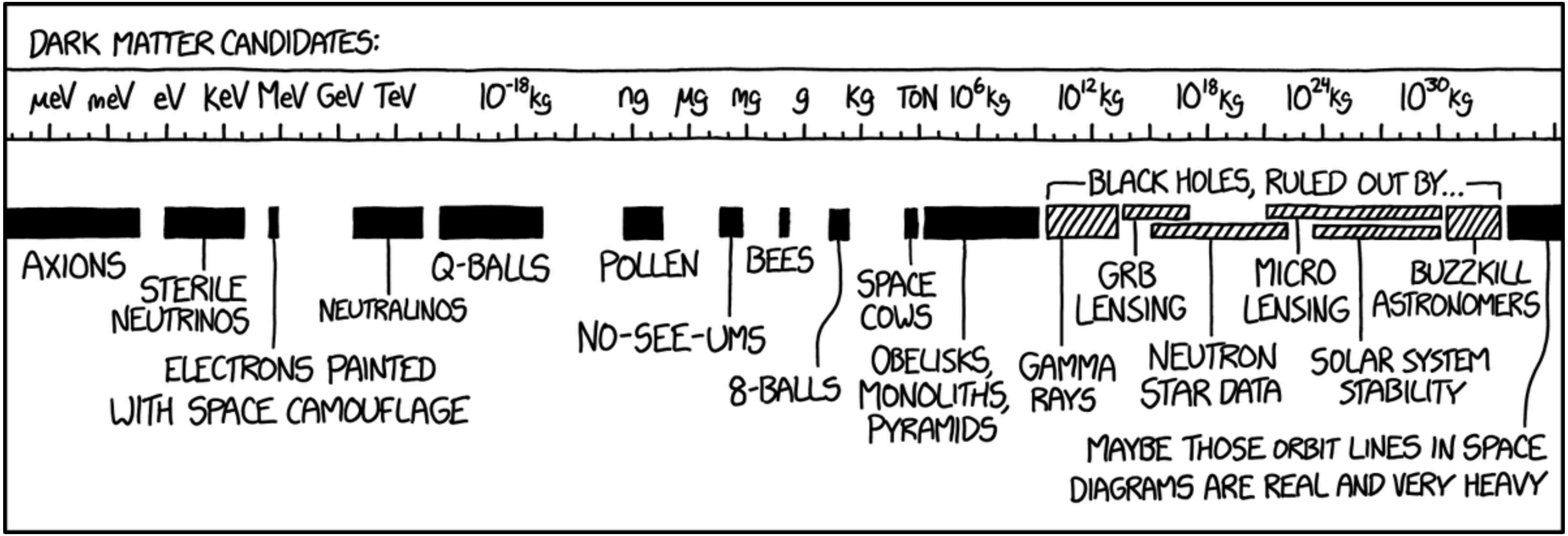
University of BRISTOL

Direct Dark Matter searches and connections to the LHC BSM programme

Henning Flächer

University of Bristol

Dark Matter Candidates



https://xkcd.com/2035/

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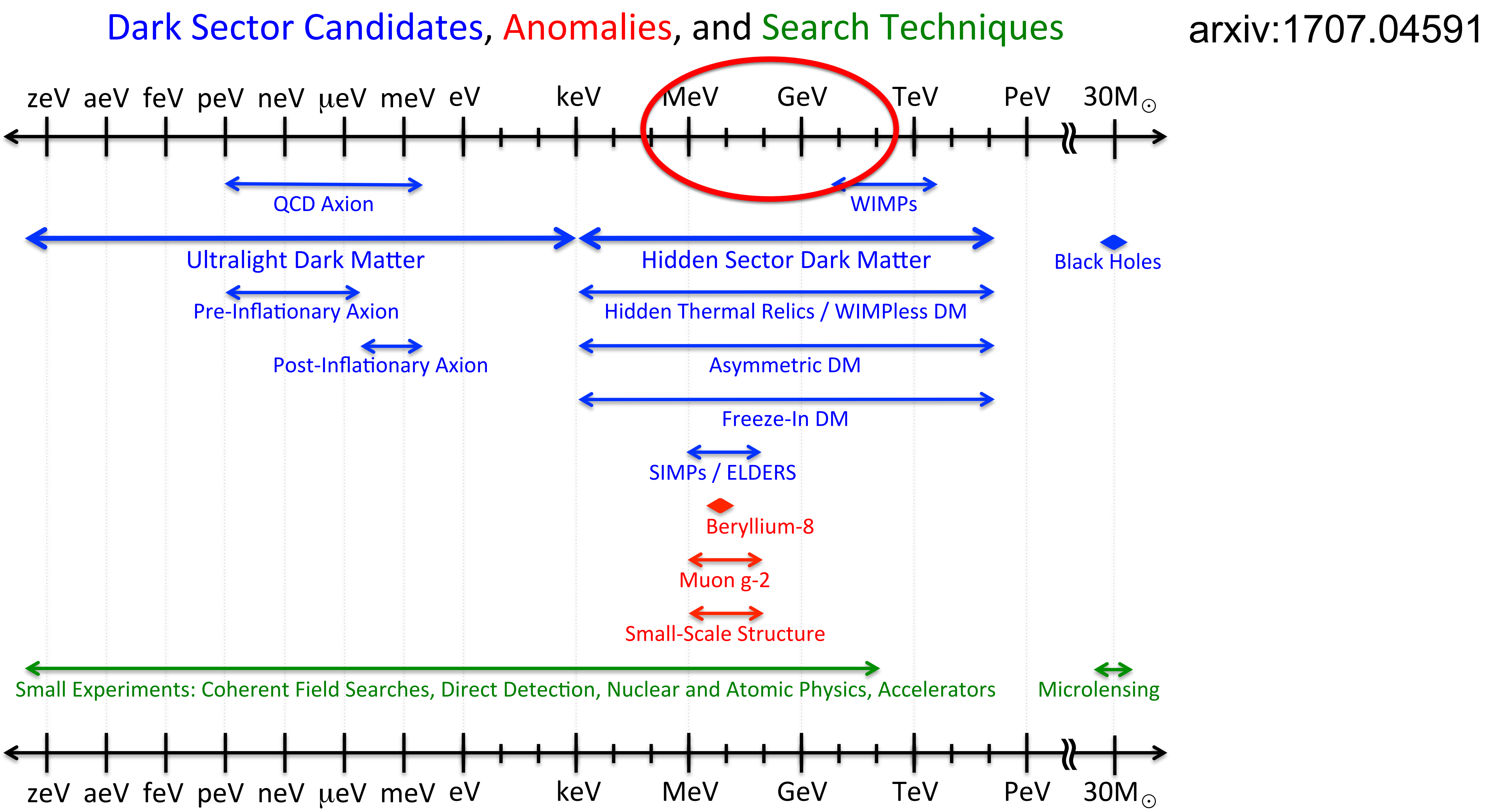

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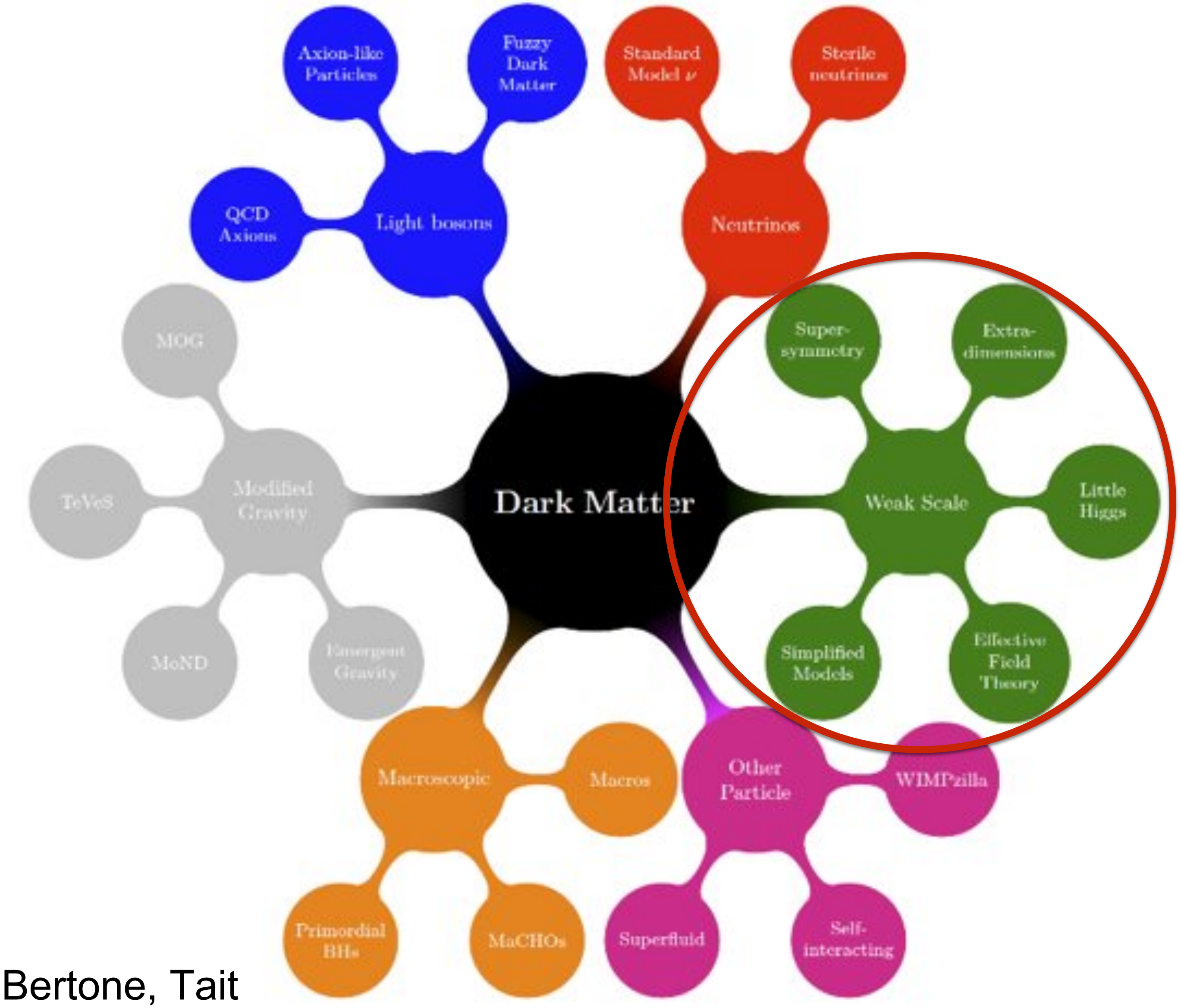
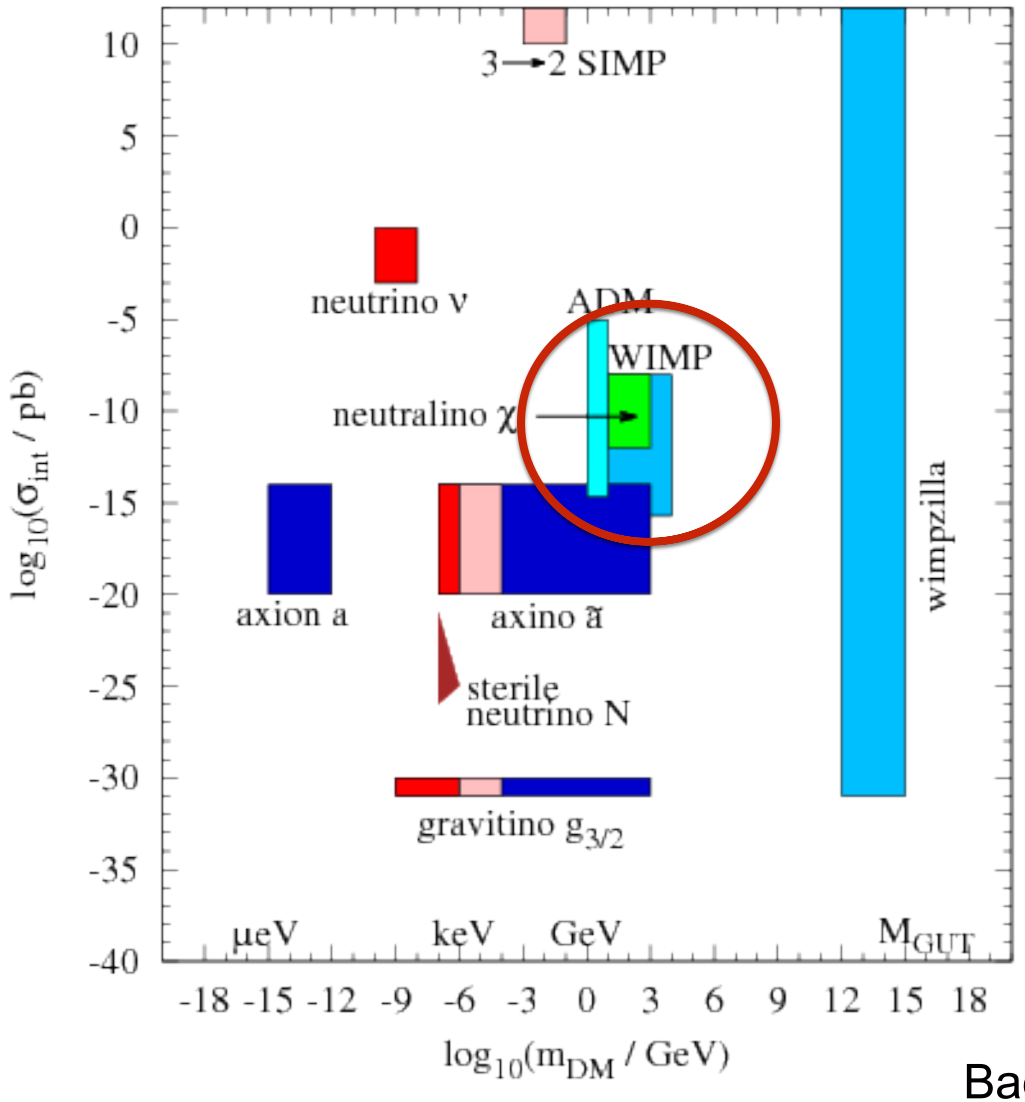


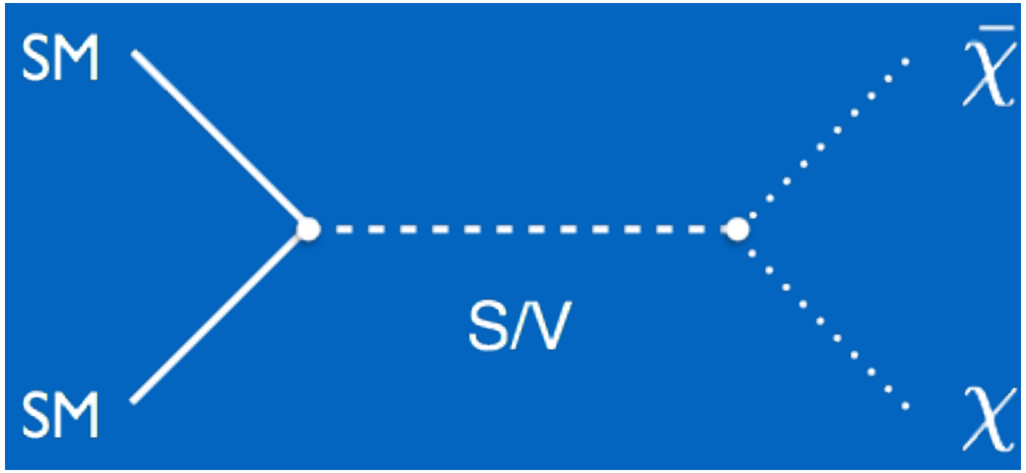
Bertone, Tait



Baer

Simplified Dark Matter models @ LHC

Start with simplest diagram:



Typically parameterized by 4 parameters:

- mass of DM particle, m_{DM}
- mass (and width) of mediator particle, m_Y, (Γ_Y)
- coupling of mediator to SM sector, g_{SM}
- coupling of mediator to DM sector, g_{DM}

Familiar examples of scalar/vector mediator:

- S: Higgs boson
- V: Z' (heavy Z)

LHC choice for couplings (LHC DM WG):

- A/A-V: $g_{SM} = 0.25$, $g_{DM} = 1$
- S/P-S: $g_{SM} = 1$, $g_{DM} = 1$

Simplified Dark Matter models @ LHC

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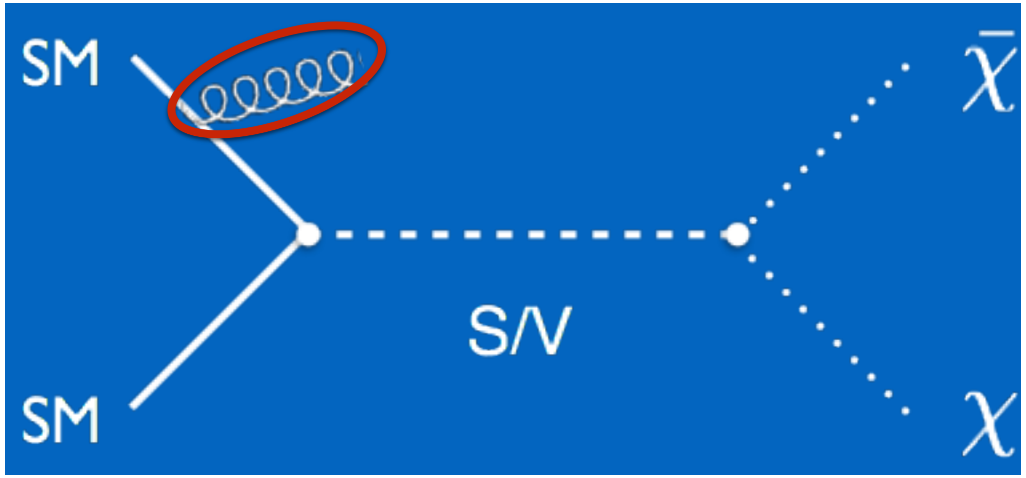

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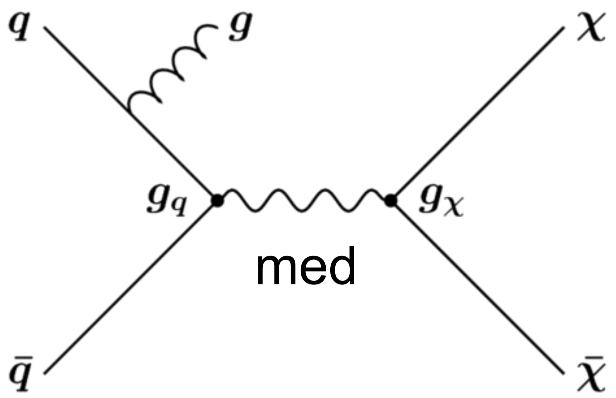
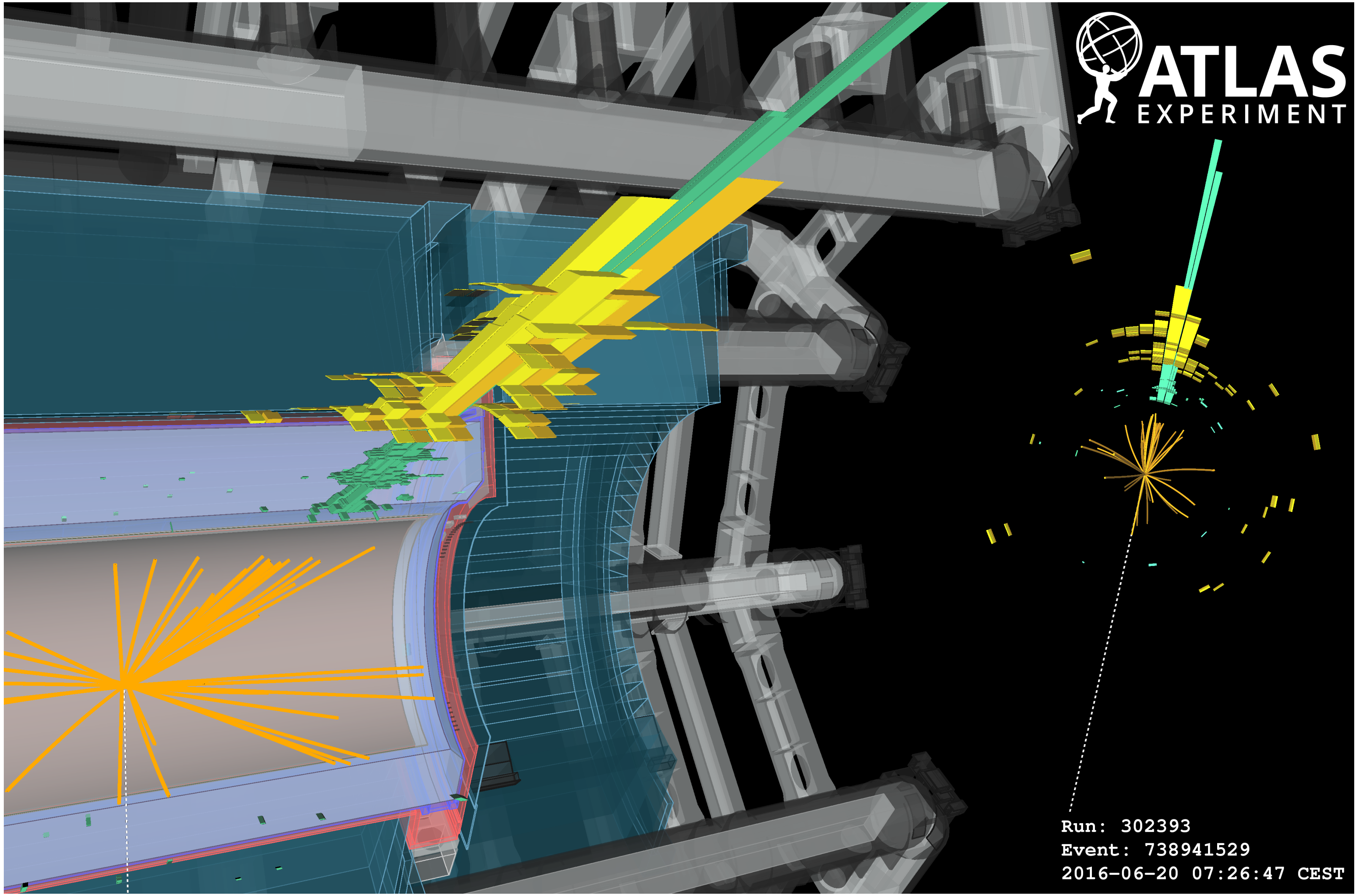
Mono-mania



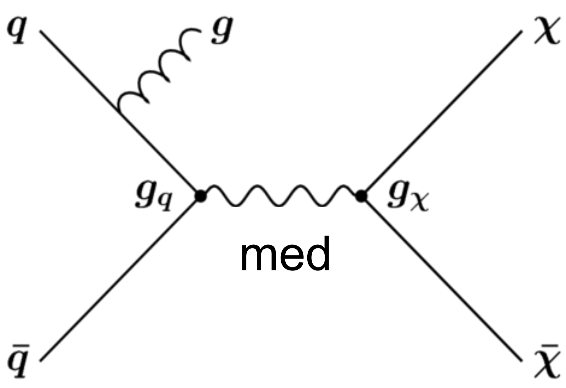
q
g
χ
g_q
g_χ
med
$\bar{q}$
$\bar{\chi}$



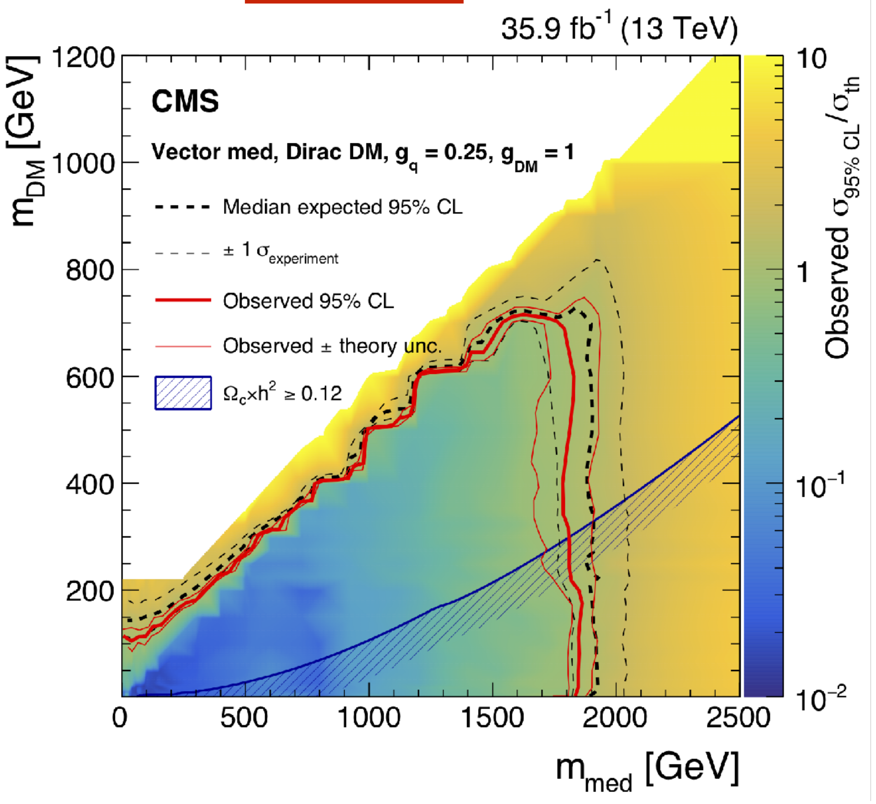
ATLAS
EXPERIMENT
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

Mono-jet & Mono-V Searches

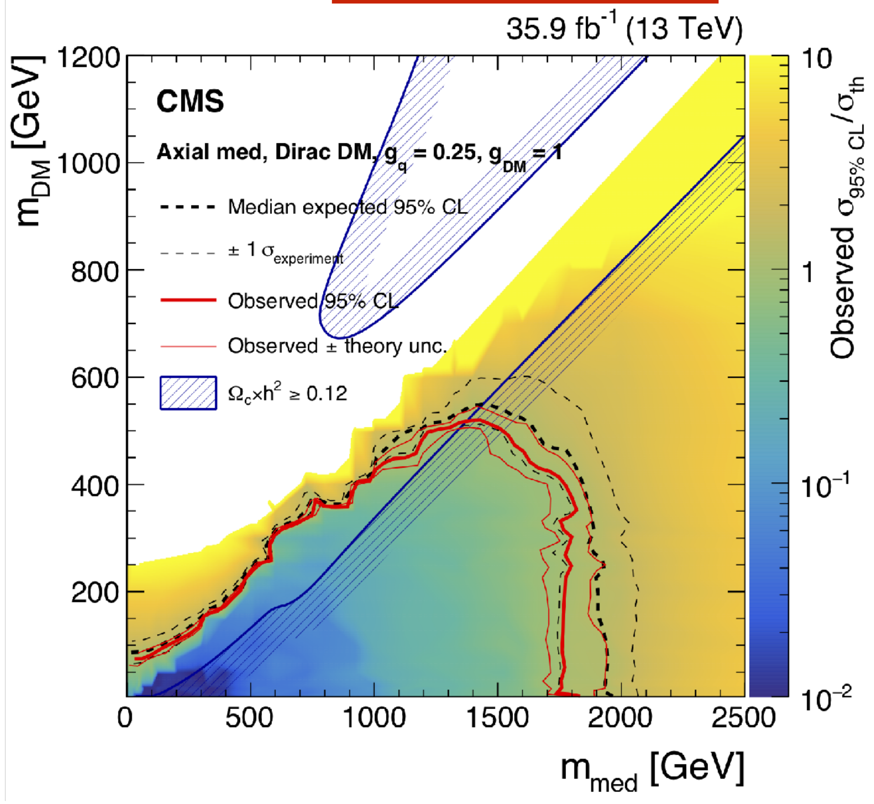
- Analysis of missing energy spectrum in Mono-X events
- Interpretation in simplified DM models
- s-channel with different mediators



Vector



Axial-Vector



CMS EXO-16-048

- Set limits on allowed masses and coupling strength

Simplified Dark Matter models @ LHC

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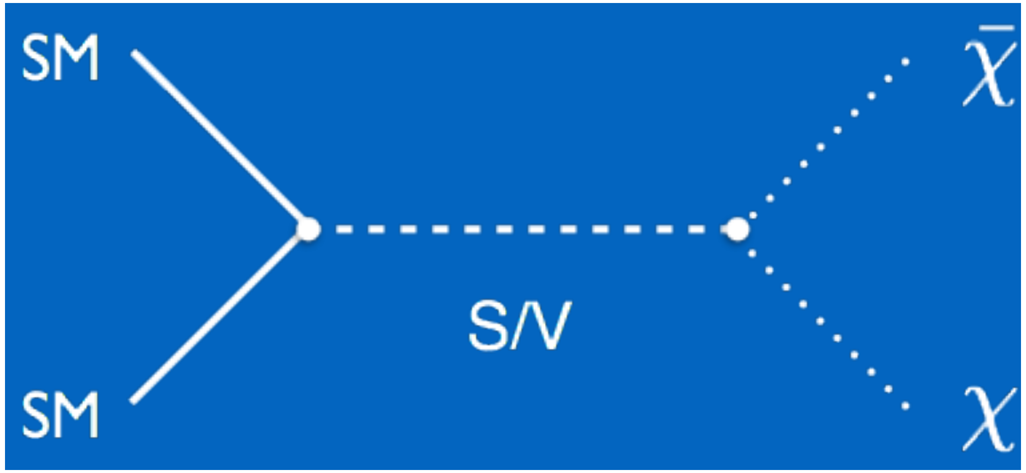

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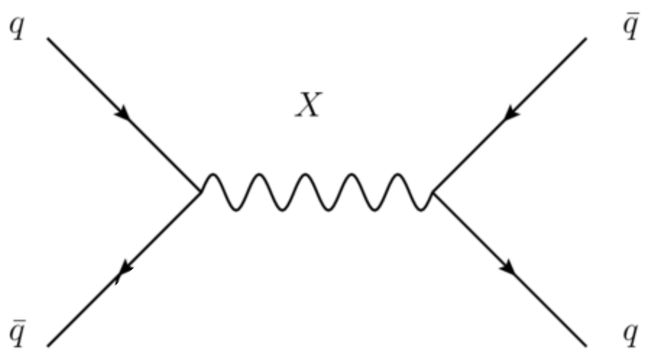
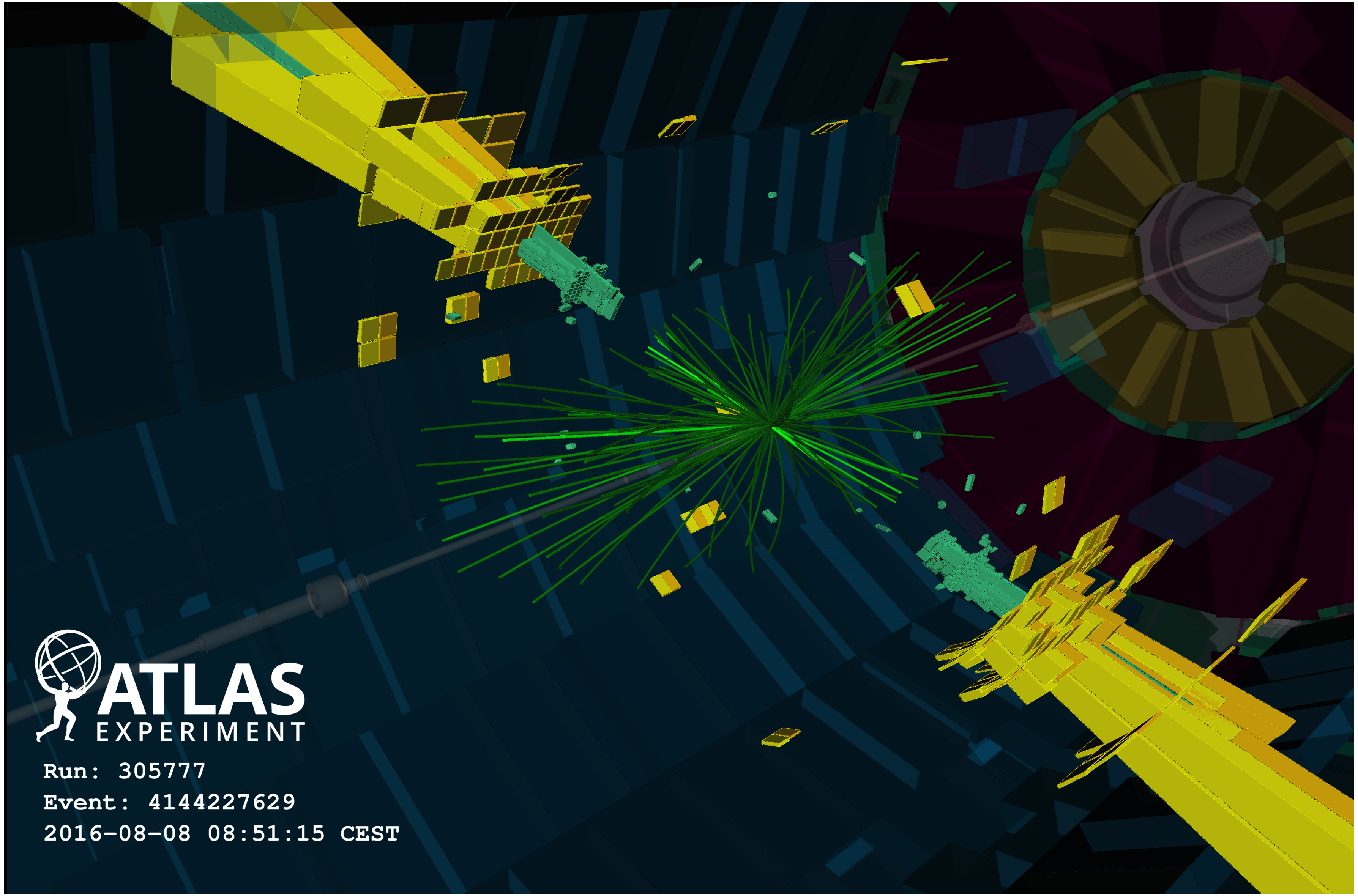
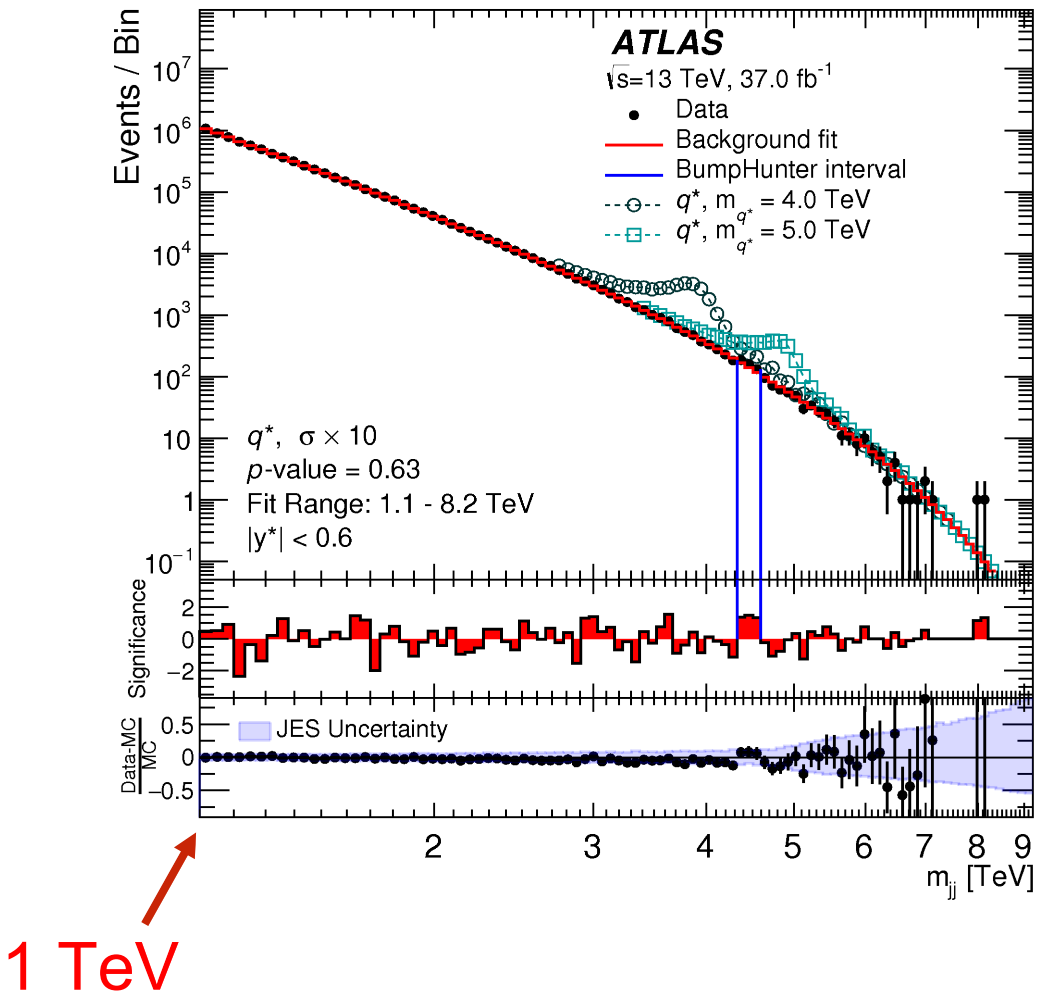
Mediator Searches

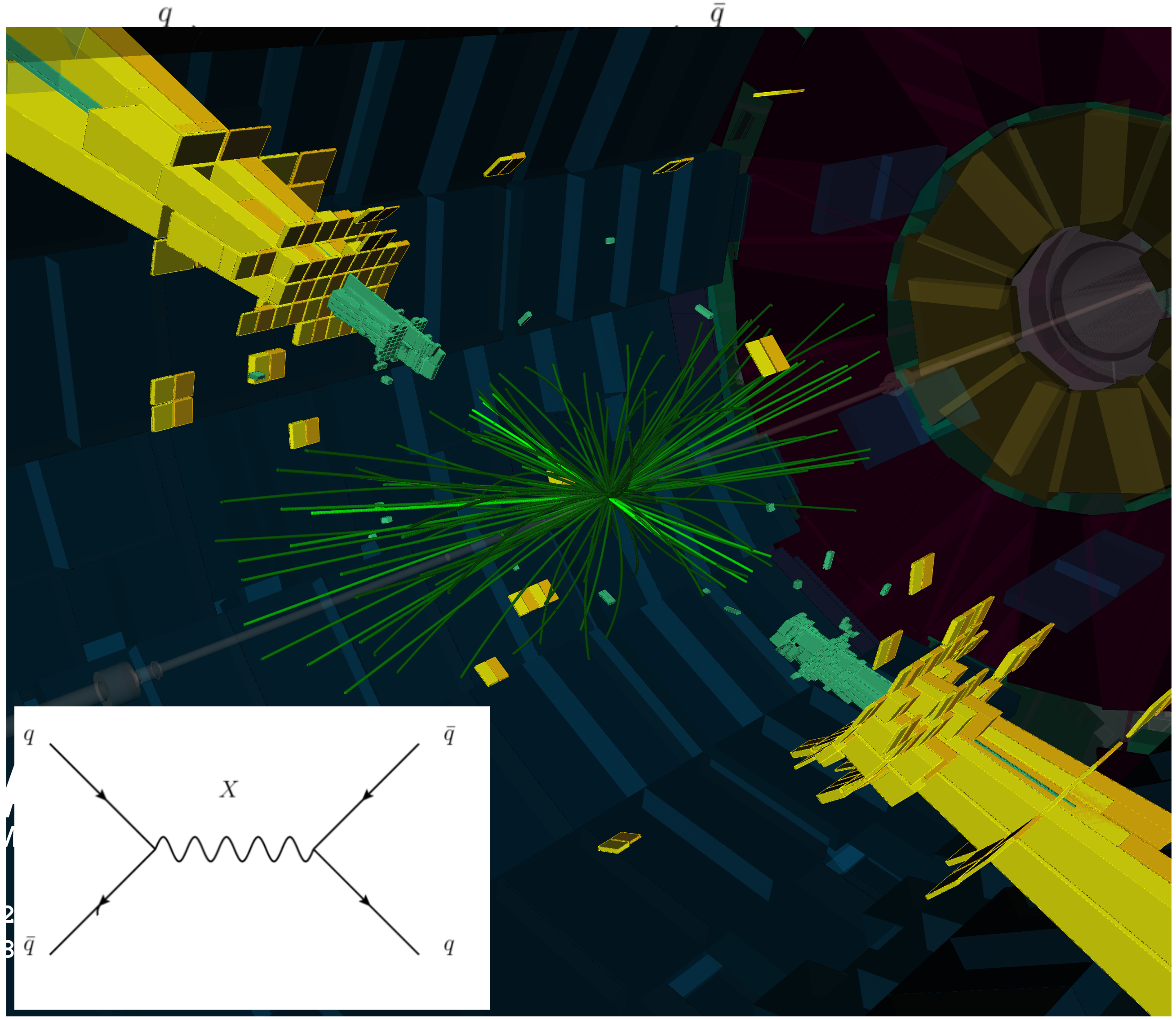




High-mass dijet resonances

- Search for resonance in dijet invariant mass spectrum

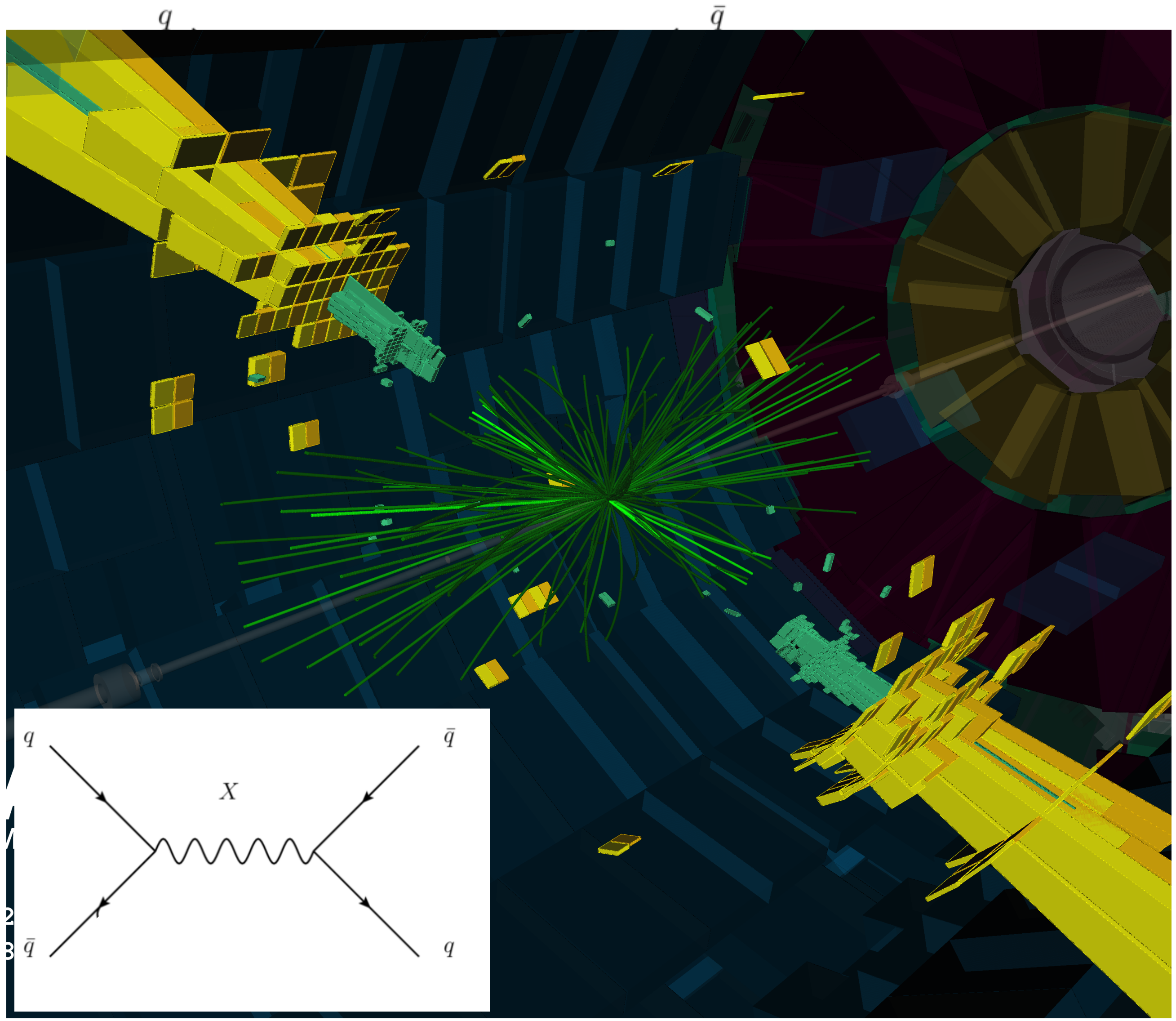




Low-mass dijet resonances

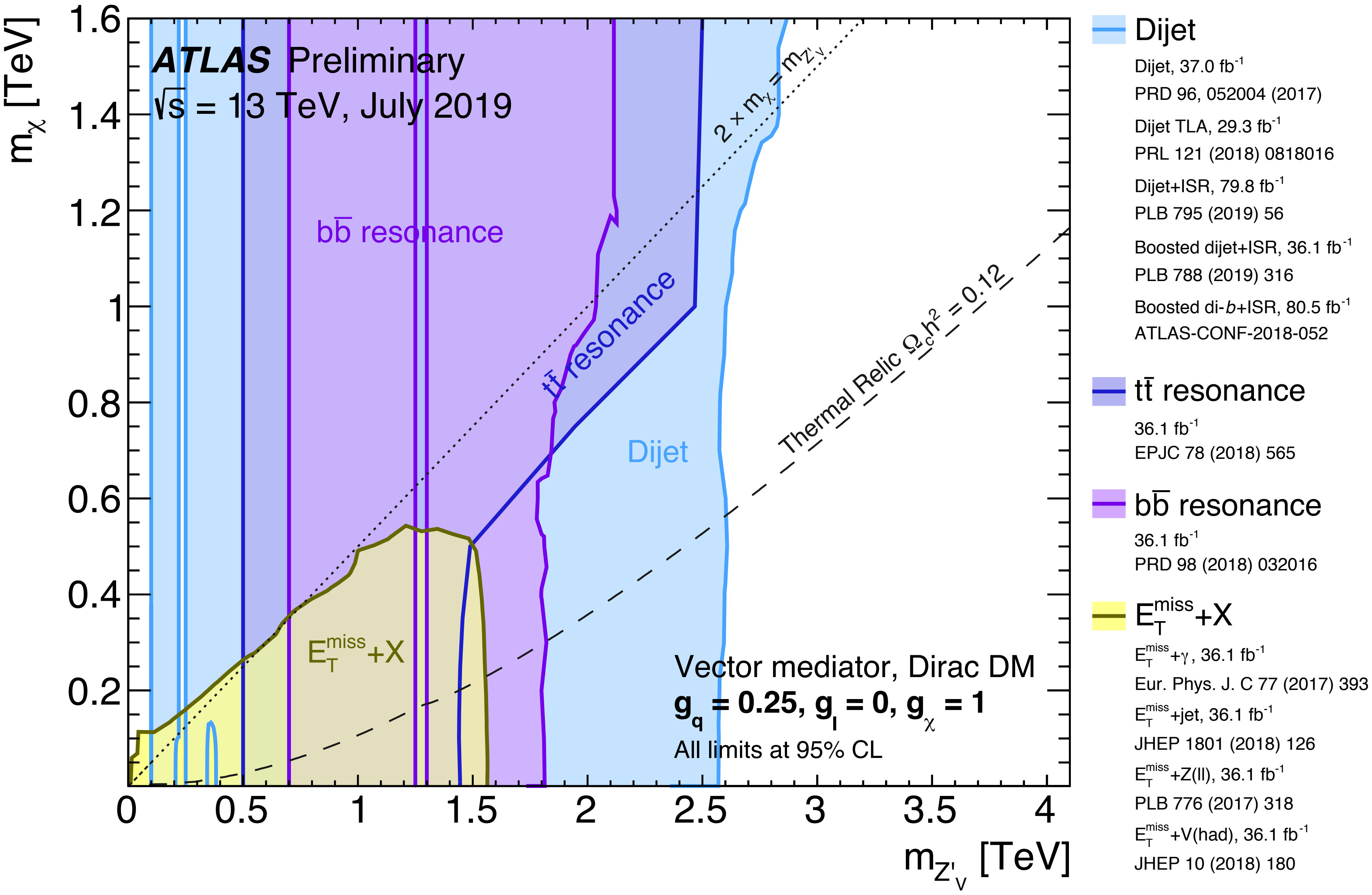
- Search for resonance in dijet invariant mass spectrum

- Low mass mediators are difficult to constrain because of huge QCD dijet background
  - difficult/impossible to cope with total event rate
- New (cool) strategies:
  - “Data scouting”: perform analysis on dataset that contains reduced event information (trigger level), allowing to store data at very high rate
  - Trigger on high-pT ISR jet or photon and search for low mass resonance in recoil system
  - Trigger on high-pT ISR jet and search for merged, boosted resonance in recoil, using jet subtructure



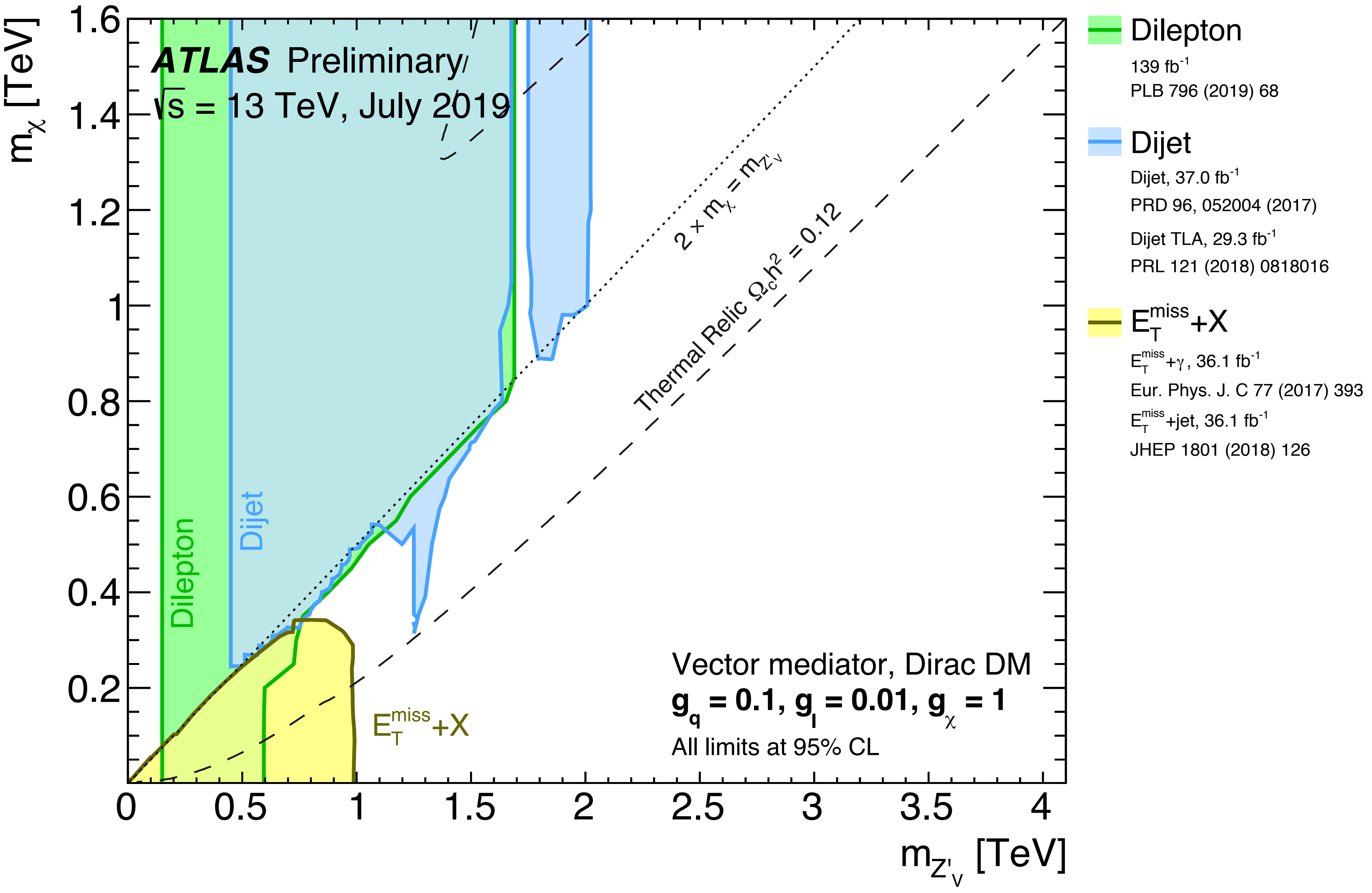
The grand(er) picture

- Can combine searches for DM signal (missing energy) and those for mediators to constrain allowed model parameter space



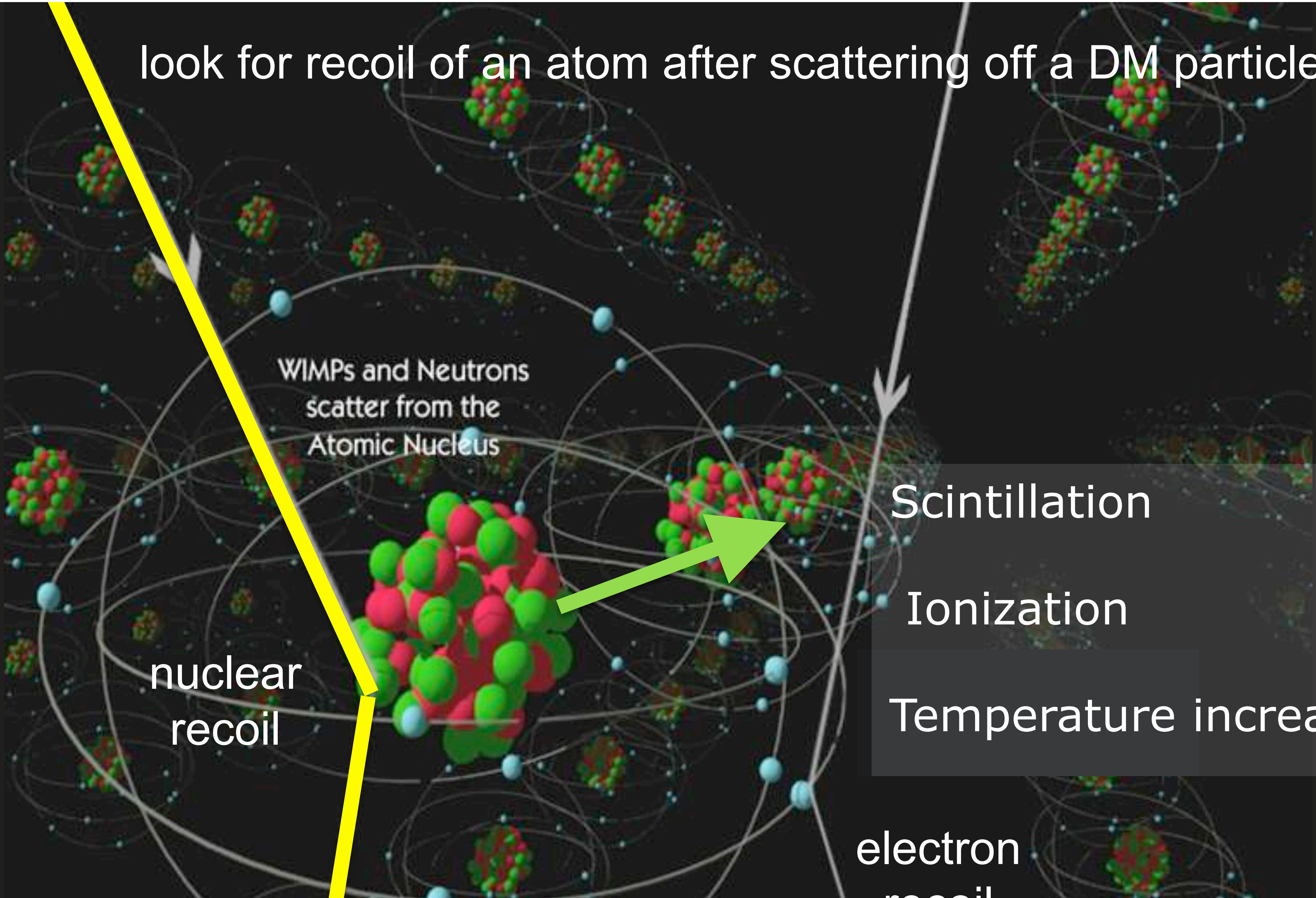
The grand(er) picture

- Can combine searches for DM signal (missing energy) and those for mediators to constrain allowed model parameter space
- Limits strongly depend on assumptions for couplings



Direct dark matter detection (solid state detectors, noble liquids)

look for recoil of an atom after scattering off a DM particle



nuclear
recoil

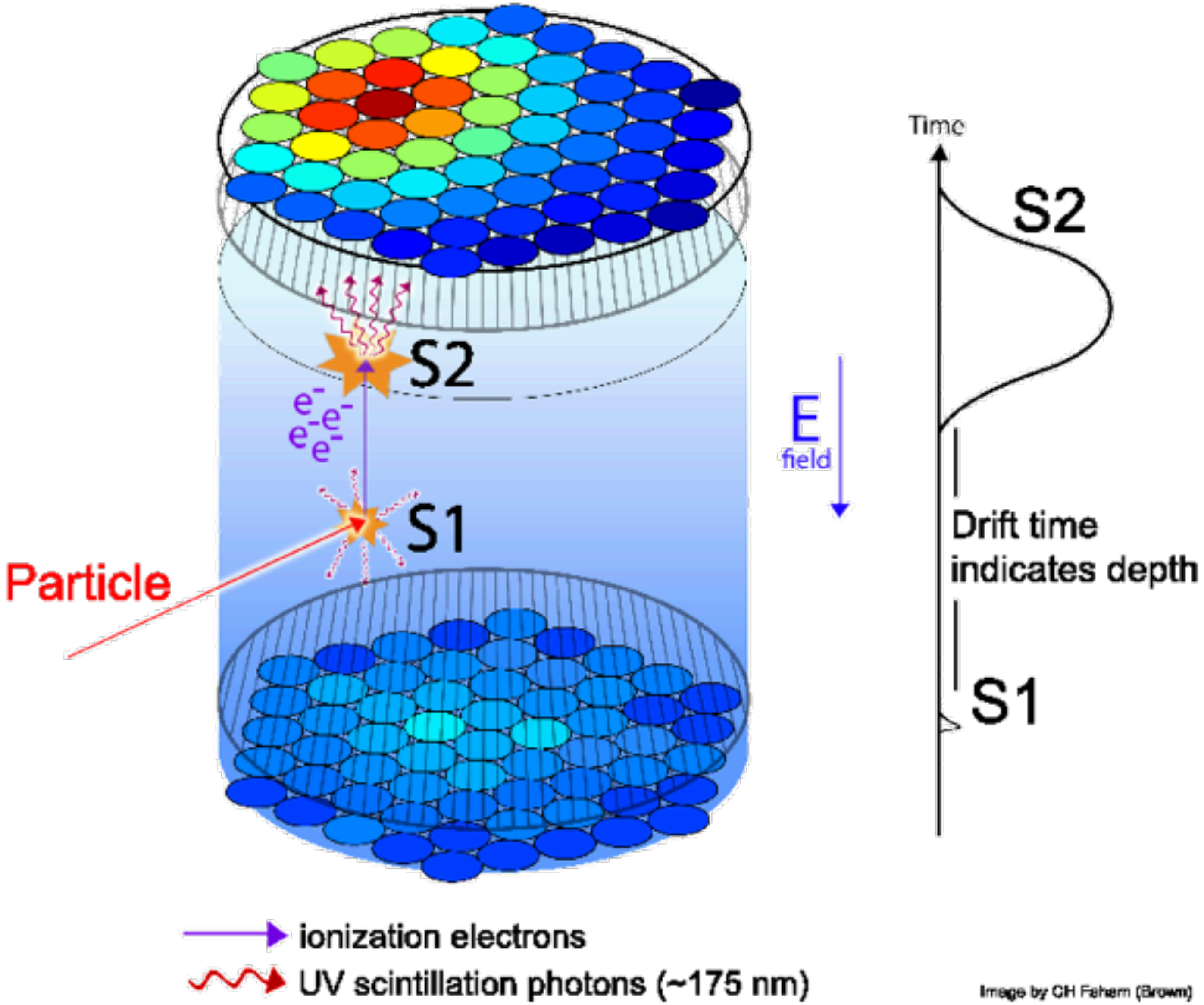
Scintillation

Ionization

Temperature increase

electron

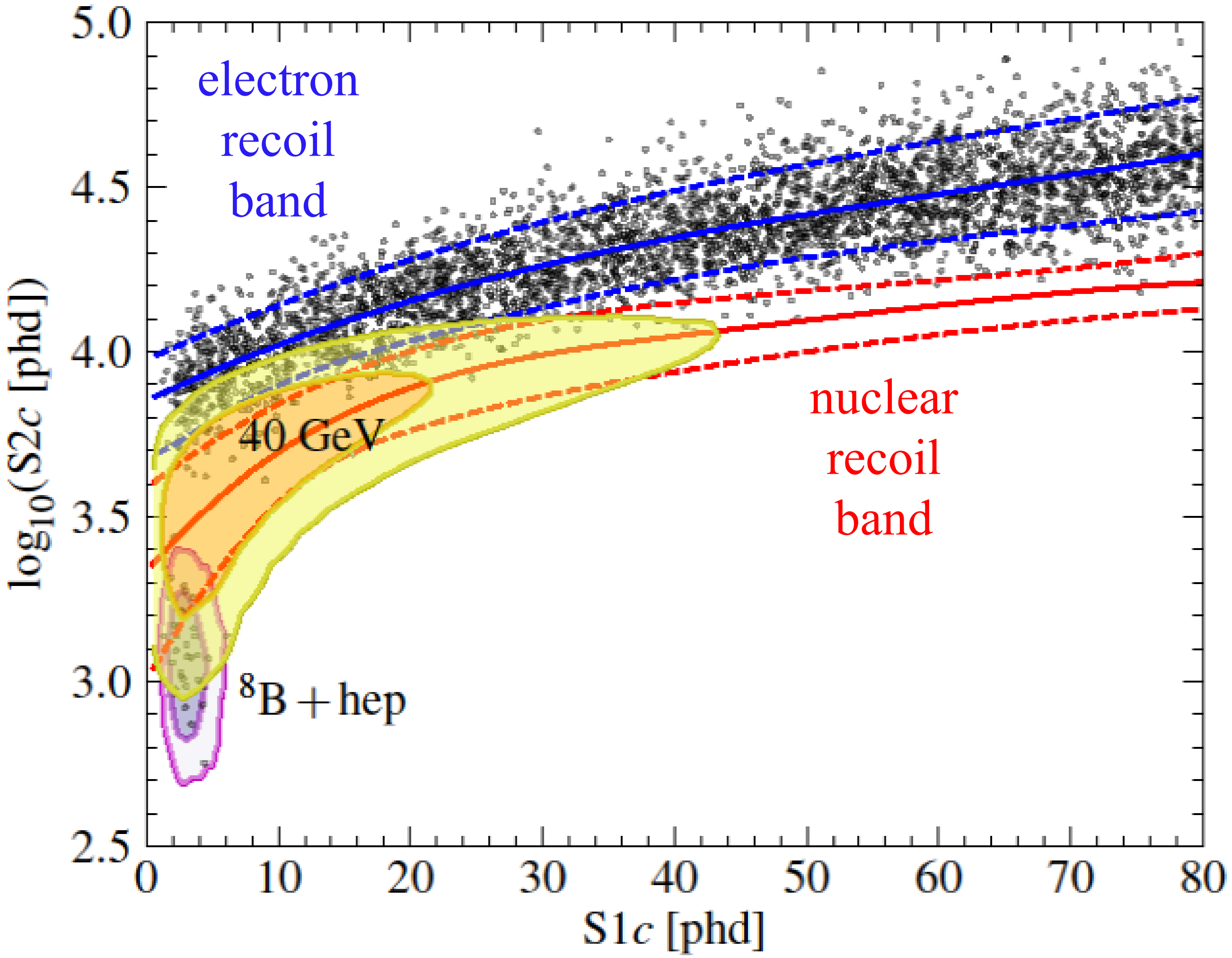
Principle of WIMP detection in LXe TPC



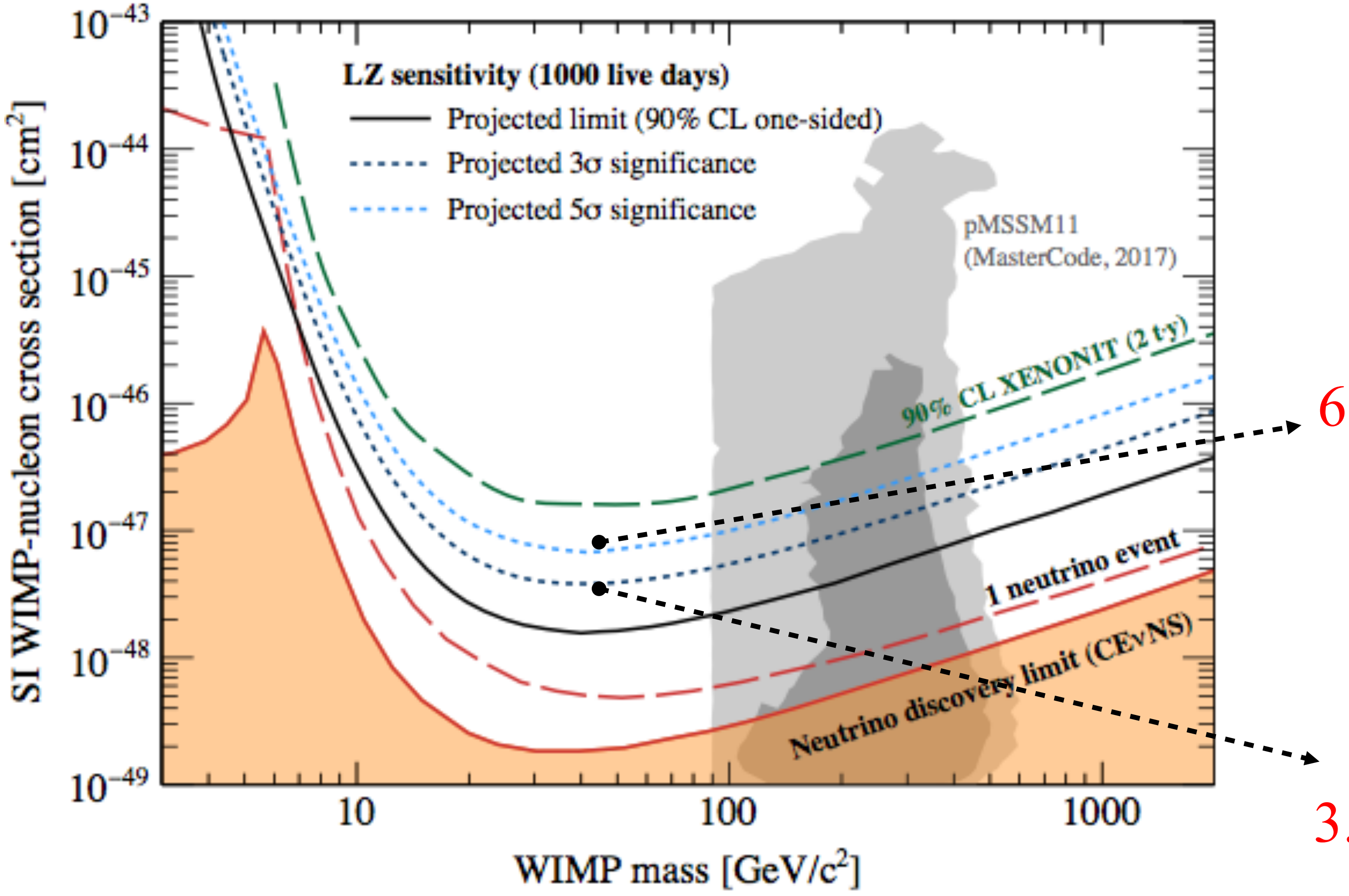
- Liquid xenon time projection chamber – LXe TPC.
- S1 – primary scintillation.
- S2 –secondary scintillation, proportional to ionisation.
- Position reconstruction based on the light pattern in the PMTs and delay between S2 and S1.

Simulated LZ full exposure

40 GeV/c^2 WIMP 1000 days, 5.6 Tons



WIMP Discovery Potential
3σ and 5σ



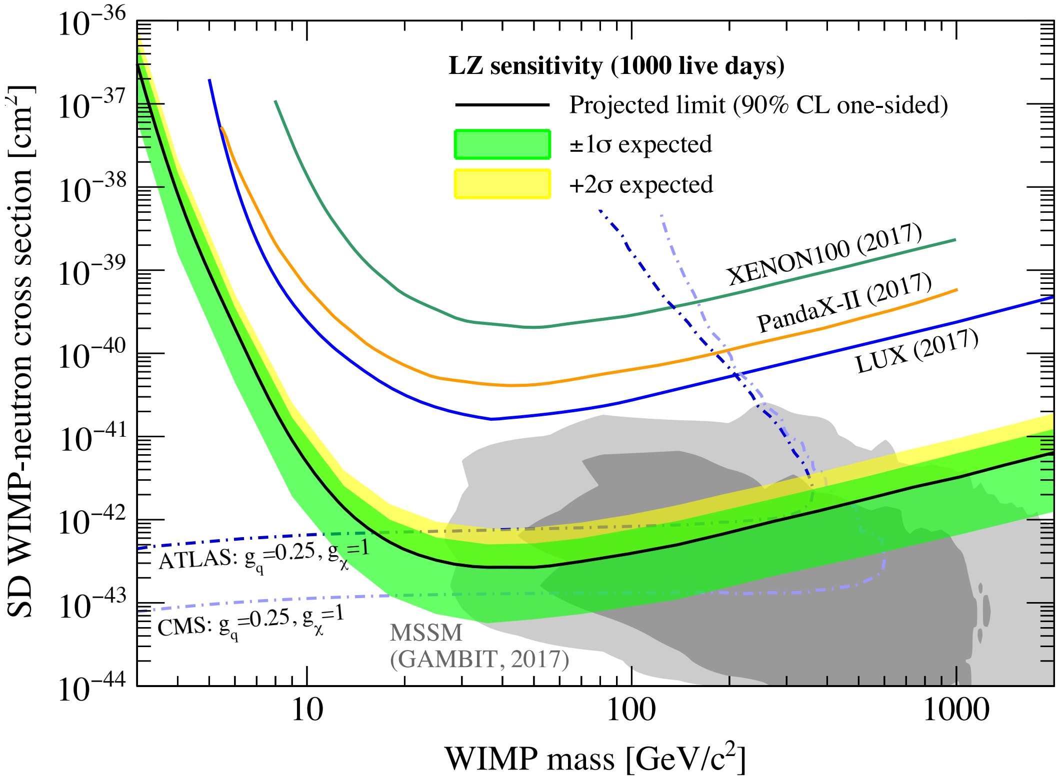
5σ: 6.7×10^{-48} cm^2

3σ: 3.8×10^{-48} cm^2

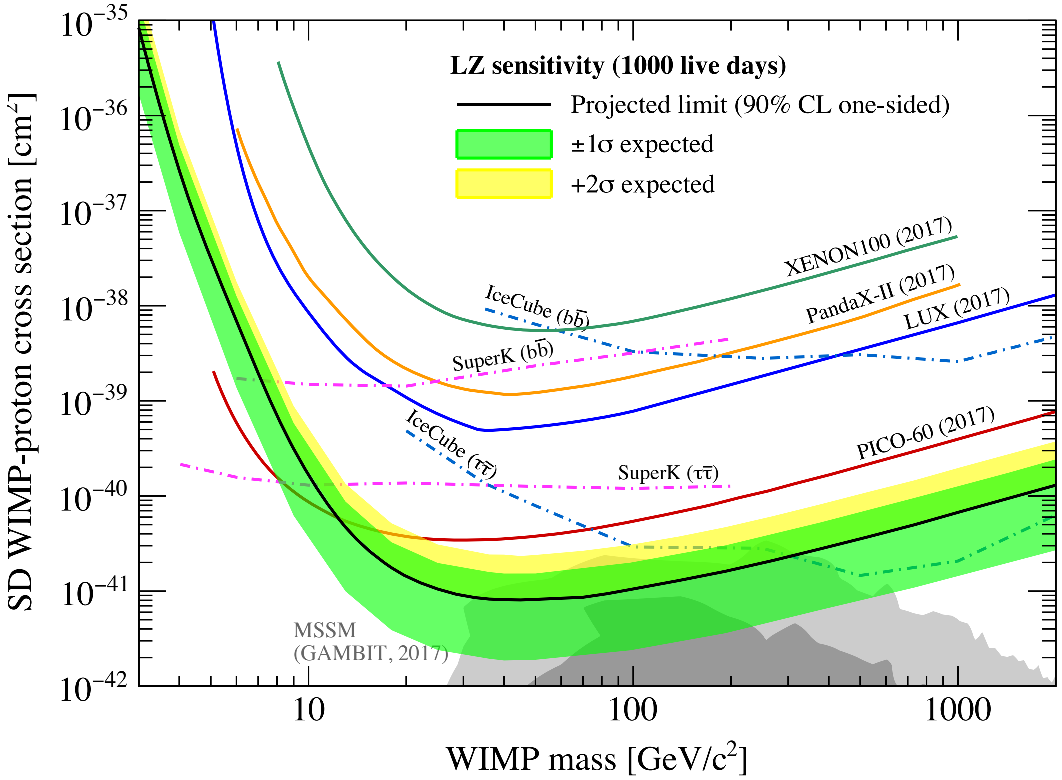
Spin-dependent scattering

- Naturally occurring Xenon has around 50% odd-neutron isotopes
  - 26.4% ^{129}Xe and 21.2% ^{131}Xe by mass

SD WIMP-neutron



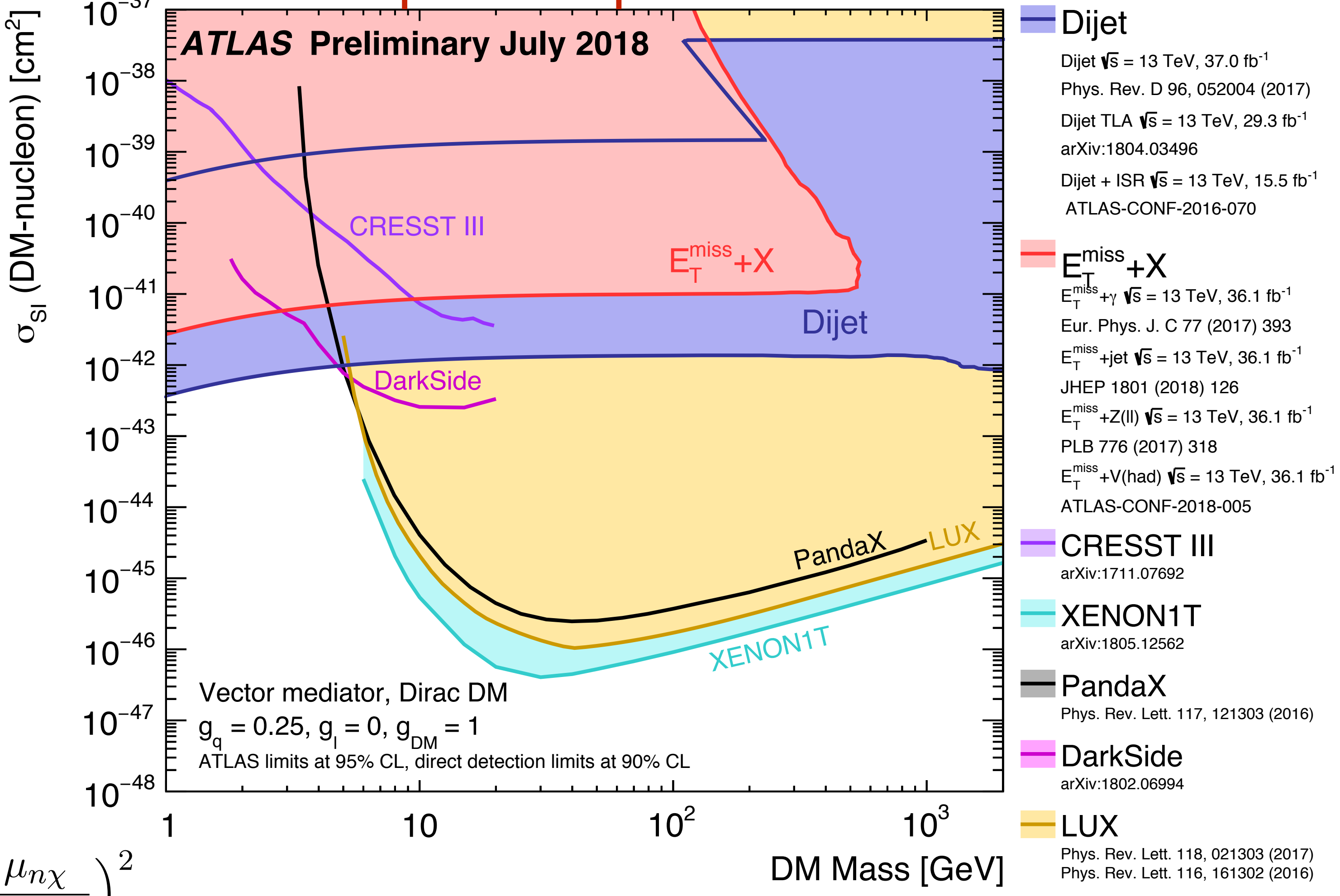
SD WIMP-proton



Comparison of Collider and Direct Detection

- We can translate limits from simplified dark matter models probed at LHC into the parameter space probed by direct detection experiments
- Caveat:
    - Limits depend on assumptions made for model parameters, i.e., fixed values for couplings
- Vector mediator ←→ spin independent DM – nucleon scattering

Spin-independent



$$\sigma_{\mathrm{SI}} \simeq 6.9 \times 10^{-43}\ \mathrm{cm}^2 \cdot \left(\frac{g_q g_{\mathrm{DM}}}{1}\right)^2 \left(\frac{125\ \mathrm{GeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$

$\mu_{n\chi} = m_n m_{\mathrm{DM}}/(m_n + m_{\mathrm{DM}})$ is the DM-nucleon reduced mass

LHC only competitive for m_{DM} < 6 GeV

Comparison with Direct Detection

- Axial-vector mediator ←→ spin dependent DM – nucleon scattering
- Limits depend on assumptions made for model parameters, e.g., fixed values for couplings

- Complementarity with Direct Detection clearly visible
  - LHC much stronger for axial-vector interaction
- Sensitivity strongly depends on type of DM interaction

$$\sigma^{\mathrm{SD}} \simeq 2.4 \times 10^{-42}\ \mathrm{cm}^2 \cdot \left(\frac{g_q g_{\mathrm{DM}}}{0.25}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$

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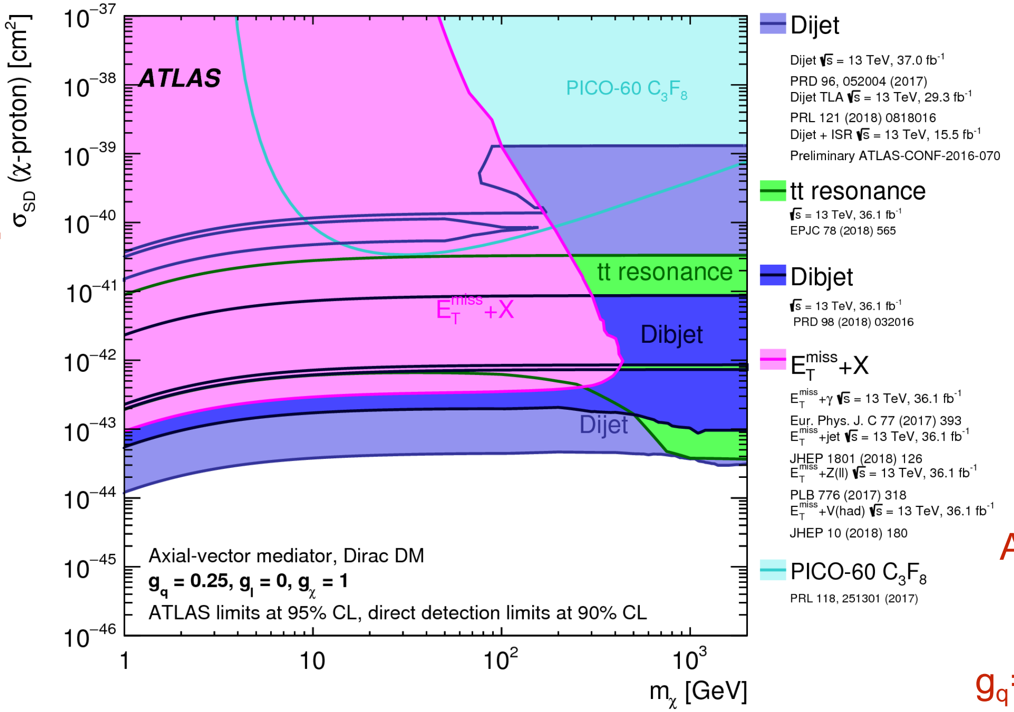
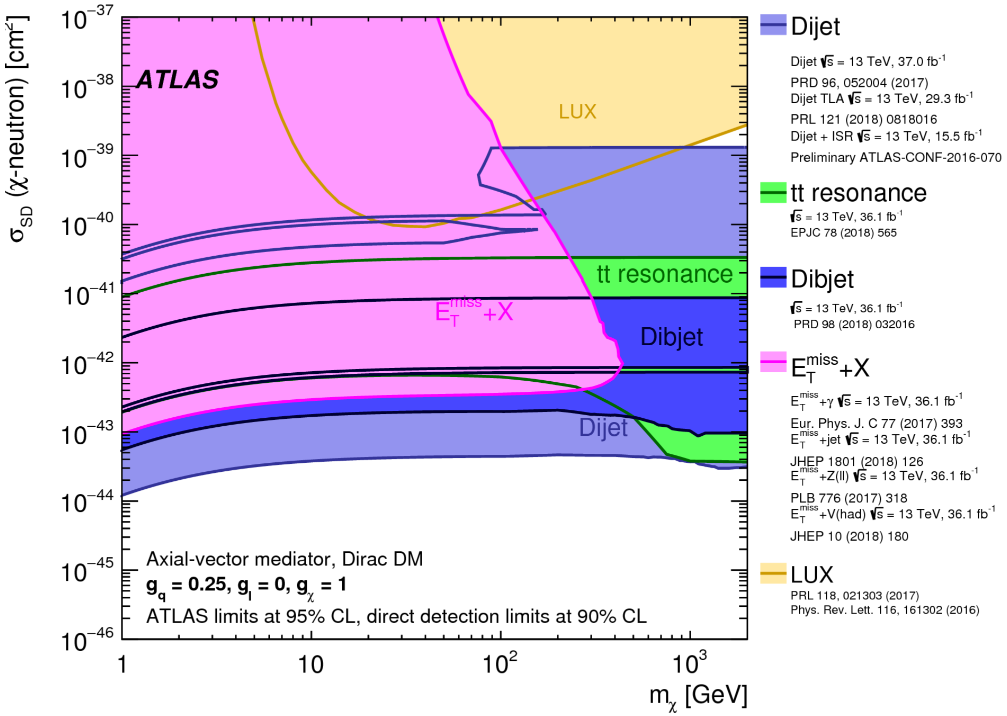
Spin-dependent

DM-proton



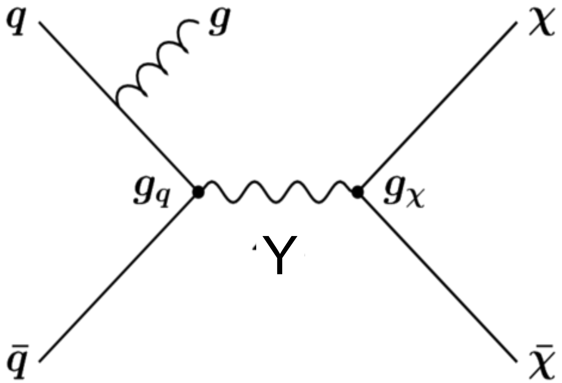
Axial-vector mediator
Dirac DM
g_q=0.25, g_χ = 1

DM-neutron



Let’s explore full model parameter space

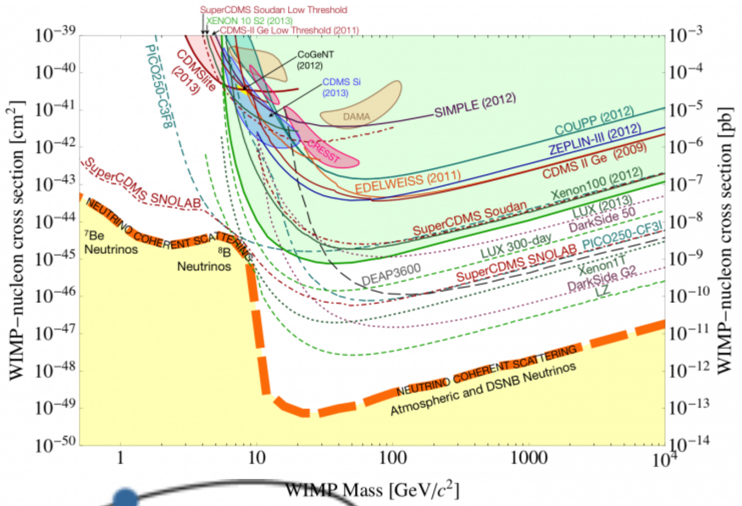
- Leptophobic DMSM with spin-1 s-channel mediator Y
  - DM Dirac fermion



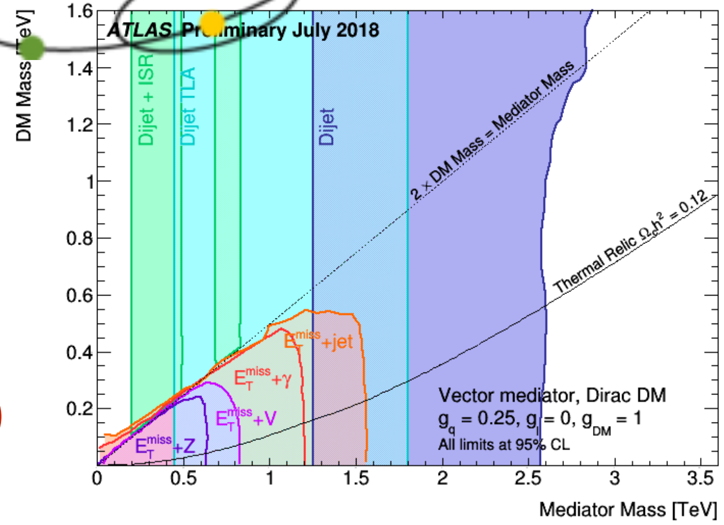
- Study pure vector and axial-vector couplings
- Flavour diagonal & flavour blind
- Calculations of observables as fcn of parameters implemented in MasterCode
  - via interfaces to MicrOMEGAs, MadGraph and FastLim

arXiv:1905.00892

Direct detection: limits on SI & SD x-secs



Collider: limits on DM production (mono-X searches)



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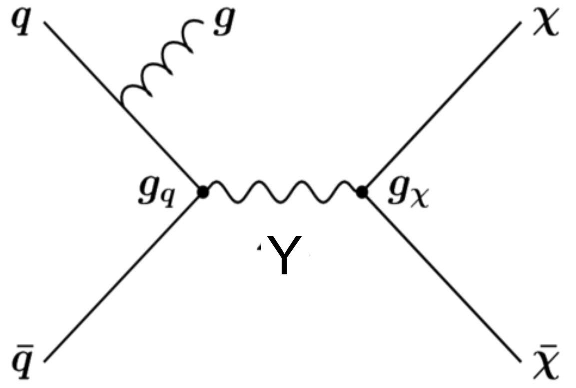

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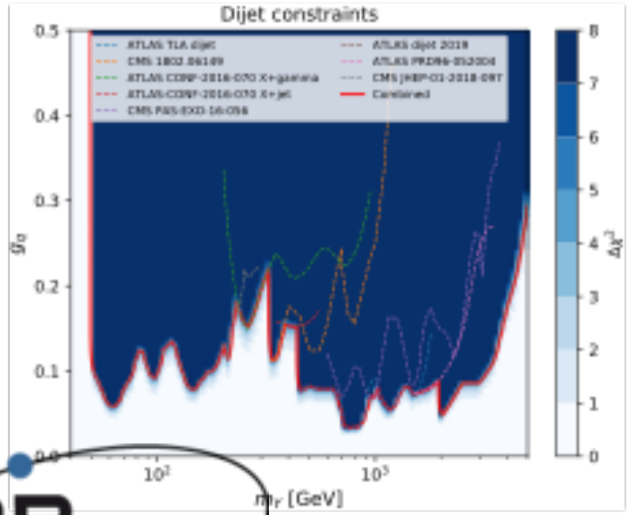
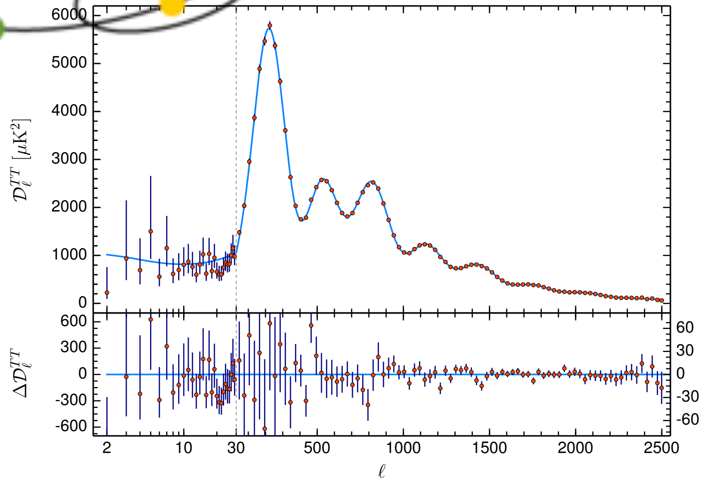
Collider: limits on mediator masses & couplings (dijet resonance searches)



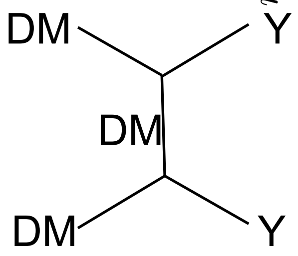
Relic density measurement by Planck

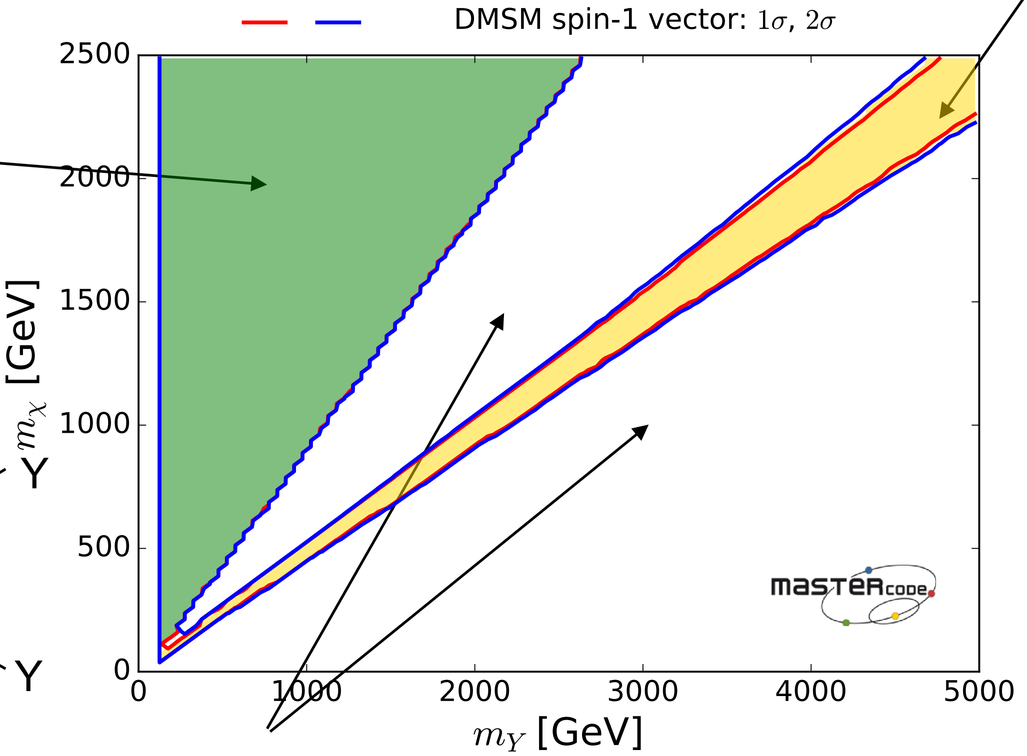


Simplified Model Analysis – Vector Mediator

Mass plane
(marginalized over couplings)

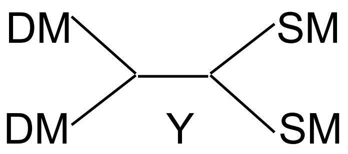
DM annihilation via t-channel exchange





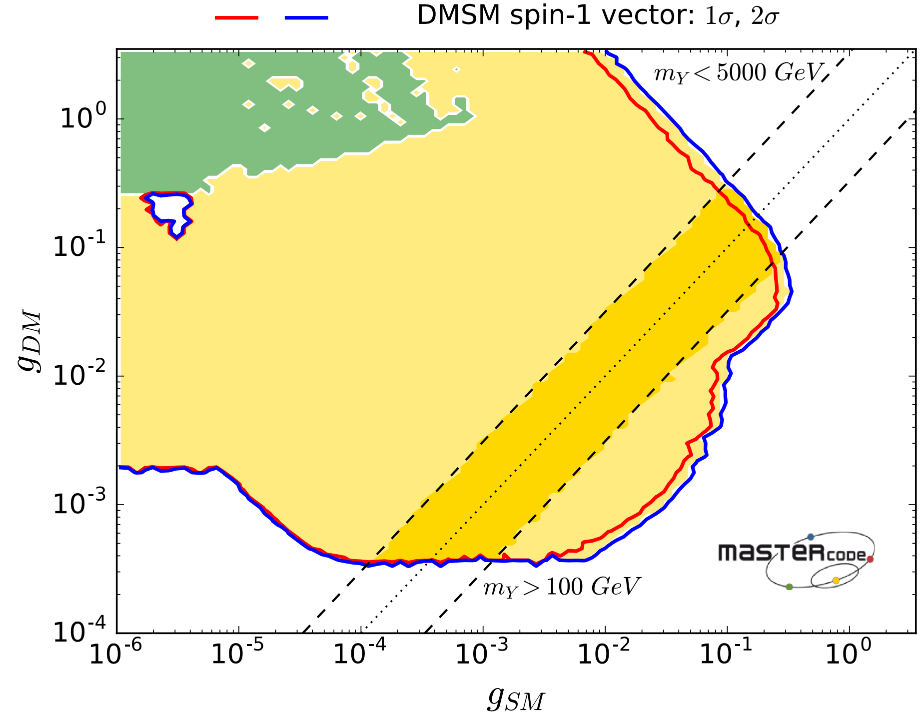
relic density constraint not fulfilled

Rapid annihilation via s-channel resonance



Parameter	Range
m_Y	$(0.1, 5)$ TeV
m_χ	$(0, 2.5)$ TeV
$g_{\rm SM}$	$(0, \sqrt{4\pi})$
$g_{\rm DM}$	$(0, \sqrt{4\pi})$

Couplings plane
(marginalized over masses)



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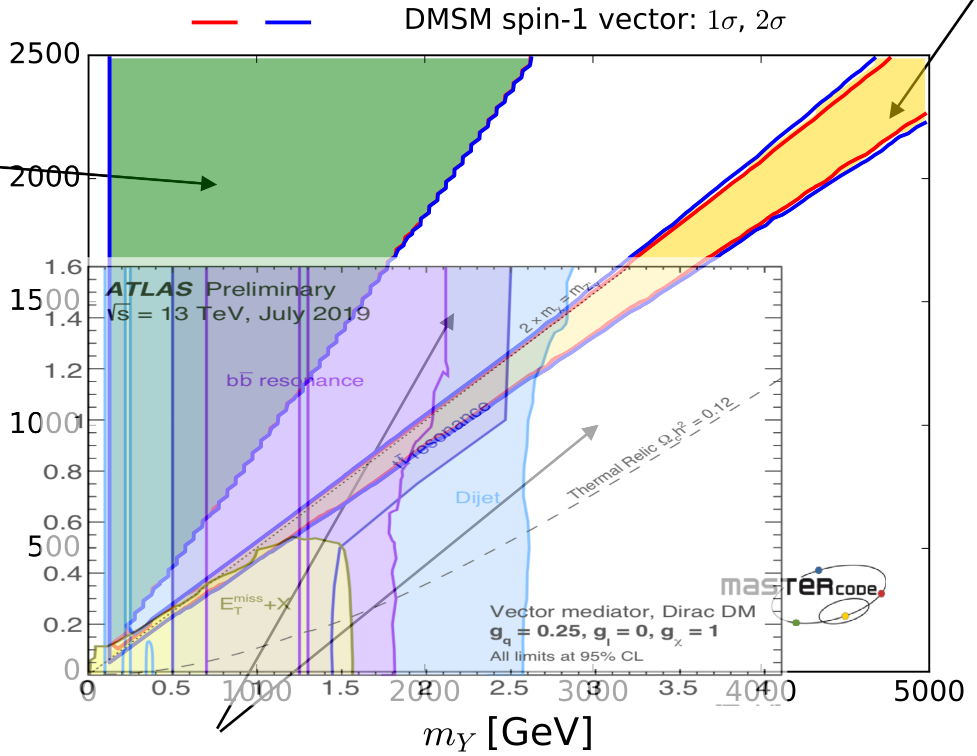
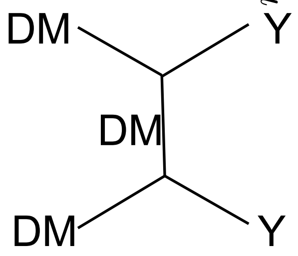


DM annihilation via t-channel exchange



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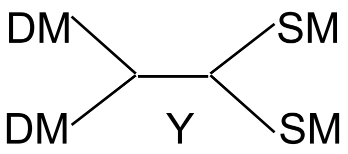

relic density constraint not fulfilled

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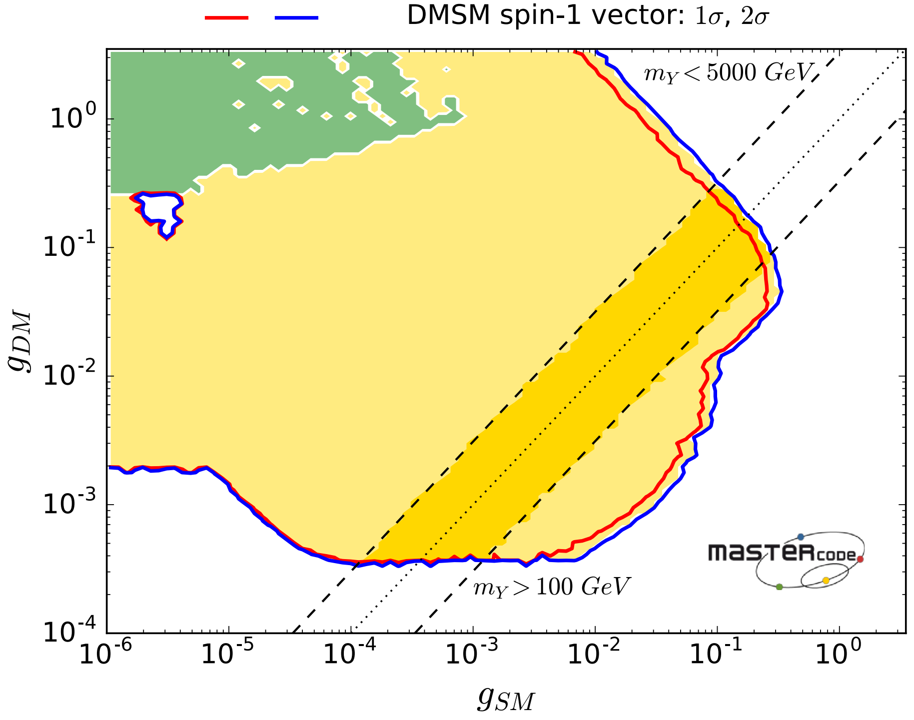

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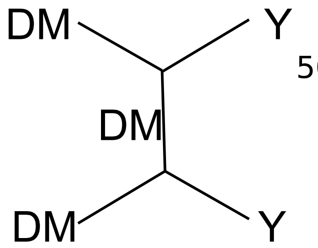
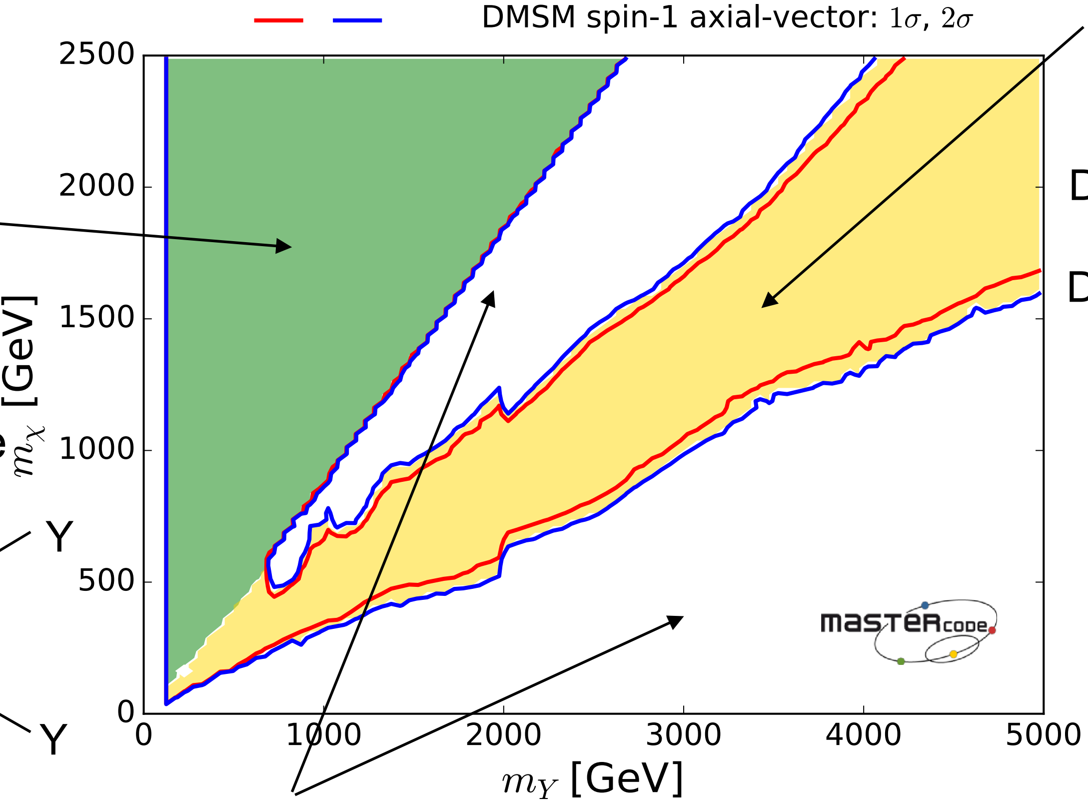
Simplified Model Analysis – Axial-Vector Mediator

Mass plane

DM annihilation via t-channel exchange





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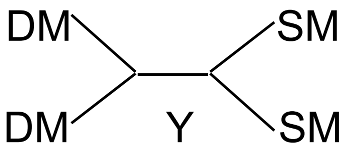
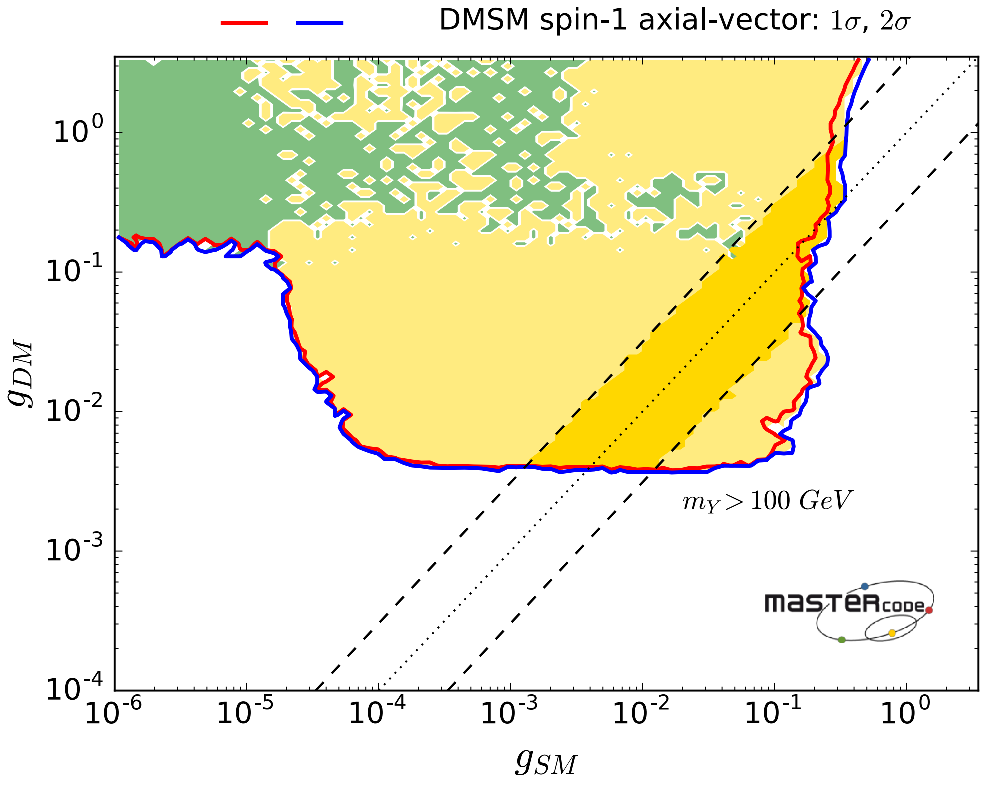


relic density constraint not fulfilled

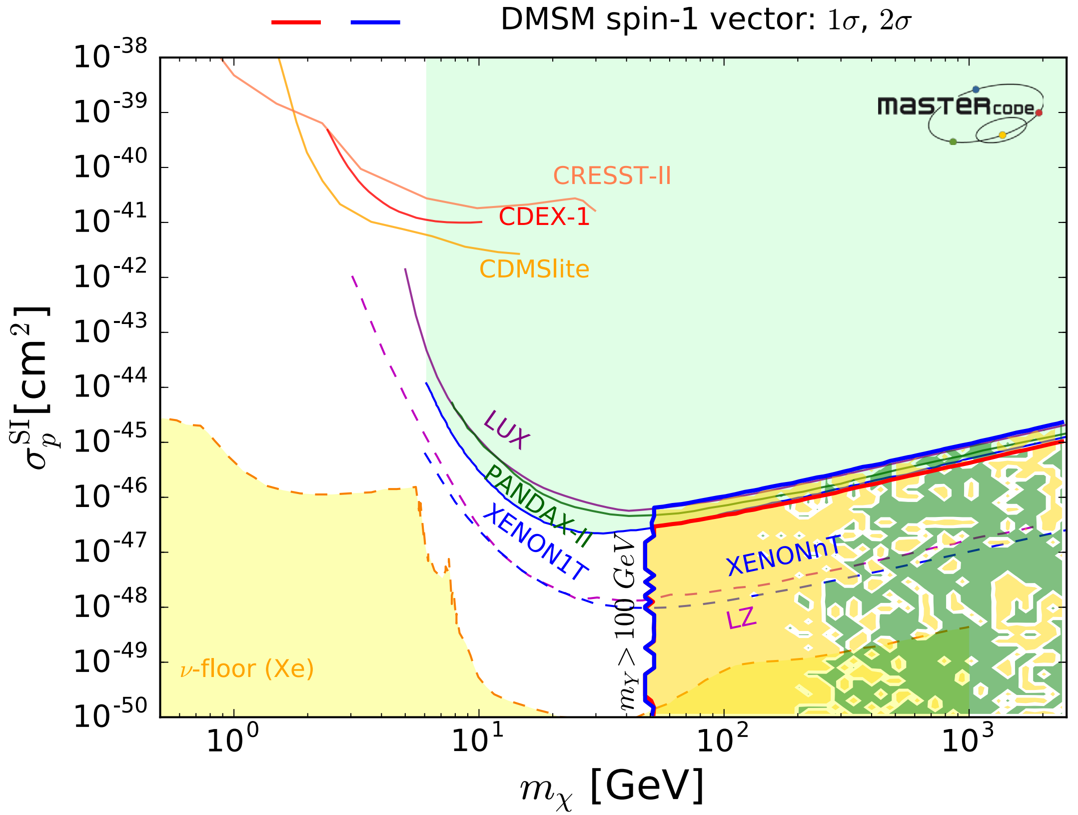
Couplings plane



Comparison with Direct Detection Experiments

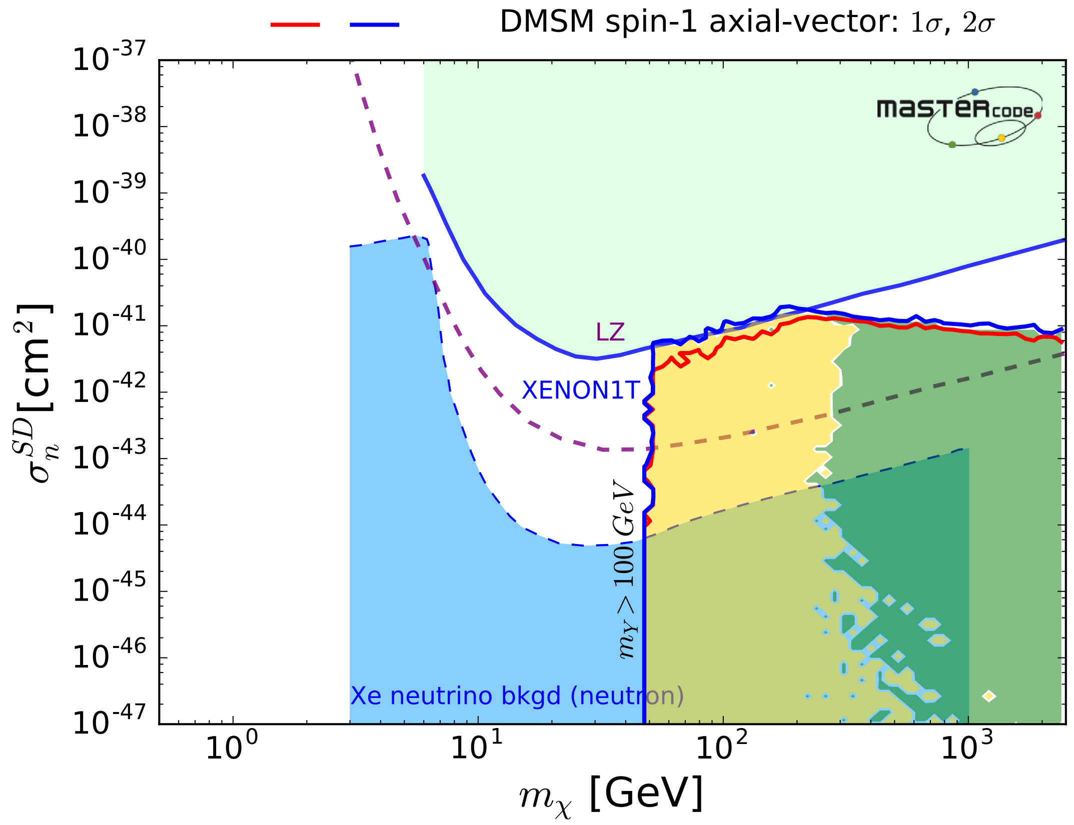
Spin-Independent Scattering

Vector Mediator



Spin-Dependent Scattering

Axial-Vector Mediator

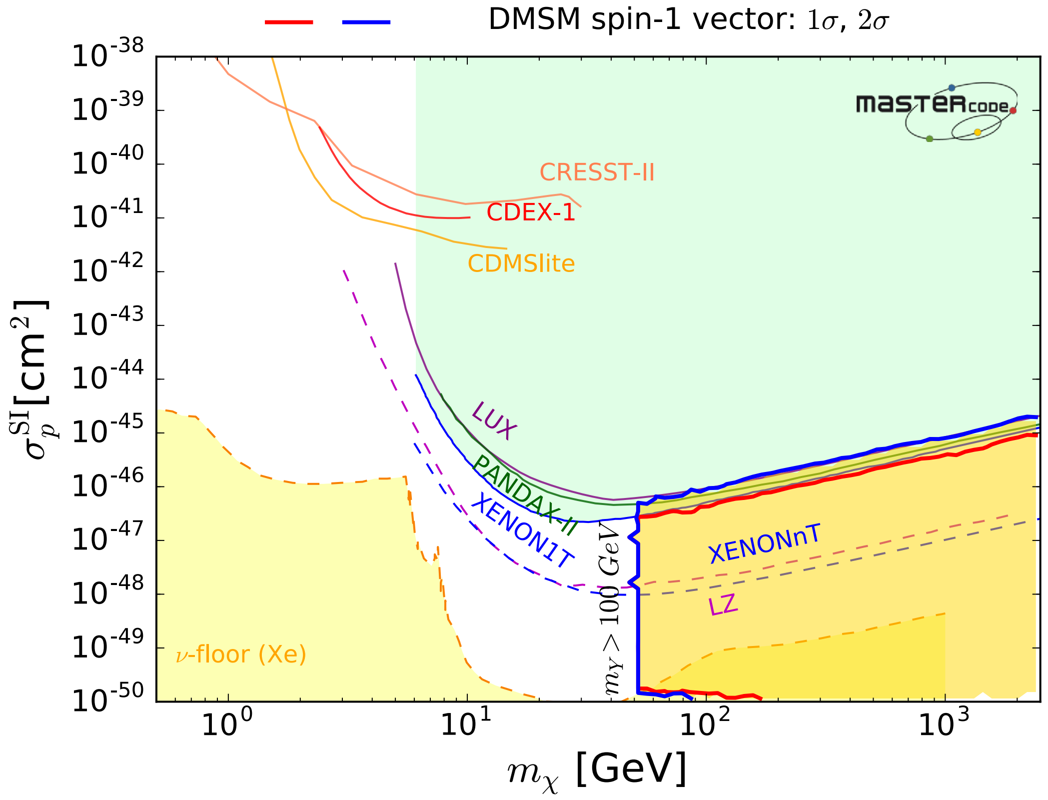


Future experiments will make significant inroads into allowed parameter space

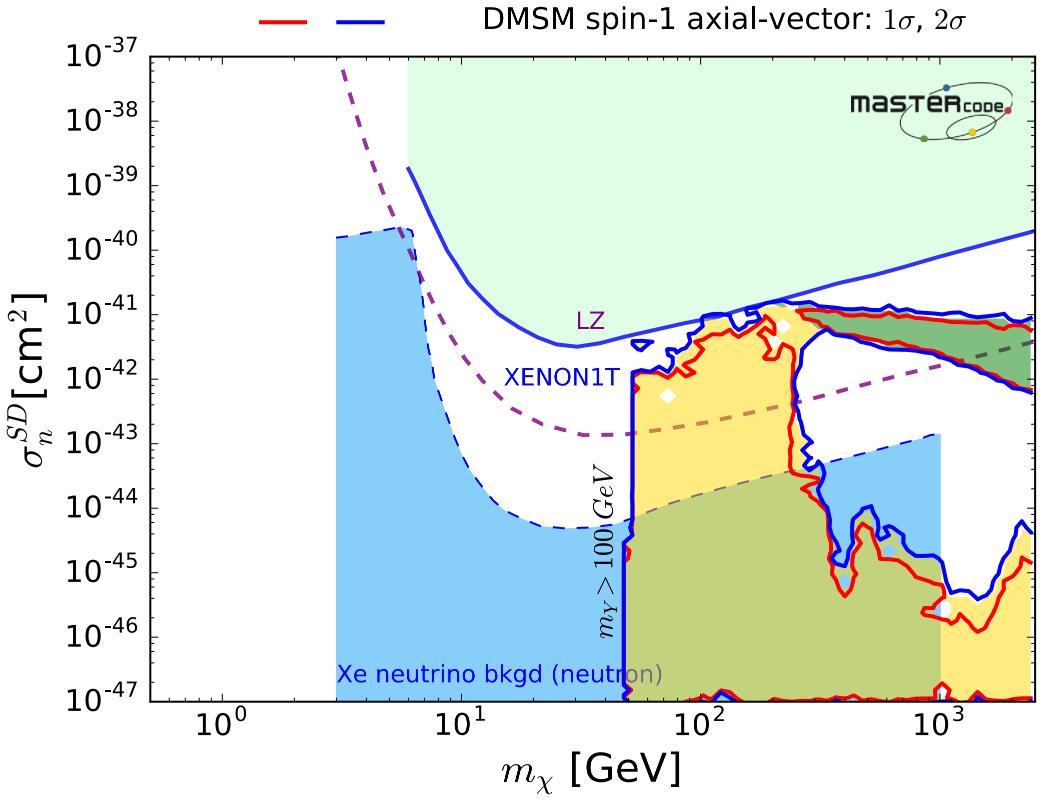
What about UV-completion? (Renormalizability etc.)

Expect spin-1 boson to have comparable couplings to SM and DM particles
restrict couplings to $1/3 < g_{SM}/g_{DM} < 3$

Spin-Independent Scattering
Vector Mediator



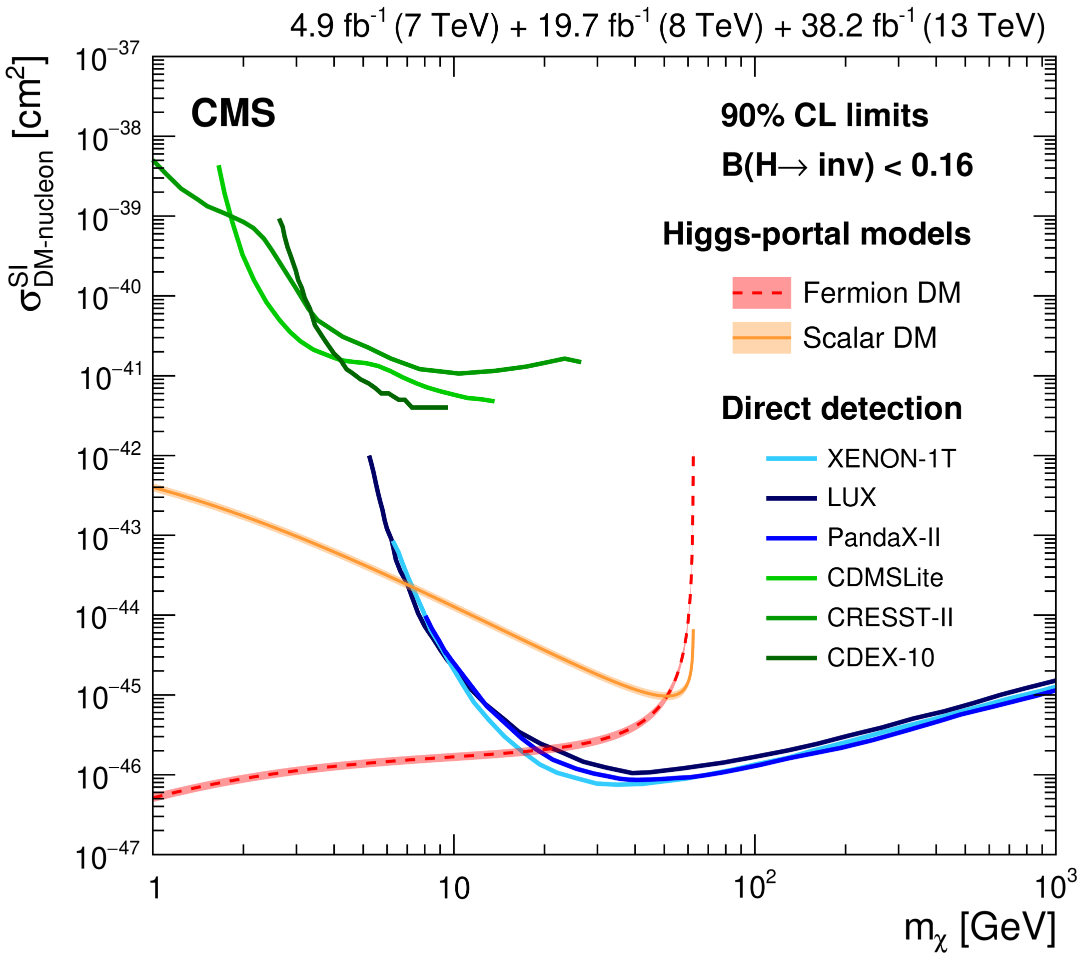
Spin-Dependent Scattering
Axial-Vector Mediator



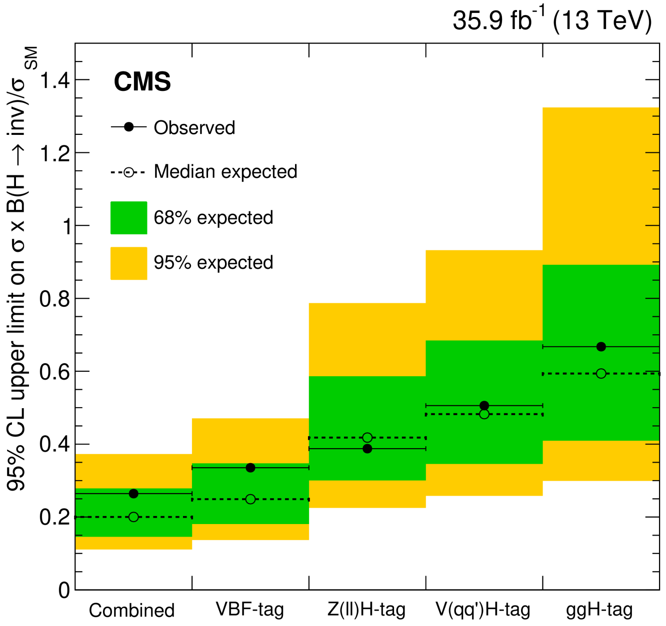
There's life beyond simplified dark matter models…

Higgs Portal Models

- Higgs coupling proportional to mass
- If DM massive, it's reasonable to assume it couples to the Higgs
- Search for invisible Higgs decays
  - Very small SM BF from H->ZZ->vvvv



- Search in all Higgs production modes
- VBF most sensitive
- ttH starting to contribute



Most stringent limits for m_χ smaller than 18 (7) GeV, assuming a fermion (scalar) DM candidate

Other attractive avenues…

Connecting flavor anomalies with dark matter – 2 for 1 offer!

Kawamura, et al: arXiv:1706.04344v2

- Recipe: Add extra fermions and scalars
  - Vector-like quarks Q' and leptons L'
  - Complex scalar X
- b➞s transition has box diagram components from Q', L', X
- $M_X < M_{Q'}$ $M_X < M_{L'}$
  - X is dark matter candidate
- Masses of extra fields O(100 GeV - 1TeV)

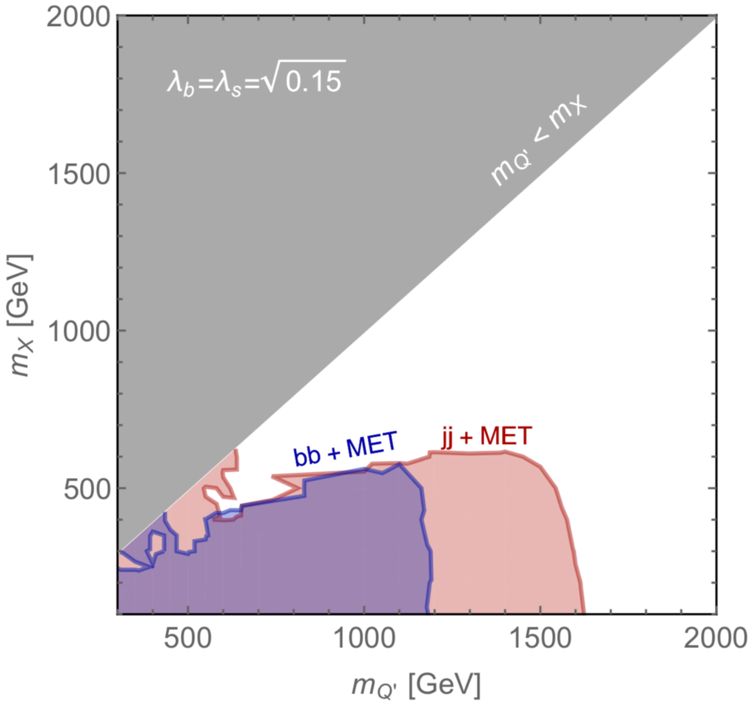
- Expected signatures:
- Pair-produced Vector-Like lepton decay:
  - μμ + MET
- Pair-produced Vector-Like quark decay:
  - D'D' ➞ tt + MET
  - U'U' ➞ bb + MET
  - Also, jj+MET, mono-jet

From Ben Kilminster – DM@LHC 2019

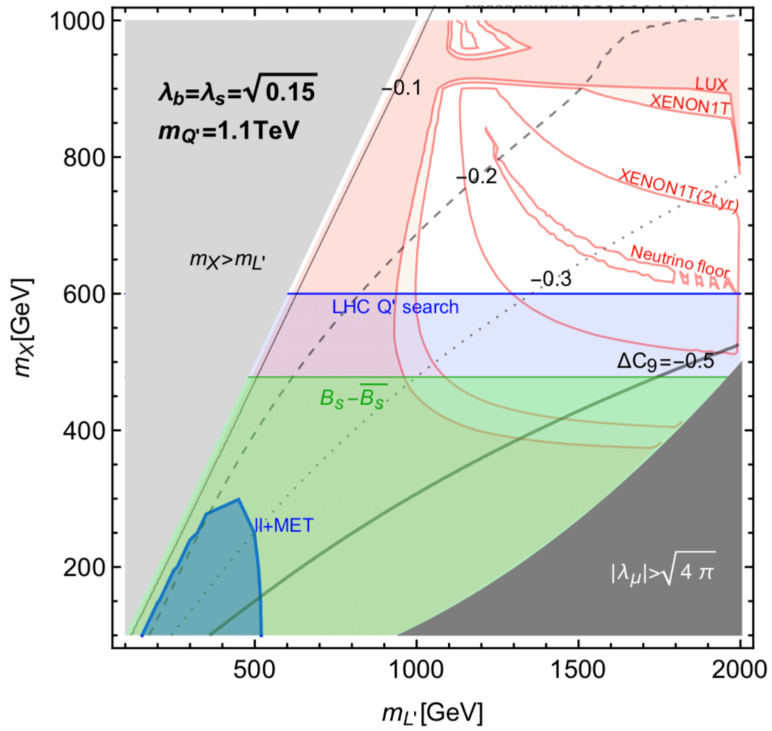
LHC direct constraints

From Kawamura, et al: arXiv:1706.04344v2

- Basic LHC constraints on Q' and X using bb+MET, jj+MET



- Constraints for couplings favored by LHC anomalies



[31] ATLAS collaboration ,ATLAS-CONF-2016-096.

[32] ATLAS collaboration ,ATLAS-CONF-2017-038.

[33] ATLAS collaboration ,ATLAS-CONF-2017-022.

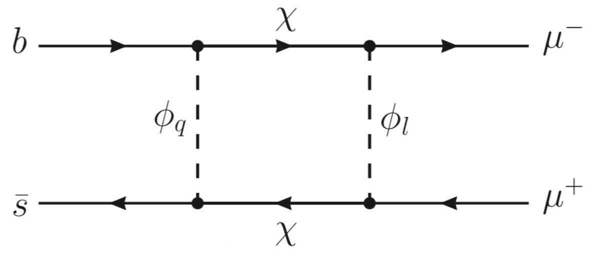
(Here, Q' can decay to 2nd or 3rd generation SM quarks)

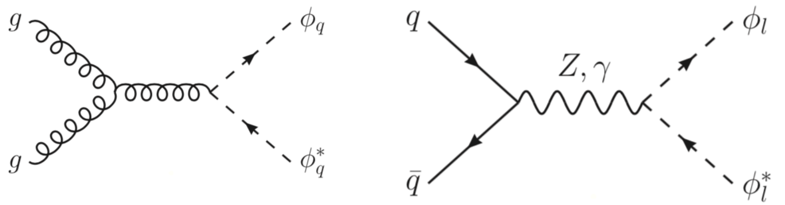
From Ben Kilminster – DM@LHC 2019

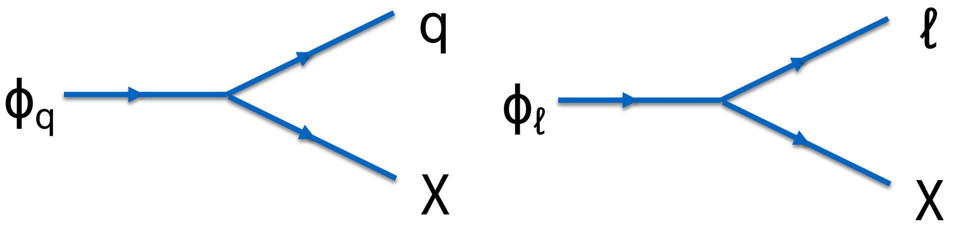
Connecting flavor anomalies with dark matter

D. G. Cerdeño, et al. 1902.01789

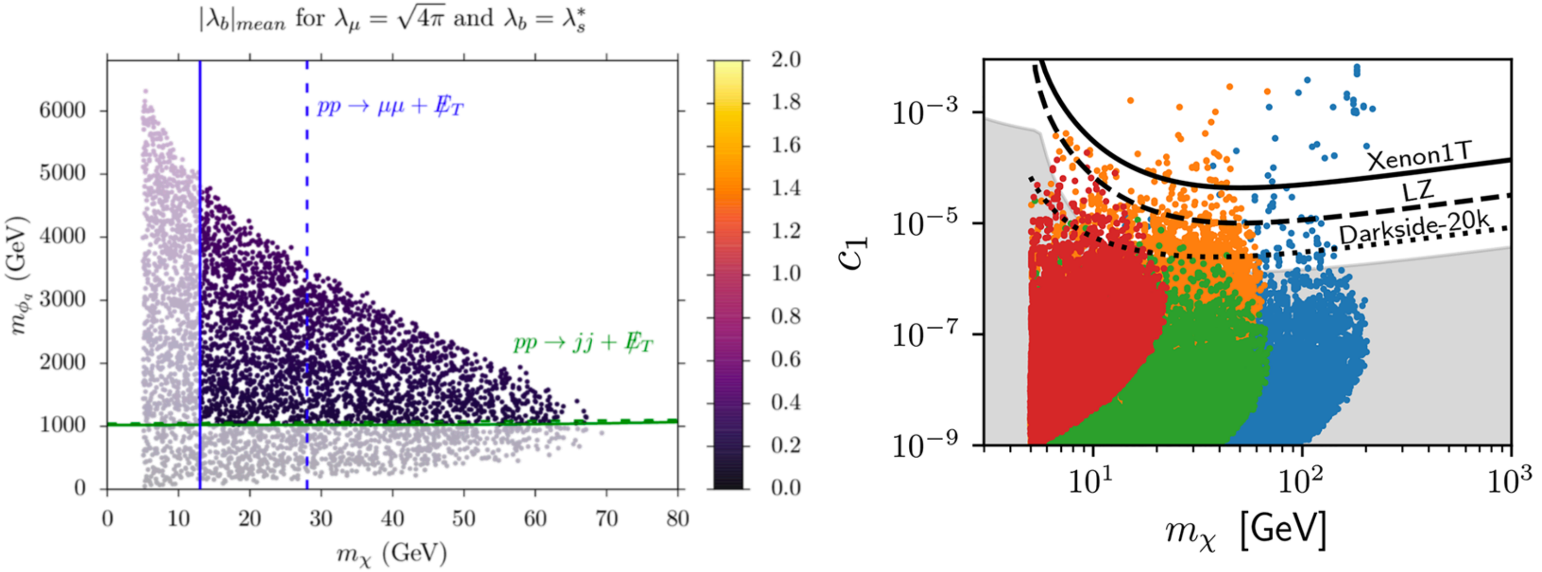
- New particle content :
  - χ, Majorana fermionic DM particle
  - Φ_q, scalar field couples to quarks
  - Φ_L, scalar field couples to leptons







Leads to LHC signatures :
pp ➞ qq + MET
pp ➞ ll + MET



Constraints based on CMS and ATLAS SUSY multi-lepton searches and tt+MET, bb+MET

1710.11412 Eur. Phys. J. C78 (2018) 18 1803.02762 Eur. Phys. J. C 78 (2018) 995

Can also be tested at upcoming direct detection experiments

From Ben Kilminster – DM@LHC 2019

So far this all seems to point to heavy dark matter…

- What about lighter dark matter?

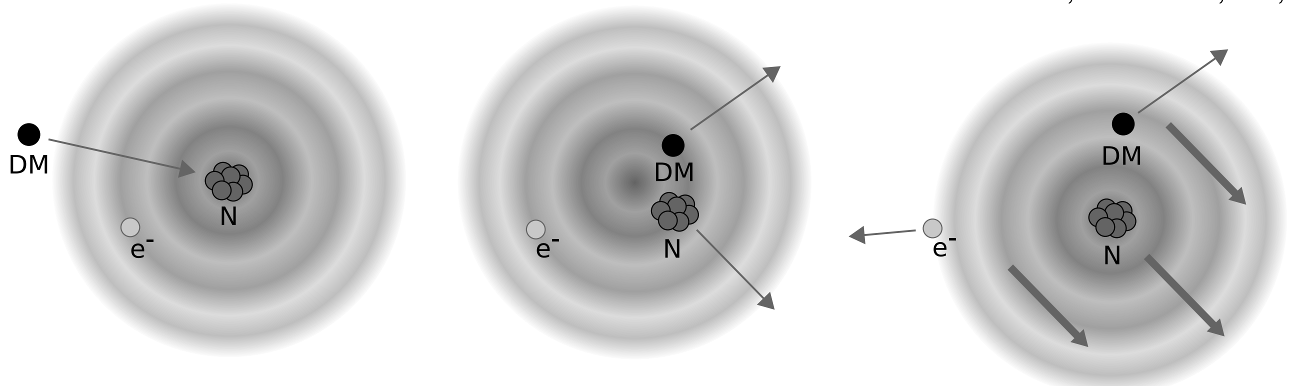
What can direct detection do at low masses?

- Smaller masses intrinsically difficult
- Smaller mass -> smaller recoil -> smaller signal
- But there are new ideas and new technologies

Extending the reach of xenon detectors

Migdal effect:

Ibe, Nakano, Shoji, Suzuki, JHEP, arXiv:1707.07258
Dolan, Kahlhoefer, CM, PRL, arXiv:1711.09906



$$|\Phi_{ec}\rangle \qquad |\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle \qquad \mathcal{P} = |\langle\Phi^*_{ec}|\Phi'_{ec}\rangle|^2$$

"…it takes some time for the electrons to catch up, which causes ionisation of the atom."

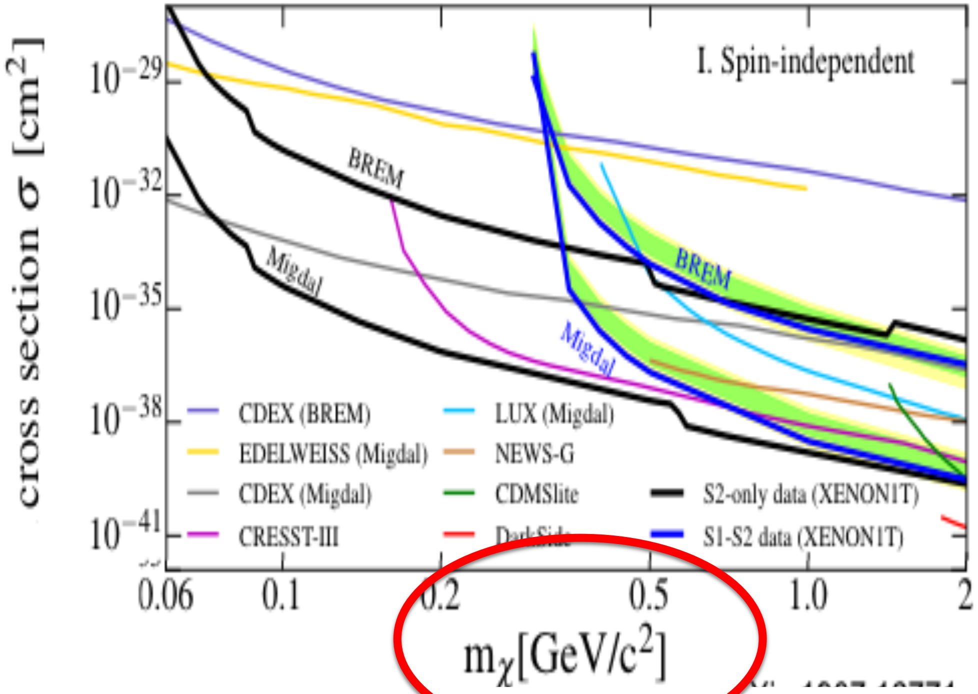
Signal: the ionised electron

[Can also be applied to other targets (Ge, LAr…)]

DM-electron recoil signals – Migdal effect

- Ionisation electron or bremsstrahlung photon easier to detect than nuclear recoil
- Xenon competing with dedicated low mass detectors
  - e.g. solid state detectors (Ge)

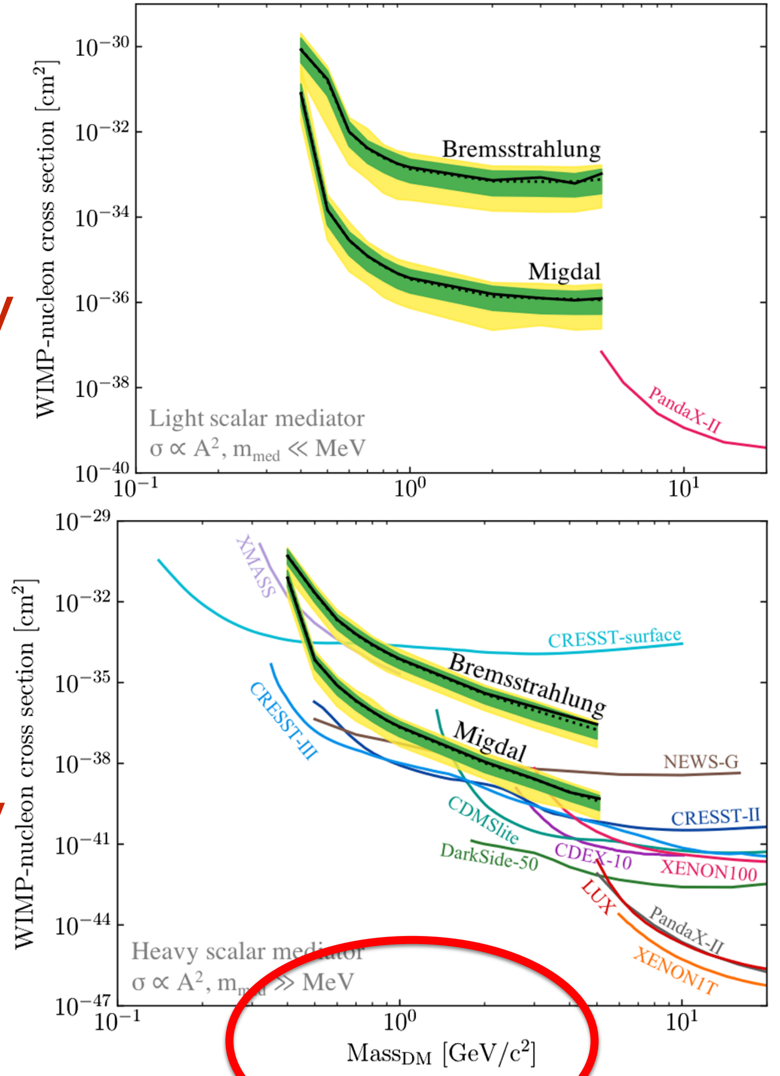
XENON1T (arxiv:1907.12771)



LUX (arXiv:1811.11241)

light scalar mediator $m_{med} \ll$ MeV

heavy scalar mediator $m_{med} \gg$ MeV



So far this all seems to point to heavy dark matter…

- What about lighter dark matter?
- How light do you want to go?

DM scattering off electrons – Dark Photon Mediators

- Benchmark model consists of a DM candidate χ, which scatters off both electrons and protons through the exchange of a massive dark photon A′

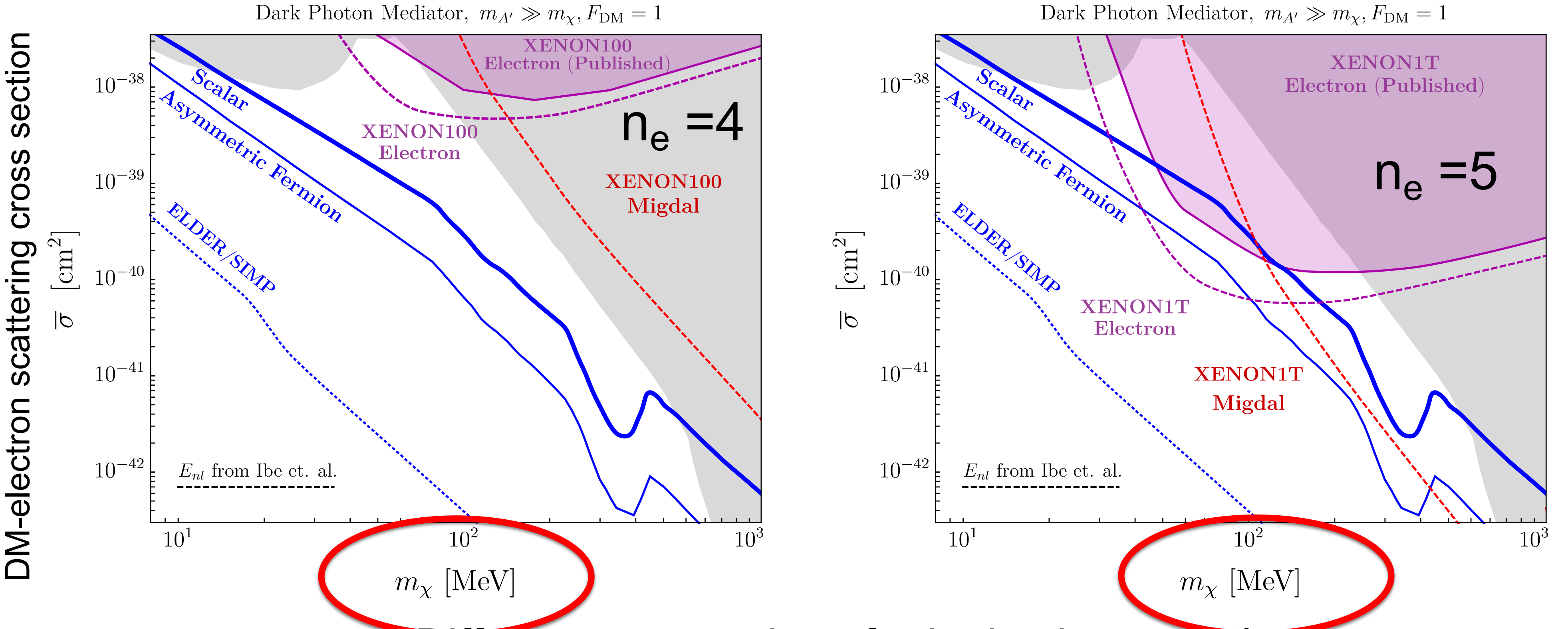
Baxter et al, arxiv:1908.00012

- Presumably also testable at LHC

$$\frac{\overline{\sigma}_e}{\mu_{\chi e}^2} = \frac{\overline{\sigma}_p}{\mu_{\chi p}^2}$$

$\mu_{\chi e/p}$ is reduced mass

sub-GeV DM



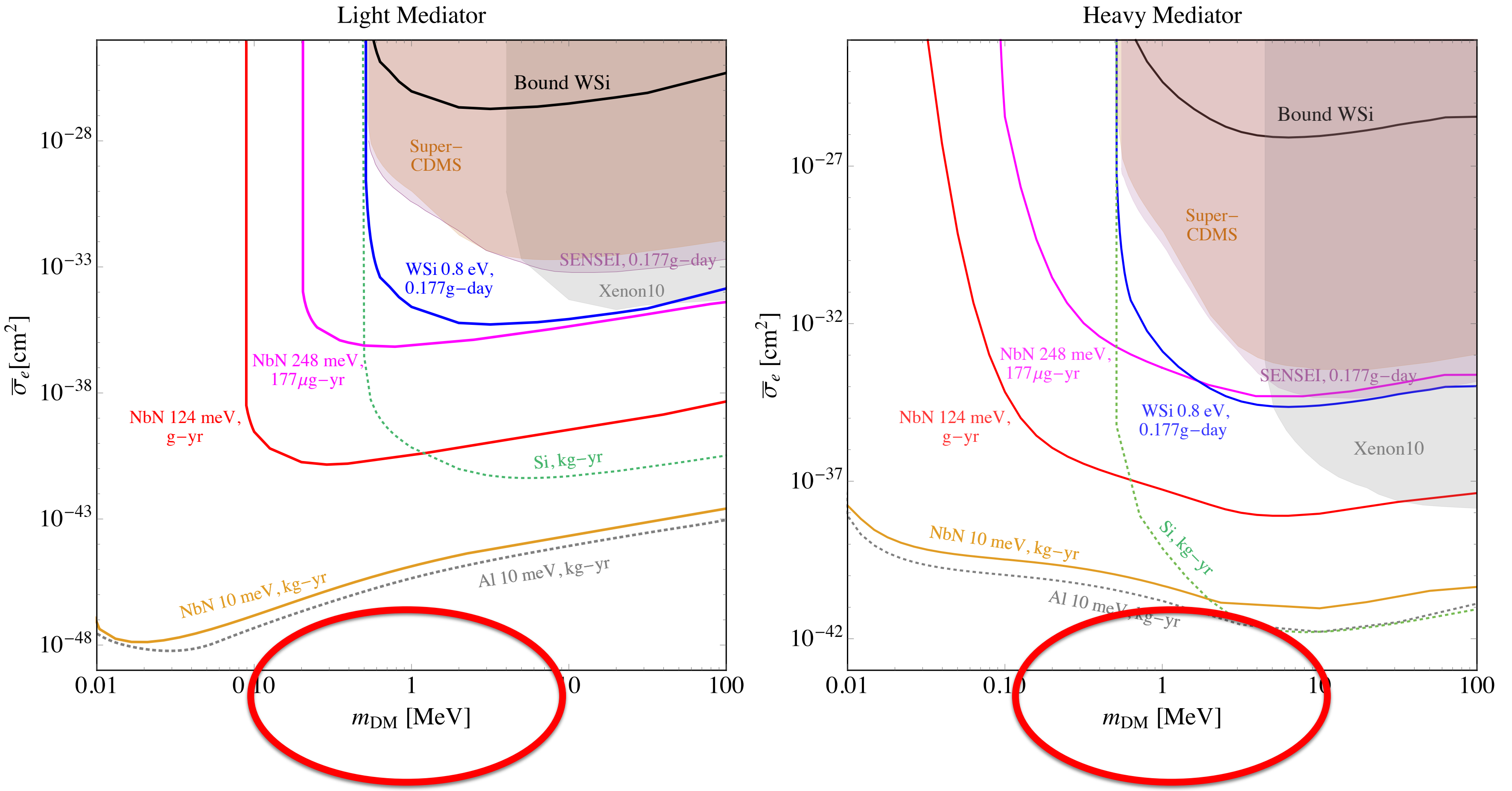
- Different assumptions for ionization model

DM scattering off electrons – Quantum Nanowires

Hochberg et al, arxiv:1903.05101

- Superconducting nanowires are sensitive to (very) small energy deposits on electrons
- Depending on material, expected sensitivity in 10 keV – 100 MeV range

Expected sensitivity



Axions and Axion like particles (ALPs)

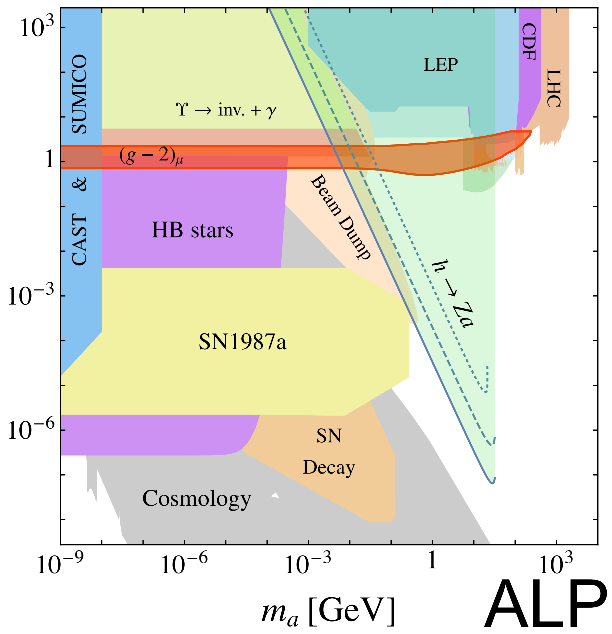
- Collider relevant for ALPs with MeV to hundreds of GeV scale masses
- Long-lived ALP would lead to missing energy signature
- ALPs with larger masses or couplings could decay inside detectors

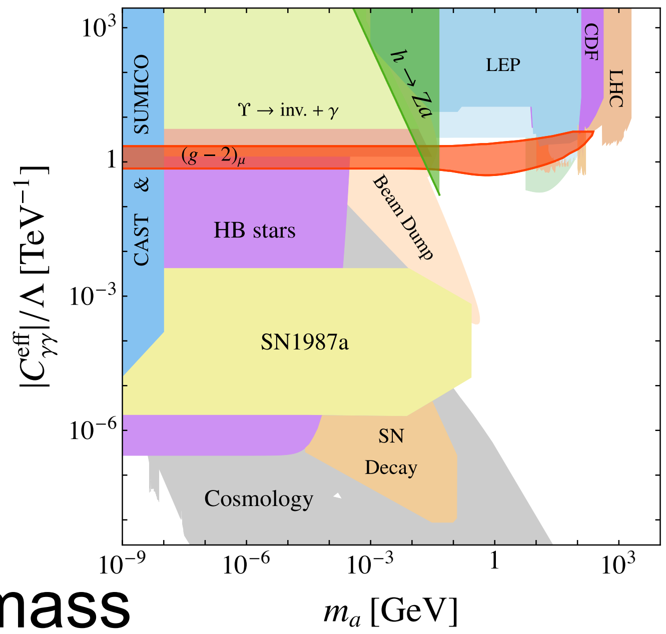
h->aa->4 γ and h-> γ γ

300/fb

current exclusion

ALP photon coupling

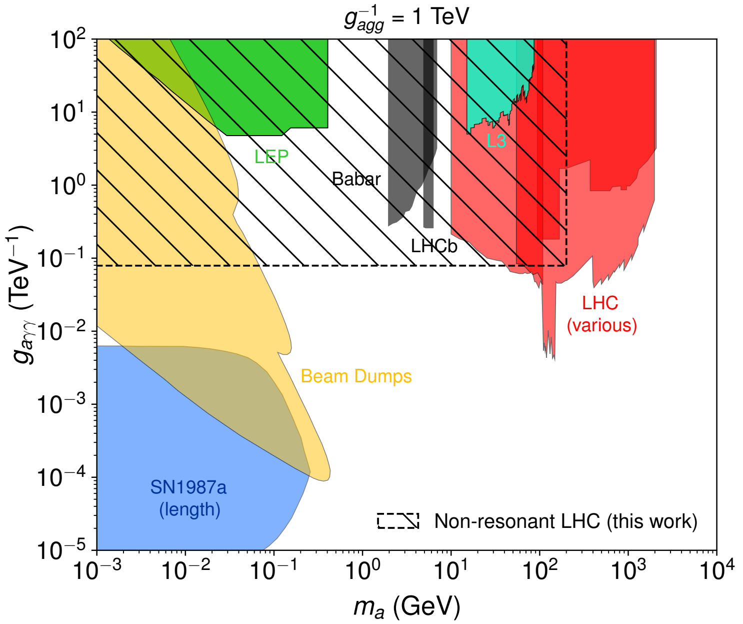




ALP mass

Bauer et al, arxiv:1708.00443

Reinterpretation of CMS search for non-res new physics (arxiv:1809.00327) in γγ final state



Gavela et al, arxiv:1905.12953

ALPs in direct detection

- Search for axioelectric coupling with the LUX experiment for two specific scenarios:
- (i) QCD axions emitted from the sun,
- (ii) keV-scale galactic ALPs that could constitute the gravitationally bound dark matter.
- Signature is electron recoil like events
- Limits on axion mass and coupling between axions and electrons
- (sub) keV dark matter

LUX
PhysRevLett.118.261301

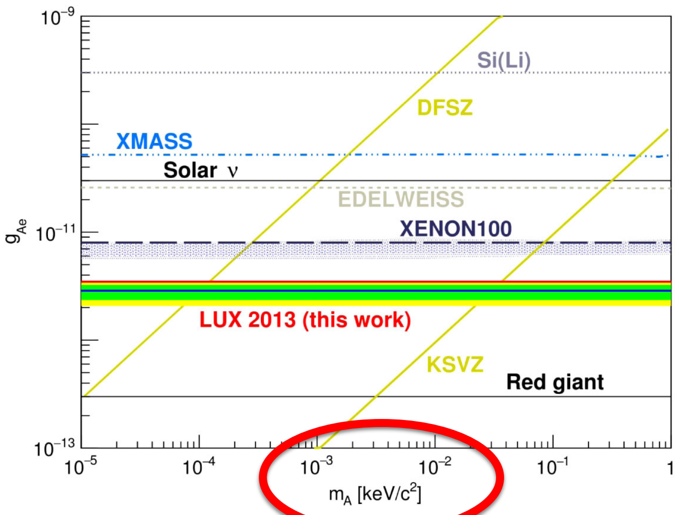


FIG. 6. Red curve: LUX 2013 data 90% C.L. limit on the coupling between solar axions and electrons. Blue curve: 90% C.L. sensitivity, $\pm 1\sigma$ (green band), and $\pm 2\sigma$ (yellow band).

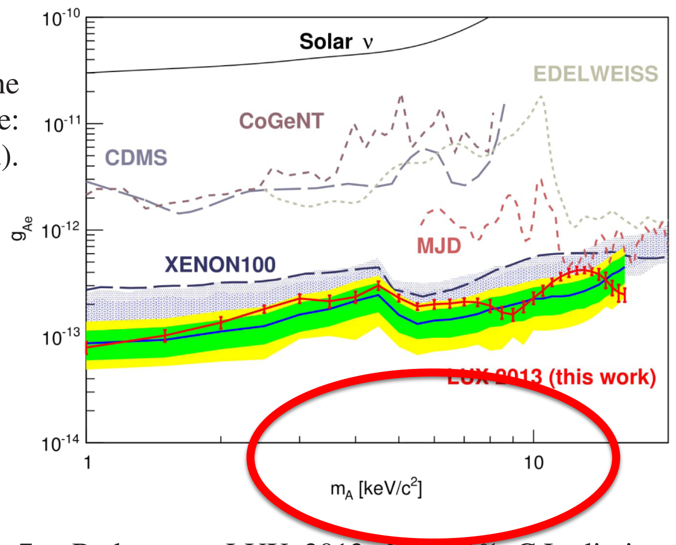


FIG. 7. Red curve: LUX 2013 data 90% C.L. limit on the coupling between galactic axionlike particles and electrons. Blue curve: 90% C.L. sensitivity, $\pm 1\sigma$ (green band), and $\pm 2\sigma$ (yellow band).

Things I didn't mention…

- Inelastic Dark Matter
  - Can be tested a collider and direct detection
- NP models (e.g. EFTs) resulting in large nuclear recoils
  - presumably to some extend also testable at LHC
- And many others…

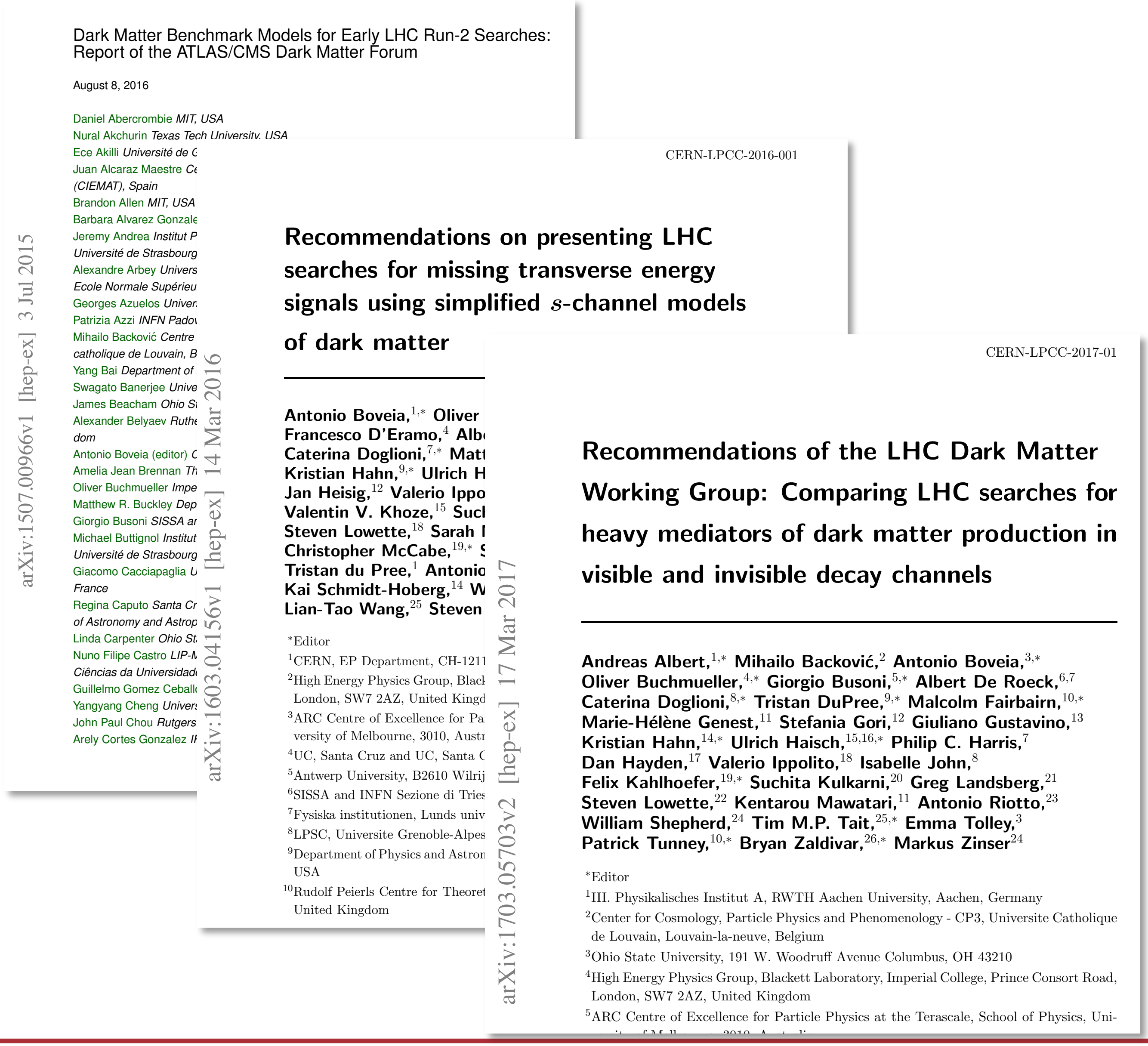
Conclusions

- No shortage of models predicting DM over a (very) large mass range
- Both collider and direct detection experiments can tackle many (most?) of them
- Sensitivity often complementary
  - Care needs to be taken on how to translate results between experimental approaches
- Complementary sensitivity will be essential if one or the other (or both?) should start seeing a signal

- Backup

Dark Matter LHC Working Group

- Systematic approach pursued through Dark Matter LHC Working group
  - https://lpcc.web.cern.ch/content/lhc-dm-wg-wg-dark-matter-searches-lhc
  - with involvement of both experimentalists and theorists
- Recommendations for models and their implementation
- Guidelines on how to compare collider searches with direct detection limits
- Recommendations for comparison of searches for heavy mediators of DM production


Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

August 8, 2016

arXiv:1507.00966v1 [hep-ex] 3 Jul 2015

CERN-LPCC-2016-001

Recommendations on presenting LHC searches for missing transverse energy signals using simplified *s*-channel models of dark matter

arXiv:1603.04156v1 [hep-ex] 14 Mar 2016

CERN-LPCC-2017-01

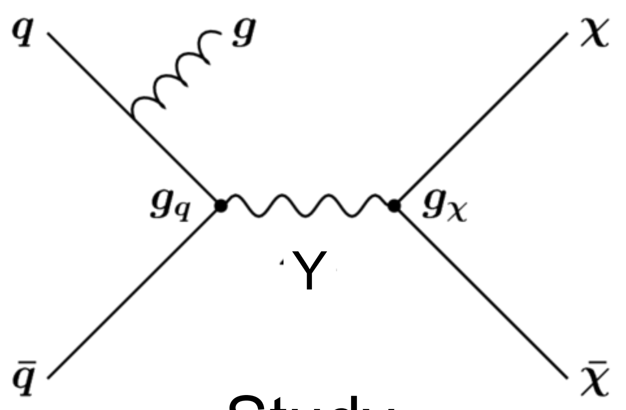
Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels

arXiv:1703.05703v2 [hep-ex] 17 Mar 2017

Andreas Albert,[1,*] Mihailo Backović,[2] Antonio Boveia,[3,*] Oliver Buchmueller,[4,*] Giorgio Busoni,[5,*] Albert De Roeck,[6,7] Caterina Doglioni,[8,*] Tristan DuPree,[9,*] Malcolm Fairbairn,[10,*] Marie-Hélène Genest,[11] Stefania Gori,[12] Giuliano Gustavino,[13] Kristian Hahn,[14,*] Ulrich Haisch,[15,16,*] Philip C. Harris,[7] Dan Hayden,[17] Valerio Ippolito,[18] Isabelle John,[8] Felix Kahlhoefer,[19,*] Suchita Kulkarni,[20] Greg Landsberg,[21] Steven Lowette,[22] Kentarou Mawatari,[11] Antonio Riotto,[23] William Shepherd,[24] Tim M.P. Tait,[25,*] Emma Tolley,[3] Patrick Tunney,[10,*] Bryan Zaldivar,[26,*] Markus Zinser[24]

*Editor
[1]III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
[2]Center for Cosmology, Particle Physics and Phenomenology - CP3, Universite Catholique de Louvain, Louvain-la-neuve, Belgium
[3]Ohio State University, 191 W. Woodruff Avenue Columbus, OH 43210
[4]High Energy Physics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London, SW7 2AZ, United Kingdom
[5]ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, Uni-

The Lagrangian for DMSM



Study
pure vector
and
pure axial-vector
couplings

Parameter	Range
m_Y	$(0.1, 5)$ TeV
m_χ	$(0, 2.5)$ TeV
g_{SM}	$(0, \sqrt{4\pi})$
g_{DM}	$(0, \sqrt{4\pi})$

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

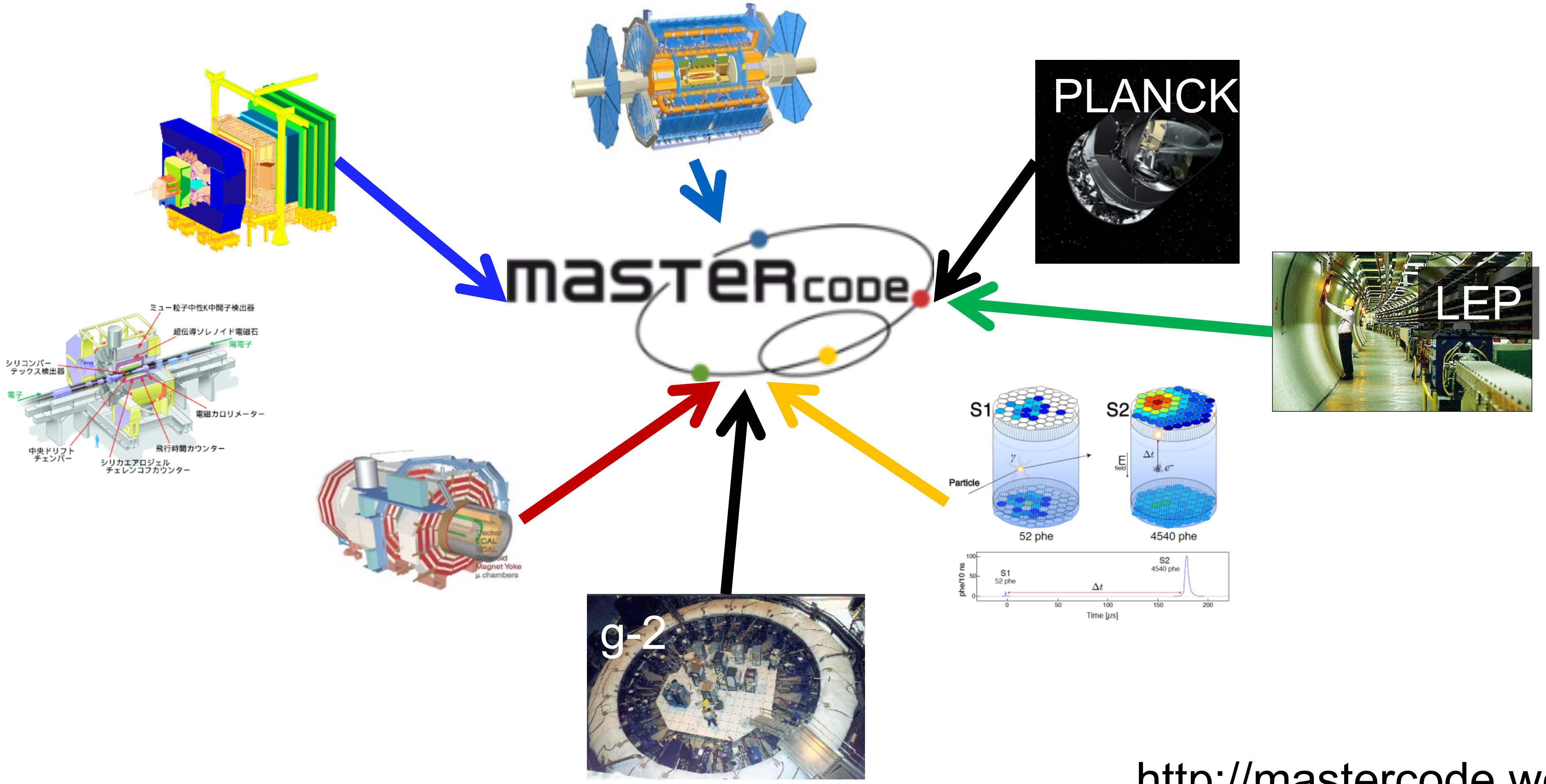
Scenarios

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

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

Experimental Constraints

Global analyses of experimental data in constrained versions of the Minimal Supersymmetric Standard Model (MSSM)



http://mastercode.web.cern.ch

Global fit of Dark Matter Simplified Models