Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Conf 12, August 2016

Exploring dark matter at the LHC

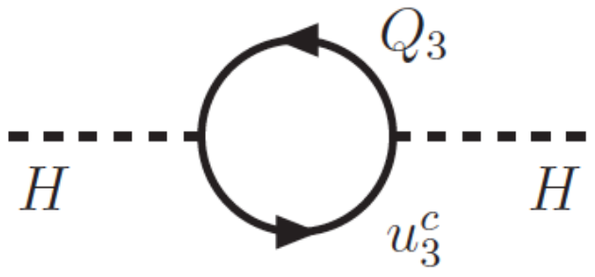
Michael Krämer (RWTH Aachen University)

Aachen Bonn Heidelberg Mainz

DFG Deutsche Forschungsgemeinschaft

BSM physics at the LHC?

The naturalness problem: why is $M_{Higgs} \ll M_{Planck}$?



$$\delta M_{\rm H}^2 \sim \frac{3\lambda_t^2}{8\pi^2}\,\Lambda_{\rm UV}^2 \sim (0.3\,\Lambda_{\rm UV})^2$$

→ new coloured (top-)partners with mass ≲ 500 GeV?

Dark matter

Weakly interacting massive particle(s) with mass ≲ 1 TeV?

WIMP dark matter: from SUSY to simplified models

WIMP dark matter: from SUSY to simplified models

Volume 105B, number 2,3 PHYSICS LETTERS 1 October 1981

MASSIVE PHOTINOS: UNSTABLE AND INTERESTING

N. CABIBBO
Istituto di Fisica, Università di Roma, INFN, Sezione di Roma, Italy

G.R. FARRAR
Rutgers University, New Brunswick, NJ, USA
and INFN, Sezione di Roma, Italy

and

L. MAIANI
Istituto di Fisica, Università di Roma, INFN, Sezione di Roma, Italy

Received 7 July 1981

Massive photinos decay into a photon and a goldstino with a calculable lifetime. Cosmological arguments indicate that photinos are either eight, $m_{\tilde{\gamma}} < 30$ eV or heavy, $m_{\tilde{\gamma}} > 0.3$ MeV. Light photinos could provide the missing mass in the galaxy and give rise to an observable UV background. Photino searches in high-energy experiments can be affected by photino decay.

WIMP dark matter: from SUSY to simplified models

Volume 105B, number 2,3 PHYSICS LETTERS 1 October 1981

VOLUME 48, NUMBER 4 PHYSICAL REVIEW LETTERS 25 JANUARY 1982

Supersymmetry, Cosmology, and New Physics at Teraelectronvolt Energies

Heinz Pagels
The Rockefeller University, New York, New York 10021

and

Joel R. Primack
Physics Department, University of California, Santa Cruz, California 95064

(Received 17 August 1981)

If one assumes a spontaneously broken local supersymmetry, big-bang cosmology implies that the universe is filled with a gravitino ($g_{3/2}$) gas—possibly its dominant constituent. From the observational bound on the cosmological mass density it follows that $m_{g_{3/2}} \lesssim 1$ keV. Correspondingly, the supersymmetry breaking parameter F satisfies $\sqrt{F} \lesssim 2\times 10^3$ TeV, requiring new supersymmetric physics in the teraelectronvolt energy region. An exact sum rule is derived and used to estimate the threshold and cross section for the production of the new states.

PACS numbers: 11.30.Pb, 11.30.Qc, 98.80.Dr

and give rise to an observable UV background. Photino searches in high-energy experiments can be affected by photino decay.

WIMP dark matter: from SUSY to simplified models

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VOLUME 48, NUMBER 4 PHYSICAL REVIEW LETTERS 25 JANUARY 1982

VOLUME 50, NUMBER 6 PHYSICAL REVIEW LETTERS 7 FEBRUARY 1983

Upper Bound on Gauge-Fermion Masses

Steven Weinberg
Department of Physics, University of Texas, Austin, Texas 78712

(Received 22 November 1982)

A large class of broken supersymmetry theories is shown to imply the existence of fermions $\lambda^{\pm}$ and λ^{0}, lighter than or nearly degenerate with the $W^{\pm}$ and Z^{0} gauge bosons, and with vanishing baryon and lepton number. If the $\lambda^{\pm}$ is appreciably lighter than the $W^{\pm}$ it can be readily produced in $W^{\pm}$ decay, as well as in e^{+}-e^{-} collisions.

PACS numbers: 11.30.Pb, 14.80.Er, 14.80. Pb

PACS numbers: 11.30.Pb, 11.30.Qc, 98.80.Dr

and give rise to an observable UV background. Photino searches in high-energy experiments can be affected by photino decay.

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VOLUME 50, NUMBER 19 PHYSICAL REVIEW LETTERS 9 MAY 1983

Constraint on the Photino Mass from Cosmology

H. Goldberg

Department of Physics, Northeastern University, Boston, Massachusetts 02115

(Received 22 February 1983)

A lower bound for the photino mass $m_{\tilde{\gamma}}$ as a function of the spin-0 fermion superpartner mass $m_{\tilde{f}}$ is derived as an extension of the calculation of Lee and Weinberg. The Majorana nature of the photino induces a p-wave threshold for annihilation $\tilde{\gamma}\tilde{\gamma} \to f\bar{f}$ into light fermions, and leads to a rather unexpected form for the bound: for 25 GeV $\lesssim m_{\tilde{f}} \lesssim 45$ GeV, $(m_{\tilde{\gamma}})_{\min} \simeq m_\tau = 1.8$ GeV; for $m_{\tilde{f}} > 45$ GeV, $(m_{\tilde{\gamma}})_{\min}$ increases approximately *linearly* with $m_{\tilde{f}}$ to a value of 20 GeV when $m_{\tilde{f}} = 100$ GeV.

PACS numbers: 14.80.Pb, 11.30.Pb, 98.80.Bp

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SUPERSYMMETRIC RELICS FROM THE BIG BANG*

John ELLIS and J. S. HAGELIN

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA

D. V. NANOPOULOS, K. OLIVE†, and M. SREDNICKI‡

CERN, CH-1211 Geneva 23, Switzerland

Received 16 September 1983

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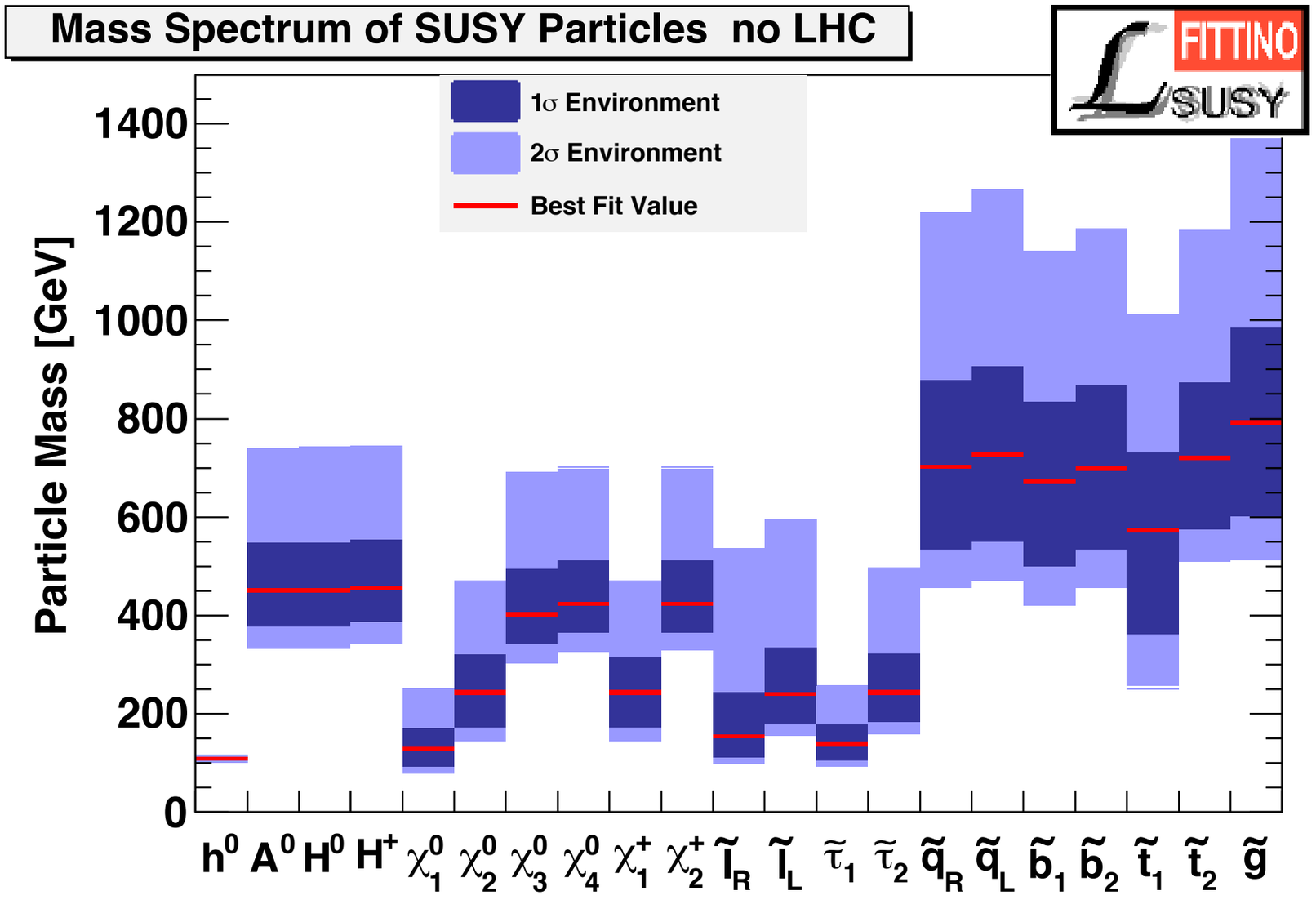
D. V. NANOPOULOS, K. OLIVE†, and M. SREDNICKI‡

CERN, CH-1211 Geneva 23, Switzerland

Bertone, Hooper , arXiv:1605.04909 [astro-ph.CO]

Great expectations…

Pre-LHC fits of SUSY models, including Ω_{DM} and $(g\text{-}2)_\mu$:



→ SUSY is just around the corner…

Lessons from the LHC: no sign of SUSY

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

ATLAS Preliminary

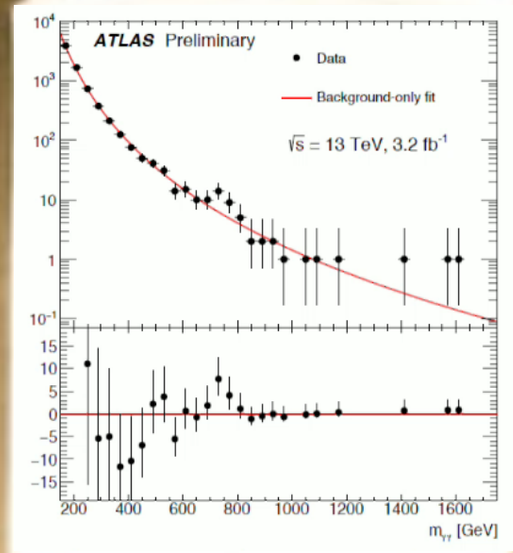
$\sqrt{s}$ = 7, 8, 13 TeV

	Model	e, μ, τ, γ	Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	$\int \mathcal{L}\, dt$[fb^{-1}]	Mass limit ($\sqrt{s}$ = 7, 8 TeV / $\sqrt{s}$ = 13 TeV)		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e, μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{q}$ 1.35 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2016-078
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$ 608 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV	1604.07773
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{g}$ 1.86 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{g}$ 1.83 TeV	m($\tilde{\chi}_1^0$)<400 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	13.2	$\tilde{g}$ 1.7 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 jets	Yes	13.2	$\tilde{g}$ 1.6 TeV	m($\tilde{\chi}_1^0$) <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.37 TeV	m($\tilde{\chi}_1^0$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$ 1.8 TeV	m($\tilde{\chi}_1^0$)>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	14.8	$\tilde{g}$ 1.89 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	14.8	$\tilde{g}$ 1.89 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.37 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	$\tilde{b}_1$ 840 GeV	m($\tilde{\chi}_1^0$)<100 GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e, μ (SS)	1 b	Yes	13.2	$\tilde{b}_1$ 325-685 GeV	m($\tilde{\chi}_1^0$)<150 GeV, m($\tilde{\chi}_1^\pm$)= m($\tilde{\chi}_1^0$)+100 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^\pm$	0-2 e, μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 150-170 GeV 200-720 GeV	m($\tilde{\chi}_1^\pm$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 90-198 GeV 205-850 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	$\tilde{t}_1$ 90-323 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-600 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e, μ (Z)	1 b	Yes	13.3	$\tilde{t}_2$ 290-700 GeV	m($\tilde{\chi}_1^0$)<300 GeV	ATLAS-CONF-2016-038
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+h$	1 e, μ	6 jets + 2 b	Yes	20.3	$\tilde{t}_2$ 320-620 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 90-335 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-475 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 355 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_{\mathrm{L}}\nu\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 715 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($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 425 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 270 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_{\mathrm{R}}\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 635 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
	GGM (wino NLSP) weak prod.	1 e, μ + γ	-	Yes	20.3	$\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	$\tilde{W}$ 590 GeV	$c\tau$<1 mm	1507.05493
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	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$ 495 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, $\tau(\tilde{\chi}_1^\pm)$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 850 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 1.57 TeV	m($\tilde{\chi}_1^0$)=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 440 GeV	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^\pm$ 1.14 TeV	m($\tilde{\chi}_1^0$)>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 1.55 TeV	m($\tilde{\chi}_1^0$)=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g}\to t_1t, t_1\to bs$	2 e, μ (SS)	0-3 b	Yes	13.2	$\tilde{g}$ 1.3 TeV	m($\tilde{t}_1$)<750 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$ 410 GeV 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e, μ	2 b	-	20.3	$\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 510 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

**Only a selection of the available mass limits on new states or phenomena is shown.*

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

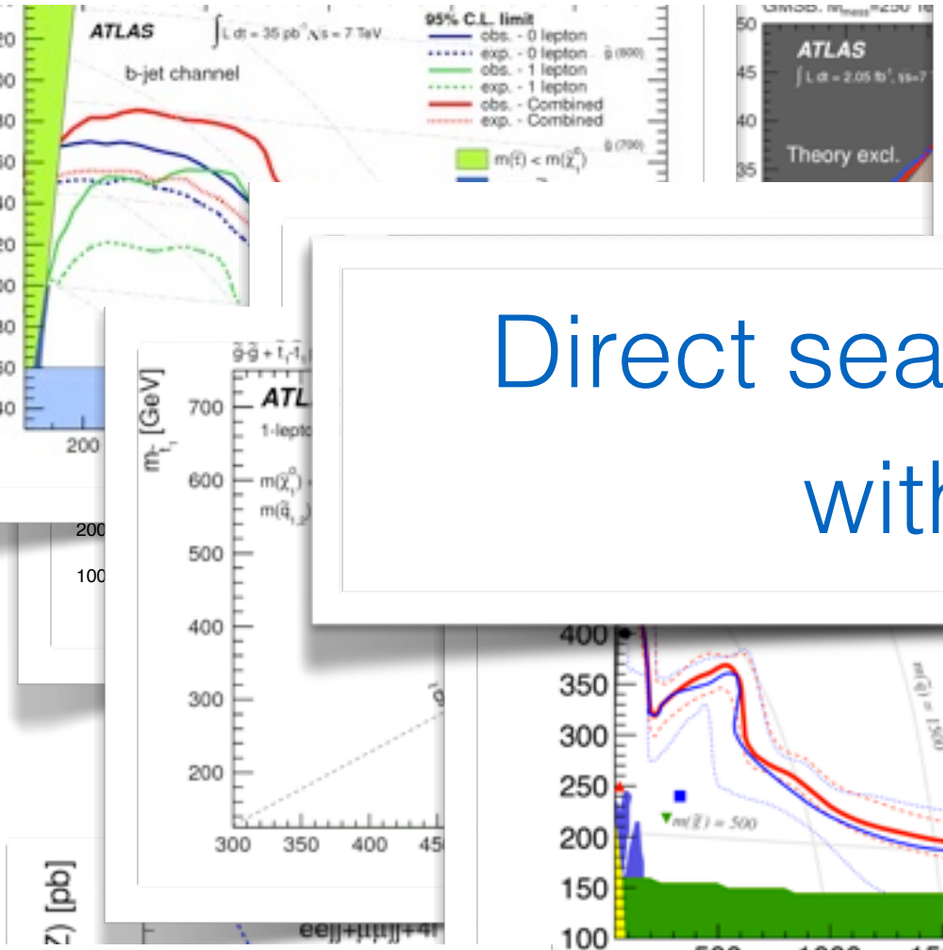
(750 GeV) **Light at the end of the tunnel?**

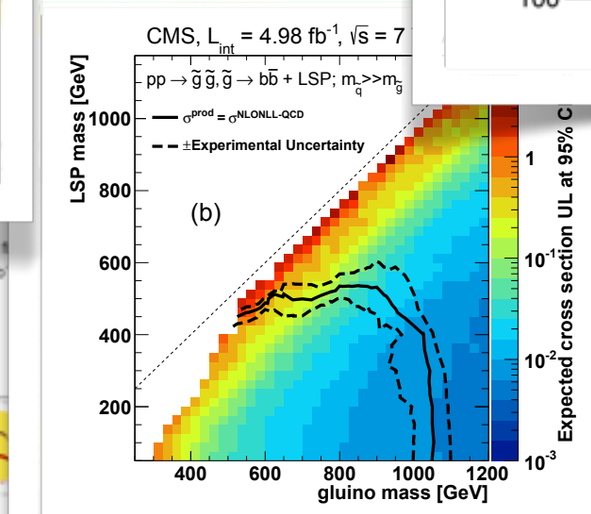


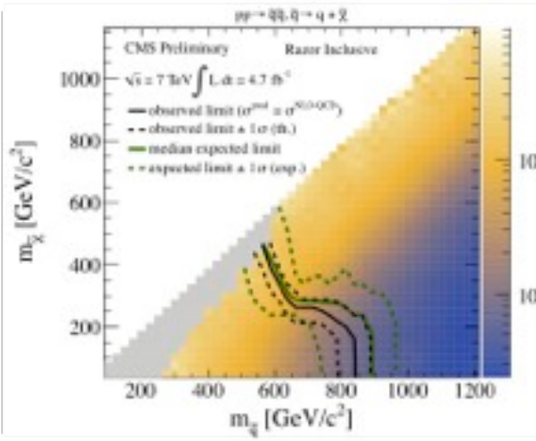
(750 GeV) **Light at the end of the tunnel?**

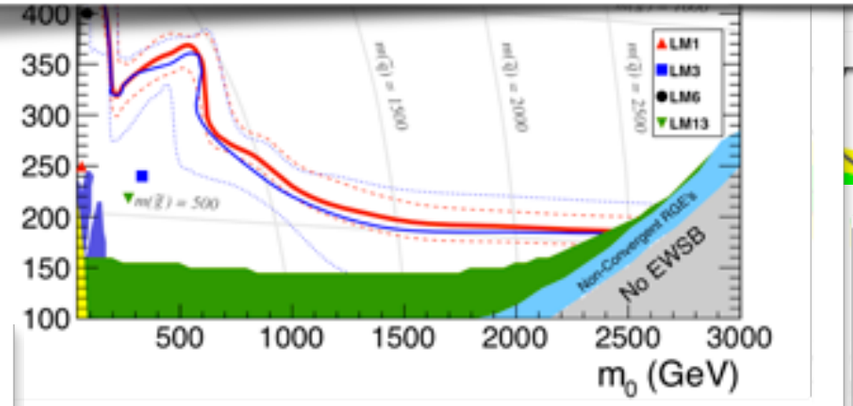
Lessons from the LHC: no sign of new physics

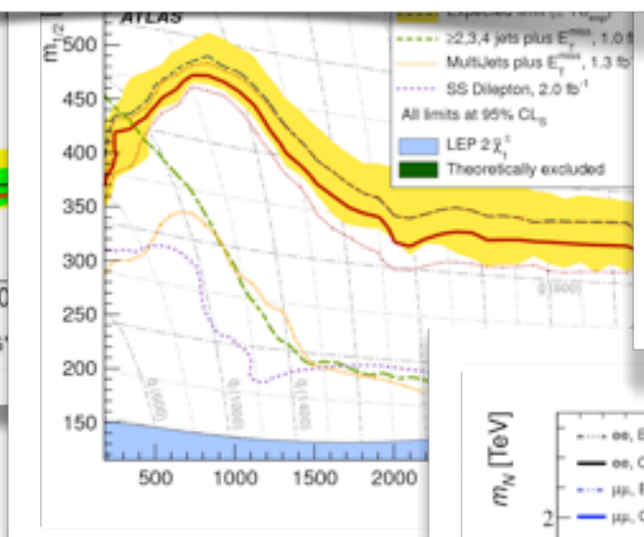
Direct searches probe new particles with masses of *O*(TeV)

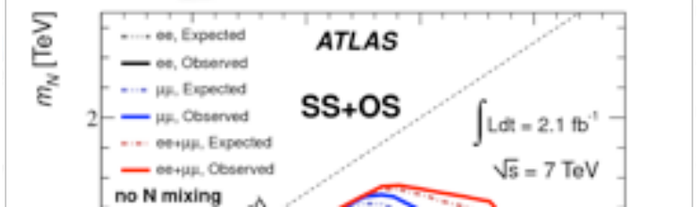


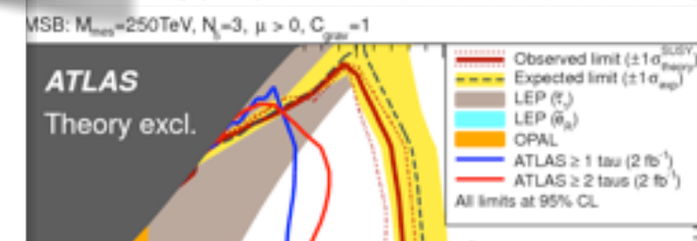












Lessons from the LHC: no sign of new physics

Direct searches probe new particles with masses of *O*(TeV)

However, searches are often theory-driven and interpreted within specific classes of models

- Do we search in all the right places?
- Can we interpret the results in a wider class of models?
- If new physics is seen, can we characterise it in terms of observed properties, with minimal reliance on untested assumptions?

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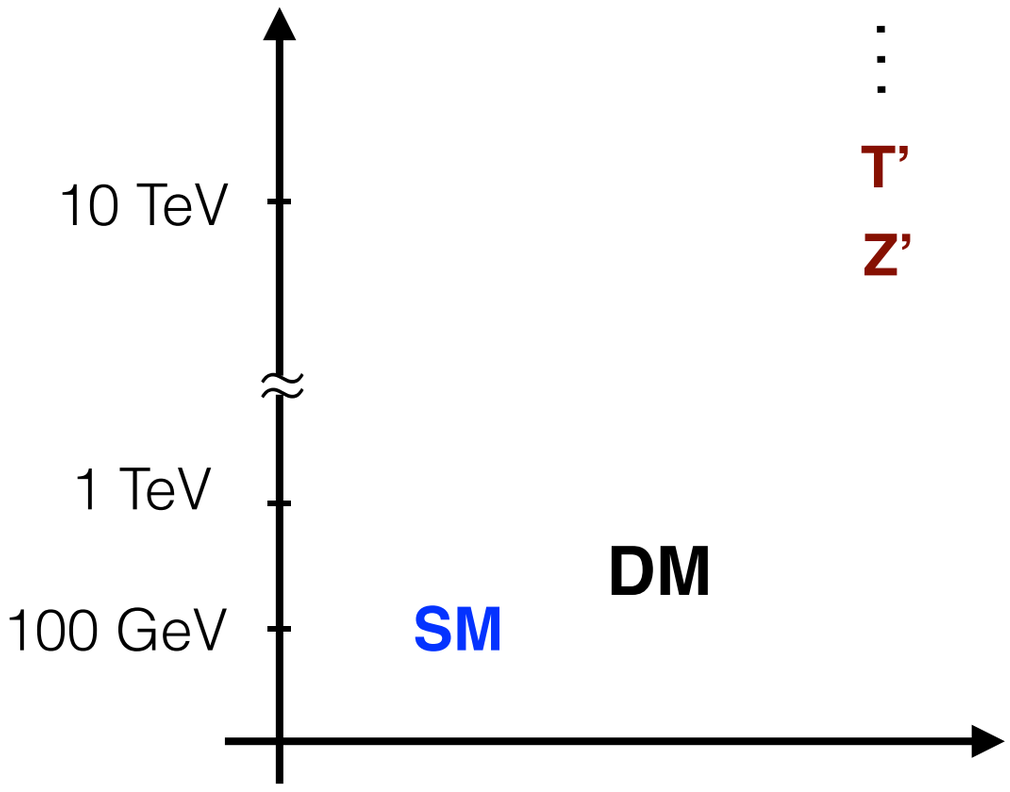
For the LHC-13 we need to

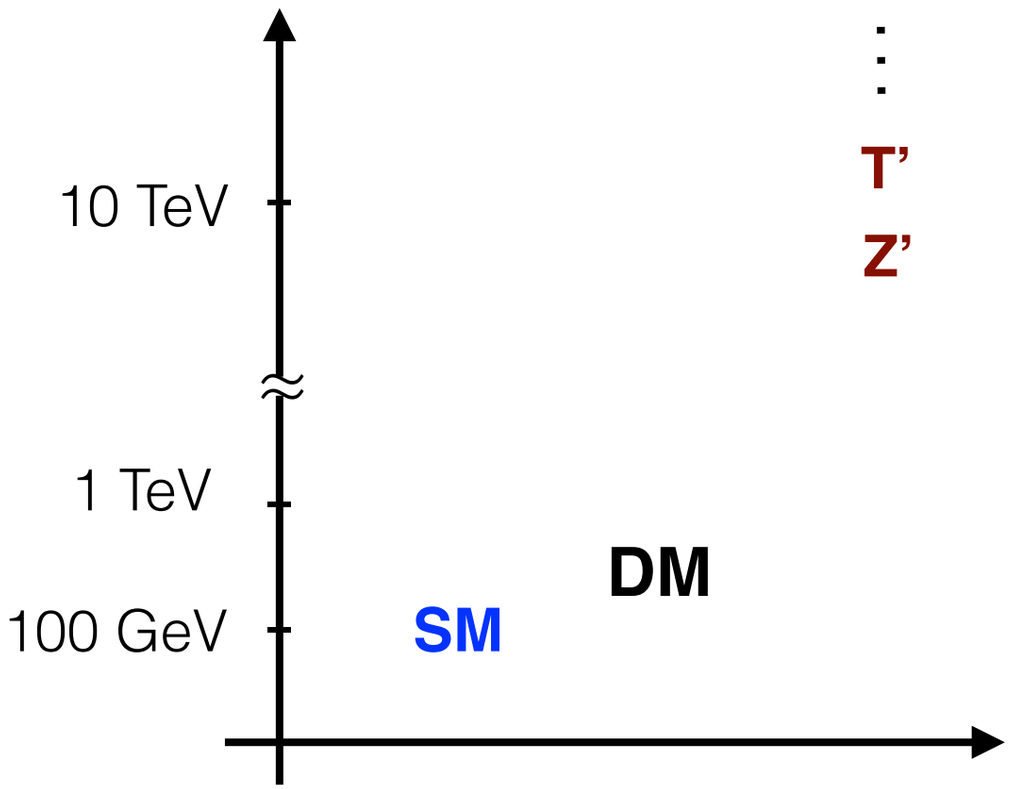
- Explore a wider range of BSM models
- and move towards more model-independent searches: effective field theories and simplified models.

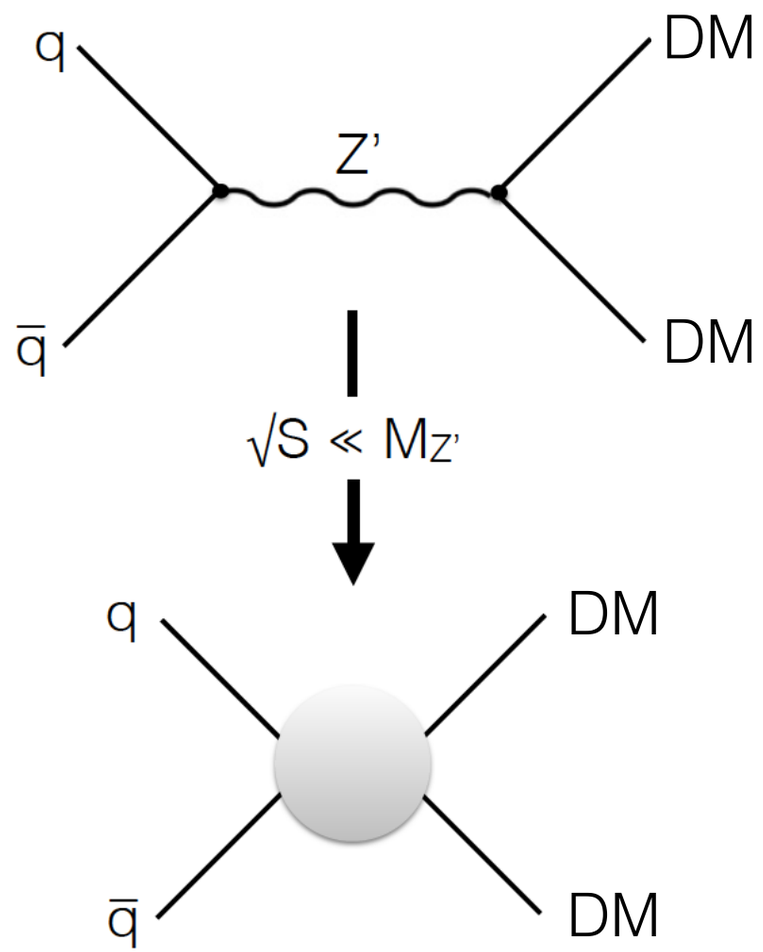
Model-independent searches for dark matter

Model-independent searches for dark matter



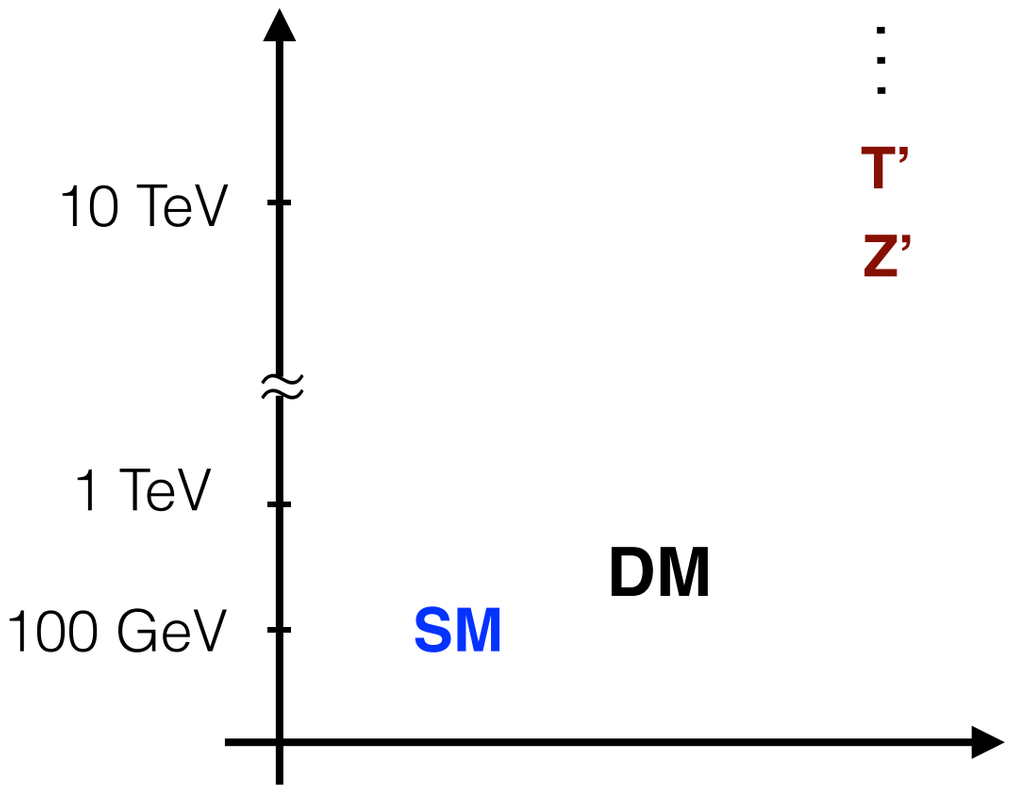
Model-independent searches for dark matter

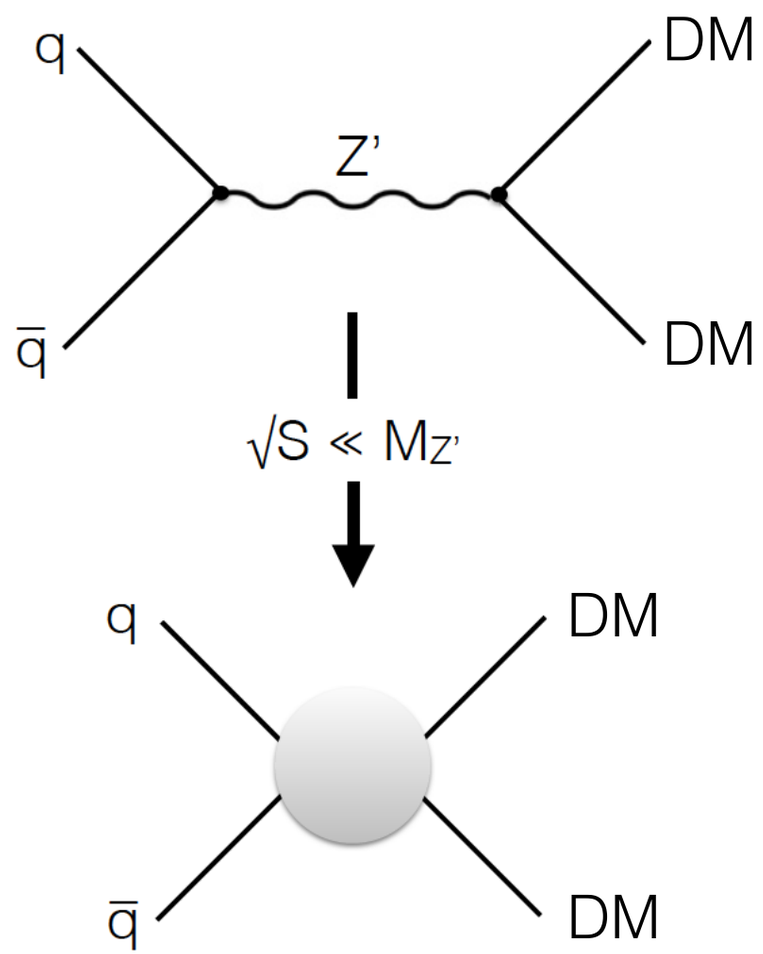




Model-independent searches for dark matter

effective field theories





$$M(q\bar{q} \to \psi_{\mathrm{DM}}\overline{\psi}_{\mathrm{DM}}) = \frac{1}{M_*^2}(\bar{q}\Gamma q)(\overline{\psi}_{\mathrm{DM}}\Gamma\psi_{\mathrm{DM}})$$

However, if $M_{Z'} \gg \sqrt{S}$, the dark matter signal is weak:

$$M(q\bar{q} \to \psi_{\rm DM}\overline{\psi}_{\rm DM}) = \frac{1}{M_*^2}(\bar{q}\Gamma q)(\overline{\psi}_{\rm DM}\Gamma\psi_{\rm DM}) = \frac{g^2}{M_{Z'}^2}(\bar{q}\Gamma q)(\overline{\psi}_{\rm DM}\Gamma\psi_{\rm DM})$$

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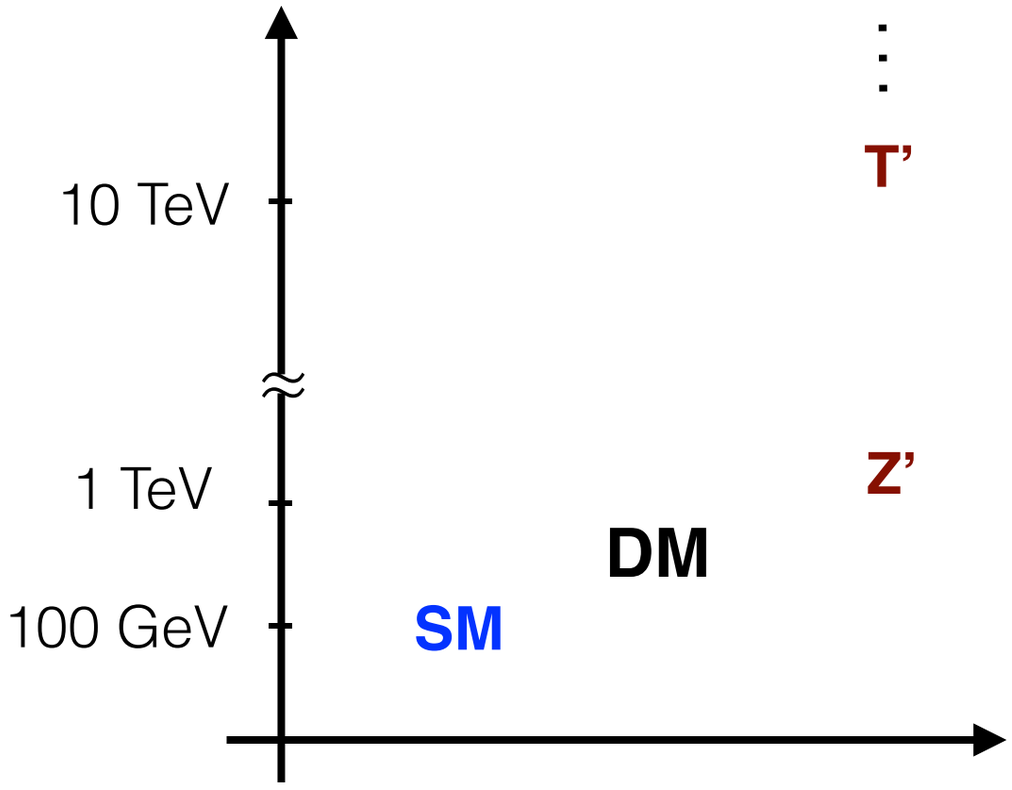
It is thus more interesting to consider simplified models, where at least one mediator is at the TeV scale:



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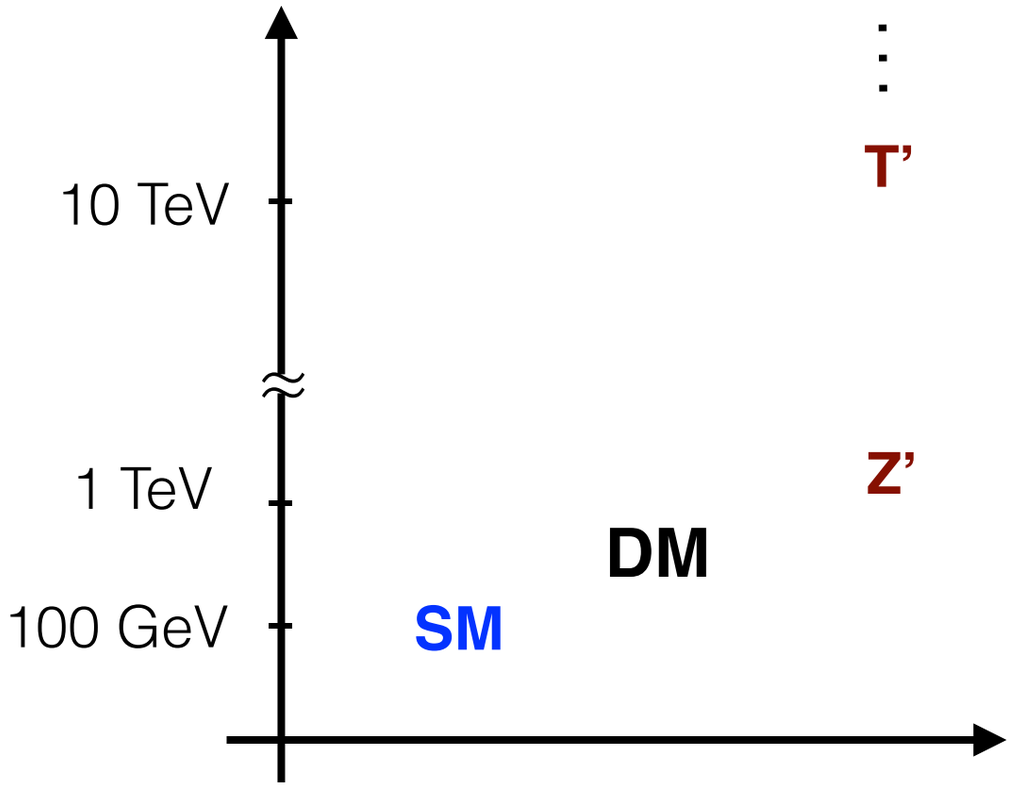
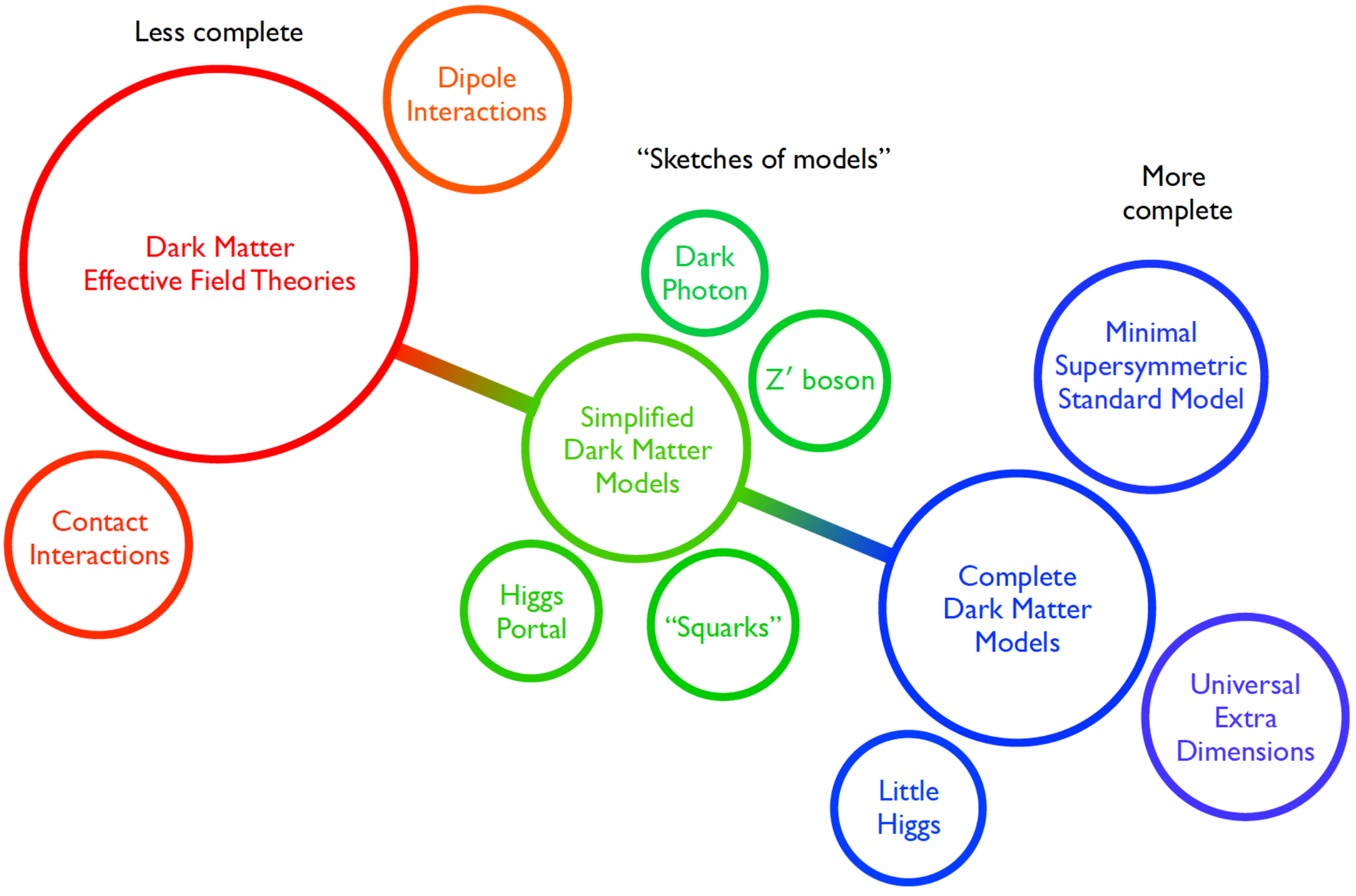


Such simplified models

- provide a reliable framework for LHC analyses;
- allow to explore constraints from mediator searches;
- allow to connect LHC analyses with direct and indirect dark matter searches.

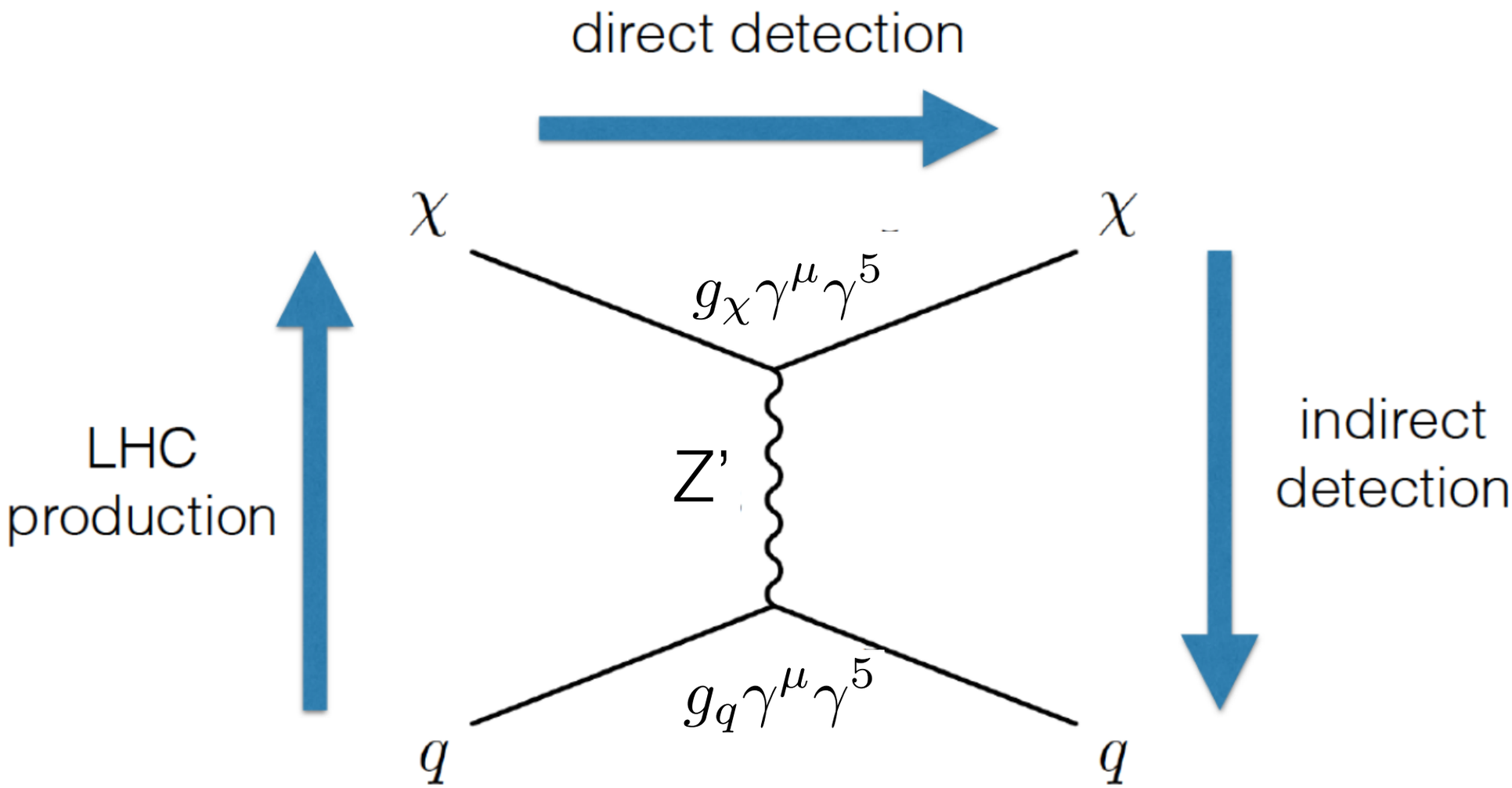
WIMP dark matter: from SUSY to simplified models

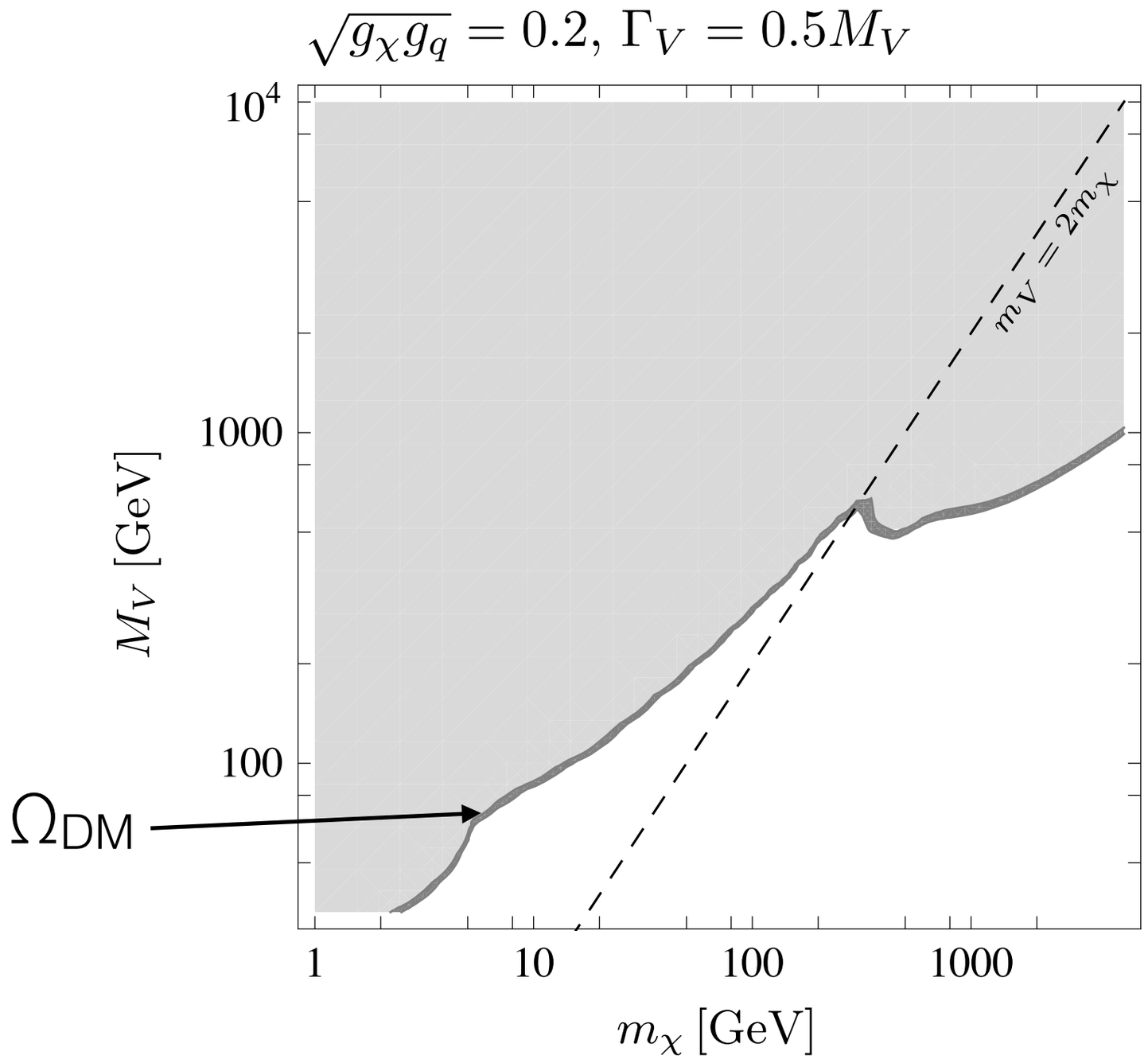


arXiv:1506.03116 [hep-ph]

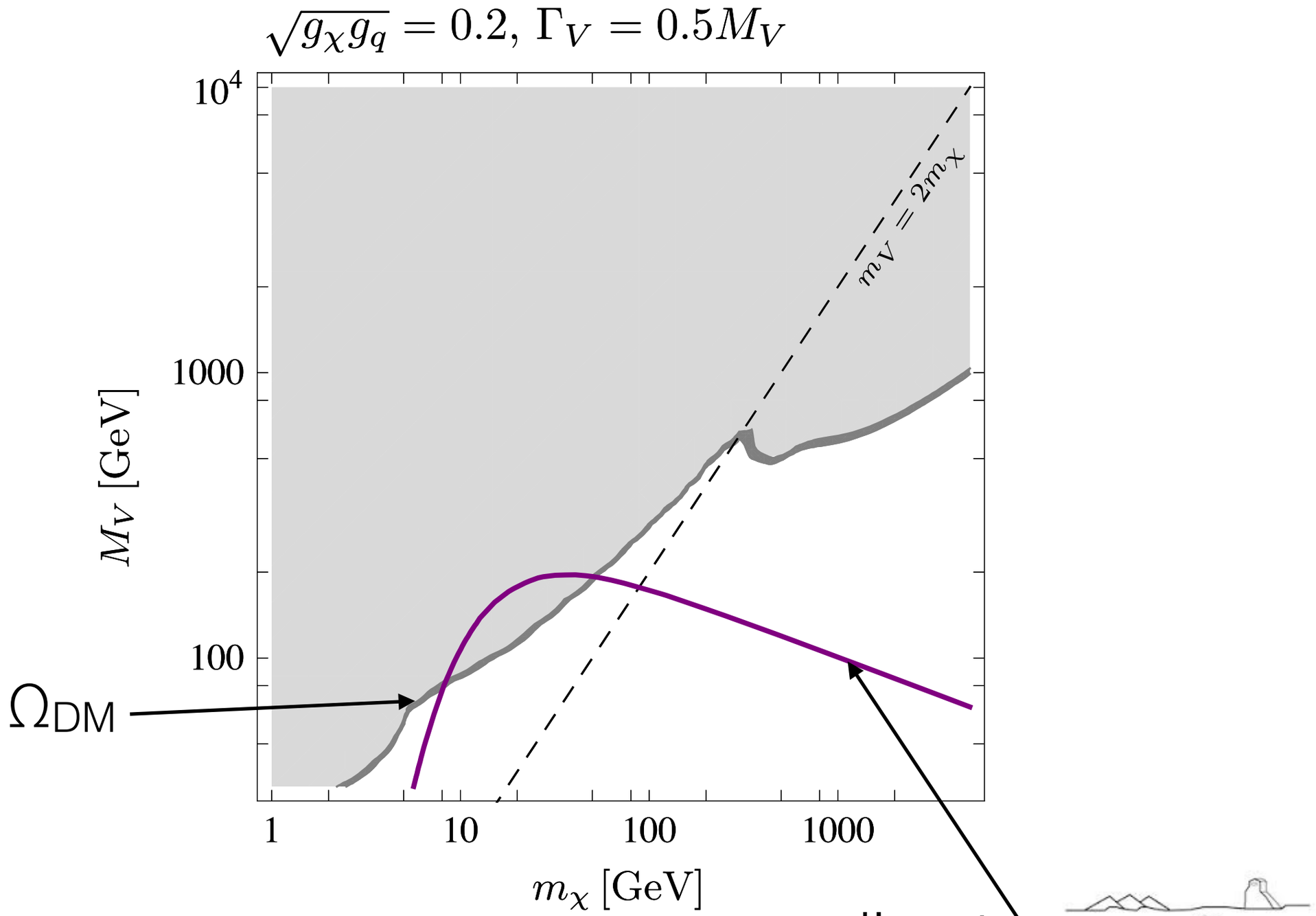
Consider a simplified dark matter model with an axial-vector mediator Z' which couples to a Majorana dark matter fermion χ and SM quarks.

The model has only four parameters (M_χ, $M_{Z'}$, $\sqrt{g_\chi\, g_q}$, $\Gamma_{Z'}$), and it can be tested in direct and indirect detection, and at the LHC.





Heisig et al., Phys. Rev. D 93, 055029 (2016)



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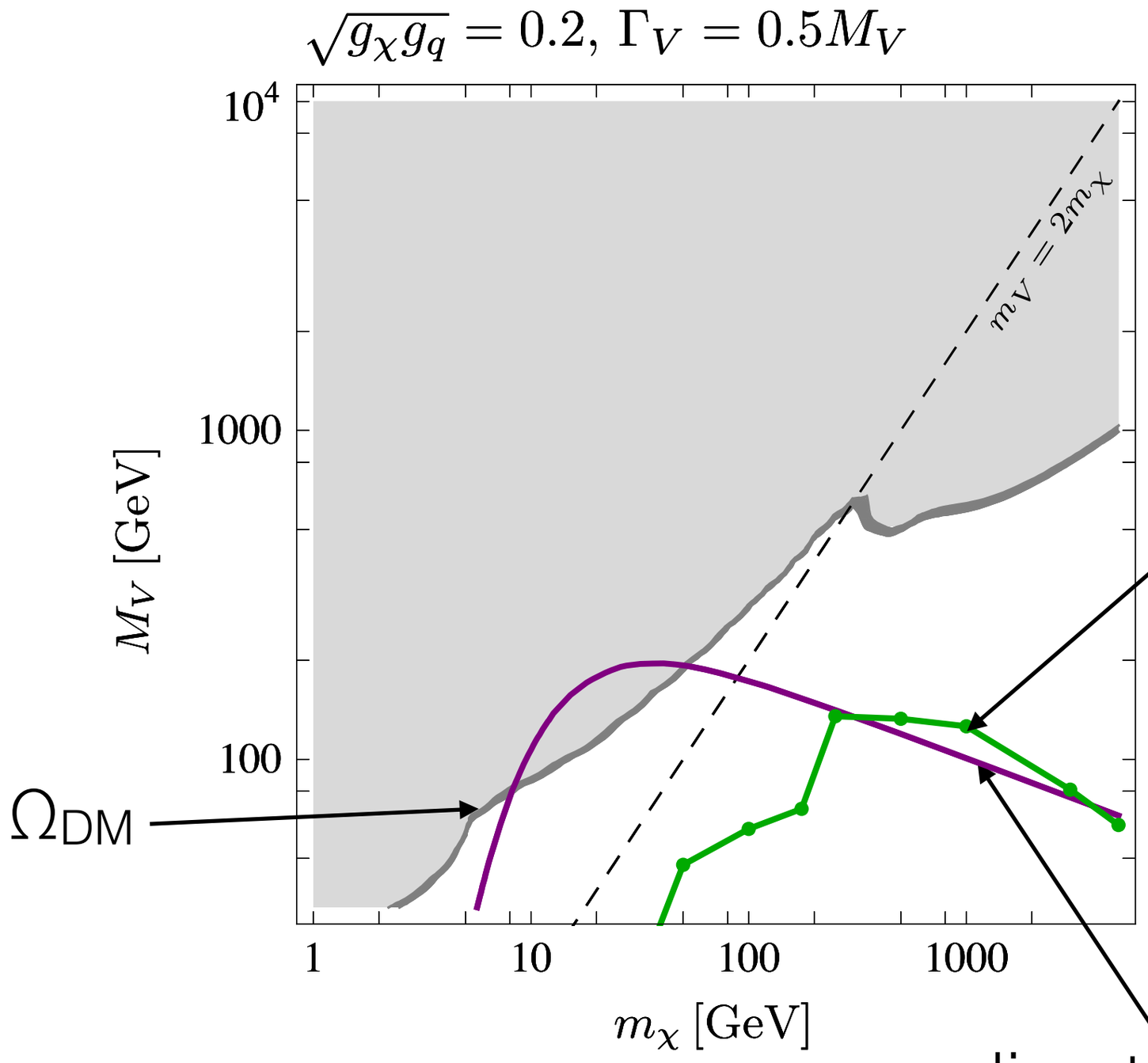


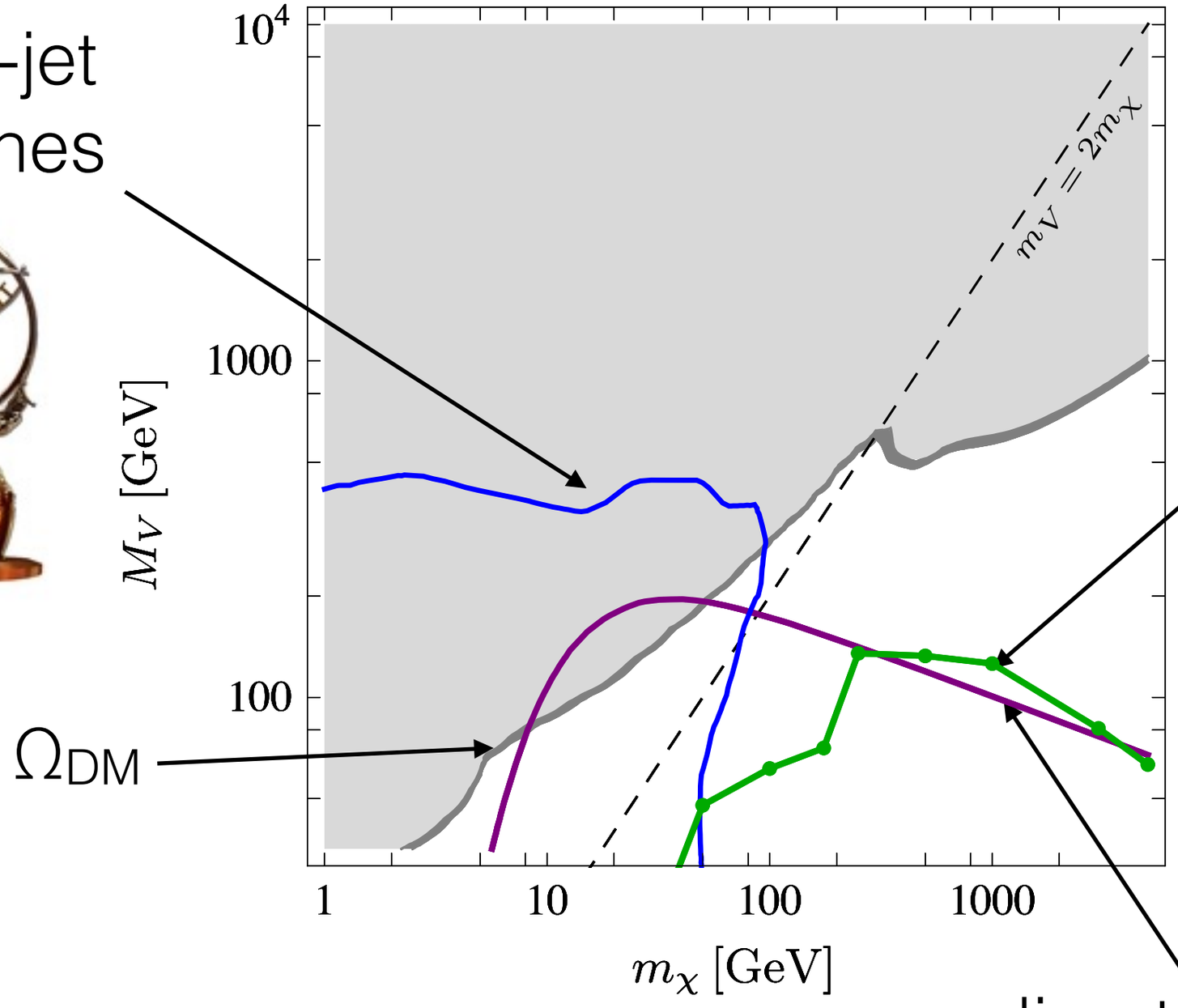
indirect detection

direct detection

Heisig et al., Phys. Rev. D 93, 055029 (2016)

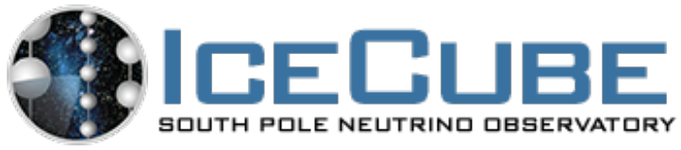
mono-jet searches

$\sqrt{g_\chi g_q} = 0.2,\ \Gamma_V = 0.5 M_V$



Ω_{DM}

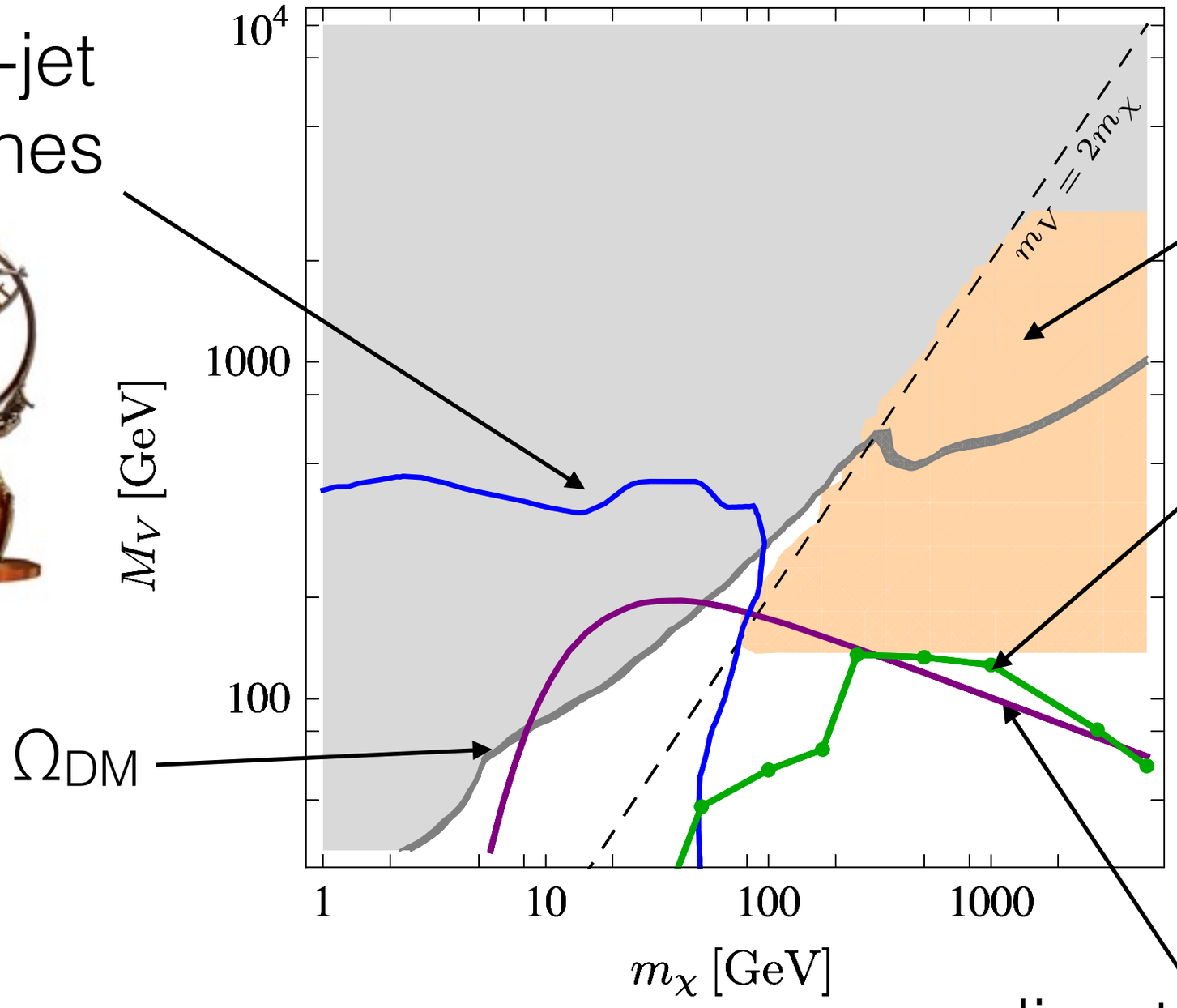
indirect detection



direct detection

Heisig et al., Phys. Rev. D 93, 055029 (2016)

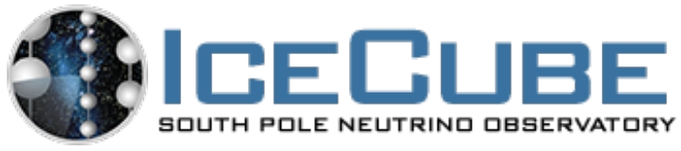
mono-jet searches



direct mediator searches

Chala et al.,
JHEP 1507 (2015) 089

indirect detection



Ω_{DM}

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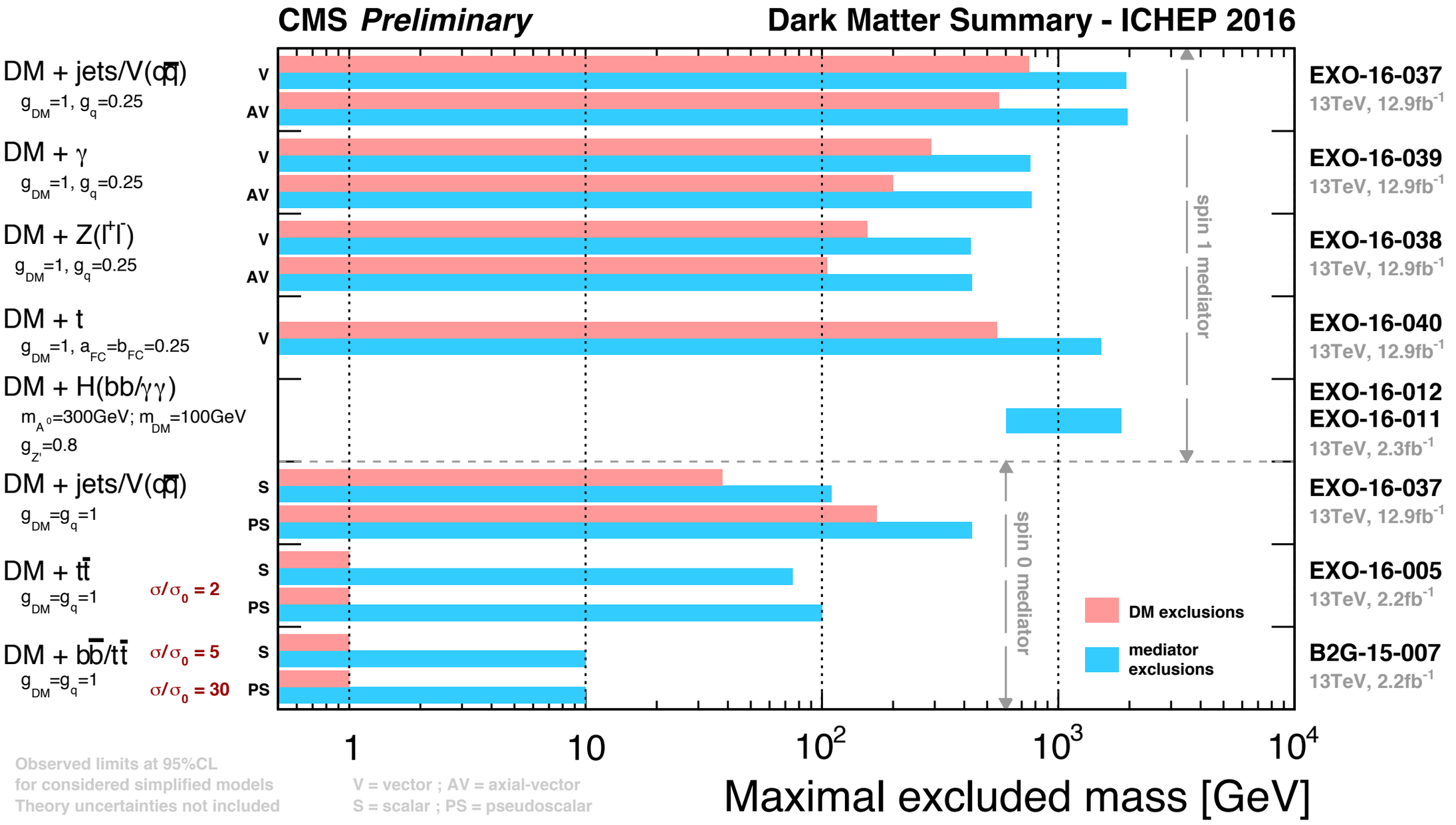
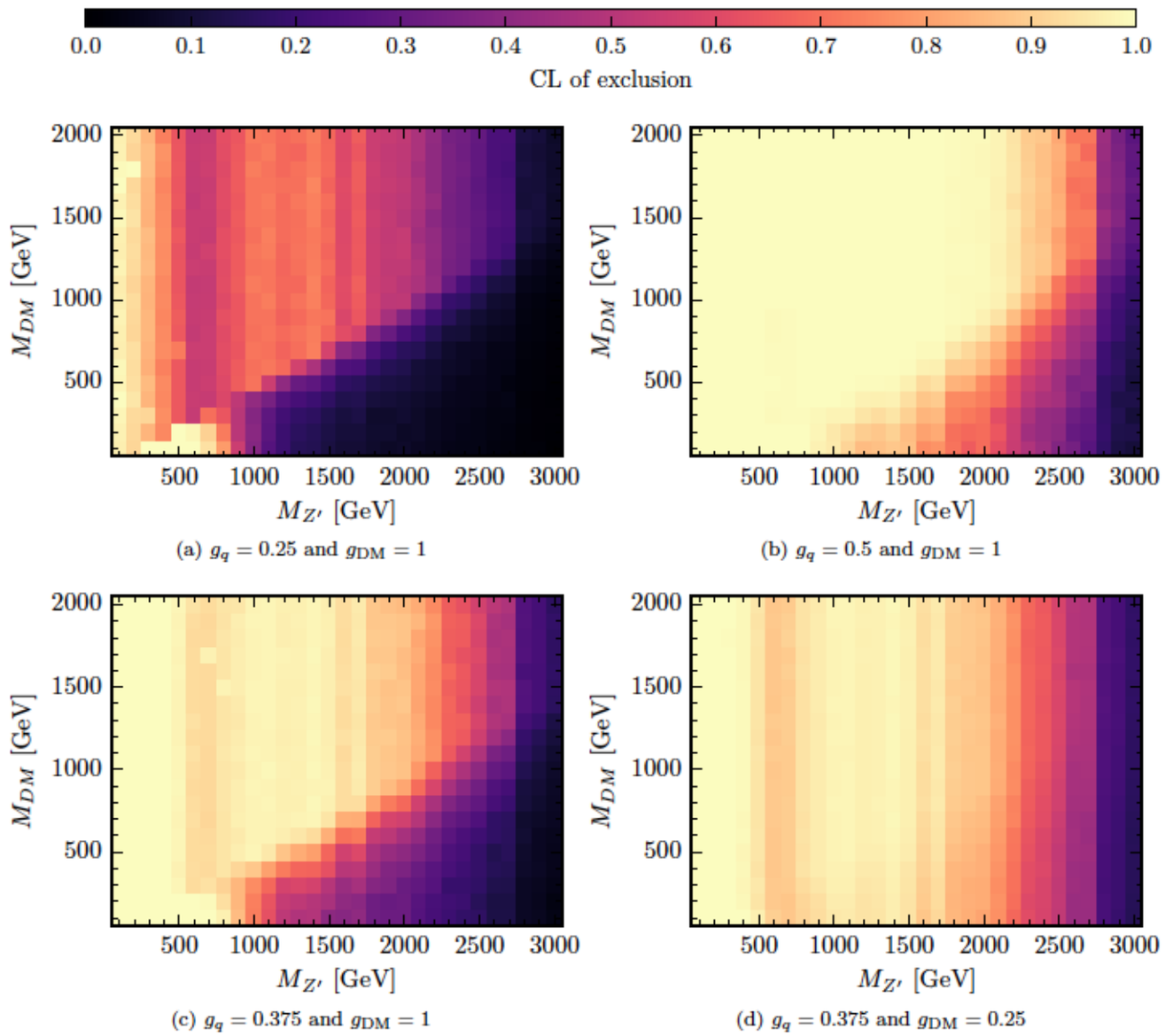
Heisig et al., Phys. Rev. D 93, 055029 (2016)

Lessons from the LHC: no sign of dark matter



Contur: Constraints On New Theories Using Rivet

A procedure for setting limits on BSM theories using SM measurements



(a) $g_q = 0.25$ and $g_{\mathrm{DM}} = 1$

(b) $g_q = 0.5$ and $g_{\mathrm{DM}} = 1$

(c) $g_q = 0.375$ and $g_{\mathrm{DM}} = 1$

(d) $g_q = 0.375$ and $g_{\mathrm{DM}} = 0.25$

Butterworth et. al., arXiv:1606.05296 [hep-ph] and https://contur.hepforge.org

Science may be described as the art of systematic oversimplification (Karl Popper)

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Consider a simplified dark matter model with a Z':

$$\mathcal{L} = Z'_\mu \bar{\chi} \left[g^V_{\mathrm{DM}} \gamma^\mu + g^A_{\mathrm{DM}} \gamma^\mu \gamma_5 \right] \chi + \sum_{q=u,d} Z'_\mu \bar{q} \left[g^V_q \gamma^\mu + g^A_q \gamma^\mu \gamma_5 \right] q$$

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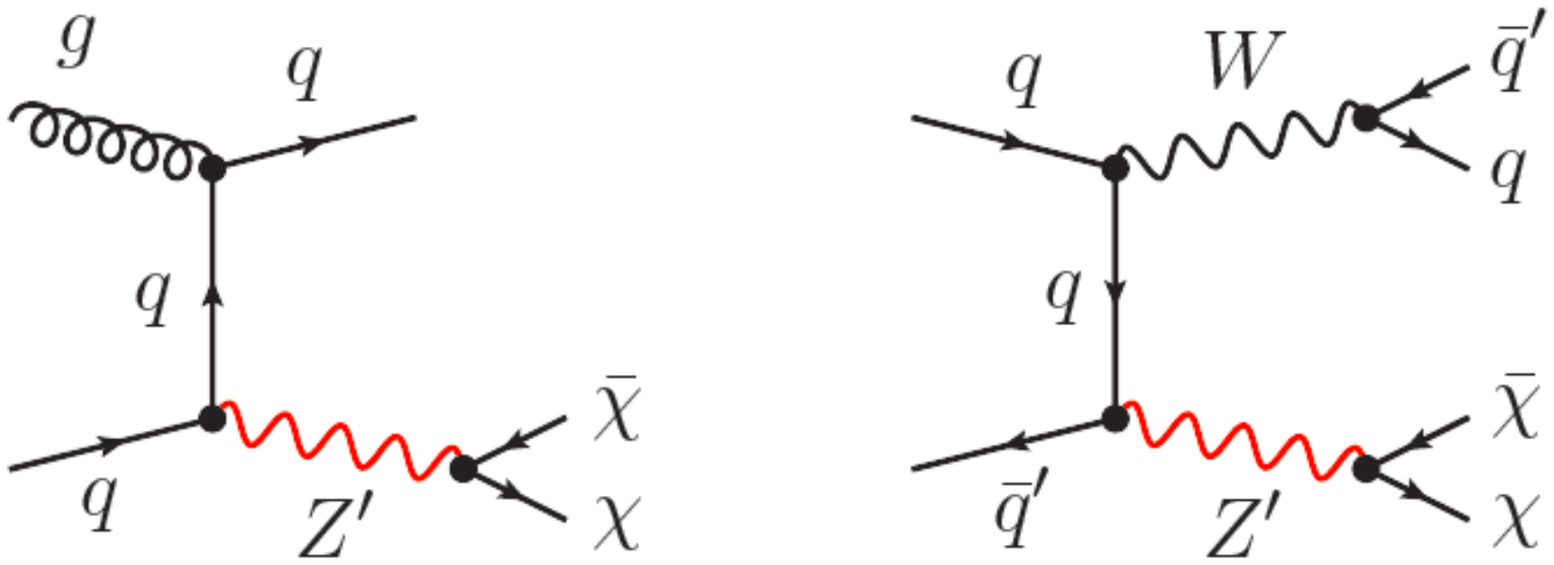

Bell et al., Phys. Rev. D 92, 053008 (2015); Haisch et al., Phys.Lett. B760 (2016) 207-213

Let us set $g^A_{\rm DM} = g^A_q = 0$ and $g^V_{\rm DM} = 1$:

$$\mathcal{L} = Z'_\mu \bar{\chi} \gamma^\mu \chi + Z'_\mu [g^V_u \, \bar{u} \gamma^\mu u + g^V_d \, \bar{d} \gamma^\mu d]$$

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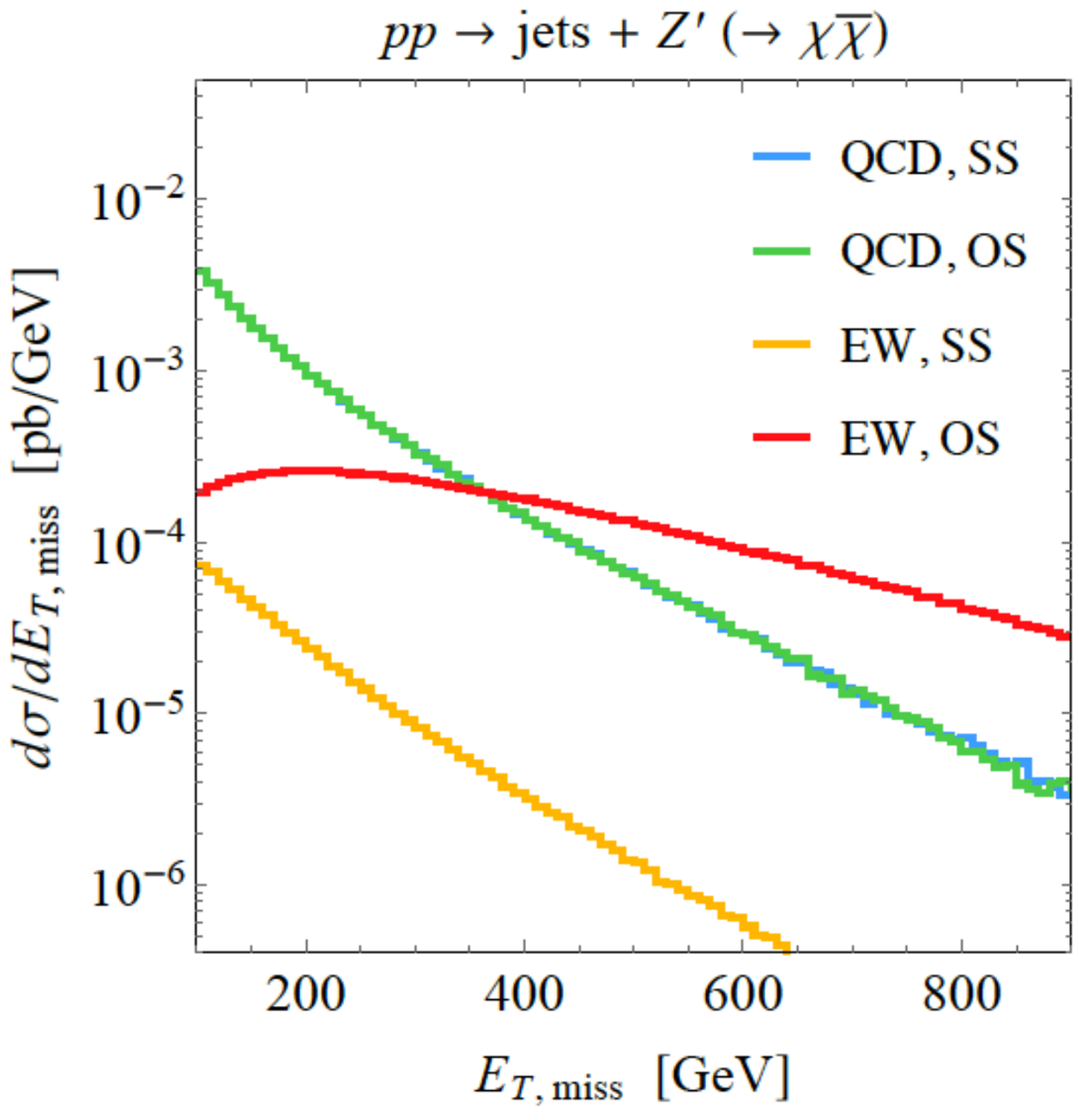

$$g^V_u = g^V_d = 0.25 \quad \text{(SS)}$$

$$g^V_u = -g^V_d = -0.25 \quad \text{(OS)}$$

Unitarity violation and the choice of couplings

A partial wave analysis of $u + \bar{d} \to W^+ + Z'$ yields:

$$\mathcal{M}(\text{p-wave}) = \frac{g}{96\pi M_W M_{Z'}} \, s \, \left(g_u^A - g_d^A - g_u^V + g_d^V \right)$$

and thus the scattering amplitude may violate unitarity.

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Impose $\quad g_u^A - g_d^A - g_u^V + g_d^V = 0$

or equivalently $\; g_u^L = g_u^V - g_u^A = g_d^V - g_d^A = g_d^L$

i.e. left-chiral u and d-quarks should have the same coupling to the Z'

Compare to the Standard Model

$$\mathcal{L}_{\mathrm{SM}} = \sum_q Z_\mu \bar{q} \left[g^V_{Z,q} \gamma^\mu + g^A_{Z,q} \gamma^\mu \gamma_5 \right] q$$

$$g^V_{Z,q} = \frac{g}{2c_W} \left(T_{3,q} - 2Q_q s^2_W \right) \quad \text{and} \quad g^A_{Z,q} = -\frac{g}{2c_W} T_{3,q}$$

Thus $g^L_{Z,u} - g^L_{Z,d} = g c_W \neq 0$

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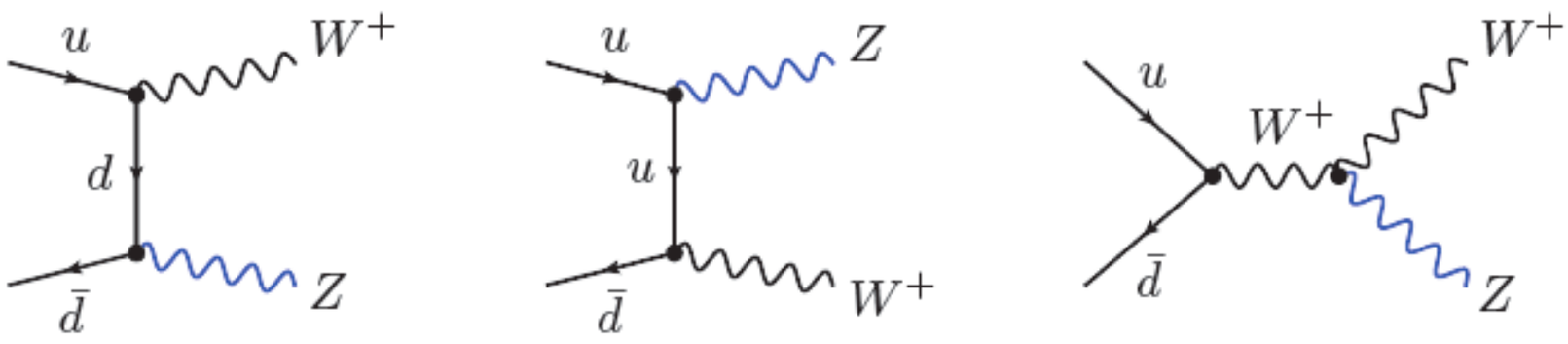
Triple gauge boson couplings come to rescue



$$|M|^2 \to \frac{3g^4 c_W^4 |V_{ud}|^2}{32 M_W^2}\,(d_1 + d_2 - 2d_3)^2 s^2 \sin^2\theta$$

(Over-)simplified models may violate unitarity

- restrict the choice of couplings
- add more particles/interactions

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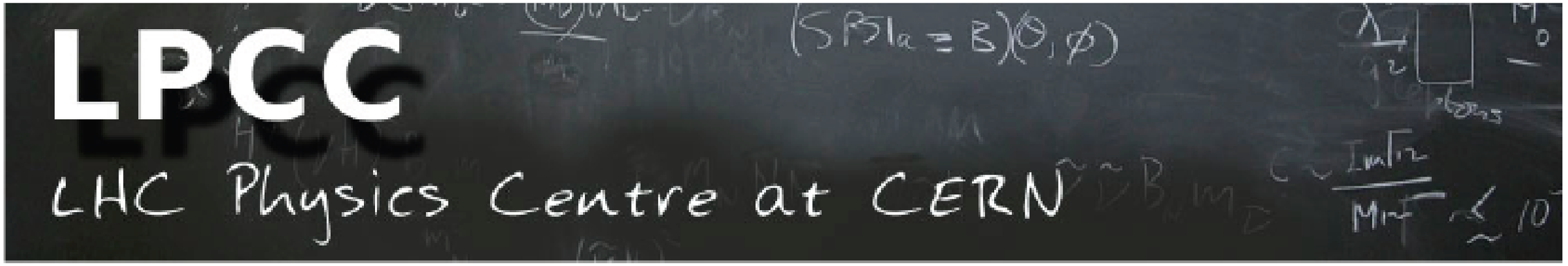

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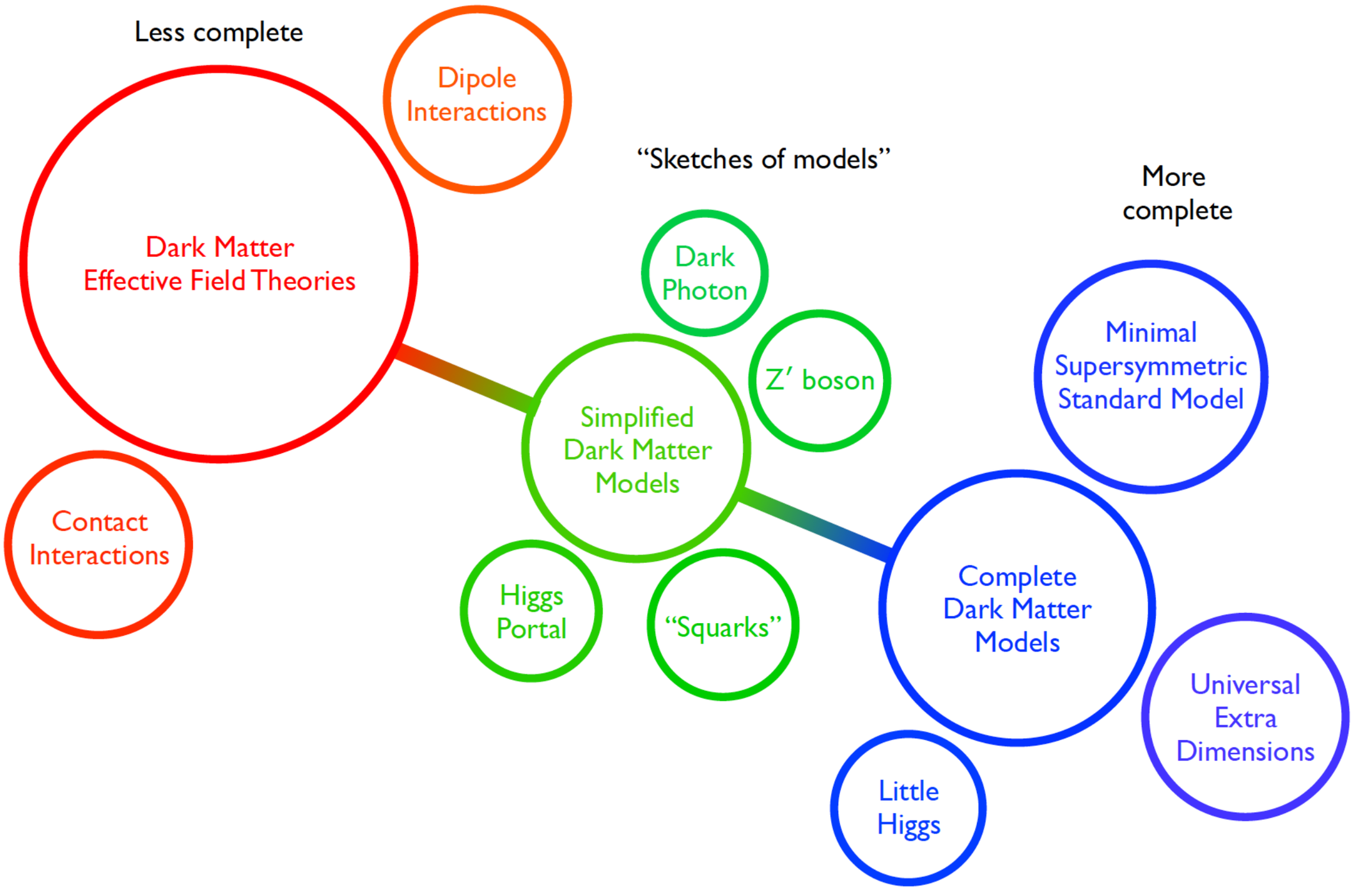
WIMP dark matter: from SUSY to simplified models



arXiv:1506.03116 [hep-ph]

Dark matter?

non-gravitational interactions?

spin?

mass?

Dark matter?

stable?

thermal relic?

particle physics

astrophysics

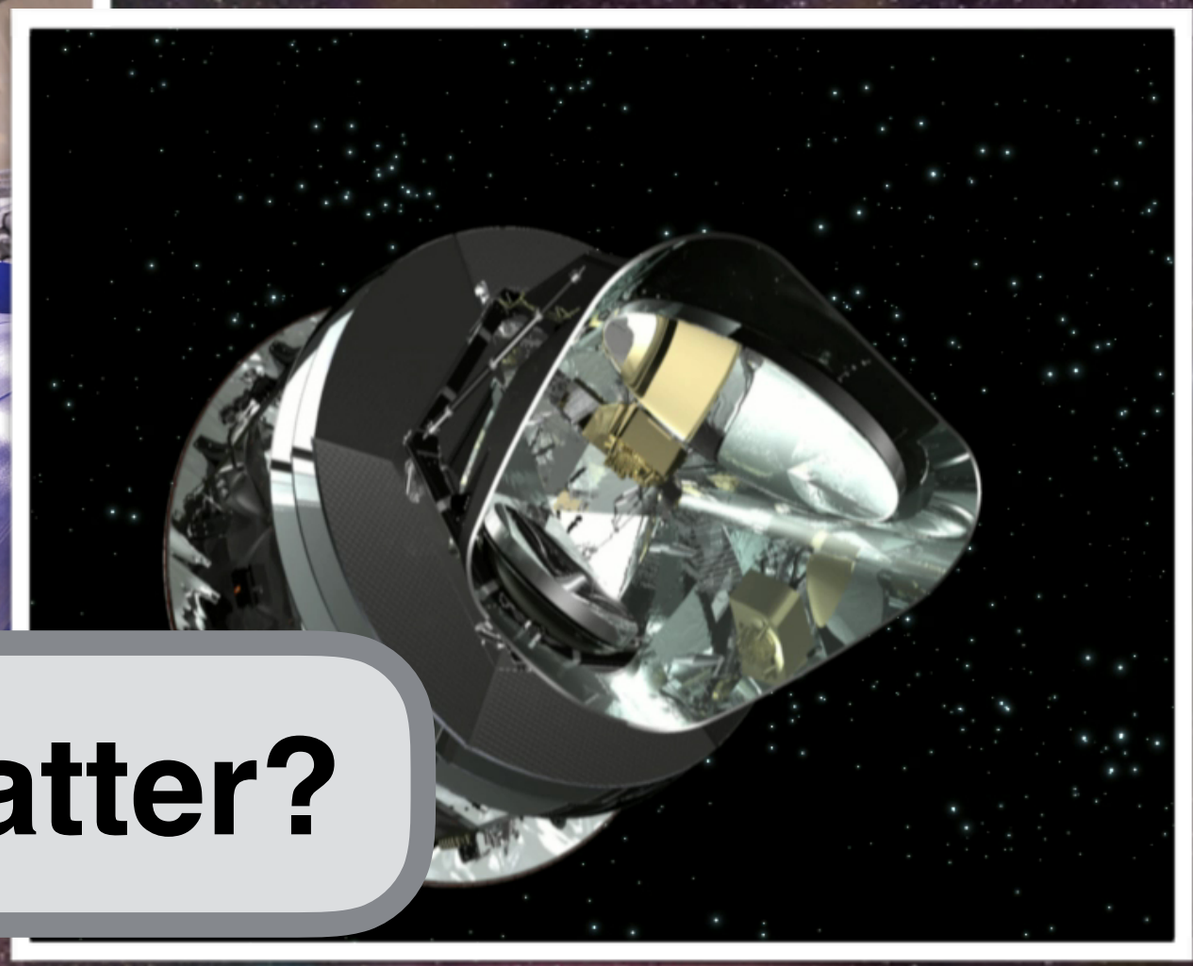
Dark matter?

cosmology

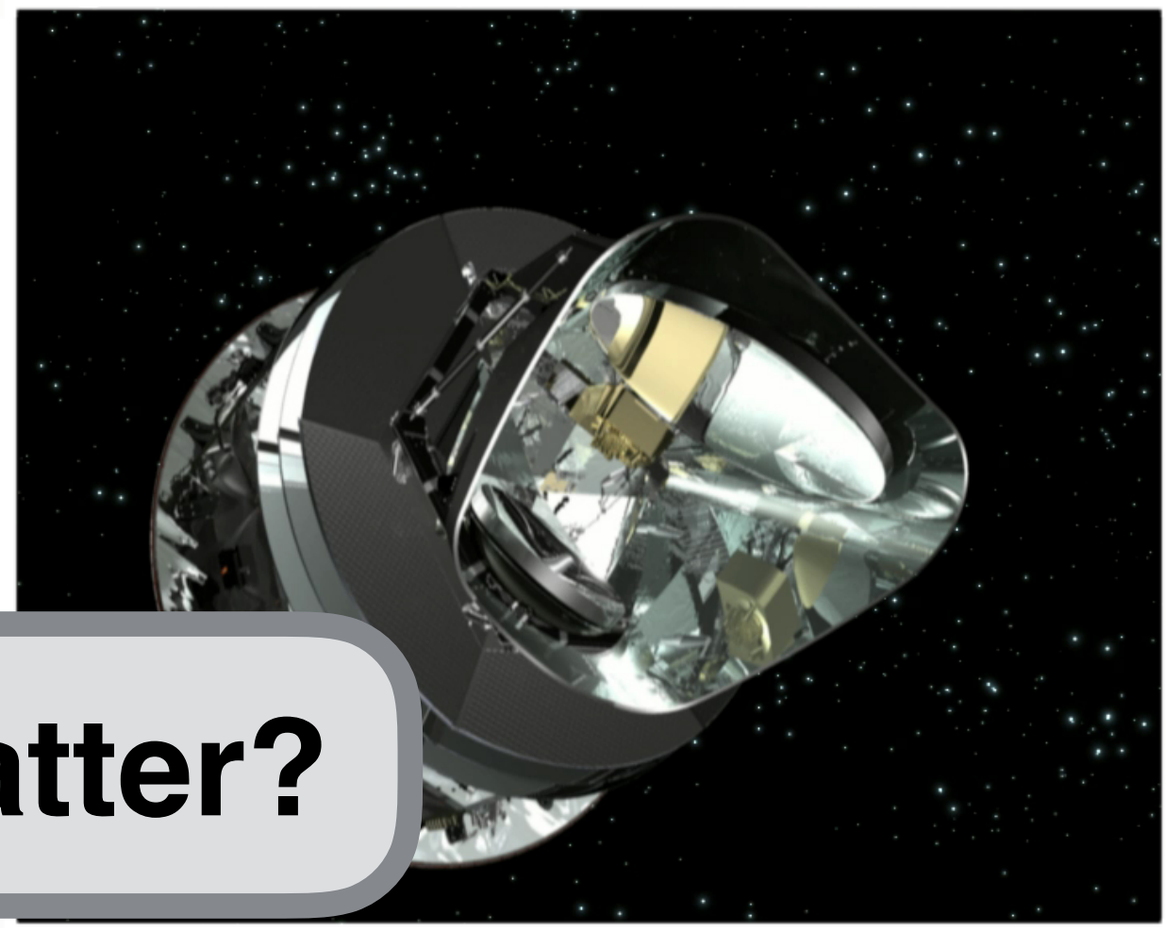
nuclear physics

Dark matter?

Dark matter?



Dark matter?



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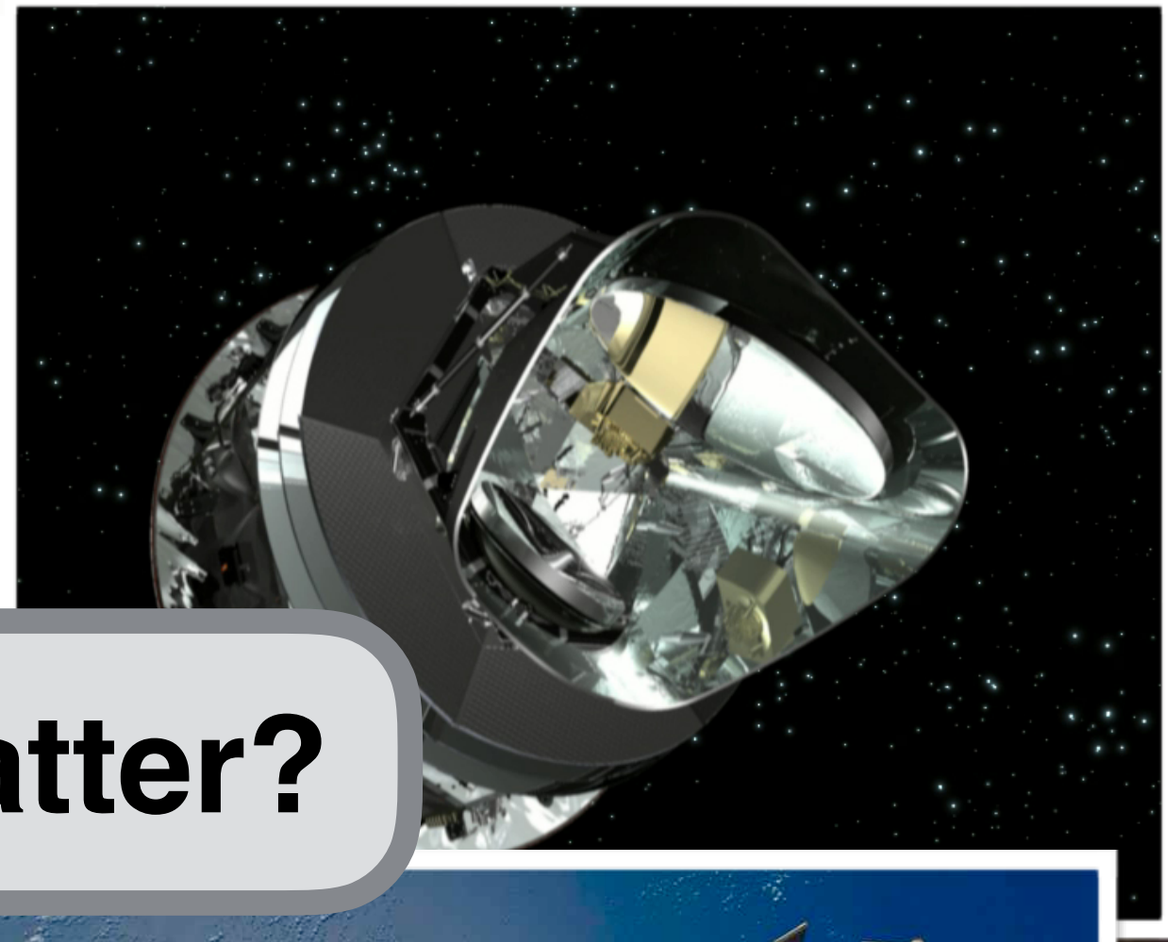

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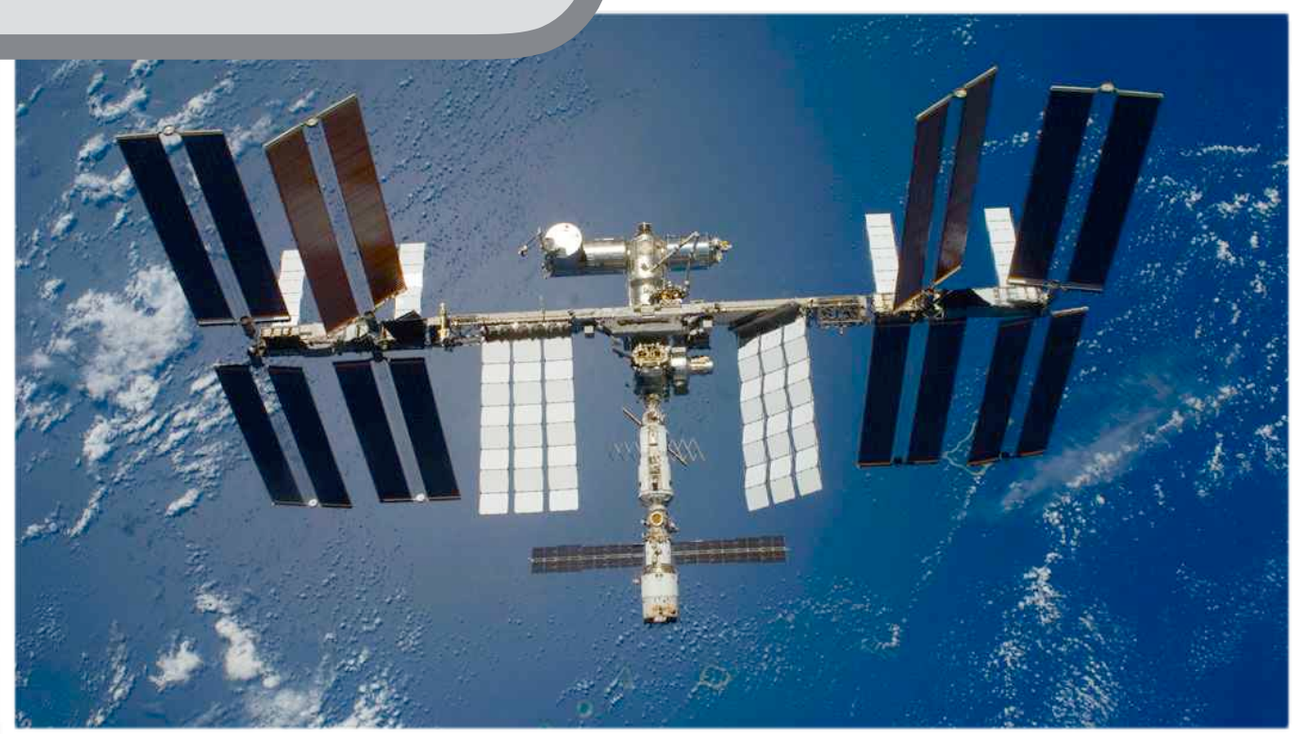

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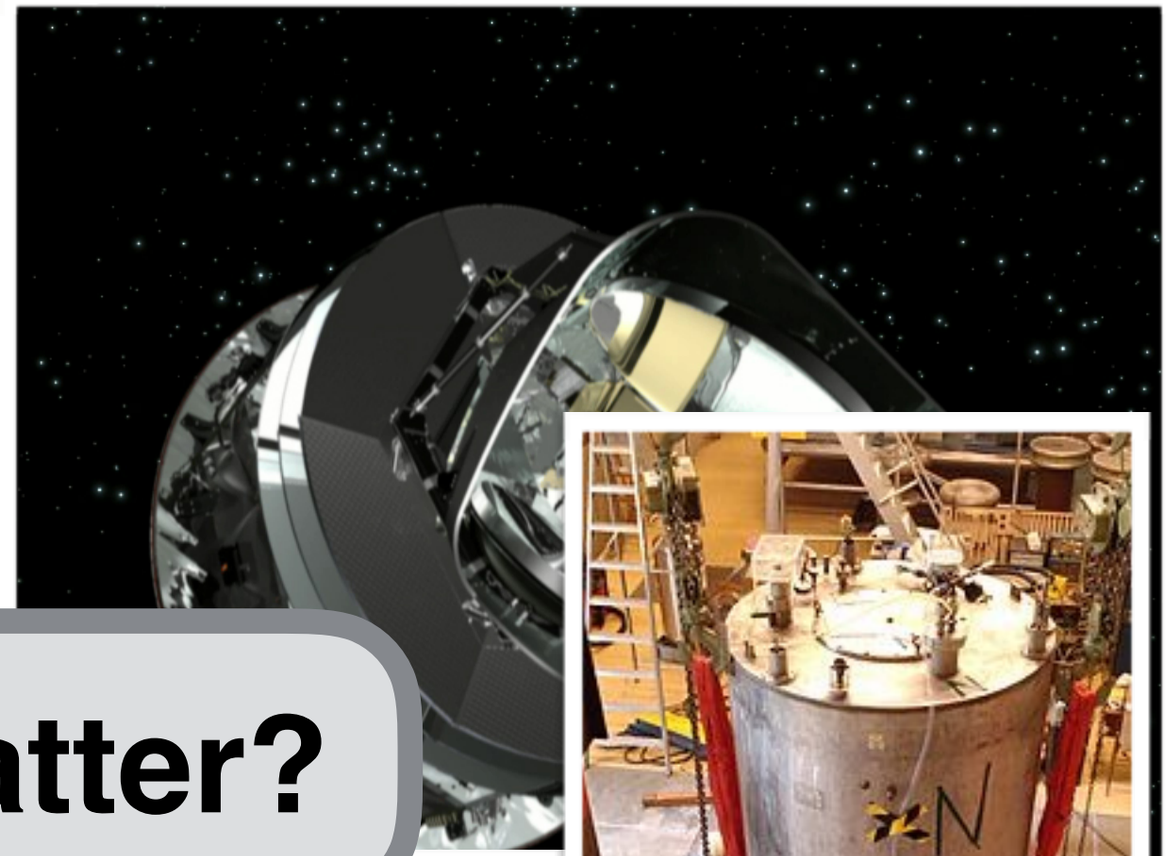

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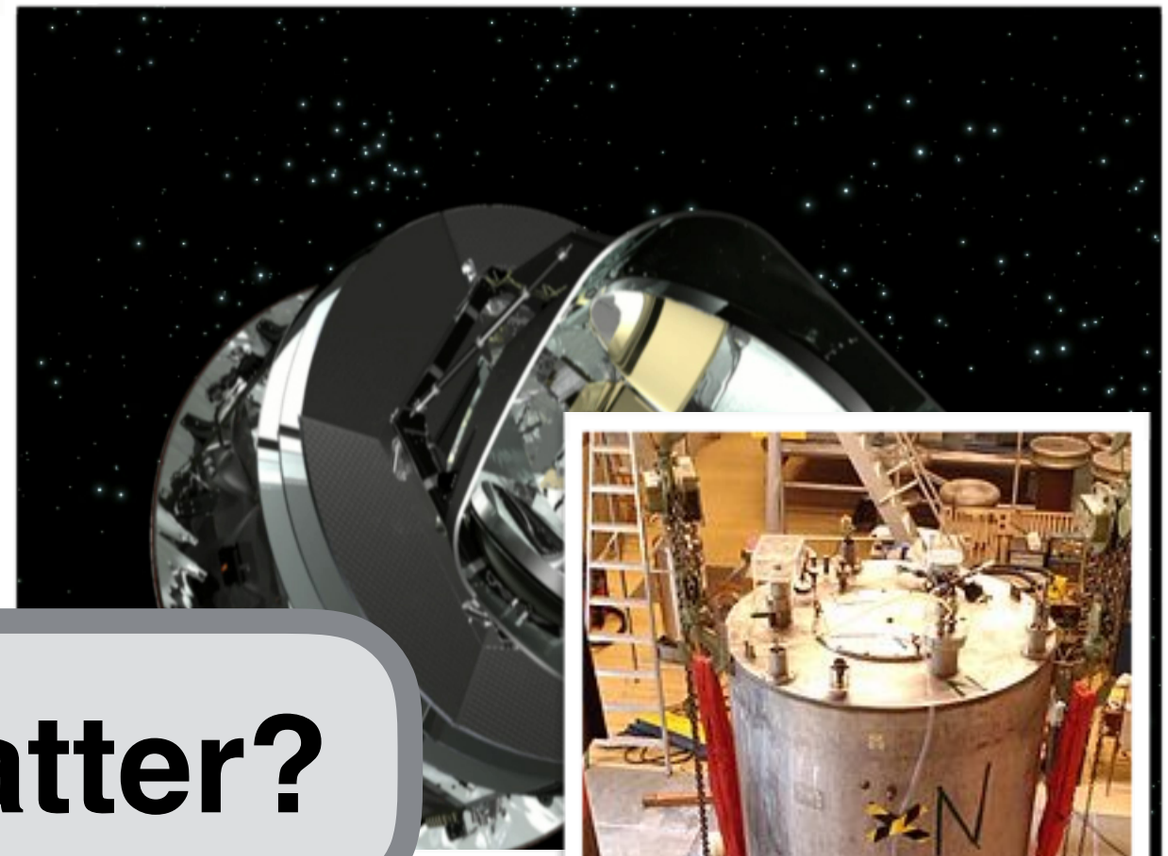
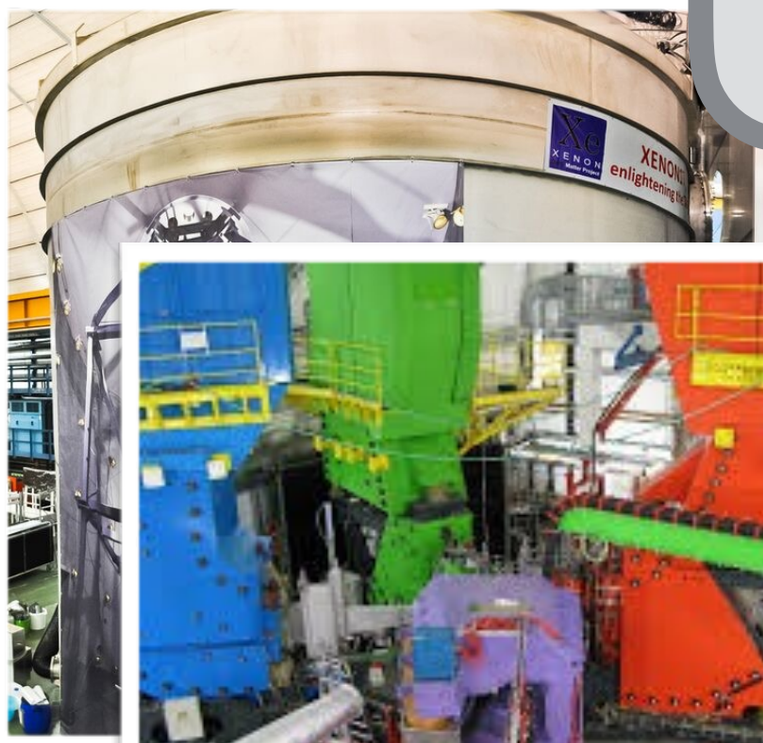
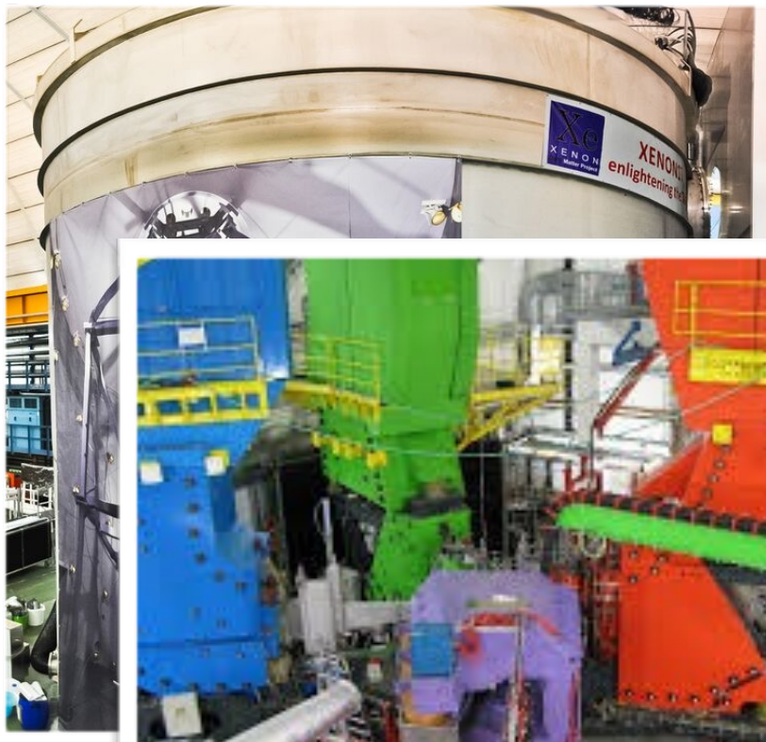
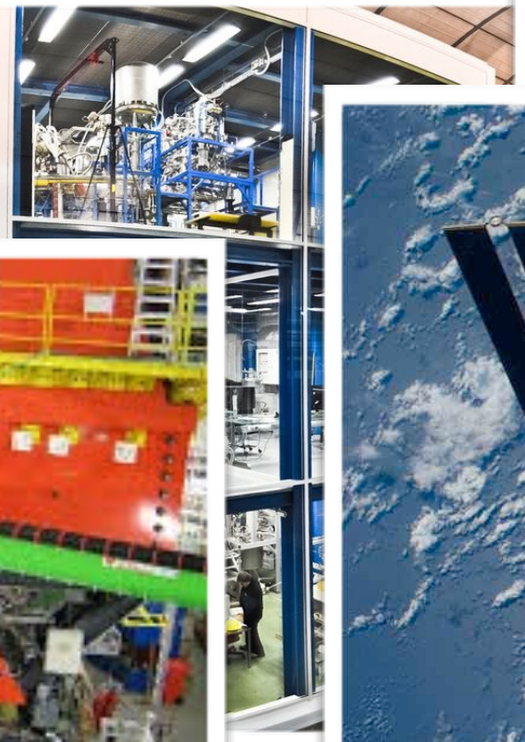




We are in a data driven era





We are in a data driven era

Wealth of new data, experiments and observations will launch new directions in dark matter (and BSM) physics