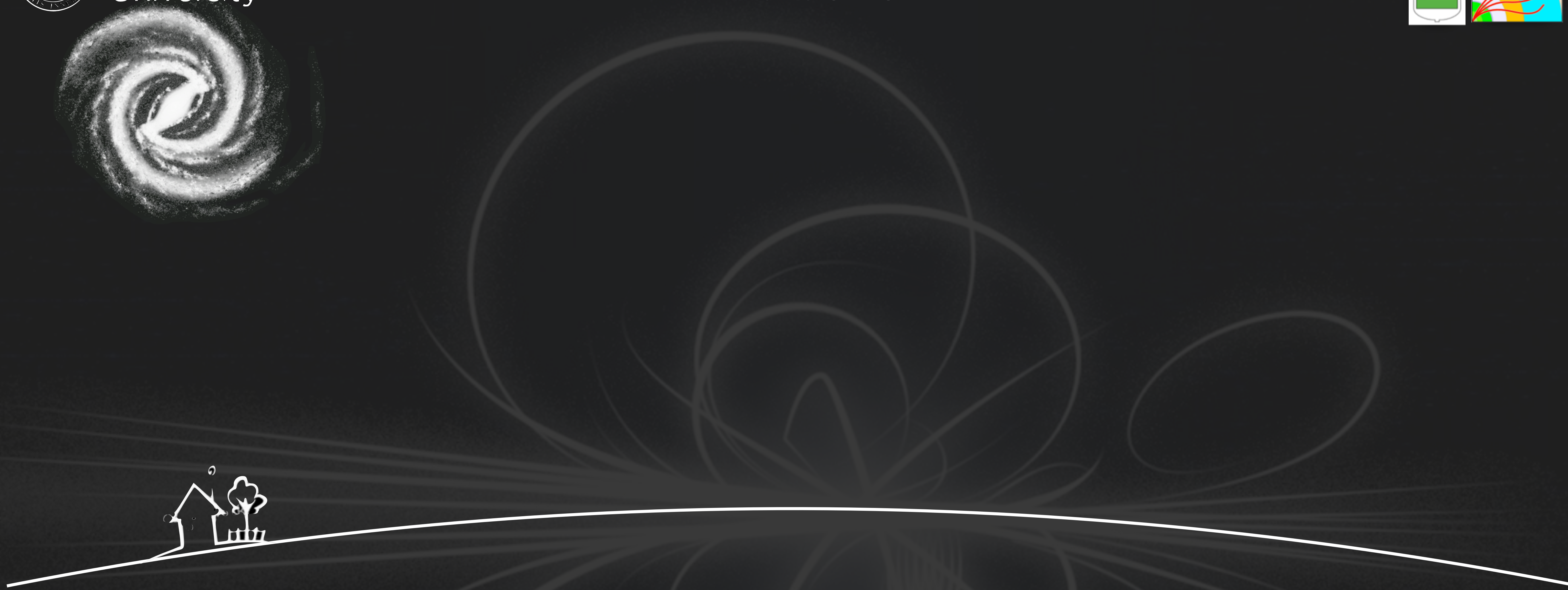
Brandeis University

Dark Matter at Collider & Interplay

Björn Penning
Brandeis & Bristol

DM Detection



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DM Detection

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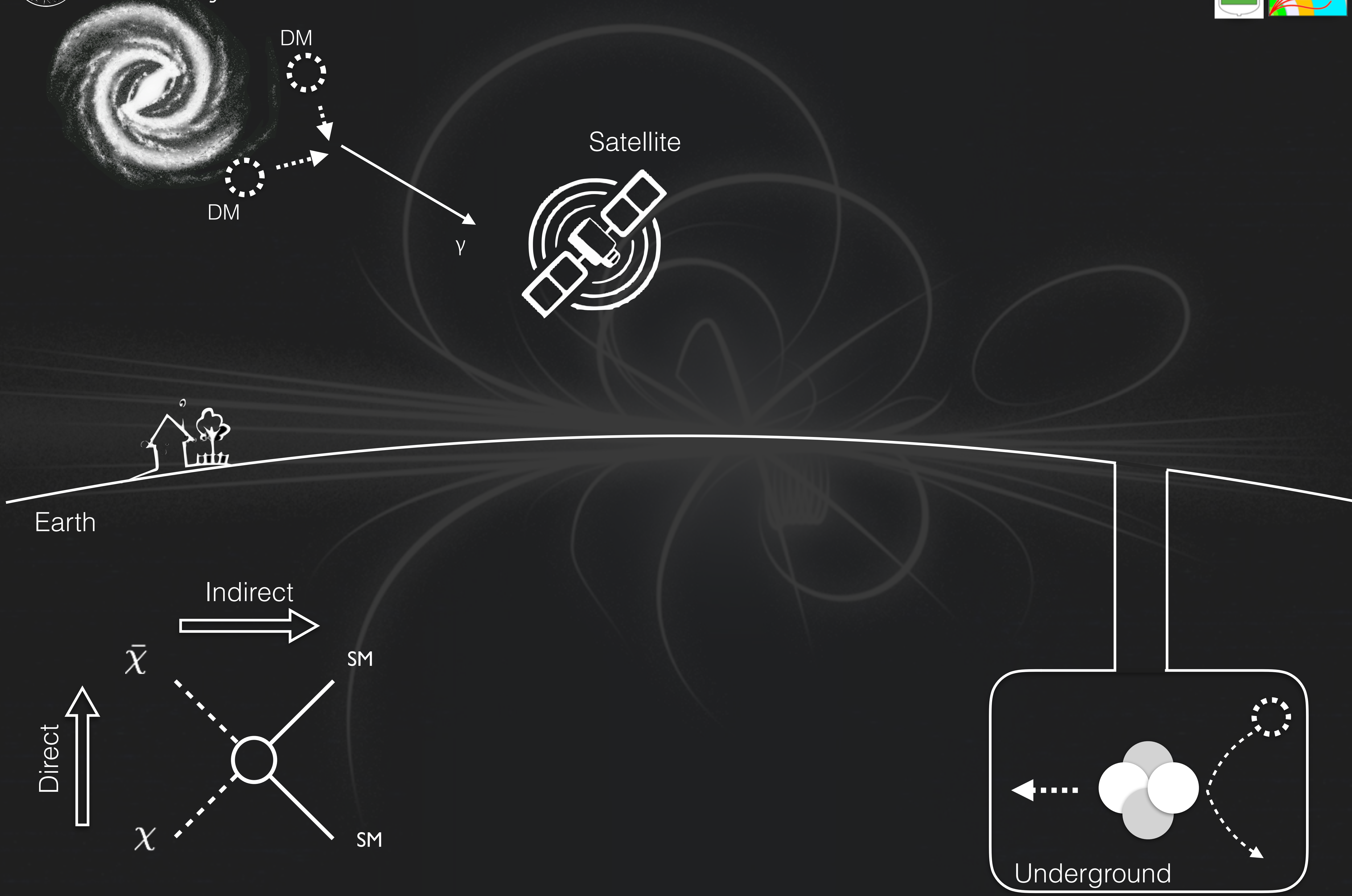

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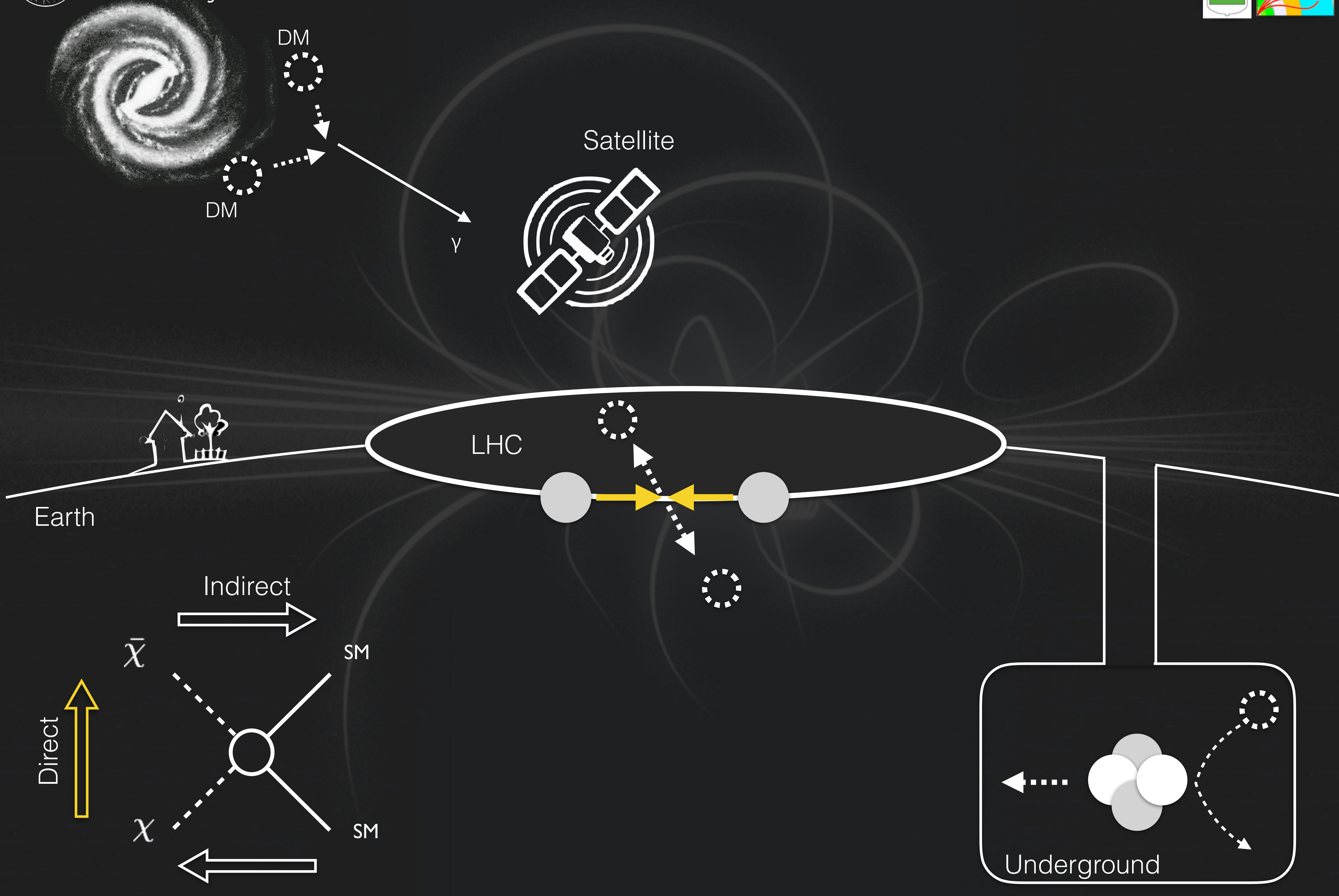
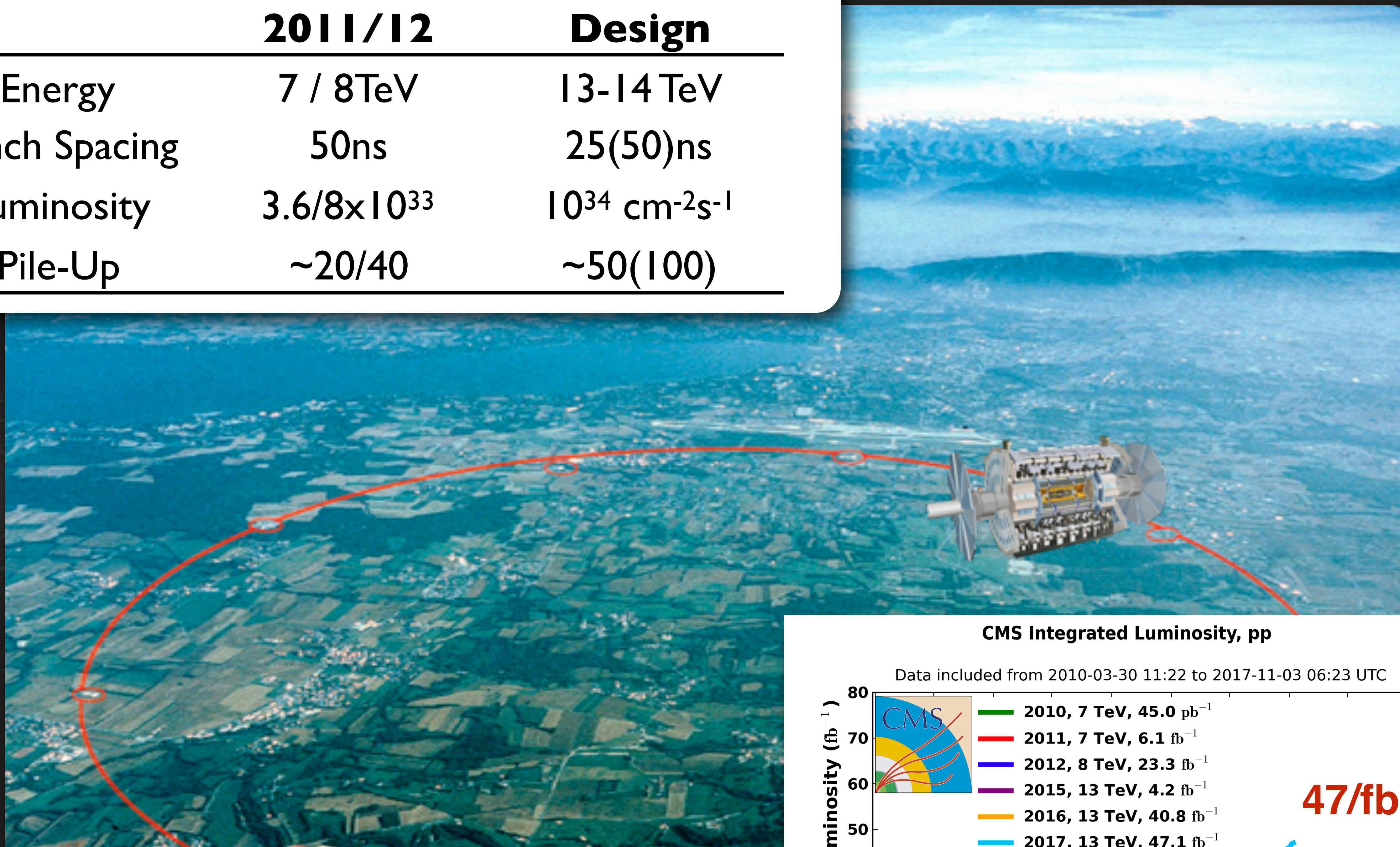
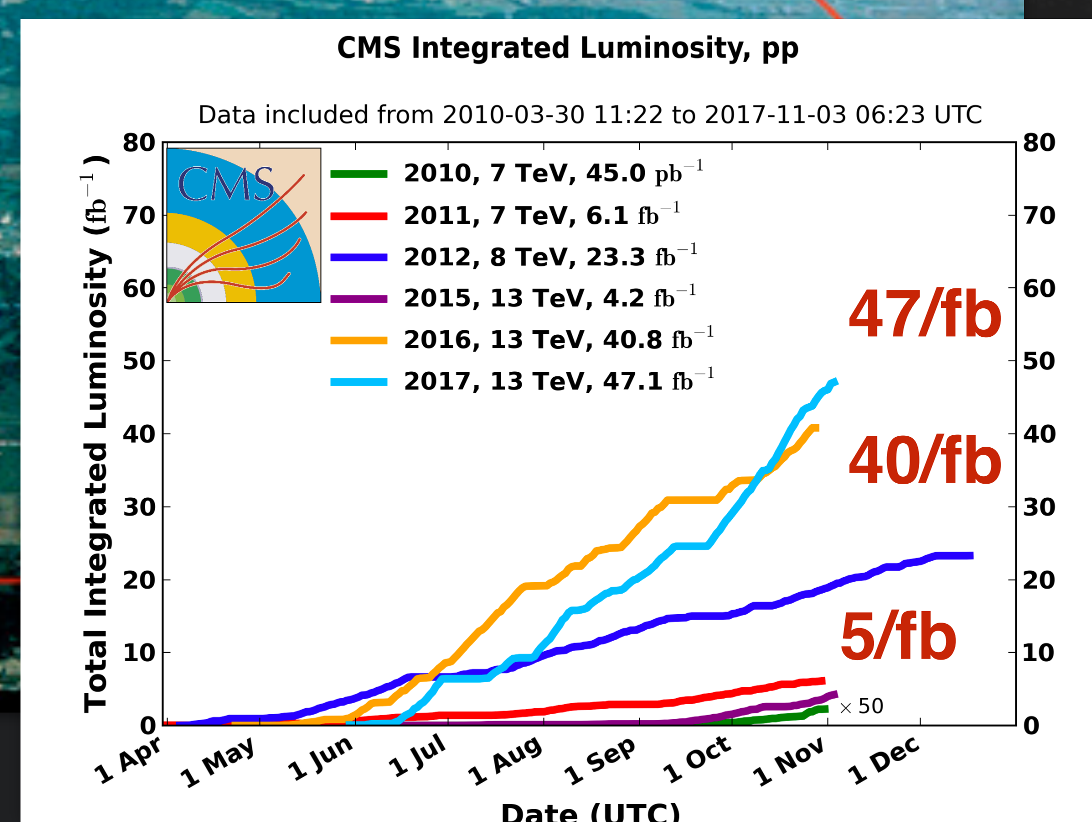


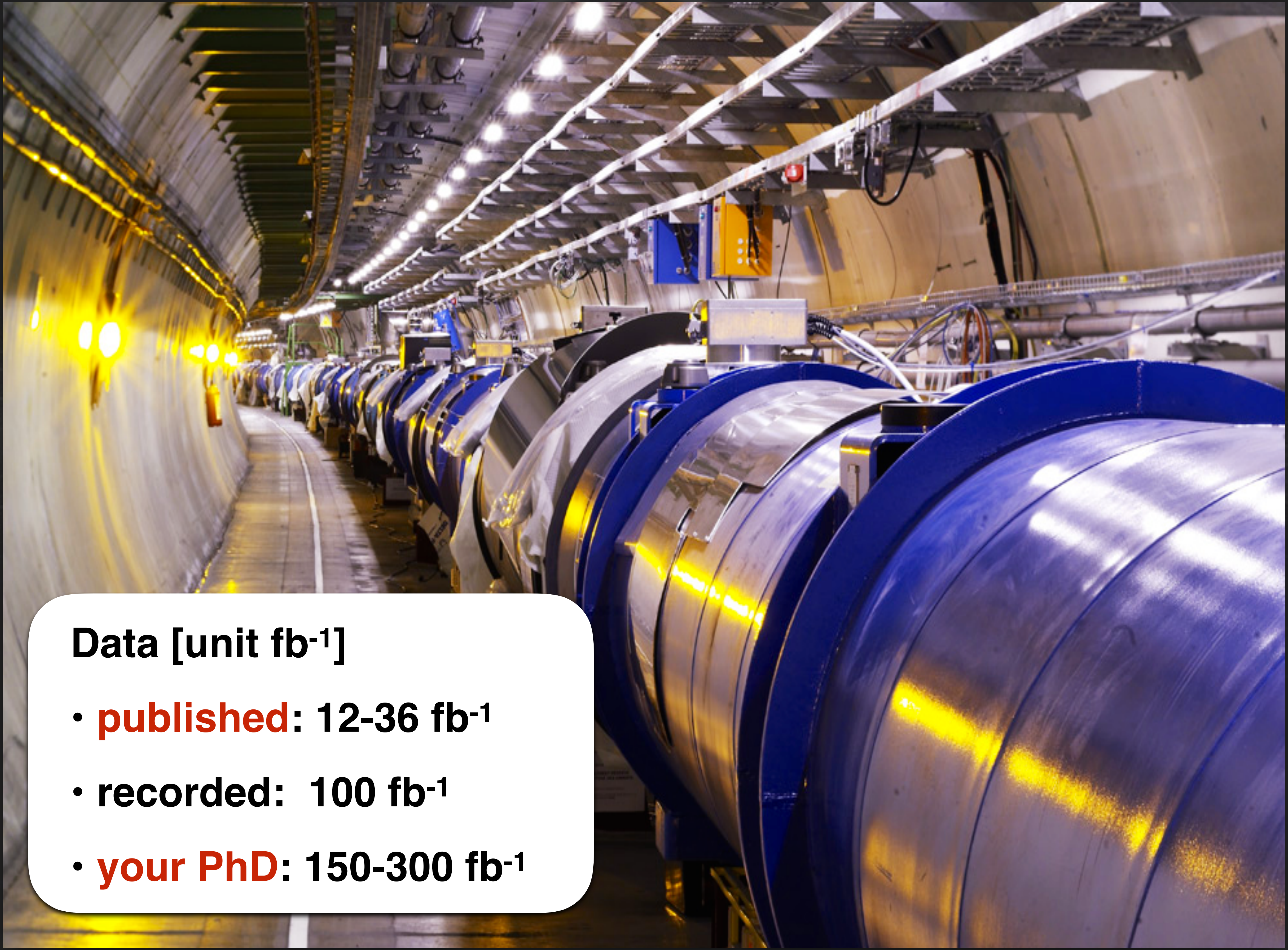
The LHC

	2011/12	Design
Energy	7 / 8TeV	13-14 TeV
Bunch Spacing	50ns	25(50)ns
Luminosity	$3.6/8x10^{33}$	10^{34} $cm^{-2}s^{-1}$
Pile-Up	~20/40	~50(100)





The LHC

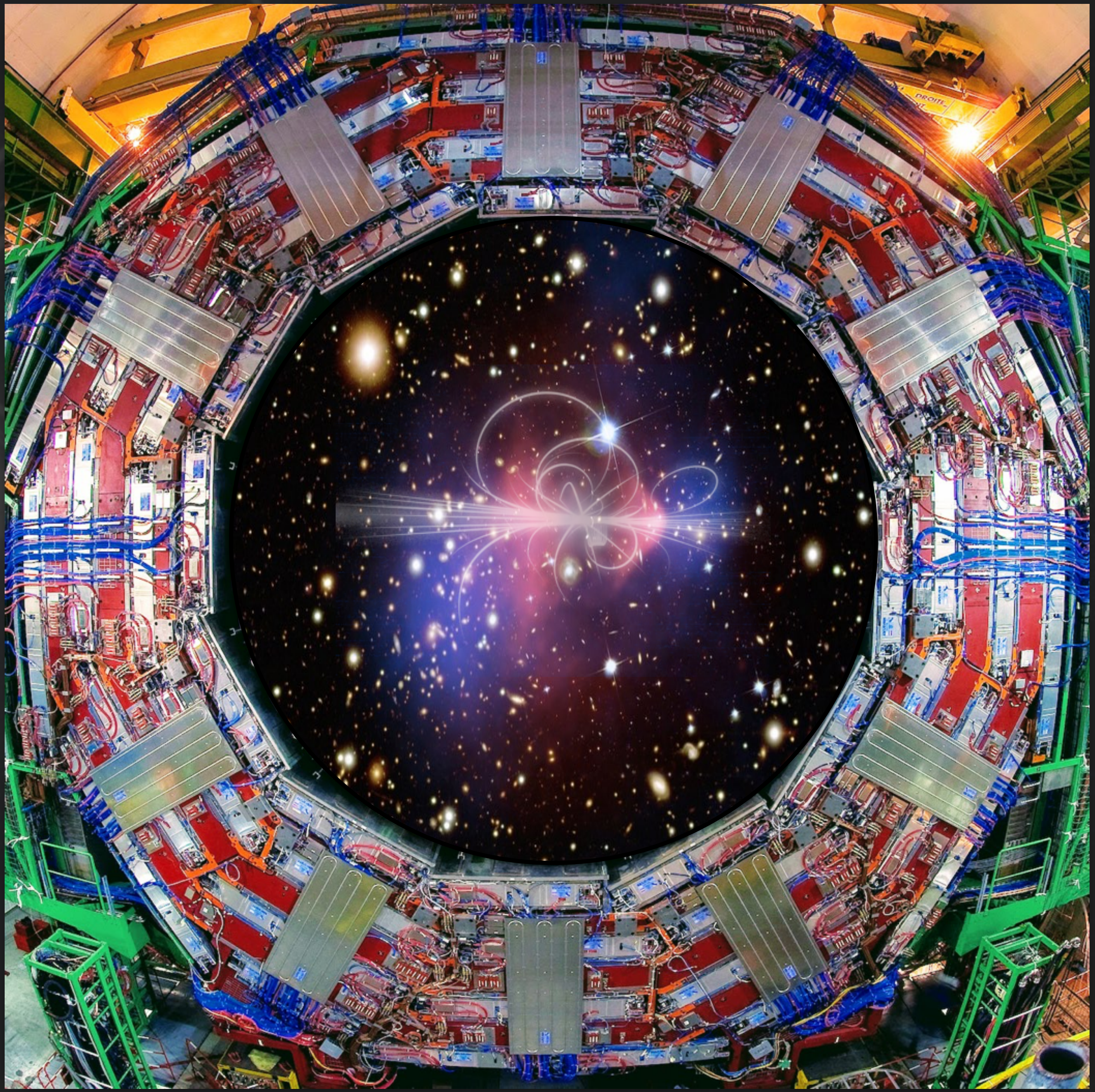


Data [unit fb^{-1}]

- **published: 12-36 fb^{-1}**
- **recorded: 100 fb^{-1}**
- **your PhD: 150-300 fb^{-1}**

DM Detection

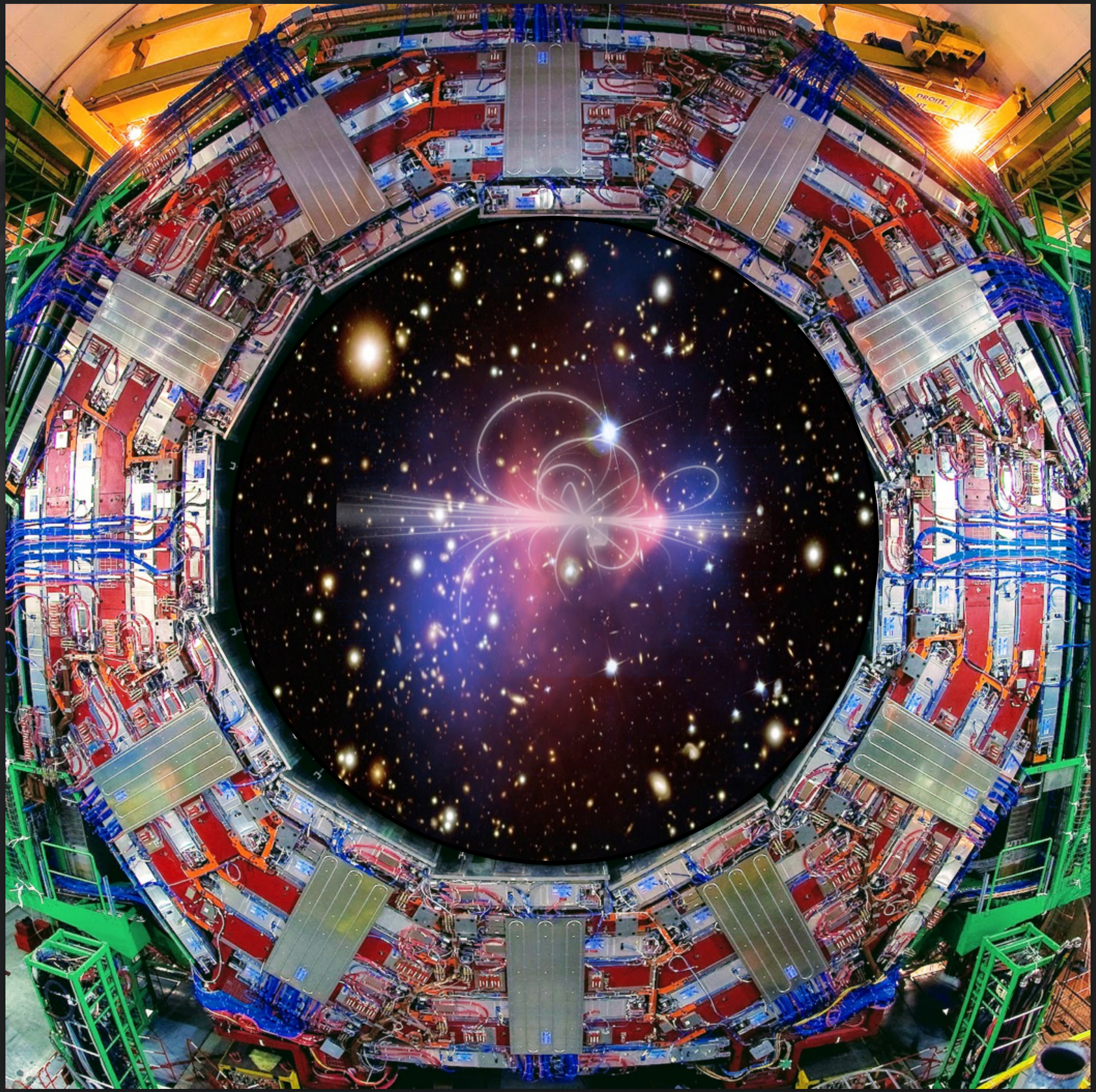
- If all evidence of DM is gravitational, why should we look for it at collider (particularly hadron)?
- Well motivated:
  - ‘WIMP paradigm’ predicts particles approximate EW scale
  - Many HEP BSM theories predict viable DM candidates
  - Complementarity, collider have different strengths and uncertainties
  - Colliders would be uniquely able to measure the WIMPs properties



DM Detection

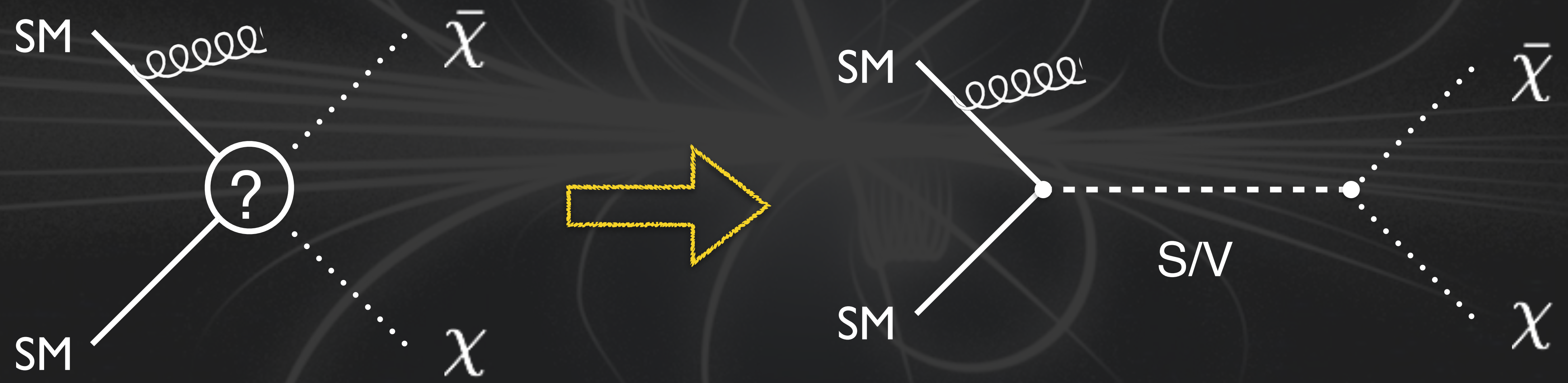
- DM has to be kinematically accessible: ~1-1000GeV
- Essentially two types of collider searches:

1. Search for DM (mono-X)
2. Search for the Mediator



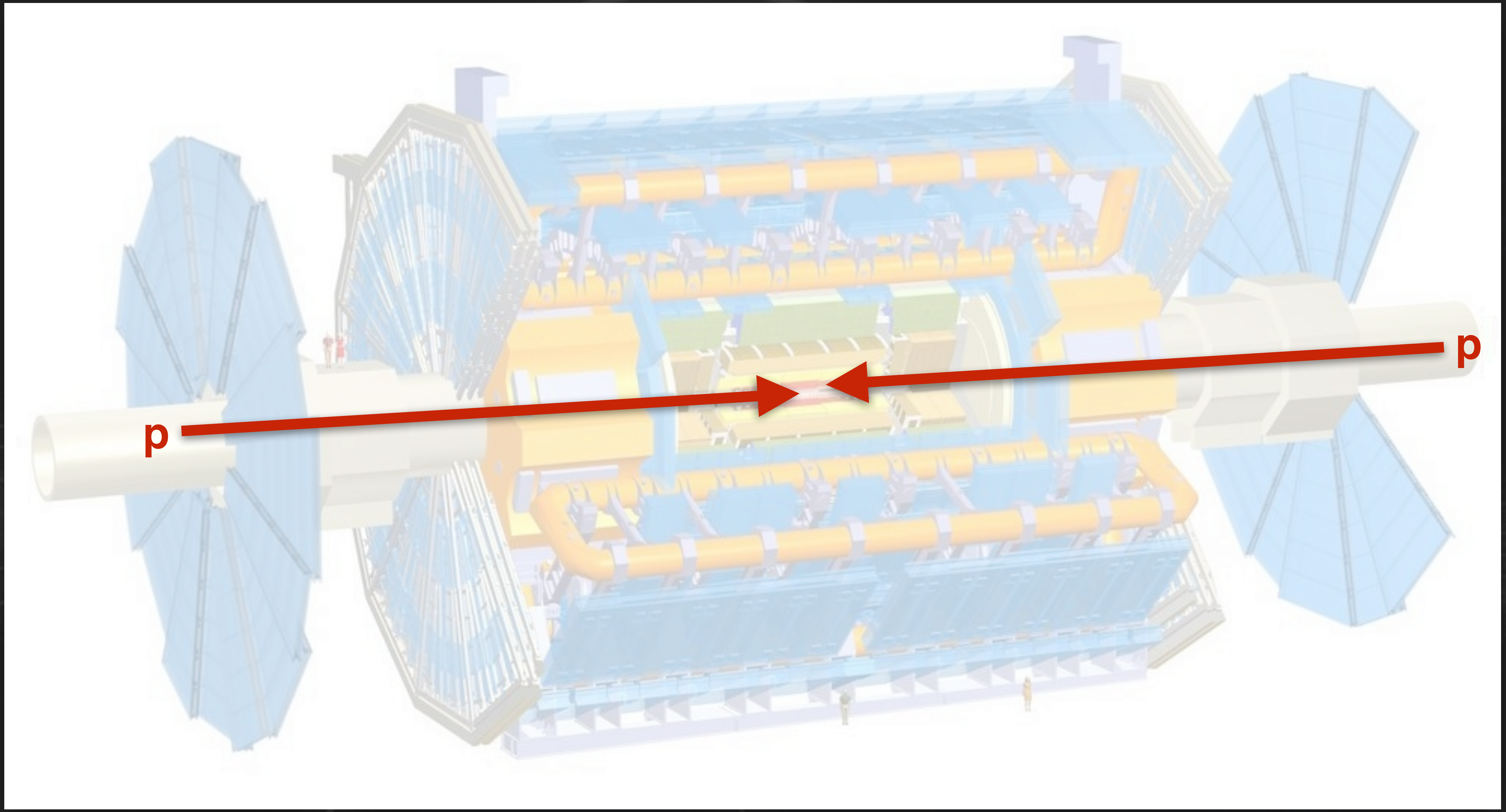
Signature

- At collider the WIMPs are invisible but are inevitably produced in association with visible particles from ISR
  → 'back-to-back' signature due to momentum conservation in the CoM
- Can be parametrize this via EFT or more commonly & robust as simplified models

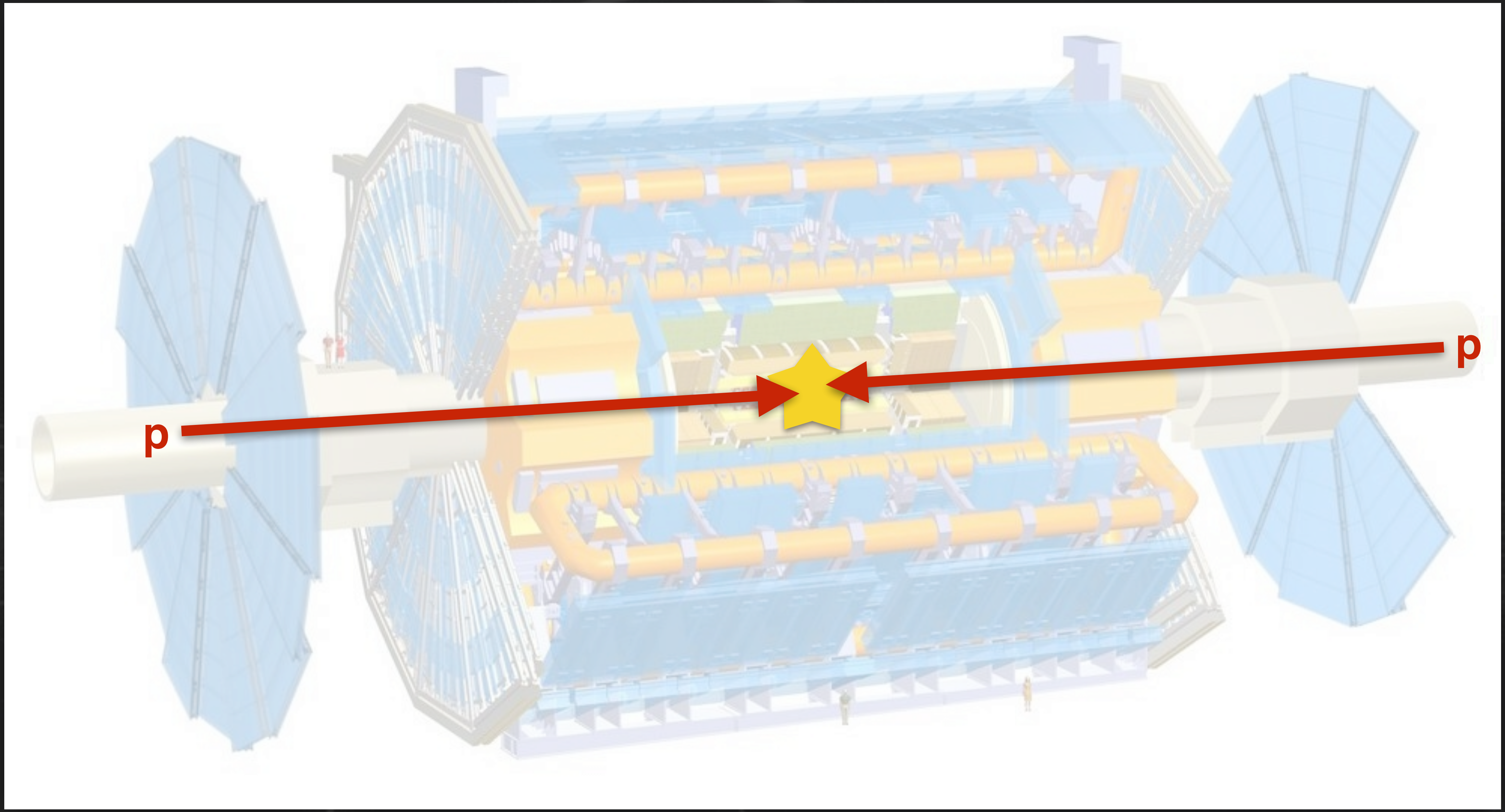


- Leads to known interactions
  - scalar (ψψ),
  - pseudo scalar ($\bar{\psi}\gamma^5\psi$)
  - vector $\bar{\psi}\gamma^\mu\psi$,
  - axial-vector ($\bar{\psi}\gamma^\mu\gamma^5\psi$)

DM Detection

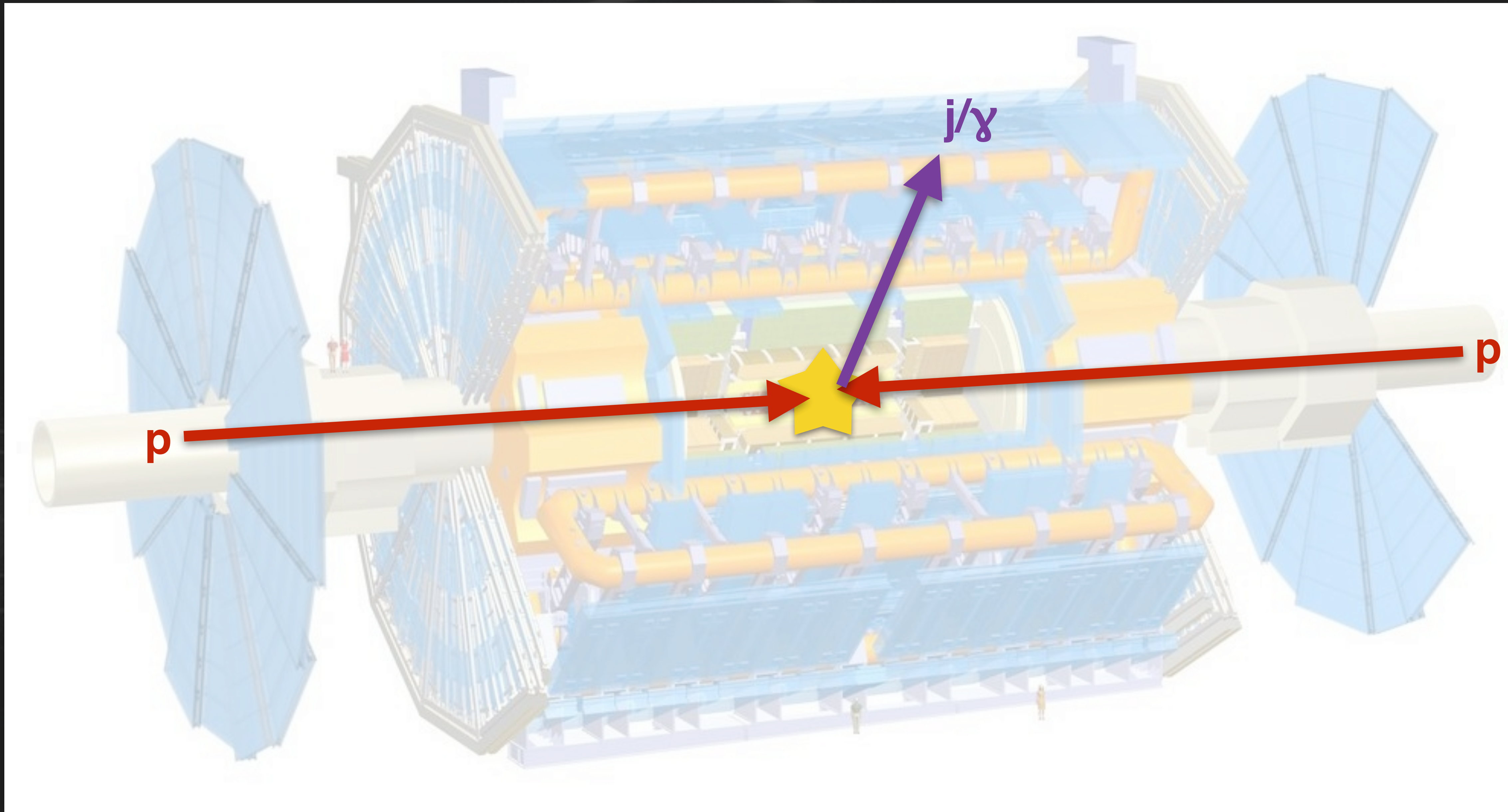


DM Detection



- Protons collide
- DM produced will escape the detector and recoil from the visible state
- Signature explores wide range of interactions and final states particles

DM Detection



- Protons collide and produce almost always visible particle
- DM produced will escape the detector and recoil from the visible state
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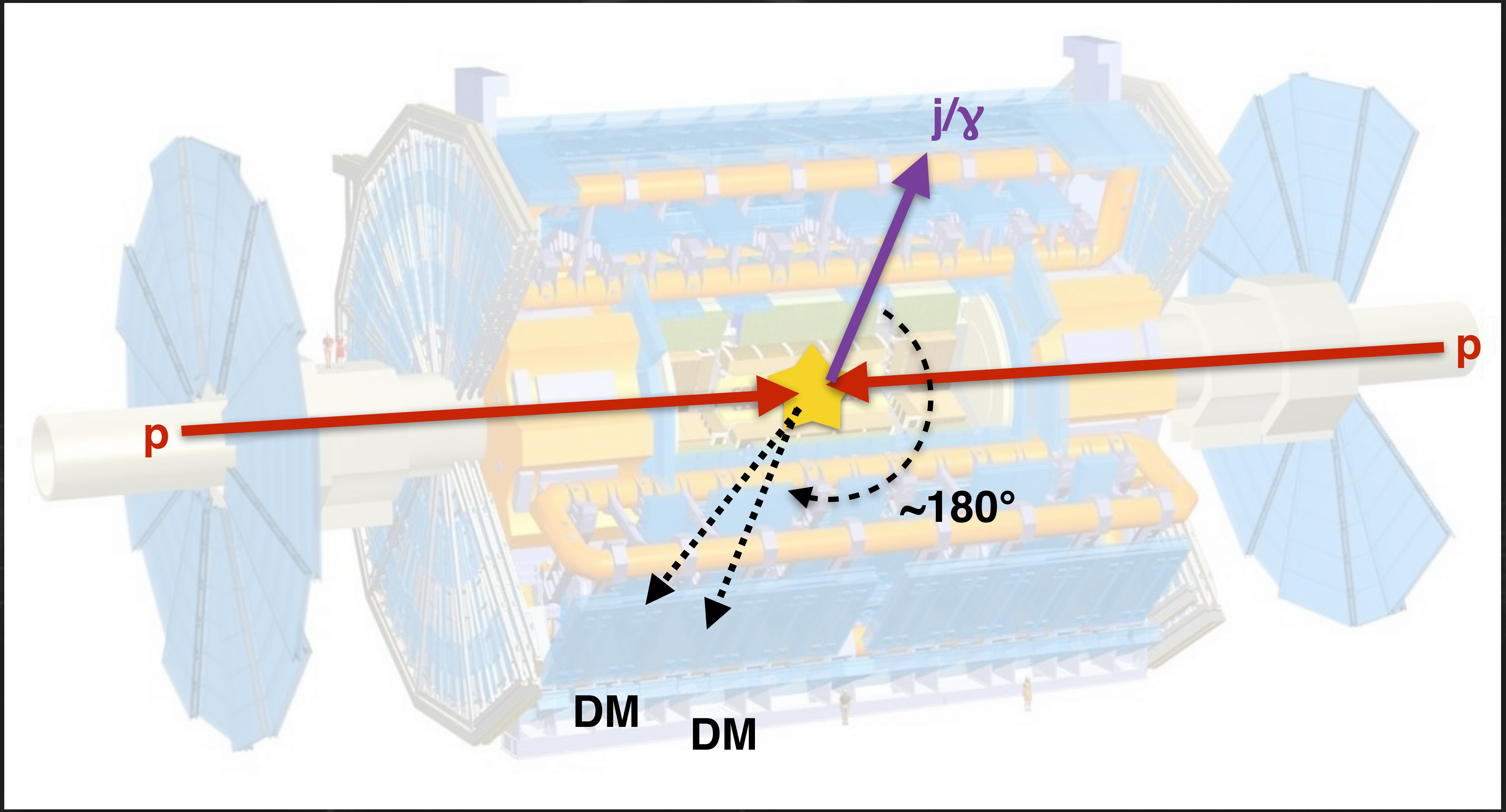
DM Detection



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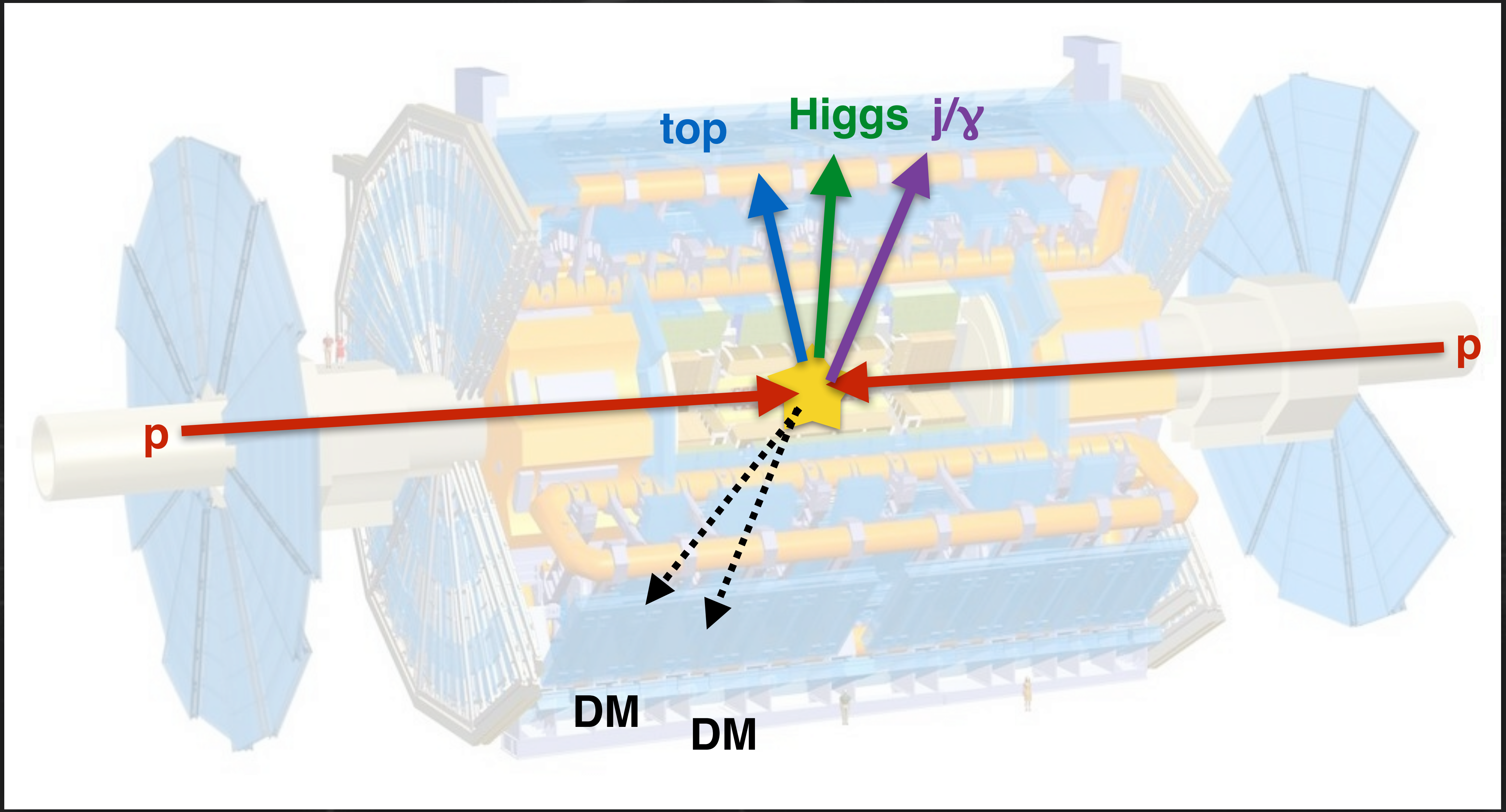

- Protons collide and produce almost always visible particle
- DM escapes the detector and recoil from the visible state
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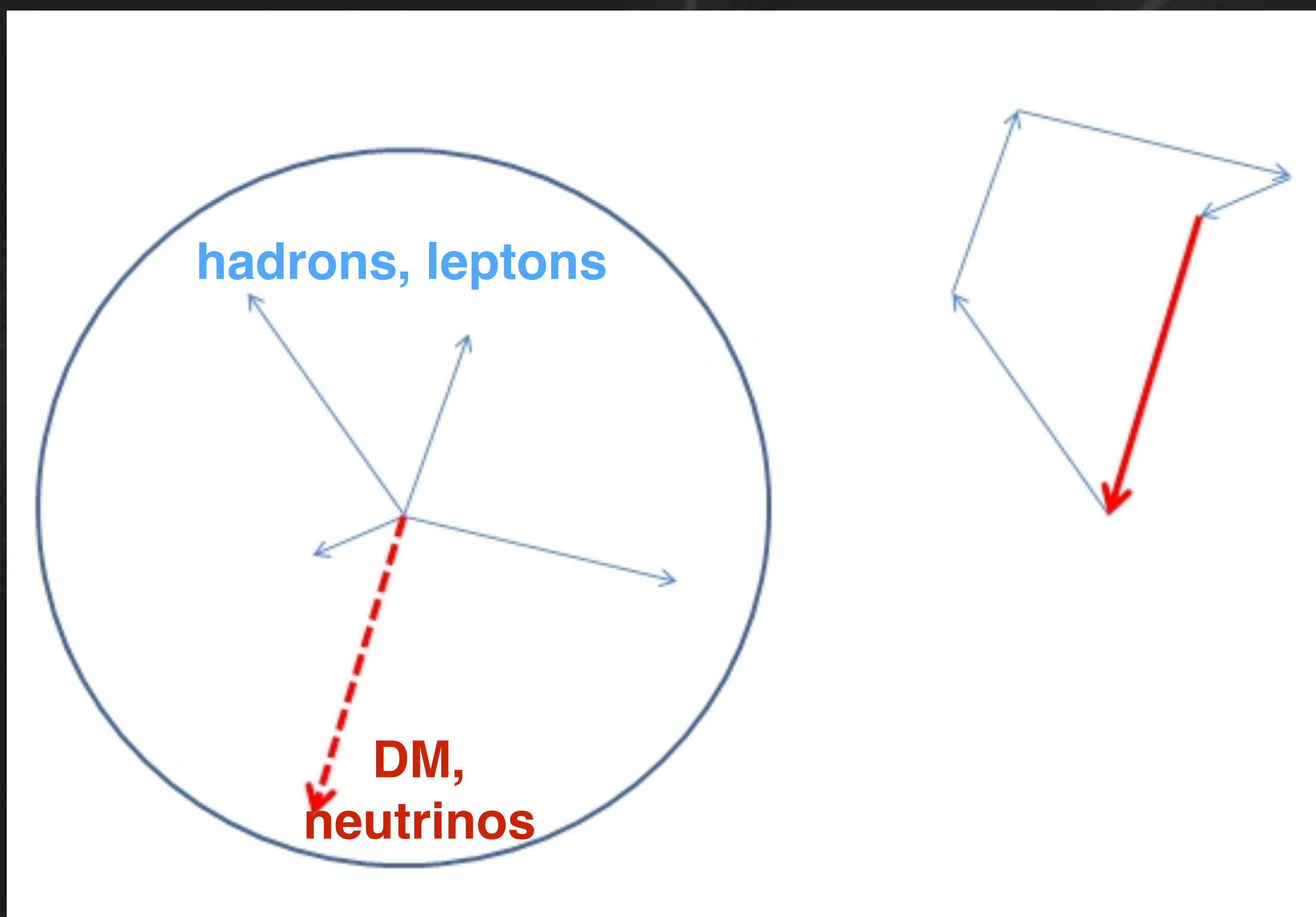
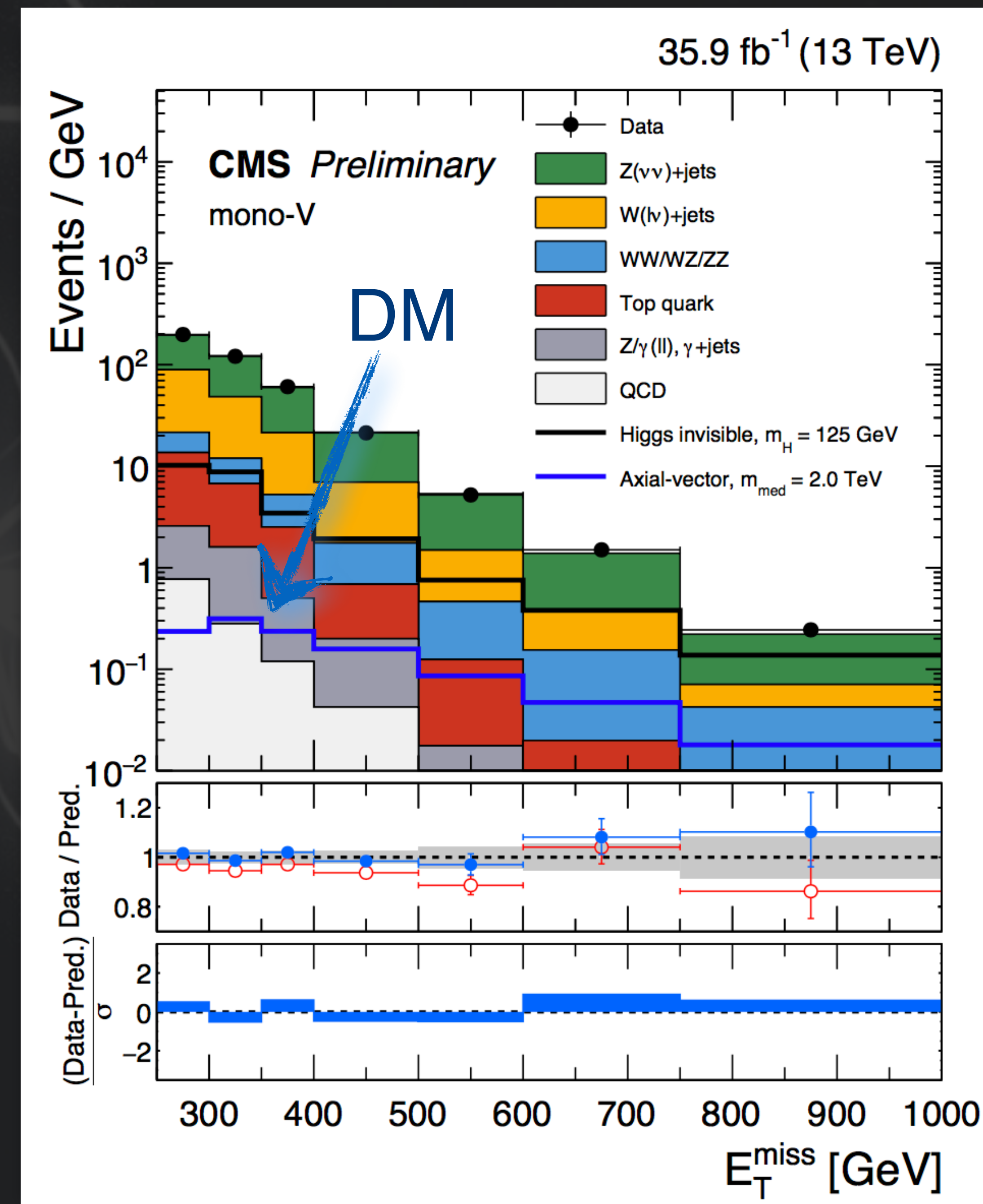
DM Detection

- Colliding protons have no transverse momentum → vectorial sum must vanish
→ non-vanishing (e.g. missing) transverse momentum indicates invisible particle escaping



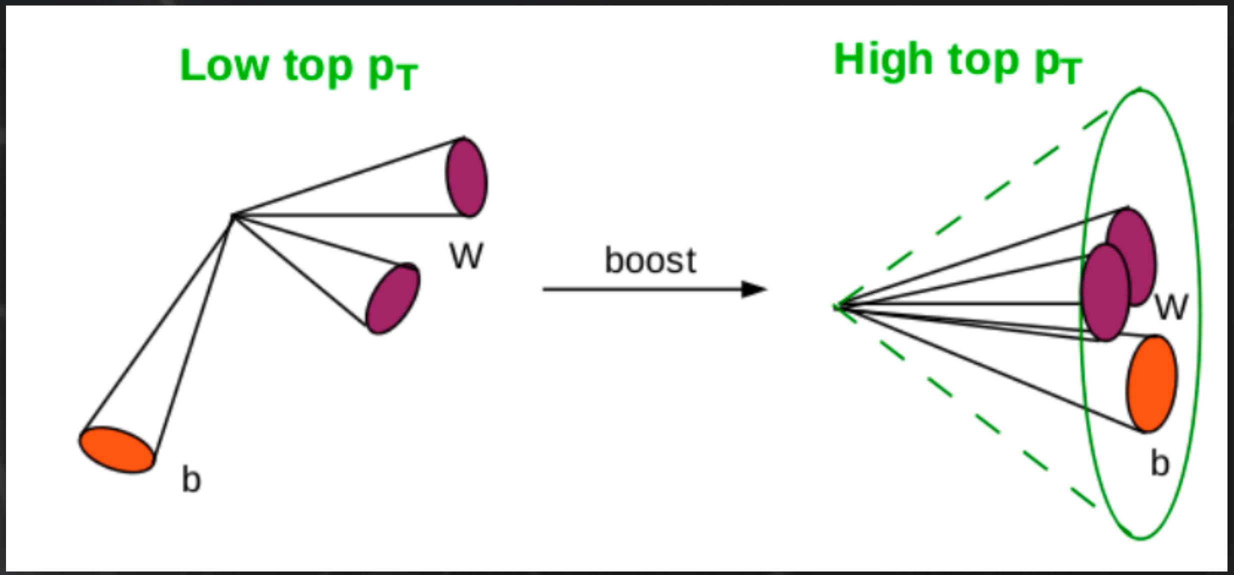


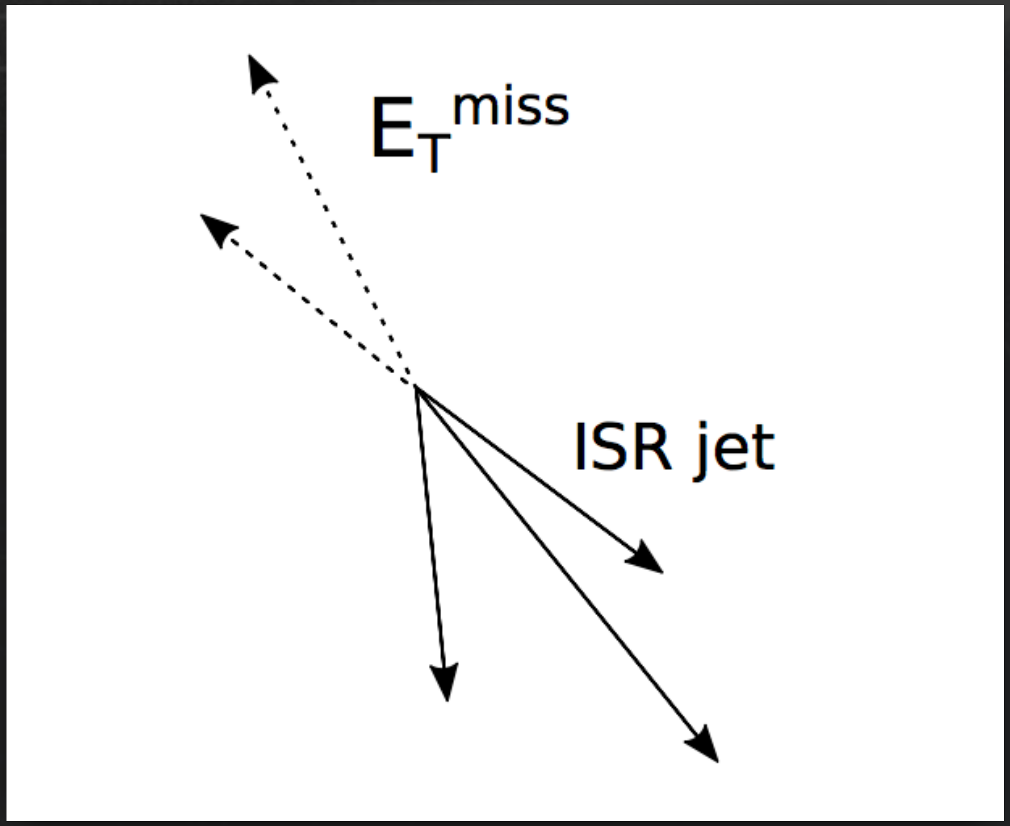
- 'Missing Energy' most powerful variable in search for new physics

- Different DM candidates couple with different strengths to different visible particles

(Hadron) Collider searches

- Searches performed in mono-X signature with $X=\gamma, j, t\bar{t}, H, W, Z$ etc
- In the simplified picture mono-jet searches often most senstitive
- Energies at LHC can boost decay particles of final states into merged 'fat jet': mono-V

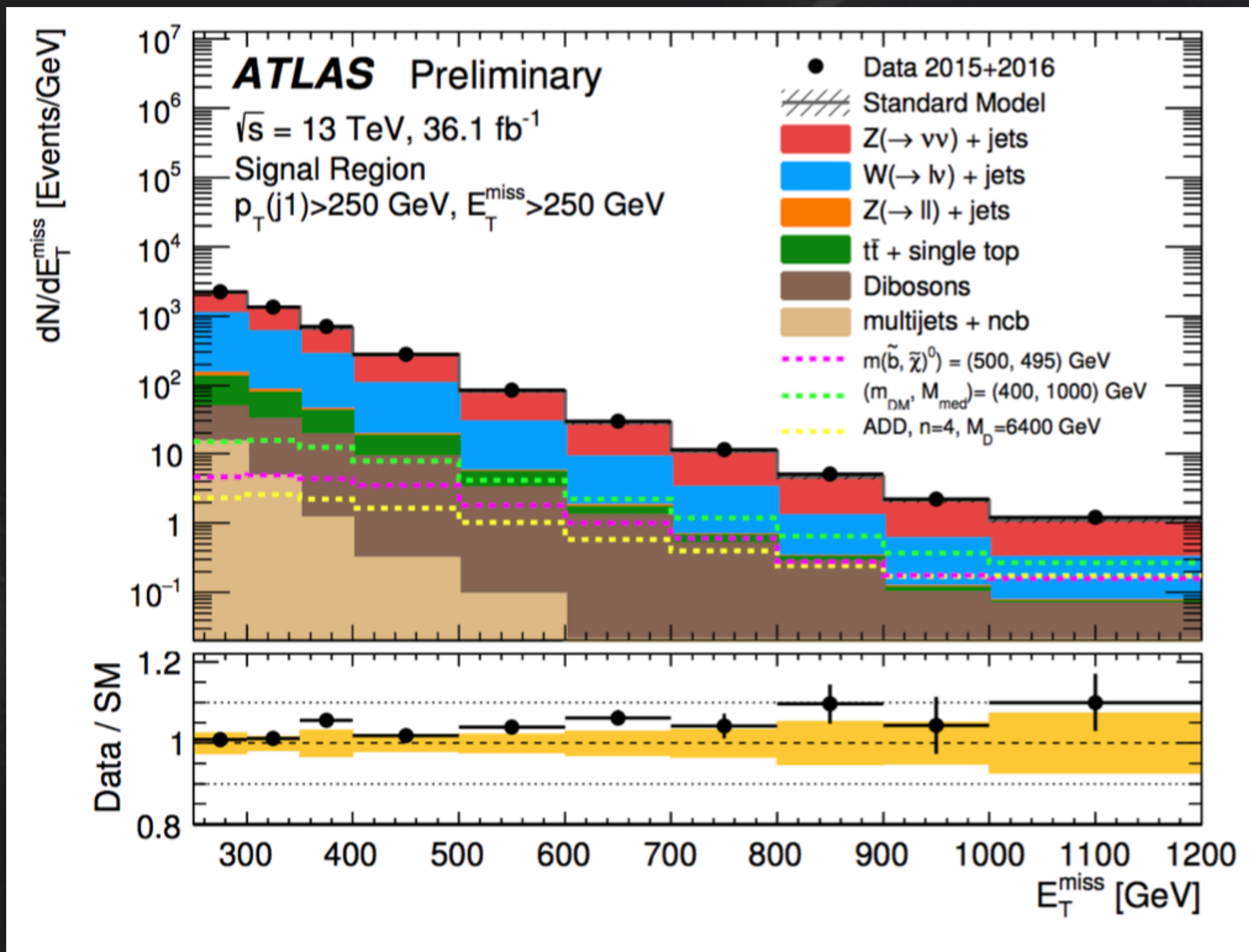


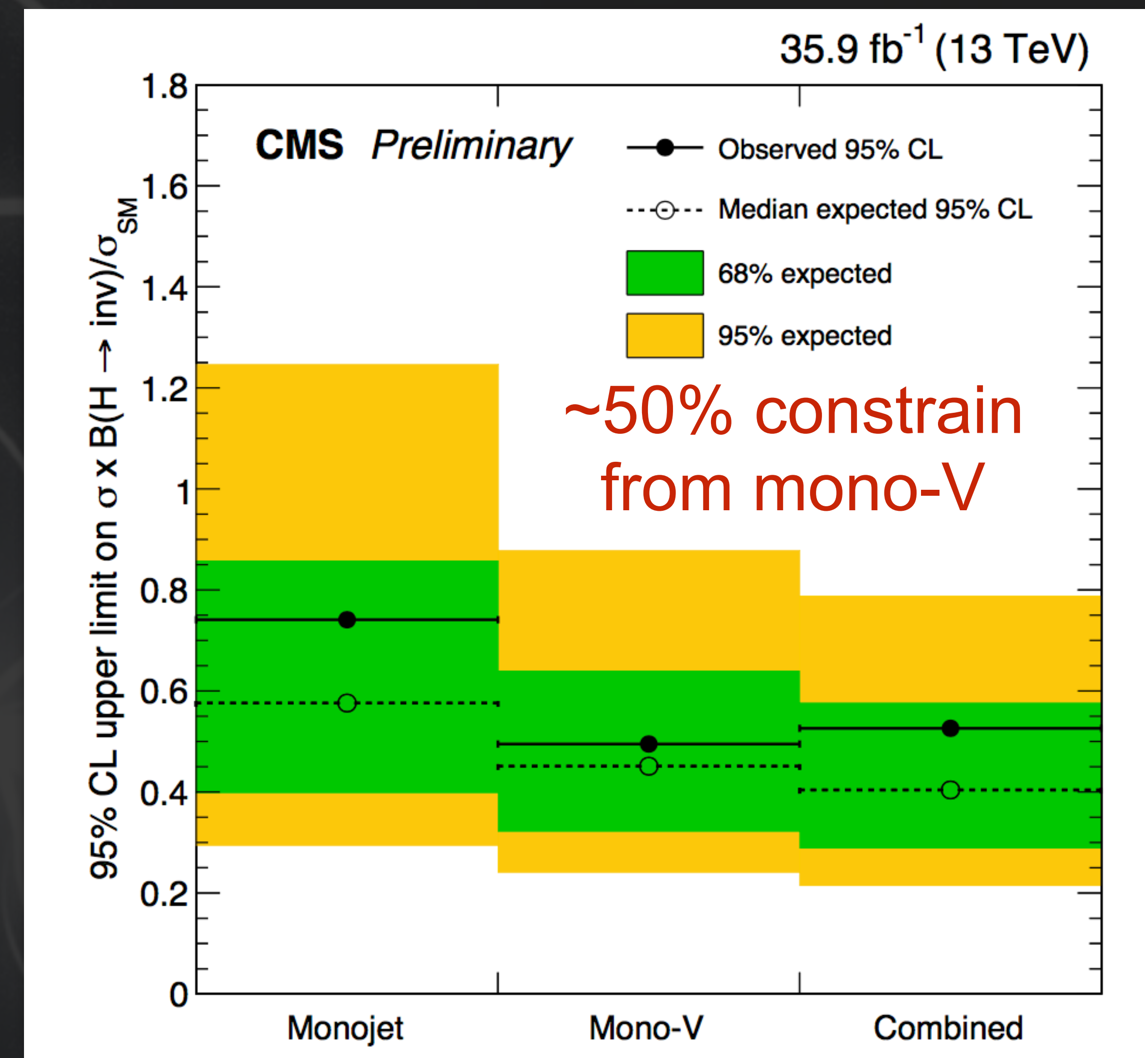


- Mono-γ, appears less sensitive bc. of α_{em}/α_s
- Such coupling difference actually lead to possibly DM natures
- Vast majority of searches probe very trigger strategy: MET and High p_T visible object

mono-j/V results

arXiv:1711.03301, 1703.01651, 1706.03794



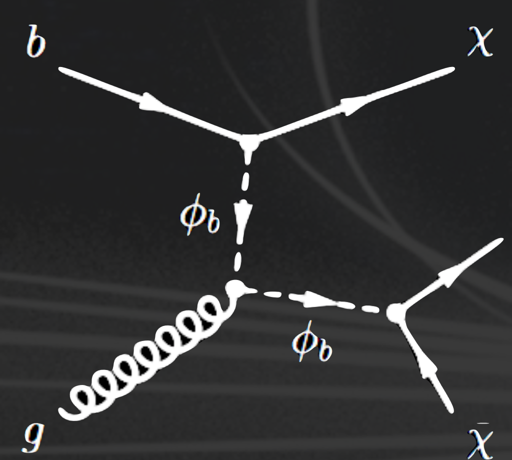


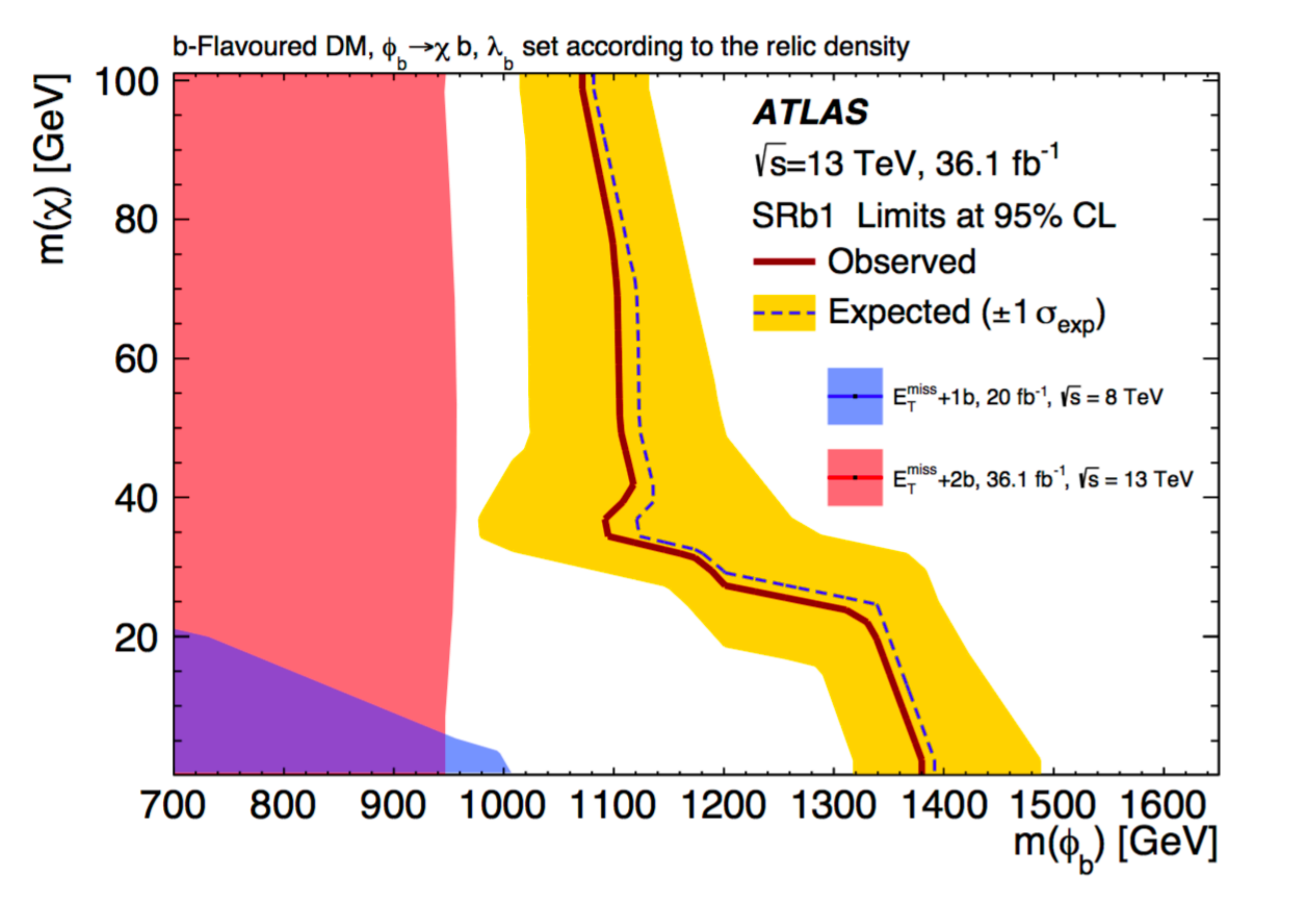
- Both ATLAS & CMS analysed 2016 dataset ($36fb^{-1}$)
- Best results for vector type couplings
- The mono-V channels also allows to constrain H→inv mostly from GF compared to dedicated searches mostly accessing VBF and VH

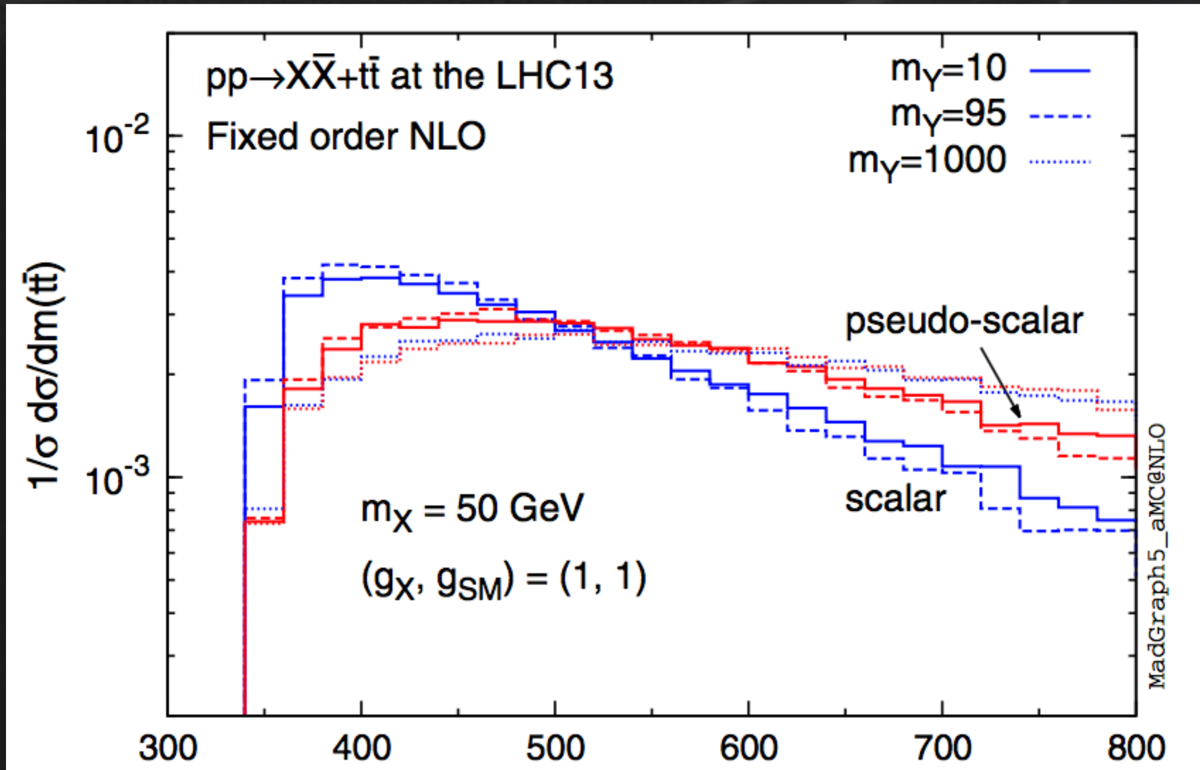
DM & heavy quarks

arXiv:1710.11412, 1706.02581

- Scalar type couplings also result in mono-$t\bar{t}$/bb with interesting features
- Also only current t-channel (b-FDM) model



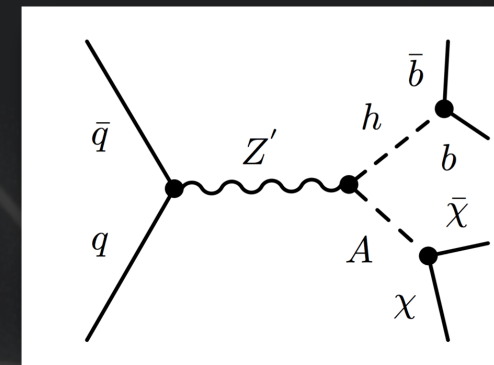


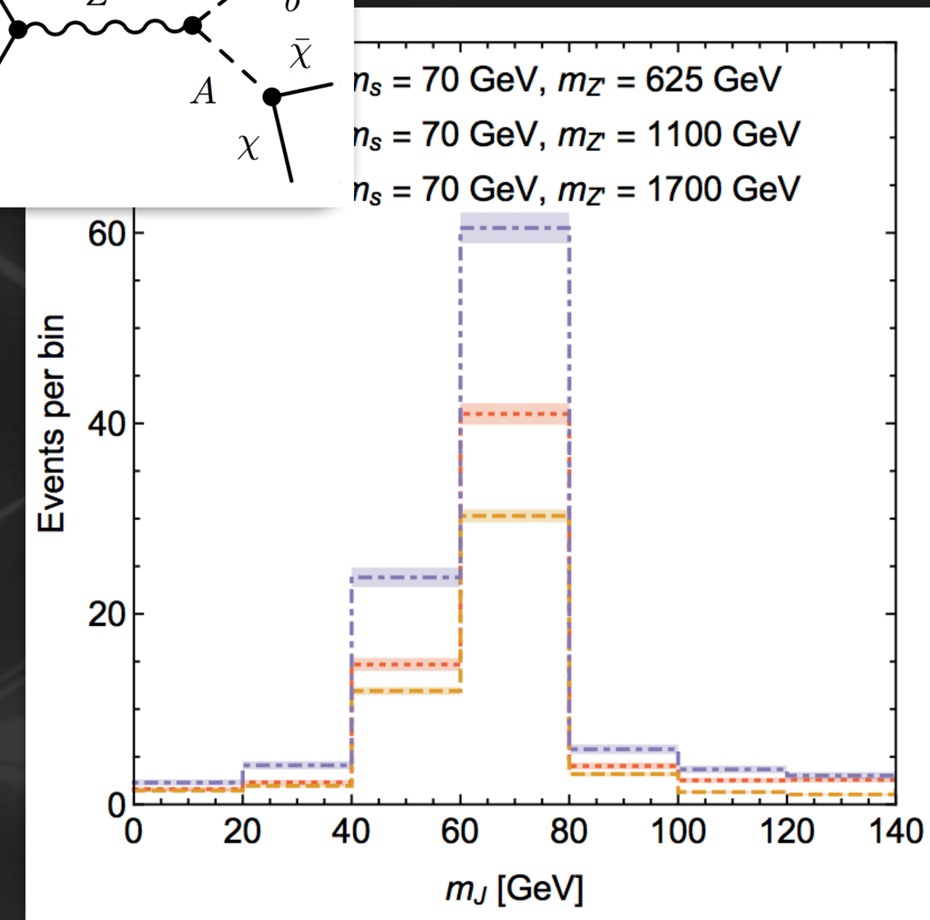


arXiv:1611.09841

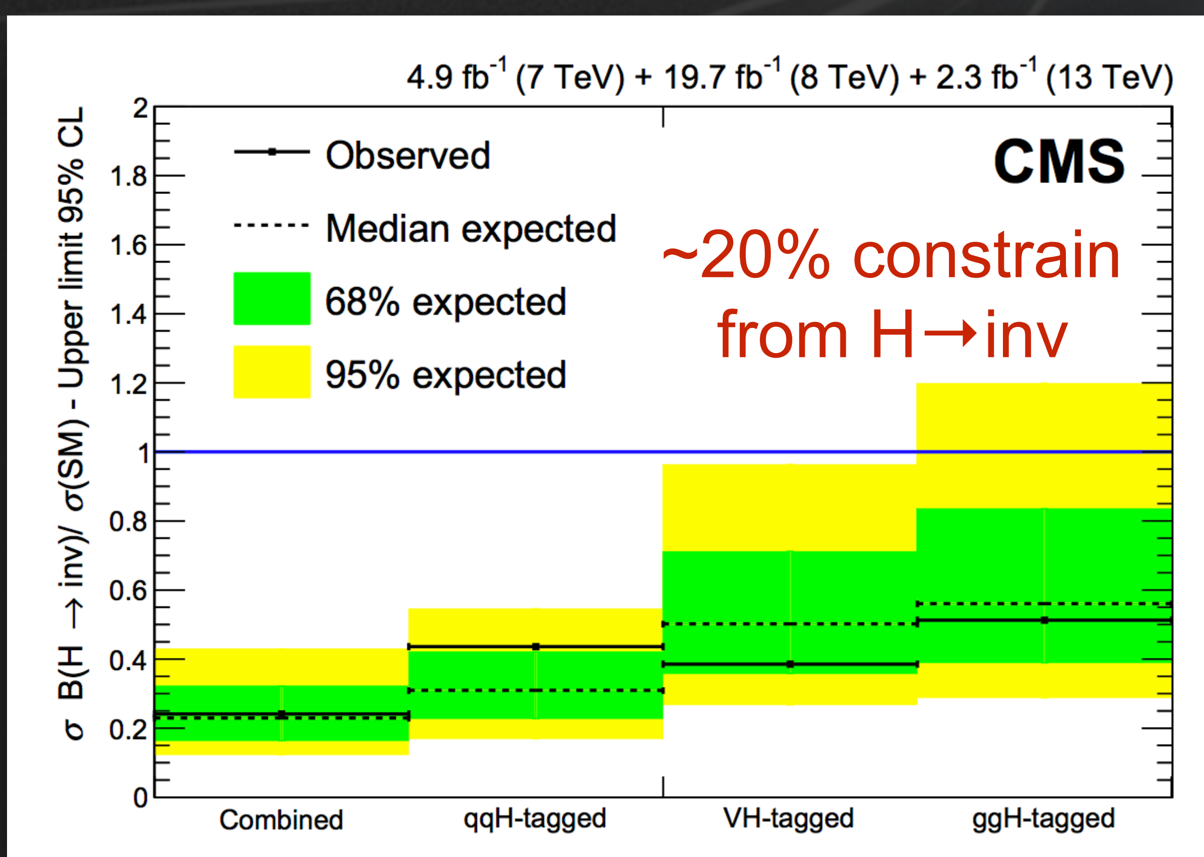
- Scalar type couplings also result in mono-$t\bar{t}$/bb with intersting features
  - CP Structure of DM impacts angular variables or m($t\bar{t}$) spectrum

Searches with Higgs bosons





- Higgs 'natural' messenger to dark world, minimal extension to Lagrangian, 'Higgs Portal'
- Search for H→XX or DM+H production
- Mono-H searches quite similar to mono-j, more interesting searches with more than one mediator
  - Allow for interesting signatures and to set relic density

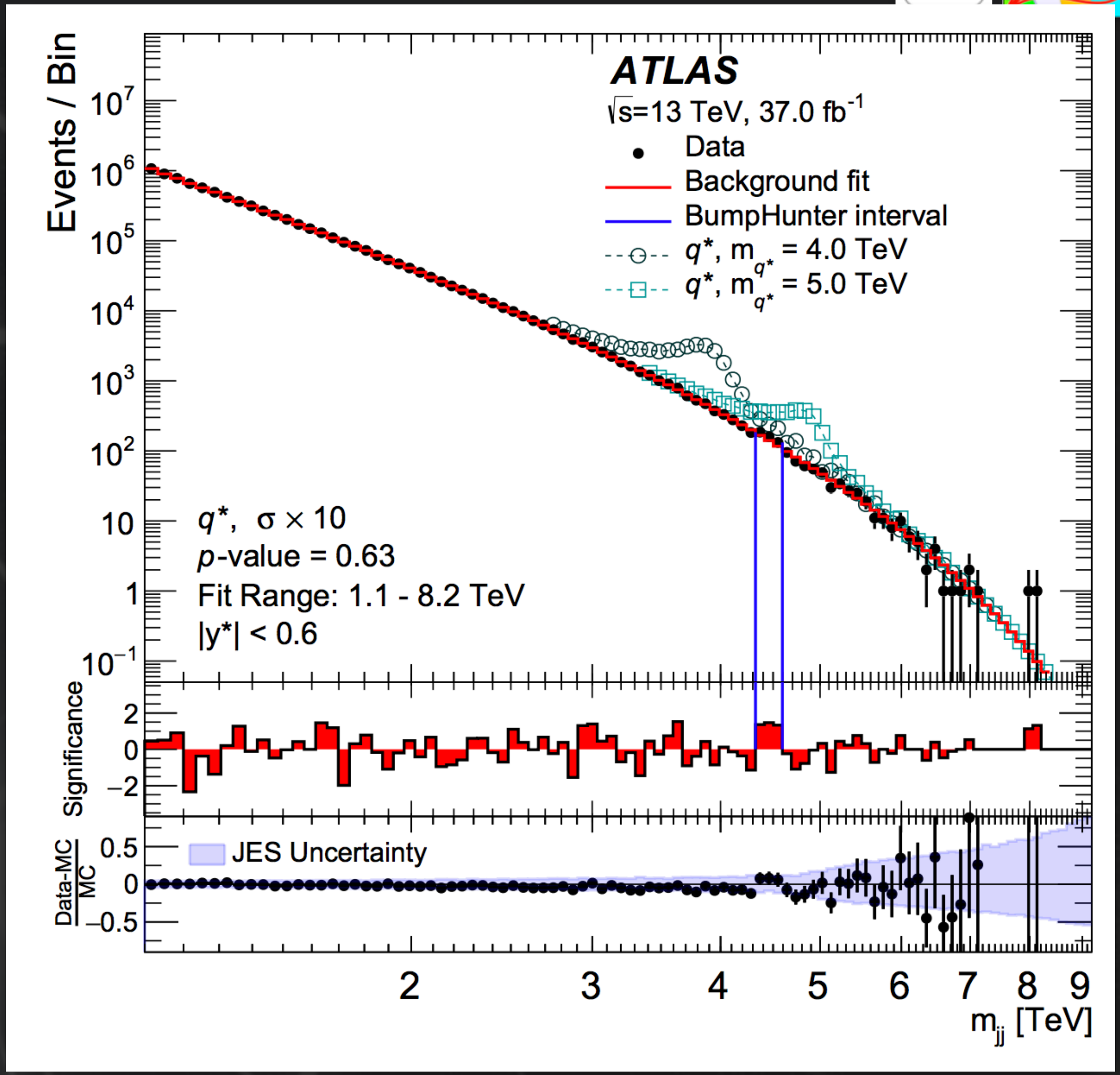


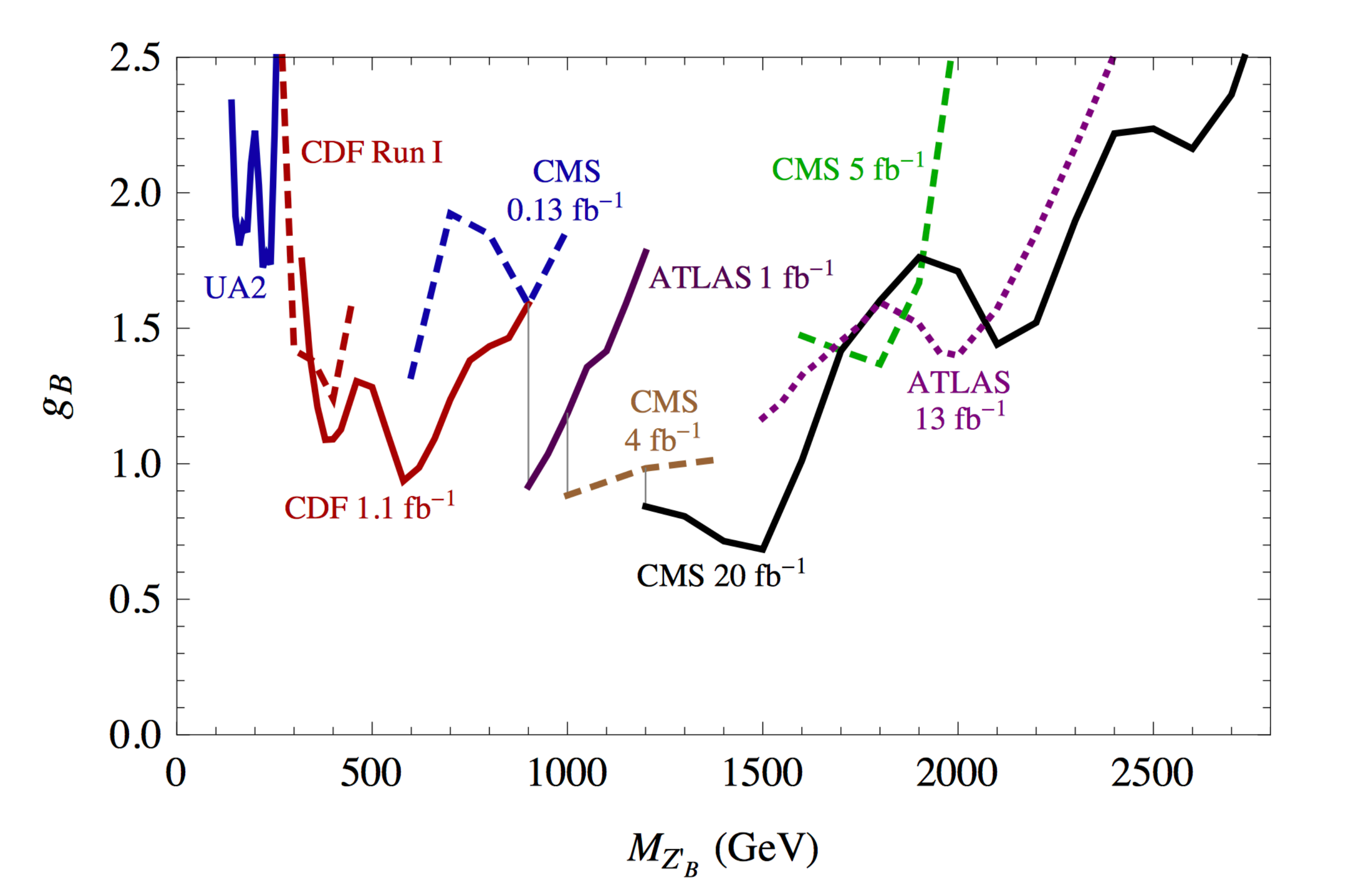
- H→XX only sensitive to masses of $m_{DM} \leq m_H$
- Leading searches utilize H→bb and H→γγ decays

Searches for Mediator

arXiv:1703.09127, 1703.09986

- Collider DM searches are actually searches for the mediator
- Search for the mediator itself in decays to hadrons and interpret them in axial-vector model
- Narrow resonance in dijet spectrum → perhaps most straightforward searches

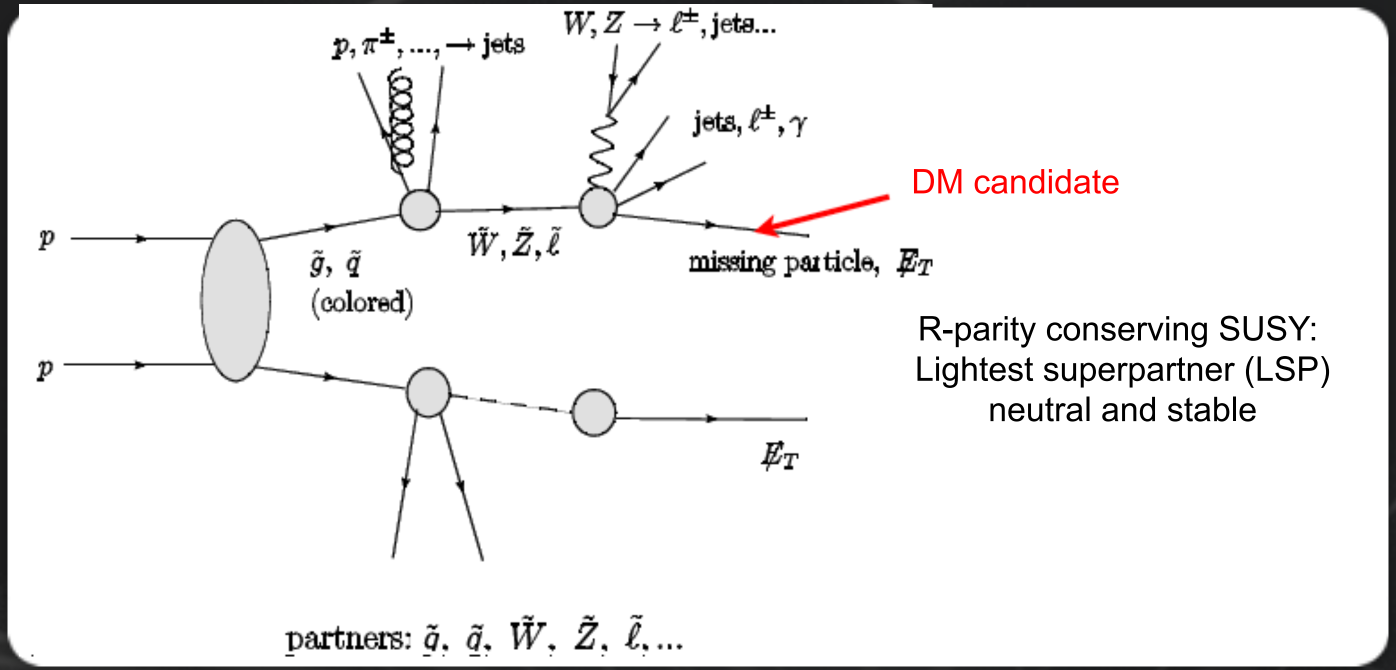




- Stringent constraints at high masses
- Not dominated by single experiment because of challenging environment
- At low masses actually not well constrained

SUSY

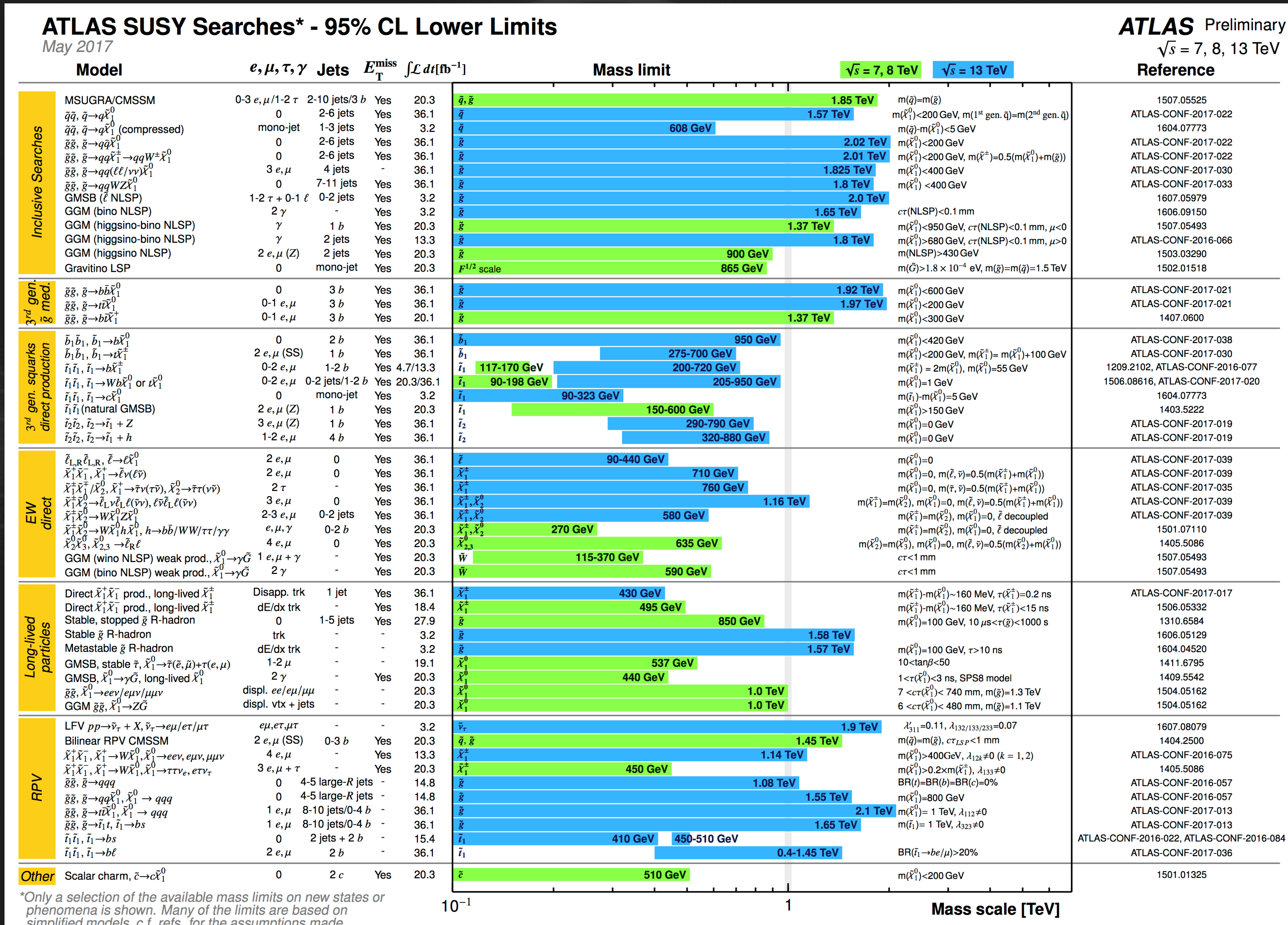
- DM part of extended sector of new physics at TeV scale



- Discovery may be rather easy, property measurement very hard

- E_T^{miss} + jets
- E_T^{miss} + b
- E_T^{miss} + 1ℓ
- E_T^{miss} + 2ℓ (ss/os)
- E_T^{miss} + single jets
- E_T^{miss} + j + ℓ + b
- E_T^{miss} + j + 2ℓ + b
- E_T^{miss} + jets + Z-boson
- E_T^{miss} + 3/4 ℓ
- E_T^{miss} + jets + γ
- E_T^{miss} + jets + γ
- ...

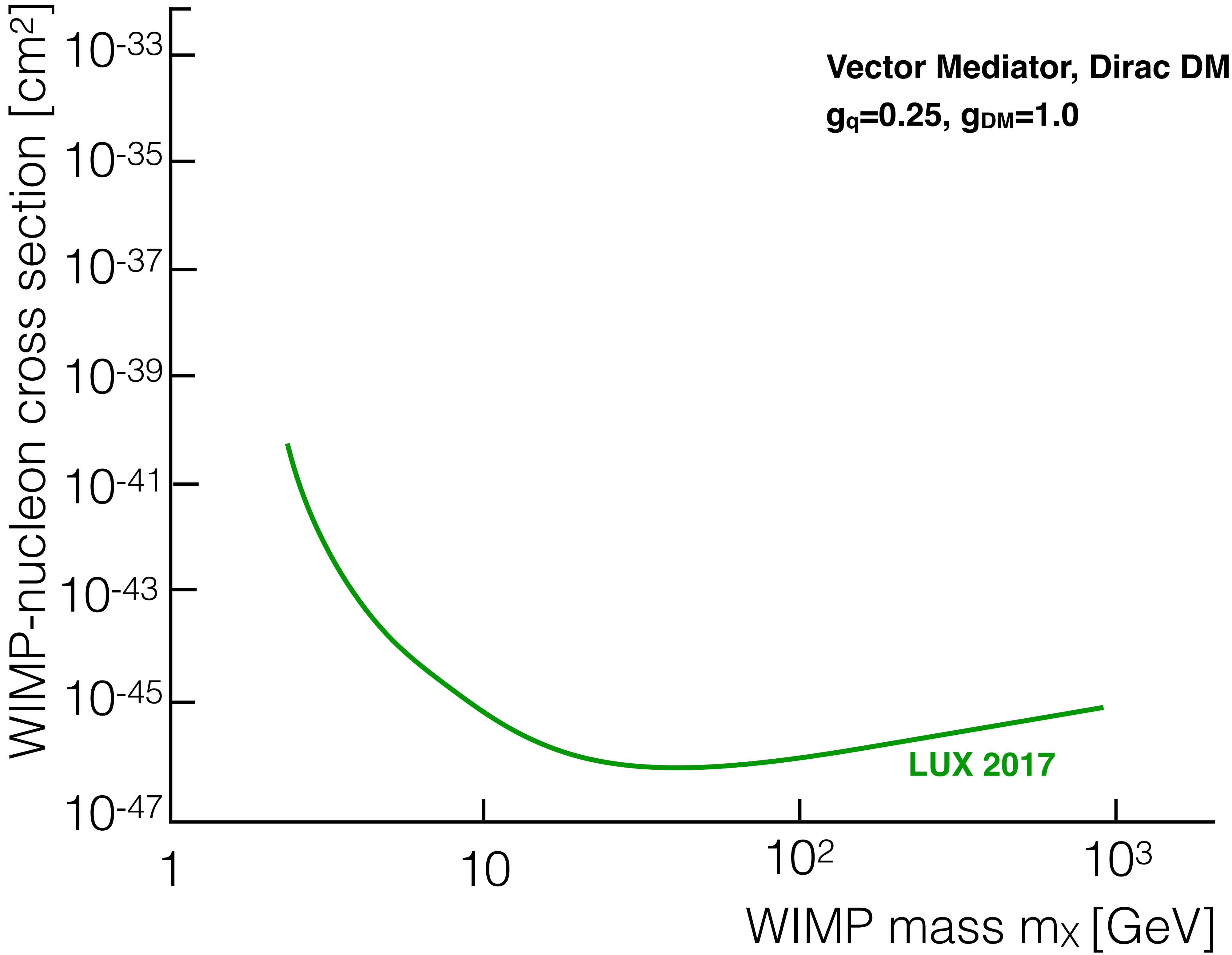
- Results interpreted in cMSSM, pMSSM and simplified models, no excess
- Often the neutralino is the DM candidate (LSP)



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/

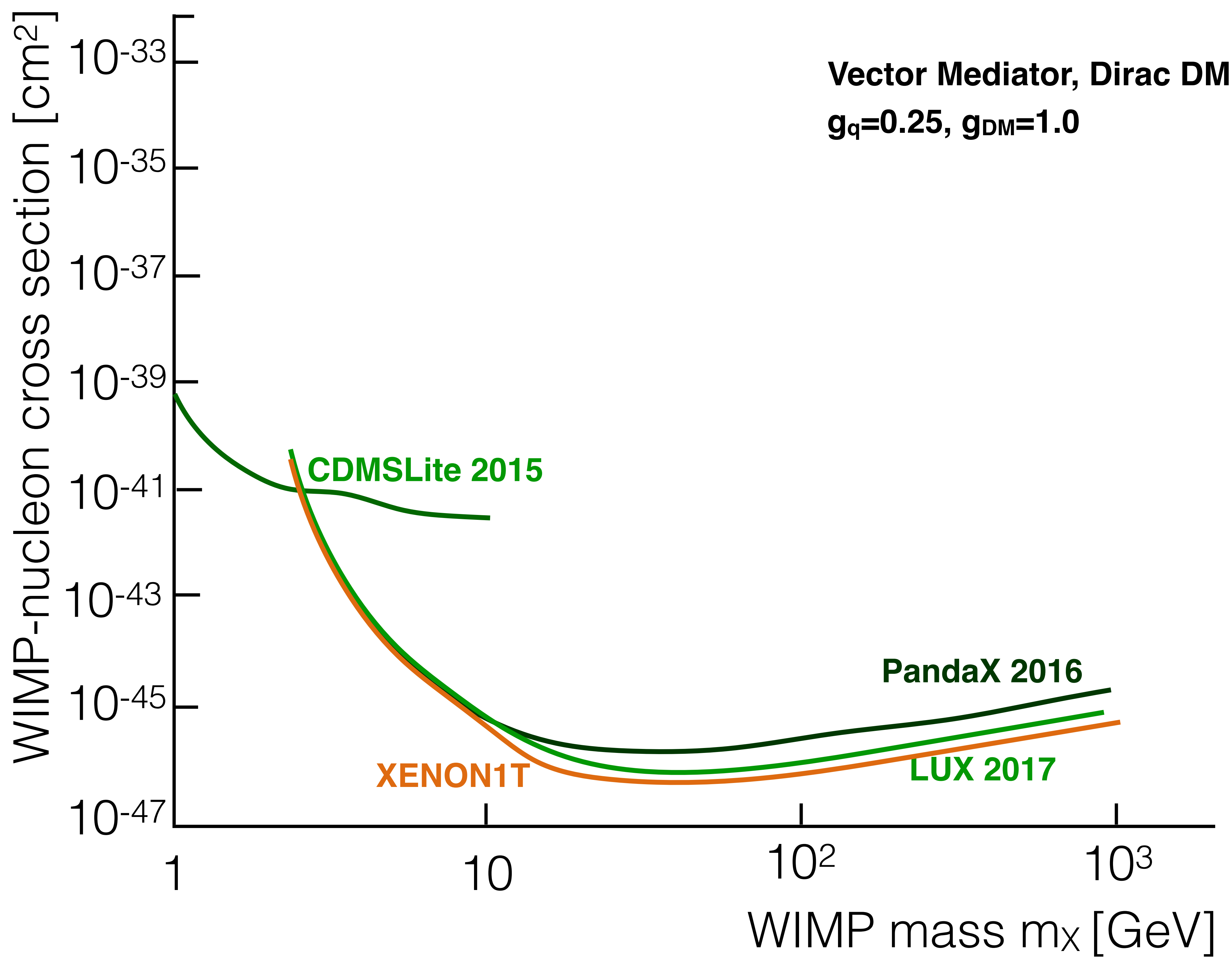
Current Results

Results



Vector Mediator, Dirac DM
gq=0.25, gDM=1.0
WIMP-nucleon cross section [cm2]
10-33
10-35
10-37
10-39
10-41
10-43
10-45
10-47
1
10
102
103
WIMP mass mX [GeV]
LUX 2017

Results



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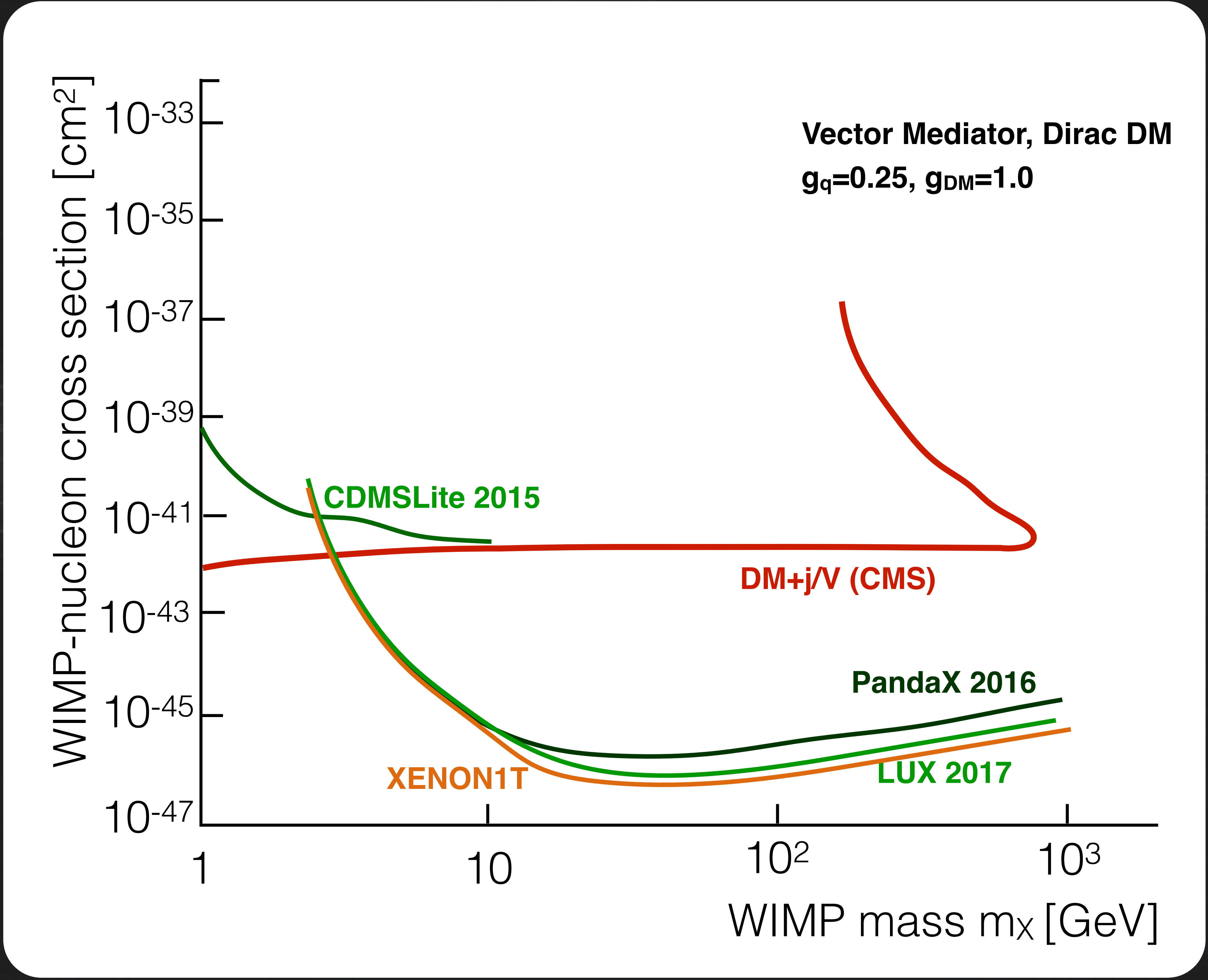
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DM+j/V (CMS)
PandaX 2016
LUX 2017
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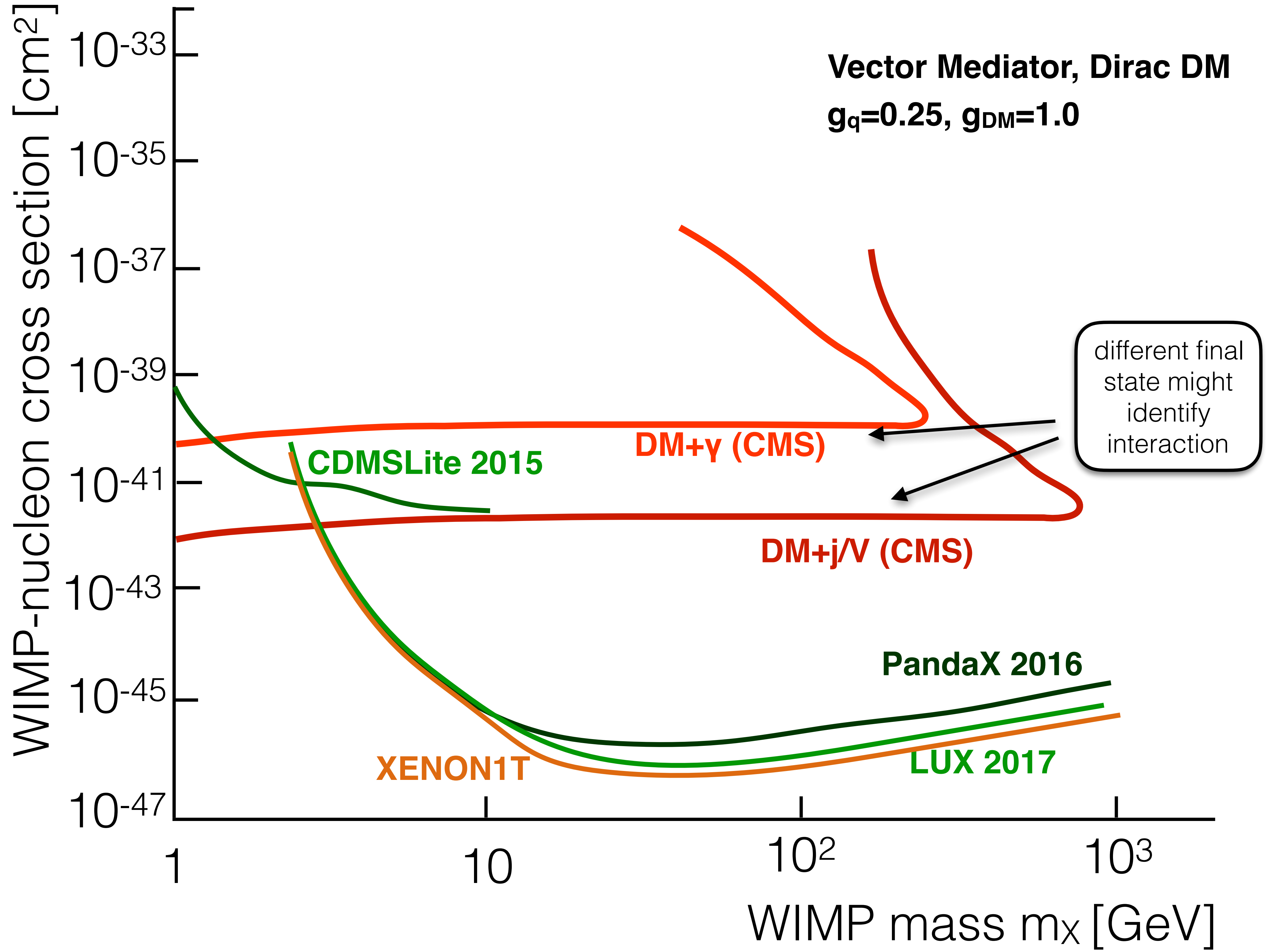
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different final state might identify interaction
DM+γ (CMS)
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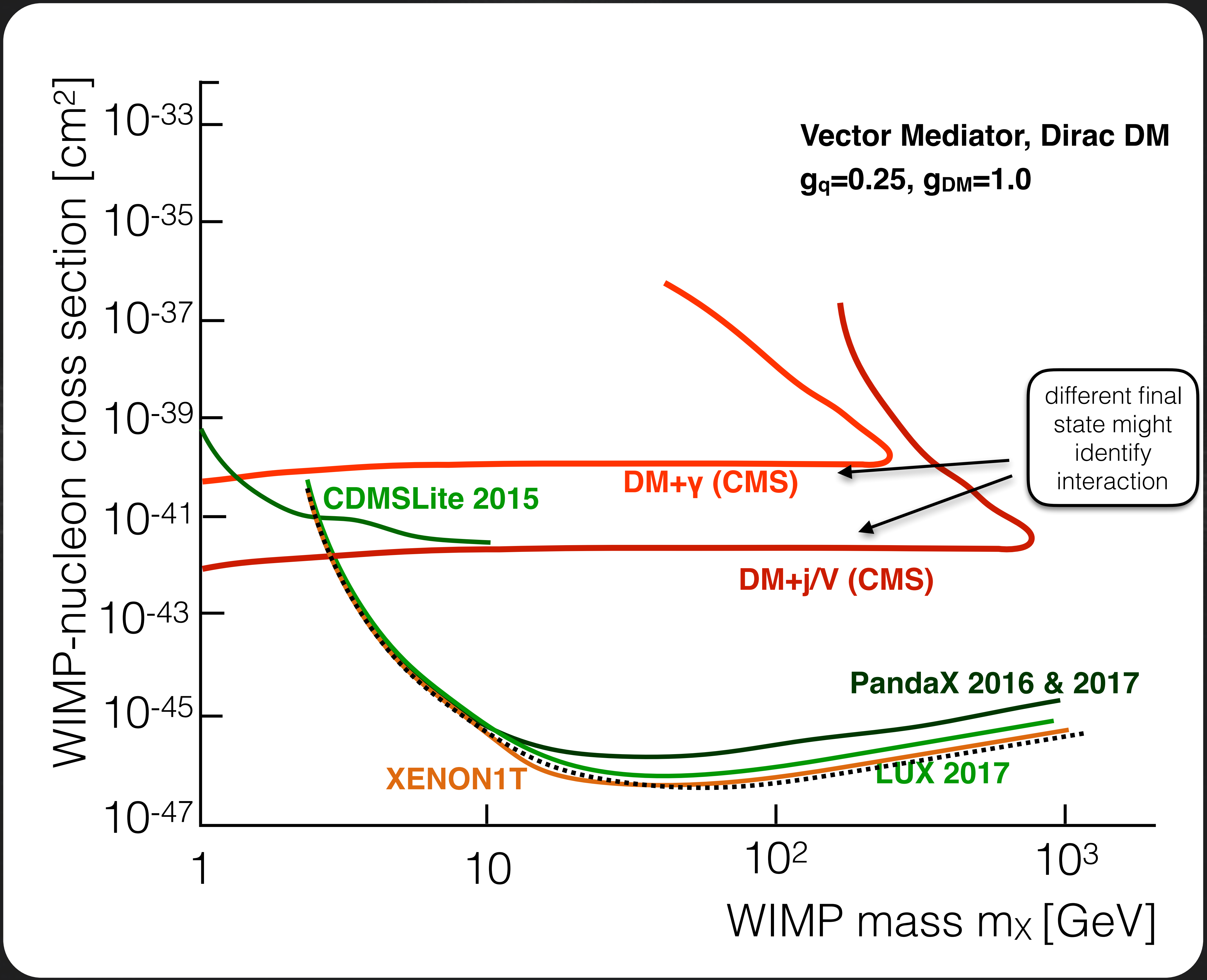
XENON1T
1
10
102
103
WIMP mass mχ [GeV]

Results



Vector Mediator, Dirac DM
gq=0.25, gDM=1.0
WIMP-nucleon cross section [cm2]
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1
10
102
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DM+γ (CMS)
CDMSLite 2015
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PandaX 2016 & 2017
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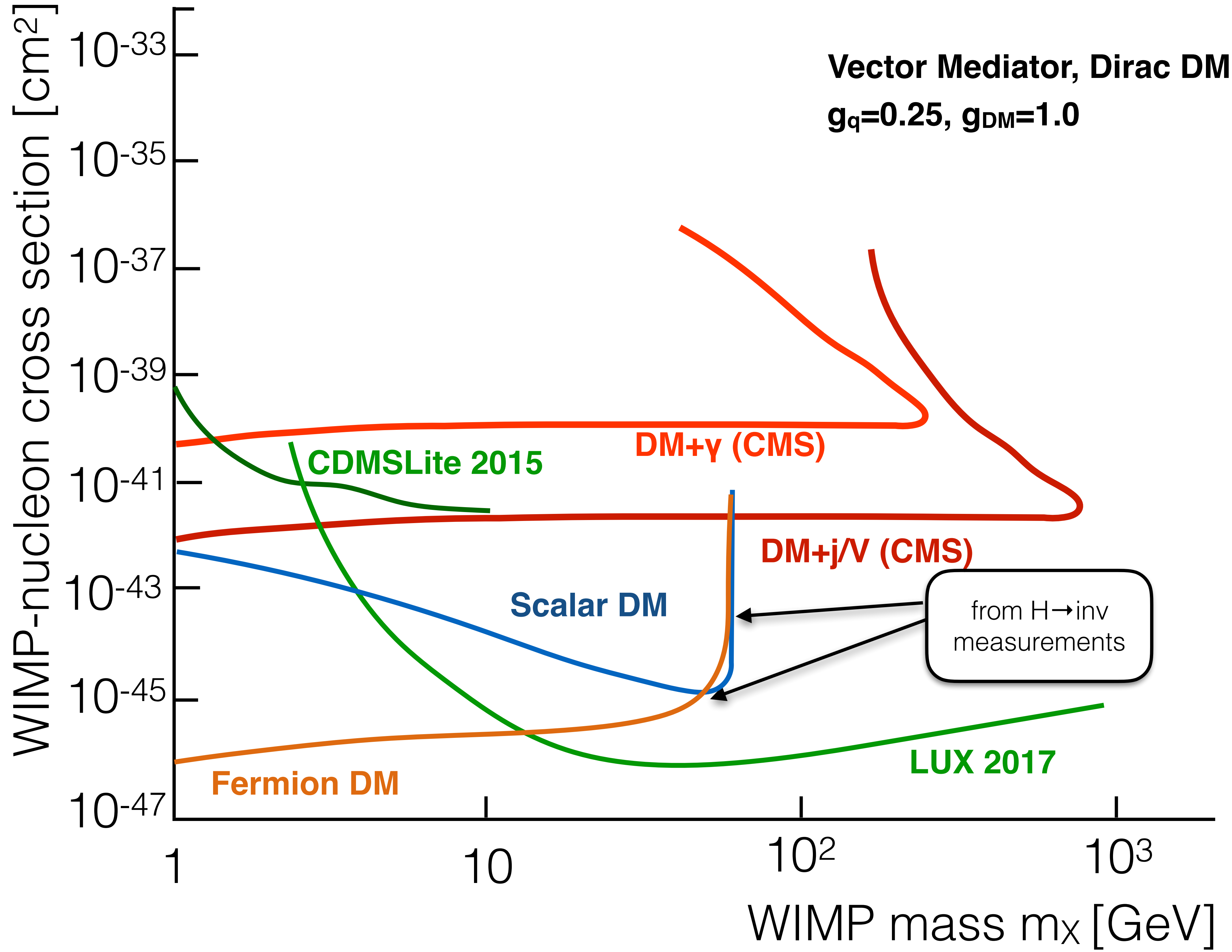
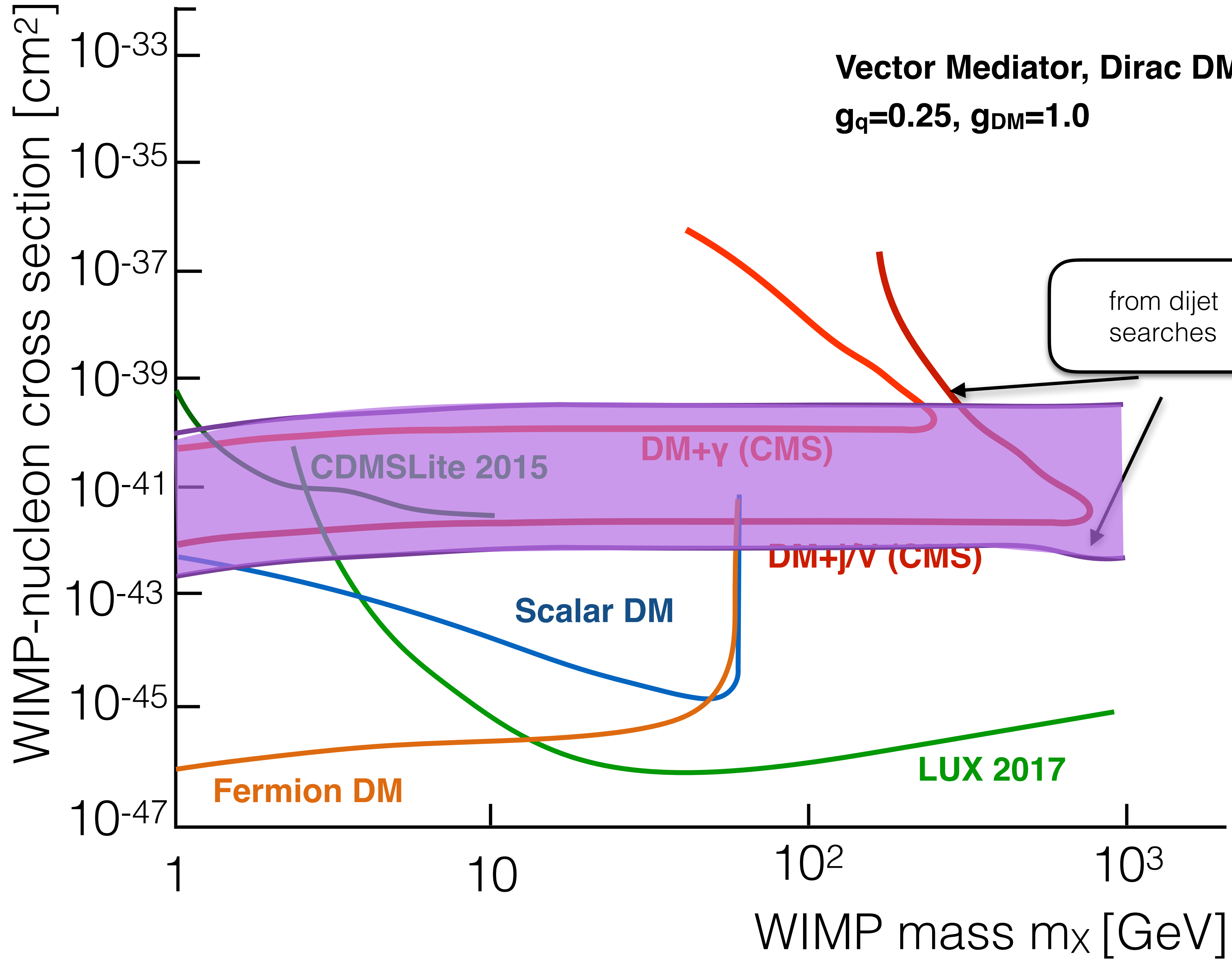

Vector Mediator, Dirac DM
g_q=0.25, g_{DM}=1.0
WIMP-nucleon cross section [cm²]
10⁻³³
10⁻³⁵
10⁻³⁷
10⁻³⁹
10⁻⁴¹
10⁻⁴³
10⁻⁴⁵
10⁻⁴⁷
1
10
10²
10³
WIMP mass mχ [GeV]
DM+γ (CMS)
CDMSLite 2015
DM+j/V (CMS)
Scalar DM
from H→inv measurements
Fermion DM
LUX 2017

Results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10²
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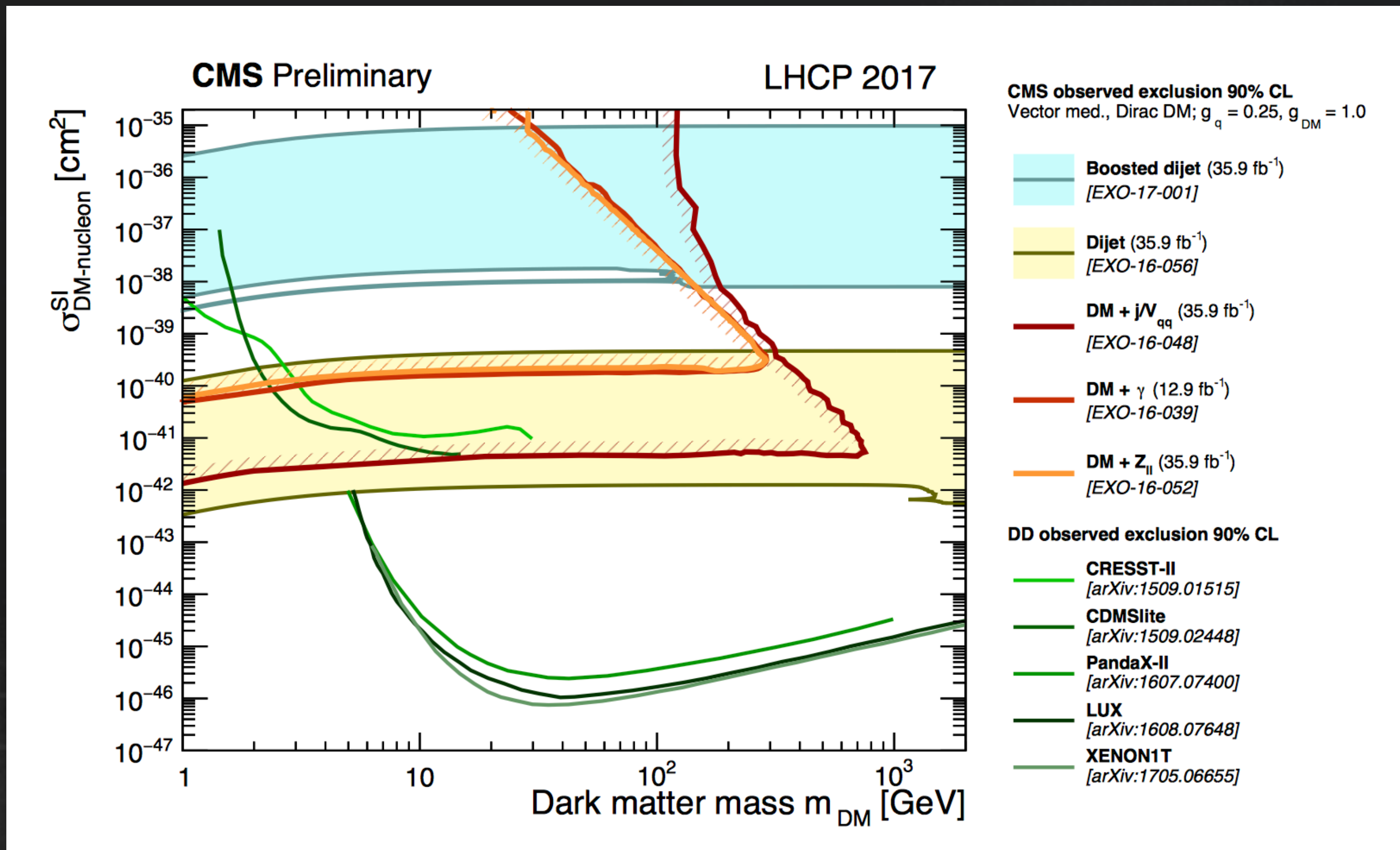
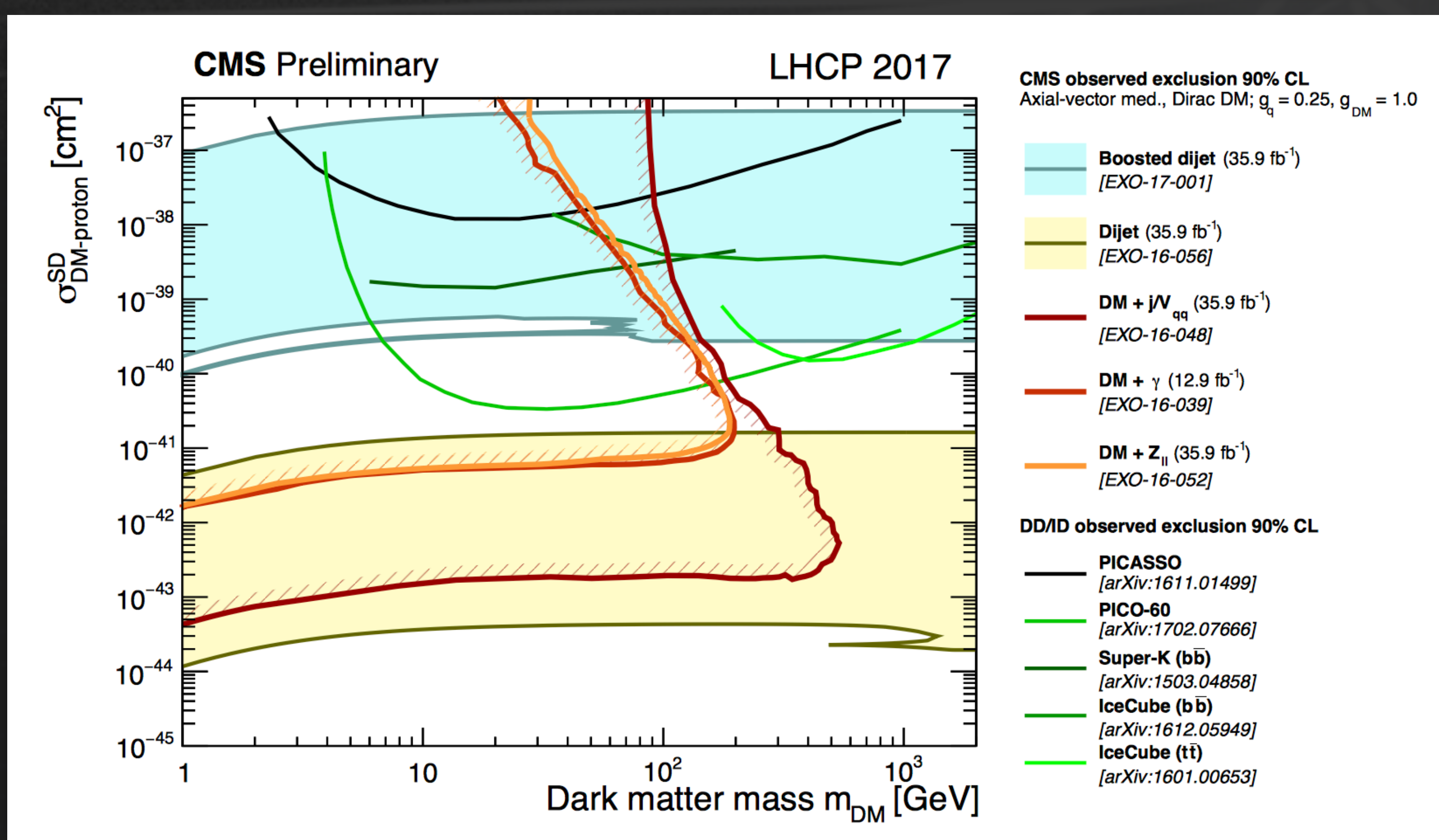
Collider Overview

spin-independent



spin-dependent

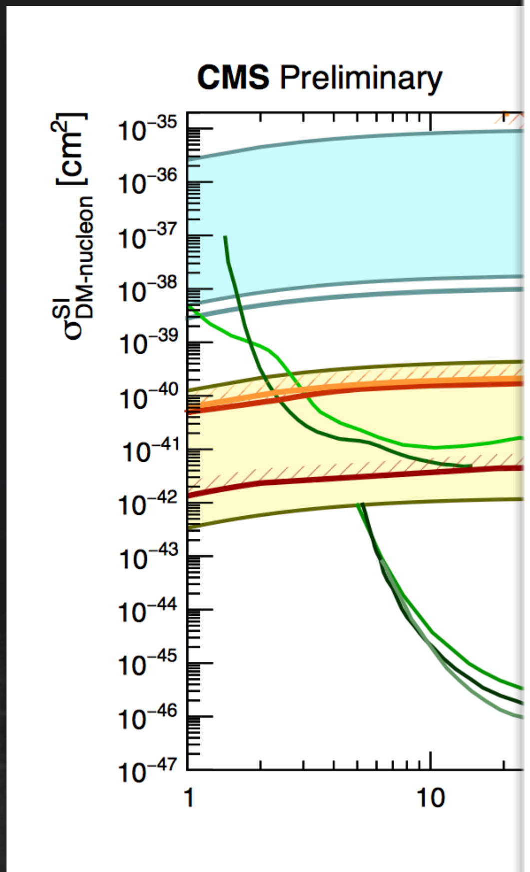


- Setting stringent constraints on spin-(in)dependent DM
- Remember, spin-independent suppressed at DD
- All searches employ similar tigger/models
- (Pseudo-)Scalar searches are just becoming sensitive
- Some model dependency
- Many more interesting searches I cannot cover here

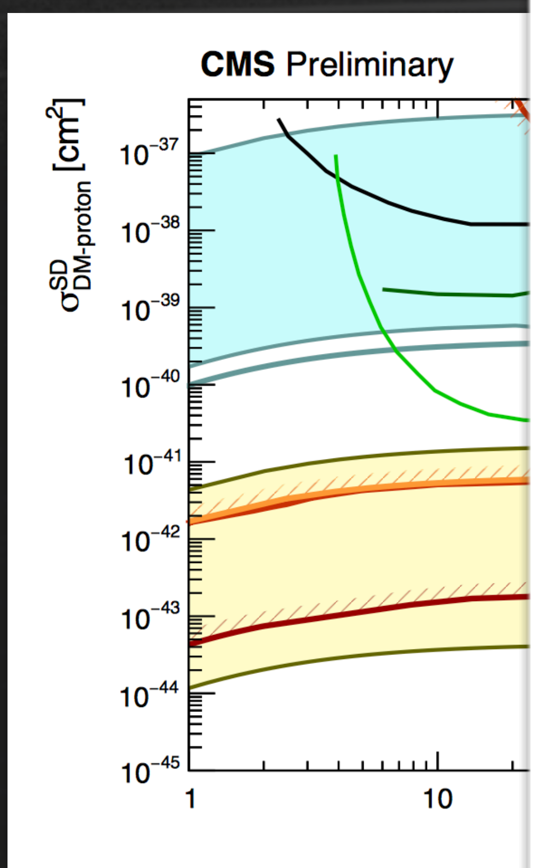
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/
https://twiki.cern.ch/twiki/pub/ CMSPublic/PhysicsResultsEXO/DM-summary-plots-Jul17.pdf

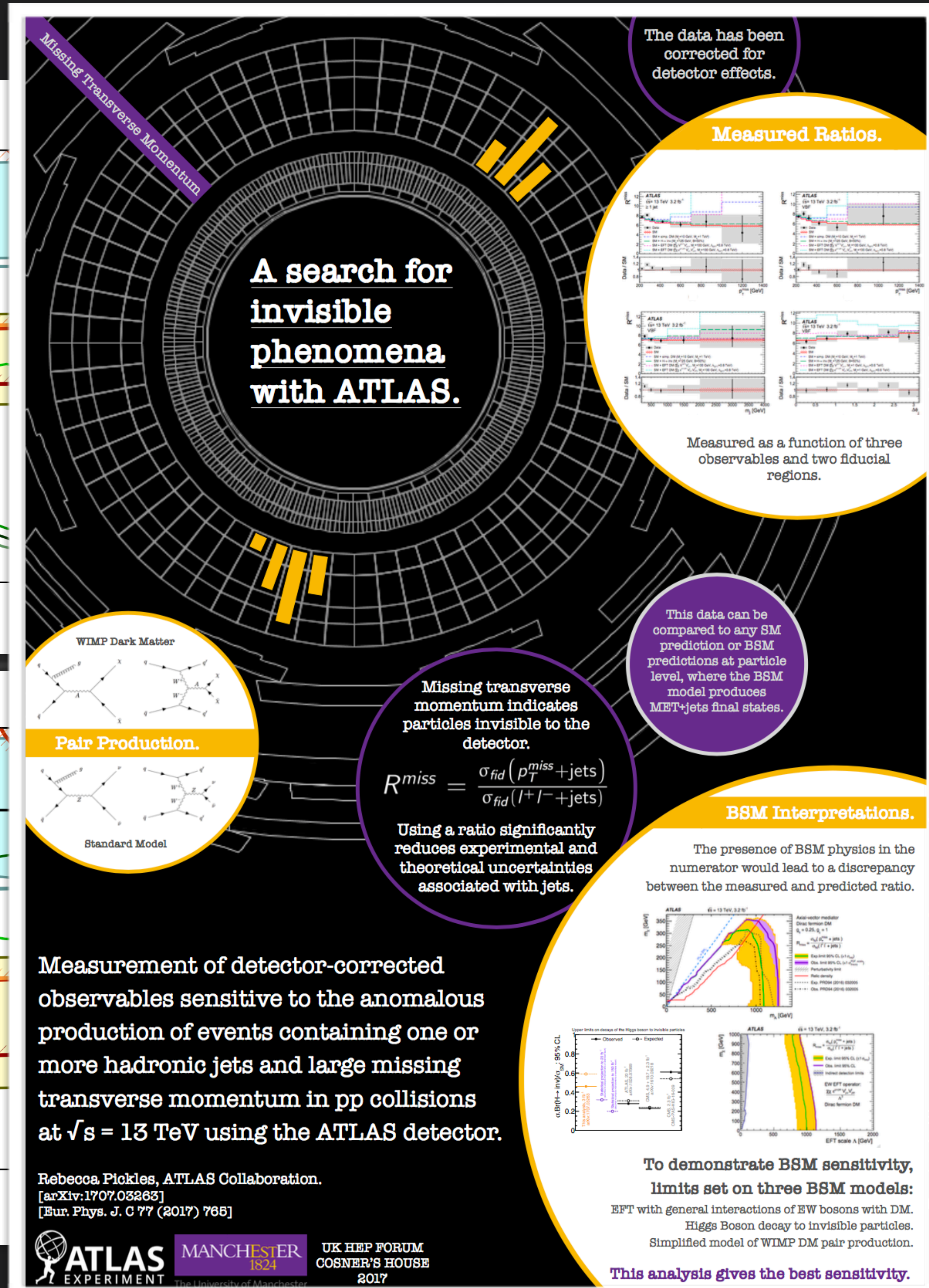
Brandeis University

spin-independent



spin-dependent





stringent constraints
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nodel dependency

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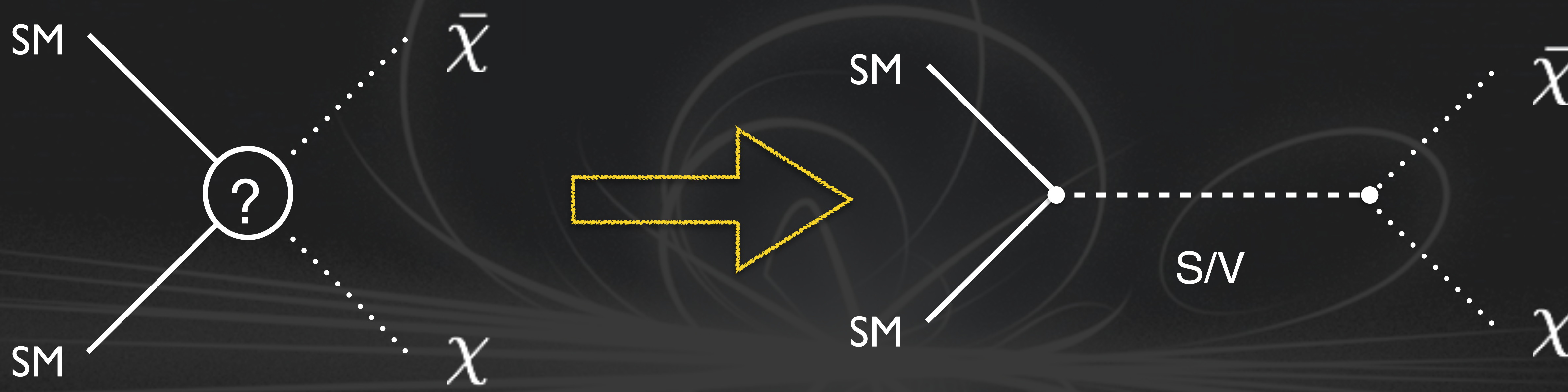
rn.ch/Atlas/GROUPS/PHYSICS/
/Plots/EXOTICS/
/twiki/pub/ CMSPublic/
)/DM-summary-plots-Jul17.pdf

How do we connect and learn from all three fields?

Reminder

- In a real life we need some mediator between the ‘dark World’ and the known Universe



- Leads to known interactions
  - scalar ($\psi\psi$),
  - pseudo scalar ($\bar{\psi}\gamma^5\psi$),
  - vector $\bar{\psi}\gamma^\mu\psi$,
  - axial-vector ($\bar{\psi}\gamma^\mu\gamma^5\psi$)
- Interesting kinematics and experimental sensitivities

Parameterizing Dark Matter

EWK style (equal to leptons)

Vector

$$g_{\mathrm{DM}} Z'_{\mu} \bar{\chi} \gamma^{\mu} \chi$$

Besides very low DM masses DD wins clearly over collider

Axial-Vector

$$g_{\mathrm{DM}} Z''_{\mu} \bar{\chi} \gamma^{\mu} \gamma^{5} \chi$$

DD and collider are equal in overall sensitivity but probe different regions of parameter space

mass based (Yukawa)

Scalar

$$g_{\mathrm{DM}} S \bar{\chi} \chi$$

DD and collider are equal in overall sensitivity but probe different regions of parameter space

Pseudo-Scalar

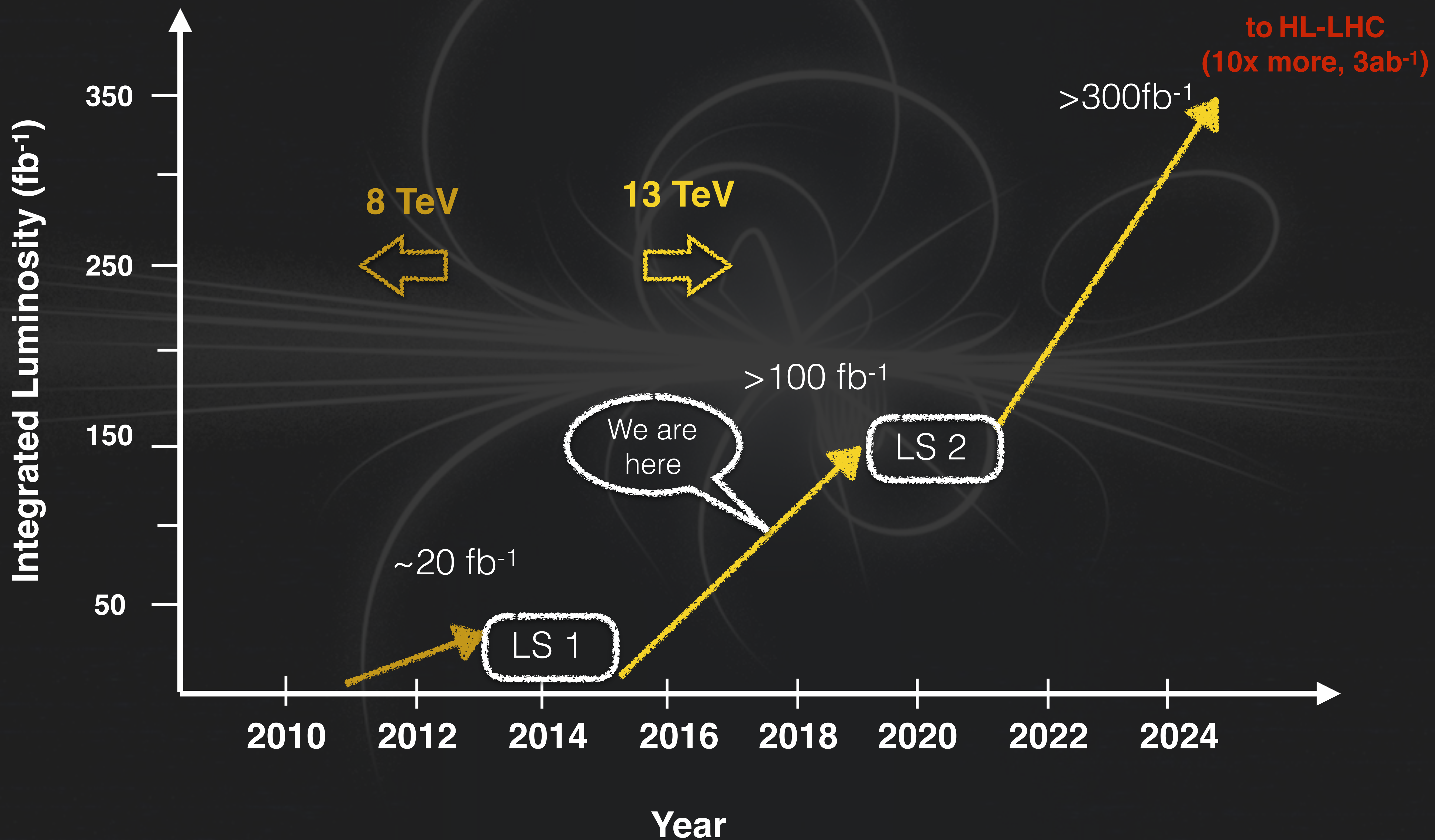
$$g_{\mathrm{DM}} P \bar{\chi} \gamma^{5} \chi$$

No limits from DD (only from ID). Collider provides limits similar to scalar couplings

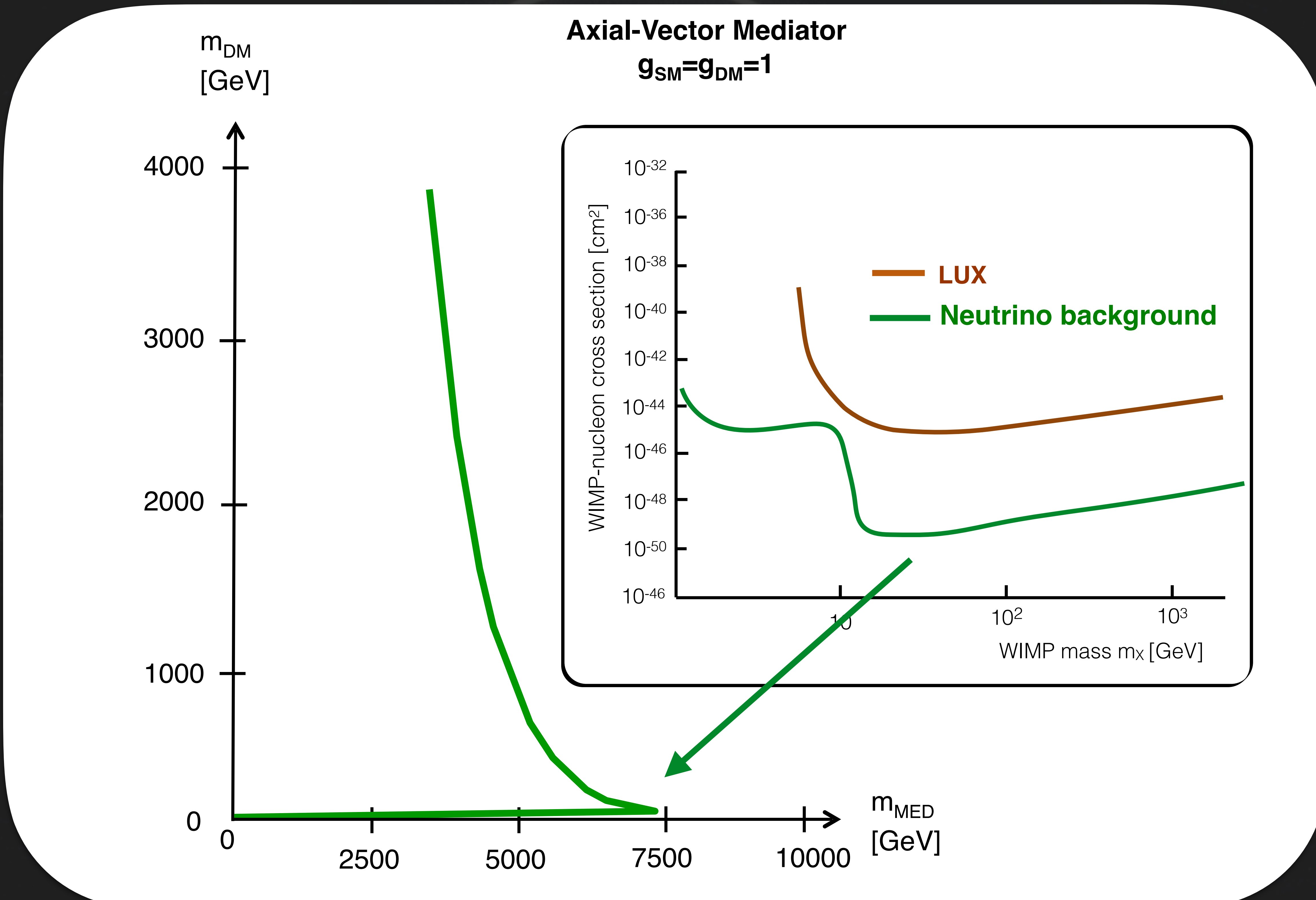
DM can only b discovered by combining these approaches

The (near) future

LHC Run Plan

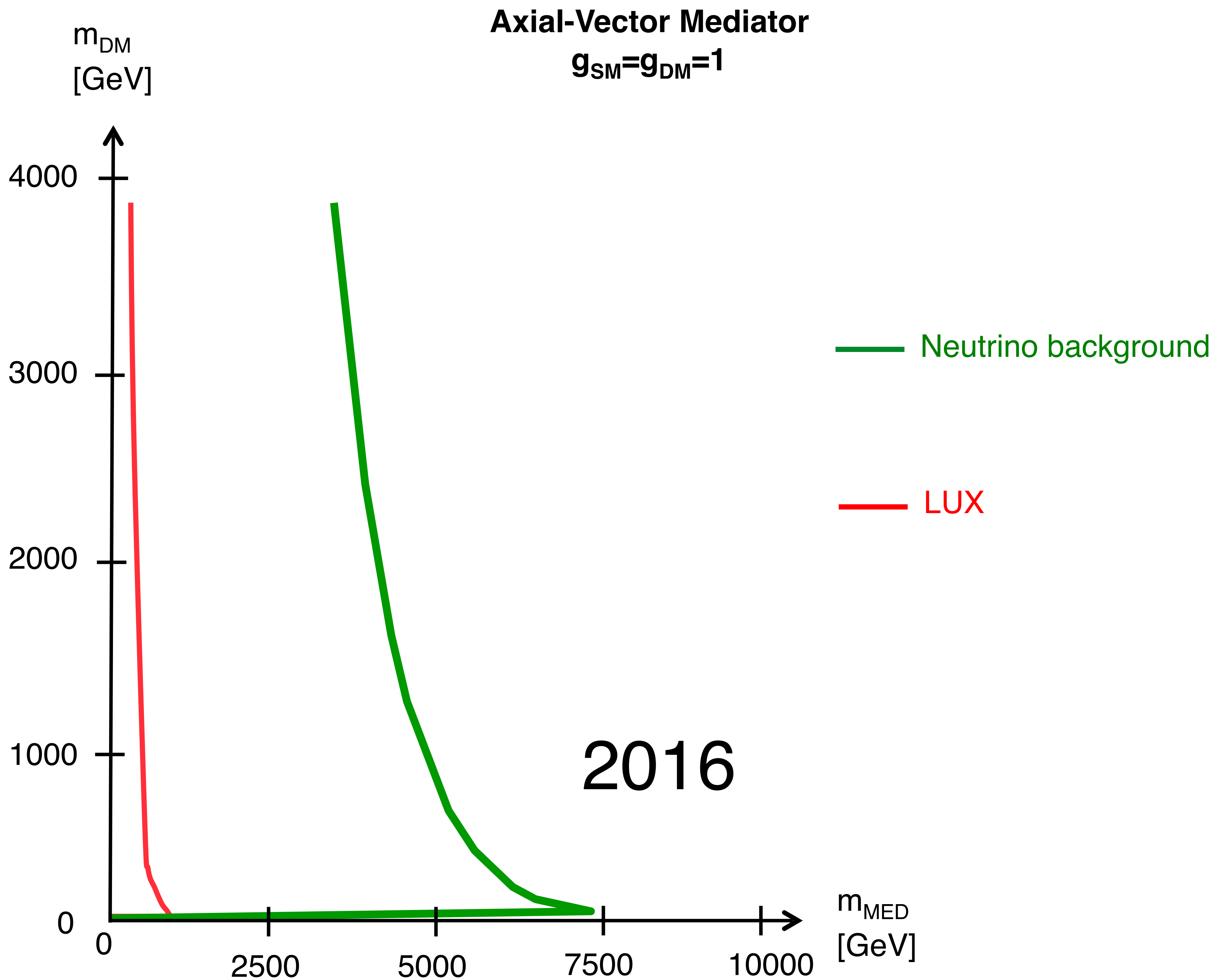

to HL-LHC
(10x more, 3ab^{-1})
>300fb^{-1}
8 TeV
13 TeV
>100 fb^{-1}
We are here
LS 2
~20 fb^{-1}
LS 1
Integrated Luminosity (fb^{-1})
350
250
150
50
2010
2012
2014
2016
2018
2020
2022
2024
Year

The Path to Discovery



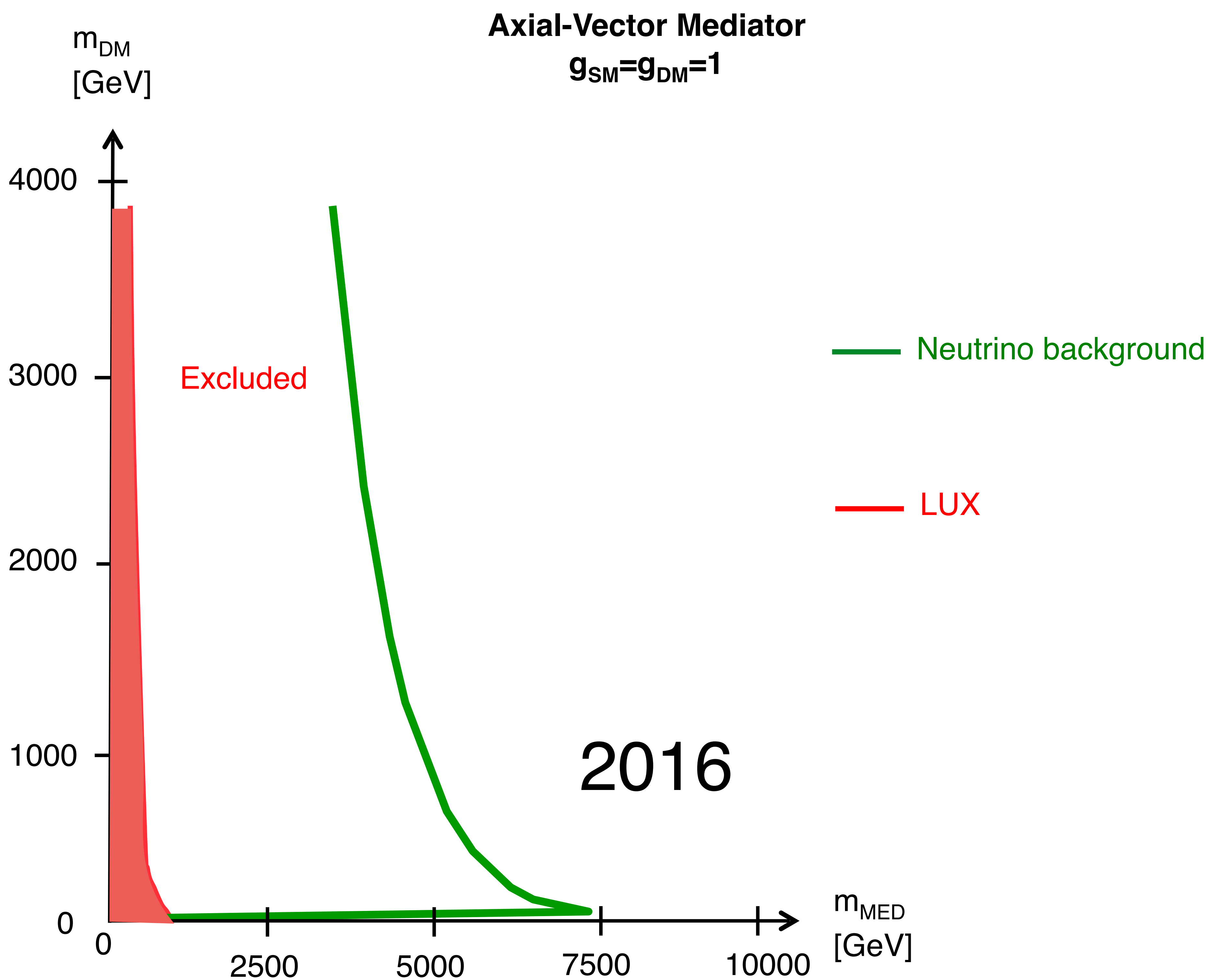
created using code from Chris McCabe

The Path to Discovery



created using code from Chris McCabe

The Path to Discovery



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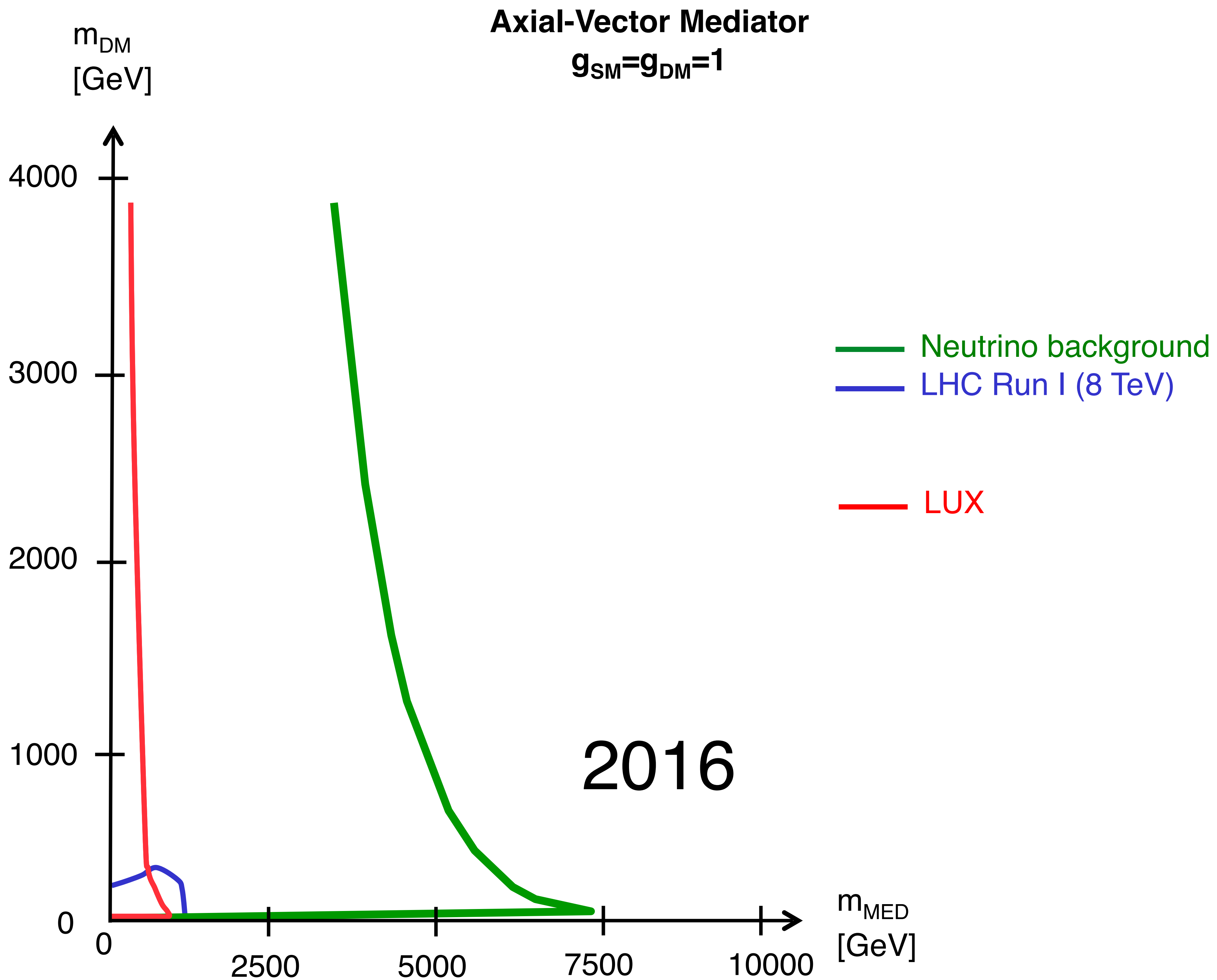

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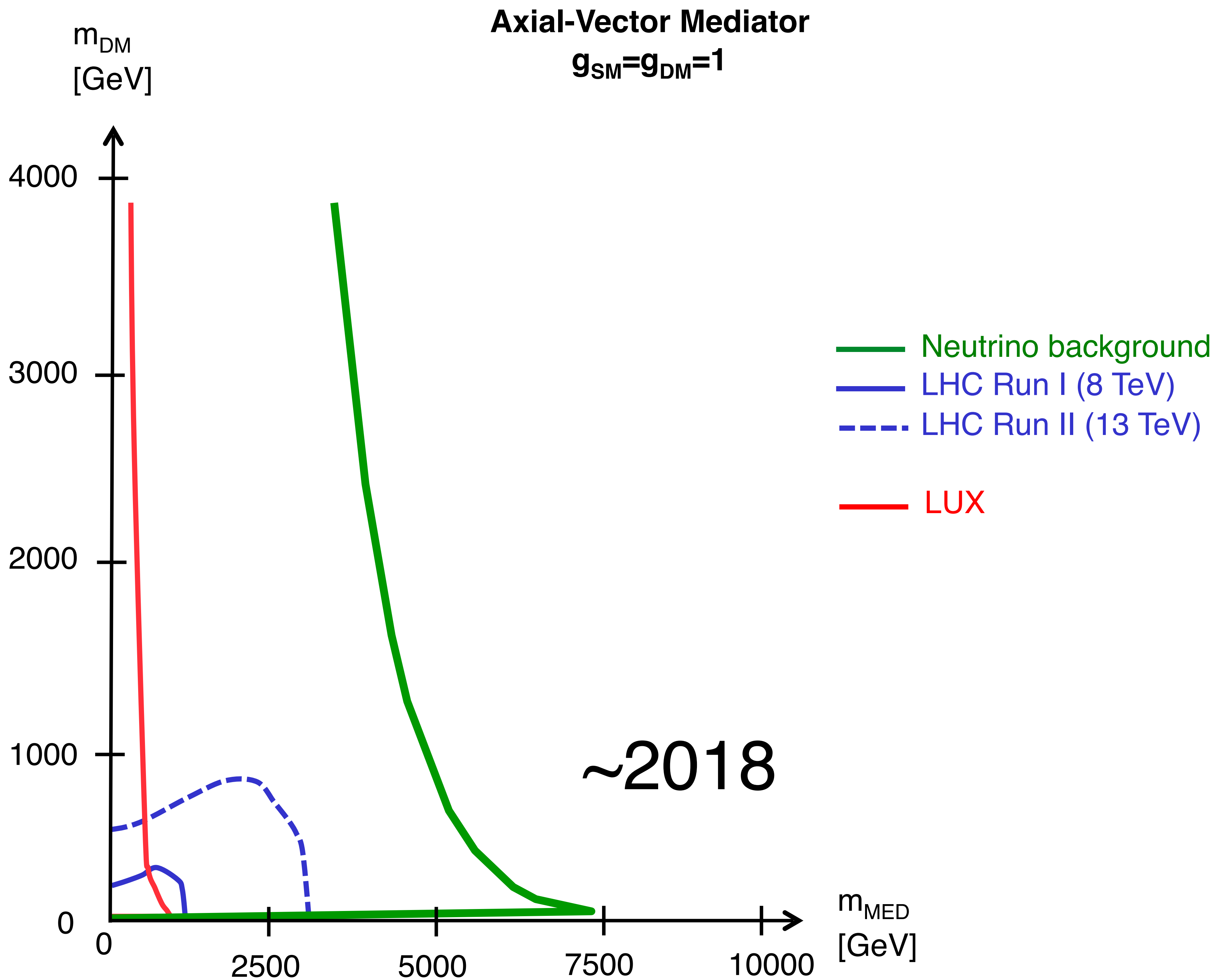

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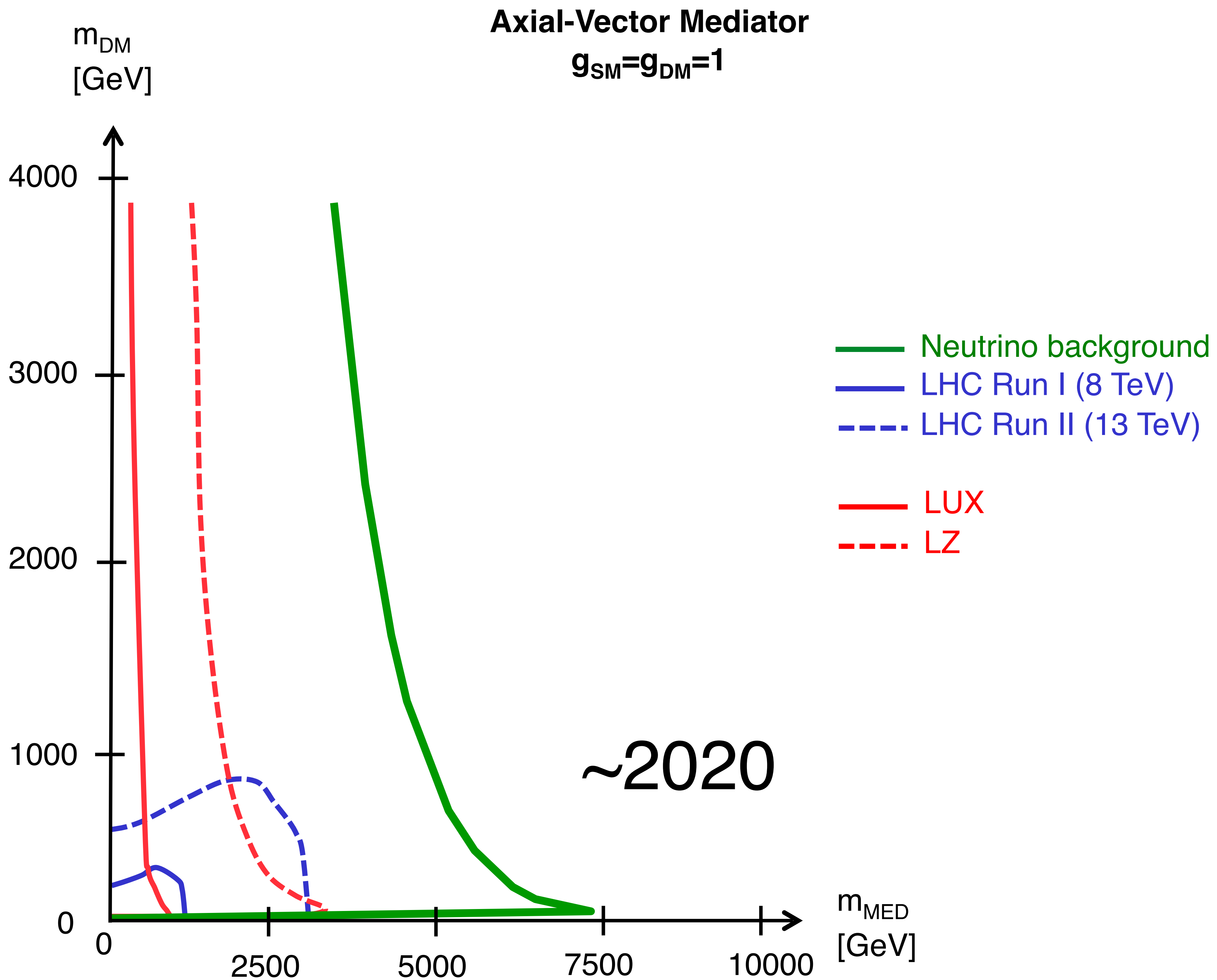

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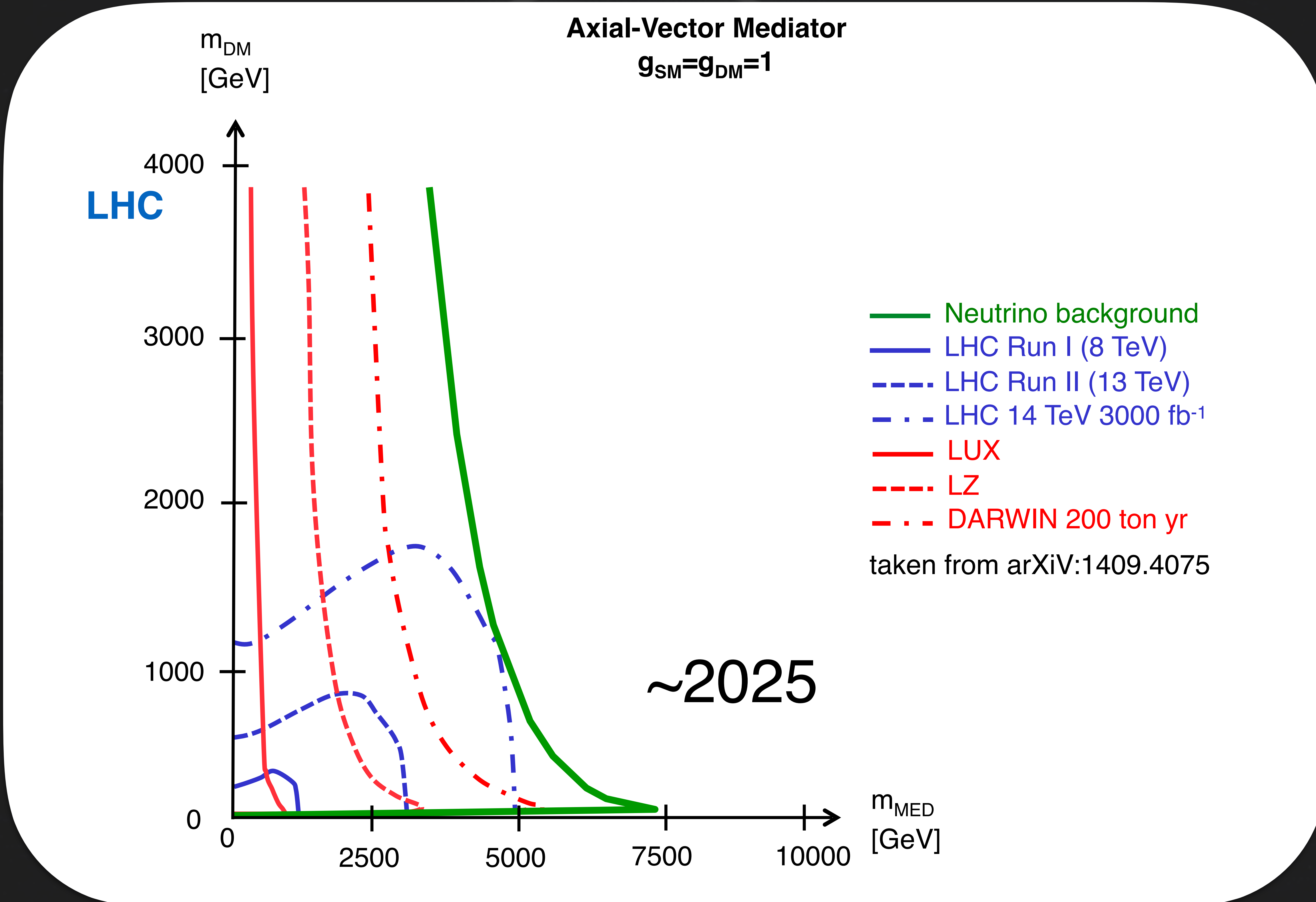

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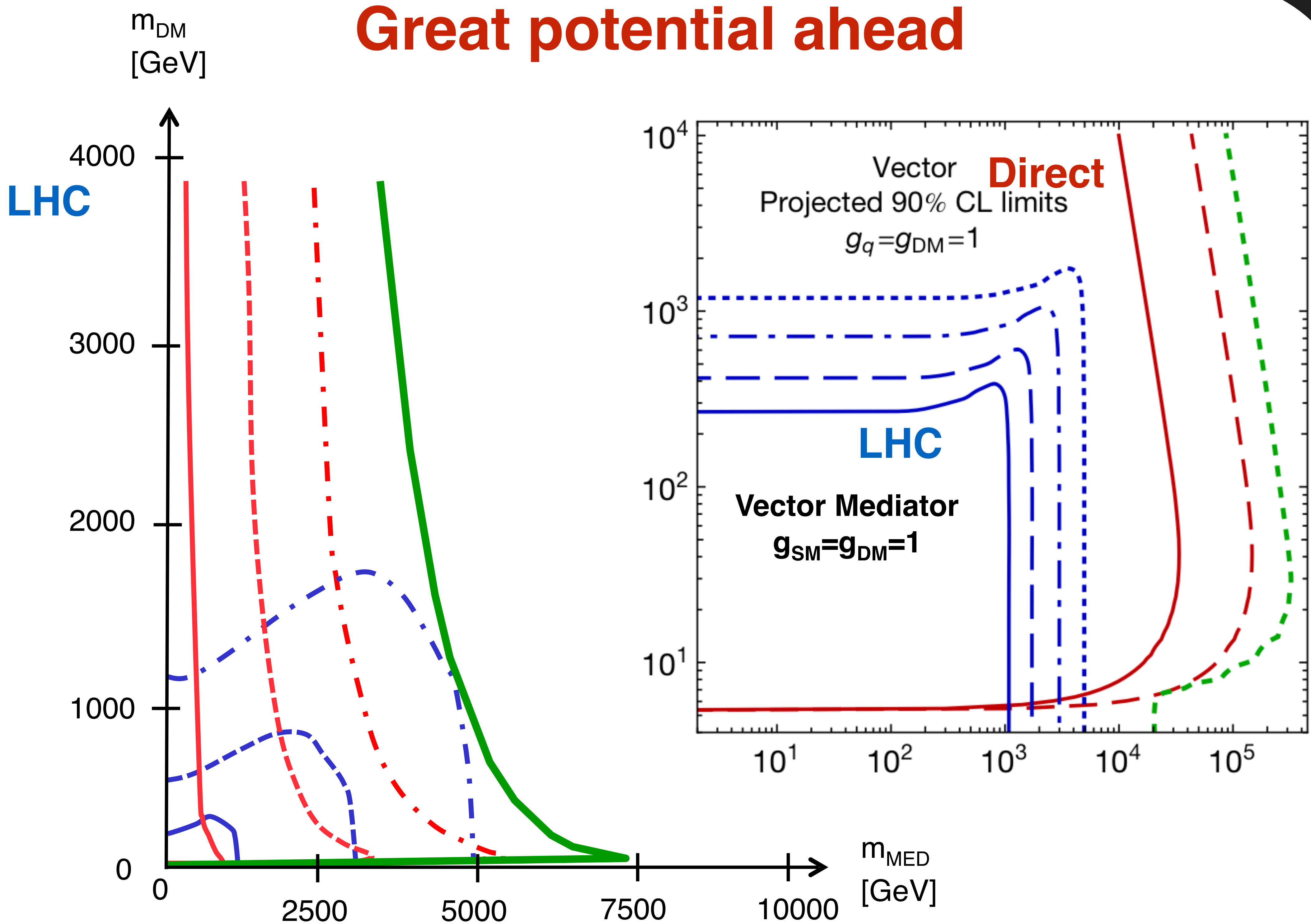
Great potential ahead



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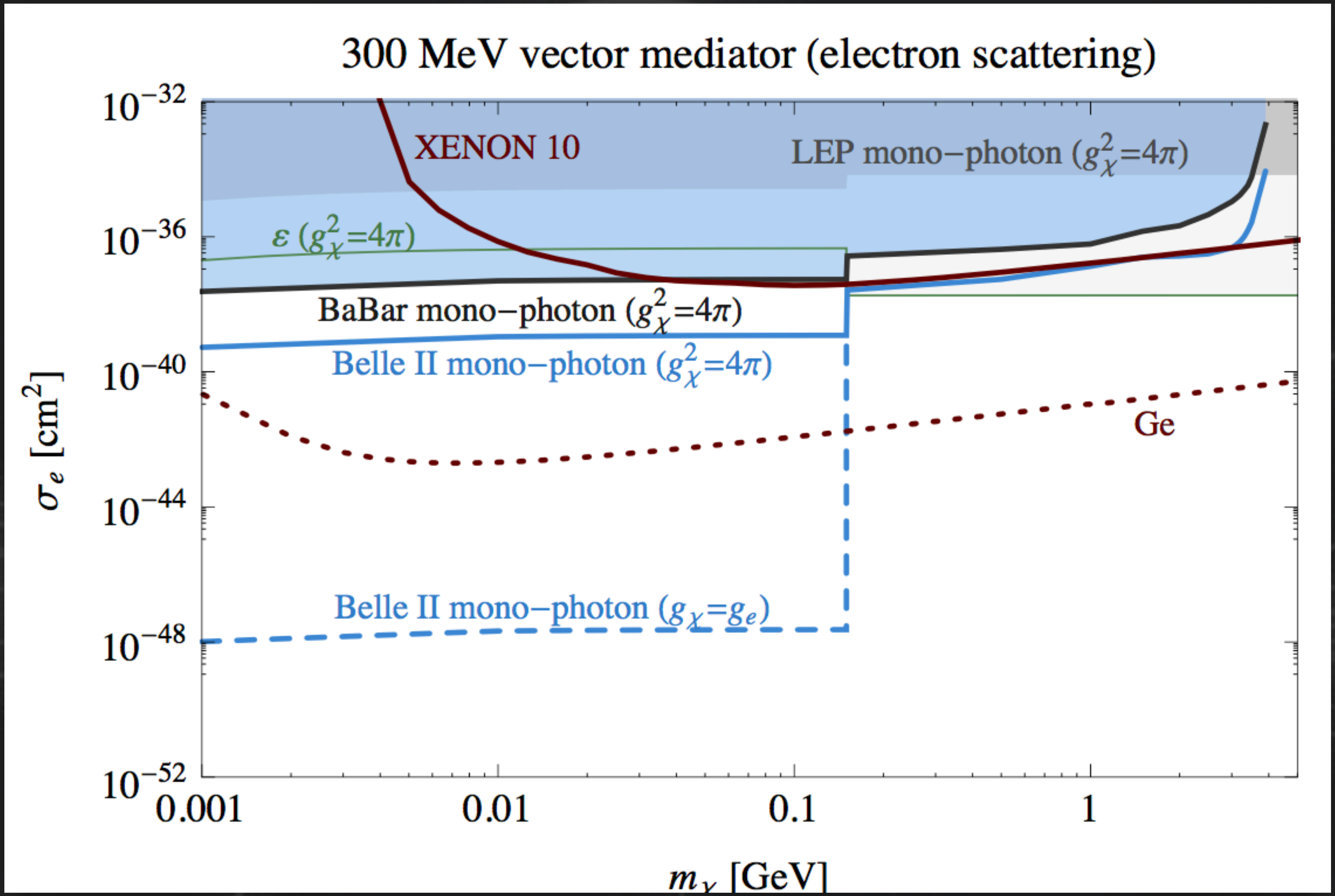
Some final remarks

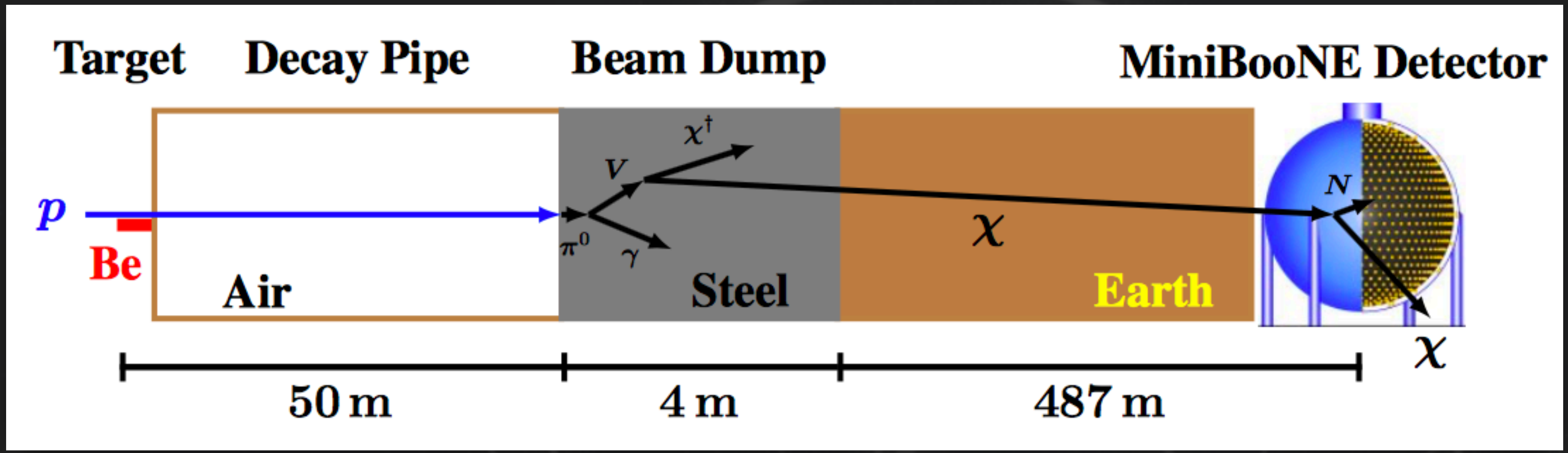
DM searches at e⁺e⁻ collider

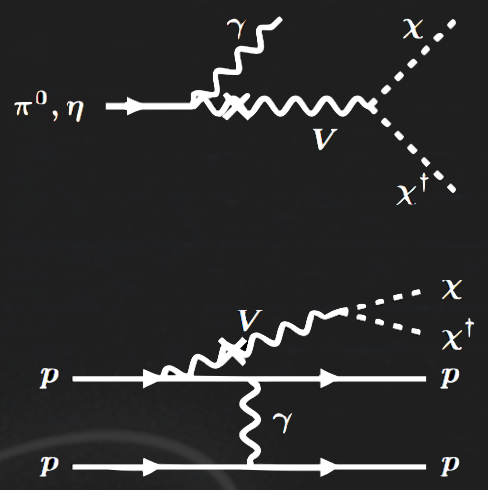
arXiv:1309.5084v2



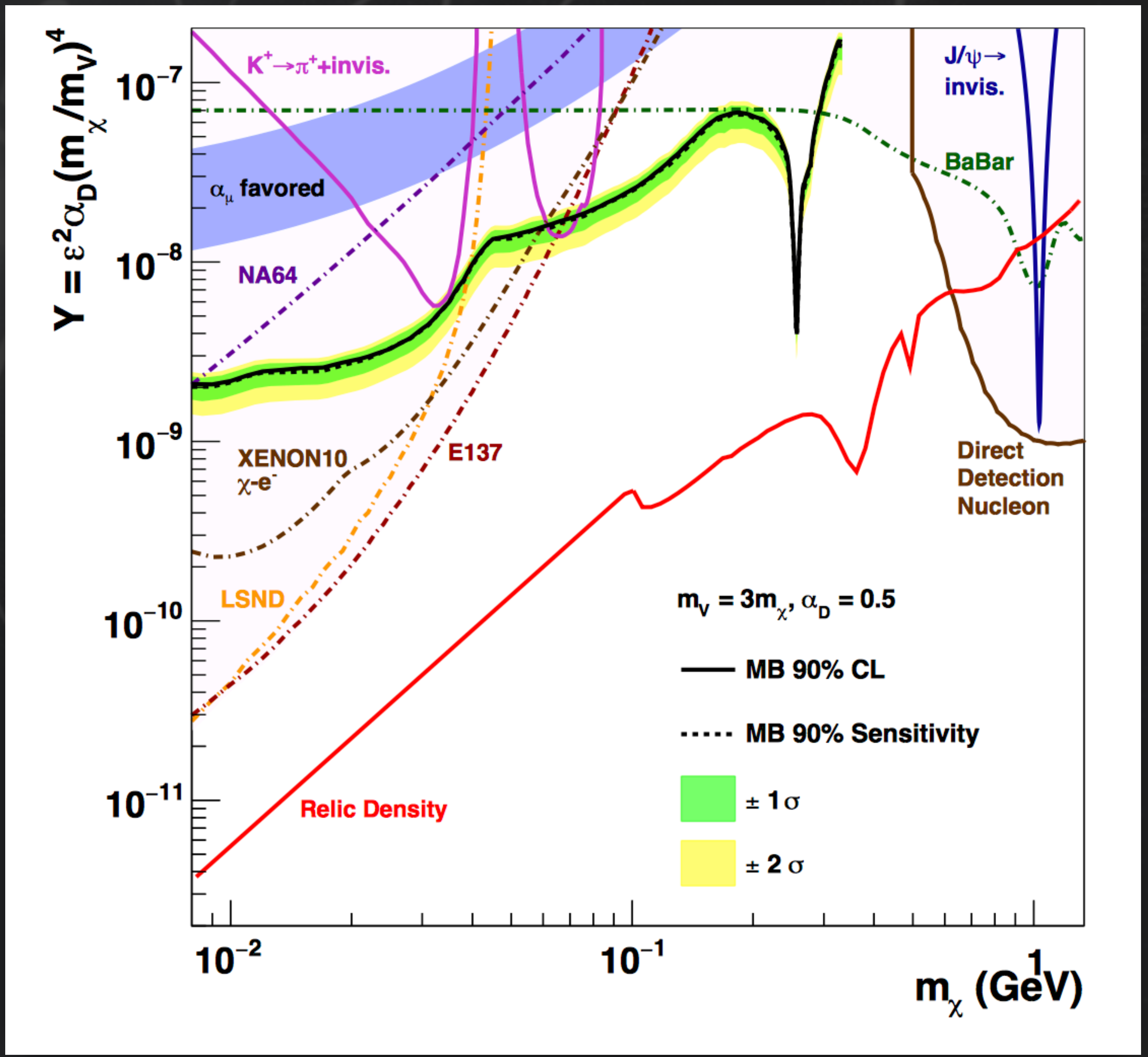
- We can also search in the clean environments of e⁺e⁻ collider for light mediators ($\sqrt{s}\lesssim$10 GeV)
- Barbar had (partial) mono-photon trigger, already advancing in uncharted territory
- Belle-II (2018) will provide great sensitivity
- Similar constraints from rare decays (KLEO etc) and LHCb searches are in preparation

Beam Dump Experiments



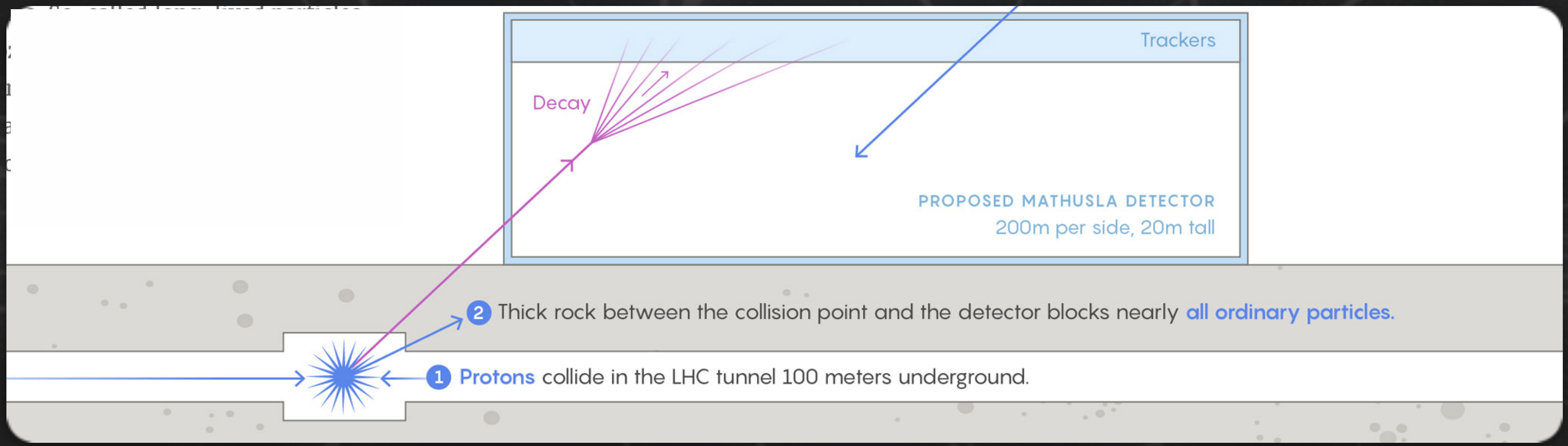


- Beam Dump experiments performed at JLab, SLAC, Fnal, others also probe light mediators using 'dark photon' or 'Vector portal'
- Limits are set using dimensionless DM annihilation xsec $Y=\varepsilon^2\alpha_D(m_\chi/m_V)^4$
- Potential to powerfully probe yet unexplored region, dedicated experiments planned



New approaches

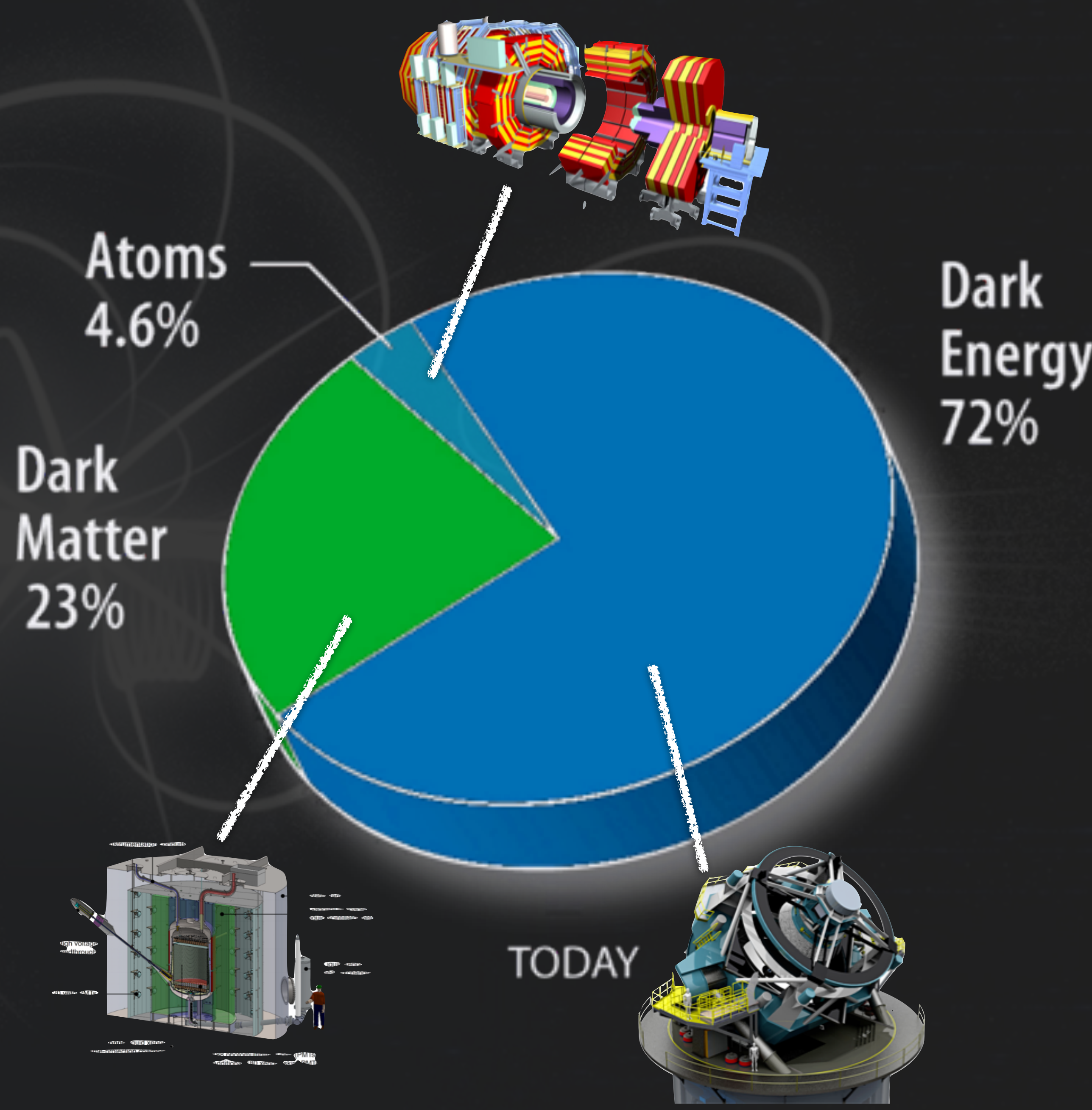
- Large experience, rapid increases in energy/lumi and great phenomenological effort led to quite comprehensive analysis of simple s-channel models that cause the prominent mono-X signature
- No excess, but variety of DM models have been ruled out and new inter-disciplinary developments instigated.
  - Present models and searches are among the most simple ones using similar phase space
  - ~5% of LHC data recorded, 2% analyzed using similar models and phase space



- New approaches will push the field far beyond today's state:
  - long-lived particle searches [1706.07407, 1704.06515]
  - new signatures [1503.00009, 1706.07407, 1308.0592]
  - new production modes [1308.0592, 1607.06680]
  - dark sectors [1707.05326]
  - dark-photon searches [1310.6752, 1311.0029]
  - Novel detectors (milliQan, Faser, MATHUSLA) [1705.06327, 1708.09389, 1410.6816].

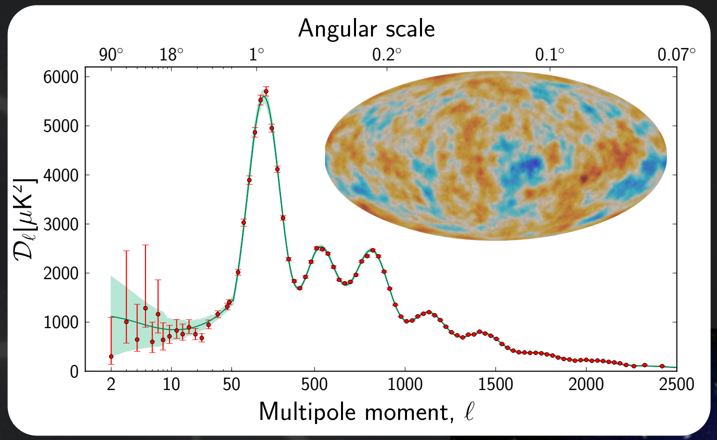
Summary

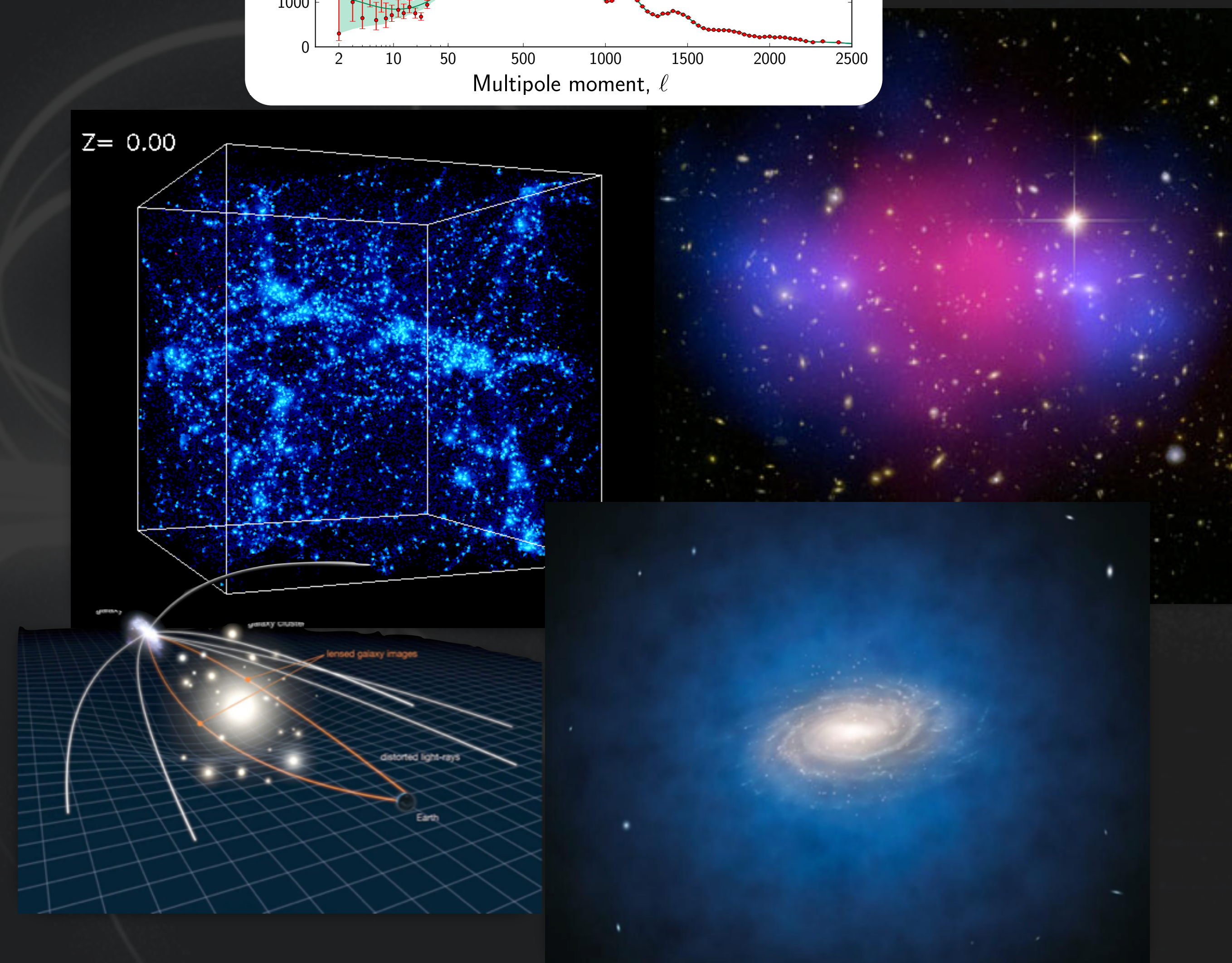
- DM is out there and will transform our understanding of the universe
- Collider searches are particularly powerful at low WIMP masses and are not subject to significant astrophysical uncertainties.
- LHC is running, direct detection, and indirect detection are improving rapidly – the field is being transformed now
- DM searches need to be interdisciplinary
  - DM has to be discovered in several fields to be confirmed and measured
- The WIMP miracle does not necessarily imply vanilla dark matter: SuperWIMPs, WIMPless DM may be warm, self-interacting…
- If discovery in DD or ID, collider might be best suited to measure DM in lab → provide physics case for future machine



What is DM?

- Dark matter is a hugely successful theory to explain plenty of observations
- It is the one theory that can successfully simulate and reproduce the universe on all scales:
  - Galaxy rotation curves
  - Galaxy clustering
  - Cluster collision
  - Large-scale structures
  - CMB fluctuations
  - Gravitational lensing
- Unambiguous evidence for new physics





- Global fit of cosmological parameters, ΛCDM:
  → $\Omega_\Lambda \approx 0.68$, $\Omega_{DM} \approx 0.27$, $\Omega_b \approx 0.05$