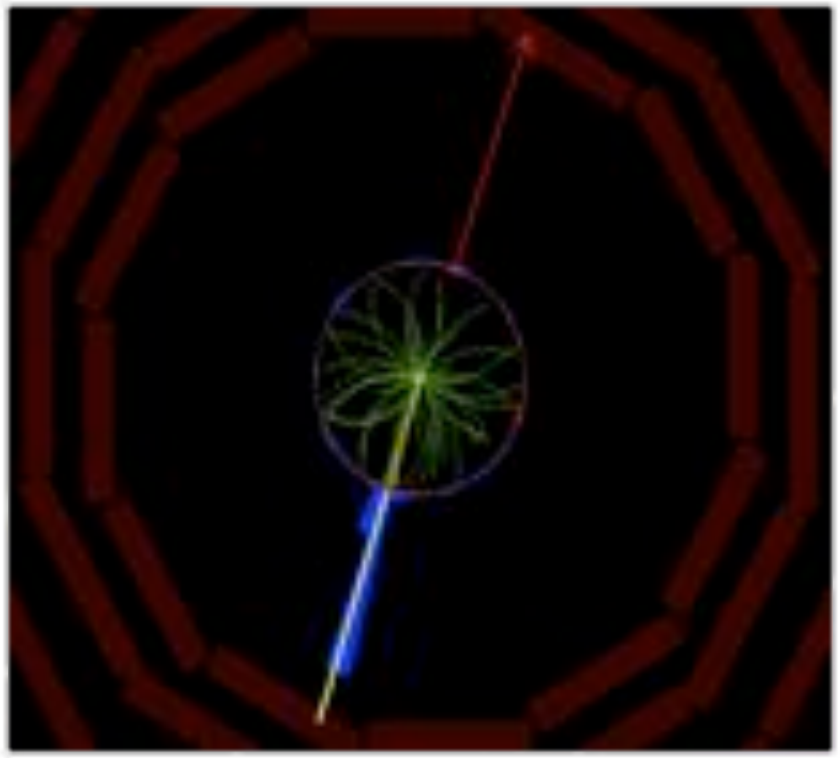
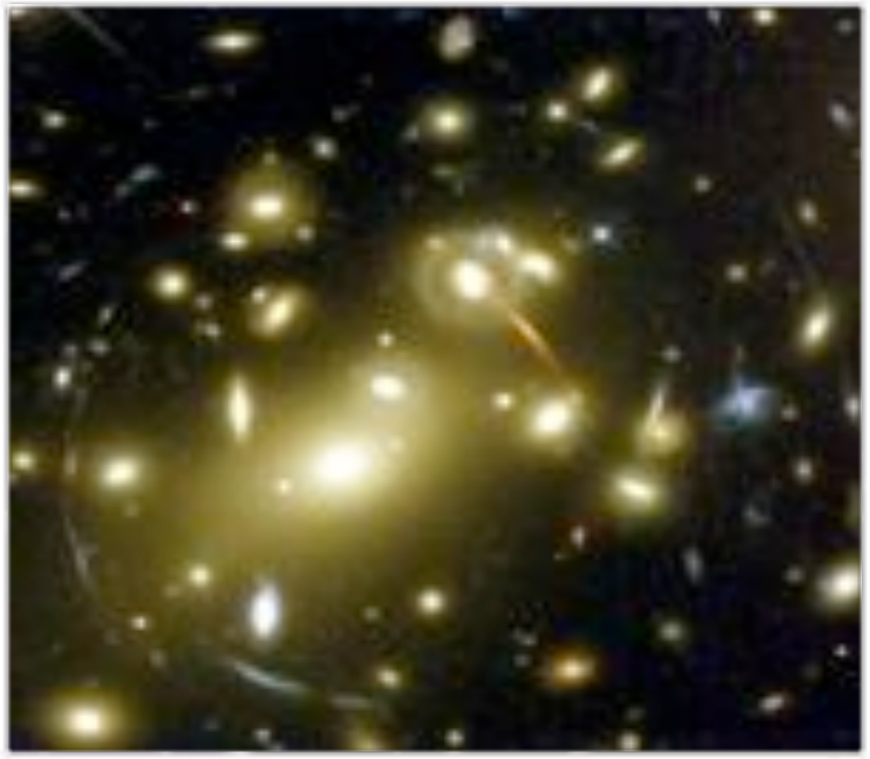


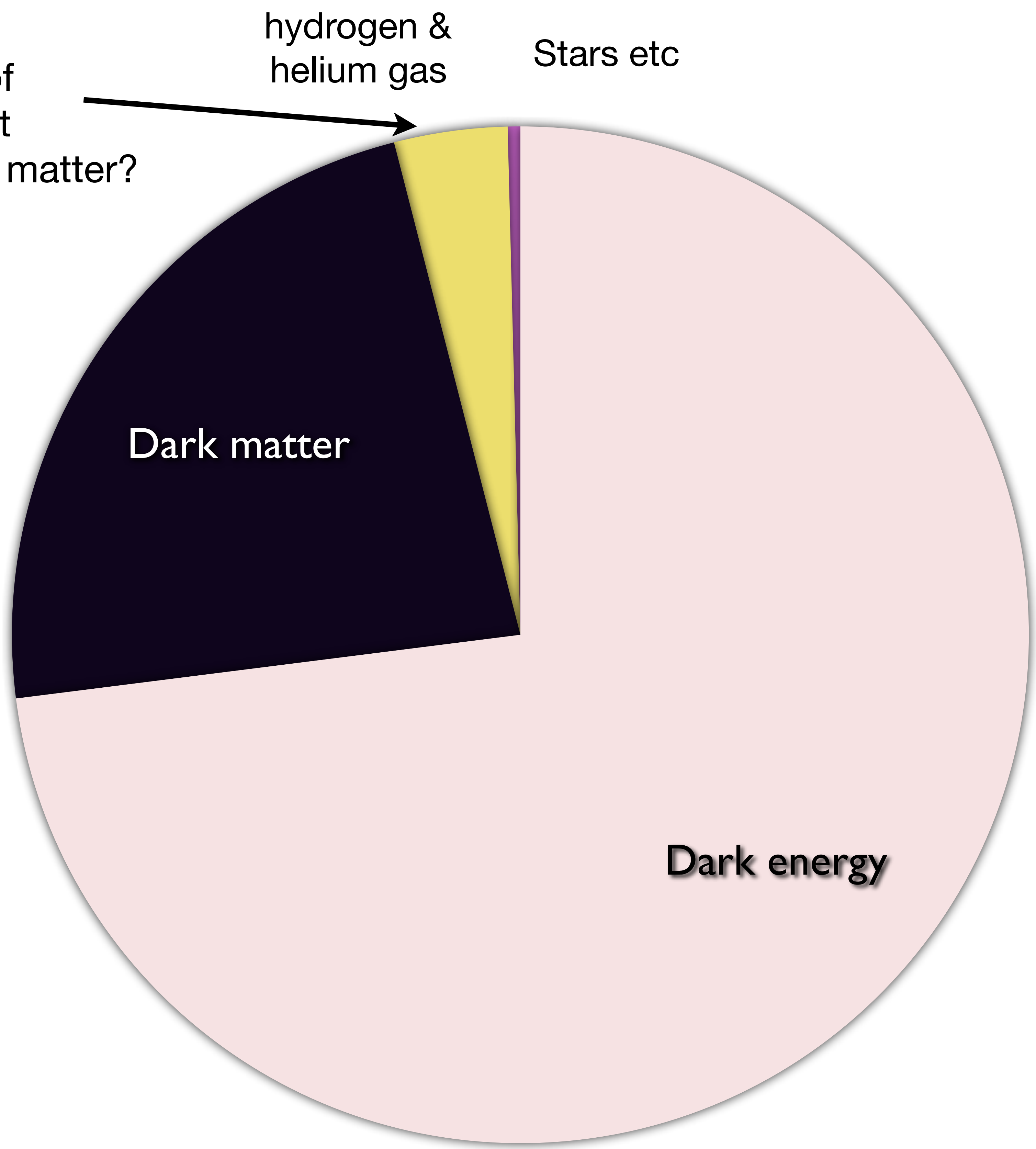


Review of the status and future prospects for dark matter searches at colliders

Sarah Alam Malik
Imperial College London

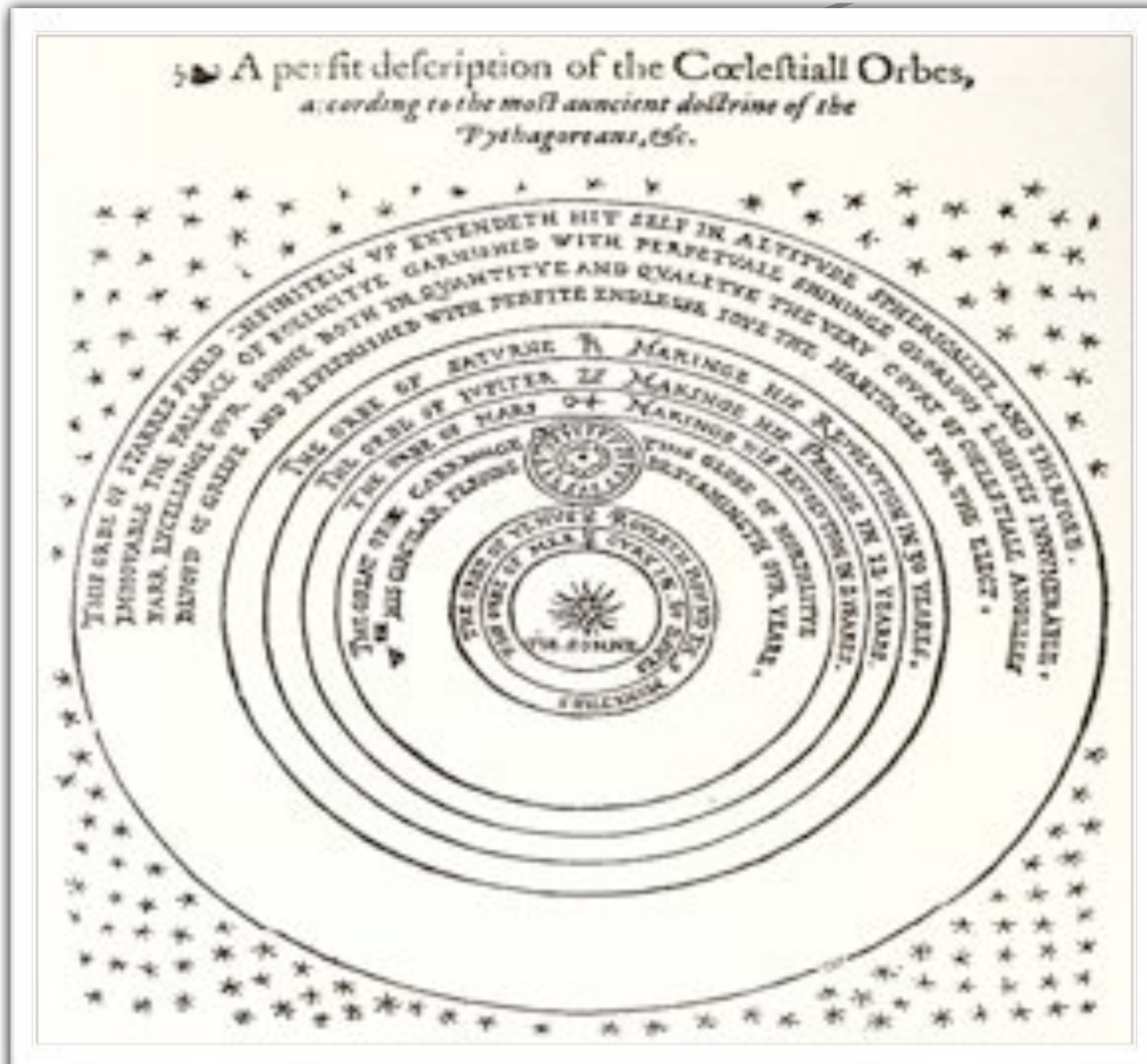
Composition of the Universe

-What we are made of
-What we know about
-Insignificant? Do we matter?



Our place in the Universe

Copernicus : Earth is not the center of the Universe!



Our place in the Universe

Galileo: use of telescope, confirmed Copernican model,
Jupiter has orbiting moons, Earth just another planet

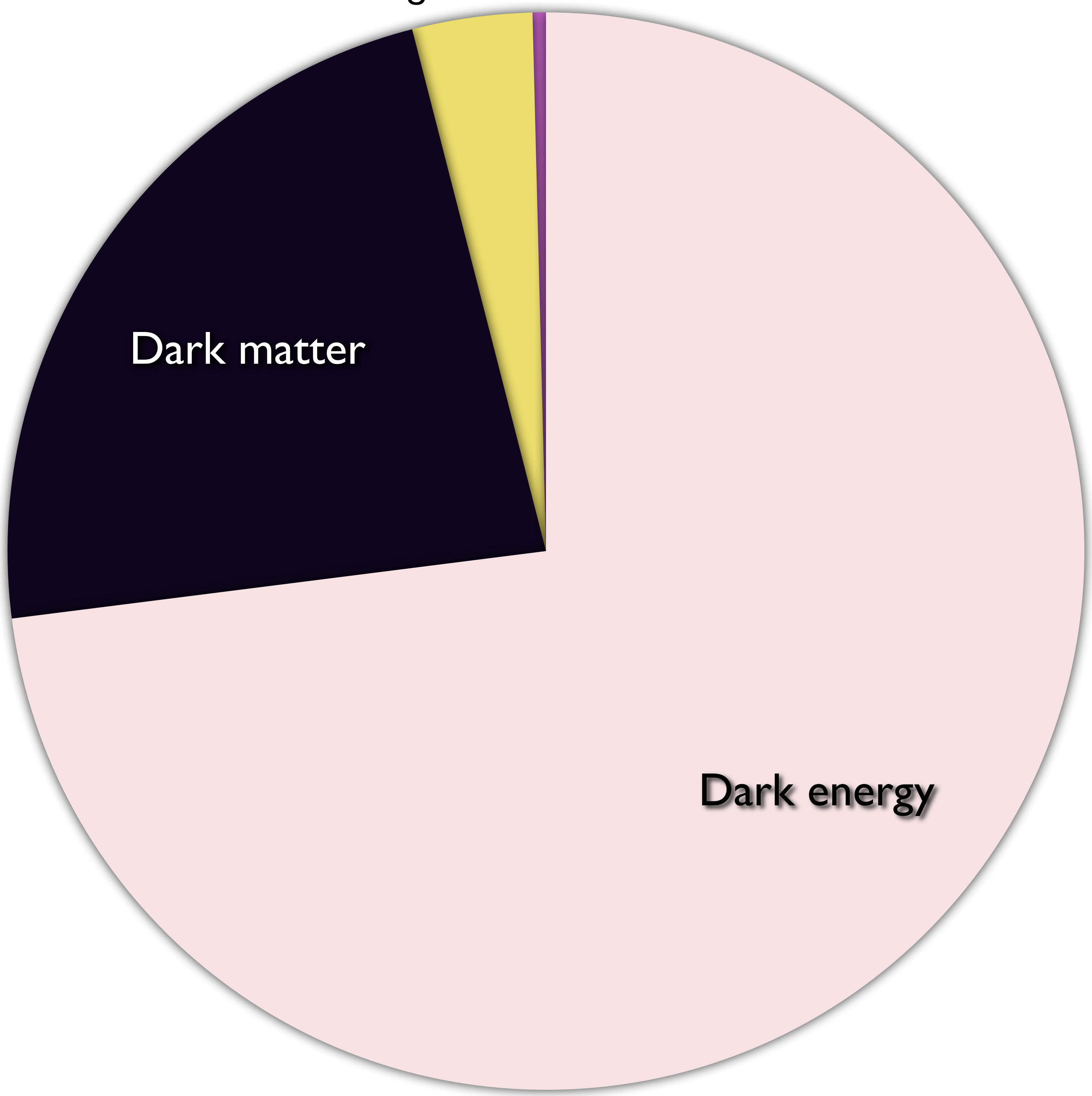
Our place in the Universe

Hubble : each speck of light is another galaxy, our galaxy one of billions.

Our place in the Universe

We only make up 4% of the Universe

How did we come to know that the most common form of matter in the universe is 'invisible' to us?



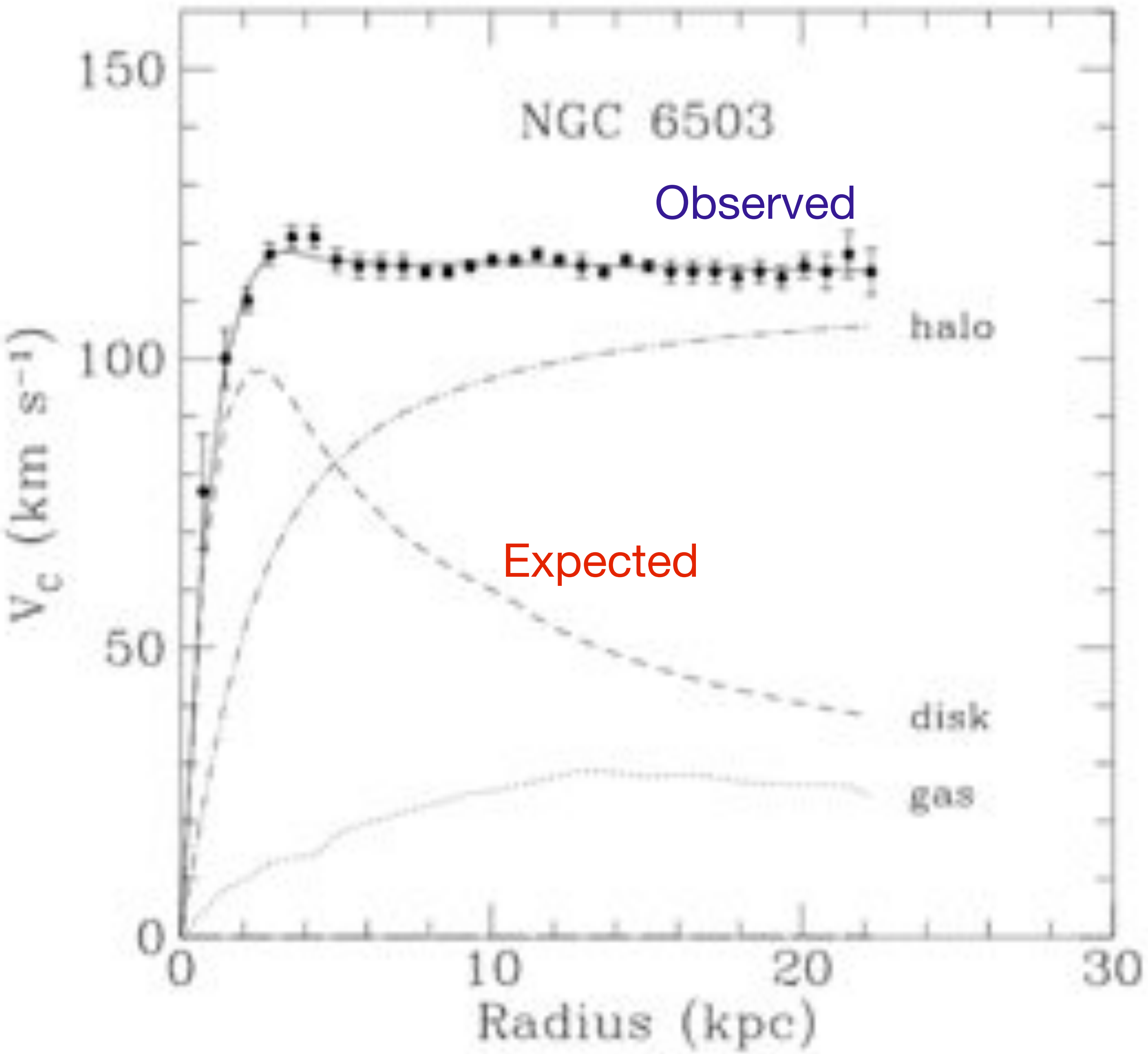
Evidence for Dark Matter

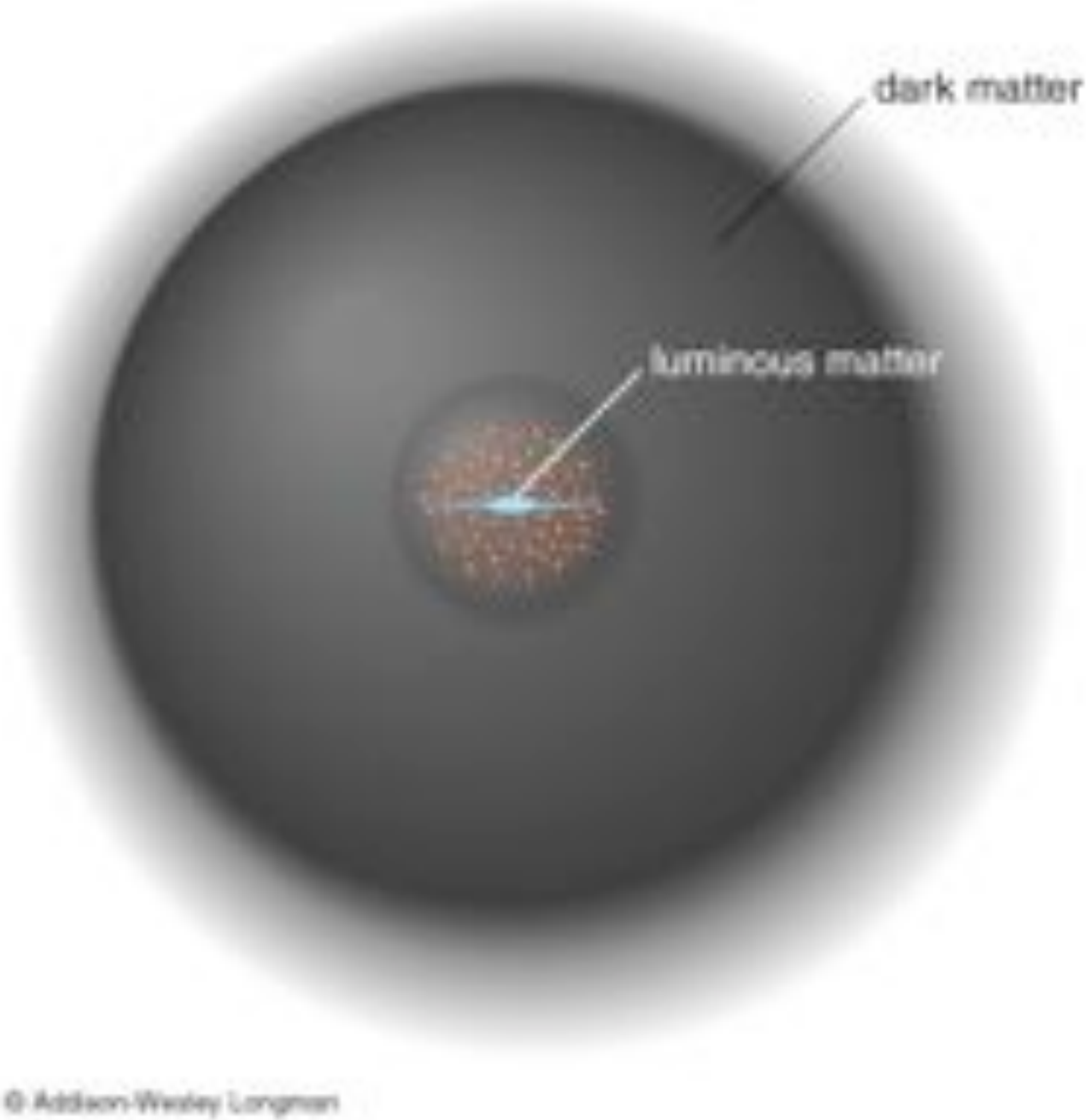
how do we know its there?

Not enough mass

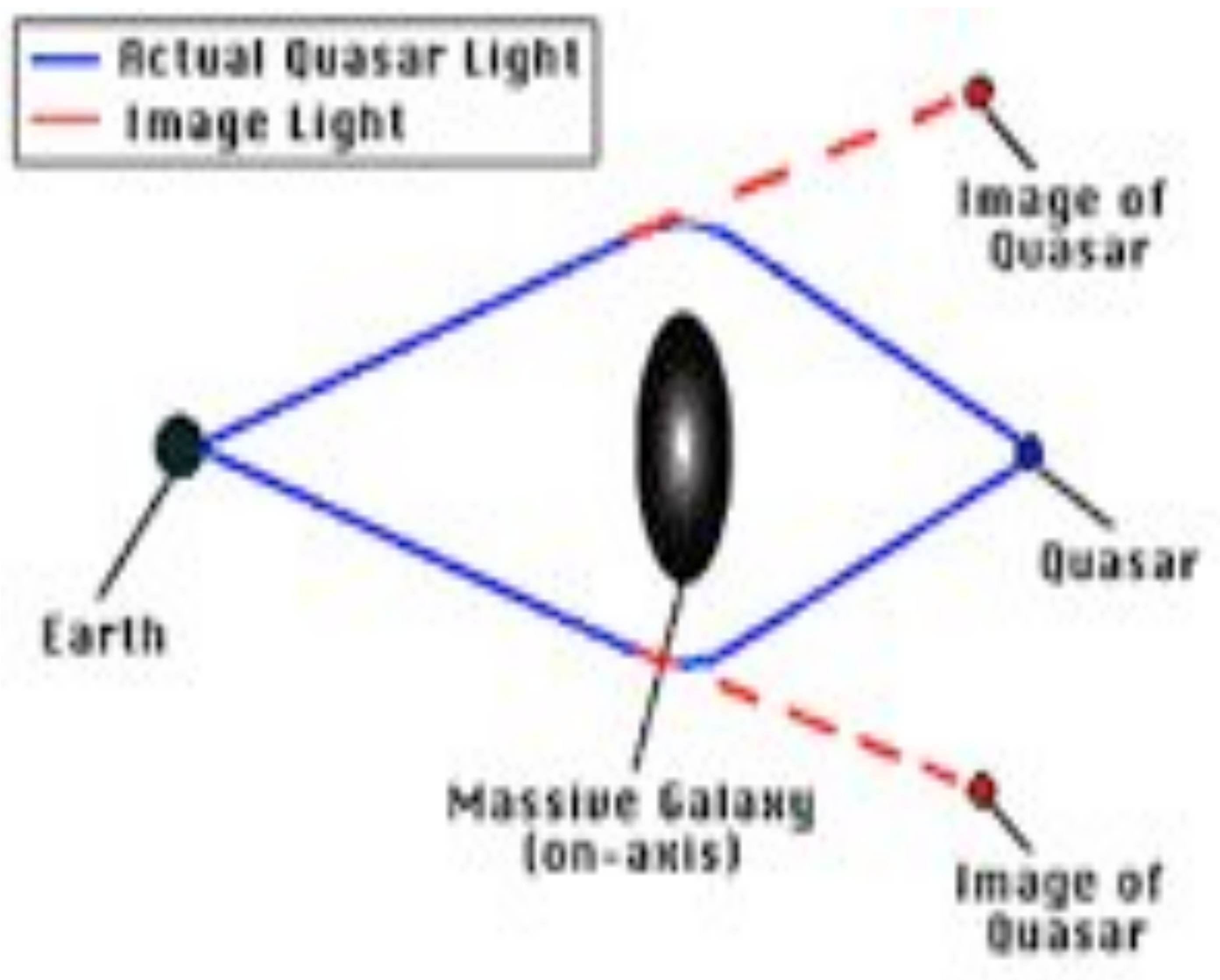
Fritz Zwicky

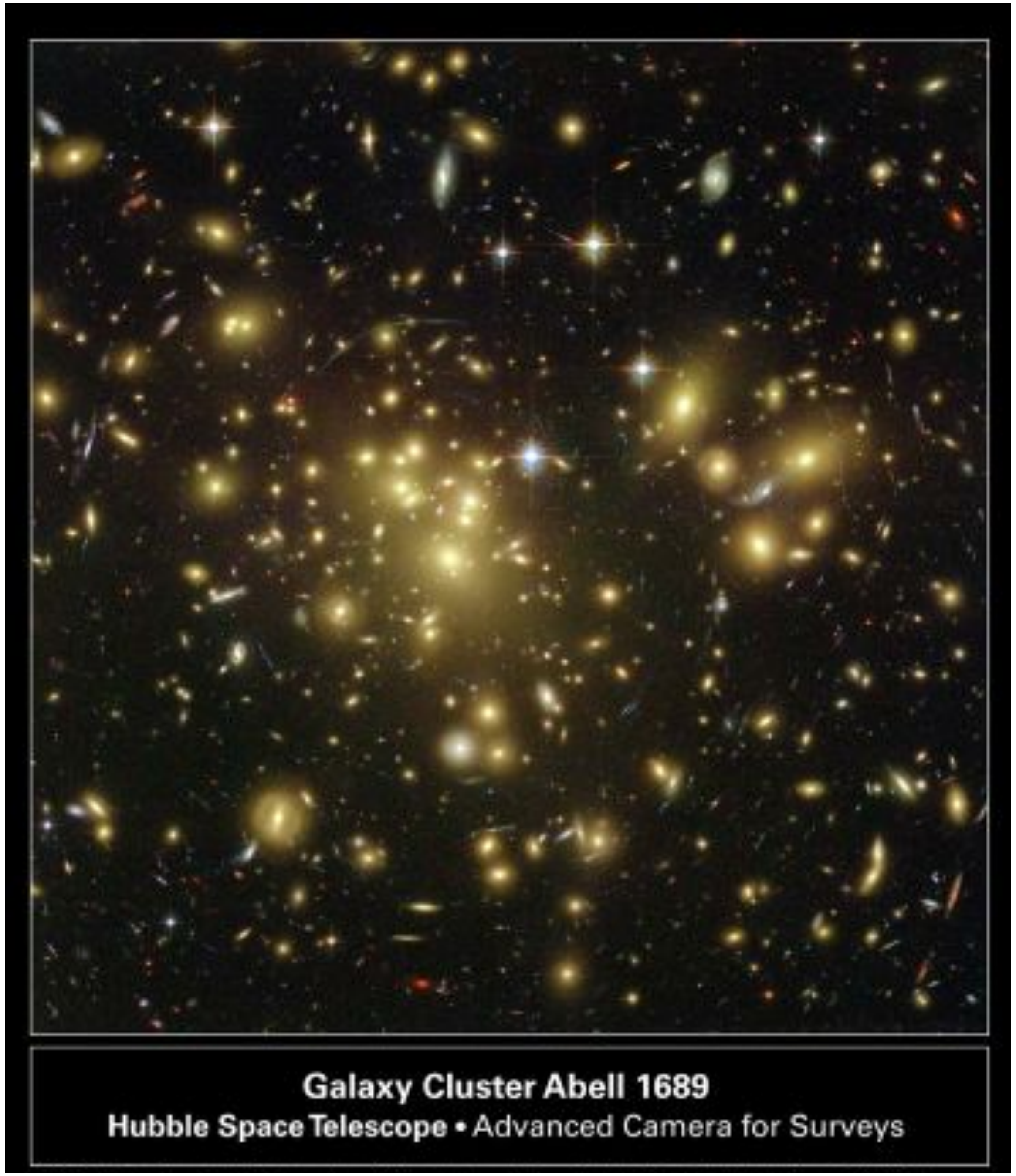
Rotation curves of galaxies





Gravitational lensing





Gravitational lensing

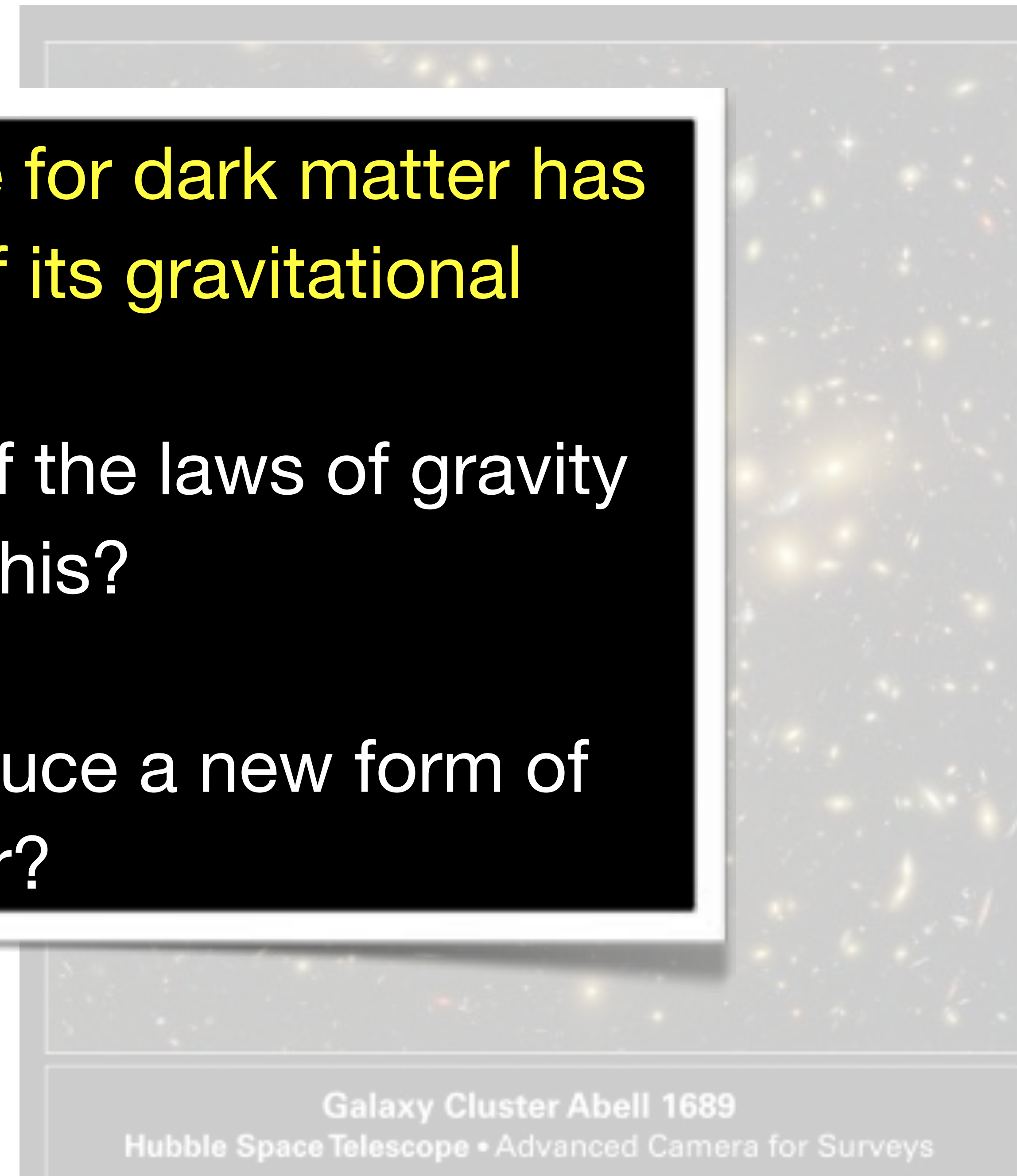
- foreground
- bending of l
give multiple

All experimental evidence for dark matter has come from observation of its gravitational influence :

- Can a modification of the laws of gravity explain this?

OR

- Do we need to introduce a new form of matter?



Bullet cluster

Optical image from Magellan and Hubble

Optical +X-ray

hot gas detected by Chandra, containing most of normal matter

Optical + gravitational lensing

Most of the mass in the cluster, measured by gravitational lensing, shown in blue


Dark matter exists
What is it made of?

What properties should a DM candidate have?

- non-relativistic

- long lived

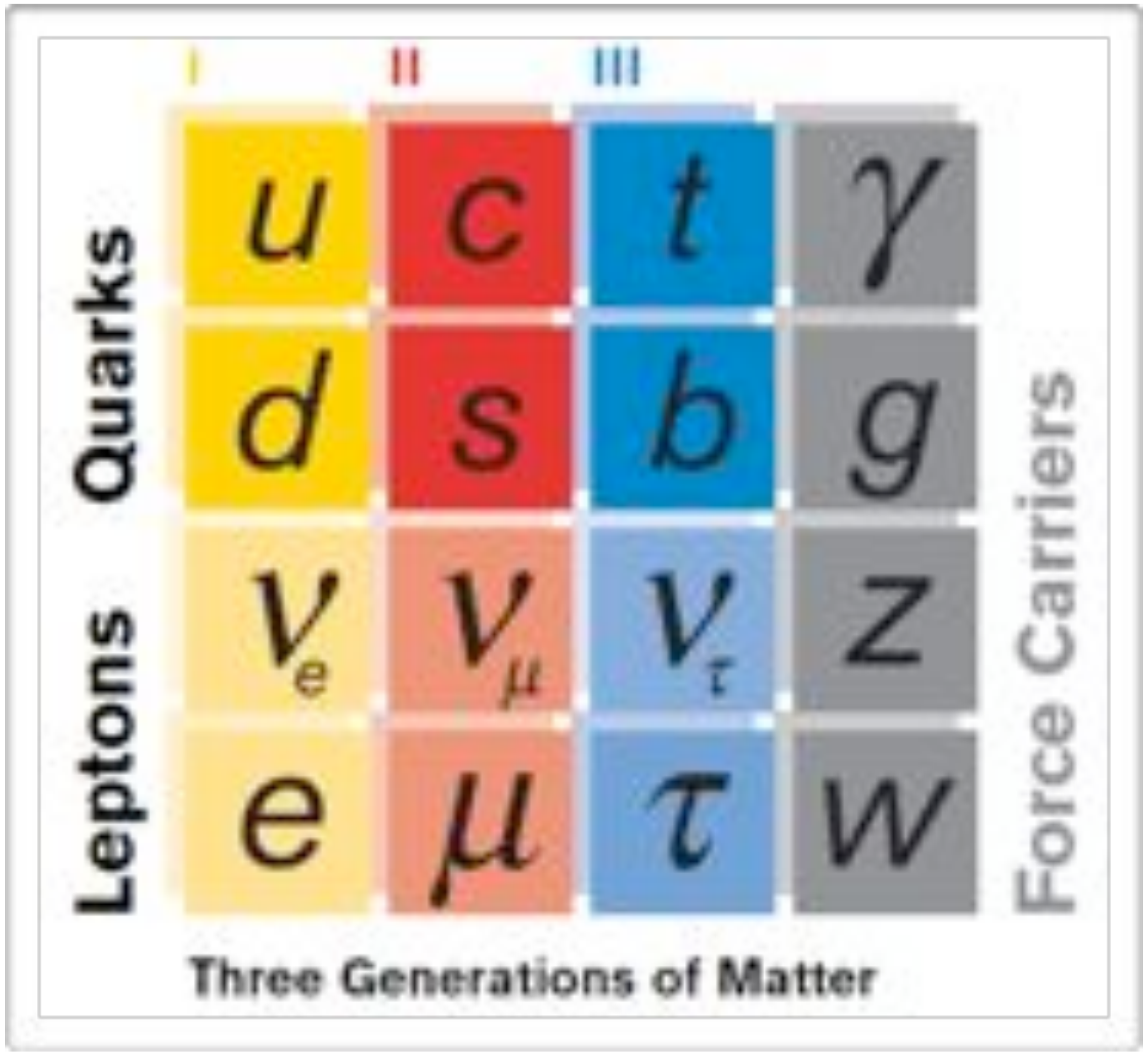
- interacts gravitationally

- no electric charge or color charge

The Standard Model

Remarkably successful theory!

Passed rigorous tests performed by decades of experiments



SM provides no candidate to explain the most common form of matter - no neutral, heavy, non-relativistic and long-lived particle

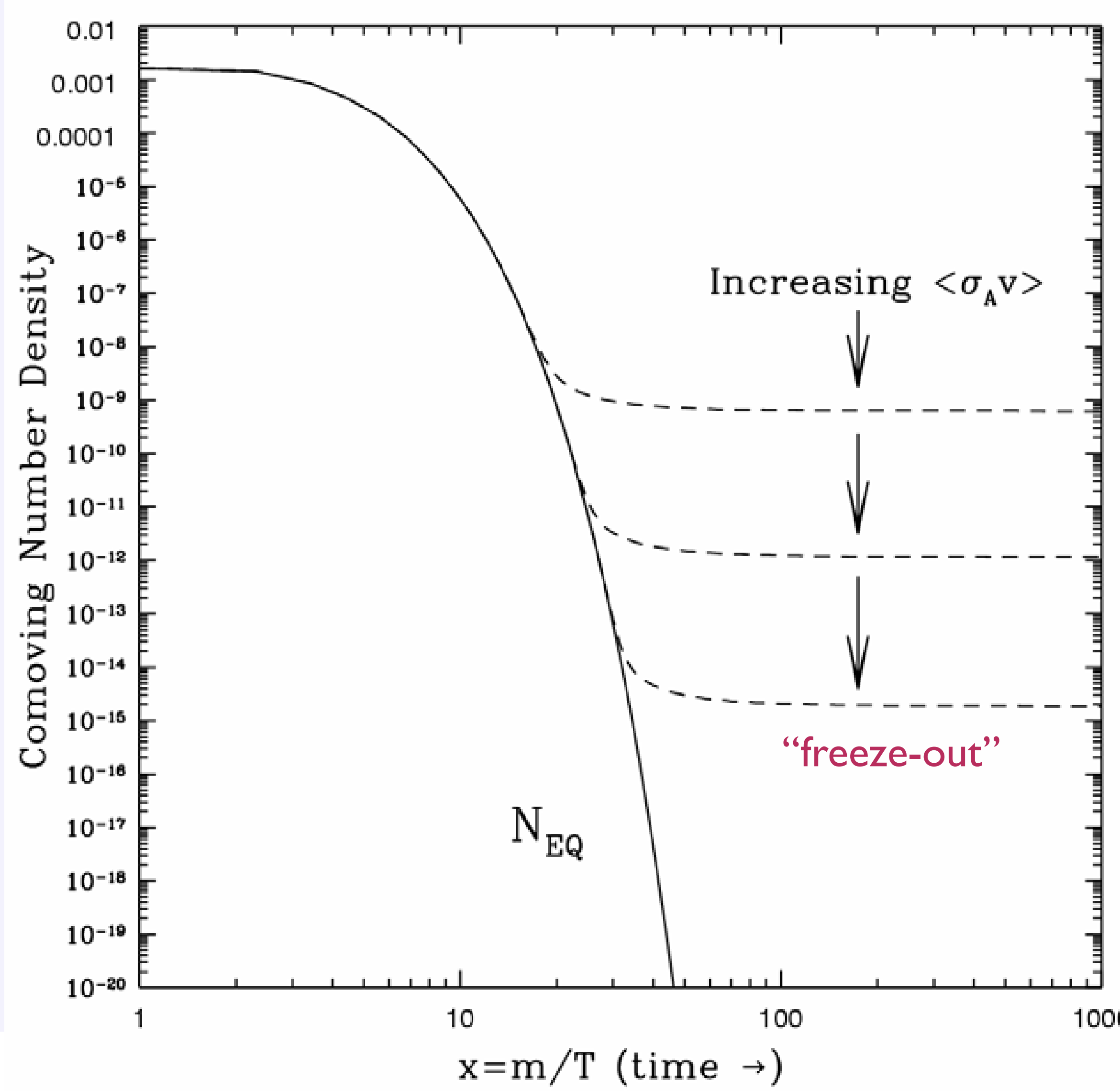
Weakly Interacting Massive Particles (WIMPs)

- Postulate a new species of elementary particles

- They are produced in the Big Bang and interact via : $\chi + \chi \leftrightarrow SM + SM$.

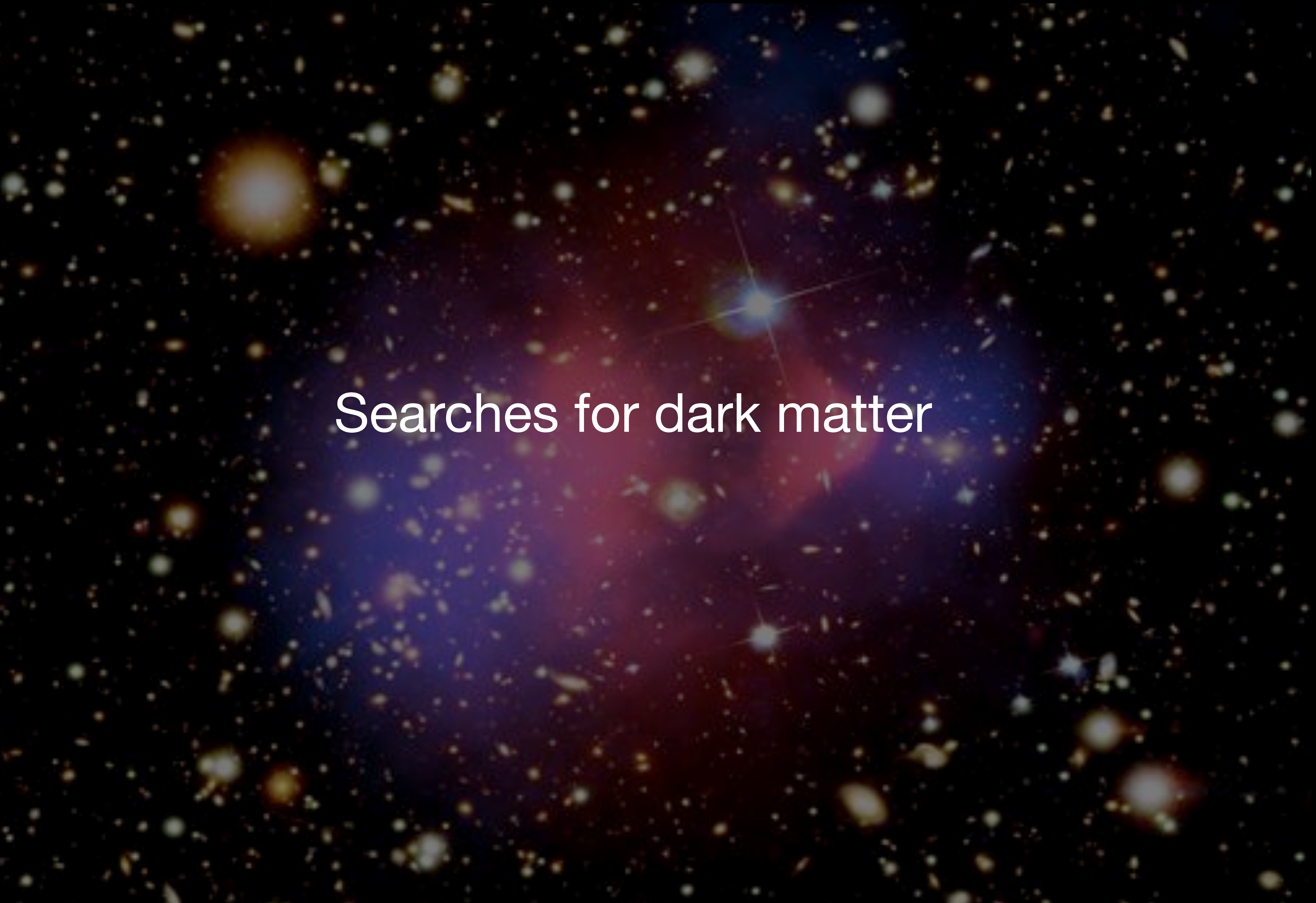
- As the universe expands and the temperature falls, they become diluted, and eventually can't find each other, so they 'freeze out'.

- Their relic density is measured by their interaction strength, inversely proportional to the annihilation cross-section ($\langle \sigma_A v \rangle$)



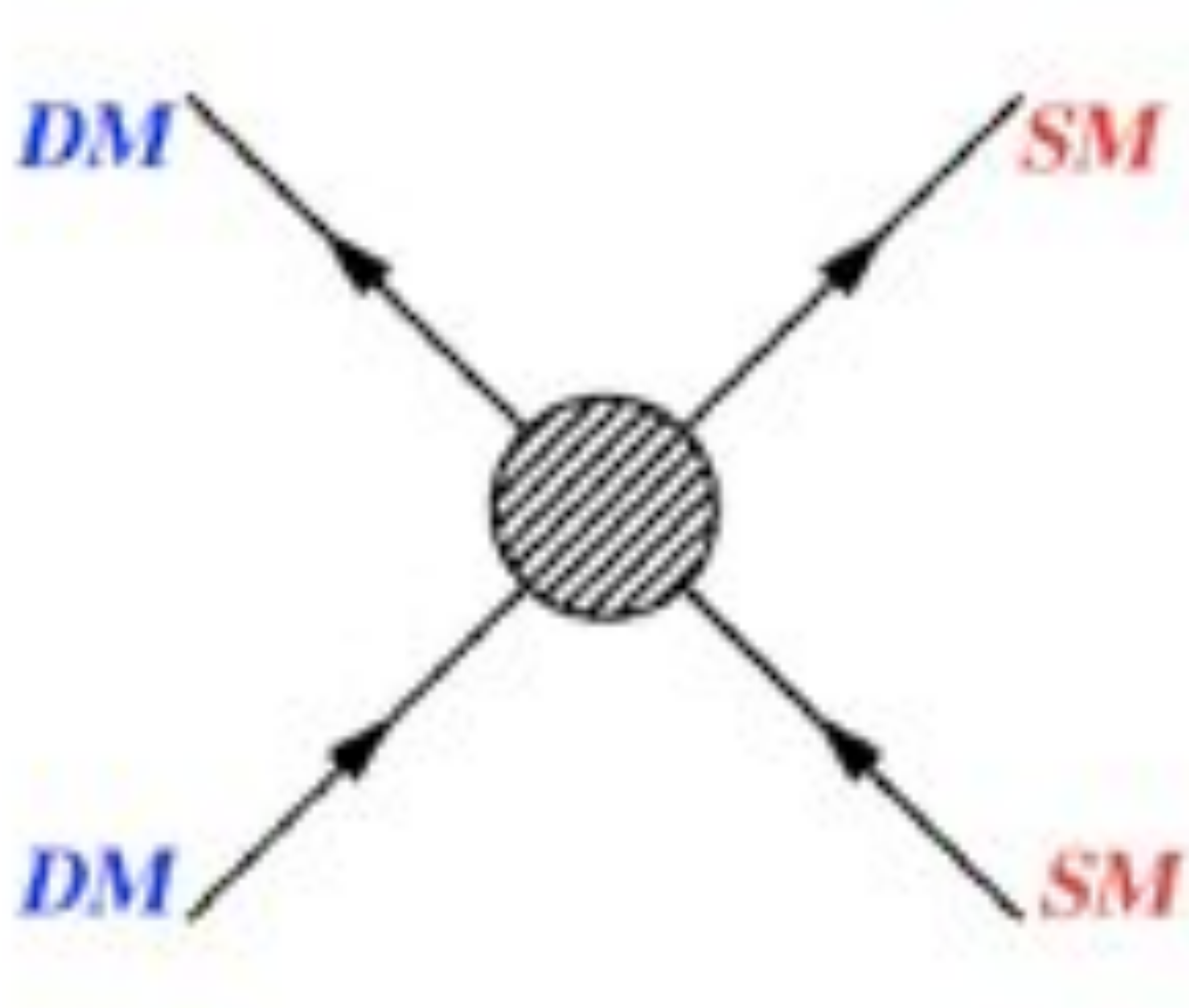
*Weakly interacting particles with weak-scale masses naturally provide the right relic abundance - **"WIMP miracle"***

Searches for dark matter



Searching for dark matter

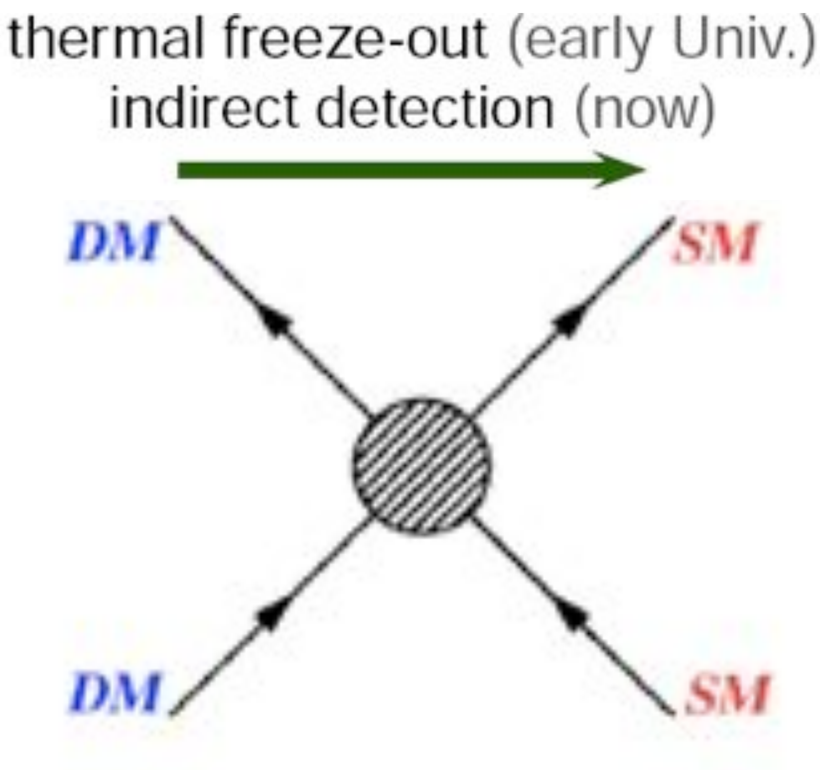
- $\chi + \chi \rightarrow \text{SM} + \text{SM}$ is the only process important for determination of relic abundance

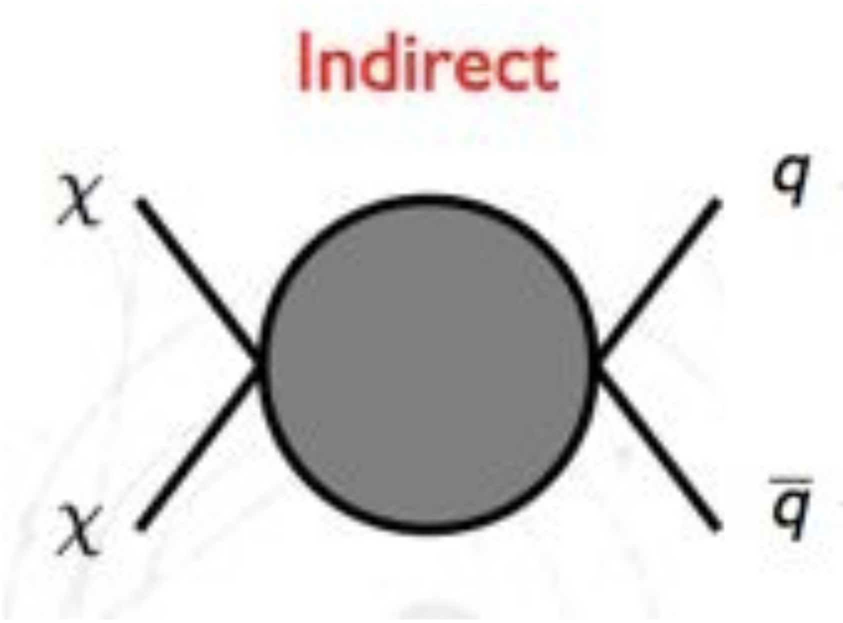


All three approaches to detecting dark matter probing the same interaction

Searching for dark matter

- $\chi + \chi \rightarrow$ SM + SM is the only process important for determination of relic abundance





Searching for dark matter

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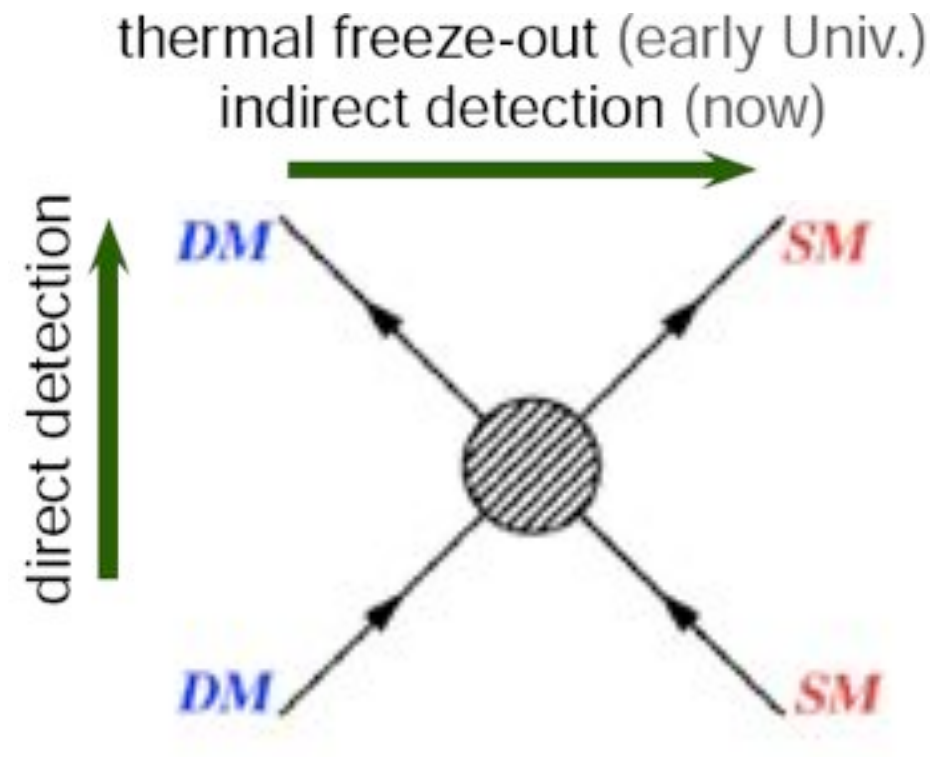

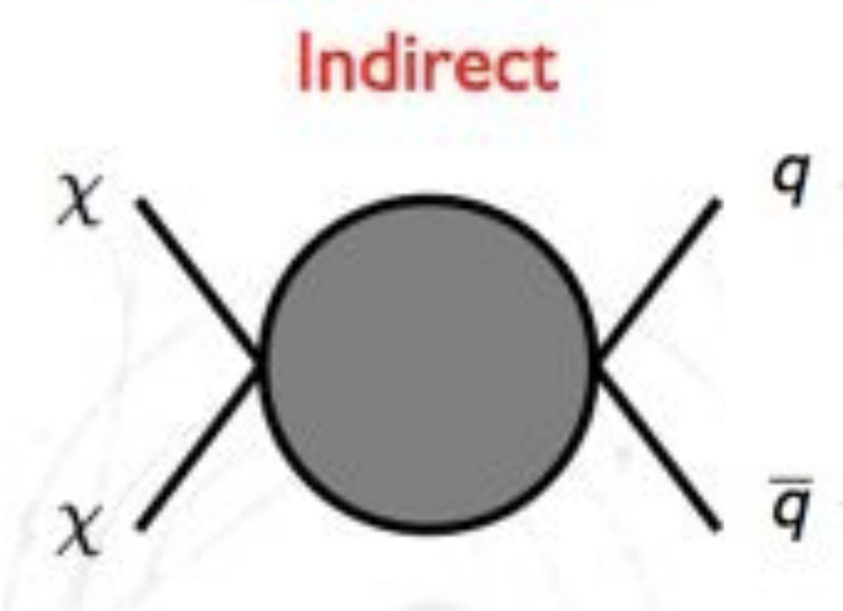

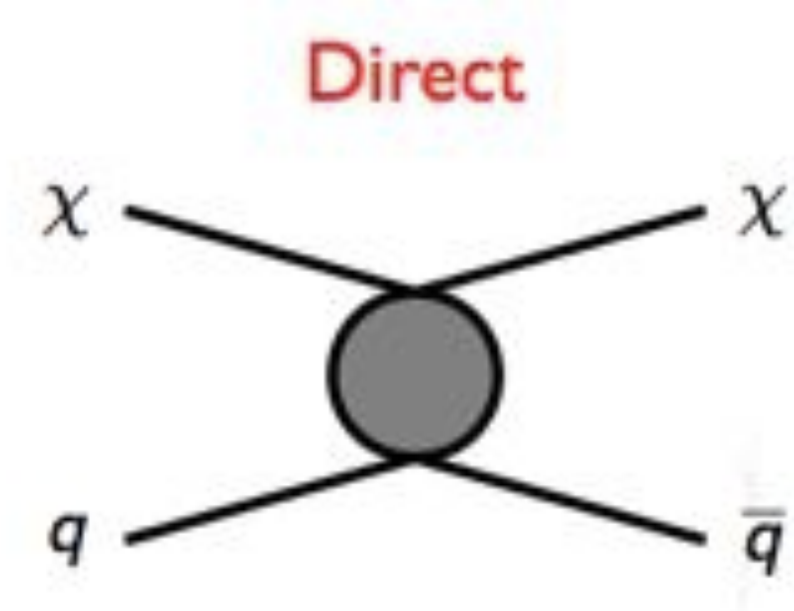

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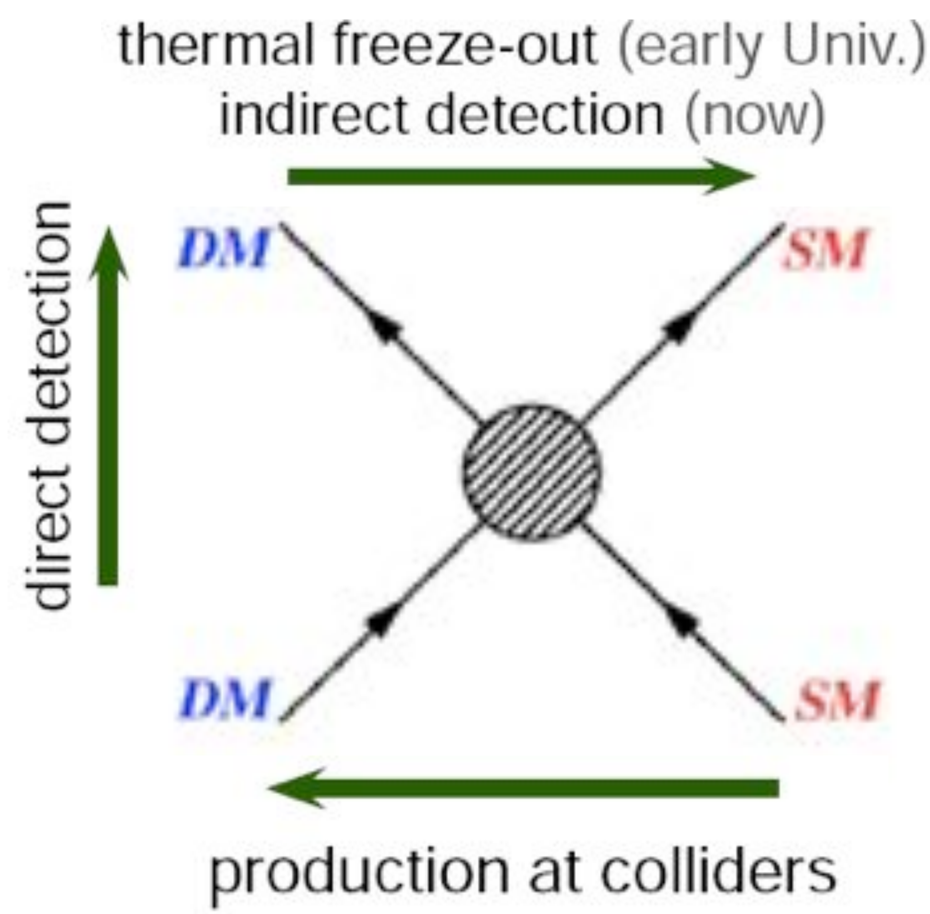

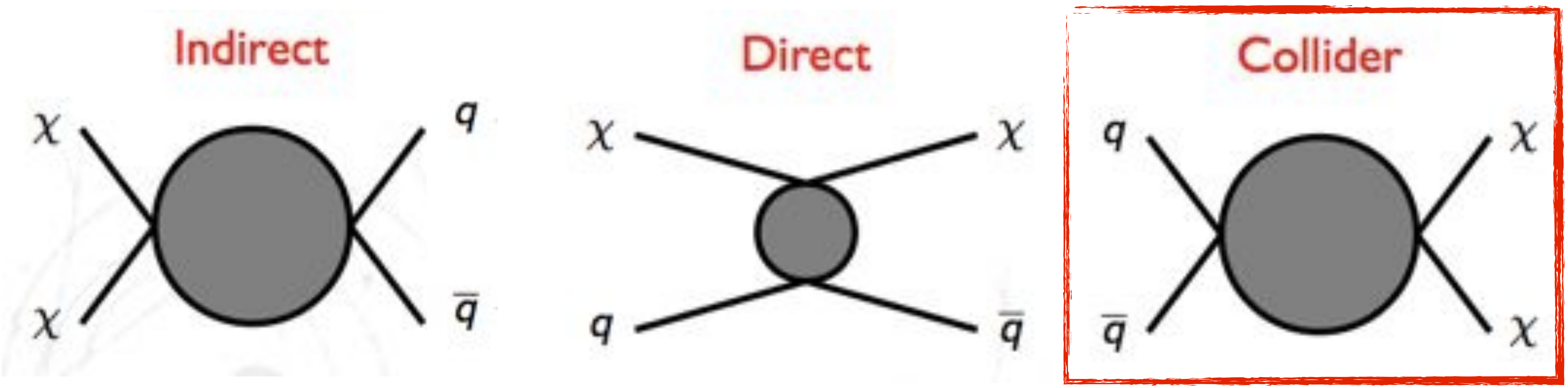

Searching for dark matter

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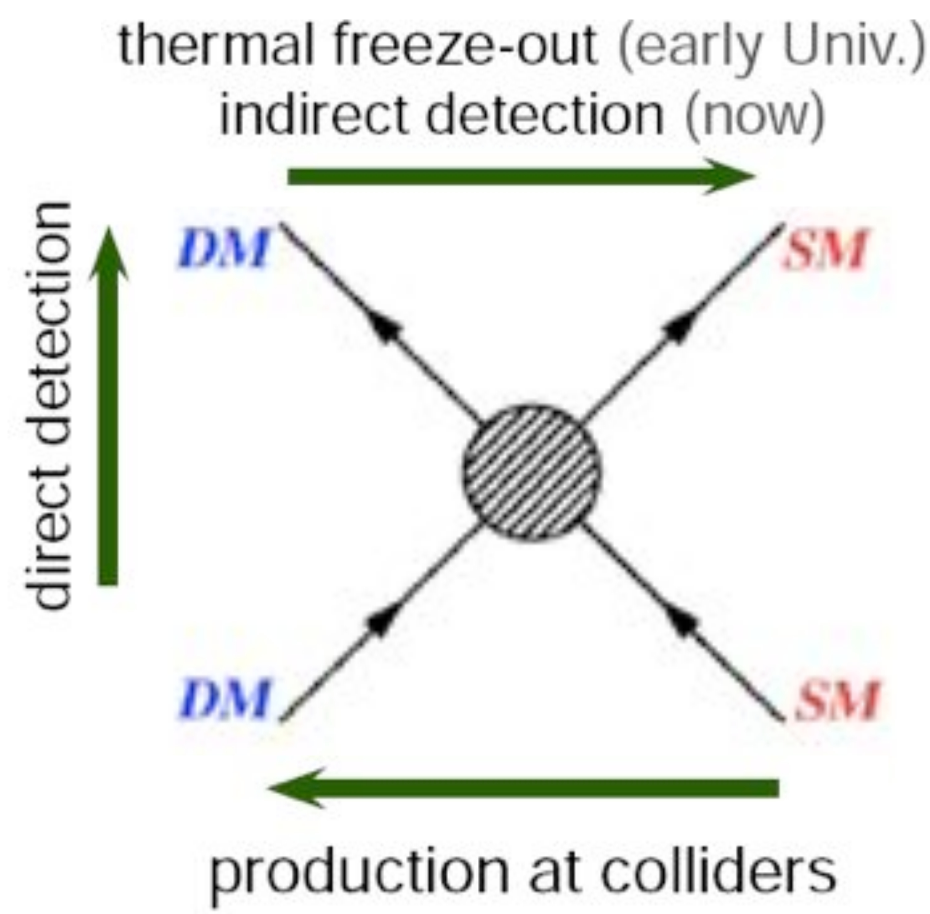
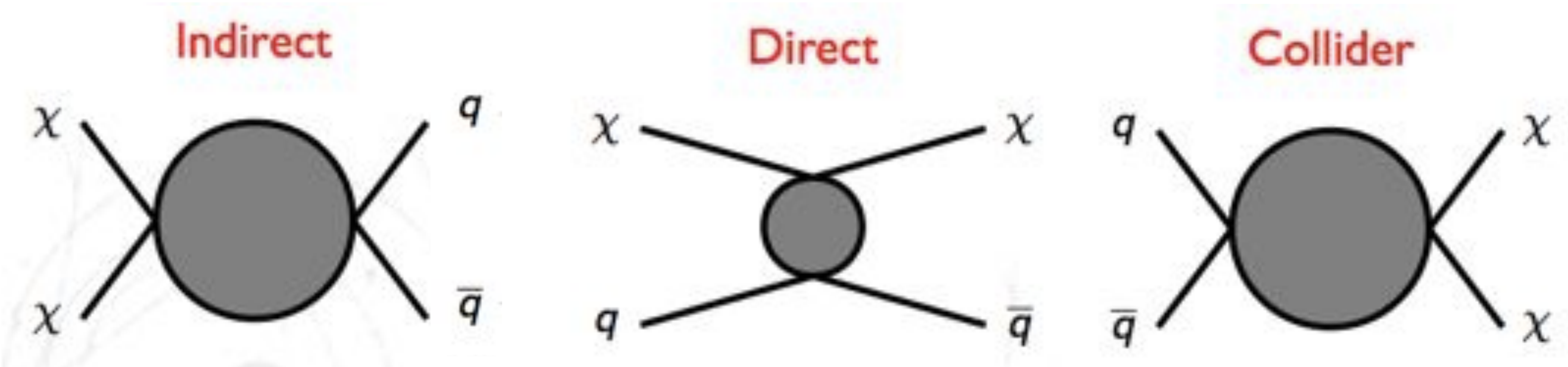
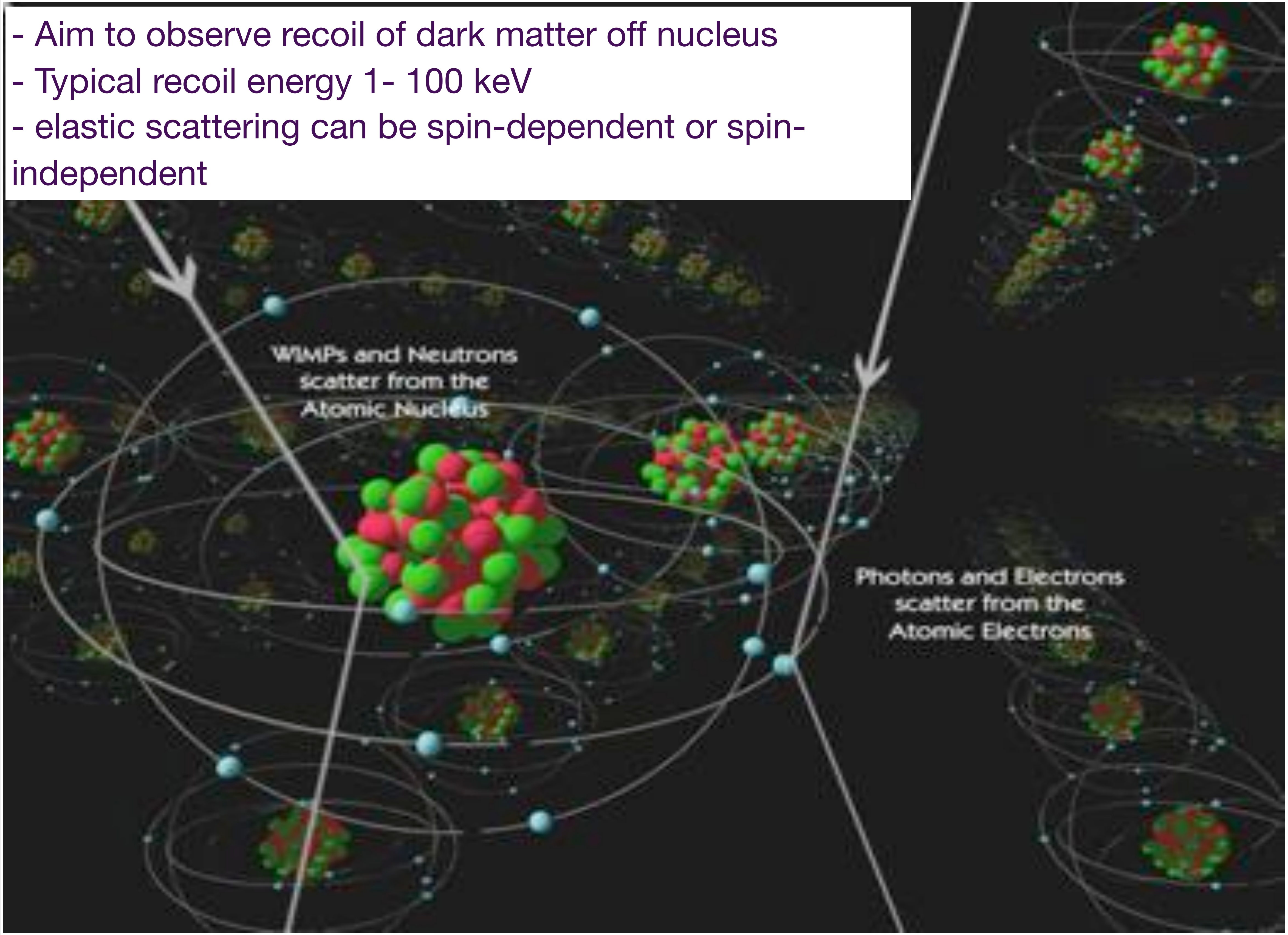




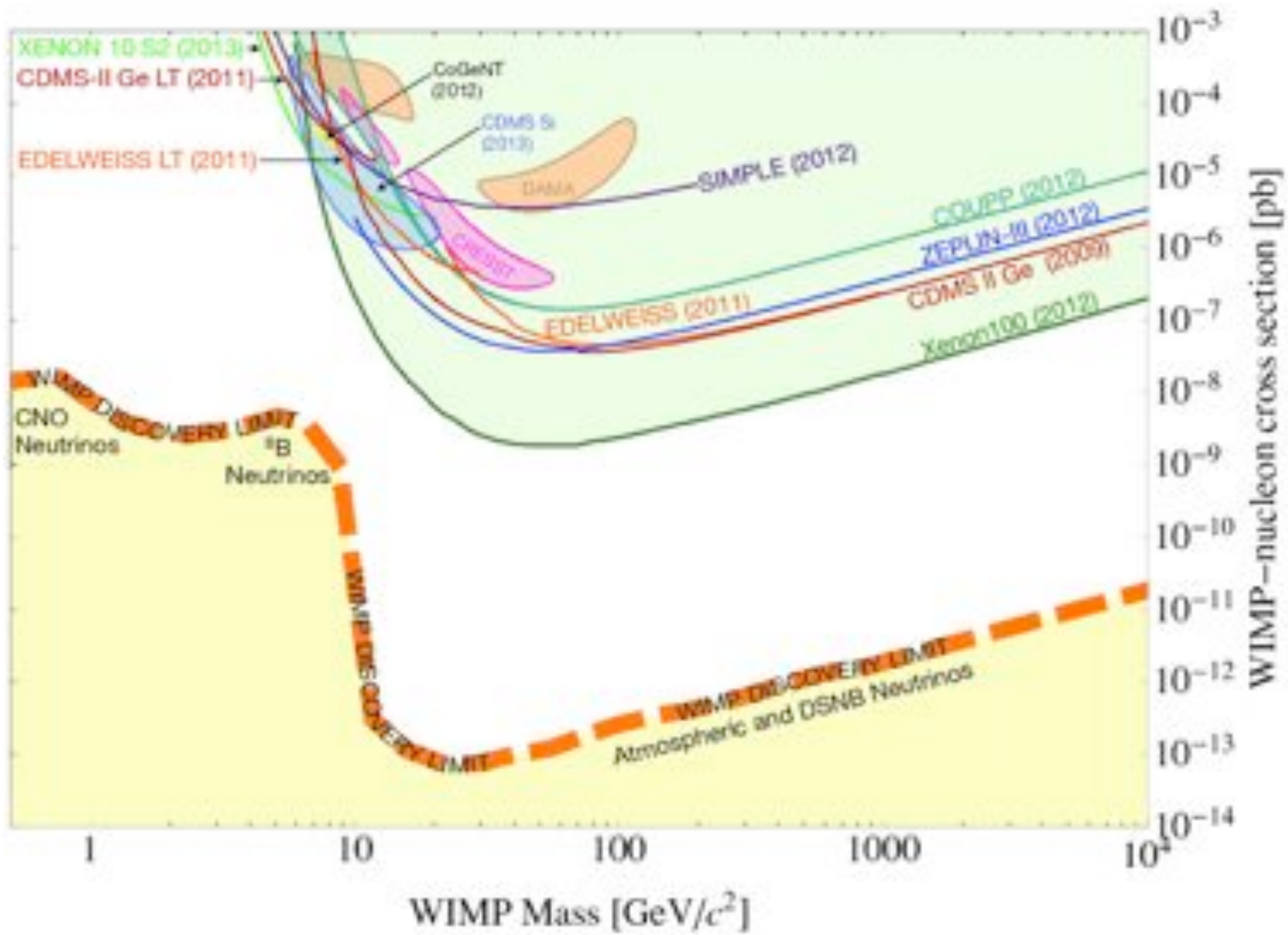
Direct detection experiments

- Aim to observe recoil of dark matter off nucleus
- Typical recoil energy 1- 100 keV
- elastic scattering can be spin-dependent or spin-independent



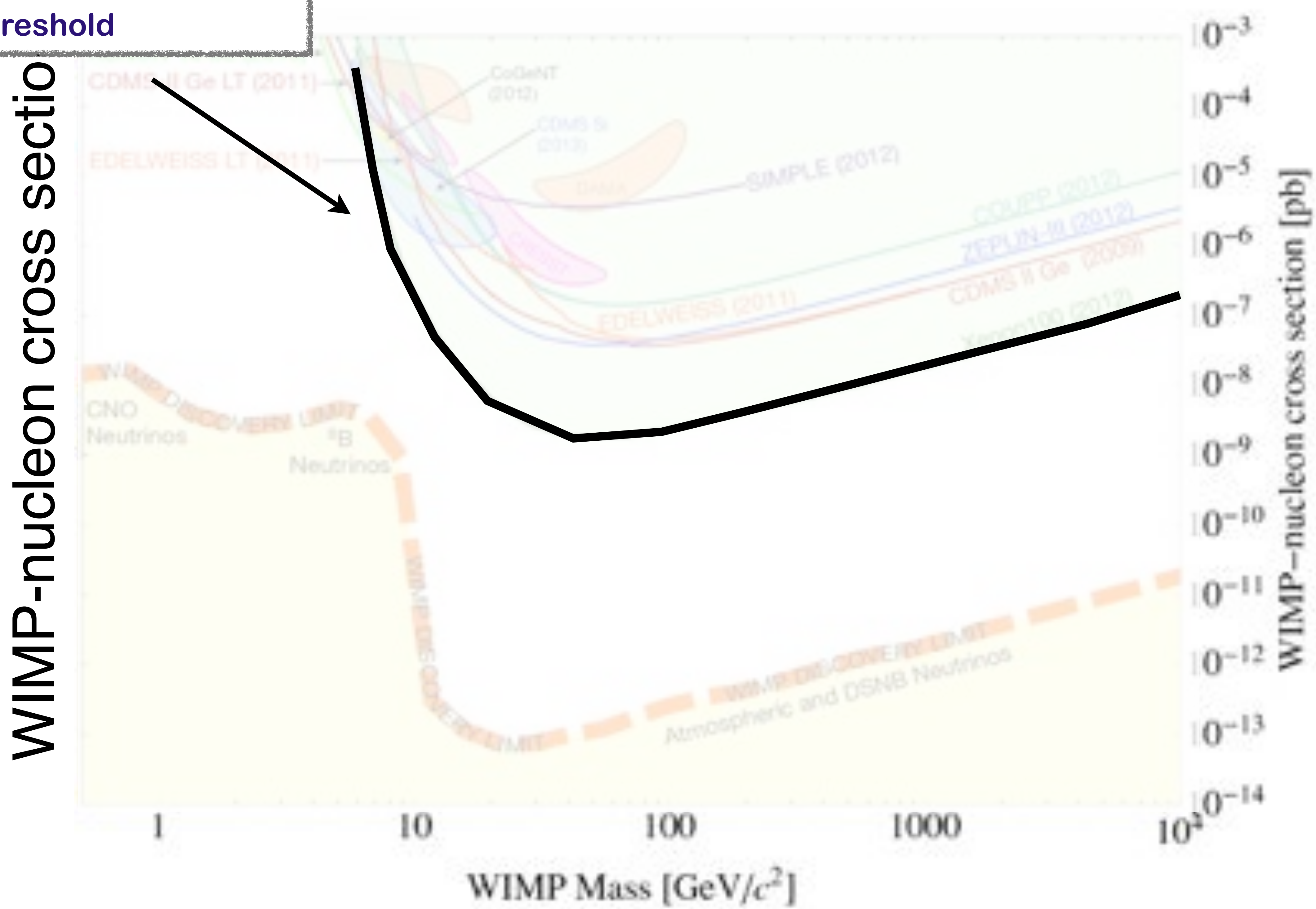
Direct detection experiments : Status and challenges

WIMP-nucleon cross section



Challenges for direct detection experiments

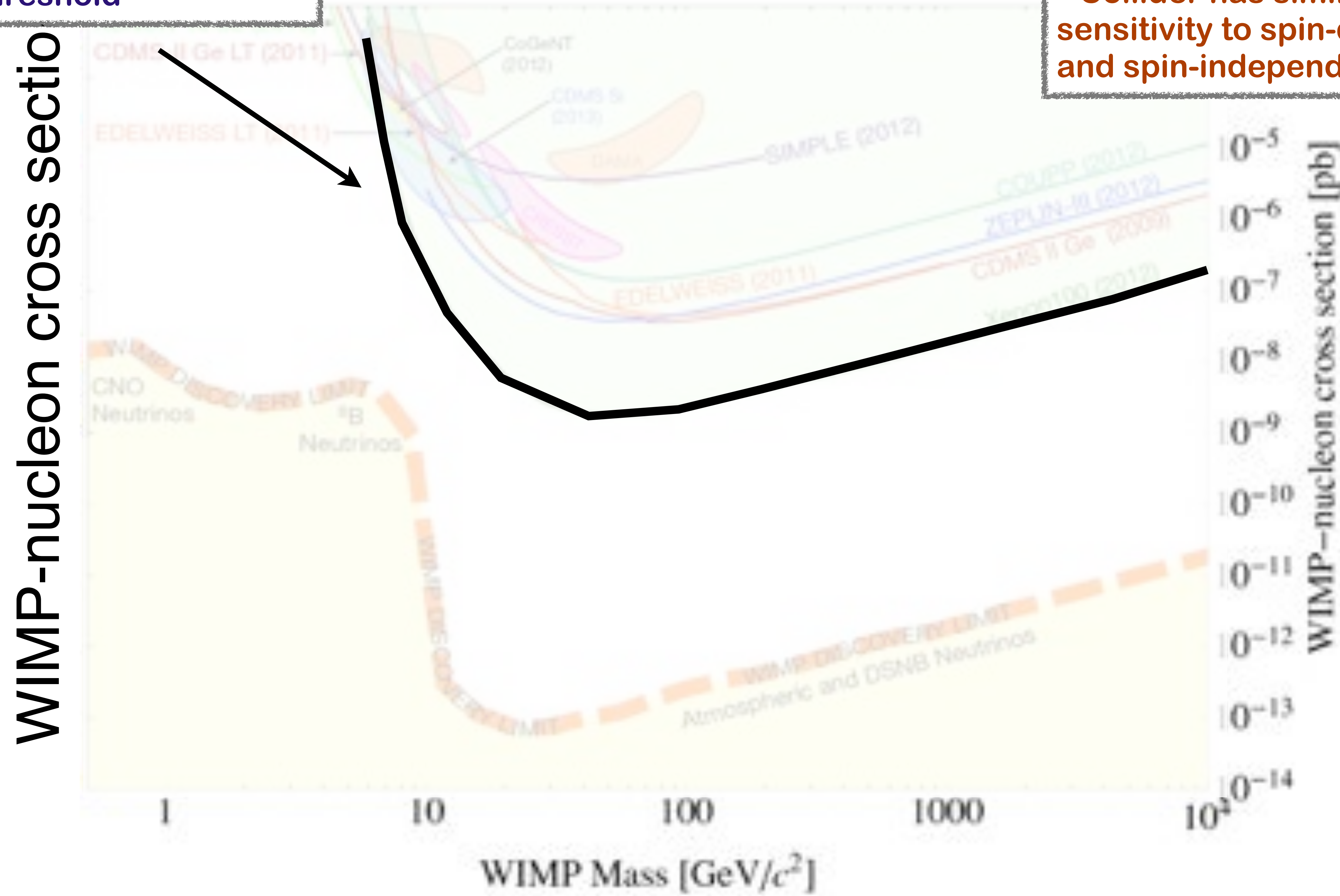
- **Low mass region difficult**
- **Collider does not have low energy threshold**



Challenges for direct detection experiments

- **Low mass region difficult**
- **Collider does not have low energy threshold**

- **Much weaker sensitivity to Spin-dependent interactions.**
- **Collider has similar sensitivity to spin-dependent and spin-independent**



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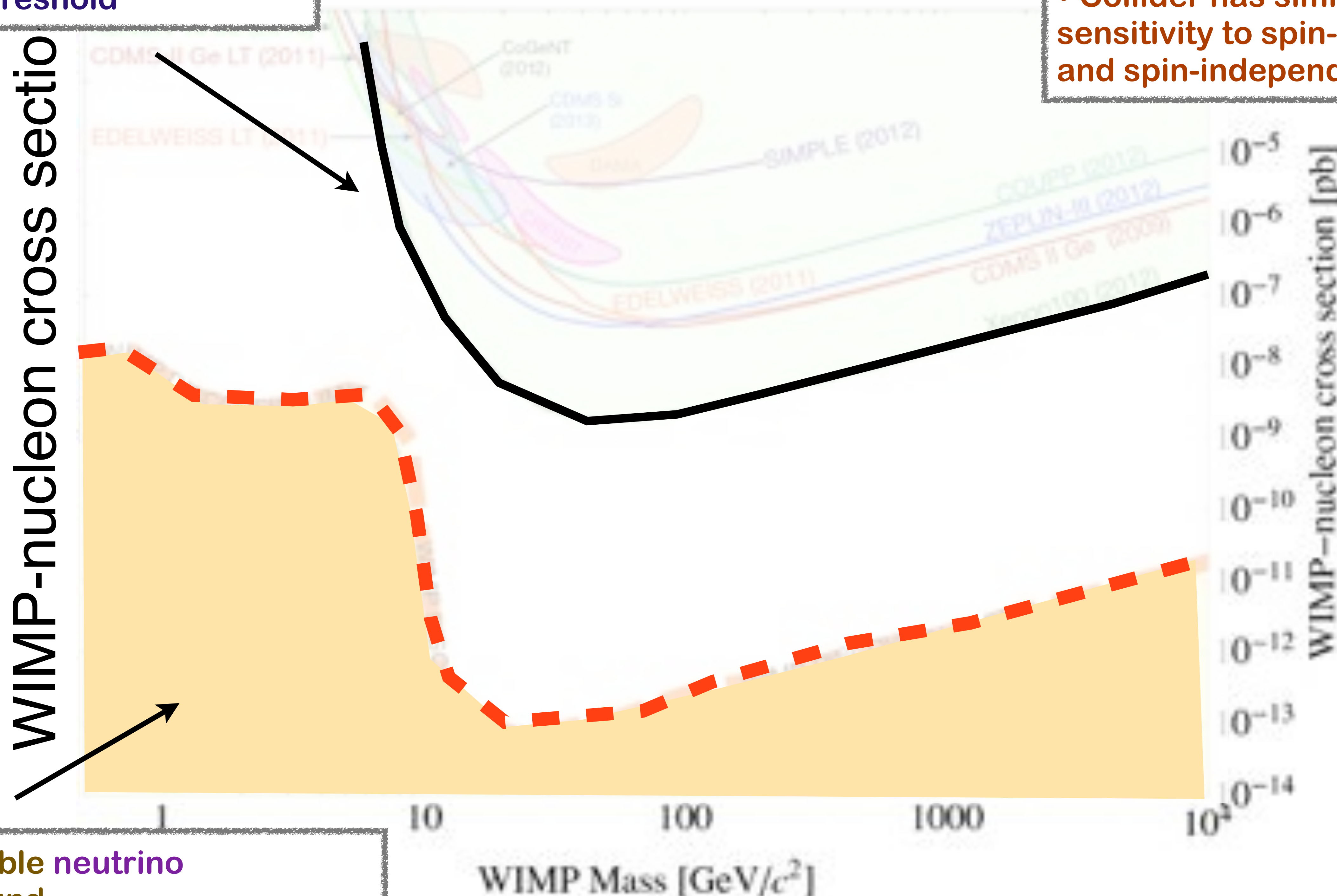

- Irreducible neutrino background
- WIMP discovery limit

Challenges for direct detection experiments

- Low mass region difficult
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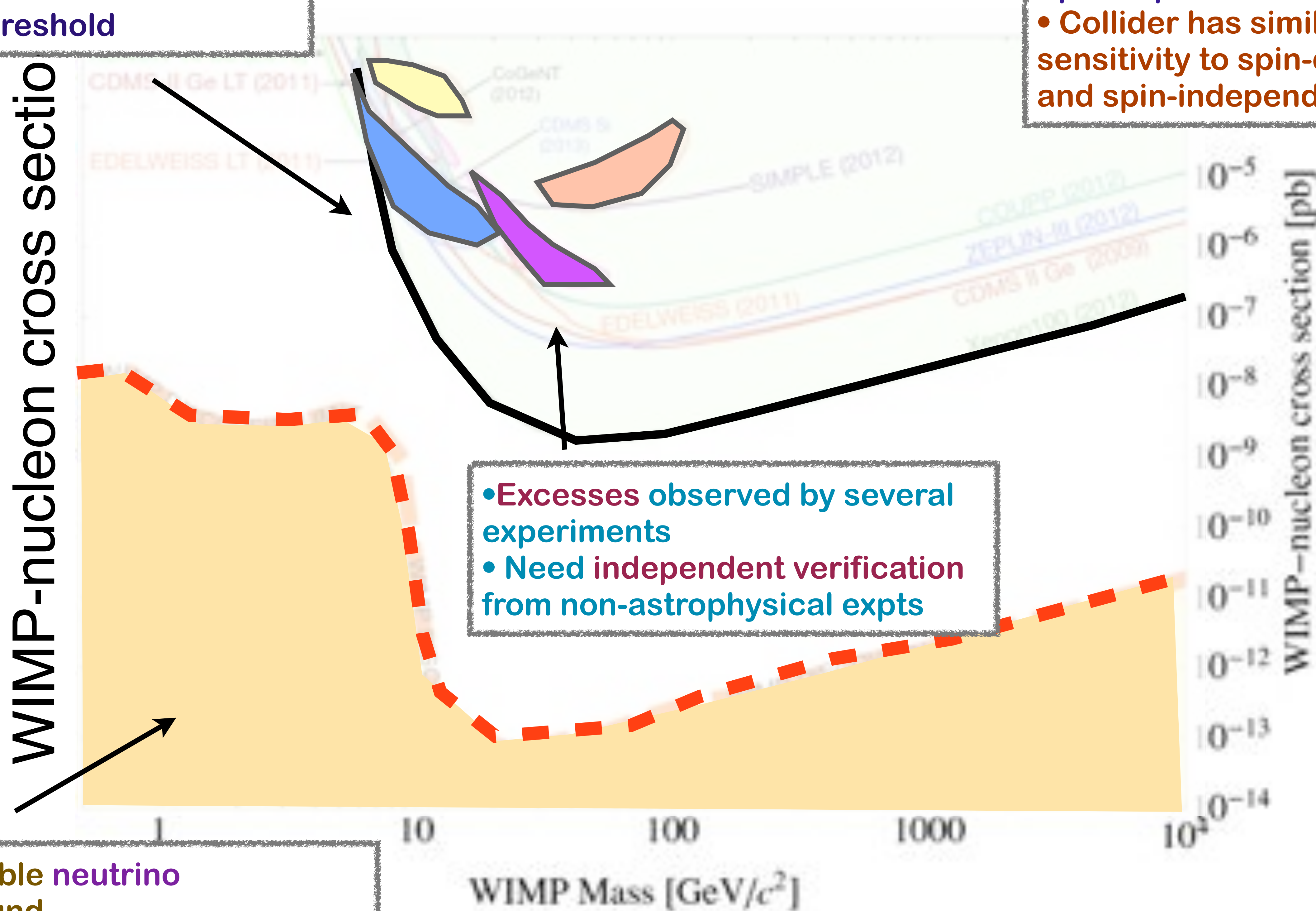
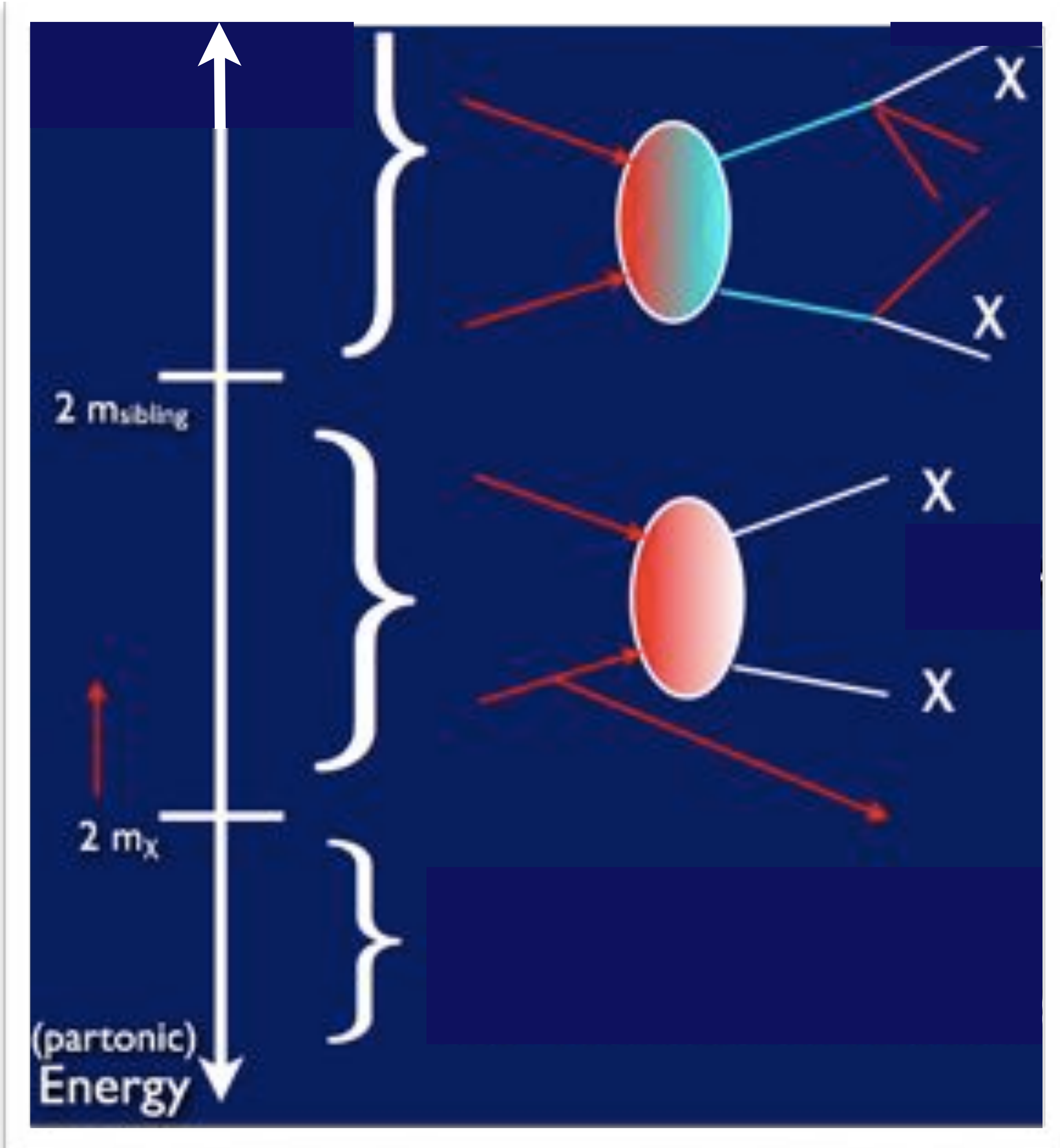


- Excesses observed by several experiments
- Need independent verification from non-astrophysical expts

- Irreducible neutrino background
- WIMP discovery limit

Searches at colliders

Searching for dark matter at colliders



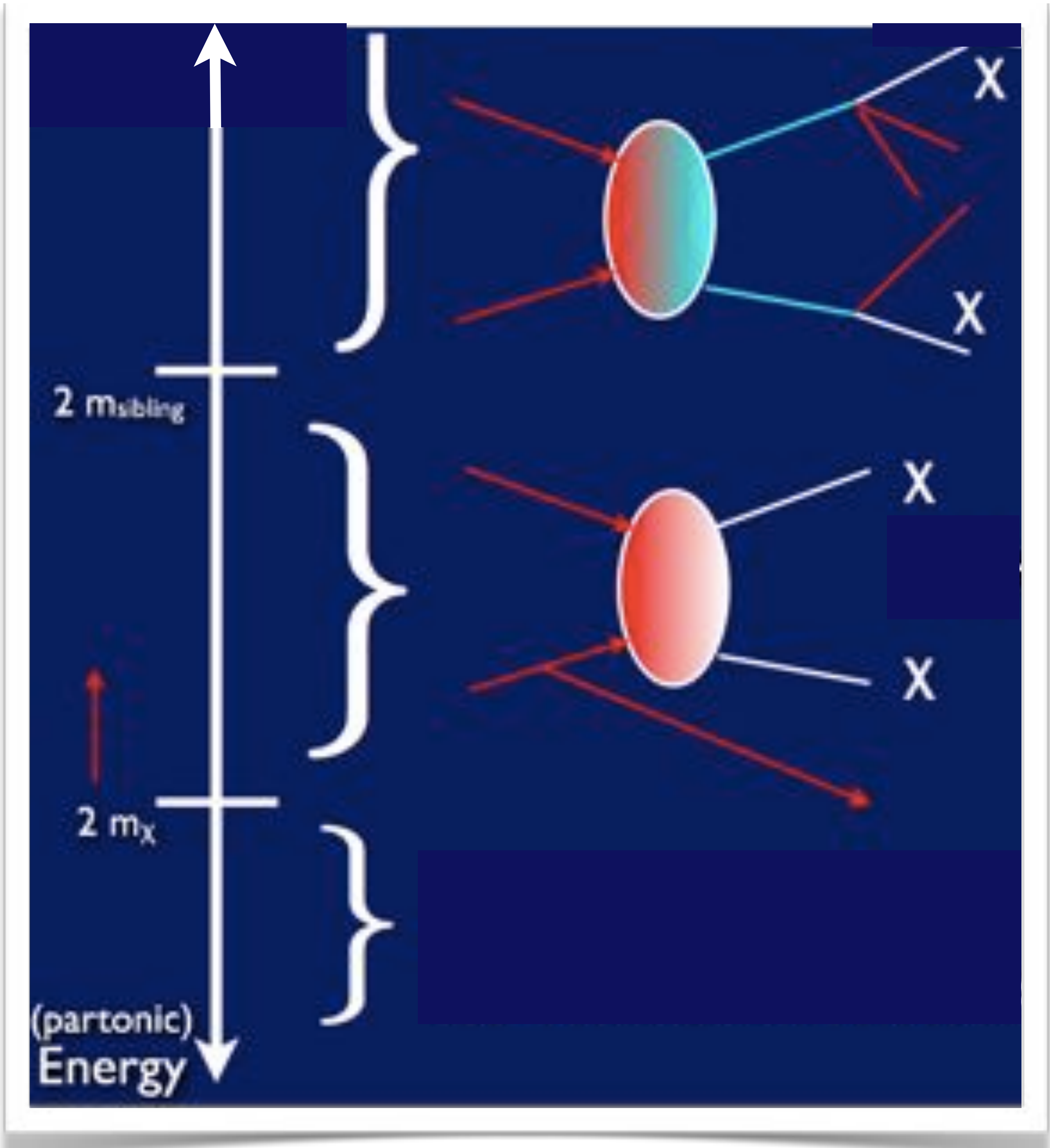
LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC can directly produce WIMP pairs

LHC cannot produce WIMPs

Slide adapted from Tim Tait talk at Moriond

Searching for dark matter at colliders



LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC can directly produce WIMP pairs

LHC cannot produce WIMPs

Searching for dark matter at colliders

Supersymmetry

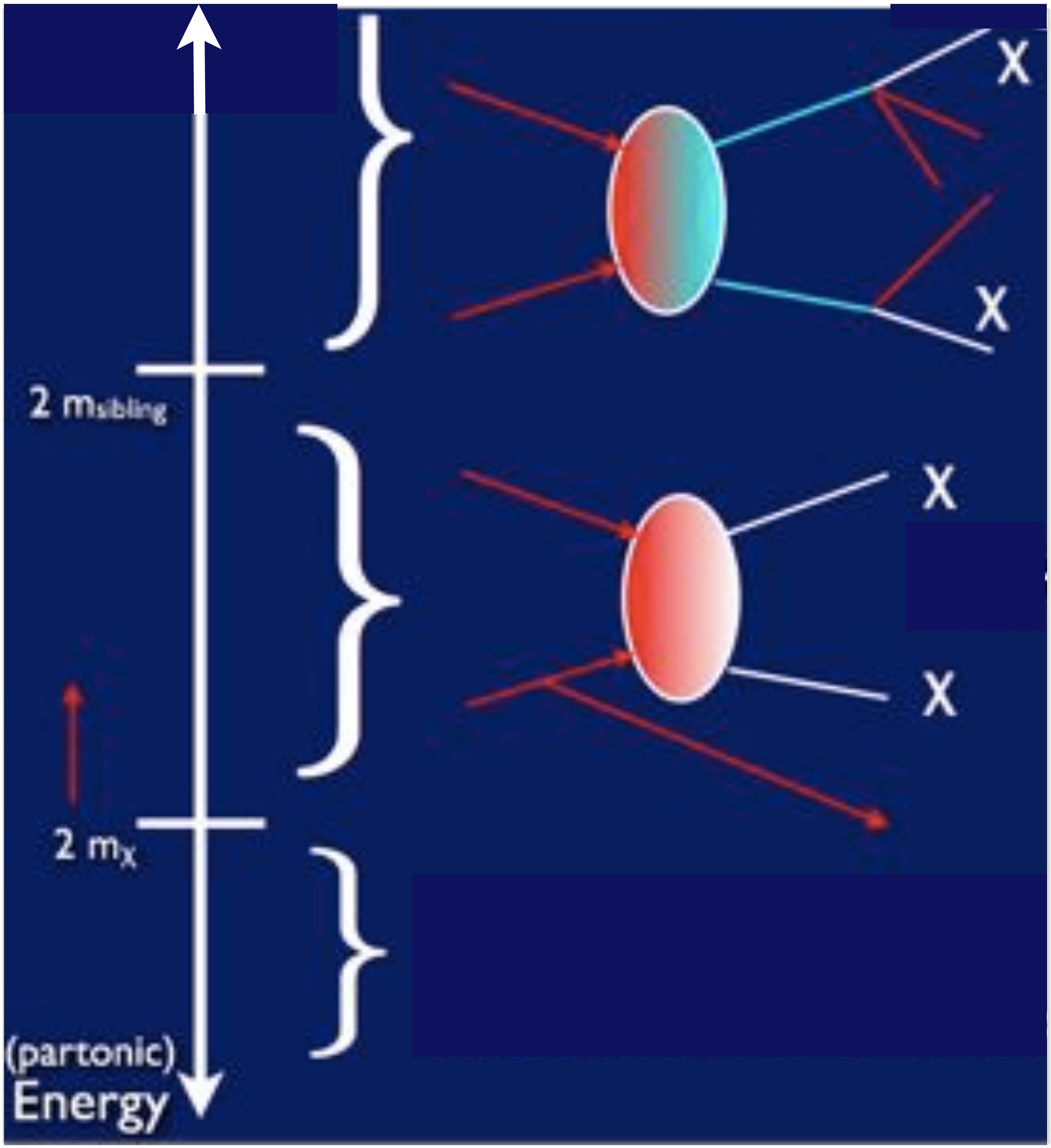
- symmetry between fermions and bosons
- heavy super-partners for each SM particle
- lightest SUSY particle (LSP) is neutral, stable. Good candidate for dark matter

Extra dimensions

-In UED, the dark matter candidate is a massive vector particle which is stable
- In Randall-Sundrum, the right-handed neutrino is stable

Theories designed to address the gauge hierarchy problem naturally
- predict stable, weakly interacting particles with mass ~ weak scale
- the correct relic abundance required to be dark matter.

Searching for dark matter at colliders



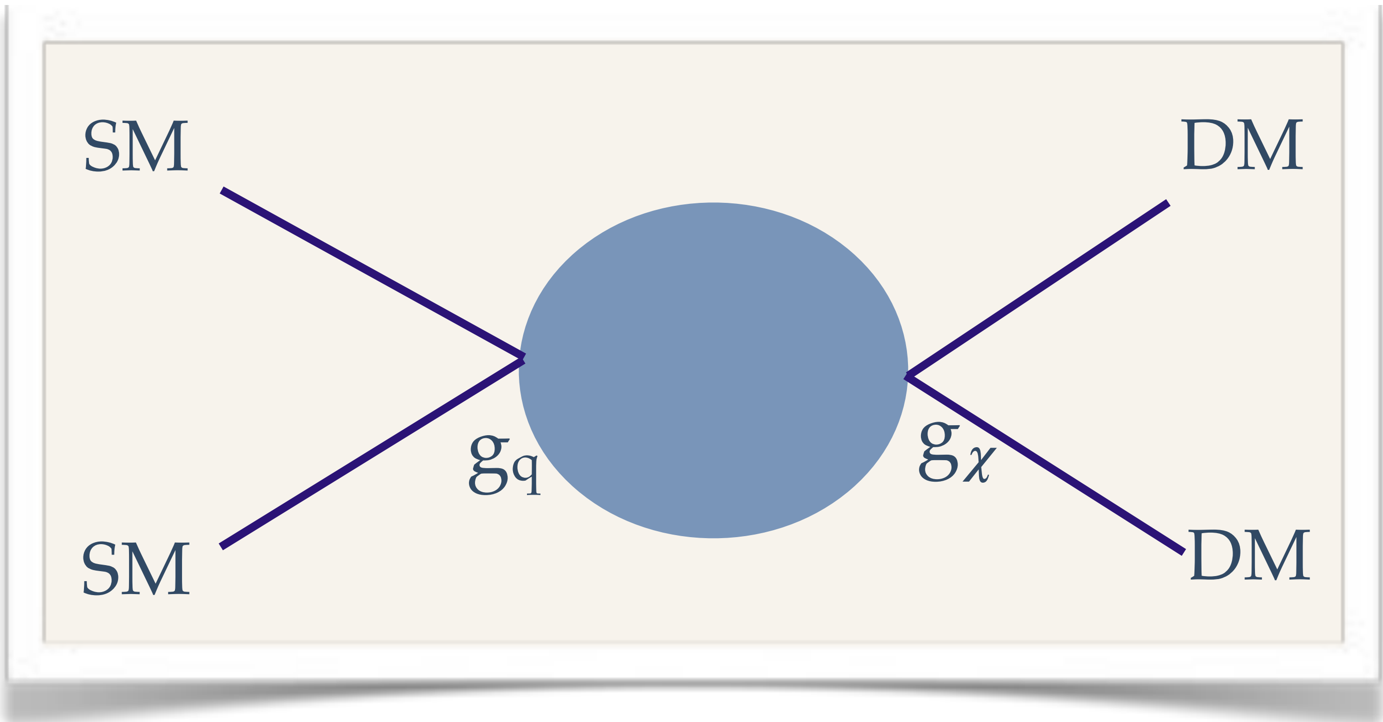
LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC can directly produce WIMP pairs

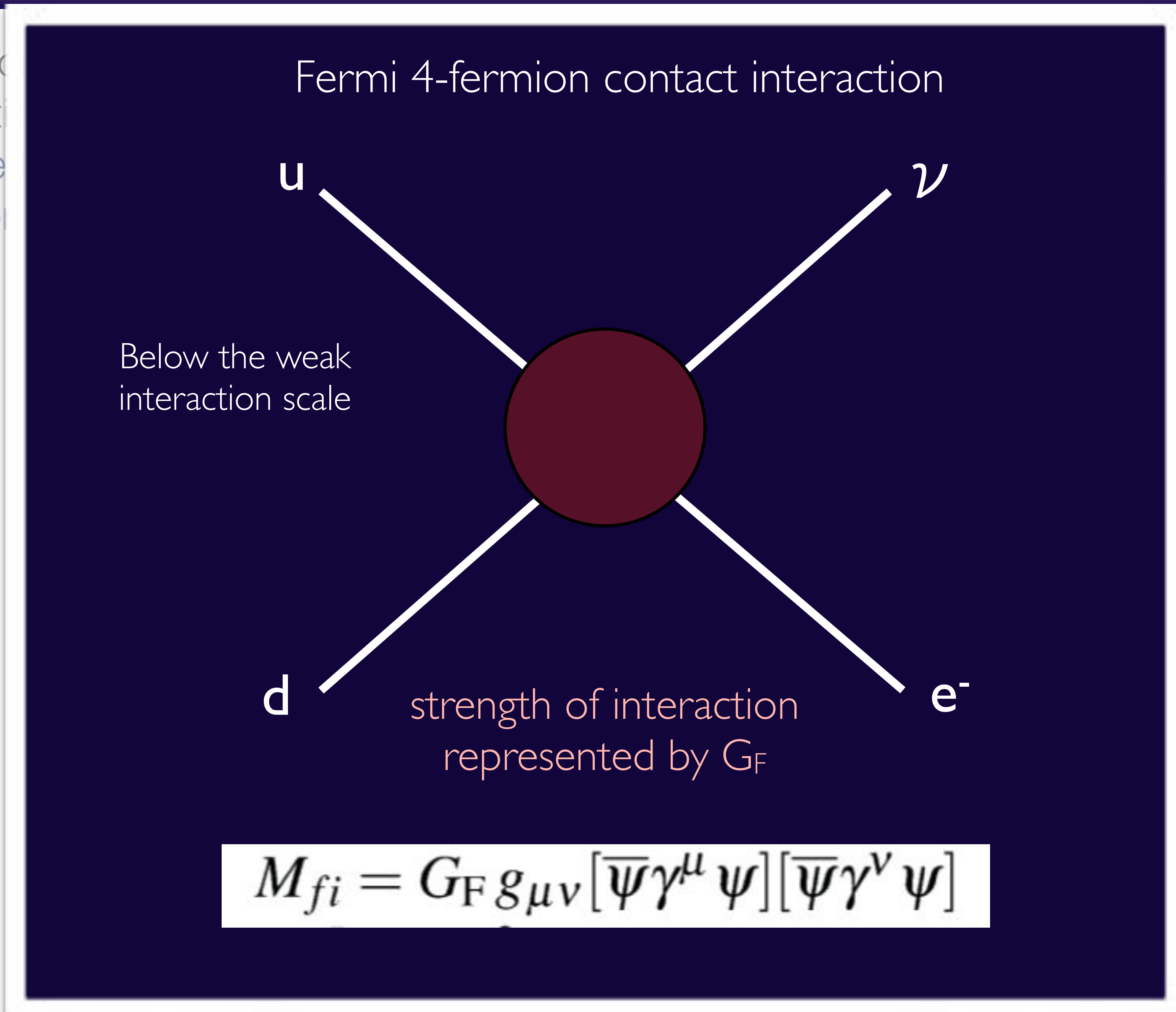
LHC cannot produce WIMPs

Phenomenology

Assumptions:
- DM particle is only new state accessible to the collider
- Effective field theory so interaction between DM and SM particles is contact interaction



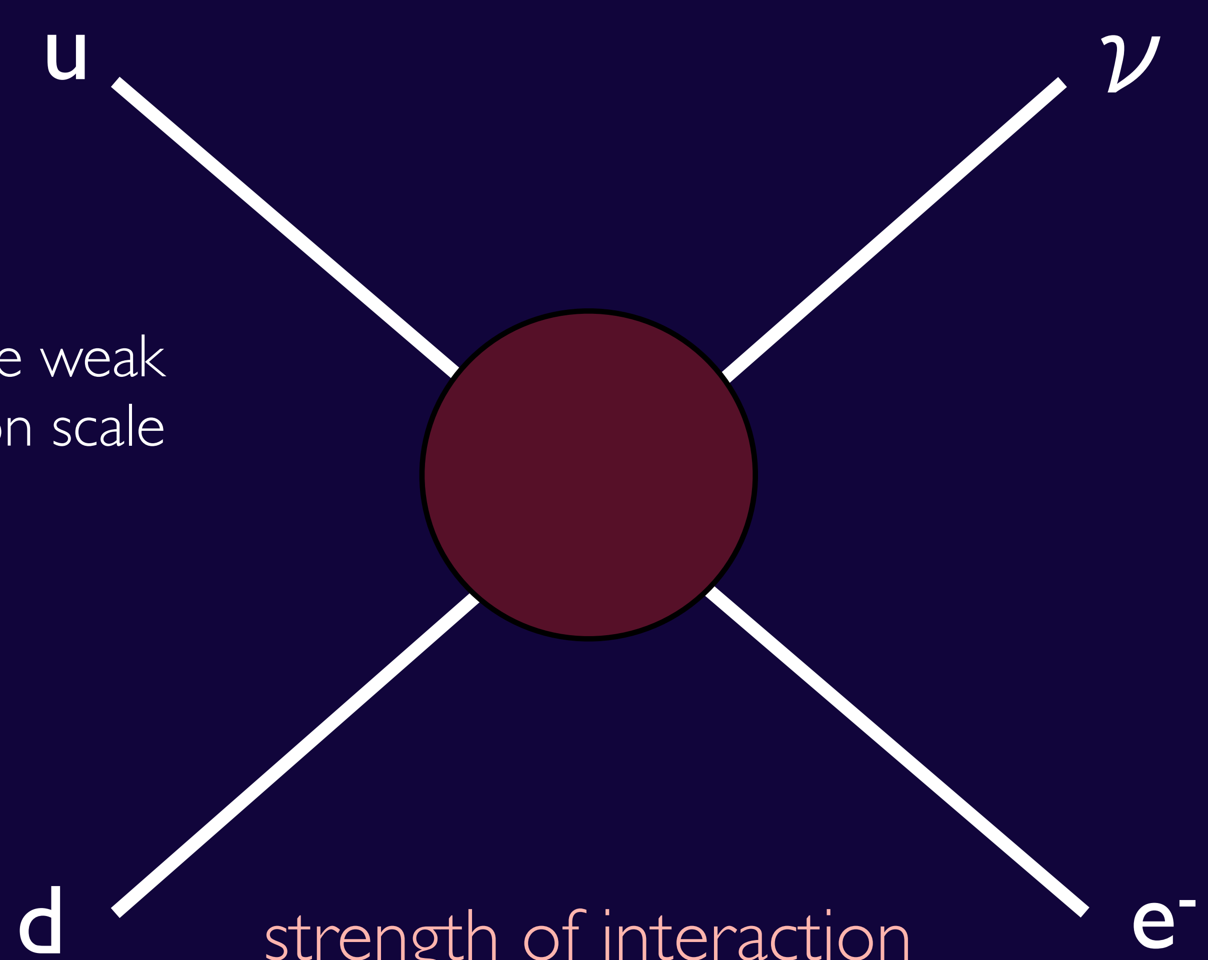
Assumptic
- DM part
- Effective ... t interaction
- Mediato



Phenomenology

Assumptic
- DM part
- Effective ... t interaction
- Mediato

Fermi 4-fermion contact interaction



Below the weak interaction scale

strength of interaction represented by G_F

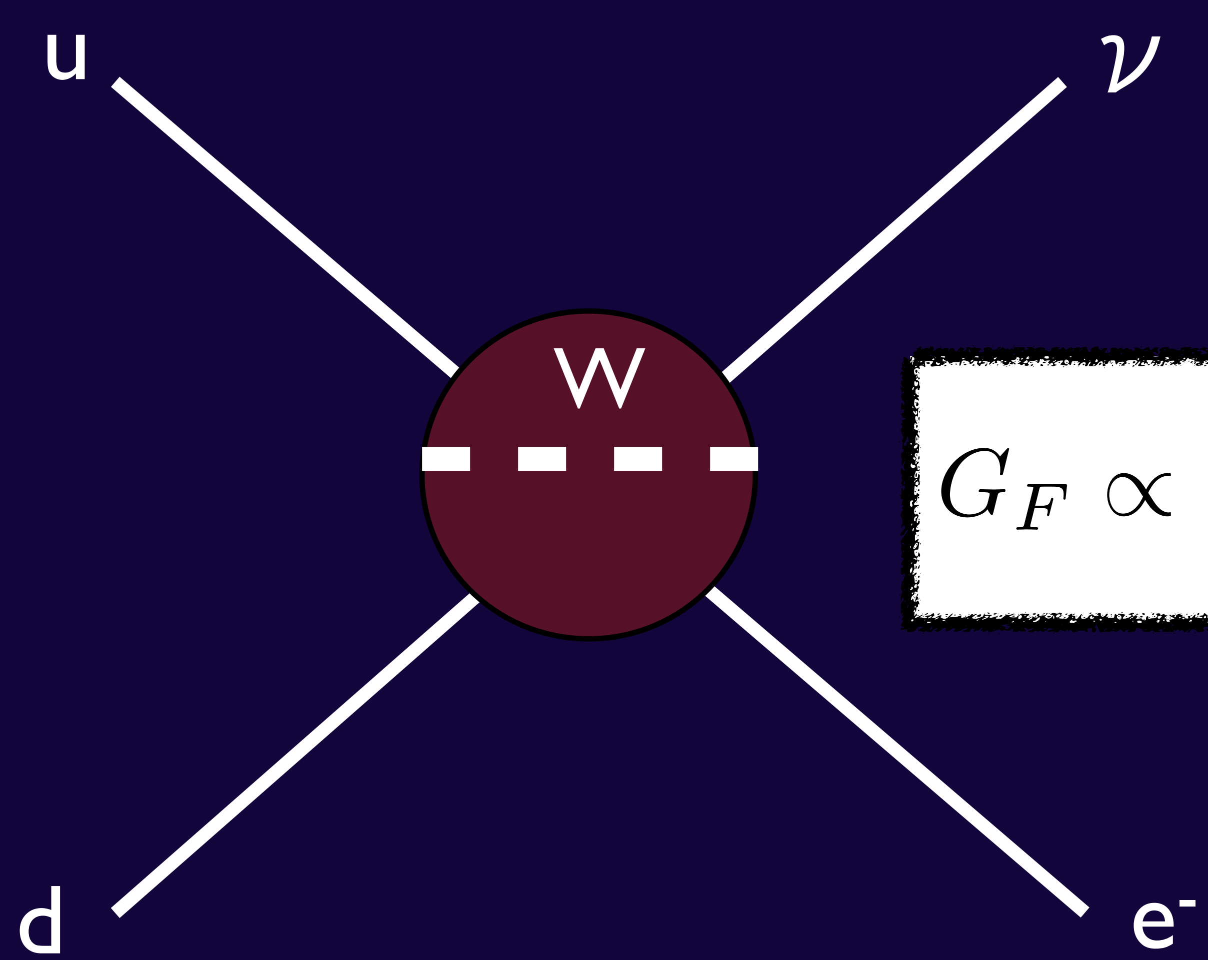
After discovery of parity violation n 1957........

$$M_{fi} = \frac{G_F}{\sqrt{2}} g_{\mu\nu} [\overline{\psi}\gamma^\mu(1-\gamma^5)\psi][\overline{\psi}\gamma^\nu(1-\gamma^5)\psi]$$

Phenomenology

Assumptio
- DM part
- Effective … t interaction
- Mediato

After discovery of W boson.........



$$G_F \propto \frac{{g_w}^2}{{M_w}^2}$$

$$M_{fi} = \left[\frac{g_W}{\sqrt{2}}\overline{\psi}\frac{1}{2}\gamma^\mu(1-\gamma^5)\psi\right]\frac{g_{\mu\nu}-q_\mu q_\nu/m_W^2}{q^2-m_W^2}\left[\frac{g_W}{\sqrt{2}}\overline{\psi}\frac{1}{2}\gamma^\nu(1-\gamma^5)\psi\right]$$

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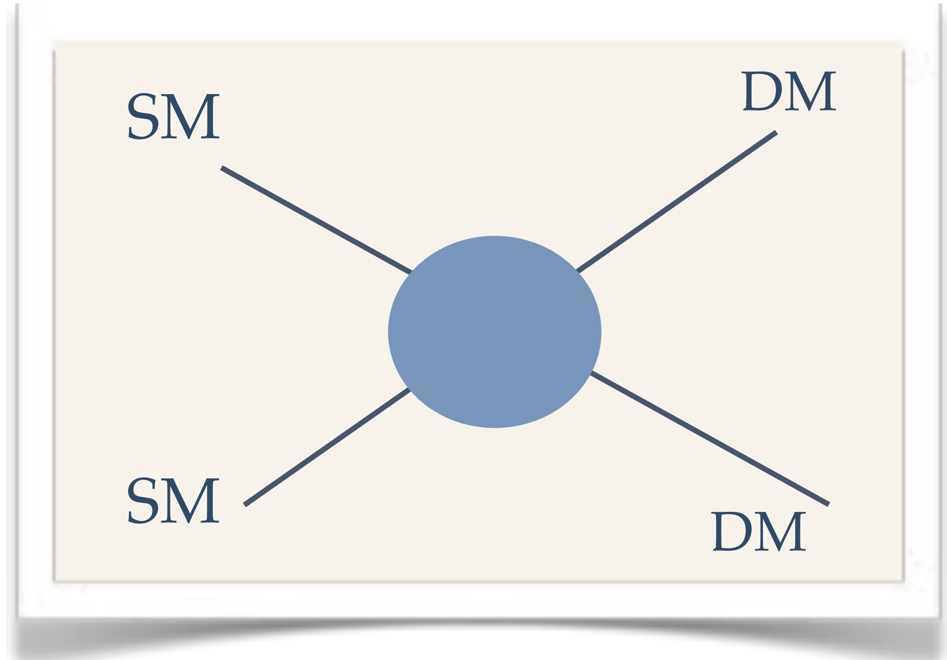


$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{X}\gamma^{\mu}\partial_{\mu}X - M_X\bar{X}X + \sum_q \sum_{i,j} \frac{G_{qij}}{\sqrt{2}} \left[\bar{X}\Gamma_i^X X\right]\left[\bar{q}\Gamma_q^j q\right],$$

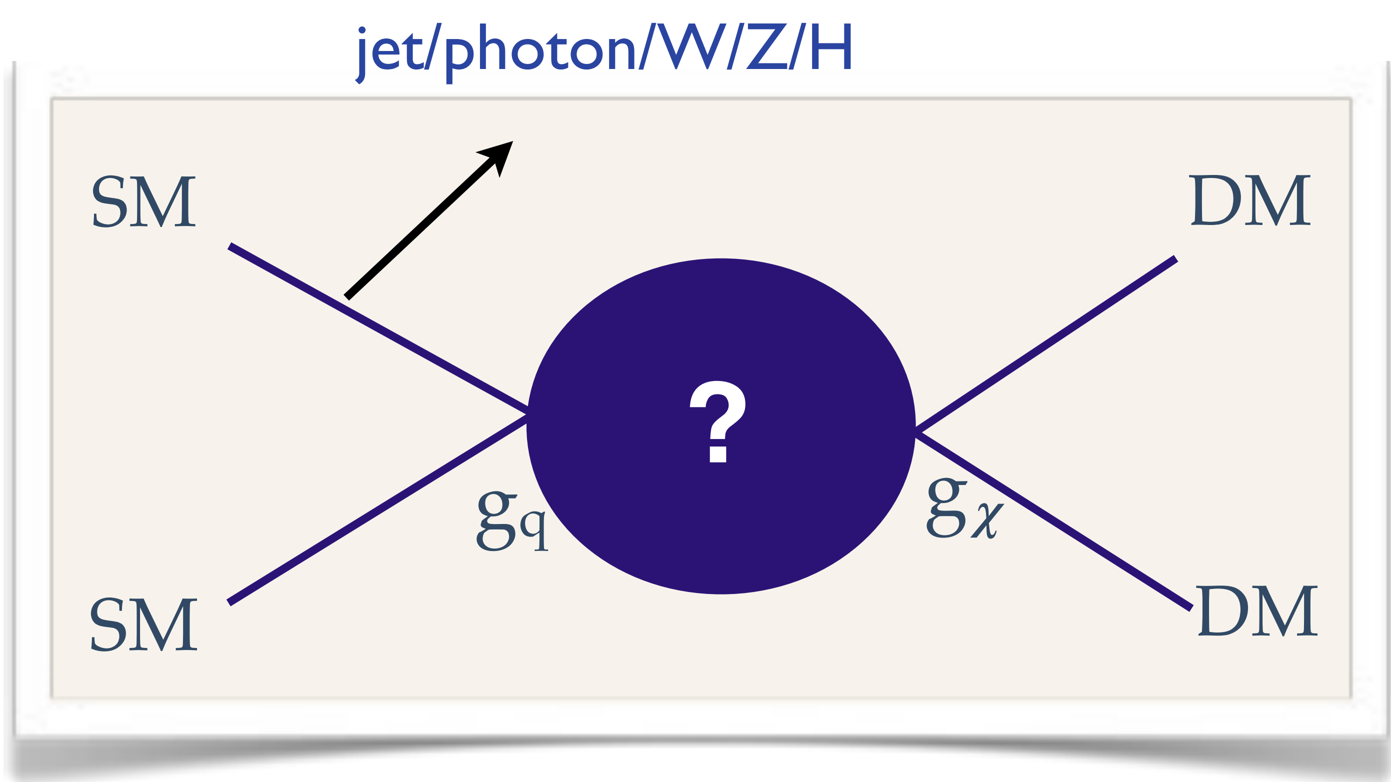
SM Lagrangian

kinetic terms for DM

set of 4-Fermion interactions between DM and SM quarks

Operators **Γ** describe scalar, pseudoscalar, vector, axial vector, tensor interactions

Phenomenology

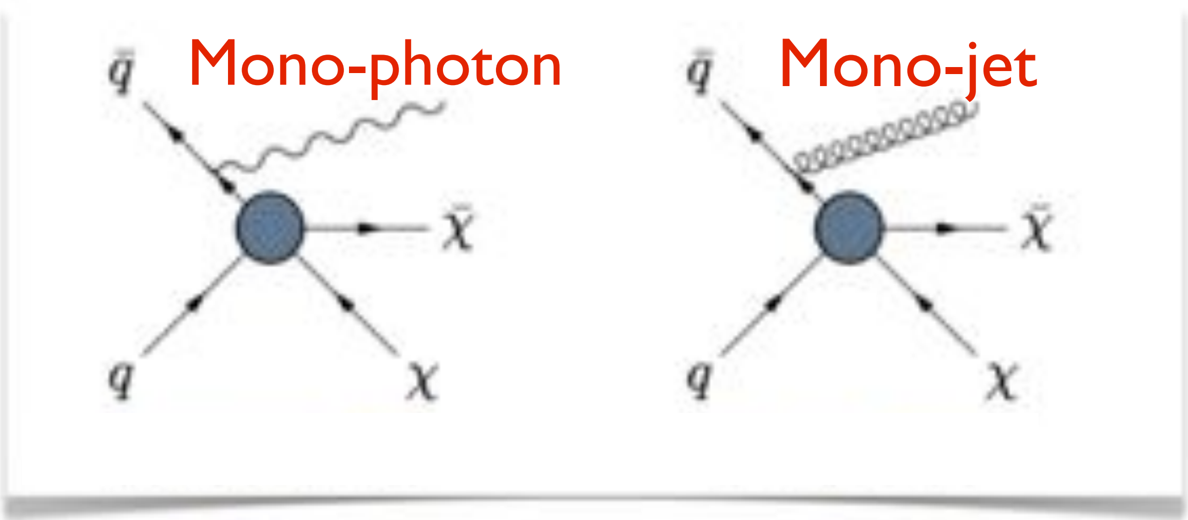


➡ DM neutral and weakly interacting, escape detection.

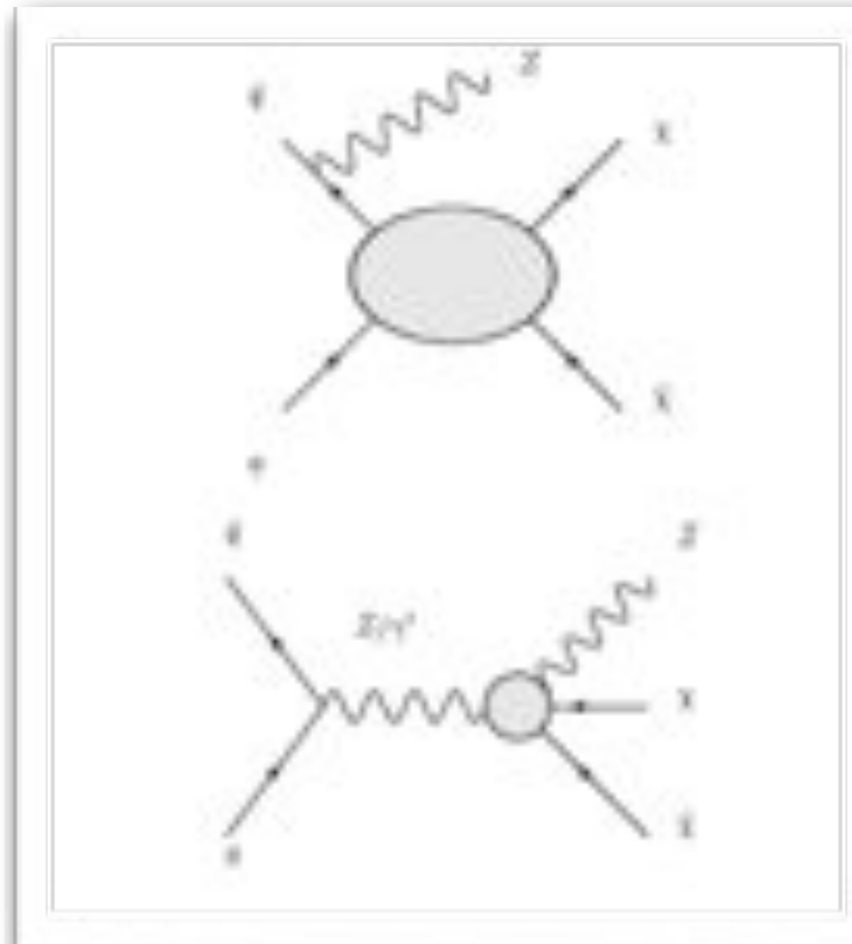
➡ only infer presence from imbalance in transverse momentum of all visible particles

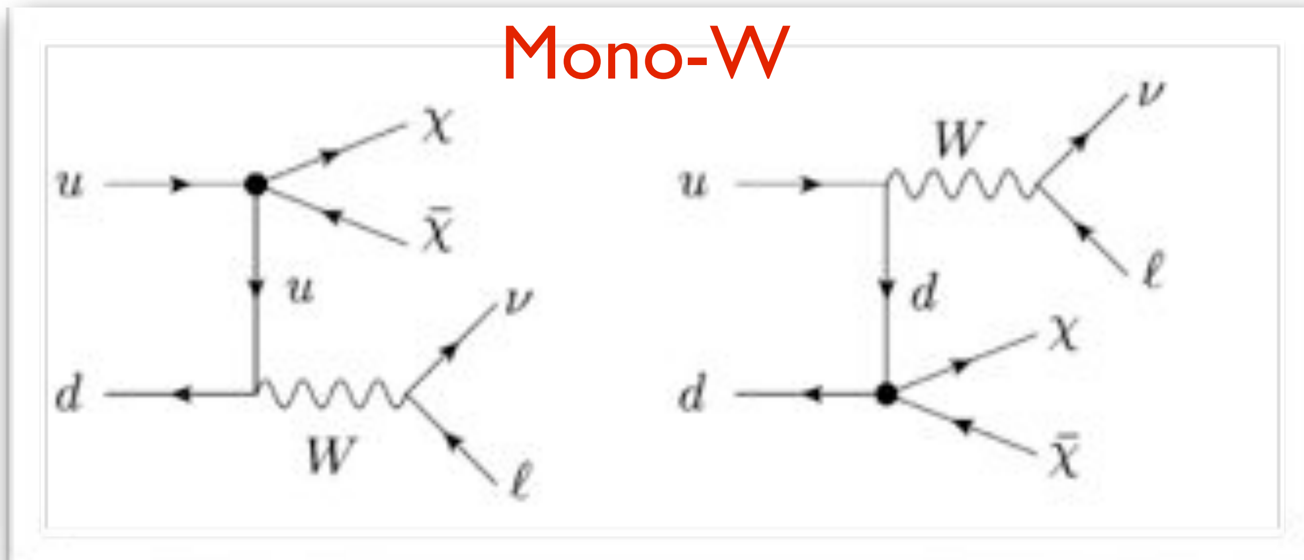
➡ Search for DM particles recoiling off a jet/photon/X from the initial state

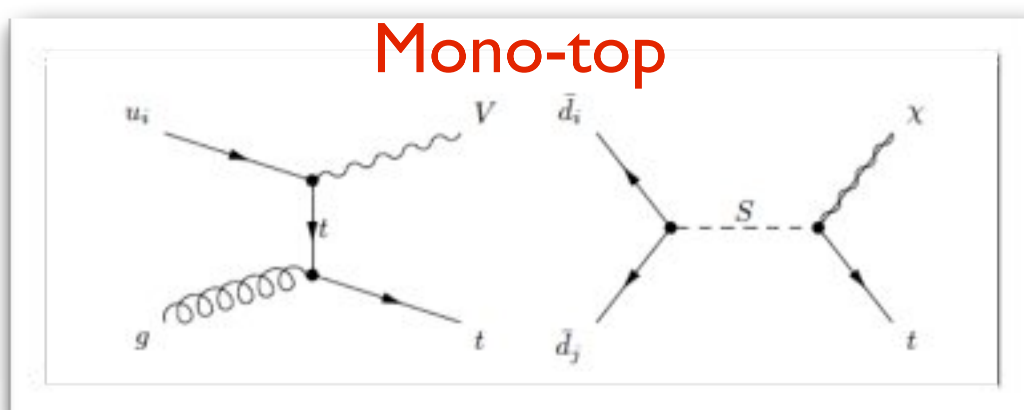
Signatures for dark matter searches: Mono-X

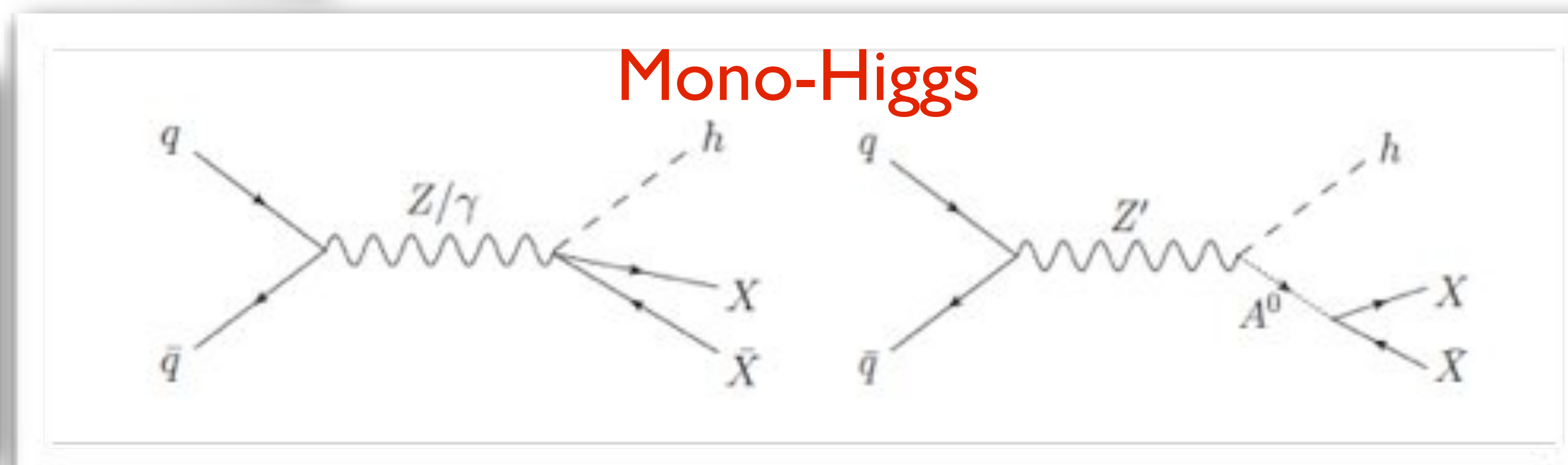


Mono-Z

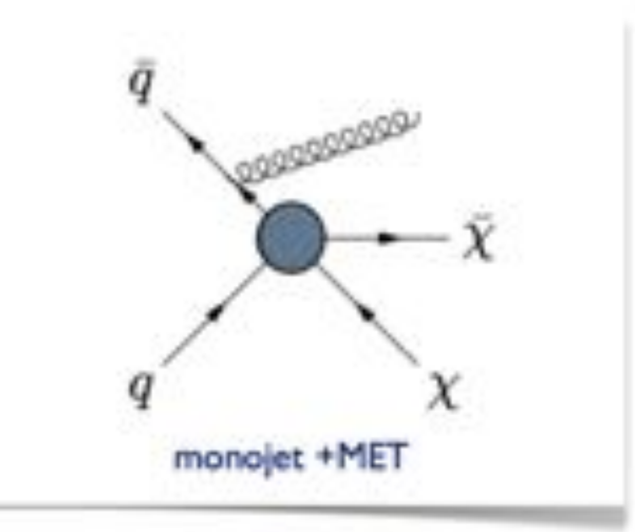


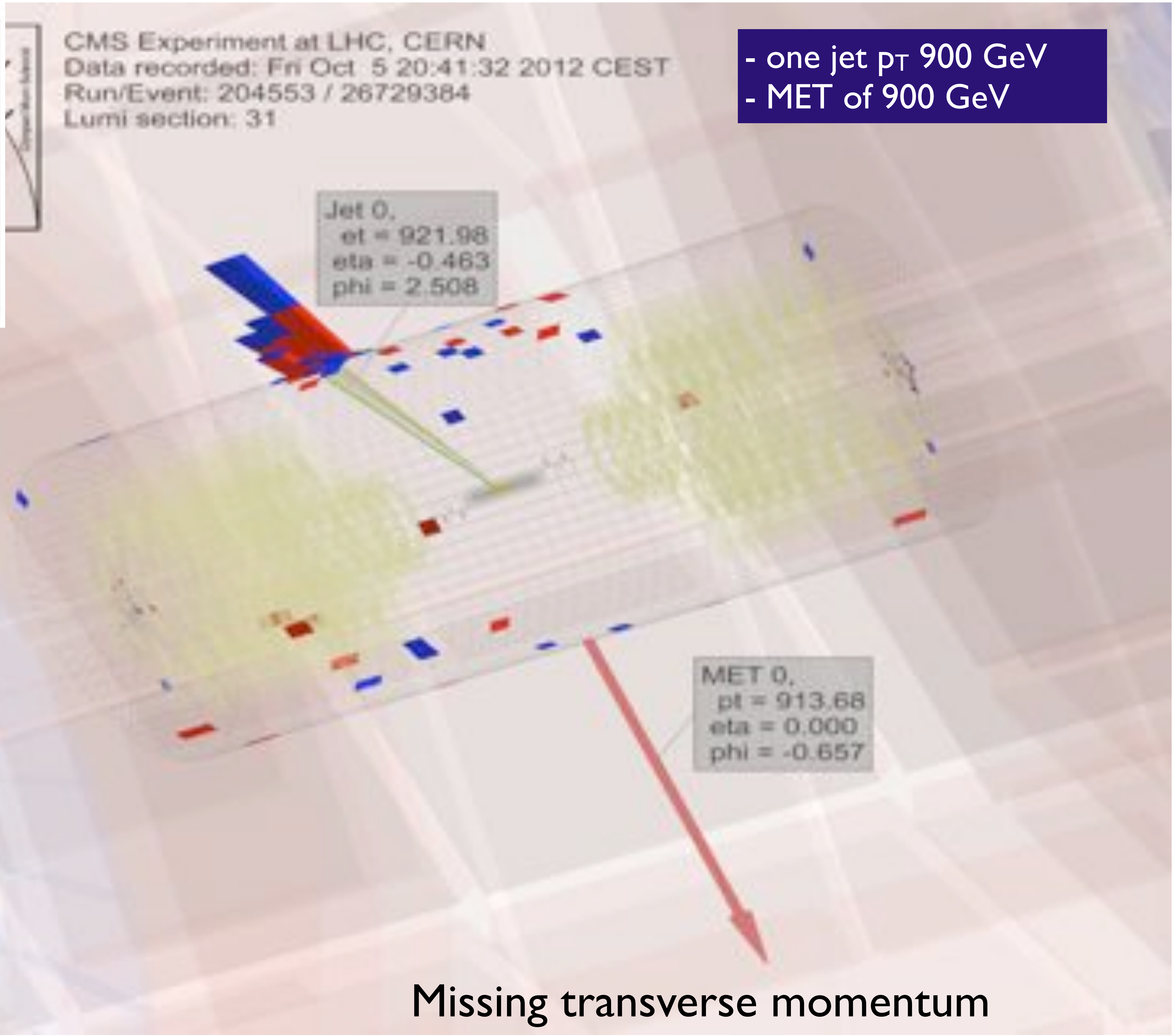






A monojet event



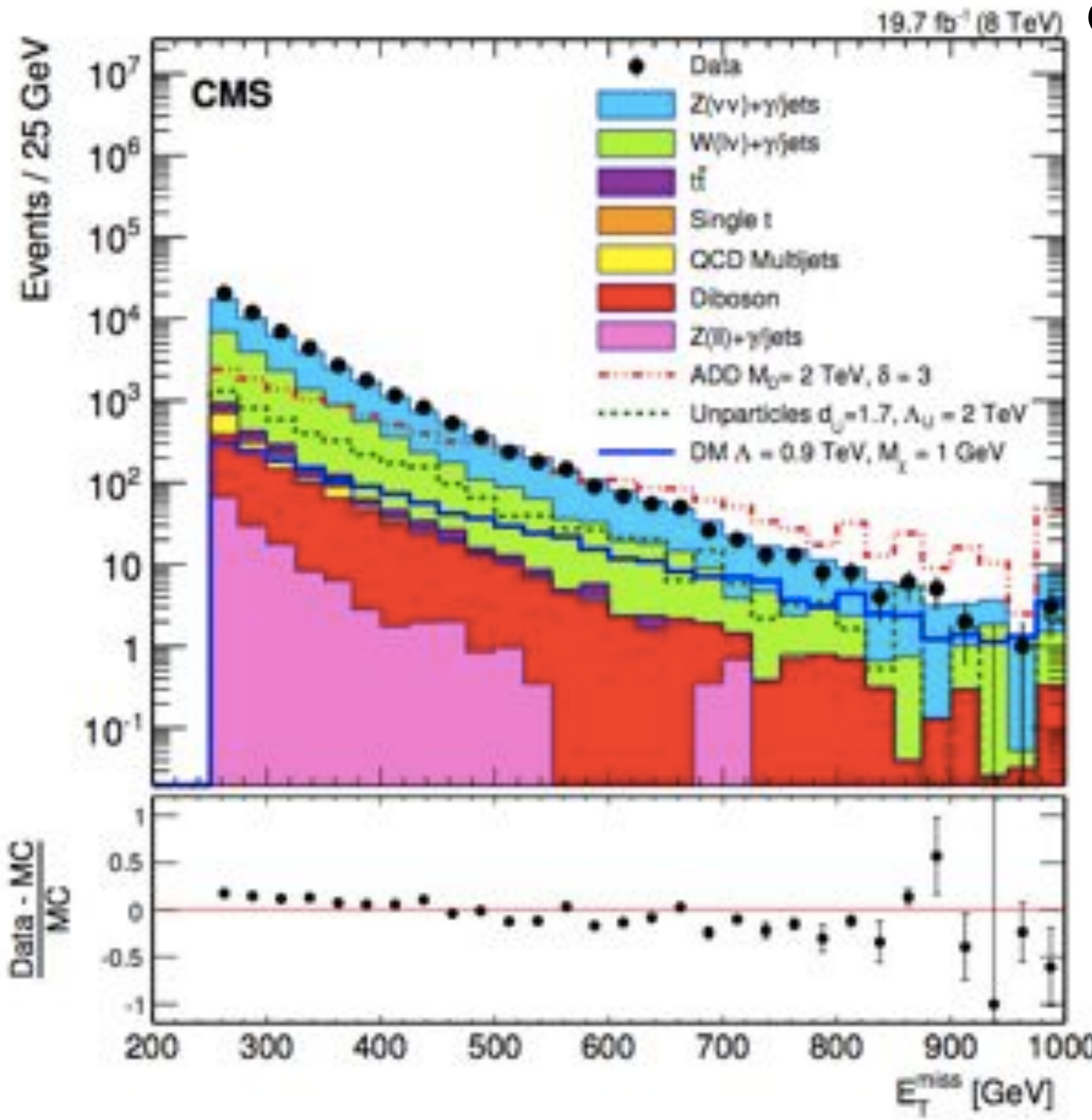


- one jet p_T 900 GeV
- MET of 900 GeV

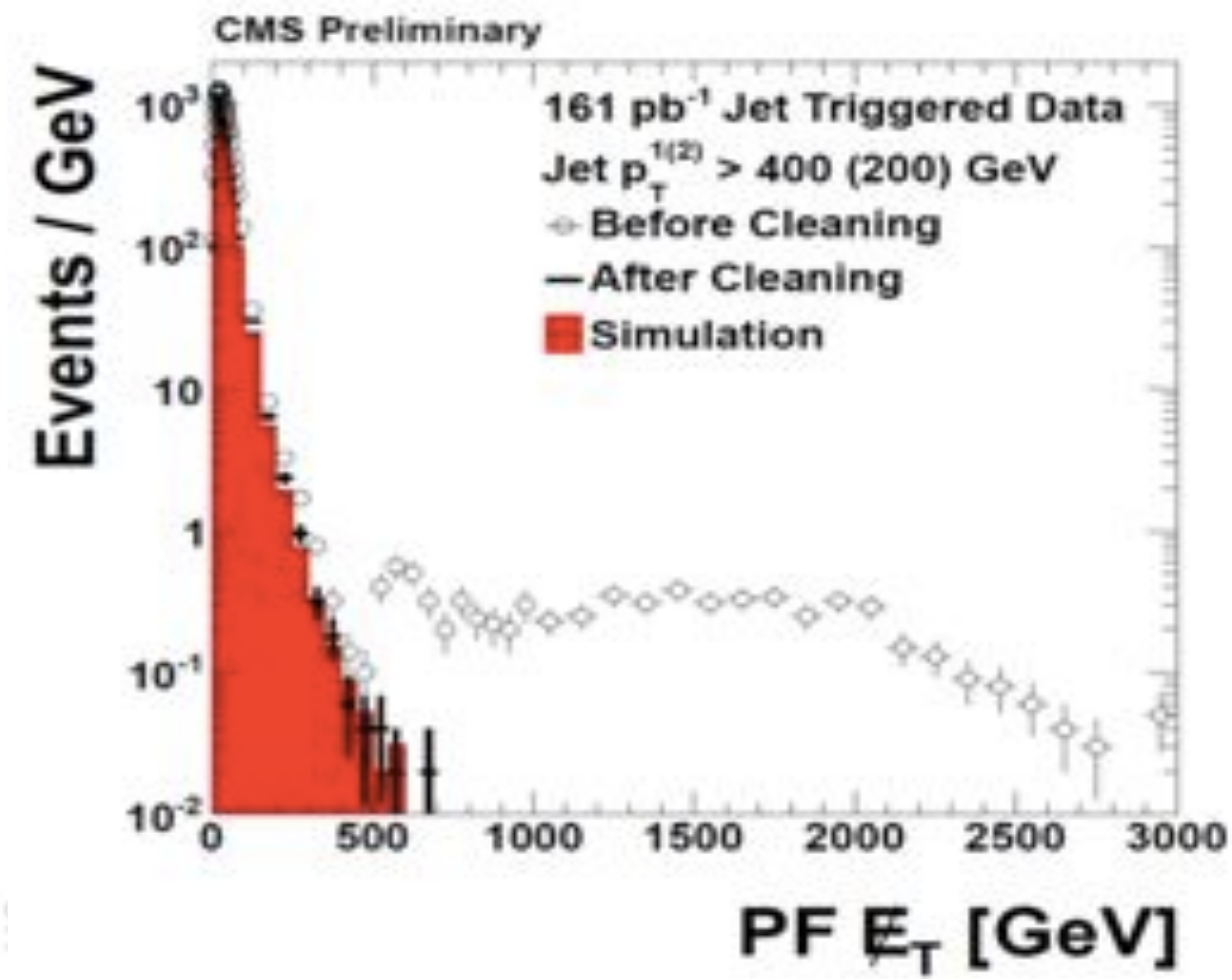
Missing transverse momentum

Monojet search

CMS EXO-12-048

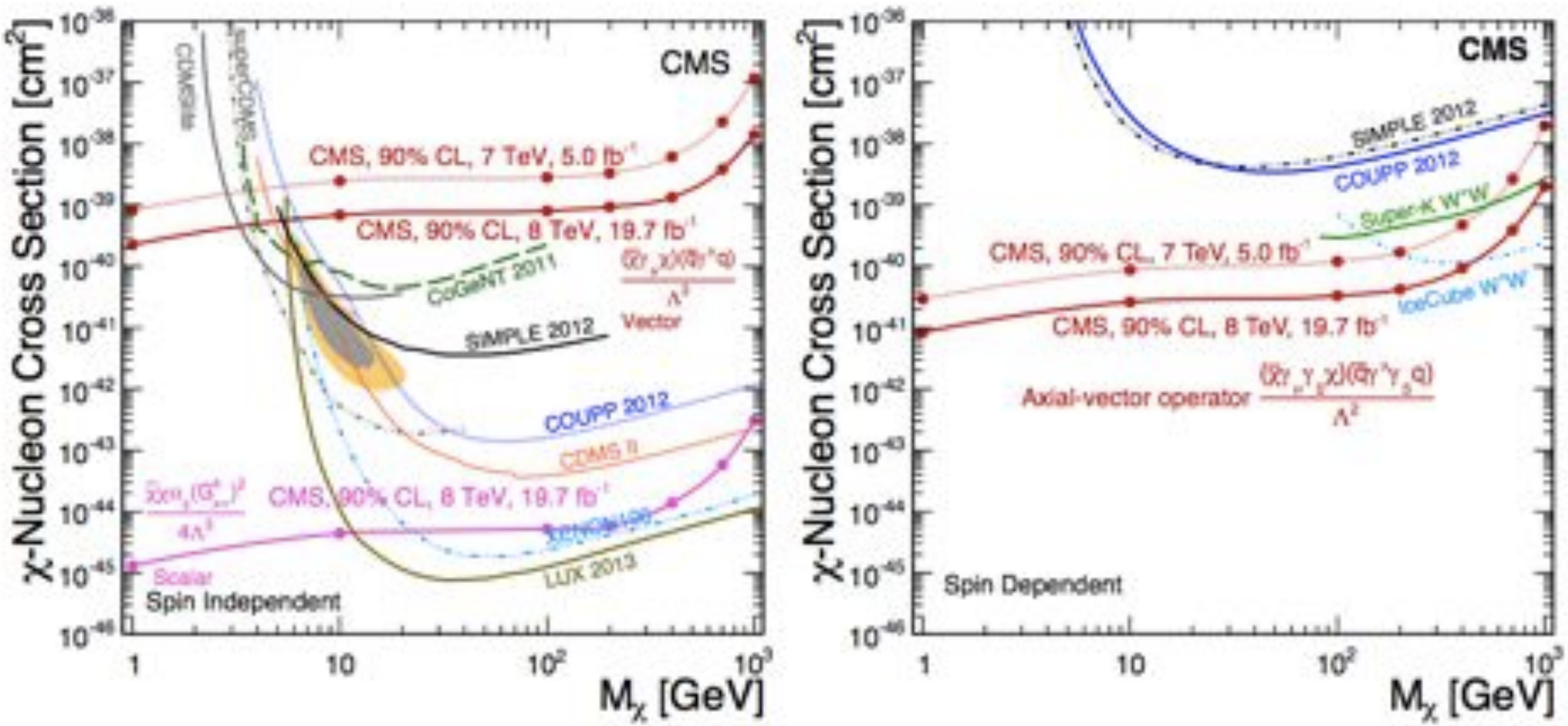


At the heart of all DM searches at colliders : Missing transverse energy (MET)



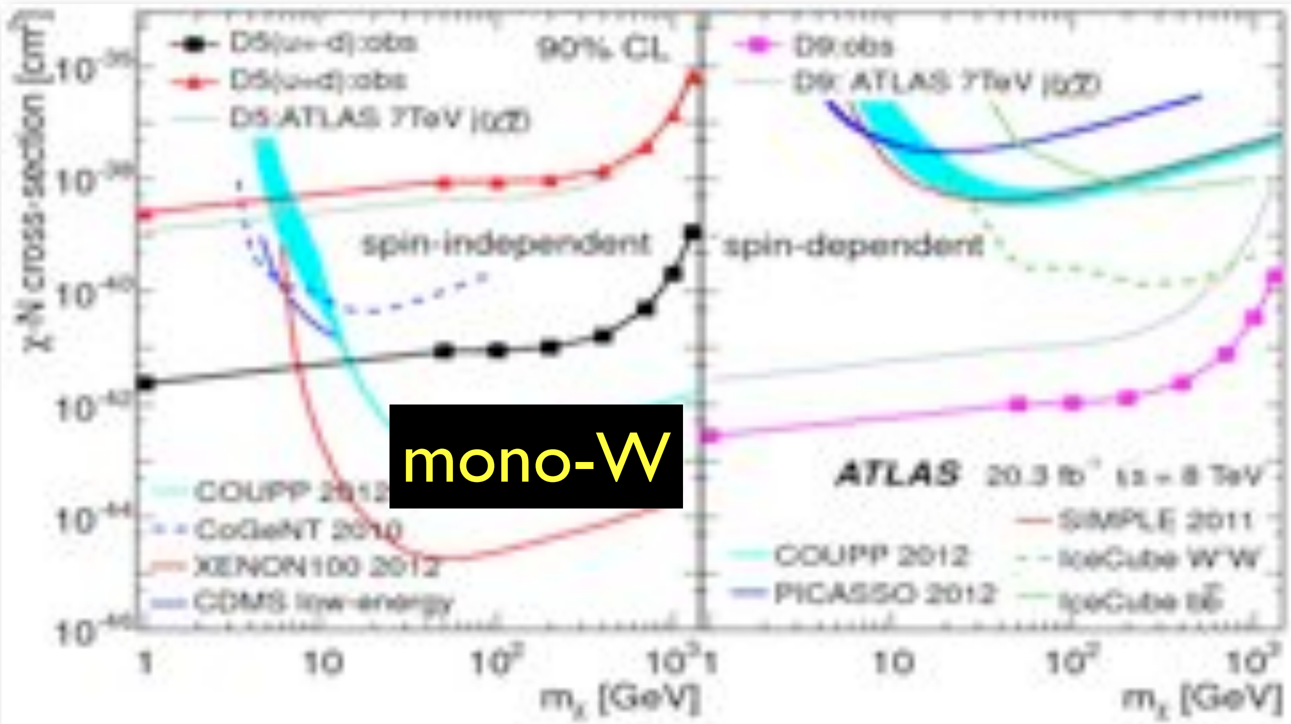
- challenging quantity to measure
- sensitive to mis-measurements, detector effects, backgrounds
- but well controlled

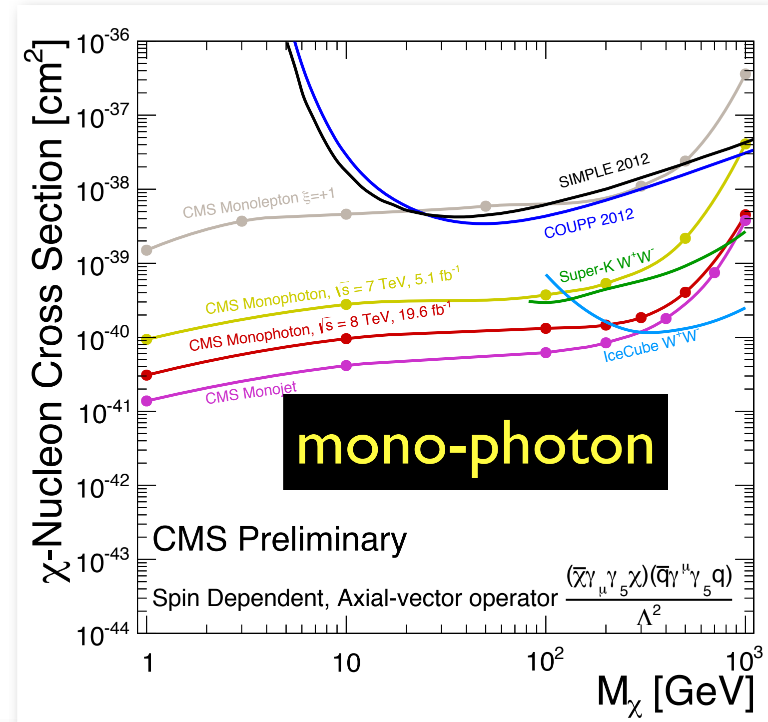
CMS EXO-12-048

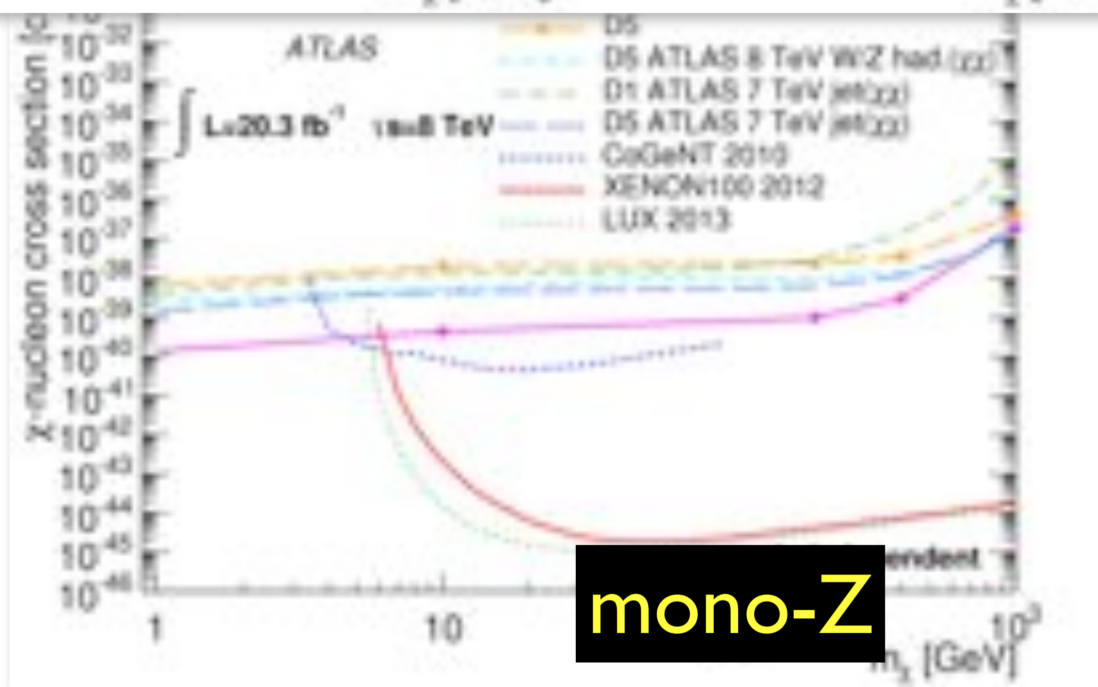


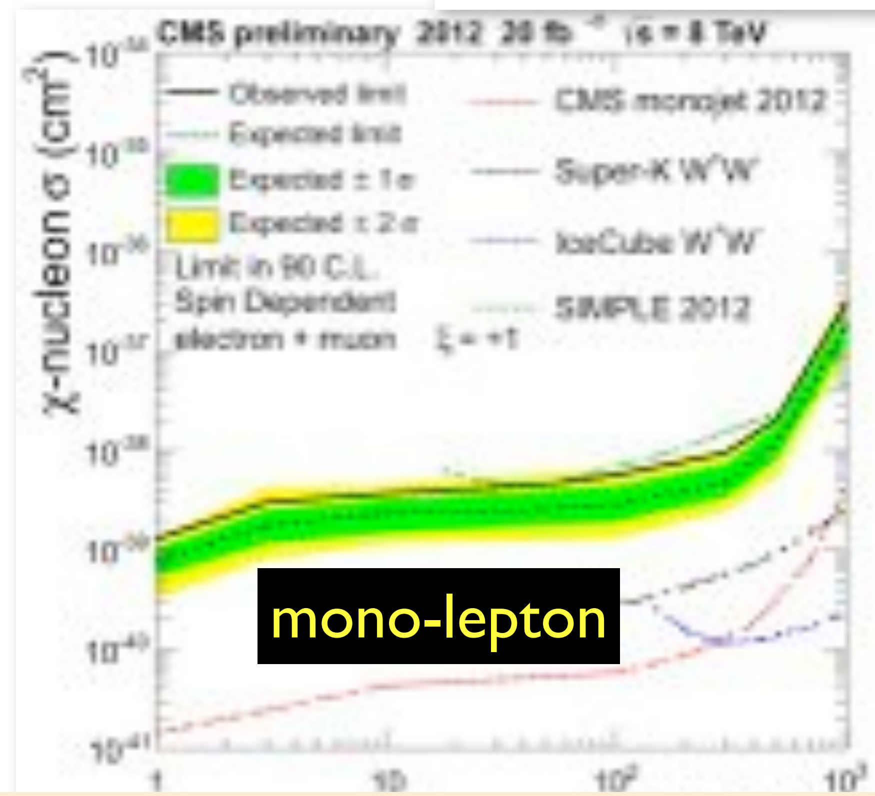
Collider limits comparable and complementary to direct detection experiments

Searches for dark matter with mono-X



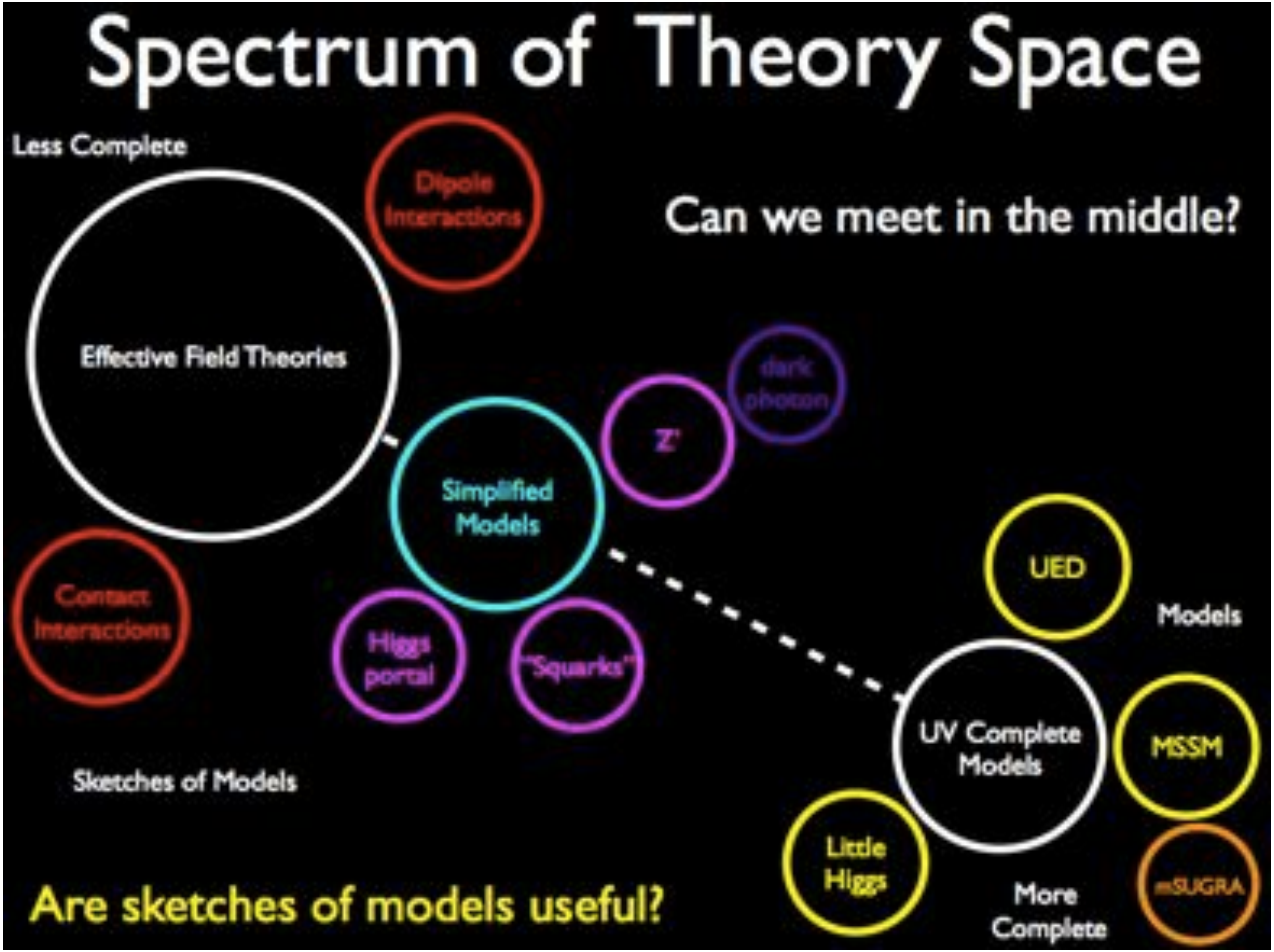






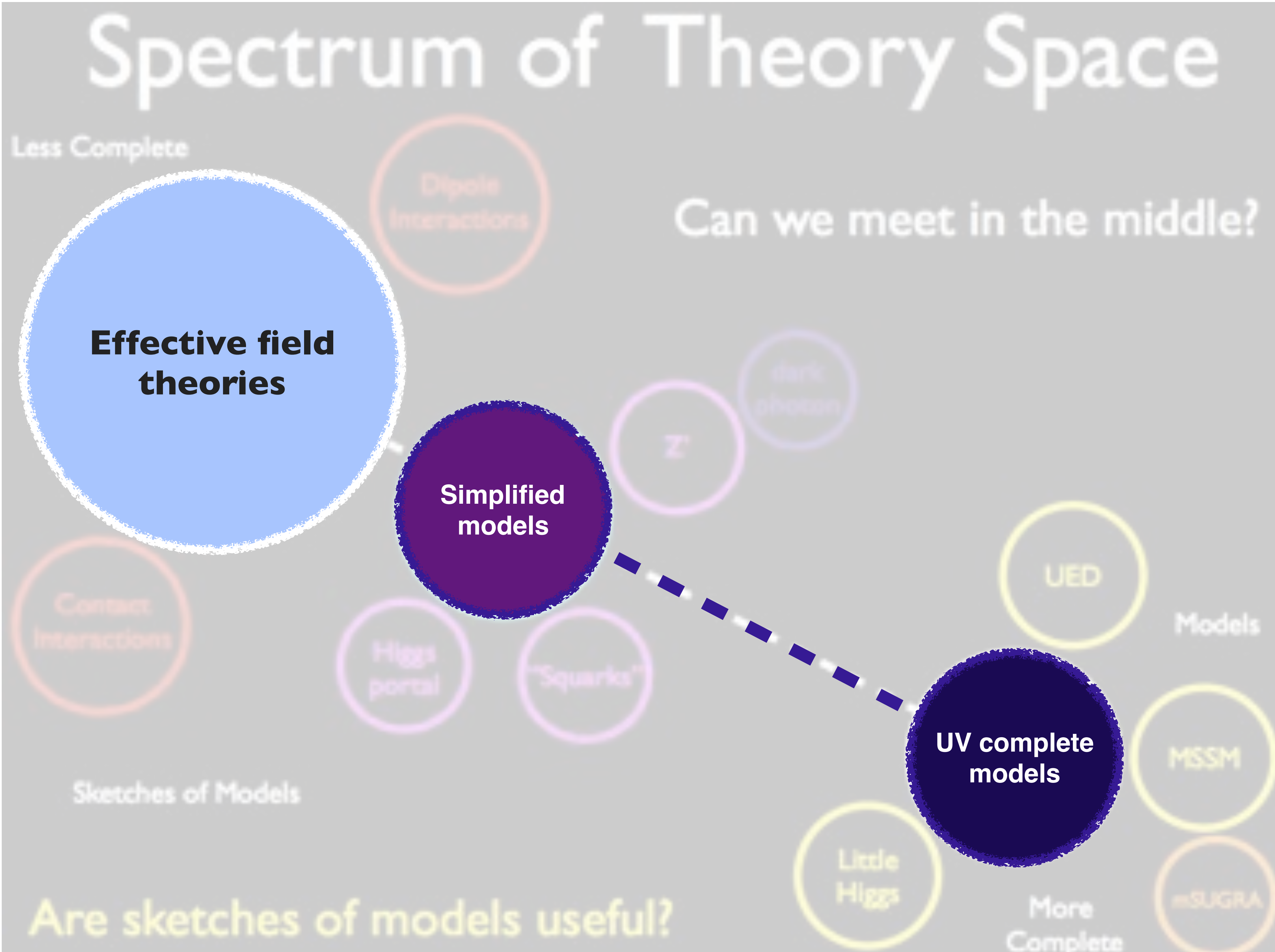
Many different signatures employed to search for dark matter at LHC, will become especially important if signal is observed by collider/DD/ID experiments

From Tim Tait

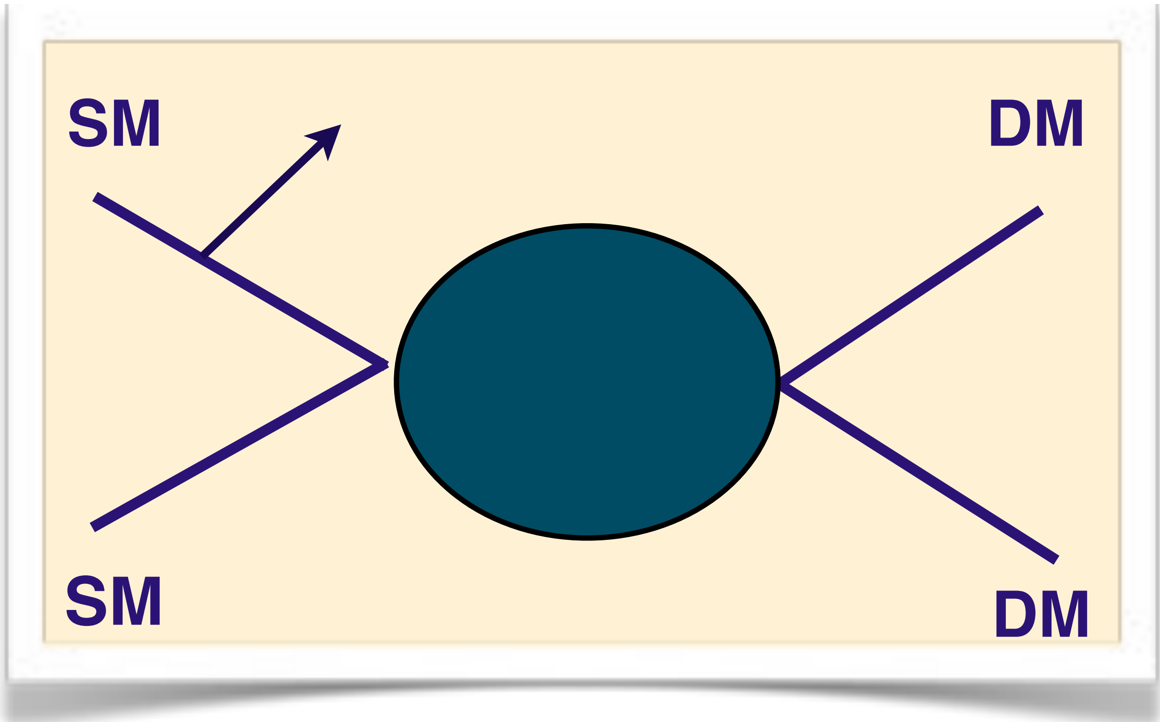


DM at colliders phenomenology

From Tim Tait



Effective field theory



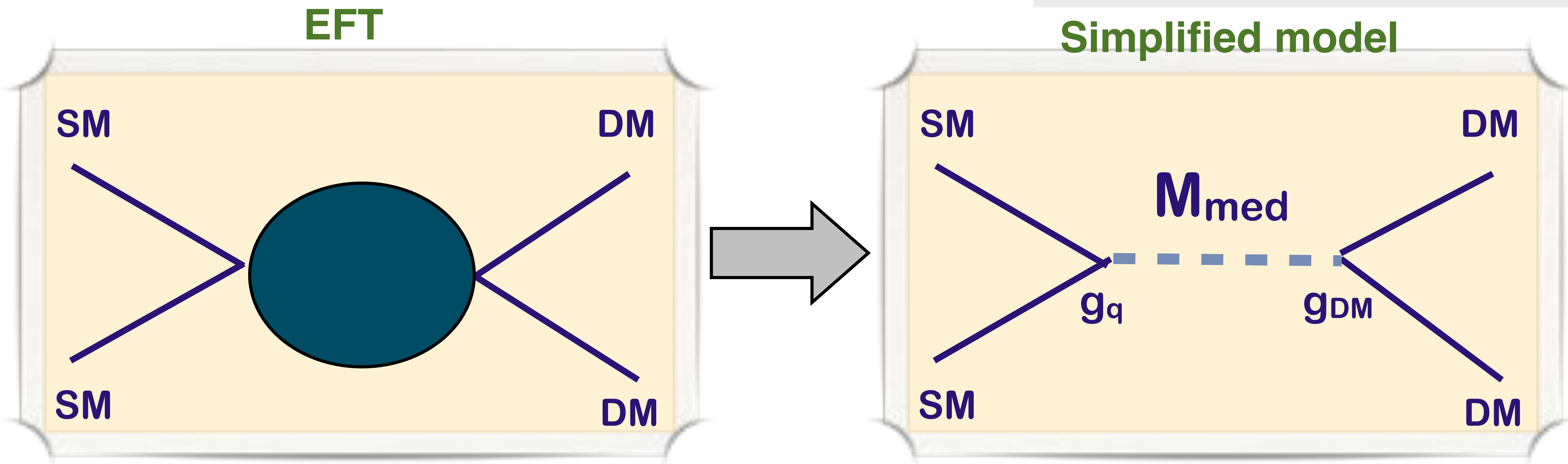
Beltran,Hooper,Kolb,Krusberg,Tait, 1002.4137
Goodman, Ibe, Rajaraman, Shepherd,Tait,Yu, 1005.1286
Bai, Fox, Harnik, 1005.3797
Goodman, Ibe, Rajaraman, Shepherd,Tait,Yu, 1008.1783
Goodman, Ibe, Rajaraman, Shepherd,Tait,Yu, 1009.0008
Fox, Harnik, Kopp,Tsai, 1103.0240
Fortin,Tait, 1103.3289
Cheung,Tseng,Yuan, 1104.5329
Shoemaker,Vecchi, 1112.5457

- Assume mediator heavy enough to be integrated out
- Use EFT operators to describe SM-DM interaction
- Pro: Limited number of degrees of freedom (interacton scale, DM mass).
- Con: Given energy scales being probed by collider, not always a valid assumption for us

Beyond EFT : Simplified models of dark matter

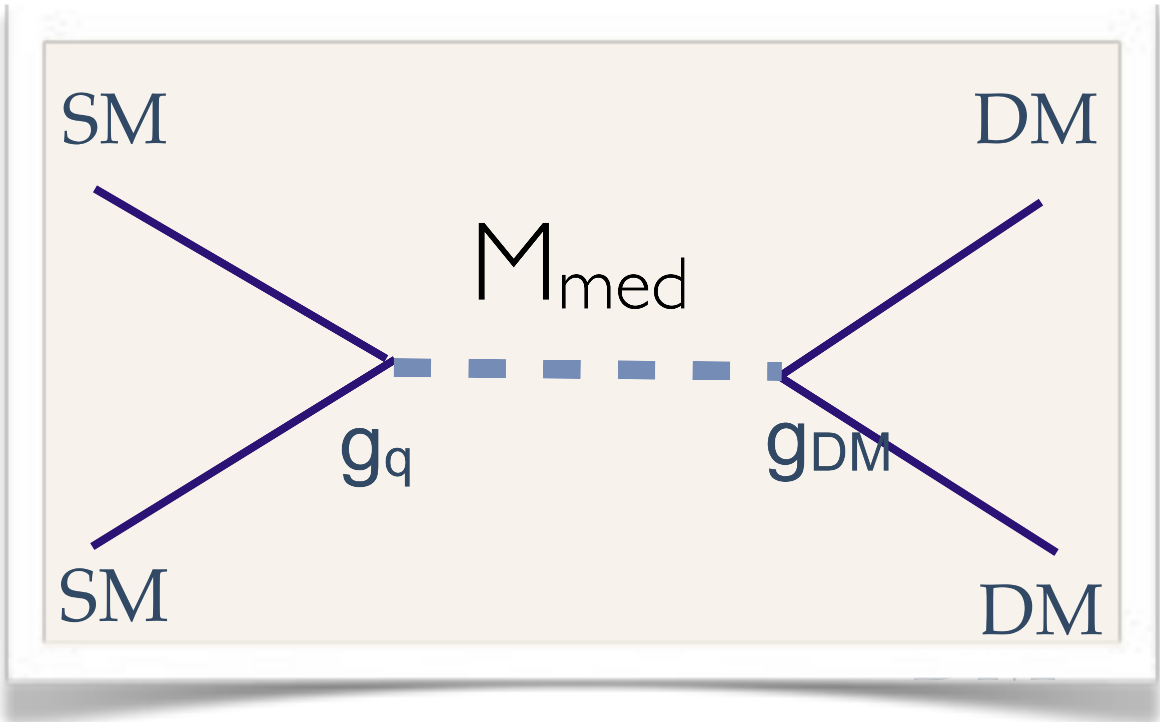
For Run-2 : focus shifted to simplified models

arXiv:1402.2285
arXiv:1308.2679
arXiv:1308.0592
arXiv:1403.4634
arXiv:1401.0221
arXiv:1312.5281
arXiv:1407.8257



Minimal Simplified model of dark matter

arXiv:1407.8257
O. Buchmueller, M. Dolan, S.A. Malik, C. McCabe



s-channel

Define simplified model with (minimum) 4 parameters	
Mediator mass (M_{med})	DM mass (M_{DM})
g_q	g_{DM}

DM	
Dirac fermion	Scalar - real
Majorana fermion	Scalar - complex

Consider comprehensive set of diagrams for mediator	
Vector	Axial-vector
Scalar	Pseudoscalar

VECTOR

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

DD competitive

AXIAL-VECTOR

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

DD less sensitive

SCALAR

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

Yukawa style coupling
(Mass based coupling)

complementarity with DD

PSEUDOSCALAR

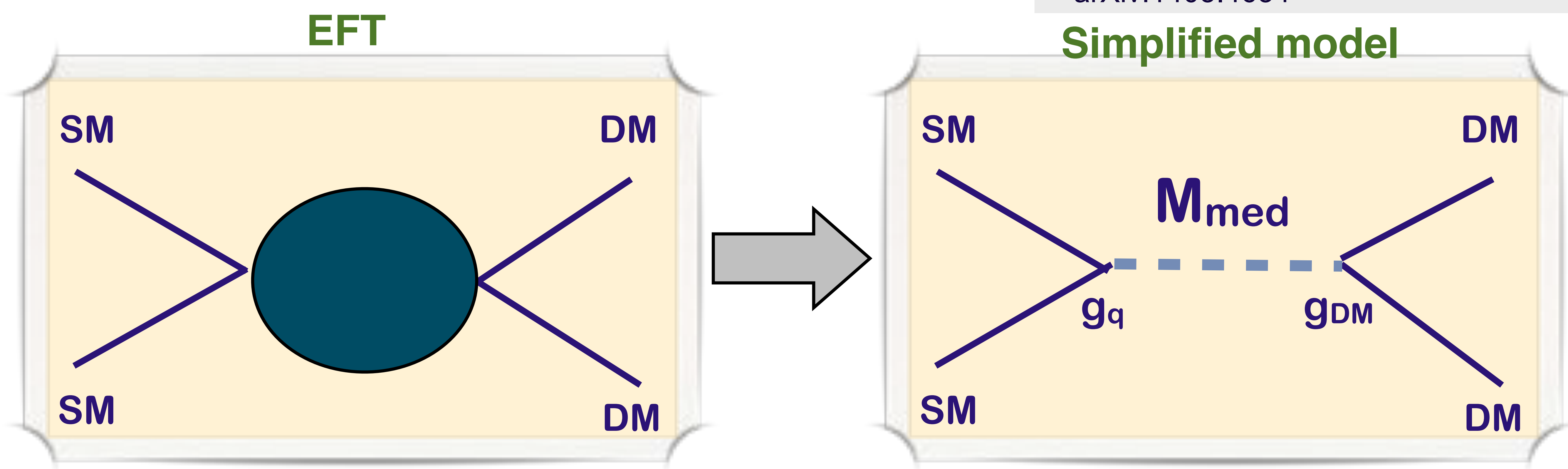
$$g_{\mathrm{DM}} P \, \bar{\chi} \gamma^{5} \chi$$

Yukawa style coupling
(Mass based coupling)
No bounds from DD
Only Cosmic bounds exist

Beyond EFT : Simplified models of dark matter

For Run-2 : focus shifted to simplified models

arXiv:1402.2285 arXiv:1401.0221
arXiv:1308.2679 arXiv:1312.5281
arXiv:1308.0592 arXiv:1407.8257
arXiv:1403.4634

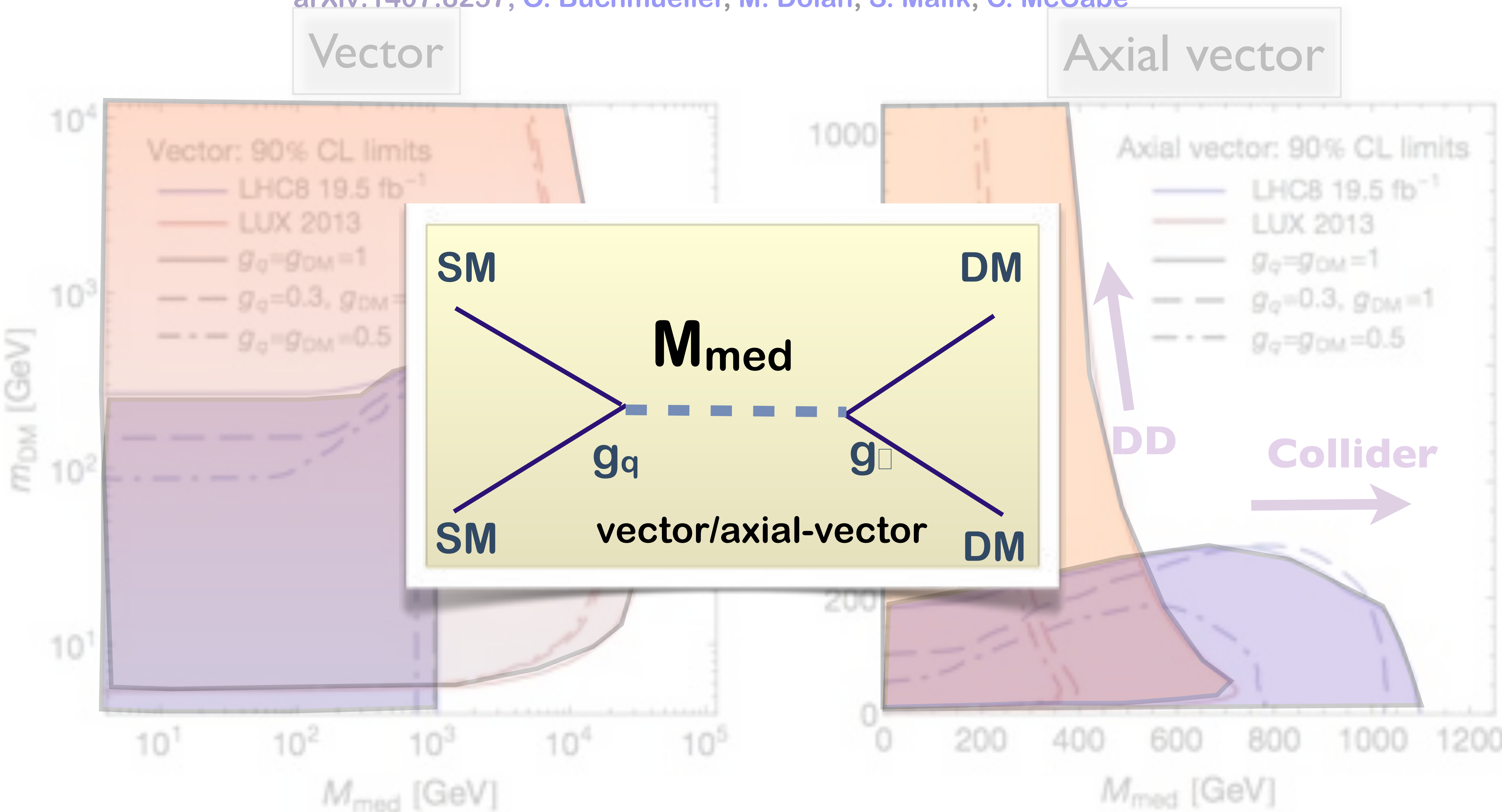


With simplified models, several additional things come into play:
- Searches for the mediator itself
- Additional search signatures
- Enables a more equal footing comparison with direct detection experiments.

ATLAS-CMS Dark Matter Forum formed; to reach consensus on prioritised, benchmark set of simplified models for early Run2 searches

Complementarity between colliders and DD

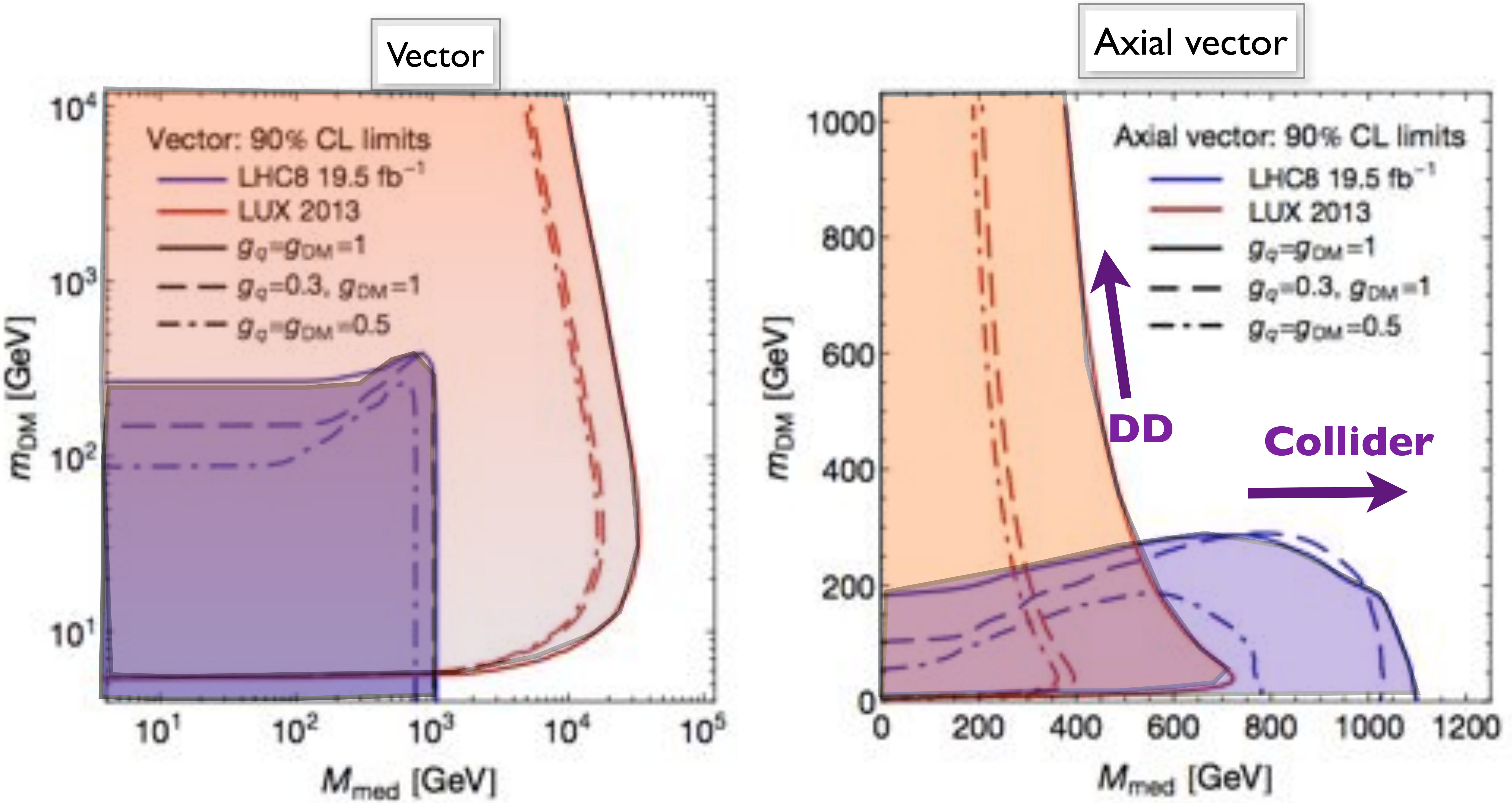
arXiv:1407.8257, O. Buchmueller, M. Dolan, S. Malik, C. McCabe



Elucidates more accurately the complementarity between collider and direct detection experiments

Complementarity between colliders and DD

arXiv:1407.8257, O. Buchmueller, M. Dolan, S. Malik, C. McCabe



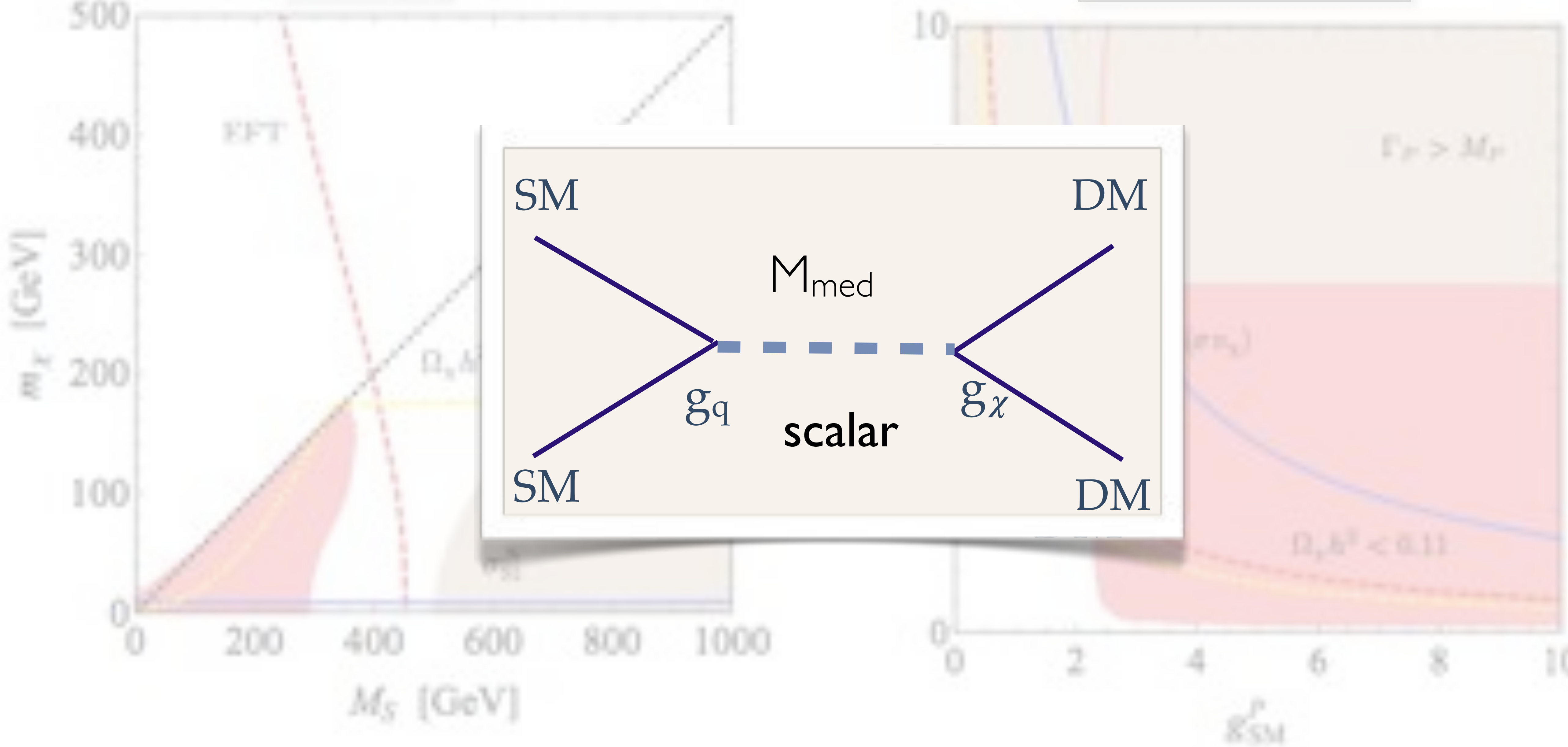
Elucidates more accurately the complementarity between collider and direct detection experiments

Complementarity between colliders and DD

arXiv:1503.00691

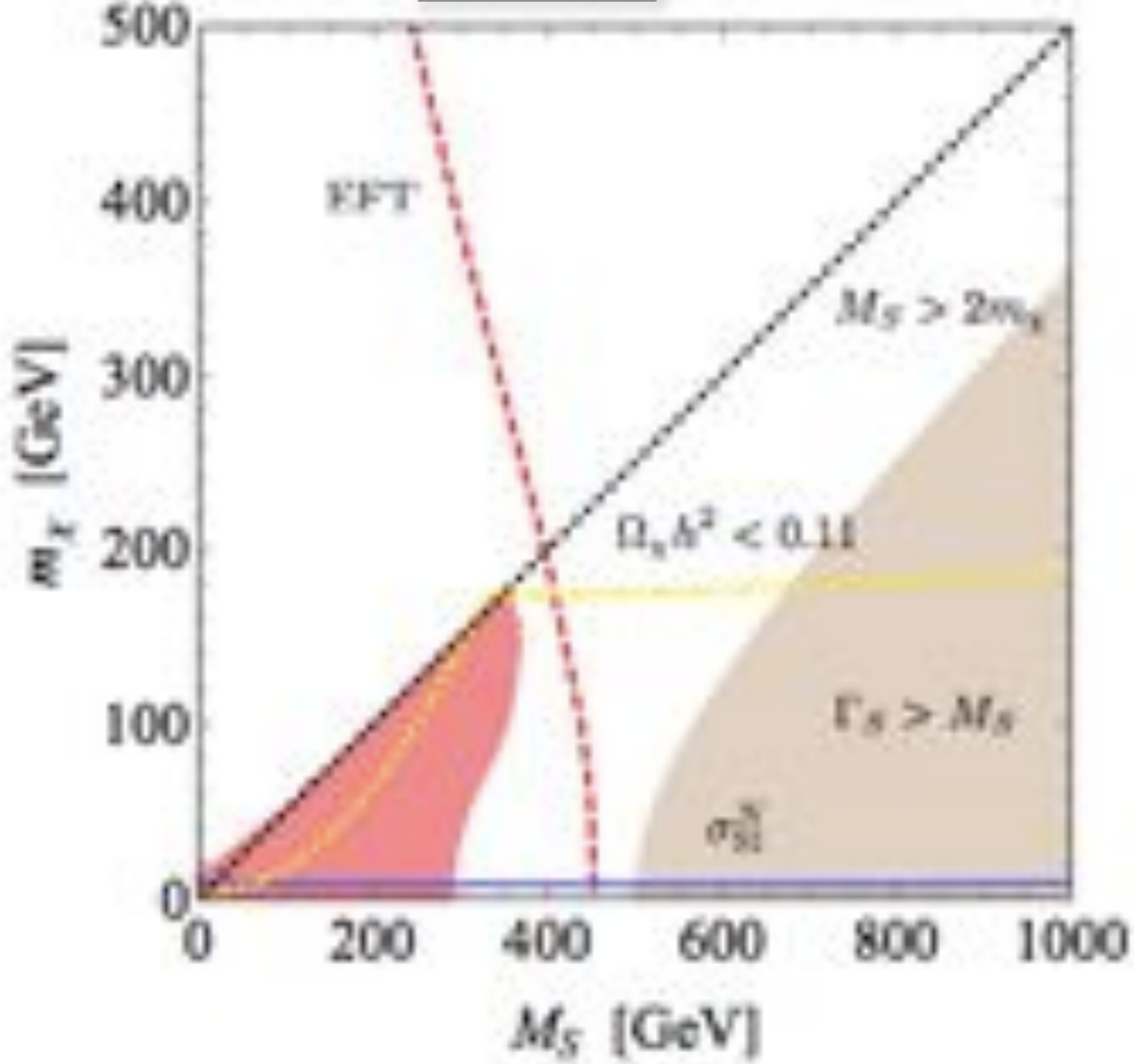
Scalar

Pseudoscalar

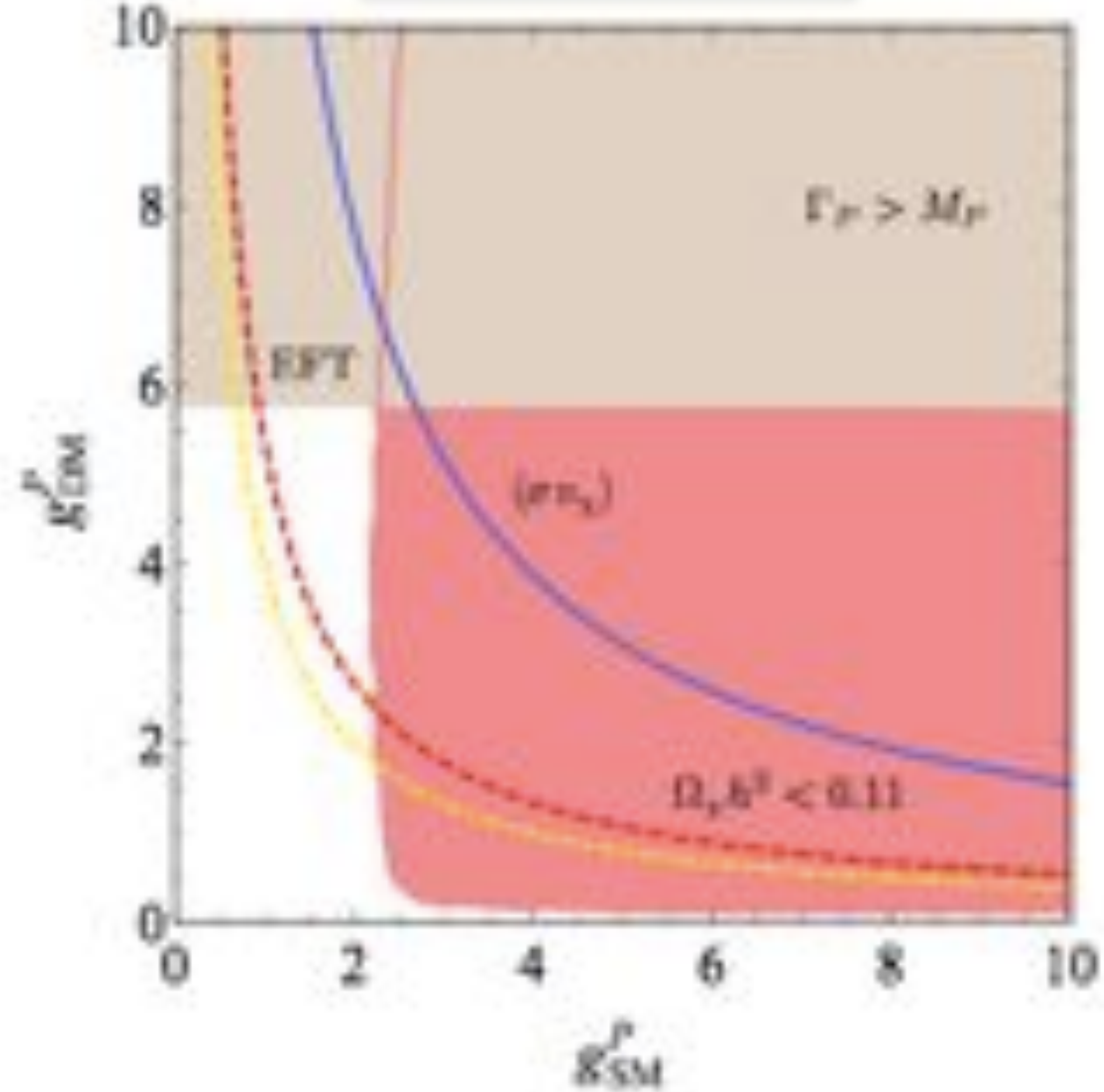


arXiv:1503.00691,
Ulrich Haisch, Emanuele Re

Scalar



Pseudoscalar



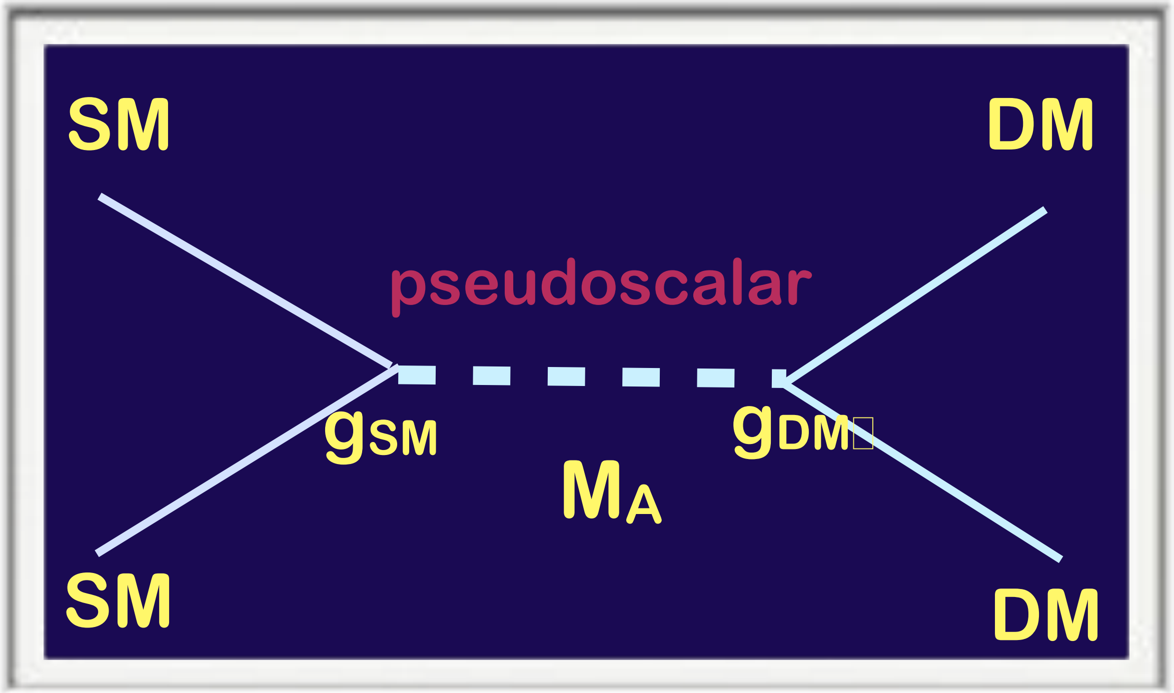
Complementarity between collider and direct/indirect searches

➡Fermi Large Area Telescope (Fermi-LAT) see a gamma-ray excess around the galactic center - generated much interest

➡Mass and annihilation cross section required to explain excess consistent with WIMPs

➡Large astrophysical uncertainties - need corroborative evidence from colliders or direct detection experiments

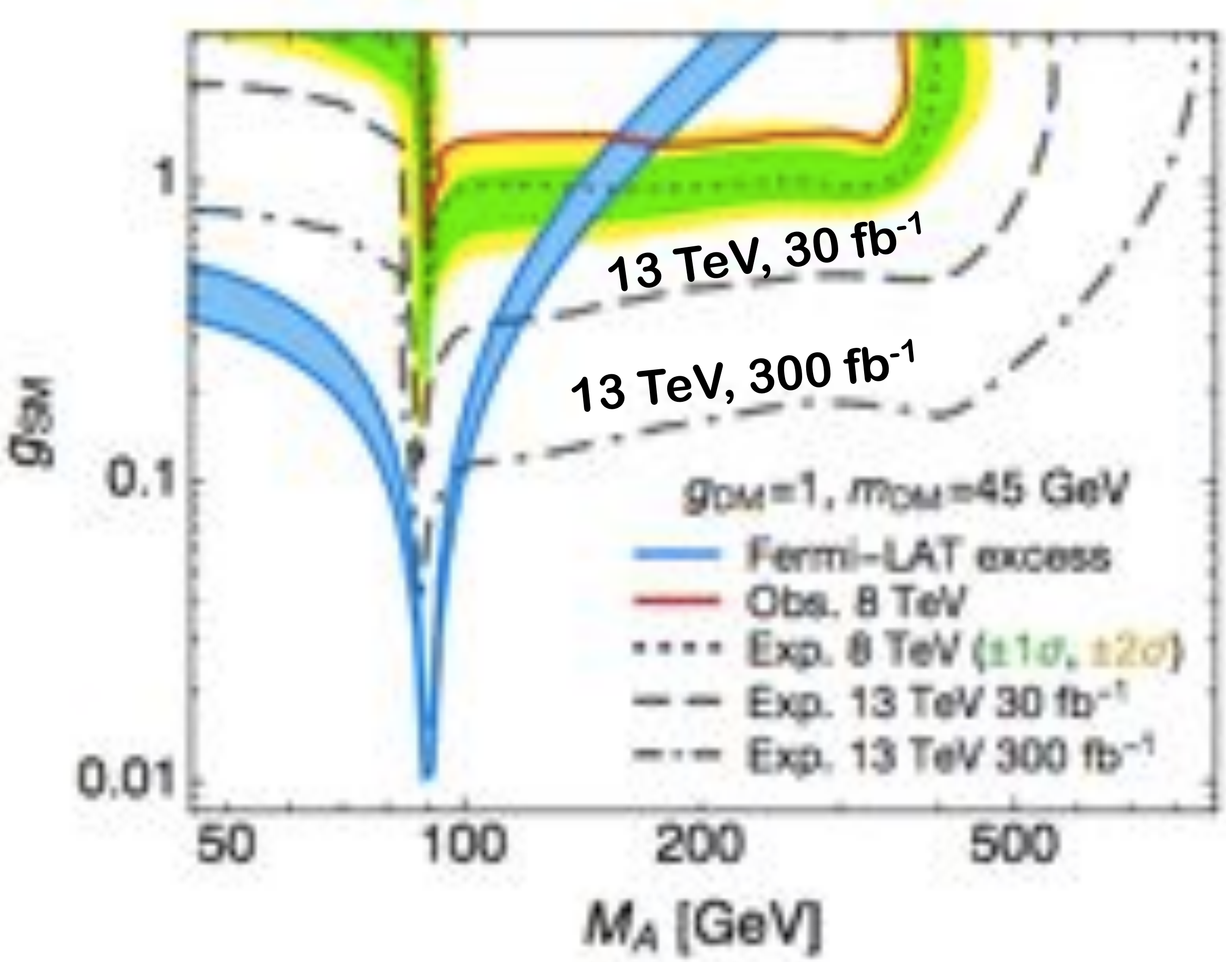
➡Many models proposed to explain excess, common feature is pseudoscalar mediator (inaccessible to direct detection expts, gives suppressed spin-dependent interactions)

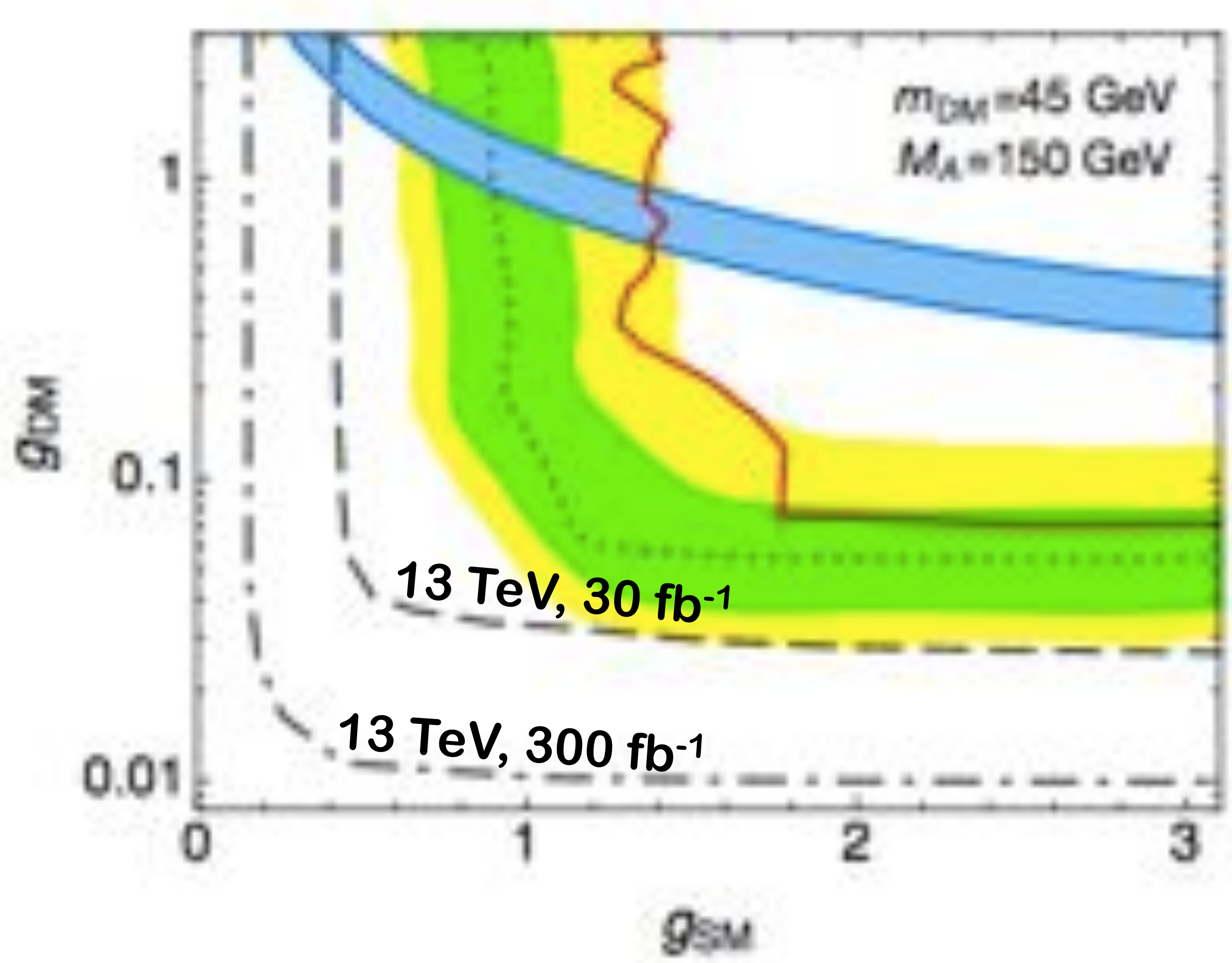


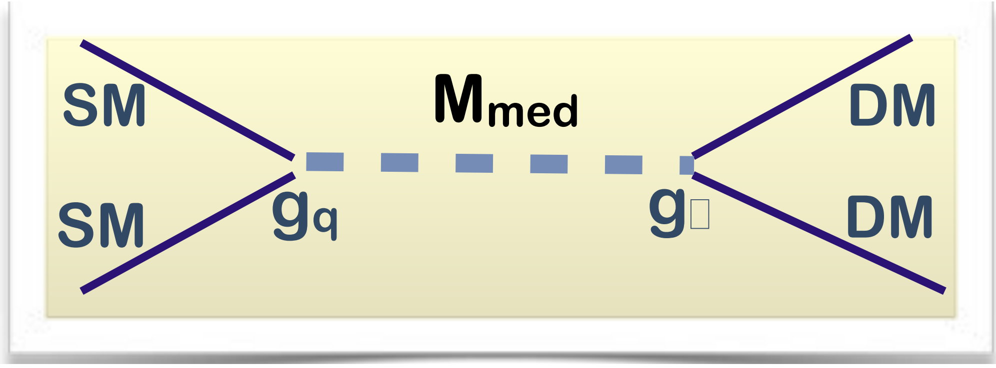
Complementarity between collider and direct/indirect searches

arXiv:1505.07826,
O. Buchmueller, S. Malik, C. McCabe, B. Penning

	2012	2015-2016	~2020
Energy	8 TeV	13 TeV	13 TeV
Luminosity	20 fb^{-1}	30 fb^{-1}?	300 fb^{-1}



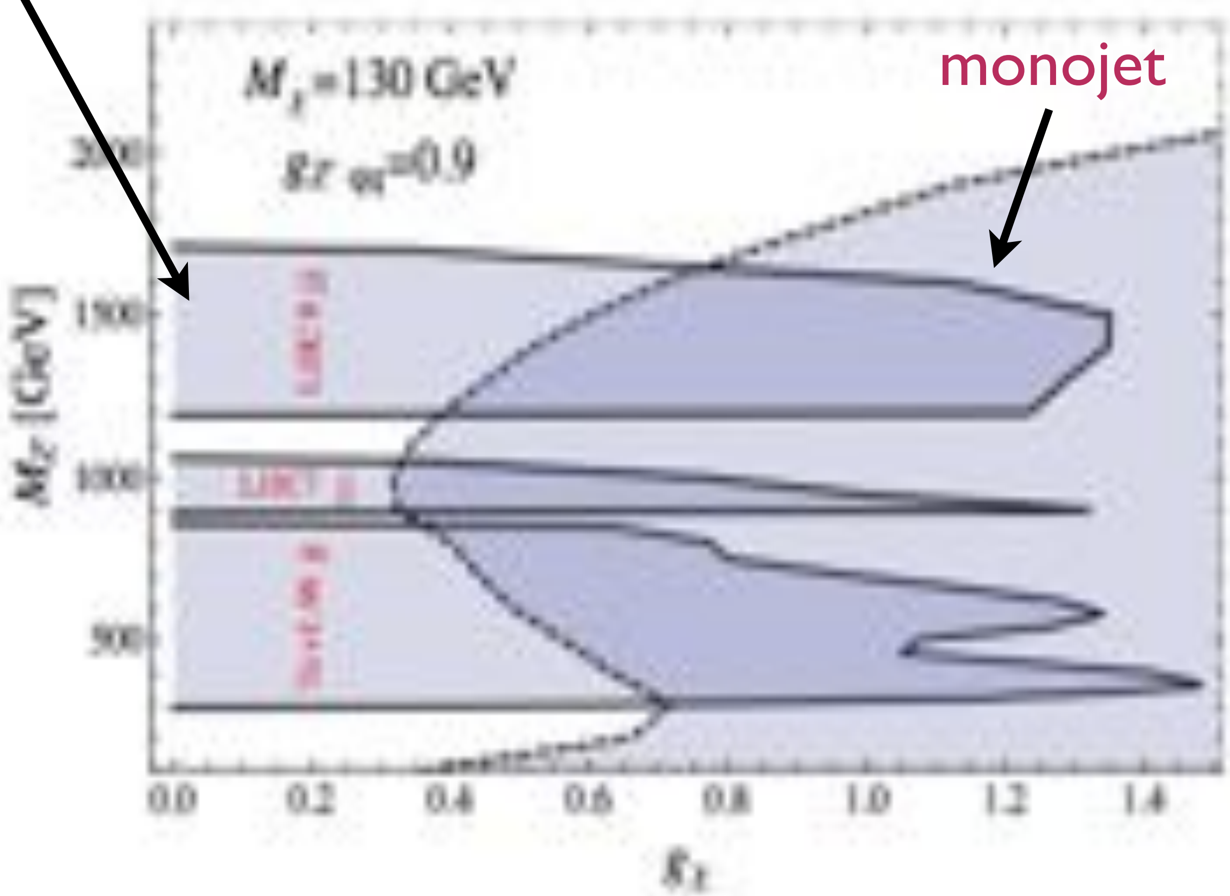




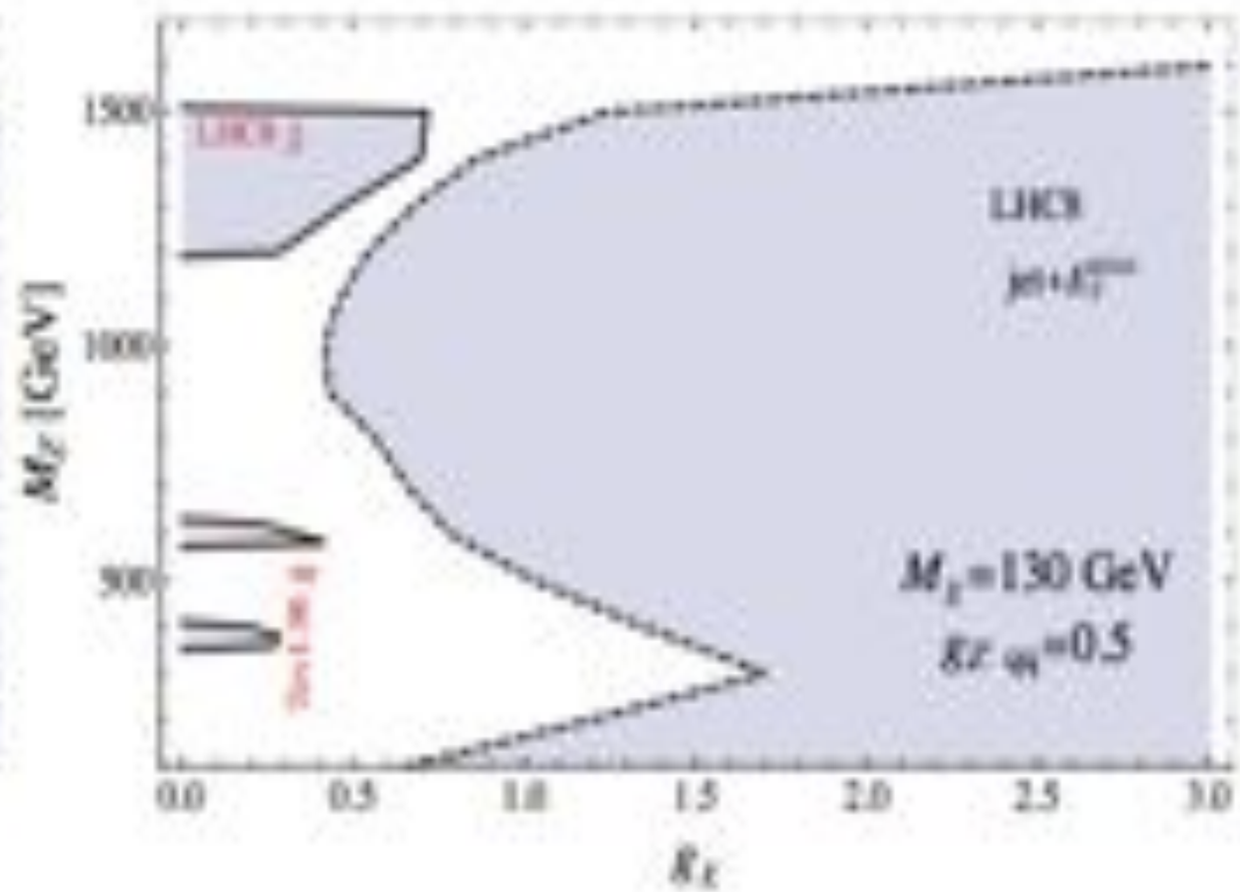
arXiv:1312.5281

dijet searches

g_q = 0.9



g_q = 0.5

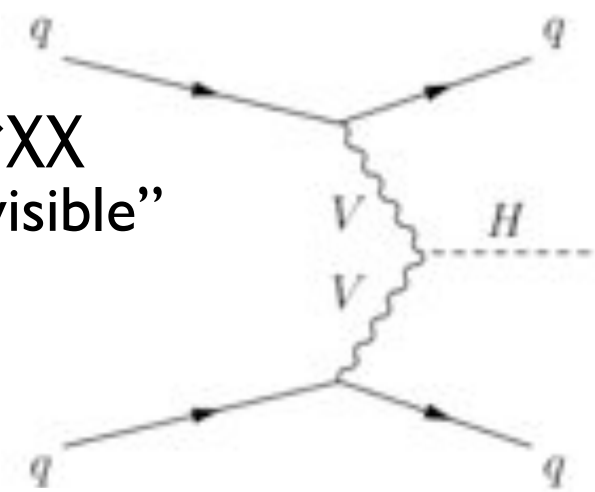


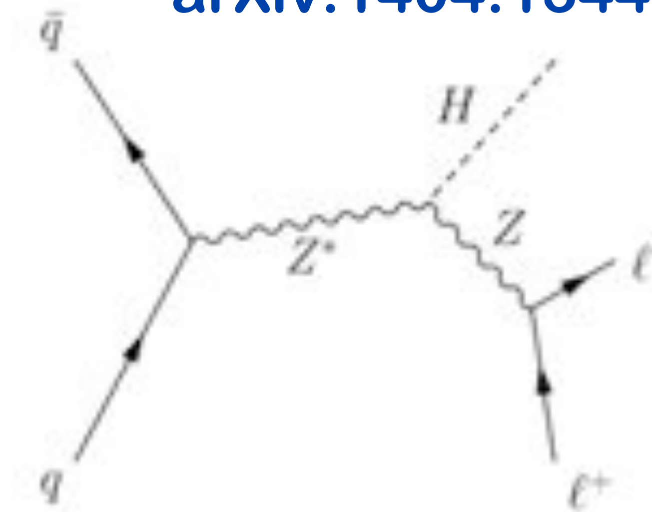
- Dijet searches take out sizeable region of parameter space for low coupling
- If we open up decay channels of mediator to leptons etc, then dilepton searches also become relevant

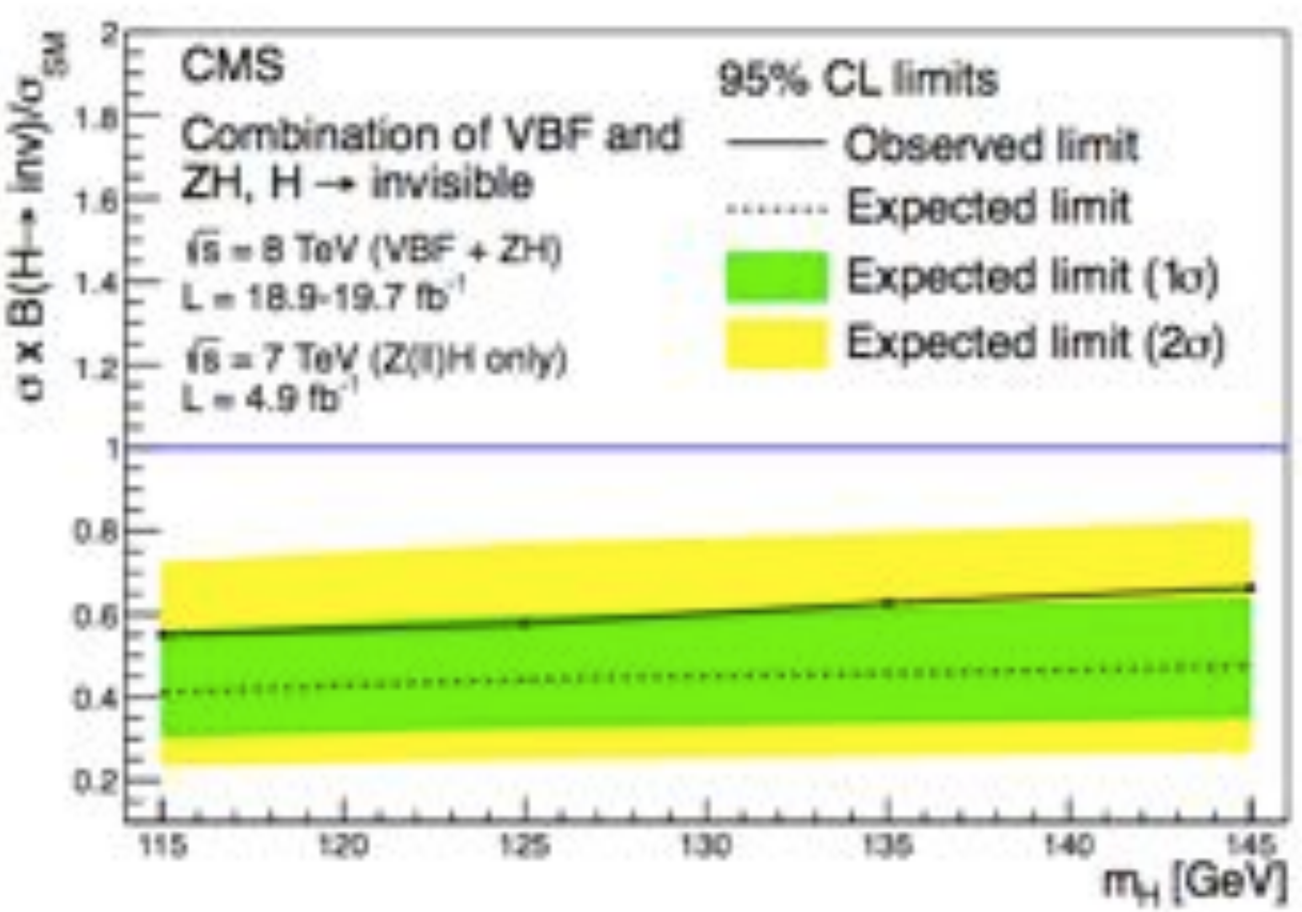
Invisible Higgs searches

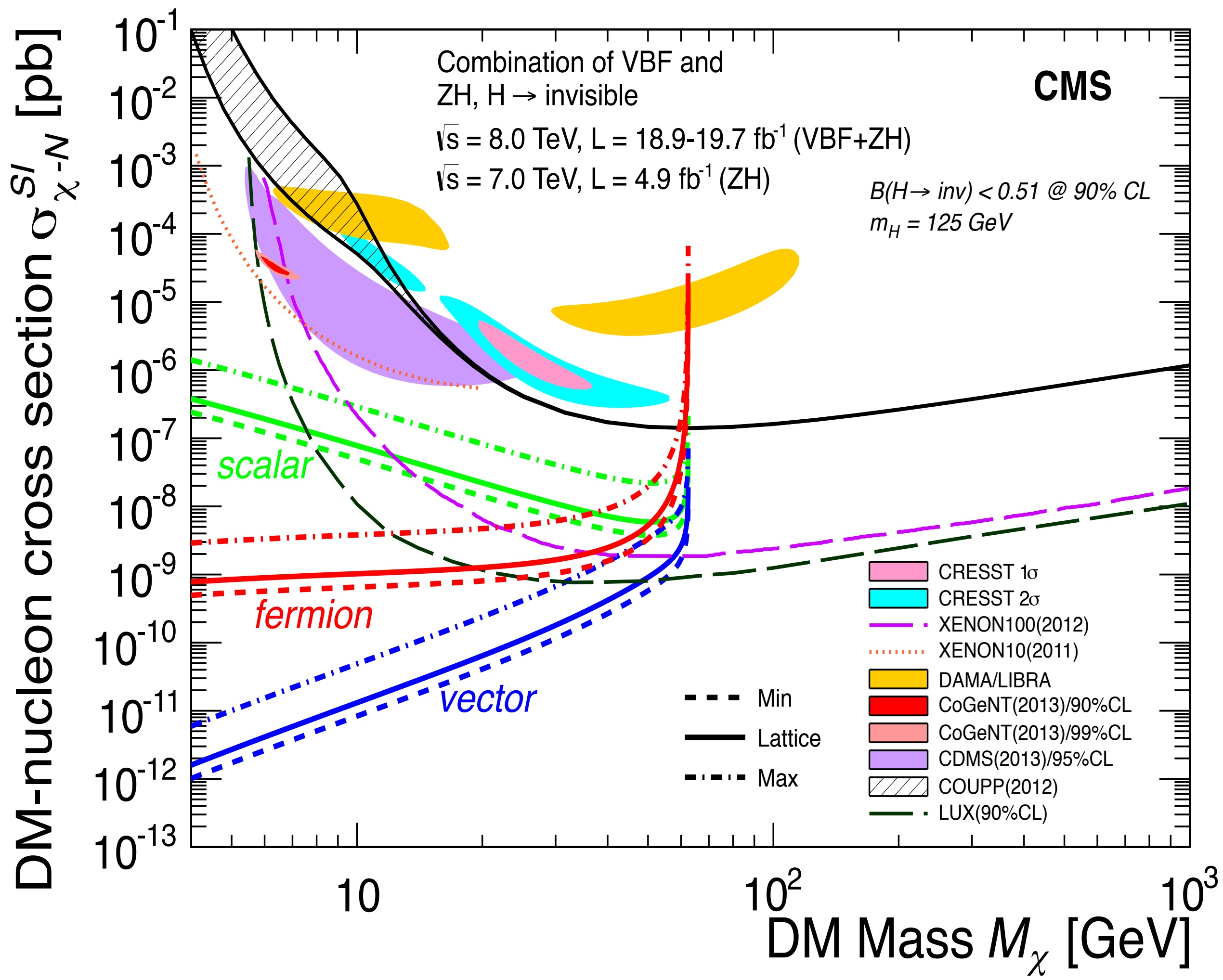
arXiv:1404.1344

DM can couple to the Higgs sector; H→χχ
- Limits on branching fraction of Higgs to "invisible" particles used for limits on DM
- Limits only up to DM mass $M_\chi < M_H/2$









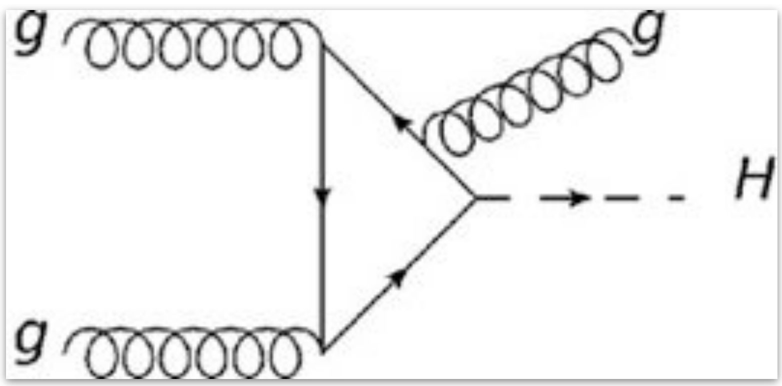
BF(H->invisible) < 0.58 @ 95%CL

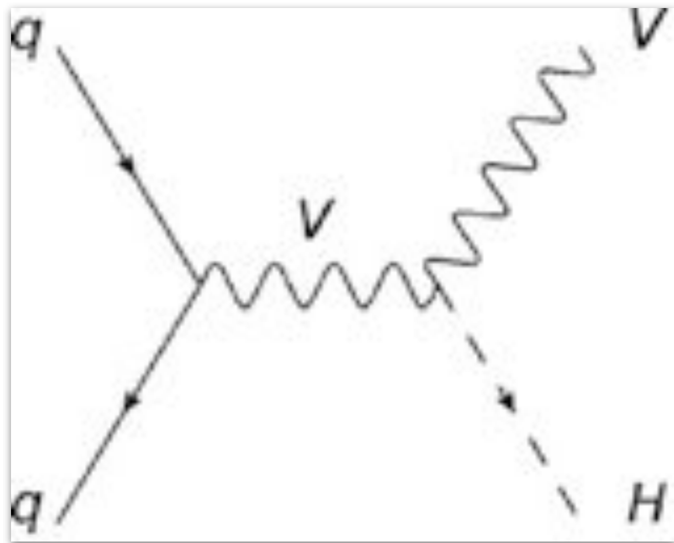
assuming SM production cross section and kinematics

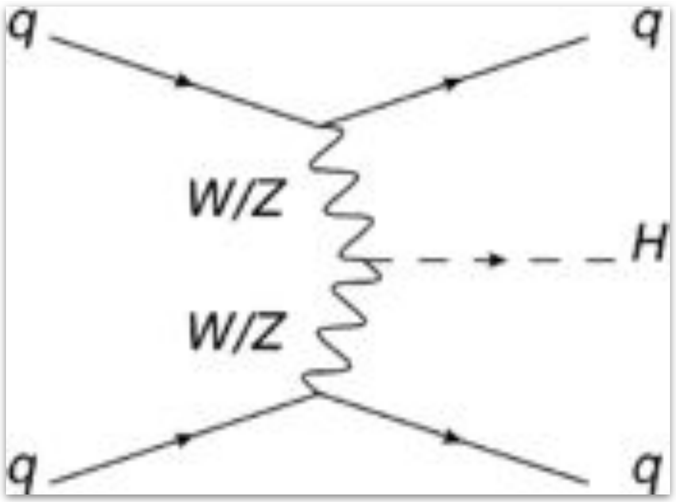
Invisible Higgs searches

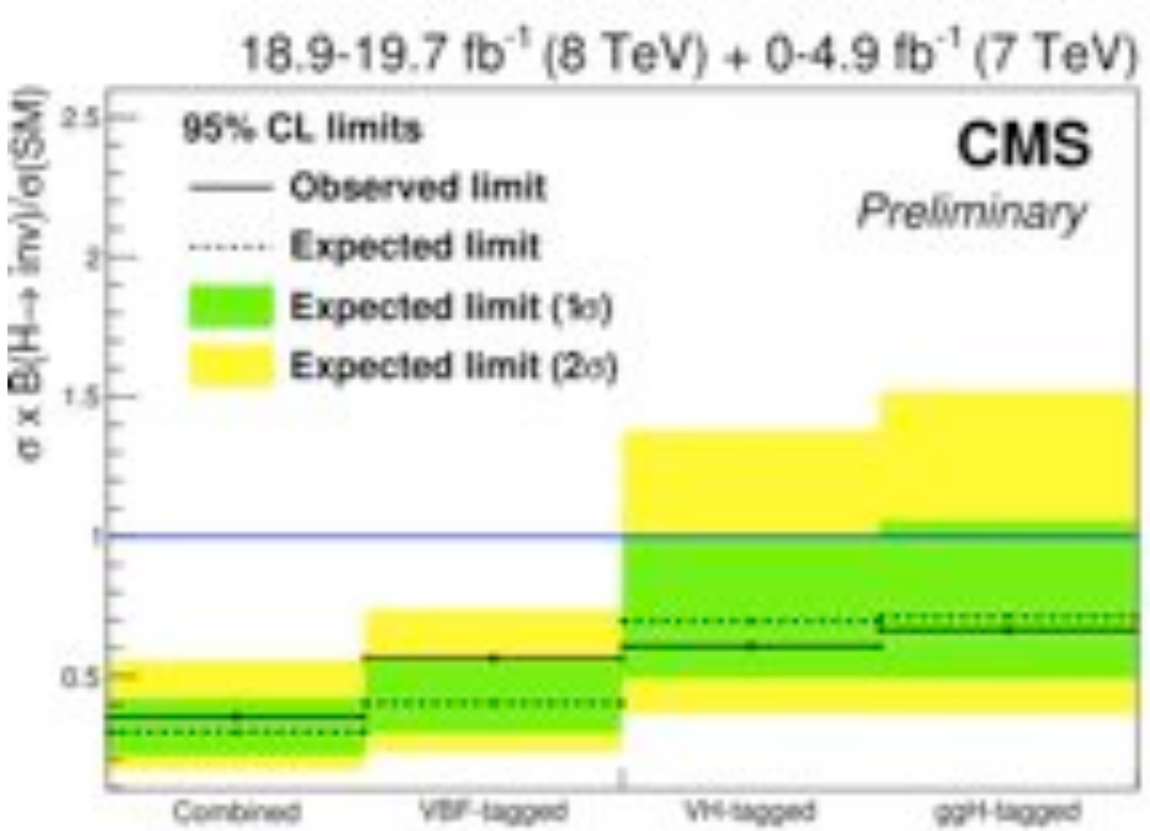
- DM can couple to the Higgs sector; H→χχ
- Limits on branching fraction of Higgs to "invisible" particles used for limits on DM

CMS-PAS-HIG-15-012





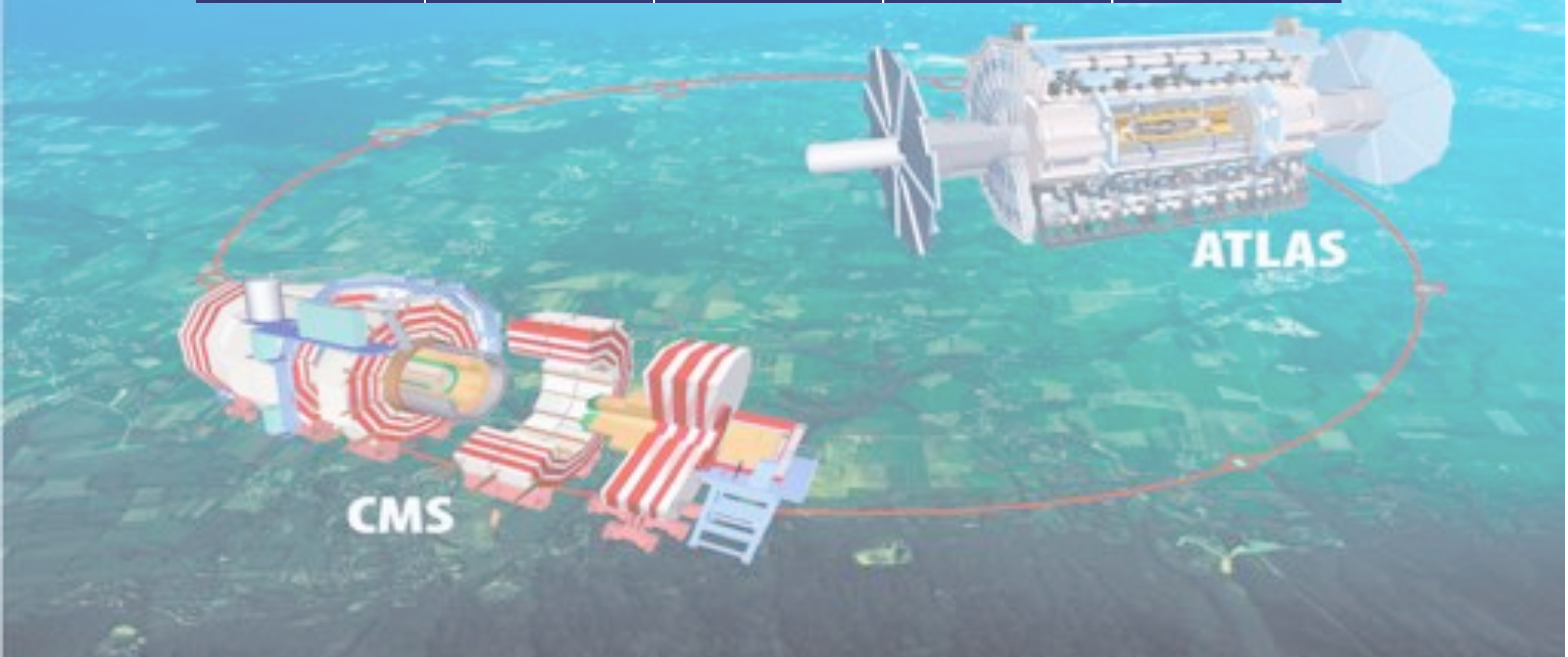




Future projections

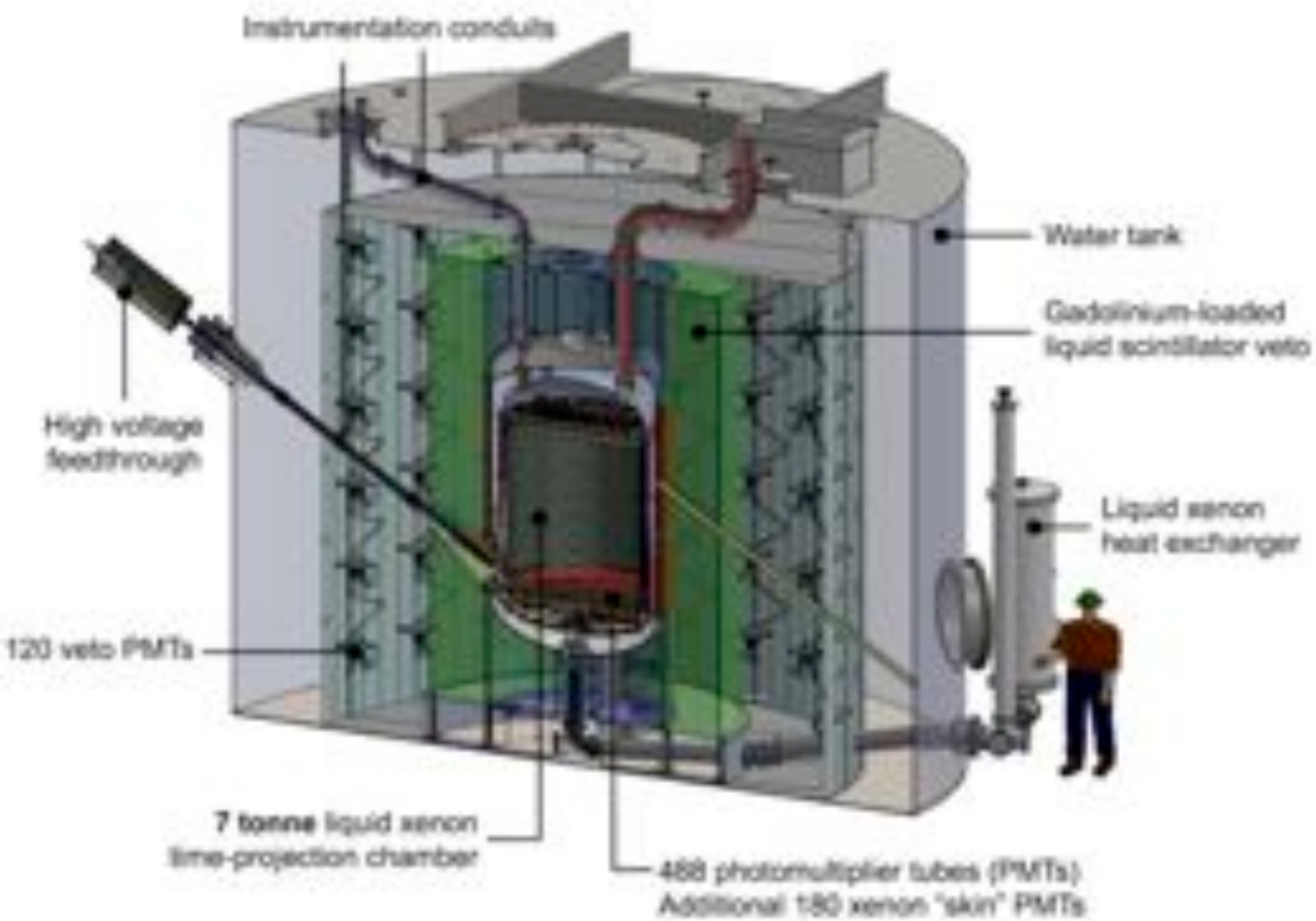
LHC scenarios

	2012	2015-2016	~2020	HL-LHC
Energy	8 TeV	13 TeV	13 TeV	13/14 TeV
Integrated luminosity	20 fb^{-1}	30 fb^{-1}?	300 fb^{-1}	3000 fb^{-1}



Future projections : direct detection experiments

LZ : LUX-ZEPLIN



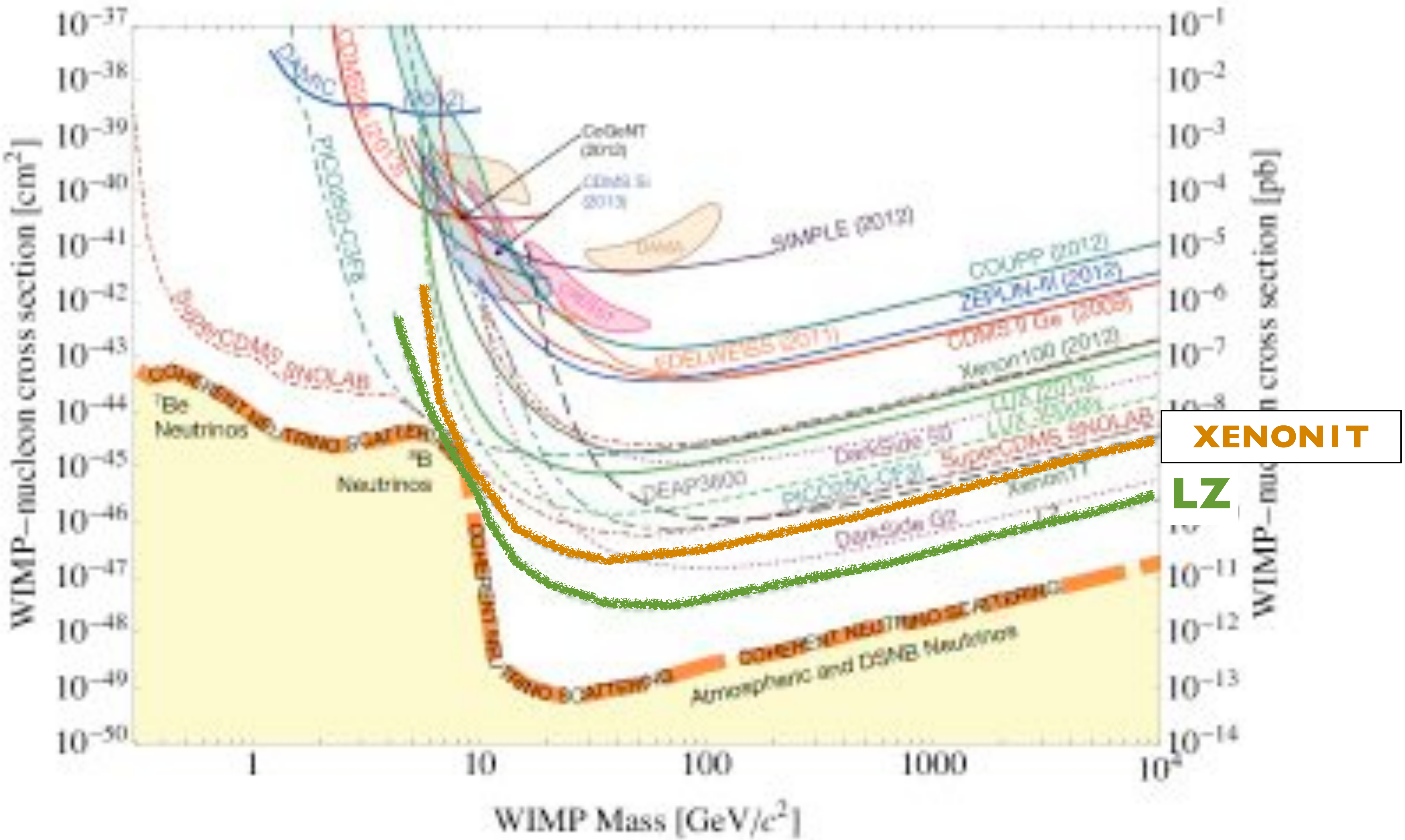
increase sensitivity by factor of 100 compared to LUX
- expected online 2019

XENON1T

- backgrounds 2 orders of magnitude lower than XENON100
- increase sensitivity by factor of 100
- expected come online 2016

Next generation of direct detection experiments also expected to come online

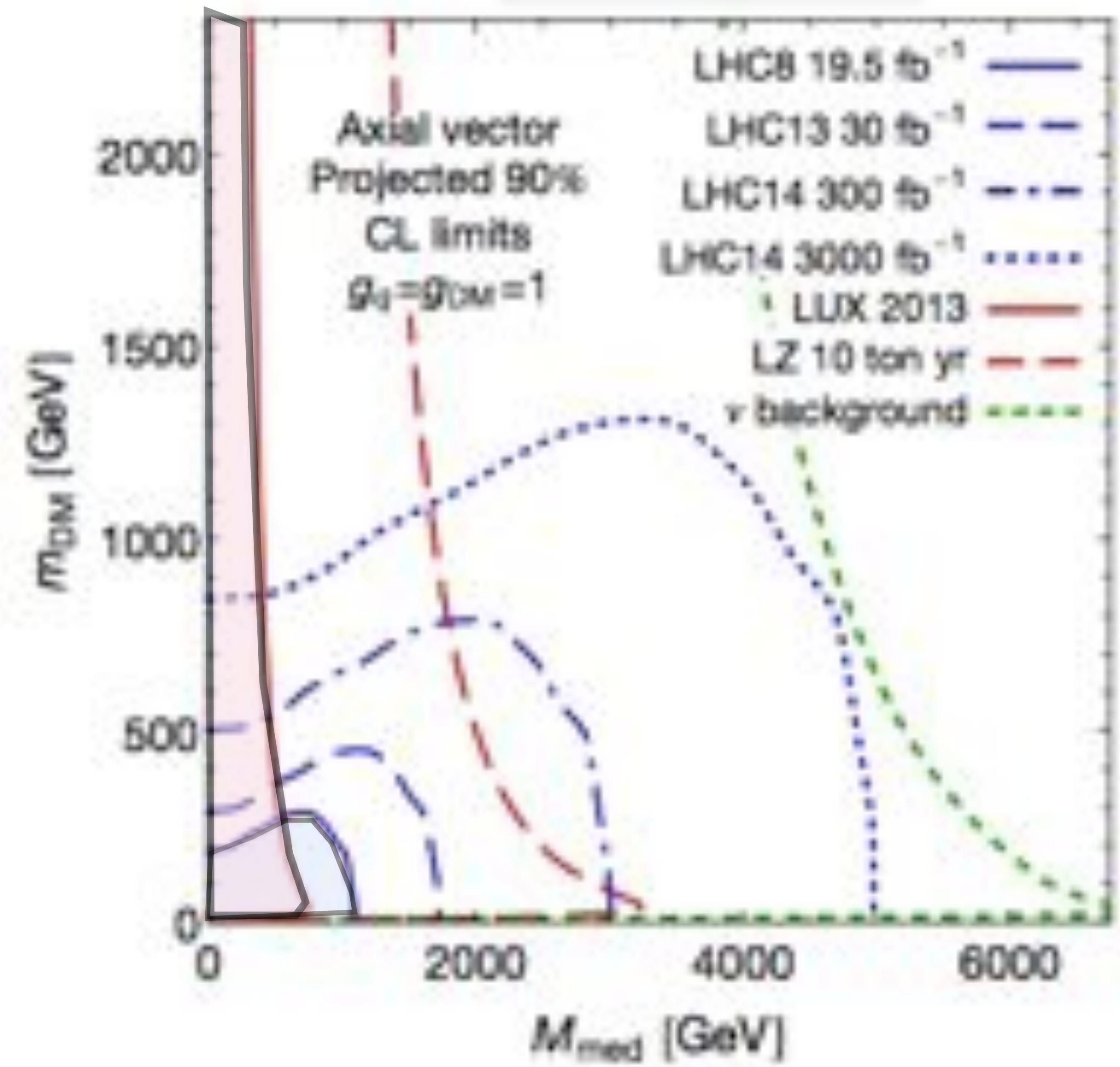
Future projections : direct detection experiments



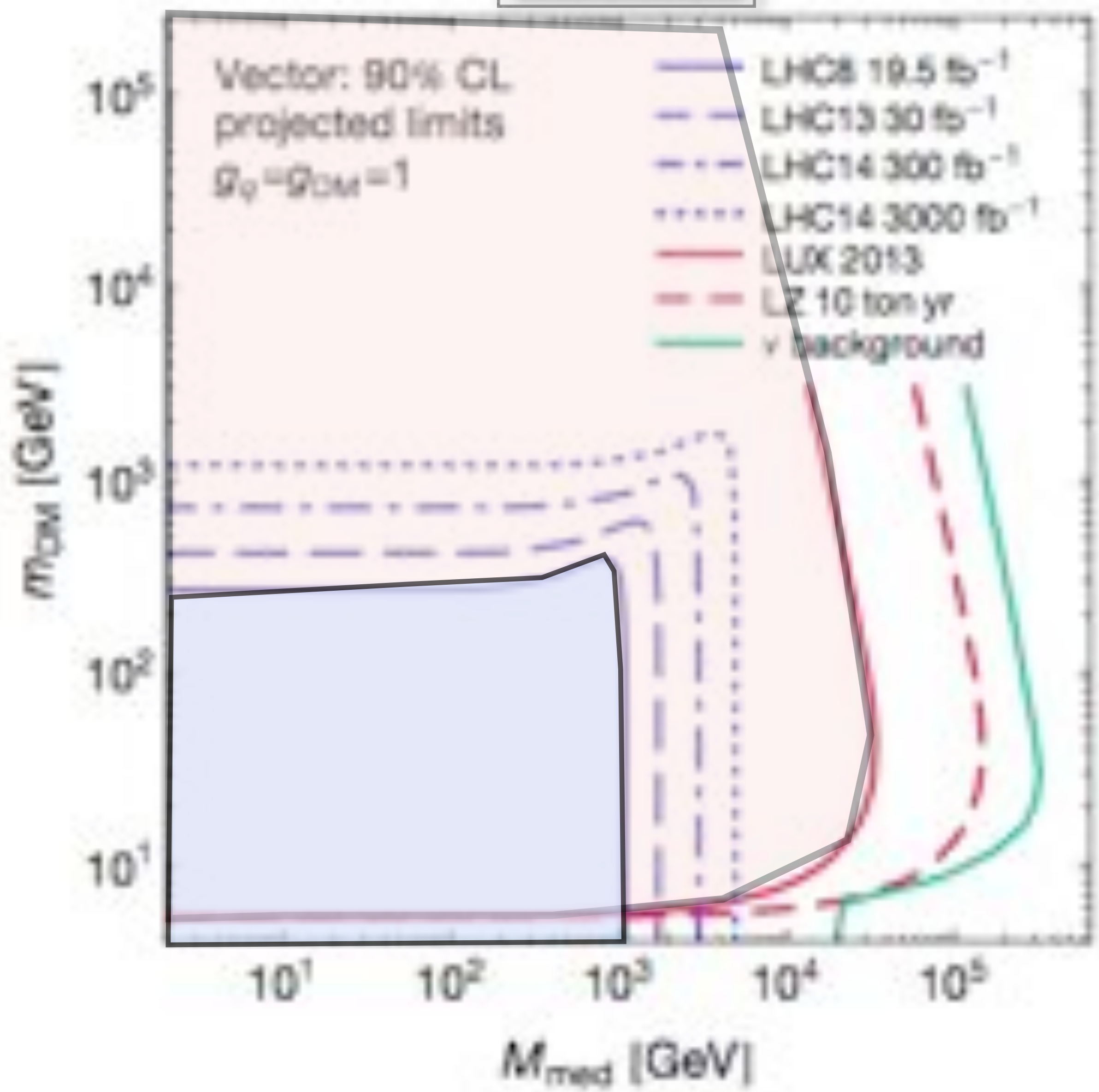
LHC - Run I

S.Malik et. al.
arXiv:1409.4075

Axial vector



Vector

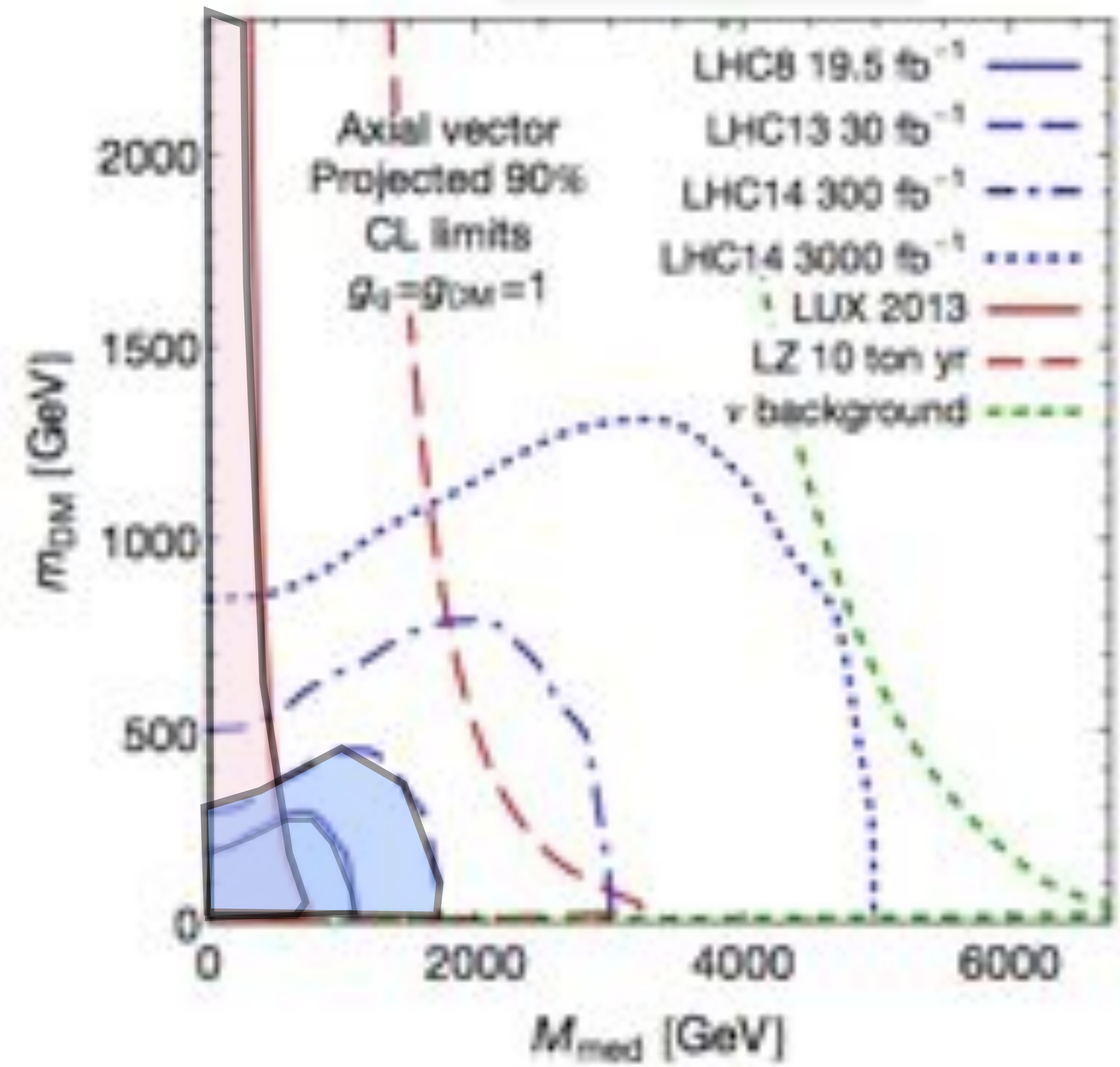


	2012	2015-2016	~2020	HL-LHC
Energy	8 TeV	13 TeV	13 TeV	13/14 TeV
Luminosity	20 fb^{-1}	30 fb^{-1}?	300 fb^{-1}	3000 fb^{-1}

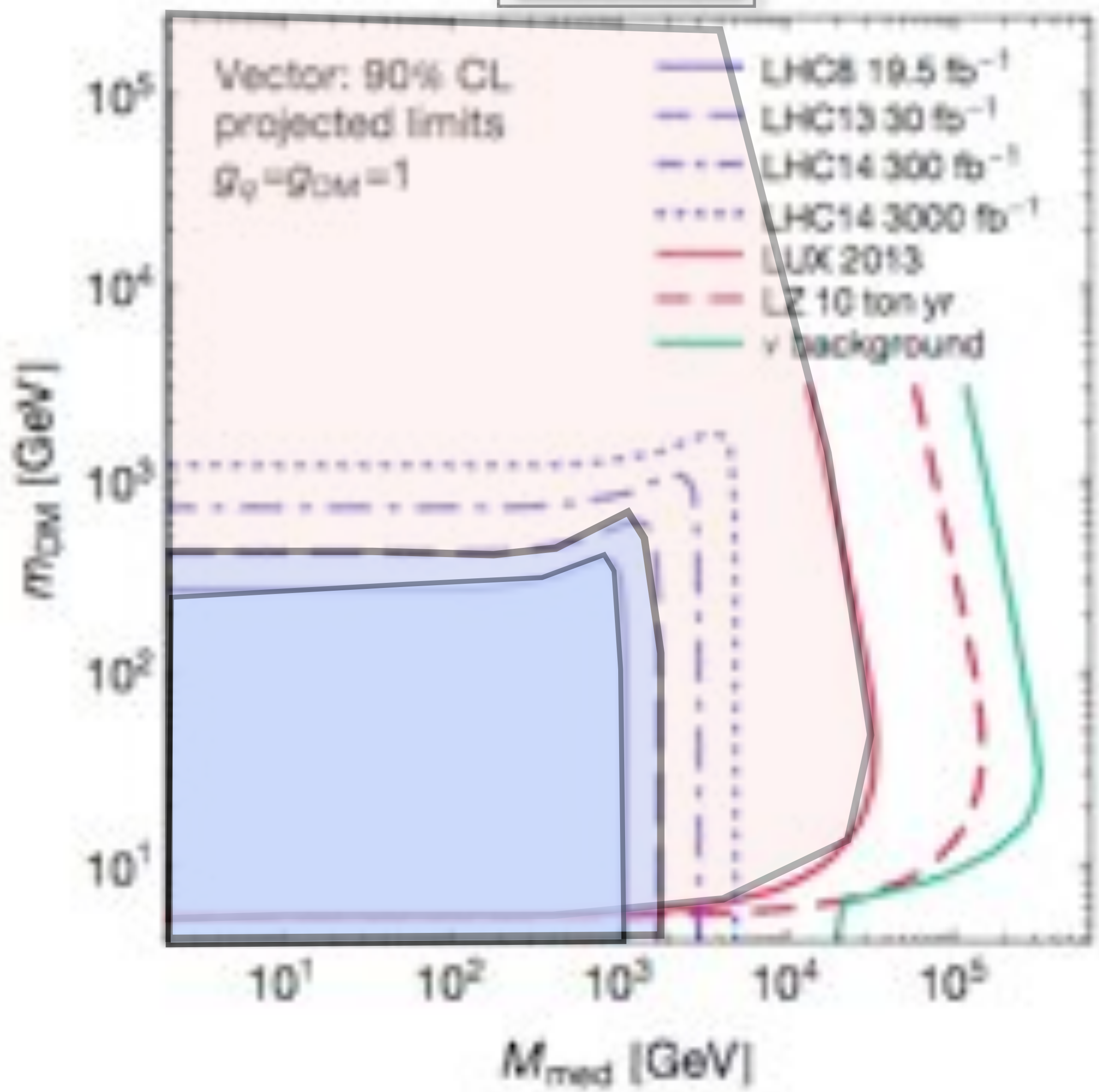
LHC - Run 2

S.Malik et. al.
arXiv:1409.4075

Axial vector



Vector



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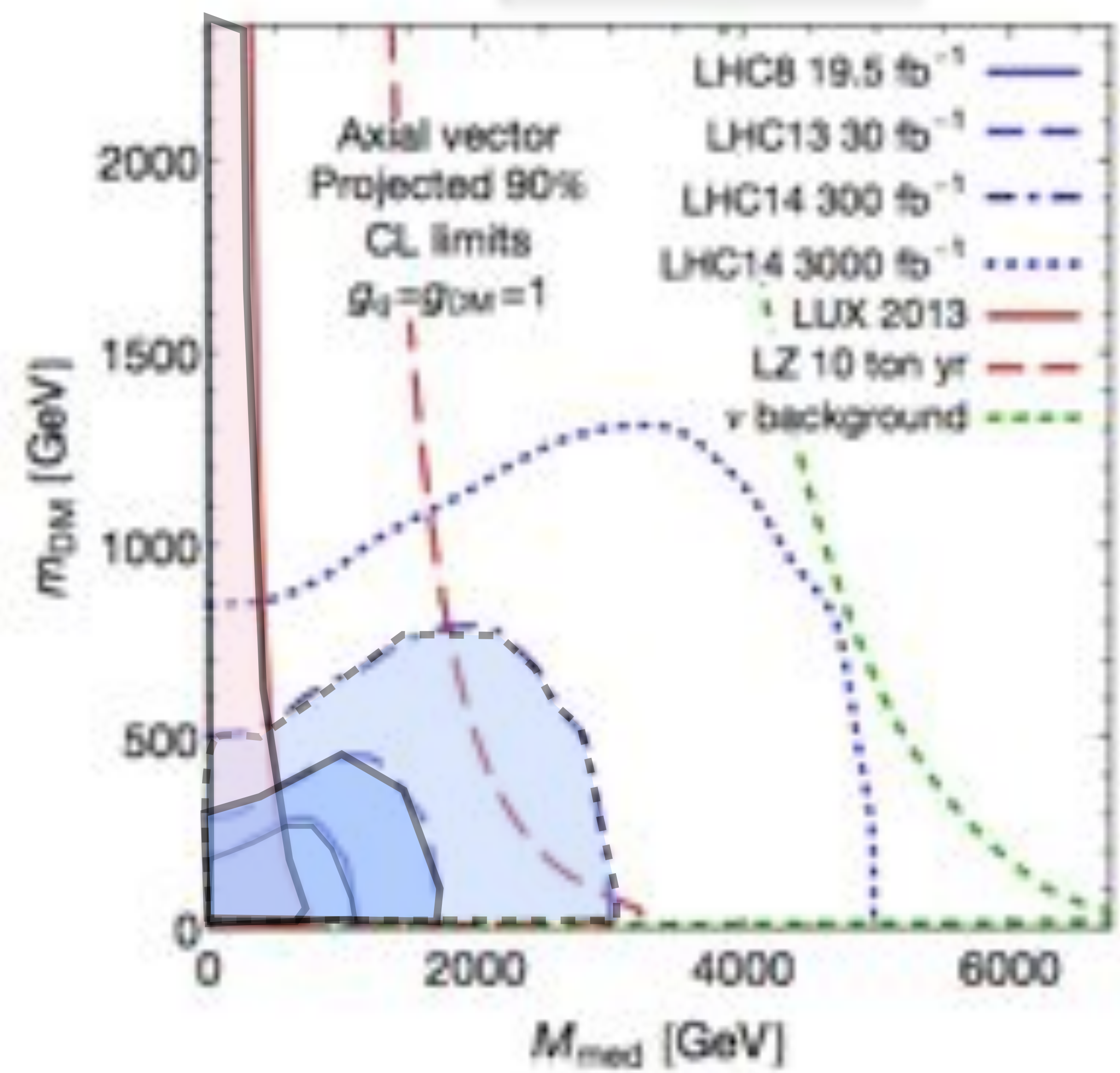
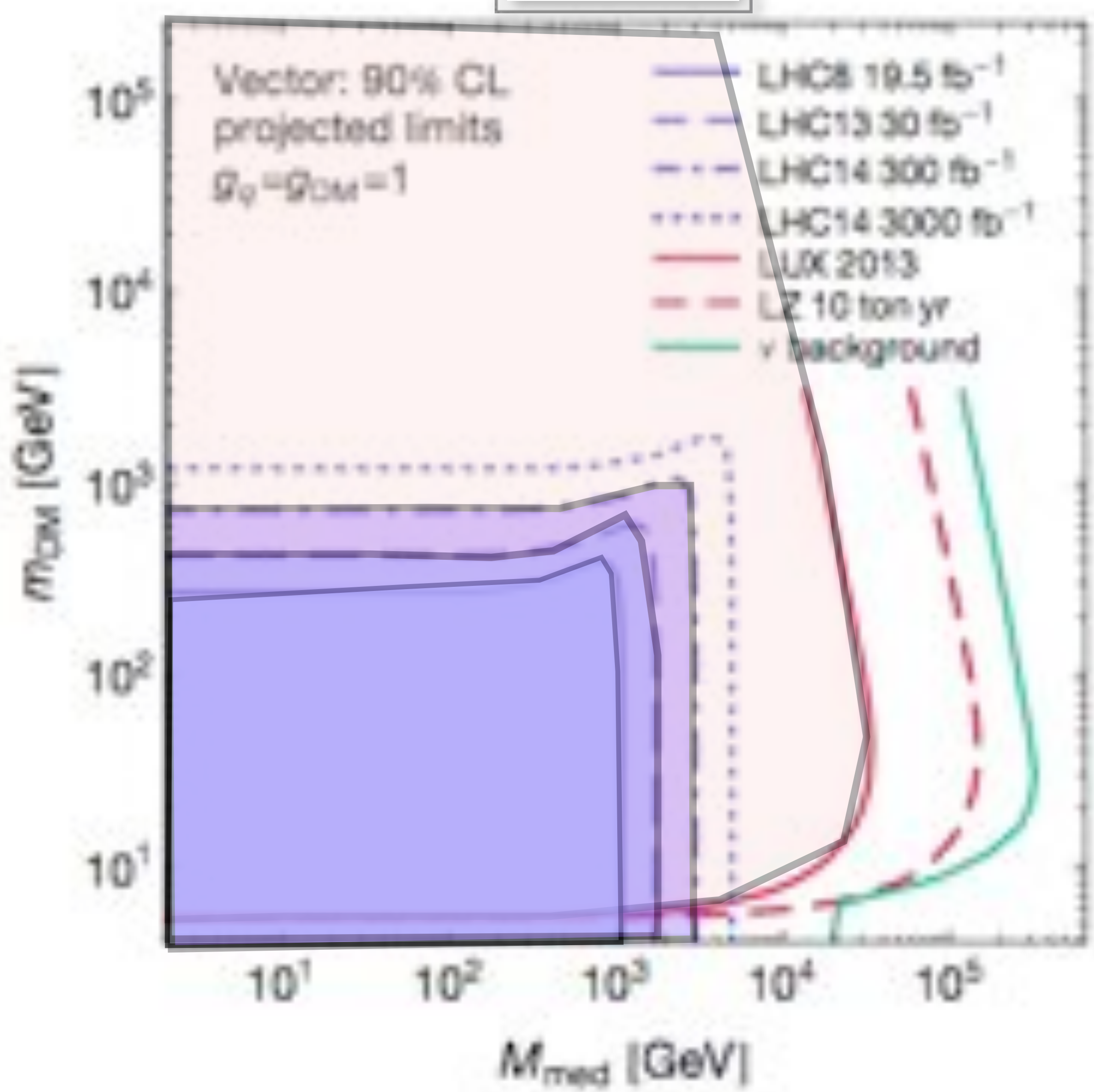
LHC - Run 2

S.Malik et. al.
arXiv:1409.4075

Axial vector



Vector



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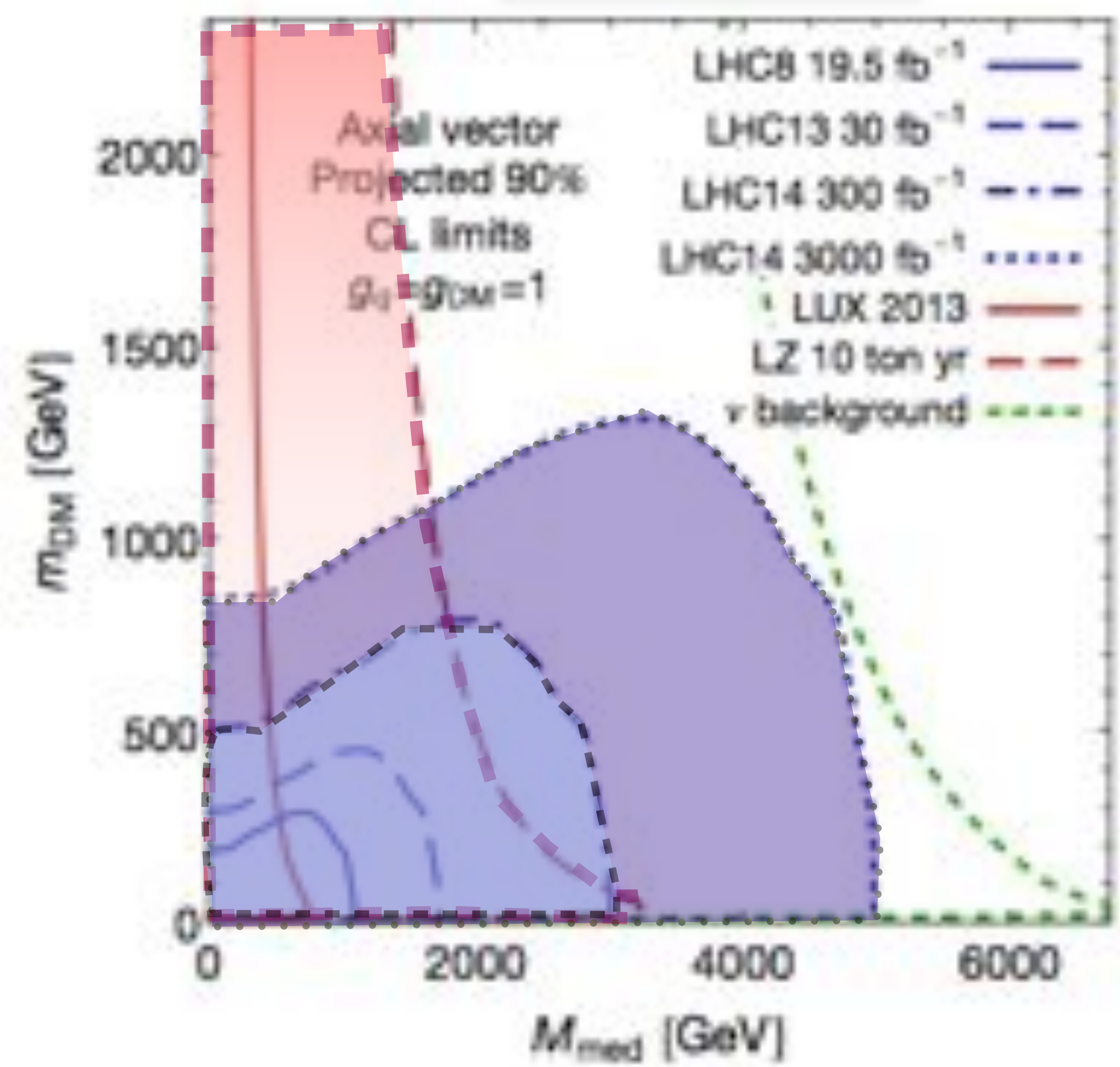
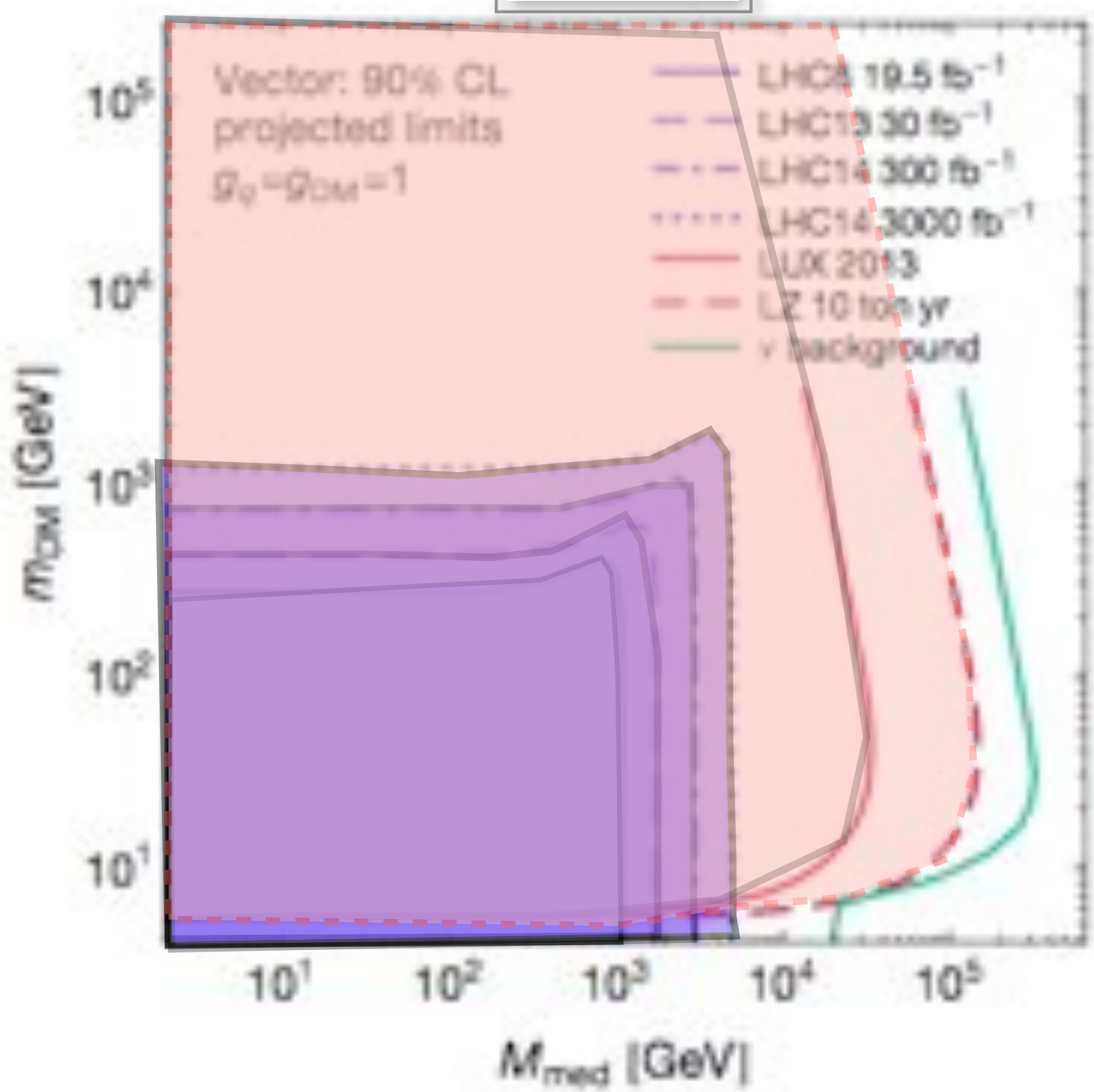
HL-LHC

S.Malik et. al.
arXiv:1409.4075

Axial vector



Vector



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Luminosity	20 fb^{-1}	30 fb^{-1}?	300 fb^{-1}	3000 fb^{-1}

HL-LHC

S.Malik et. al.
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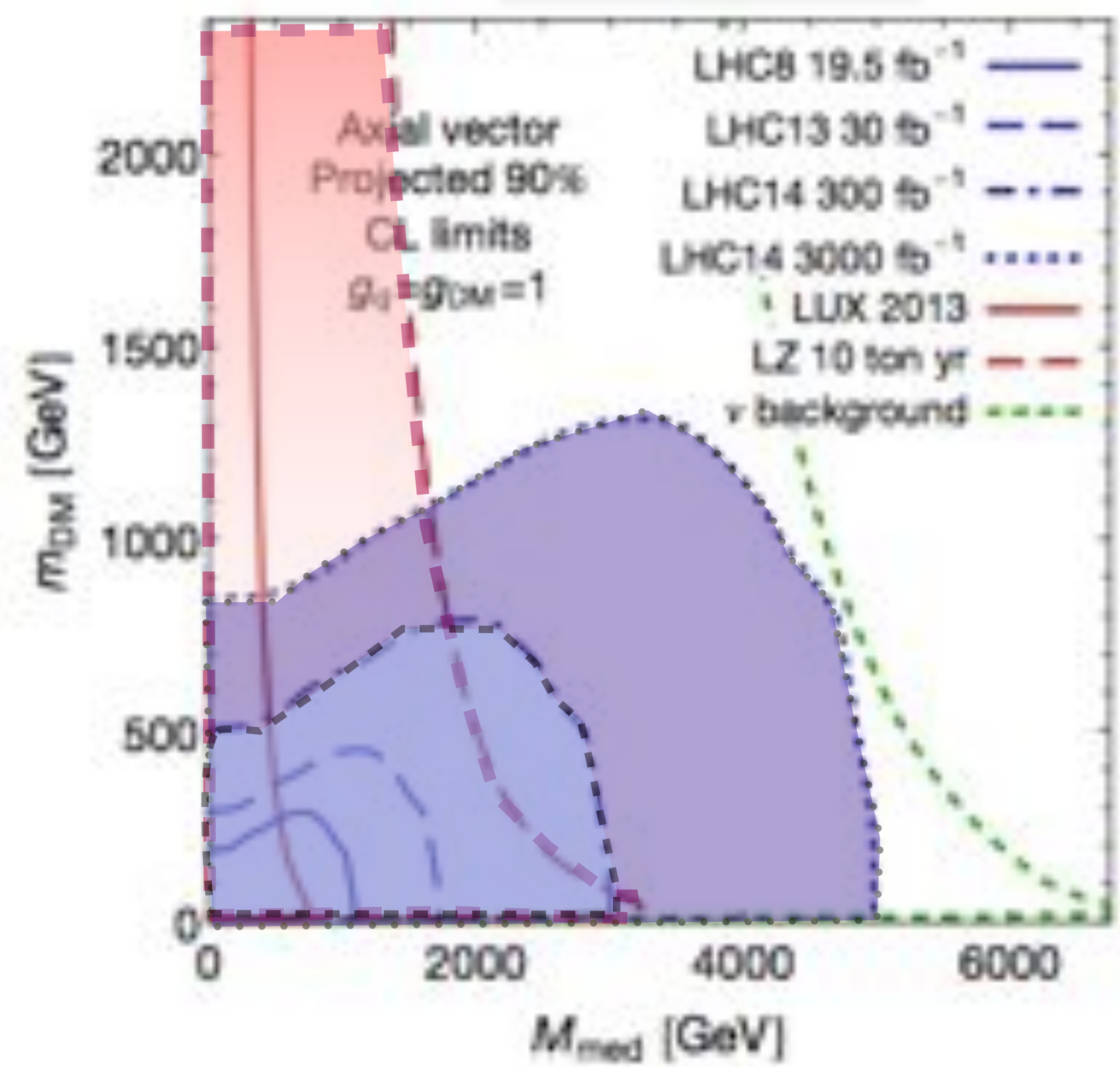
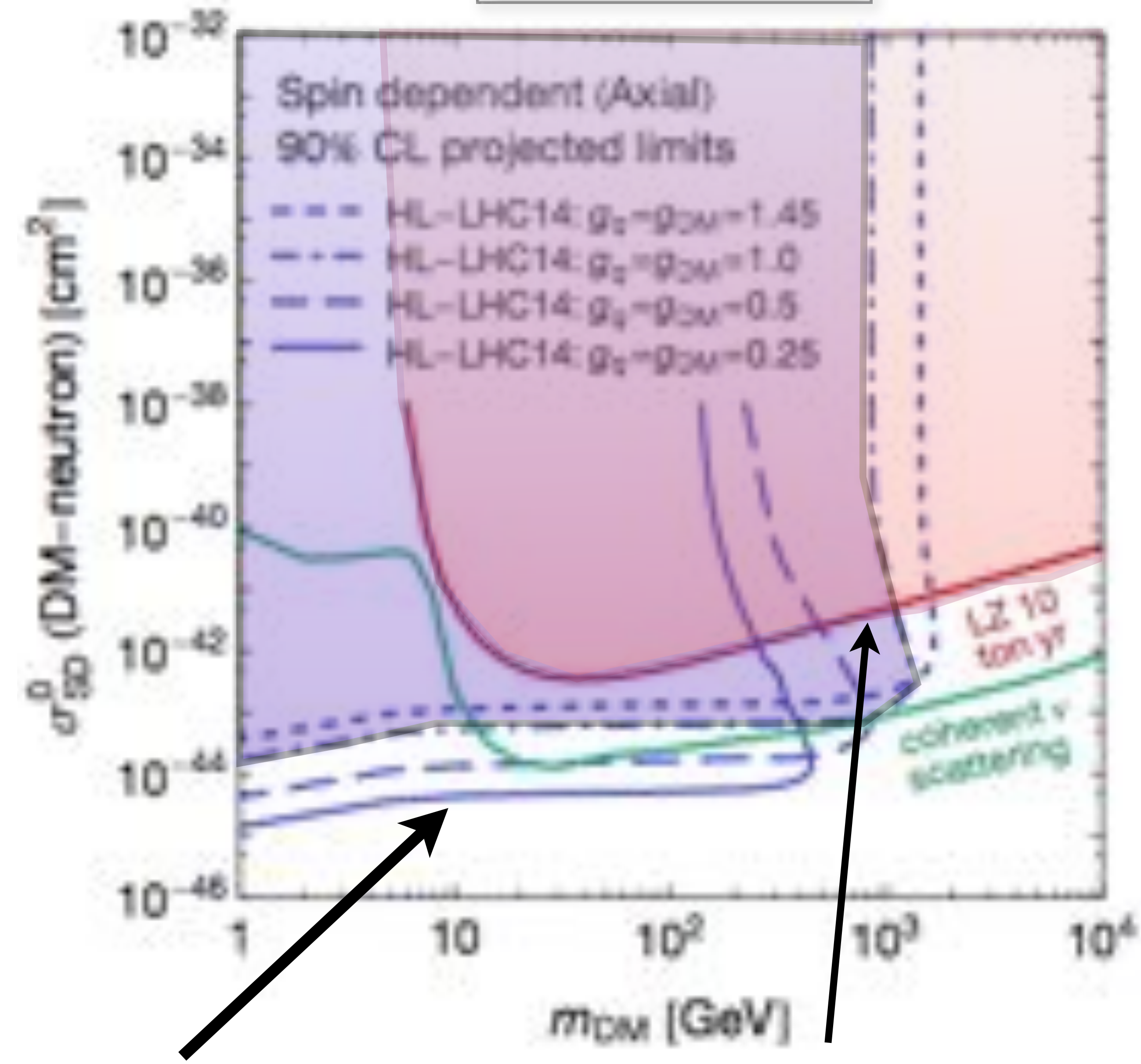
Axial vector



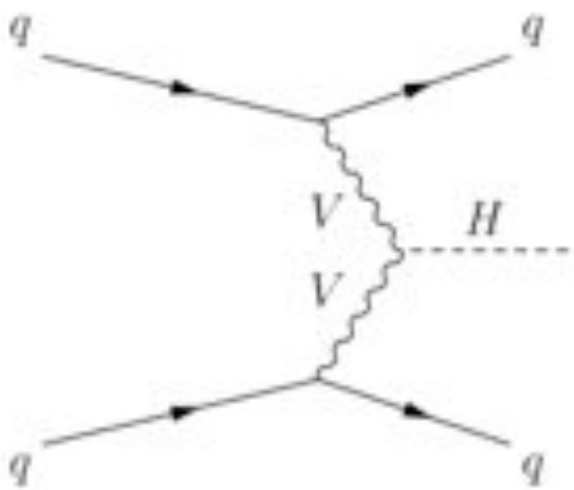
Axial vector

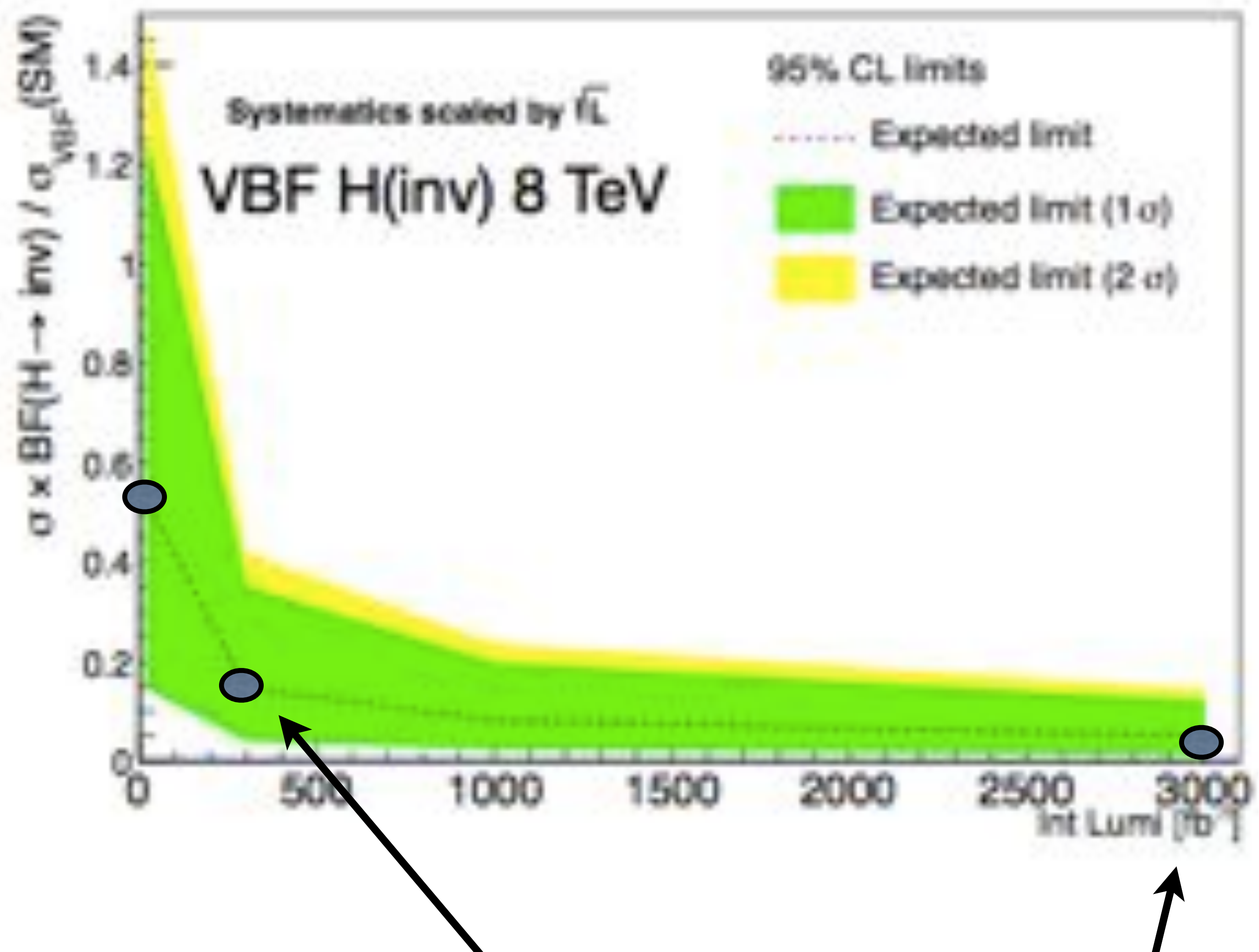


Colliders able to probe all the way up to and beyond neutrino barrier with HL-LHC

reach of next generation of DD expt

Projections for Higgs--> invisible





	2012	~2020	HL-LHC
Energy	8 TeV	13 TeV	13/14 TeV
Luminosity	20 fb^{-1}	300 fb^{-1}	3000 fb^{-1}

Studies on future projections with 14 TeV, High Luminosity LHC 3000 fb^{-1} show that we may be able to constrain BF($H_{125}\rightarrow$invisible) at few-% level

Summary

➡ Searches for Dark matter at collider:
- via UV complete models like SUSY
- via generic mono-X signatures
- Higgs invisible decays

➡ Interpretation of searches:
- Shift from effective field theory approach which has several limitations to simplified models
- Mediator also accessible to collider, can be constrained from other collider searches

➡ Complementarity with direct detection experiments
- low mass DM
- spin-dependent interactions of DM

➡ Future projections, similar complementarity between collider and DD experiments
- Collider can probe all the way upto and beyond neutrino floor for some DM models
- Exclude/confirm an excess in the direct/indirect detection experiments