Searches for Squeezed Spectra

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1707.02460


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squeezed spectra

- basic scenario
  - dark matter χ is a gauge-singlet Majorana fermion ...
  - ... which couples to SM fermion f ...
  - ... through exchange of SM-charged scalar(s) $\tilde{f}_{1,2}$
  - χ and $\tilde{f}_{1,2}$ charged under Z_2 symmetry which stabilizes DM
- arises in a variety of frameworks
  - MSSM with bino-like LSP (our main example)
    - scalars = sfermions
  - WIMPless dark matter with DM = Majorana fermion (easy to generalize)
- we're interested in the case of a squeezed spectrum ...
  - small mass splitting between DM and lightest mediating scalar ($\mathcal{O}$(1-10) GeV)
- ... and when f = u, d, s (light quarks)
- interesting phenomenology for LHC, direct detection and early Universe

new features

- LHC
  - standard sfermion searches fail, since MET and visible fermions are soft
  - can use ISR jets to give transverse boost to system
  - sensitivity reduced

- direct detection
  - can get large enhancement in scattering cross section from resonance
  - boost sensitivity for SI, SD, or even v-suppressed cross sections

- early Universe
  - co-annihilation processes can widen mass range for which correct thermal relic density can be achieved

upshot

- direct detection can have higher mass reach than LHC
  - even for small scalar mixing, if mass splitting is small
  - twist-2 operators important

- models escaping LHC searches and direct detection bounds can still get the right thermal relic density via co-annihilation

current LHC constraints ($\tilde{q}$)

- MSSM squark search
  - gluinos, etc. decoupled
- very tight bounds when bino-squark splitting is large
- hard to search for squeezed spectra at LHC
  - decay products (visible and invisible) are softer
  - need to boost with an extra hard jet
- assume $m_{\tilde{q}}$ > 400 GeV required
- but bounds on specific scenarios can be tighter

- if 8 degenerate light squarks, bino much lighter
  - $m_{\tilde{q}}$ > 1.4 TeV (CMS 1704.07781)
- for bino-squark splitting of order 20-25 GeV (8 degenerate squarks)
  - need $m_{\tilde{q}}$ > 700 GeV (ATLAS-CONF-2017-060)
- for very small bino-squark splitting (~ 1 GeV), weaker still, like monojet search
  - see parallel talks from Maria and Sushil from Monday

splitting and precision EW

- we'll assume a couple of squarks are light & degenerate, rest heavy
- but can't really decouple scalars
  - gauge invariance
- splitting constrained by precision electroweak variables (ρ)
- but direct detection and co-annihilation processes dominated by lightest squarks
- if squark-squark splitting larger than bino-squark, can effectively ignore heavier squarks
- not true for LHC constraints

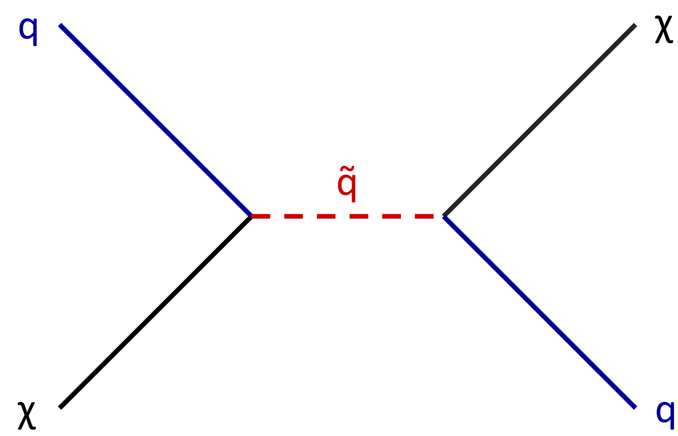
- ρ parameter constrained to within 1%
- need $\delta m \equiv m_2 - m_1 < \mathcal{O}(100)$ GeV
- light squark dominates if $\delta m \gg \Delta m \equiv m_1 - m_\chi$
- true for most of our parameter space

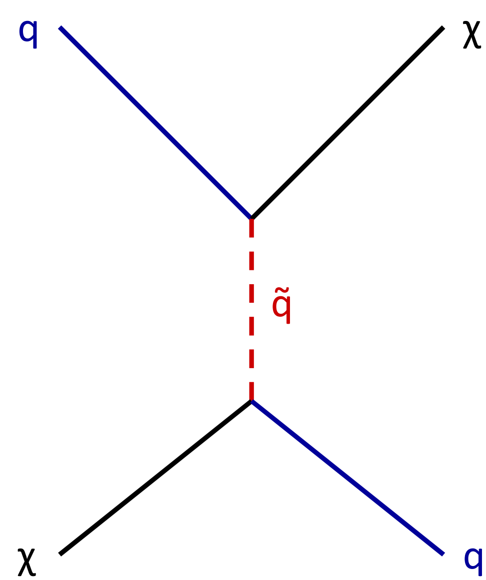
$$\delta\rho \approx \frac{c^2}{16\pi^2}\mathcal{O}\left(\frac{\delta m^2}{m_Z^2}\right)$$

c = $\mathcal{O}(1)$ coupling of scalars to weak gauge boson

direct detection

- assume light scalar(s) are quark partners ($\tilde{u}$, $\tilde{d}$, $\tilde{s}$)
  - exchanged in s-/u-channel
- each scalar a mixture of $\tilde{q}_L$ and $\tilde{q}_R$
  - mixing angle α
  - need not be small, but can be (MFV)
  - we assume no flavor changing
- in fully non-relativistic limit, scalar propagator goes as $(m_\chi{}^2 - m_{\tilde{q}}{}^2)^{-1} \sim (2m\, \Delta m)^{-1}$
- cross section enhanced in quasi-degenerate regime
- we'll expand in contact operators





dimension-6 operators

- take propagator to 0th order in momentum
- DM is Majorana (some operators vanish)
- look for operators yielding either velocity-independent and/or coherently-enhanced matrix elements
  - these will tend to dominate
- assume CPV small
- three main dim-6 operators
- coefficients α_{qi} scale as $(2m\,\Delta m)^{-1}$
  - enhanced in quasi-degenerate limit

$$\mathcal{O}_{q1} = \alpha_{q1}\left(\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\right)\left(\bar{q}\gamma_{\mu}q\right)$$

$$\mathcal{O}_{q2} = \alpha_{q2}\left(\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\right)\left(\bar{q}\gamma_{\mu}\gamma^{5}q\right)$$

$$\mathcal{O}_{q3} = \alpha_{q3}\left(\bar{\chi}\chi\right)\left(\bar{q}q\right)$$

- $\mathcal{O}_1$ (anapole): A^2-enhanced terms, v-suppressed
- $\mathcal{O}_2$ (axial): SD
- $\mathcal{O}_3$ (scalar): A^2-enhanced (SI), α-suppressed
- others suppressed by CPV or more powers of v

a twist-2 operator

- also consider dim-8 operators
  - arise from expanding propagators to next order in p
- most important is twist-2
  - A^2-enhanced (SI), α–independent and "v-independent"
  - p-suppression absorbed in nucleon form factor
- heuristically, fermion bilinear structure similar to vector current
  - cancels between diagrams for Majorana fermion
  - but keeping the p-dependence kills the cancelation

$$\mathcal{O}_{qT2} = \alpha_{qT2}\left(i\bar{\chi}\gamma^{\mu}\partial^{\nu}\chi\right) \times\left[\left(\frac{i}{2}\right)\left(\bar{q}\gamma_{\mu}\partial_{\nu}q + \bar{q}\gamma_{\nu}\partial_{\mu}q - \frac{1}{2}g_{\mu\nu}\bar{q}\gamma_{\lambda}\partial^{\lambda}q\right)\right]$$

- p-dependence of propagator re-expressed as a derivative expansion
- but get $(m_N / \Delta m)$ suppression, in addition to nucleon form factor suppression
- interferes with $\mathcal{O}_{q3}$

from high scale to nucleon to nucleus

- coefficients α_{qi} defined at the high scale (we take as m_Z)
- RG-evolve coefficients from high-scale to nucleon scale (1-2 GeV) (Hill, Solon 1409.8290)
- couple to nucleon matrix elements (nucleon form factors)
  - vector factors fixed by gauge-inv.
- convolve with nuclear response functions (Anand, Fitzpatrick, Haxton 1308.6288)
  - standard for all operators except $\mathcal{O}_1$, which has terms coupling to L (neither SI nor SD)

$$B_u^{p(S)} = B_d^{n(S)} = 9.85$$

$$B_u^{n(S)} = B_d^{p(S)} = 6.67$$

$$B_s^{p,n(S)} = 0.499$$

most uncertainty... we take values with small strange content (1411.2634)

$$B_u^{p(T2)} = B_d^{n(T2)} = 0.40$$

$$B_u^{n(T2)} = B_d^{p(T2)} = 0.22$$

$$B_s^{p,n(T2)} = 0.02$$

suppressed by momentum factors (1409.8290)

$$\Delta_u^p = \Delta_d^n = 0.787$$

$$\Delta_u^n = \Delta_d^p = -0.319$$

$$\Delta_s^{p,n} = -0.040$$

SD form factors relatively precise

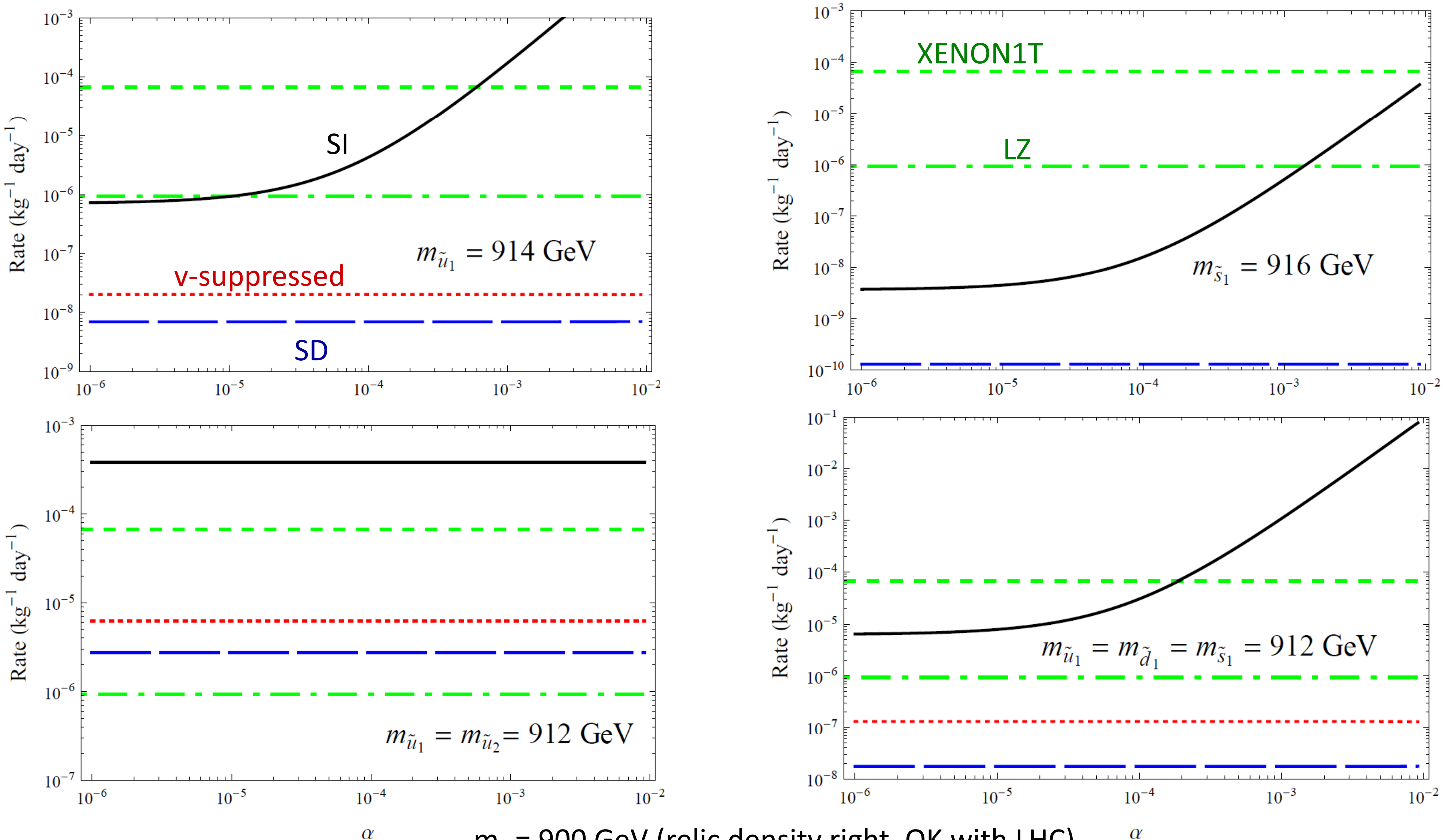
what's important?

- at large scalar mixing, $\mathcal{O}_3$ should dominate event rate
  - coherent enhancement, no v-suppression, helicity suppression taken small

- at smaller scalar mixing, others can dominate
  - $\mathcal{O}_{1,T2}$ both have coherent enhancement and no helicity suppression
  - $\mathcal{O}_1$ is v-suppressed, and vanishes for strange quarks
  - $\mathcal{O}_{T2}$ is not "really" v-suppressed, but v-suppression absorbed into nucleon form factor
    - essentially, momentum of the parton, not the nucleon
    - m_N / Δm

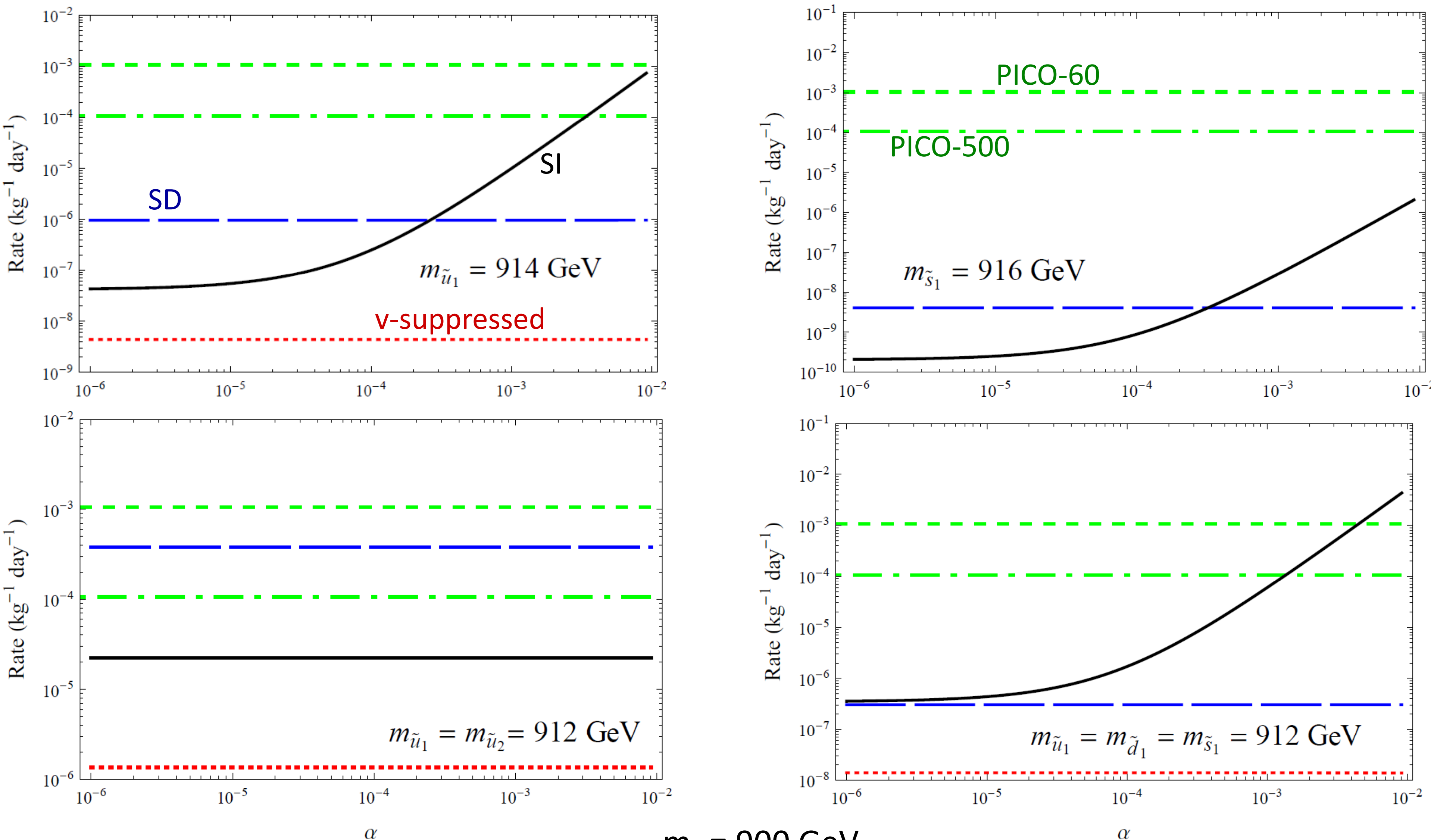
- $\mathcal{O}_2$ gives SD scattering
  - relatively more important for targets like fluorine

scattering rates - xenon



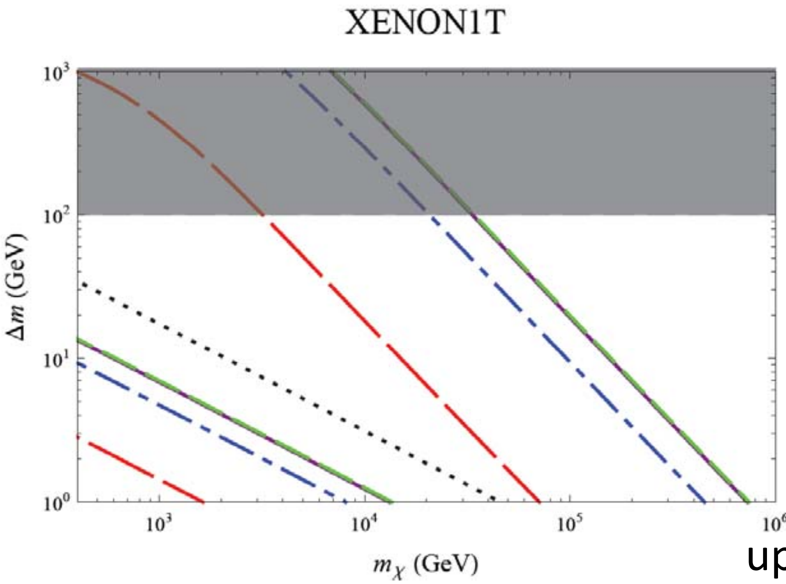
m_χ = 900 GeV (relic density right, OK with LHC)

scattering rates - fluorine

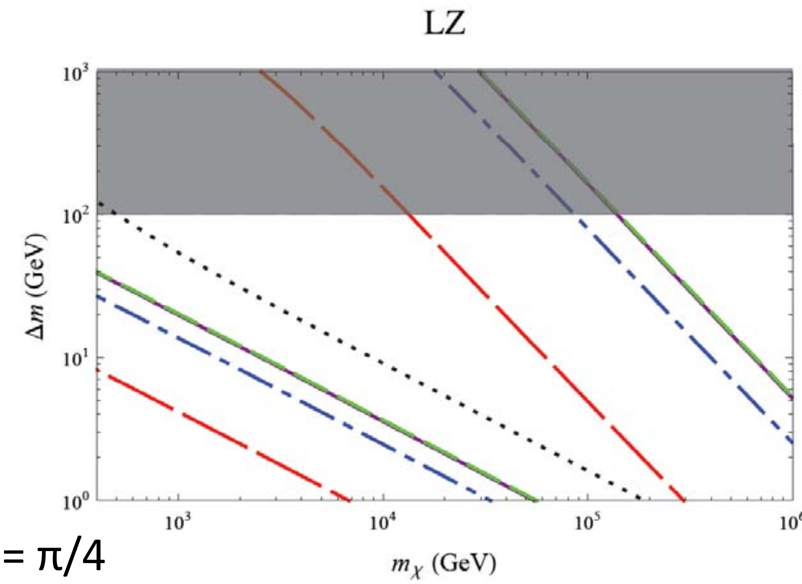


m_χ = 900 GeV

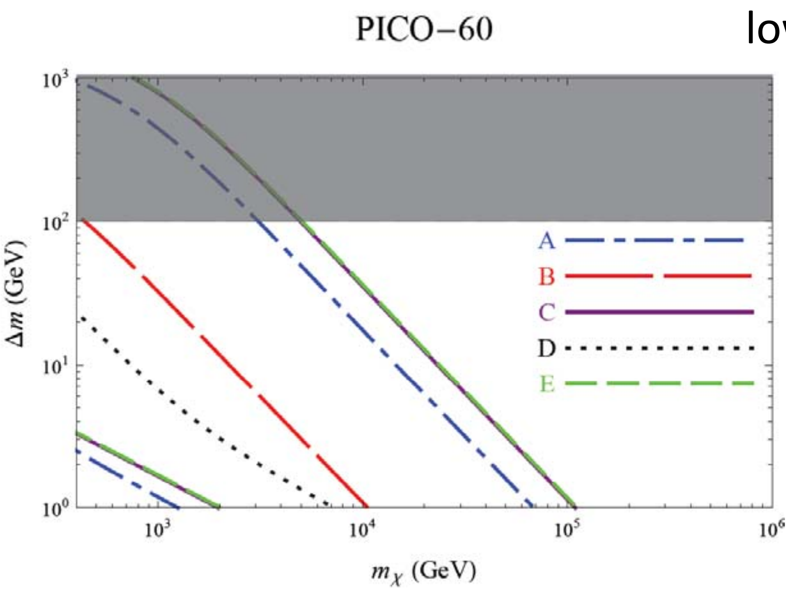
sensitivity

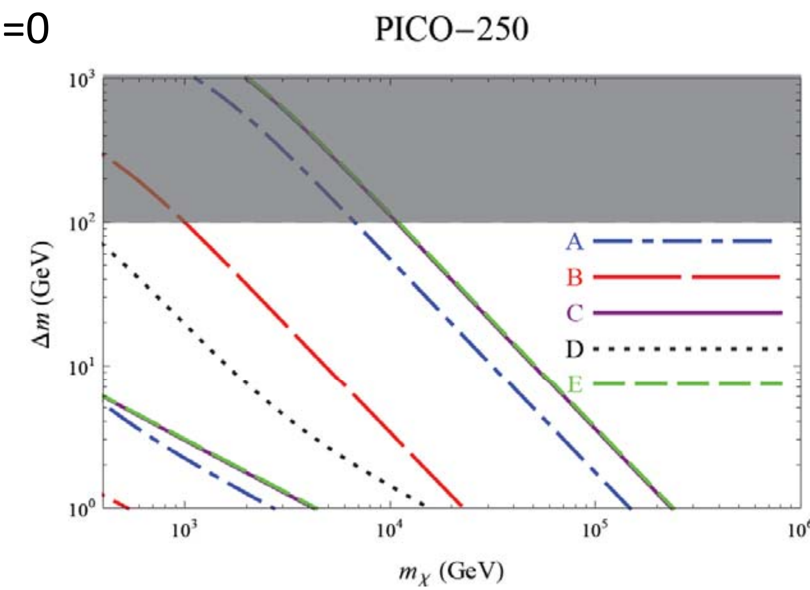


A = $\tilde{u}_1$
B = $\tilde{s}_1$
C = $\tilde{u}_1, \tilde{d}_1$
D = $\tilde{u}_1, \tilde{u}_2$
E = $\tilde{u}_1, \tilde{d}_1, \tilde{s}_1$



upper contour: $\alpha = \pi/4$
lower contour: $\alpha = 0$





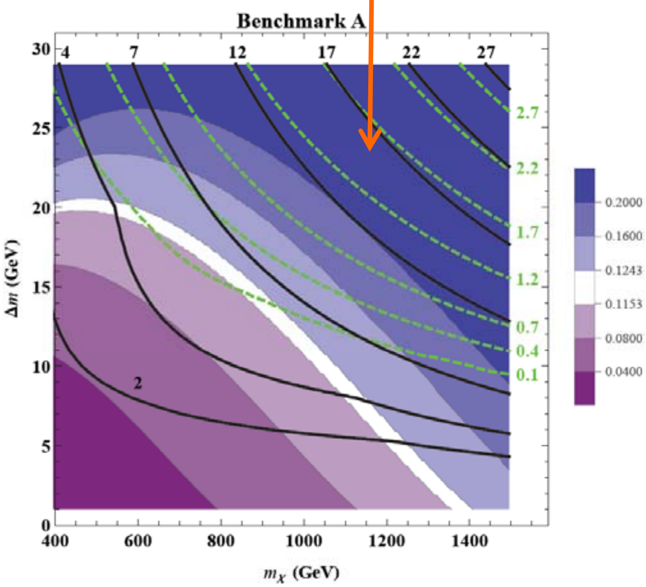
co-annihilation

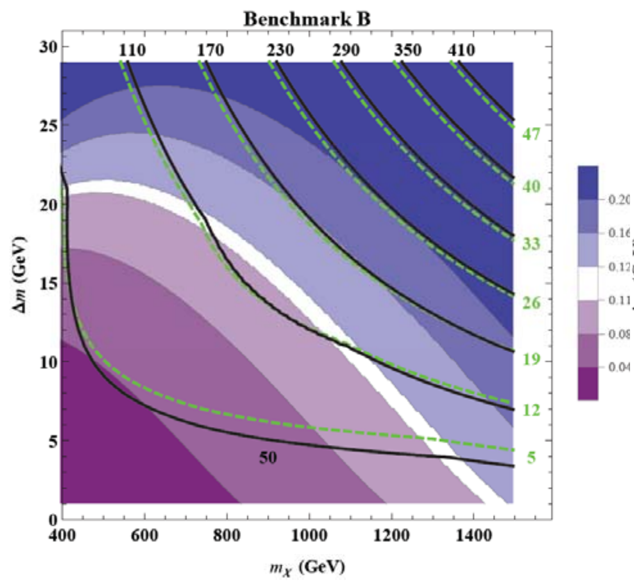
- if $\Delta m / m_\chi \ll 1$, then charged scalar might still be around at freeze-out
- co-annihilation processes will not have p-wave/chirality suppression
- extends dark matter thermal mass range beyond standard "bulk"
- main processes
  - $\chi\chi \rightarrow \bar{q}q$: "bulk" annih. process, v/α-suppressed, important at larger splitting
  - $\chi\tilde{q} \rightarrow qg$: dominates at smaller splitting
  - $\tilde{q}^*\tilde{q} \rightarrow gg, gZ$: dominate at very small splitting
- little dependence on α for small splitting
- similar $\tilde{t}$ co-annihilation regime (some kinematic differences)
- in MSSM scenario, some Higgs processes are not m_q-suppressed
  - not required by gauge-invariance, and don't change the picture much
- not including Sommerfeld-enhancement, but doesn't change qualitatively
  - de Simone, Giudice, Strumia (1402.6287); Liew, Luo (1611.08133)

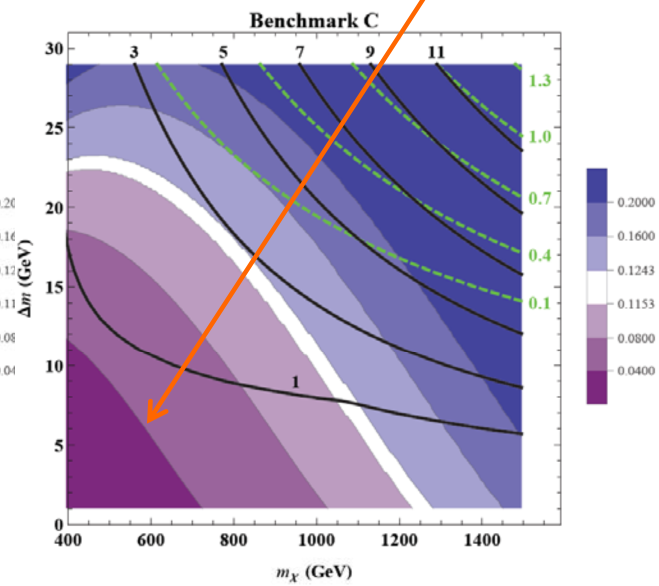
results

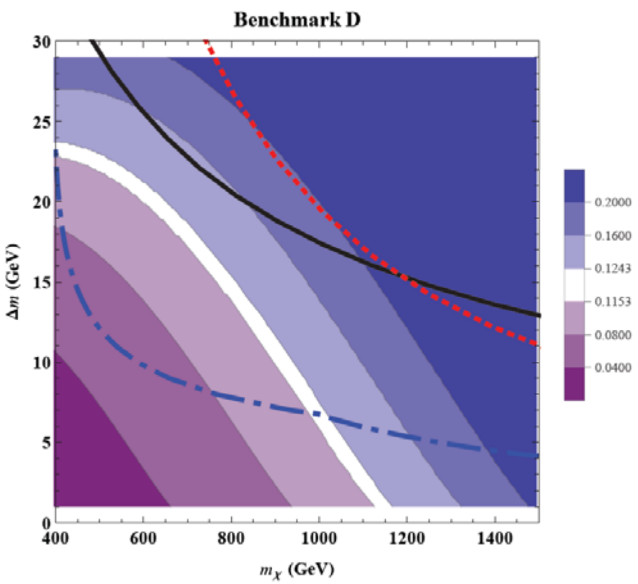
overdense
assume non-thermal

underdense
assume multi-component









A = $\tilde{u}_1$
B = $\tilde{s}_1$
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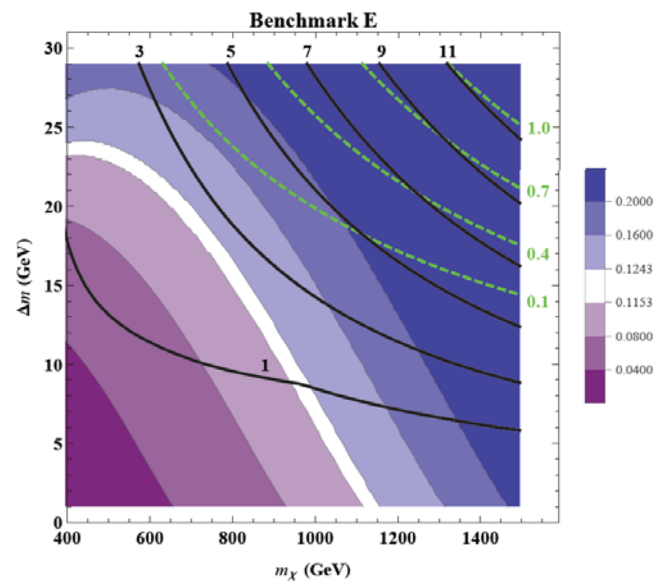
D = $\tilde{u}_1$, $\tilde{u}_2$
E = $\tilde{u}_1$, $\tilde{d}_1$, $\tilde{s}_1$

A, B, C, E: α (10^{-4})
for XENON1T
and LZ

D: XENON1T (excluded),
PICO-60, PICO-500

white band = correct relic density (α~0)



conclusion

- small splitting between DM and charged mediator has a big effect on phenomenology
  - enhances direction detection signal, even if L-R mixing is small
  - co-annihilation processes extend thermal relic mass range
  - LHC bounds weakened

- direct detection can probe models well beyond maximum LHC reach
  - but models probed at such large mass scale are fine-tuned
- some models beyond current LHC, LZ reach for which DM can be a thermal relic

Mahalo!

Back-up slides