Dark Matter and Colliders

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Counter–examples: axions; Gravitinos; FIMPs; dark atoms; primordial black holes; keV neutrinos: not covered in this talk. Note: Proves that LHC does *not* "recreate conditions of the early universe"!

The "WIMP Miracle"

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- Indicates weak–scale $\chi\chi$ annihilation cross section: $\langle \sigma(\chi\chi \to \text{any}) v \rangle \simeq (2 \text{ to } 4.5) \cdot 10^{-26} \text{cm}^3 \text{s}^{-1}$

WIMPs and Early Universe

$\Omega_\chi h^2$ can be changed a lot in non–standard cosmologies (involving $T \gg T_{\rm BBN}$):

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Determining $\sigma(\chi\chi \to {\rm SM})$ allows probe of very early Universe, once χ has been established to be “the” DM particle! e.g. MD, Iminniyaz, Kakizaki, arXiv:0704.1590

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- $\Omega_\chi h^2$ determined from $\sigma(\chi\chi \to \mathrm{SM})$ near threshold ($T_F \simeq m_\chi/20 \Longrightarrow s \simeq 4m_\chi^2$). At colliders need ≥ 3 body final state to get signature (e.g. $e^+e^- \to \chi\chi\gamma$, $q\bar{q} \to \chi\chi g$) $\Longrightarrow$ typically need $\sigma(\chi\chi \to \mathrm{SM})$ at $s \gtrsim 6 \text{ to } 10 m_\chi^2$!

“Model-independent” approach

Goodman et al., arXiv:1005.1286 and 1008.1783; Bai, Fox, Harnik, arXiv:1005.3797; Wang, Li, Shao, Zhang, arXiv:1107.2048; Fox, Harnek, Kopp, Tsai, arXiv:1103.0240

Parameterize χ interaction with relevant SM fermion through dim–6 operator; e.g. for hadron colliders:

$$\mathcal{L}_{\rm eff} = G_{\chi,q}\,\bar\chi\Gamma_\chi\chi\,\bar q\Gamma_q q$$

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χ Majorana $\Longrightarrow \Gamma_\chi \in \{1, \gamma_5, \gamma_\mu\gamma_5\}$

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If $\Gamma_\chi,\, \Gamma_q \in \{1, \gamma_5\}:\ G_{\chi,q} = m_q/(2M_*^3)$ (chirality violating!), else $\Gamma_\chi = 1/(2M_*^2)$ Rajamaran, Shepherd, Tait, Wijango, arXiv:1108.1196.

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Compare monojet signal from $q\bar q \to \chi\chi g$ with monojet limits (current bound) and background (ultimate reach)!

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Approach can only work if the "mediator" mass m_M is (much) larger than the highest relevant momentum scale: $m_M \gg 2m_\chi,$ missing $E_T \simeq 400$ GeV

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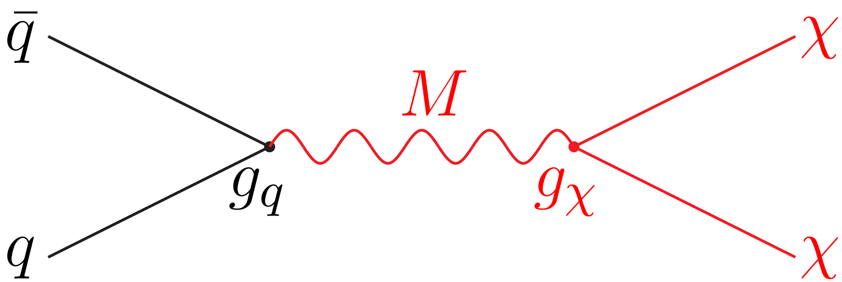
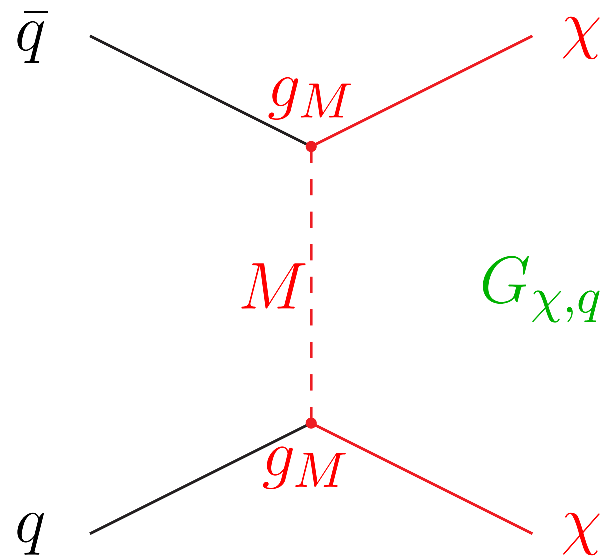
LHC can only hope to be sensitive if χ couples to quarks at tree level. Two options:

$s-$channel



$G_{\chi,q} = \frac{g_\chi g_q}{m_M^2}$

$t-$channel



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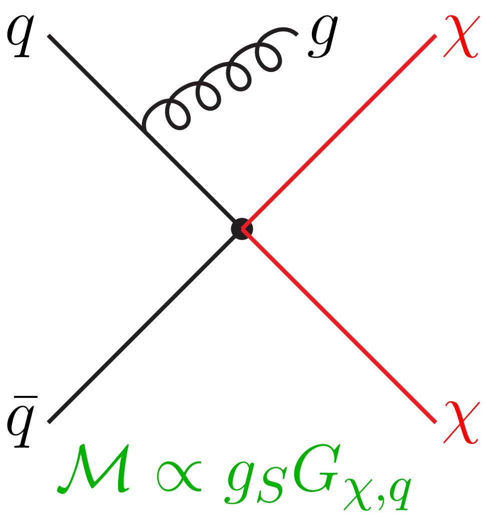
Case $\Gamma_\chi = \Gamma_q = \gamma_5$ also has poor LHC reach. Gives velocity–dependent interaction for $\chi p \rightarrow \chi p \Longrightarrow$ very poor reach in direct detection as well

Monojet analysis is not model-independent!

Contributing diagrams:



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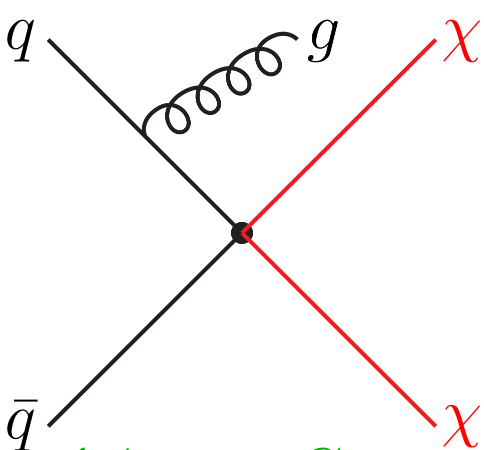

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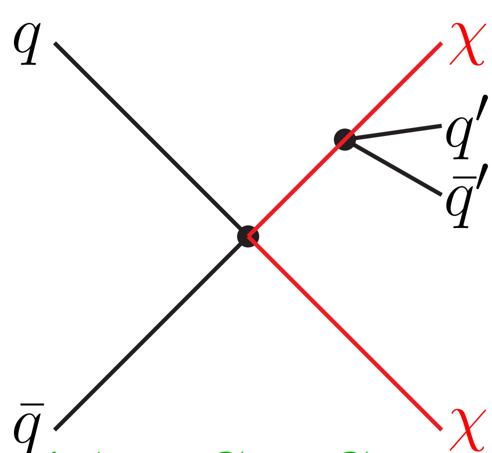

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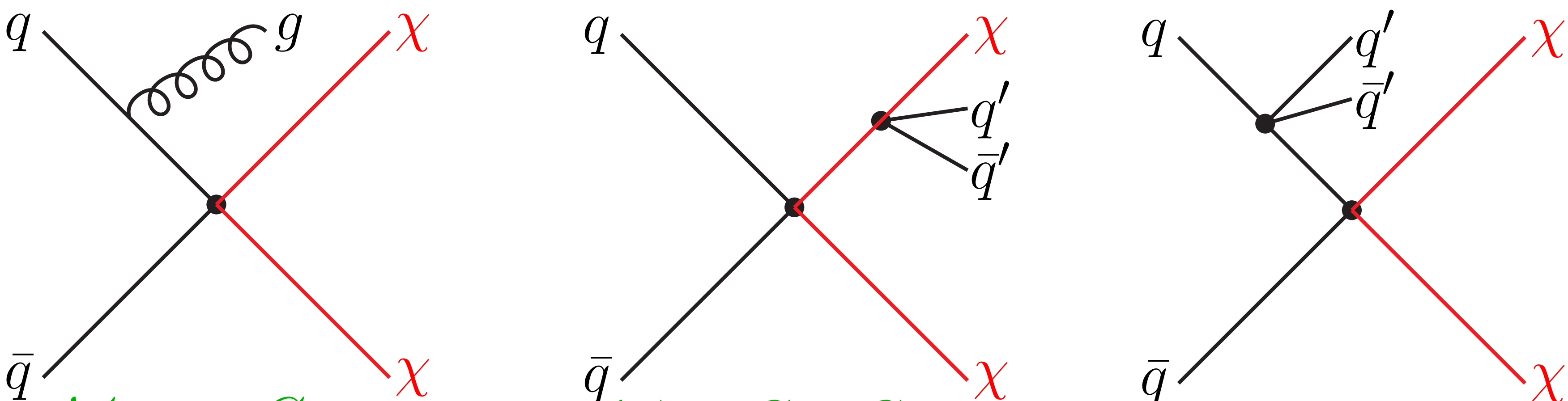

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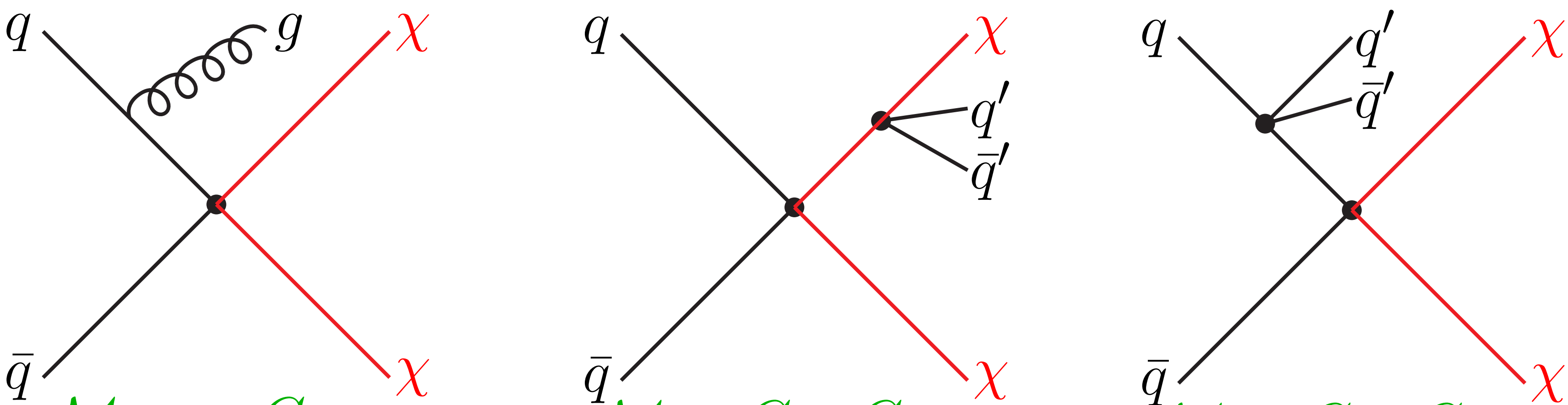

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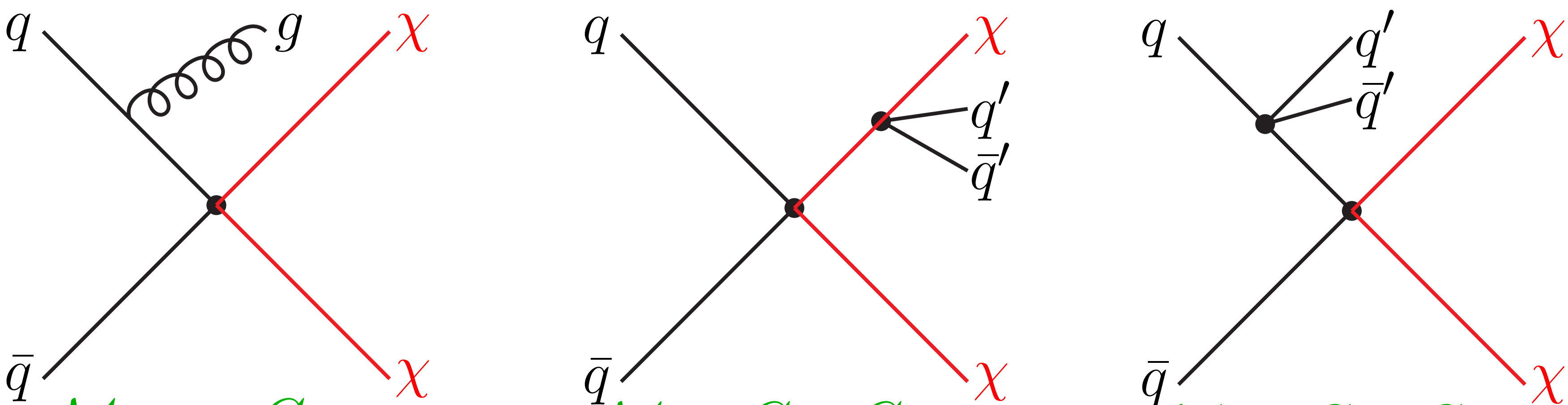

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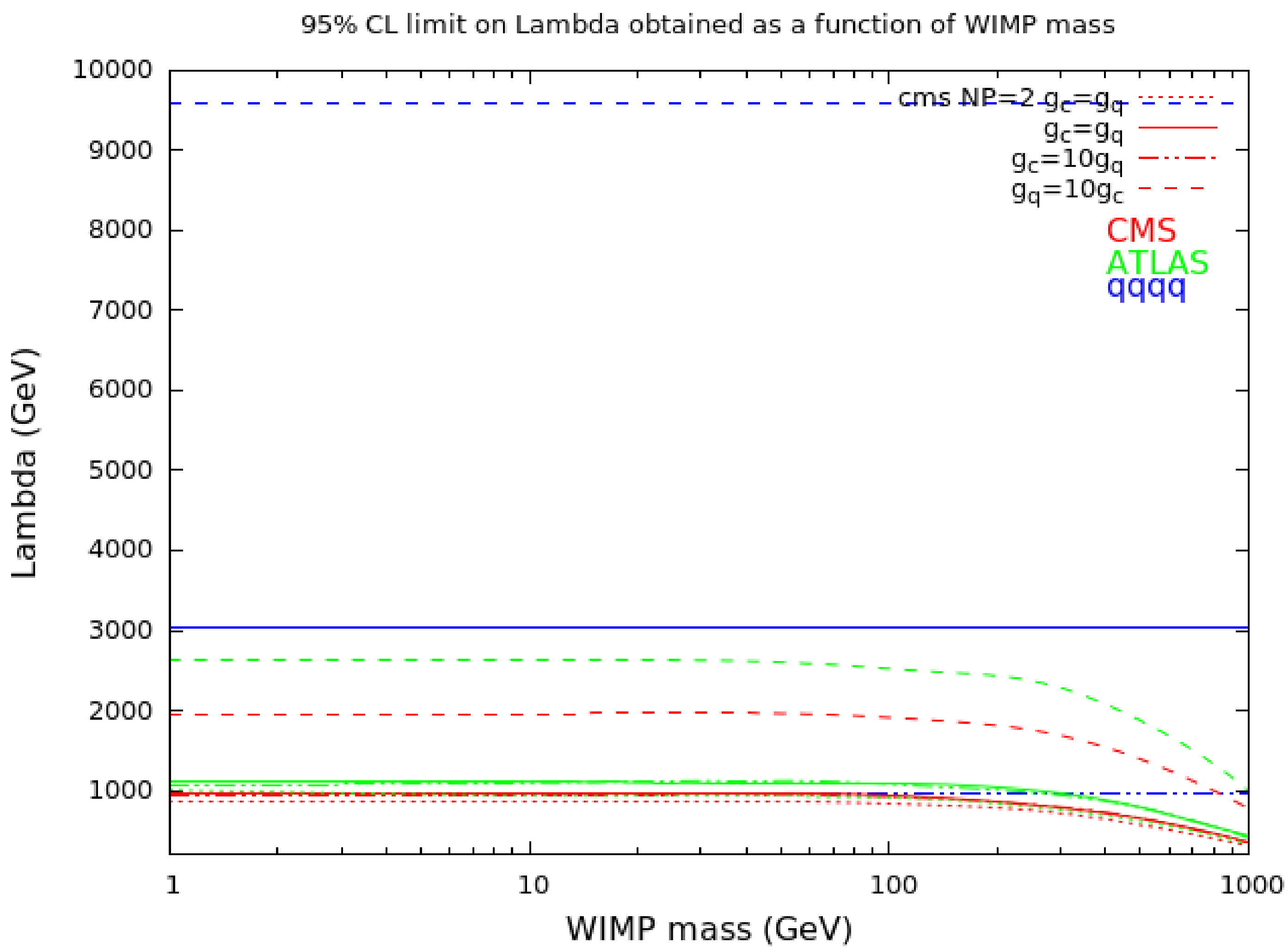
For $s-$channel: bound on $4q$ contact interaction stronger than bound from monojet searches, unless $g_\chi \gg g_q$!

Bounds on Λ

S. Belwal, MD, J.S. Kim, in preparation



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For perturbative couplings: search for off–shell mediator $\rightarrow \chi\chi$ is hopeless! E.g. SUSY: signal for $\tilde{\chi}\tilde{\chi}\, j$ is *much* smaller than $Z\,(\rightarrow \nu\bar{\nu})\, j$ background, even for 100 GeV higgsino–like $\tilde{\chi}$

(Baer, Mustafayev, Tata, arXiv:1401.1162)

DM and Light (Gauge) Bosons

(At least) 3 kinds of WIMP models require light ($m \leq$ few GeV) (gauge) bosons U:

- MeV DM: Suggested as explanation of 511 keV line ($\Rightarrow$ slow e^+) excess from central region of our galaxy (Boehm et al., astro-ph/0309686). Should have $m_\chi \leq 10$ MeV (γ constraints)
  $\Rightarrow m_\chi \leq m_U \leq 200$ MeV to mediate $\chi\chi \to e^+e^-$; fixes $g_{U\chi\chi} g_{Ue^+e^-}/m_U^2$! (Unless $2m_\chi \simeq m_U$.)

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- PAMELA/FermiLAT inspired TeV DM: Needs light boson for Sommerfeld enhancement (e.g. Arkani-Hamed et al., arXiv:0810.0713(4)) ($\chi\chi \to UU \to 4l$ is also somewhat less constrained by γ spectrum than $\chi\chi \to 2l$.)

- DAMA/CoGeNT inspired few GeV DM: Needs light mediator to achieve sufficiently large $\sigma_{\chi p}$. (2 different mediators for isospin violation to evade bounds: Cline, Frey, arXiv:1108.1391)

Light Gauge Bosons (cont'd)

In all cases: U couplings to (most) SM particles must be $\ll 1$ to evade bounds! ($g_\mu - 2$, meson decays, ν cross sections, APV, . . .).

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$U\chi\chi$ coupling may well be large.

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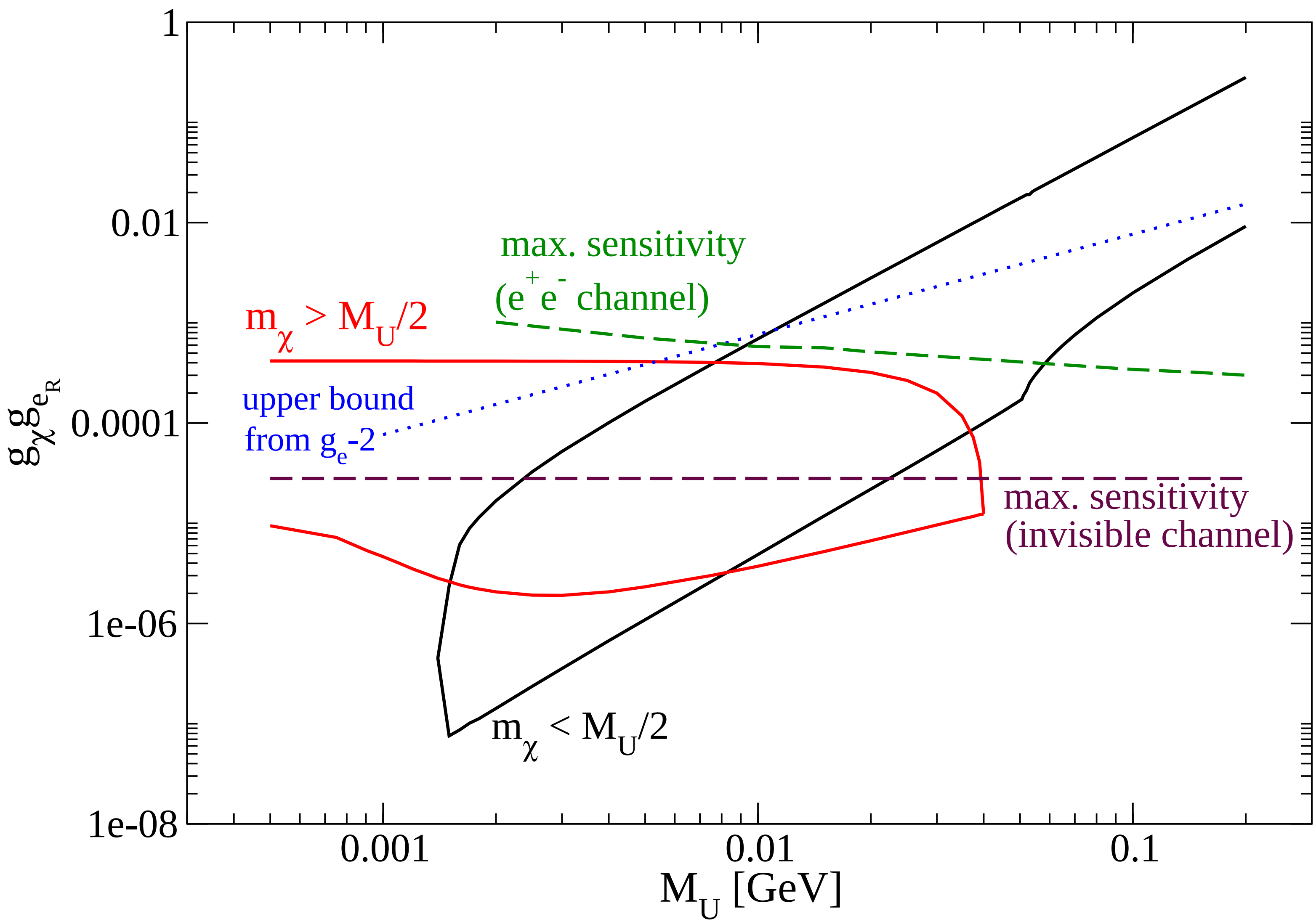
- Instrumental backgrounds (not from e^+e^- annihilation) seem large

Sensitivity at $B-$factories (100 fb^{-1})



Red, black: Regions allowed by Ω_χ, $\sigma(\chi\chi \to e^+e^-)$.

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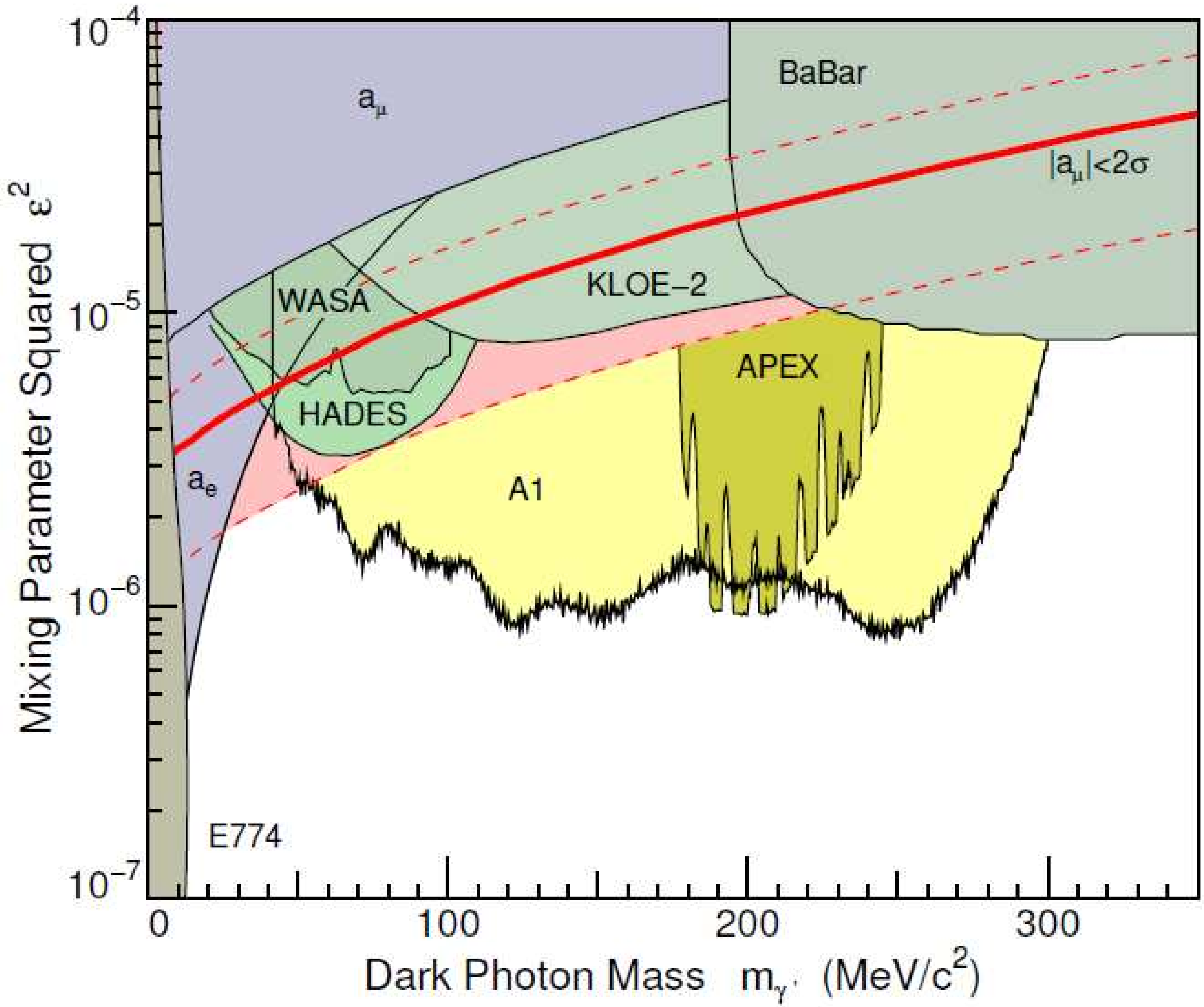
Also, KLOE-2 performed search, mostly for $\phi \to U\eta$: no signal. arXiv:1107.2531

A1 results



BaBar
a_μ
$|a_\mu|<2\sigma$
WASA
KLOE−2
APEX
HADES
a_e
A1
E774
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
100
200
300
Mixing Parameter Squared ε^2
Dark Photon Mass $m_{\gamma'}$ (MeV/c^2)

SUSY DM and the LHC

Saw above: WIMP searches at colliders not promising, *if* WIMP is only accessible new particle. Fortunately, in many cases the WIMP is the lightest of *many* new particles! True in SUSY. (Also in Little Higgs, UED.)

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- HLS theorem, relation to superstrings: don't single out weak scale.

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- In simplest, $R-$parity invariant scenario: lightest superparticle LSP is stable: satisfies one condition for DM candidate!

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- but DM–allowed regions of parameter space do exist even in constrained models!

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- Note: DM–allowed region of $(m_0, m_{1/2})$ plane of cMSSM depends on $A_0, \tan\beta$!

Generic SUSY searches at LHC

Strongly interacting sparticles have biggest cross sections; may decay via long decay "cascades". Example:

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gg \longrightarrow \tilde{g}\tilde{g} &\longrightarrow (\tilde{b}_1 \bar{b})\,(\tilde{u}_L \bar{u}) \\
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$\mathcal{O}(100)$ searches have been performed, but no signal has been found.

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- In pMSSM10: $m_{\tilde{\chi}_1^0} \simeq 50$ GeV still ok! de Vries et al., arXiv:1504.03260

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- WIMP couplings: Determine cross sections and final states in indirect searches; determine cross sections in direct searches
- Most interesting to me: Predict $\Omega_\chi h^2$, compare with observation: Constrain very early universe!

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- Searches for mediators *are* promising at colliders!
- Scenarios with new light gauge bosons with suppressed couplings to SM fermions are now being probed at low$-E$ colliders, fixed–target expts.
- Absence of missing E_T signal at LHC is disappointing, but plenty of parameter space in reasonably well motivated WIMP models left to explore