Dark Matter with *t*-channel mediator

A simple step beyond contact interaction

Hao Zhang

University of California, Santa Barbara

For Institute of High Energy Physics, Chinese Academy of Sciences

2014 Working Month on the Frontier of Physics, May 19th - Jun 7th, 2014, Beijing, Shanghai

Based on the work arXiv:1308.0592[hep-ph] in collaboration with Haipeng An and Lian-Tao Wang

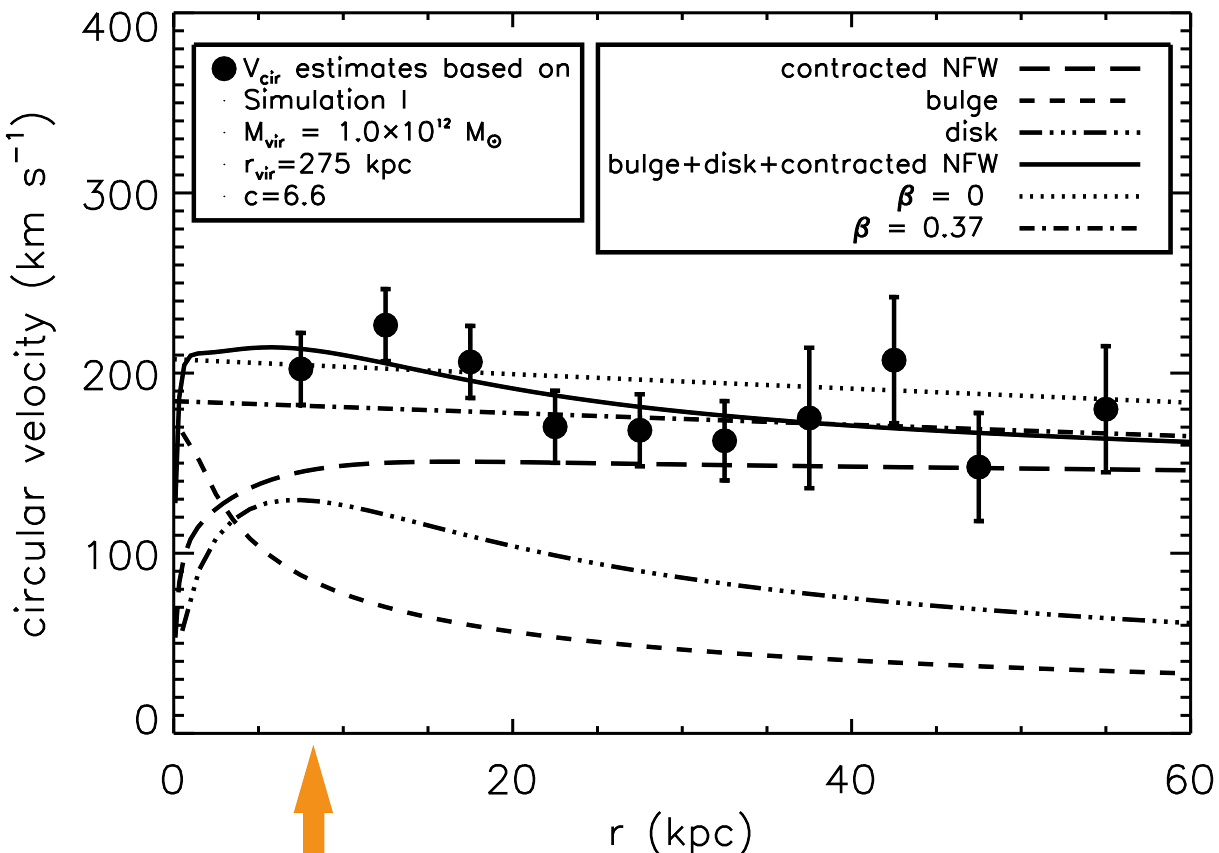
Outline

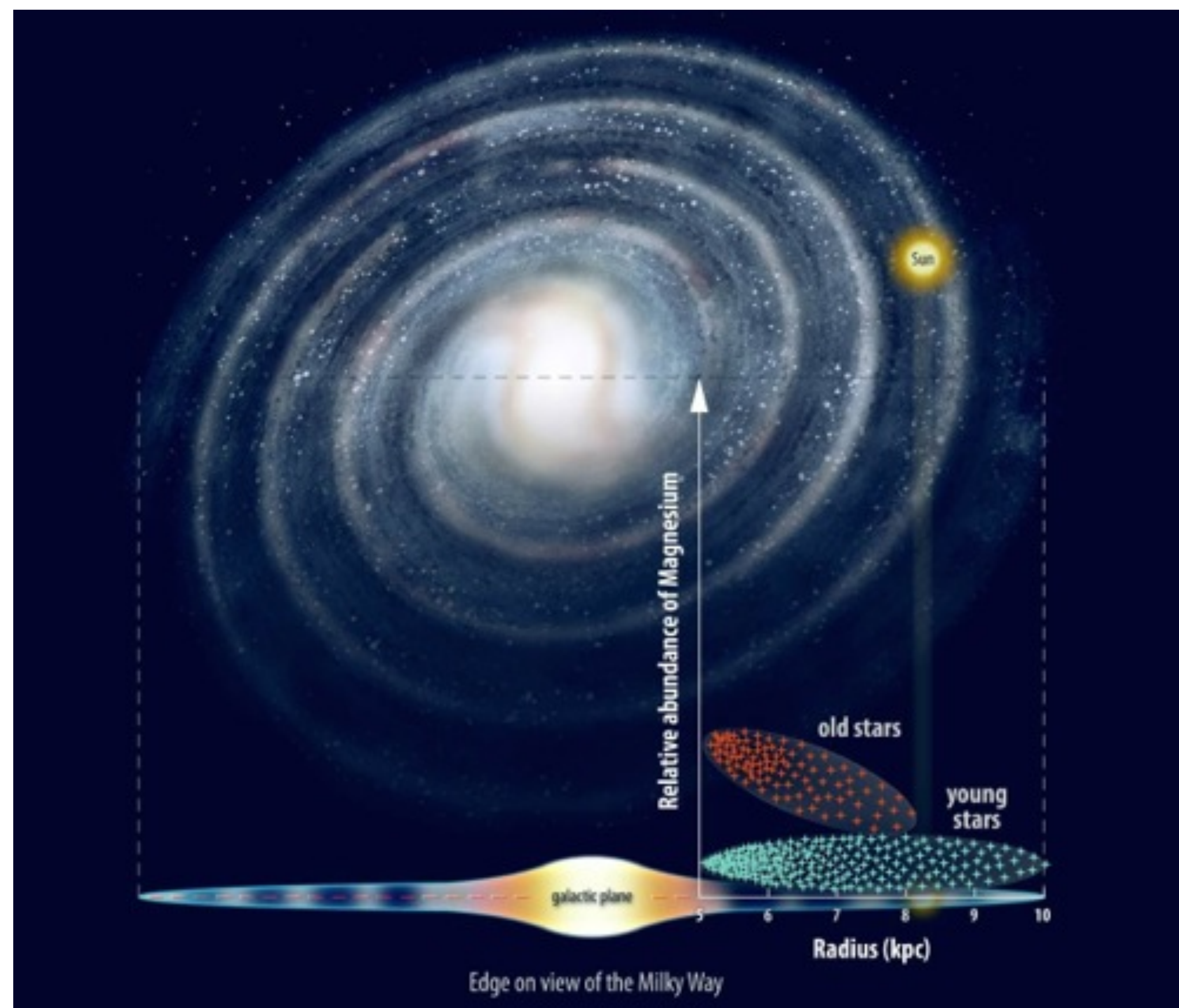
- Dark matter in the Universe
- Dark matter searching, direct detection vs. LHC
- EFT? Dark matter with t-channel mediator
- Conclusion

Dark matter in the Universe

Dark matter in the Universe

- Galaxy rotation curve.

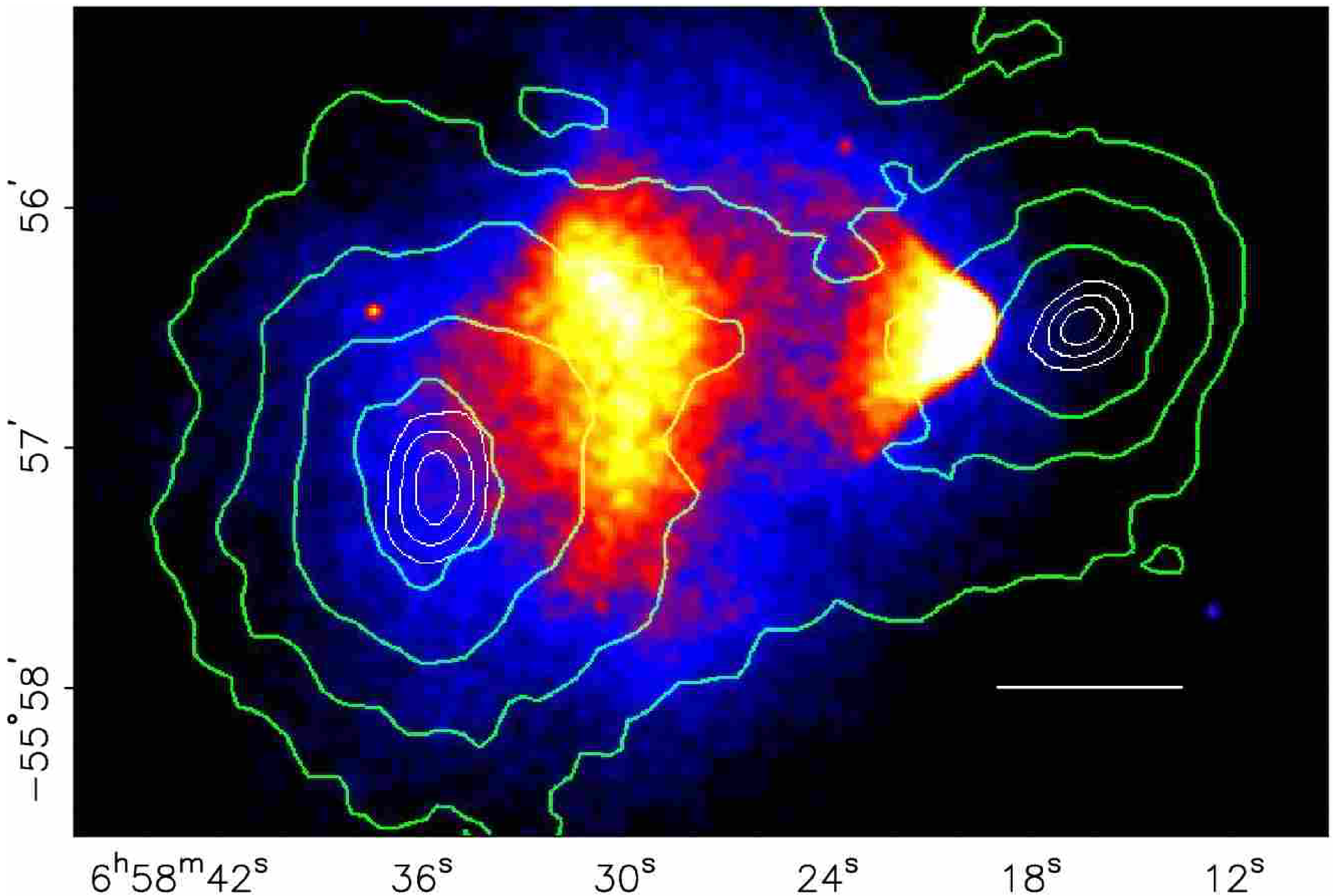




Xue, X.-X et al., 2008, ApJ, 684, 1143

Dark matter in the Universe

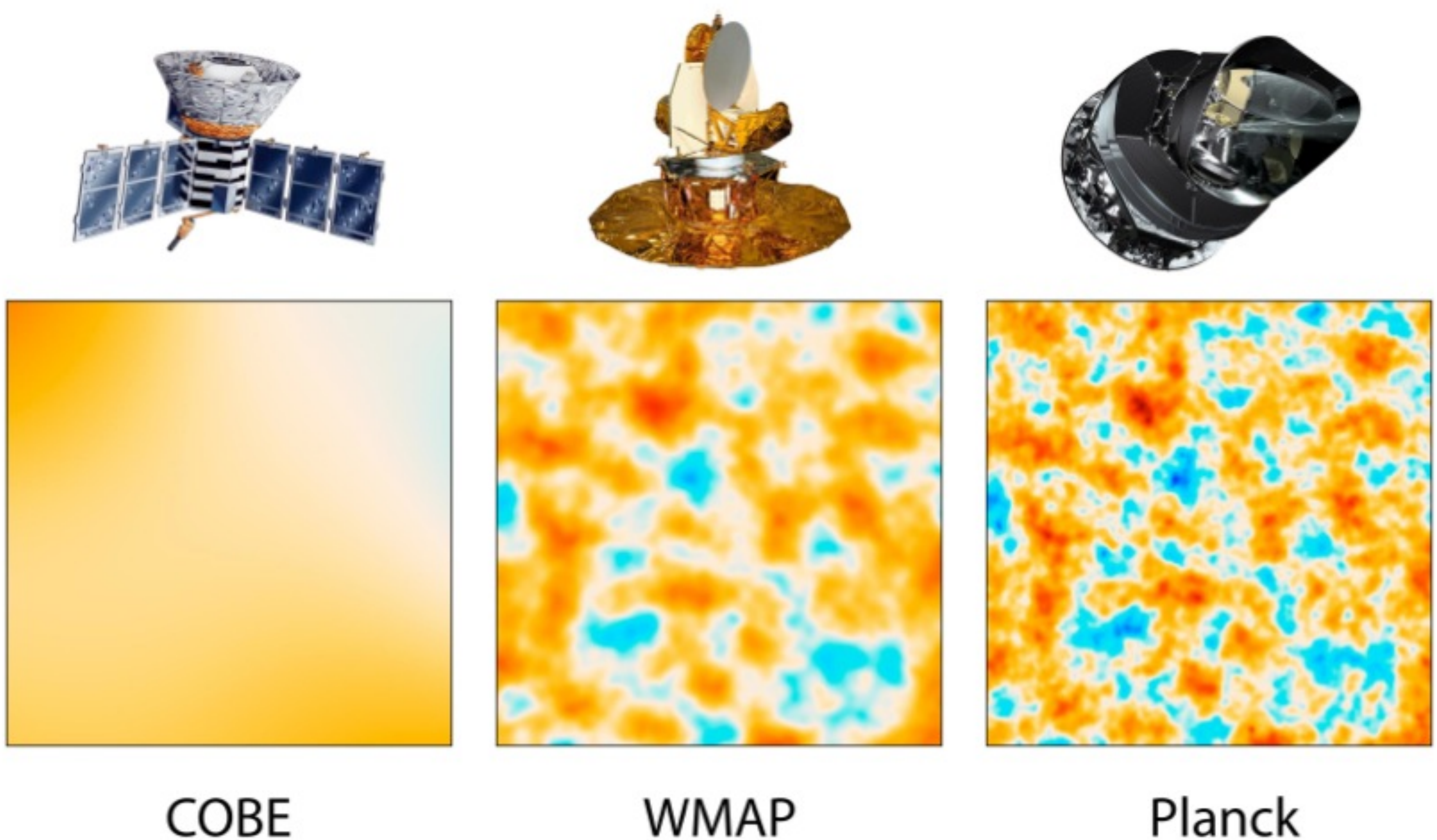
- Galaxy rotation curve.
- Bullet cluster.



1E0657-558, D. Clowe et al., 2006, ApJ, 648, L109

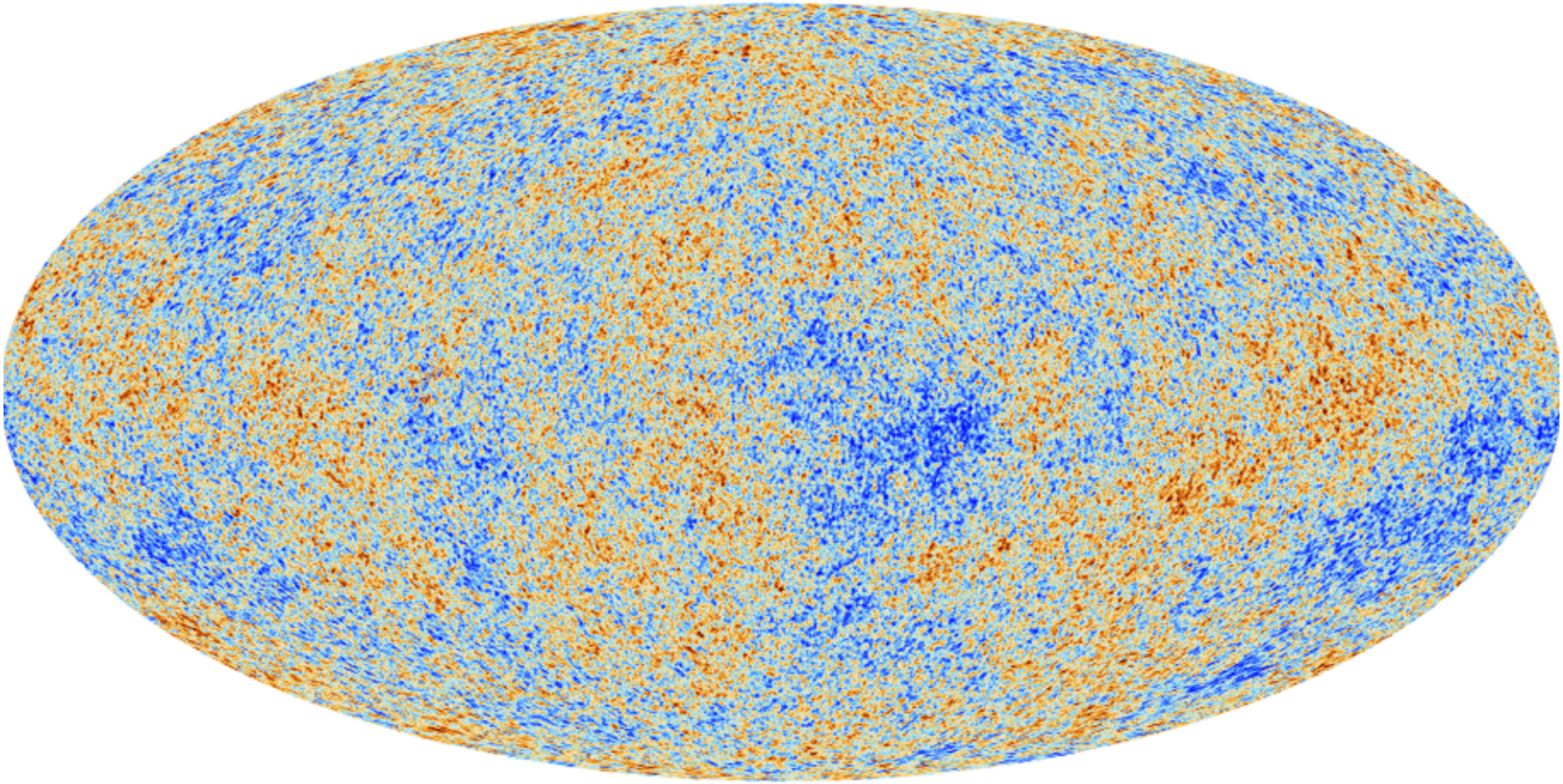
Dark matter in the Universe

- Galaxy rotation curve.
- Bullet cluster.
- Standard cosmology: ΛCDM



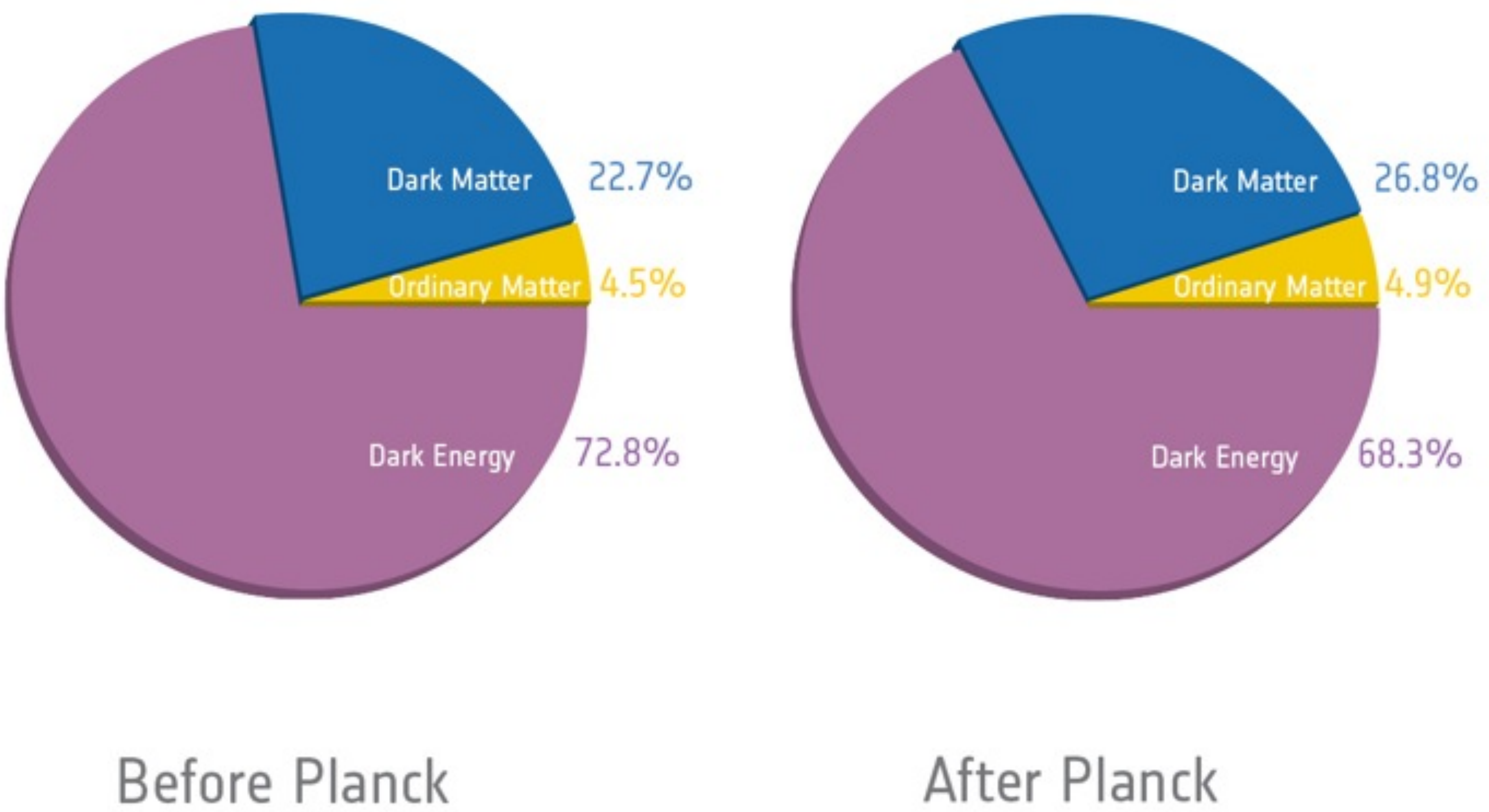
Dark matter in the Universe

- Galaxy rotation curve.
- Bullet cluster.
- Standard cosmology: ΛCDM



Dark matter in the Universe

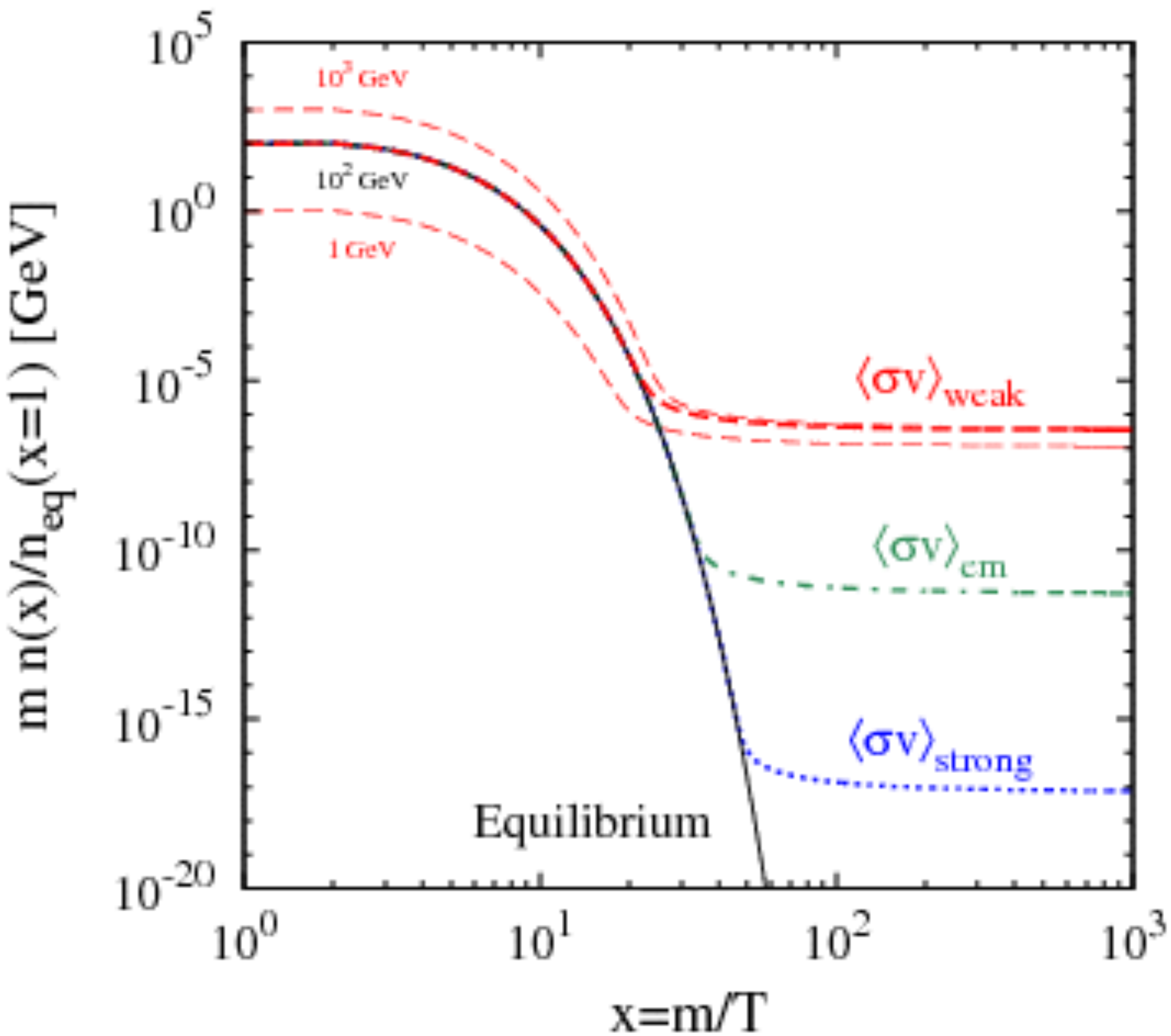
- Galaxy rotation curve.
- Bullet cluster.
- Standard cosmology: ΛCDM



Dark matter in the Universe

- Weakly Interacting Massive Particle (WIMP) is one of the most popular dark matter candidates in particle physics.

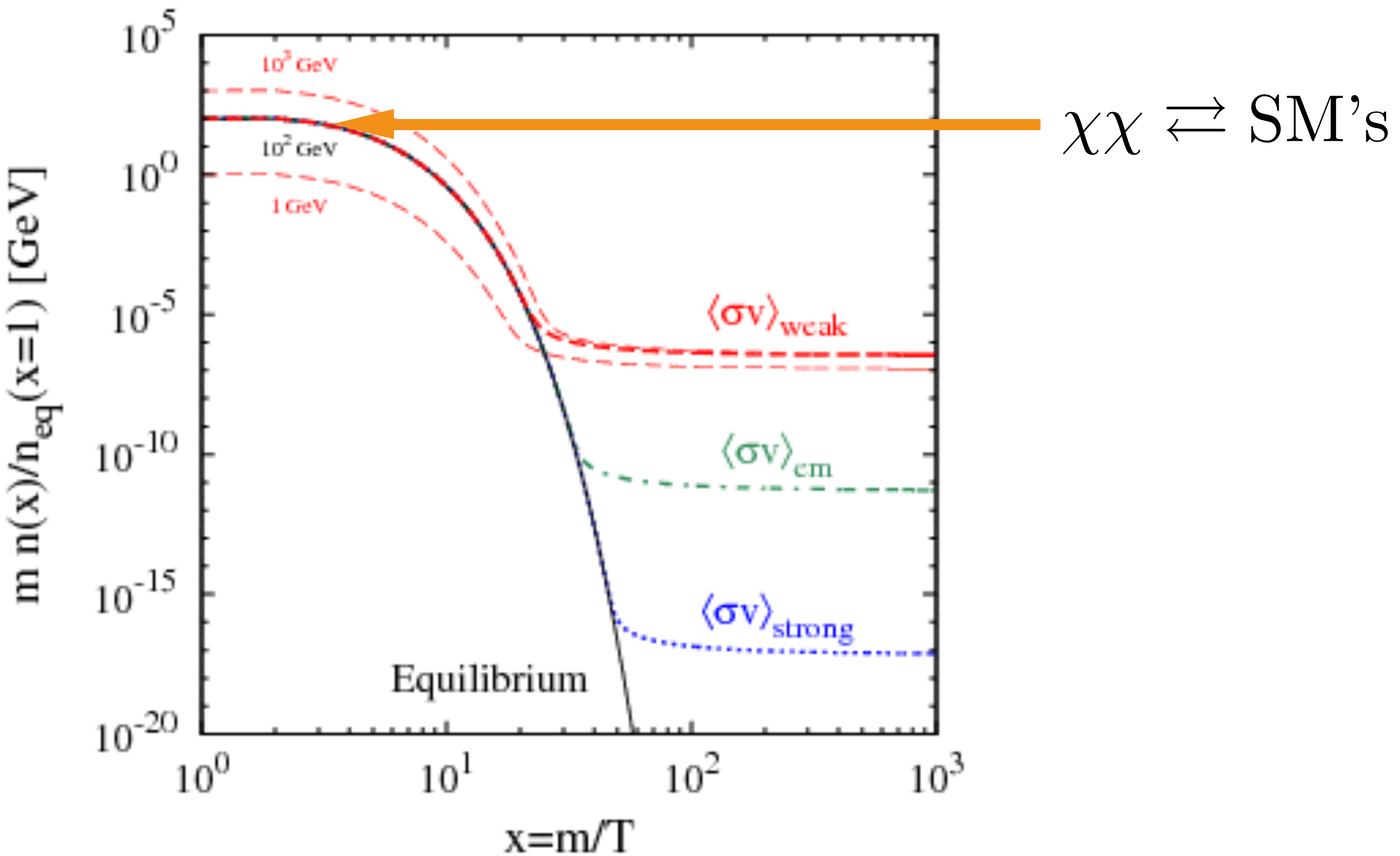
$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{eq}^2\right)$$



Dark matter in the Universe

- Weakly Interacting Massive Particle (WIMP) is one of the most popular dark matter candidates in particle physics.

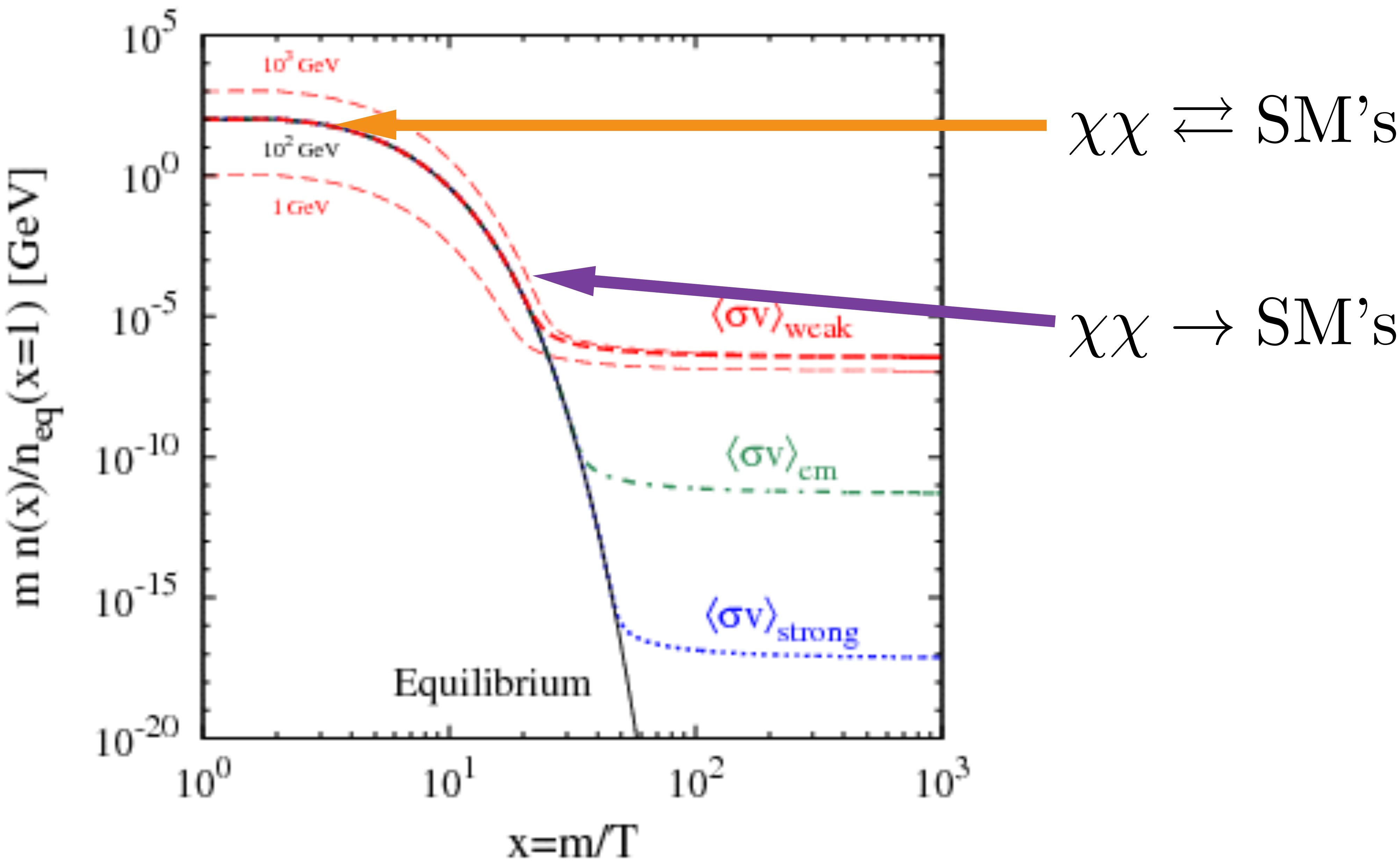
$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right)$$



Dark matter in the Universe

- Weakly Interacting Massive Particle (WIMP) is one of the most popular dark matter candidates in particle physics.

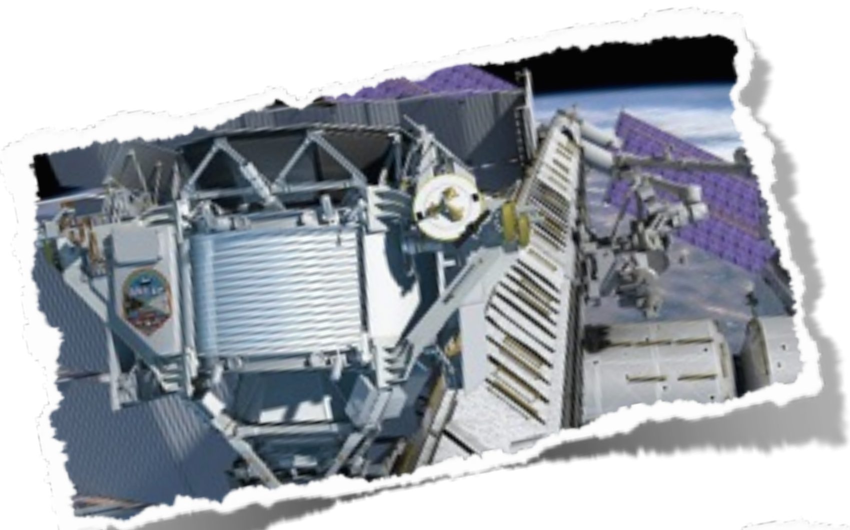
$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{eq}^2\right)$$

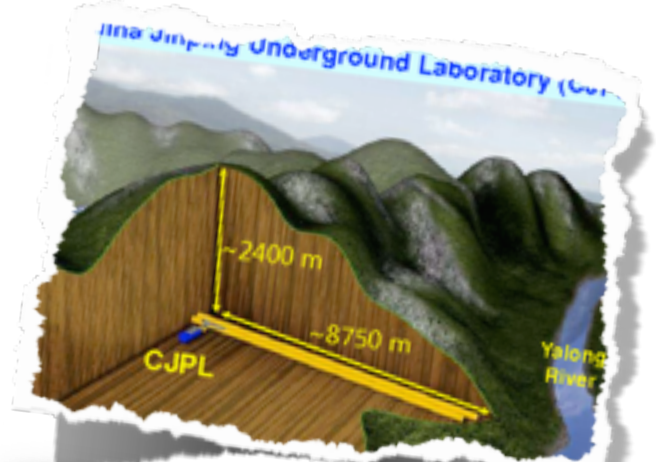


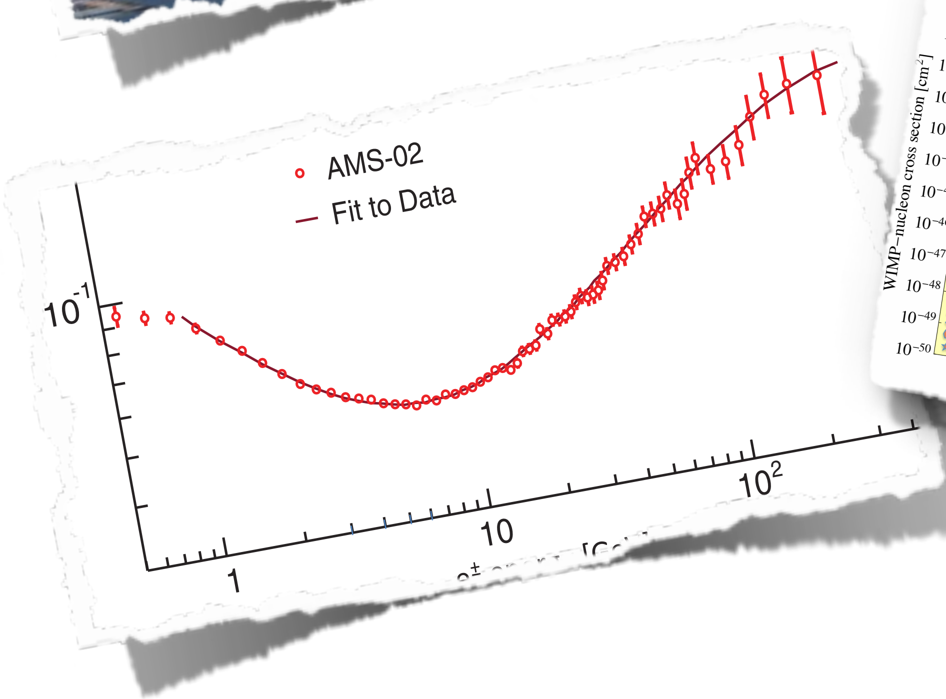
Dark matter Searching

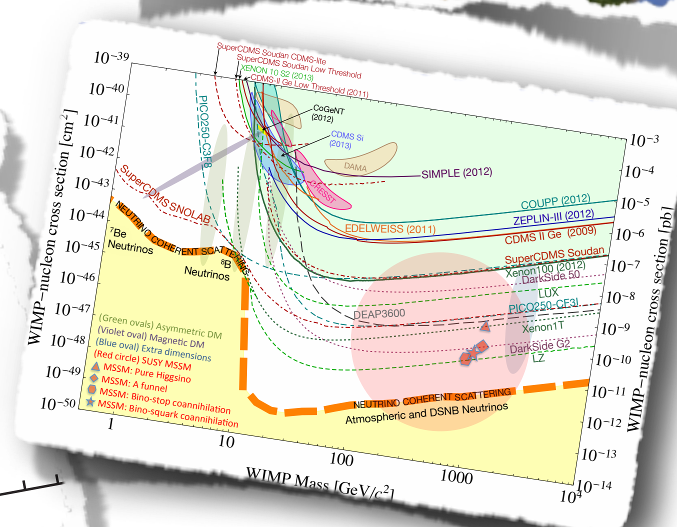
Dark Matter Searching

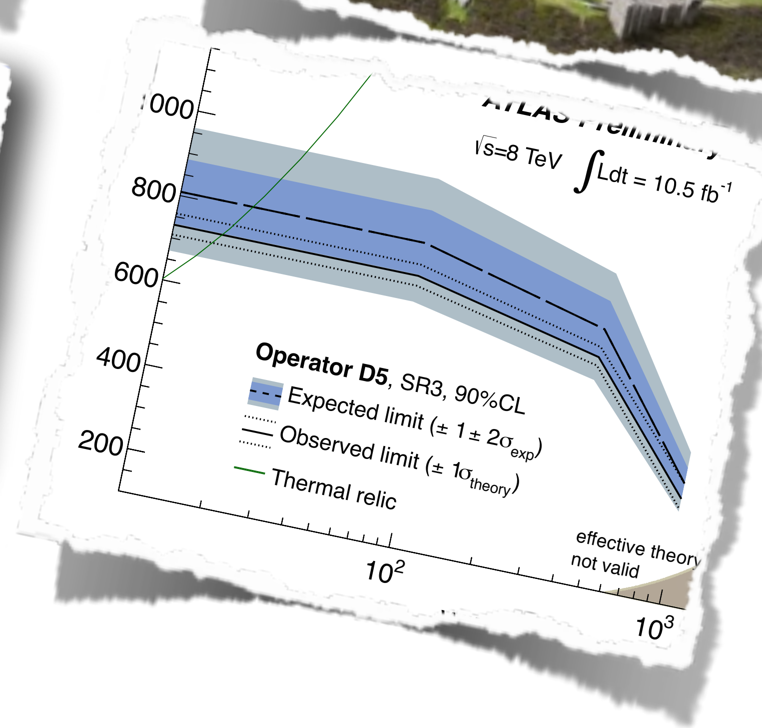
- The interaction between WIMP and the SM particles makes it detectable by satellites (indirect detection), underground detectors (direct detection), and colliders.





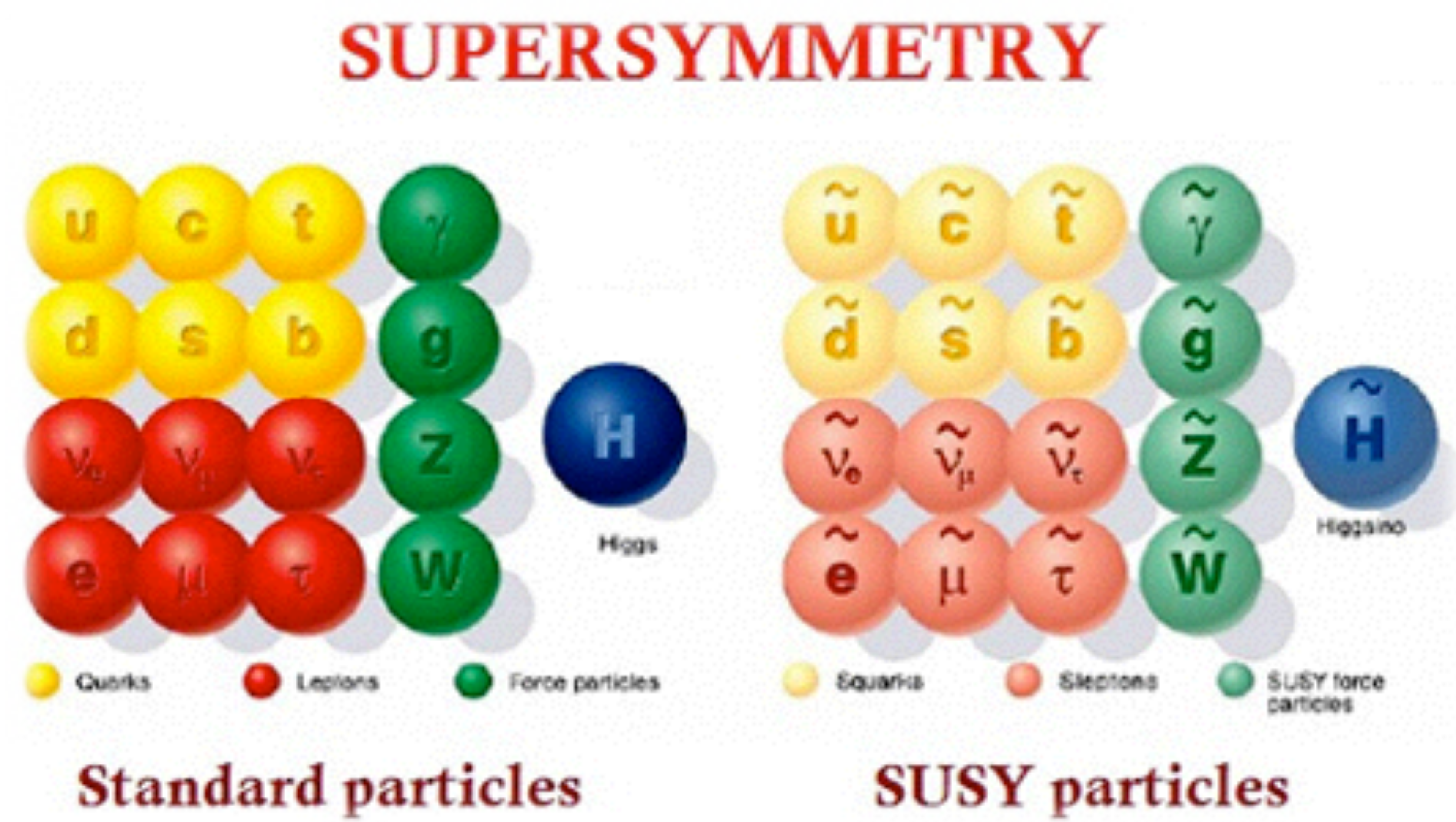






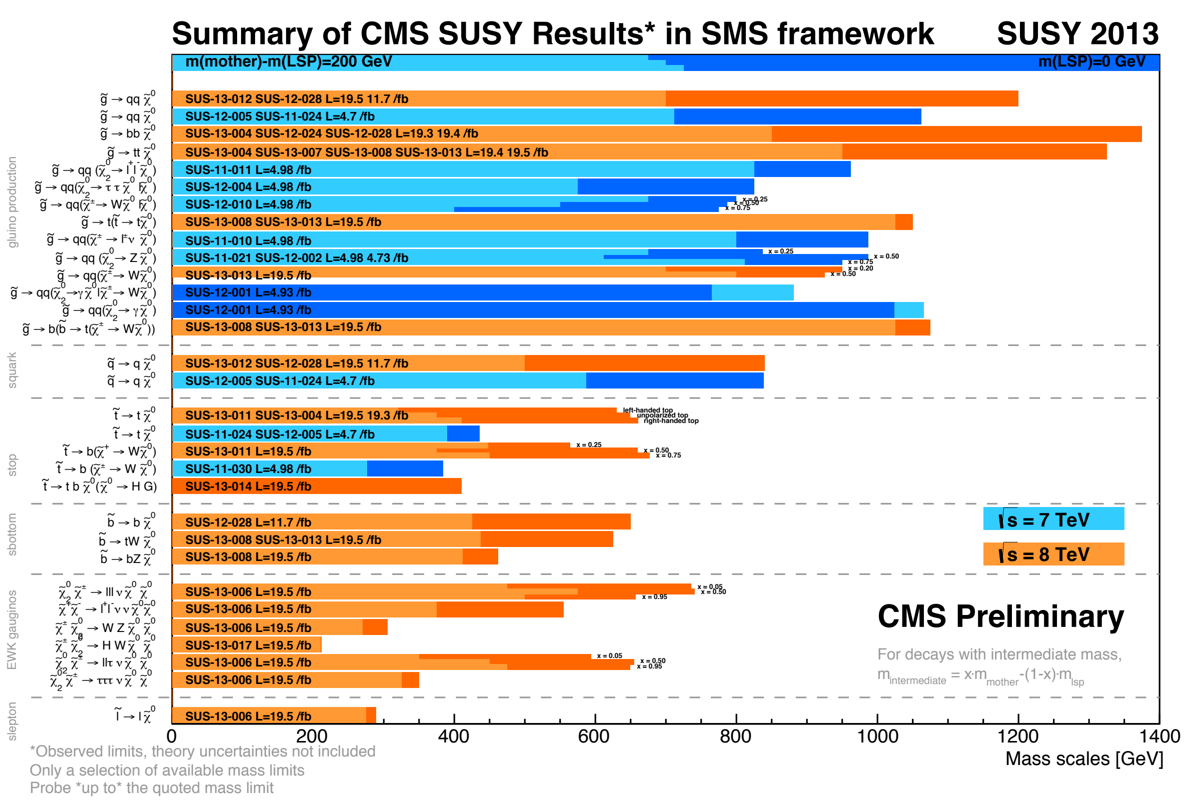
Dark Matter Searching

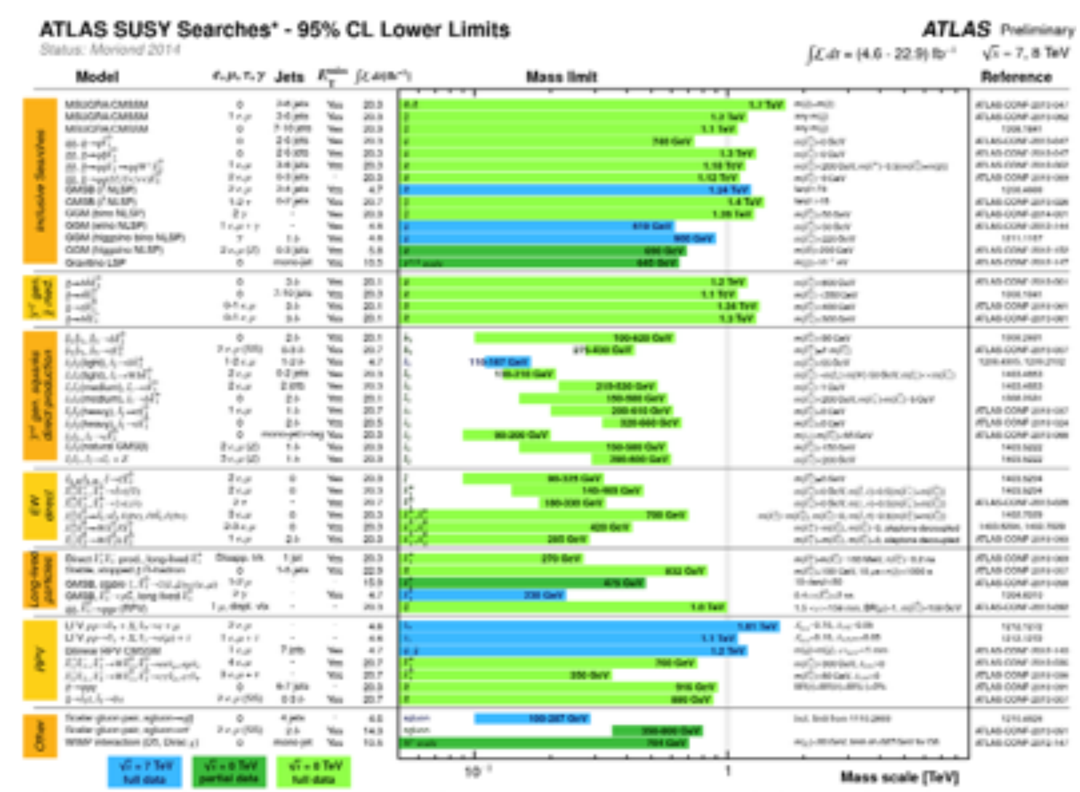
- New physics models?
- Supersymmetry, etc :)
- More than 100 parameters and tens more particles...



Dark Matter Searching

- New physics models?
- Supersymmetry, etc :)
- More than 100 parameters and tens more particles...

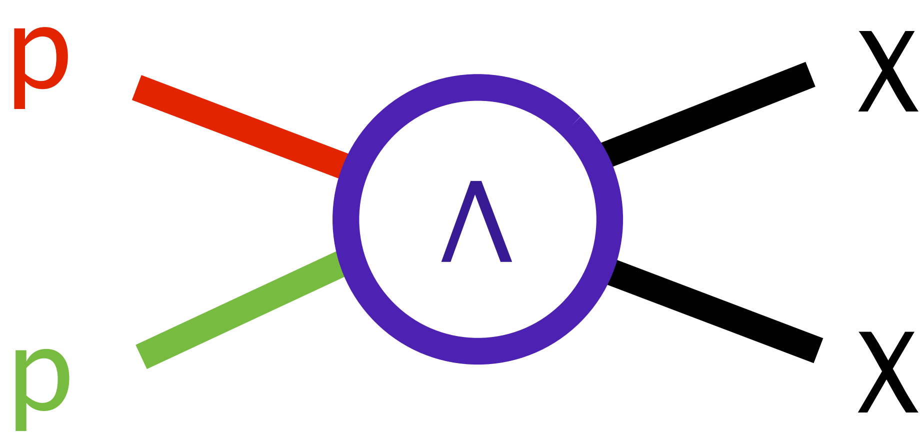




Dark Matter Searching

- Effective operator method: model independent, less free parameters.

$$\frac{C_{AB}}{\Lambda^n}\bar{\chi}\Gamma^A\chi\bar{q}\Gamma^B q$$



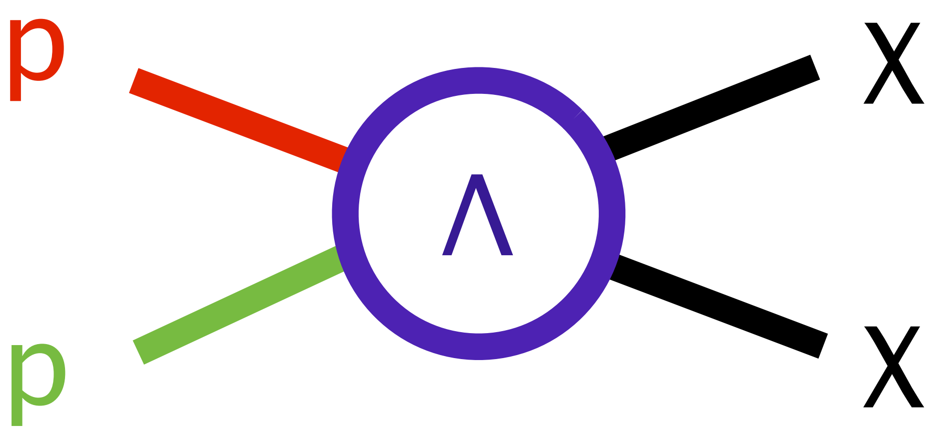
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

J Goodman, et al., PRD82 116010(2010)

Dark Matter Searching at the LHC

- Effective operator method: model independent, less free parameters.

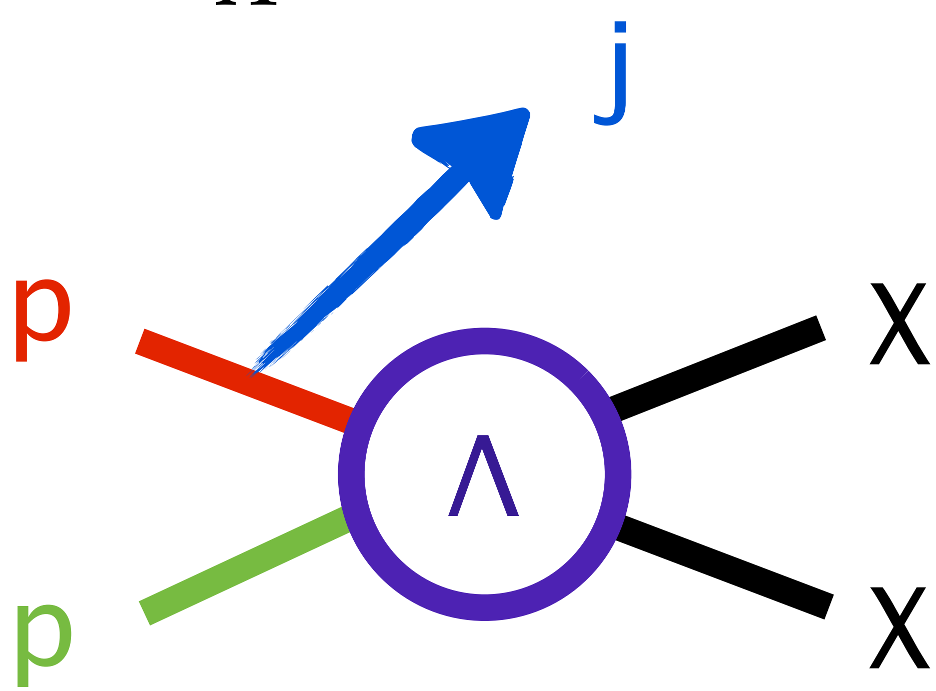
$$\frac{C_{AB}}{\Lambda^n}\bar{\chi}\Gamma^A\chi\bar{q}\Gamma^B q$$

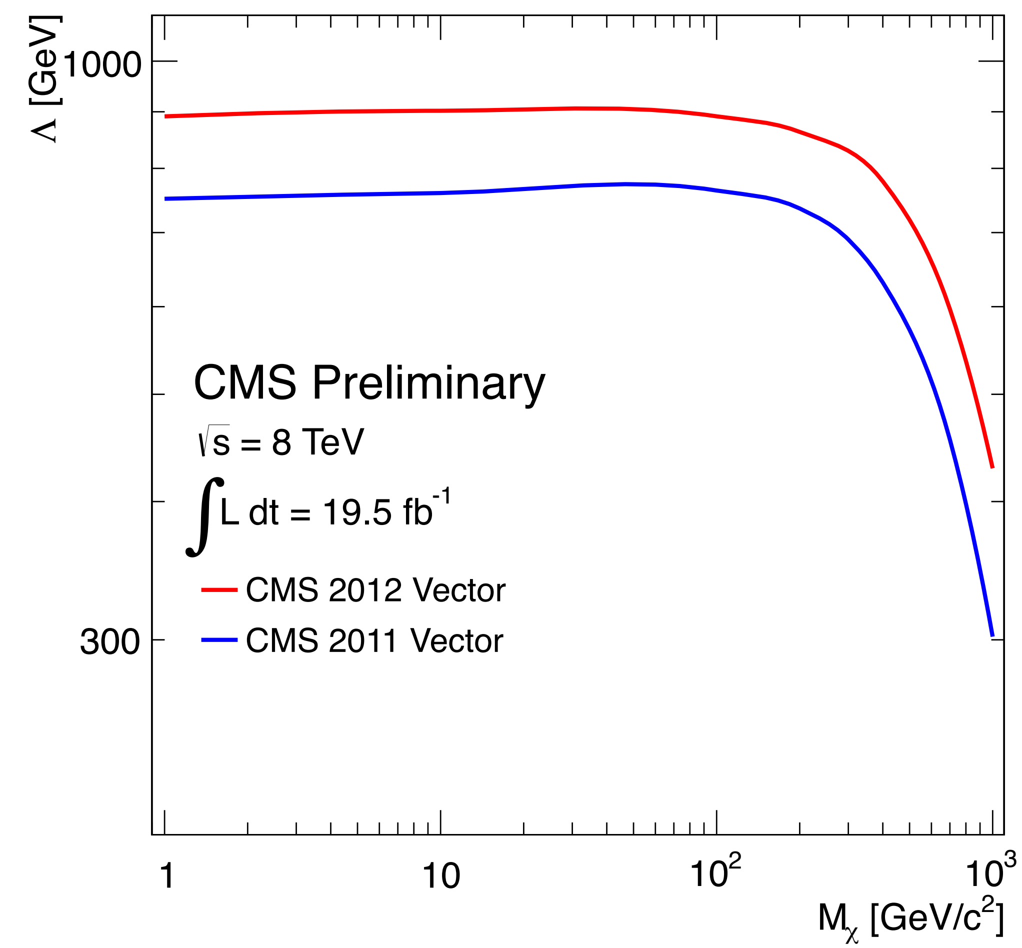


Dark Matter Searching at the LHC

- Effective operator method: model independent, less free parameters.

$$\frac{C_{AB}}{\Lambda^n}\bar{\chi}\Gamma^A\chi\bar{q}\Gamma^B q$$



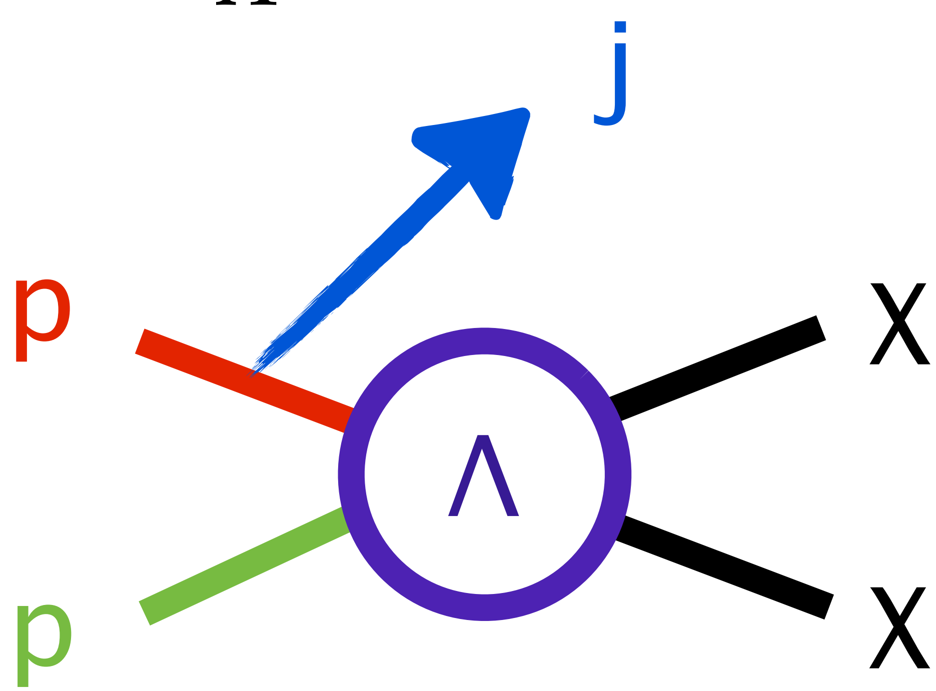


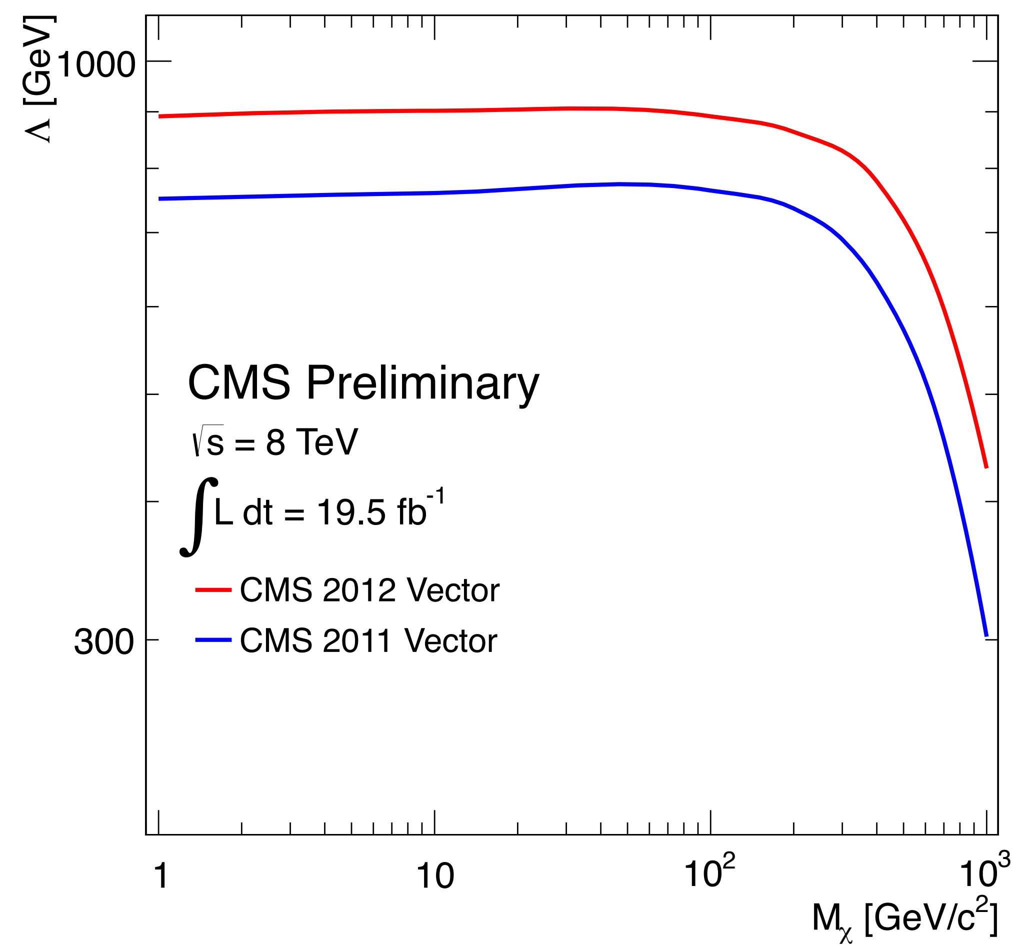
CMS PAS EXO-12-048

Dark Matter Searching at the LHC

- Effective operator method: model independent, less free parameters.

$$\frac{C_{AB}}{\Lambda^n}\bar{\chi}\Gamma^A\chi\bar{q}\Gamma^B q$$





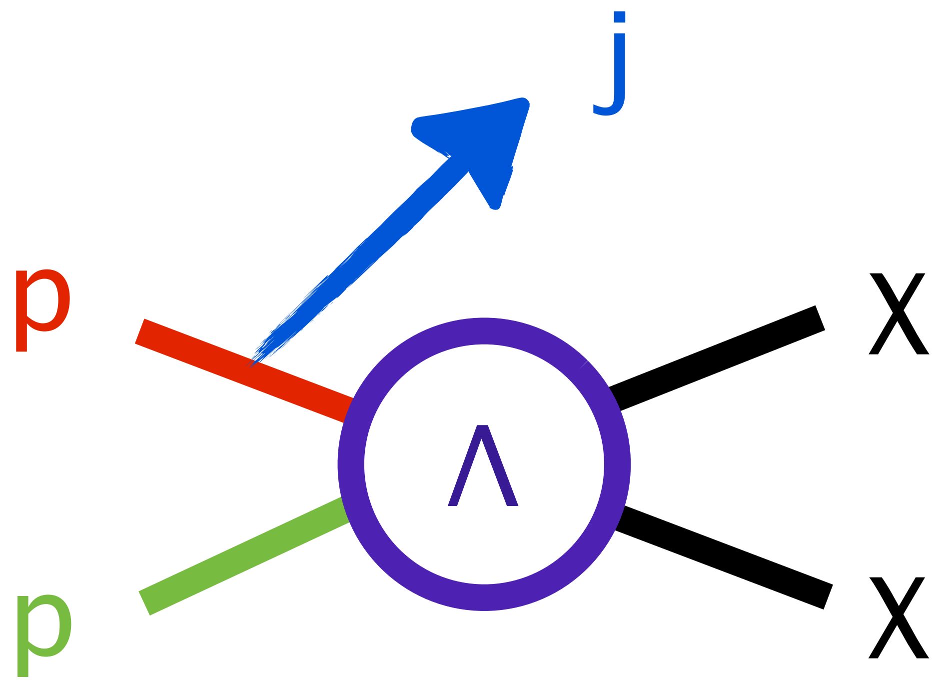
CMS PAS EXO-12-048

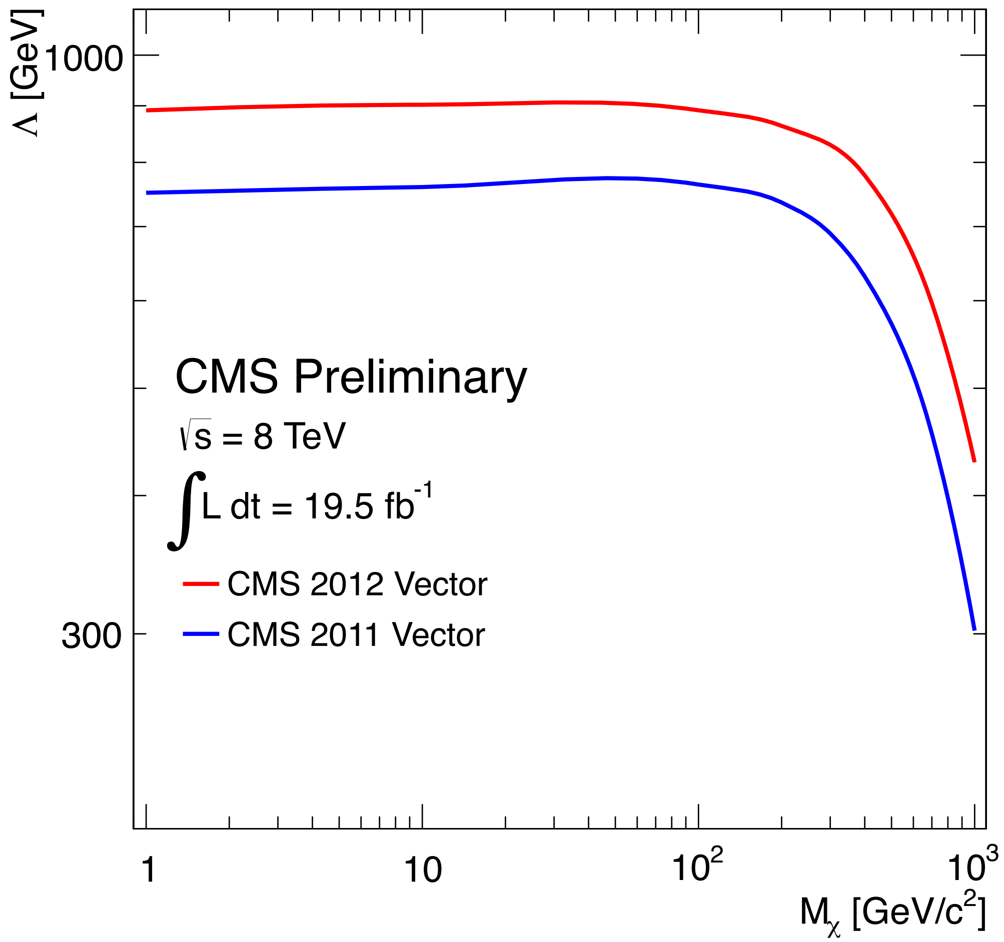
- The cutoff scale ~ **hundreds GeV**.
- The typical energy of the jets pass cut ~ **hundreds GeV**.
- The mass of dark matter ~ **hundreds GeV**.
- Effective energy of c.m.s ~ TeV.

Dark Matter Searching at the LHC

- Effective operator method: model independent, less free parameters.

$$\frac{C_{AB}}{\Lambda^n}\bar{\chi}\Gamma^A\chi\bar{q}\Gamma^B q$$





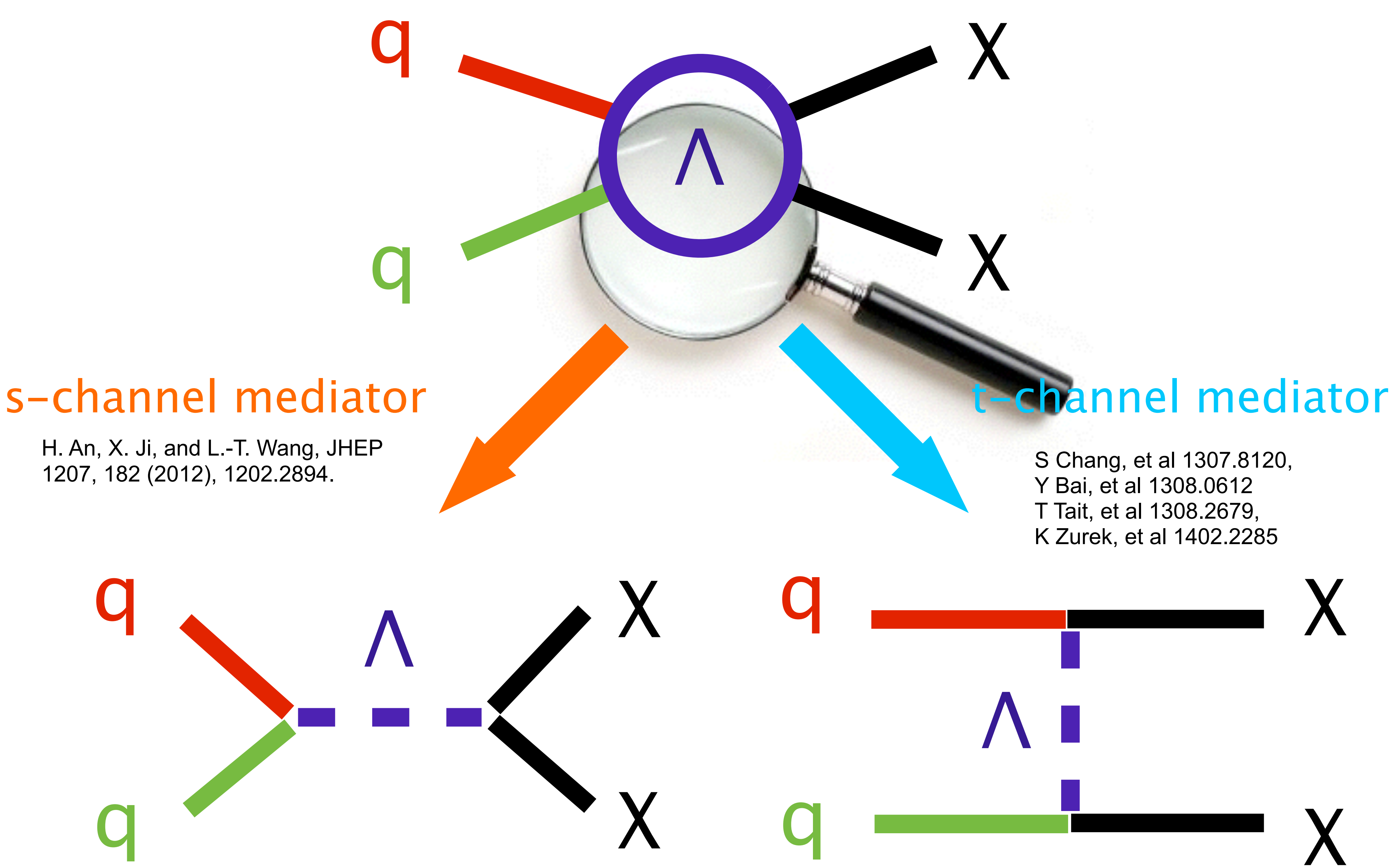
CMS PAS EXO-12-048

We need to go beyond the EFT!

Dark matter with t-channel mediator

DM with t-channel mediator

- A simple step beyond the EFT.
- Adding a mediator to reduce the dimension of the effective operators in the theory to be smaller than 5.



DM with t-channel mediator

- The effective Lagrangian of a simple t-channel mediator theory can be written as

$$\mathcal{L}_\chi = \lambda_q \bar{\chi} \phi^* q + \text{h.c.}$$

- Generally, there are strong constraints from flavor physics.

$$\mathcal{C}_{\text{SM}} \sim \frac{g_2^4 |V_{\text{CKM}}|^2}{16\pi^2 m_W^2}, \ \mathcal{C}_{\text{NP}} \sim \frac{g^2}{\Lambda^2}, \quad \Rightarrow \Lambda \sim \frac{4\pi v}{|V_{\text{CKM}}|} \sim 100\text{TeV}$$

- Minimal Flavor Violation scenario (MFV).

- The SM Yukawa interaction is the unique source of the flavor changing.

- Other interactions (including the new interaction from TeV new physics) should be invariant under flavor symmetry group

$$G_f \equiv SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R} \otimes SU(3)_{L_L} \otimes SU(3)_{E_R}$$
$$\otimes U(1)_B \otimes U(1)_L \otimes U(1)_Y \otimes U(1)_{PQ} \otimes U(1)_{E_R}$$

G. D'Ambrosio et al. Nucl Phys B 645 (2002) 155-187

DM with t-channel mediator

- The effective Lagrangian of a simple t-channel mediator theory can be written as

$$\mathcal{L}_\chi = \lambda_q \bar{\chi} \phi^* q + \text{h.c.}$$

- The quarks in the effective Lagrangian could be right-handed or left-handed. In the MFV scenario,

$$\begin{aligned}
\mathcal{L}_\chi \;=\; & \lambda_Q \bar{\chi} \mathbb{P}_L Q \phi_Q^* + \lambda_u \bar{\chi} \mathbb{P}_R u \phi_u^* + \lambda_d \bar{\chi} \mathbb{P}_R d \phi_d^* \\
& + \frac{\lambda_{Qu}^{(1)} \bar{\chi} H \phi_Q^* Y_u \mathbb{P}_R u}{\Lambda} + \frac{\lambda_{Qd}^{(1)} \bar{\chi} \tilde{H} \phi_Q^* Y_d \mathbb{P}_R d}{\Lambda} \\
& + \frac{\lambda_{Qu}^{(2)} \bar{Q} H Y_u \phi_u \mathbb{P}_R \chi}{\Lambda} + \frac{\lambda_{Qd}^{(2)} \bar{Q} \tilde{H} Y_d \phi_d \mathbb{P}_R \chi}{\Lambda} \\
& + \text{h.c.}\;,
\end{aligned}$$

DM with t-channel mediator

- The effective Lagrangian of a simple t-channel mediator theory can be written as

$$\mathcal{L}_\chi = \lambda_q \bar{\chi} \phi^* q + \text{h.c.}$$

- The quarks in the effective Lagrangian could be right-handed or left-handed. In the MFV scenario,

$$\begin{aligned}\mathcal{L}_\chi \;=\;& \lambda_Q \bar{\chi} \mathbb{P}_L Q \phi_Q^* + \lambda_u \bar{\chi} \mathbb{P}_R u \phi_u^* + \lambda_d \bar{\chi} \mathbb{P}_R d \phi_d^* \\ & + \frac{\lambda_{Qu}^{(1)} \bar{\chi} H \phi_Q^* Y_u \mathbb{P}_R u}{\Lambda} + \frac{\lambda_{Qd}^{(1)} \bar{\chi} \tilde{H} \phi_Q^* Y_d \mathbb{P}_R d}{\Lambda} \\ & + \frac{\lambda_{Qu}^{(2)} \bar{Q} H Y_u \phi_u \mathbb{P}_R \chi}{\Lambda} + \frac{\lambda_{Qd}^{(2)} \bar{Q} \tilde{H} Y_d \phi_d \mathbb{P}_R \chi}{\Lambda} \\ & + \text{h.c.}\ ,\end{aligned}$$

Direct detection

- Direct detection

$$\mathcal{O}_1 = \frac{\lambda^2}{2M_\phi^2}\bar{\chi}_L\gamma_\mu\chi_L\bar{q}_R\gamma^\mu q_R$$

- The direct detection cross section from this effective operator has been well studied.

- There are other operators induced by the t-channel mediator!

$$\mathcal{O}_2 = \frac{\alpha_S}{4\pi}G^{a\mu\nu}G^a_{\mu\nu}\chi^2, \qquad \mathcal{O}_3 = m_q\bar{q}q\chi^2$$

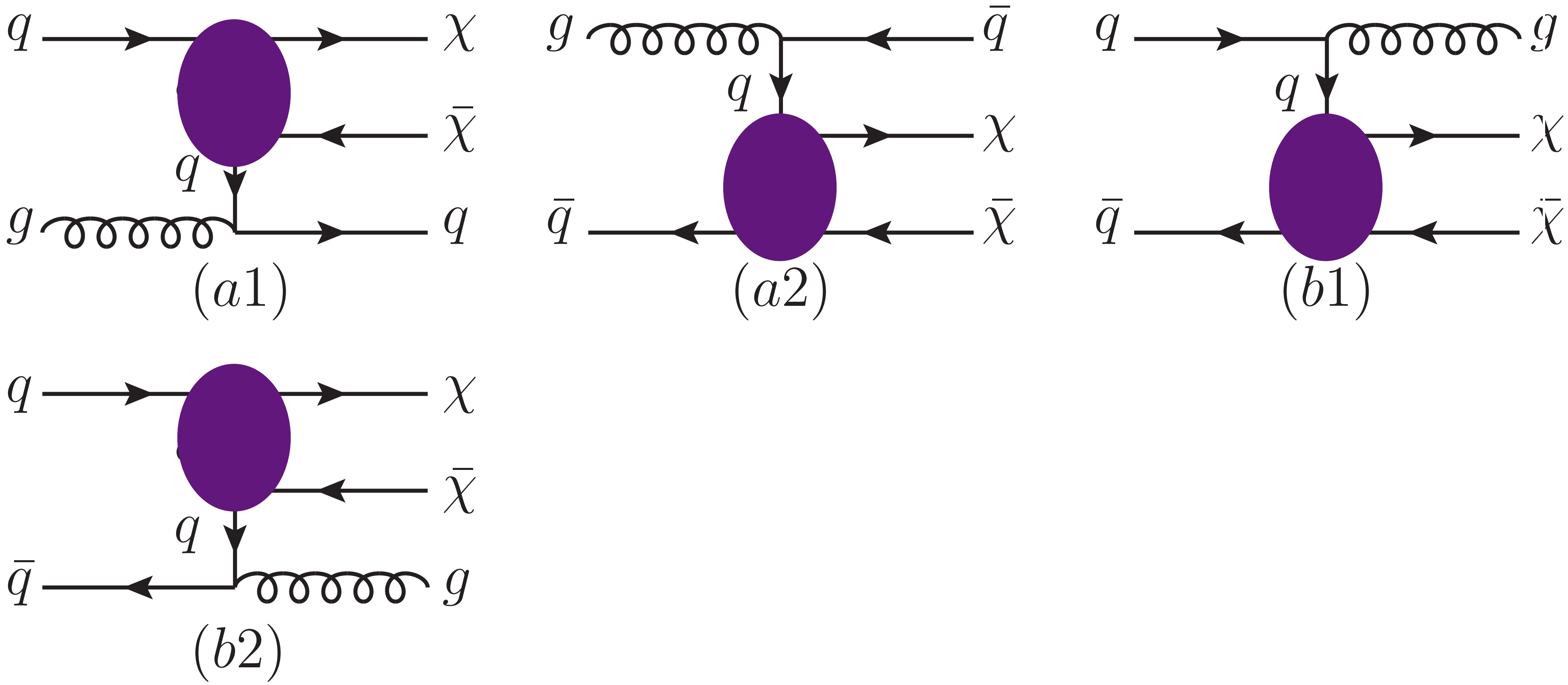
- Those operators are dim-7 and loop-induced from the t-channel mediator.

- The chiral symmetry enforces the Wilson coefficients to be proportional to the mass of the WIMP.

$$C_2 \sim \frac{\lambda^2 M_\chi}{M_\phi^4}, \qquad C_3 \sim \frac{\lambda^2 m_t^2 M_\chi}{32\pi^2 M_\phi^2 v_{\rm ew}^2 M_h^2}$$

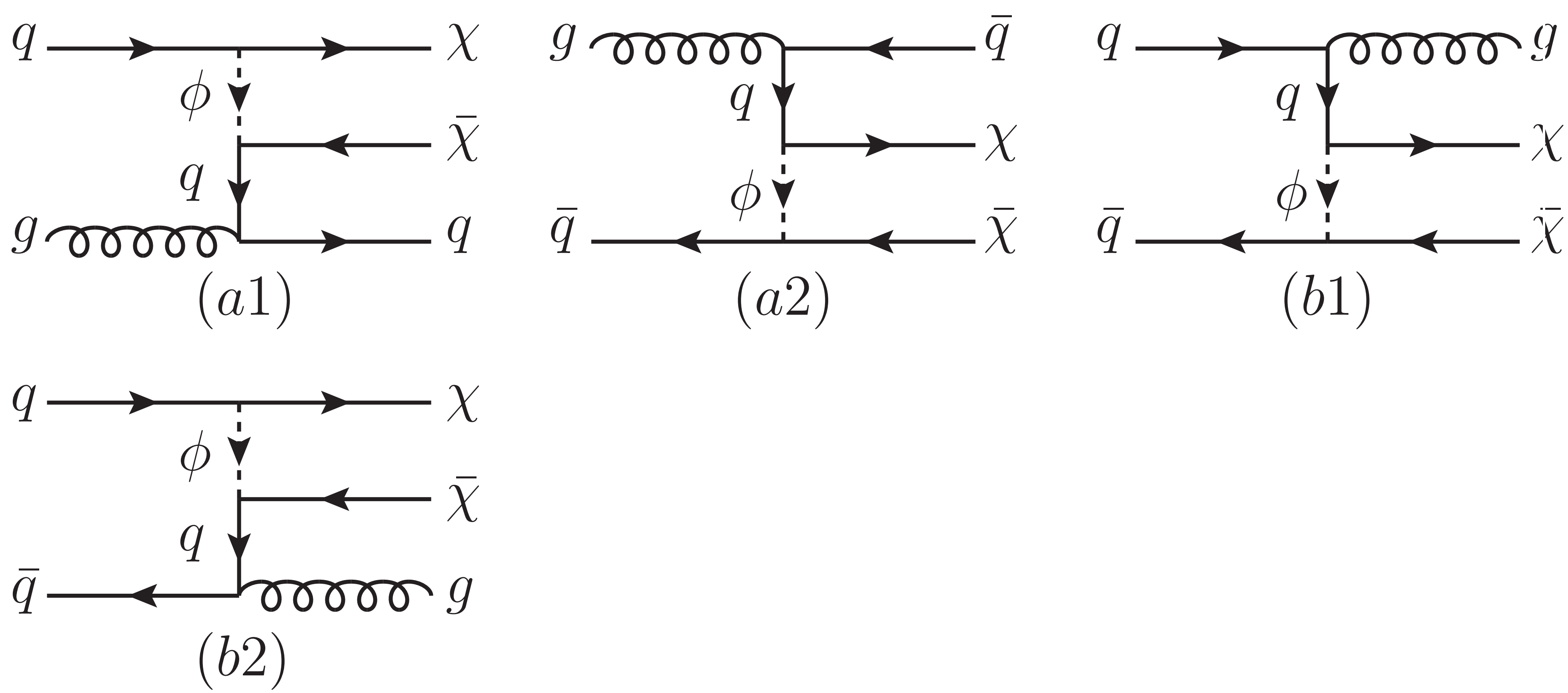
LHC phenomenology I: monojet

- Dark matter production process: monojet + missing ET.



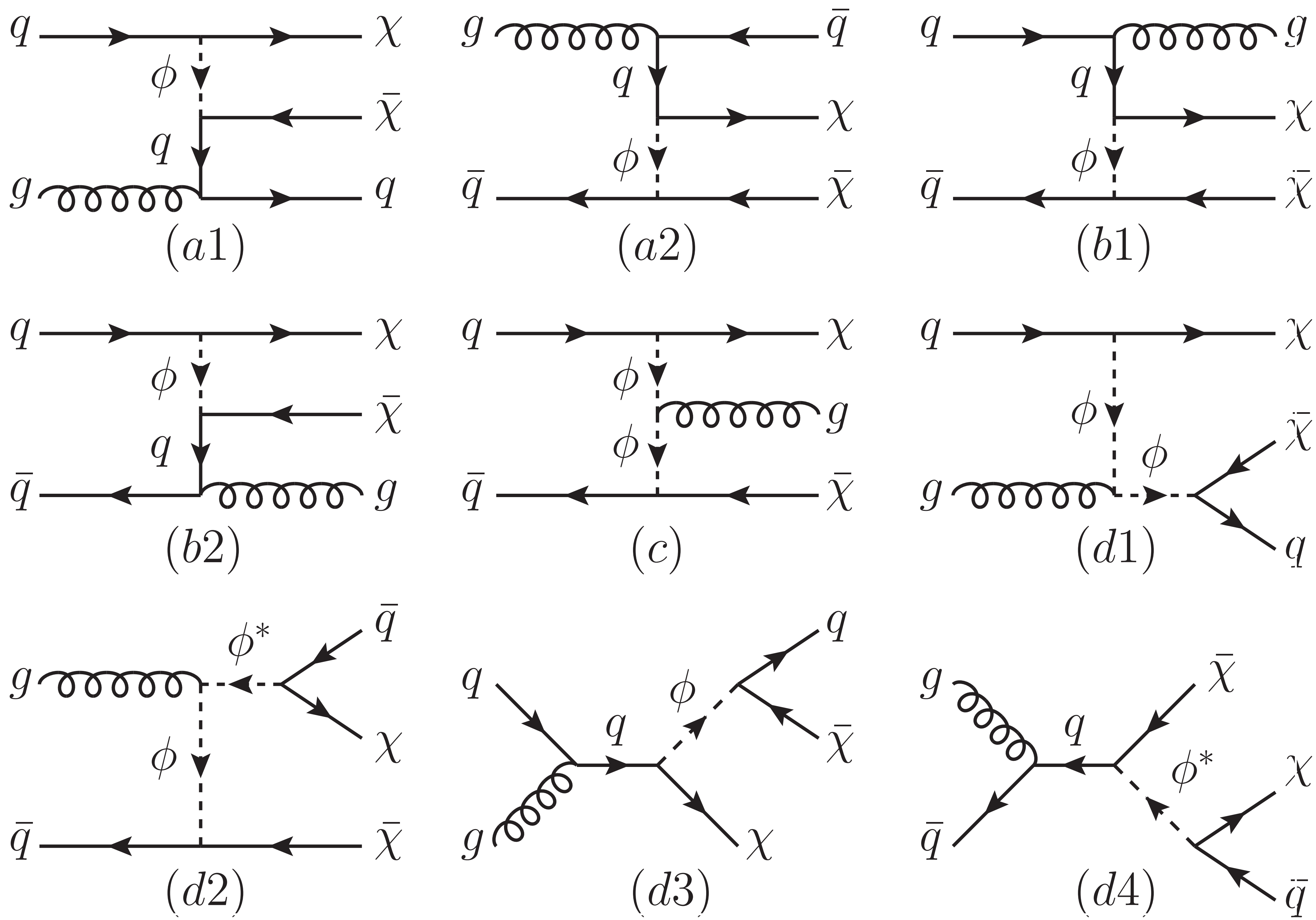
LHC phenomenology I: monojet

- Dark matter production process: monojet + missing ET.



LHC phenomenology I: monojet

- Dark matter production process: monojet + missing ET.



LHC phenomenology I: monojet

- New contributions:

(c) ---- from dim-7 operator $\mathcal{O}_8 = -\frac{i g_S \lambda^2}{M_\phi^4} T^a_{ij} A^a_\mu \left(\bar{\chi} P_R q_j\right) \overleftrightarrow{\partial}^\mu \left(\bar{q}_i P_L \chi\right)$

  - Higher suppressed by the mediator mass
  - No logarithm enhancement as the initial state QCD jet

(d1-d4) ---- WIMP-mediator associated production

  - Two-body phase space enhancement
  - High pT jet from heavy mediator decay

- The most recent monojet+missing ET constraint from the LHC is from CMS collaboration with 19.5 fb^{-1} dataset from 8 TeV proton-proton collision.

LHC phenomenology I: monojet

- We use MadGraph5/MadEvent generate parton level event, shower it using PYTHIA6.4 and simulate the detector effects using PGS4 with anti-k_T jet algorithm with a distance parameter of 0.5.
- Cuts:

At least one central jet $p_T > 110\ \mathrm{GeV},\ |\eta| < 2.4$

At most two jets s.t. $p_T > 30\ \mathrm{GeV},\ |\eta| < 4.5$

No isolated electron with $p_T > 10\ \mathrm{GeV},\ |\eta| < 1.44$ or $1.56 < |\eta| < 2.5$

No isolated muon with $p_T > 10\ \mathrm{GeV},\ |\eta| < 2.1$

$\not{E}_T > 120\ \mathrm{GeV}$

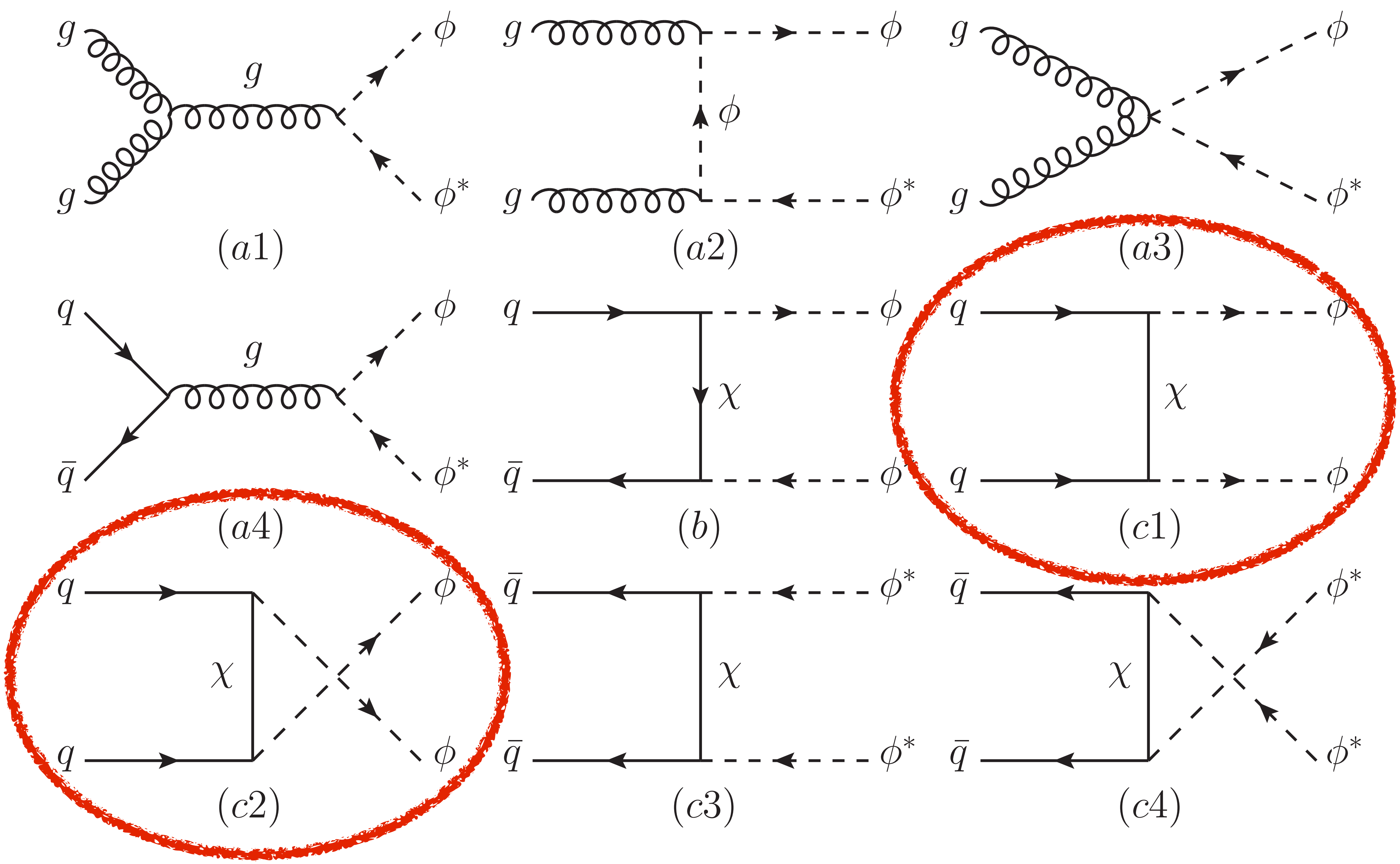
For events with a second jet, $\Delta\phi_{j_1 j_2} < 2.5$

- Events which pass those cuts are separated in seven signal regions according to the missing ET in the event.

CMS PAS EXO-12-048

LHC phenomenology I: monojet

- The mediator is colored particle which can be produced by purely QCD process. They also contribute to the "monojet" signal due to the cut.



LHC phenomenology I: monojet

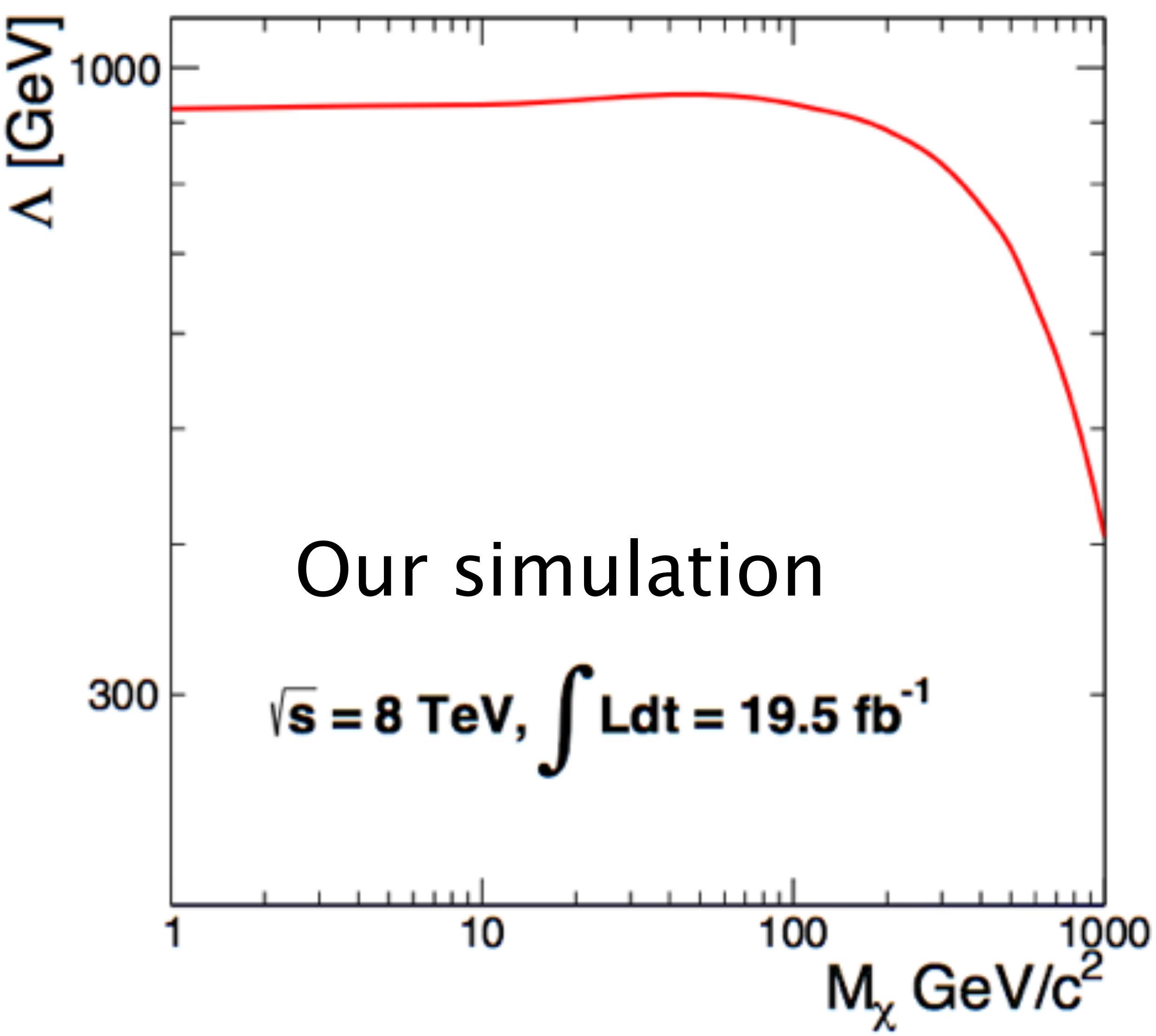
- Checking our simulation using vector current contact effective operator.

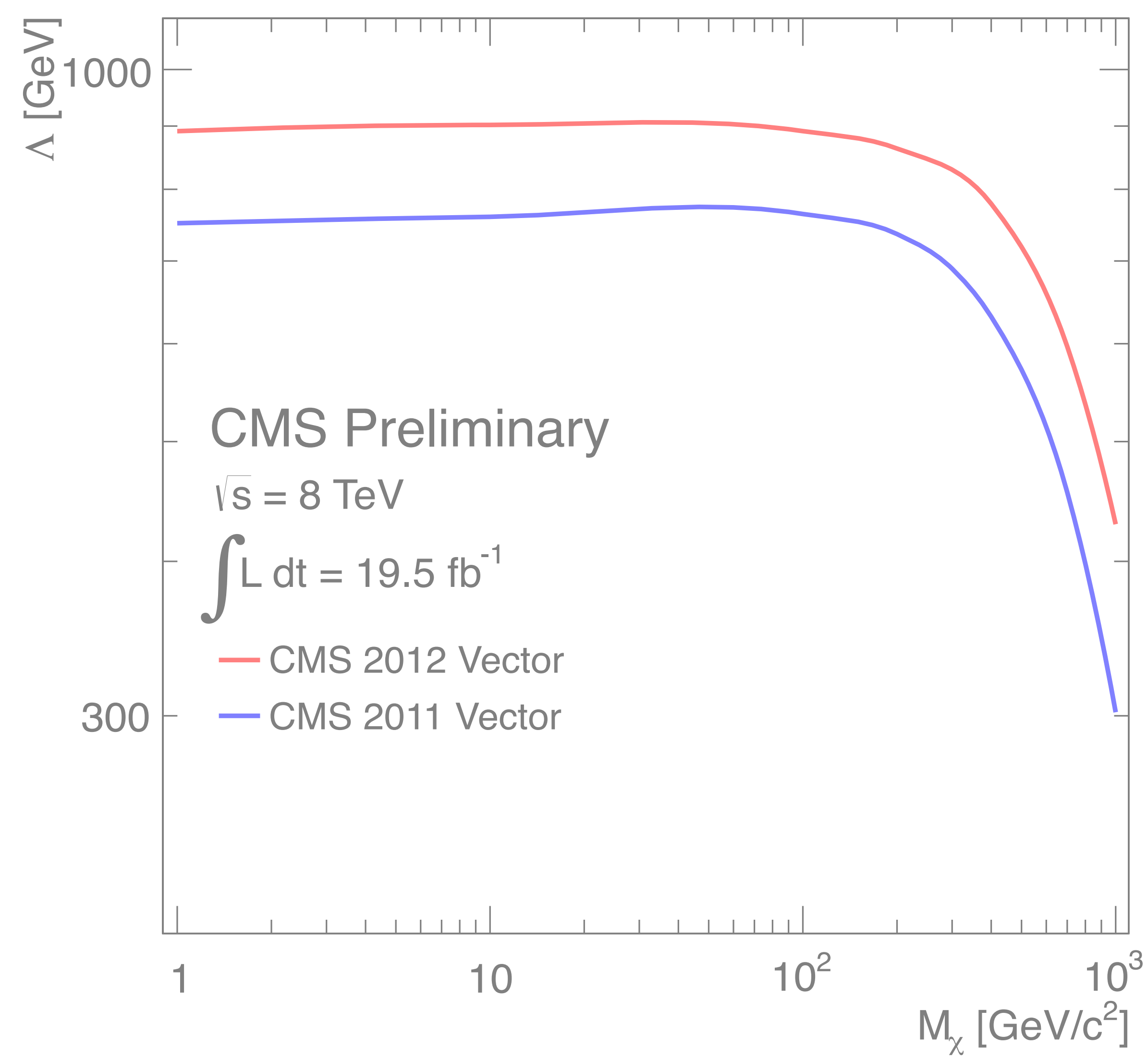
E_T^{miss} (GeV) $\rightarrow$	> 250	> 300	> 350	> 400	> 450	> 500	> 550
Z($\nu\nu$)+jets	30600 $\pm$ 1493	12119 $\pm$ 640	5286 $\pm$ 323	2569 $\pm$ 188	1394 $\pm$ 127	671 $\pm$ 81	370 $\pm$ 58
W+jets	17625 $\pm$ 681	6042 $\pm$ 236	2457 $\pm$ 102	1044 $\pm$ 51	516 $\pm$ 31	269 $\pm$ 20	128 $\pm$ 13
$t\bar{t}$	470 $\pm$ 235	175 $\pm$ 87.5	72 $\pm$ 36	32 $\pm$ 16	13 $\pm$ 6.5	6 $\pm$ 3.0	3 $\pm$ 1.5
Z($\ell\ell$)+jets	127 $\pm$ 63.5	43 $\pm$ 21.5	18 $\pm$ 9.0	8 $\pm$ 4.0	4 $\pm$ 2.0	2 $\pm$ 1.0	1 $\pm$ 0.5
Single t	156 $\pm$ 78.0	52 $\pm$ 26.0	20 $\pm$ 10.0	7 $\pm$ 3.5	2 $\pm$ 1.0	1 $\pm$ 0.5	0 $\pm$ 0
QCD Multijets	177 $\pm$88.5	76 $\pm$38.0	23 $\pm$11.5	3 $\pm$1.5	2 $\pm$1.0	1 $\pm$ 0.5	0 $\pm$ 0
Total SM	49154 $\pm$ 1663	18506 $\pm$ 690	7875 $\pm$ 341	3663 $\pm$ 196	1931 $\pm$ 131	949 $\pm$ 83	501 $\pm$ 59
Data	50419	19108	8056	3677	1772	894	508
Exp. upper limit	3580	1500	773	424	229	165	125
Obs. upper limit	4695	2035	882	434	157	135	131

CMS PAS EXO-12-048

LHC phenomenology I: monojet

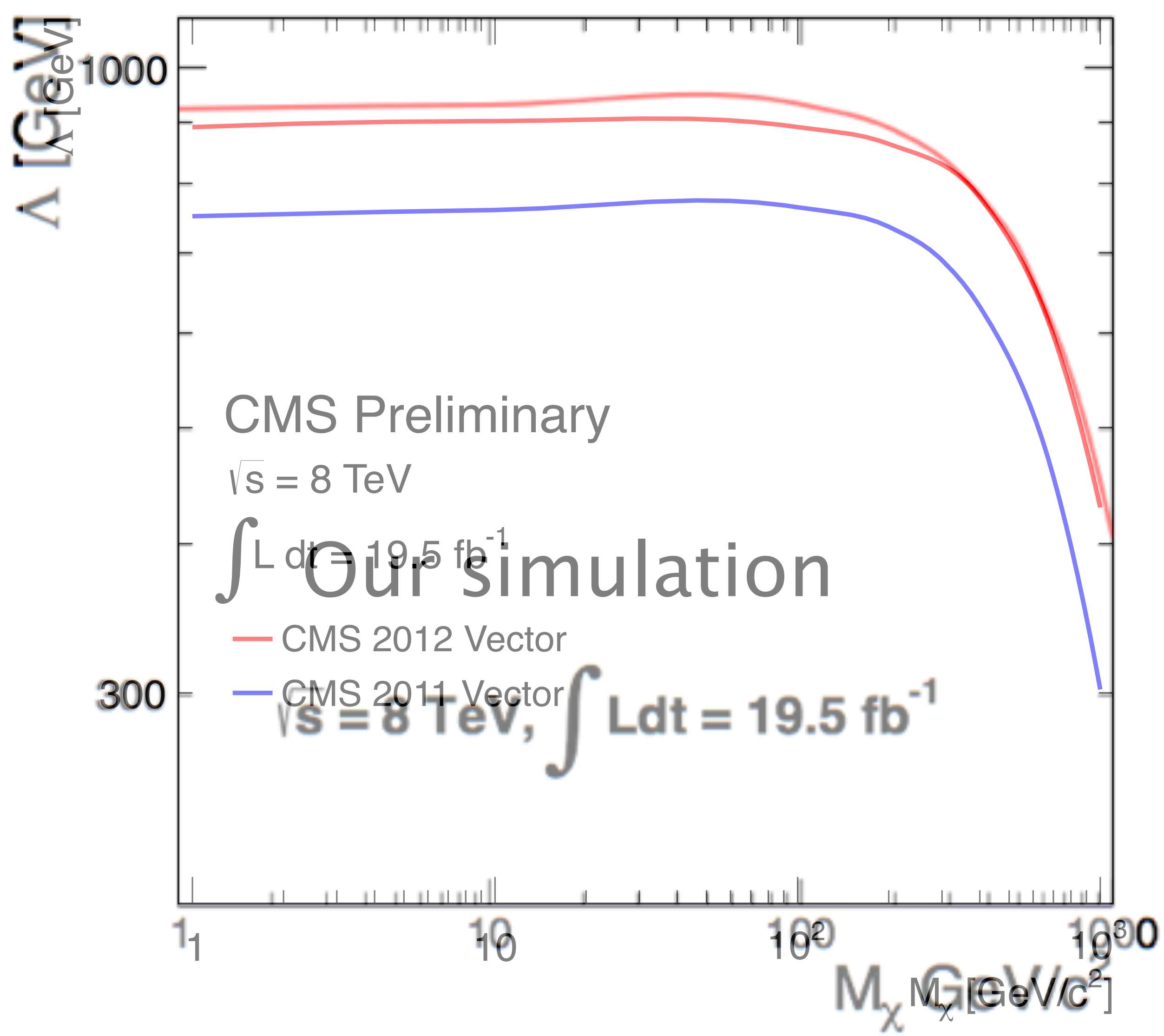
- Checking our simulation using vector current contact effective operator.





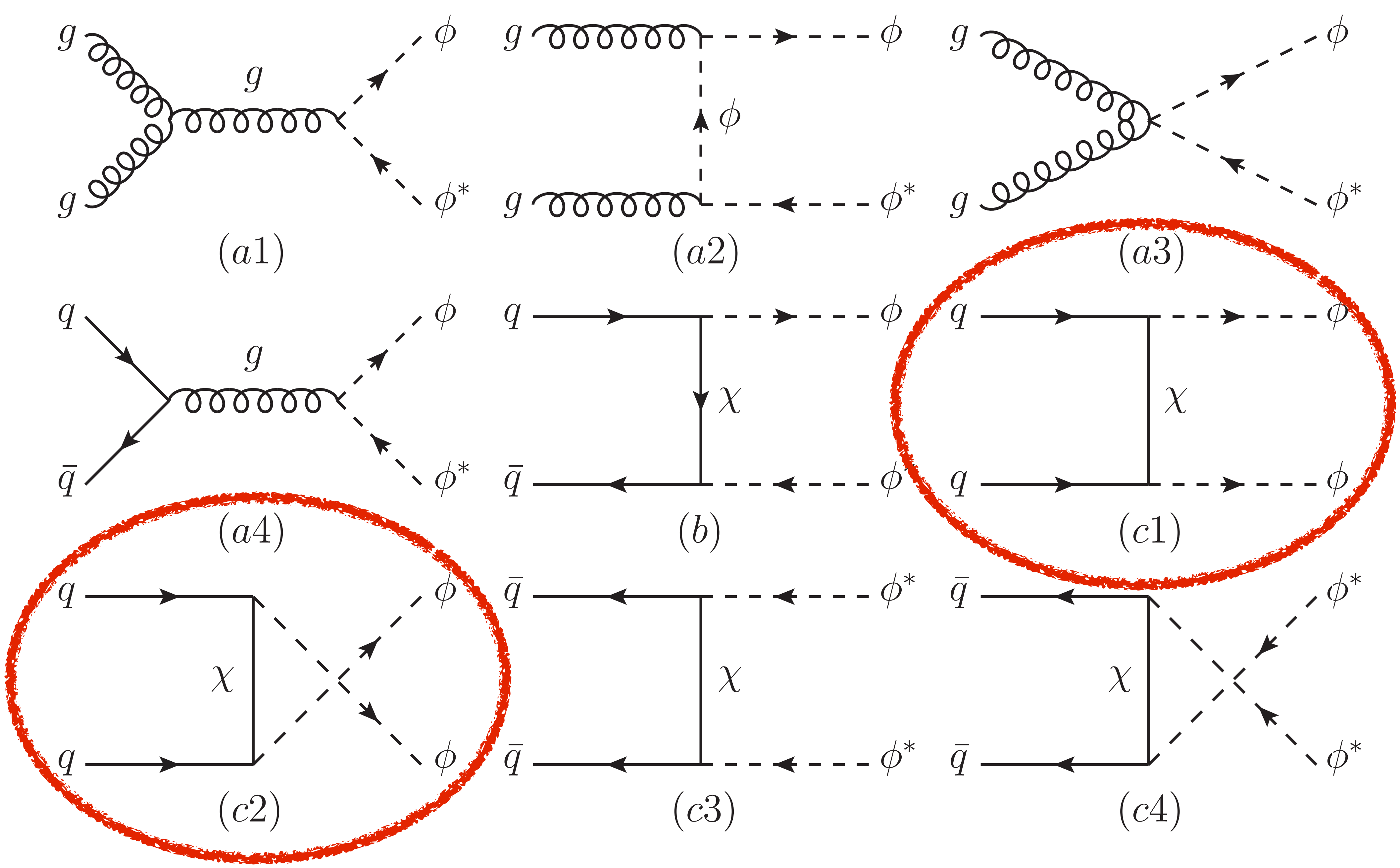
LHC phenomenology I: monojet

- Checking our simulation using vector current contact effective operator.



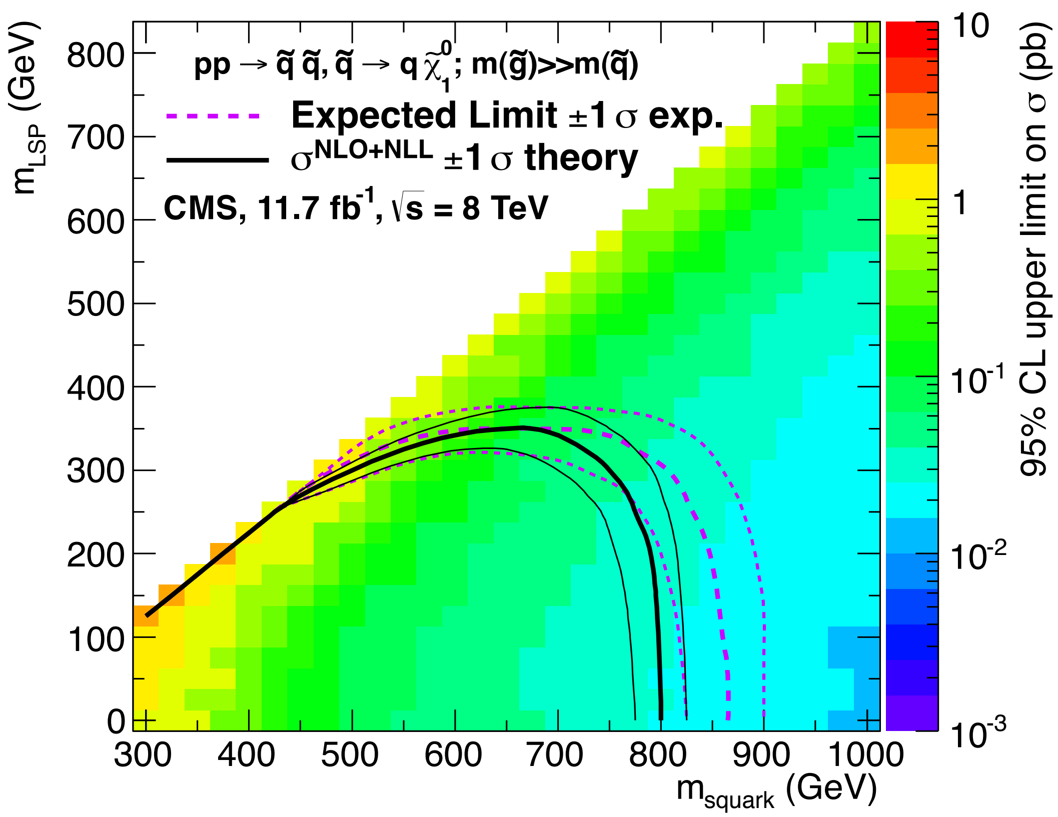
LHC phenomenology II: dijet

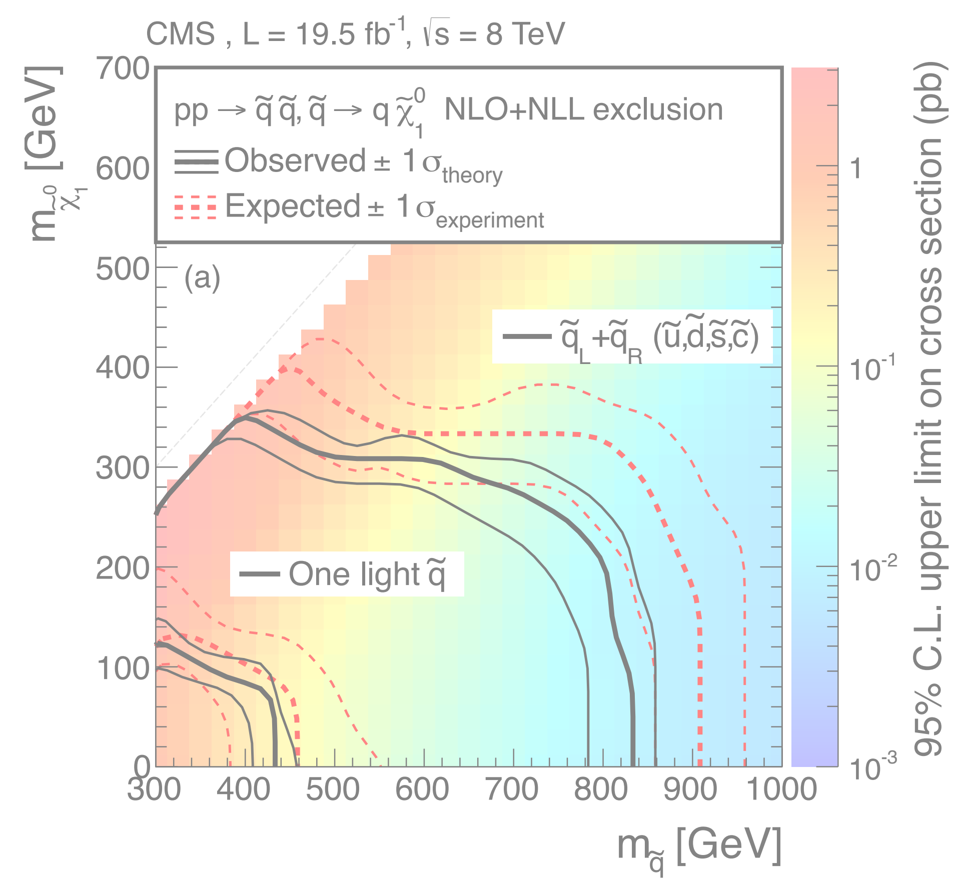
- The mediator is colored particle which can be produced by purely QCD process.



LHC phenomenology II: dijet

- The total cross section is calculated using MadGraph5/MadEvent
- A typical value of the K-factor is smaller than 1.05. We will neglect it in our calculation.
- We compare the parton level cross section with the unfolded result of squark search given by the CMS collaboration.

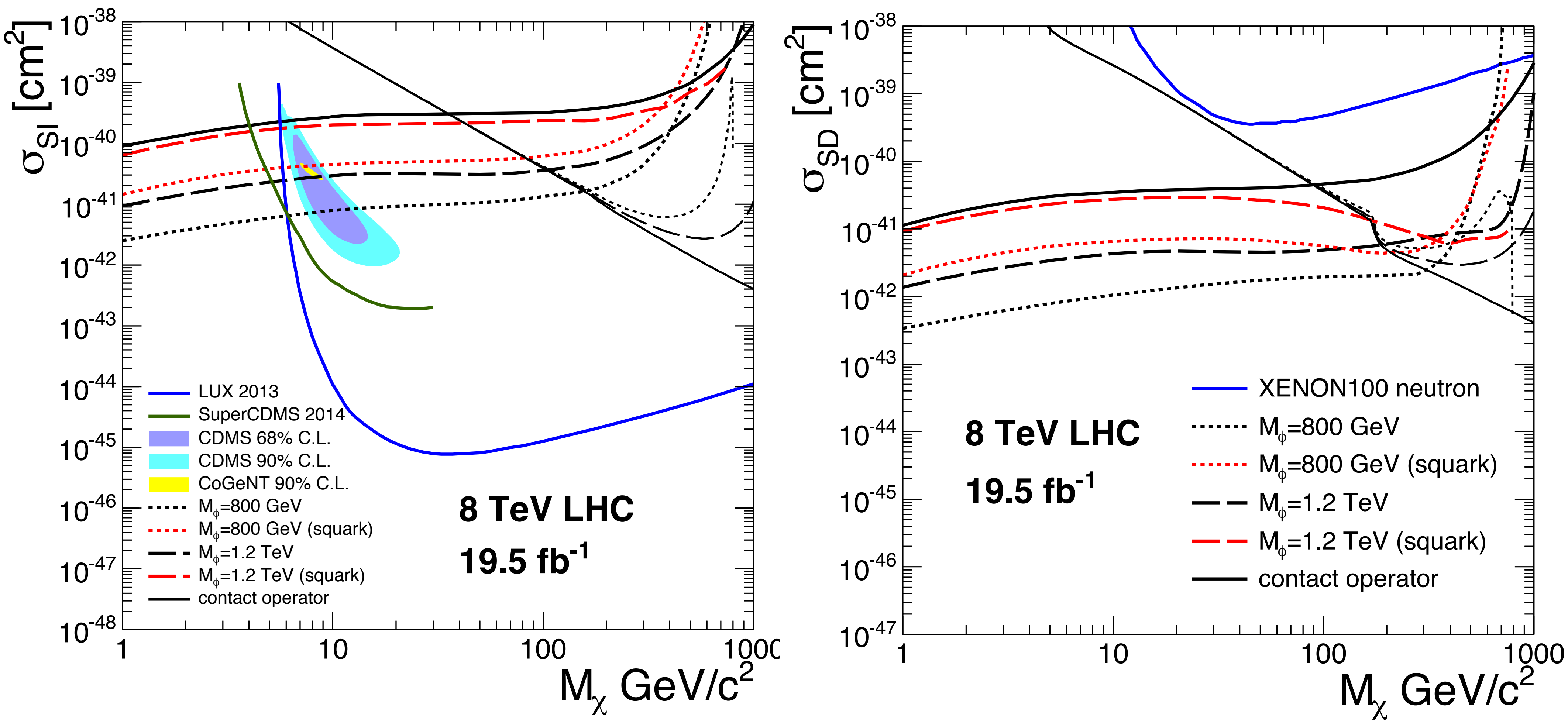




CMS collaboration, arXiv:1303.2985, 1402.4770

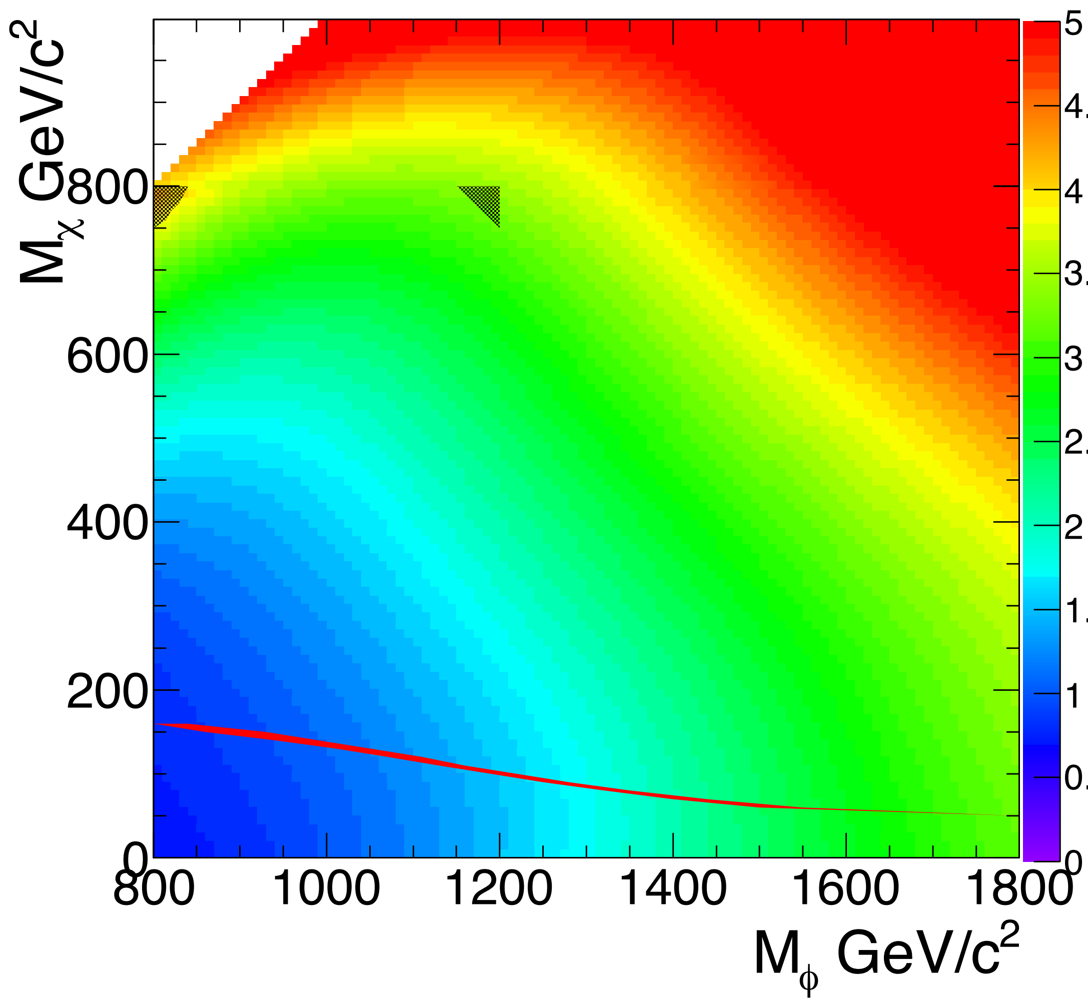
DM with t-channel mediator

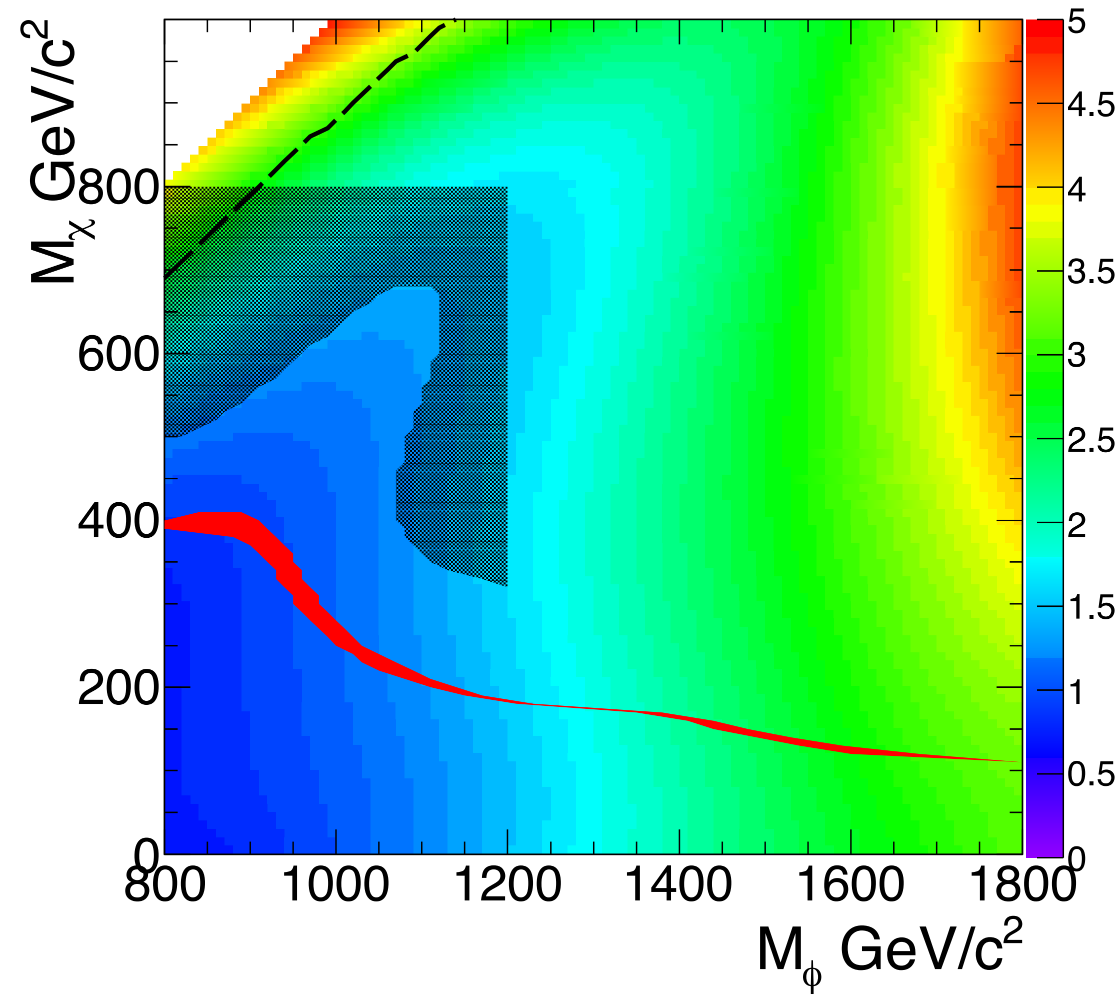
- We compare the constraints to the t-channel mediator model from direct detection and 8 TeV LHC.
- The difference between the t-channel mediator model and the effective operator approximation is shown clearly in the figures.



DM with t-channel mediator

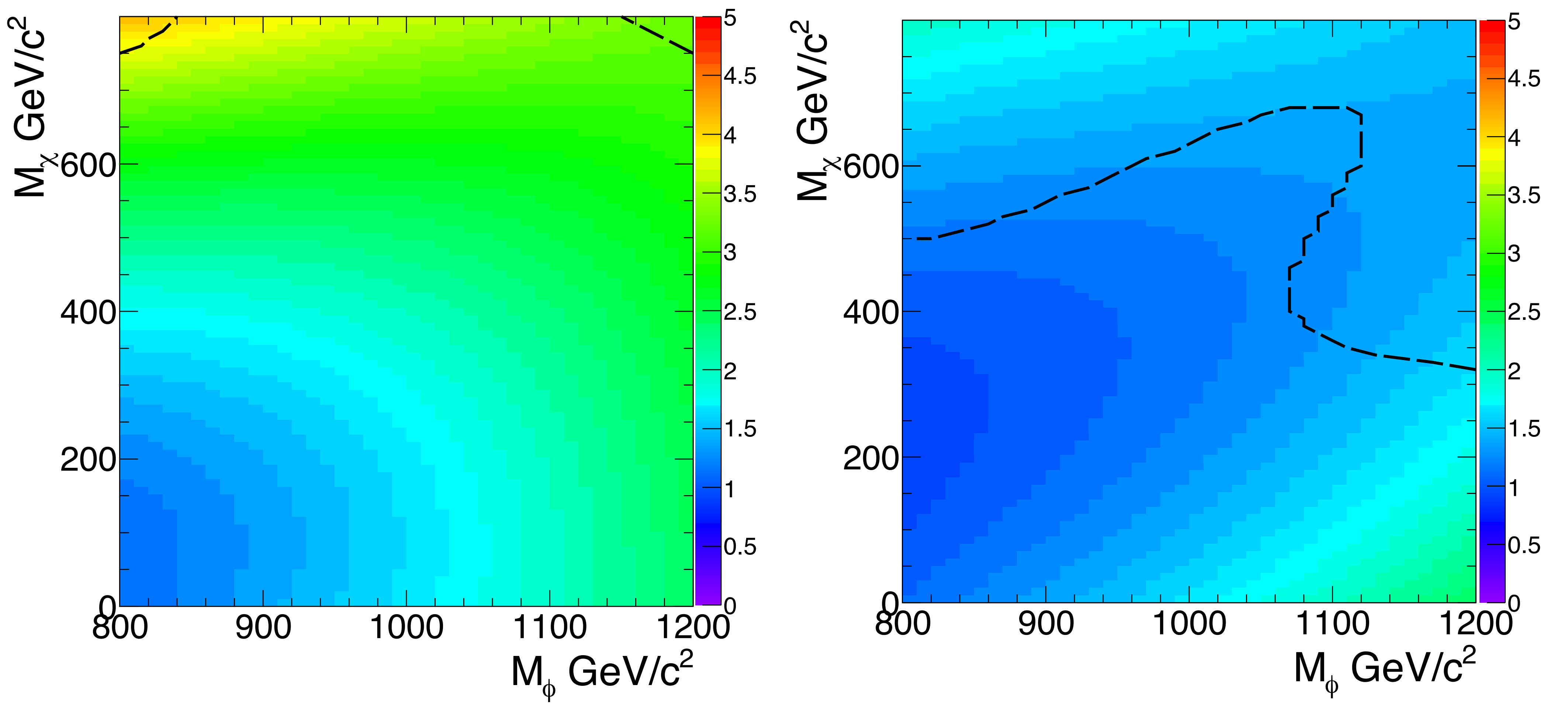
- We compare the constraints to the t-channel mediator model from direct detection and 8 TeV LHC.
- The difference between the t-channel mediator model and the effective operator approximation is shown clearly in the figures.





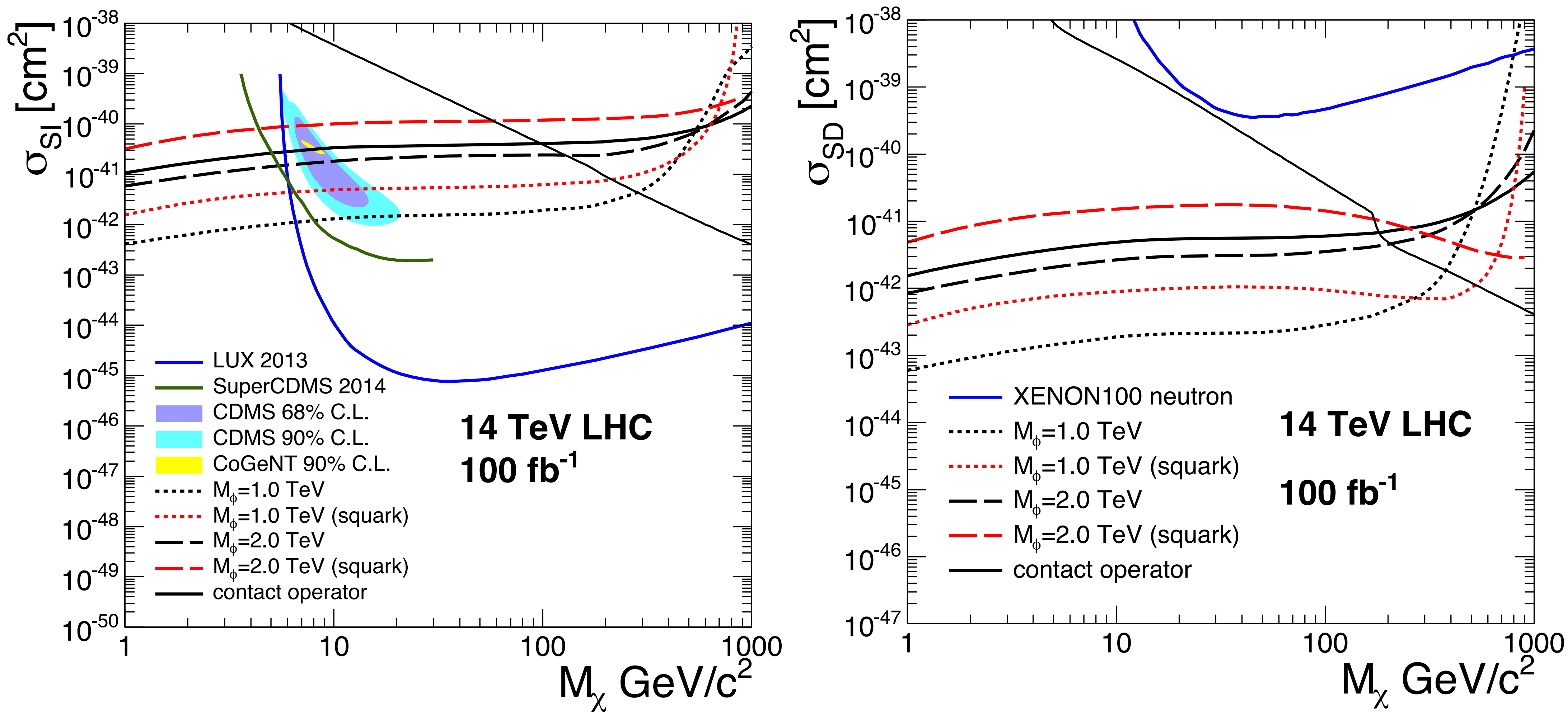
DM with t-channel mediator

- We compare the constraints to the t-channel mediator model from direct detection and 8 TeV LHC.
- The difference between the t-channel mediator model and the effective operator approximation is shown clearly in the figures.



DM with t-channel mediator

- The significance from 14 TeV LHC is predicted.
- Monojet: jet Et > 500 GeV.
- Squark search: missing Et > 150 GeV, pT1 > 200 GeV, pT2 > 130 GeV.



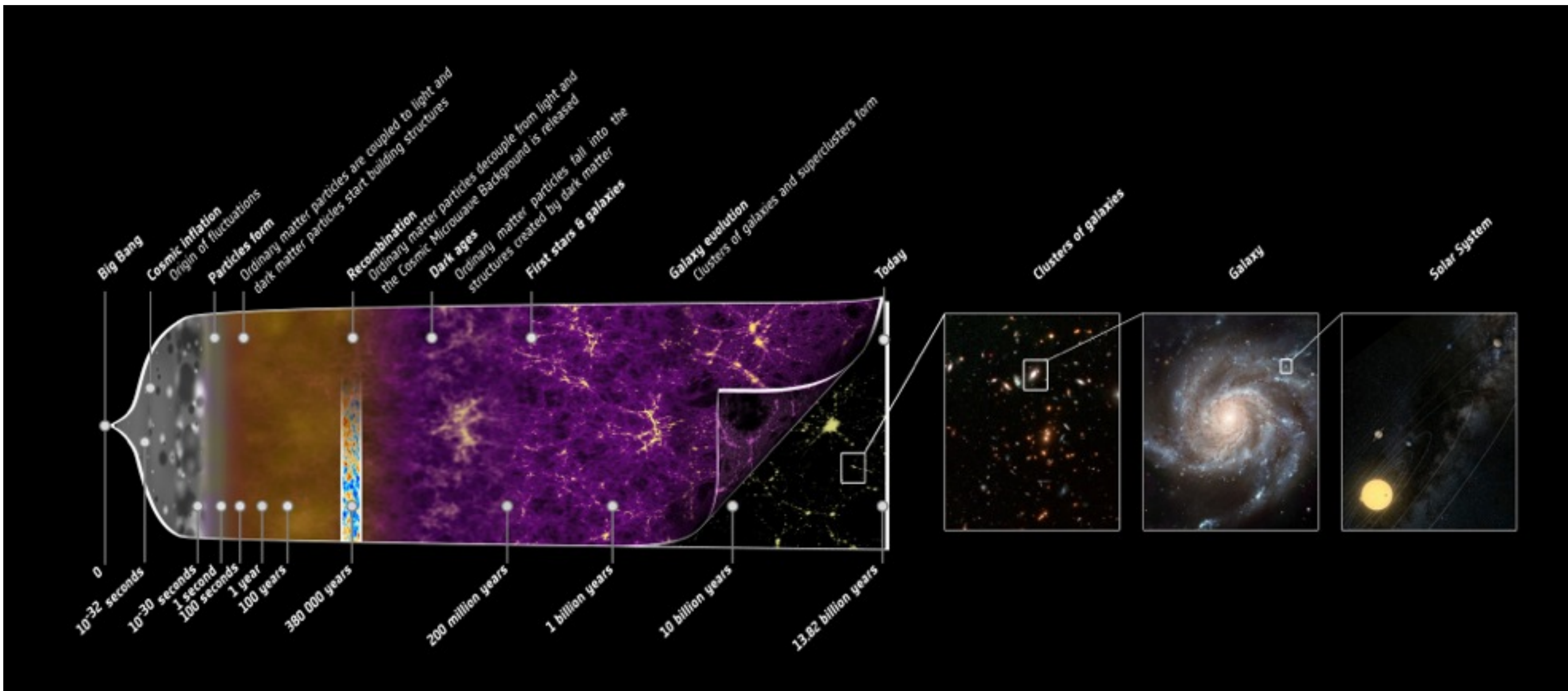
Conclusion

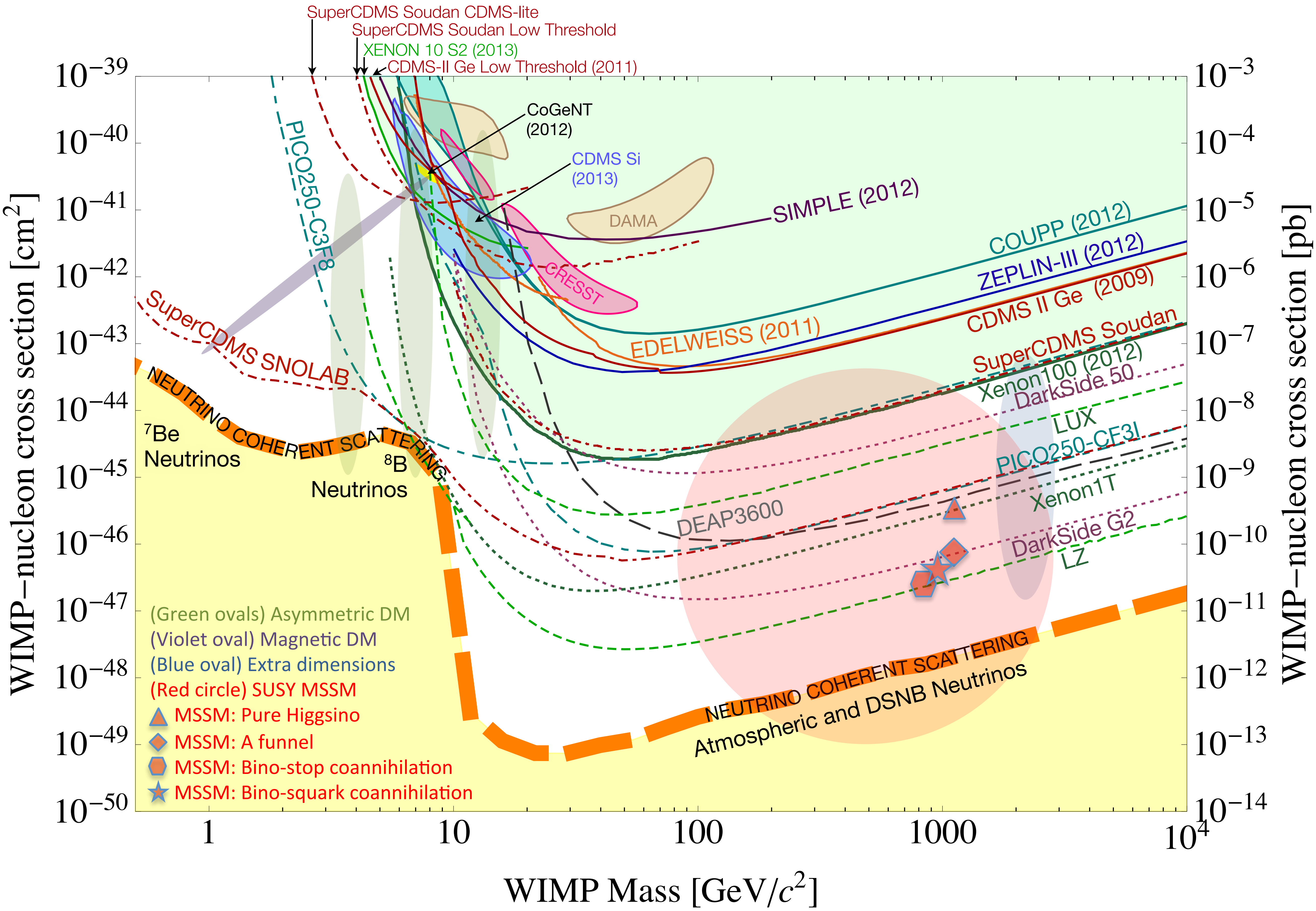
- We study a simplified *t*-channel UV completion model where the interaction between DM and SM particles are mediated by colored mediators couples to the DM particle and the right-handed quarks.
- In this scenario, the relevant processes at the LHC are dark matter pair production associated with a quark or gluon, mediator-dark matter associated production, mediator pair production.
- The EFT is not a good approximation and the mediators must be considered.
- For light DM, the constraint from the LHC is always stronger than direct detection.
- If the DM is a Majorana fermion, the constraint from the LHC is always stronger than direct detection due to a weak constraint to the SD cross section.


Thank you!

Dark matter in the Universe

- Galaxy rotation curve.
- Bullet cluster.
- Standard cosmology: ΛCDM





SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
PICO250-C3F8
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
SuperCDMS SNOLAB
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DEAP3600
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c2]