# The LHC versus Direct and Indirect Detection

Stefan Vogl

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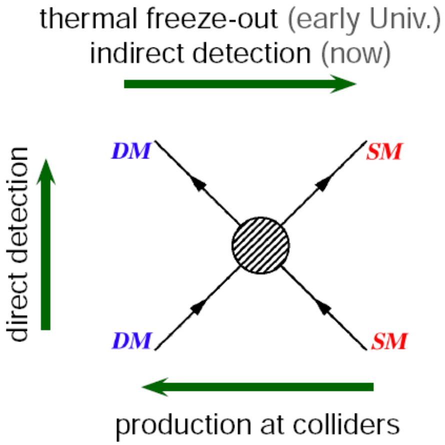
in collaboration with:
T. Bringmann, M. Garny, X. Huang, A. Ibarra, M. Pato,
S. Rydbeck and C. Weniger

Technische Universität München

# Outline

# Interaction with SM?



# What are the interactions of Dark Matter with the SM?

## Assumptions

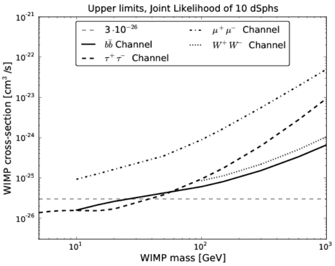
- dark matter $\longleftrightarrow$ massive particle with interaction strength $\approx$ weak strength
- dark matter produced thermally in early universe

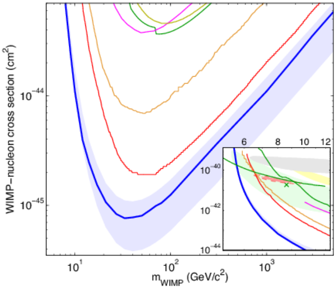
## Questions

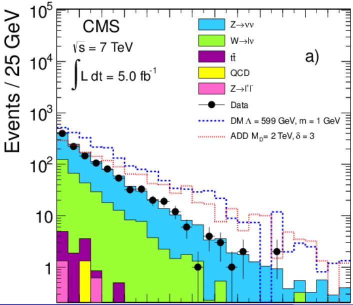
- How can we search for Dark Matter?
- What are the signatures of Dark Matter we might expect?
- How are they correlated?

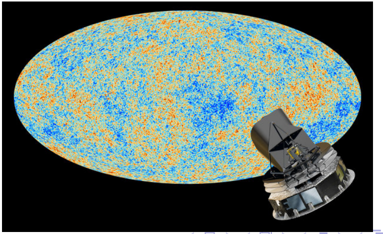
- no compelling fundamental theory
- stay agnostic as to the fundamental interactions
- try to go for more "model independent" approach

# All the observations



# Simplified Model

- stay a little less agnostic as to the fundamental interactions
- write down "simplified model" $\rightarrow$ use it as phenomenology generator
- DM at LHC: simple options limited (Higgs, Z', new mediators ...)

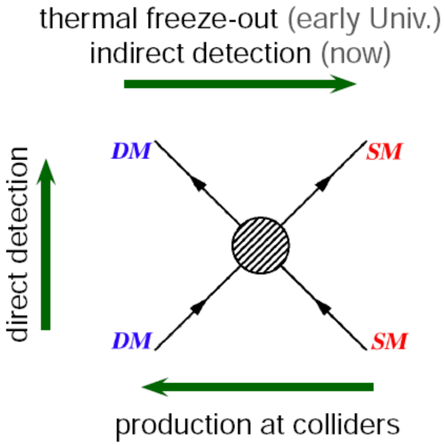
## t-channel mediator

- Majorana fermion $\chi$ as dark matter
- $\chi$ singlet under SM gauge group
- interactions $\rightarrow$ scalar mediator $\eta$
- Yukawa interactions with the fermions (leptons, heavy quarks, ...), here light quarks

$$\mathcal{L}_{int} = -f\bar{q}_R\chi\eta + \text{h.c.}$$

- Examples:
  - stop/stau coannihilation in MSSM
  - models for radiative neutrino masses and dark matter Ma 2009, Bergstrom 2012

# Should we care about the mediator?



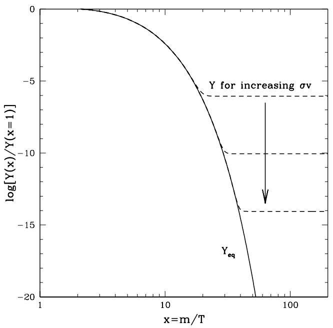
# Thermal Relics

- dark matter was in thermal equilibrium
- abundance decreases with $T$

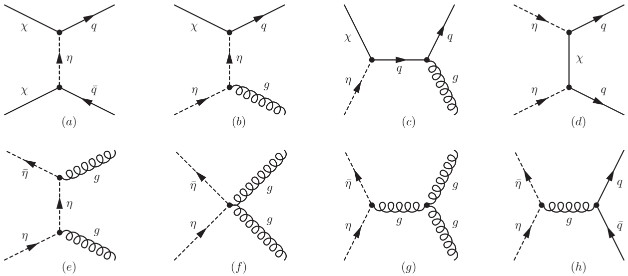
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\sigma v \left[ n_\chi^2 - (n_\chi^{EQ})^2 \right]$$

- interaction rate becomes small compared to expansion of universe; freeze-out

$$\rightarrow \Omega h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\sigma v_{\mathrm{thermal}}}$$



# Does the mediator matter? Coannihilations

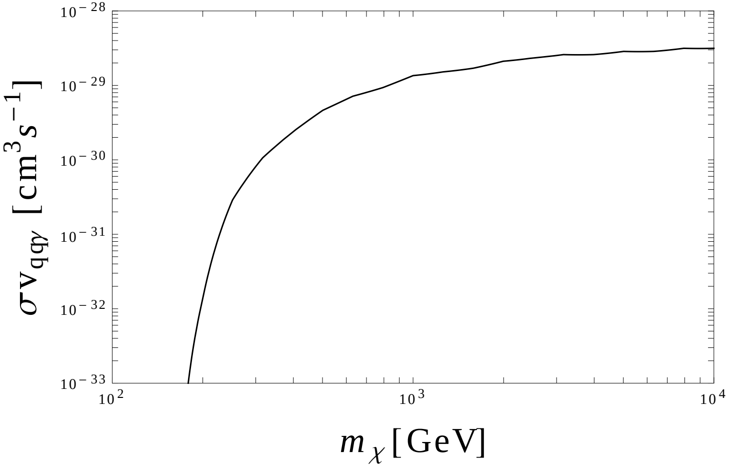



- $m_\eta \lesssim 1.2\ m_\chi$ coannihilations become important Griest, Seckel 1991
- use effective cross section at freeze-out $\sigma v_{thermal} \to \sigma v_{eff}$

$$\sigma v_{eff} = \sigma v(\chi\chi) + \sigma v(\chi\eta) e^{-\frac{m_\eta - m_\chi}{T}} + \sigma v(\eta\eta) e^{-\frac{2(m_\eta - m_\chi)}{T}}$$

- semi-analytic Ellis, Olive, Santoso 2001; Gondolo, Edsjo 1997 or numeric micrOMEGA calculation of the relic density

# Thermal cross section




- thermal cross section for $m_\eta / m_\chi = 1.1$
- Note: unusual cross section

# A lower limit on Thermal Dark Matter?

- three contributions to the effective cross section

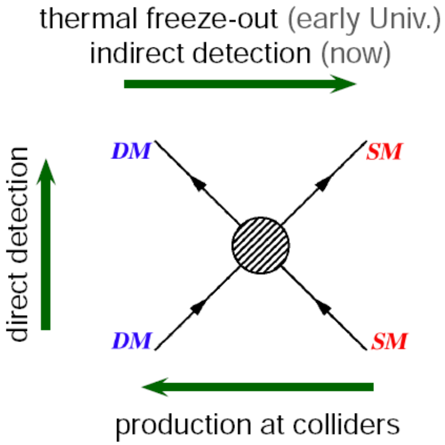
$$\sigma v_{eff} = \sigma v(\chi\chi) + \sigma v(\chi\eta) e^{-\frac{m_\eta - m_\chi}{T}} + \sigma v(\eta\eta) e^{-\frac{2(m_\eta - m_\chi)}{T}}$$

- only two cross sections depend on f, $\eta\eta \to$ SM mediated by gauge interactions

$$\Omega h^2 \sim \frac{1}{\sigma v_{eff}} = \frac{m_\chi^2}{f^4\, C_{\chi\chi} + f^2\, g^2\, C_{\chi\eta} + g^4\, C_{\eta\eta}}$$

- gauge interactions force $\Omega h^2$ to become small for some small $m_\chi$
- degenerate $\eta$ and strong interactions, high lower limit

# Indirect Searches and a gamma-ray feature

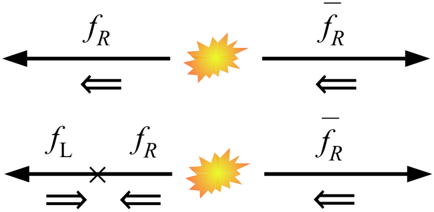


# $\chi\chi \to q\,\bar{q}$

- thermal cross section can be expanded into partial waves

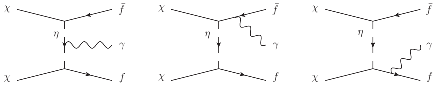
$$\sigma v = a + bv^2 + \mathcal{O}(v^4)$$

- today: $v \simeq 10^{-3} \to$ p-wave suppressed
- s-wave suppressed by helicity $m_f^2/m_\chi^2$
  SM example: pion decay to $e$ and $\mu$

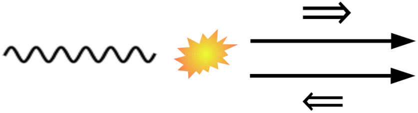



- total cross section suppressed

# A Higher Order Process - Internal Bremsstrahlung

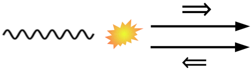


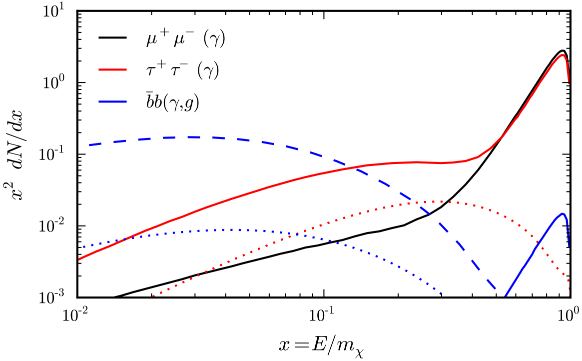

- helicity suppression can be lifted by emission of a boson



- $\gamma$, gluon Bergstrom 1989; Bergstrom, Bringmann, Edsjo 2008, W or Z Bell, Dent, Jaques, Weiler 2011; Ciafaloni, Cirelli, Comelli, De Simone, Riotto, Urbano 2011; Garny, Ibarra, SV 2011
- Note: cross section is still suppressed
  maybe higher sensitivity?

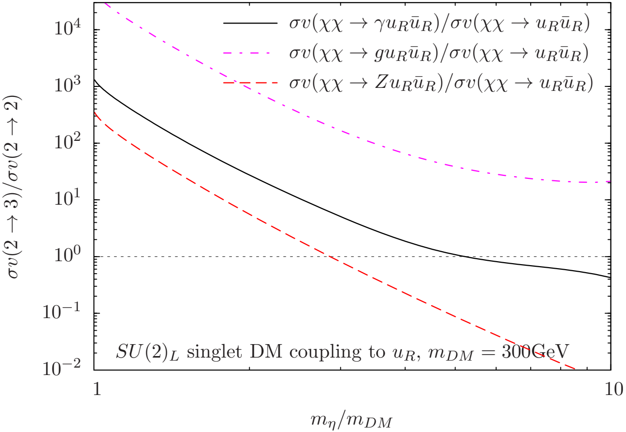
# Internal Bremsstrahlung spectrum





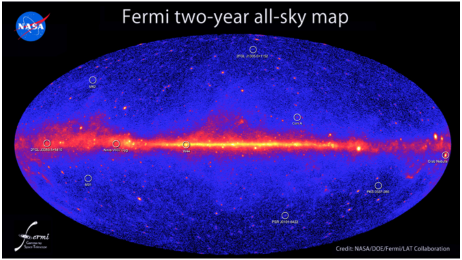

- line like spectral feature in gamma rays

# Three body cross section




- enhanced for small mass splitting $\frac{m_\eta}{m_\chi} \simeq 1$
- Internal Bremsstrahlung suppressed by higher power of propagator mass
  $\Rightarrow$ for large $\frac{m_\eta}{m_\chi}$ loop process $\chi\chi \to \gamma\gamma$ should be included

# A little detour: searching dark matter in gamma rays




## Problems

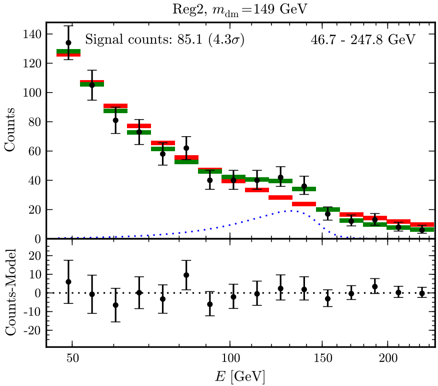
- astrophysical backgrounds everywhere
- need to distinguish DM signal from background

## Solutions

- look at objects which are background free $\rightarrow$ dwarf galaxies
- model the background
- look for unique signal $\rightarrow$ spectral features

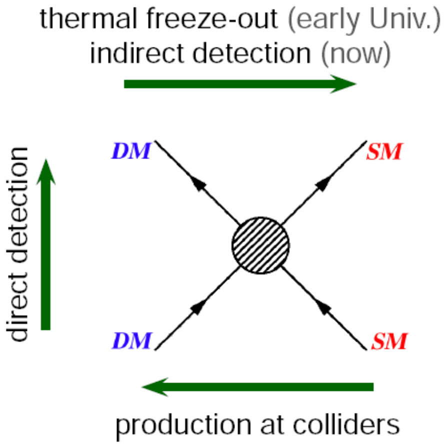
# Searches for spectral features

- select appropriate target region (somewhere close to Galactic Center)
- spectra of cosmic-rays follow roughly a power law
- assumption: astrophysical gamma ray spectrum is locally a power law
- select energy window and look for bump on top of power law

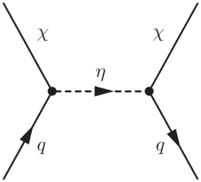



Bringmann, Huang, Ibarra, SV, Weniger 2012

# Direct Dark Matter Detection



# Scattering of DM off quarks

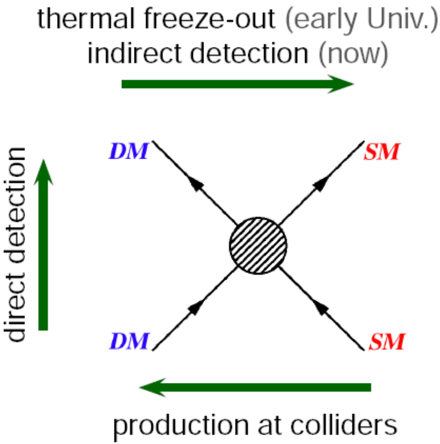



- $Q^2 \ll m_\chi^2 \to$ effective operators
- interactions with light quarks
- SD scattering at lowest order
- contribution to SI scattering cancels at lowest order for Majorana DM with chiral interaction; expansion to higher order necessary Drees, Nojiri 93
- resonant enhancement of interactions for small mass difference

Drees, Nojiri 93, Hisano, Ishiwata, Nagata 2011

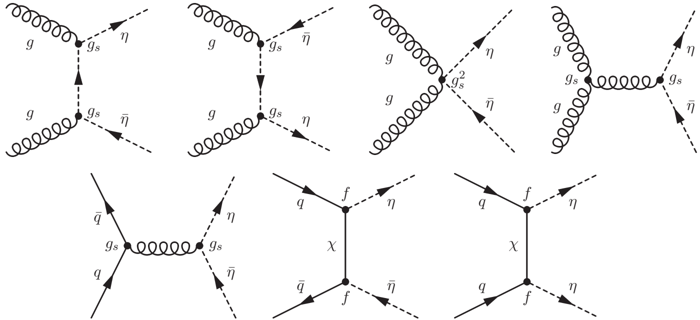
$$\sigma_{SD(SI)} \sim \left[\frac{1}{m_\eta^2 - (m_\chi + m_q)^2}\right]^{2(4)}$$

# Dark Matter at the LHC



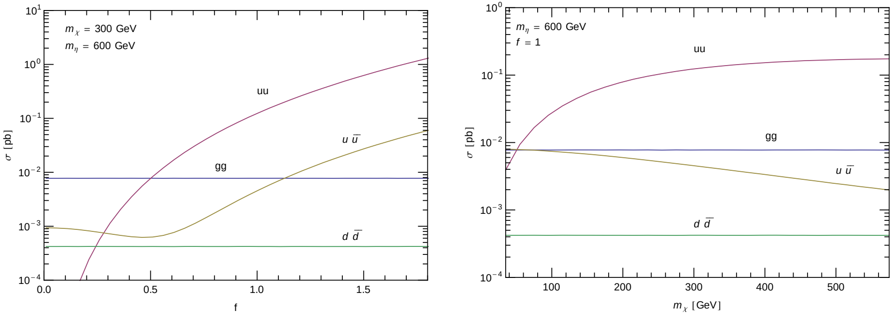
# Testing the Dark Sector

- conceptual difference between collider and ID/DD: LHC sensitive to all particles of "dark sector"




- LHC produces $\eta$
- search for decay $\eta \to q\chi$

# Production cross section at LHC at $\sqrt{s} = 8\text{TeV}$

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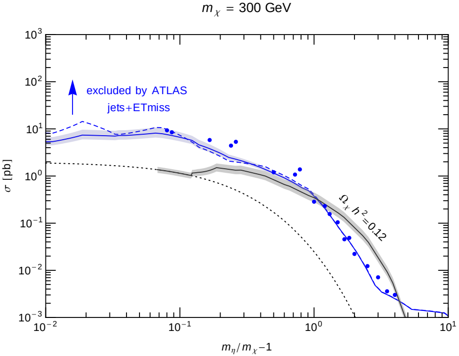
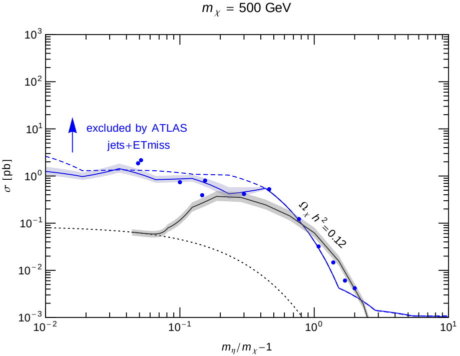
- three production modes
  - QCD $\rightarrow \eta\bar{\eta}$
  - dark matter t-channel $u\bar{u} \rightarrow \eta\bar{\eta}$
  - dark matter t-channel $uu \rightarrow \eta\eta$
- t-channel enhanced for sizeable Yukawa
- $\eta\eta$ enhanced by pdf

# experimental searches

- ATLAS search for $n \geq 2$ jets and missing energy ATLAS-CONF-2013-047
  $p_T \geq 130$ GeV, $E_T^{miss} \geq 160$ GeV, $\mathcal{L} = 20.3\ \text{fb}^{-1}$
- model independent upper limits limits on the number of signal events $S_{95}^{obs}$
- upper limits on production cross section by $S_{95}^{\text{obs}} = \sigma_{\text{vis}} \times \mathcal{L} = \sigma \times \epsilon \times \mathcal{L}$
- interpretation of limit depends on efficiency $\epsilon$, model dependent
- experimental interpretation in terms of simplified SUSY (degenerate light squarks)
- simplified SUSY: only QCD, no t-channel
  $\Longrightarrow$ different efficiency
- determine efficiency $\epsilon = N_{\text{after cuts}}/N_{\text{generated}}$ with Monte Carlo study using MadGraph (event generation) + Pythia (parton shower) + Delphes (detector simulation)

# Excluded cross sections

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# Collider uncertainty

- higher order QCD corrections to production cross section?
  generically large in related SUSY models
  $\rightarrow$ "educated" guess: $0.8 - 1.3$

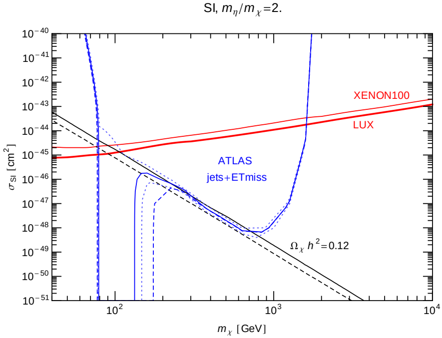
## Technical Corner

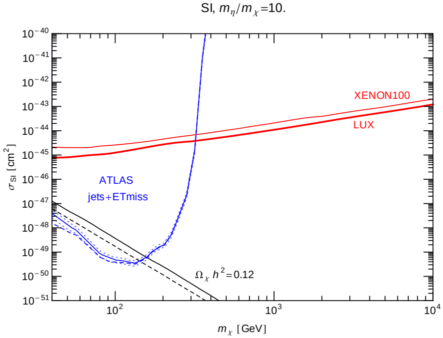
- $\geq 2$ hard jets required by search
- for $\Delta m \lesssim 100$ GeV jets from $\eta \rightarrow q\chi$ get soft
  $\Rightarrow$ need additional hard QCD emission (ISR/FSR) to get into signal region
- simulate up to two additional hard partons and use jet-matching (MLM) to account for double counting by parton shower

- finite statistics in Monte Carlo $\Rightarrow$ uncertainty of $\epsilon$
- uncertainty related to jet matching

# Putting it all together

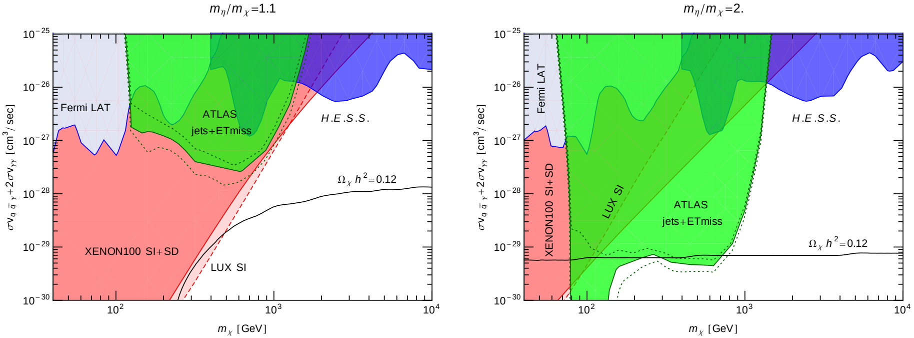
# Direct detection versus the LHC



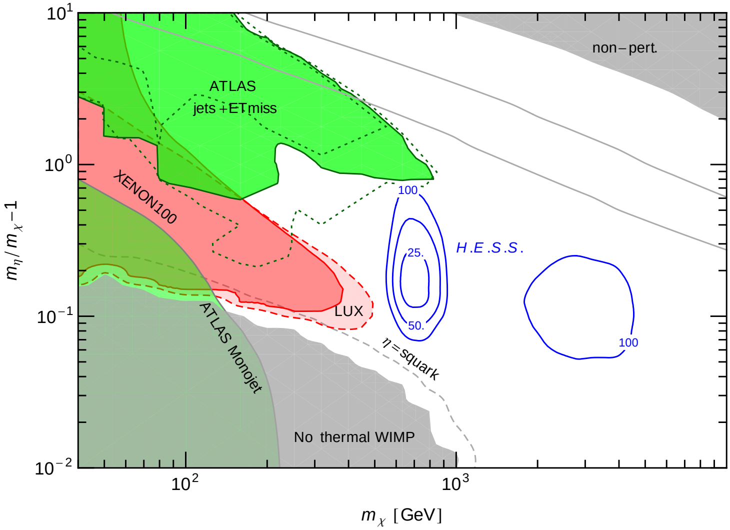

- for $\Delta m = \mathcal{O}(m_\chi)$ limits on $\sigma_{SI} = 10^{-45} - 10^{-48}$
- Notice: for some mass range QCD production excluded $\Rightarrow$ not contribution to dark matter allowed
- similar picture for SD

# Indirect detection




- DD and LHC strong for $m_\chi \lesssim 1$ TeV
- ID most relevant for multi-TeV masses

# Exclusion limits on thermal Dark Matter

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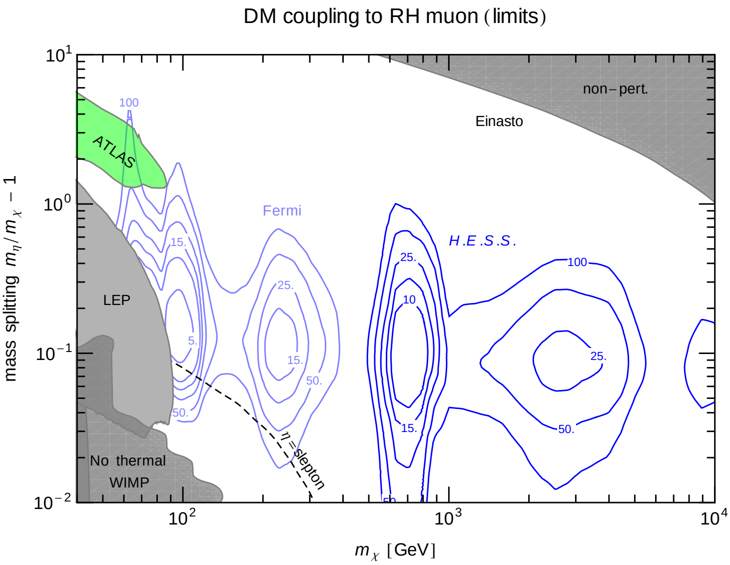
# Conclusions

- working with simplified models allows comparison of different search strategies
- LHC constraints most stringent for $\Delta m \sim m_\chi$
- LHC excludes $\sigma_{SI} = 10^{-45} - 10^{-48}$ cm$^2$
- some combinations of $m_\chi$ and $m_\eta$ are excluded
- search for gamma-ray features competitive for mulit-TeV masses
- remember: model dependence

# backup sildes



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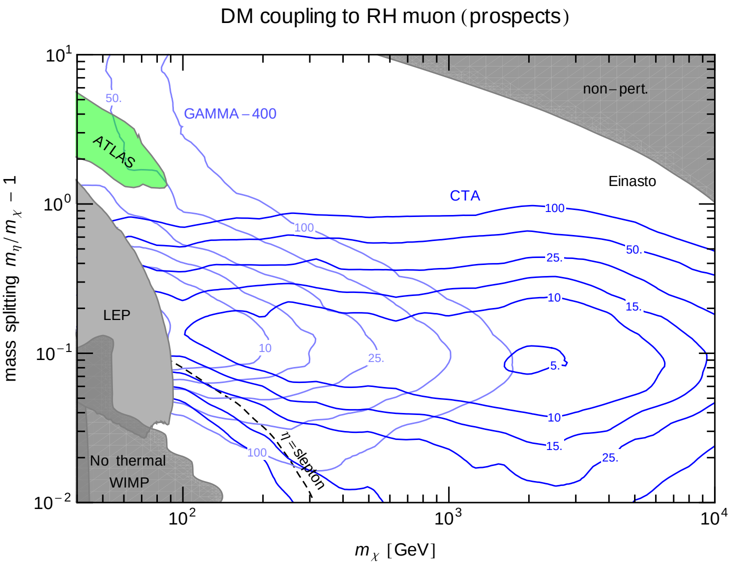
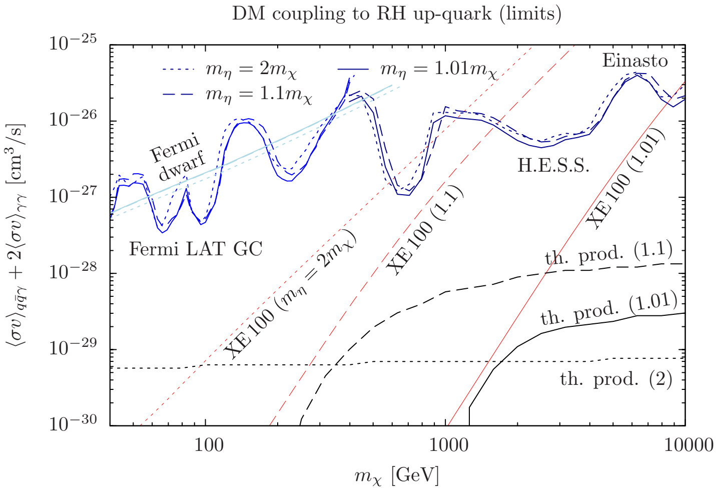


# Combined Limits on Dark Matter

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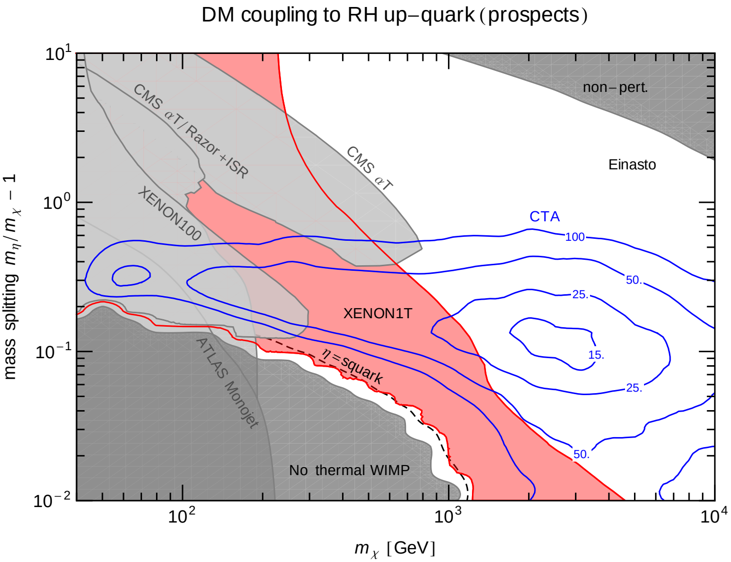
# Prospects for upcoming experiments

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