
Alexis

Global Fit to Dark Matter with Leptophobic Mediators

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1. Previous SUSY analyses
2. Introduction to non-SUSY analyses
3. Set-up and validation
4. General Results
5. Towards UV completions
6. Conclusions

1. Previous SUSY analyses

GUT based models:

1.) CMSSM: m_0, $m_{1/2}$, A_0, $\tan\beta$, sign μ

2.) NUHM1: CMSSM + 1 scalar mass parameter
m_0, $m_{1/2}$, A_0, $\tan\beta$, sign μ and M_A

3.) NUHM2: CMSSM + 2 scalar mass parameters
m_0, $m_{1/2}$, A_0, $\tan\beta$, μ and M_A

4.) SU(5): CMSSM + 3 scalar mass parameters
m_5, m_{10}, $m_{1/2}$, A_0, $\tan\beta$, m_{H_u}, m_{H_d}

5.) mAMSB: different mechanism for SUSY breaking
$m_{3/2}, m_0, \tan\beta$, sign(μ)

6.) sub-GUT: CMSSM, but unification at lower scale
m_0, $m_{1/2}$, A_0, $\tan\beta$, sign μ and $M_{\rm in}$

7.) ...

⇒ wide variety of models covered!

Problem: We cannot be sure about the SUSY-breaking mechanism

⇒ it is possible that with the CMSSM, NUHM, SU(5), mAMSB, sub-GUT
we missed the "correct" mechanism

⇒ hint: strong connection between colored and uncolored sector
tension between low-energy EW effects and (colored) LHC searches

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tension between low-energy EW effects and (colored) LHC searches

Solution: investigate also the "general MSSM"

⇒ 11 parameters are manageable ⇒ pMSSM11

- squark mass parameters: $m_{\tilde{q}_{1,2}} =: m_{\tilde{q}}$, $m_{\tilde{q}_3}$
- slepton mass parameter(s): $m_{\tilde{l}}$, $m_{\tilde{\tau}}$
- gaugino masses: M_1, M_2, M_3
- trilinear coupling: A
- Higgs sector parameters: M_A, $\tan\beta$
- Higgs mixing paramter: μ

What if we still did not get it right?

– low-energy model different?

– richer SUSY structure?

– no SUSY model? $\Rightarrow$ not really realistic! ;-)

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Lagrangian according to LHC-DM-WG recommendation:

The Lagrangians

- We consider DMSMs with a spin-1 (Y_1) s-channel mediator.
- The dark matter candidate is a Dirac fermion (X_D).
- We use the model files provided by the DMSIMP package for our implementation.

Spin-1 mediator

- Interaction Lagrangian mediator-DM
  $\mathcal{L}_{X_D}^{Y_1} = \bar{X}_D \gamma_\mu \left(g_{X_D}^V + g_{X_D}^A \gamma_5 \right) X_D Y_1^\mu .$
- Interaction Lagrangian mediator-quarks
  $$\mathcal{L}_{\text{quarks}}^{Y_1} = \sum_{i,j} \left[\bar{d}_i \gamma_\mu \left(g_{d_{i,j}}^V + g_{d_{i,j}}^A \gamma_5 \right) d_j + \bar{u}_i \gamma_\mu \left(g_{u_{i,j}}^V + g_{u_{i,j}}^A \gamma_5 \right) u_j \right] Y_1^\mu$$
- Interaction Lagrangian mediator-leptons
  $$\mathcal{L}_{\text{leptons}}^{Y_1} = \sum_{i,j} \left[\bar{l}_i \gamma_\mu \left(g_{l_{i,j}}^V + g_{l_{i,j}}^A \gamma_5 \right) l_j \right] Y_1^\mu$$

Scenarios

- Leptophobic, $g_{l_{i,j}}^V = g_{l_{i,j}}^A = 0$ (no constraints from dilepton searches).
- Flavor diagonal, $g_{u/d_{i,j}}^{V/A} = 0$ if $i \neq j$.
- Flavor blind, $g_{u_{i,j}}^{V/A} = g_{d_{i,j}}^{V/A}$.

1. $g_{X_D}^V \equiv g_{DM}$ $\quad g_{X_D}^V = 0$
   $g_{u/d}^V \equiv g_{SM}$ $\quad g_{u/d}^A = 0$,
   pure vector.
2. $g_{X_D}^V = 0$ $\quad g_{X_D}^V \equiv g_{DM}$
   $g_{u/d}^V = 0$ $\quad g_{u/d}^A = g_{SM}$,
   pure axial-vector.

[taken from E. Bagnaschi]

Our tool: **Mastercode**

⇒ collaborative effort of theorists and experimentalists
[*Bagnaschi, Borsato, Buchmüller, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flächer, Hahn, SH, Isidori, Lucio, Martinez Santos, Olive, Trifa, Sakurai, Weiglein*]

Über-code for the combination of different tools:

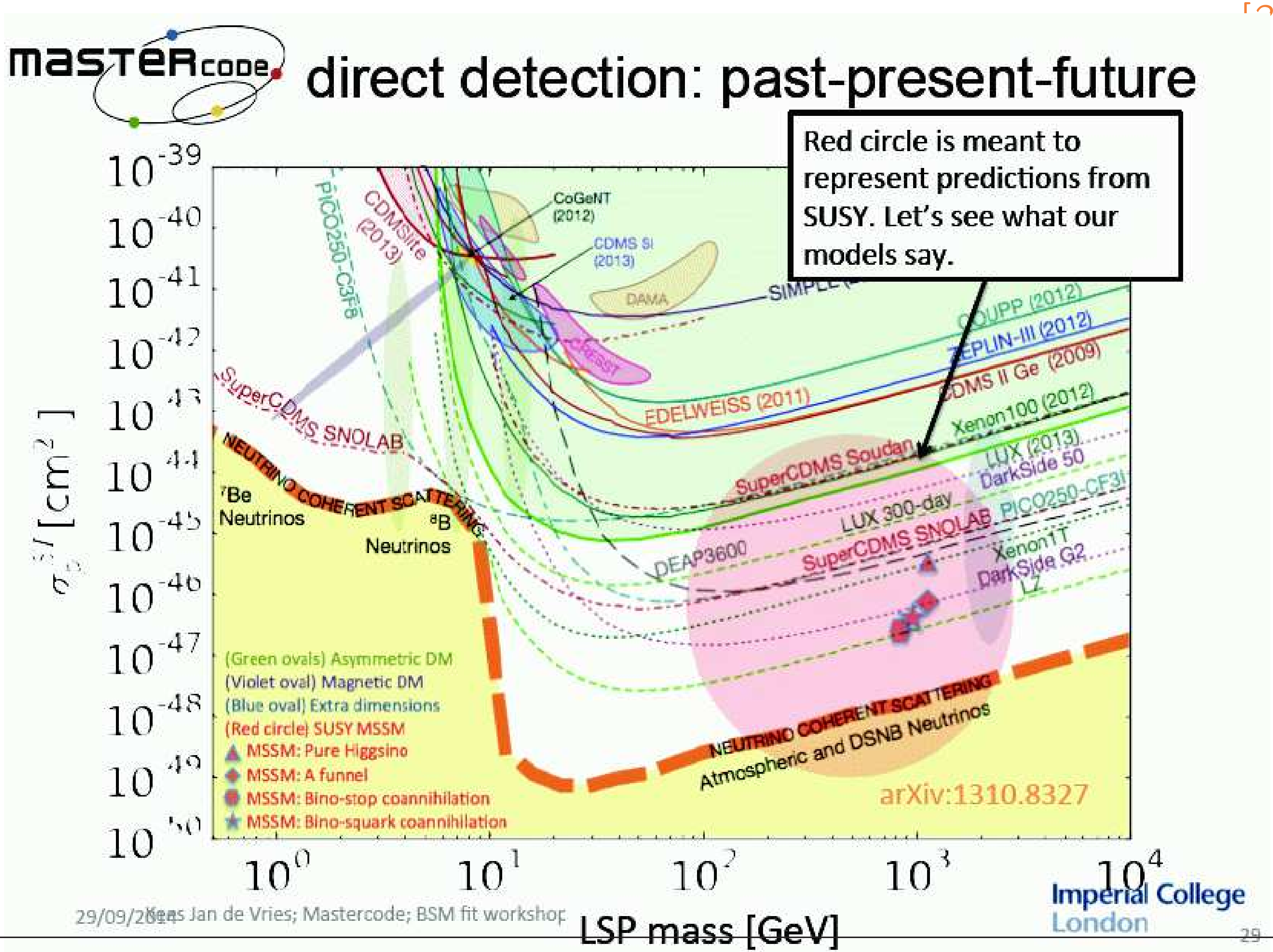
– Über-code original in Fortran, now re-written in C++
– tools are included as subroutines
– compatibility ensured by collaboration of authors of "MasterCode" and authors of "sub tools" /SLHA(2)
– sub-codes in Fortran or C++

⇒ evaluate observables of one parameter point consistently with various tools

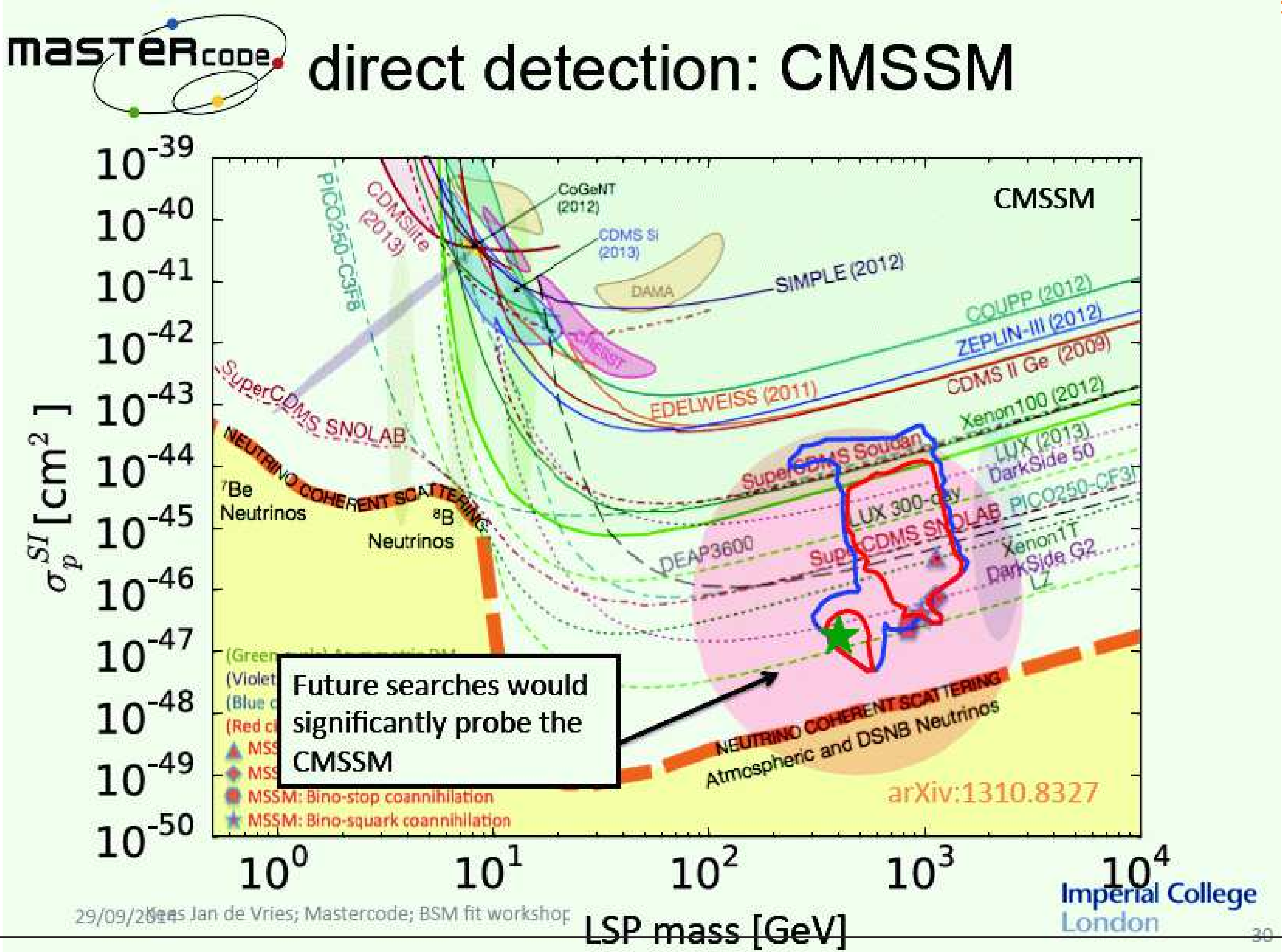
cern.ch/mastercode

MSSM Direct Detection prediction

[2014]



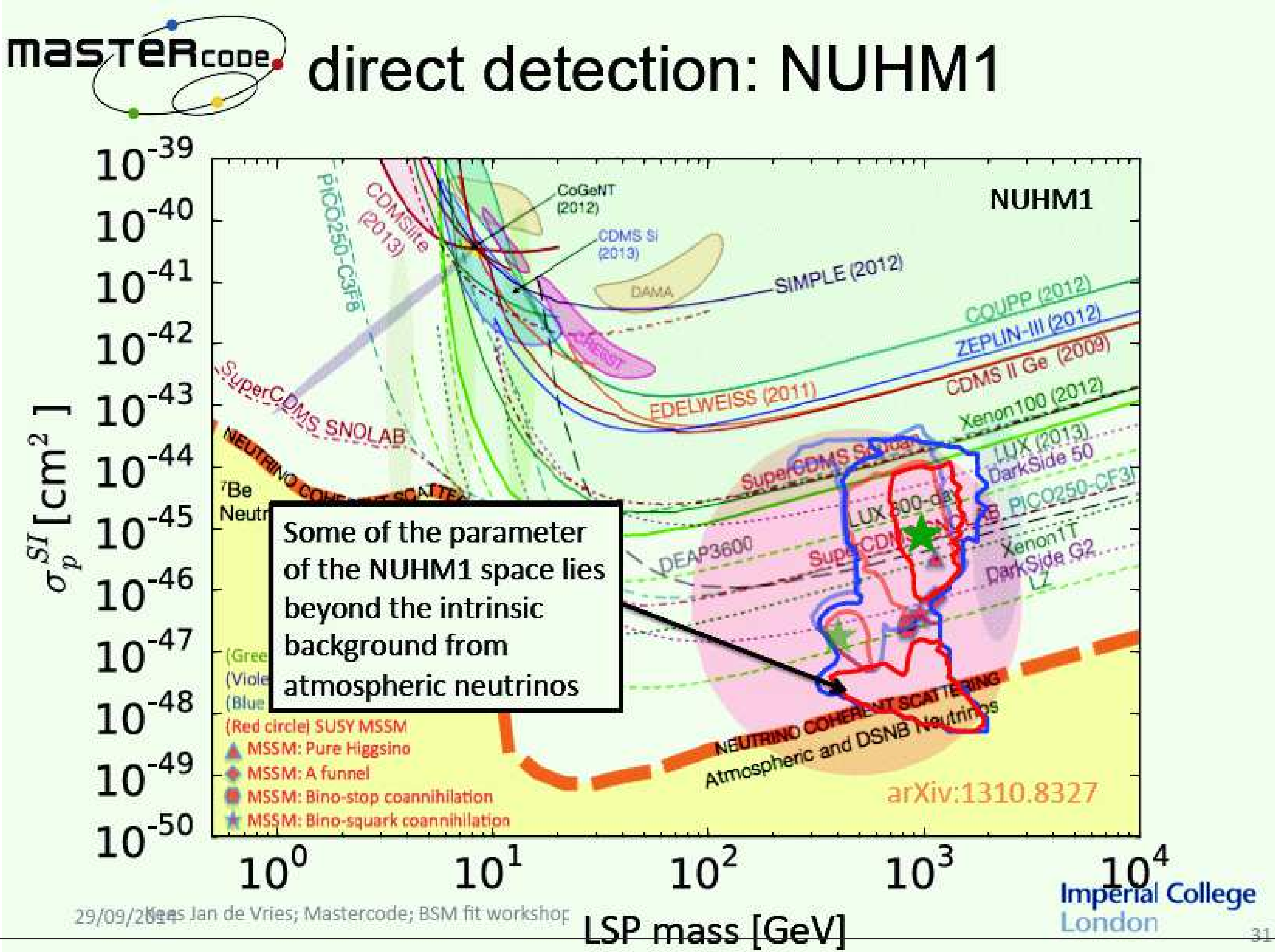
[2014]



direct detection: CMSSM
CMSSM
CoGeNT (2012)
CDMS Si (2013)
DAMA
CRESST
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
DarkSide 50
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
SuperCDMS Soudan
LUX 300-day
SuperCDMS SNOLAB
DEAP3600
PICO250-C3F8
CDMSlite (2013)
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
Atmospheric and DSNB Neutrinos
Future searches would significantly probe the CMSSM
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
arXiv:1310.8327
σ_p^{SI} [cm^2]
LSP mass [GeV]
29/09/2014 Kees Jan de Vries; Mastercode; BSM fit workshop
Imperial College London
30

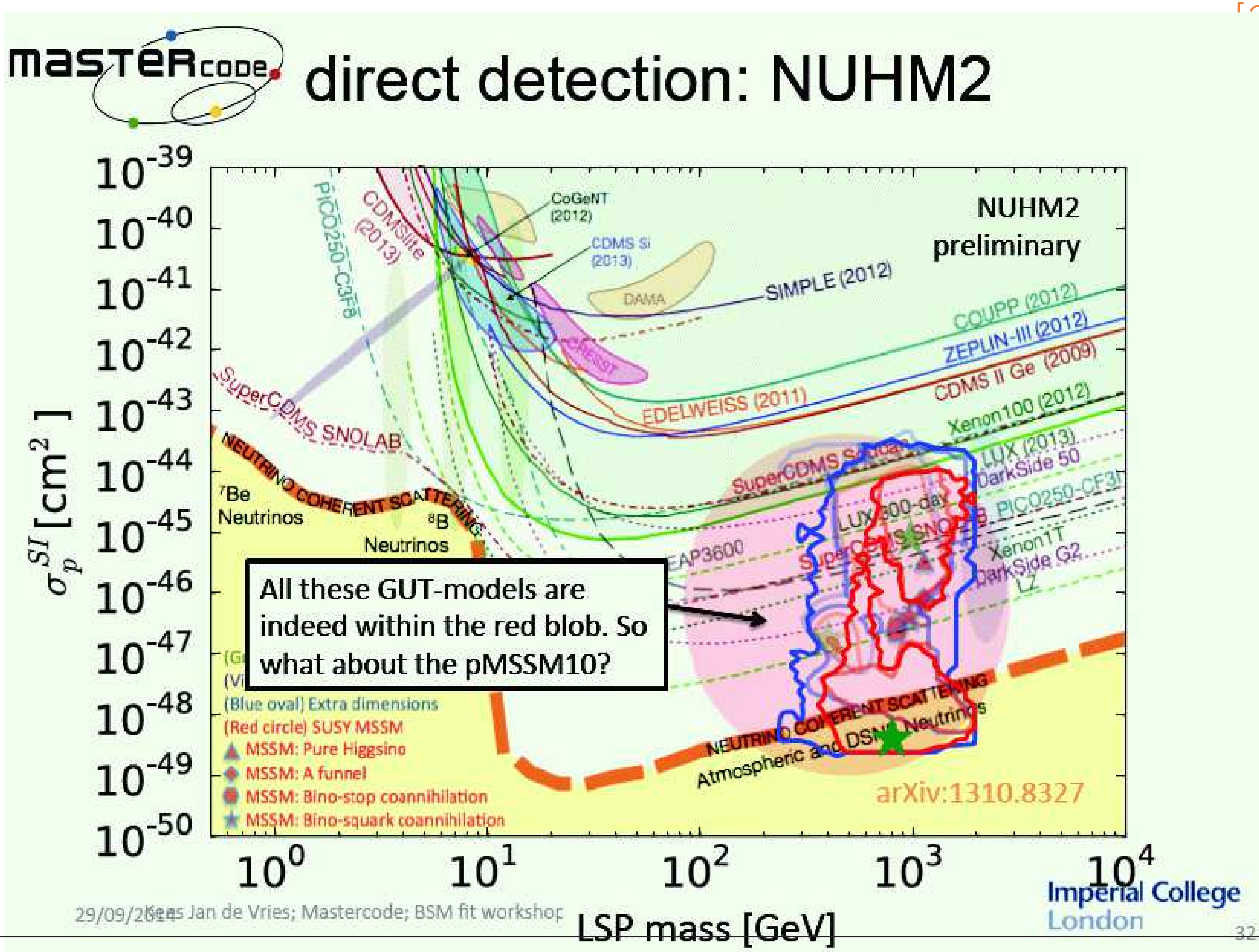
MSSM Direct Detection prediction: NUHM1

[?2014]



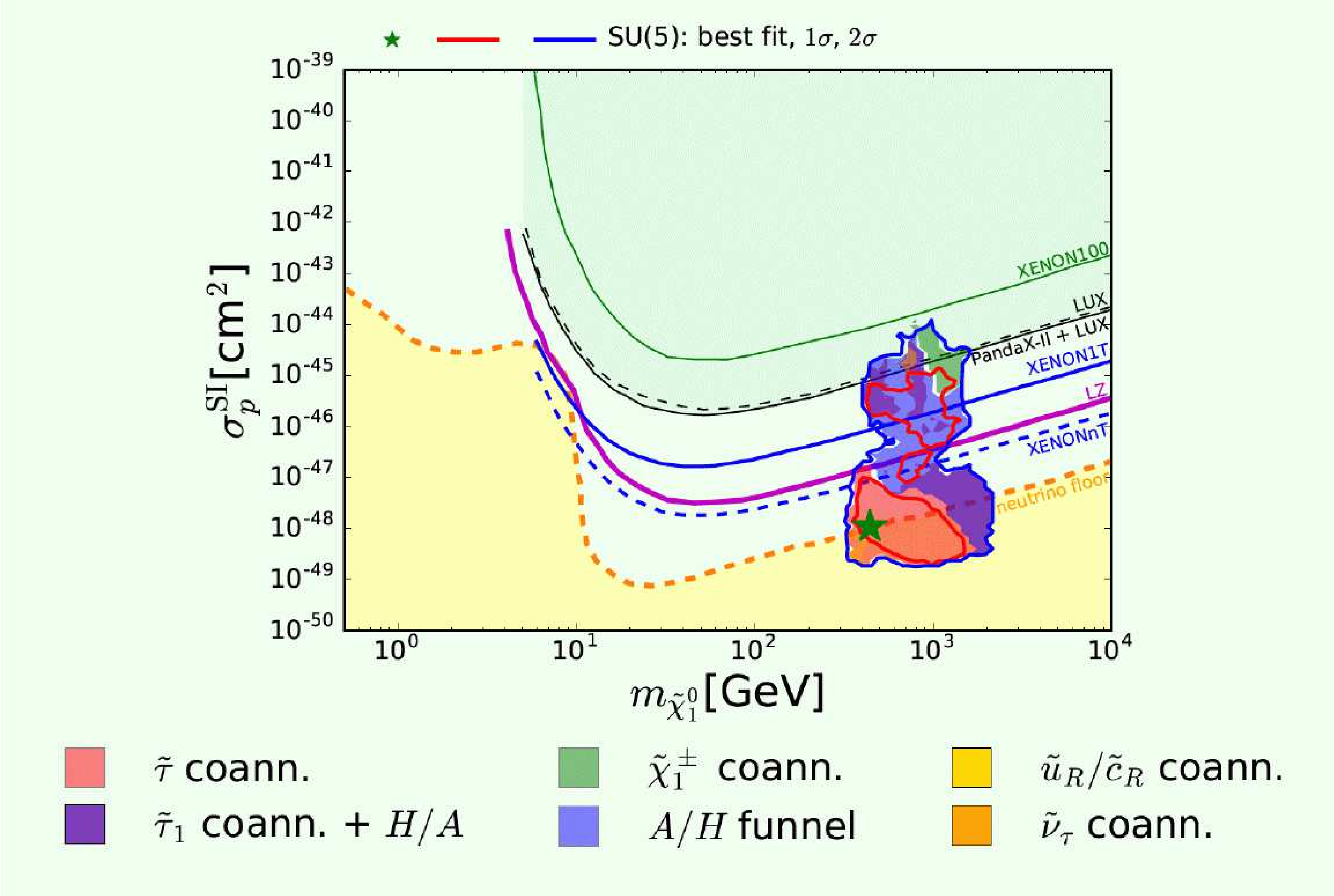
MSSM Direct detection prediction: NUHM2

[?2014]



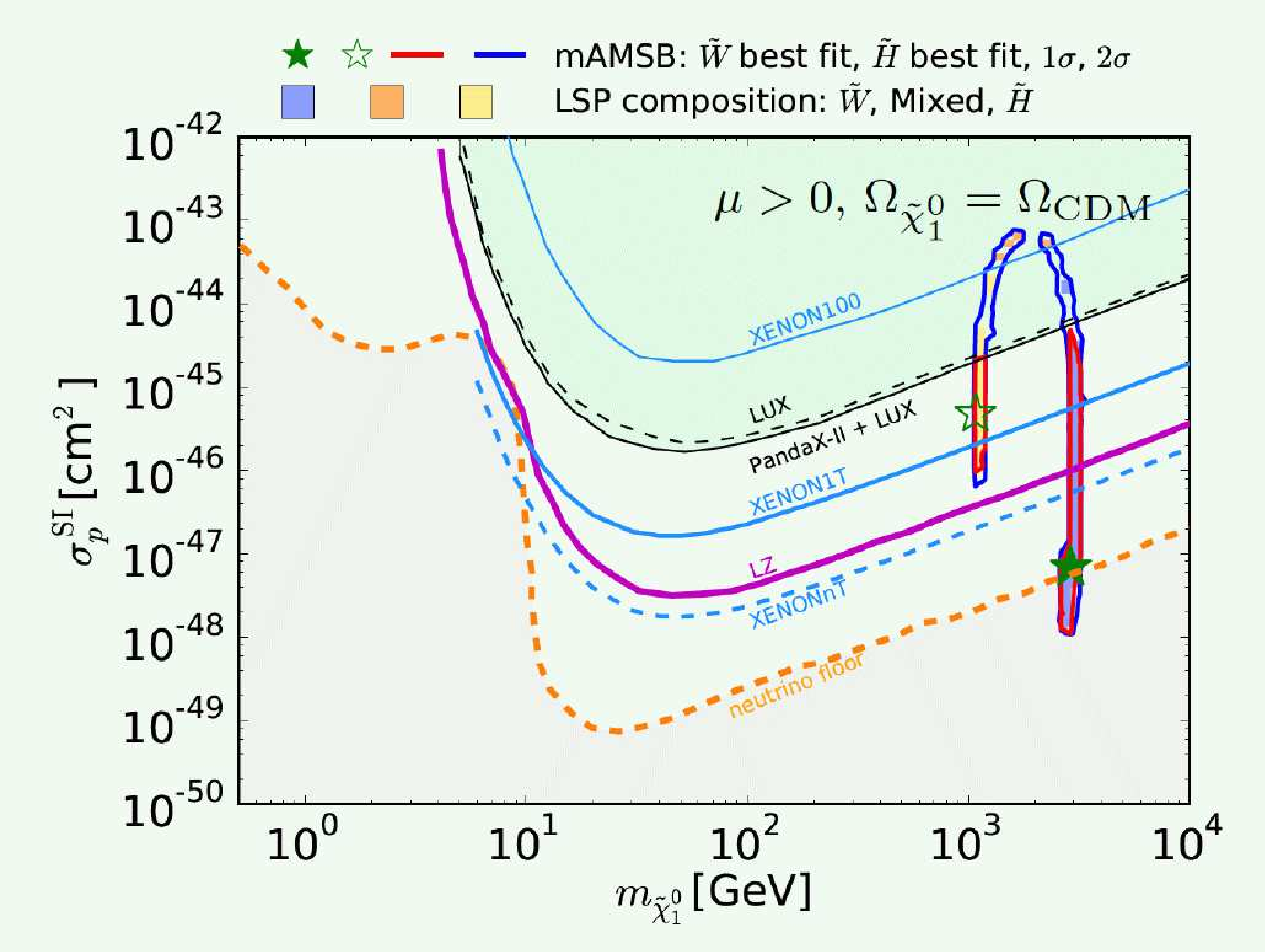
MSSM Diret Detection prediction: SU(5)

[2016]

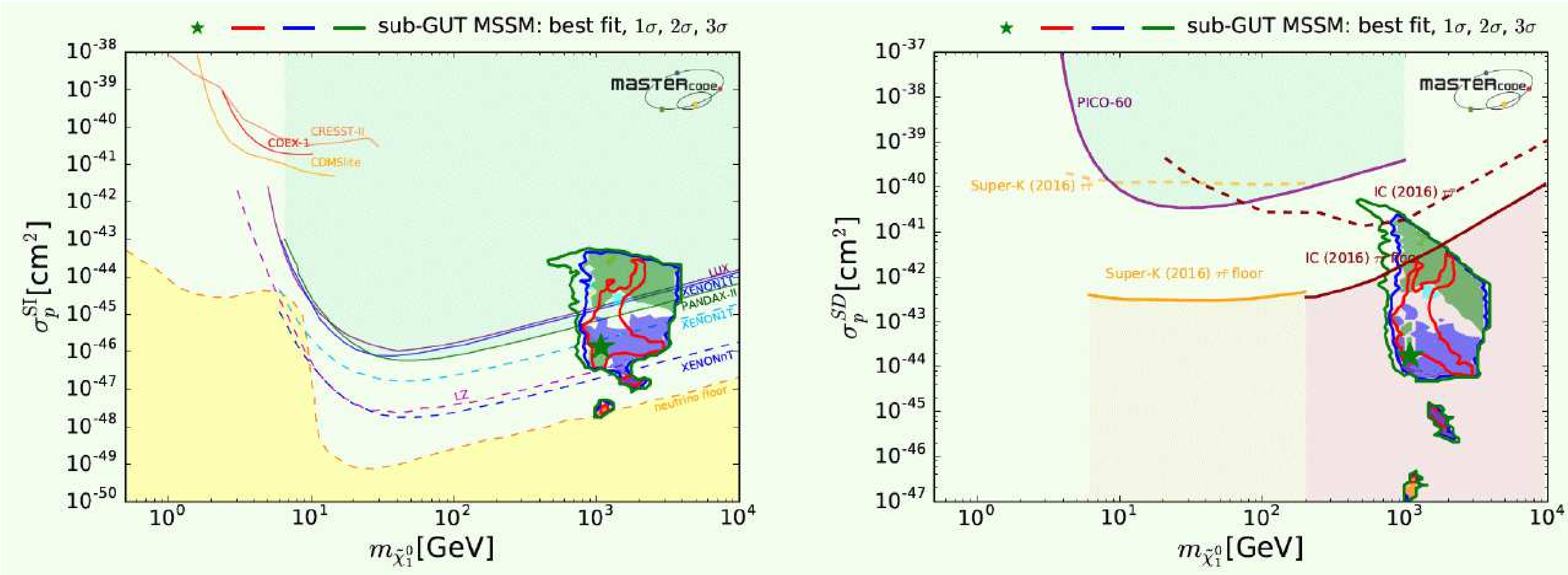


MSSM Diret Detection prediction: mAMSB:

[2016]



MSSM Diret Detection prediction: sub-GUT

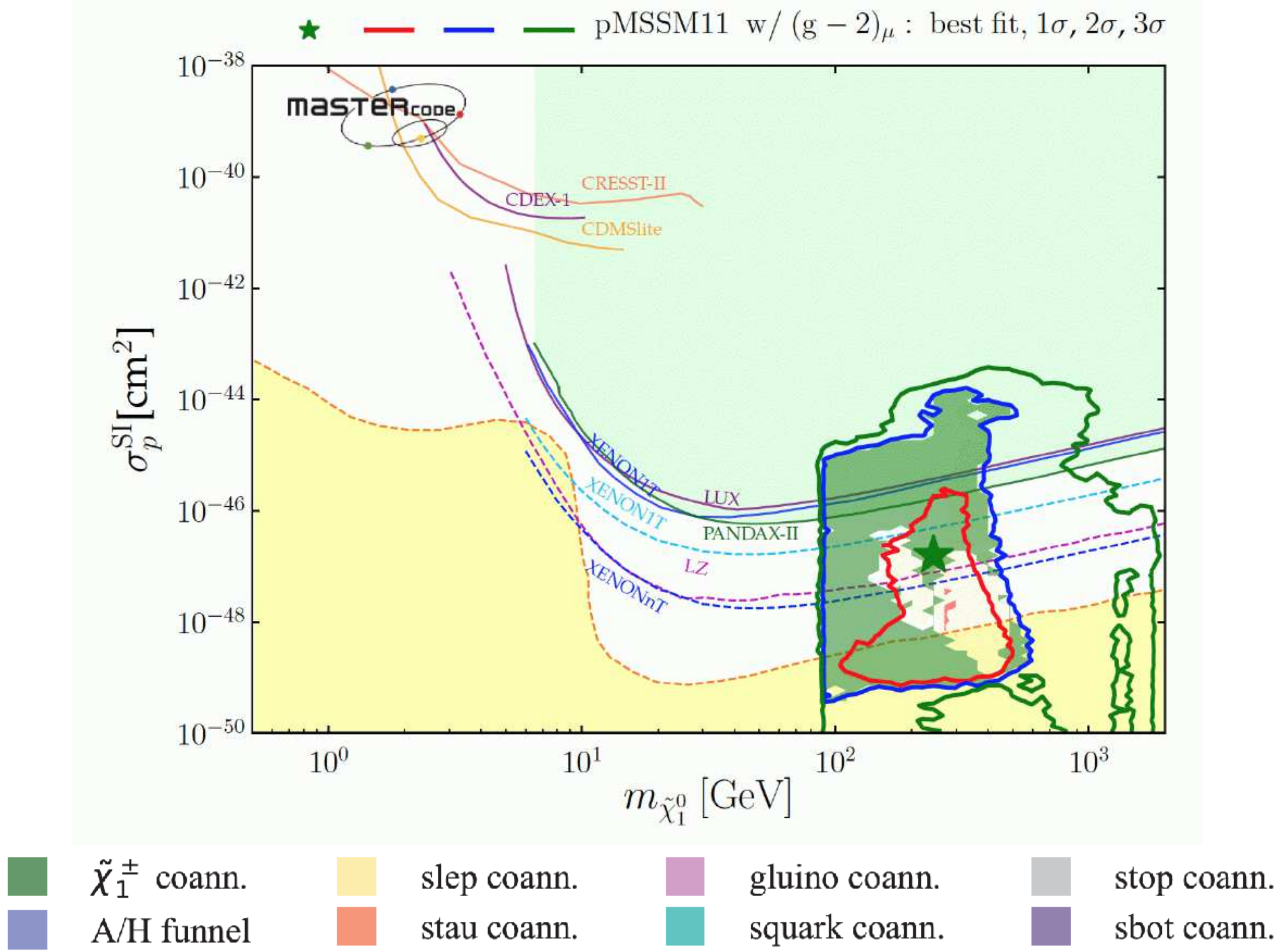


- $\tilde{\chi}_1^\pm$ coann.
- A/H funnel
- $\tilde{t}_1$ coann.
- $\tilde{\tau}_1$ coann.
- focus point
- $\tilde{t}_1$ coann. + H/A funnel
- $\tilde{\tau}_1$ + $\tilde{t}_1$ coann.
- $\tilde{t}_1$ + $\tilde{\chi}_1^\pm$ coann.
- $\tilde{\tau}_1$ coann. + $\tilde{t}_1$ coann. + H/A

σ_p^{SI} : good prospects, all above the neutrino floor

σ_p^{SD} : unclear prospects, best-fit regions below the neutrino floor

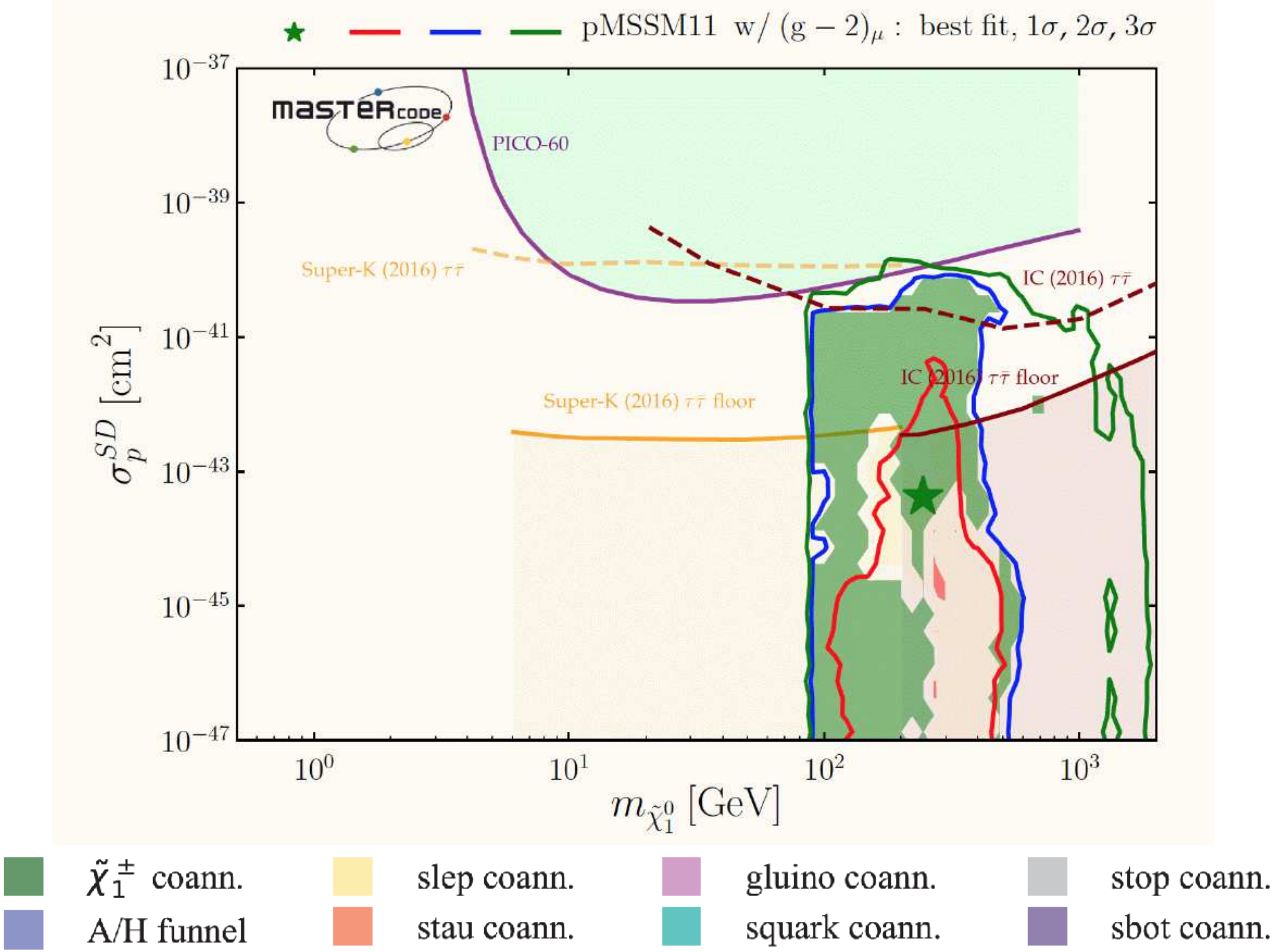
MSSM Direct detection prediction: pMSSM11: $m_{\tilde{\chi}_1^0}$ vs. $\sigma_p^{\rm SI}$: [2017]



⇒ best-fit point covered by future experiments

⇒ but very low cross sections possible at $1\,\sigma$, below neutrino floor

MSSM Direct detection prediction: pMSSM11: $m_{\tilde{\chi}_1^0}$ vs. σ_p^{SD}: [2017]

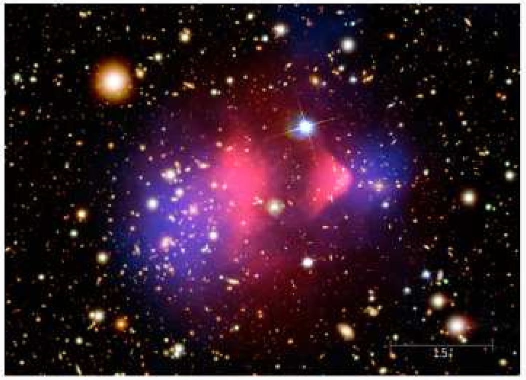


⇒ slim prospects for future experiments

⇒ large regions allowed at $1\,\sigma$, below neutrino floor

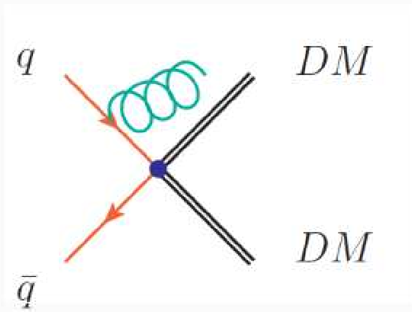
Dark Matter @ LHC

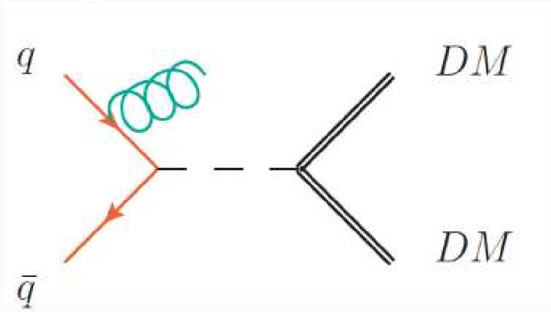
- We infer the existence of Dark Matter (DM) from indirect observations (cosmological, astrophysical).
- Can we probe DM at the LHC? Yes, if we assume that it couple sufficiently strongly to the SM (freeze-out points to that). *Unknown: the mass.*
- DM searches at the LHC fully underway.



How to predict the signals and interpret the results? Different possibilities have been studied:

1. EFT approach.
2. *Dark Matter Simplified Models*
3. Complete models (e.g. SUSY).





[*taken from E. Bagnaschi*]

Approach at the LHC for DMSMs: example for spin-1 mediator

Spin-1 mediator

- Interaction Lagrangian mediator-DM
  $$\mathcal{L}^{Y_1}_{X_D} = \bar{X}_D \gamma_\mu \left(g^V_{X_D} + g^A_{X_D} \gamma_5 \right) X_D Y_1^\mu .$$
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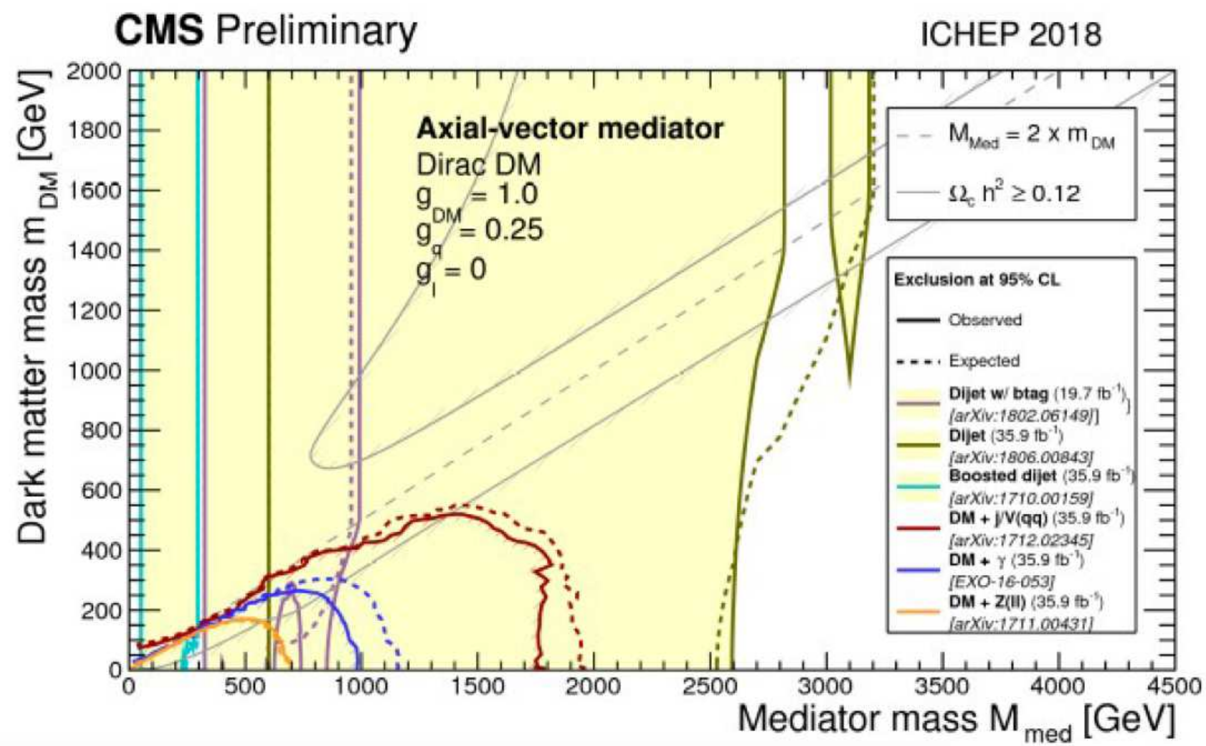


– simplifying assumptions on the Lagrangian (more soon)

– Results for fixed values of $m_{\rm med}$, $m_{\rm DM}$, $g_{\rm SM}$, $g_{\rm DM}$

– overlay results from mono-jet search

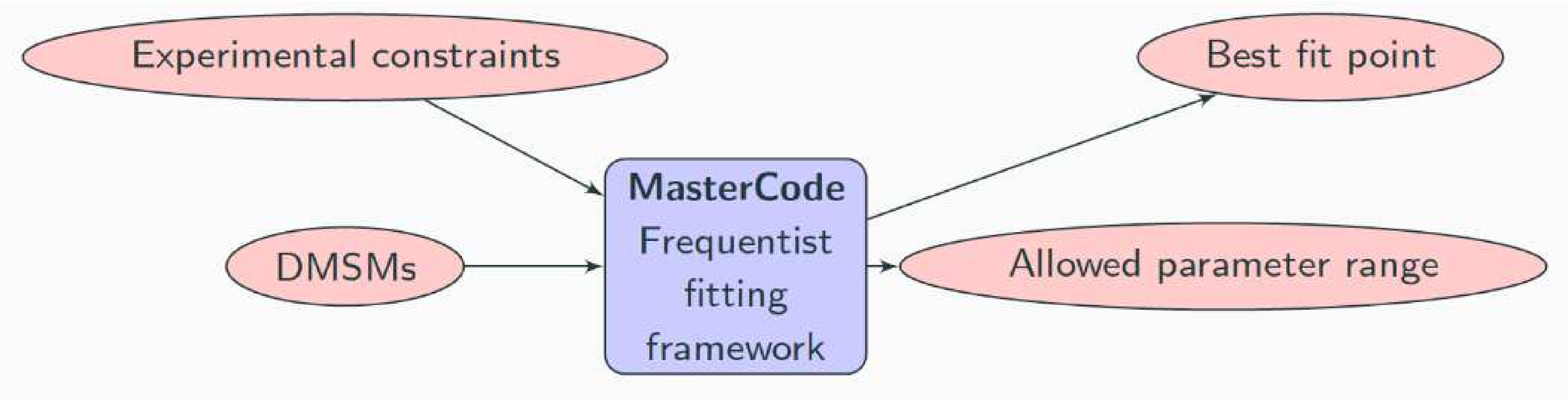
– overlay results from di-jet searches

– . . .

MasterCode approach

[2019]

Fit to the full Lagrangian (some simplifying assumptions)



Included into the fit:

– DM relic density
– DM direct detection limits
– LHC mono-jet searches
– LHC di-jet searches

⇒ global picture of status and prospects

3. Set-up and validation

Lagrangian according to LHC-DM-WG recommendation:

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Scenarios

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2. $g_{X_D}^V = 0$ $\quad g_{X_D}^V \equiv g_{DM}$
   $g_{u/d}^V = 0$ $\quad g_{u/d}^A = g_{SM},$
   pure axial-vector.

[taken from E. Bagnaschi]

MasterCode set-up :

- Frequentist fitting framework written in Python/Cython and C++
- Multinest algorithm is used to sample the parameter space
- udocker used for deployment

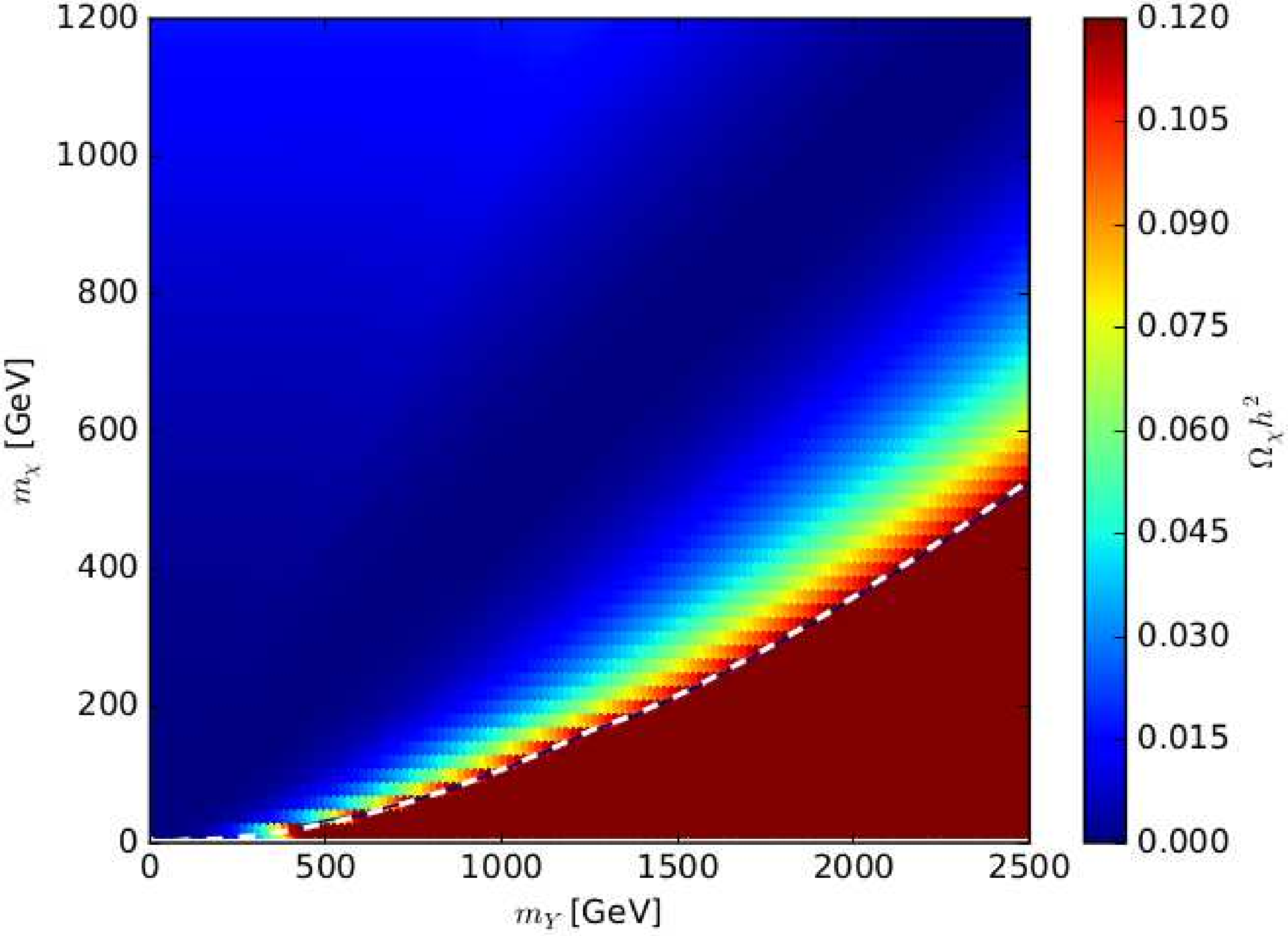
Scan ranges:

Parameter	Range	# of Segments
m_Y (mediator)	$(0.1, 5)$ TeV	10
m_χ (DM)	$(0, 2.5)$ TeV	8
$g_{\rm SM}$	$(10^{-6}, \sqrt{4\pi})$	2
$g_{\rm DM}$	$(10^{-6}, \sqrt{4\pi})$	2
Total # of segments		320

DM constraints:

[2019]

⇒ micrOMEGAs for relic density and DD cross sections

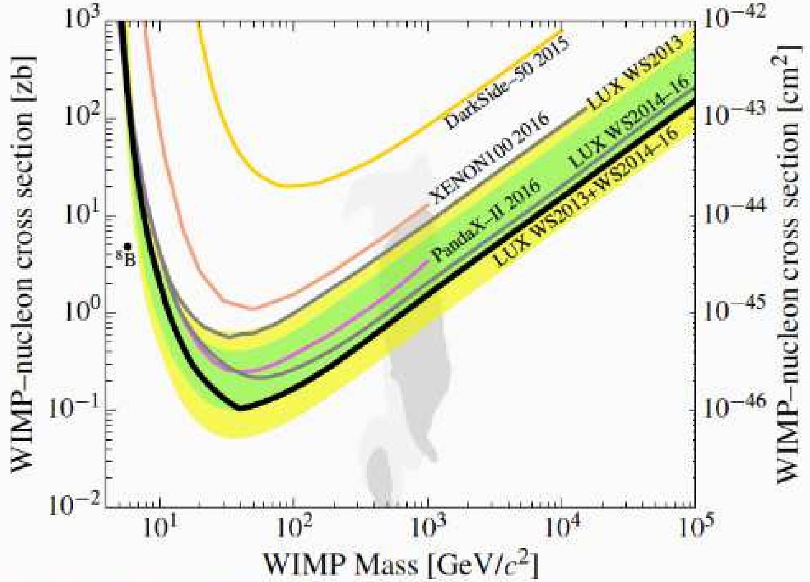


⇒ full agreement with ATLAS/CMS results (here: vector model)

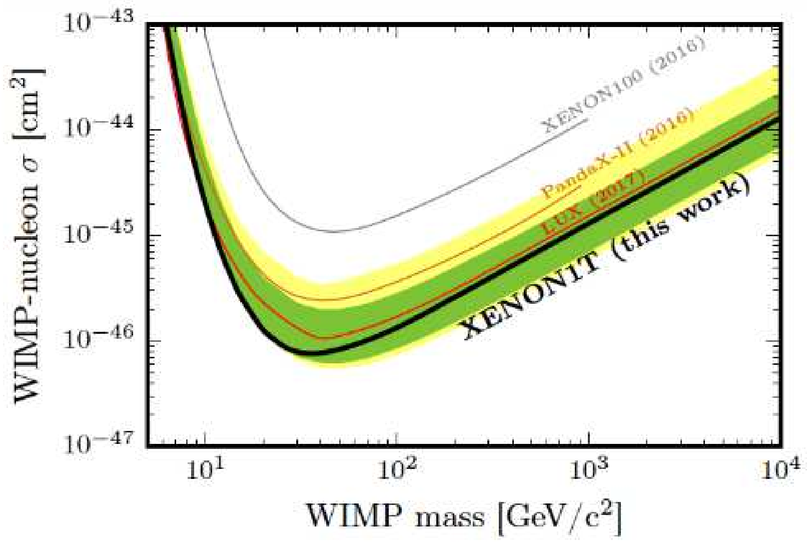
Non-LHC constraints

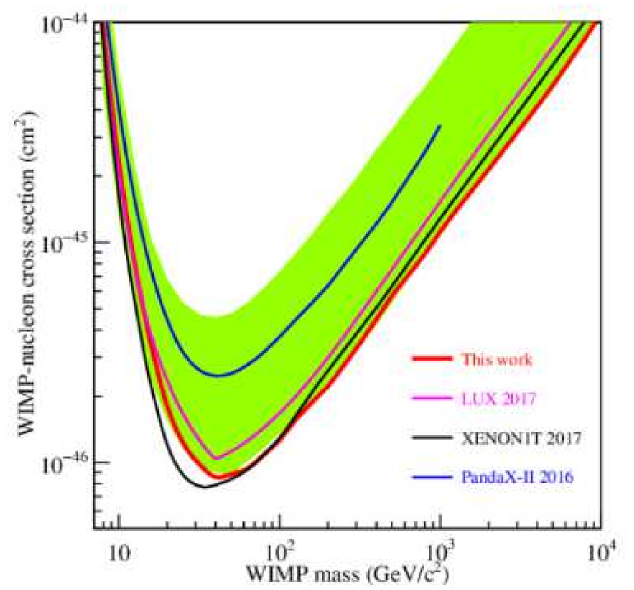
Dark matter

- Relic density constraints from Planck.
- Direct detection constraints on σ_p^{SI} from LUX, XENON1T and PANDAX.
- Direct detection constraints on σ_p^{SD} from PICO60.



[1608.07648, 1705.06655, 1708.06917]



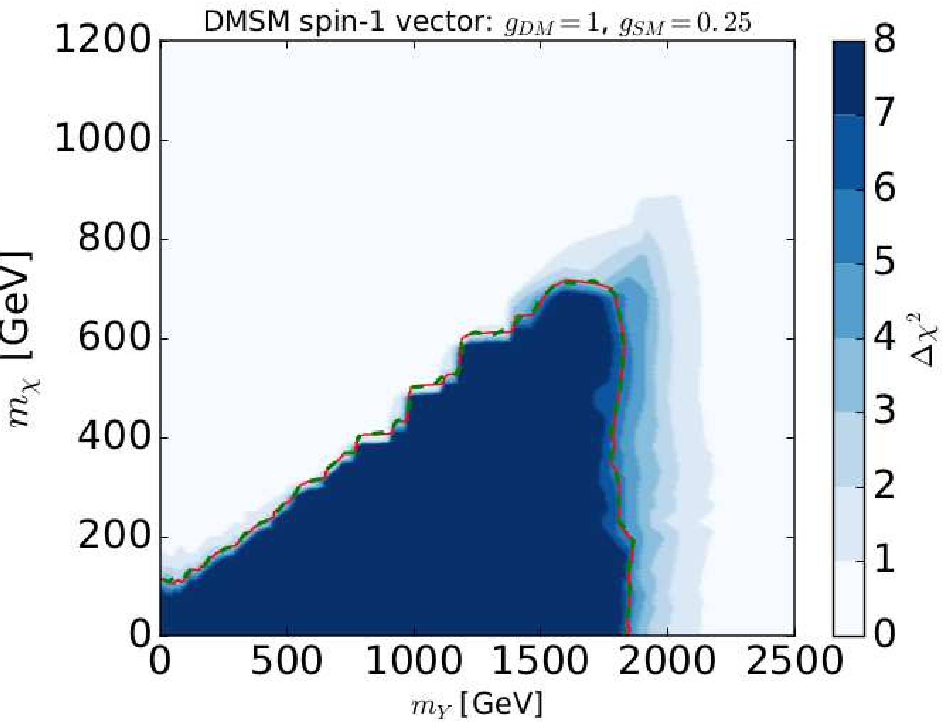


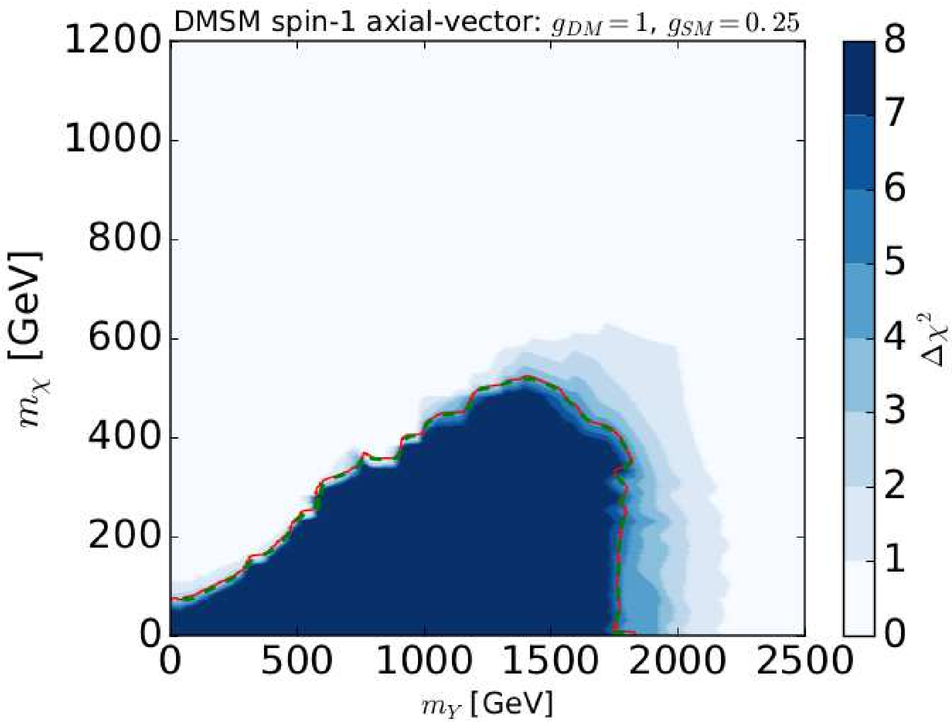
[*taken from E. Bagnaschi*]

Mono-jet constraints

[2019]

⇒ MG5 aMC(N)LO, Fastlim approach



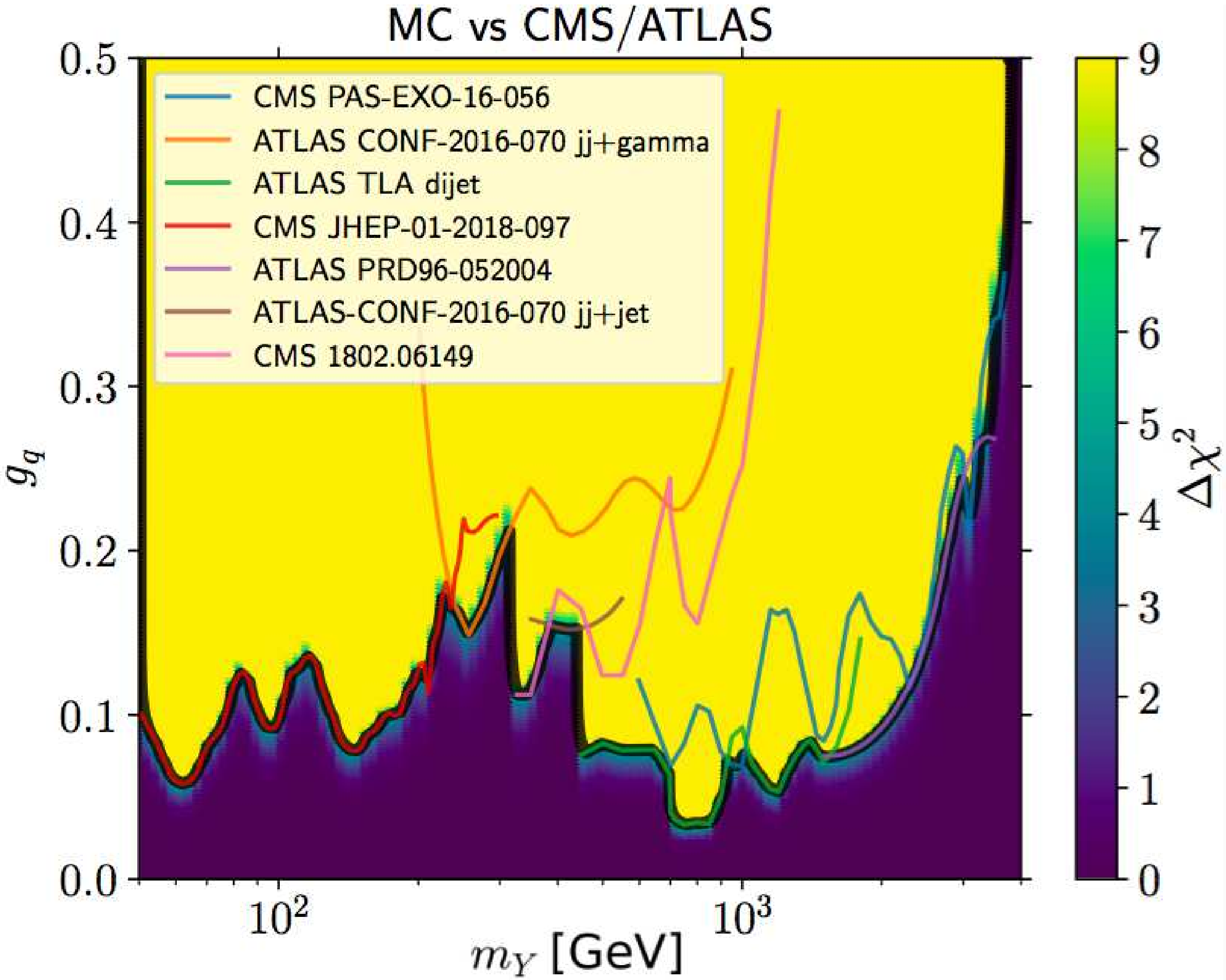


⇒ full agreement with ATLAS/CMS (red-dashed)

Di-jet constraints

[2019]

⇒ MG5 aMC(N)LO, Fastlim approach



⇒ full agreement with ATLAS/CMS

4. General Results

[2019]

- Results for vector mediator model

- Results for axial-vector mediator model

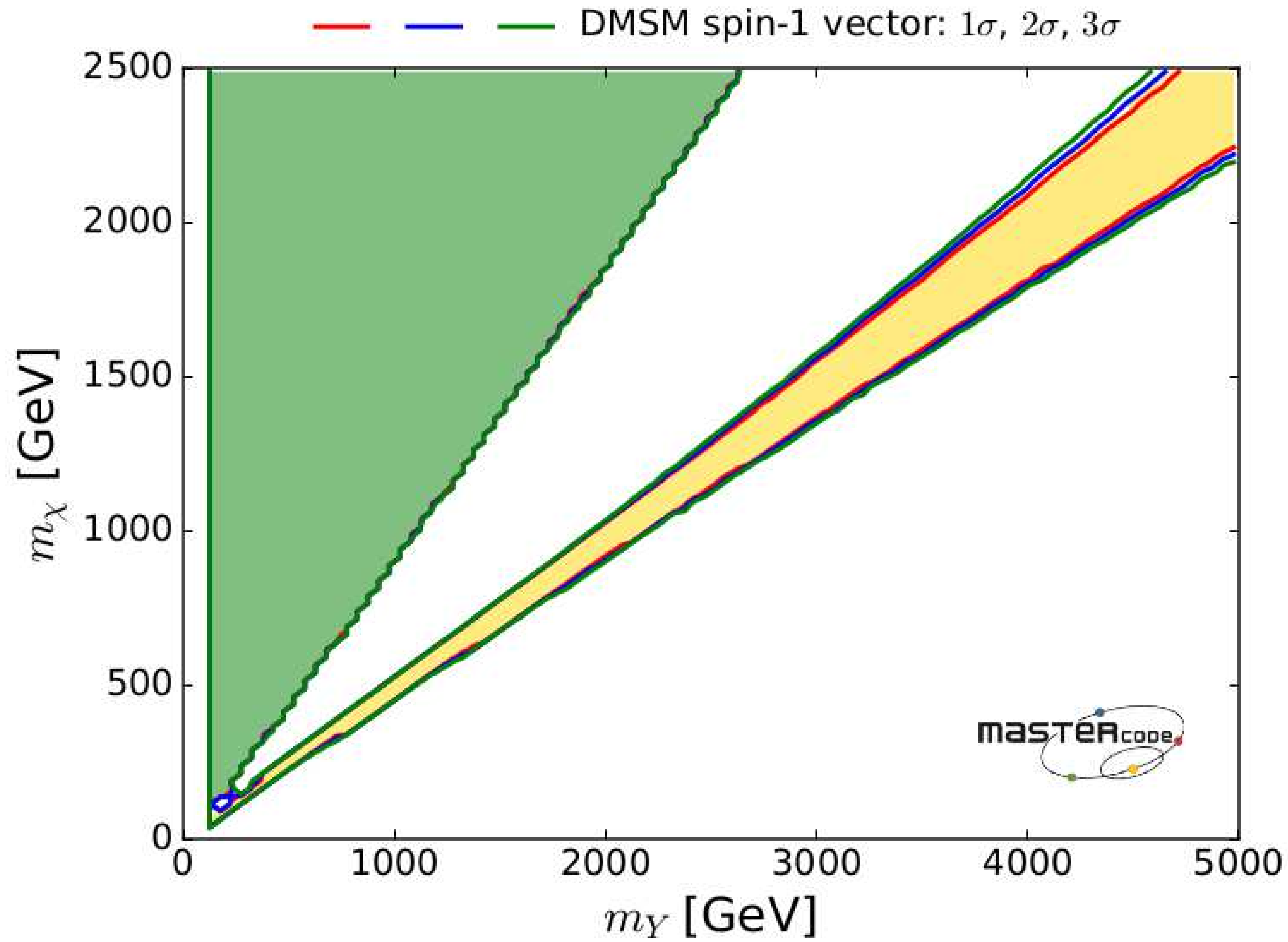
- No restrictions on couplings or masses

- Color coding:

  green: annihilation via t-channel χ exchange into pairs of mediator particles Y that subsequently decay into SM particles

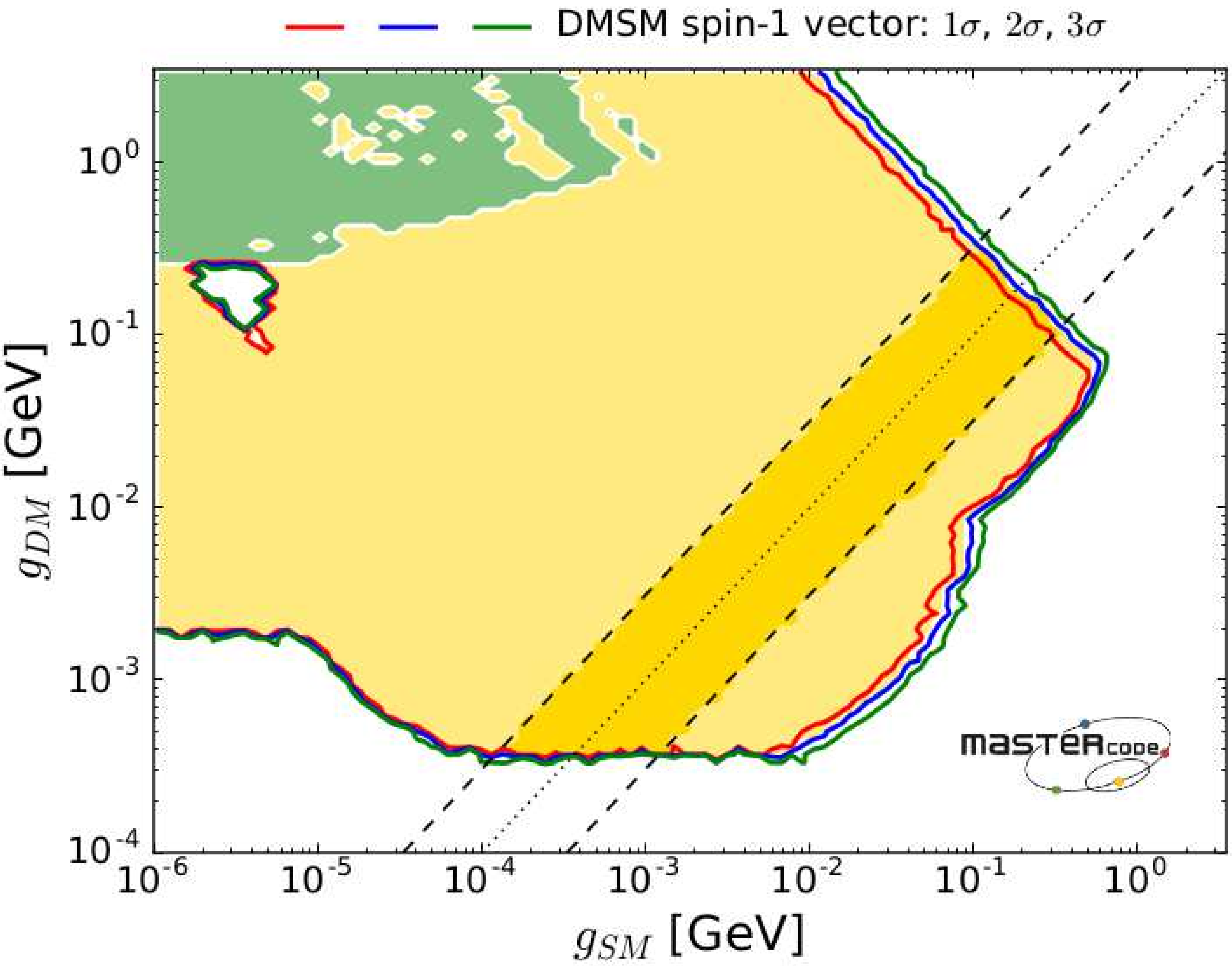
  yellow: rapid annihilation directly into SM particles via the s-channel Y resonance

Vector mediator (I): [2019]



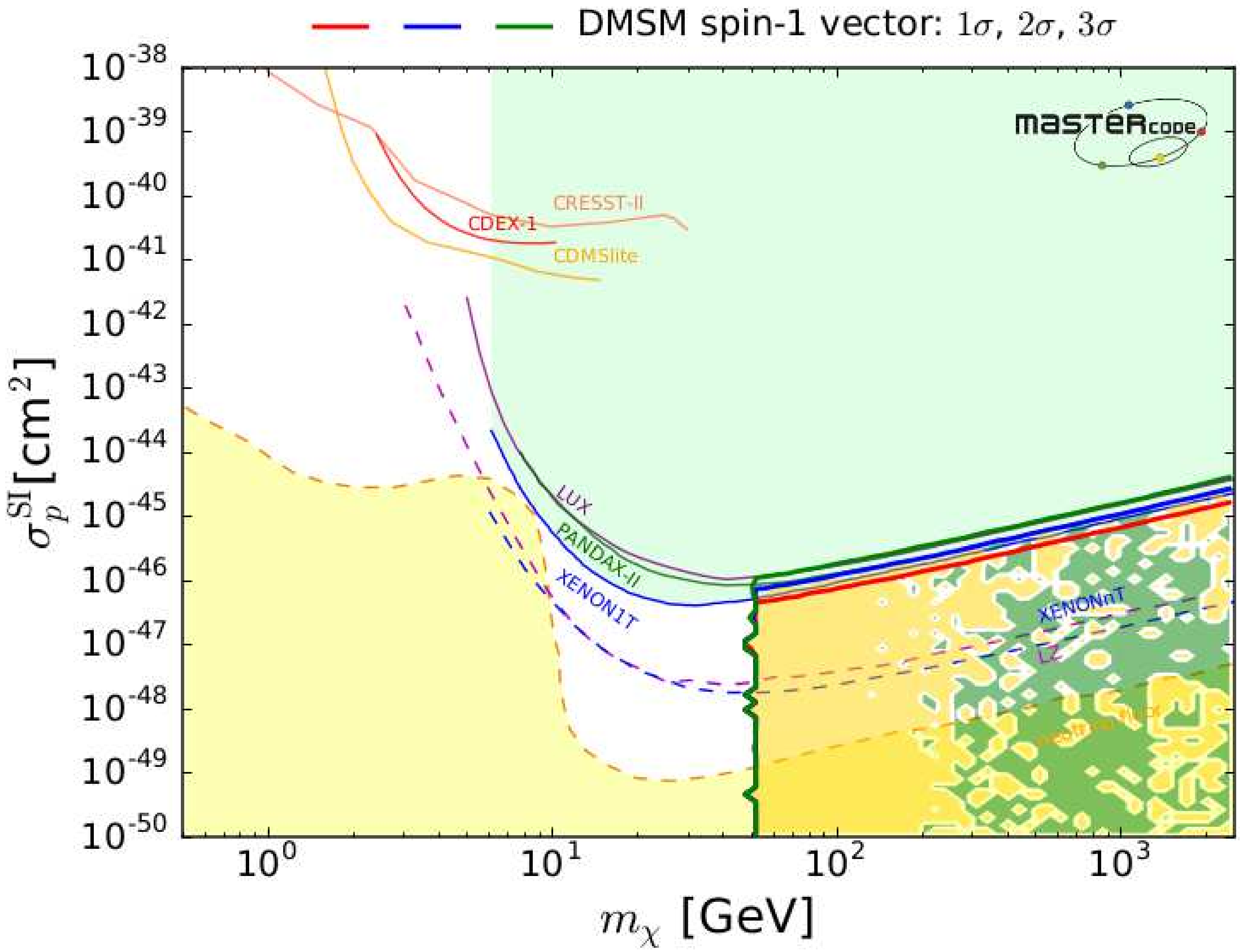
⇒ clear separation between s- and t-channel

Vector mediator (II): [2019]



$\Rightarrow$ large ranges allowed, t-channel only for $g_{\text{DM}} \gg g_{\text{SM}}$

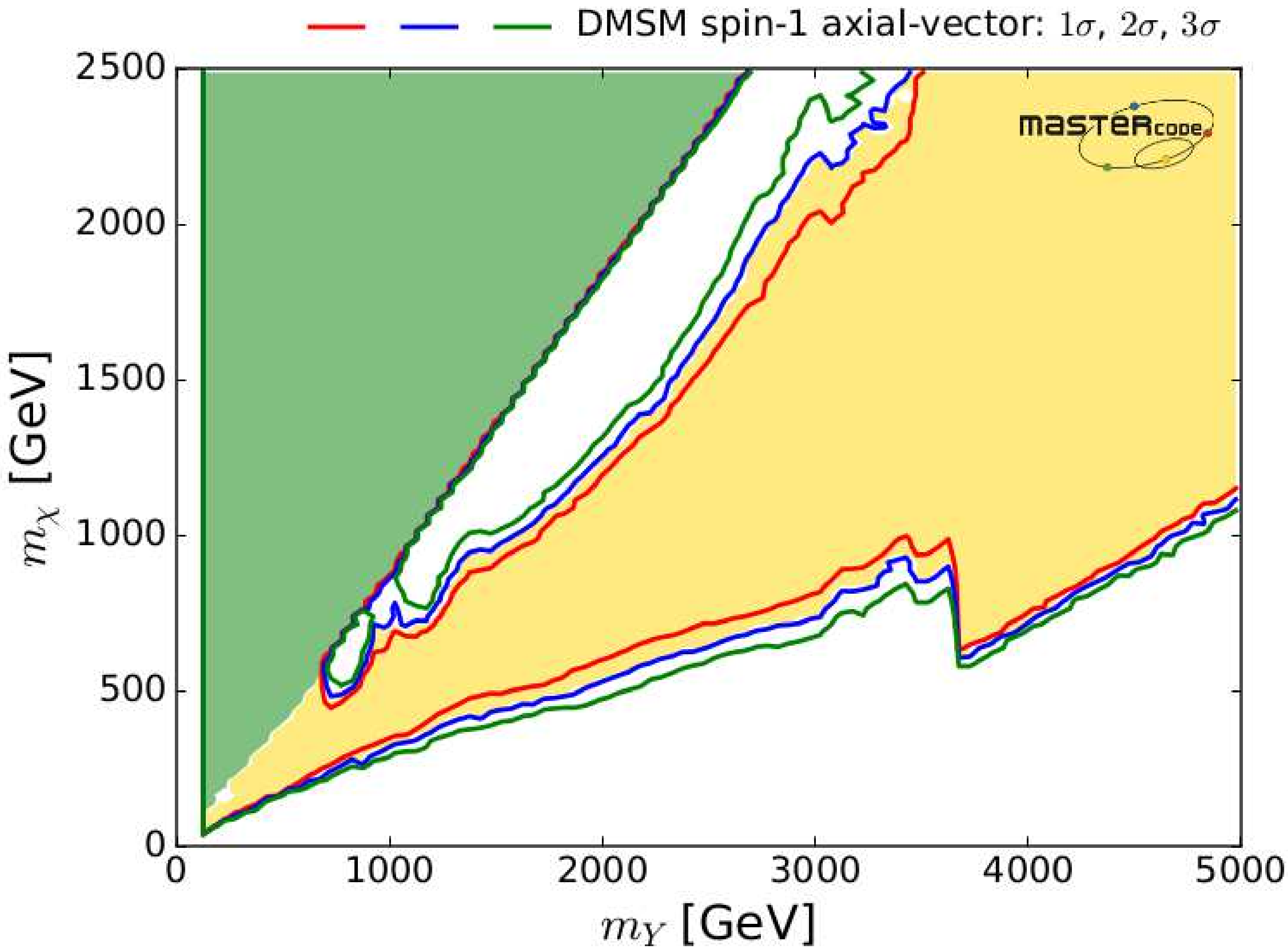
Vector mediator (III): [2019]



$\Rightarrow$ mixed prospects, both for s- and t-channel case

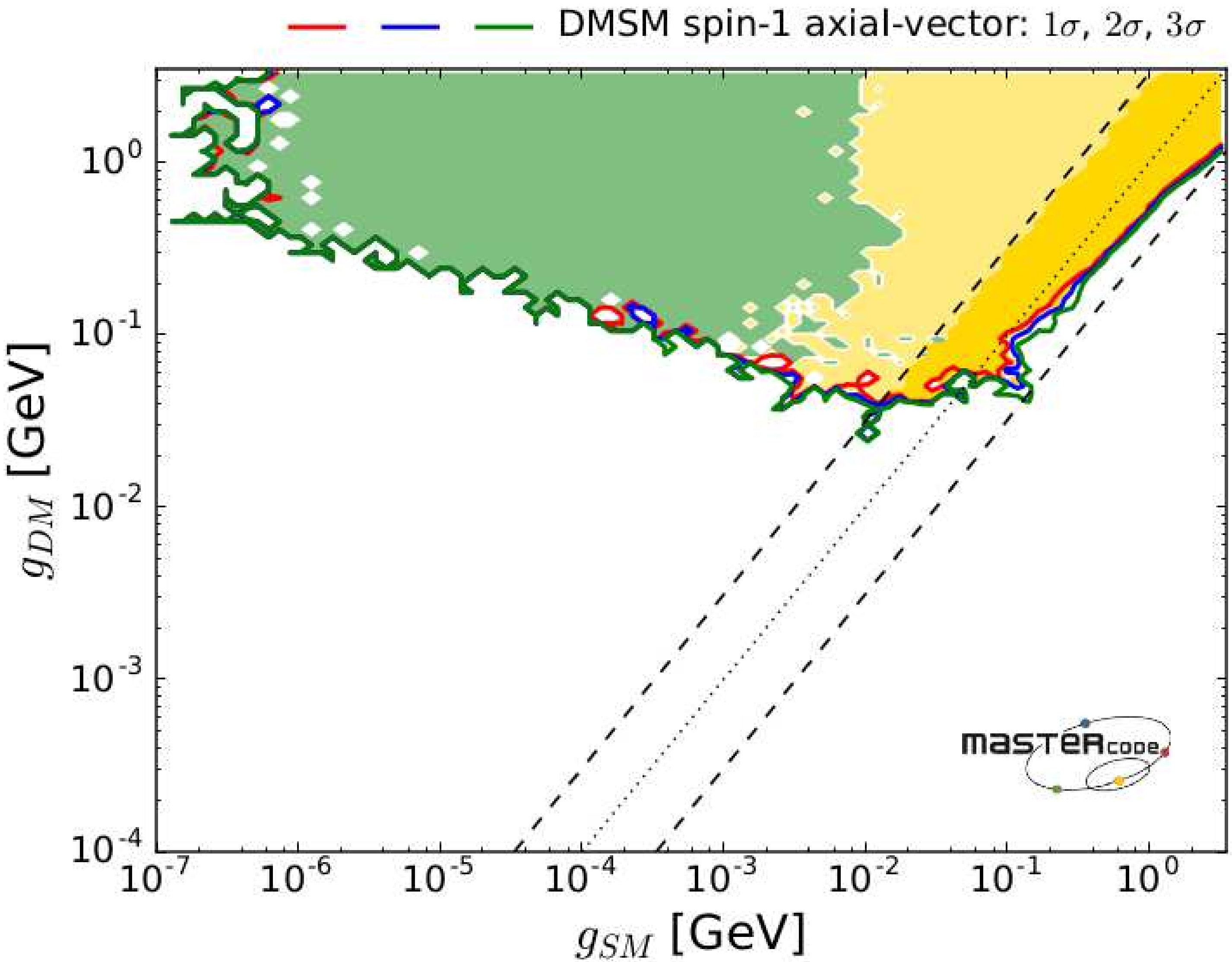
Axial-vector mediator (I):

[2019]



⇒ Larger s-channel region, continous with t-channel

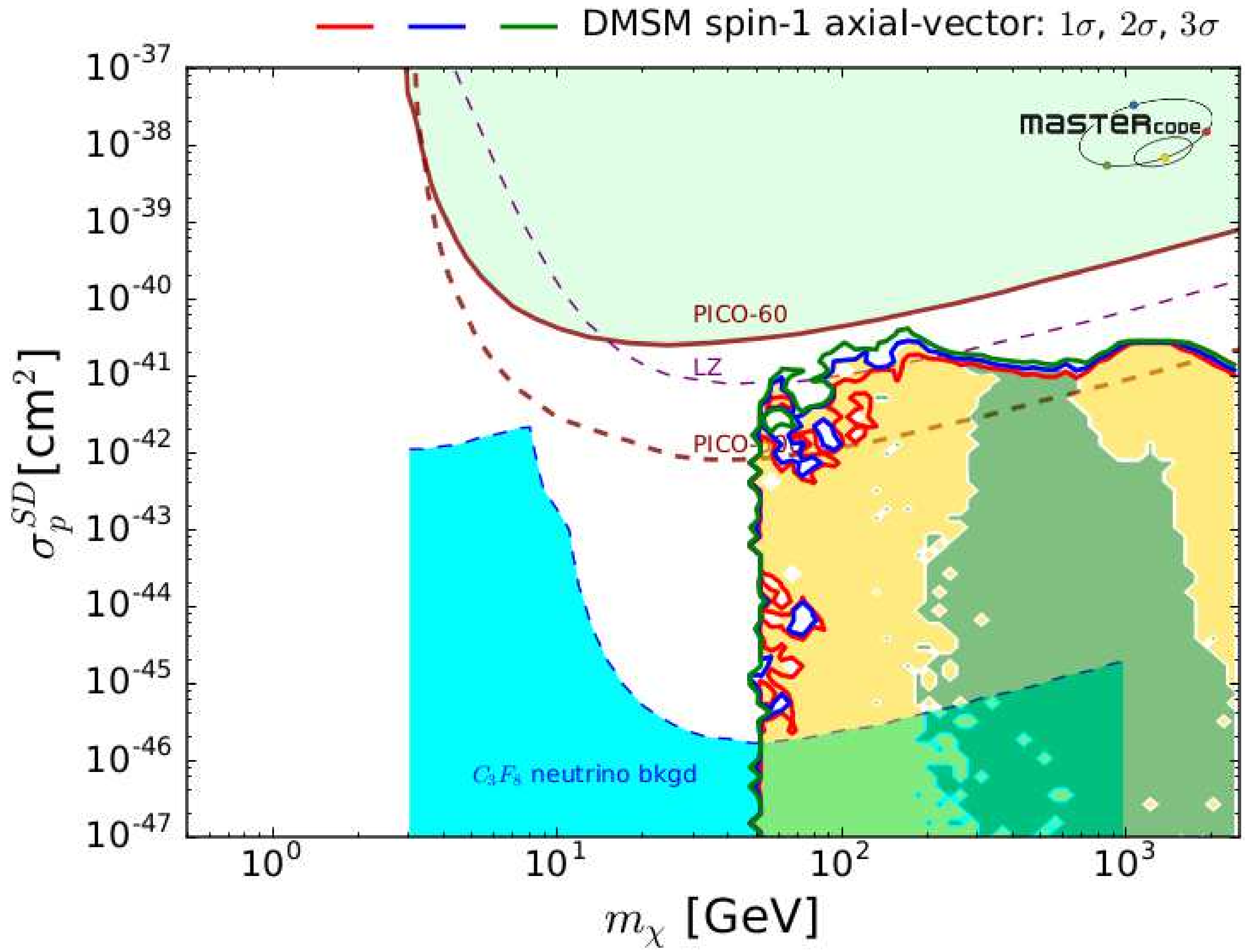
Axial-vector mediator (II): [2019]



$\Rightarrow$ t- (s-)channel for $g_{\text{SM}} \lesssim (\gtrsim) 10^{-2}$

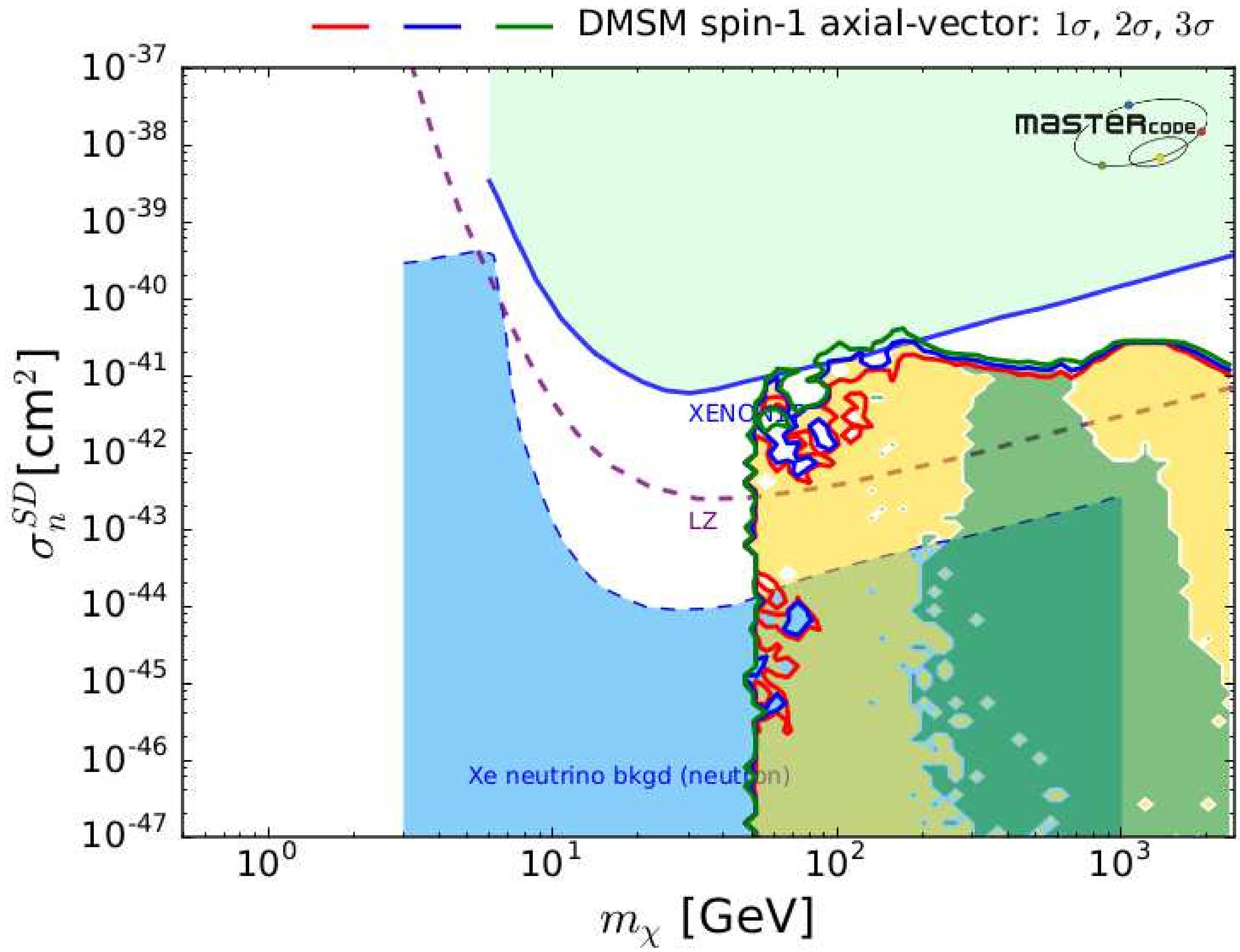
Axial-vector mediator (III):

[2019]



⇒ will not be easy for PICO!

Axial-vector mediator (III): [2019]



⇒ neither for LZ!

5. Towards UV completions

$\Rightarrow$ So far no UV completion considered!

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In any UV completion the spin-one boson could be expected to have comparable couplings to SM and DM particles, modulo possible group-theoretical factors and mixing angles!

$$g_{\mathrm{DM}}/g_{\mathrm{SM}} = \mathcal{O}(1)$$

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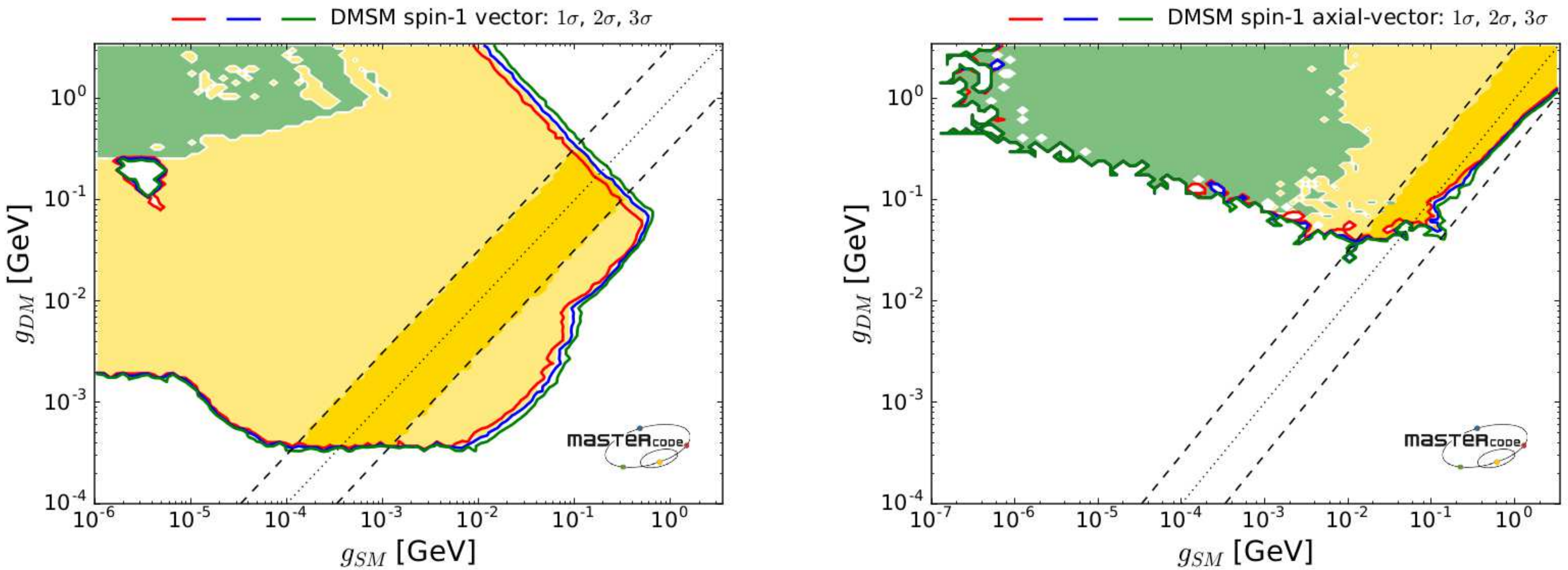
$\Rightarrow$ So far no UV completion considered!

In any UV completion the spin-one boson could be expected to have comparable couplings to SM and DM particles, modulo possible group-theoretical factors and mixing angles!

$$g_{\rm DM}/g_{\rm SM} = \mathcal{O}(1)$$

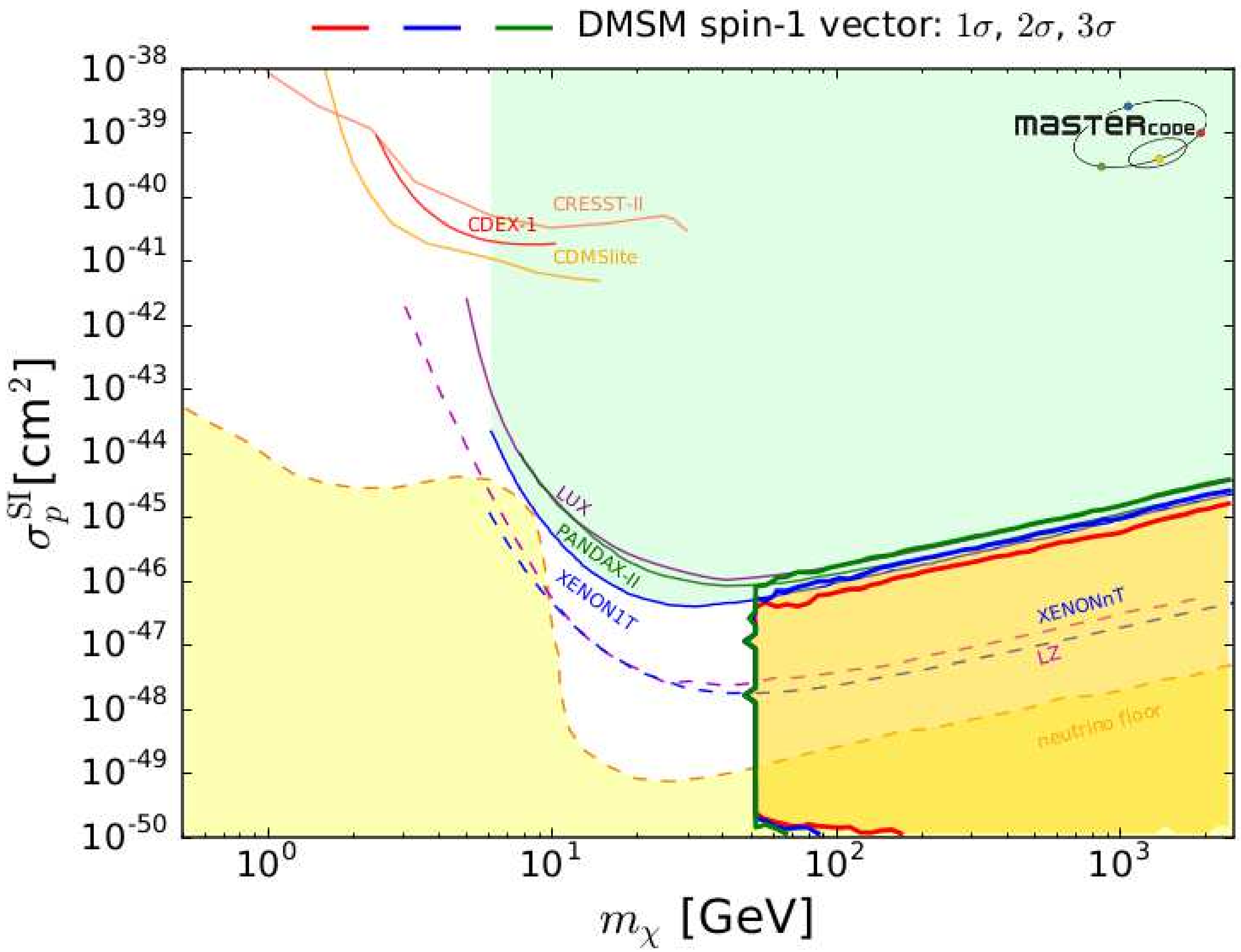
$$1/3 < g_{\rm DM}/g_{\rm SM} < 3$$



$\Rightarrow$ dark yellow regions $\Rightarrow$ s-channel favored!

Vector mediator: towards UV completions

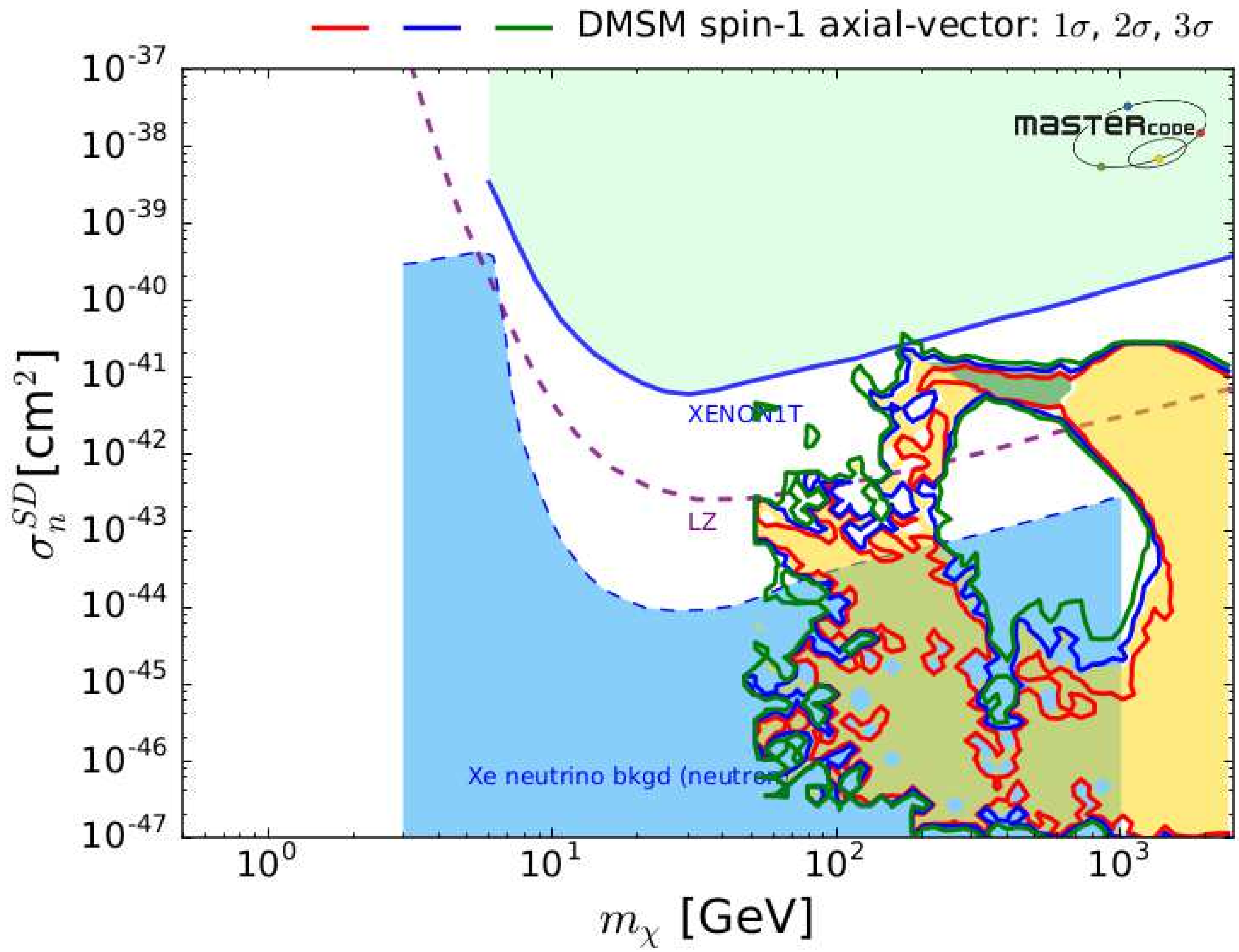
[2019]



⇒ mixed prospects for discovery

Axial-vector mediator: towards UV completions

[2019]



$\Rightarrow$ t-channel can fully be probed, s-channel only partially

6. Conclusions

- Many SUSY analyses performed, with mixed prospects for DD
- EFT vs. DMSM vs. full theories
- Lagrangian for vector or axial-vector mediator
- So far results presented for fixed values for some of $g_{\rm SM}$, $g_{\rm DM}$, $m_{\rm med}$, $m_{\rm DM}$ and other constraints (mono-jet, di-jet) overlaid
- MasterCode approach: full fit of the model, including
  - DM relic density
  - DM direct detection limits
  - LHC mono-jet searches
  - LHC di-jet searches
- Vector mediator: s- and t-channel separated, mixed prospects for DD
- Axialvector: s- and t-channel continous, mixed prospects for DD
- UV-completions: $1/3 < g_{\rm SM}/g_{\rm DM} < 3 \Rightarrow s$-channel preferred
  $\Rightarrow$ prospects for DD not improved


Further Questions?