Loopy Ideas About Dark Matter

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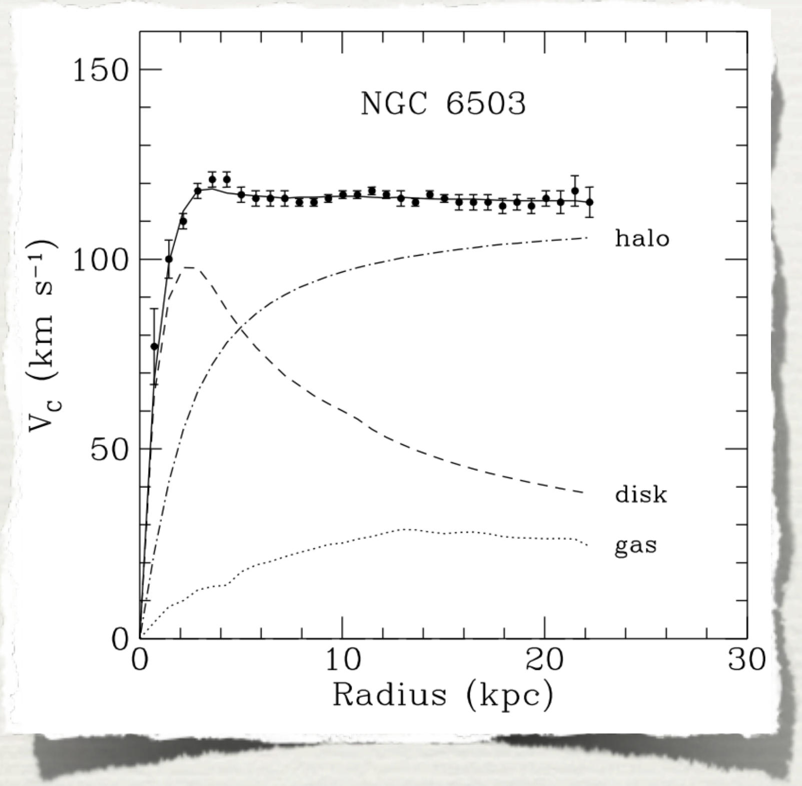
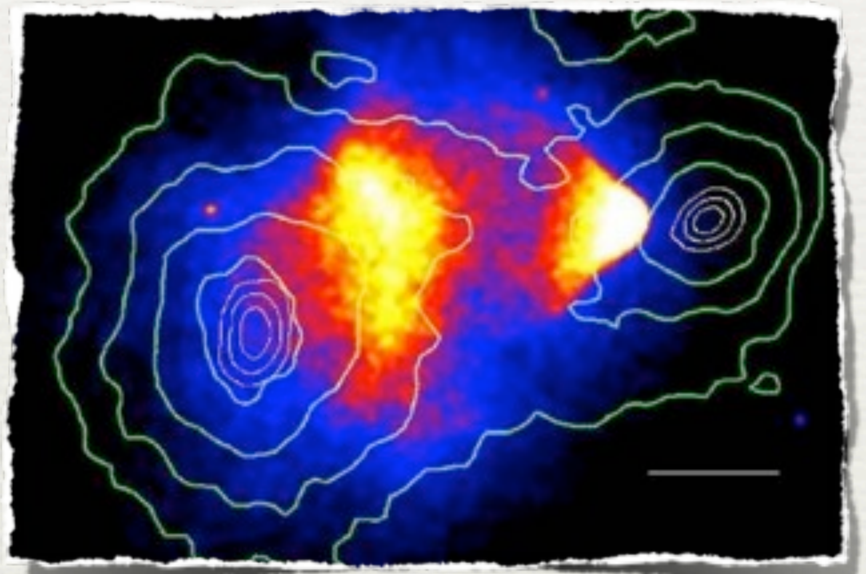
based on 1208.4605, 1302.4454 & 13xx.xxxx
with Kahlhoefer, Re & Unwin

LHC - The First Part of the Journey, KITP, Santa Barbara, July 8-12, 2013

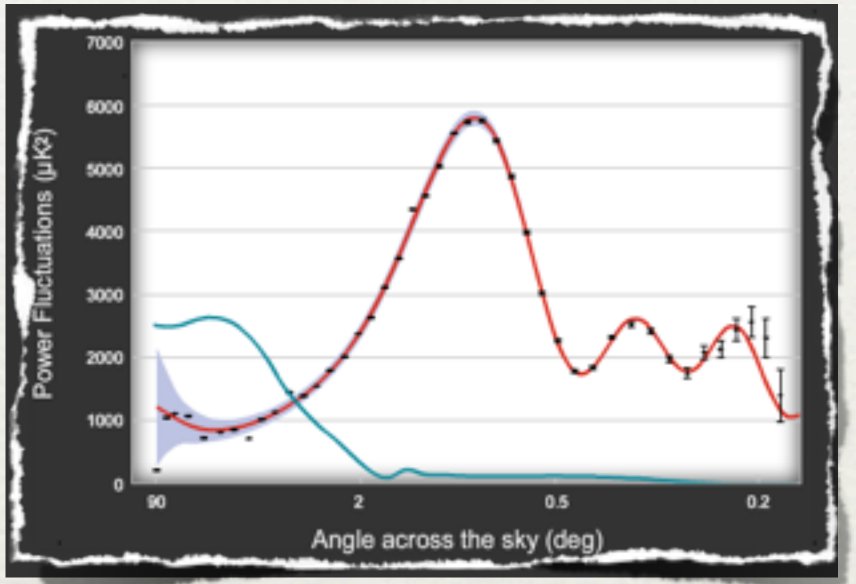
Evidence For Dark Matter



Galactic scales



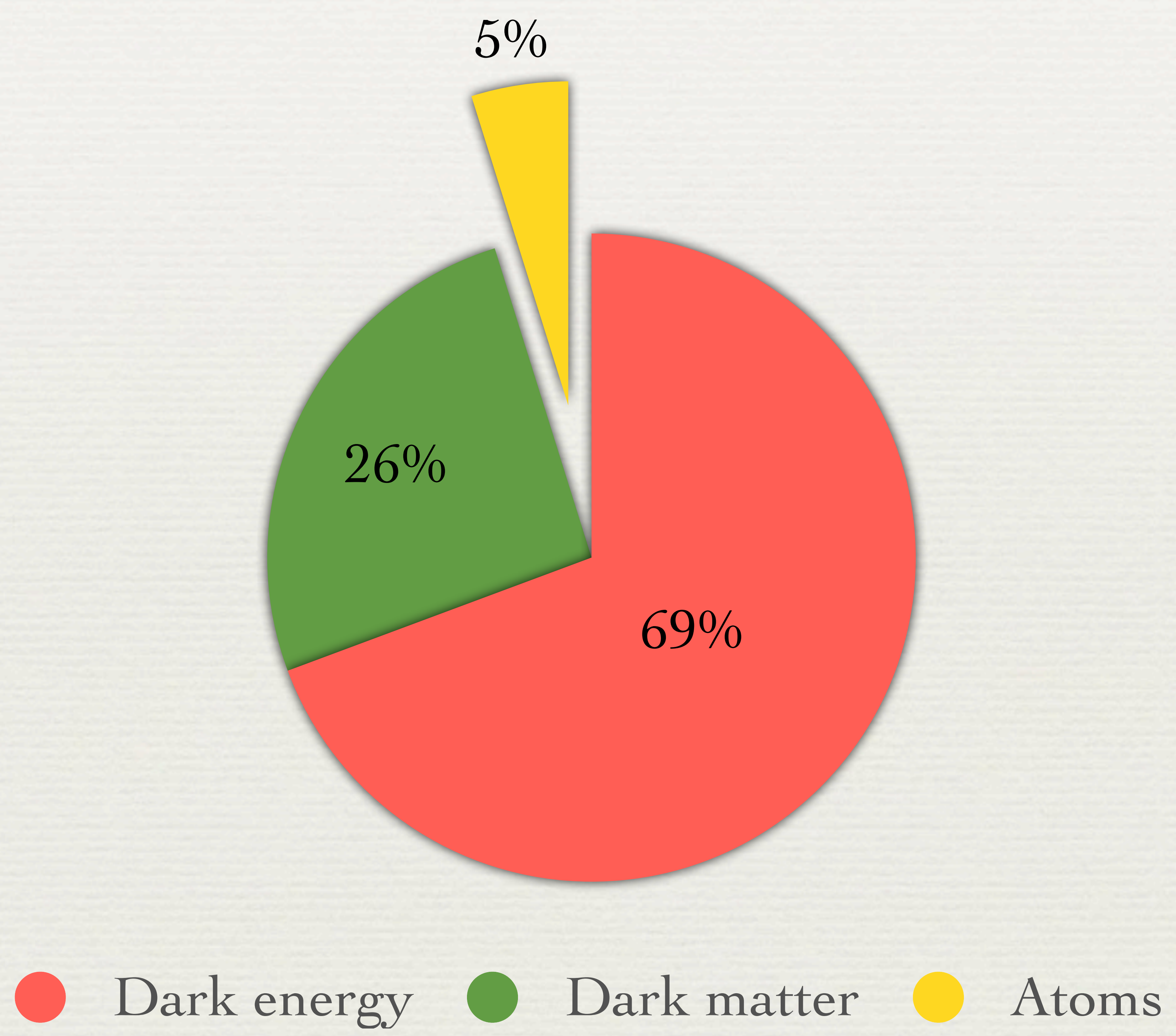
Galaxy cluster scales



Cosmological scales

Conclusive observational evidence for dark matter (DM) over a wide range of astrophysical scales

Evidence For Dark Matter



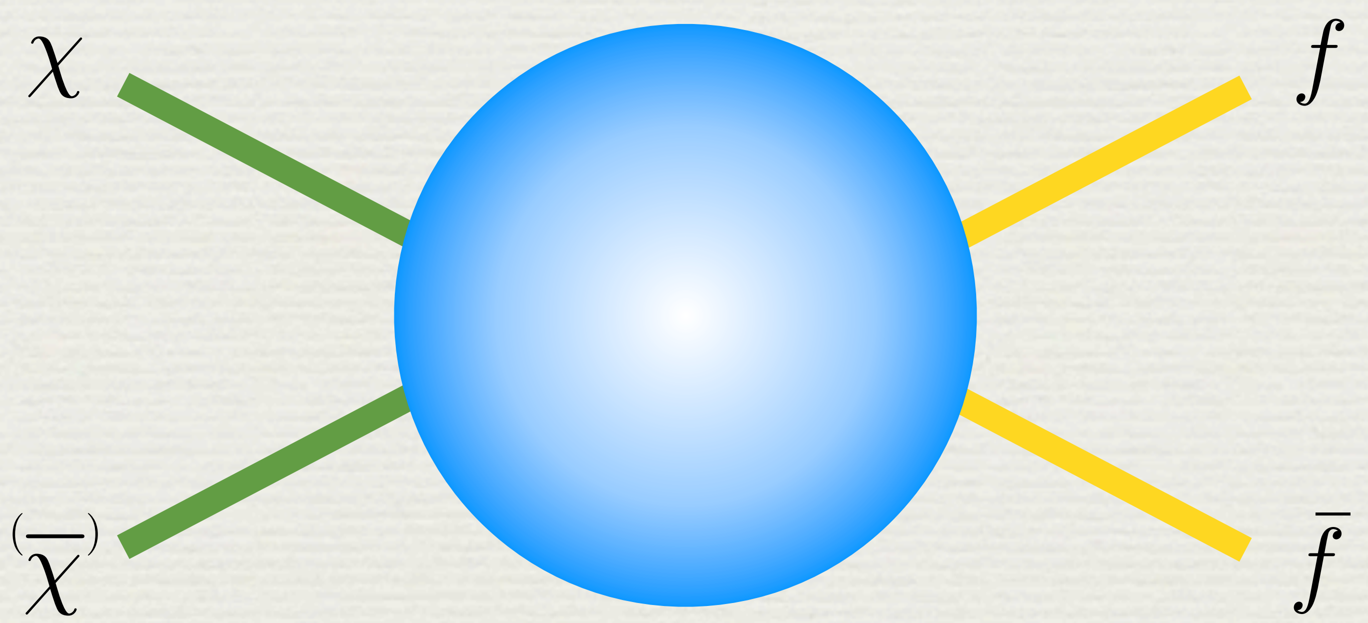
[Planck, 1303.5076]

Particle Candidates For DM

- Most popular candidate is WIMP, a cold thermal relic with weak-scale mass & interactions (e.g. lightest supersymmetric particle) which can have required relic abundance: the WIMP miracle
- But many alternative exists:
  - Asymmetric DM (same origin as baryon asymmetry)
  - Warm DM (e.g. sterile keV neutrinos)
  - Axions
  - ...

Detecting DM Particles

- For most DM candidates, one expects some interactions with Standard Model (SM) particles, leading to a thermal equilibrium in early universe



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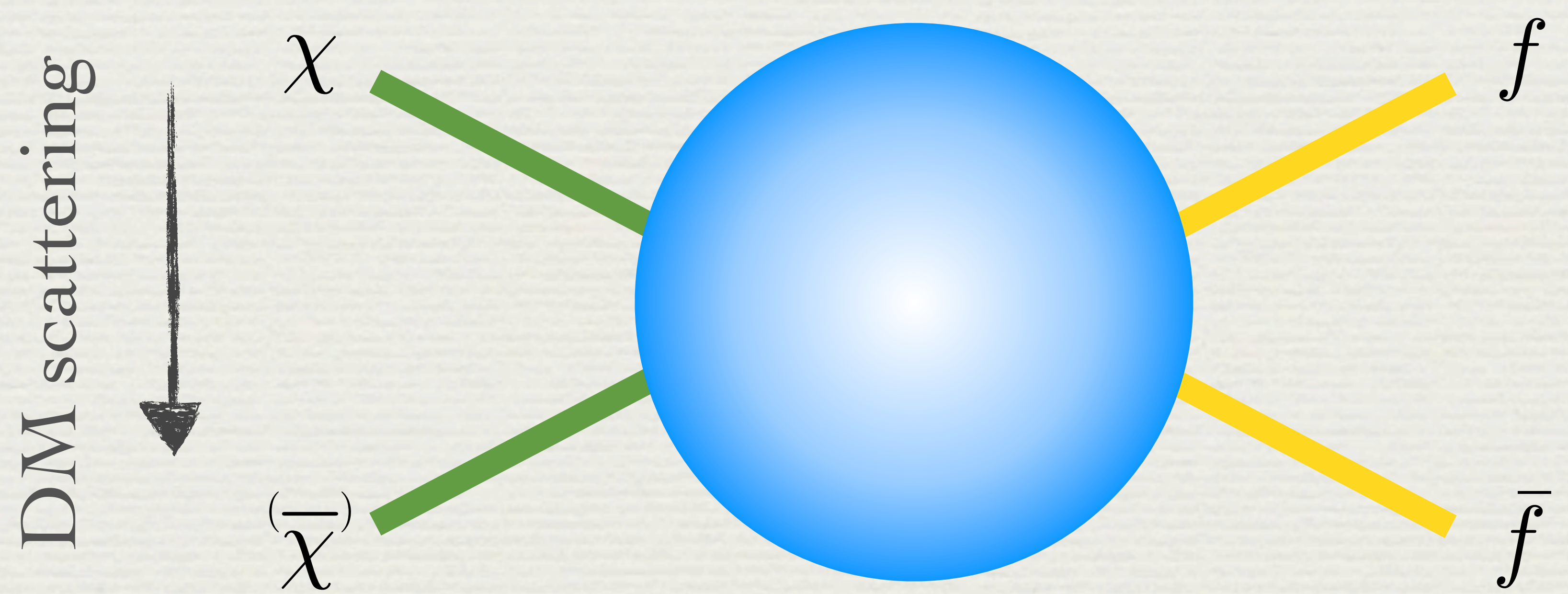

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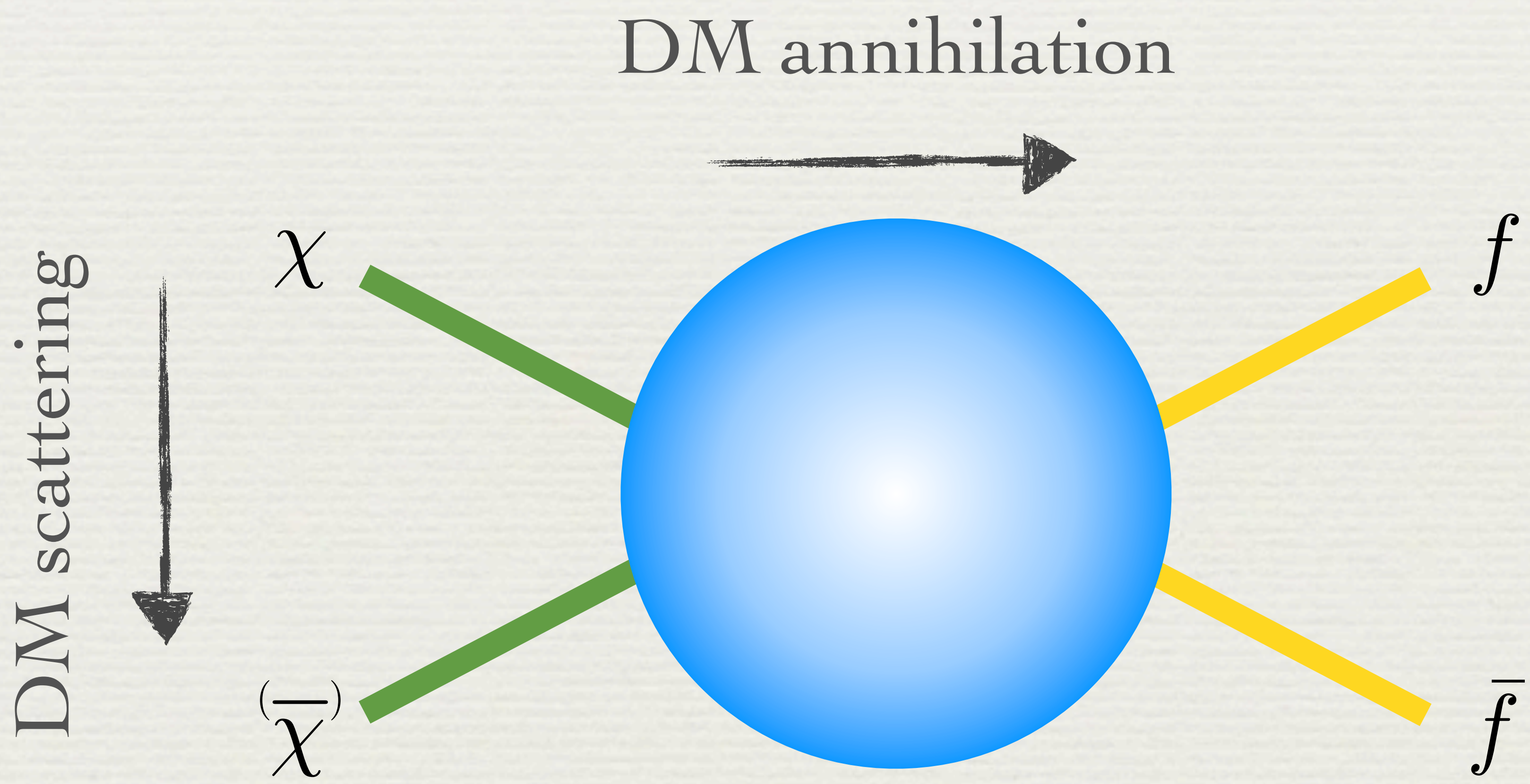

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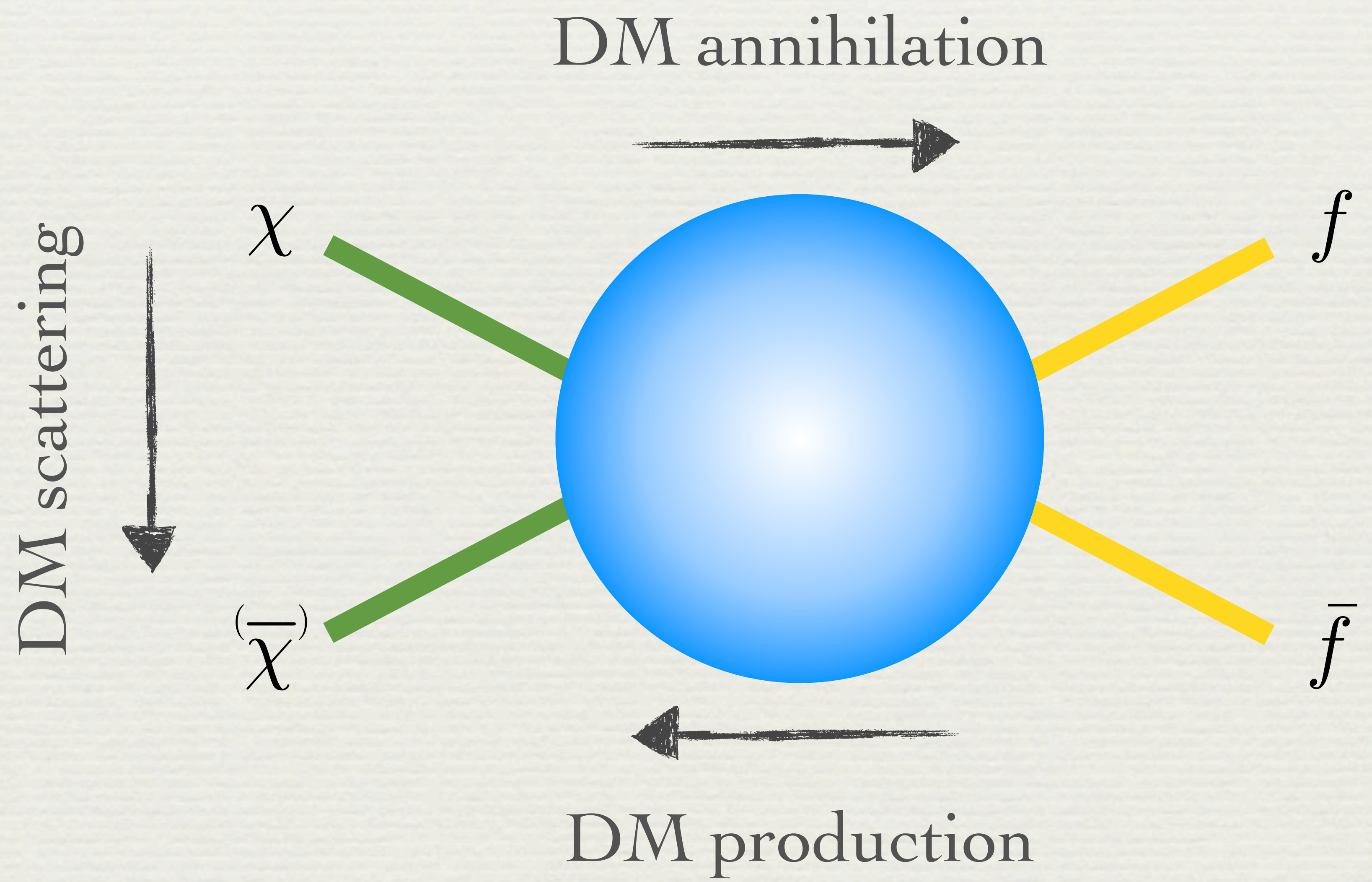
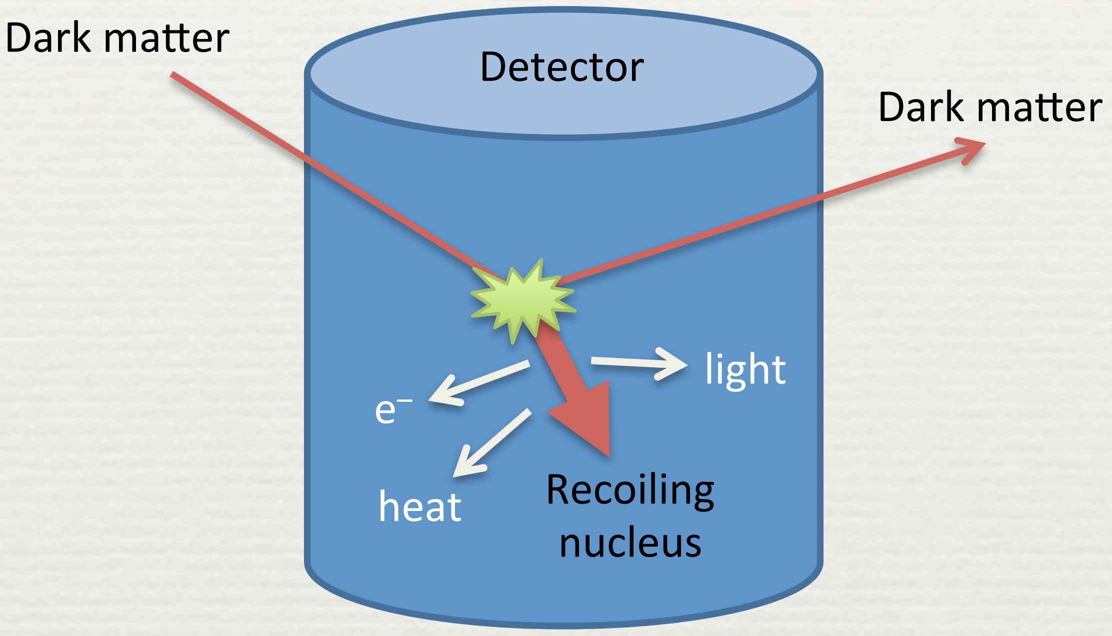


DM Direct Detection

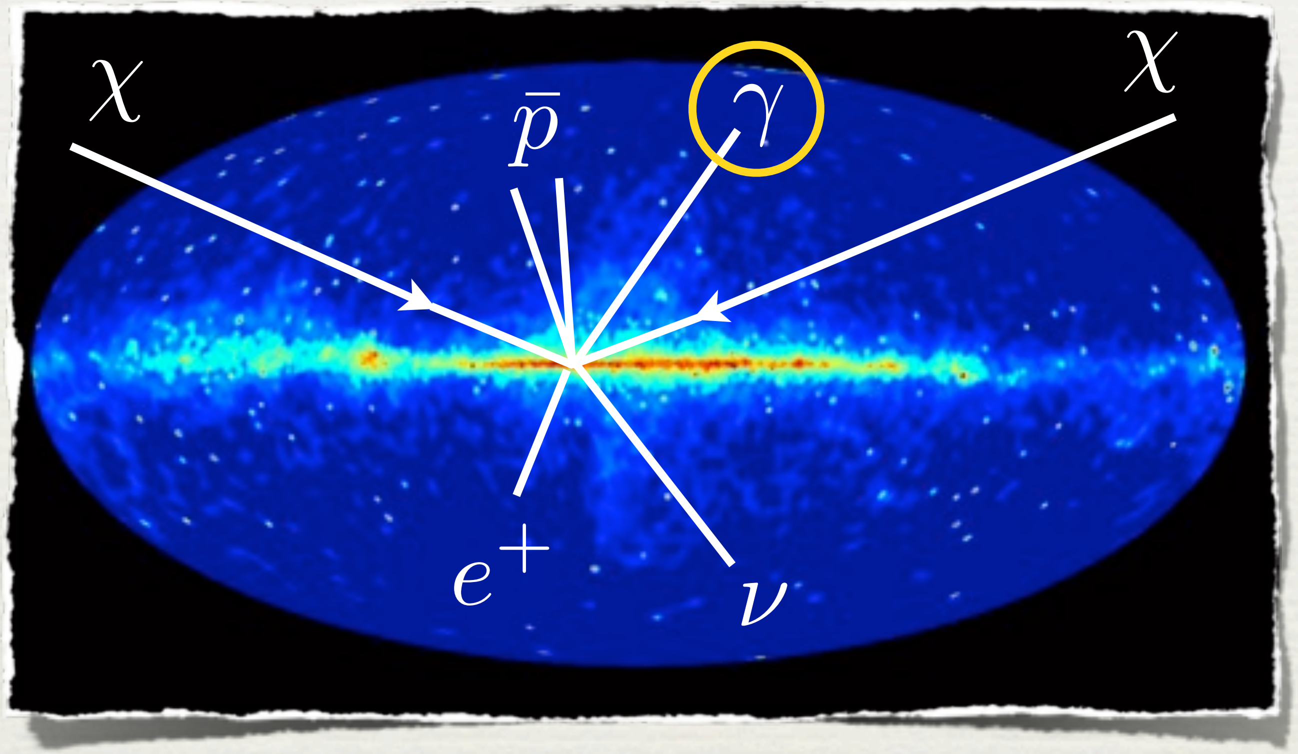
- DM particles from galactic halo pass through earth & will occasionally scatter off nuclei
- Resulting recoil energy of nucleus can be measured in dedicated low background detectors



Typical event rates less than 1 event per kg per year.
A great experimental challenge

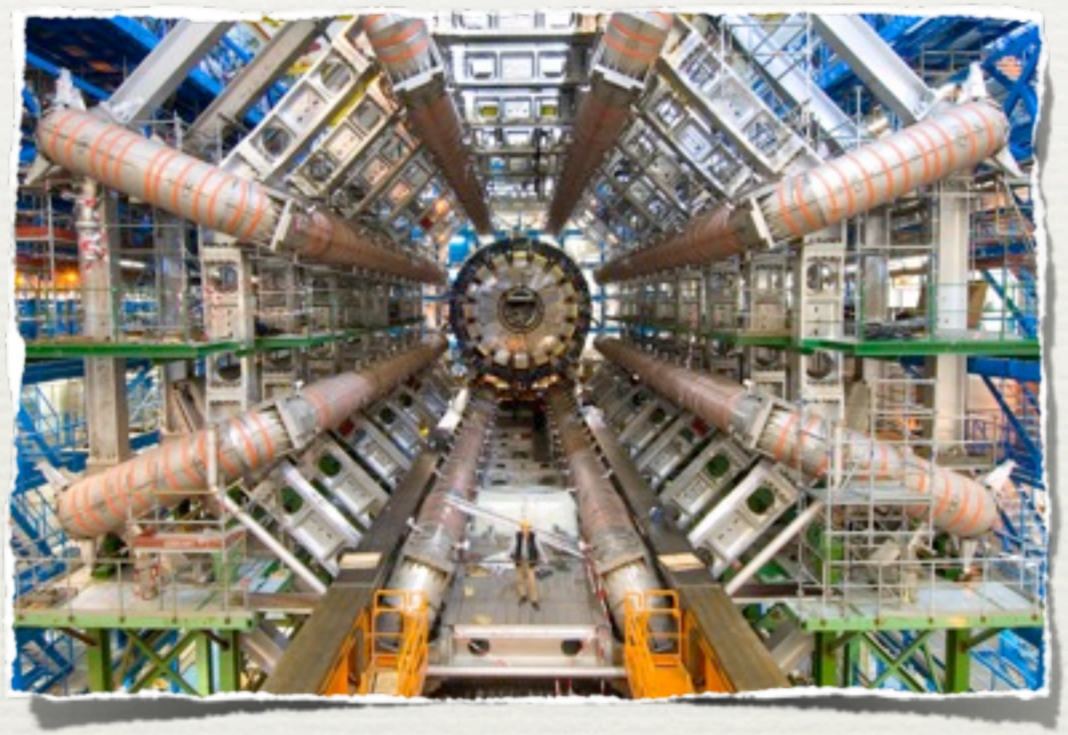
DM Indirect Detection

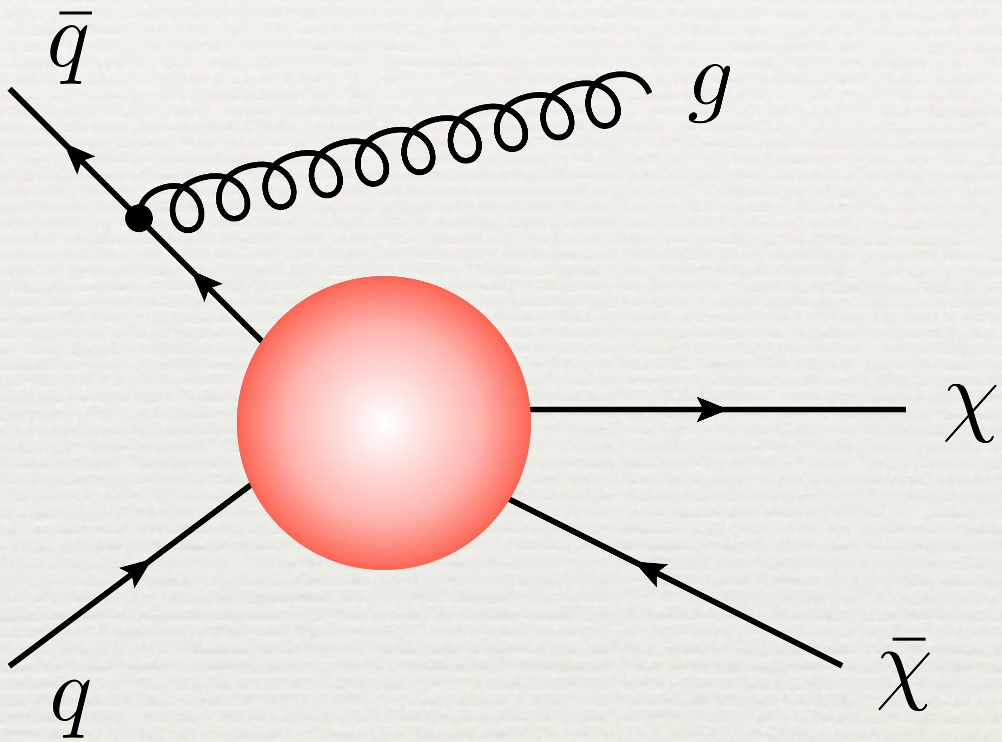
- Indirect detection experiments search for products of DM annihilation in regions of high DM density (e.g. galactic centre) with satellites, ballons & telescopes



Difficulties arise from astrophysical backgrounds & unknown DM density profile

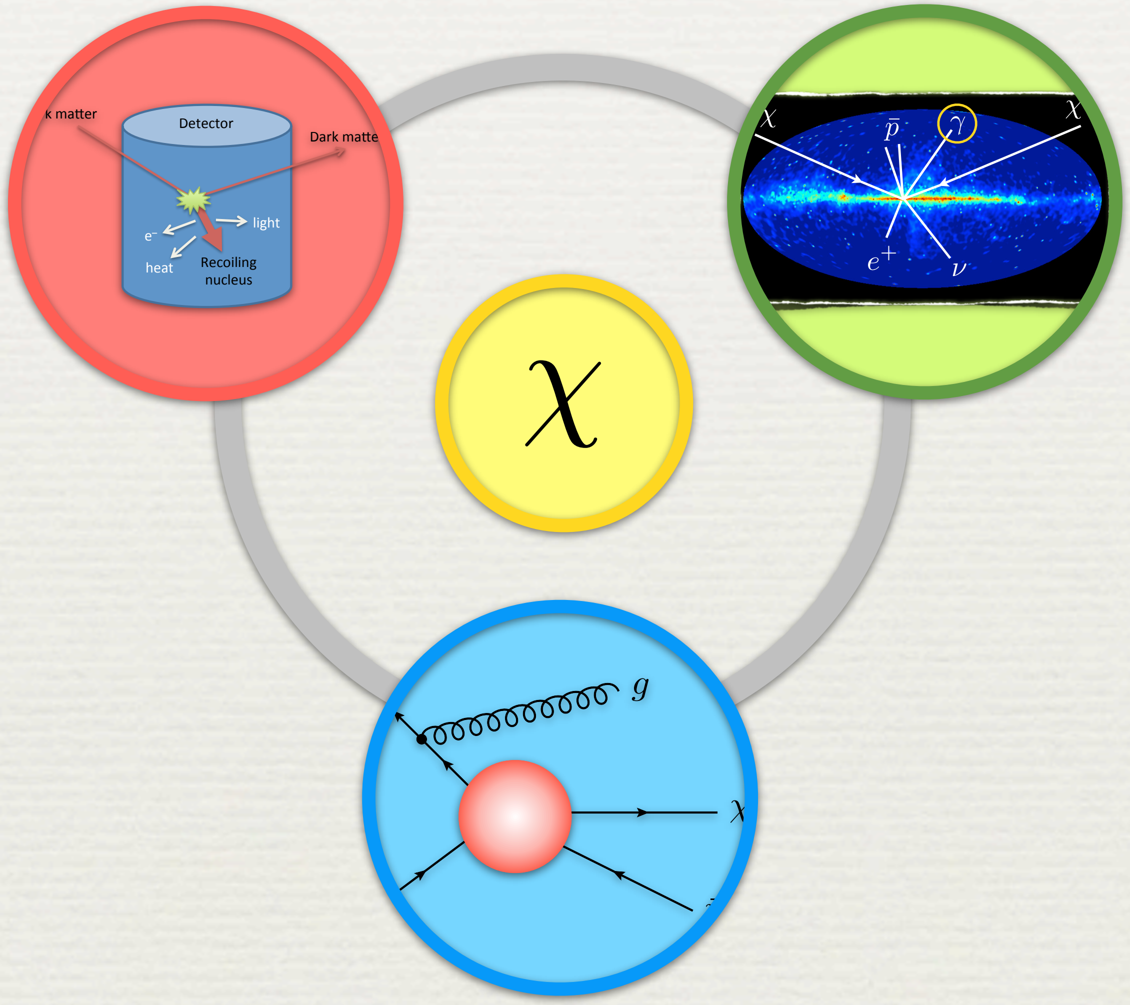
DM Searches At Colliders





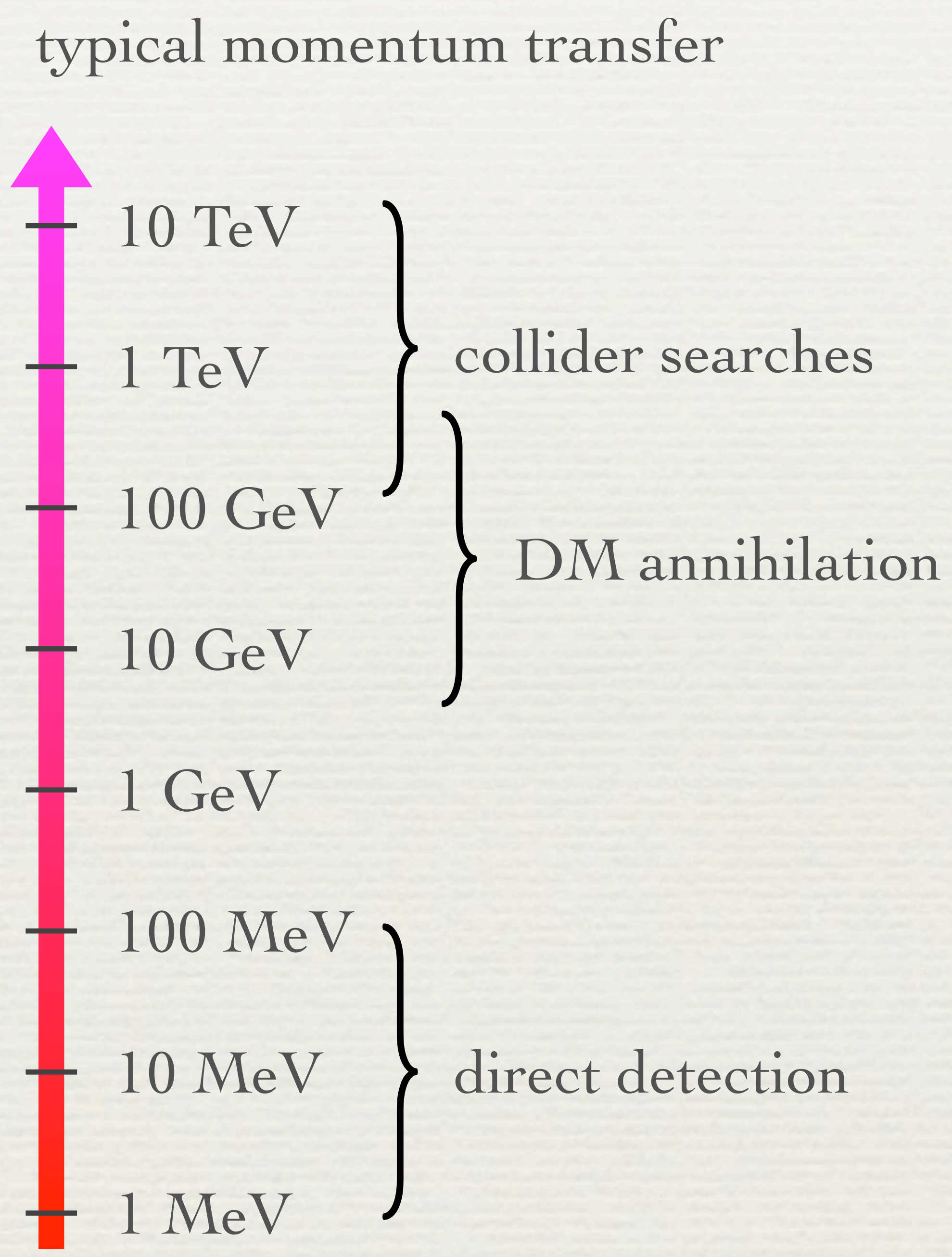
Any DM particle produced directly at collider escapes detector unnoticed. But if DM pair is produced in association with a jet or photon, will observe large amount of missing transverse energy

Synergy & Complementarity



If DM particles give signal in one search, expect to see related processes with distinctive signature in other searches. Conversely, can translate bounds from one kind of search strategy to another

Synergy & Complementarity



- While LHC probes TeV scale, DM direct detection tests non-relativistic limit ($v \approx 10^{-3} \cdot c$)
- Interactions that look very similar at LHC might look quite different in direct detection

Synergy & Complementarity

- Assume that DM particle interacts with quarks via exchange of spin-1 mediator which couples to

$$\bar{\chi}\gamma_\mu\chi \qquad\qquad \bar{\chi}\gamma_\mu\gamma_5\chi$$

- At LHC: impossible to distinguish between vector & axial couplings since mono-jet cross sections essentially the same

- In direct detection:

vector couplings ➡ spin independent: $\sigma \propto A^2 = O(10^4)$

axial couplings ➡ spin dependent: $\sigma \propto 1$

mixed couplings ➡ momentum suppressed: $\sigma \propto v^2$

Effective Theory Of DM

- To compare LHC measurements to direct detection, useful to describe interactions between DM & SM particles in terms of effective operators, which arise from integrating out heavy mediators. E.g.:

$$\mathcal{O}_V = \frac{1}{M_*^2} (\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)$$

vector operator: spin independent

$$\mathcal{O}_{AX} = \frac{1}{M_*^2} (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$$

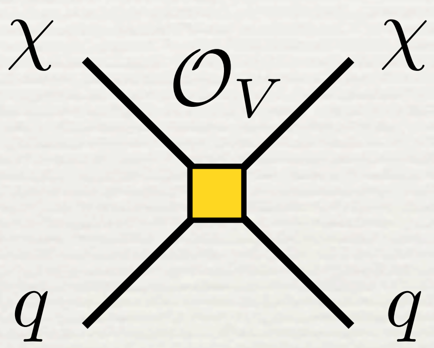
axial operator: spin dependent

$$\mathcal{O}_{AN} = \frac{1}{M_*^2} (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu q)$$

anapole operator: momentum dependent

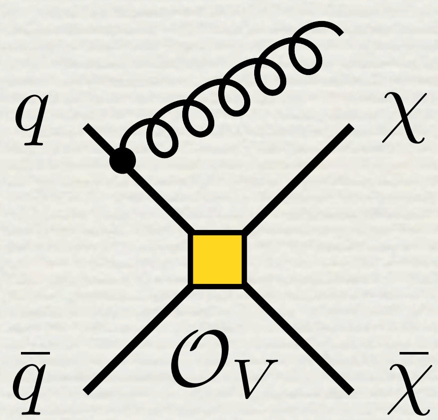
Direct Detection vs. LHC

- Direct detection cross section per nucleon reads



$$\sigma_N^{\mathrm{SI}} \propto \frac{m_{\mathrm{red}}^2}{M_*^4} \qquad m_{\mathrm{red}} = \frac{m_\chi m_N}{m_\chi + m_N}$$

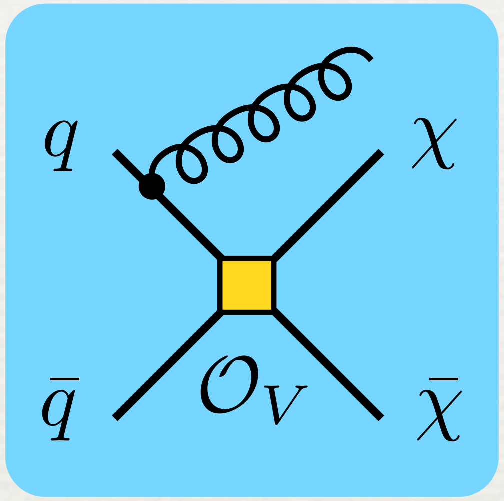
- Mono-jet cross section given by



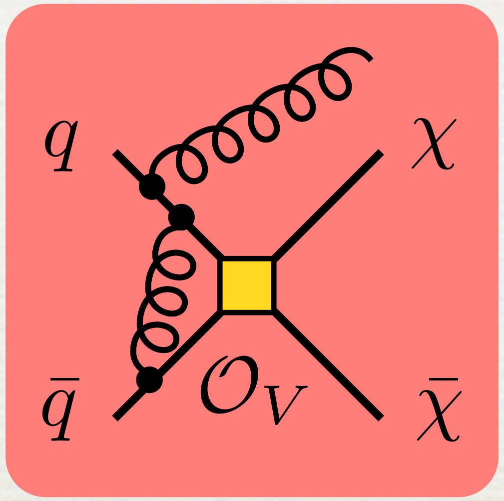
$$\sigma_{j+\not{E}_T} \propto \frac{1}{M_*^4} \propto \sigma_N^{\mathrm{SI}}$$

Provided effective theory applicable at LHC, can directly relate mono-jet (-photon) searches & direct detection experiments

POWHEG Goes DM



LO



NLO

[UH, Kahlhoefer & Re, 13xx.xxx]

m_χ [GeV]	M_* in $\mathcal{O}_V$ [GeV]
10	786^{+16}_{-22}
20	785^{+17}_{-21}
50	784^{+17}_{-22}
100	782^{+15}_{-21}
200	765^{+18}_{-20}
500	623^{+11}_{-16}
1000	335^{+6}_{-10}

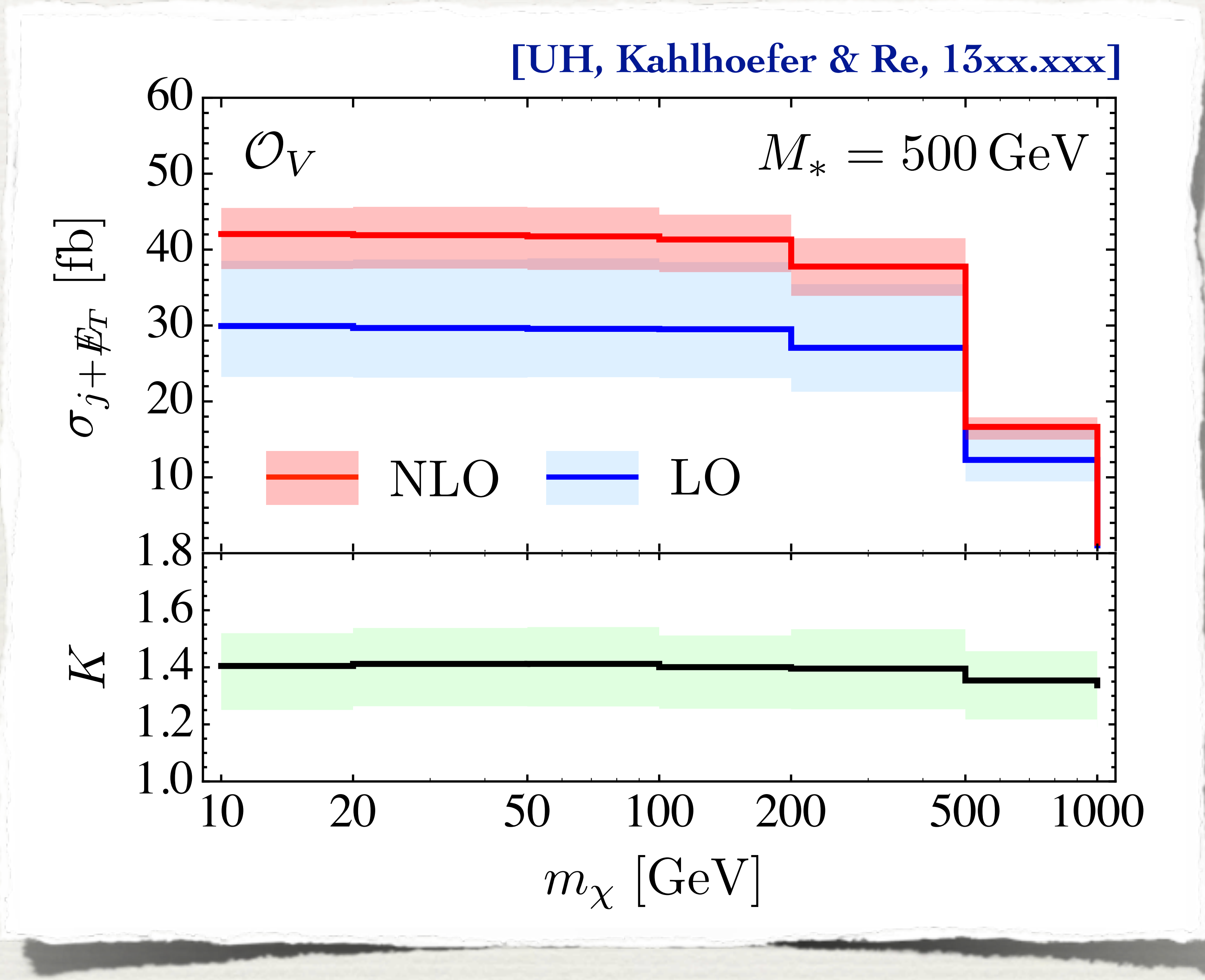
LHC 7 TeV:

$$\not{E}_T, p_T^{j_1} > 500\,\text{GeV}$$

$$|\eta_{j_1}| < 2 \qquad |\Delta\phi_{\not{\vec{p}}_T, \vec{p}_T^{j_2}}| > 0.5$$

[see also MCFM implementation by Fox & Williams, 1211.6390]

POWHEG Goes DM



Including NLO corrections reduces scale uncertainties by a factor of 3. Constant K factor of about 1.4 for m_χ < 1 TeV

Operator Mixing

- So far, have ignored an important aspect: to calculate direct detection cross sections, must evolve effective operators from new-physics scale M_* down to hadronic scale m_N
- In evolution, new interactions may be induced radiatively, leading to additional operators, which are absent (or small) at M_*
- A full computation should include mixing of all operators & resummation of large logarithms using renormalization group (RG) techniques

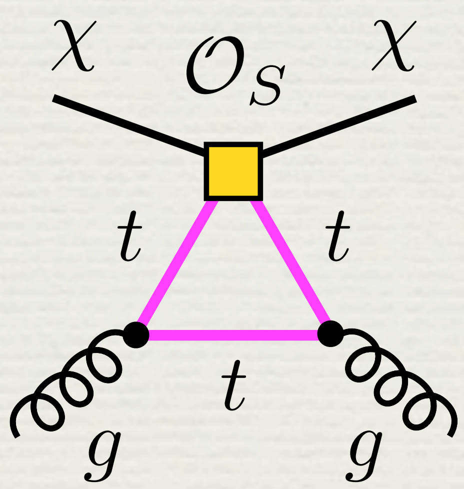
Mixing & Matching

- Consider scalar operator

$$\mathcal{O}_S = \frac{m_q}{M_*^3} \left(\bar{\chi}\chi\right) \left(\bar{q}q\right)$$

which may arise from exchange of a spin-0 mediator with couplings proportional to quark mass m_q

- At tresholds, heavy quarks can be integrated out leading to a DM-gluon-gluon coupling



$$\mathcal{O}_G = \frac{1}{M_*^3} \mathcal{C}_G \left(\bar{\chi}\chi\right) \left(G_{\mu\nu}\right)^2$$

$$\mathcal{C}_G(m_t) = -\frac{\alpha_s(m_t)}{12\pi}$$

[Shifman et al., Sov. J. Nucl. Phys. (1979) 30]

Matrix Elements

- At low energies need to evaluate hadronic matrix elements of scalar & gluon operator sandwiched between nucleus states:

$$\sum_q \langle A|\mathcal{O}_q|A\rangle = 2m_N A \left(\sum_q f_q\right) F_{\rm Helm} \approx \underline{0.14}\, m_N A F_{\rm Helm}$$

$$\langle A|\mathcal{O}_G|A\rangle = -2\,\frac{8\pi}{9\alpha_s}\, m_N A f_G F_{\rm Helm}\, \mathcal{C}_G \approx \underline{0.41}\, m_N A F_{\rm Helm}$$

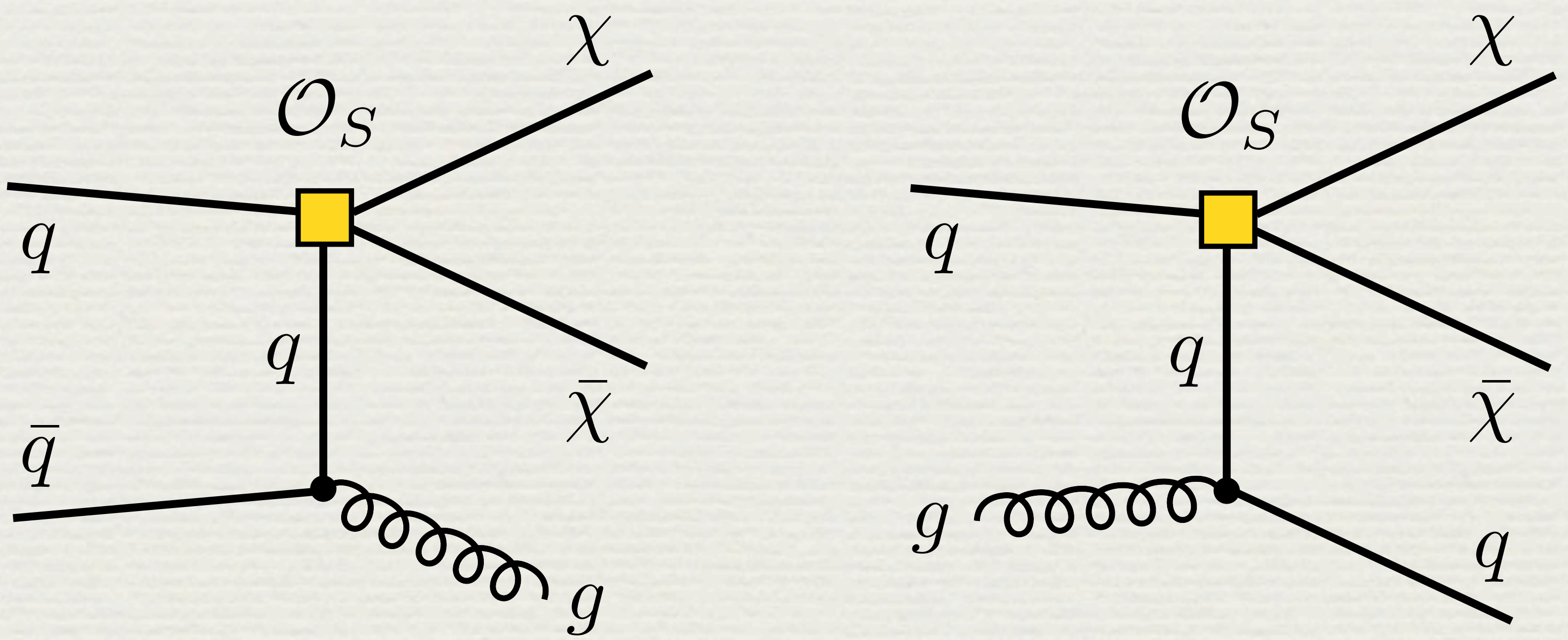
$$f_u \approx 0.021 \quad f_d \approx 0.038 \quad f_s \approx 0.013 \quad f_G = 1 - \sum_q f_q \approx 0.928$$

Loop suppression of DM-gluon-gluon contribution to direct detection overcompensated by large gluon density in nucleons

Scalar Interactions

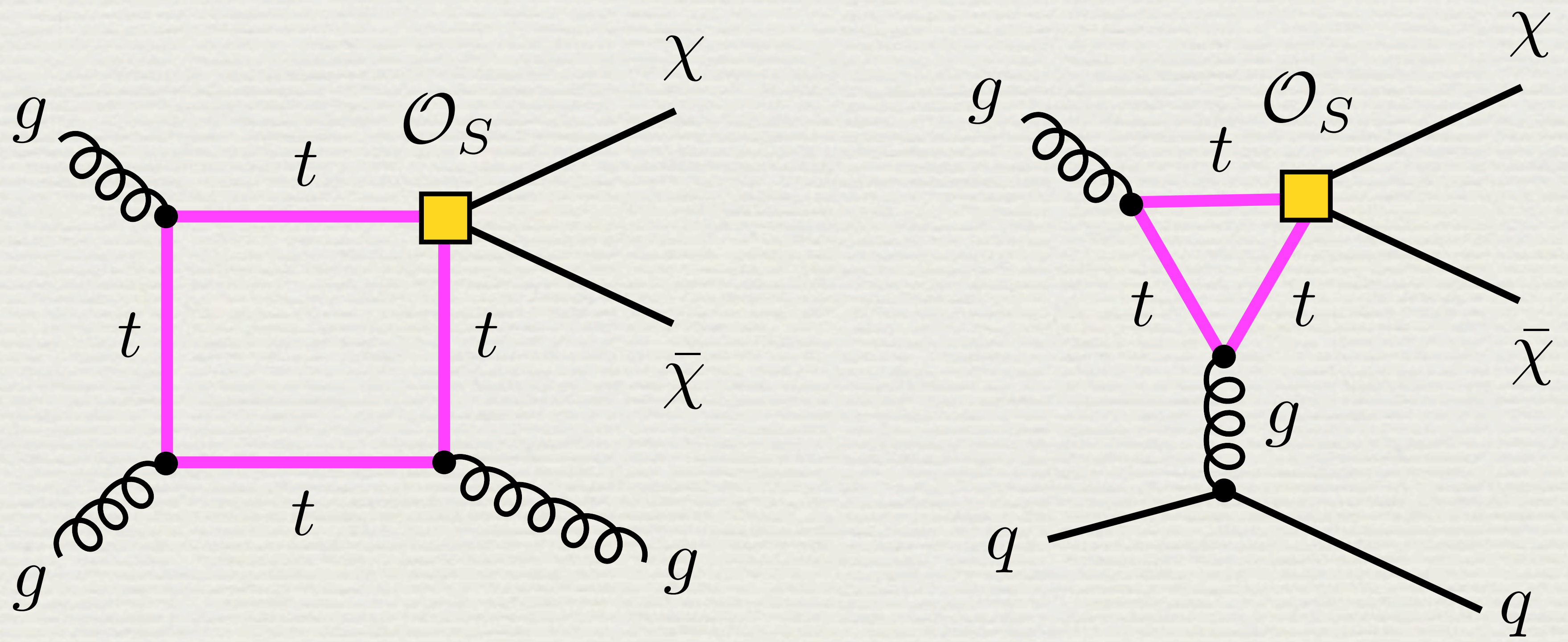
- What is correct way to analyze constraints from LHC mono-jet searches for scalar operators?

- Tree-level cross sections are small because heavy-quark luminosities are tiny & light quarks suffer Yukawa suppression



Scalar Interactions

- What is correct way to analyze constraints from LHC mono-jet searches for scalar operators?
- At 1-loop level heavy-quark loops start to contribute to mono-jet cross section & expected to lift Yukawa suppression



Mono-Jet Analysis

- Mono-jet cross sections have been obtained using FeynArts, FormCalc & LoopTools & results were cross-checked with MCFM, modifying $pp \to h + j \to \tau^+\tau^- + j$

[Ellis et al., Nucl. Phys. B297 (1988) 221]

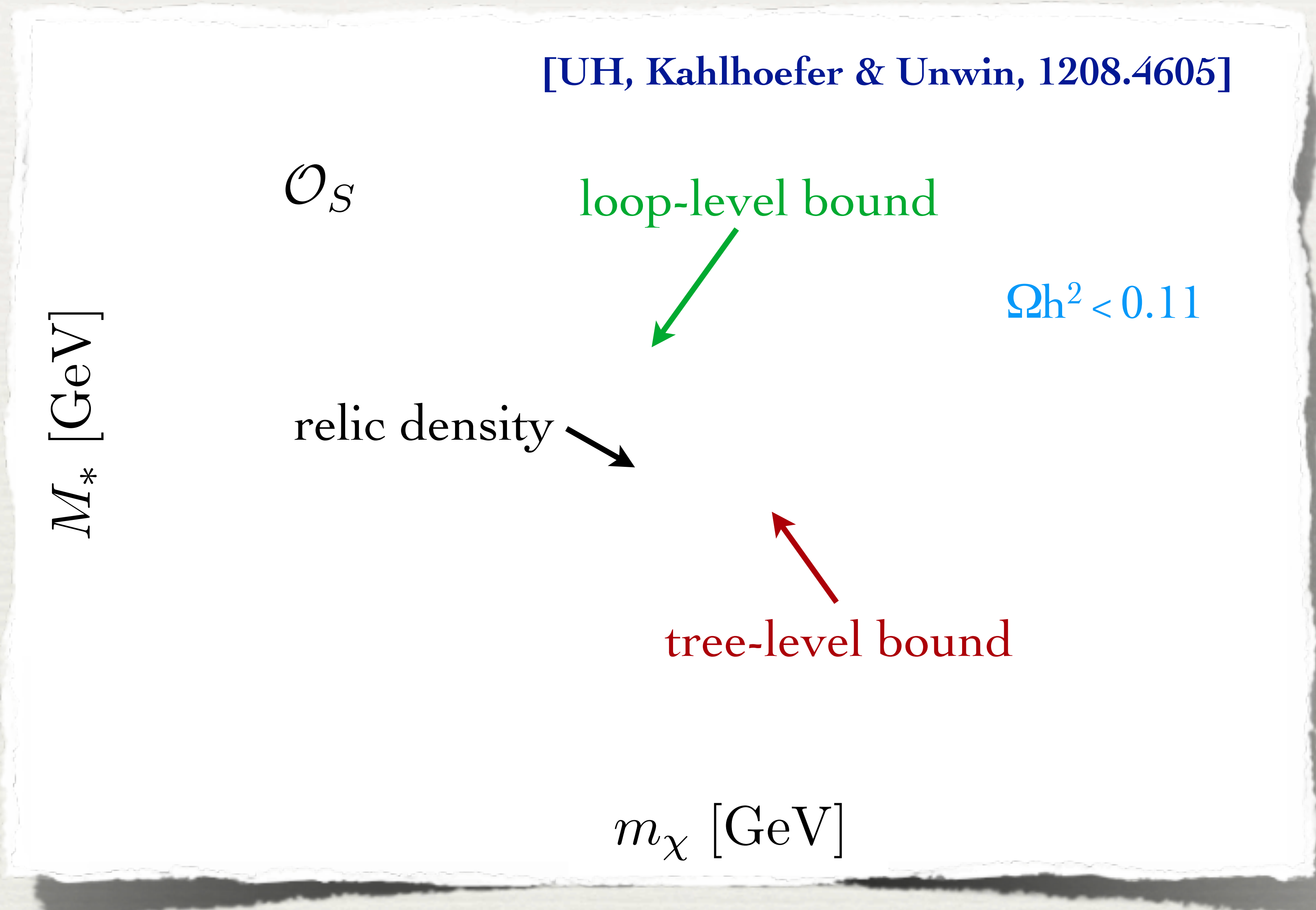
- Analysis incorporates all cuts imposed in 5 fb^{-1} CMS search

[Chatrchyan et al., 1206.5663]

- Shower & hadronization effects are not included, but are expected to be small, because primary jet has very large p_T

[Bai, Fox & Harnik, 1005.3797]

LHC Bounds: Scalar Case



Inclusion of top-quark loops increases mono-jet cross sections (bound on M_*) by a factor of around 500 (3)

Full Calculation Needed?

- Tempting to consider $m_t \to \infty$ limit & use operator

$$\mathcal{O}_G = -\frac{\alpha_s}{12\pi}\frac{1}{M_*^3}\left(\bar{\chi}\chi\right)\left(G_{\mu\nu}\right)^2$$

to calculate cross sections

- Effective theory calculation overestimates cross sections by at least a factor of 3 & error grows rapidly reaching a factor of 40 for m_χ = 1 TeV

- Result unsurprising, as high-p_T jet able to resolve structure of top-quark loop. Same happens in h + j production for $p_T >> m_t$

[Baur & Glover, Nucl. Phys. B339 (1990) 38]

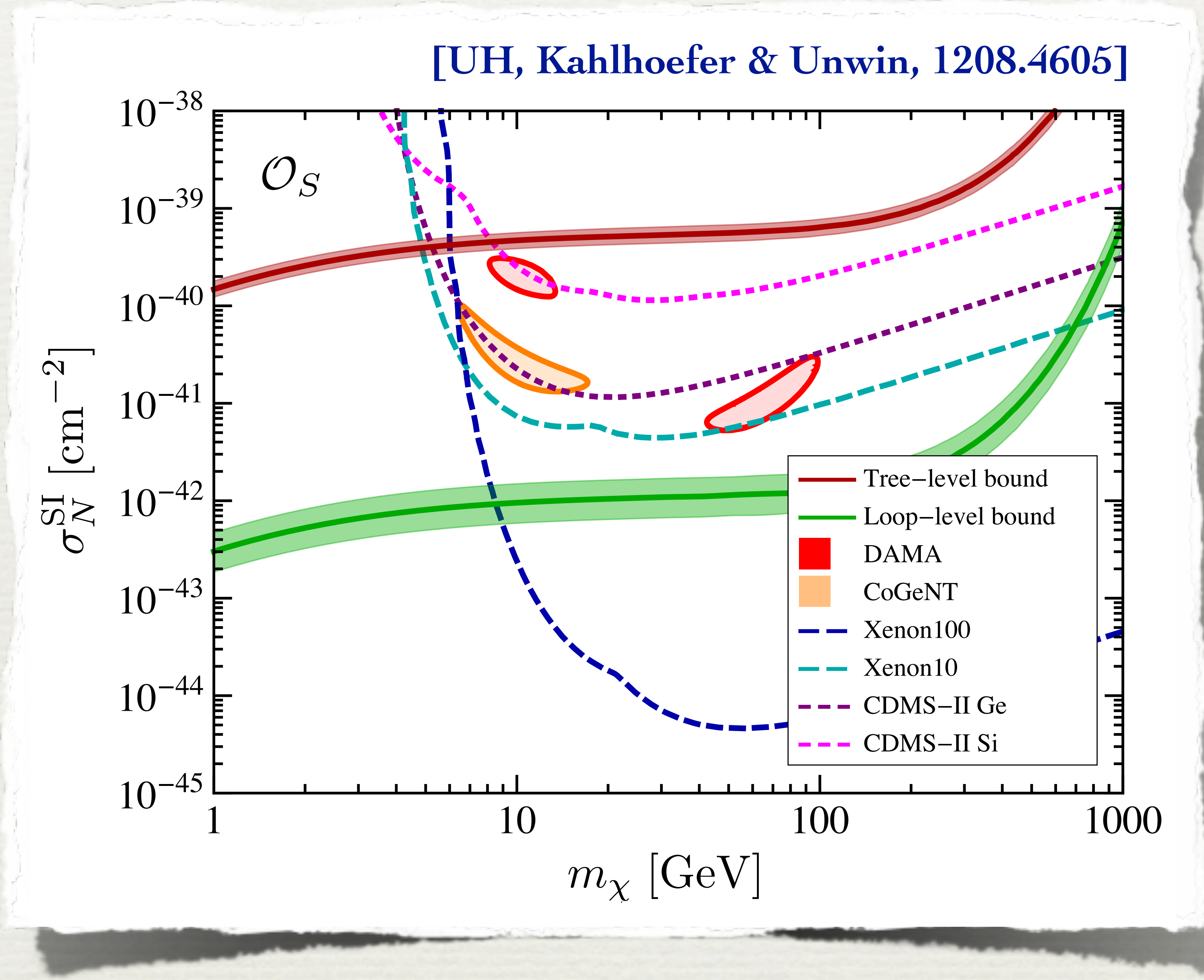
Accuracy Of Calculation

- For $pp \to h+j$ ratio between NLO & LO is around 1.5, but unclear how this translates into K factor for mono-jet signal, since Higgs result based on $m_t \to \infty$ limit

- Secondary jets allowed in LHC analyses & their impact can be studied by looking at $pp \to h+2j$. Depending on cuts can lead to enhancements of cross section by a factor of 2

- LO results for mono-jet production via (pseudo-)scalar DM-top-quark interactions are therefore not very accurate, but should give conservative lower bounds on new-physics scale

LHC & Direct Detection Bounds



Parameter regions favored by DAMA & CoGeNT clearly excluded by loop-level bound

Pseudoscalar Interactions

- For pseudoscalar operator

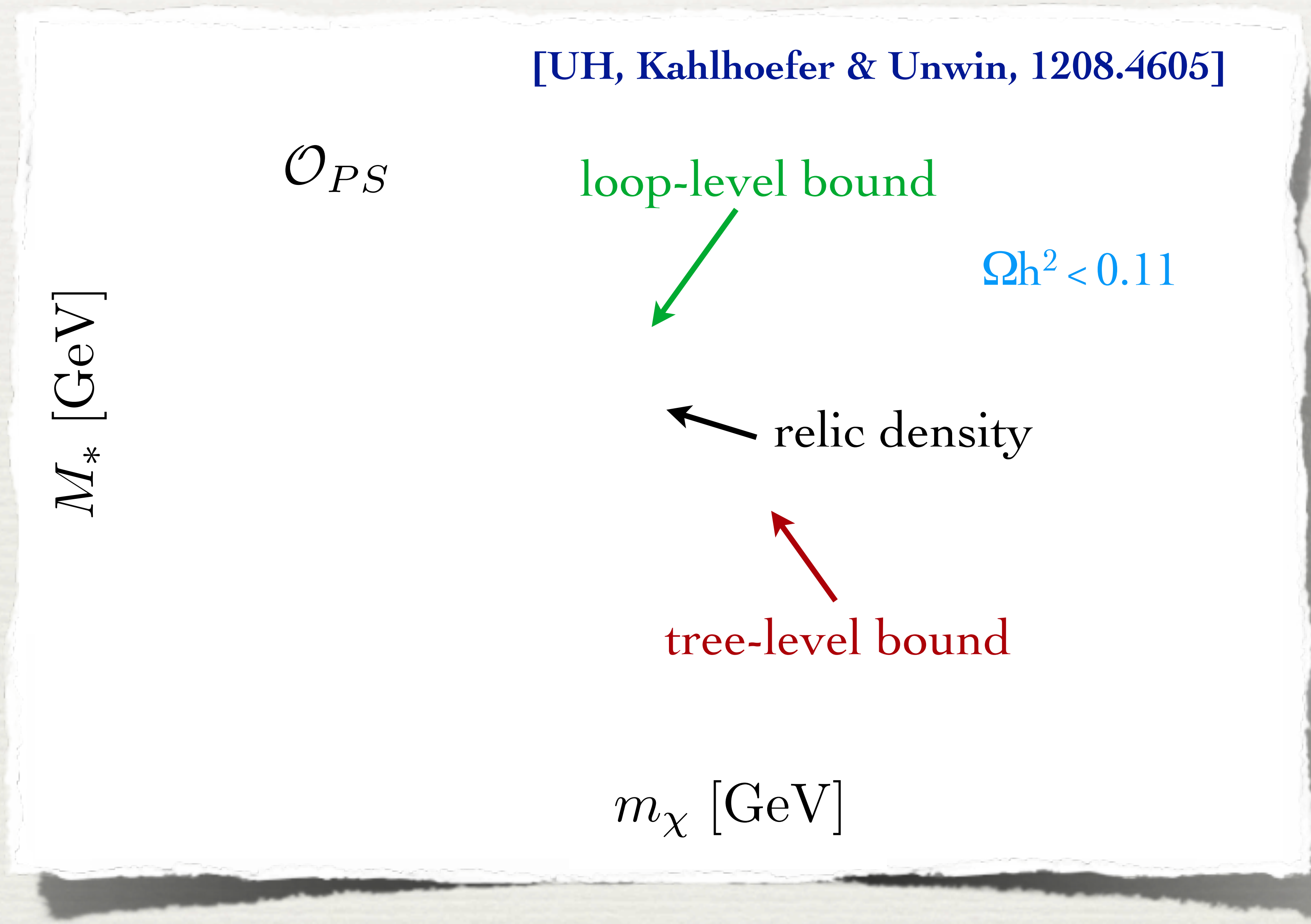
$$\mathcal{O}_{PS} = \frac{m_q}{M_*^3} \left(\bar{\chi}\gamma_5\chi\right) \left(\bar{q}\gamma_5 q\right)$$

  DM scattering is spin dependent & in addition suppressed by a factor of $q^4/m_N^4 << 1$

- As a result, no relevant constraint on M_* derives from direct detection experiments (at present & in future)

- At LHC scalar & pseudoscalar interactions look very similar, so that one can obtain strong bounds on new-physics scale

LHC Bounds: Pseudoscalar Case



Imposing that DM is not overproduced leads to $m_\chi > 44$ GeV (Dirac fermion) & $m_\chi > 55$ GeV (Majorana fermion)

Spin-Dependent Interactions

- Two operators lead to spin-dependent interactions:

$$\mathcal{O}_{AX} = \frac{1}{M_*^2} (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$$ axial operator

$$\mathcal{O}_T = \frac{1}{M_*^2} (\bar{\chi}\sigma_{\mu\nu}\chi)(\bar{q}\sigma^{\mu\nu} q)$$ tensor operator

- For spin-dependent interactions, direct detection bounds are weak due lack of coherent enhancement

- Mono-jet searches should thus be superior in constraining spin-dependent cross sections. Naive expectation true?

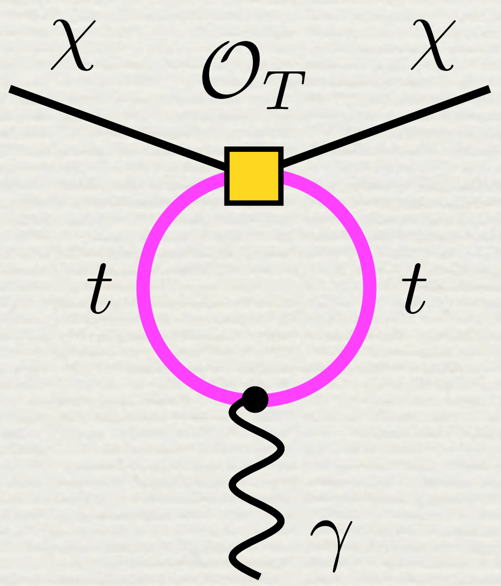
Let There Be Light!

- However, direct detection bounds boosted if spin-dependent operator induces spin-independent interactions via loops

- Effect most striking in case of tensor operator, since top-quark loops induce a DM magnetic dipole moment:

$$\mathcal{O}_M = \frac{1}{M_*^2}\,\mathcal{C}_M\,(\bar{\chi}\sigma_{\mu\nu}\chi)\,F^{\mu\nu}$$

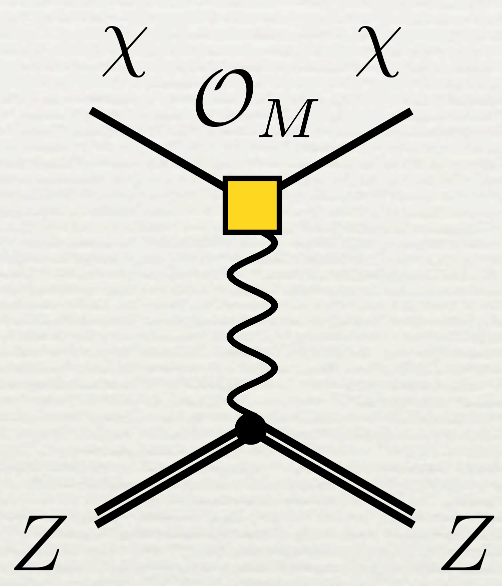
$$\mathcal{C}_M \simeq \frac{e}{2\pi^2}\,m_t \ln\frac{M_*^2}{m_t^2}$$



[UH & Kahlhoefer, 1302.4454; in context of leptophilic DM see also Kopp et al., 0907.3159]

Induced Dipole Moments

- Due to photon pole, DM-nucleon scattering cross sections strongly enhanced for small momentum transfer



- DM dipole moments are thus severely constrained by direct detection

- Resulting constraints can be translated into bounds on M_* & direct detection limits on new-physics scale typically stronger than those from LHC mono-jet searches

Bounds On Tensor Operator

[UH & Kahlhoefer, 1302.4454]

$\mathcal{O}_T$

M_* [GeV]

m_χ [GeV]

Bounds On Tensor Operator

[UH & Kahlhoefer, 1302.4454]

LHC mono-jet searches (width reflects scale uncertainties)

M_* [GeV]

m_χ [GeV]

Bounds On Tensor Operator

[UH & Kahlhoefer, 1302.4454]

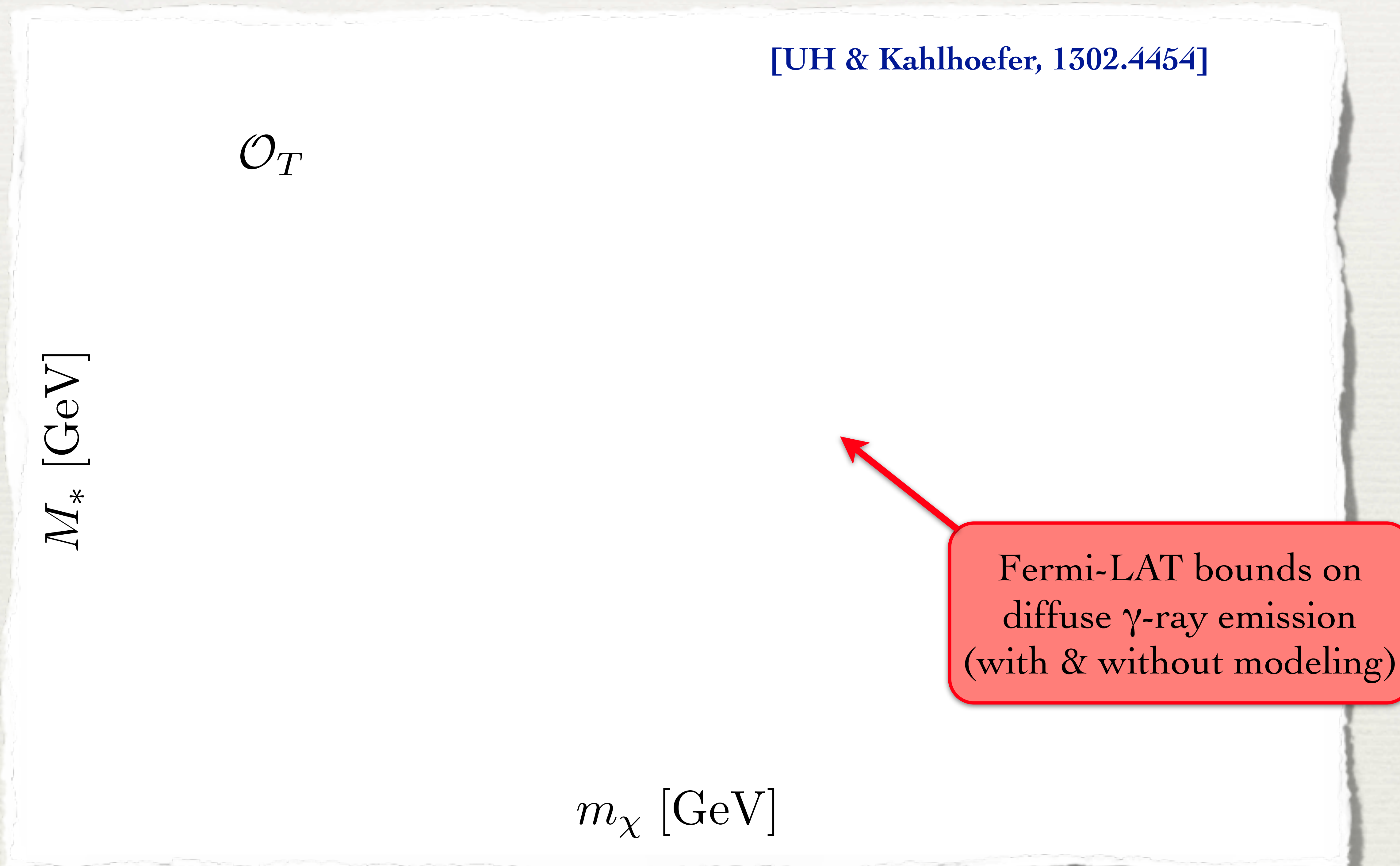
$\mathcal{O}_T$

Relic density constraint (overproduction above line)

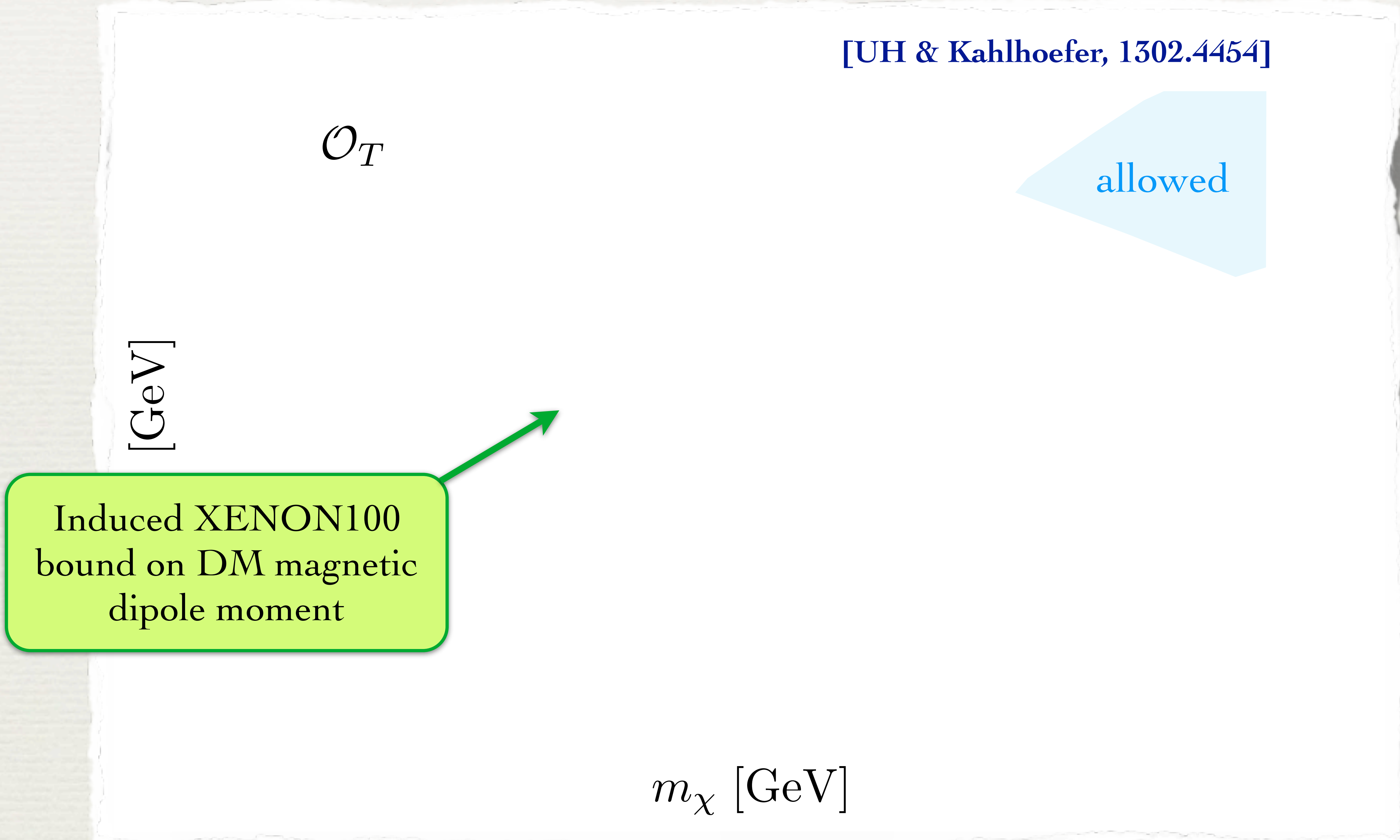
M_* [GeV]

m_χ [GeV]

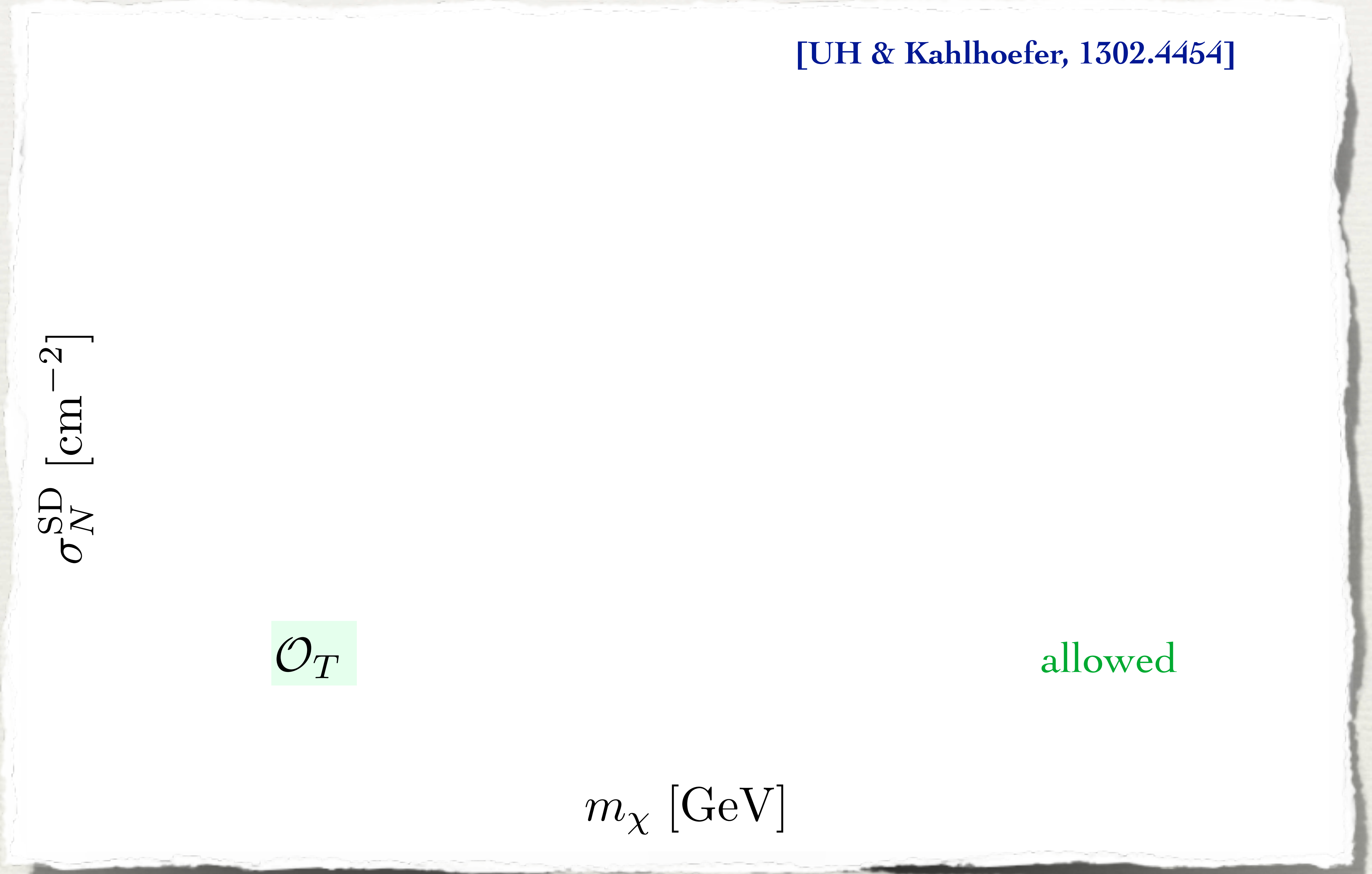
Bounds On Tensor Operator



Bounds On Tensor Operator



Loop- vs. Tree-Level Bounds



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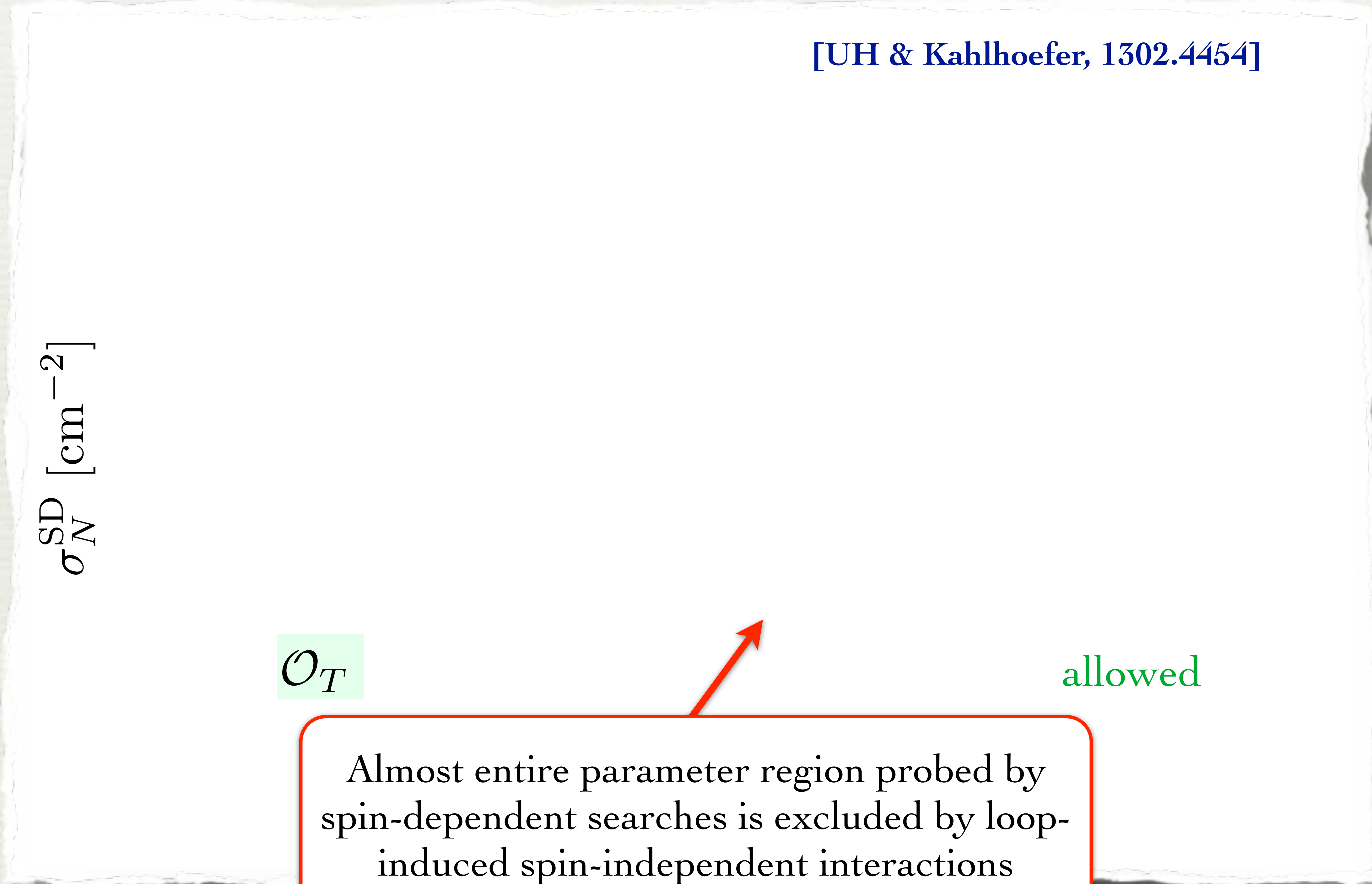
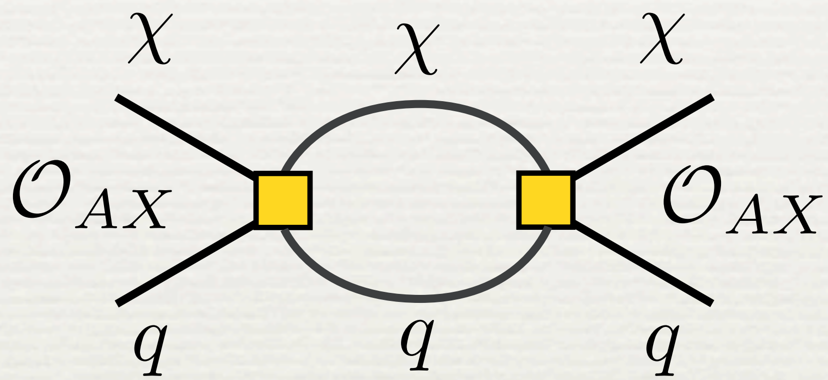


Almost entire parameter region probed by spin-dependent searches is excluded by loop-induced spin-independent interactions

Axial Operator

- In case of axial operator spin-independent interactions are induced by loop graphs with two operator insertions

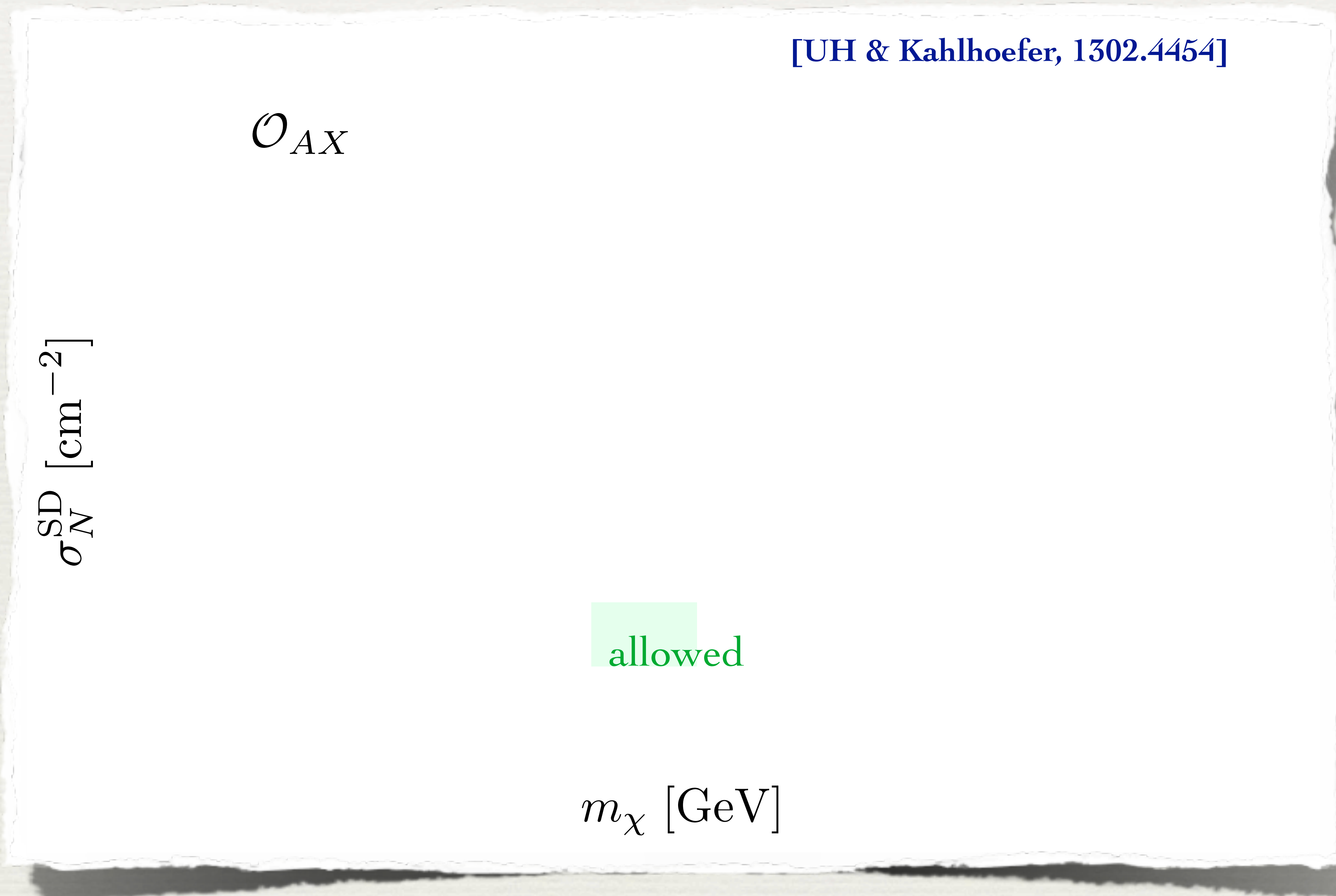


- A contribution to vector operator is not induced but scalar operator receives logarithmic correction of form:

$$\mathcal{O}_S = \frac{m_q}{M_*^3} \mathcal{C}_S \, (\bar{\chi}\chi)\,(\bar{q}q) \qquad \mathcal{C}_S \simeq -\frac{1}{2\pi^2} \frac{m_\chi}{M_*} \ln \frac{M_*^2}{m_\chi^2}$$

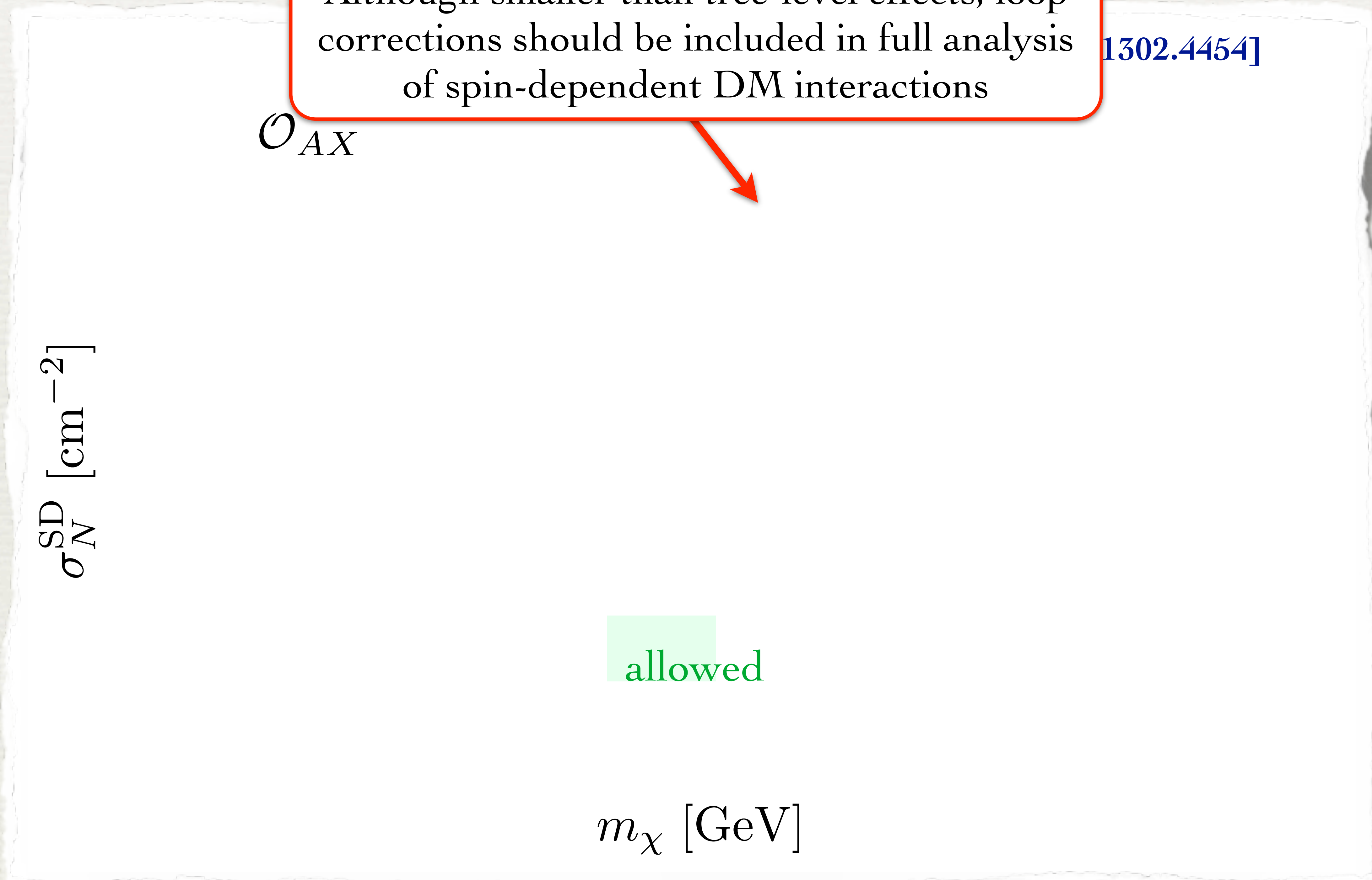
[UH & Kahlhoefer, 1302.4454; see also Cirelli, Fornengo & Strumia, 0512090; Essig, 0710.1668]

Loop- vs. Tree-Level Bounds



Loop- vs. Tree-Level Bounds

Although smaller than tree-level effects, loop corrections should be included in full analysis of spin-dependent DM interactions



Conclusions

- Because of large separation of scales, different interactions may be relevant for different kind of DM searches
- For scalar interactions, loops lead to striking enhancement of mono-jet cross section, but need to include full top-quark mass dependence to obtain accurate results
- Certain spin-dependent interactions induce DM dipole moments through heavy-quark loops (& other spin-independent effects), which are strongly constrained by direct detection
- Further studies of loop effects may play an essential part in combining the virtues of different search strategies & may be needed to solve DM problem

LHC Mono-Jet Analyses

- POWHEG analysis based on 7 TeV ATLAS search for jets & missing energy (MET) with integrated luminosity of 4.7 fb^{-1}

[ATLAS, 1210.4491]

- SR4 cuts: $\not{E}_T, p_T^{j_1} > 500\,\text{GeV}$

  $|\eta_{j_1}| < 2$

  $|\Delta\phi_{\not{\vec{p}}_T, \vec{p}_T^{j_2}}| > 0.5$ (suppresses back-to-back di-jets)

  $N_j \leq 2$

  lepton veto

- ATLAS result excludes new contribution to cross section in excess of 6.9 fb at 95% confidence level

Bounds On Pseudotensor Operator

[UH & Kahlhoefer, 1302.4454]

$\mathcal{O}_{PT}$

M_* [GeV]

m_χ [GeV]

Bounds on New-Physics Scale

[UH & Kahlhoefer, 1302.4454]

m_χ [GeV]	M_* in $\mathcal{O}_T$ [GeV]	M_* in $\mathcal{O}_{PT}$ [TeV]
10	1880^{+360}_{-450}	$65.6^{+5.5}_{-5.6}$
20	3360^{+520}_{-600}	$123.7^{+9.6}_{-9.6}$
50	3740^{+560}_{-640}	$158.2^{+12.0}_{-11.9}$
100	3220^{+500}_{-580}	$144.2^{+11.0}_{-11.0}$
200	2690^{+430}_{-510}	$123.6^{+9.6}_{-9.6}$
500	2070^{+380}_{-470}	$98.3^{+7.9}_{-7.9}$
1000	1680^{+330}_{-440}	$81.6^{+6.7}_{-6.7}$

Bounds On Axial Operator

[UH & Kahlhoefer, 1302.4454]

$\mathcal{O}_{AX}$

M_* [GeV]

m_χ [GeV]

Top-Flavored MFV DM

- Assumption of minimal flavor violating (MFV) automatically leads to stable DM candidate

[Batell, Pradler & Spannowsky, 1105.1781]

- Can build simple MFV model where DM carries top flavor:

$$\chi \sim (1,1,0)_{G_{\rm SM}} \otimes (1,3,1)_{G_F} \qquad \phi \sim (3,1,2/3)_{G_{\rm SM}} \otimes (1,1,1)_{G_F}$$

$$\mathcal{L} \supset -\,\bar{\chi}\left(m_0 + m_1\, Y_u^\dagger Y_u + \ldots\right)\chi$$

$$+\left[\bar{q}_R\left(g_0 + g_1\, Y_u^\dagger Y_u + \ldots\right)\chi\phi + \text{h.c.}\right]$$

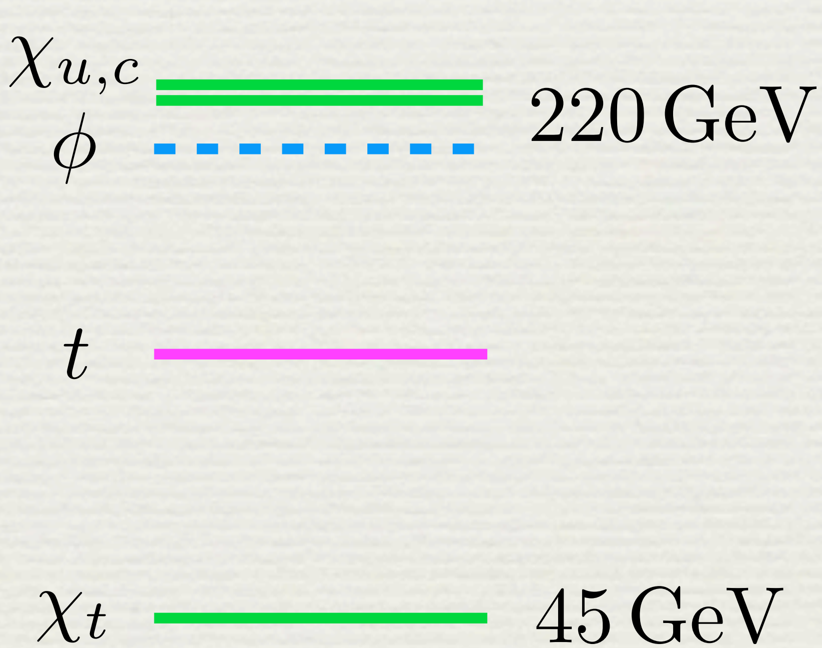
[Kumar & Tulin, 1303.0332]

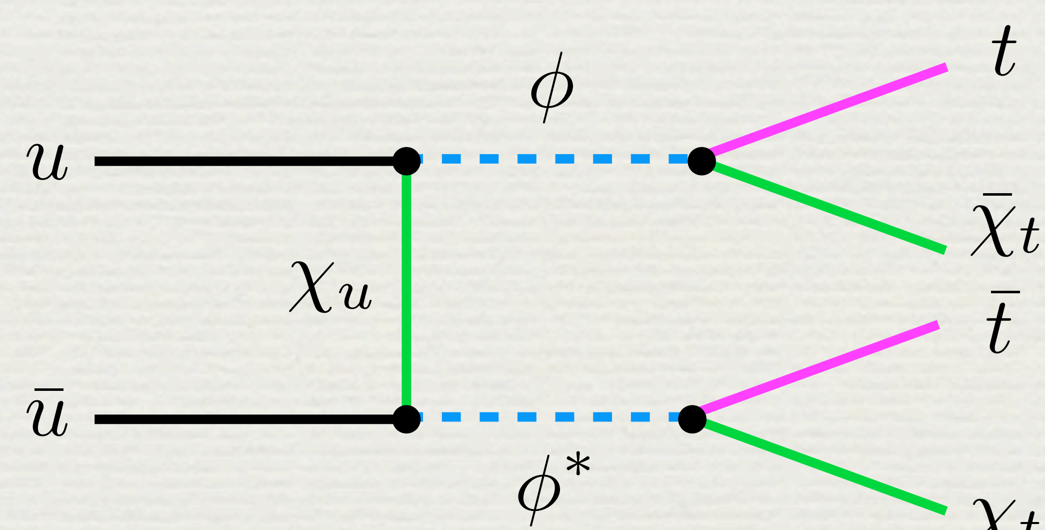
Top-Flavored MFV DM

- Assumption of minimal flavor violating (MFV) automatically leads to stable DM candidate

[Batell, Pradler & Spannowsky, 1105.1781]

- Top-flavored MFV DM able to explain large top-asymmetry

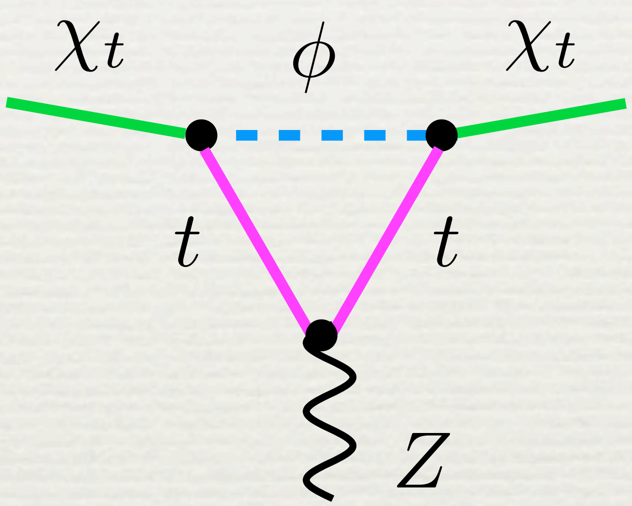


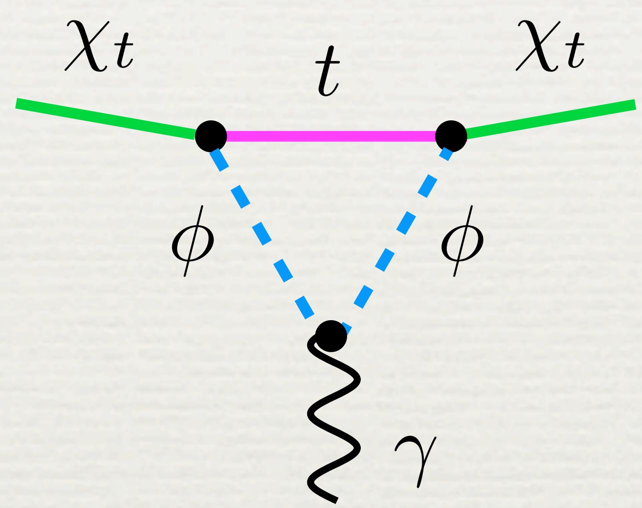


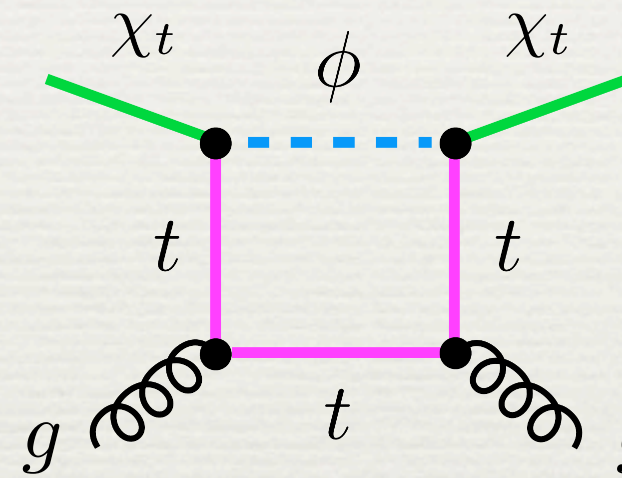
[Kumar & Tulin, 1303.0332]

Top-Flavored MFV DM

- MFV top-flavored DM model has interesting loop structure







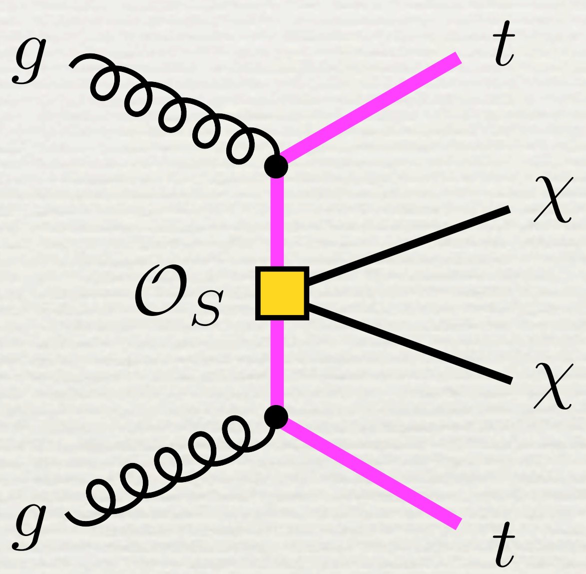
direct detection, relic density & invisible Z width

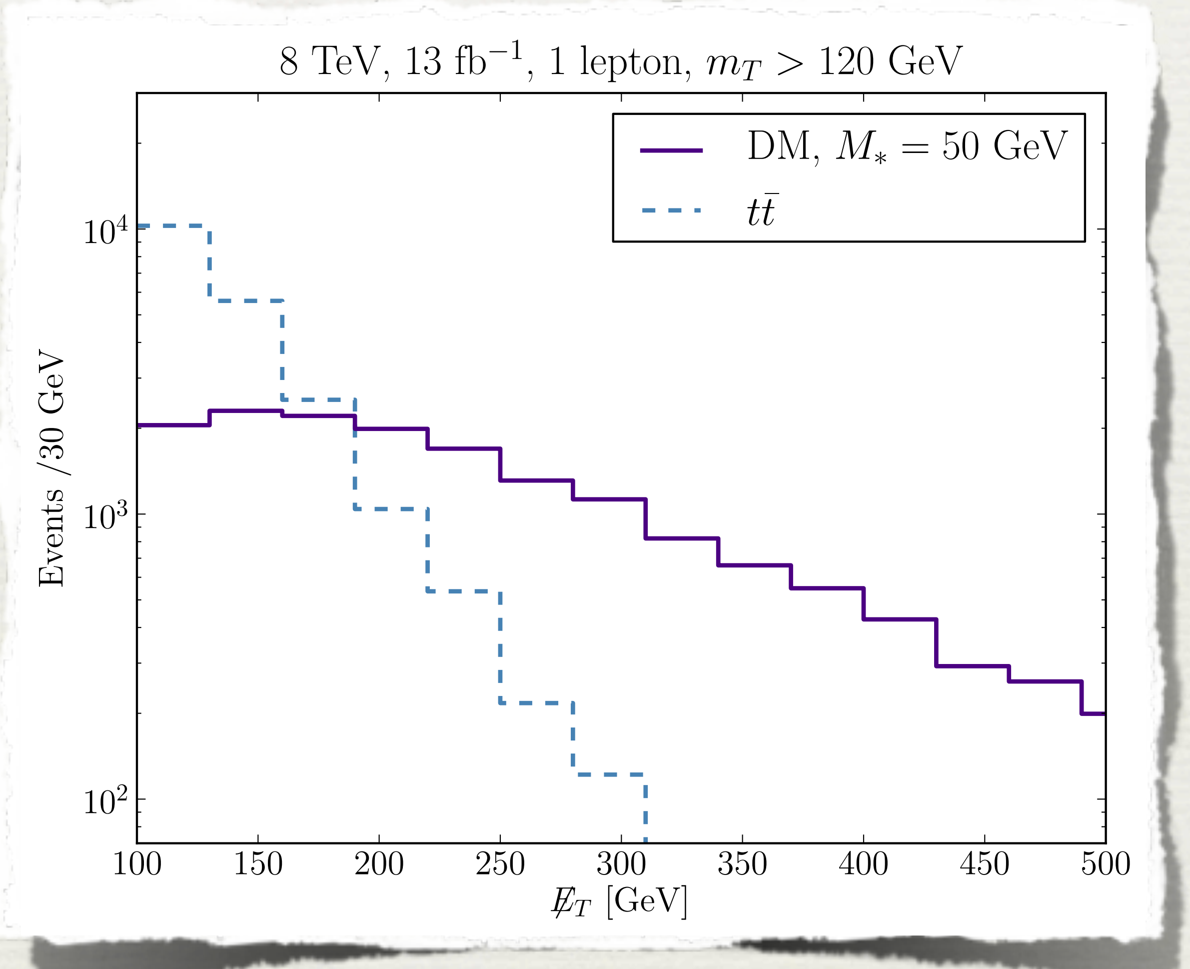
magnetic dipole moment

mono-jet searches (?)

DM Couplings To Top Quarks

- Scalar interactions between top quarks & DM can also be probed in top-pair production plus missing energy (MET)





- Naively not as powerful as mono-jets, but shape differences may allow to improve $t\bar{t}$ + MET search

[Lin, Kolb & Wang, 1303.6638]

What About Indirect Detection?

arXiv:1204.2797v2 [hep-ph] 8 Aug 2012

A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

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Abstract. The observation of a gamma-ray line in the cosmic-ray fluxes would be a smoking-gun signature for dark matter annihilation or decay in the Universe. We present an improved search for such signatures in the data of the Fermi Large Area Telescope (LAT), concentrating on energies between 20 and 300 GeV. Besides updating to 43 months of data, we use a new data-driven technique to select optimized target regions depending on the profile of the Galactic dark matter halo. In regions close to the Galactic center, we find a 4.6σ indication for a gamma-ray line at $E_\gamma \approx 130$ GeV. When taking into account the look-elsewhere effect the significance of the observed excess is 3.2σ. If interpreted in terms of dark matter particles annihilating into a photon pair, the observations imply a dark matter mass of $m_\chi = 129.8 \pm 2.4\,^{+7}_{-13}$ GeV and a partial annihilation cross-section of $\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} = \left(1.27 \pm 0.32\,^{+0.18}_{-0.28}\right) \times 10^{-27}$ cm^3 s^{-1} when using the Einasto dark matter profile. The evidence for the signal is based on about 50 photons; it will take a few years of additional data to clarify its existence.

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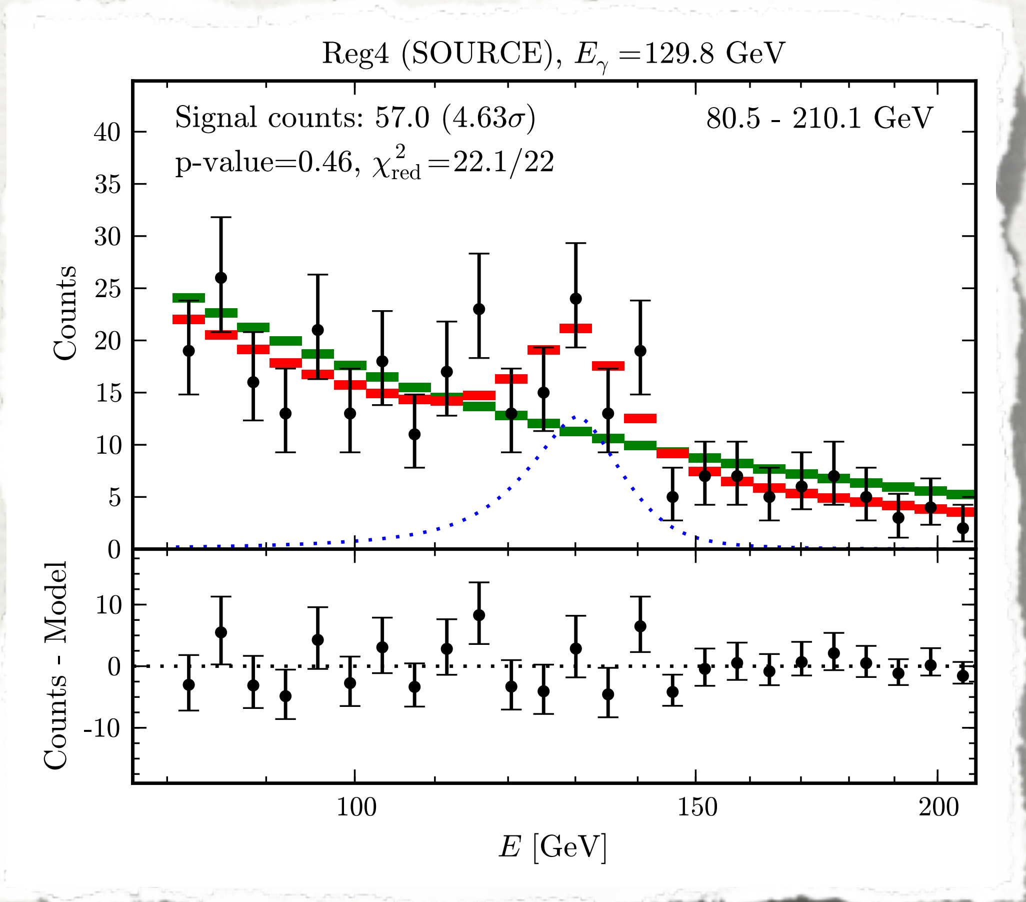
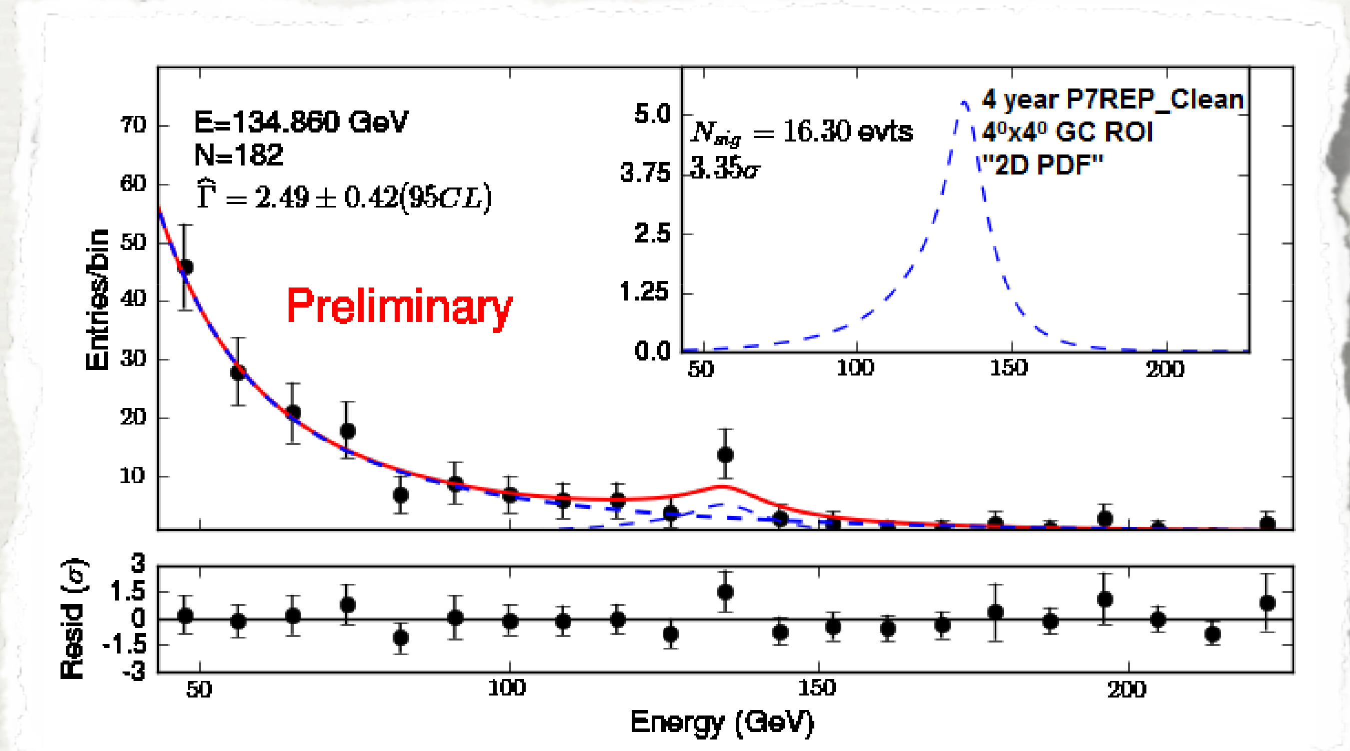
arXiv ... 2012

Significance Of Line

[Weniger, 1204.2797]



[Albert, The Fermi Symposium 2012]



Official Fermi-LAT analysis shows less significant effect at around 135 GeV. Unfortunately, there is also line-like feature at same energy in earth limb data (where there should be none)

Cross Section Estimates

- Consider effective DM-photon-photon interactions

$$\mathcal{L}_{\rm eff} = \frac{\alpha}{4\pi}\frac{1}{M_*^{2d_\chi}}\,(\bar\chi\chi)\,(F_{\mu\nu})^2$$

- Depending on whether DM particle is a scalar or fermion get different annihilation cross sections into γ-rays:

$$\langle\sigma_\chi v\rangle_{\gamma\gamma} \propto \begin{cases} \dfrac{m_\chi^2}{\pi}\left(\dfrac{\alpha}{4\pi}\dfrac{1}{M_*^2}\right)^2 & \text{s-wave annihilation} \\ \dfrac{v^2 m_\chi^4}{\pi}\left(\dfrac{\alpha}{4\pi}\dfrac{1}{M_*^3}\right)^2 & \text{p-wave annihilation} \end{cases}$$

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- To obtain a γ-ray signal close to 130 GeV with a cross section of $1.3\cdot 10^{-27}$ cm^3 s^{-1} requires lowish new-physics scales:

$$\langle\sigma_\chi v\rangle_{\gamma\gamma} \propto \begin{cases} \dfrac{m_\chi^2}{\pi}\left(\dfrac{\alpha}{4\pi}\dfrac{1}{M_*^2}\right)^2 & \Rightarrow\; M_* \approx 100\,\mathrm{GeV} \\[2ex] \dfrac{v^2 m_\chi^4}{\pi}\left(\dfrac{\alpha}{4\pi}\dfrac{1}{M_*^3}\right)^2 & \Rightarrow\; M_* \approx 10\,\mathrm{GeV} \end{cases}$$

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Numbers suggest that to get signal in explicit model, need either many states in loop or have resonant s-channel production

Direct Detection From γ-Rays?

- In view of large γ-ray signal & impressive sensitivity of direct detection experiments, should ask if constraints on DM can arise from latter searches if DM-quark & -gluon interactions loop suppressed

- Loop-induced spin-independent direct detection cross sections scale as :

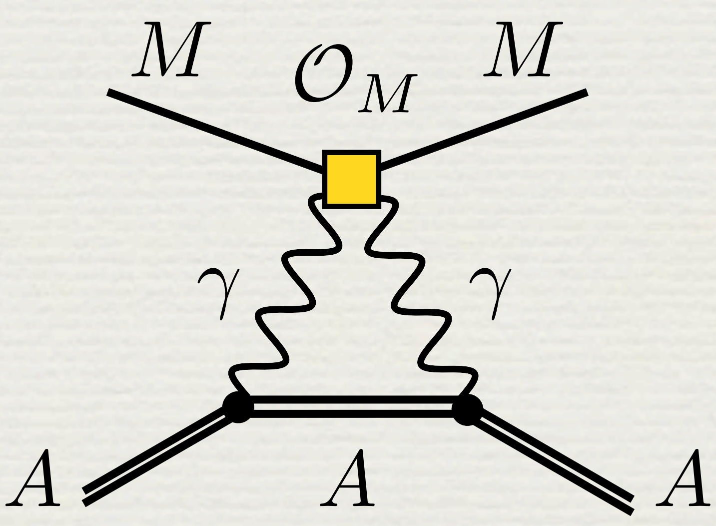
$$\sigma_N^{\rm SI} \propto \begin{cases} \dfrac{m_{\rm red}^2}{M_*^4} & \text{scalar DM} \\[2ex] \dfrac{m_{\rm red}^2 m_\chi^2}{M_*^6} & \text{fermionic DM} \end{cases}$$

- Formulas imply that only if DM is fermionic (γ-ray signal is v^2-suppressed) direct & indirect bounds may be competitive

Rayleigh DM

- Interesting operator that gives rise to direct detection signals is hence (M = Majorana fermion)

$$\mathcal{O}_M = \mathcal{C}_M \left(\bar{M} M\right) \left(F_{\mu\nu}\right)^2$$



- Photons interact coherently with entire nucleus (similar to Rayleigh scattering)

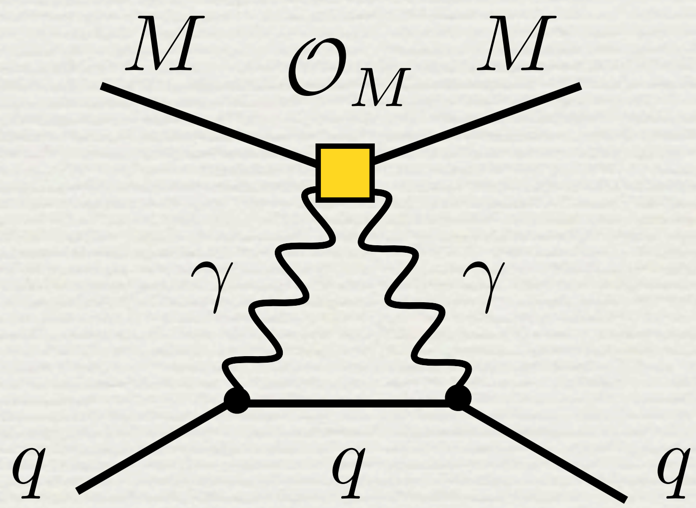
- Amplitude thus proportional to Z^2 & cross section proportional to Z^4

[Weiner & Yavin, 1206.2910]

RG Evolution

- But if DM-photon-photon interaction induced at M_*, QED radiation will lead to DM-quark coupling:

$$\mathcal{O}_q = \mathcal{C}_q m_q \left(\bar{M} M\right) (\bar{q} q) \qquad \mathcal{C}_q(m_N) \simeq -\frac{3e_q^2 \alpha}{\pi} \ln\left(\frac{M_*^2}{m_N^2}\right) \mathcal{C}_M(M_*)$$

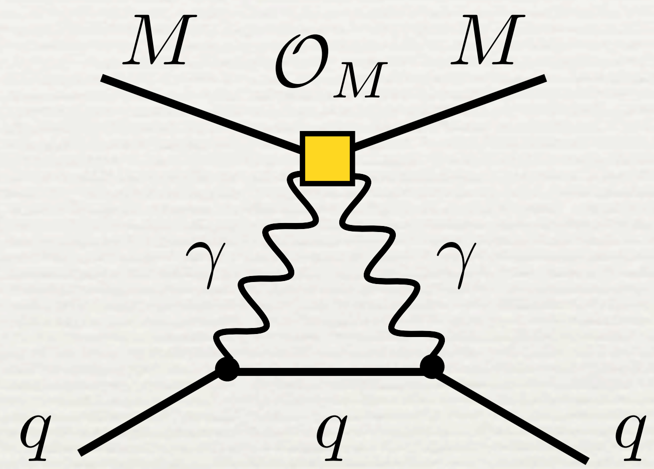


- At scale m_N this leads to standard spin-independent interactions

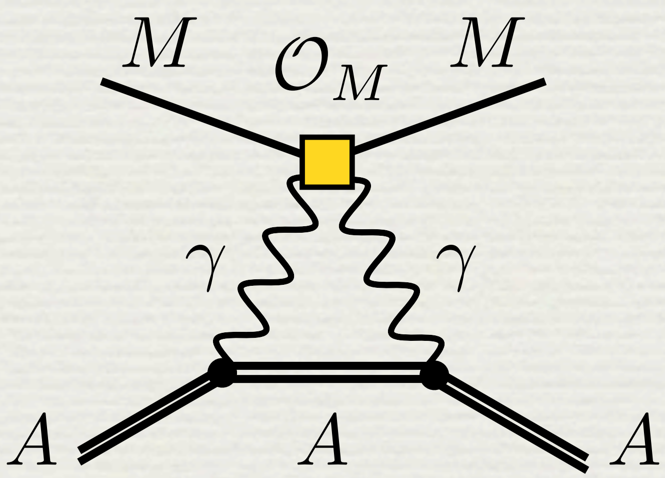
- Amplitude proportional to target nucleus mass, resulting in cross section proportional to A^2

[Frandsen et al., 1207.3971]

Loop-Induced Direct Detection



$$\mathcal{C}_q(m_N) \simeq -\frac{3e_q^2\alpha}{\pi}\,\ln\left(\frac{M_*^2}{m_N^2}\right)\mathcal{C}_M(M_*)$$



[Frandsen et al., 1207.3971]

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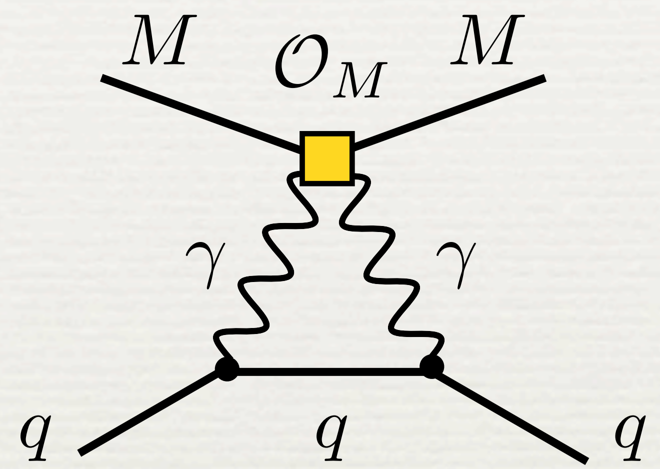

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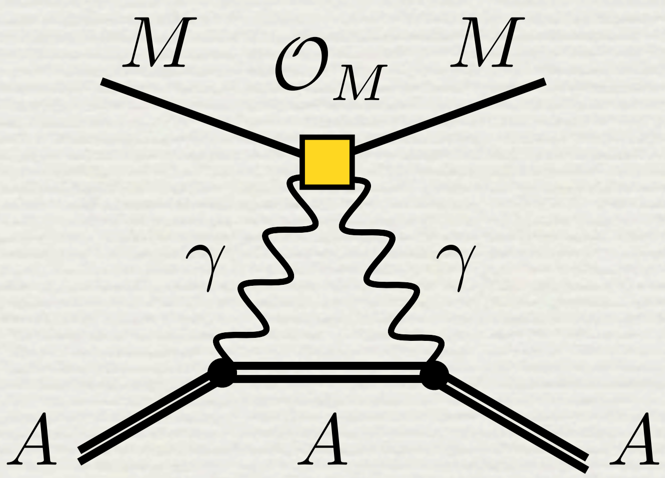
Two effects interfere destructively



[Frandsen et al., 1207.3971]

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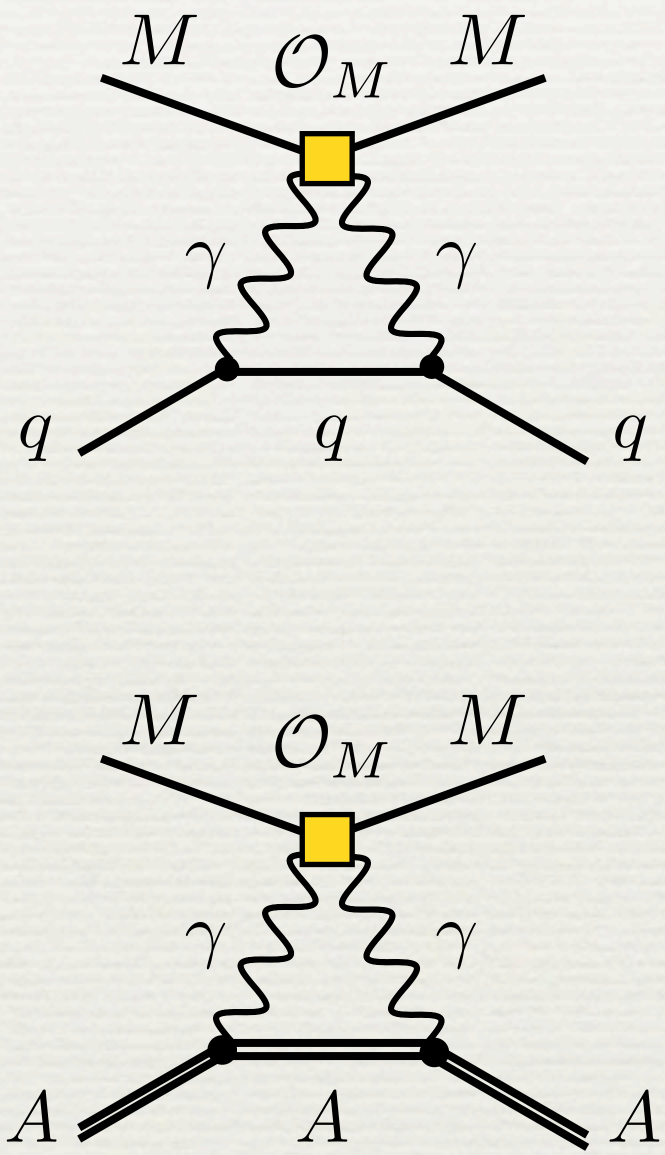

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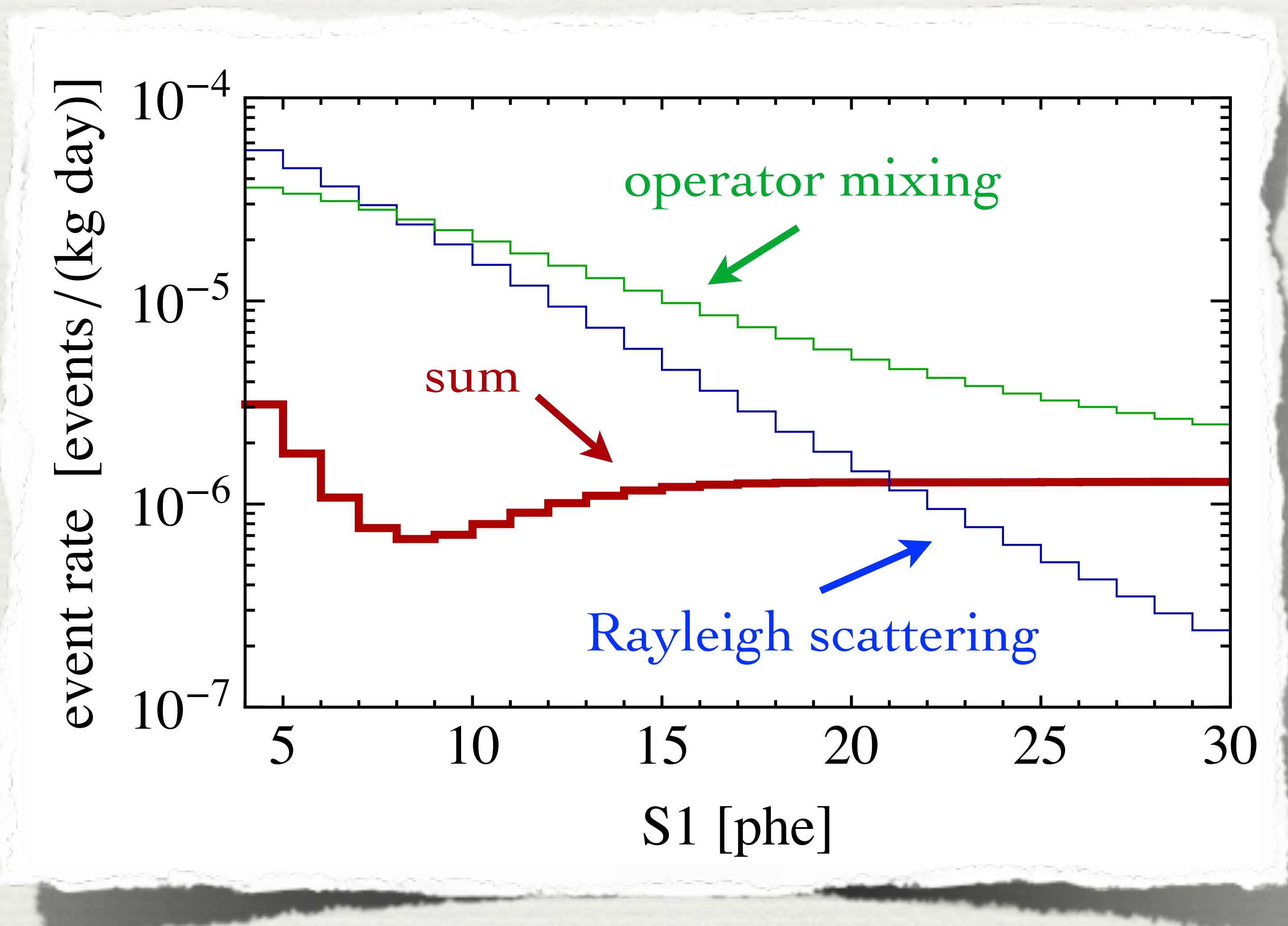

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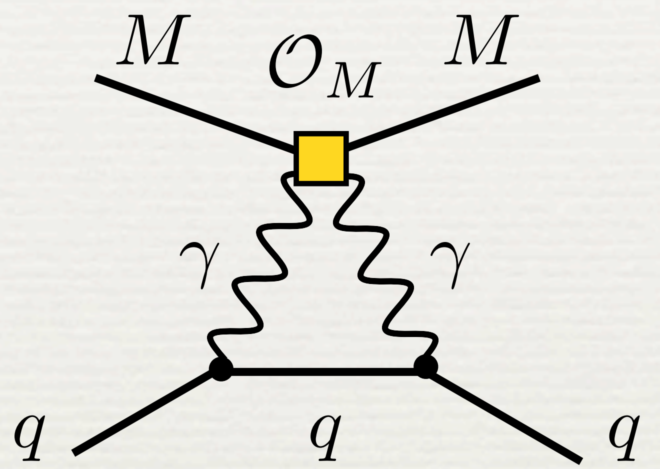

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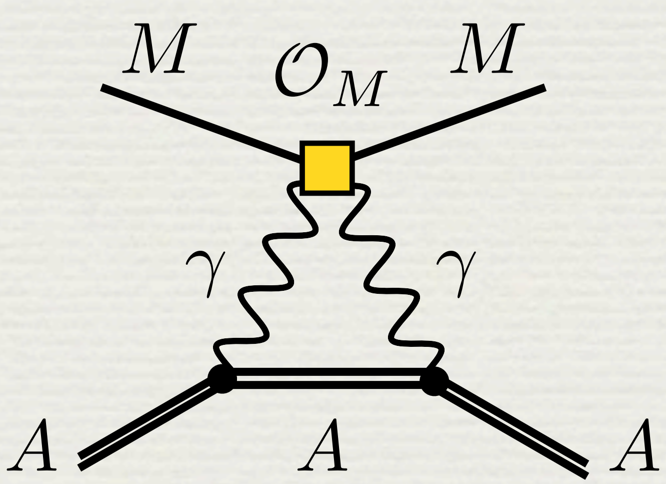

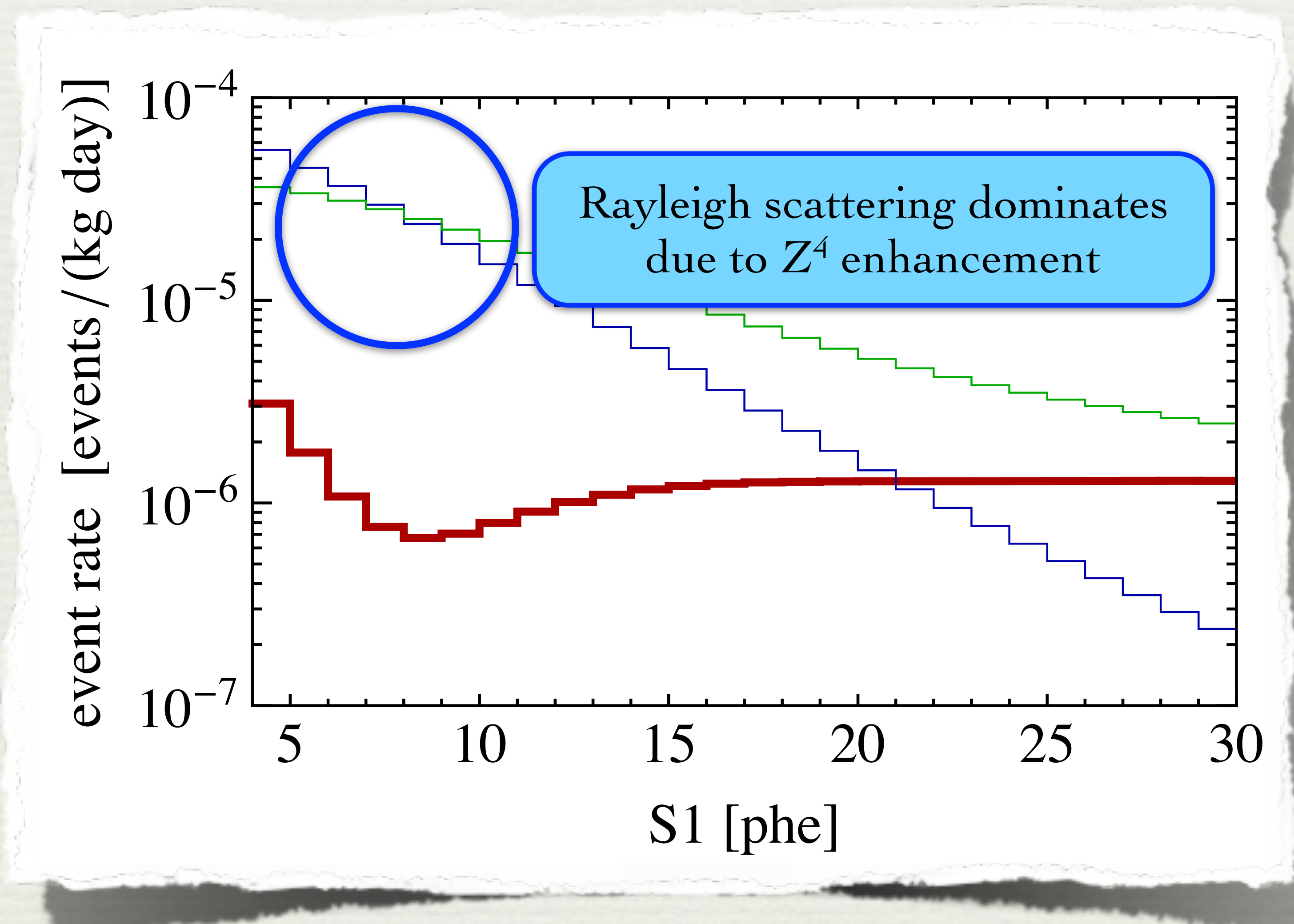

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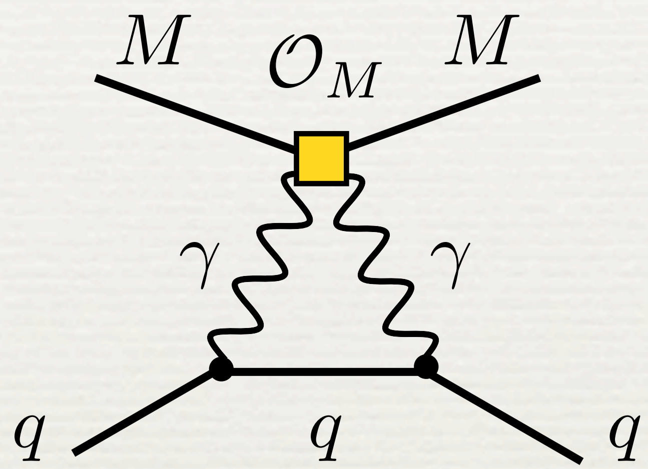

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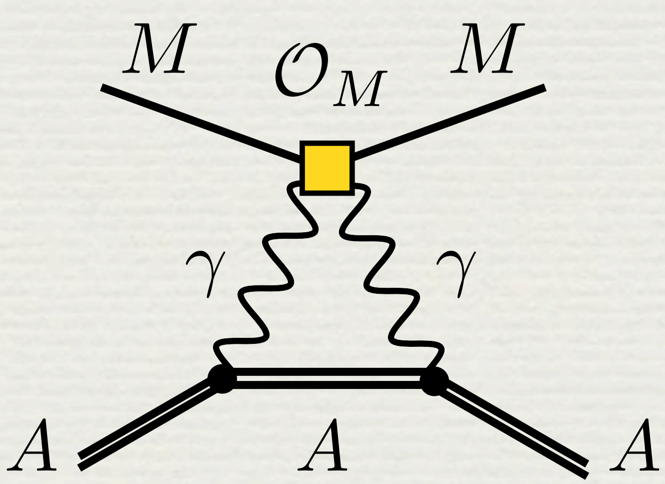

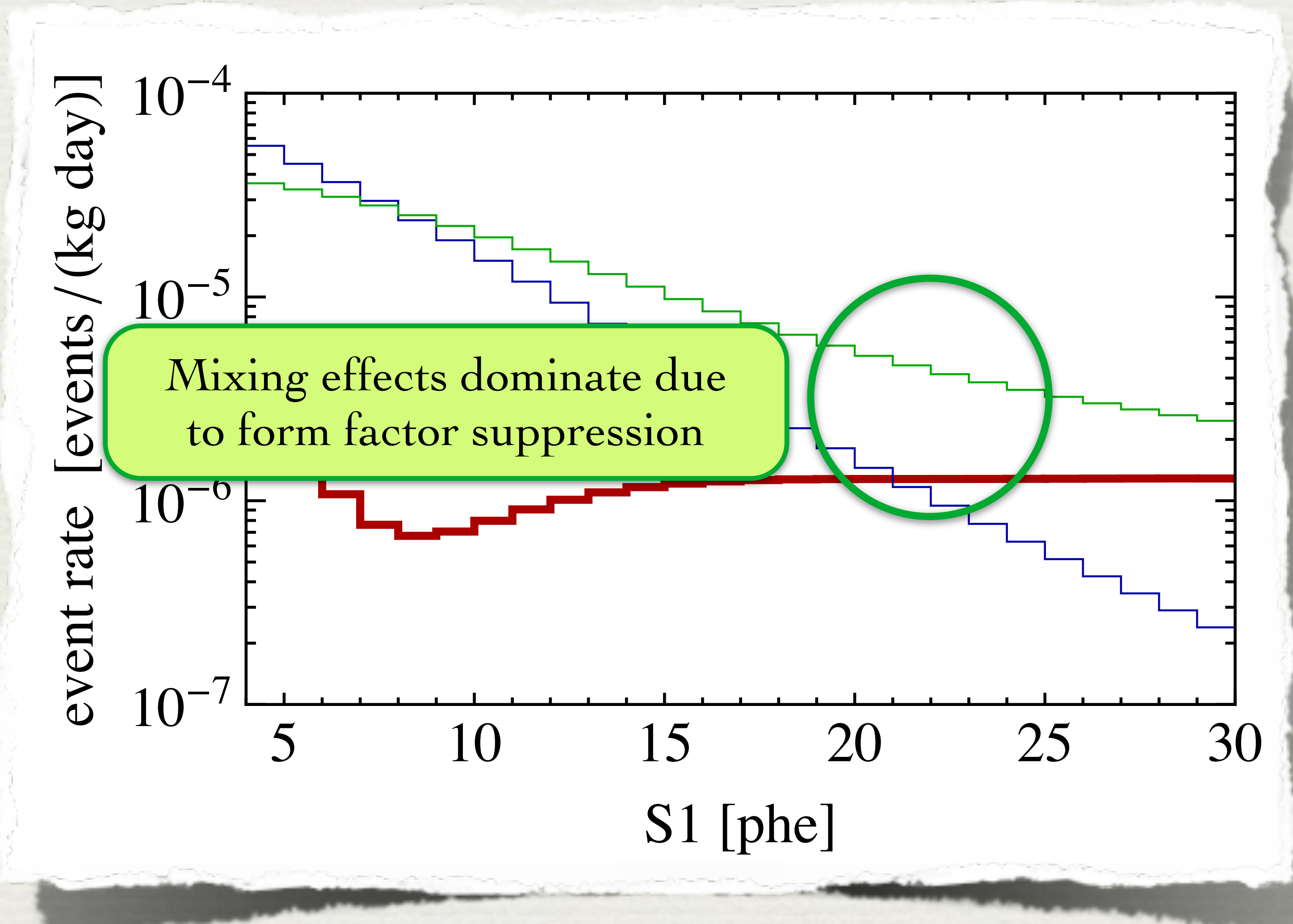

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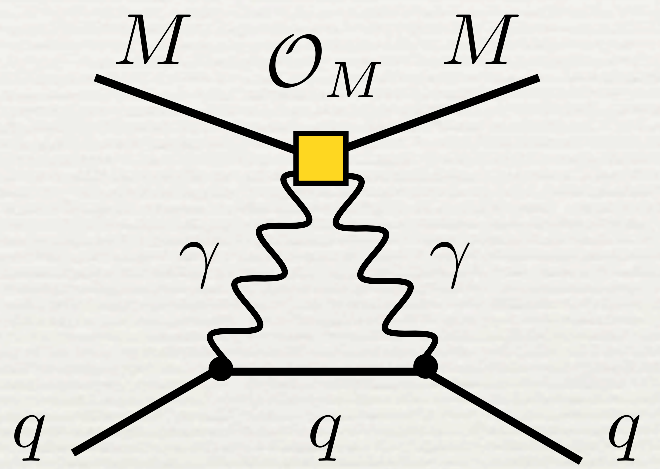

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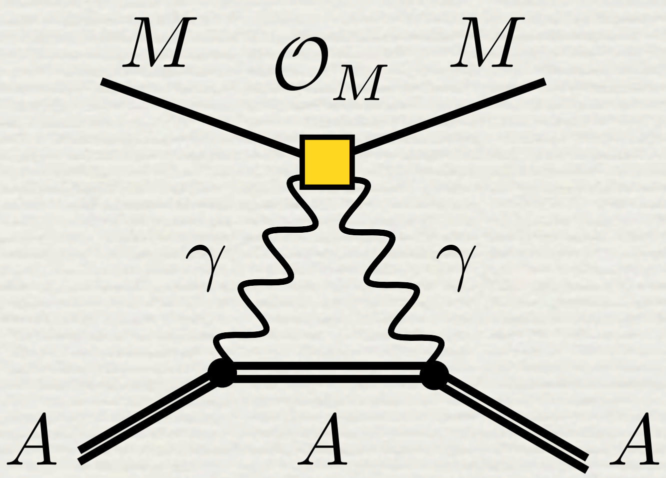
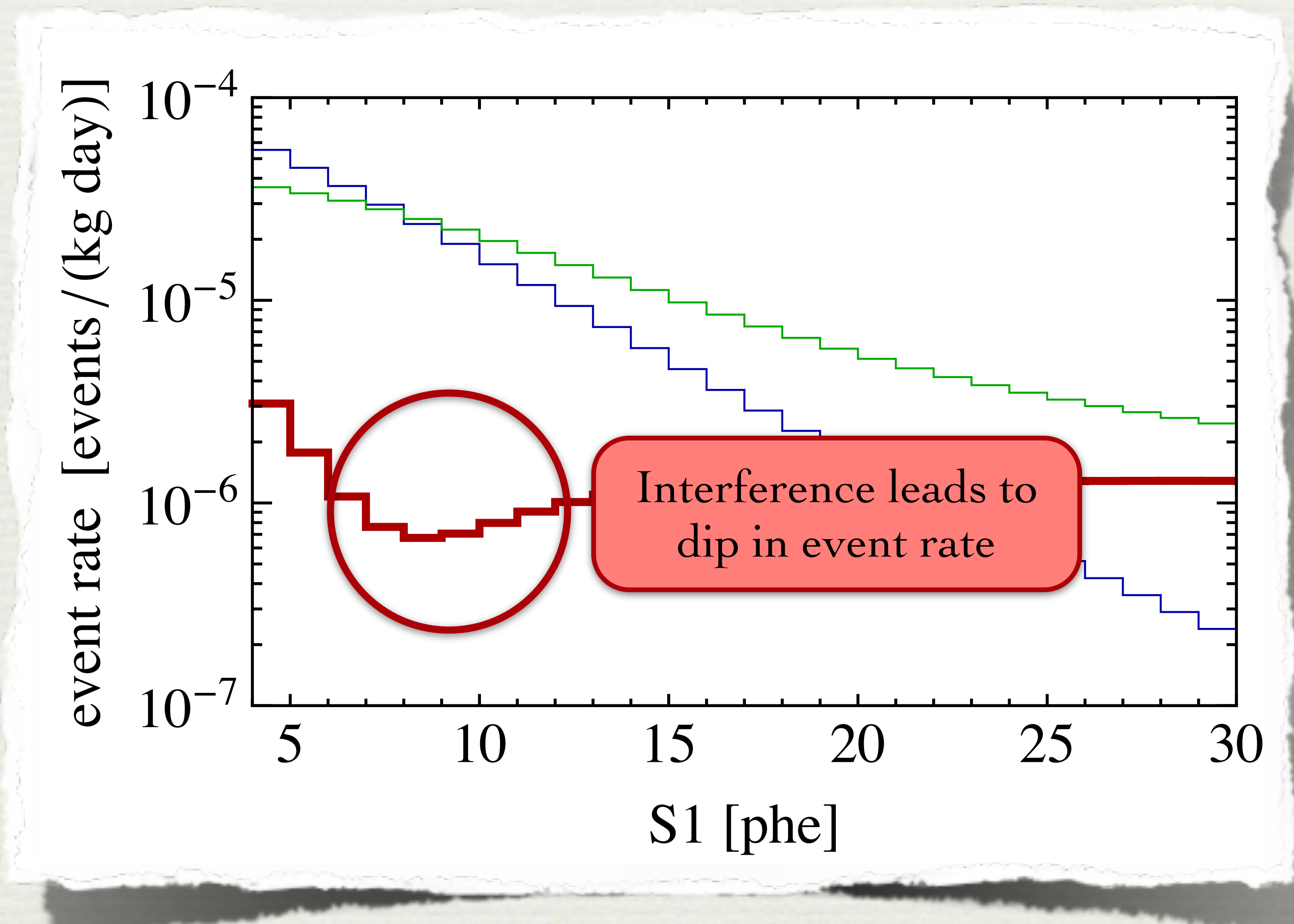
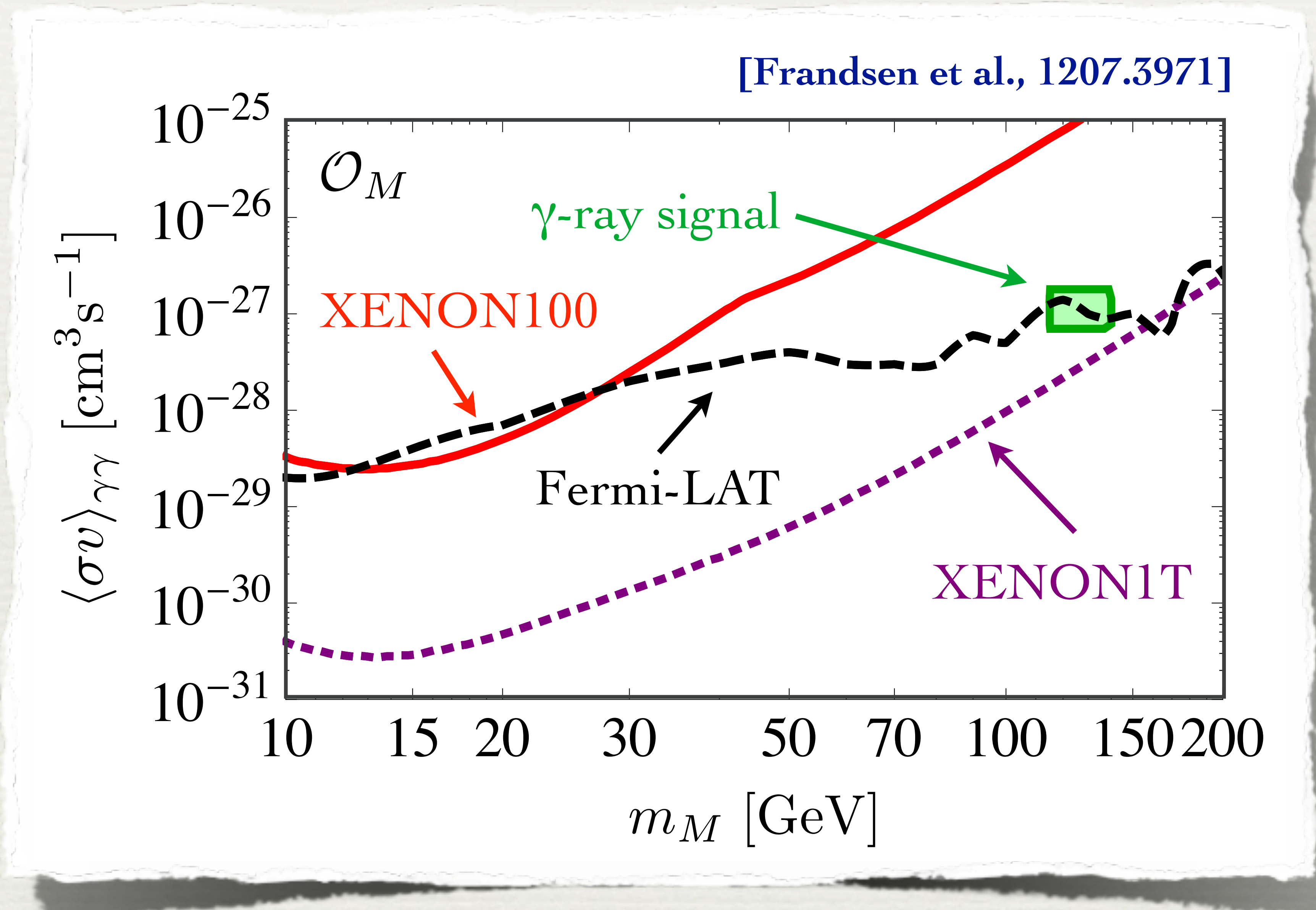




[Frandsen et al., 1207.3971]

Sensitivity Of XENON



If Majorana DM operator is responsible for γ-ray excess, claim can be tested in future with XENON1T