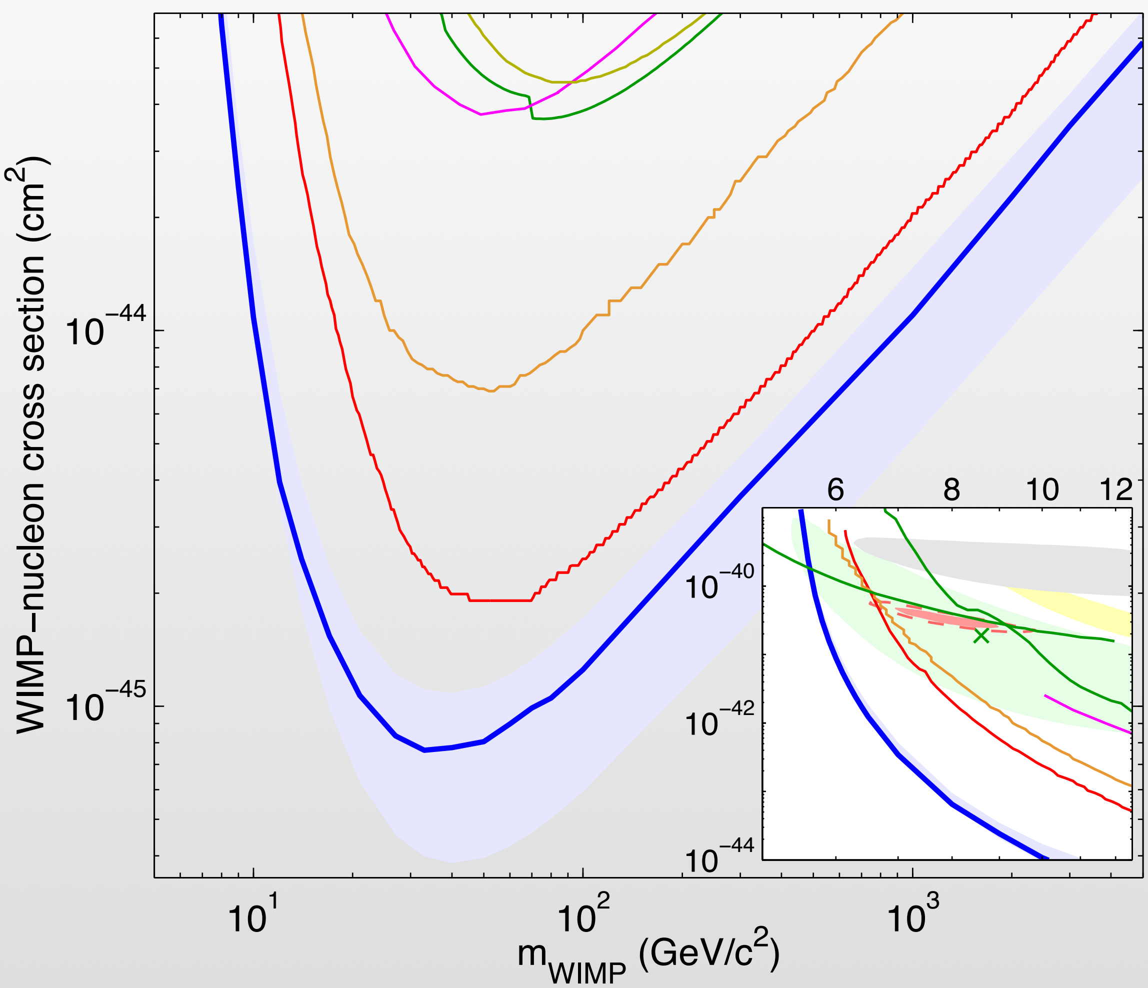
LSD collaboration, 1301.1693

$$\frac{e}{\Lambda_{\rm dQCD}}\,\overline{n}_d\sigma^{\mu\nu}n_d\,F_{\mu\nu}$$

c) Dimension-7 operator:

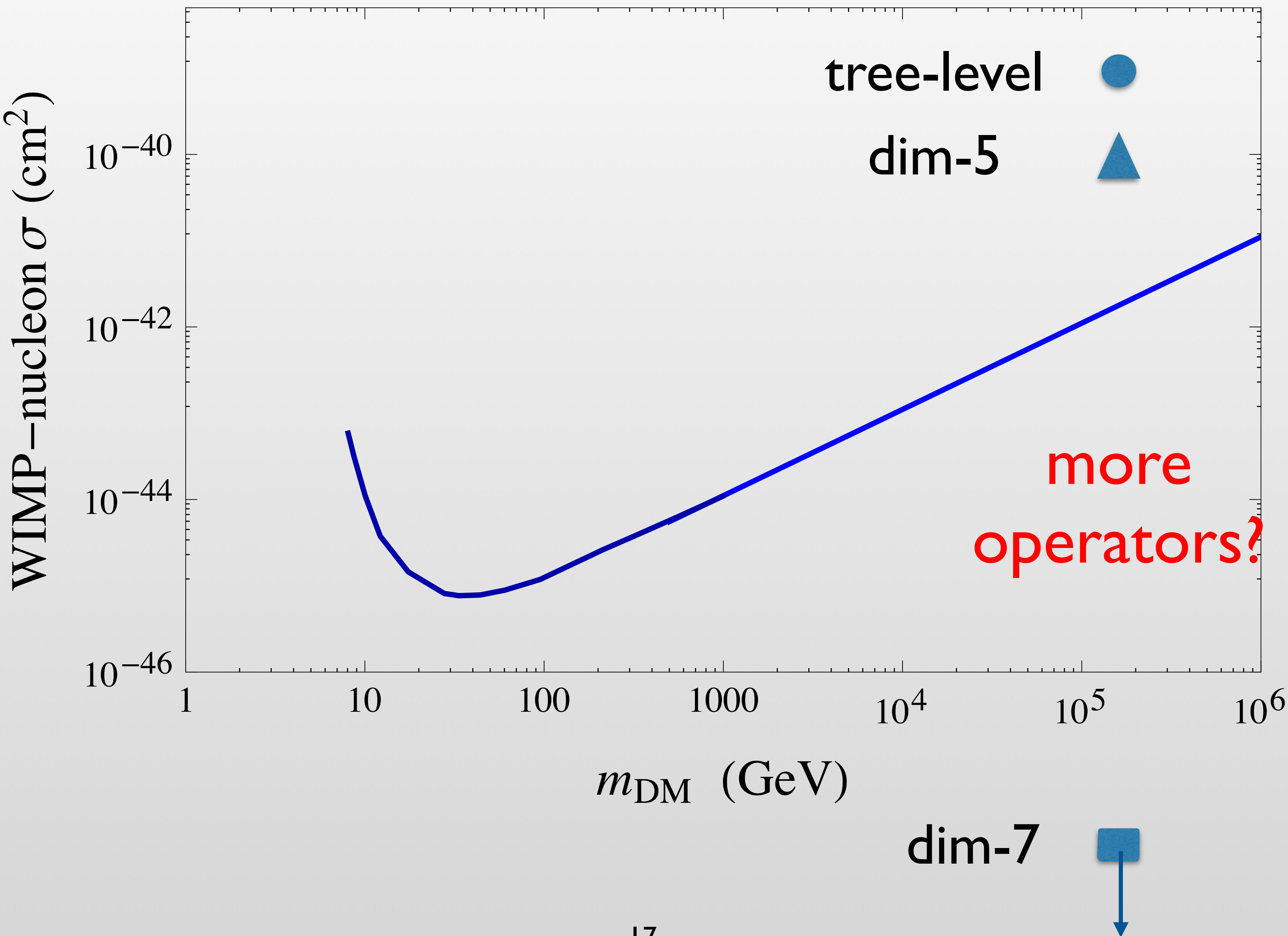
$$\frac{g_s^2}{\Lambda_{\rm dQCD}^3}\,\overline{n}_d n_d\,(G^a_{\mu\nu})^2$$

Direct Detection from LUX



at higher masses, the limits become weaker and are proportional to the dark matter mass

Direct Detection from LUX



- Thermal dark matter

- Asymmetric dark matter

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm Baryon}} = \frac{m_{\rm DM} n_{\rm DM}}{m_{\rm p} n_p} \approx 5 \sim 6$$

Two conditions:

(1): $n_{\rm DM} \sim n_p$

(2): $m_{\rm DM} \sim m_p$

(1): $n_{\rm DM} \sim n_p$

The first condition can be satisfied by introducing some non-trivial number density history

Barr, Chivukula, Farhi, PLB, 241, 387 (1990)

David B. Kaplan, PRL, 68, 741 (1992)

Dodelson, Greene, Widrow, NPB, 372, 467 (1992)

Fujii, Yanagida, PLB, 542, 80 (2002)

Kitano, Low, PRD, 71, 023510 (2005)

Farrar, Zaharijas, PRL, 96, 041302 (2006)

Gudnason, Kouvaris, Sannino, PRD, 73, 115003 (2006)

Kaplan, Luty, Zurek, PRL, 79, 115016 (2009)

Shelton, Zurek, PRD, 82, 123512 (2010)

Davoudiasl, Morrissey, Sigurdson, Tulin, PRL, 105, 211304 (2010)

Buckley, Randall, JHEP, 1109, 009 (2011)

....

(2): $m_{\rm DM} \sim m_p$

The dark matter could be like ordinary baryons from an asymmetry mechanism

The dark matter mass is related to the QCD scale

If dark matter is a "dark baryon" from a new QCD-like strong dynamics in the dark matter sector

$$\Lambda_{\rm dQCD} \sim \Lambda_{\rm QCD} \quad ?$$

Need to have QCD and dQCD gauge couplings related to each other

Dimensional Transmutation

$$\Lambda^2_{\rm QCD} \approx M^2_{\rm Pl}\, e^{4\pi/[\beta_0^s\, \alpha_s(M^2_{\rm Pl})]} \qquad \beta_0 < 0$$

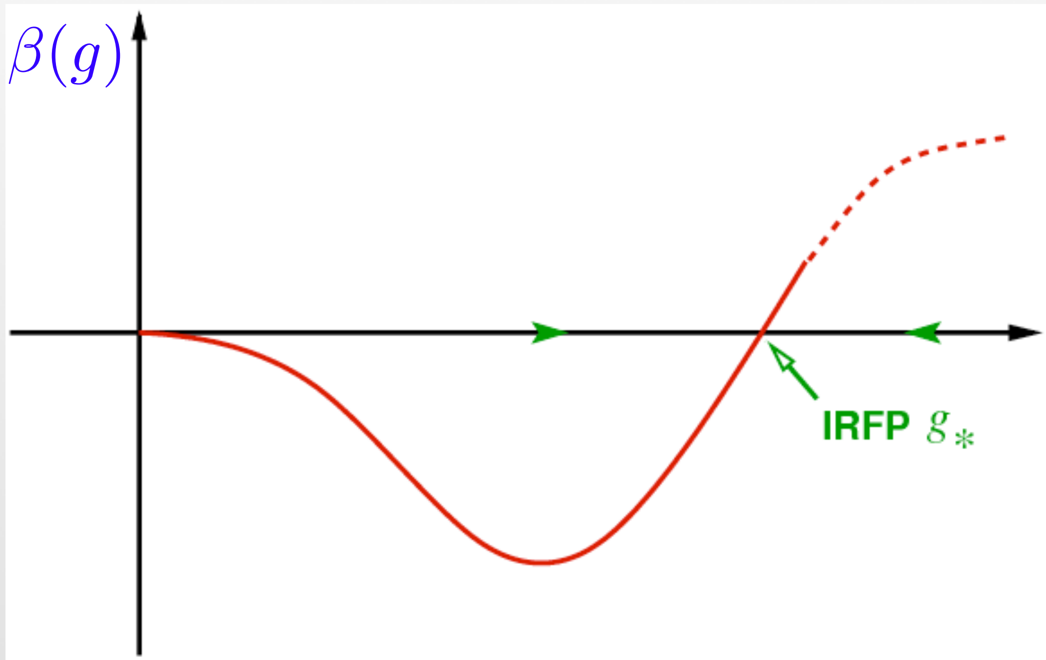
$$\Lambda^2_{\rm dQCD} \approx M^2_{\rm Pl}\, e^{4\pi/[\beta_0^d\, \alpha_d(M^2_{\rm Pl})]}$$

The confinement scale is sensitive to the beta function (matter content) and the coupling at a UV scale

Need a mechanism to relate the gauge couplings of two gauge groups in an infrared scale

Our idea

Banks-Zaks fixed point



Particles charged under both gauge groups can induce Infrared Fixed Points (IRFP) and have both gauge couplings related to each other in the IR

Matter Content

$$G_{\text{gauge}} = SU(N_c)_{\text{QCD}} \times SU(N_d)_{\text{dQCD}}$$

Field	$SU(N_c)_{\text{QCD}}$	$SU(N_d)_{\text{darkQCD}}$	multiplicity
SM fermion	N_c	1	n_{f_c}
SM scalar	N_c	1	n_{s_c}
DM fermion	1	N_d	n_{f_d}
DM scalar	1	N_d	n_{s_d}
joint fermion	N_c	N_d	n_{f_j}
joint scalar	N_c	N_d	n_{s_j}

a general matter content

upper bounds on multiplicities from asymptotic freedom

Gauge Coupling Running

$$\frac{dg_c}{d(\log\mu)} = \beta_c(g_c, g_d)\,, \qquad\qquad \frac{dg_d}{d(\log\mu)} = \beta_d(g_c, g_d)$$

Jones, PRD, 25, 581 (1982)

$$\begin{aligned}
\beta_c(g_c, g_d) \;=\; & \frac{g_c^3}{16\pi^2}\left[\frac{2}{3}\,T(R_f)\,2(n_{f_c} + N_d\, n_{f_j}) + \frac{1}{3}\,T(R_s)\,(n_{s_c} + N_d\, n_{s_j}) - \frac{11}{3}\,C_2(G_c)\right] \\
& + \frac{g_c^5}{(16\pi^2)^2}\left[\left(\frac{10}{3}C_2(G_c) + 2C_2(R_f)\right)\,T(R_f)\,2\,(n_{f_c} + N_d\, n_{f_j})\right. \\
& \qquad \left. + \left(\frac{2}{3}C_2(G_c) + 4C_2(R_s)\right)\,T(R_s)\,(n_{s_c} + N_d\, n_{s_j}) \;-\; \frac{34}{3}\,C_2^2(G_c)\right] \\
& + \frac{g_c^3\, g_d^2}{(16\pi^2)^2}\left[2C_2(R_f)\,T(R_f)\,2\,N_d\, n_{f_j} \;+\; 4C_2(R_s)\,T(R_s)\,N_d\, n_{s_j}\right]\,.
\end{aligned}$$

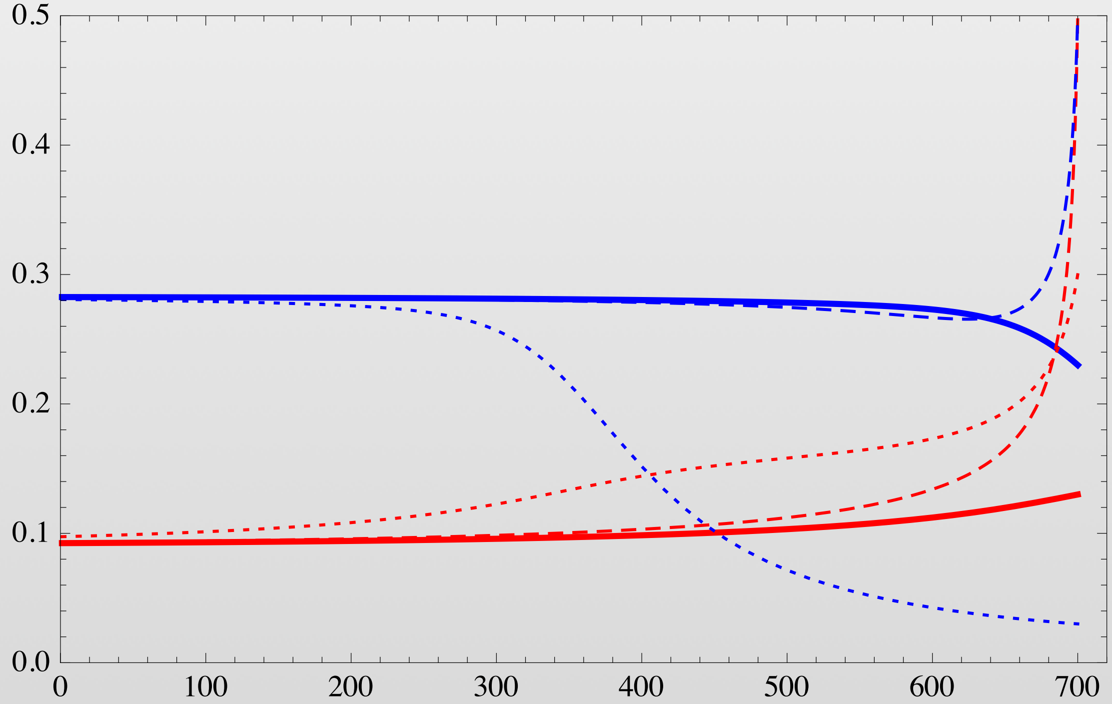
$$c \leftrightarrow d \qquad \text{for} \qquad \beta_d(g_c, g_d)$$

Infrared Fixed Point

$$\beta_c(g_c, g_d) = \beta_d(g_c, g_d) = 0$$

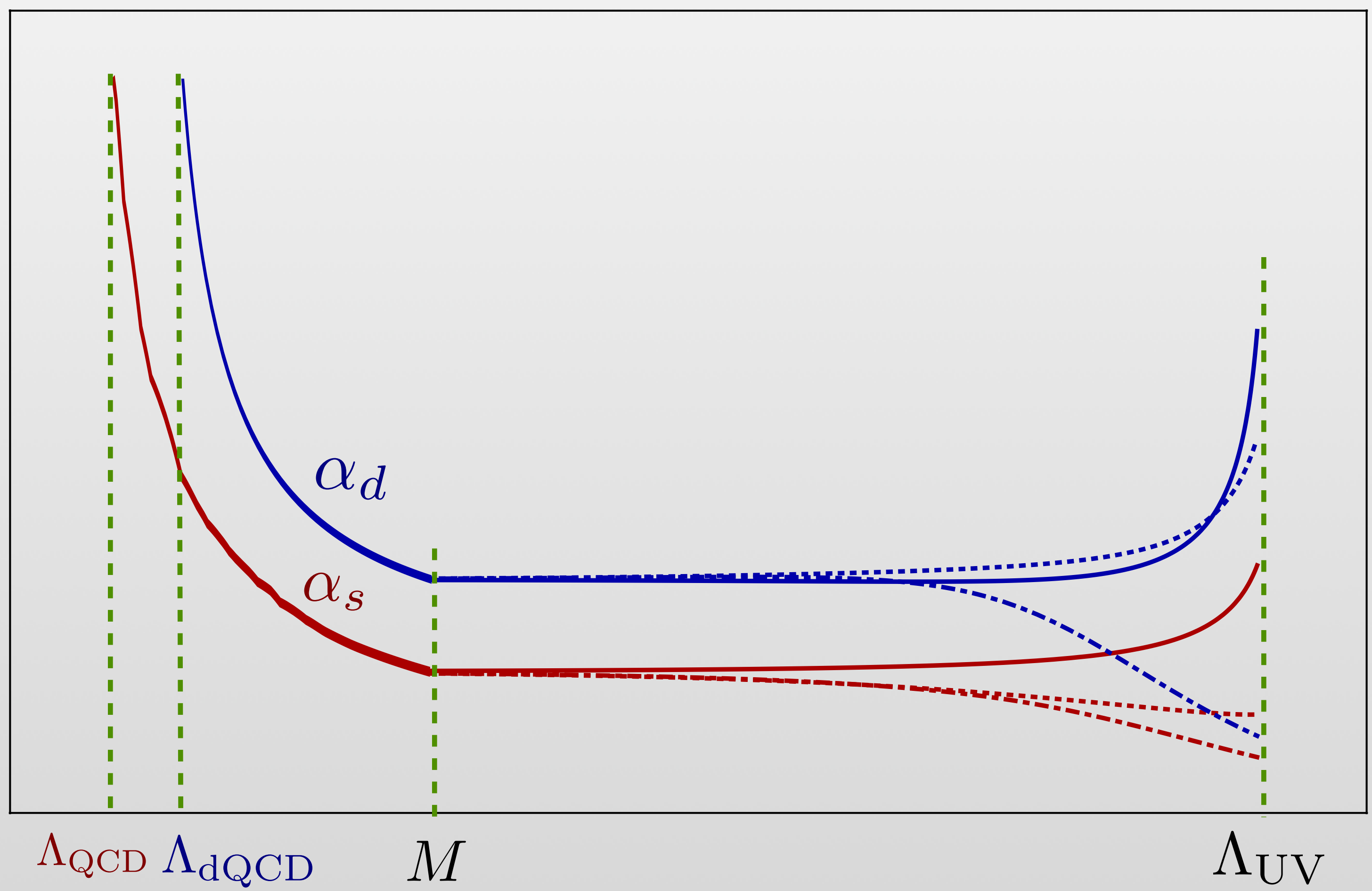
$$\alpha_s^* \equiv \alpha_s^*(n_{f_c}, n_{s_c}, n_{f_d}, n_{s_d}, n_{f_j}, n_{s_j})$$

$$\alpha_d^* \equiv \alpha_d^*(n_{f_c}, n_{s_c}, n_{f_d}, n_{s_d}, n_{f_j}, n_{s_j})$$



Dark QCD Scales

Decouple all particles except dark quarks at a common scale M



Dark QCD Scales

$$\alpha_s(M_Z) + \alpha_s^*$$

$$\swarrow \qquad \downarrow$$

$$\Lambda_{\rm QCD} \qquad M$$

$$+\ \alpha_d^*$$

$$\downarrow$$

$$\alpha_d(\Lambda_{\rm dQCD})$$

$$\downarrow$$

$$\Lambda_{\rm dQCD}$$

Estimation of Dark Baryon Masses

Require non-perturbative tools like Lattice QCD

Following the analysis of the Cornwall, Jackiw, Tomboulis effective potential for chiral symmetry breaking, one has

$$\alpha_d C_2(R_f) > \pi/3 \qquad \alpha_d > \pi/4$$

Using this condition to approximately determine the confinement scales, we have

$$m_p \approx 1.5\Lambda_{\rm QCD}$$

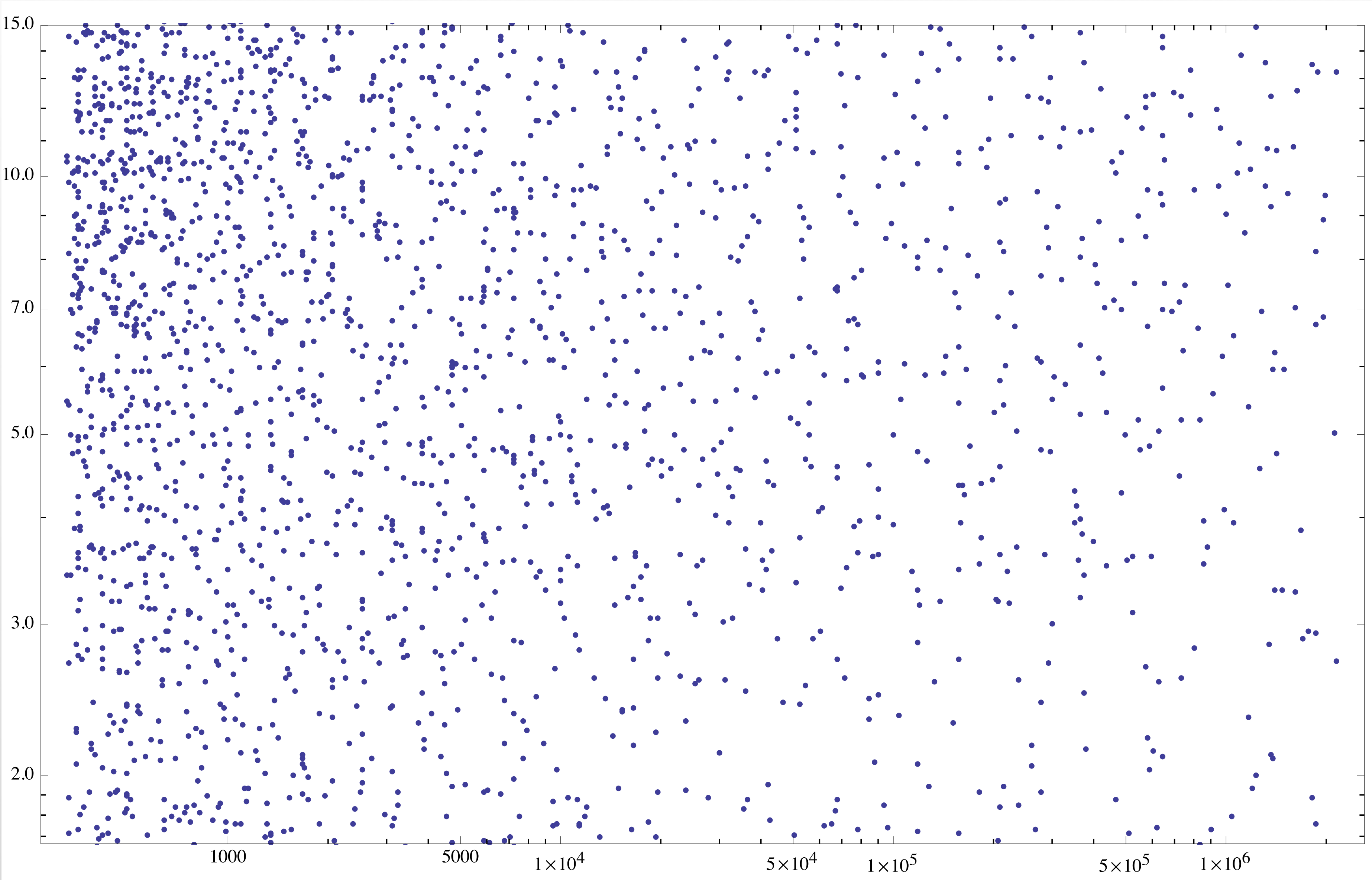
Lattice inputs required

so, $$m_D \approx 1.5\Lambda_{\rm dQCD}$$

A Sample of Representations

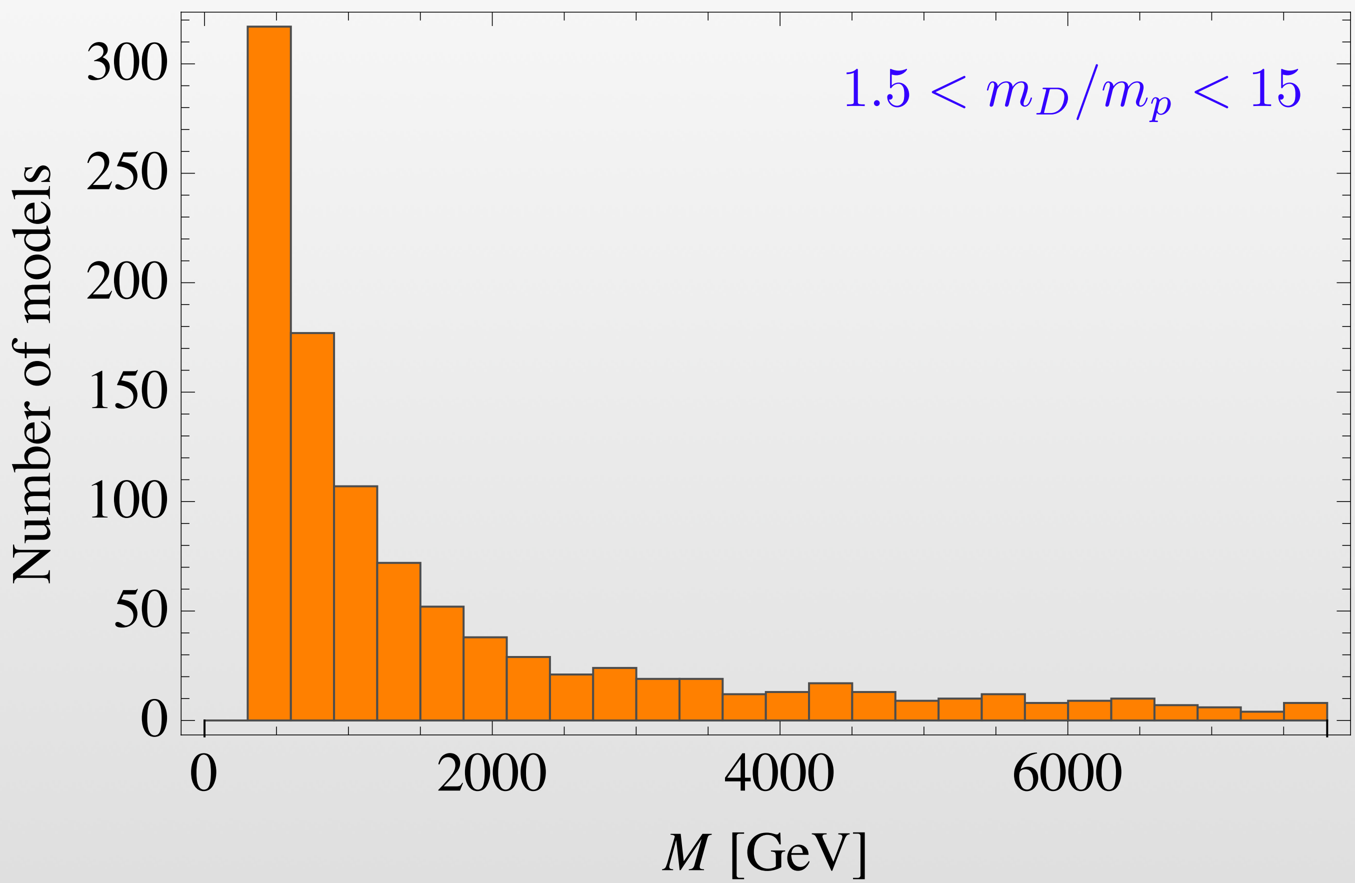
Model	n_{f_c}	n_{f_d}	n_{f_j}	n_{s_c}	n_{s_d}	n_{s_j}	α_s^*	α_d^*	M (GeV)	m_D (GeV)
A	6	5	3	0	2	0	0.095	0.175	518	31
B	6	6	3	1	0	0	0.083	0.120	2030	8.6
C	6	6	3	2	2	0	0.070	0.070	13500	0.32
D	7	7	2	2	0	2	0.078	0.168	3860	72
E	7	7	2	2	1	2	0.090	0.133	869	3.5
F	8	8	2	2	0	1	0.074	0.149	7700	29
G	8	8	2	2	1	1	0.082	0.118	2244	1.2

Many Models



15.0
10.0
7.0
5.0
3.0
2.0
1000
5000
1×10^4
5×10^4
1×10^5
5×10^5
1×10^6

Statistic Distribution of M



The bi-fundamental of QCD and dark QCD prefers to have masses below 2 TeV

Example Model for Number Density

(I): $n_{\rm DM} \sim n_p$

The general idea: generating asymmetry for the bi-fundamental particles

$$\Phi : \ (\bar{3}, 3)_{1/3}$$

The baryon and dark baryon have comparable number densities from its decay

$$\Phi \to X_L \bar{d}_R$$

$$\downarrow$$

$$n_D \sim n_p$$

Asymmetry of the bi-fundamental

$$\mathcal{L} \supset k_i \bar{Y}_1 \Phi N_i + \text{h.c.}.$$

Generate number asymmetries for $\quad \Delta n_\Phi = -\Delta n_{Y_1}$

$$\epsilon = \frac{\Gamma(N_1 \to Y_1 \Phi^\dagger) - \Gamma(N_1 \to \bar{Y}_1 \Phi)}{\Gamma(N_1 \to Y_1 \Phi^\dagger) + \Gamma(N_1 \to \bar{Y}_1 \Phi)} \approx -\frac{3}{2}\frac{1}{8\pi}\frac{\Im m[k_1^2 (k_2^*)^2]}{|k_1|^2}\frac{M_1}{M_2}$$

$$\mathcal{L} \supset \kappa_1 \Phi \bar{Y}_1^c Y_2 + \kappa_2 \Phi \bar{Y}_2 e_R + \kappa_3 \Phi \bar{X}_L d_R + \text{h.c.},$$

$$Y_1 \to \bar{Y}_2 \Phi^\dagger \qquad Y_2 \to \Phi e_R$$

$$\downarrow$$

$$\Delta n_\Phi = -3 \Delta n_{Y_1}$$

Asymmetries of Baryon and Dark Baryon

Without weak interaction and electroweak sphaleron processes

$$\Phi \to X_L \bar{d}_R \longrightarrow \begin{aligned} \Delta n_{d_R} &\equiv 3\, n_B = 3\, \Delta n_{Y_1}\,, \\ \Delta n_{e_R} &\equiv n_L = -\Delta n_{Y_1}\,, \\ \Delta n_X &\equiv 3\, n_D = -3\, \Delta n_{Y_1}\,, \end{aligned}$$

After taking the weak processes into account

$$n_B = \frac{28}{79} n_{B-L}$$

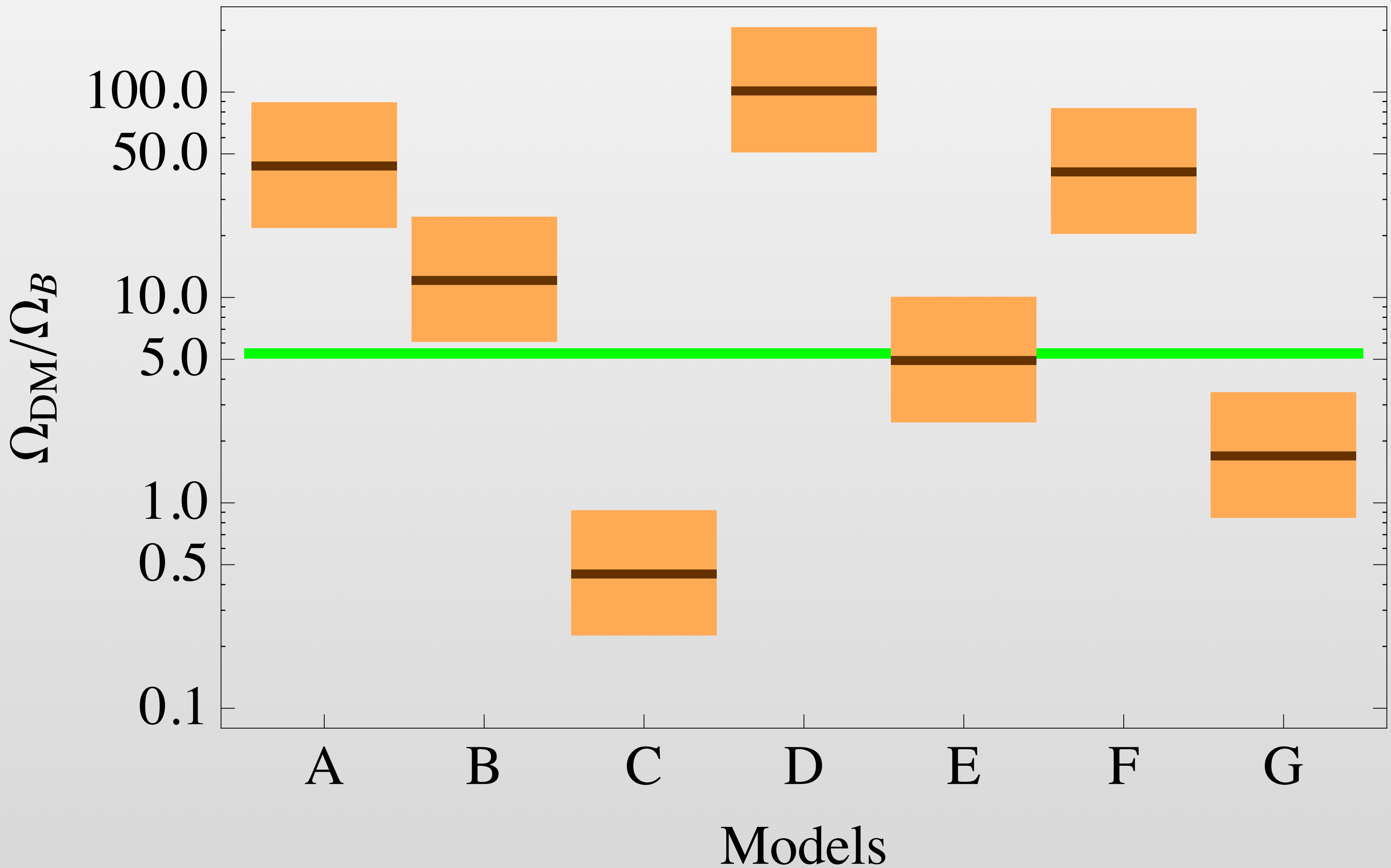
Chung, Garbrecht, Tulin
arXiv:0807.2283

$$\downarrow$$

$$\frac{|n_D|}{n_B} = \frac{79}{56}$$

Ratios of Energy Densities

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm Baryon}} = \frac{n_D m_D}{n_B m_p} \approx \frac{79}{56}\frac{m_D}{m_p}$$



Dark Matter Phenomenology

All relevant phenomenology depends on the bi-fundamental particles, which have a mass at 1-2 TeV

Integrate out the Φ field

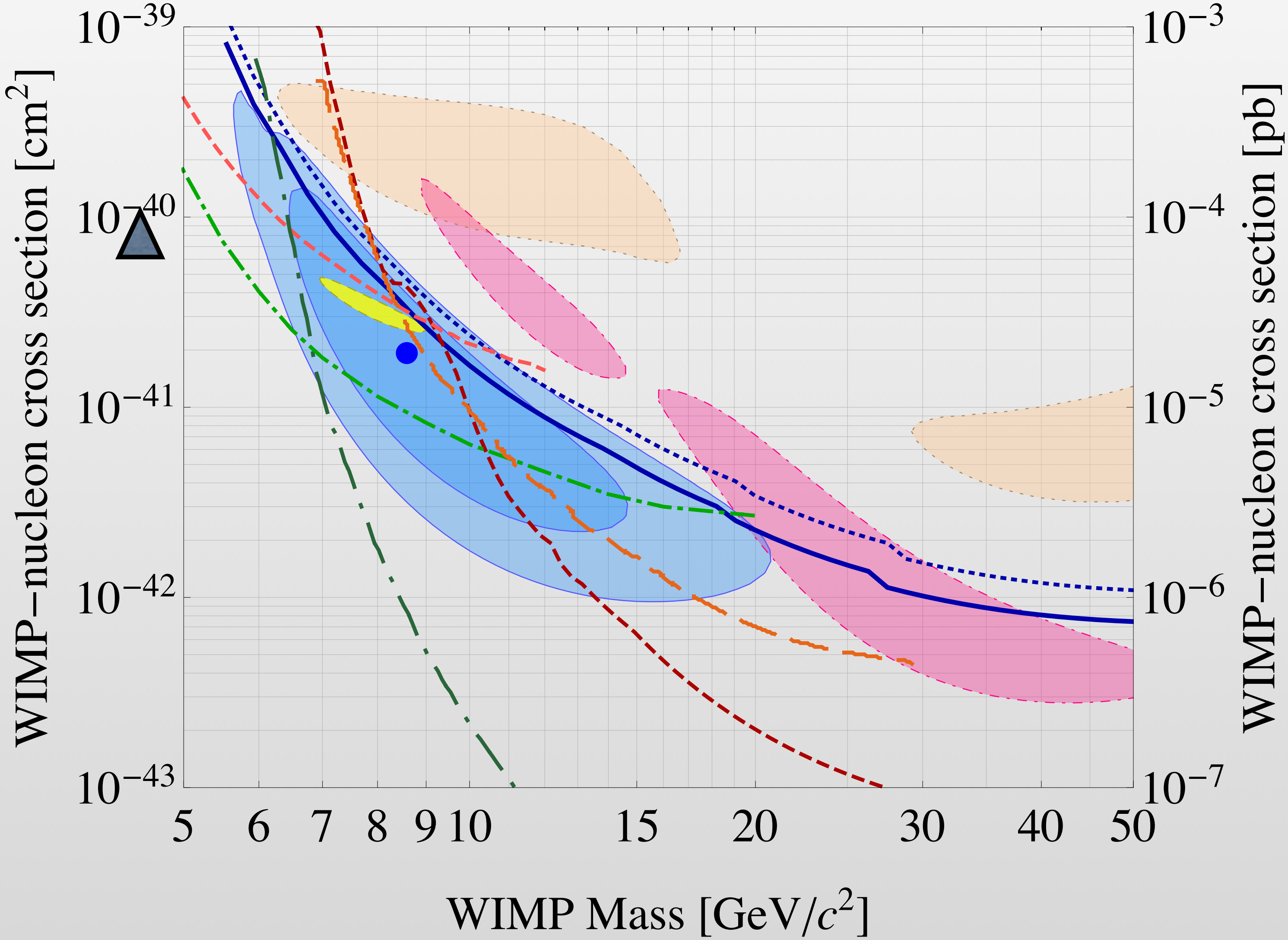
$$\frac{\kappa_3^2\,\overline{X}_L\gamma_\mu X_L\,\overline{d}_R\gamma^\mu d_R}{M_\Phi^2}$$

Spin-independent dark baryon-neutron cross section

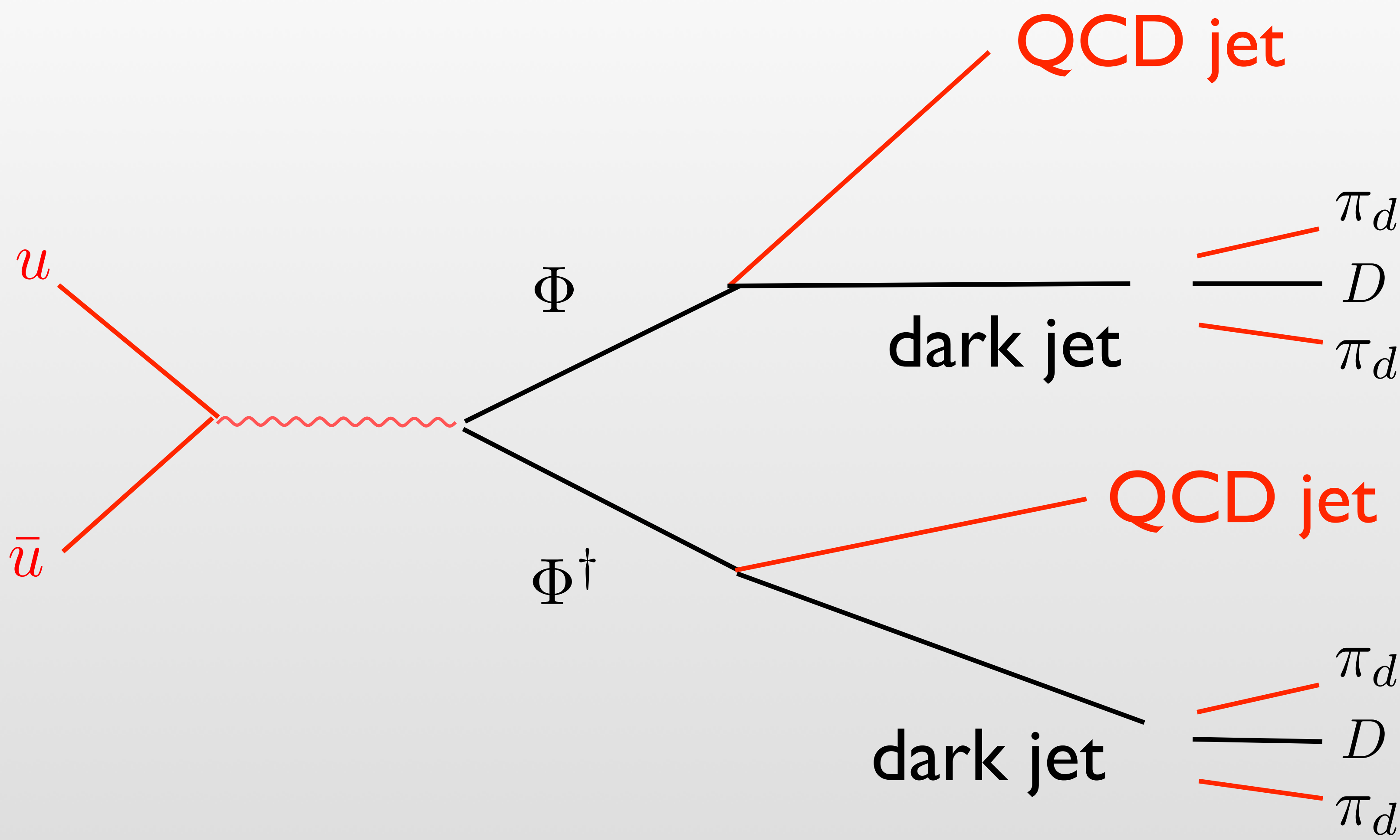
$$\sigma_{D-n}^{\rm SI} = \frac{2^2\,3^2\,\kappa_3^4\,\mu_{D-n}^2}{16\,\pi\,M_\Phi^4} = \left(\frac{1\ \mathrm{TeV}}{M_\Phi/\kappa_3}\right)^4 \times 3\times 10^{-40}\ \mathrm{cm}^2$$

Dark Matter Phenomenology

CDMS, 1304.4279



Collider Phenomenology



missing energy is dramatically reduced

Conclusions

- ★ Thermal dark neutron points to the dark QCD scale to be ~ 100 TeV. The direct detection depends on the explicit models of how to relate the dark sector to our sector
- ★ For asymmetry DM models, infrared fixed points can relate the QCD and dark QCD confinement scales and explain why dark baryon masses are at the same scale with the proton mass
- ★ More inputs from Lattice are required to calculate coefficients of order of unit

Thanks