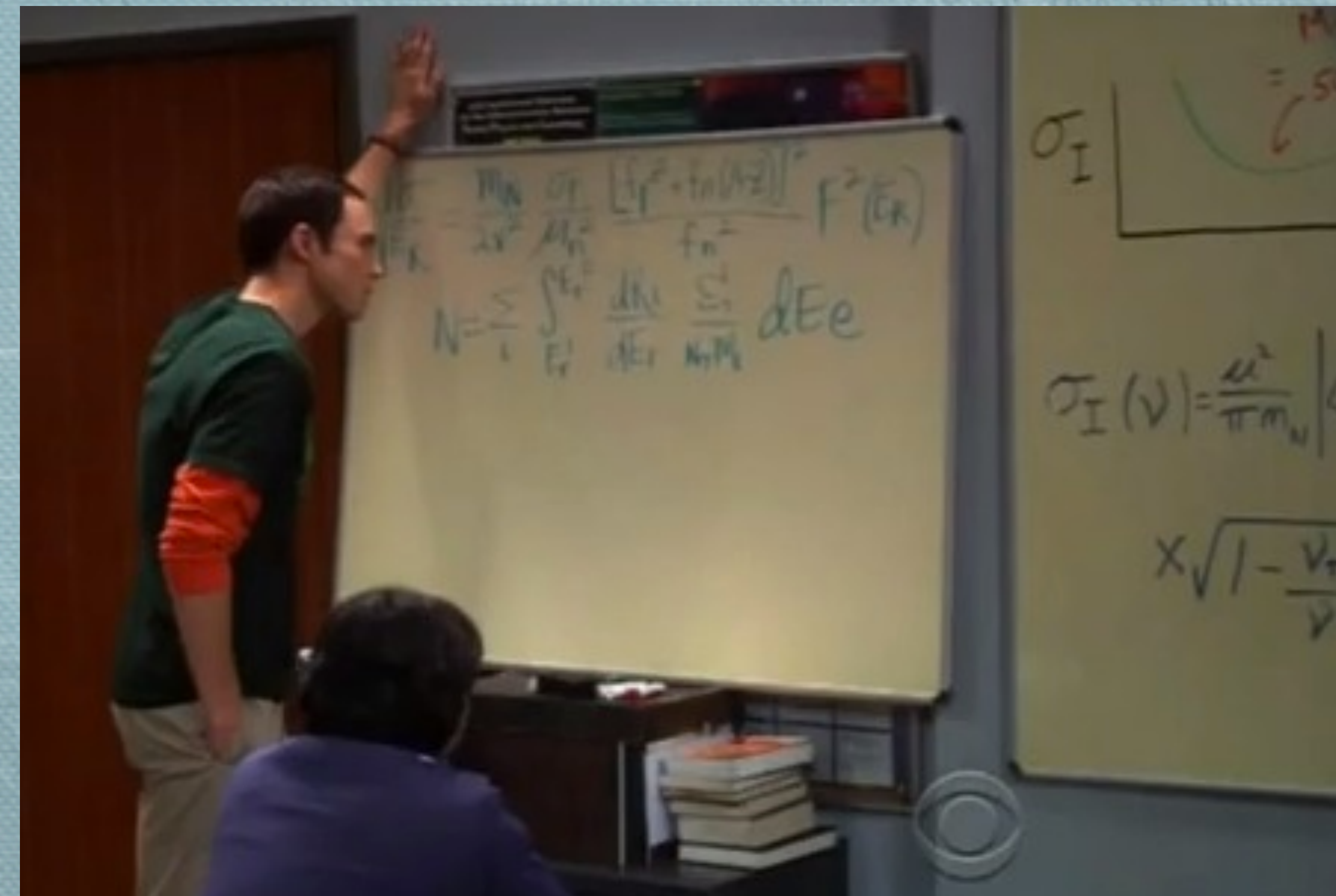


Big Bang Theory

Effective WIMPs

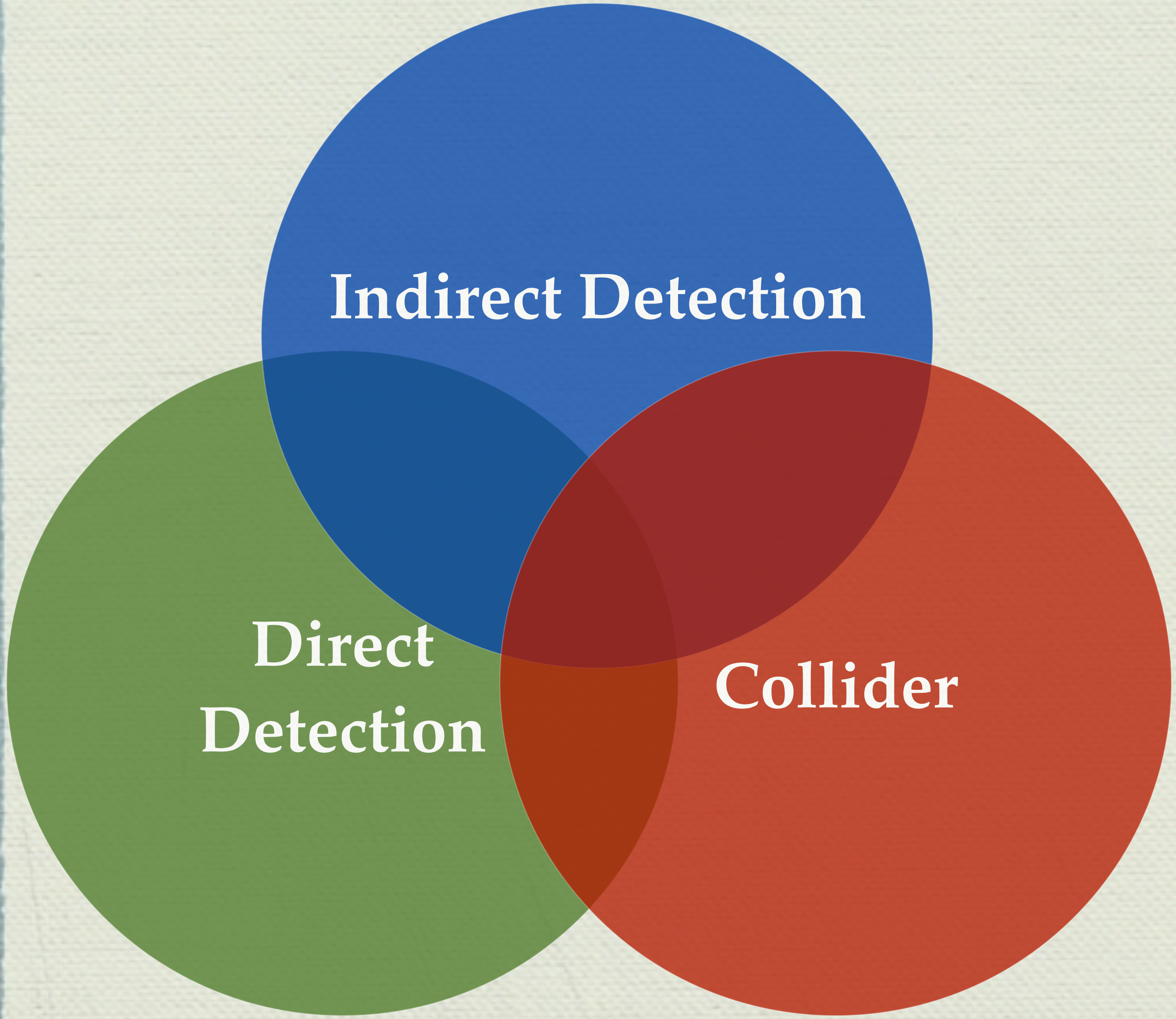
Spencer Chang (University of Oregon)

w/ R. Edezhath, J. Hutchinson, M. Luty

arXiv:1307:8120

Also see
An et.al.
1308.0592
Bai et.al.
1308.0612

Shedding Light on Dark Matter



Many Experimental Probes of Dark Matter

What we want to know

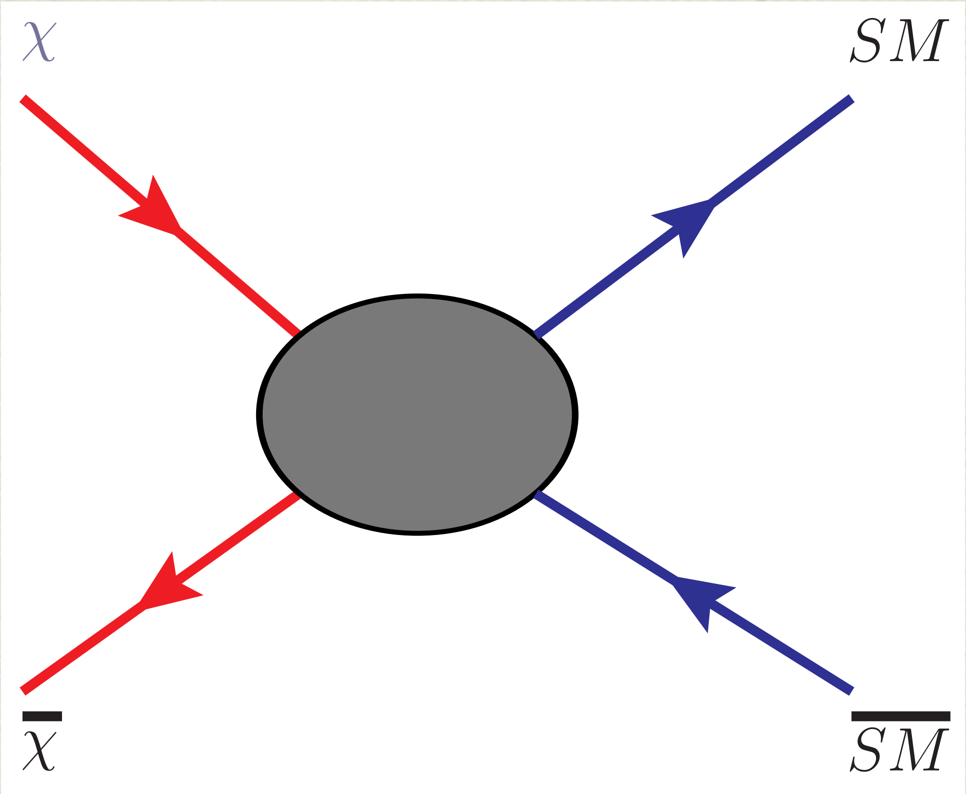
Quantum numbers

Interactions w/ SM

Theoretical Framework

(e.g. axions, WIMP, ADM)

WIMP Paradigm



Thermal equilibrium set by Dark Matter annihilation into Standard Model particles

$$\langle \sigma(\chi + \overline{\chi} \to SM + \overline{SM}) v \rangle \sim 1 \text{ pb}$$

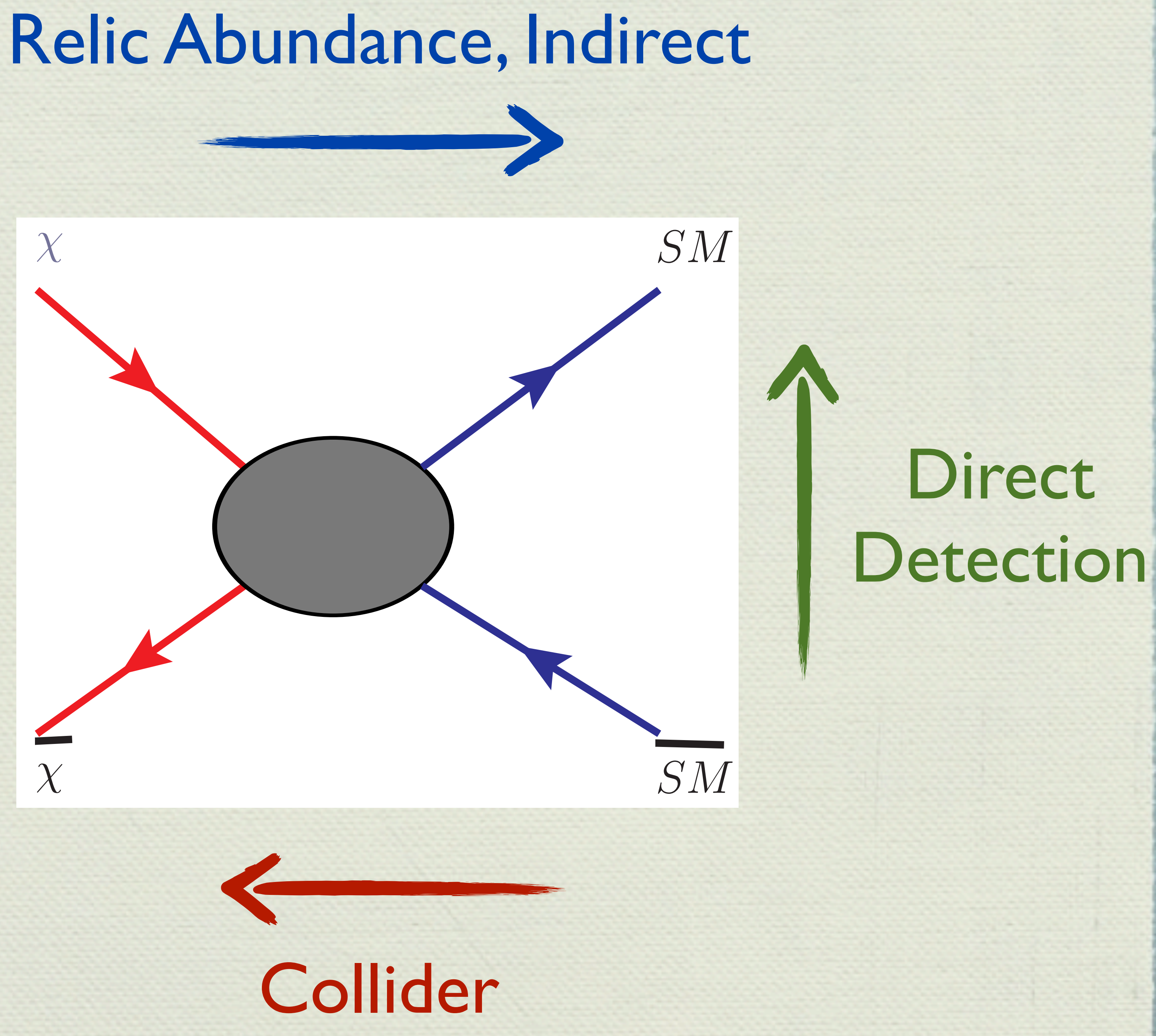
WIMP Miracle: Weak scale particles with EW strength couplings have correct abundance

Experimental Crossing Symmetry

WIMP has the potential to be probed by all three frontiers

However, no <u>simple</u> scaling between experimental rates

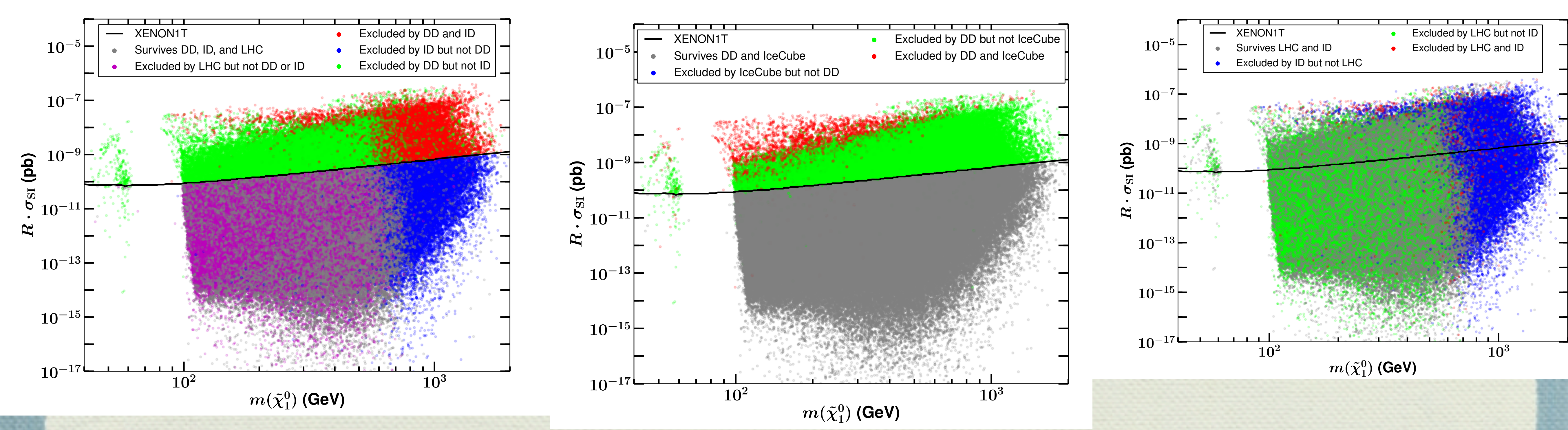
see e.g. Profumo et.al. 1307.6277



Approaches

- A complete WIMP theory, e.g. Supersymmetric Dark Matter
- Effective Operators, aka "Effective Dark Matter"
- We are proposing a useful compromise: "Effective WIMPs"

A Complete Model: PMSSM Study Cahill-Rowley et.al. 1305.6921



Pros: Theoretically Motivated, All Effects (e.g. NLO, coannihilation)

Cons: Multi-dimensional parameter space, obscured physics, sensitive to theory priors

Effective DM

see e.g. Beltran e.t.al., Goodman et.al., Bai et.al.

Consider only dark matter state w/ one effective operators to SM at a time

$$\mathcal{O}_{DM}\mathcal{O}_{SM} = \frac{1}{M_*^2}\left(\bar{\chi}\gamma_\mu\chi\right)\left(\bar{q}\gamma^\mu q\right)$$

Pros: Simple 2-d parameter space, allows comparison between monojets and direct detection

Cons: WIMP miracle put in by hand, some observables sensitive to UV completion, multiple operators may be important

Effective WIMP

For a UV complete model, typically have to add new particles (however see Minimal DM, Higgs Portal)

$$\mathcal{L}_{\rm int} = \lambda\, \chi (SM)(\widetilde{SM})^*$$

If we assume DM is gauge singlet, have to introduce partners to SM particles

3 parameters: masses of DM, partner and interaction strength. However, can fix one by relic abundance

Natural Z_2 symmetry for DM stability

Discrete Choices

Will consider DM of spin 0, 1/2, 1
with renormalizable
couplings to left-handed quarks

From flavor assume quark partners are
degenerate and DM couples to
all, first two or just third generation

DM can be "real or complex"

Take Home Message

- Effective WIMPs are an alternative approach for DM
- Discrete set of models, with 2-d parameter space (mass of DM, partner)
- Direct detection and colliders are complementary in the parameter space
- New collider process of same sign quark partner production through t-channel dark matter exchange

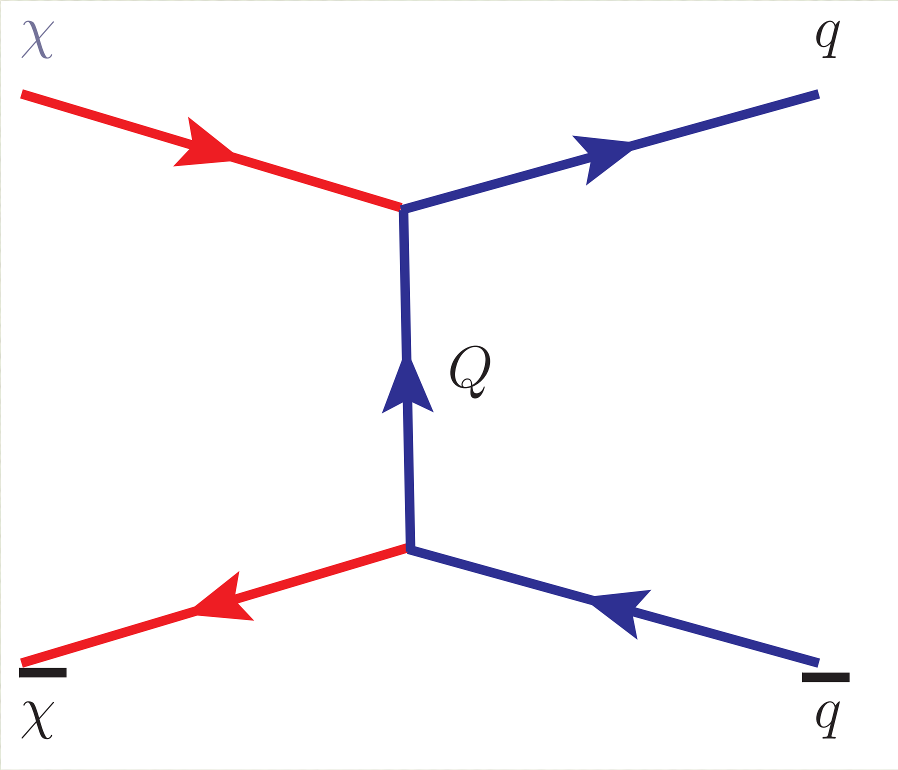
Discrete set of Models

Model Particles		$\mathcal{L}_{\text{int}}$
Dark matter χ	Quark partner Q	
Majorana fermion	Complex scalar	$\lambda(\chi q)Q^* + \text{h.c.}$
Dirac fermion	Complex scalar	$\lambda(\chi q)Q^* + \text{h.c.}$
Real scalar	Dirac fermion	$\lambda(Q^c q)\chi + \text{h.c.}$
Complex scalar	Dirac fermion	$\lambda(Q^c q)\chi + \text{h.c.}$
Real vector	Dirac fermion	$\lambda\left(q^\dagger \bar{\sigma}^\mu Q\right)\chi_\mu + \text{h.c.}$
Complex vector	Dirac fermion	$\lambda\left(q^\dagger \bar{\sigma}^\mu Q\right)\chi_\mu + \text{h.c.}$

Note: χ is DM, q left-handed quark
Q is quark partner
Fermions are 2-component

Effective Interaction

Relic Abundance, Indirect



$$|M|^2 \propto \lambda^4$$

Direct Detection

Caveat: QCD production of Q

Collider

Quick Overview of Probes

- Relic abundance
- Direct detection
- Collider
- Indirect detection

Simplifying matters, direct detection rules out complex dark matter models unless mass is multi-TeV

Relic Abundance

For given masses of DM and Q, interaction strength is fixed

$$\langle \sigma v \rangle = a + b\, v^2 + \cdots \sim \ \mathrm{pb}$$

Suppression effects lead to larger couplings

Velocity (typically p-wave) $v^2 \sim 0.1$

Chiral $\dfrac{m_q^2}{m_\chi^2}$

Suppression Argument 1

Majorana DM s-wave is chirally suppressed

For fermion-antifermion pair

$$CP = (-1)^{L+S}(-1)^{L+1} = (-1)^{S+1}$$

For Majorana s-wave annihilation,

L = 0, C=+1 ⇒ CP =−1

With only left-handed quarks, S = +1, so CP = +1

Thus, we need quark mass under CP conservation

Whereas for Dirac, do not require initial C=+1

Suppression Argument 2

Scalar DM has chirally suppressed s-wave

Integrate out quark partner to get

$$\mathcal{L}_{\rm eff} \sim \frac{\lambda^2}{m_Q^2}\chi^\dagger q^\dagger i\bar{\sigma}^\mu \partial_\mu(\chi q)$$
$$= \frac{\lambda^2}{2m_Q^2}\left(\chi^\dagger \overleftrightarrow{\partial}_\mu \chi\right)\left(q^\dagger i\bar{\sigma}^\mu q\right) + O(m_q)$$

For real scalar first term is zero

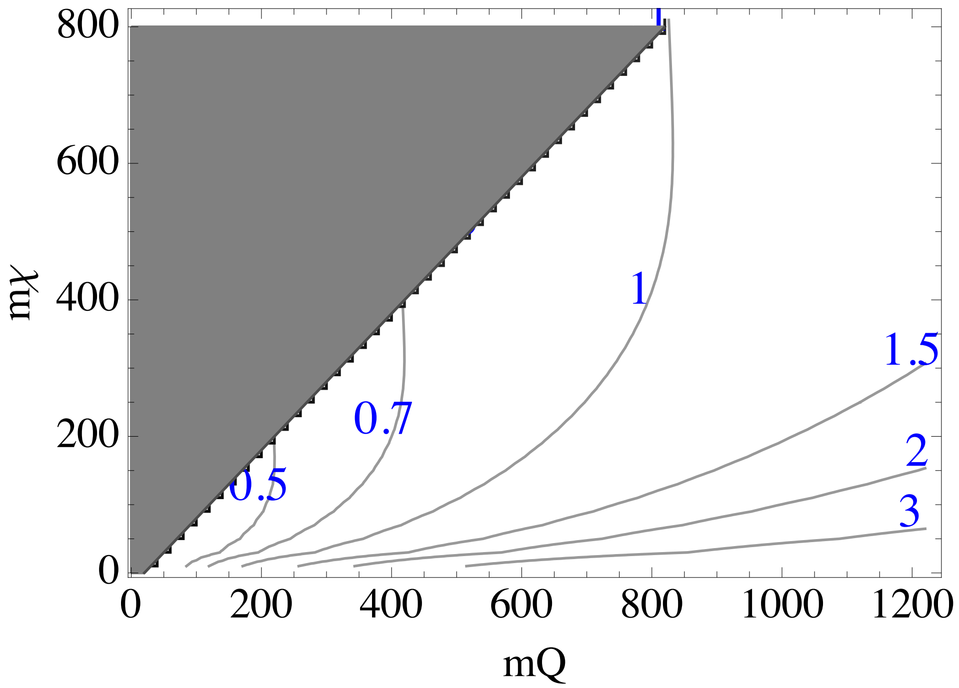
For complex, this is a p-wave term, so s-wave is still chirally suppressed

Relic Abundance Summary

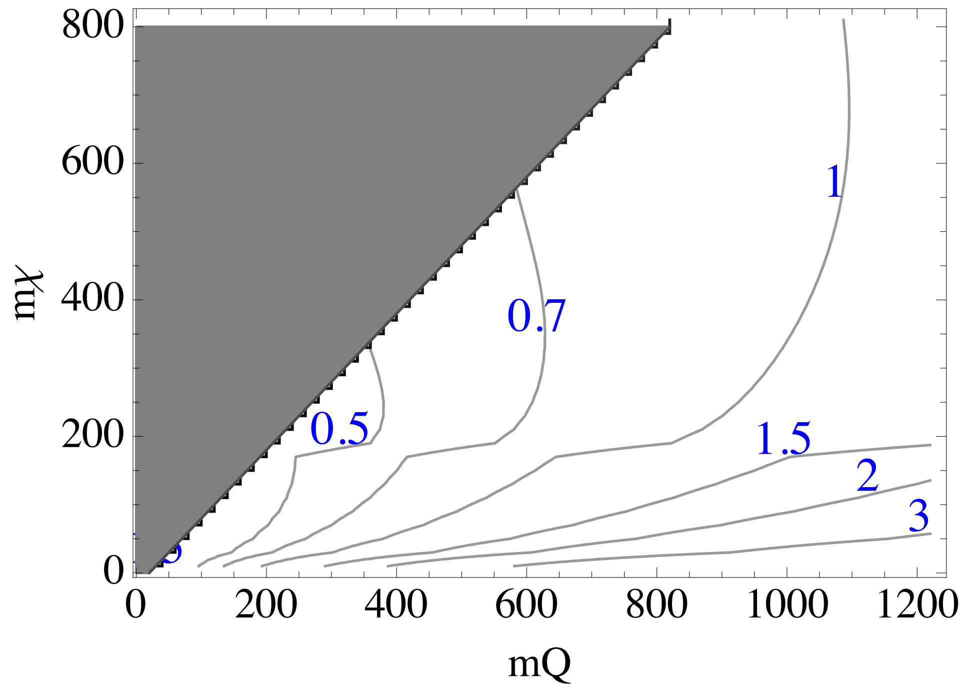
- Majorana and both scalar DM models have chirally suppressed s-wave cross section
- Real scalar DM also has chirally suppressed b v^2 cross section

Example Interaction Strengths

Majorana Model



Lightest Quarks

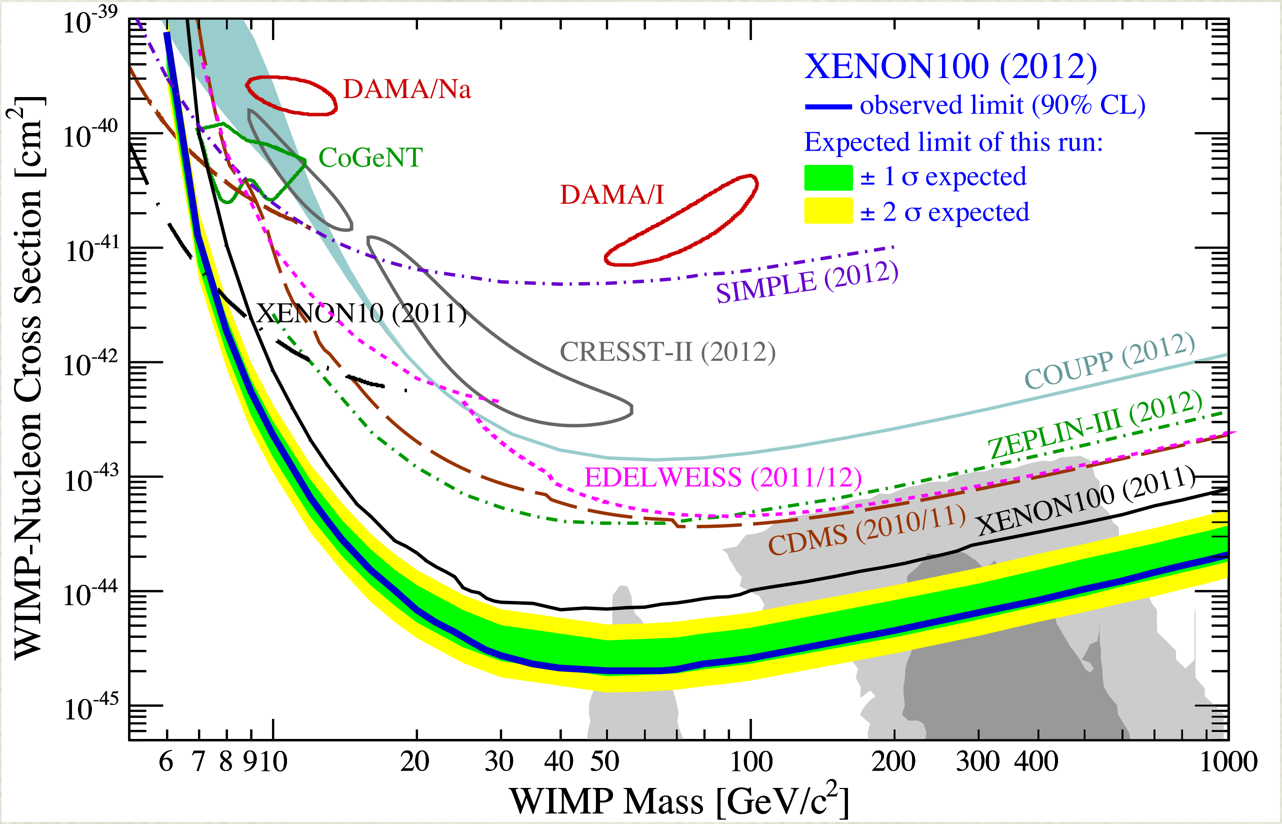


All Quarks

Noticeable effect of top quark threshold

Direct Detection Constraint

We apply latest XENON100 spin-independent limit



We neglect spin-dependent limits which are flavor dependent and thus model dependent
(e.g. 3rd gen models have no SD limits)

Direct Detection

- Direct detection is in the nonrelativistic regime $v \sim 10^{-3} c, q \sim m_\chi v$
- For spin-independent interactions, vector quark operator has largest matrix element in NR limit
- DM quantum #'s can restrict this

For real dark matter models, vector operator vanishes on equation of motion

Majorana $\bar{\chi}\gamma_\mu\chi = 0$

Following require integration by parts

Real Scalar $\chi\partial_\mu\chi\,(\bar{q}\gamma^\mu P_L q) = \chi^2(m_q\bar{q}q)$

Real Vector $\chi_\nu\partial_\mu\chi^\nu\,(\bar{q}\gamma^\mu P_L q) = \chi_\nu\chi^\nu(m_q\bar{q}q)$

For complex DM, no way to forbid vector leads to strong XENON100 constraints

$$\frac{\lambda^2}{m_Q^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

$$\frac{\lambda^2}{m_Q^2}\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$$

$$\frac{\lambda^2}{m_Q^2}\chi_\nu^\dagger\partial_\mu\chi^\nu\bar{q}\gamma^\mu q$$

$$\sigma_{nucleon} = \frac{\lambda^4 m_{nucleon}^2}{4\pi m_Q^4}$$

$$\sim \frac{m_{nucleon}^2}{m_\chi^2}\sigma_{ann}$$

$$\sim \frac{m_{nucleon}^2}{m_\chi^2}10^{-36}\text{cm}^2$$

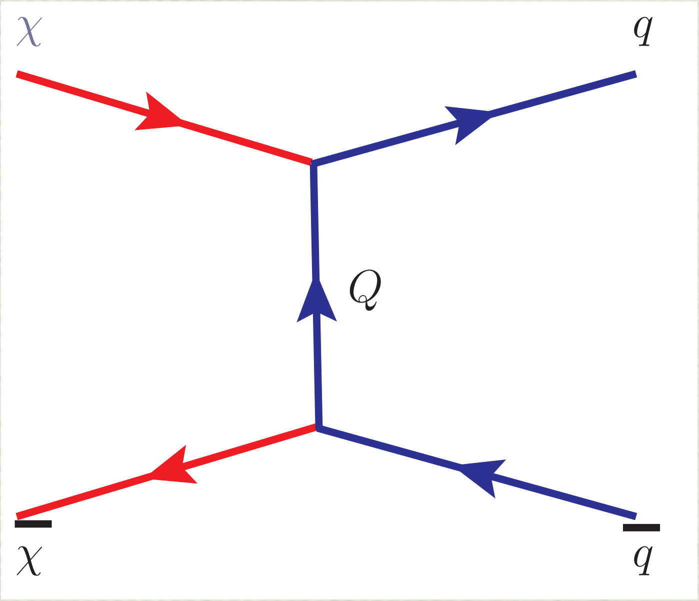
XENON100 limit requires multi-TeV DM which is uninteresting for colliders

Subdominant Operators

$$\langle n|m_q\bar{q}q|n\rangle \sim 0.01 m_{nucleon}$$

$$\langle n|\frac{i}{2}\bar{q}\left(D_\mu\gamma_\nu + D_\nu\gamma_\mu - \frac{1}{2}g_{\mu\nu}\right)|n\rangle \sim 0.1 m_{nucleon}$$

Suppression allows real DM w/ sub-TeV masses



However, there is a resonant enhancement when Q, DM degenerate

Hisano et.al. PLB706

Makes DD complementary to colliders!

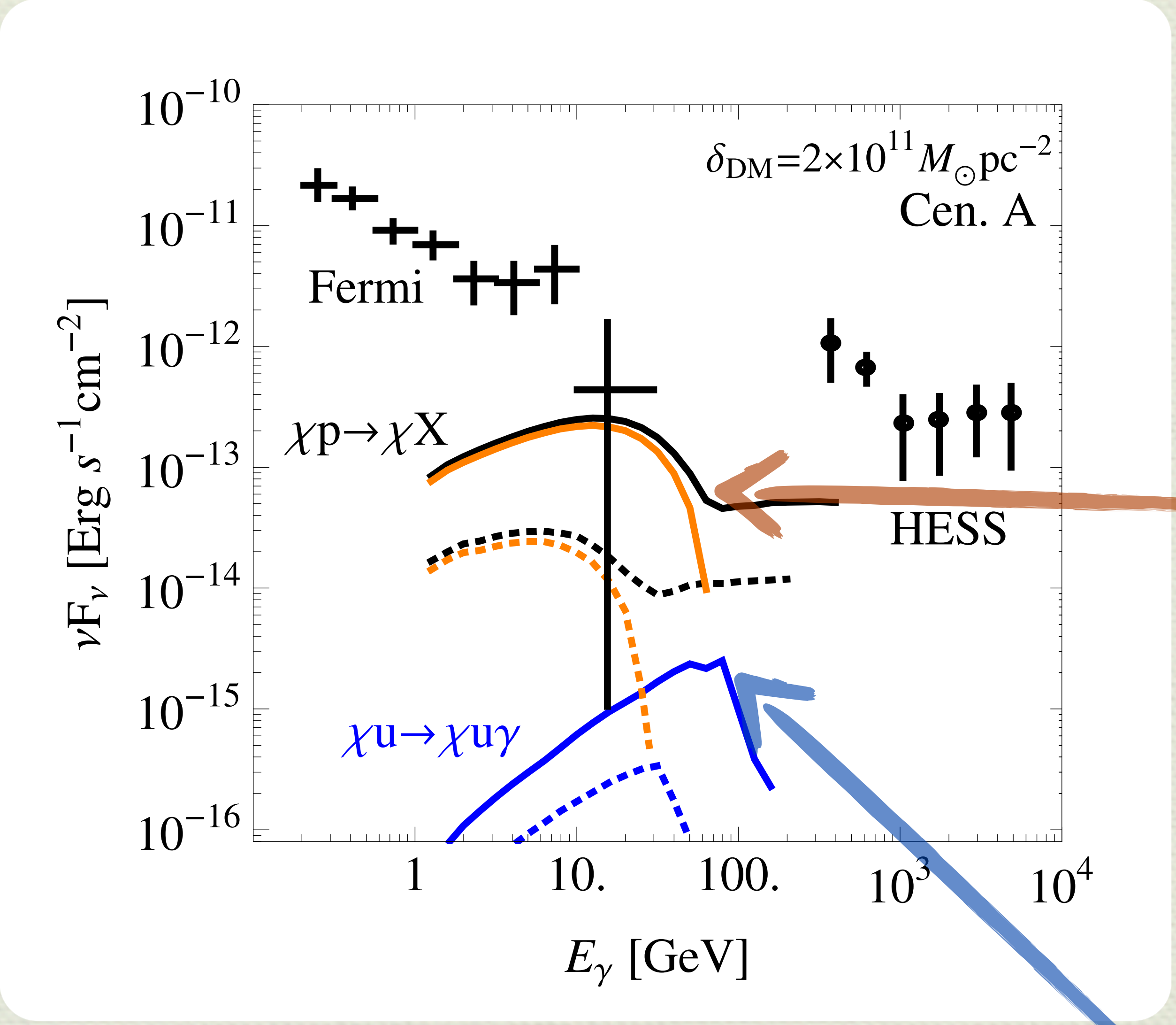
Indirect Detection

Typically constraints are too weak to constrain relic annihilation cross section

Two interesting possibilities

1) Stacked Analysis of Dwarf Galaxies by gamma ray telescopes

2) Observations of gamma rays from DM scattering off AGN jets



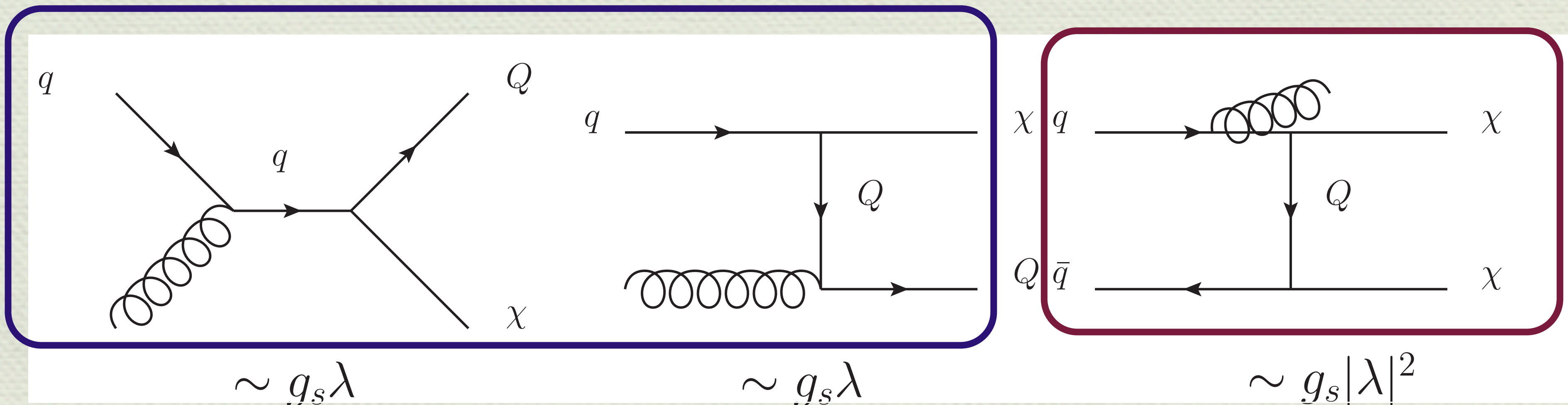
Gamma Rays off of AGN proton jets

In SC, Gao, Spannowsky we found hadronization photons boosted the signal beyond the parton level analysis of Gorchtein, Profumo, Ubaldi

Increase due to multiplicity and
lack of α suppression, but still challenging to see

Collider Signals

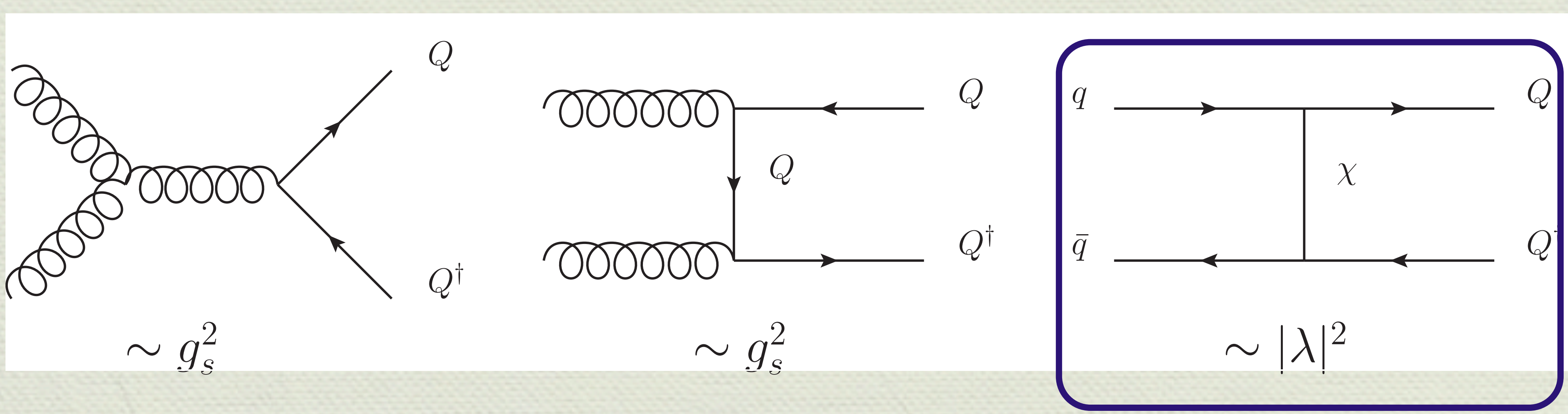
Monojet



New Process

Effective DM

Dijets +MET



New t-channel Process

"Simulation" Details

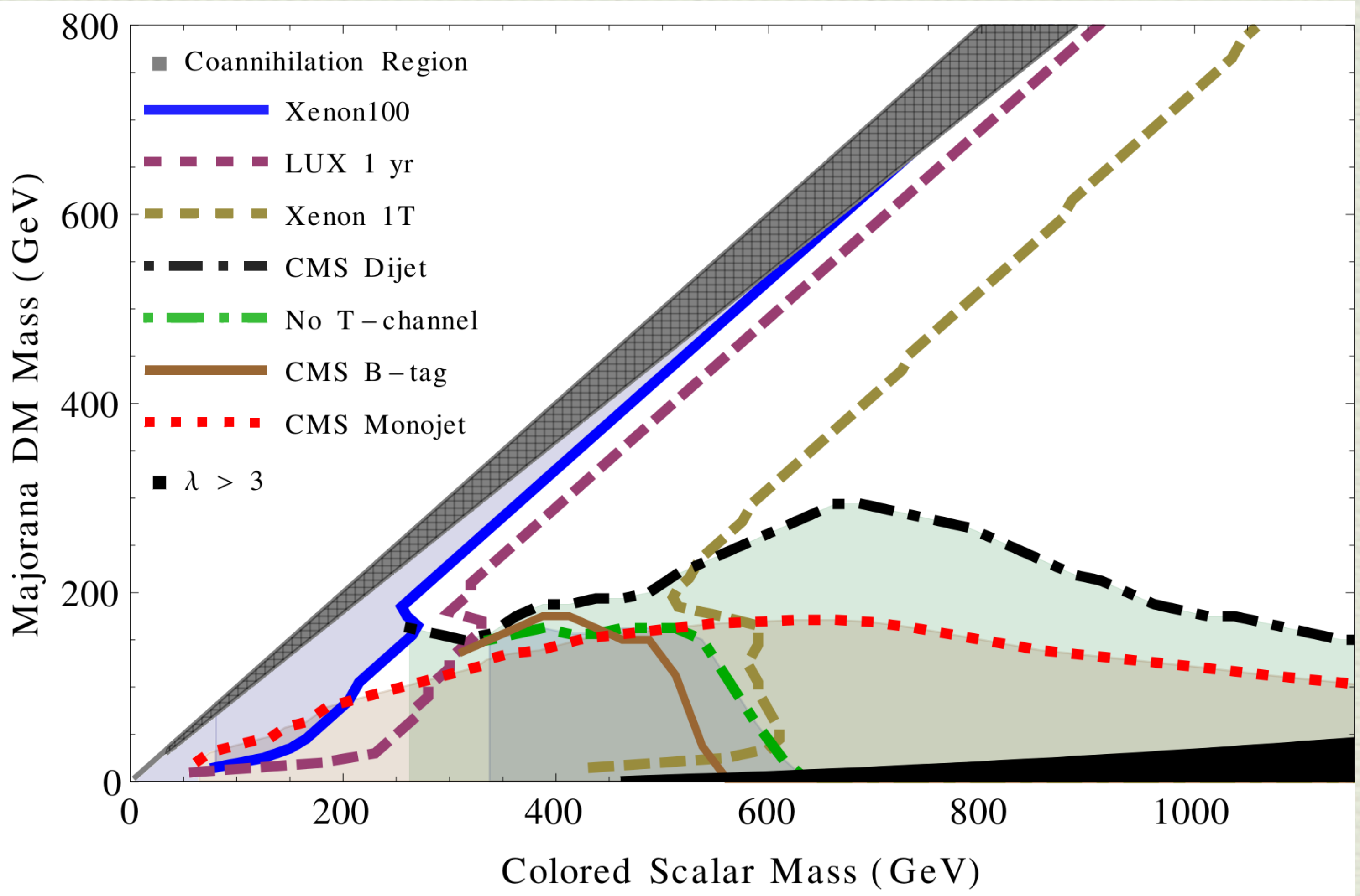
Madgraph
Parton-level analysis with default factorization/renormalization scale

Compare to latest limits from CMS Simplified search for squarks CMS-PAS-SUS-13-012
sbottoms CMS-SUS-12-028
and monojets CMS-PAS-EXO-12-048

Putting it all together

Dish at Alinea

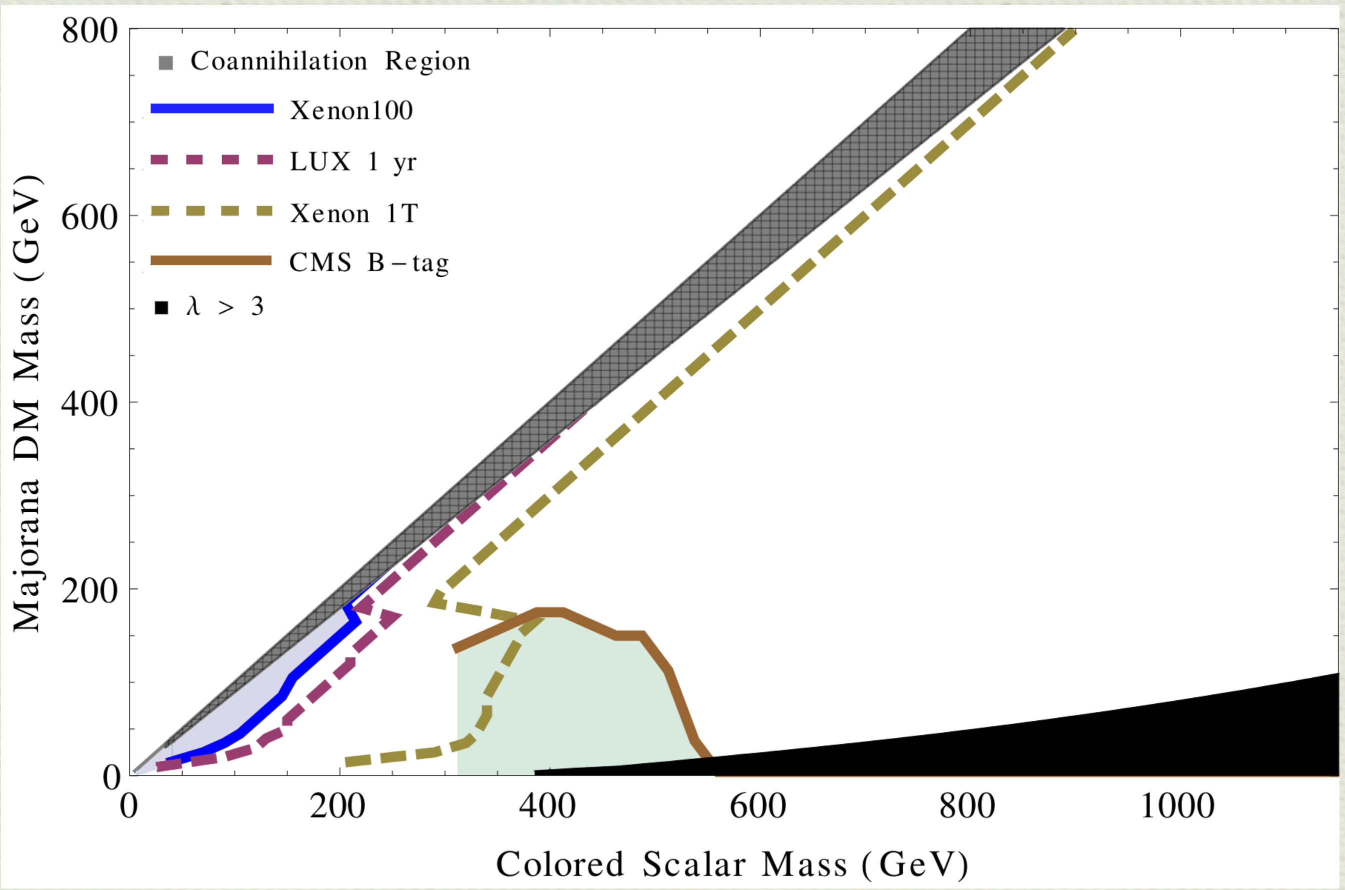
Majorana DM Coupled To All Quarks



As mentioned direct detection constrains diagonal where collider searches lose sensitivity

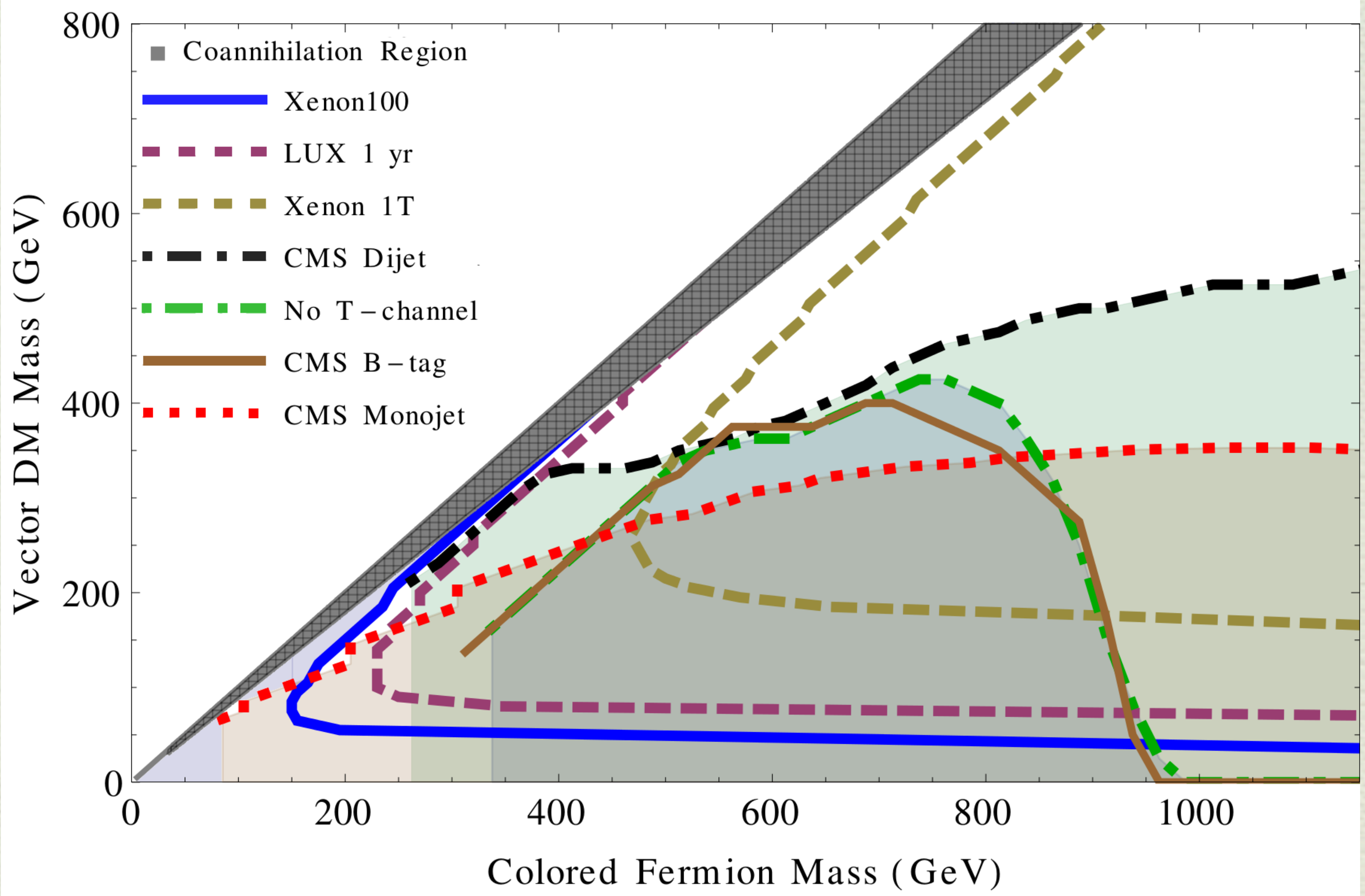
Note that new t-channel helps in extending squark search

Majorana 3rd Gen Only



Much weaker constraints from colliders and direct detection due to small b-quark content of proton

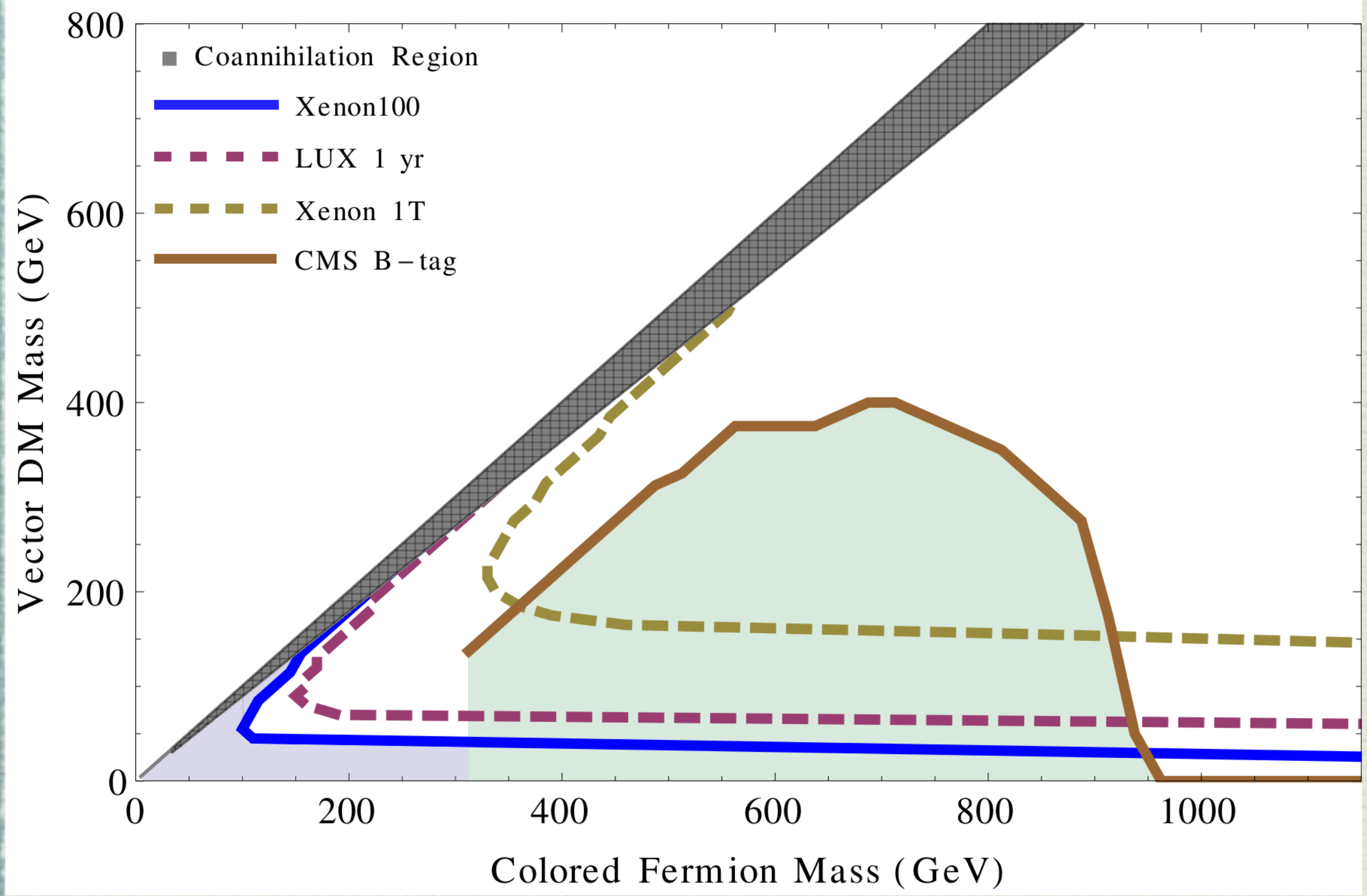
Vector All Quarks



Major boost to dijet search due to fermion Q xsec

Smaller direct detection limits due to smaller interaction strength

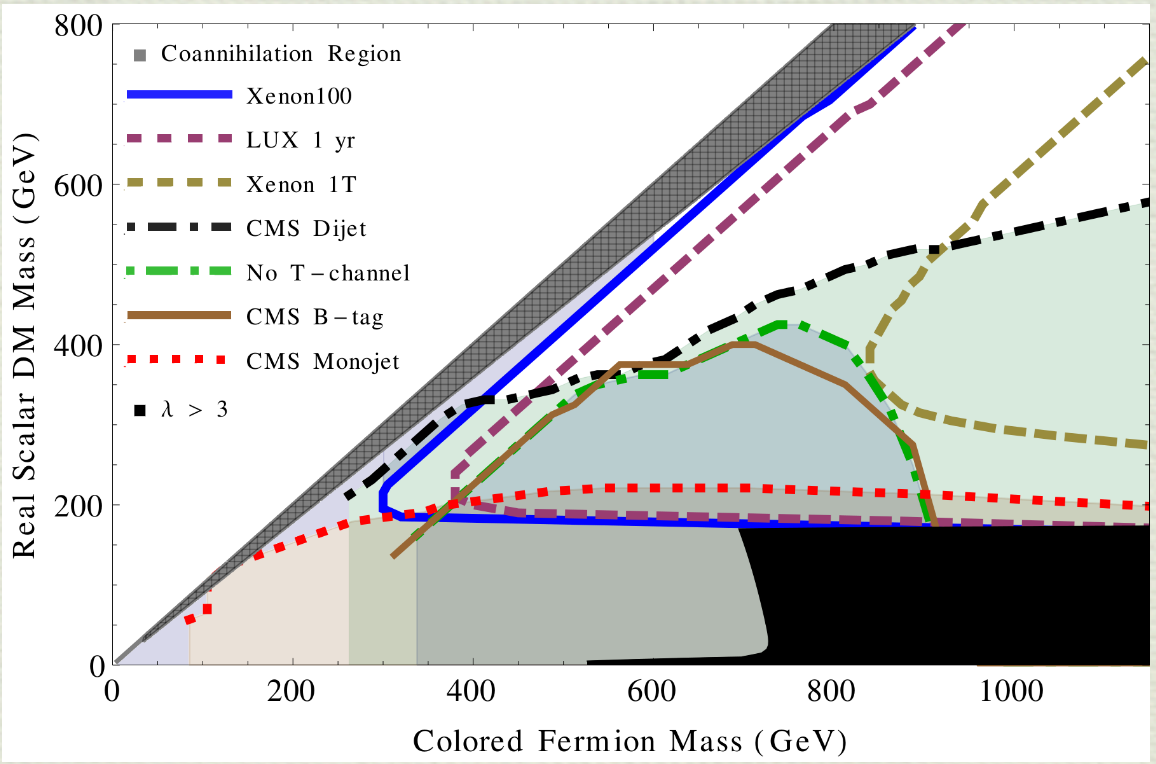
Vector 3rd Generation Quarks

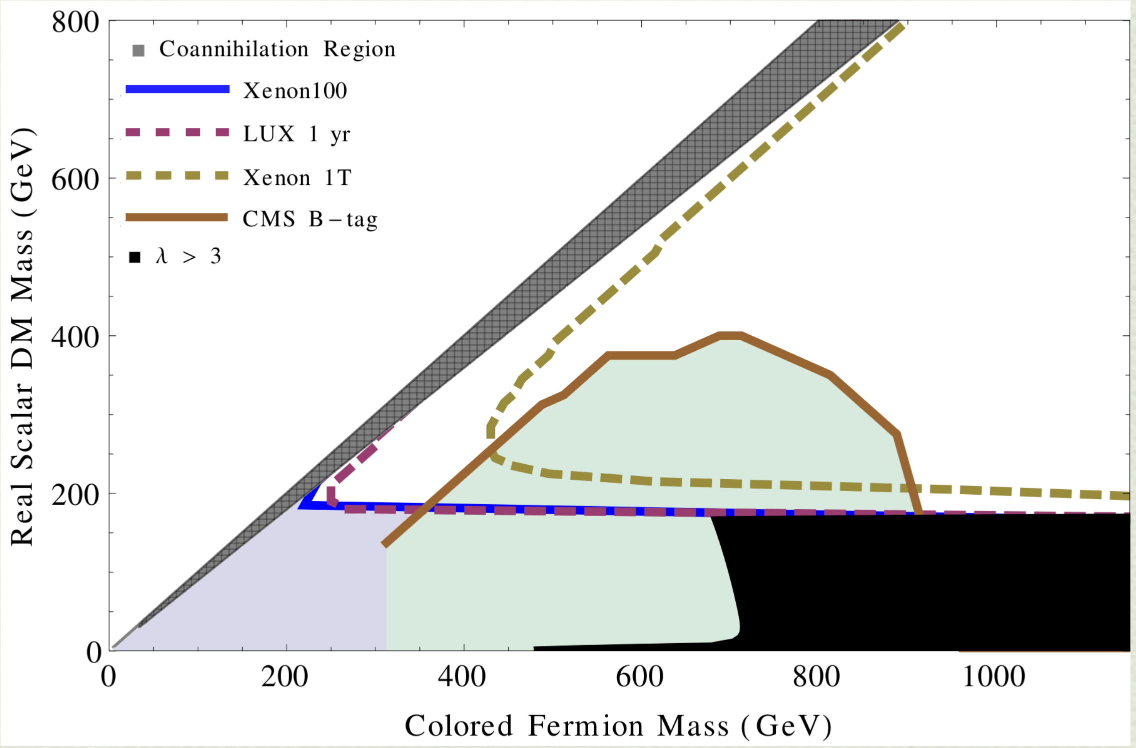


Collider constraints stronger on fermionic b quark partners

Direct detection still weak

Real Scalar DM





All quarks **3rd gen quarks**

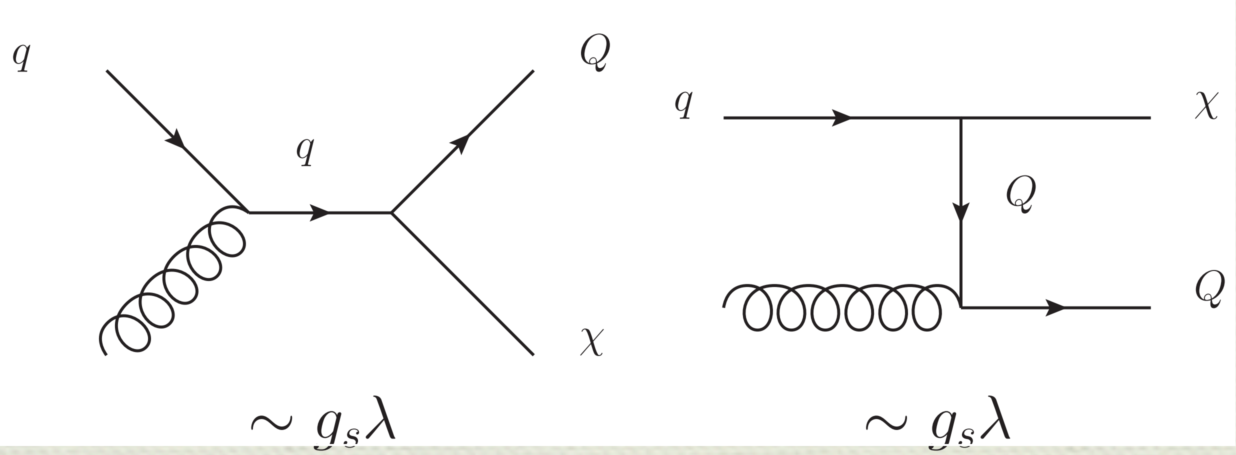
Light gen quark model is completely ruled out by XENON100 and colliders

Complementarity of Direct Detection and Colliders is useful

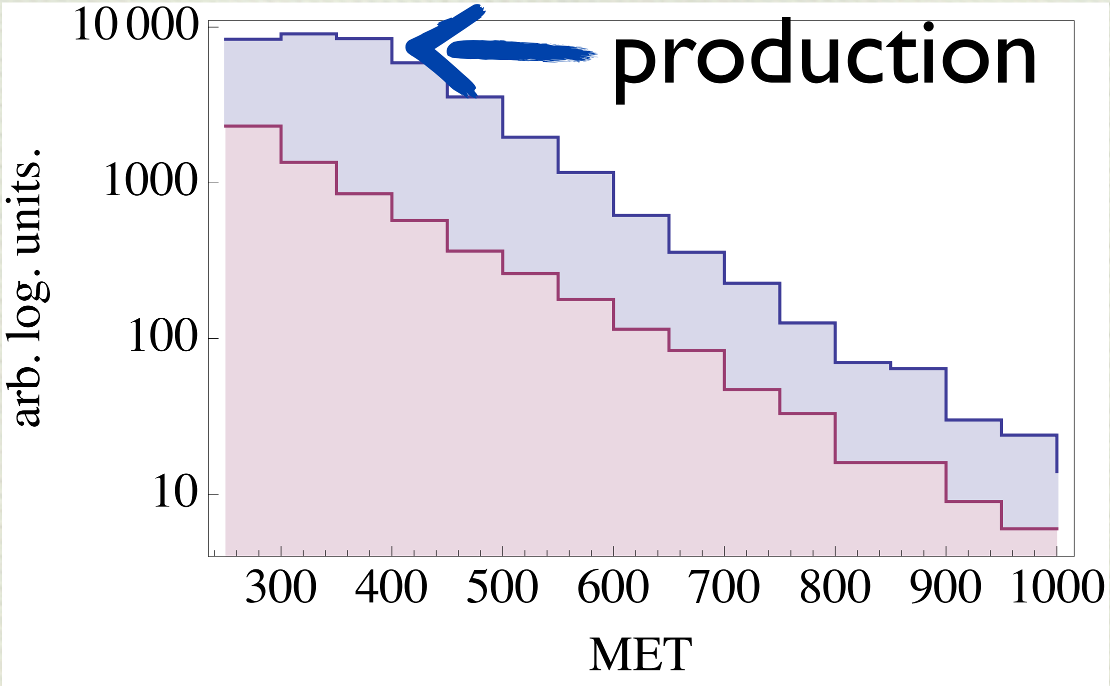
1) Shows where to push improvements

2) Indicates where correlated signals can appear

Monojet features



Associated Qχ production



$$p_{jet}^{T} \sim \frac{m_Q^2 - m_\chi^2}{2m_Q}$$

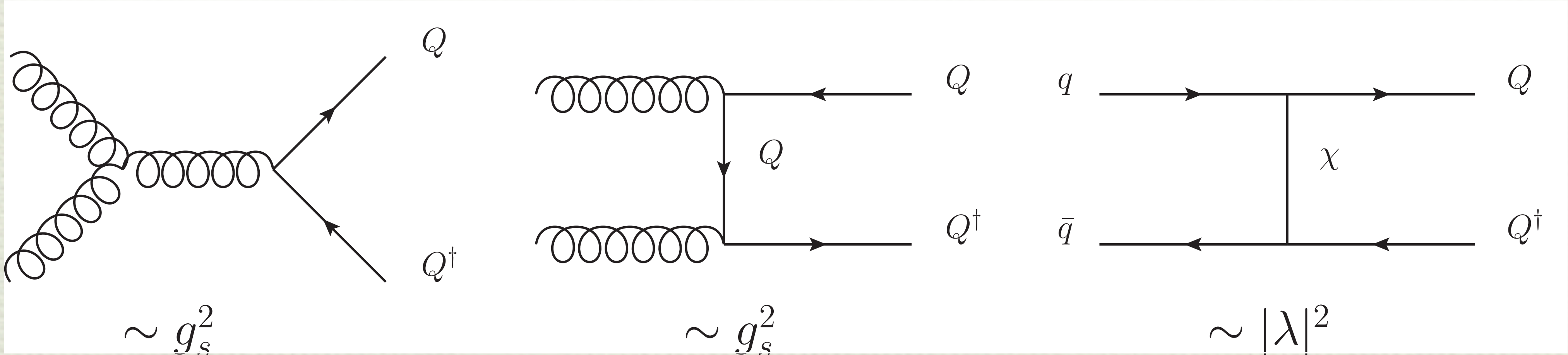
Example

(mQ,mχ) = (800,100) GeV

Expect feature at

~ 400 GeV

ISR Modeling



Near degeneracy, jets from ISR crucial for jets+MET searches

Typically dominated by gluon fusion but t-channel process has different ISR

Not precisely modeled by simplified models

Effective WIMPs Recap

- Complete WIMP theory with simple parameter space and minimal content
- A natural first explanation of jets+MET and/or direct detection

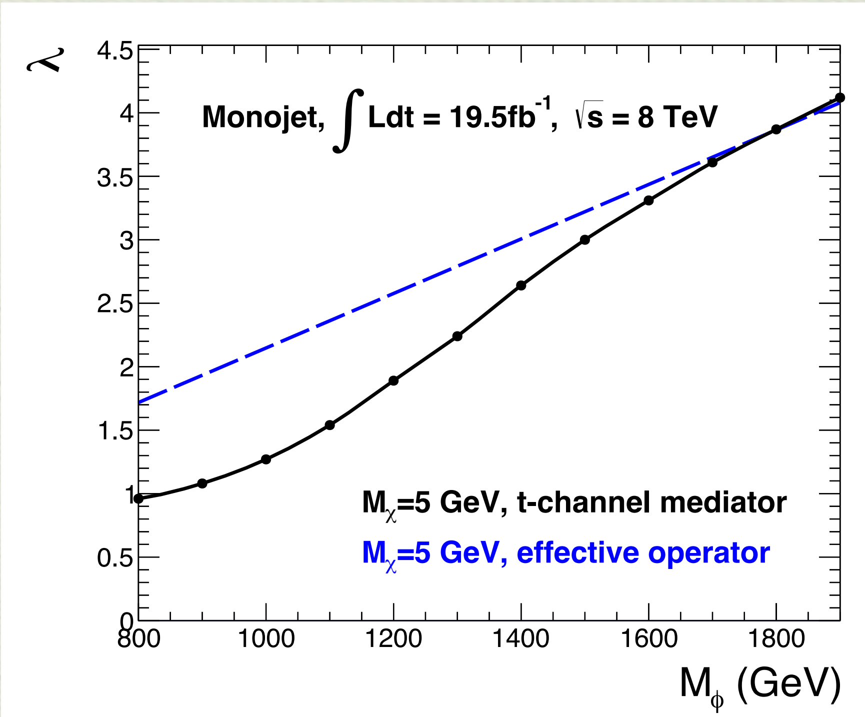
Effective WIMP Recap

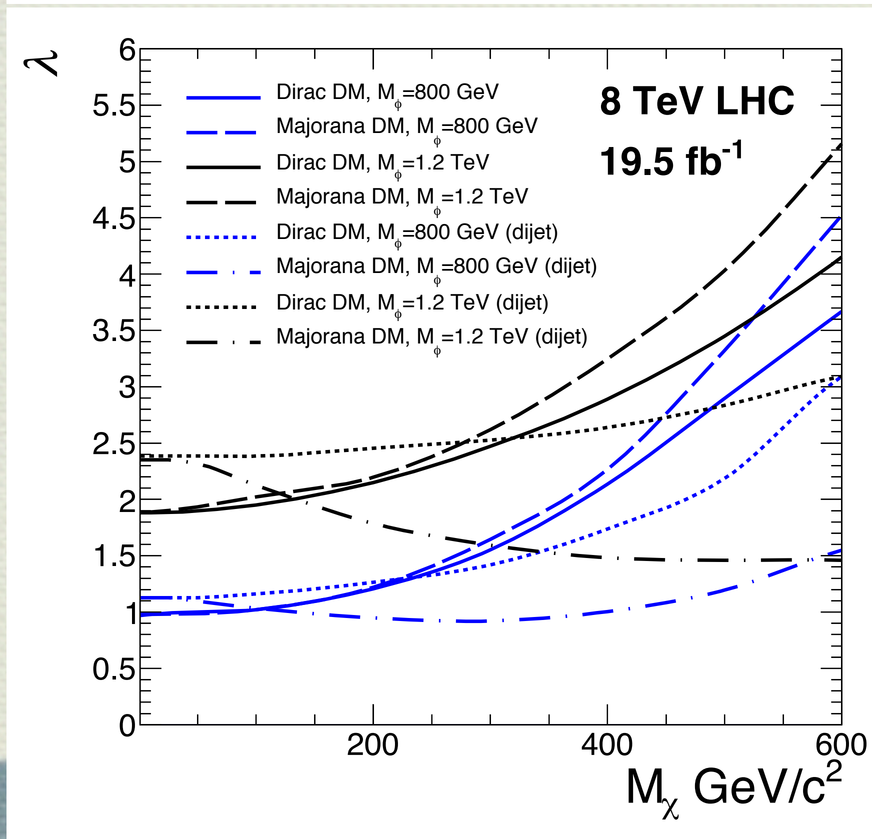
- Improved reach for collider searches through new process of t-channel DM exchange constraining ~ TeV quark partners
- Monojet has a MET "bump" due to $Q\chi$ production

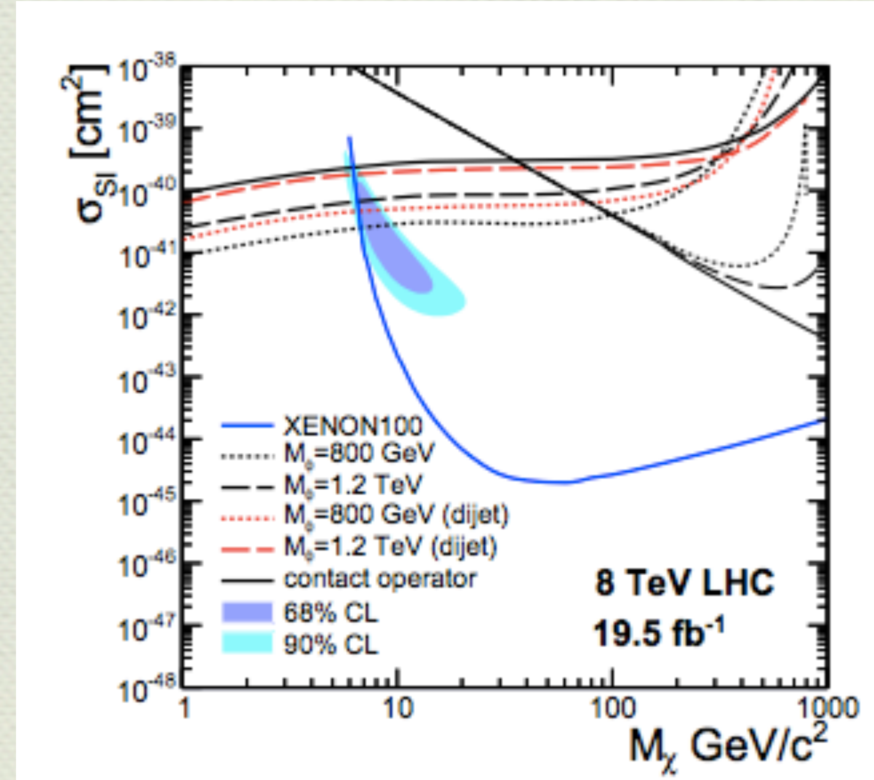
Thanks!

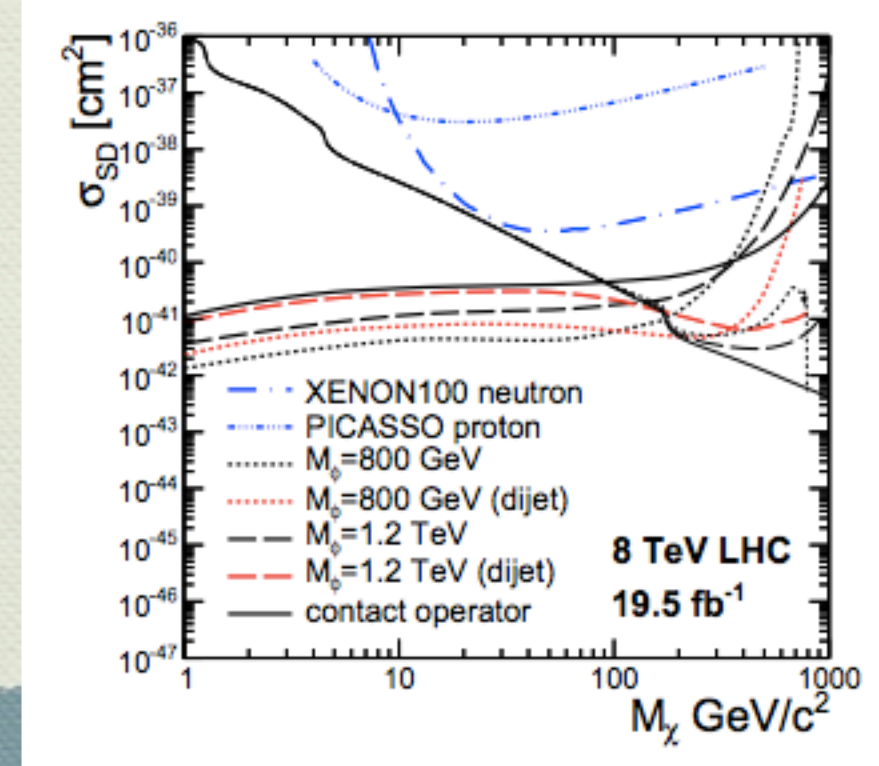
An et.al. arXiv: 1308.0592

Comparison of effective operator vs full mediator

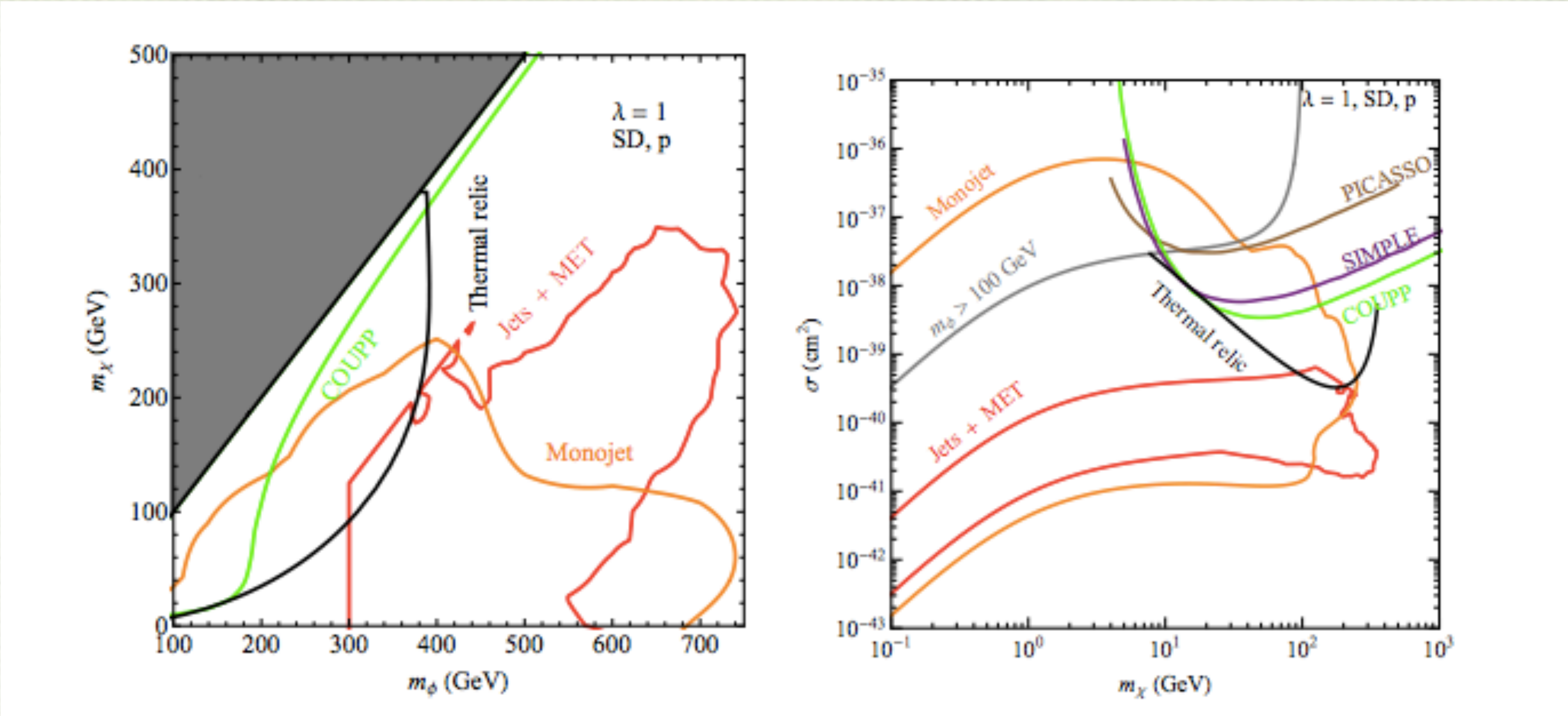




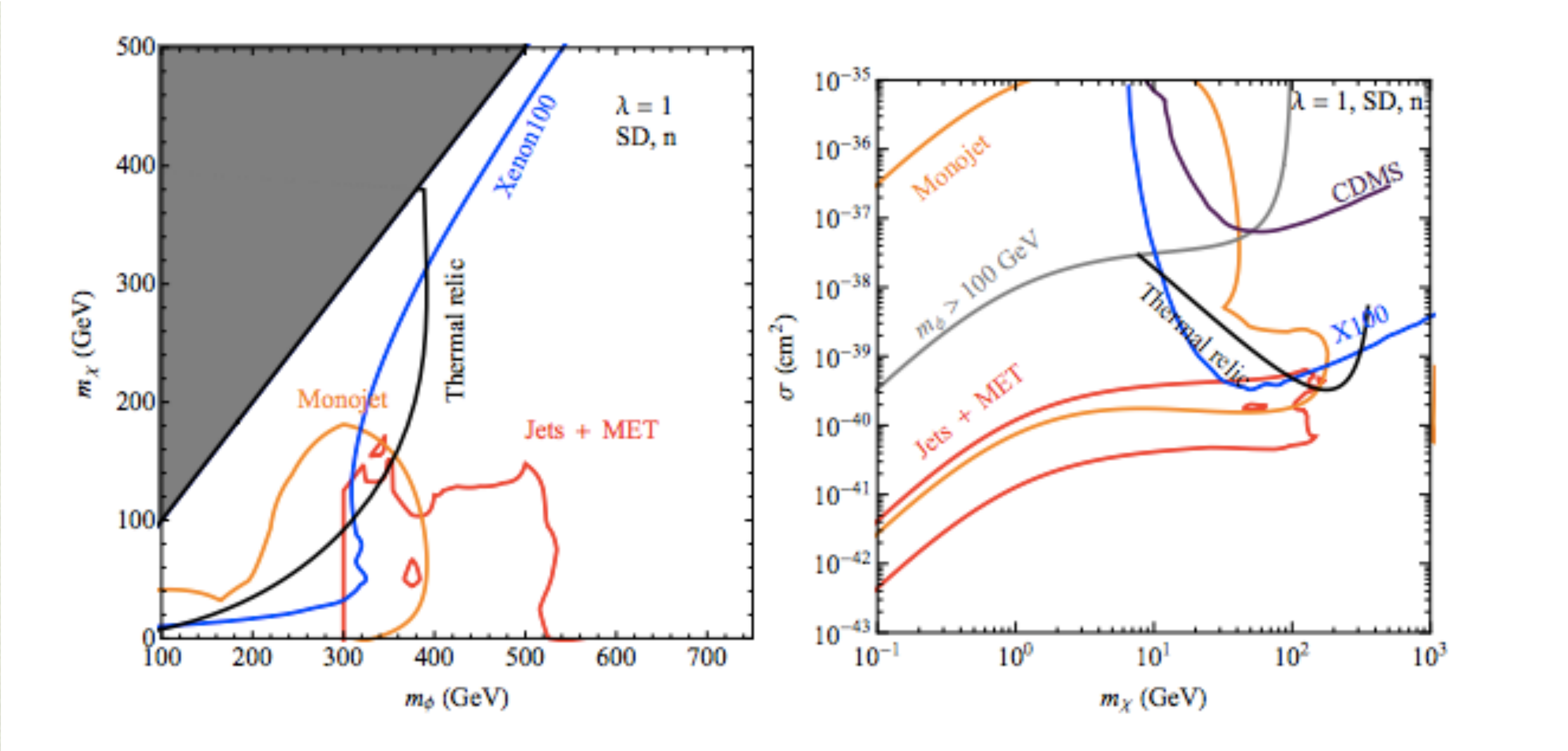




Majorana Analysis by Bai, Berger 1308.0612

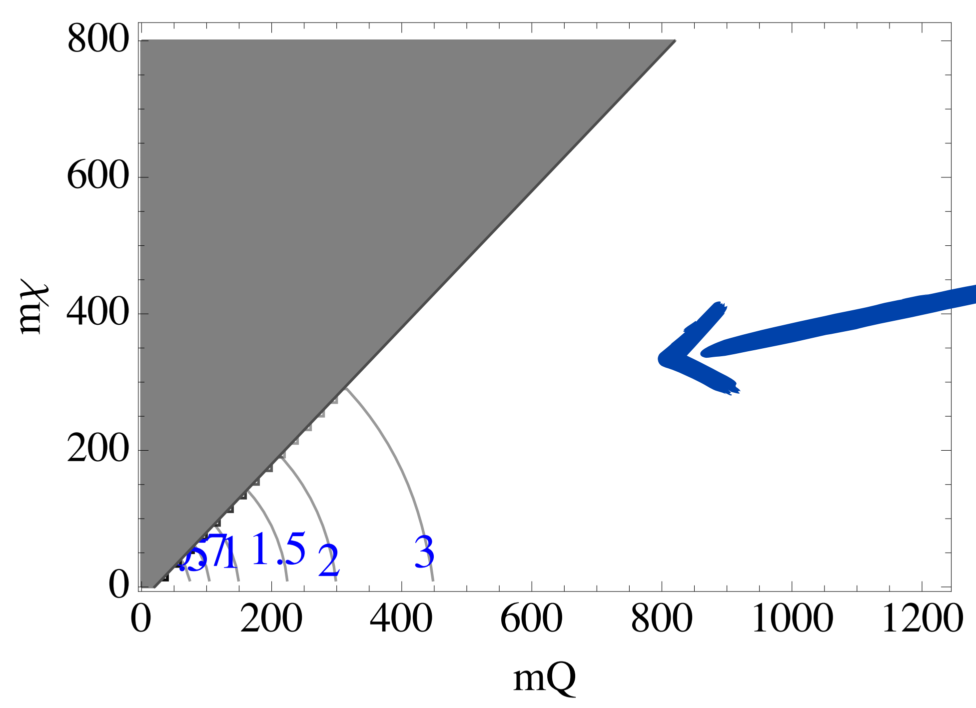


Coupled to up quarks



Coupled to down quarks

Real Scalar DM coupled to light quarks



Nonperturbative Coupling

Perturbative Region ruled out by monojet and XENON100