BEYOND WIMPS: SEARCHING FOR DARK MATTER PAST, PRESENT, FUTURE

Rencontres de Blois
May 29, 2017

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THE SEARCH FOR PHYSICS BEYOND THE STANDARD MODEL

Gravity

Neutrino masses

inflation

Unification

flavor

CC naturalness

Dark matter

Weak scale naturalness

strong CP naturalness

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THIS IS A STORY OF LAMP POSTS

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WHAT IS DARK MATTER?

THE ZOOLOGY OF DARK MATTER

Three basic categories of dark matter:

THE ZOOLOGY OF DARK MATTER

Three basic categories of dark matter:

- Reasonable

THE ZOOLOGY OF DARK MATTER

Three basic categories of dark matter:

Reasonable Weird

THE ZOOLOGY OF DARK MATTER

Three basic categories of dark matter:

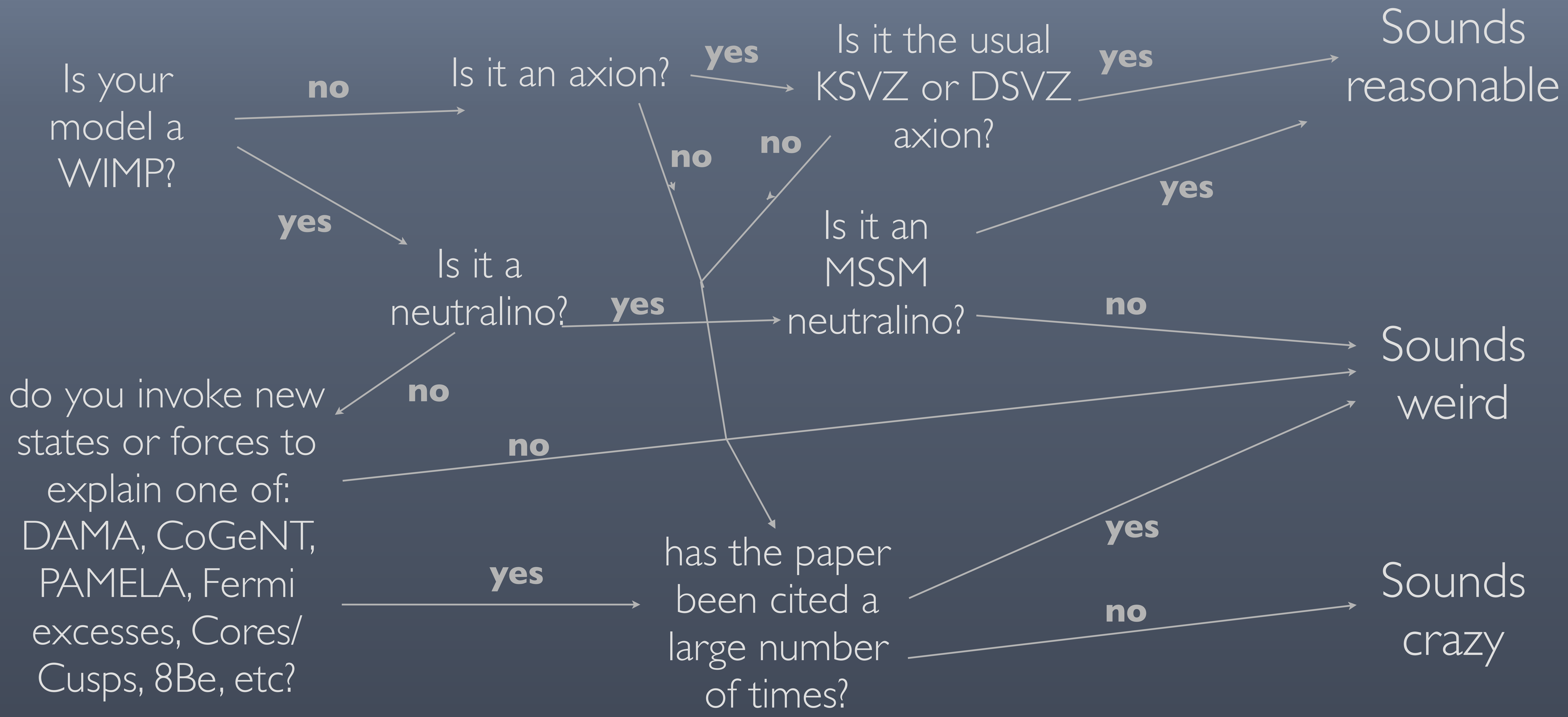
Reasonable	Weird	Crazy

THE ZOOLOGY OF DARK MATTER

Three basic categories of dark matter:

Reasonable Weird Crazy

sometimes also
called “normal”



Is your model a WIMP?

no

Is it an axion?

yes

Is it the usual KSVZ or DSVZ axion?

yes

Sounds reasonable

no

no

yes

Is it a neutralino?

yes

Is it an MSSM neutralino?

yes

no

Sounds weird

no

do you invoke new states or forces to explain one of: DAMA, CoGeNT, PAMELA, Fermi excesses, Cores/ Cusps, 8Be, etc?

no

yes

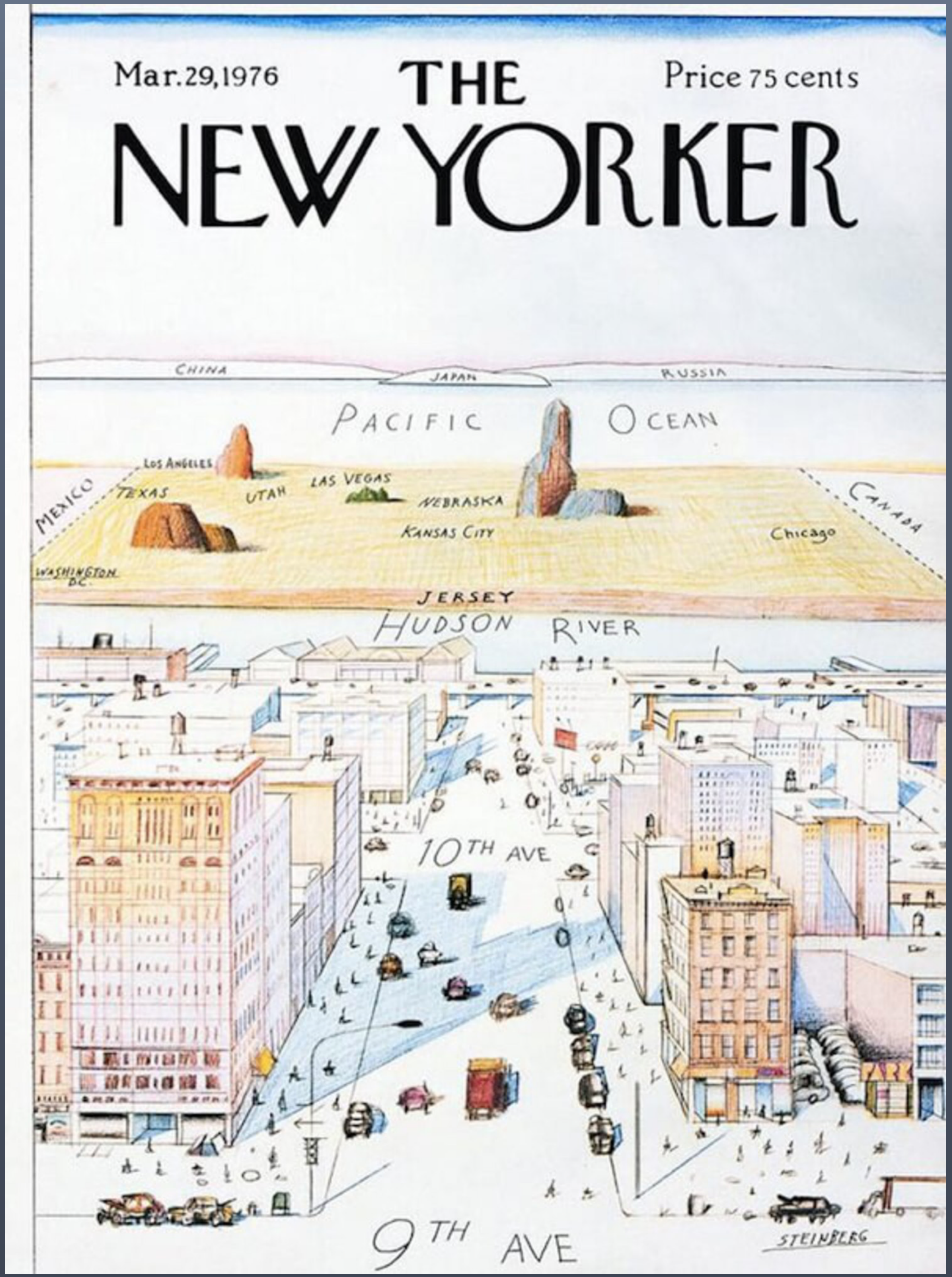
has the paper been cited a large number of times?

yes

no

Sounds crazy

A PERSPECTIVE ON DARK MATTER



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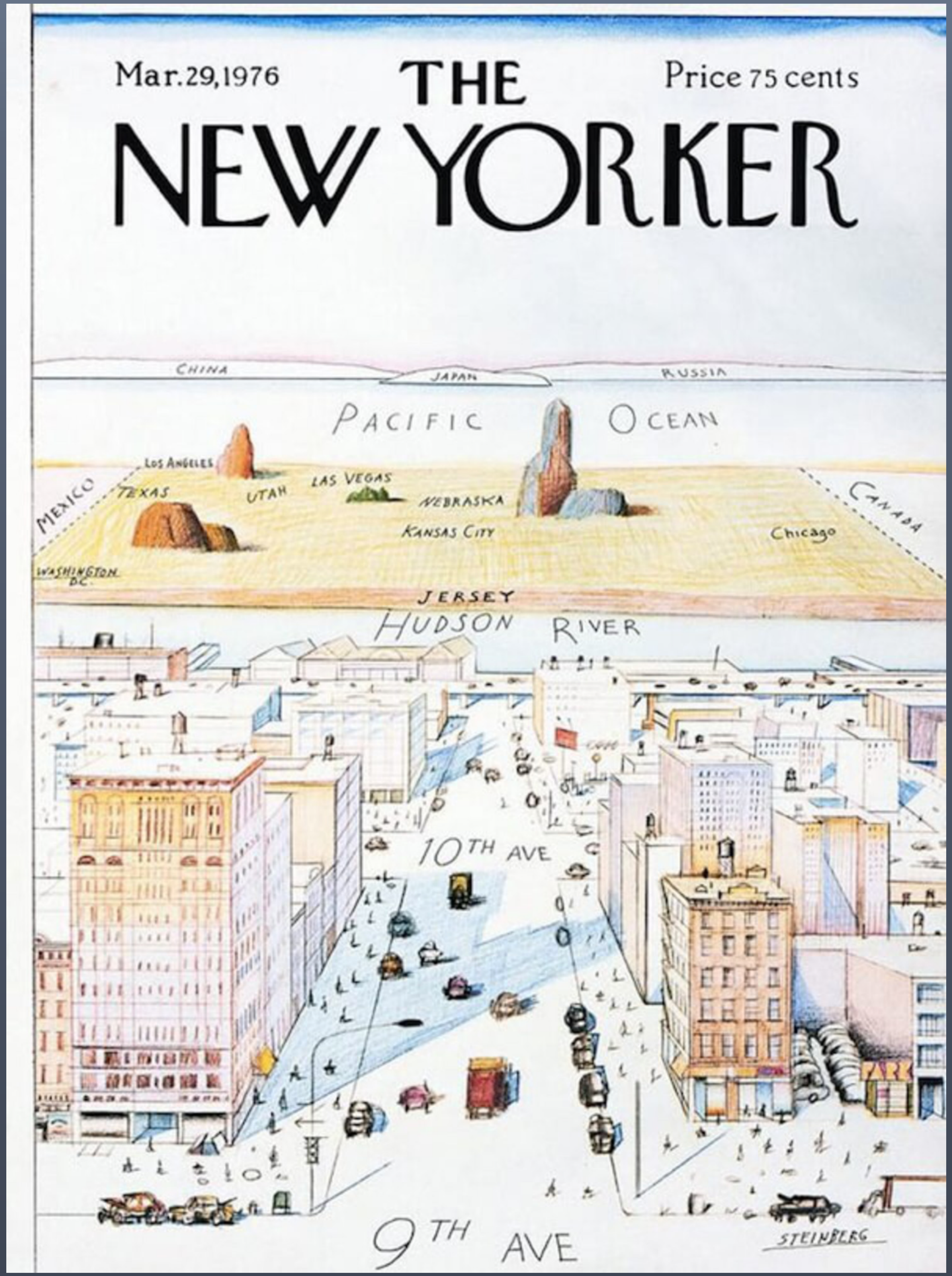

WIMPland

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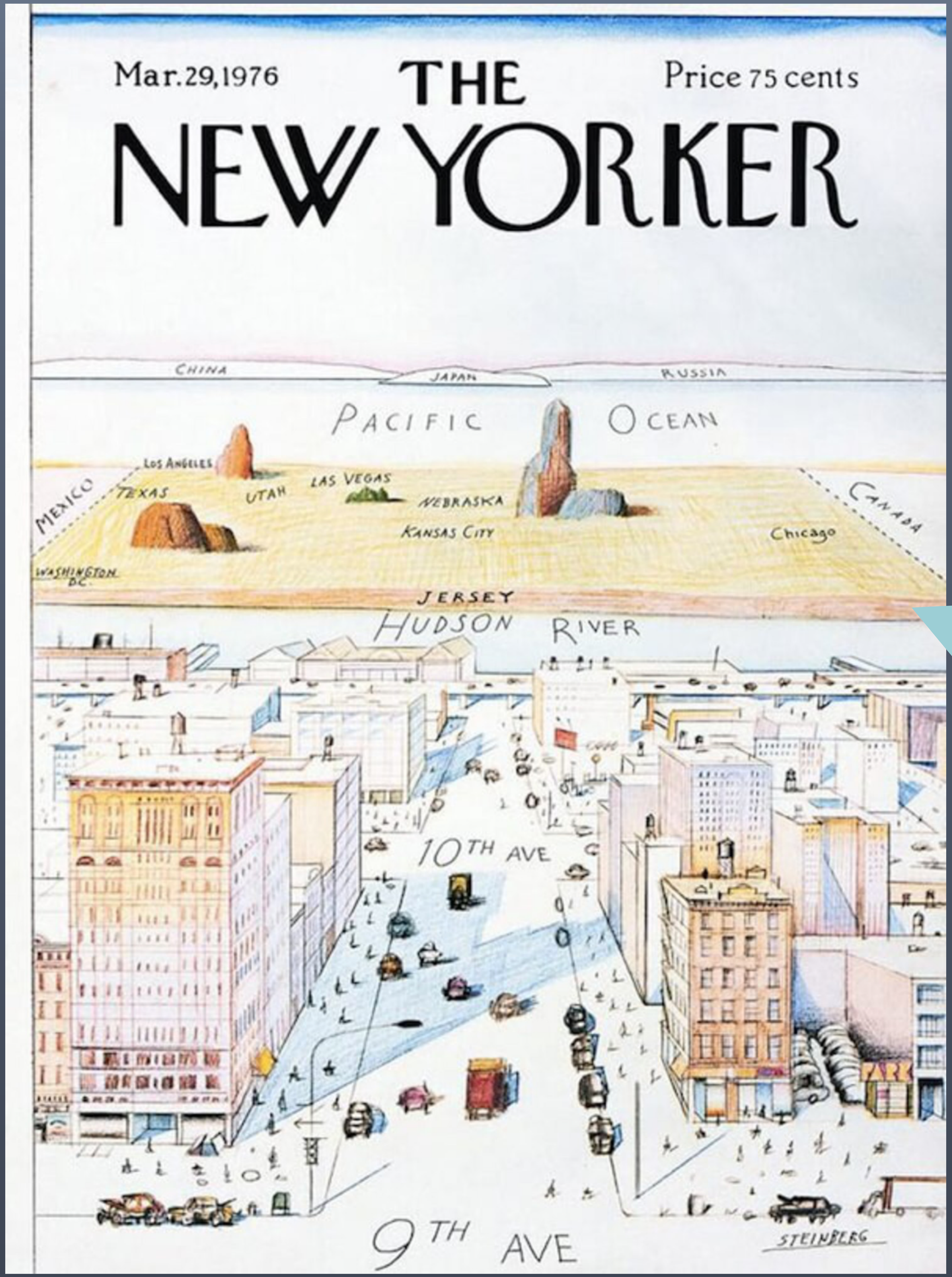
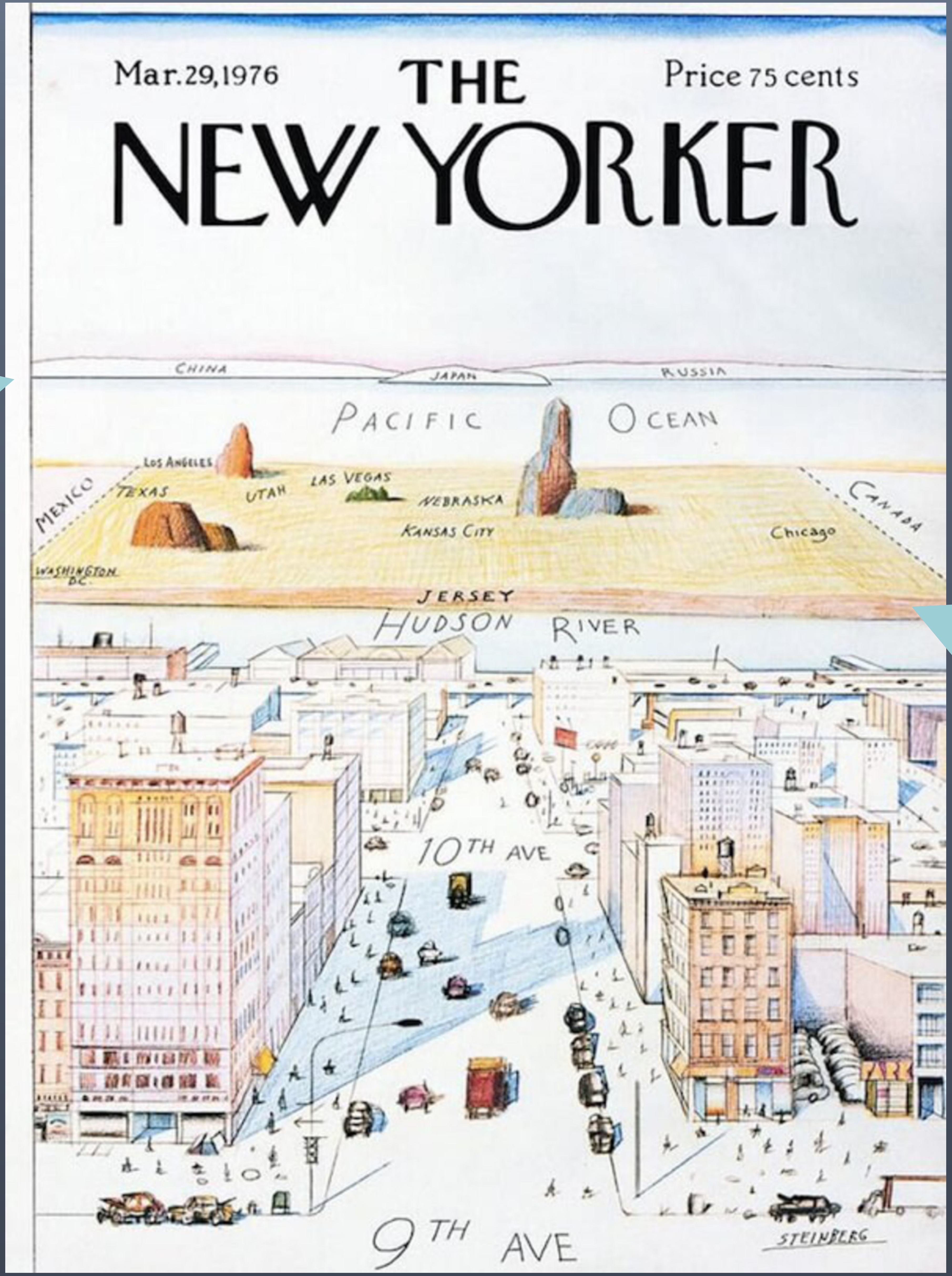


WIMPland

Axiurbia

A PERSPECTIVE ON DARK MATTER

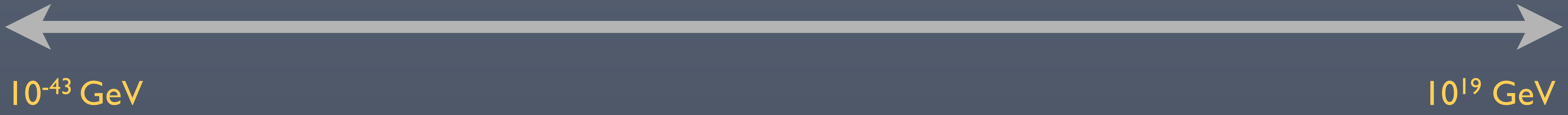


United Nations
of
other DM

WIMPland

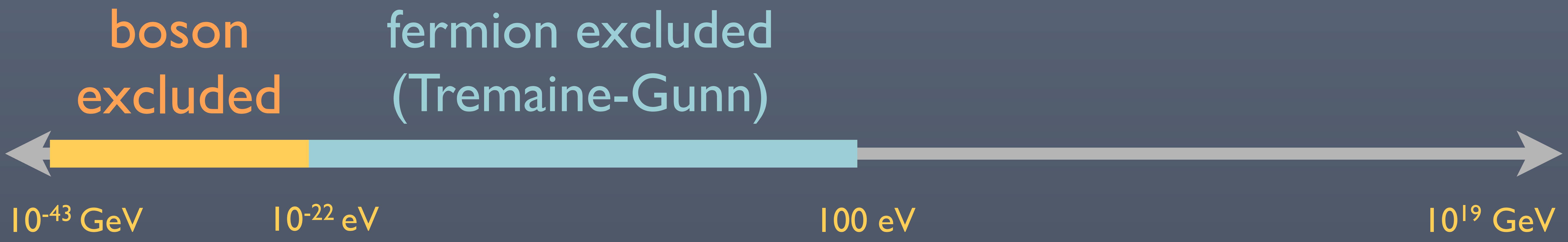
Axiurbia

THE SCALES OF *particle* DARK MATTER



(courtesy S. Rajendran)

THE SCALES OF *particle* DARK MATTER



boson
excluded

fermion excluded
(Tremaine-Gunn)

10^{-43} GeV

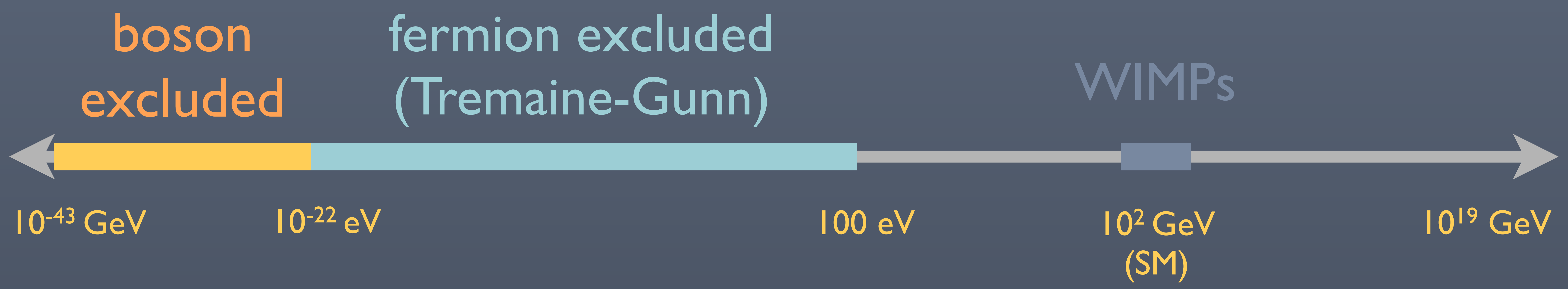
10^{-22} eV

100 eV

10^{19} GeV

(courtesy S. Rajendran)

THE SCALES OF *particle* DARK MATTER



(courtesy S. Rajendran)

Broader question: how was dark matter **formed?**

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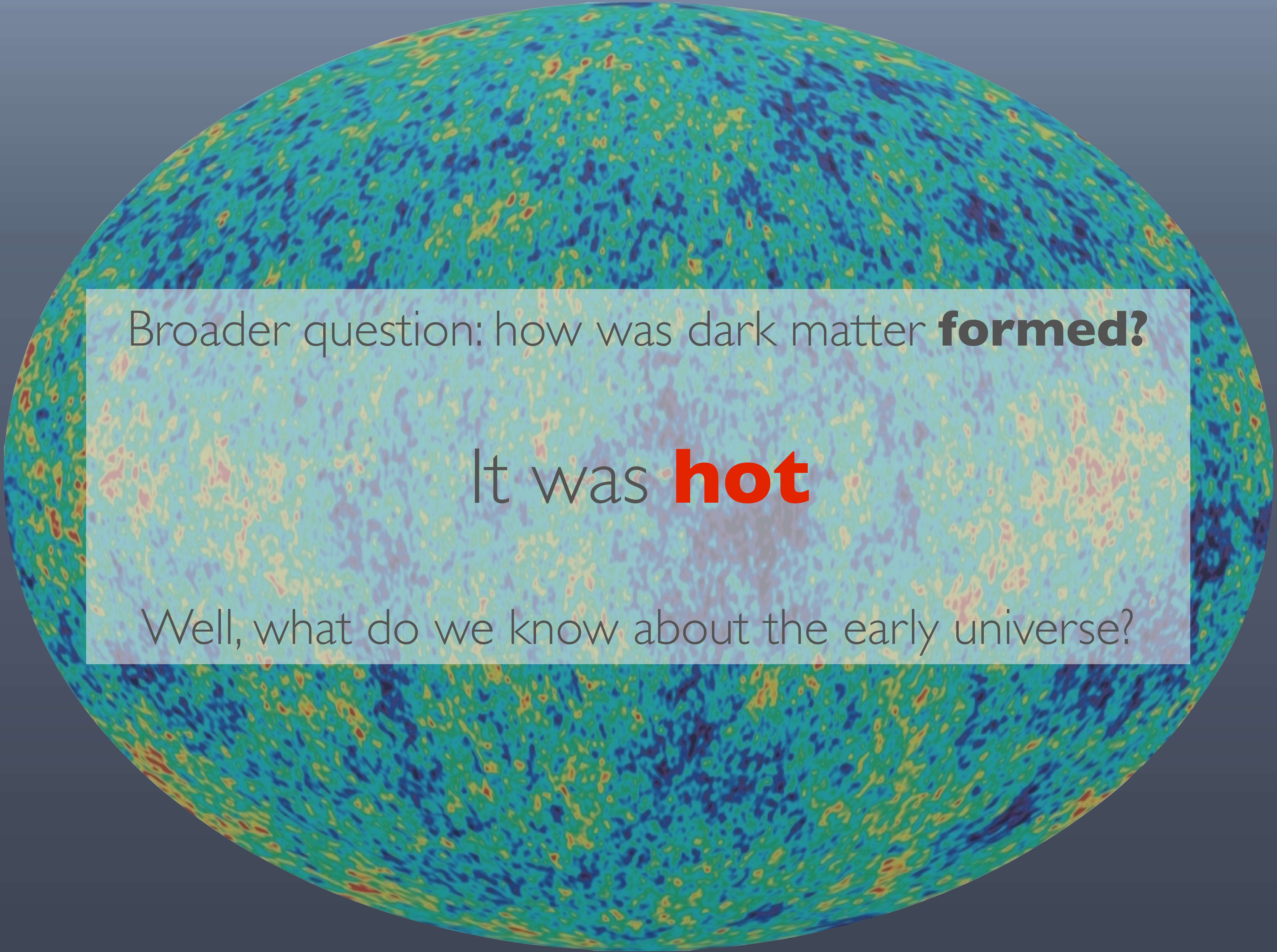
Well, what do we know about the early universe?



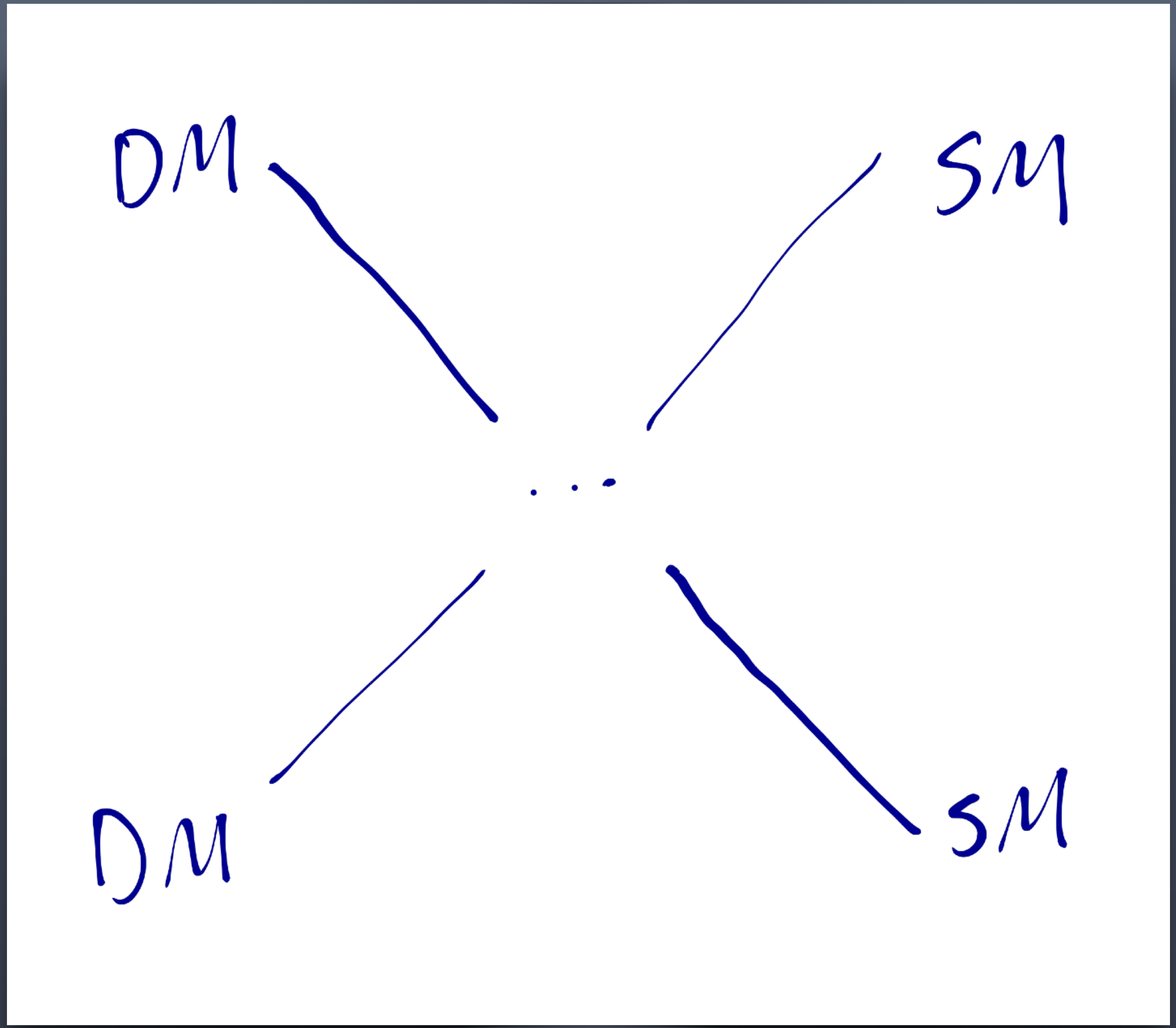
Broader question: how was dark matter **formed?**

It was **hot**

Well, what do we know about the early universe?

A THERMAL RELIC

Assume dark matter is in thermal contact with the SM bath, and then at some temperature T (when DM is non-relativistic) it decouples



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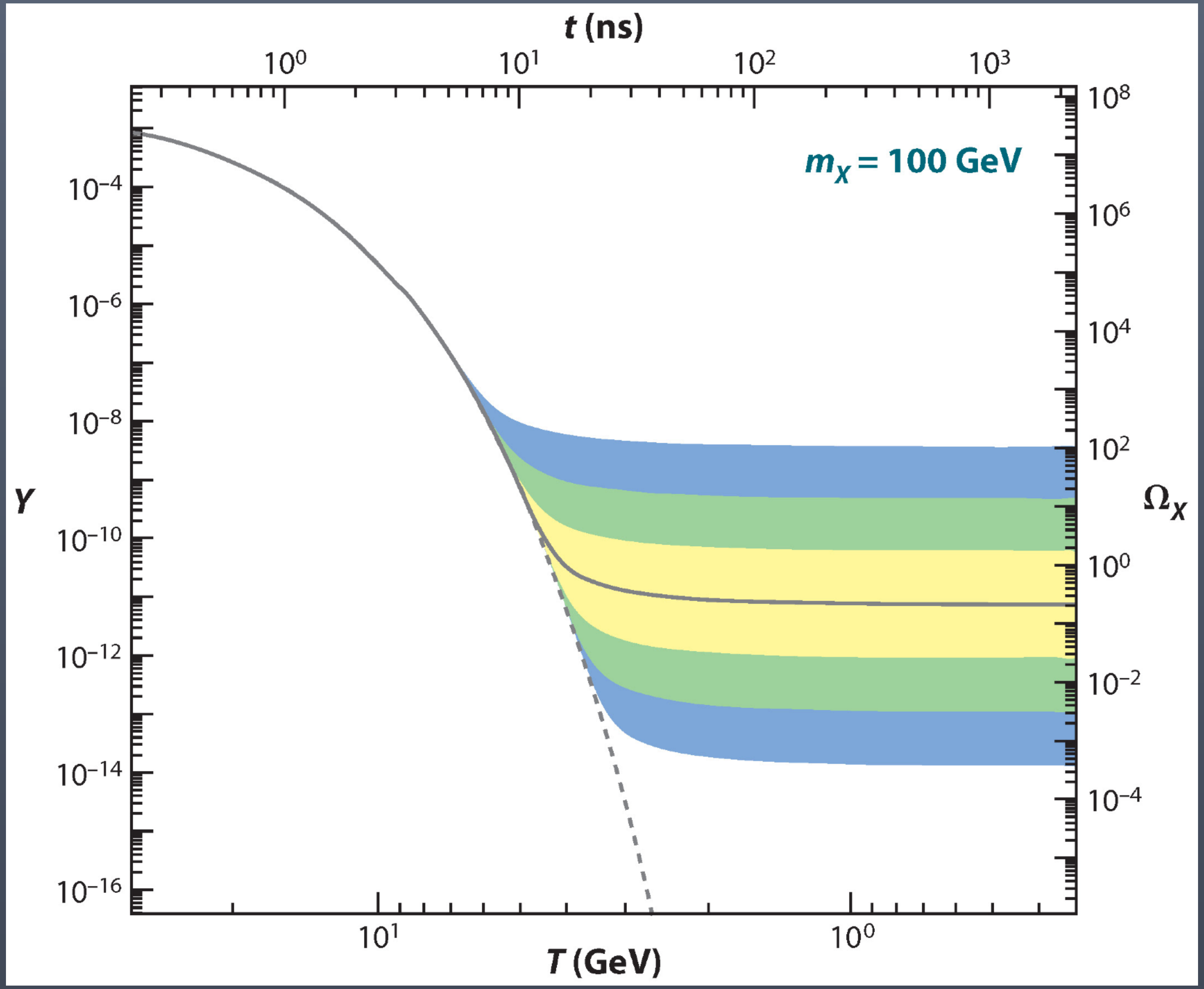

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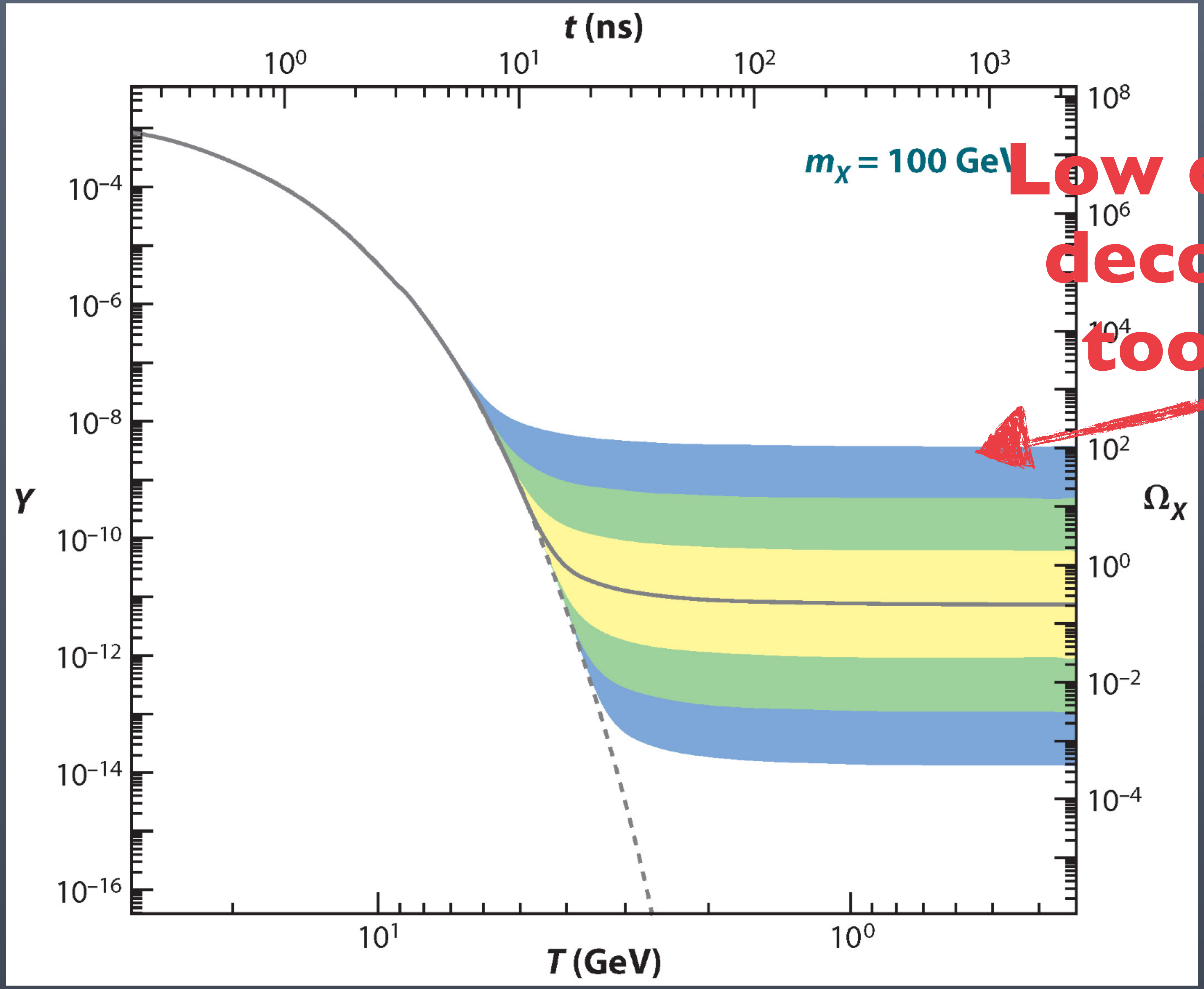

Low cross section decouples early too much DM

A THERMAL RELIC

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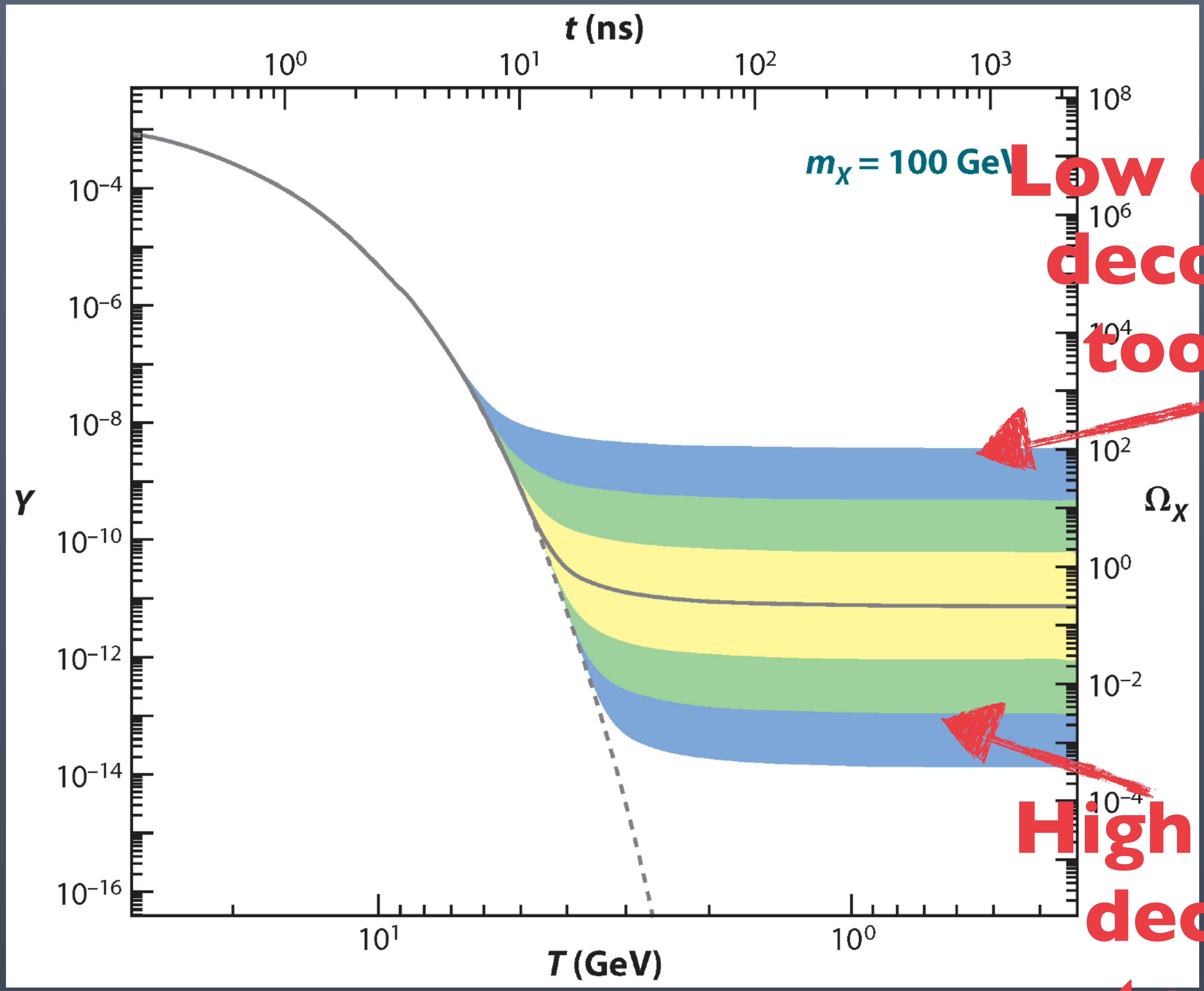
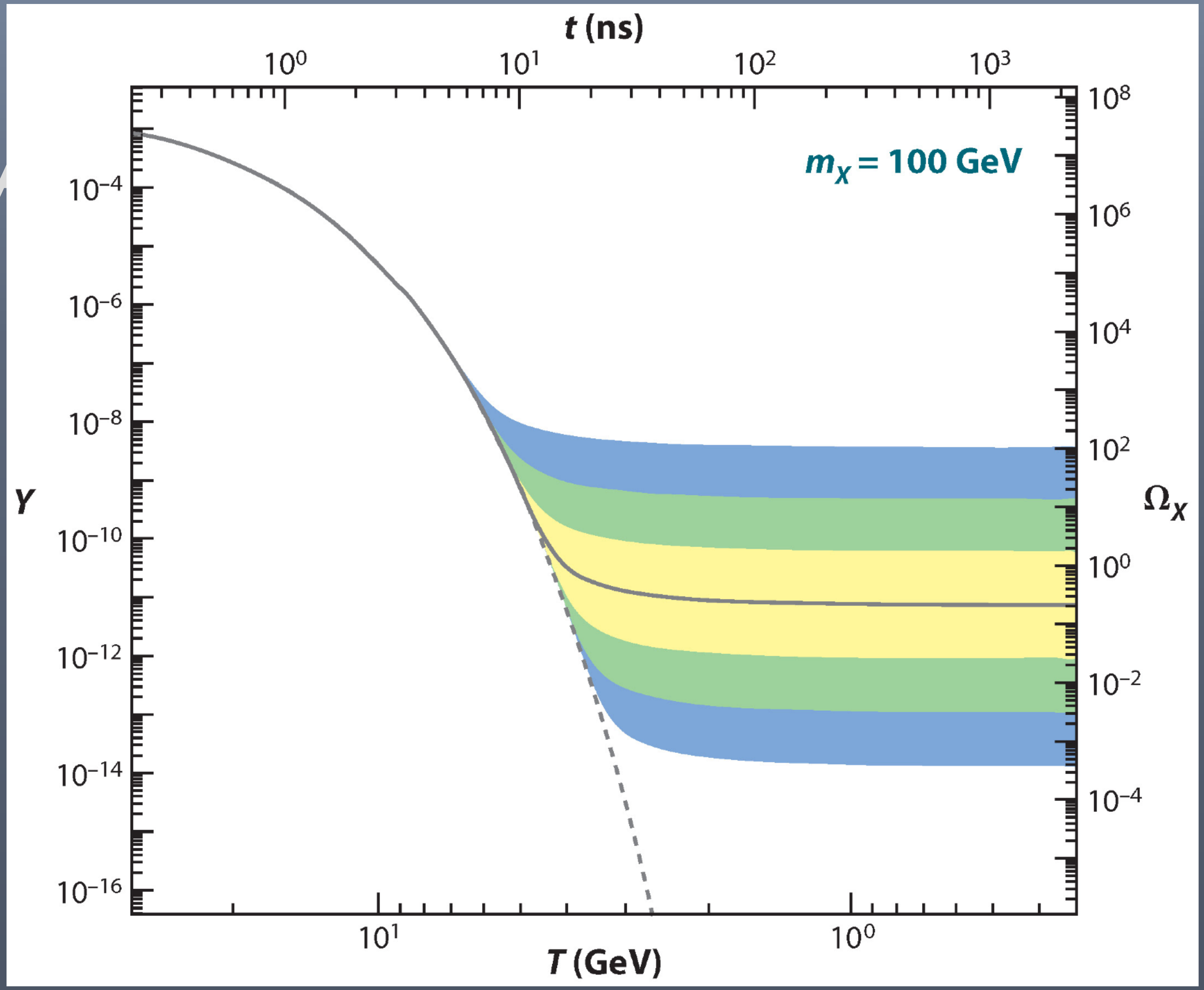


Low cross section decouples early too much DM

High cross section decouples late too little DM



For a thermal relic, you learn precisely one number, namely the annihilation cross section

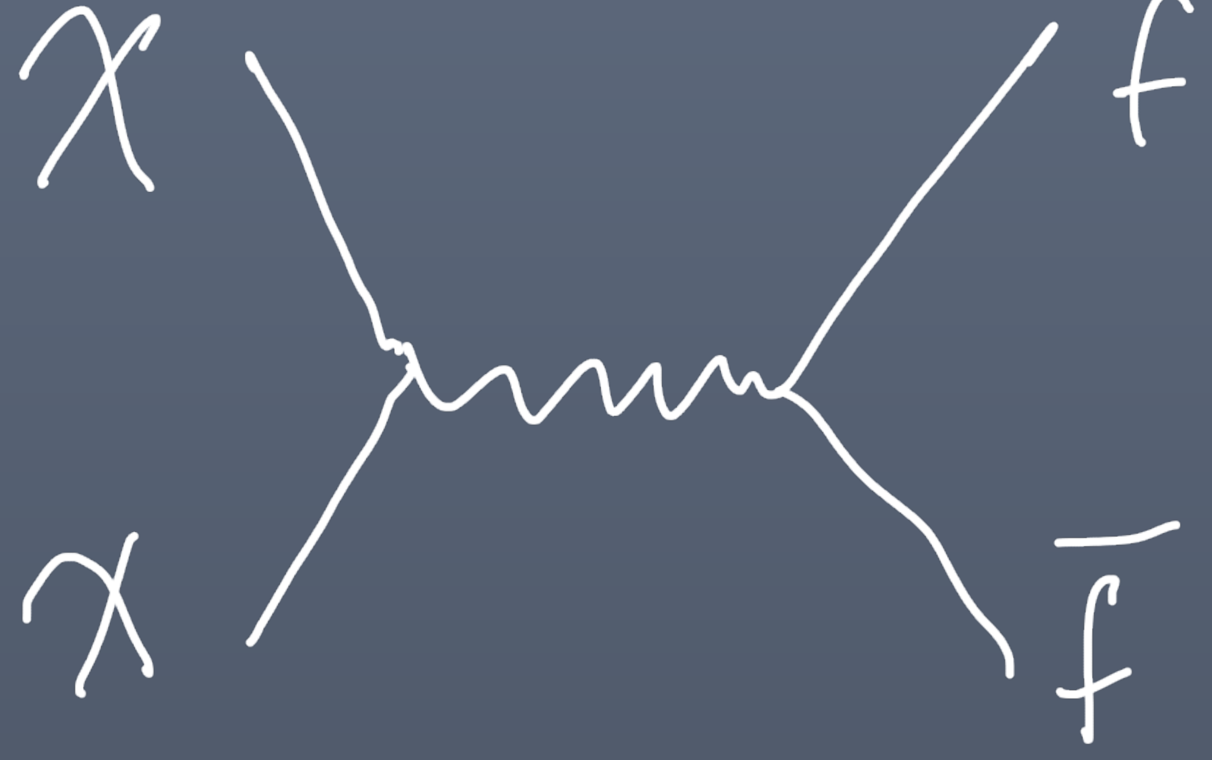
$$< \sigma v >_{ann} \approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{sec}^{-1}$$
$$\approx \frac{\alpha^2}{(200\mathrm{GeV})^2}$$

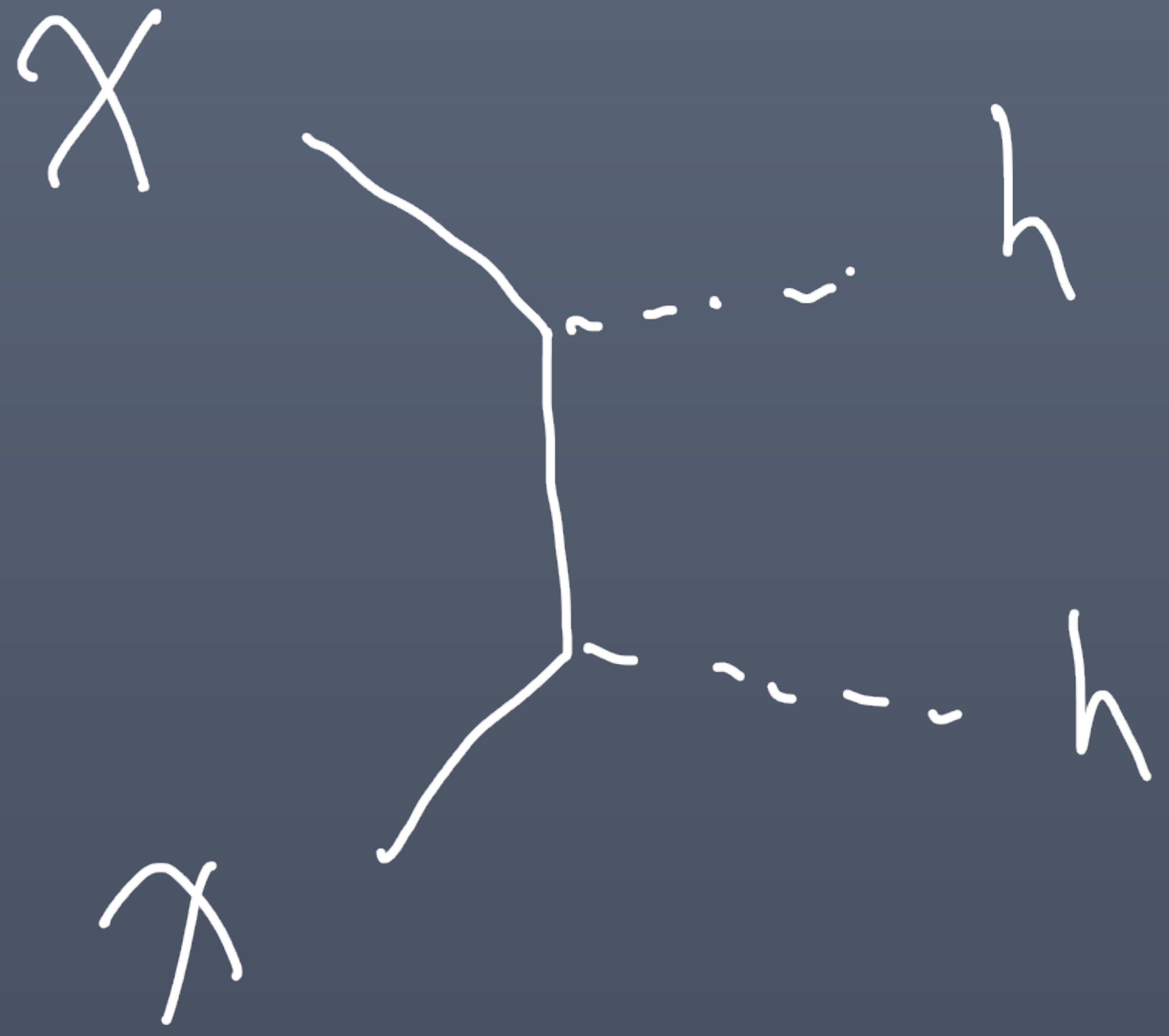
THE “WIMP MIRACLE”

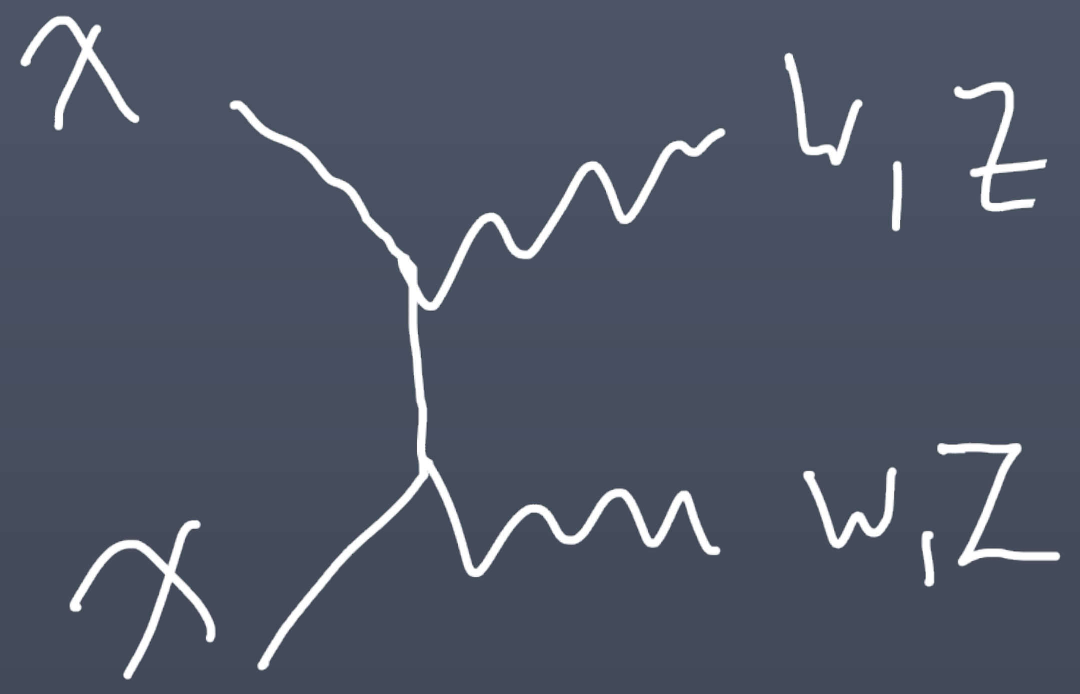
$$\begin{aligned} < \sigma v >_{ann} &\approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{sec}^{-1} \\ &\approx \frac{\alpha^2}{(200\mathrm{GeV})^2} \end{aligned}$$

NB1: This is only a pretty good miracle $O(10^{\pm 3})$

Freezeout "classic"

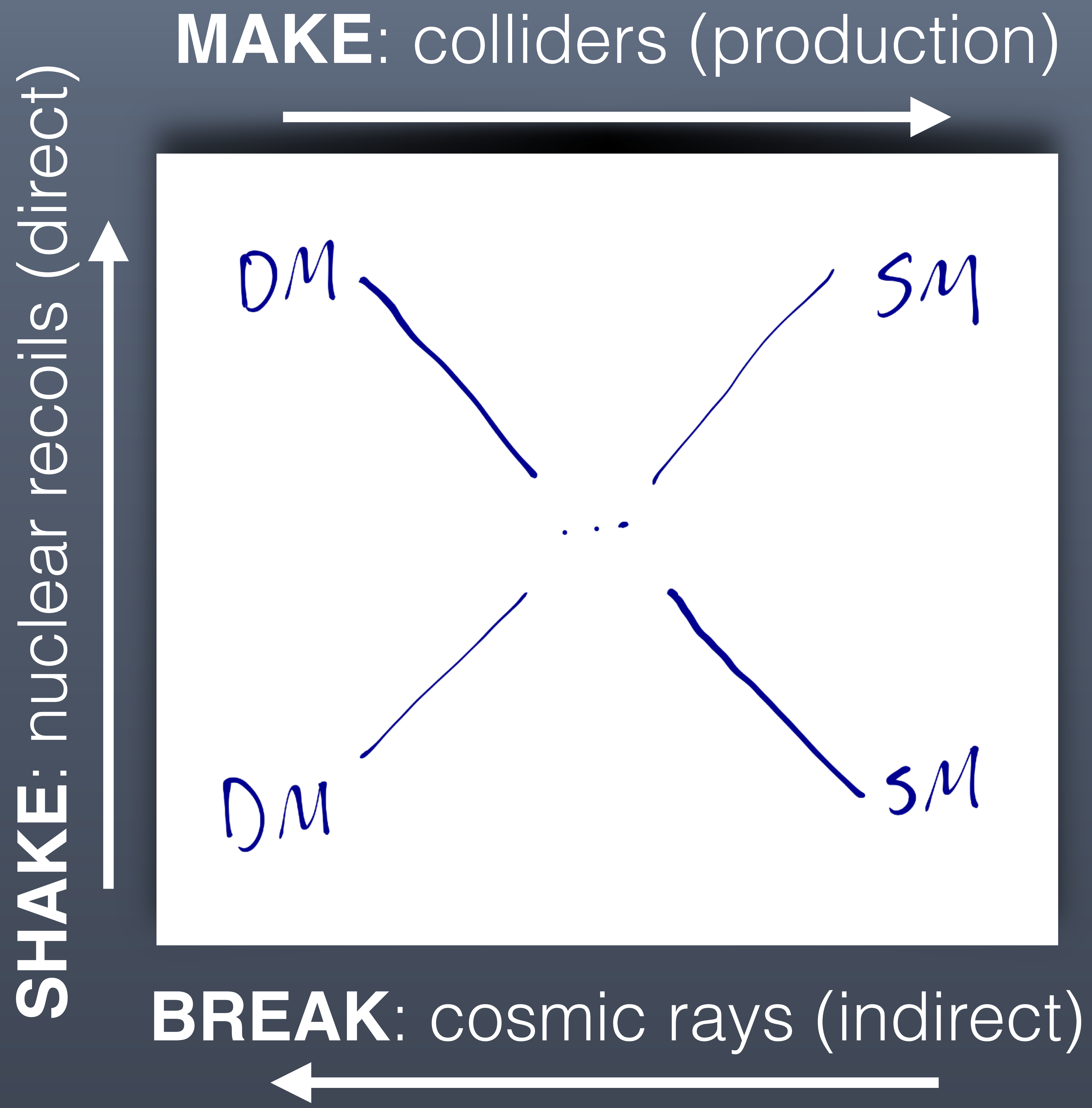






An elegant idea with minimal additions

THE "WIMP MIRACLE"

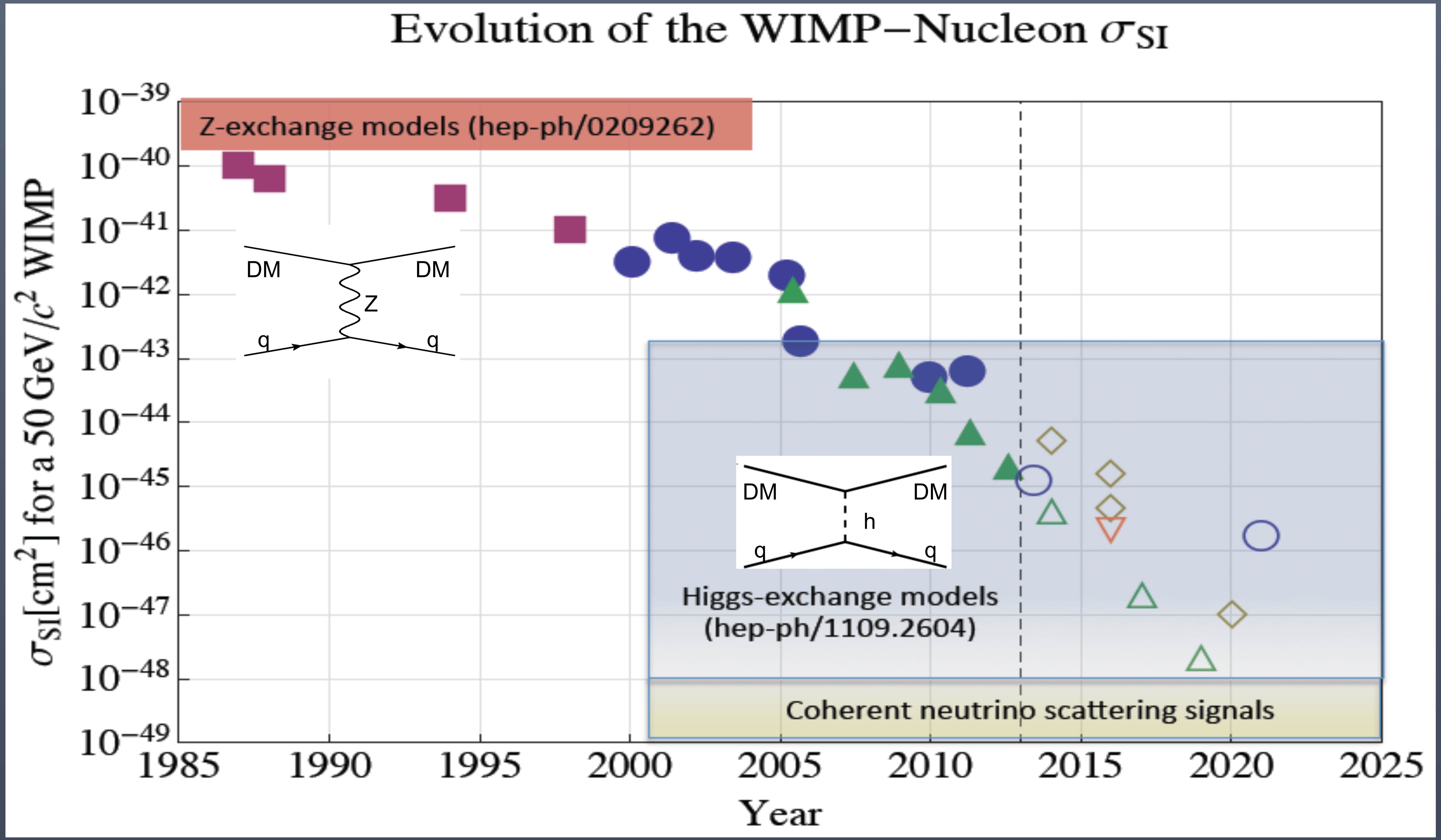


MAKE: colliders (production)

SHAKE: nuclear recoils (direct)

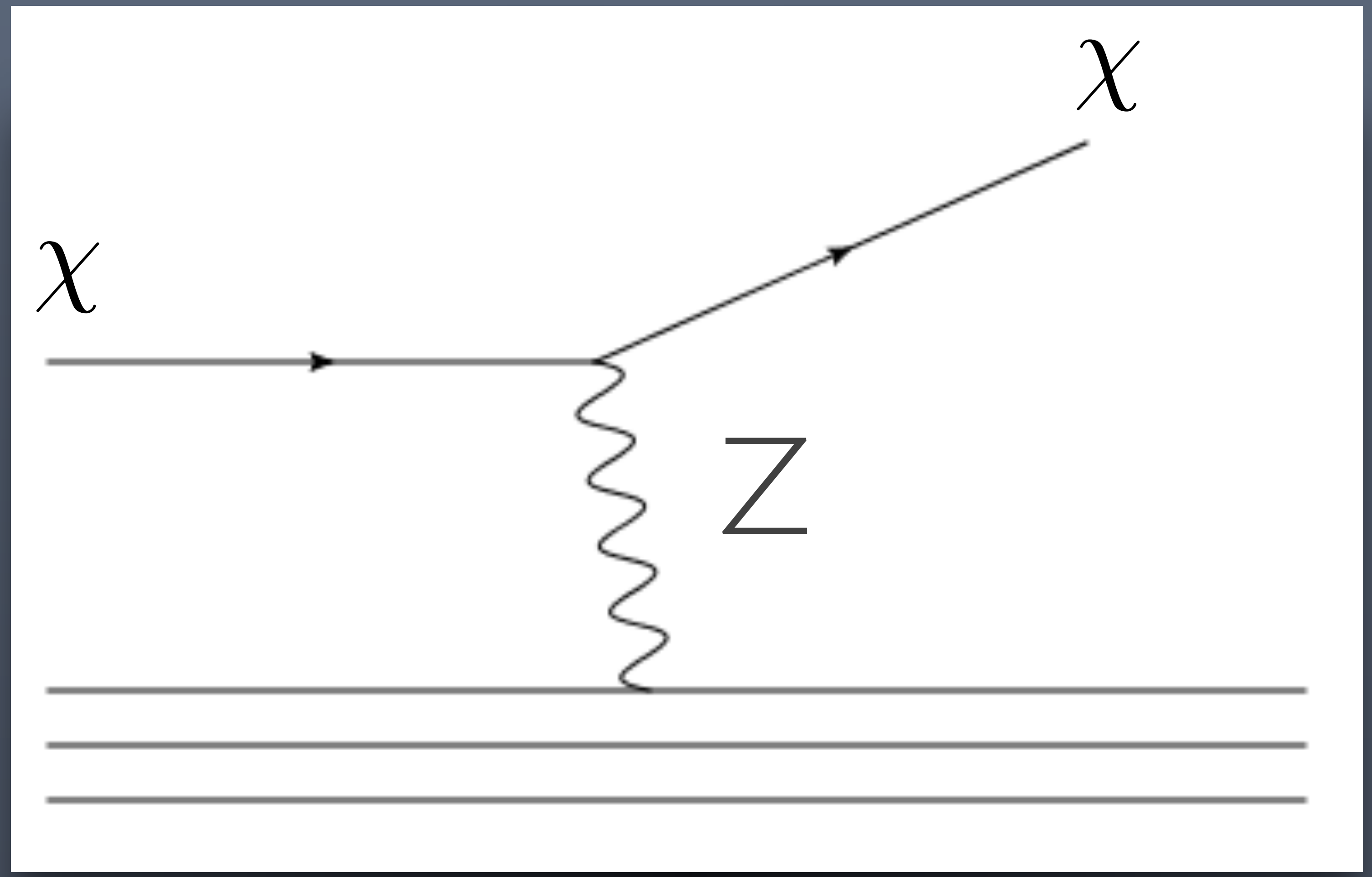
BREAK: cosmic rays (indirect)

SO WHAT ABOUT THE SEARCH FOR WIMPS?

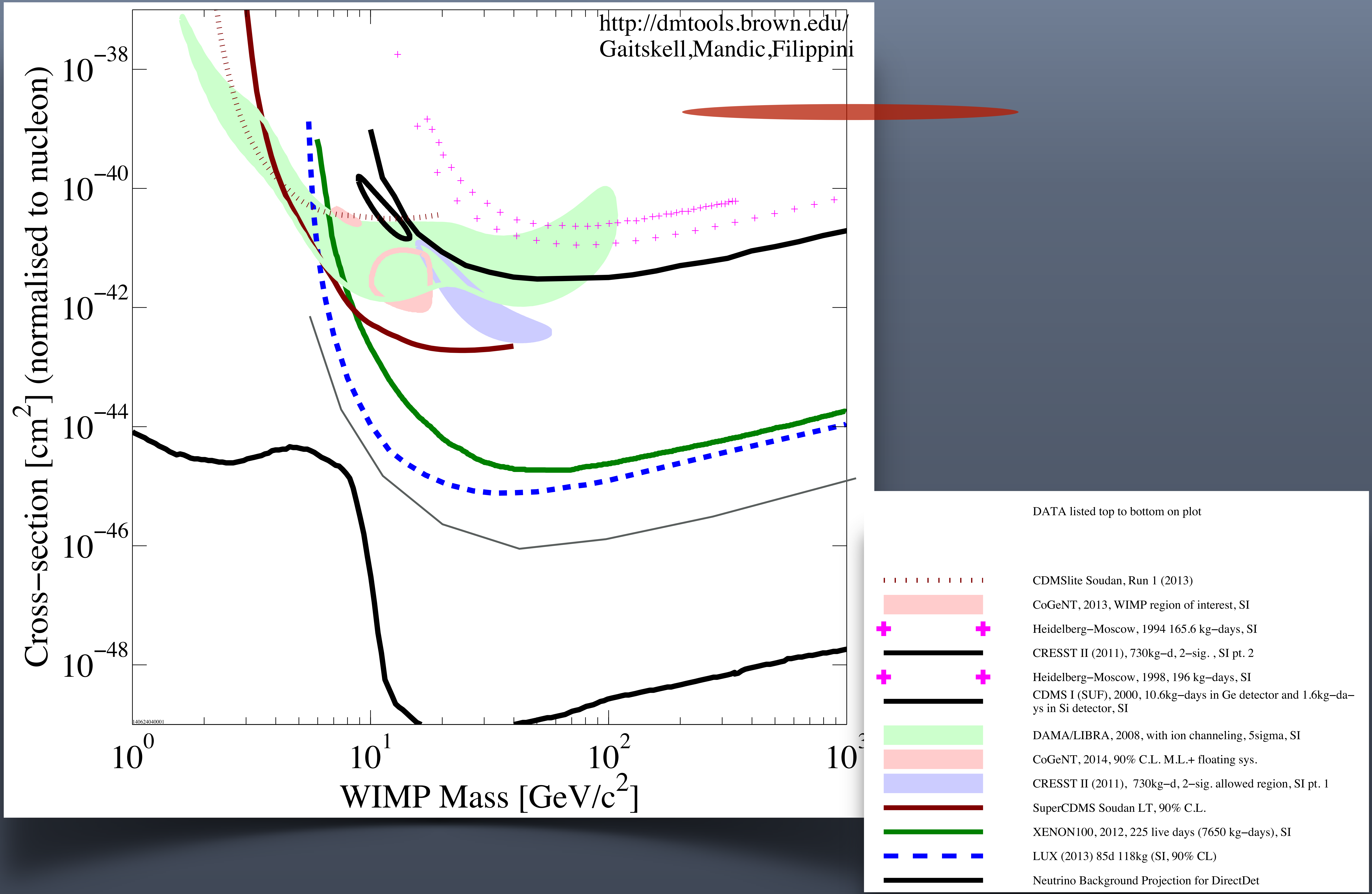


slide from J Feng

MODEL 1: HEAVY DIRAC "NEUTRINO"



$$\sigma_0 \approx \frac{G_f^2 \mu^2}{2\pi} \sim 10^{-39} \mathrm{cm}^2$$


http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
Cross−section [cm^2] (normalised to nucleon)
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
WIMP Mass [GeV/c^2]
10^0
10^1
10^2
10^3
140624040001
DATA listed top to bottom on plot
CDMSlite Soudan, Run 1 (2013)
CoGeNT, 2013, WIMP region of interest, SI
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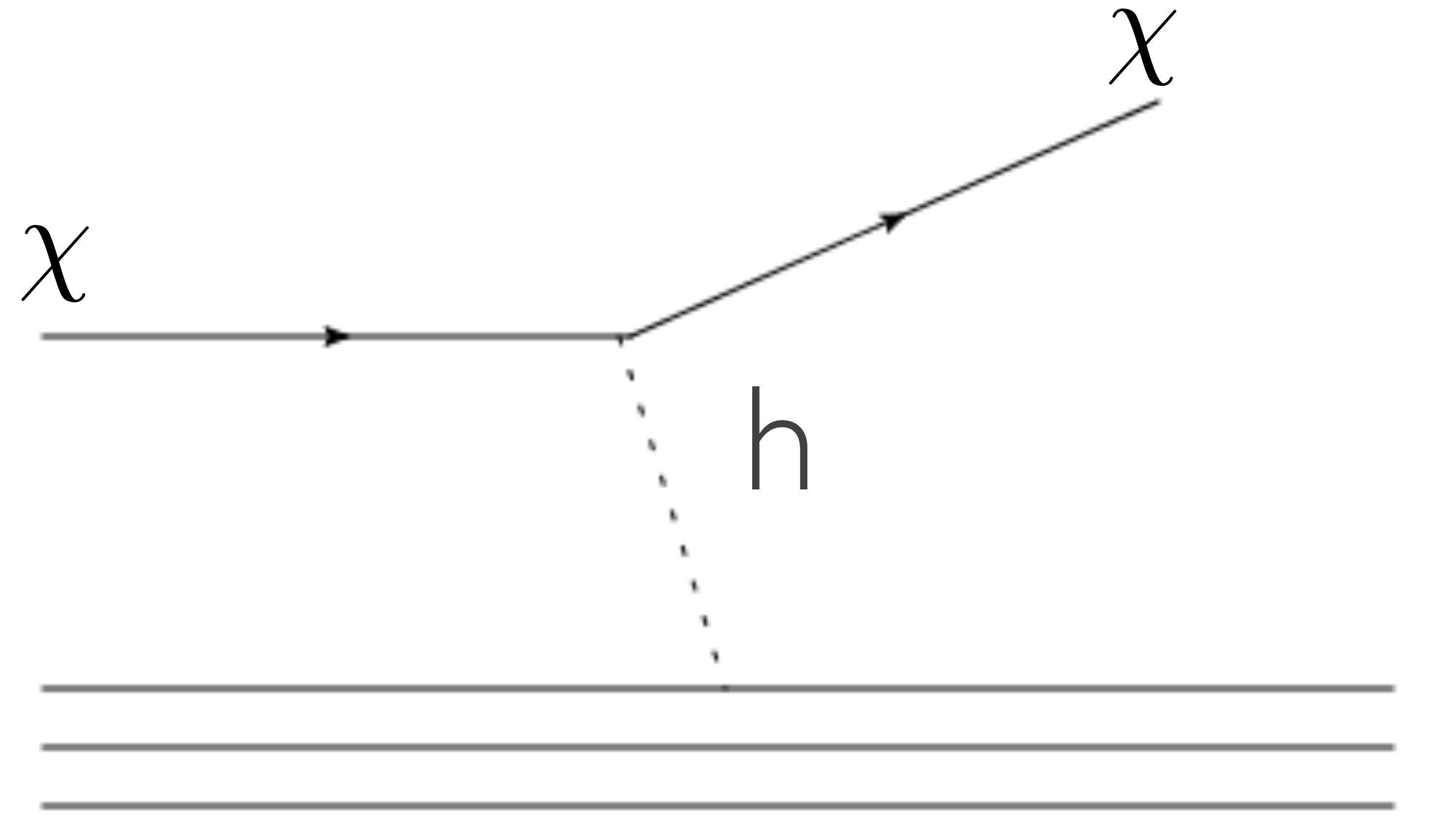
Neutrino Background Projection for DirectDet

MAJORANA DOUBLET WIMP: HIGGS MEDIATED



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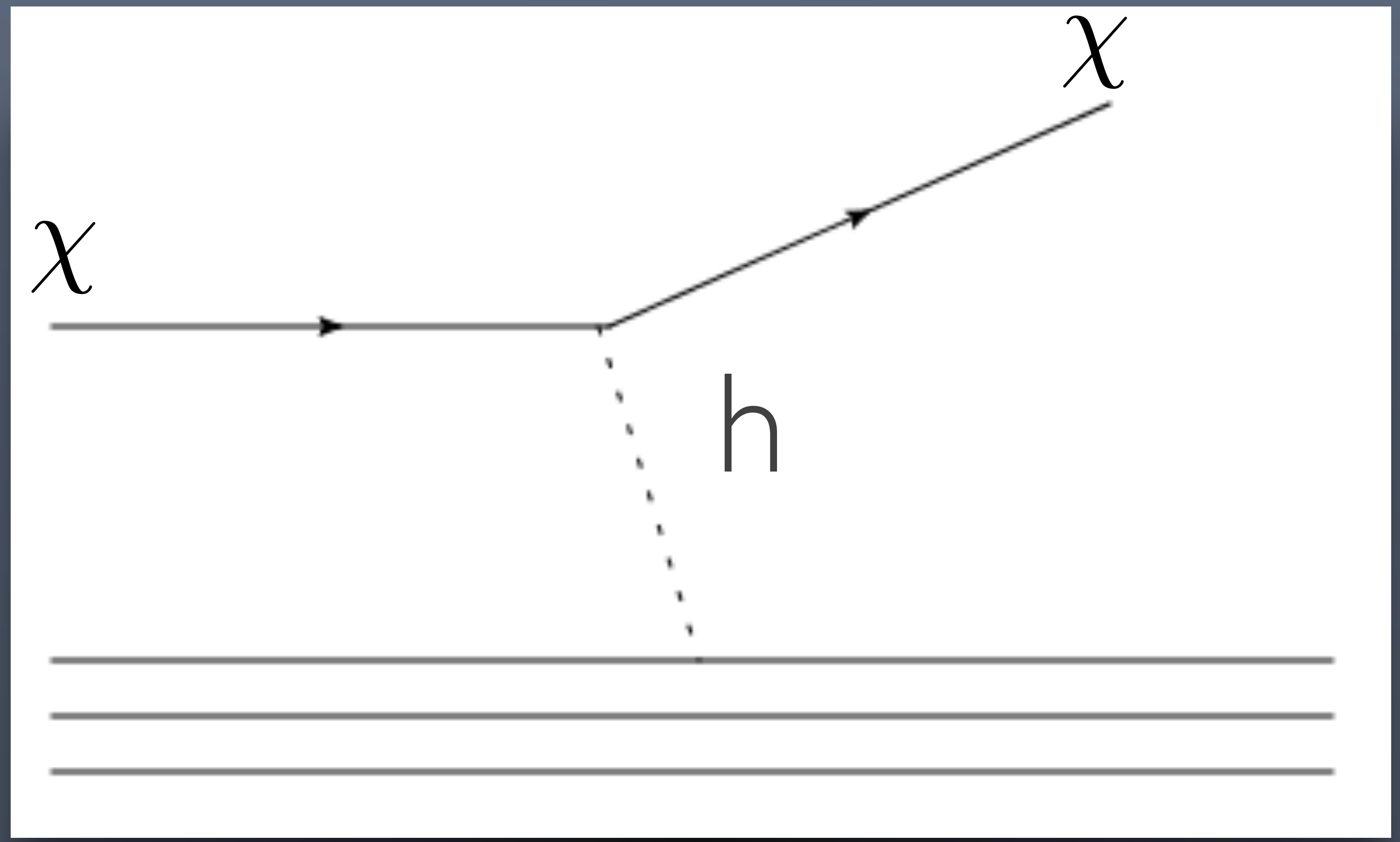

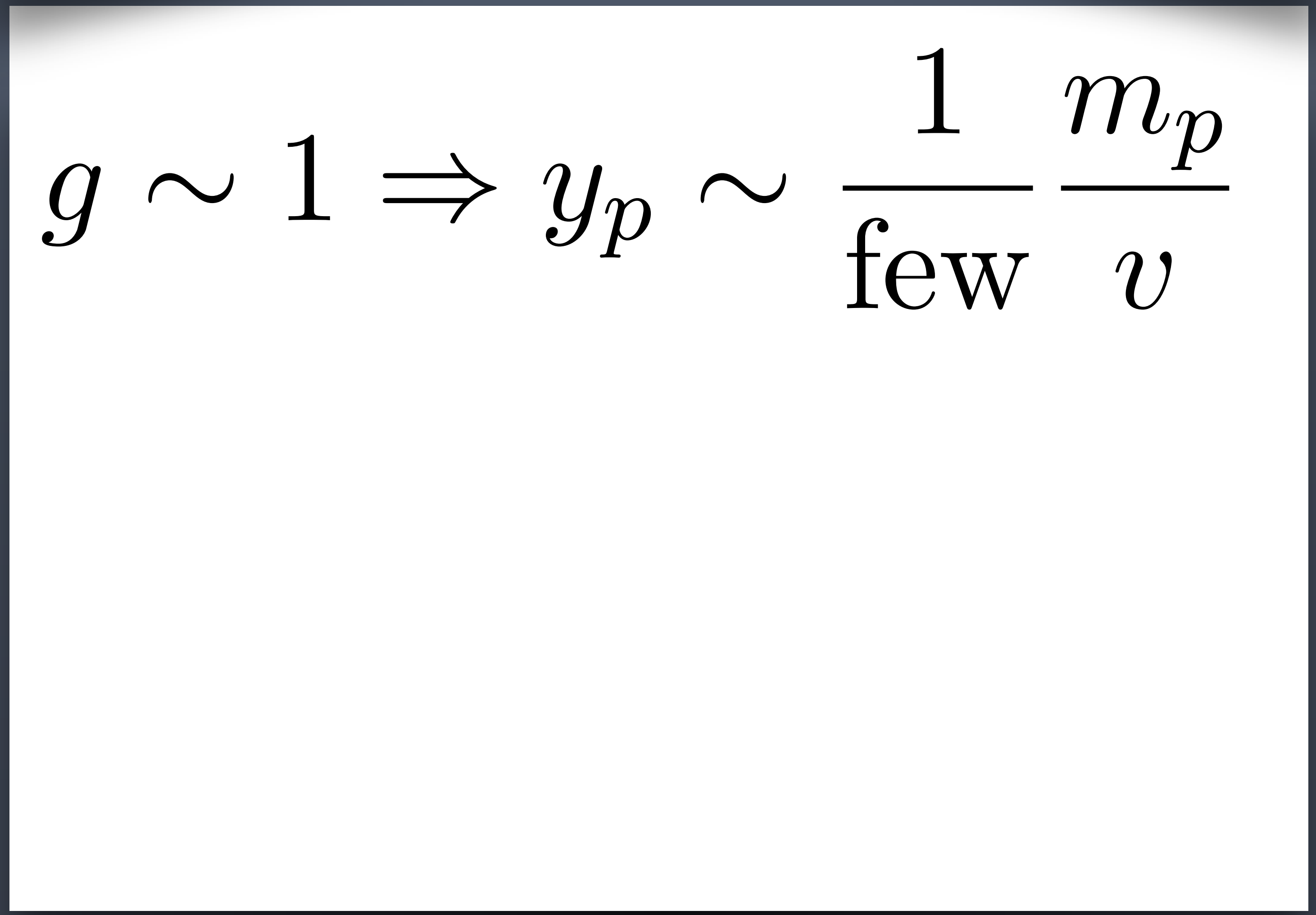

$$g \sim 1 \Rightarrow y_p \sim \frac{1}{\text{few}} \frac{m_p}{v}$$

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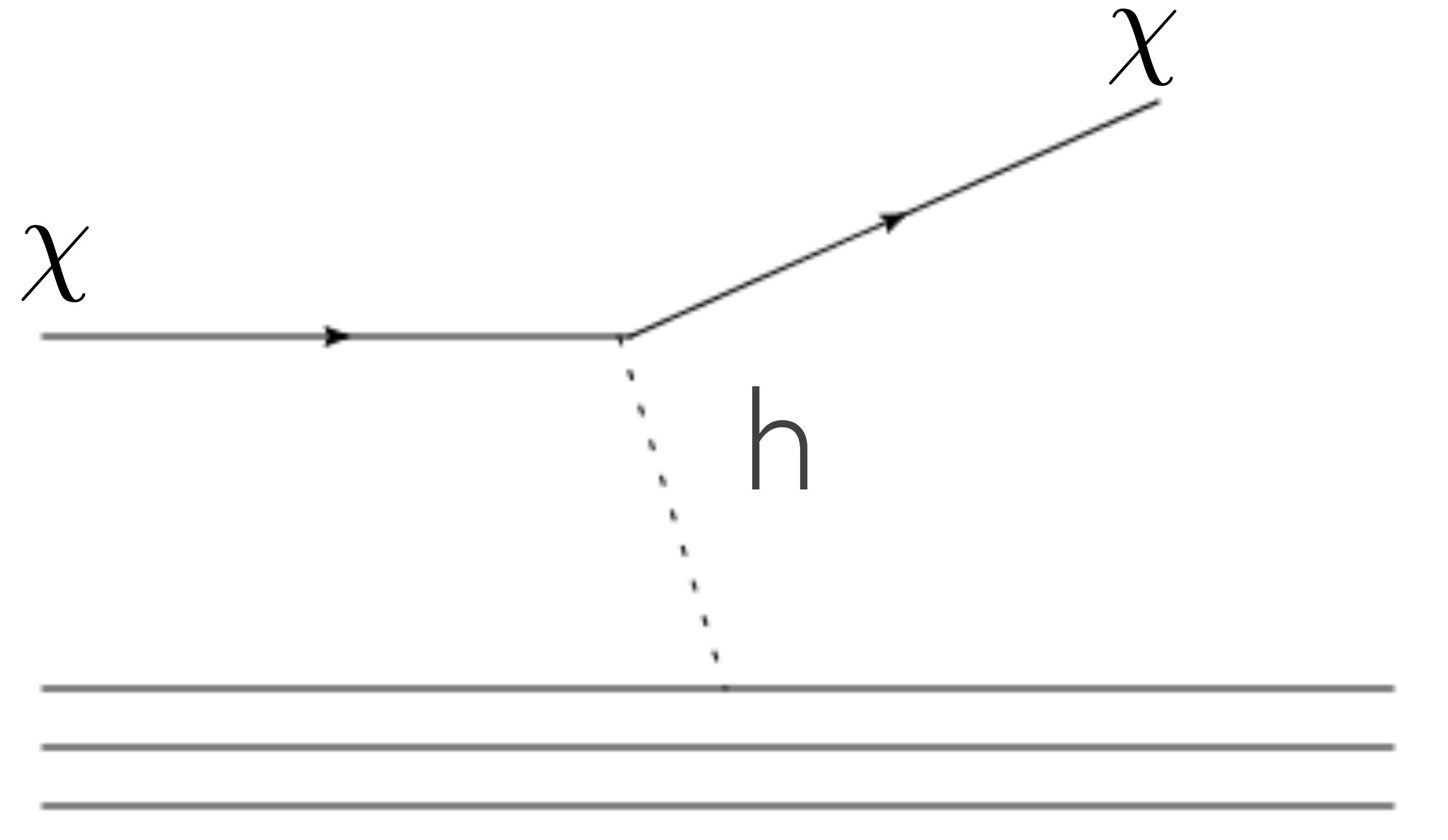
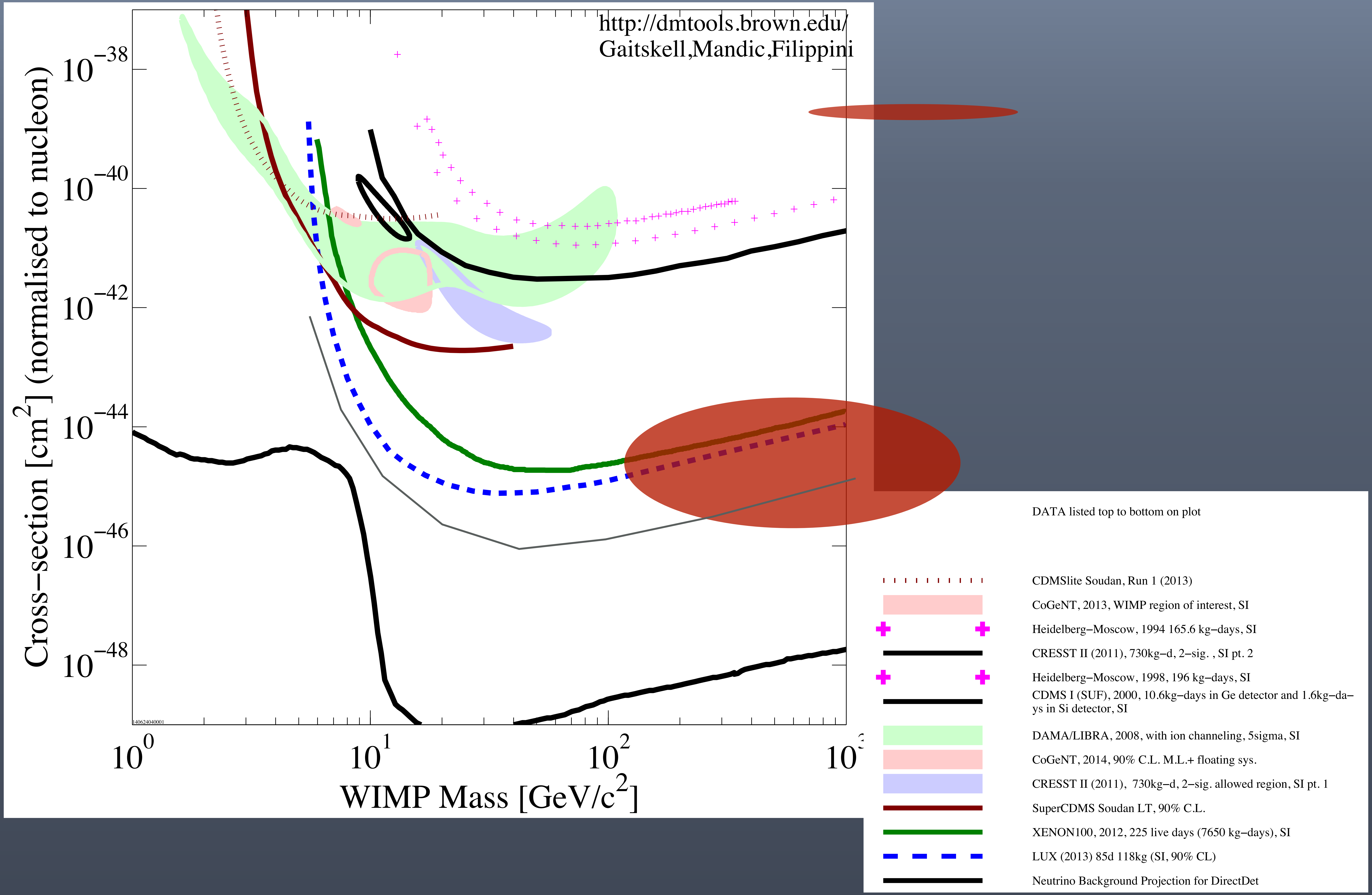


$$g \sim 1 \Rightarrow y_p \sim \frac{1}{\text{few}} \frac{m_p}{v}$$

$$\sigma_0 \sim 10^{-39}\text{cm}^2 \times 10^{-6}$$
$$\sim 10^{-45}\text{cm}^2$$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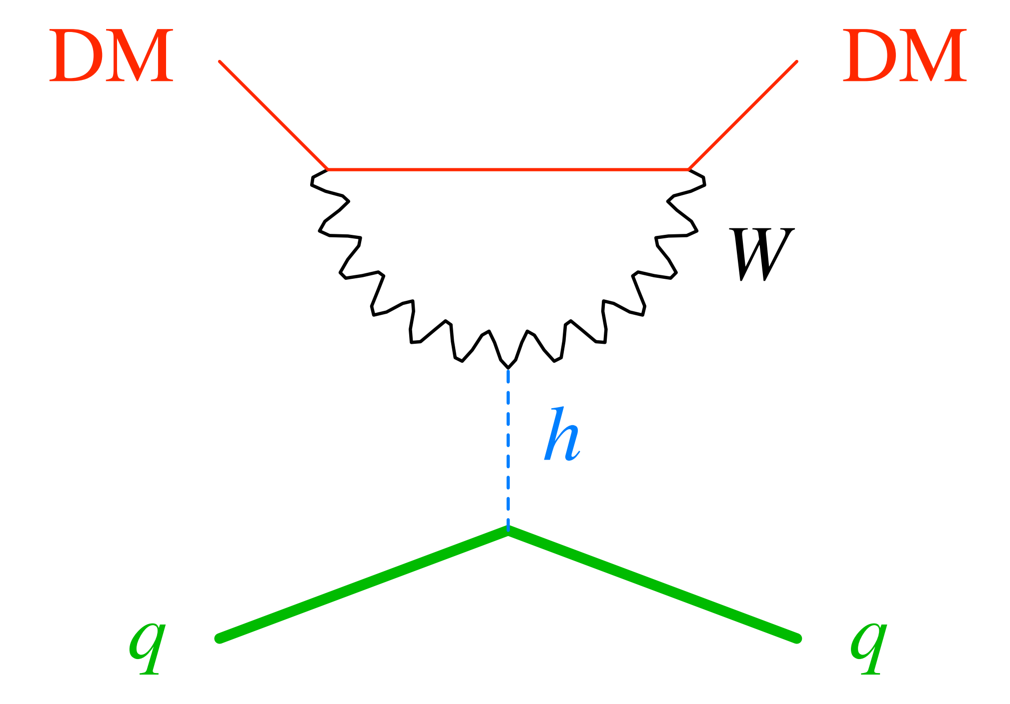
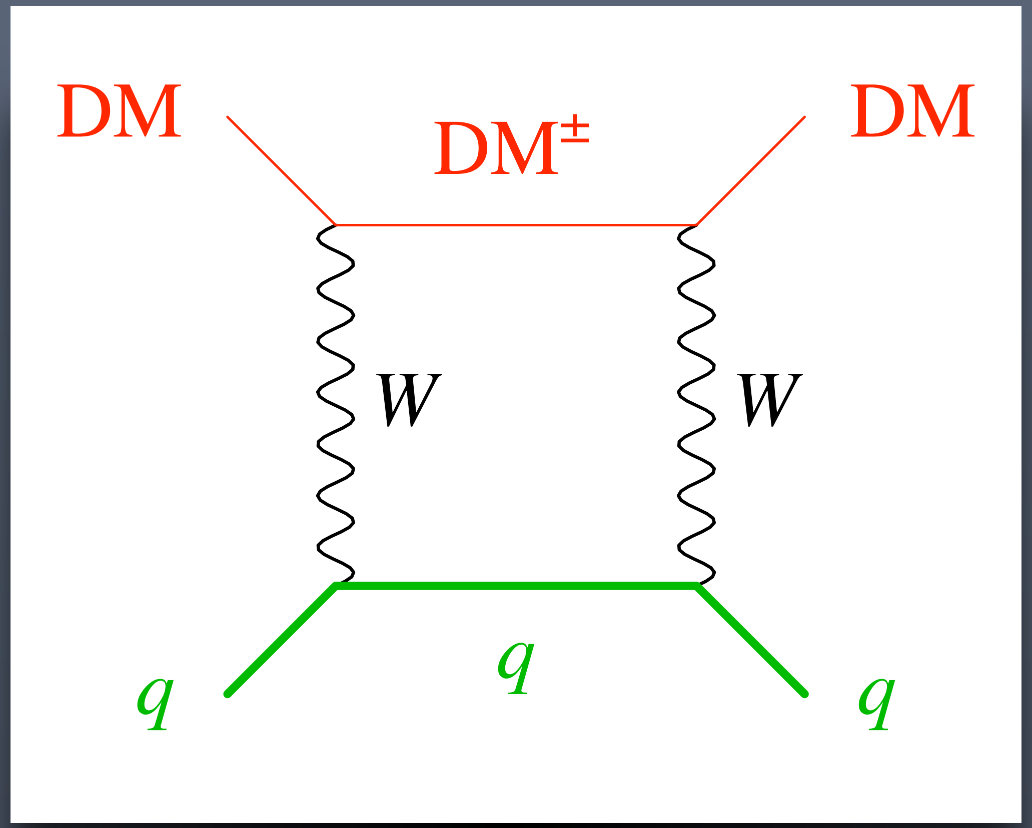
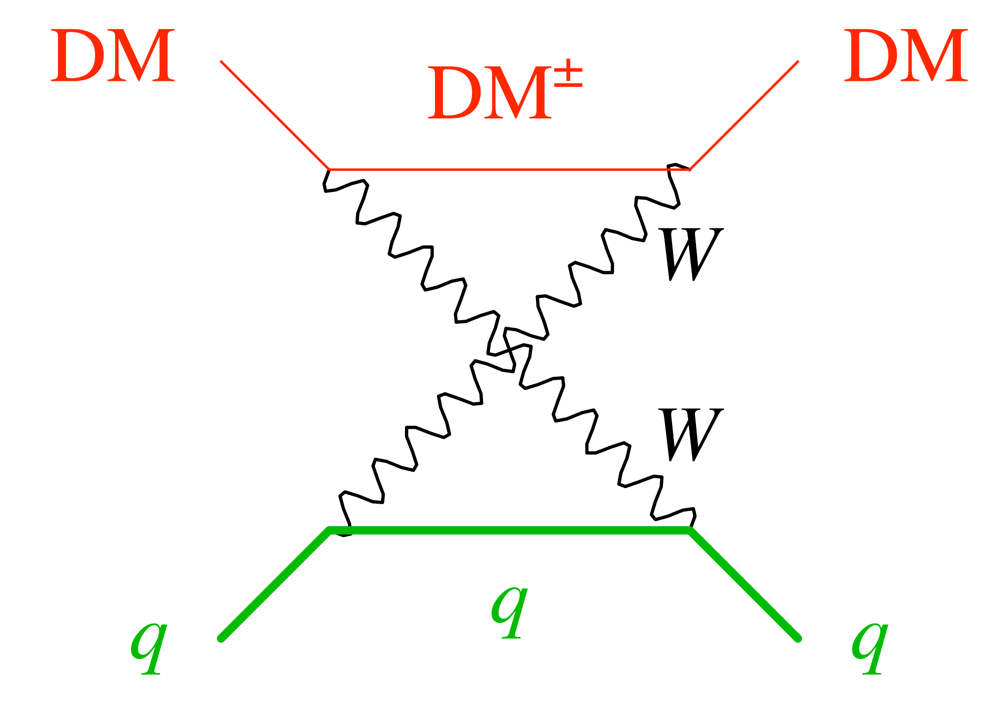
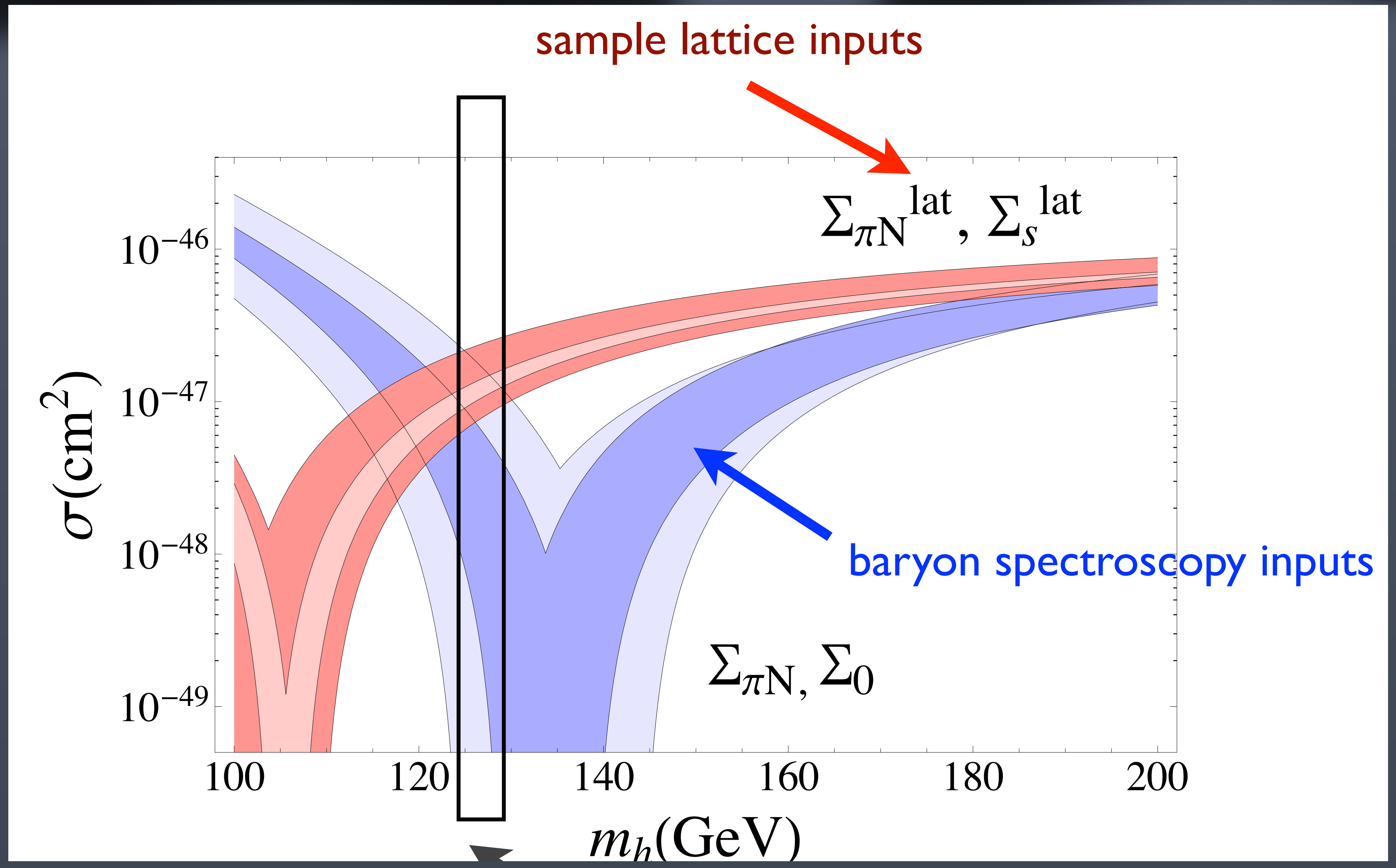
MAJORANA TRIPLET: LOOP MEDIATED



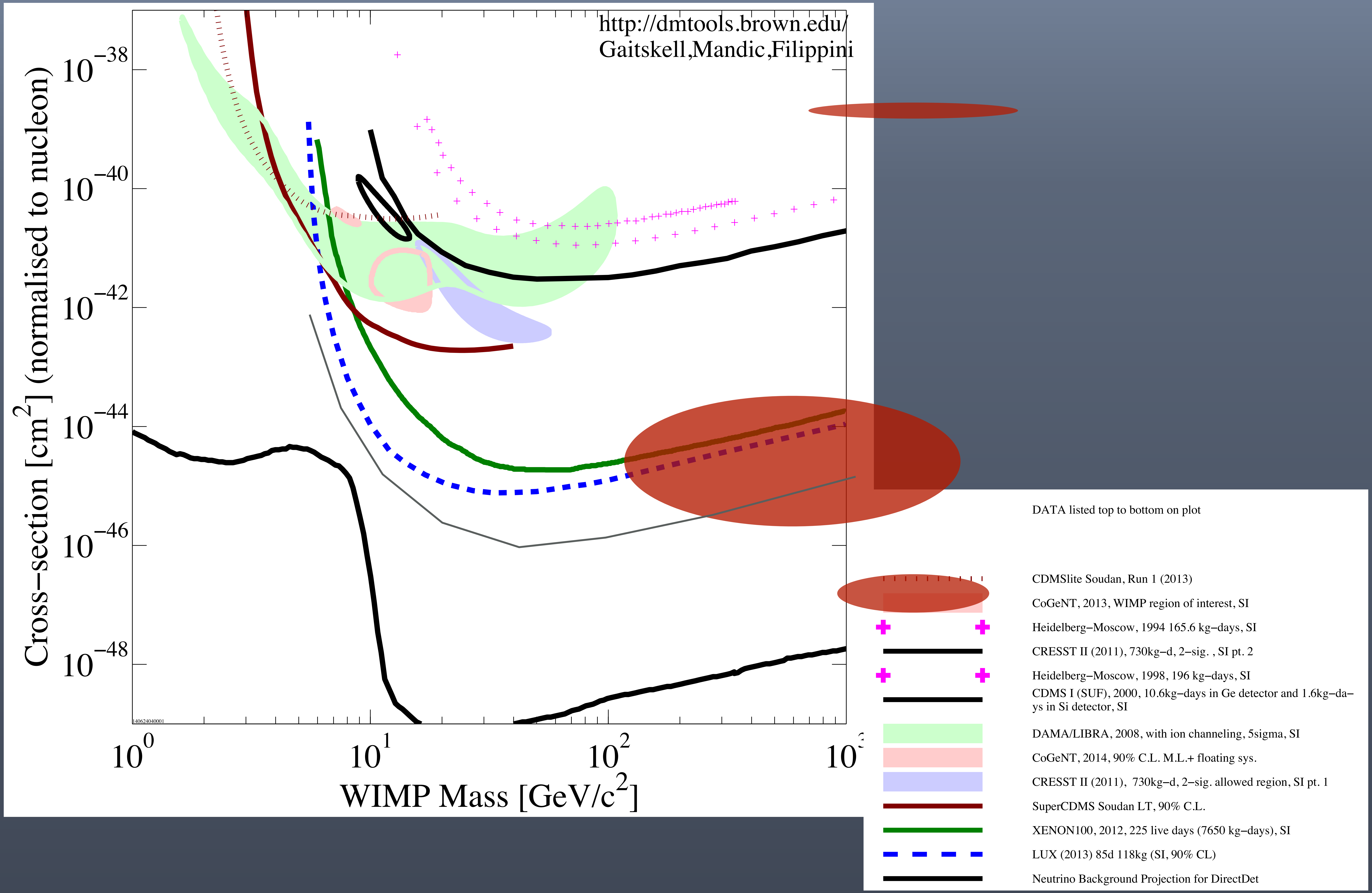
DM







Hill + Solon ’13;
Hill + Solon ‘14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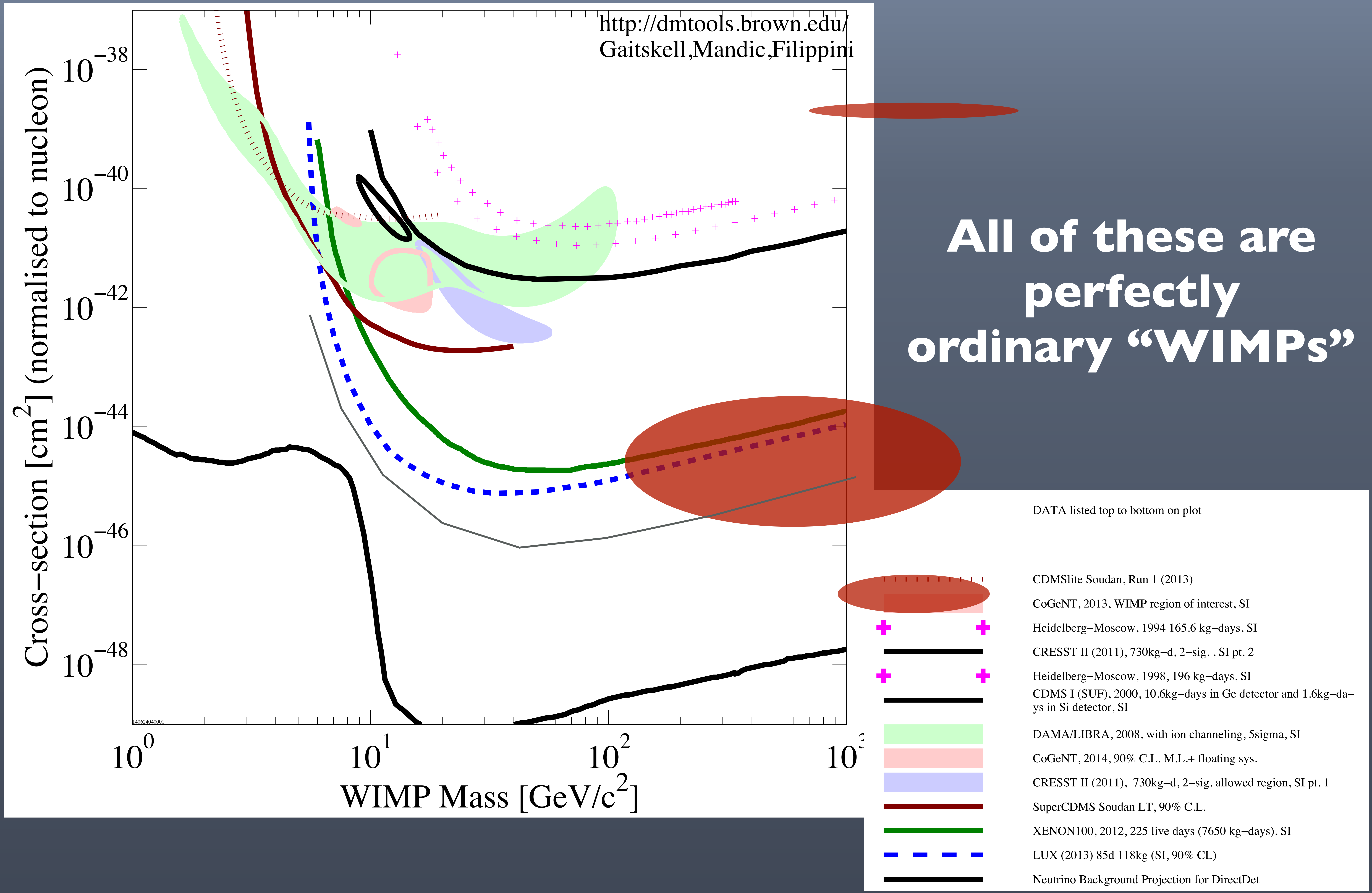
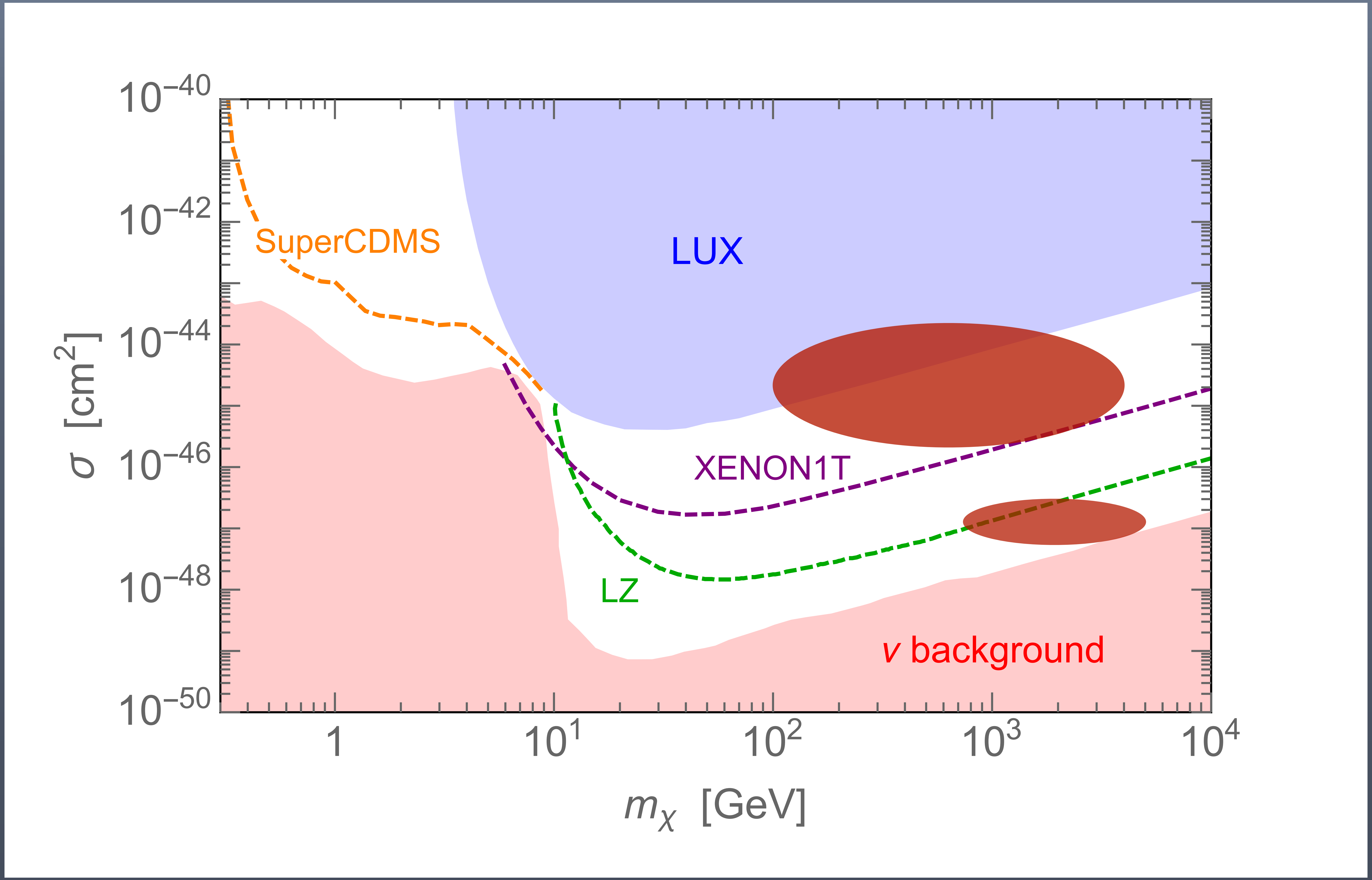
All of these are perfectly ordinary “WIMPs”



Plot from Josh Ruderman



A mature field - exciting, but nervous time

- This era will answer the question: does the dark matter couple at O(0.1-0.01) to the Higgs boson

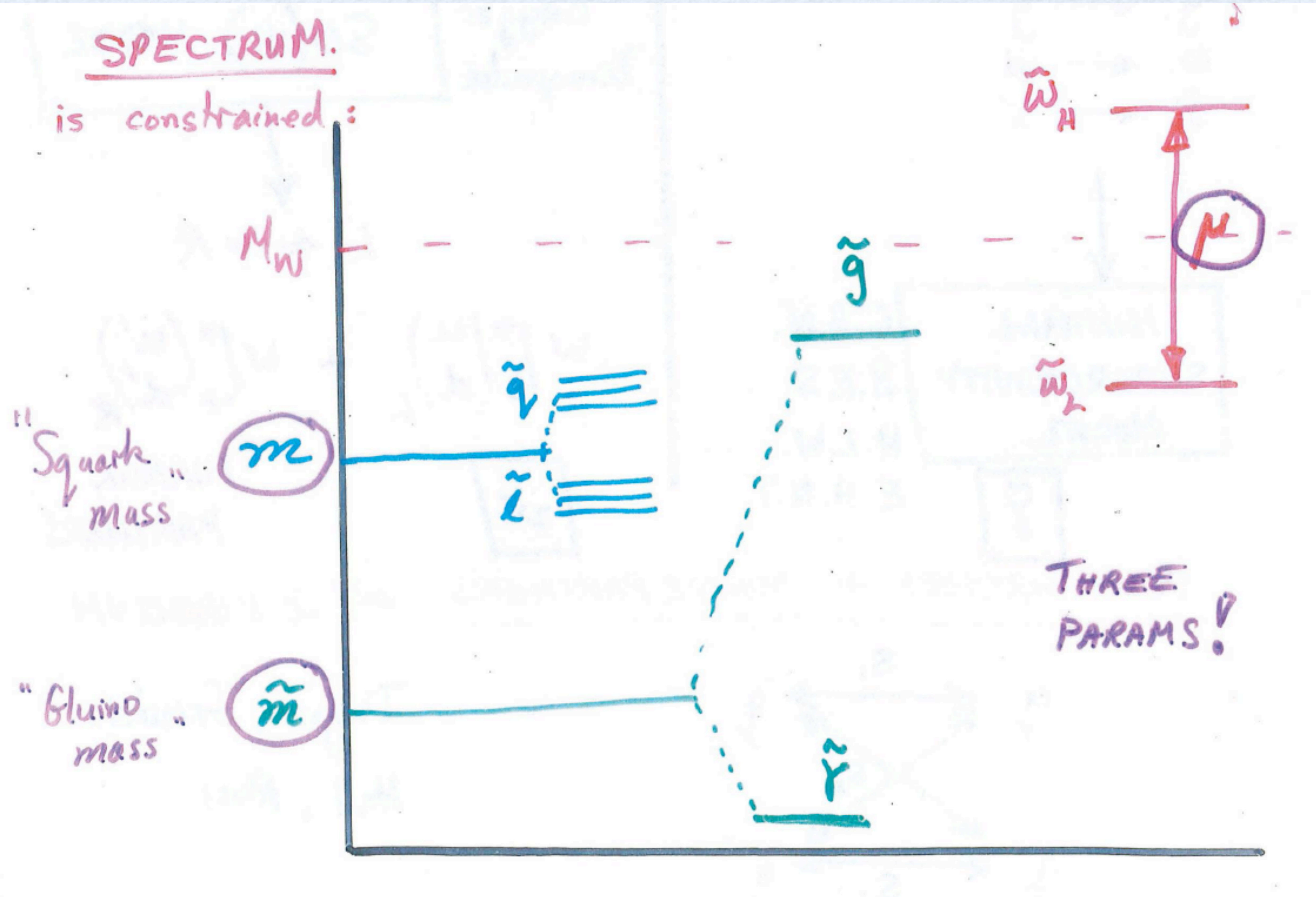
- But perfectly plausible WIMPs can have *very* weak nucleon interactions

SHOULDN'T YOU HAVE FOUND NEW PHYSICS BY NOW

- we have just gone through and unprecedented era of data (still in it) and haven't found BSM physics

- what's up with that?

SUSY Spectrum, 1984



Lawrence Hall, Savasfest 2012

(cf Matt Reece talk LHCP2013)

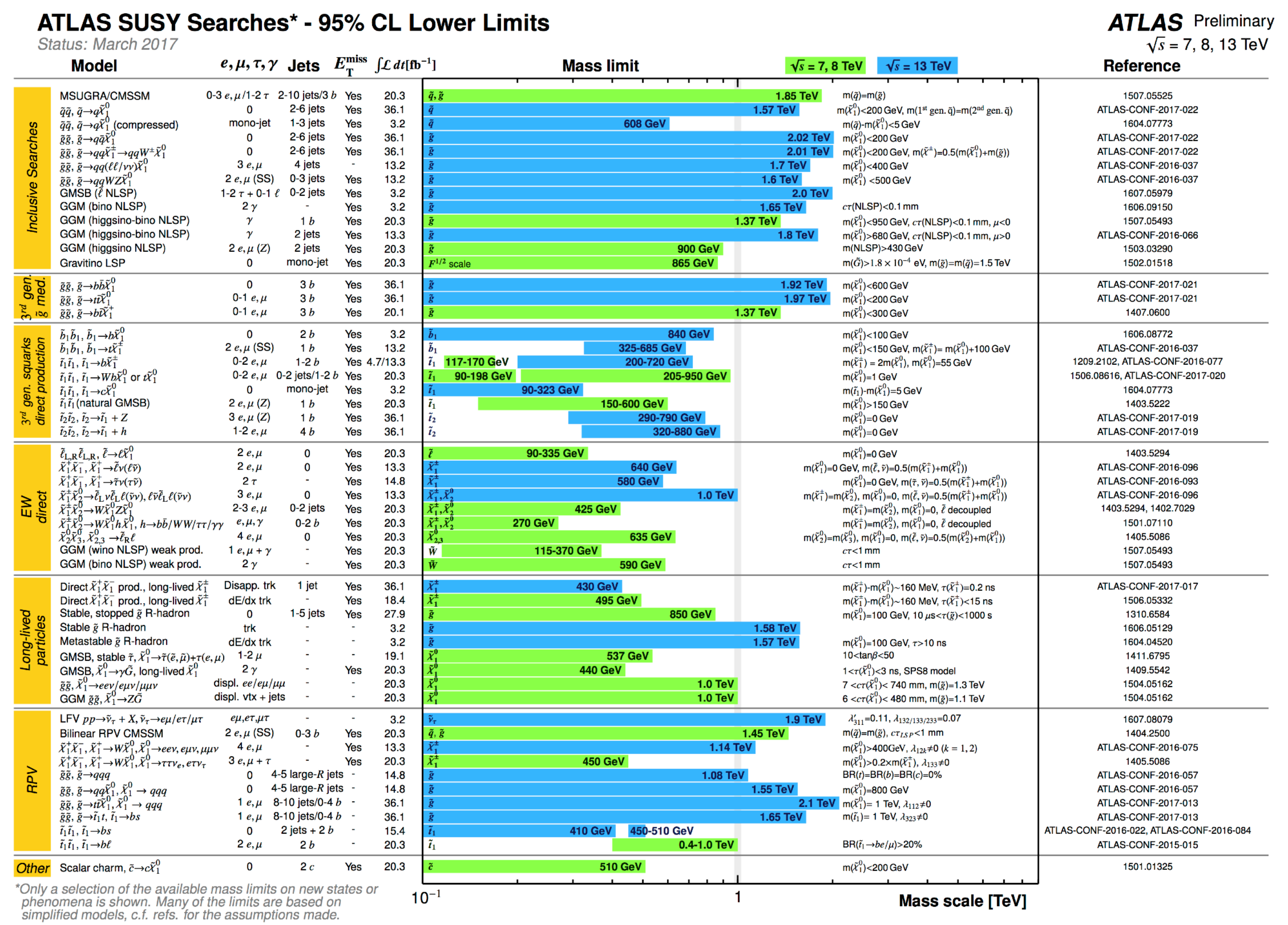
gluino limits ~ 1400 GeV

squark limits ~ 700 GeV

Lawrence Hall, Savasfest 2012

(cf Matt Reece talk LHCP2013)

LHC - NO SIGN OF WEAK SCALE BSM



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2017

ATLAS Preliminary

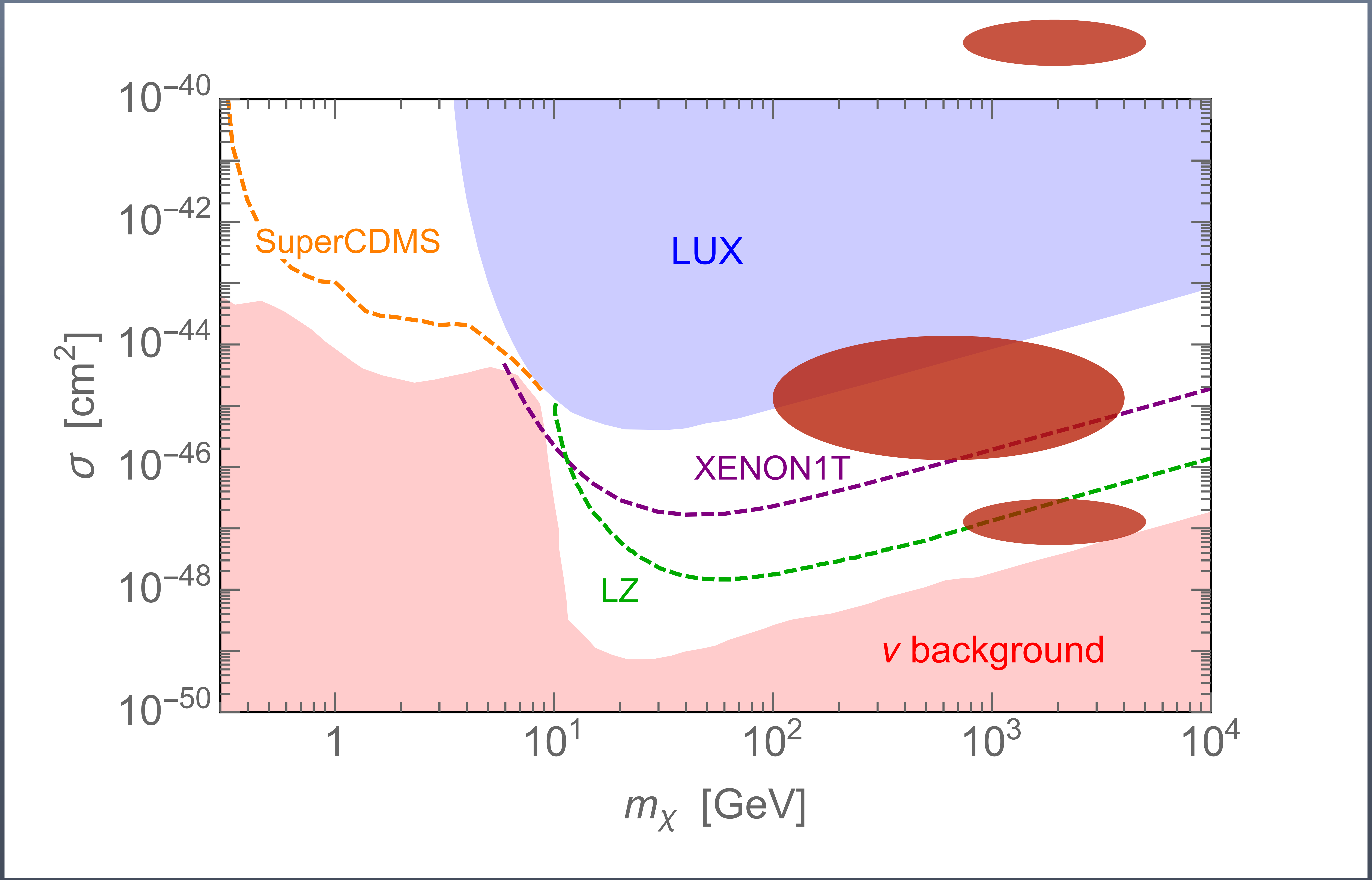
$\sqrt{s}$ = 7, 8, 13 TeV

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

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Mass limit			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	36.1	$\tilde{q}$	🟦 1.57 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (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	36.1	$\tilde{g}$	🟦 2.02 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	🟦 2.01 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	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, $\mu<0$	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, $\mu>0$	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	$m(\tilde{G})>1.8\times10^{-4}$ 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	36.1	$\tilde{g}$	🟦 1.92 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$	🟦 1.97 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	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	$\tilde{t}_1$	🟩 117-170 GeV 🟦 200-720 GeV	$m(\tilde{\chi}_1^{\pm})$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=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	20.3	$\tilde{t}_1$	🟩 90-198 GeV 🟩 205-950 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	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	36.1	$\tilde{t}_2$	🟦 290-790 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$	🟦 320-880 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2017-019
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	$\tilde{\ell}$	🟩 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	13.3	$\tilde{\chi}_1^{\pm}$	🟦 640 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-2016-096
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	14.8	$\tilde{\chi}_1^{\pm}$	🟦 580 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-2016-093
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	13.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	🟦 1.0 TeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2016-096
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	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
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	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 $e,\mu+\gamma$	-	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	36.1	$\tilde{\chi}_1^{\pm}$	🟦 430 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2017-017
	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
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	🟦 2.1 TeV	$m(\tilde{\chi}_1^0)$= 1 TeV, $\lambda_{112}\neq0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	🟦 1.65 TeV	$m(\tilde{t}_1)$= 1 TeV, $\lambda_{323}\neq0$	ATLAS-CONF-2017-013
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	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. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*

Plot from Josh Ruderman



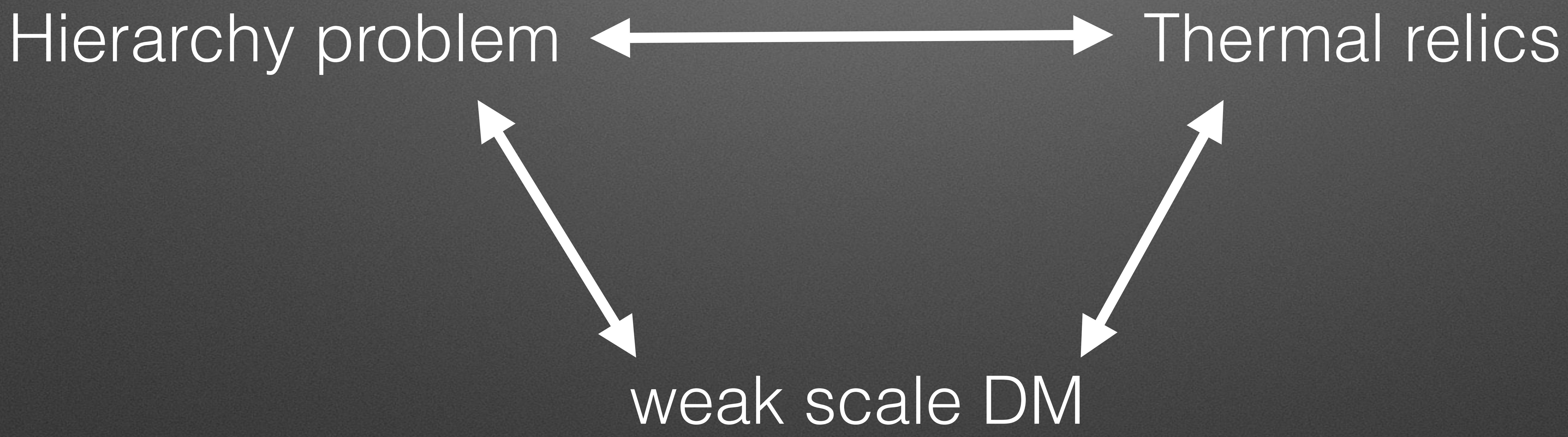
No sign of WIMPs so far

MOVING TO AN ERA OF NEW PRIORS

THE ERA OF STRONG PRIORS
199X~2016

- Hierarchy problem
- Weak scale DM
- Questions of the SM (unification, neutrino mass, strong CP…)

Dark matter in the era of strong priors

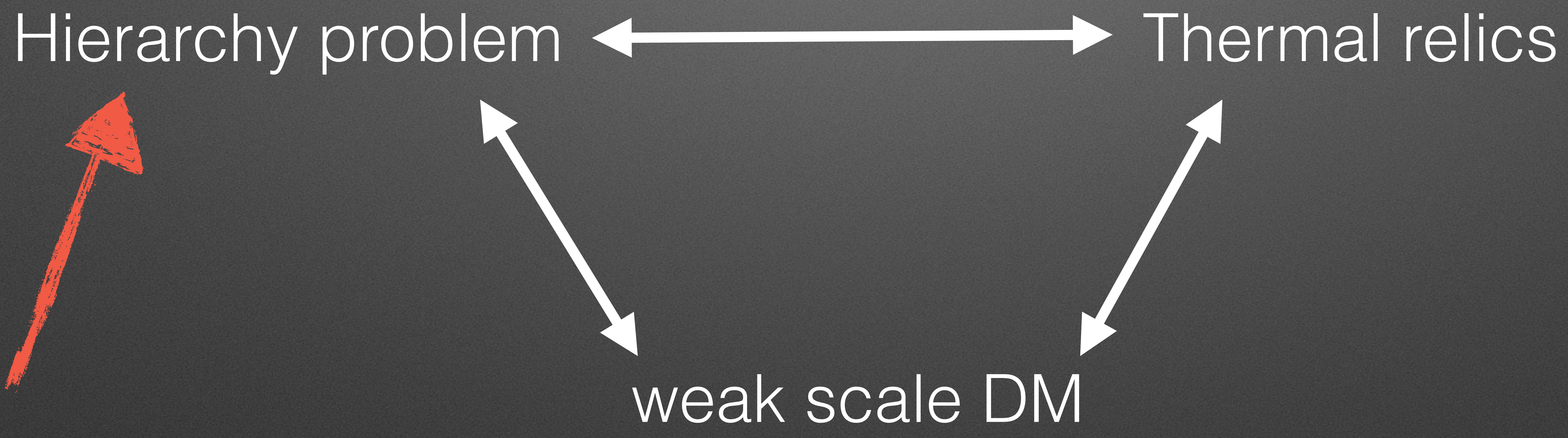


Hierarchy problem

Thermal relics

weak scale DM

Dark matter in the era of strong priors



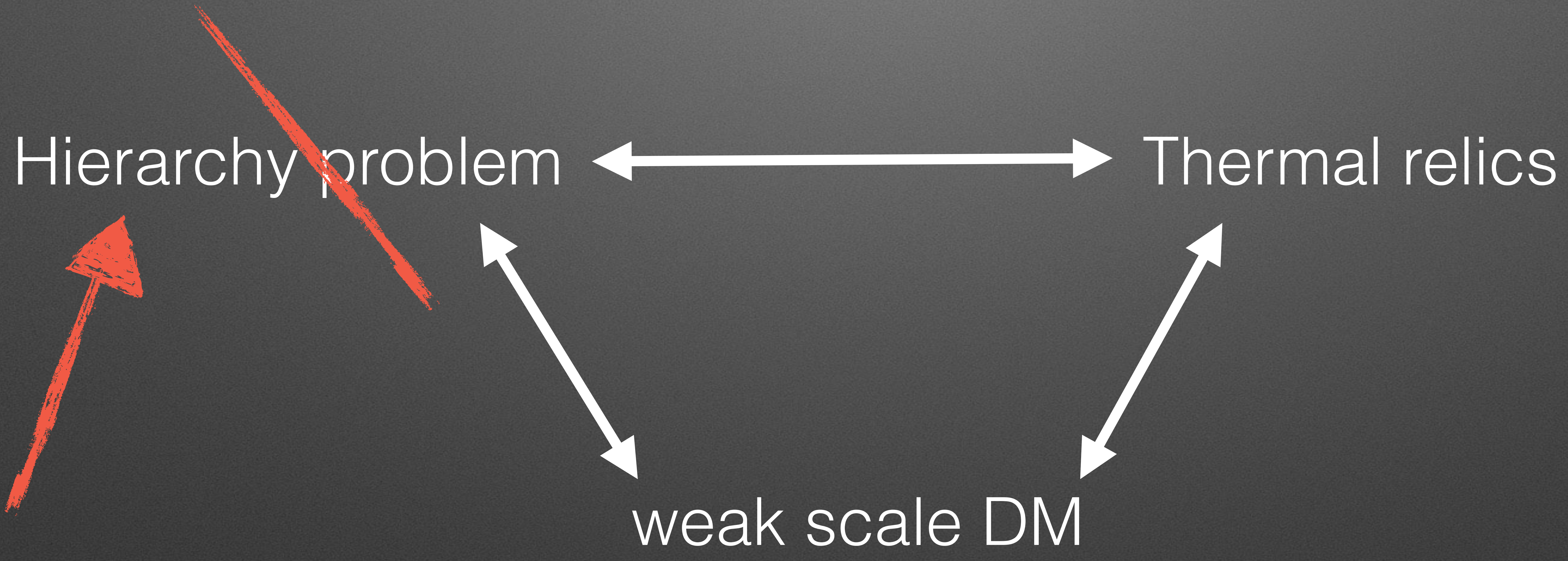
Hierarchy problem

Thermal relics

weak scale DM

baggage

Dark matter in the era of strong priors



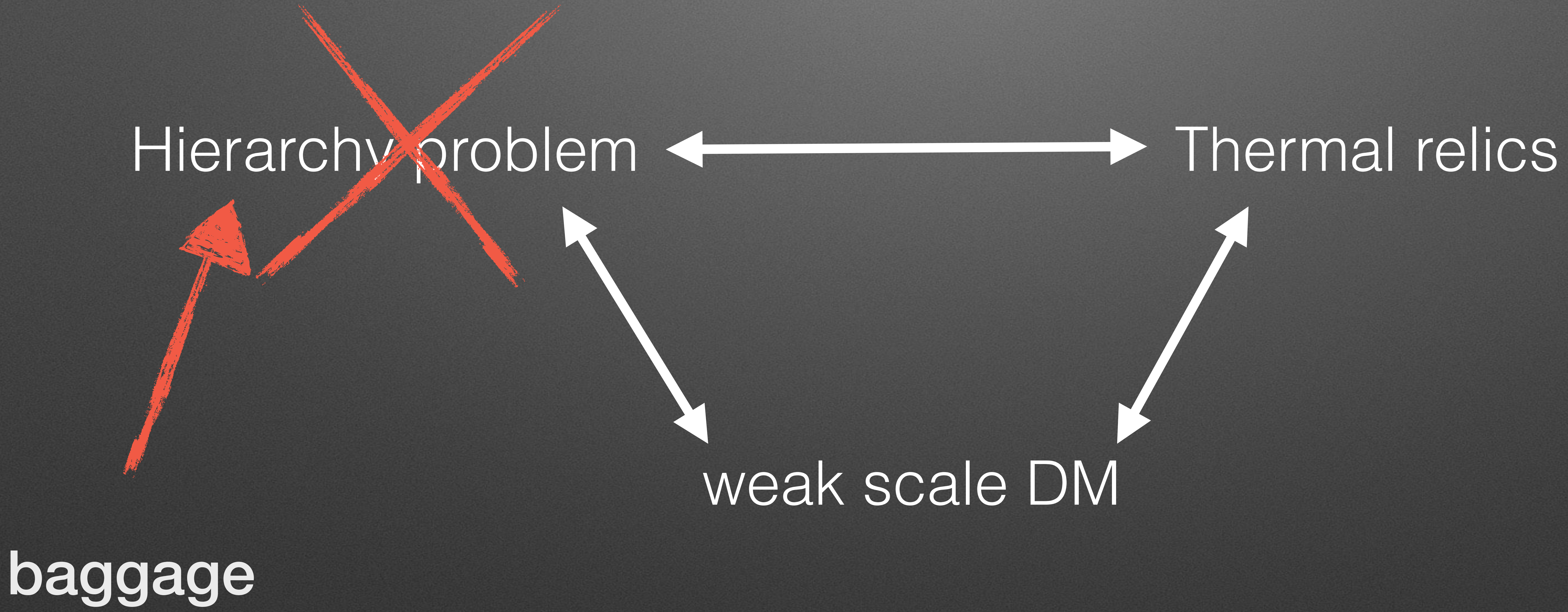
~~Hierarchy problem~~

Thermal relics

weak scale DM

baggage

Dark matter in the era of strong priors



~~Hierarchy problem~~

Thermal relics

weak scale DM

baggage

WE HAVE PURSUED SCENARIOS UNDER VERY STRONG ASSUMPTIONS

- Where do we go from here?

MOVING BEYOND THE ERA OF STRONG PRIORS

- No priors?
- Weak priors?
- New priors?

The Priorhedron

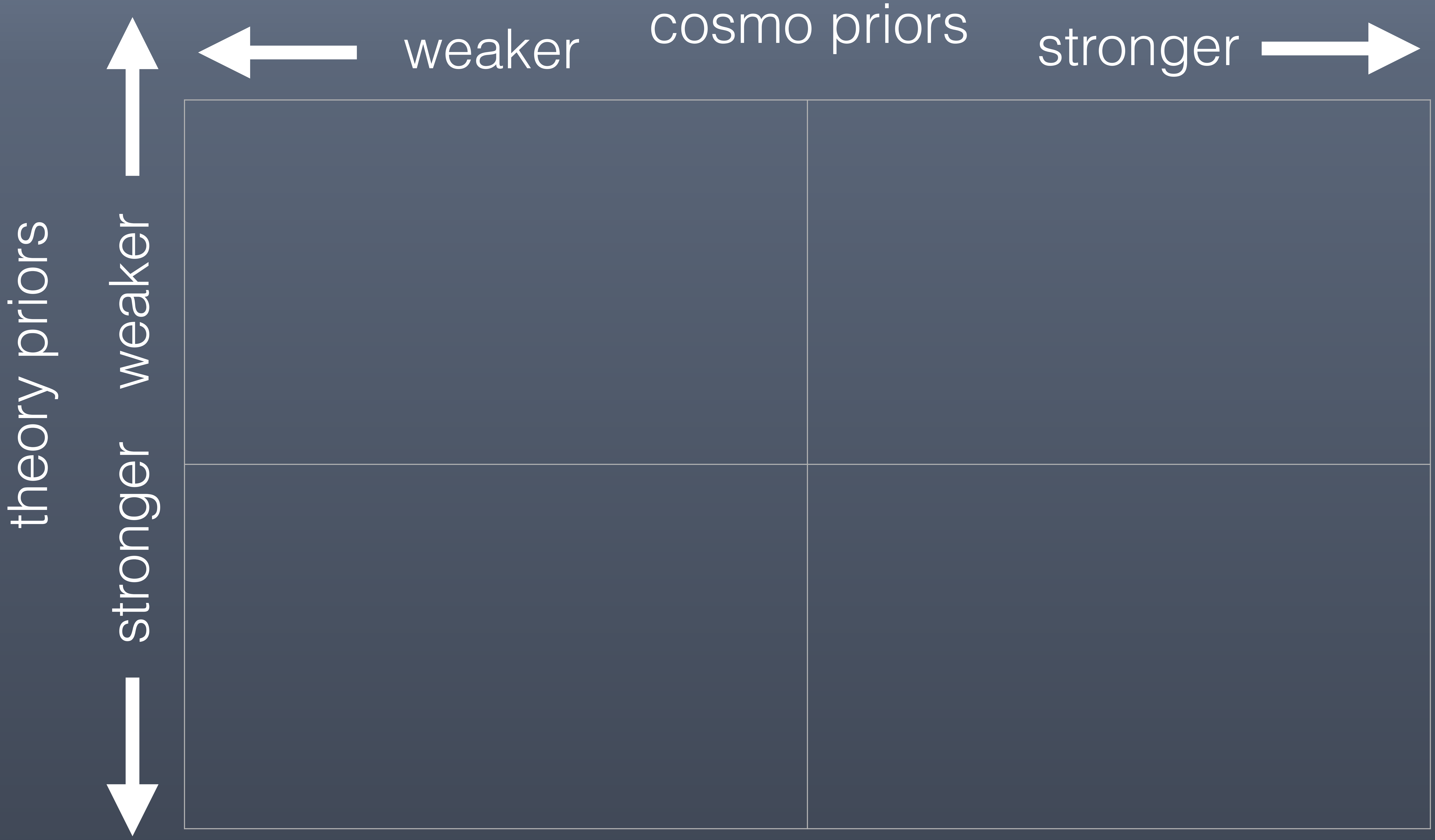
← weaker cosmo priors stronger →

theory priors

↑ weaker

stronger ↓

The Priorhedron



cosmo priors

weaker

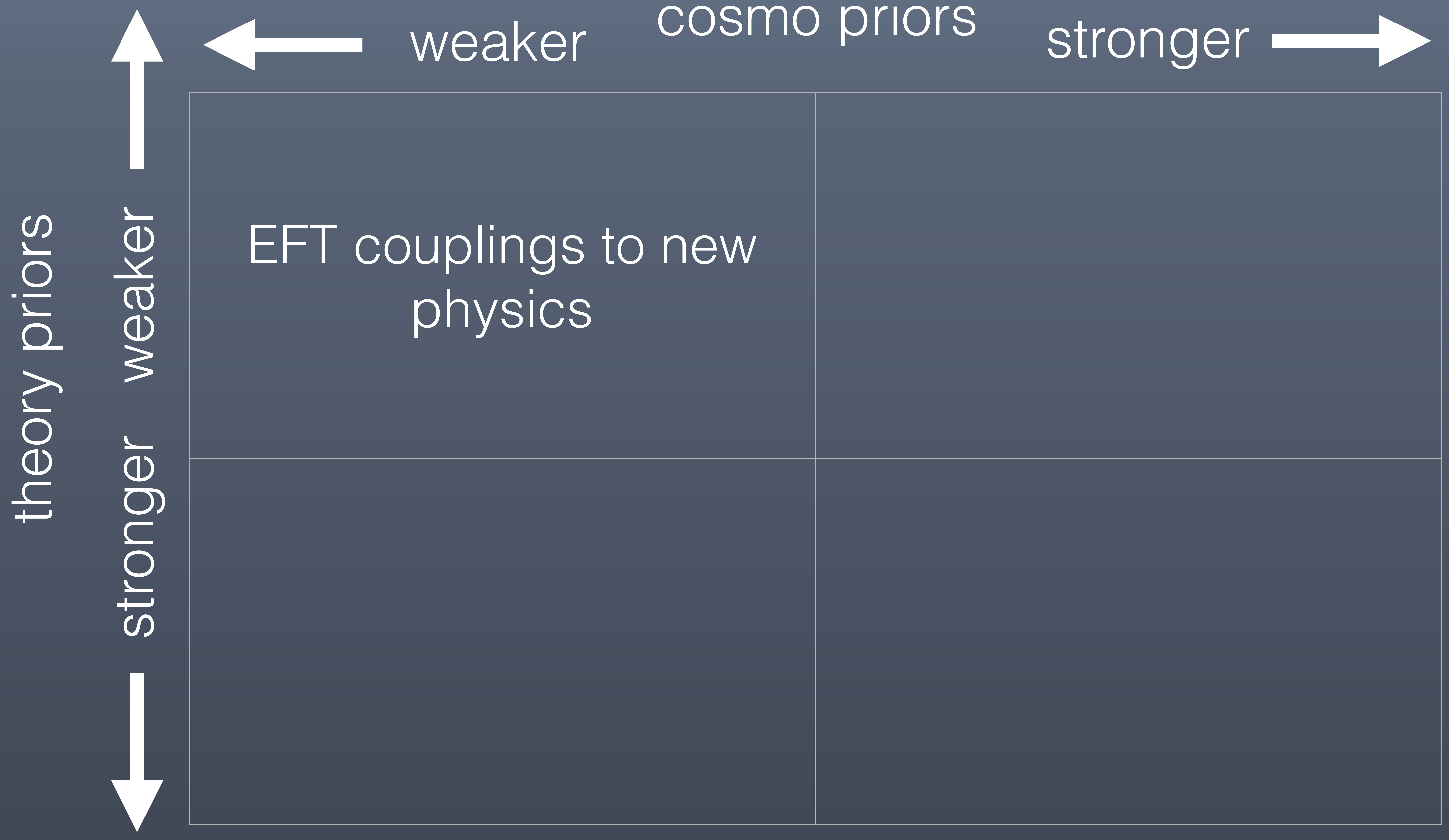
stronger

theory priors

weaker

stronger

The Priorhedron



cosmo priors

weaker

stronger

theory priors

weaker

stronger

EFT couplings to new physics

The Priorhedron

cosmo priors

theory priors

theory priors \ cosmo priors	← weaker	stronger →
↑ weaker	EFT couplings to new physics	thermal and quasi thermal relics, scalars from EUPT
stronger ↓		

The Priorhedron

cosmo priors

theory priors

	weaker	stronger
weaker	EFT couplings to new physics	thermal and quasi thermal relics, scalars from EUPT
stronger	QCD axions w/o cosmology; scale-free DM	

The Priorhedron

cosmo priors

theory priors

	← weaker	stronger →
↑ weaker	EFT couplings to new physics	thermal and quasi thermal relics, scalars from EUPT
stronger ↓	QCD axions w/o cosmology; scale-free DM	WIMPs; “classic” PQ axions

BSM IN THE ERA OF MODERATE PRIORS

- Opportunity to ask broader questions
- Can't simply be fishing expedition
- Take one step back on some prior axis and find target regions
  - e.g., consider a thermally connected particle
  - a broader class of axion like particles

BROADENING THE THERMAL SCOPE

structure "bound":
DM not enough SSS
if $T_{DM} \sim T_{SM}$

BBN "bound"
no new relativistic
DOF at BBN
if $T_{DM} \sim T_{SM}$

unitarity bound:
too much DM

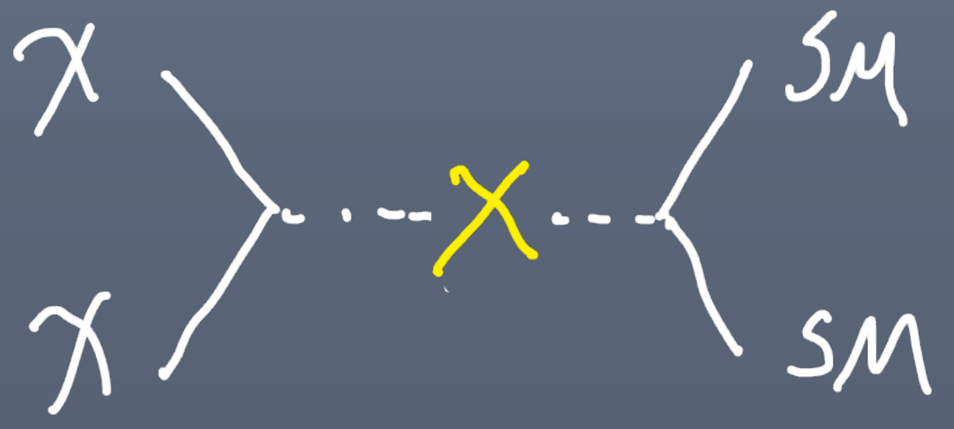
Huge range of possibilities from keV to GeV scale

COUPLING AND DECOUPLING A LIGHT PARTICLE

A light DM particle needs a new interaction to stay in equilibrium

The portals

$\epsilon h^\dagger h \phi^\dagger \phi \rightarrow$



$\propto y \epsilon$

$\epsilon F^D_{\mu\nu} B^{\mu\nu} \rightarrow$

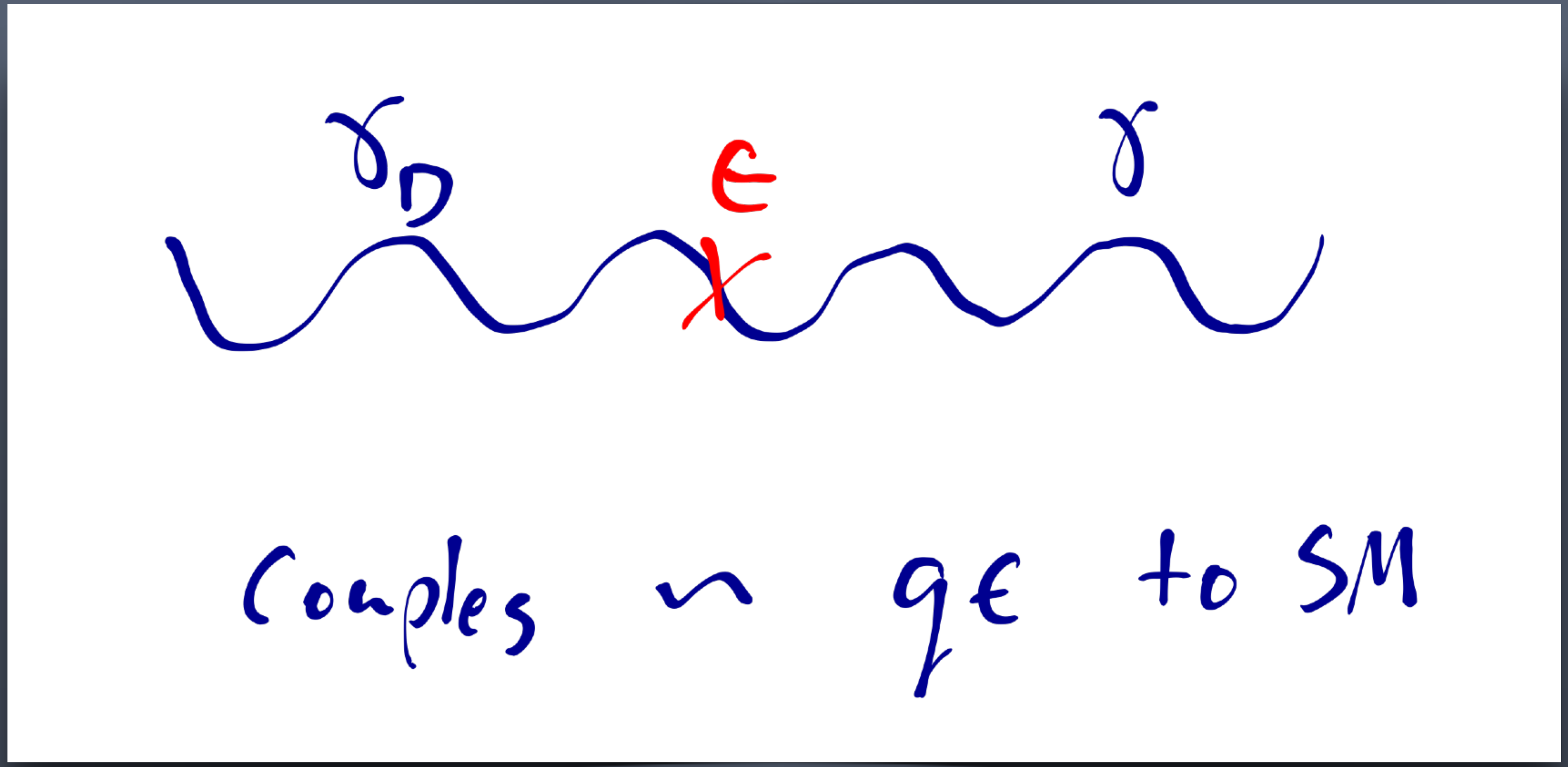
$\propto Q \epsilon$

$\epsilon h L n$

$\propto \epsilon V \sim m_\nu$

COUPLING AND DECOUPLING A LIGHT PARTICLE

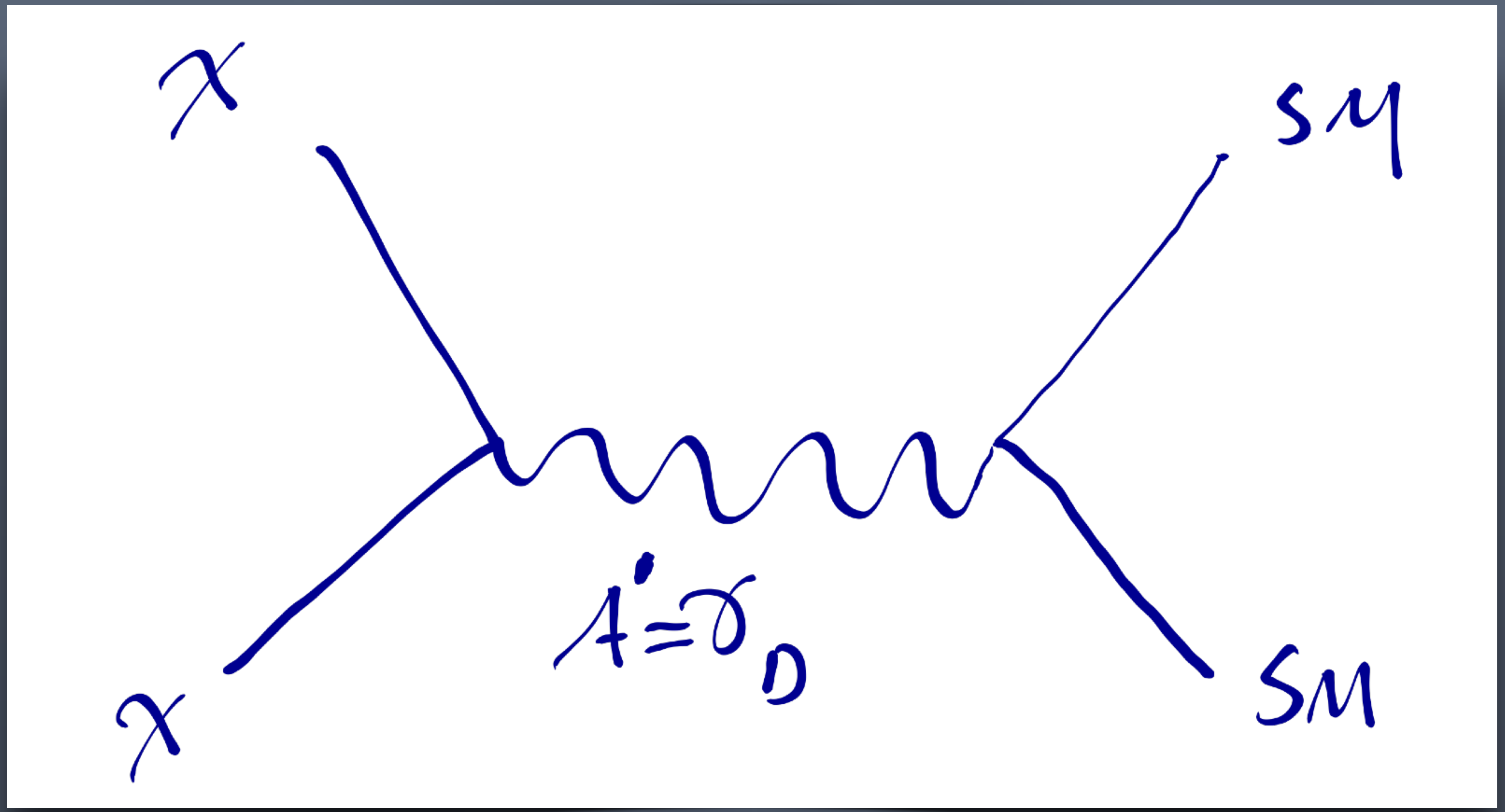
A light DM particle needs a new interaction to stay in equilibrium



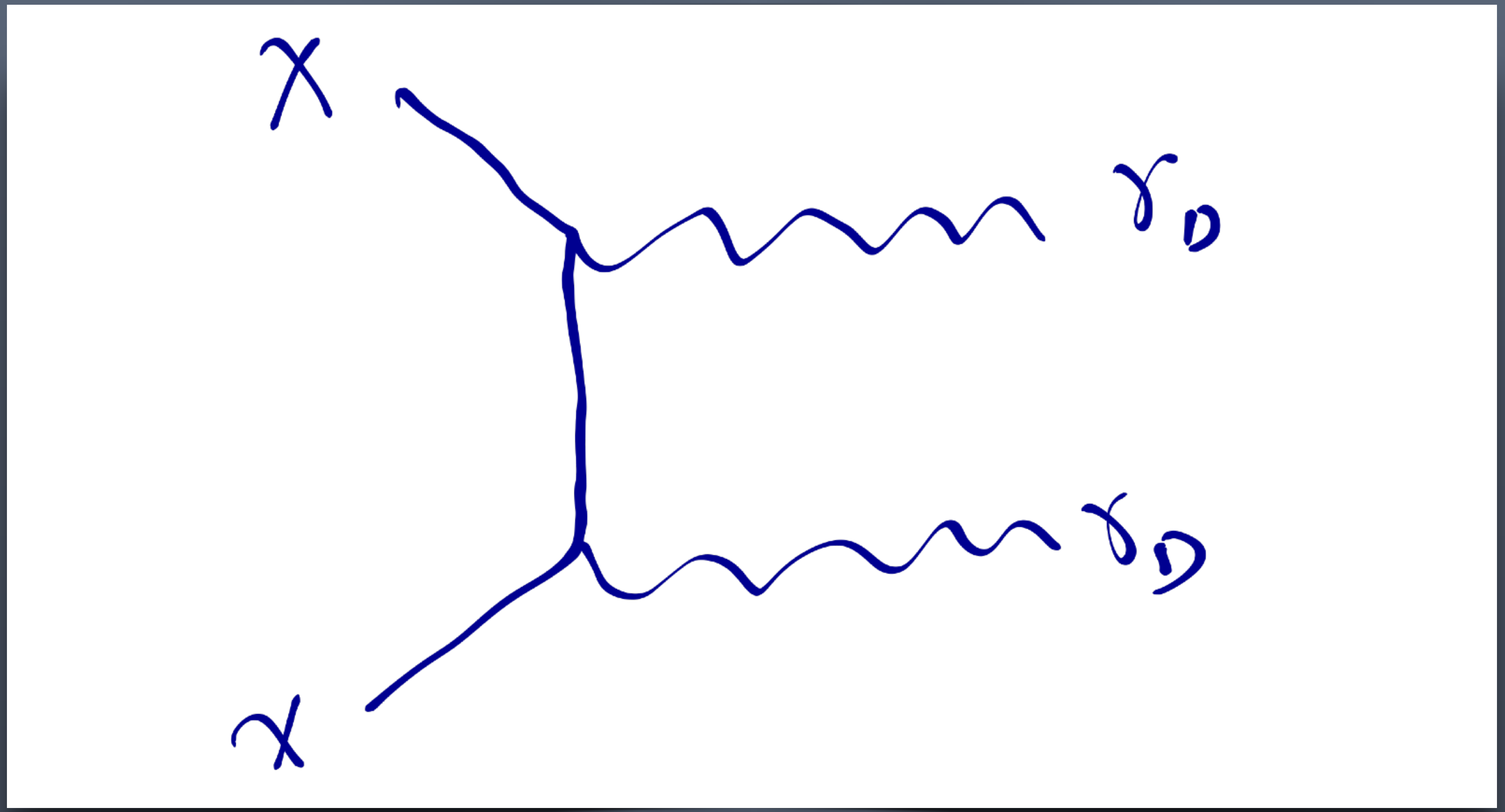
Couples $\sim q\epsilon$ to SM

Simple example a “dark photon” - can naturally be very weakly mixed

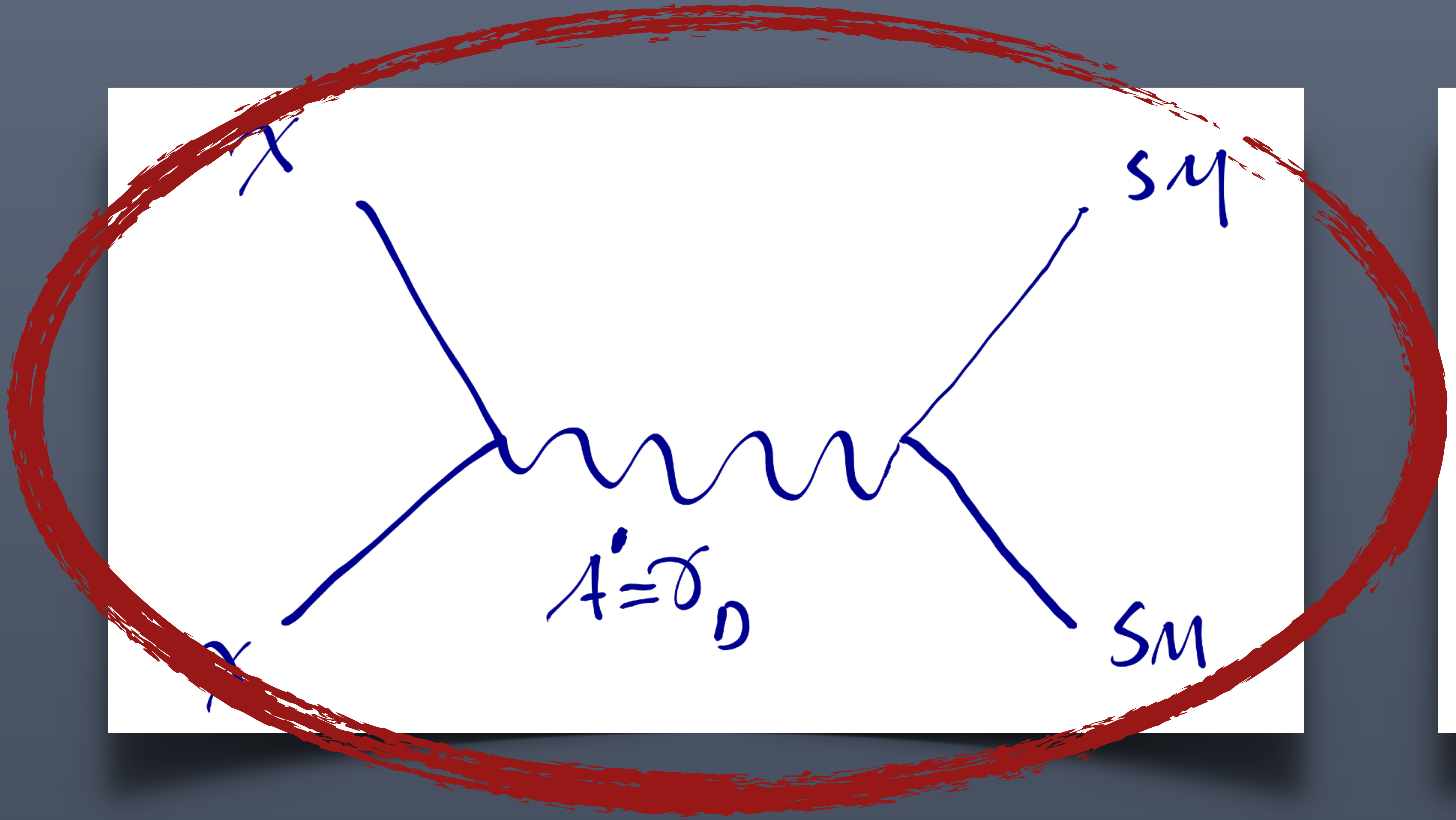
Holdom; Boehm + Fayet



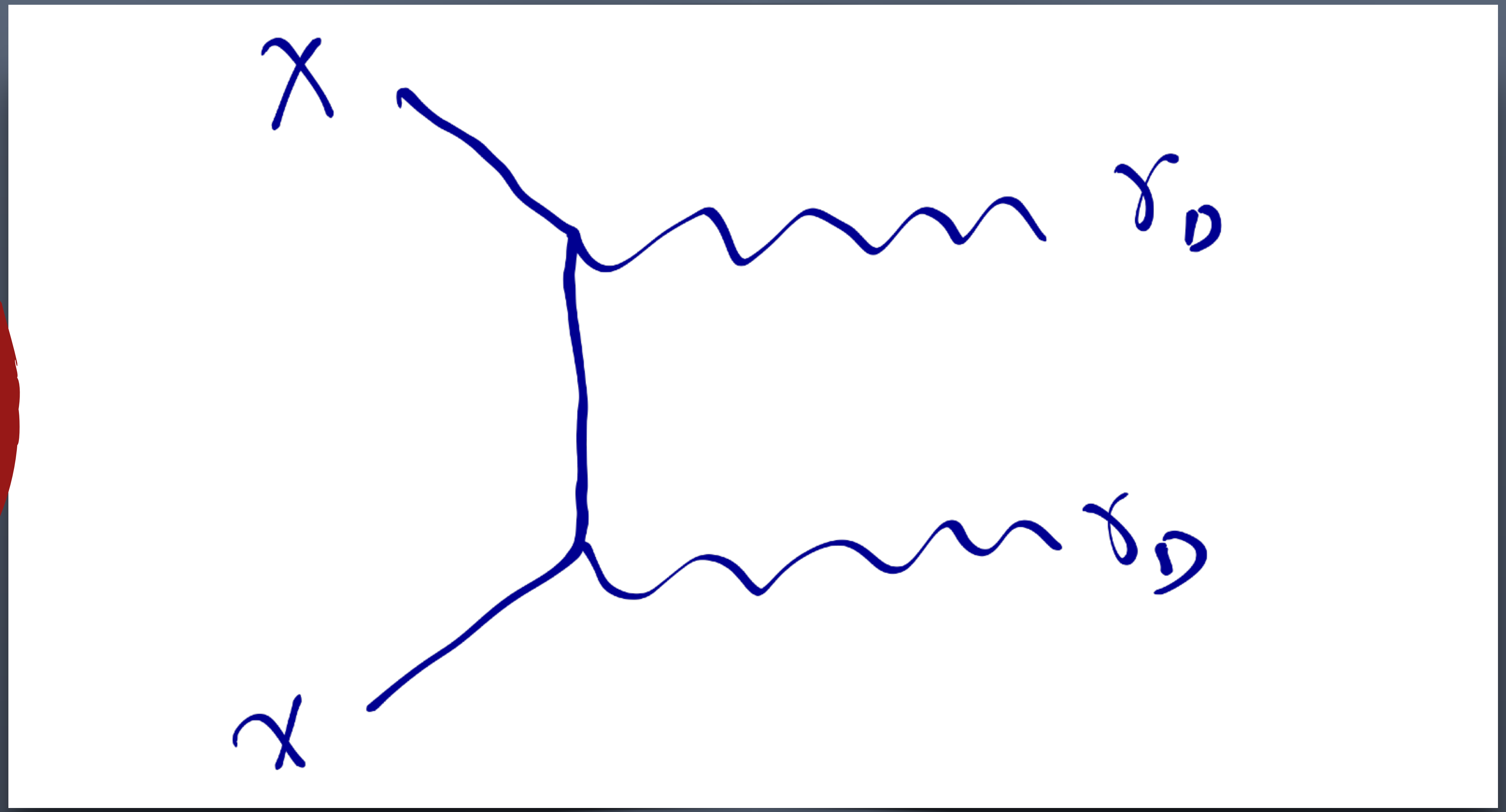
SM Annihilation



Hidden Sector Annihilation

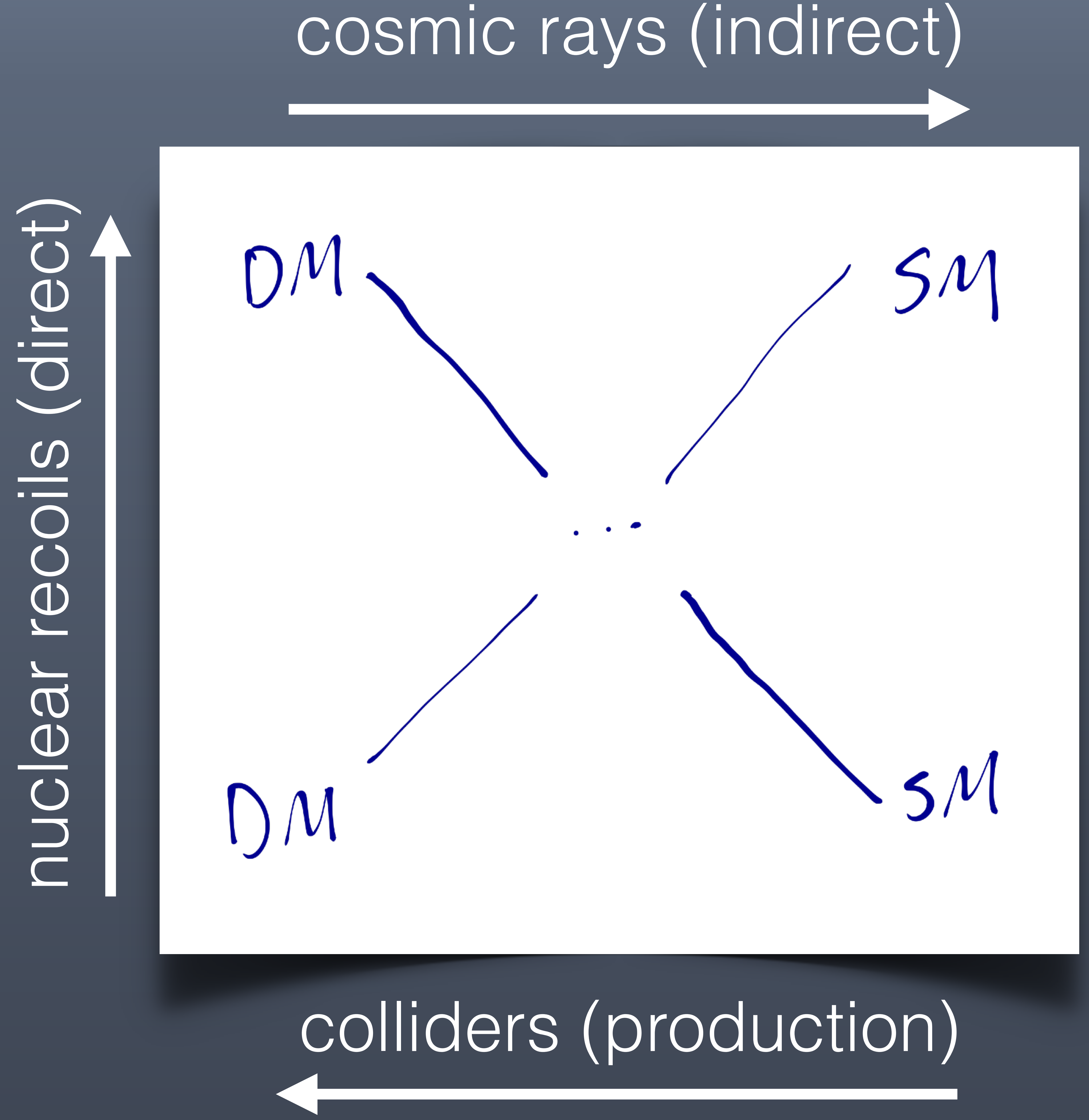


SM Annihilation



Hidden Sector Annihilation

WIMP COMPLEMENTARITY

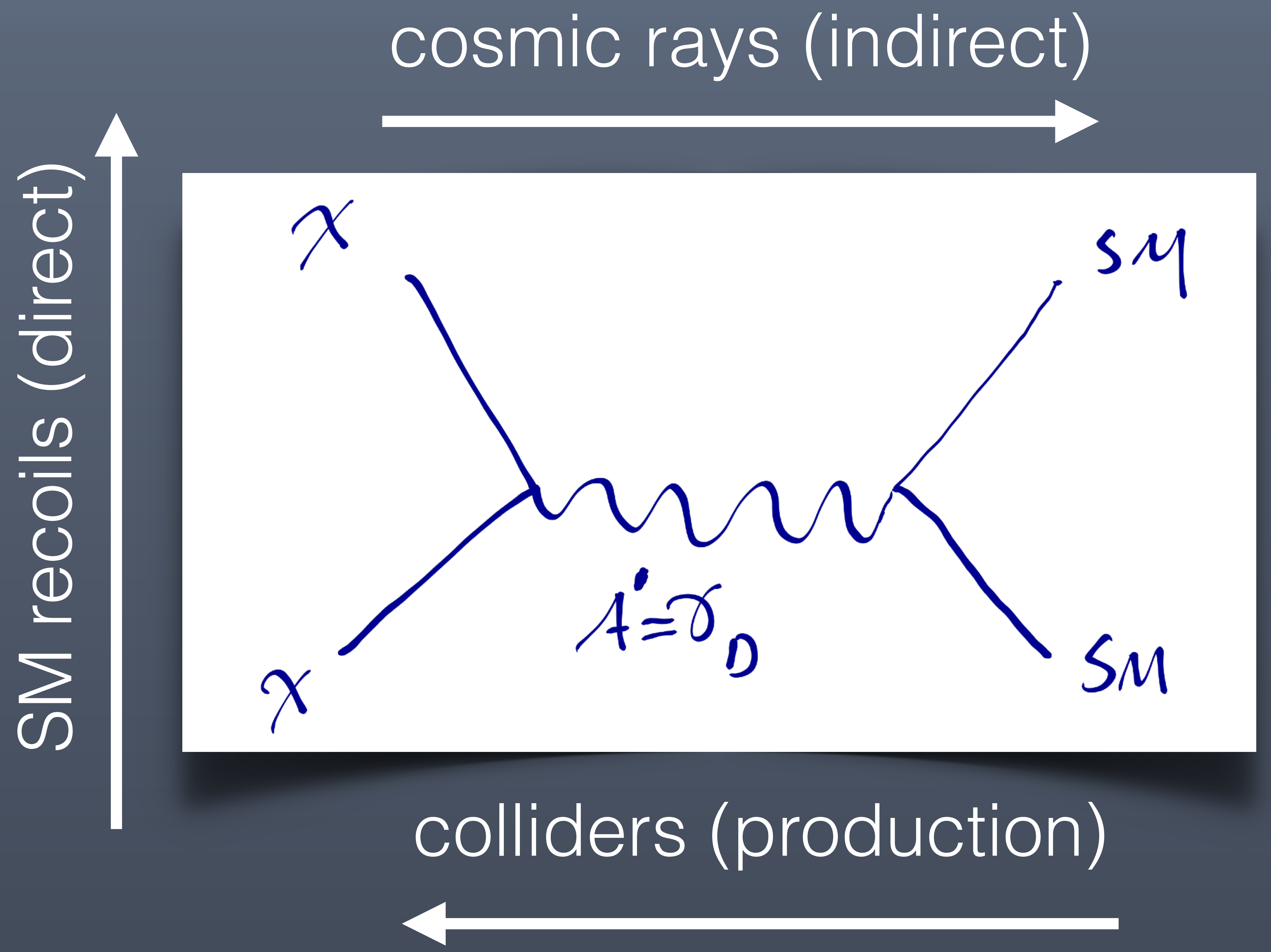


cosmic rays (indirect)

nuclear recoils (direct)

colliders (production)

COMPLEMENTARITY "CLASSIC"



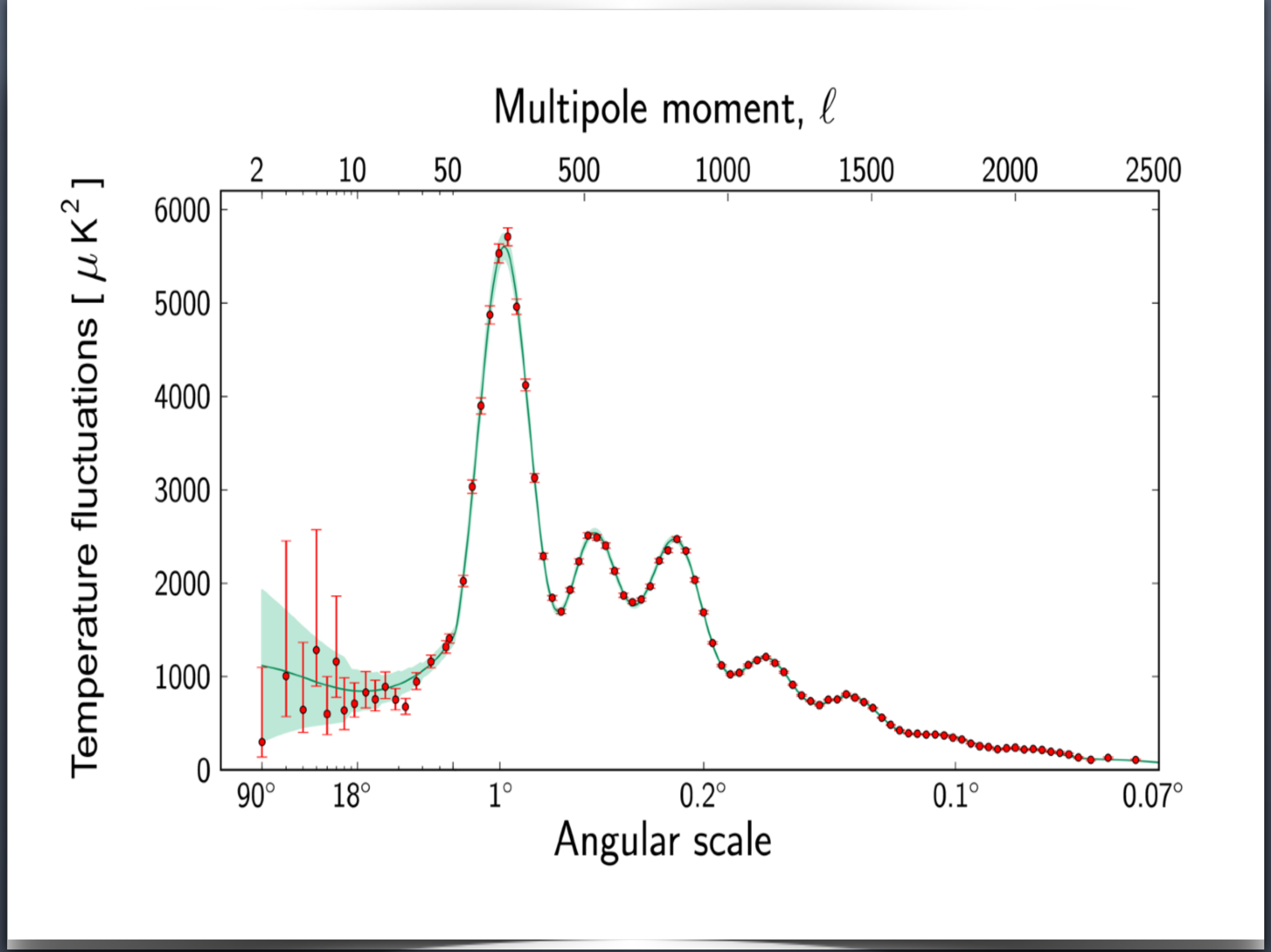
cosmic rays (indirect)

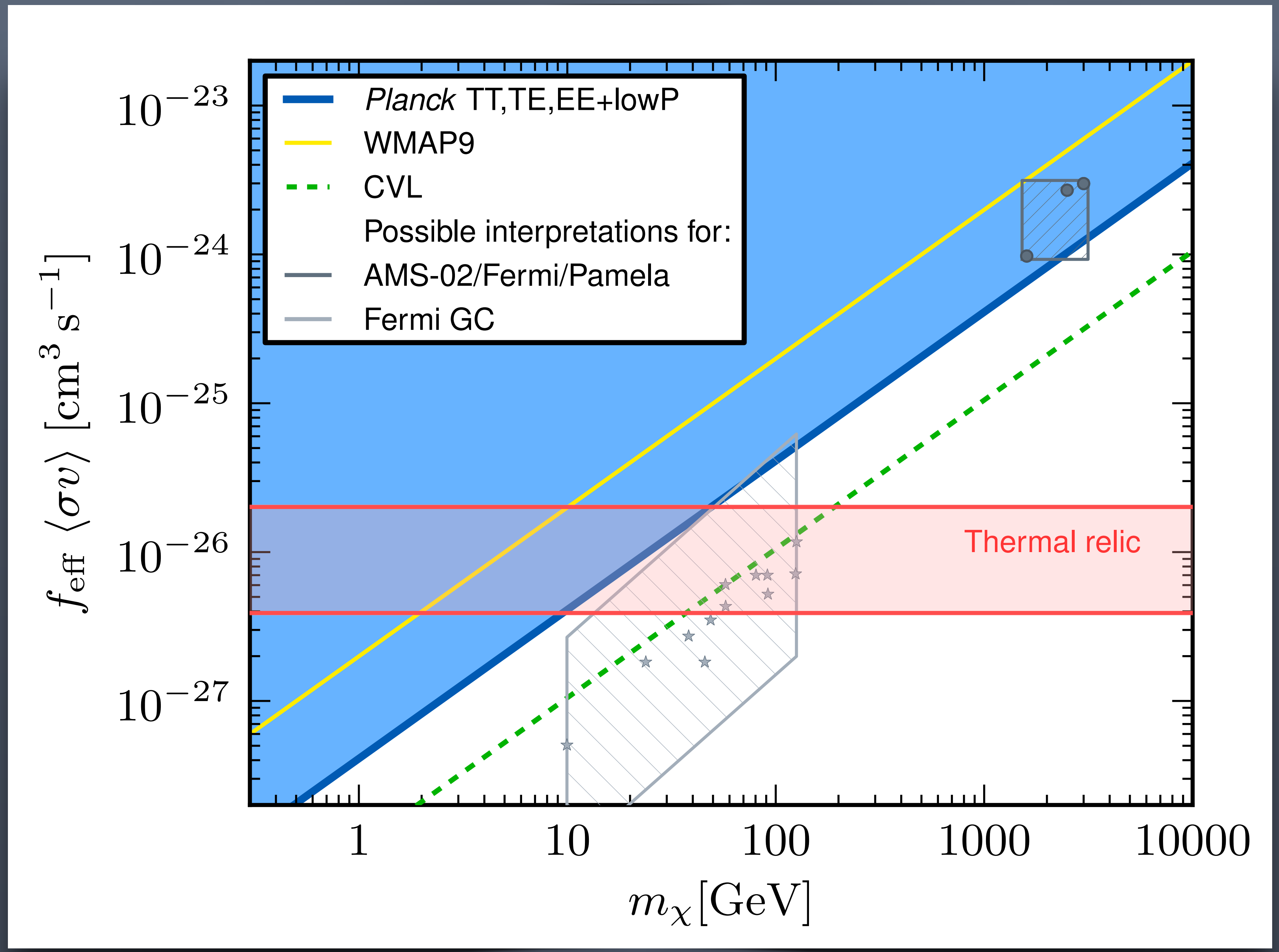
SM recoils (direct)

colliders (production)

Limited final states so complementarity is more robust

COSMOLOGY: ALREADY POWERFUL





- CMB, LSS much more advanced than in 90's
- CMB constraints light relics more effectively

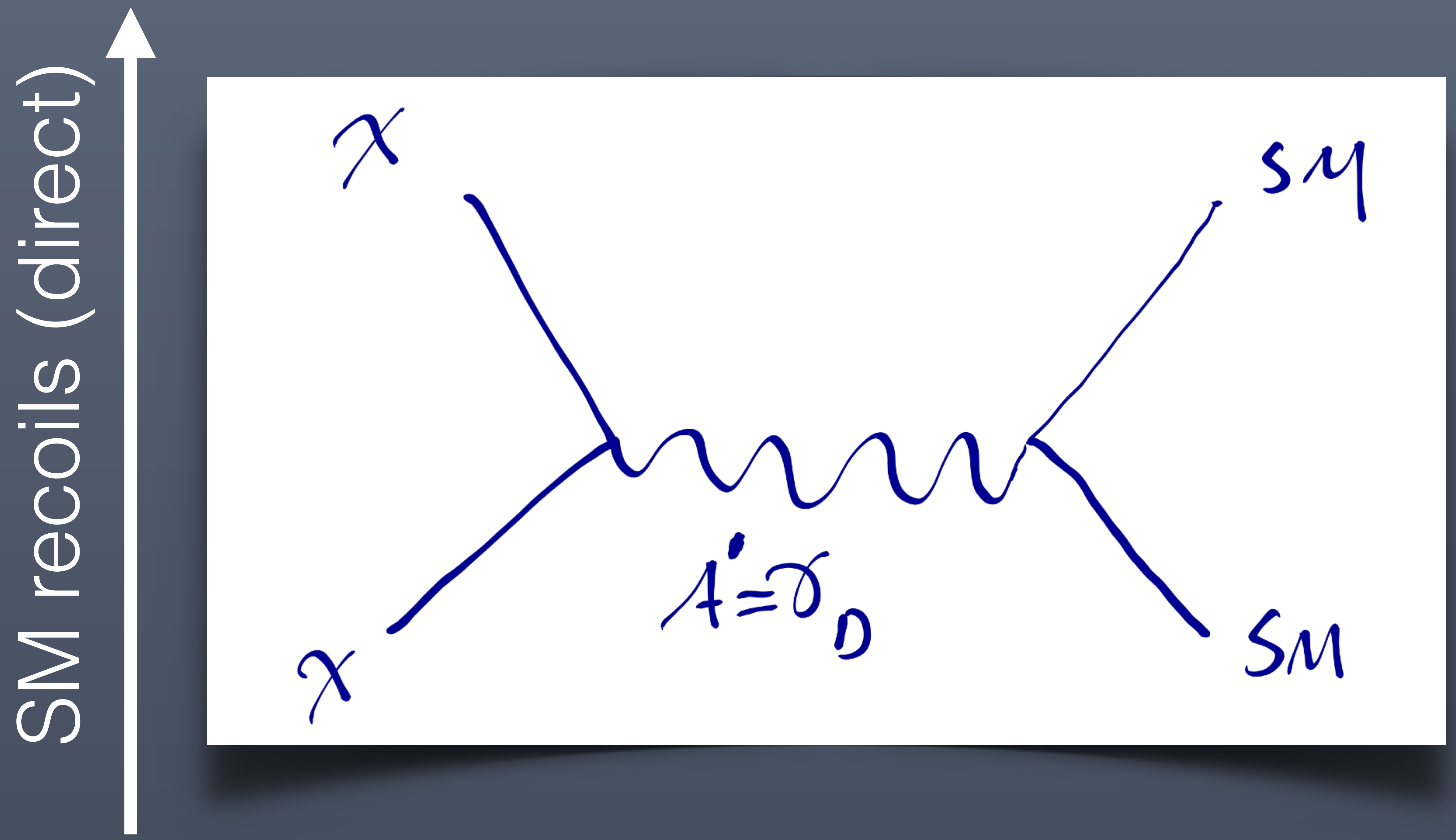
A SIGNAL FROM Z=1100

$$E/\text{vol} \sim n_\chi^2 \langle \sigma v \rangle m_\chi$$

$$\sim \frac{\rho_\chi^2 \langle \sigma v \rangle}{m_\chi}$$

- Need to turn off annihilation at recombination
  - Annihilation is p-wave (velocity suppressed) [scalar]
  - Mass splitting between Majorana states [pseudo-Dirac fermion]

DIRECT DETECTION

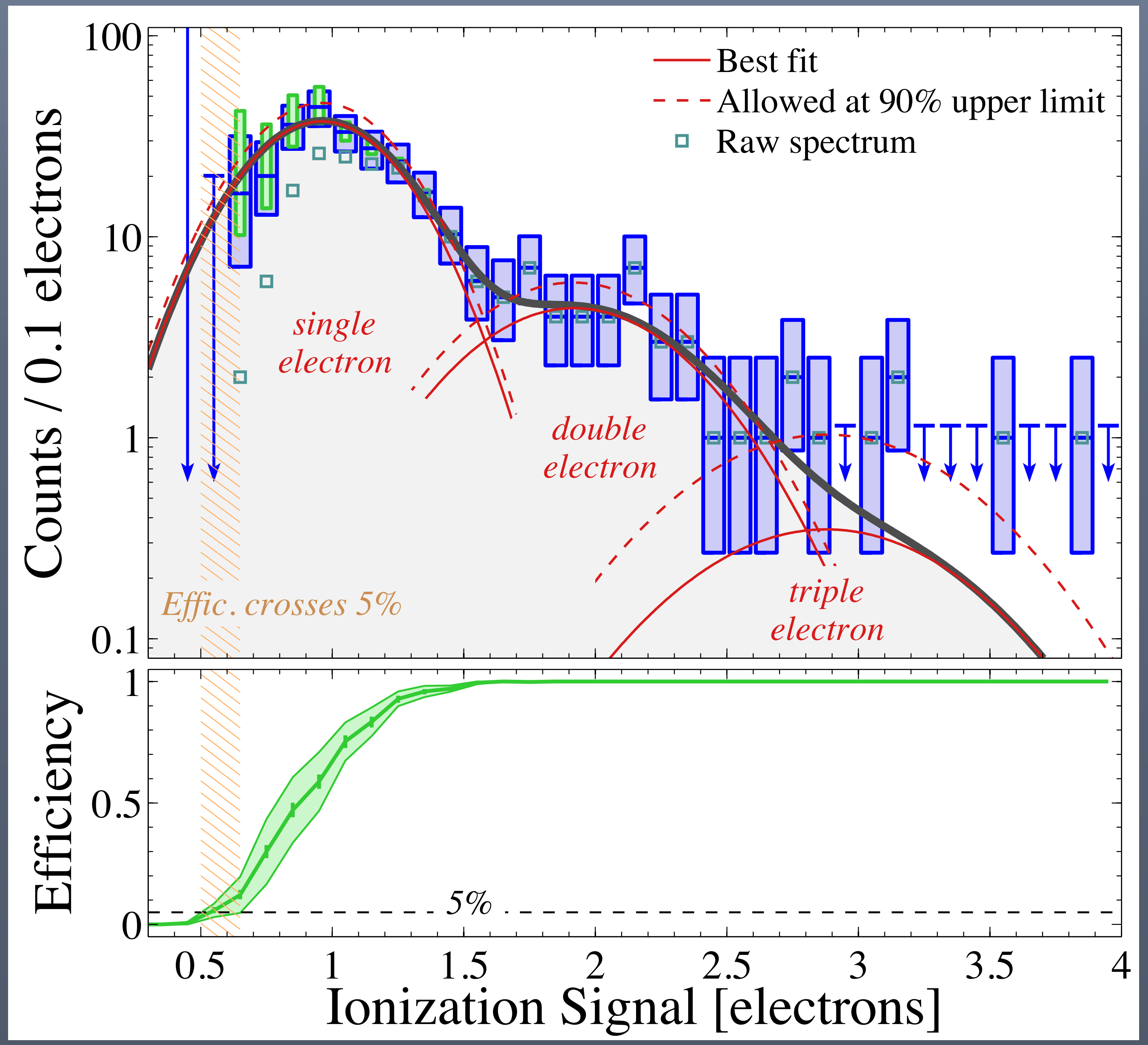


SM recoils (direct)

Not just nuclear anymore

THE ENERGY SCALES FOR LIGHT DM

- $(10^{-3})^2$ x 100 GeV = 100 keV
- $(10^{-3})^2$ x 100 MeV = 100 eV



Light WIMPs don’t knock nucleons!

Essig, Manalaysay, Mardon, Sorensen, Volansky ‘12

SENSEI: Read out CCDs to tiny backgrounds!

Tiffenberg (PI), Bebek, Guardincerri, Haro, Holland, RE, Mardon, Volansky, Yu

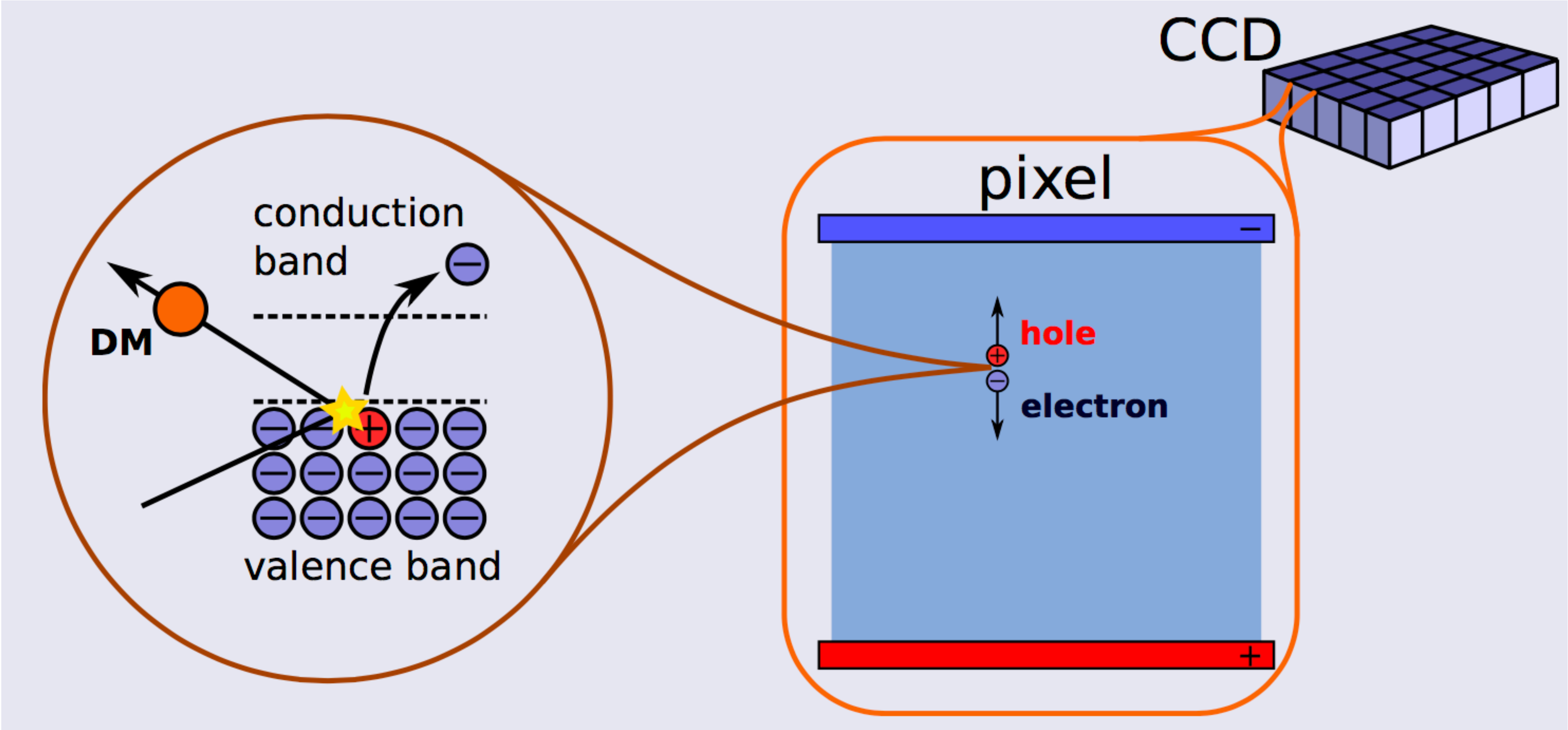
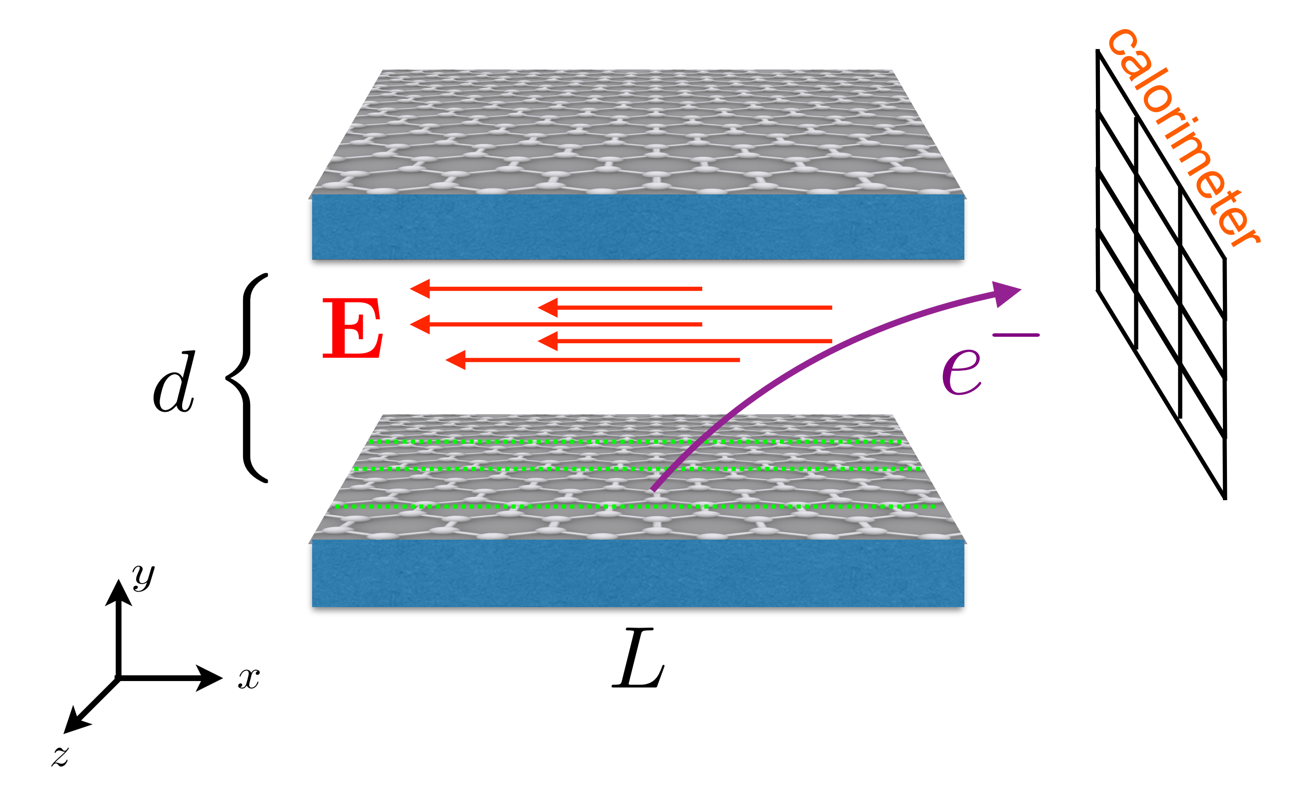
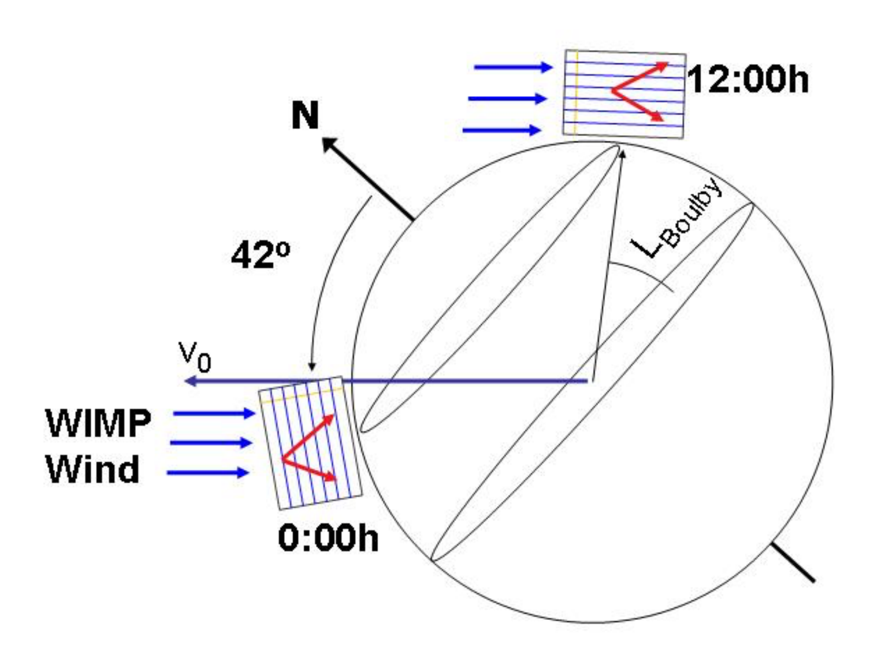


Figure credit: J. Tiffenberg

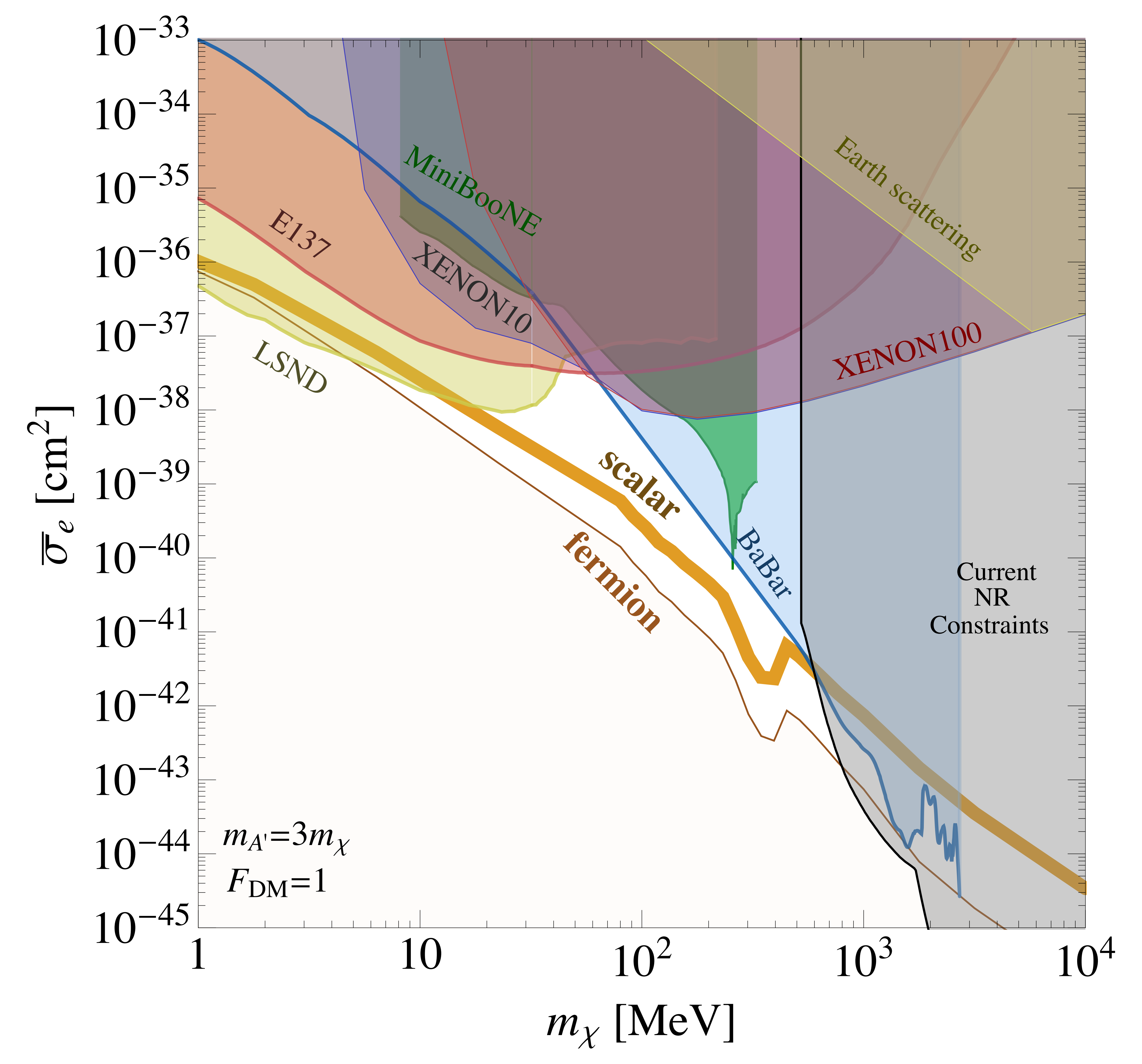


PTOLEMY-G^3: Hochberg, Kahn, Lisanti, Tully, Zurek, '16

Look for *daily* modulation



The Thermal Target



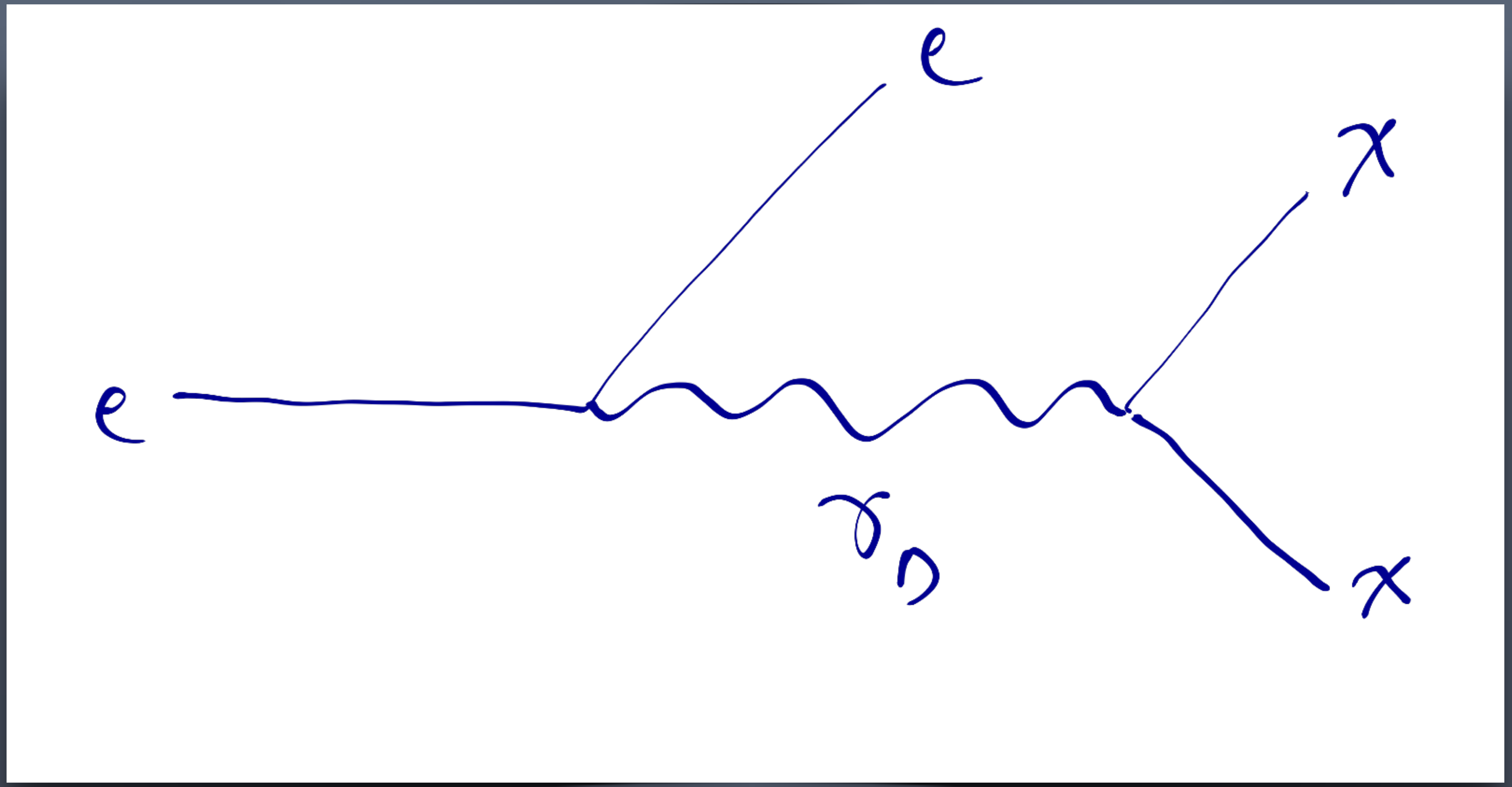
Plot from Essig

"NEW" COMPLEMENTARITY

- Look for mediator

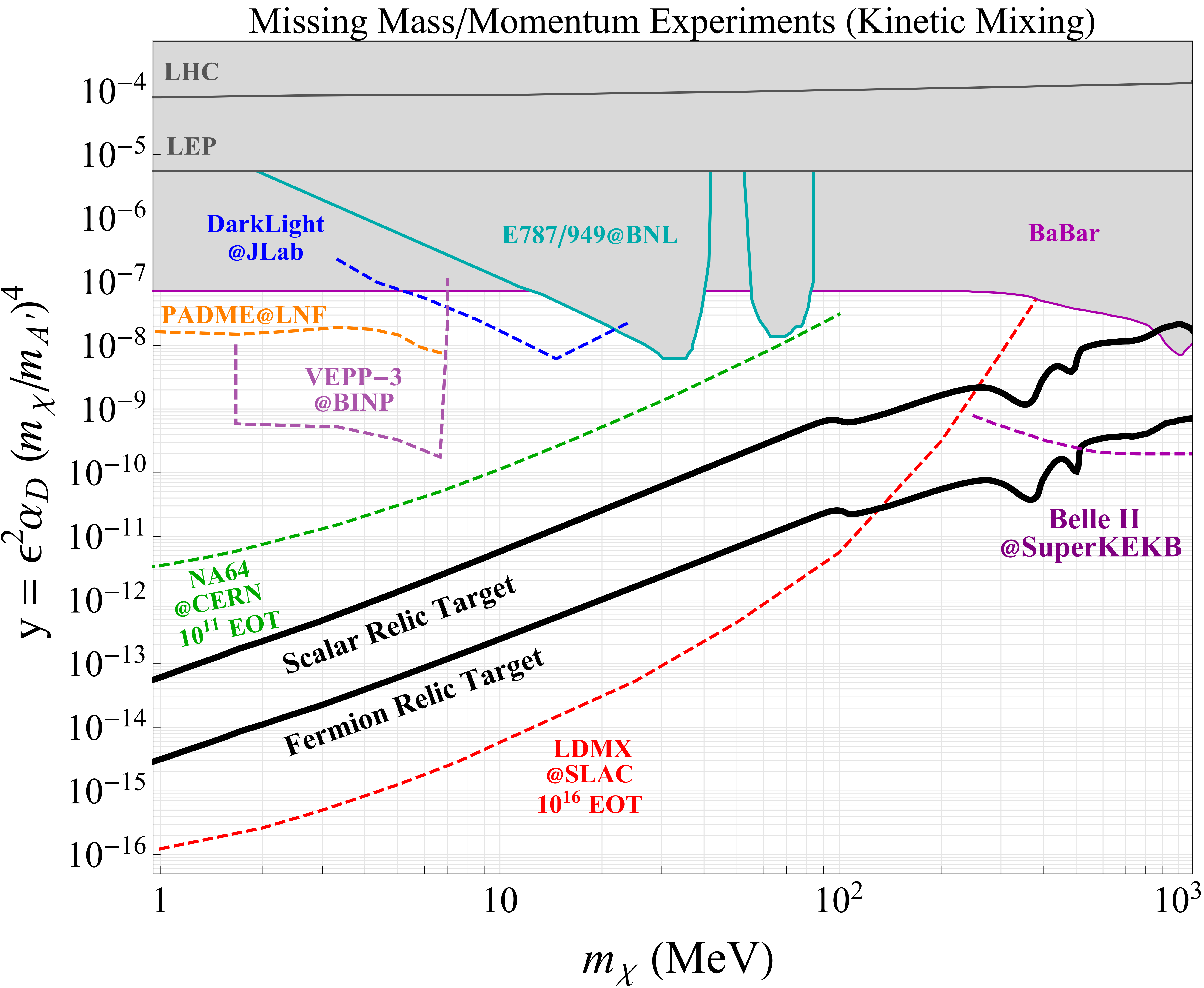
- Cut , stretch+ flip

  - accelerator signals

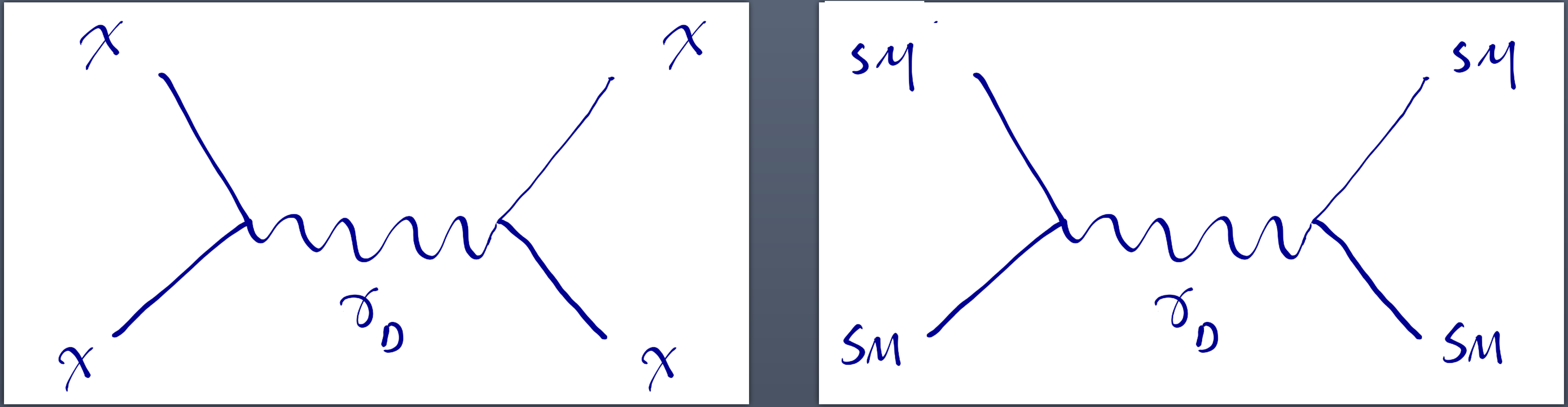


- Signals in self interaction? Anomalies like 8Be?

Parametrically linked tightly to thermal diagram


Missing Mass/Momentum Experiments (Kinetic Mixing)
LHC
LEP
DarkLight
@JLab
E787/949@BNL
BaBar
PADME@LNF
VEPP–3
@BINP
NA64
@CERN
10^{11} EOT
Scalar Relic Target
Fermion Relic Target
LDMX
@SLAC
10^{16} EOT
Belle II
@SuperKEKB
$y = \epsilon^2 \alpha_D (m_\chi / m_{A'})^4$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
1
10
10^2
10^3
m_χ (MeV)

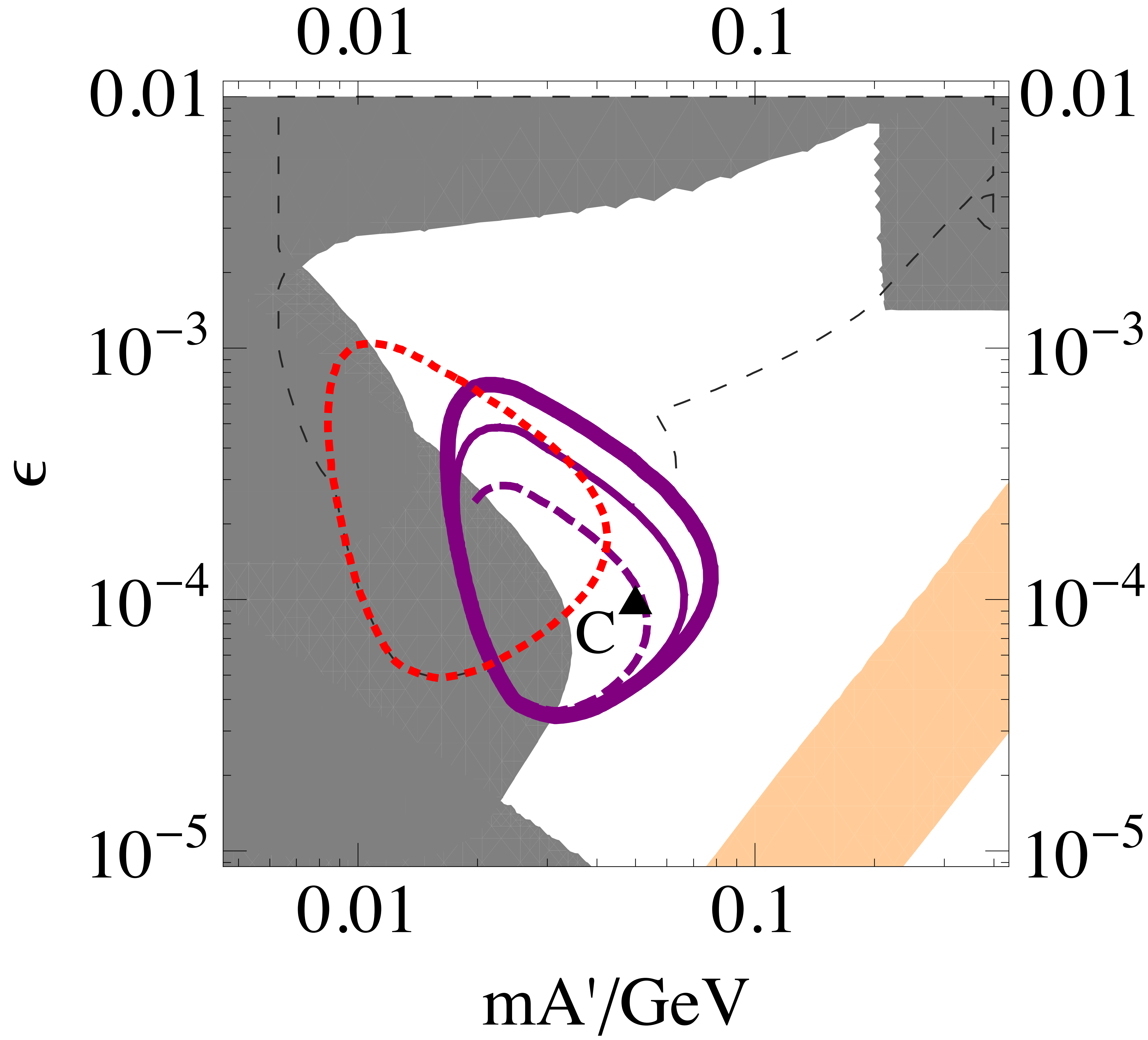
"NEW" COMPLEMENTARITY



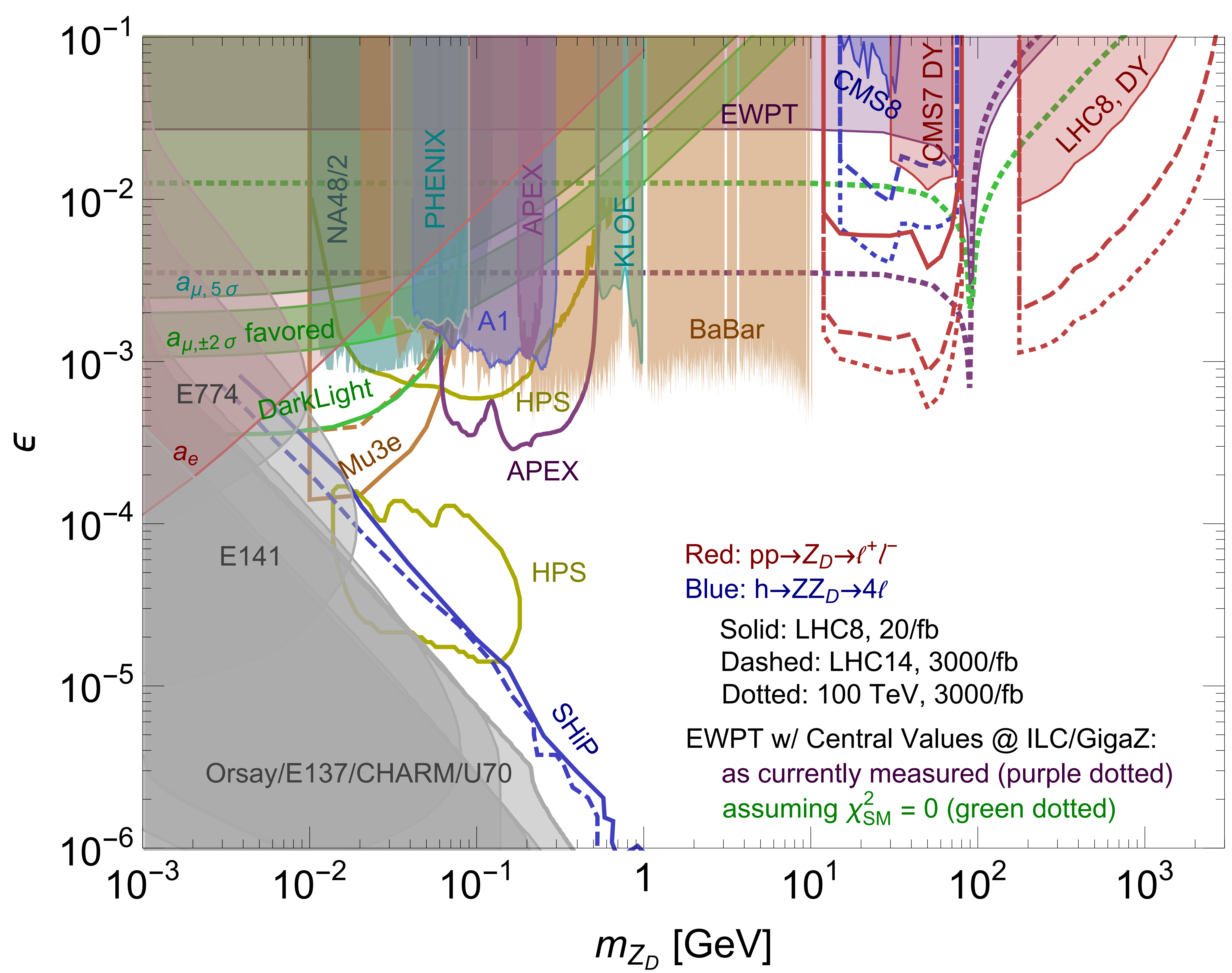
Parametrically linked more weakly to thermal diagram

DM self interaction? Signals of a new force?

SEARCHES FOR DARK FORCES



Bjorken, Essig, Schuster, Toro ‘08



Curtin, Essig, Gori, Shelton ‘14

THERMAL(ISH)

- Elastically decoupling DM (ELDERs)
- Late-dominated interactions (freeze-in)
- Kinematically forbidden DM (forbidden DM)
- 3->2 processes (SIMPs, cannibal DM)

MOVING AWAY FROM THERMAL(ISH) MODELS

A STRONG CP PR0BLEM

$$\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$$

leads to neutron EDM => less than 10^{-10}

A STRONG CP PR0BLEM

$$\theta G_{\mu\nu} \tilde{G}^{\mu\nu}$$

leads to neutron EDM => less than 10^{-10}

critical point 1: quark mass matrix phase contributes

critical point 2: this is a real problem for QFT

A STRONG CP PR0BLEM

$$\theta\, G_{\mu\nu}\tilde{G}^{\mu\nu} \longrightarrow \frac{a}{f_a}\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

idea -> make ϴ a field

QCD effects generate potential that relaxes ϴ (a) to 0

The axion acquires a mass $m_a \approx \frac{m_\pi f_\pi}{f_a} \approx 0.6\,\mathrm{meV}\left(\frac{10^{10}\mathrm{GeV}}{f_a}\right)$

COUPLINGS TO OTHER MATTER

$$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu} \longrightarrow \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

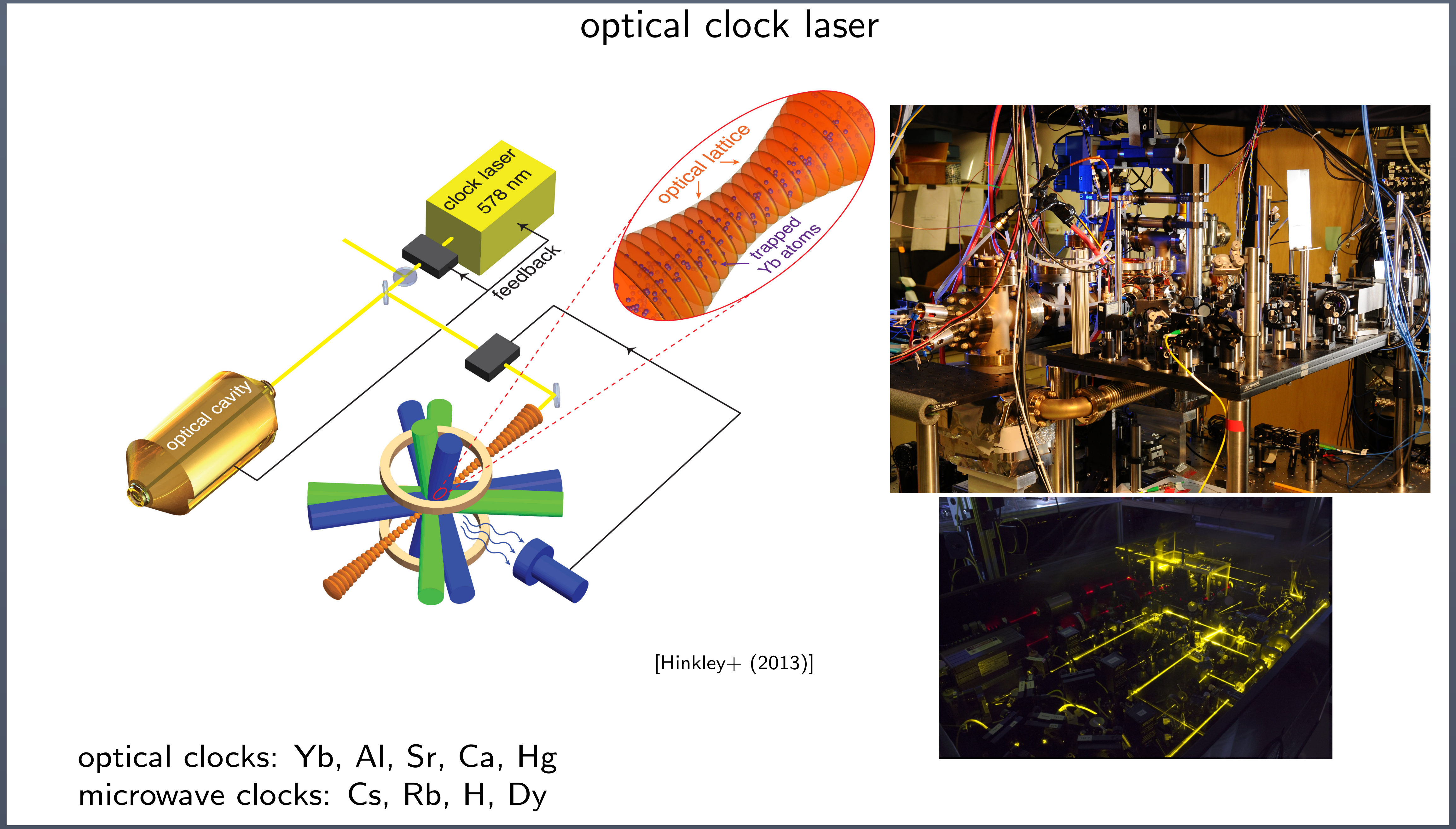
Axion parameters

(adapted from Essig et al 1311.0029 via PDG)

AMDX-II

AMDX-HF

BUT, FUNDAMENTALLY, THE AXION IS AN OSCILLATING SCALAR FIELD



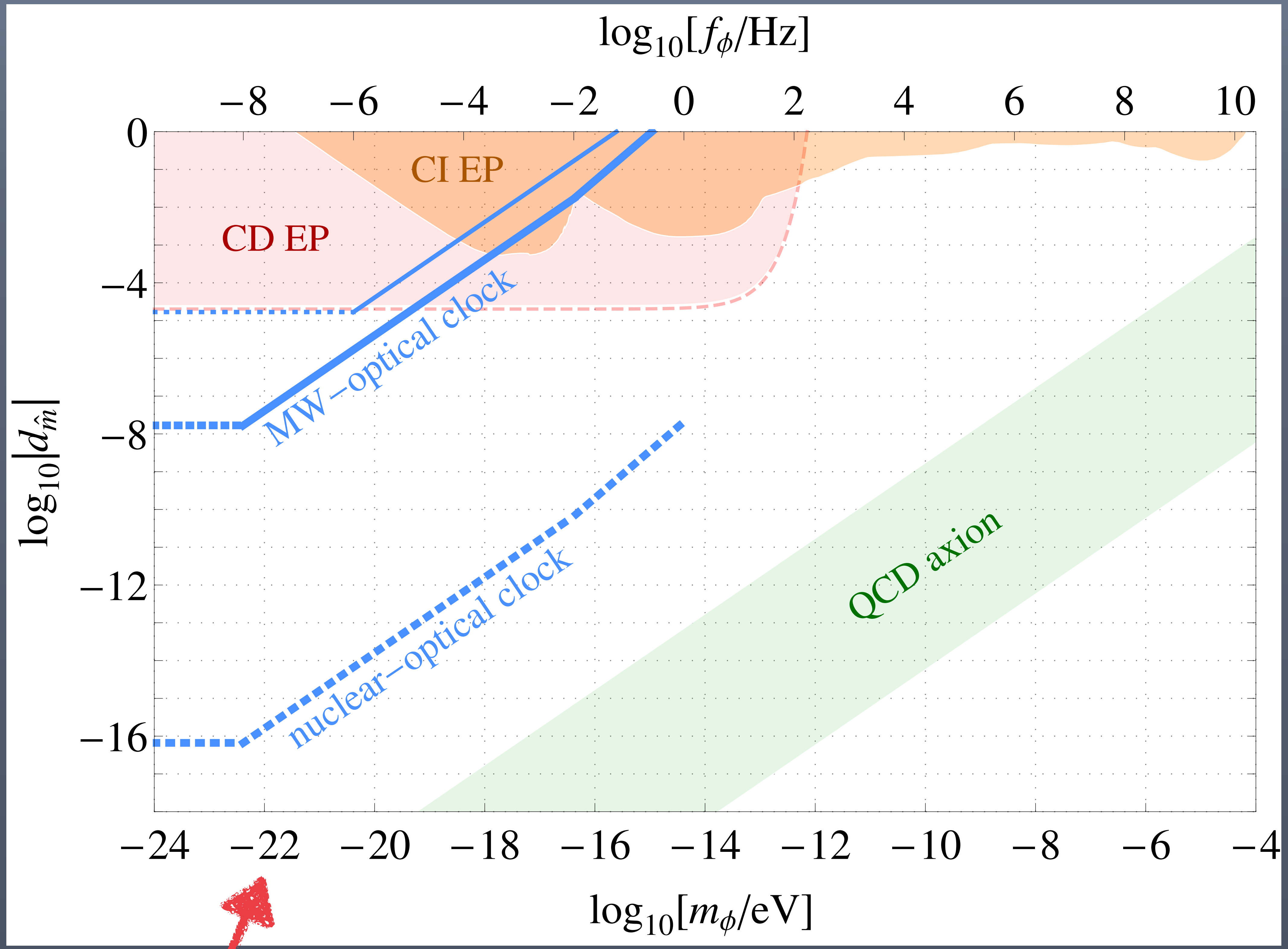
optical clock laser

[Hinkley+ (2013)]

optical clocks: Yb, Al, Sr, Ca, Hg
microwave clocks: Cs, Rb, H, Dy

(from talk by Ken van Tilburg)

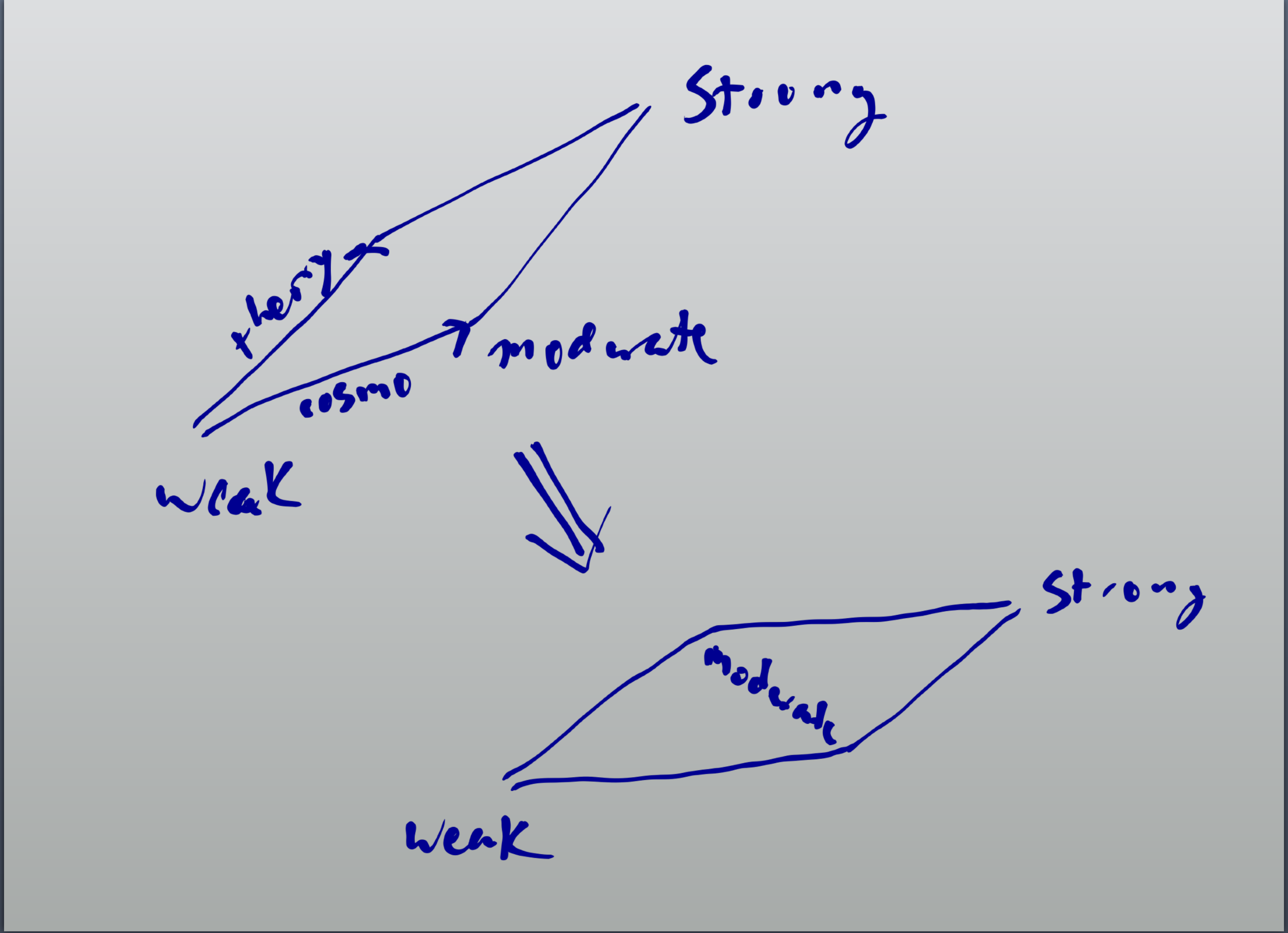
If that oscillating field talks to us - wouldn't fundamental properties oscillate, too?



"fuzzy" dark matter

Arvanitaki, Huang, van Tilburg '14

REBALANCING OUR PRIORHEDRON



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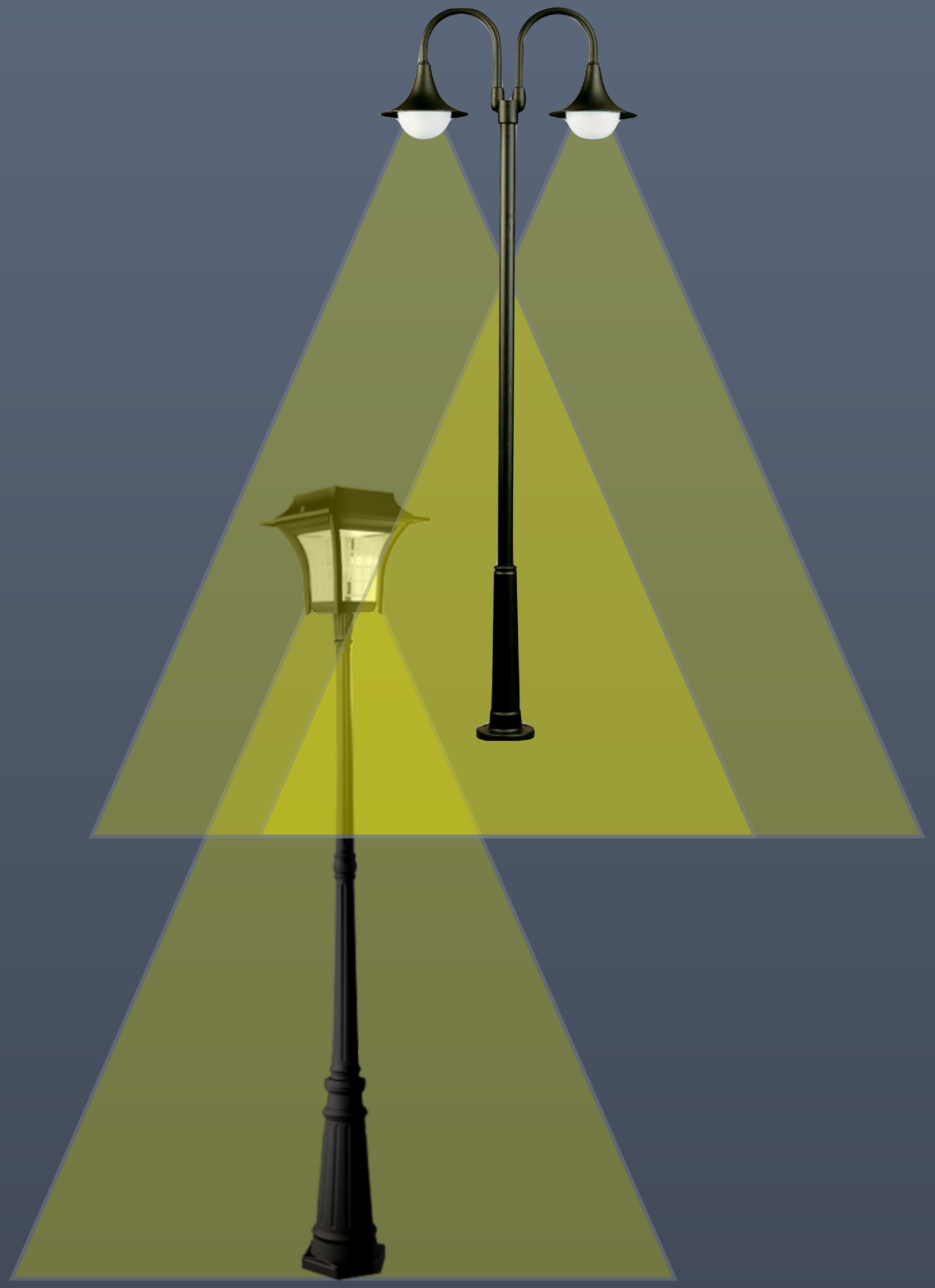

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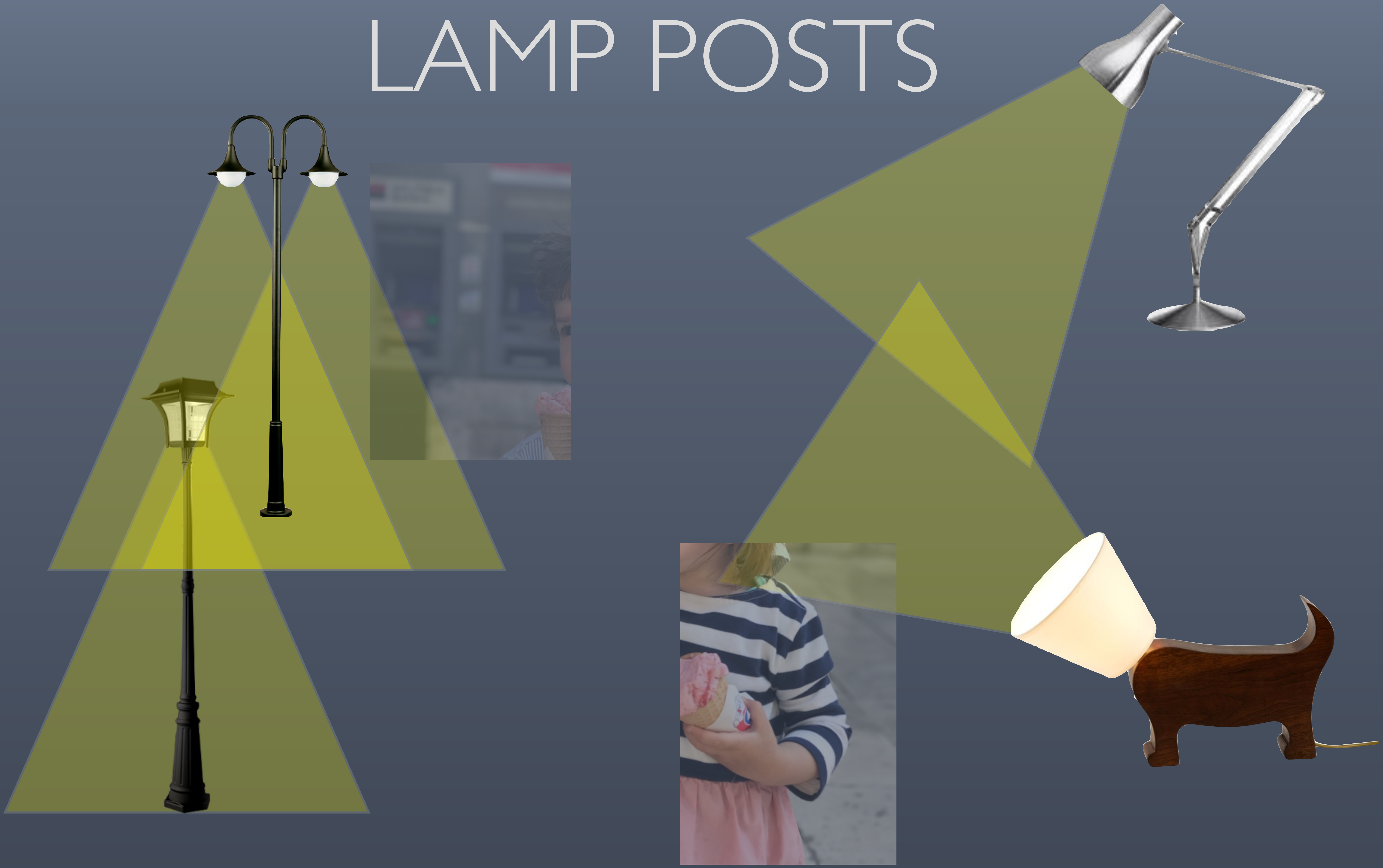

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THE SEARCH FOR DARK MATTER

- Finding dark matter is hard because it's dark and we don't know what it is - theory input is critical
- New ideas about dark matter are gaining attention as we relax priors on physics beyond the standard model
- In this era, we will learn important qualitative results about dark matter, whether or not it is found
- We have many well motivated lamp posts being pursued, and there are tremendous prospects in the coming decade
- But it may be that the lamp post that best illuminates dark matter is still unconsidered - new ideas coming ever faster!

THANK YOU VERY MUCH!