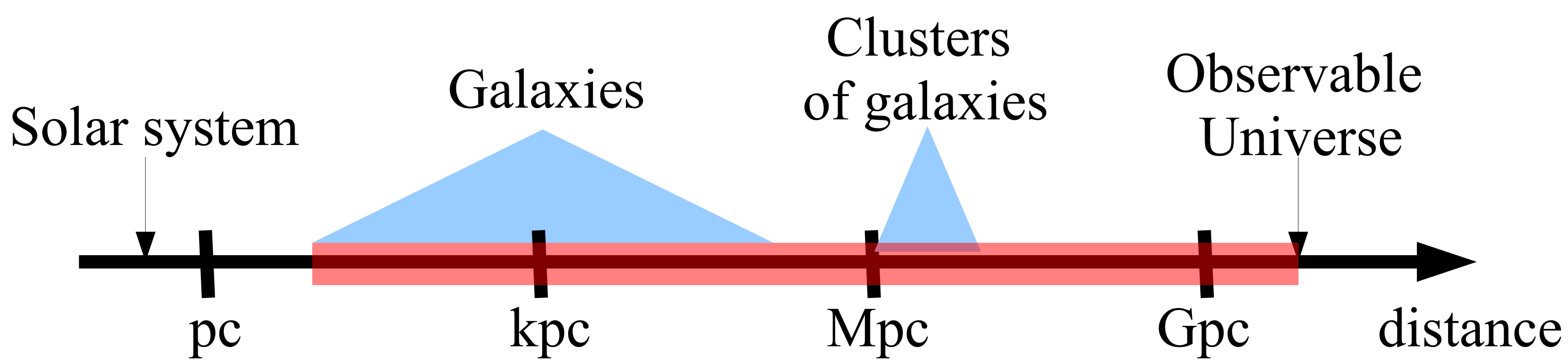
Theoretical overview of dark matter

Alejandro Ibarra
Technische Universität München

SUSY'17
Mumbai
14 December 2017

There is evidence for dark matter in a wide range of distance scales



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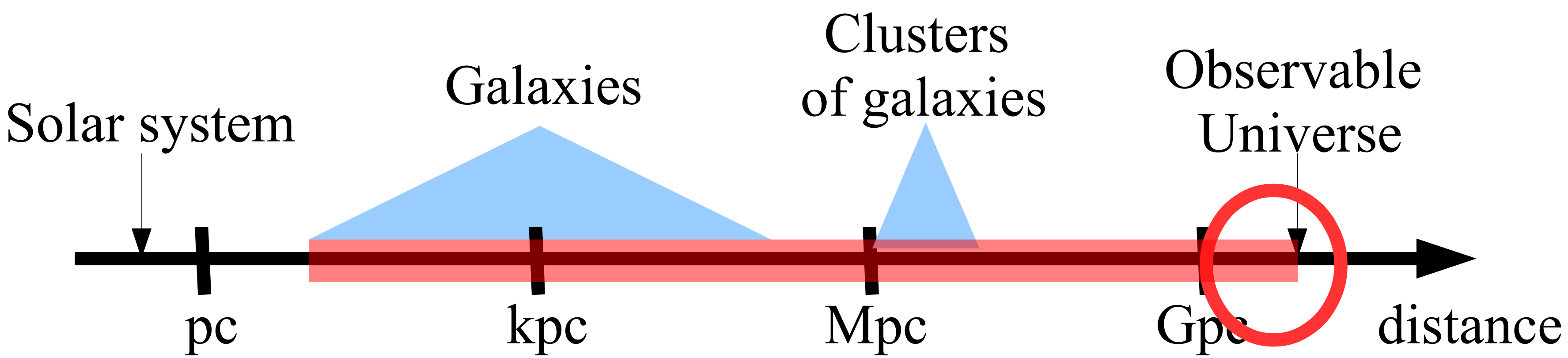

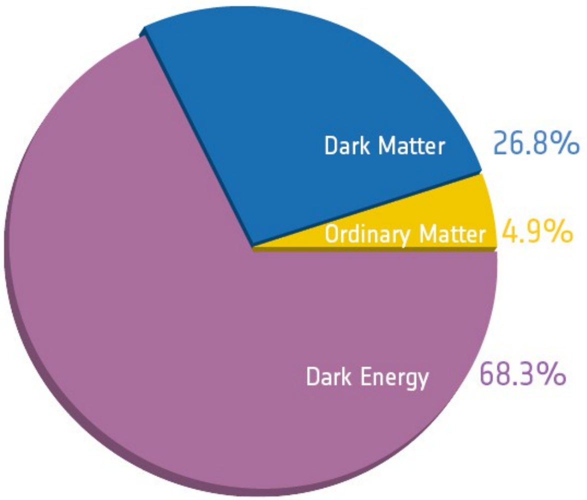

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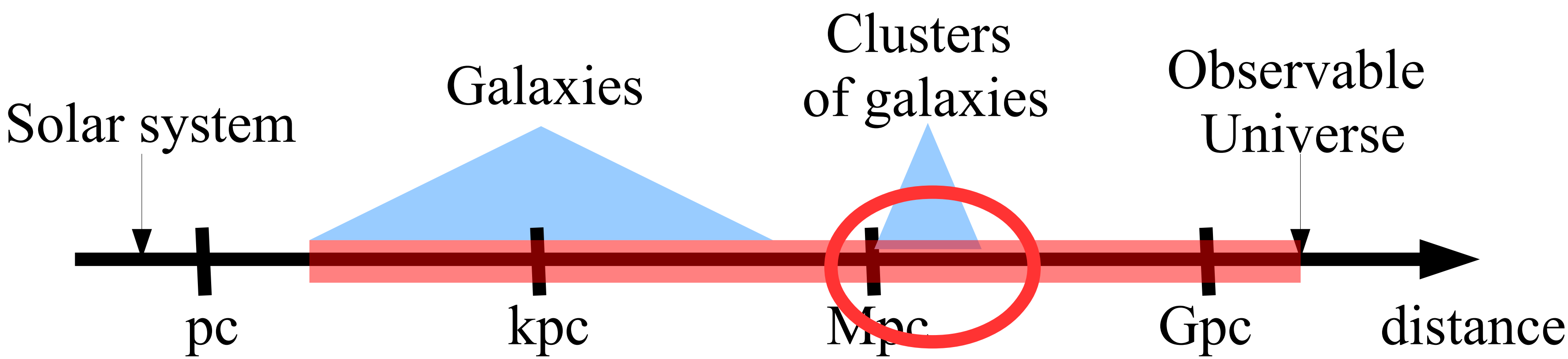

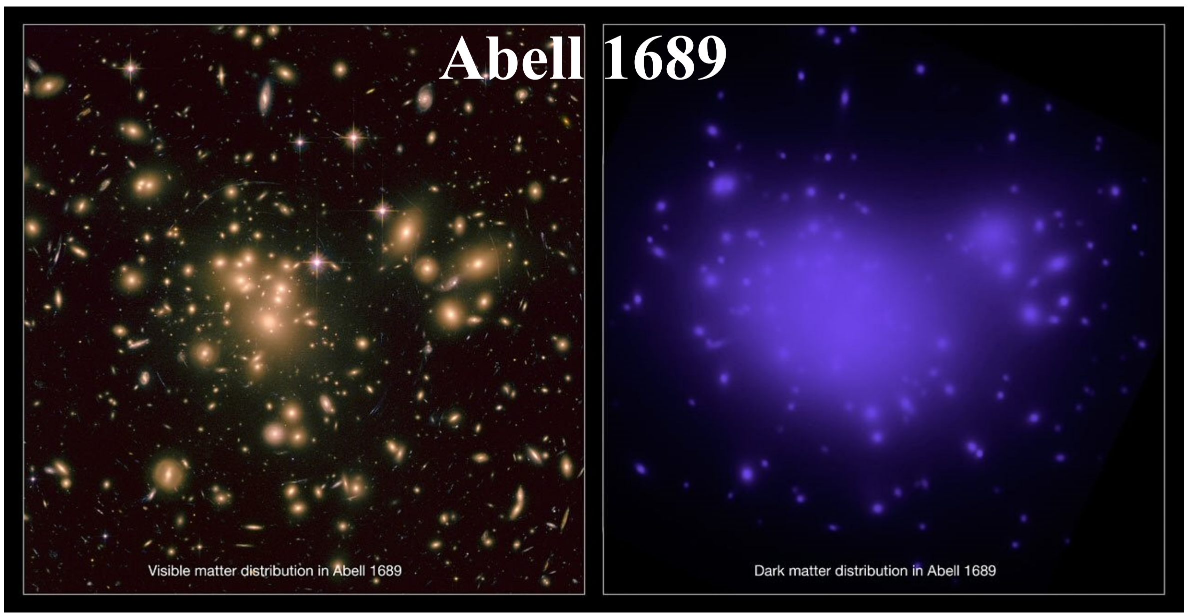

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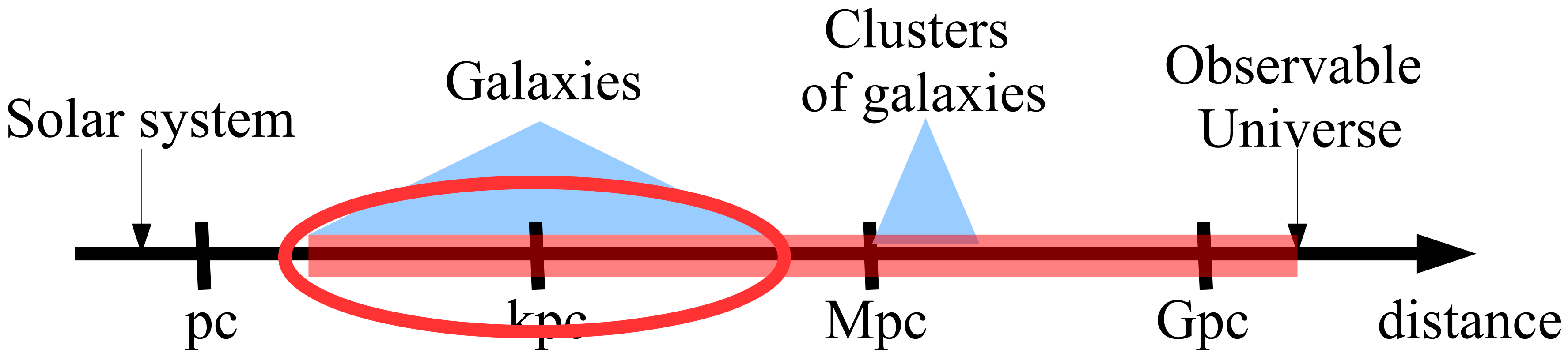

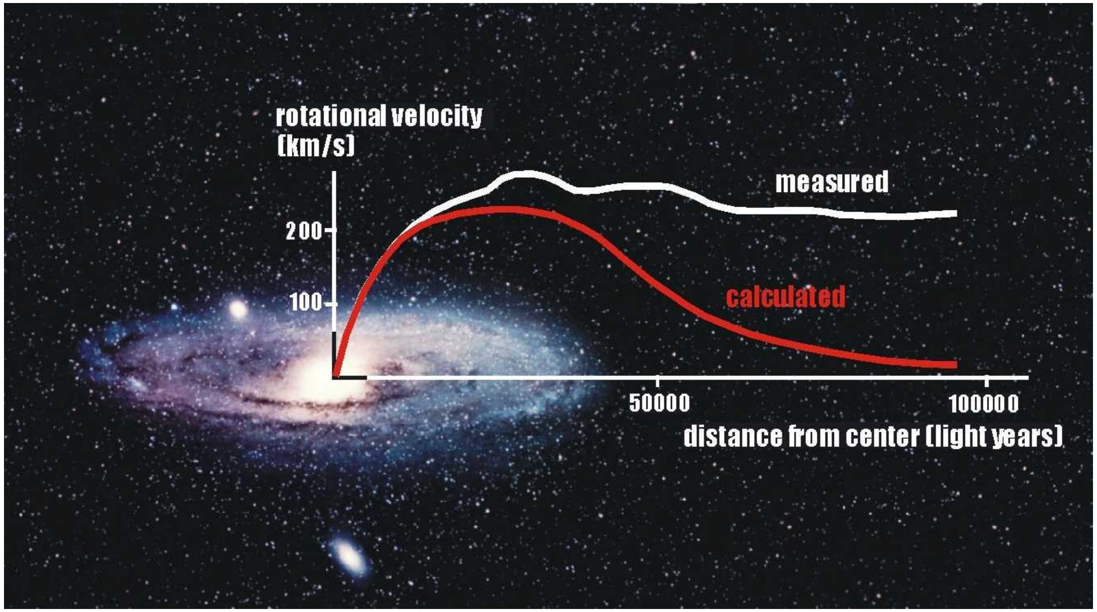

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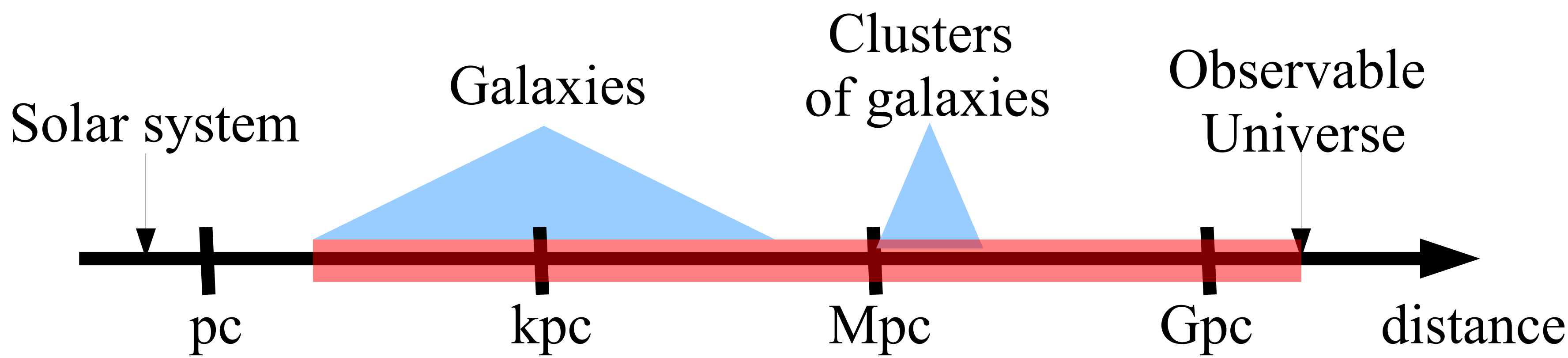
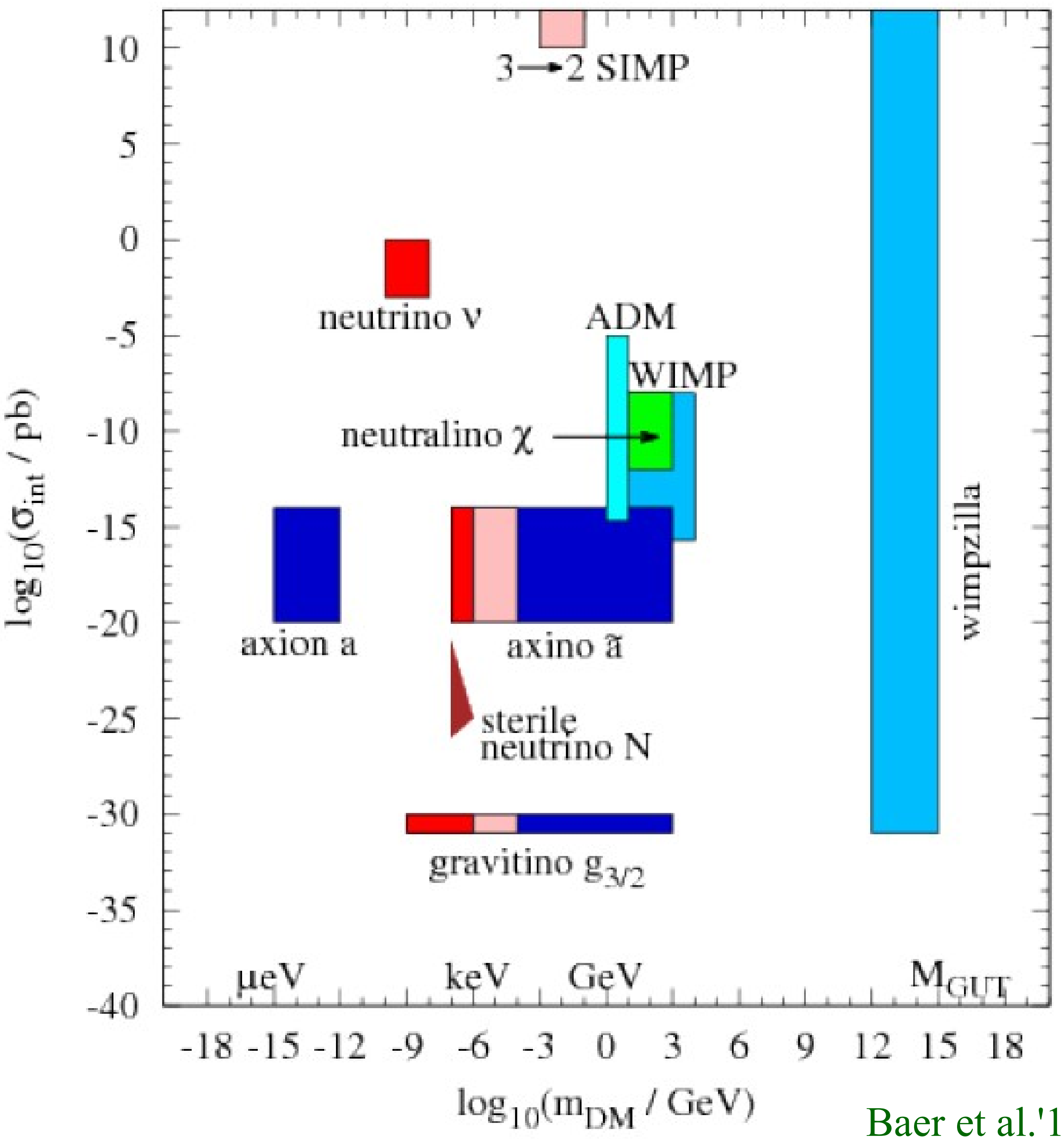


Cosmological and astronomical observations are consistent with the dark matter being constituted by new particles not contained in the Standard Model

Candidates of particle dark matter



Baer et al.'14

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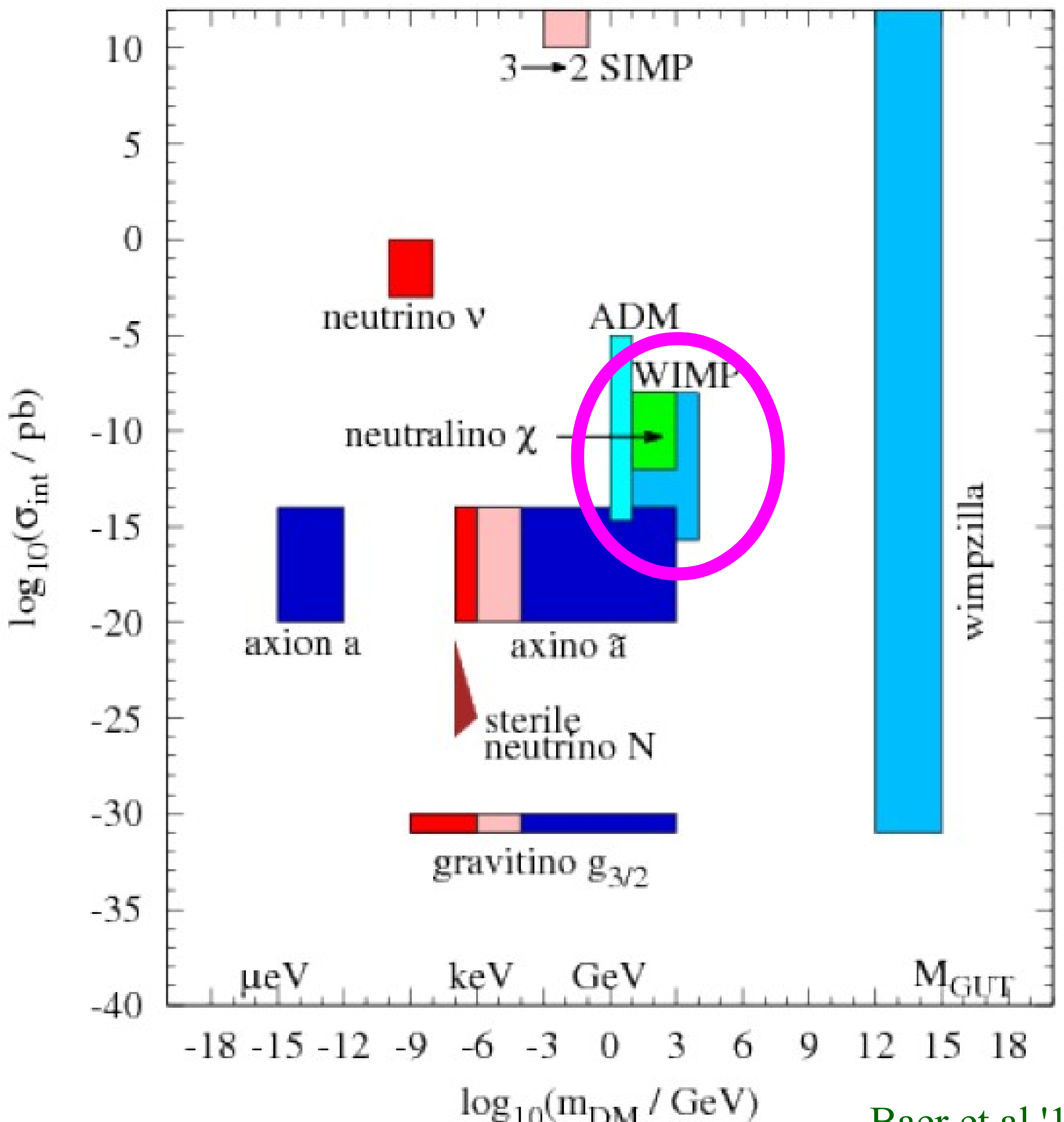
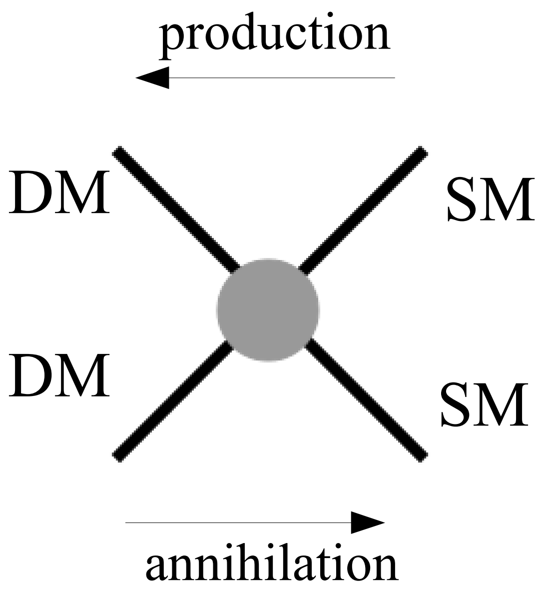


Baer et al.'14

WIMPs in the early Universe



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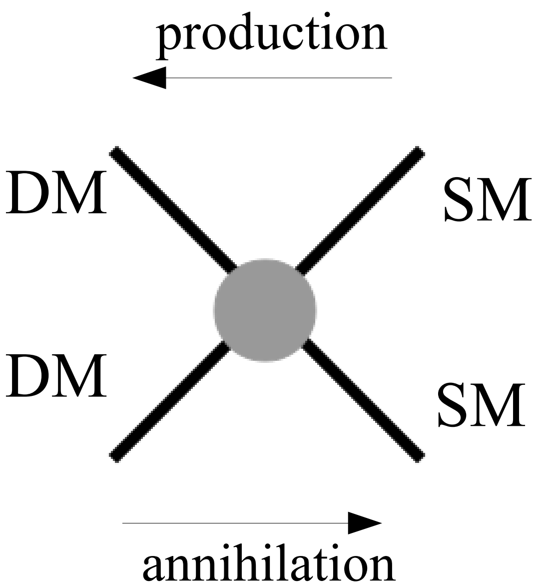

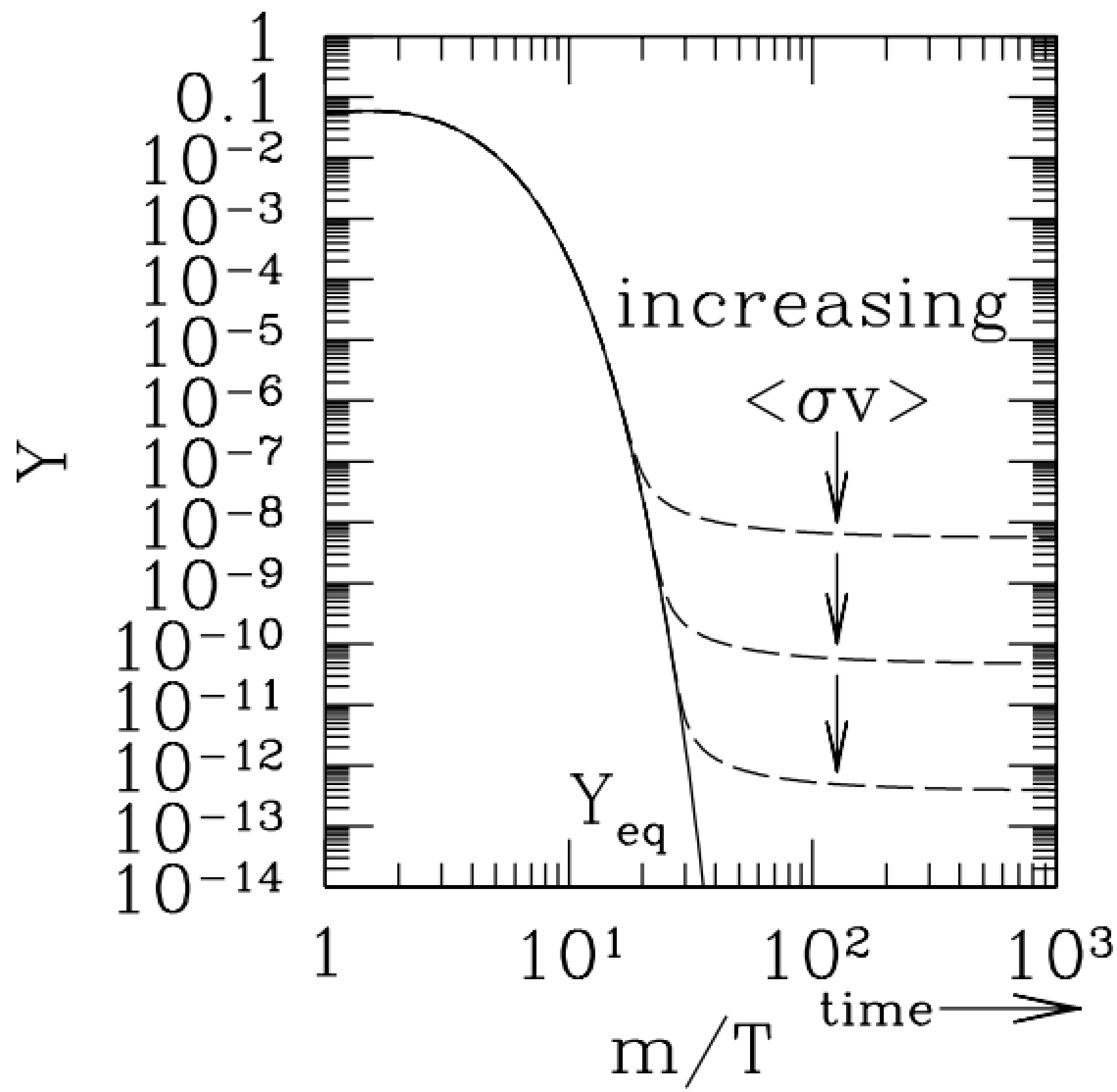

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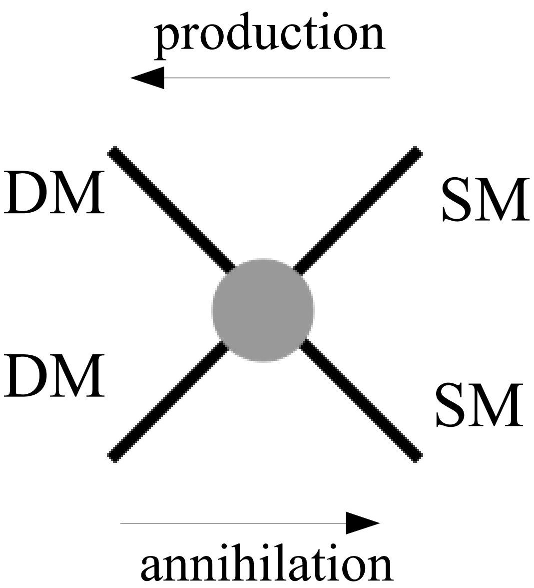

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$$\Omega h^2 \simeq \frac{3 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

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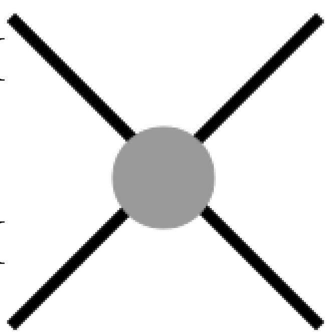

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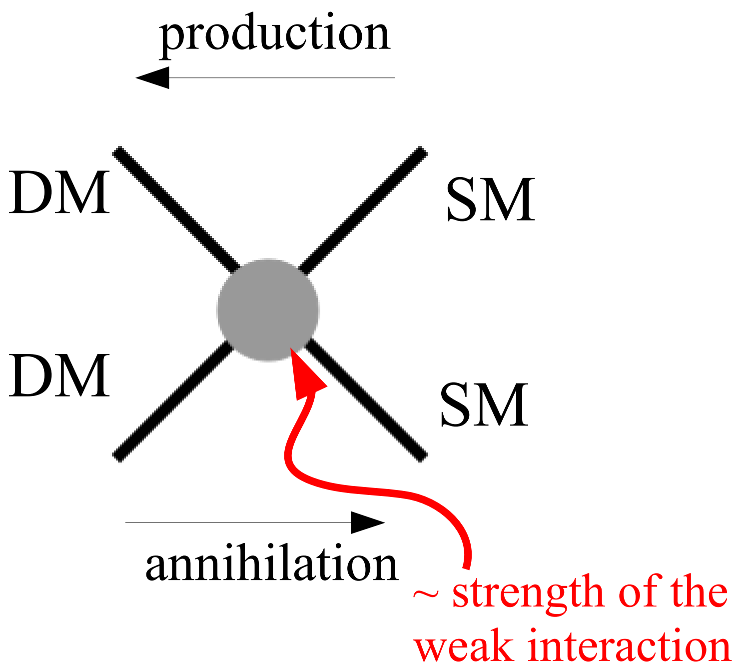

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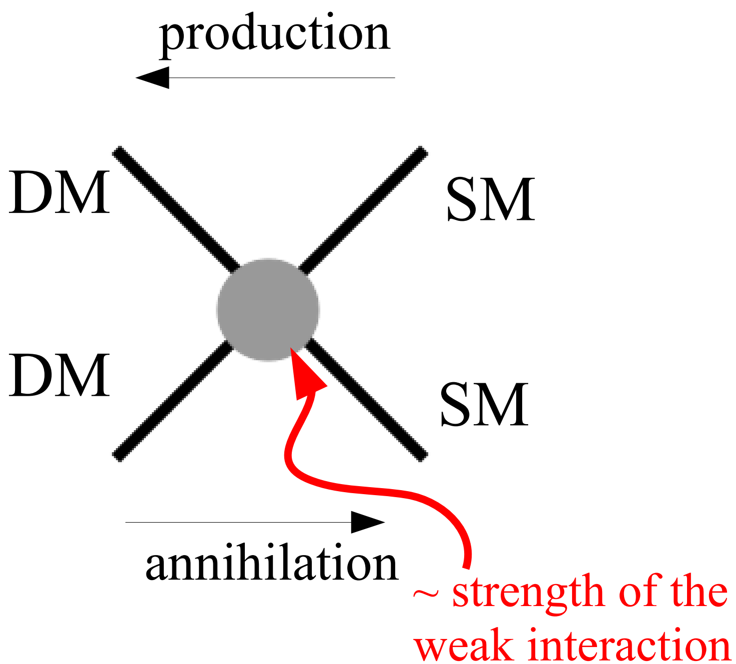

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$$\sigma \sim \frac{g^4}{m_{\mathrm{DM}}^2} = 1\,\mathrm{pb}$$

$m_{\mathrm{DM}} \sim$ a few GeV – a few TeV

(for g ~ 0.01 - 1)

LUX

CMS

ATLAS

MAGIC

Xe
XENON
Dark Matter Project

fermi
Gamma-ray
Space Telescope

PaMeLa

PANDA X

H E S S

VERITAS

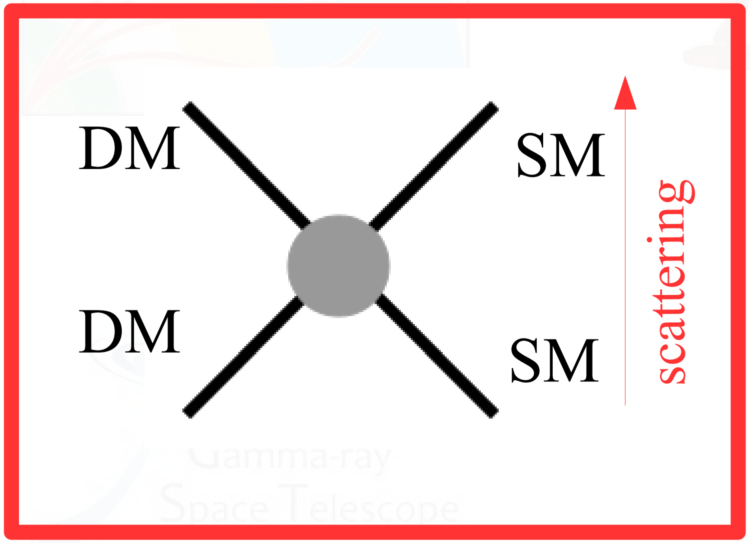
Alpha Magnetic Spectrometer
AMS-02
Europe - Asia
North America

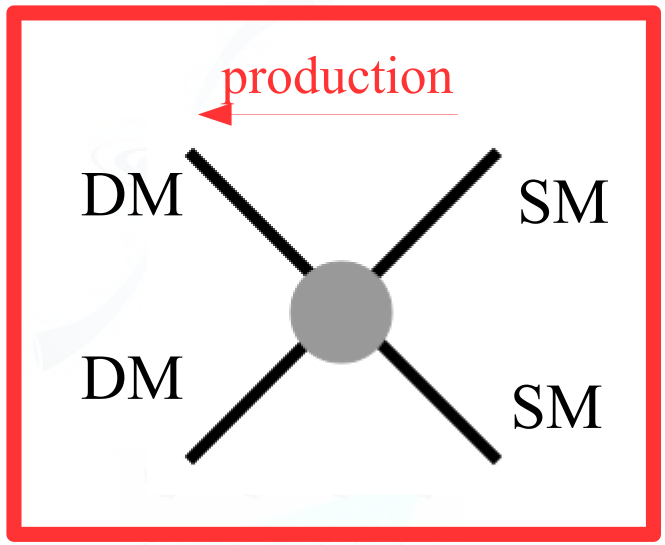
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

LUX

Xe
XENON
Dark Matter Project

PandaX

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DM
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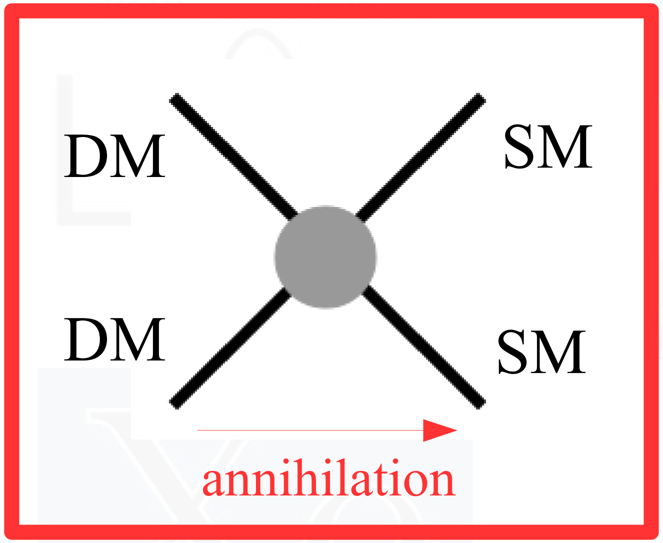

MAGIC

Fermi
Gamma-ray Space Telescope

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H E S S

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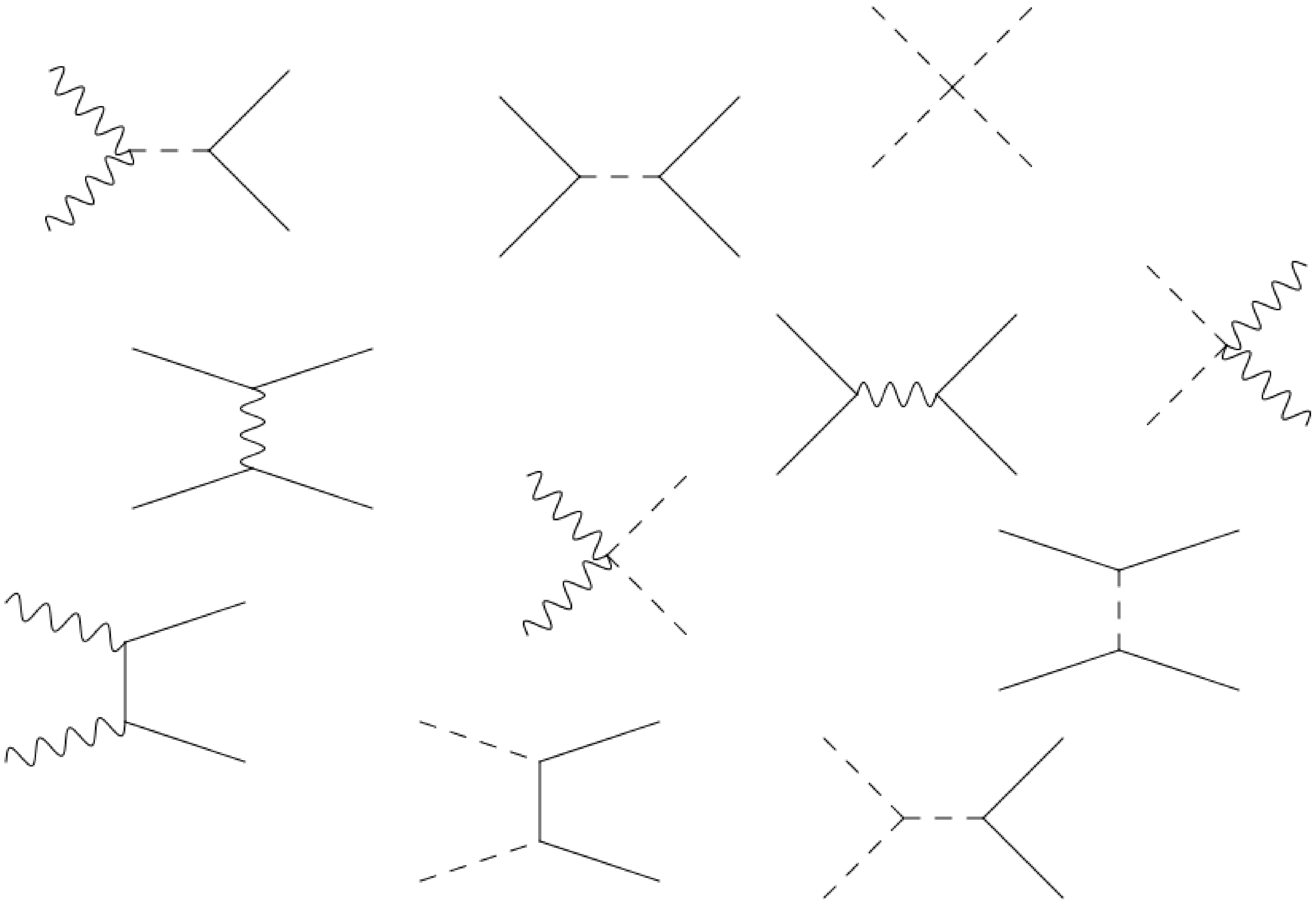
Many possible realizations of the effective interaction

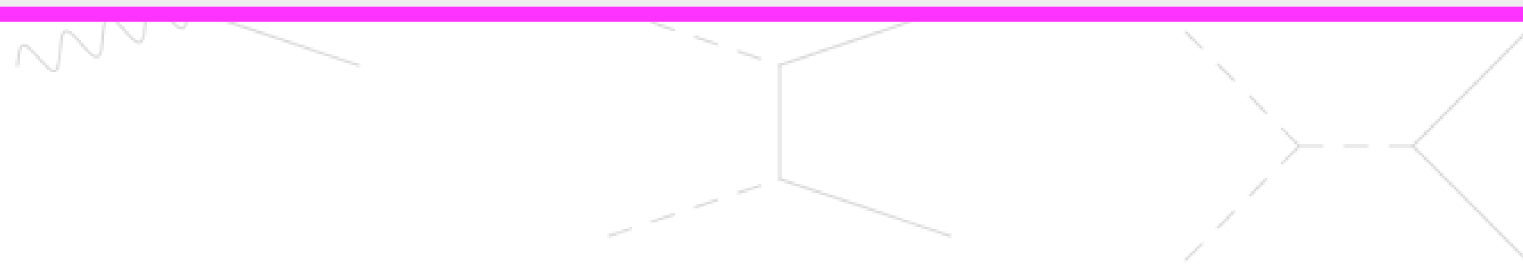


Many possible realizations of the effective interaction

Which dark matter particle?

Which mediator (if any)?

What is the role of the mediator in the phenomenology?



Classification of models (according to minimality)

Number of new fields

Number of new symmetries

	1	2	...
0	"minimal DM"	"next-to-minimal DM" ...	
1	Scalar singlet DM Inert doublet model Pure Wino Pure Higgsino ...	"simplified models" ...	
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"Minimal Dark Matter"

Cirelli, Fornengo, Strumia '05

Assumption: Add to the SM a new particle with electroweak interactions and with the characteristics of the dark matter.

Select the SU(2)×U(1) representation such that:

- Contains a neutral component
- Cosmologically long-lived

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2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
3	0	1/2	LH	2.4 ± 0.06	166	$0.8 \div 4.0$	1.3
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	1.7
3	1	1/2	LH	1.8 ± 0.05	525	$27 \div 90$	1.7
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.10 \div 0.6$	1.6
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.10$	7.5
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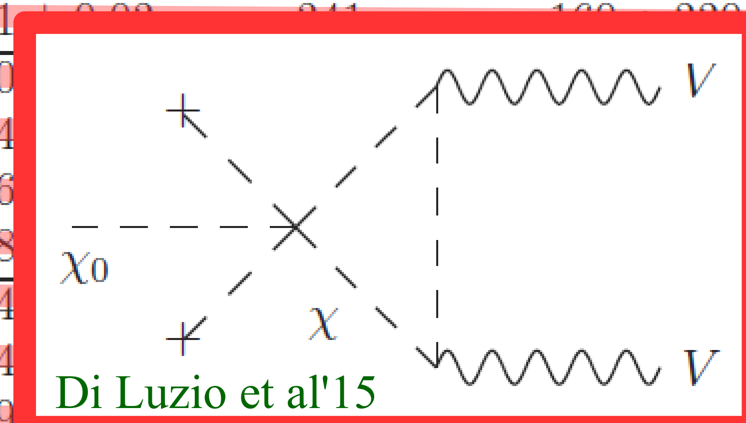

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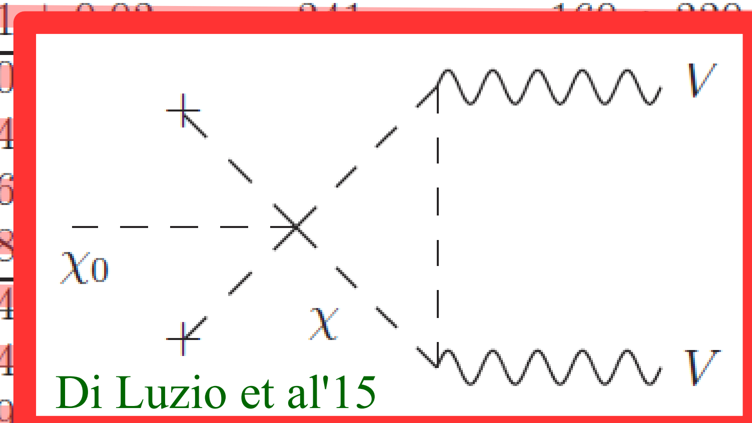

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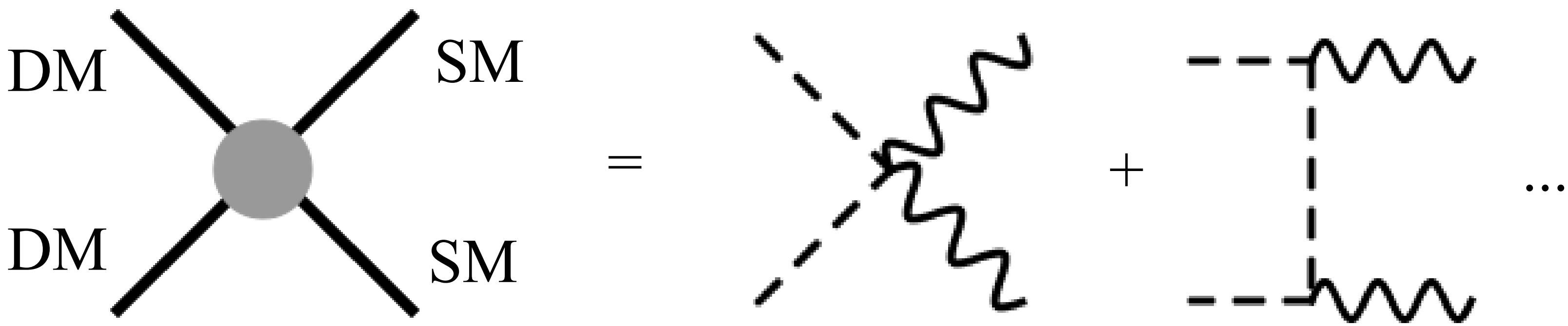

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Correct DM abundance if:

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\,\text{cm}^3\,\text{s}^{-1} \quad \Rightarrow \quad m_{\text{DM}} \approx 4.4\,\text{TeV}$$

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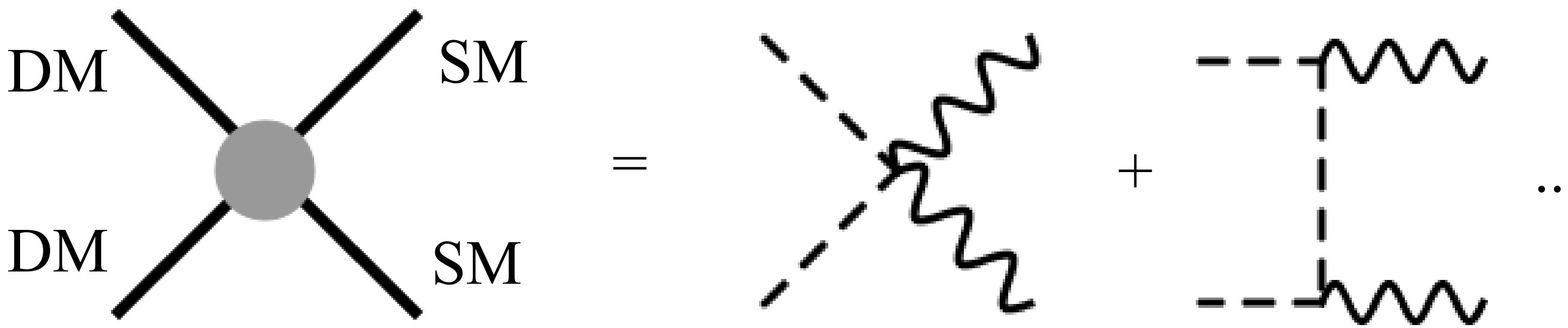

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~~$m_{\rm DM} \simeq 4.4\ \text{TeV}$~~

$$m_{\rm DM} \approx 10\ \text{TeV}$$

Including non-perturbative effects

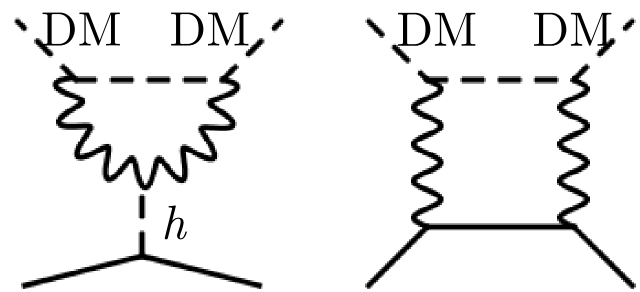
Very predictive framework.

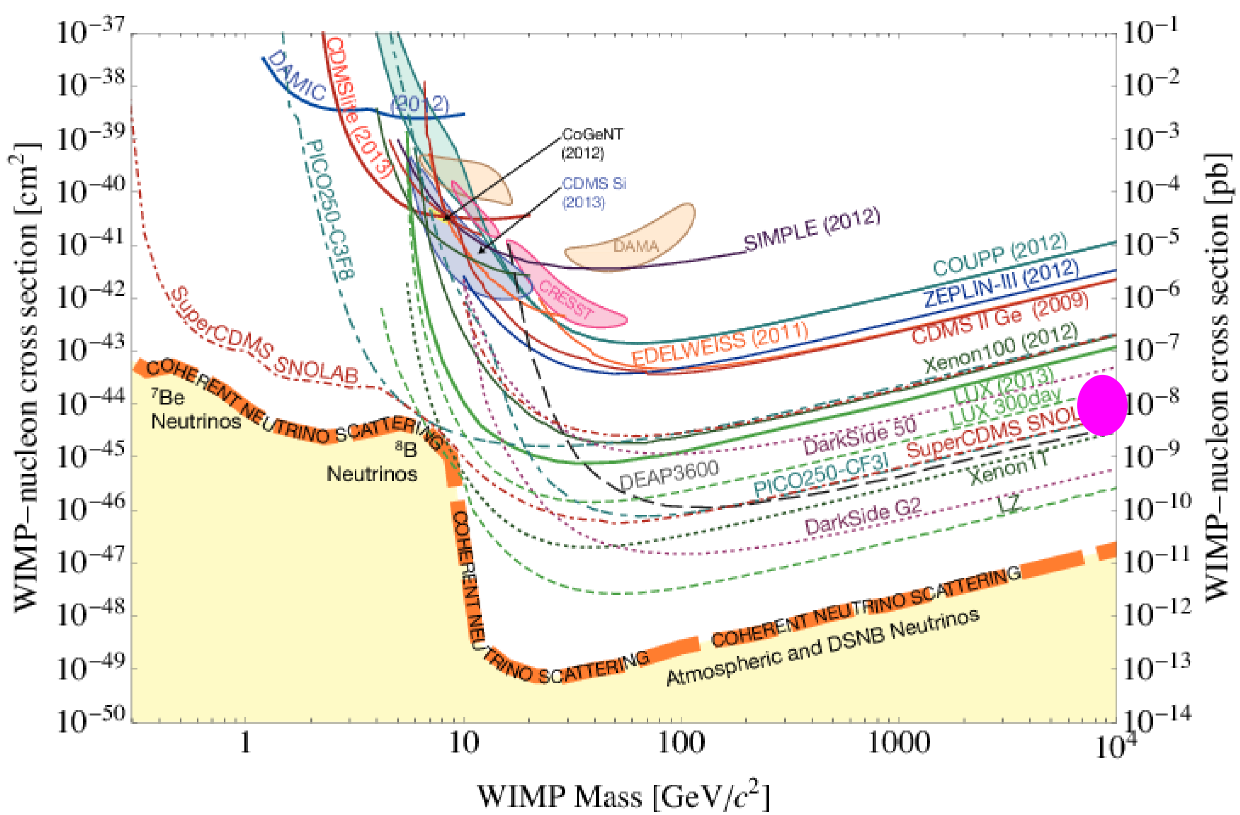
"Minimal Dark Matter": tests

Direct detection

Cirelli et al'07

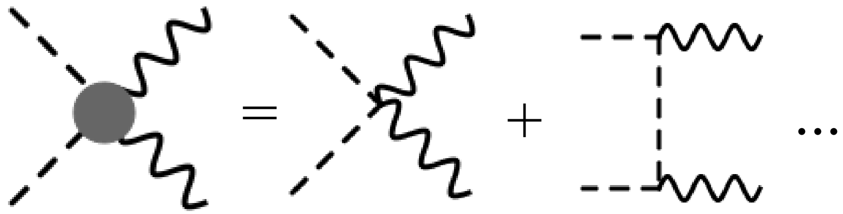
Interactions with nucleons at the one-loop level





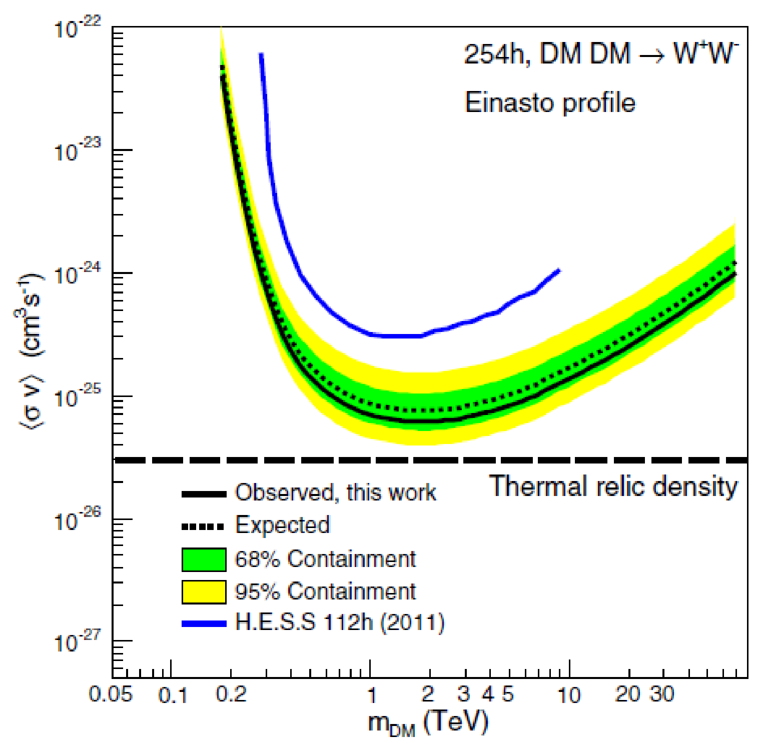
"Minimal Dark Matter": tests

Indirect detection



Naive estimate:

$$(\sigma v) \simeq 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$



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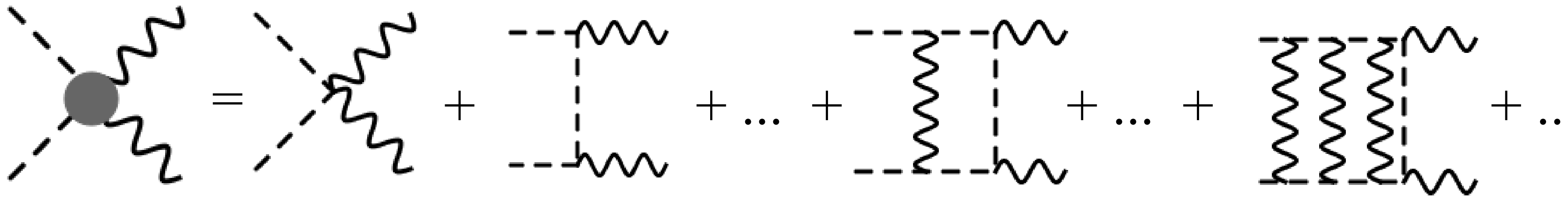
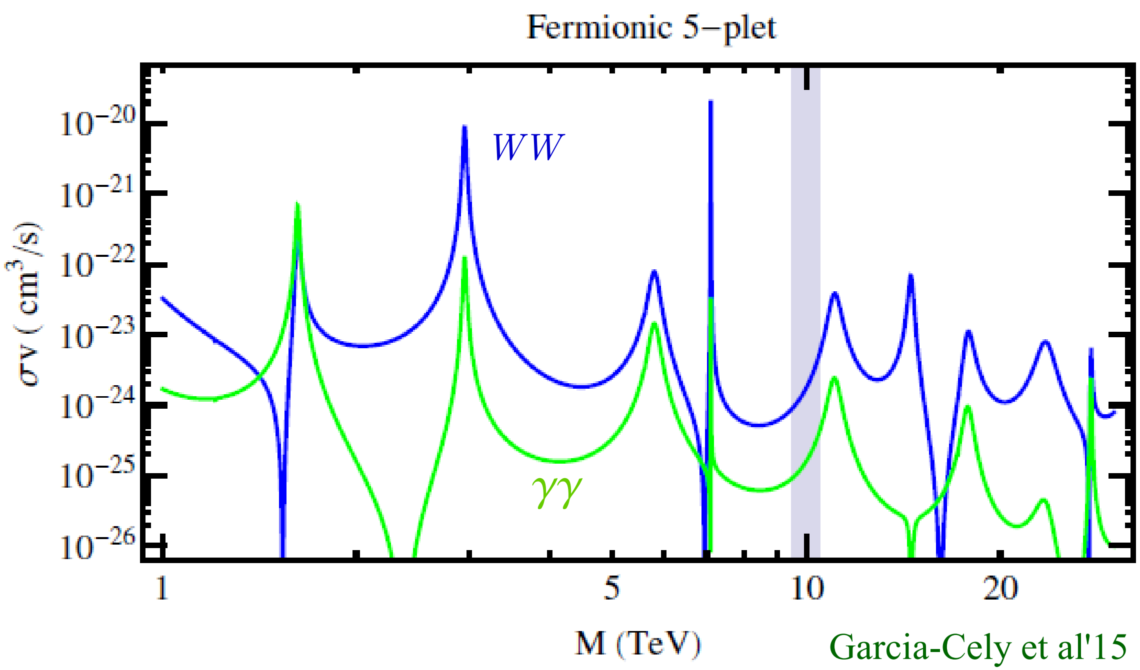


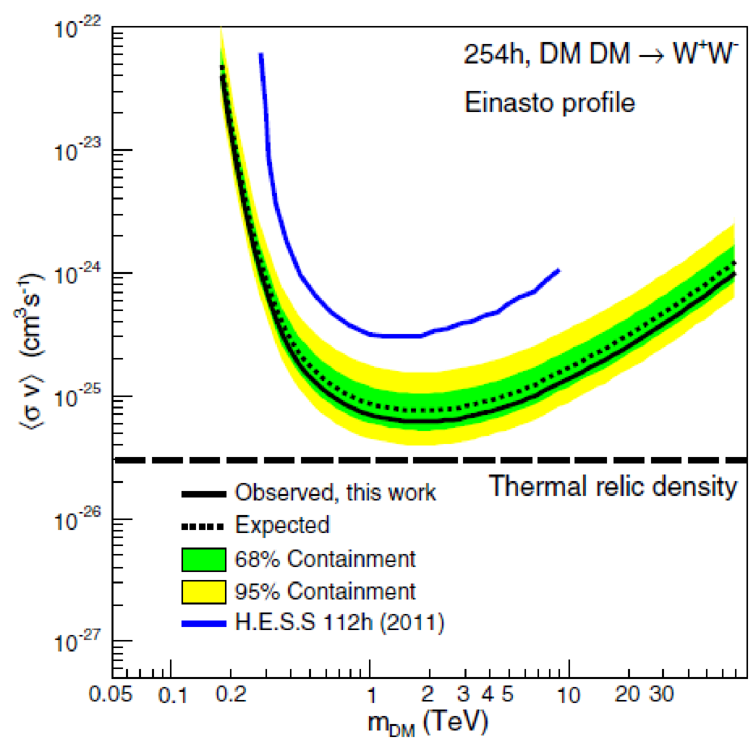
In models where the dark matter interacts with a lighter mediator, the naive calculation cannot be trusted ↪ Necessary to resum diagrams at all loops.

Hisano et al'03,04

"Sommerfeld enhancement" of the cross section

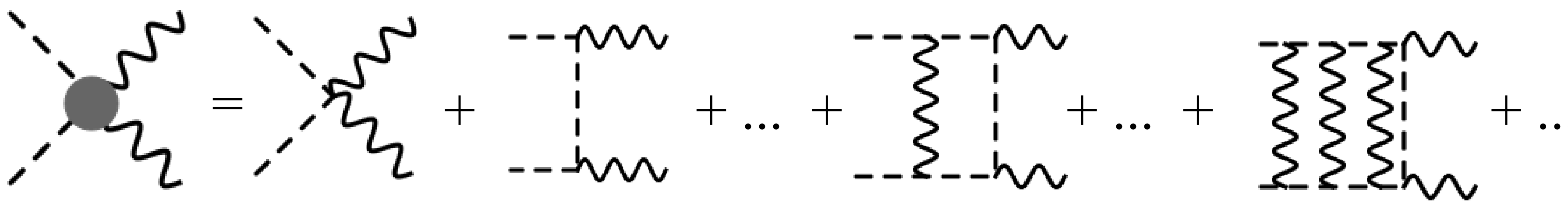


Garcia-Cely et al'15



“Minimal Dark Matter”: tests

Indirect detection



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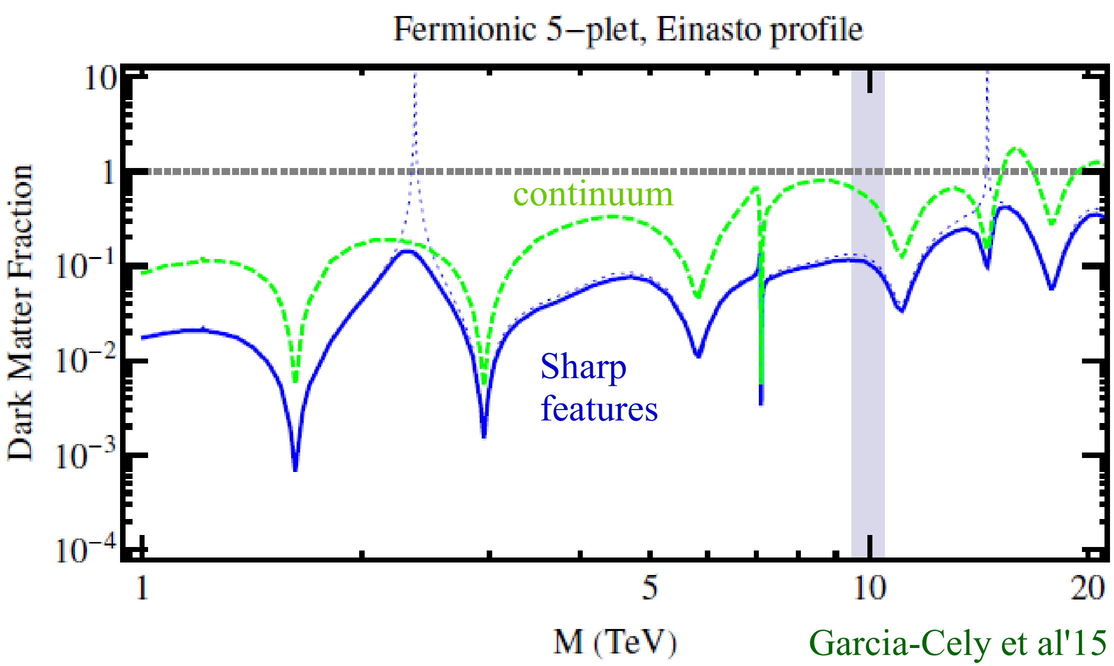
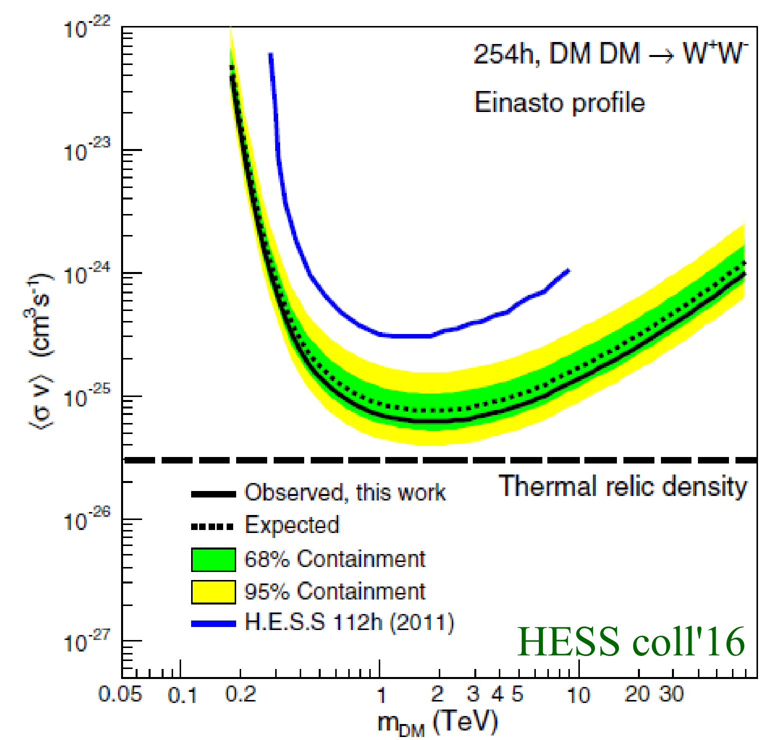


Garcia-Cely et al'15



HESS coll'16

"Minimal Dark Matter": tests

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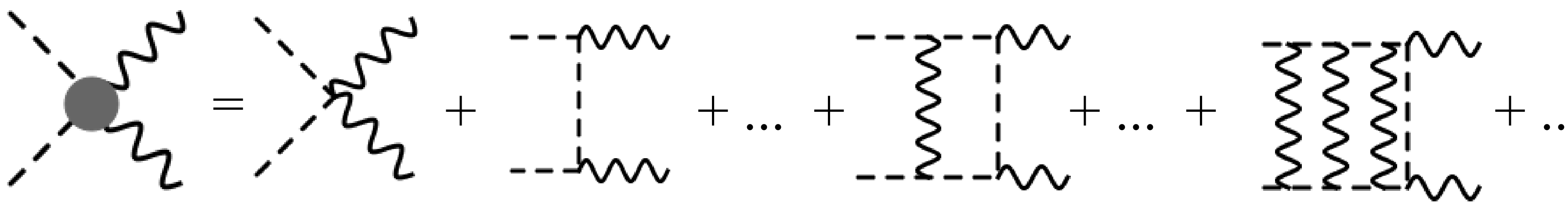

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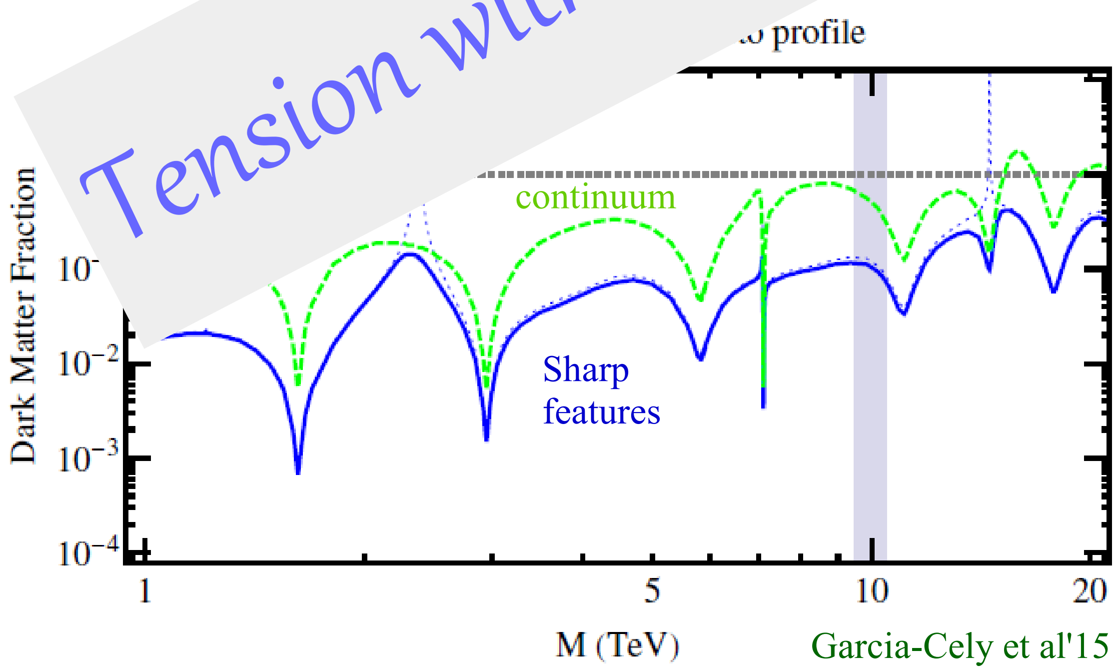
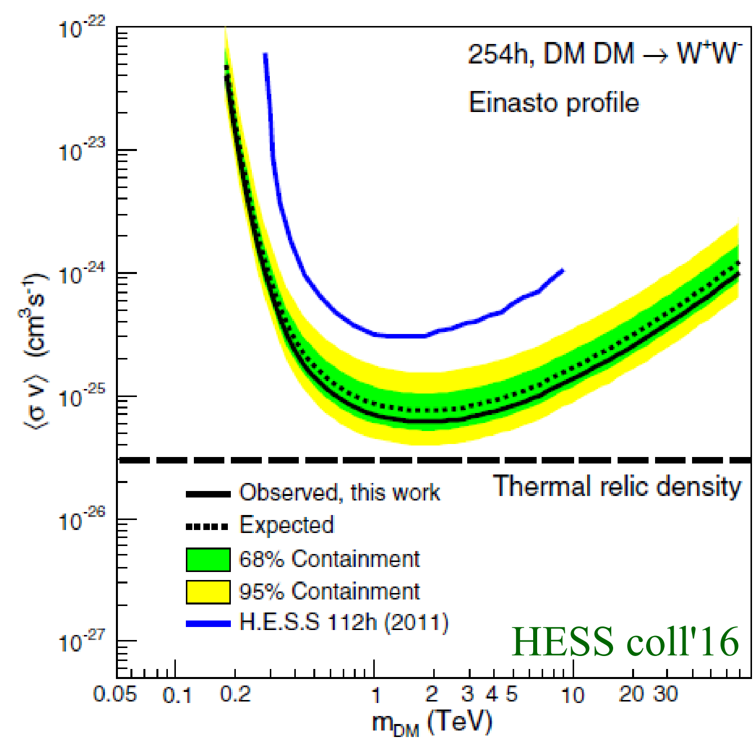
"Sommerfeld [...] cross section

Tension with data



Garcia-Cely et al'15



HESS coll'16

Classification of models (according to minimality)

Number of new fields

Number of new symmetries	1	2	…
0	"minimal DM"	"next-to-minimal DM" …	
1	Scalar singlet DM Inert doublet model Pure Wino Pure Higgsino …	"simplified models" …	
…			

Singlet scalar dark matter

Assumption: Add to the SM a real scalar field, ϕ, singlet under the SM gauge group. Silveira, Zee '85, McDonald '07

$$\mathcal{L} \supset -\frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4!}\lambda_\phi\phi^4 - \frac{1}{2}\lambda_{\phi H}\phi^2|H|^2 - \mu\phi|H|^2$$

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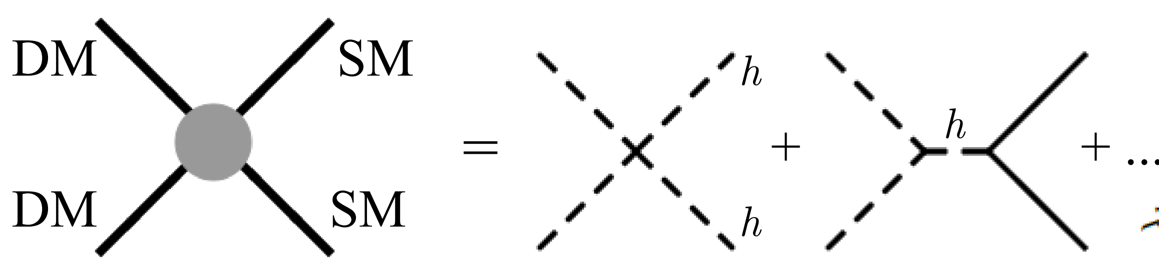
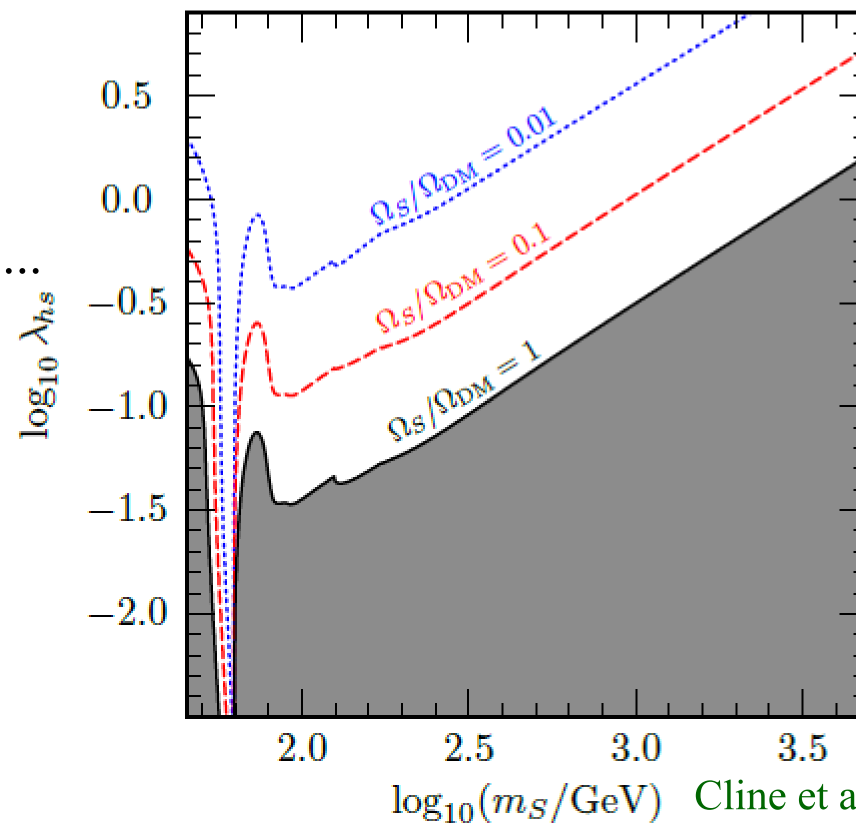




Cline et al'13

Singlet scalar dark matter: tests

Collider searches

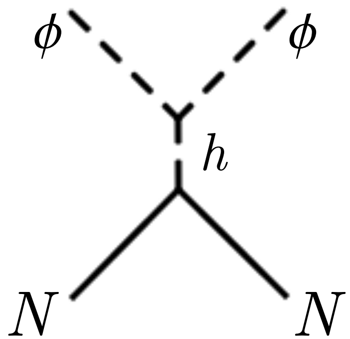
For $m_\phi < m_h/2$, measurements of the Higgs decay width exclude $\lambda_{\phi H} \gtrsim 0.03$

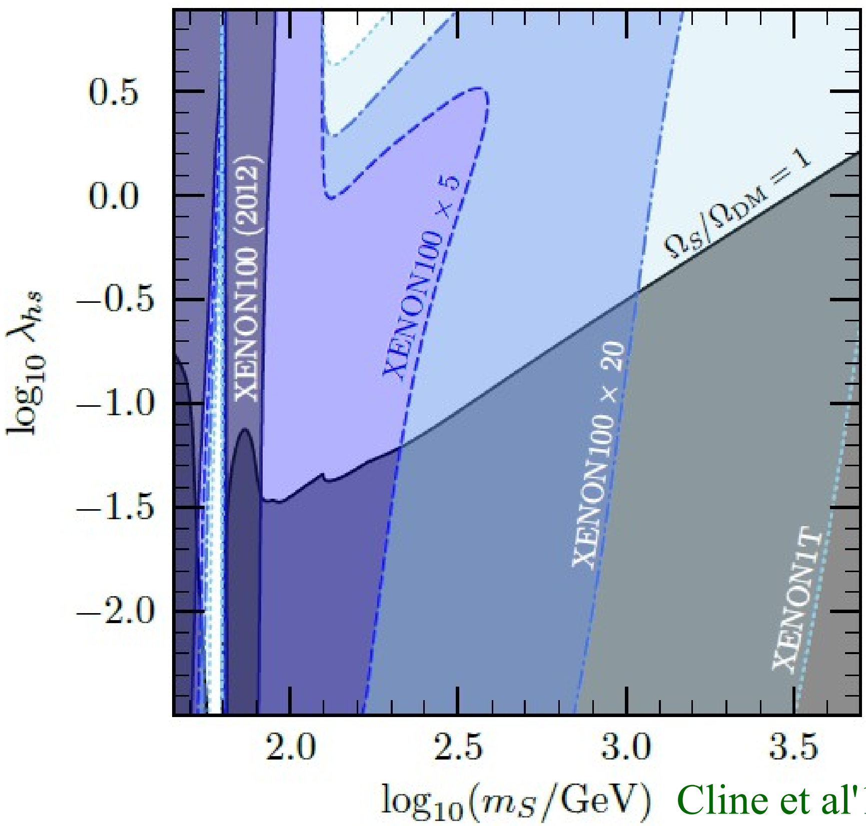
Indirect searches

Dwarf galaxy observations + CMB constrain the annihilation rate for low DM masses.

Direct searches

Interactions with nucleons via Higgs exchange:





Cline et al'13

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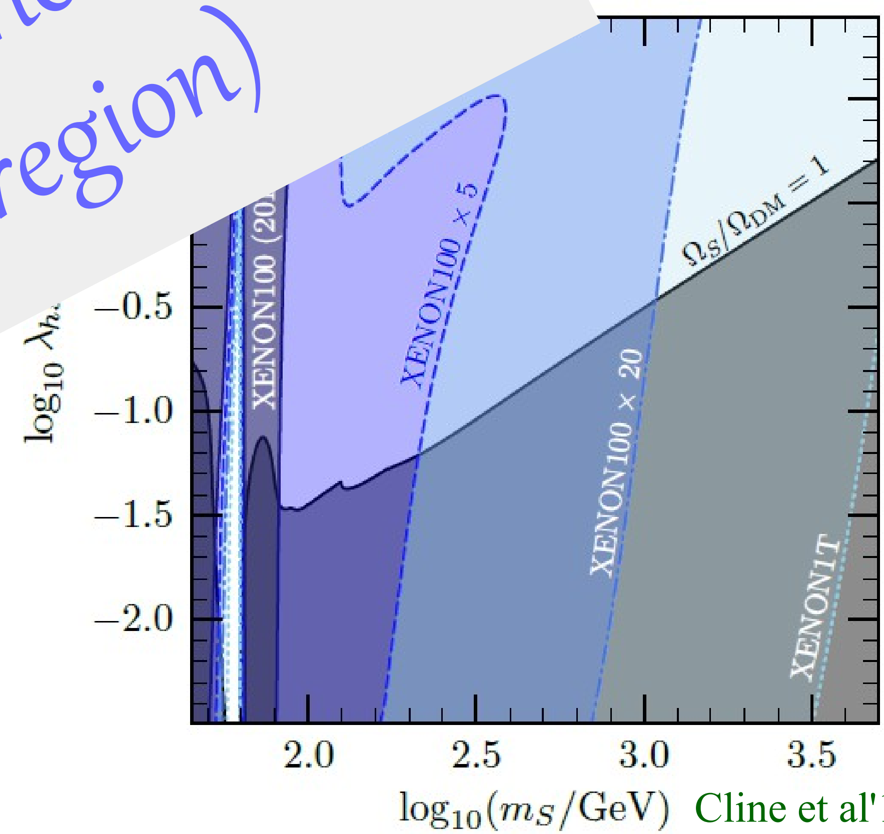
excha...



Cline et al'13

DM mass pushed to the TeV scale
(or resonant region)

Classification of models (according to minimality)

Number of new fields

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	1	2	...
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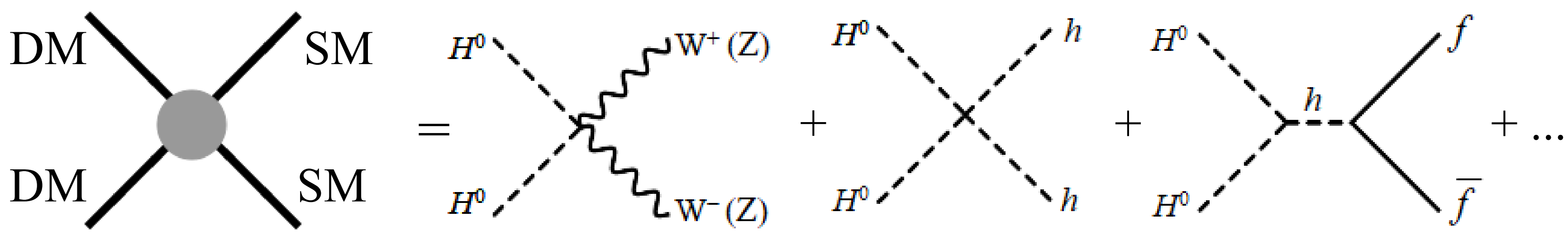
Inert doublet dark matter model

Assumption 1: Add to the SM a scalar doublet with hypercharge 1/2, η, (copy of the SM Higgs)

Assumption 2: Impose a $\mathbb{Z}_2$ symmetry $\eta \to -\eta$, SM $\to$ SM

The lightest component of the doublet is stable and constitutes a dark matter candidate

$$\eta = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(H^0 + iA^0\right) \end{pmatrix}$$



As in minimal DM

As in singlet scalar DM

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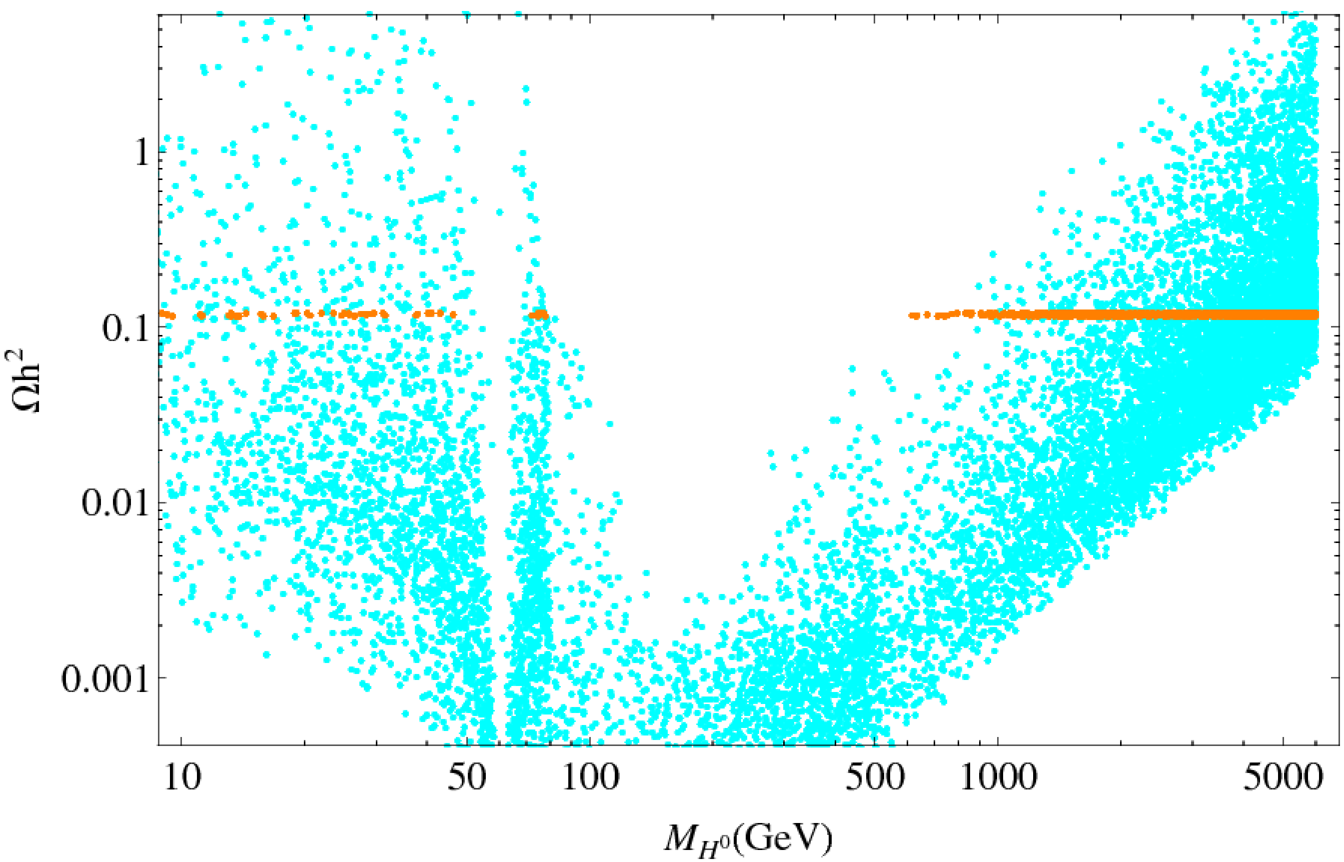

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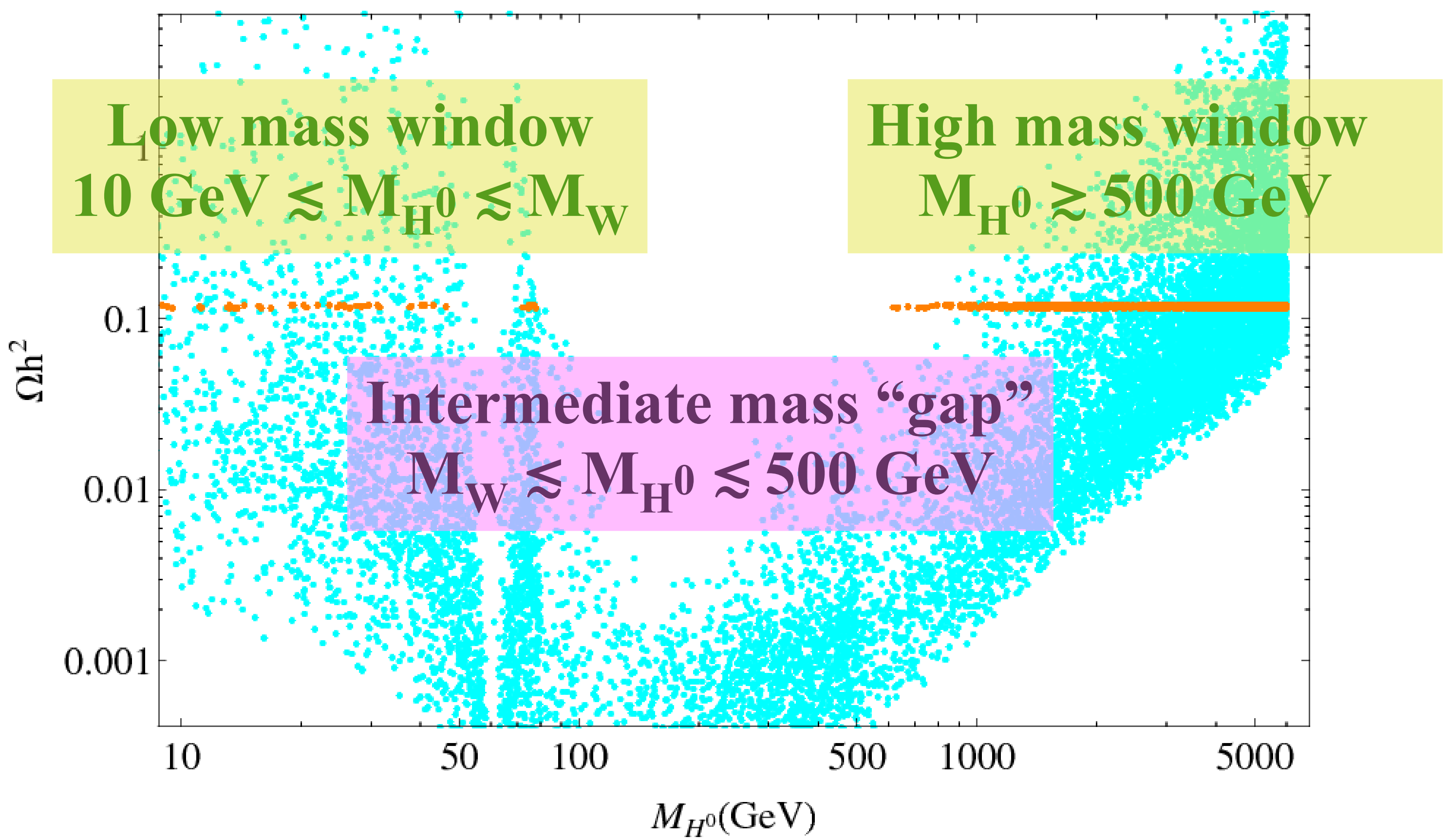

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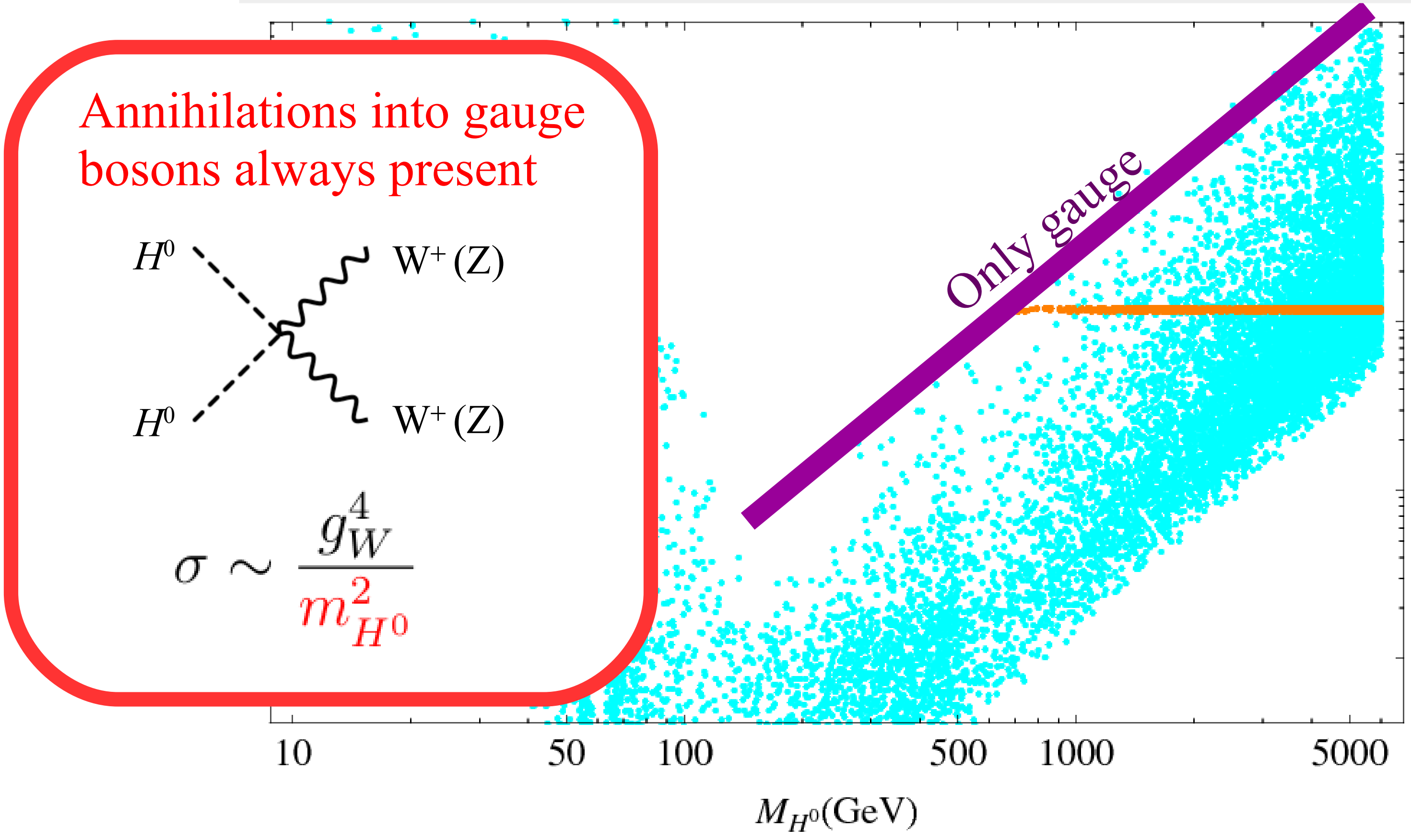

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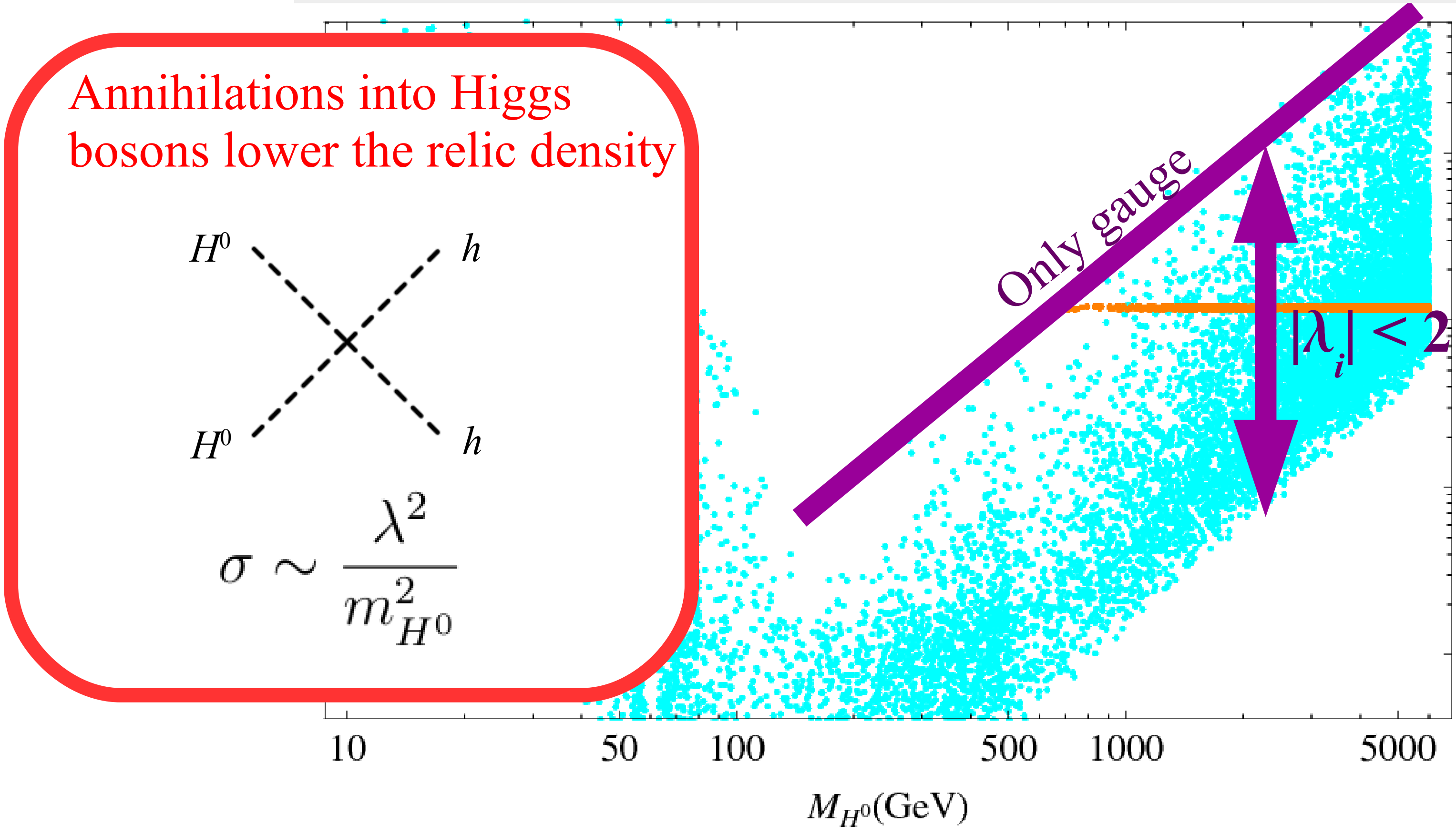

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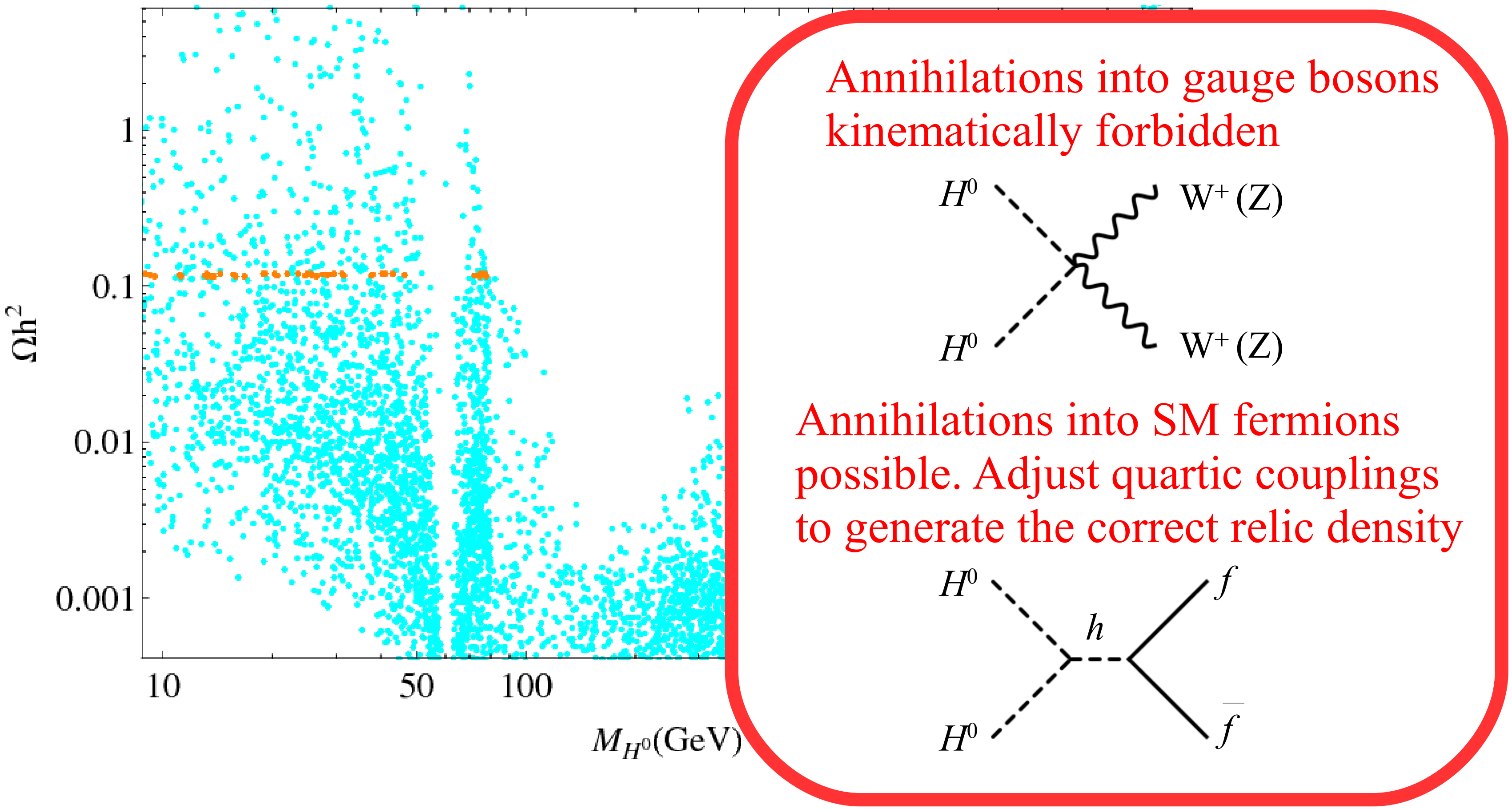

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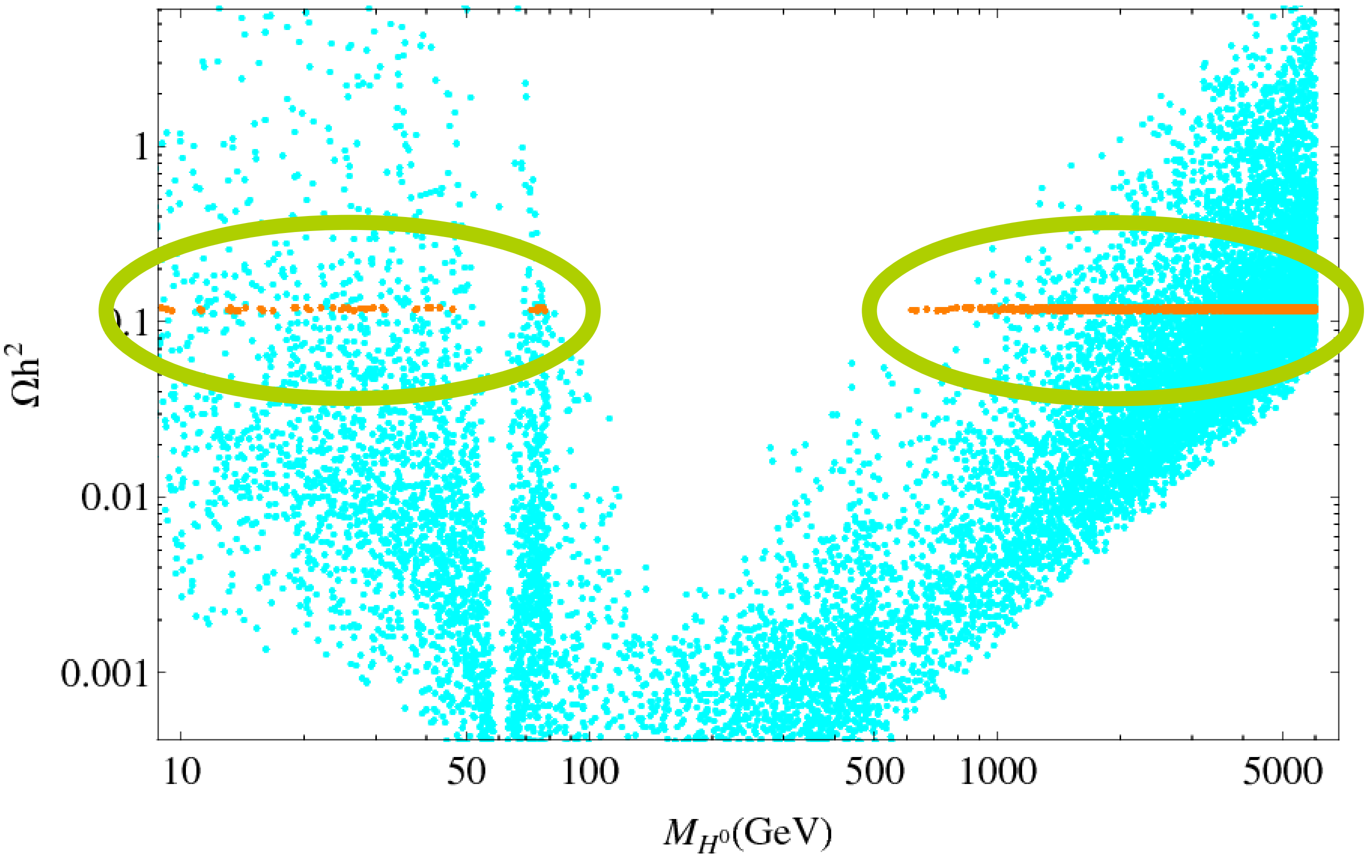
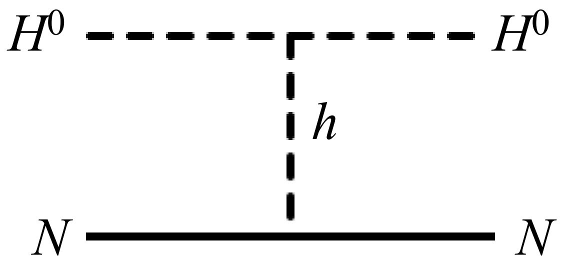
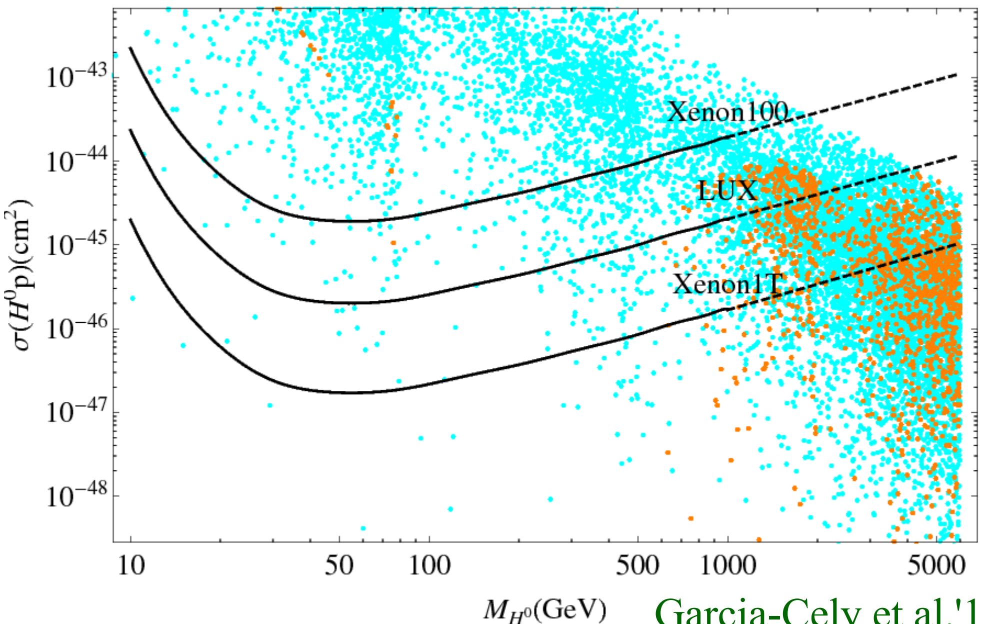


Inert doublet dark matter model: tests

Direct detection



$$\sigma(H^0 p) \simeq 4 \times 10^{-44} \lambda_{H^0}^2 \left(\frac{1\,\mathrm{TeV}}{M_{H^0}}\right)^2 \mathrm{cm}^2$$



Garcia-Cely et al.'13

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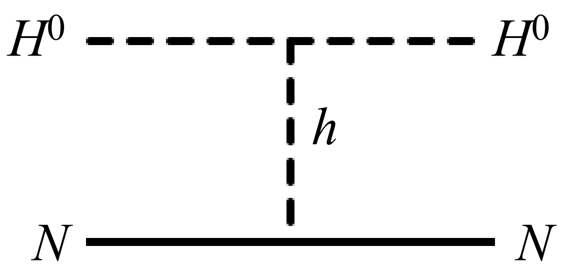

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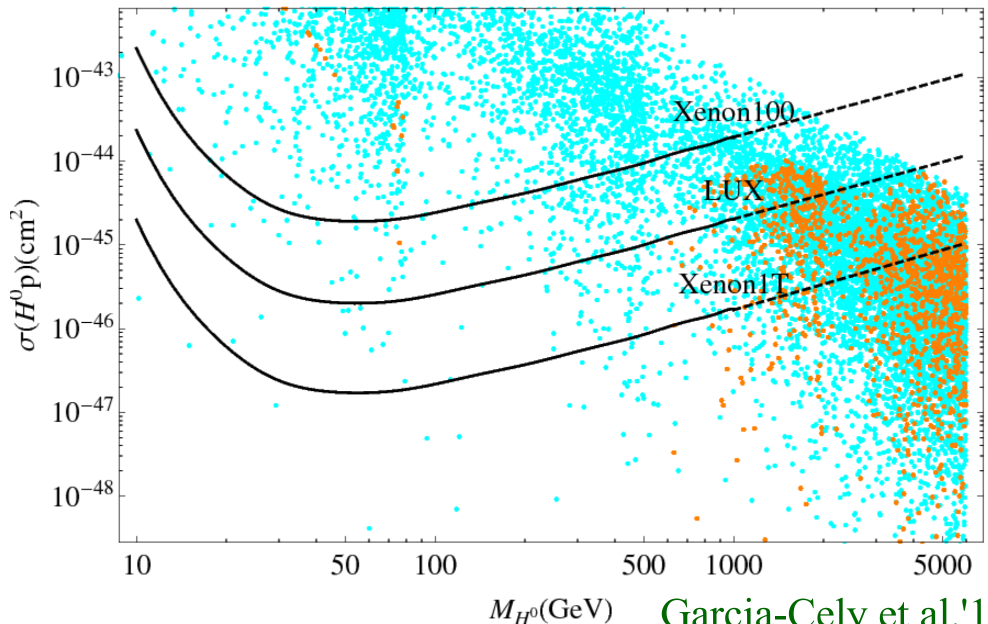
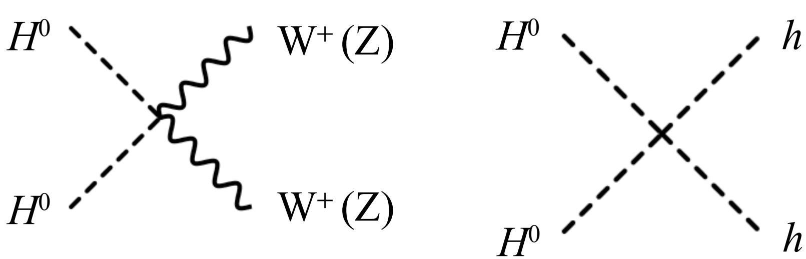
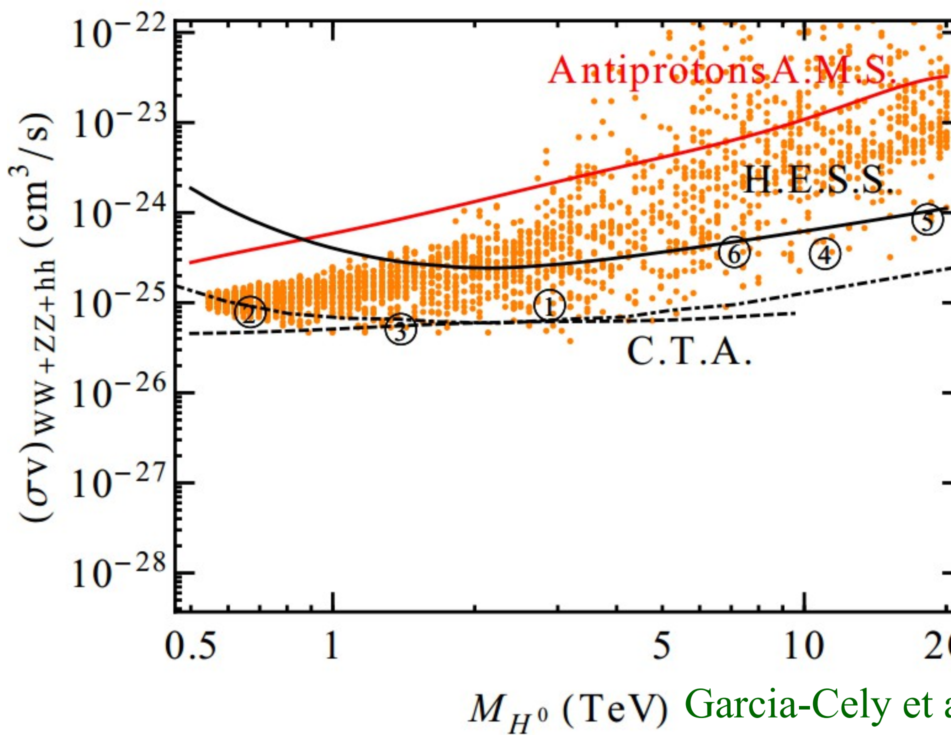


Garcia-Cely et al.'13

Indirect detection

Annihilations into W, Z and h





Garcia-Cely et al.'17

H^0 has electroweak charge
→ Sommerfeld enhancement of the cross section

Inert doublet dark matter model: tests

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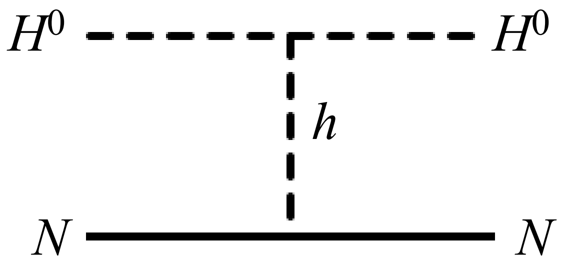

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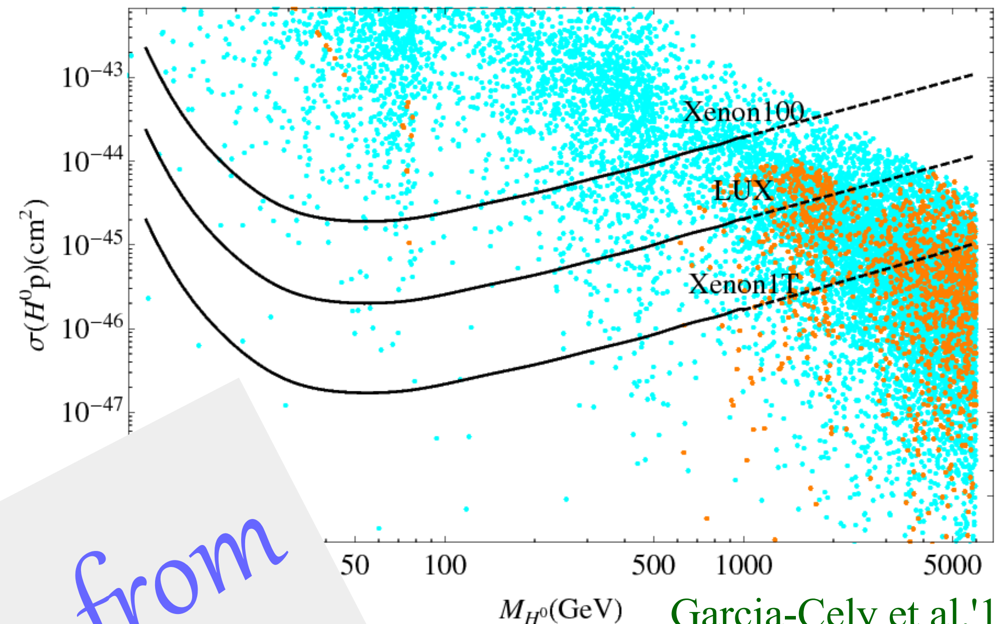

Garcia-Cely et al.'13

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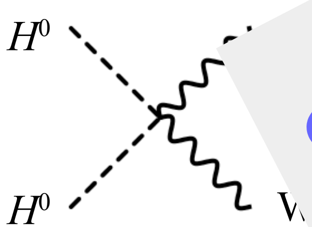
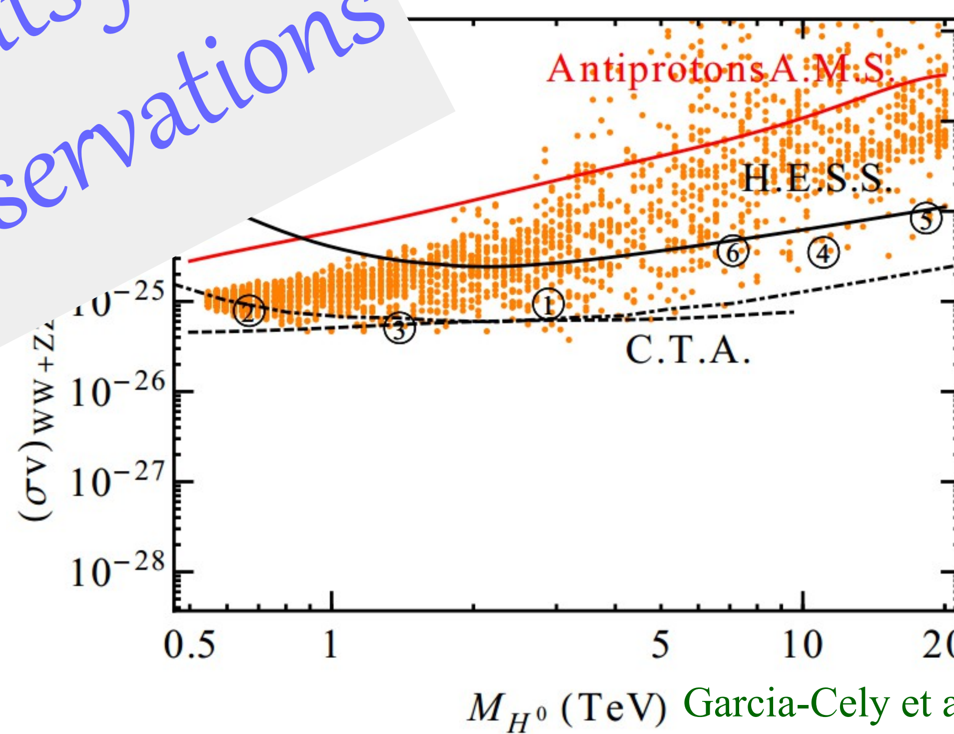
Annihilations in



Strong constraints from gamma-ray observations



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Assumption 1: Add to the SM a dark matter candidate, χ, and a mediator, η, heavier than the DM candidate.

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χ is the lightest particle of the $\mathbb{Z}_2$-odd sector and is stable

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Many possible realizations:

- DM spin/parity
- DM gauge quantum numbers
- t-channel or s-channel mediation
- Coupling to the left- and/or right-handed electron, to the up-quark, to the bottom-quark...

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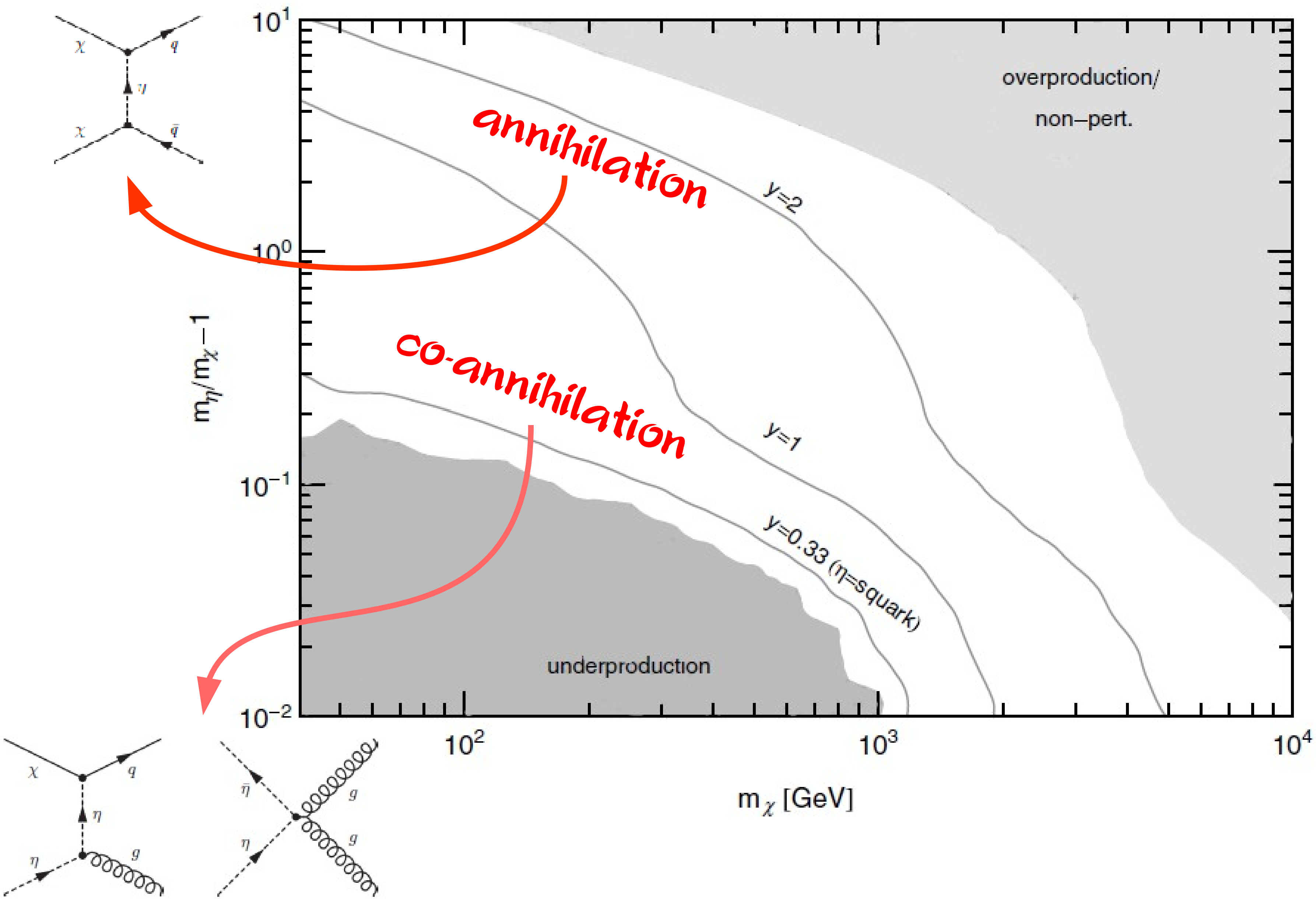
e.g. Majorana fermion dark matter, coupling to a right-handed up-quark via a scalar mediator.

Free parameters: DM mass (m_χ), mediator mass (m_η), Yukawa coupling (y)

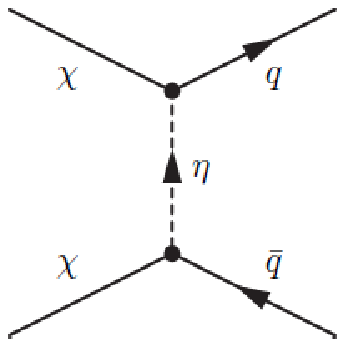
"Simplified models"

Dark matter production fixes one of the parameters of the model.



“Simplified models”: tests

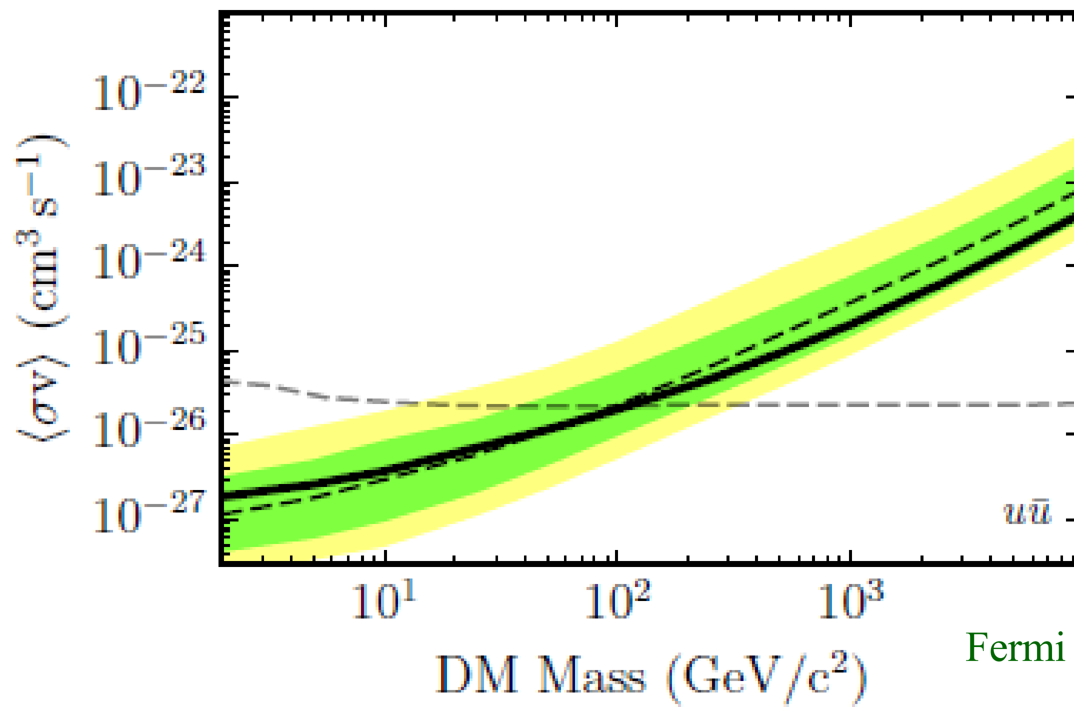
Indirect detection



p-wave suppressed, helicity suppressed.

Expected annihilation cross-section in our Galaxy ~ 5-6 orders of magnitude smaller than the thermal cross section.

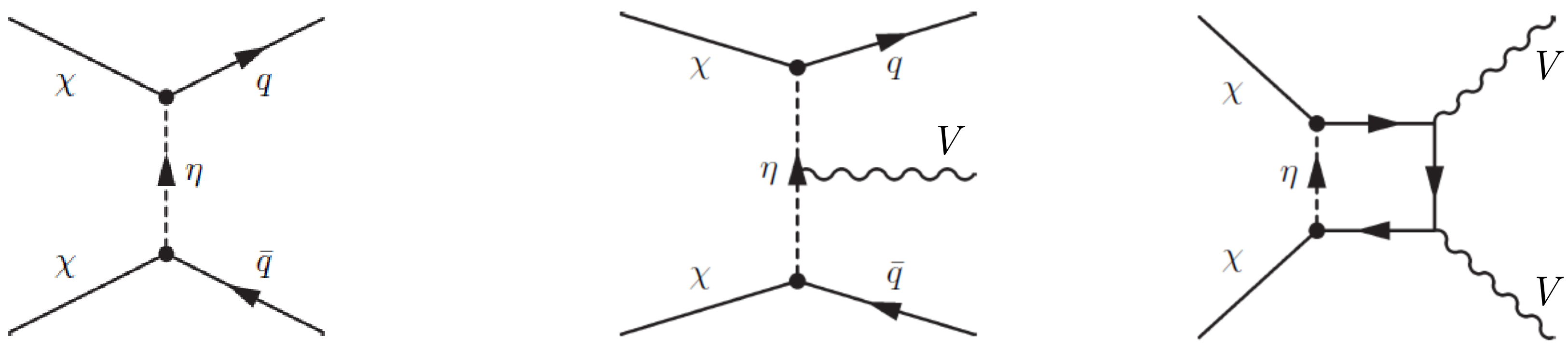
Limits from dwarf galaxy observations on the $u\bar{u}$ final state do not constrain this model.

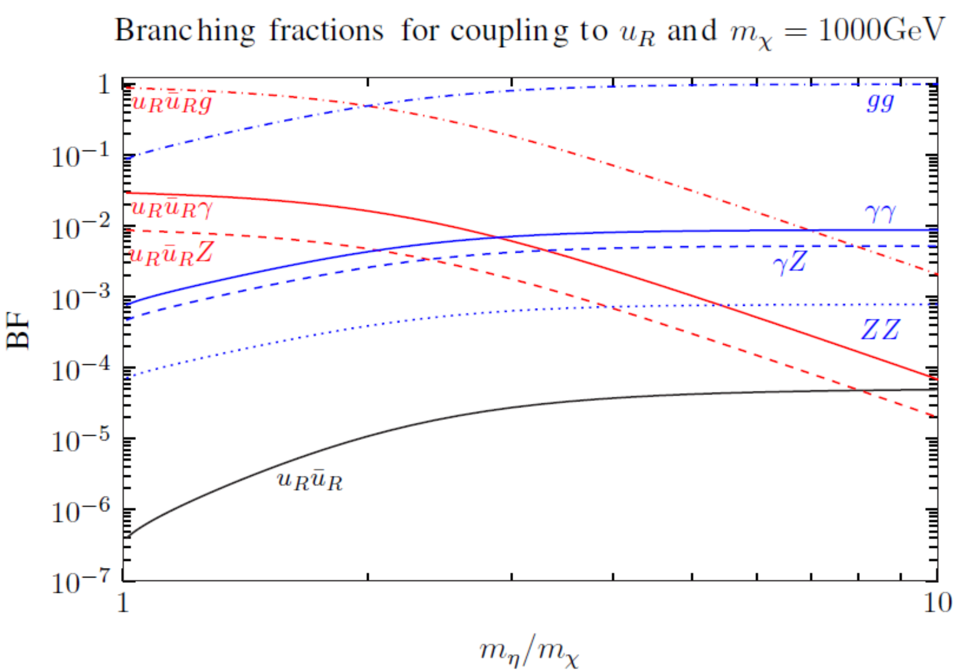


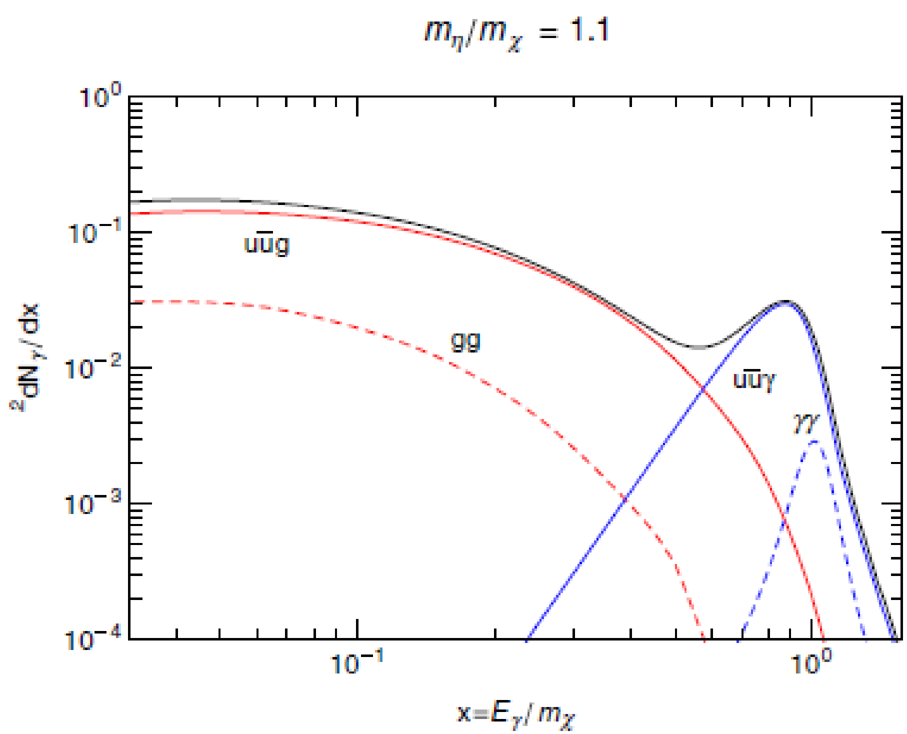
Fermi coll.'15

“Simplified models”: tests

Indirect detection

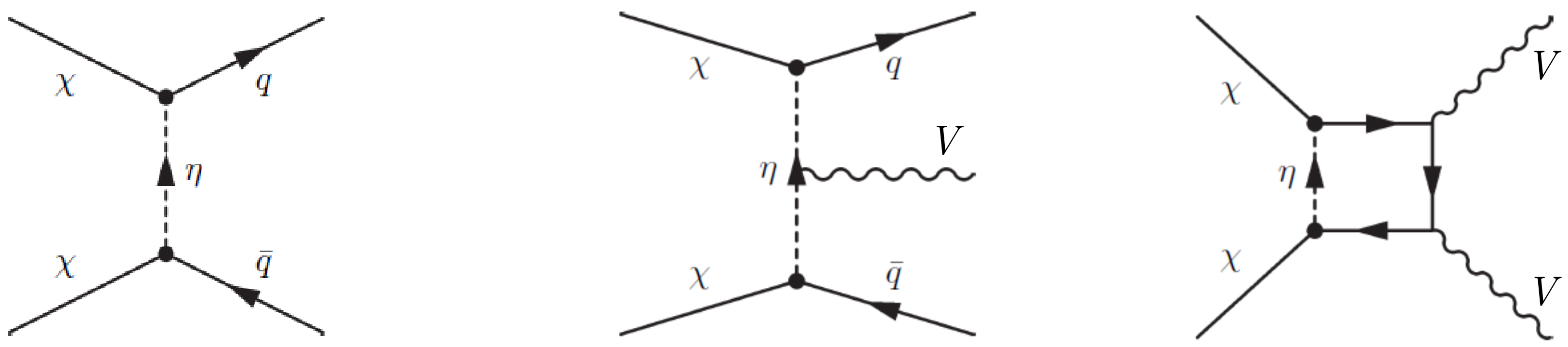


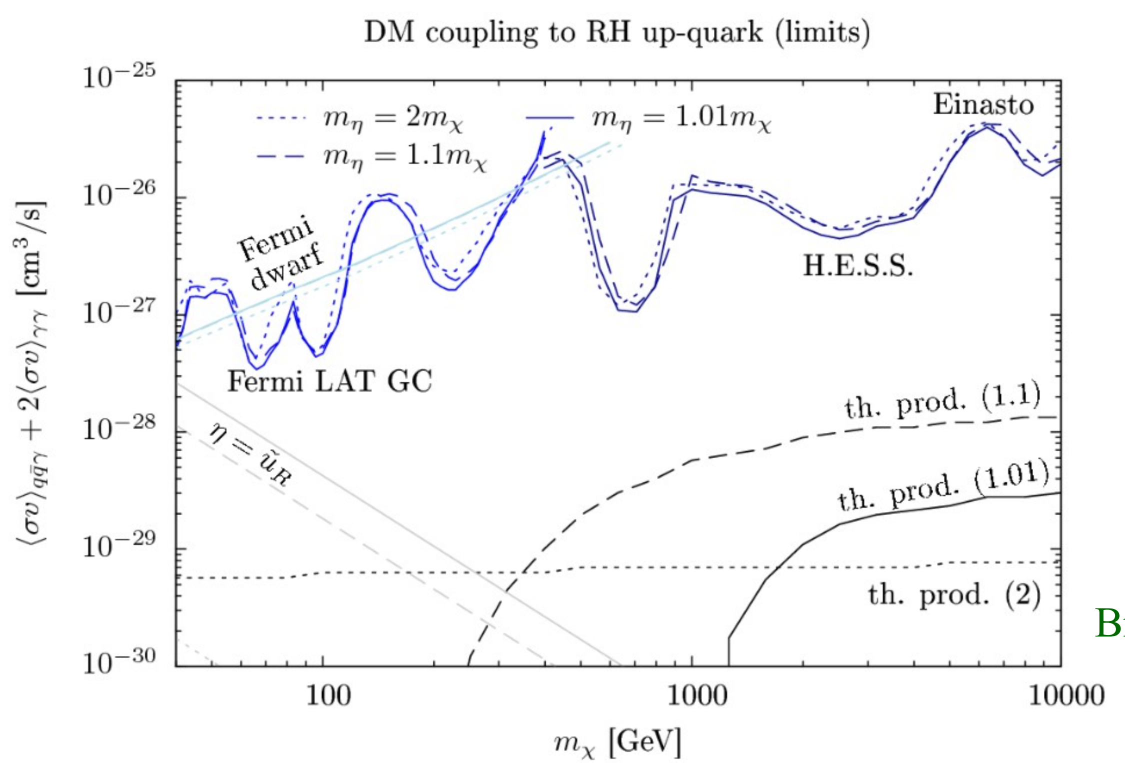




“Simplified models”: tests

Indirect detection

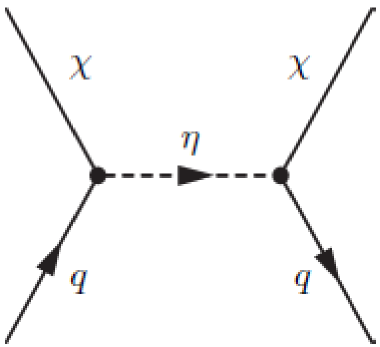




Bringmann et al.'12

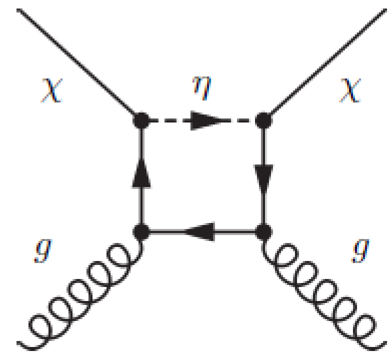
“Simplified models”: tests

Direct detection



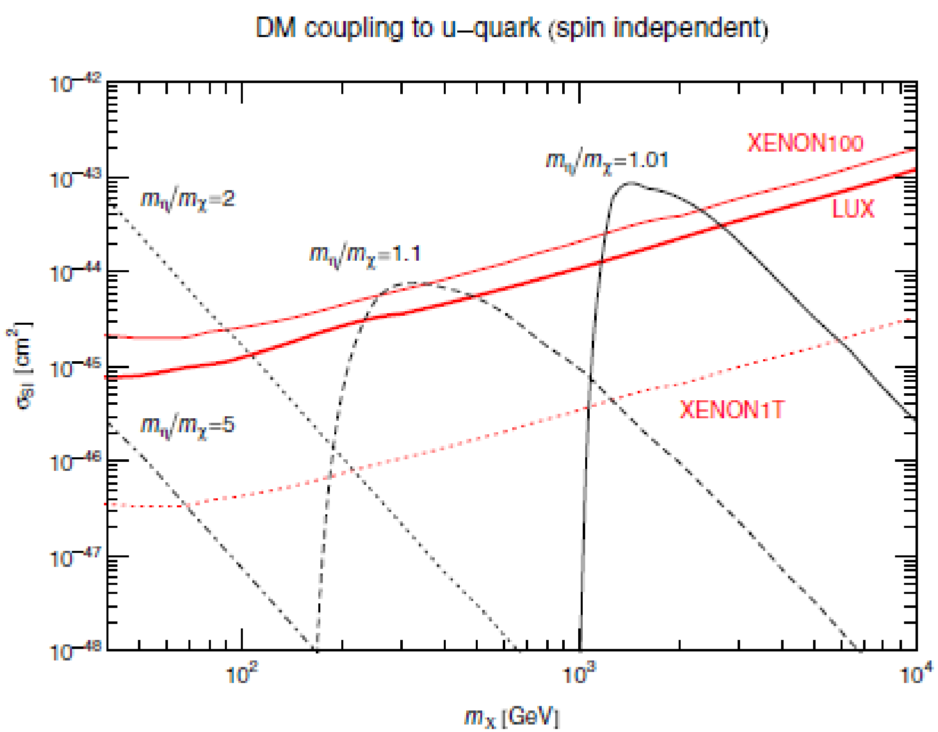
SI at dim-8
SD at dim-6

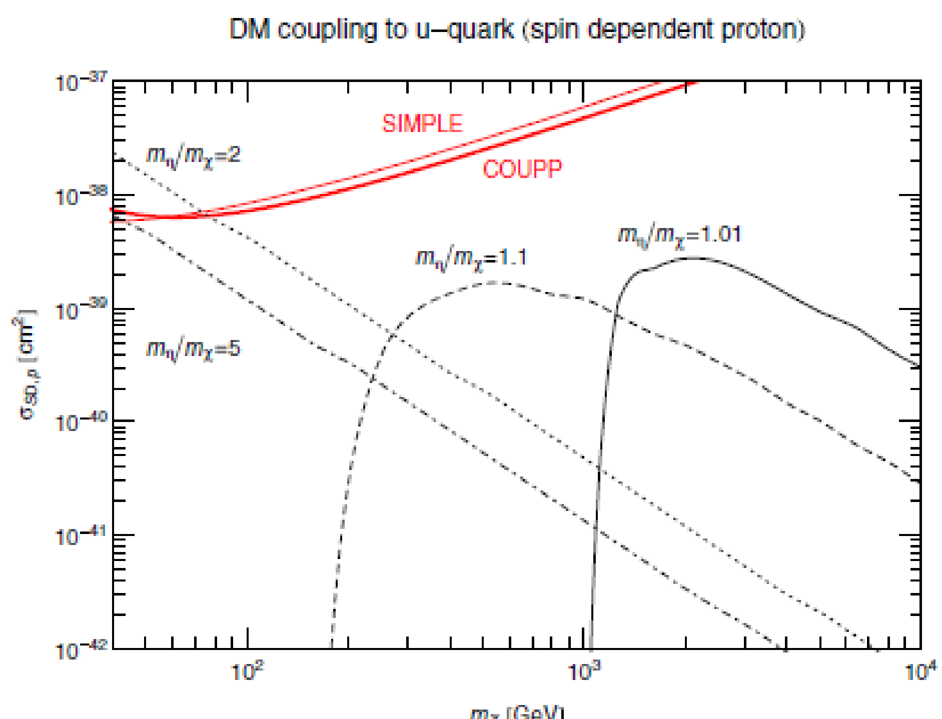
tree-level
resonant



SI at dim-7

one-loop
non-resonant





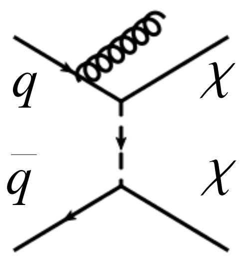
Garny et al.'15

“Simplified models”: tests

Collider searches

$m_\eta \gg m_\chi$

The scalar mediator cannot be produced at the collider, but only the DM.

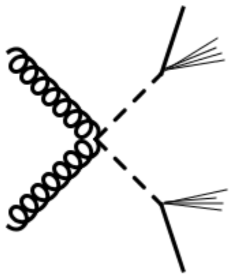


Mono-X + missing p_T

$m_\eta = \mathcal{O}(m_\chi)$

The scalar mediator can be produced at the collider, and then decays into the DM plus a quark.

e.g



jets + missing p_T

$m_\eta \simeq m_\chi$

The scalar mediator can be produced at the collider, and then decays into the DM plus a quark. However the jet is too soft to be detected.

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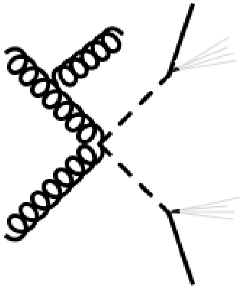

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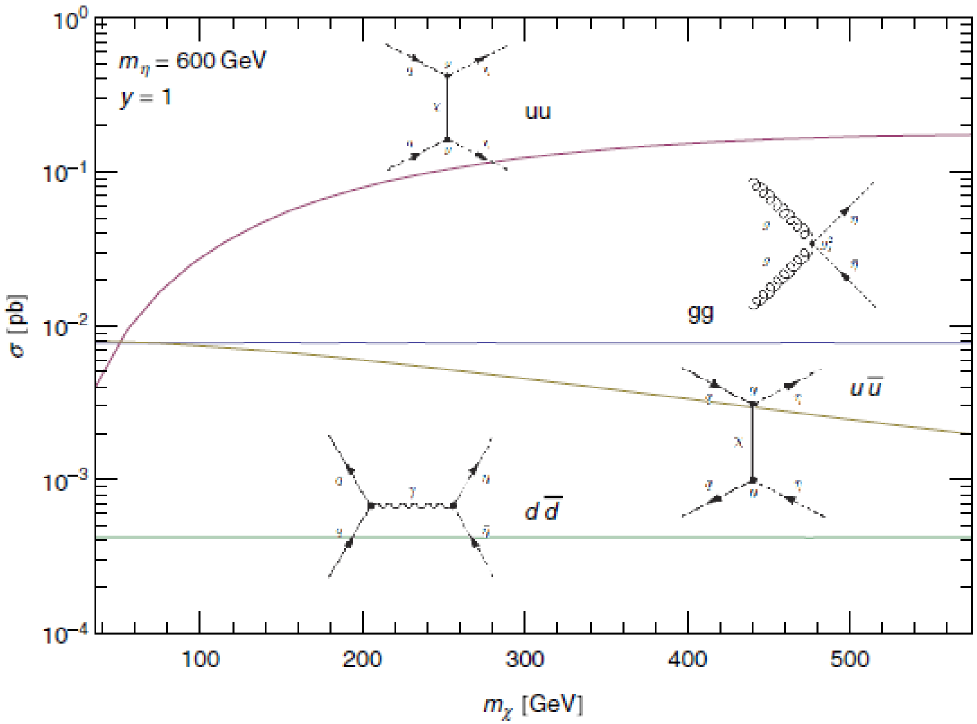
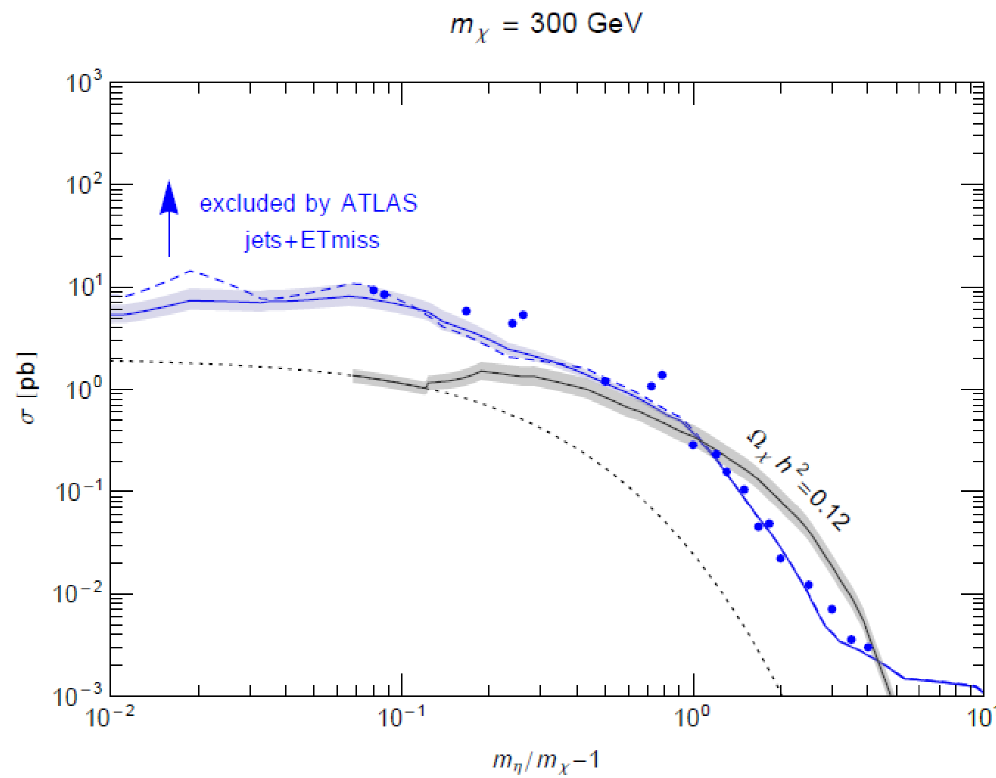
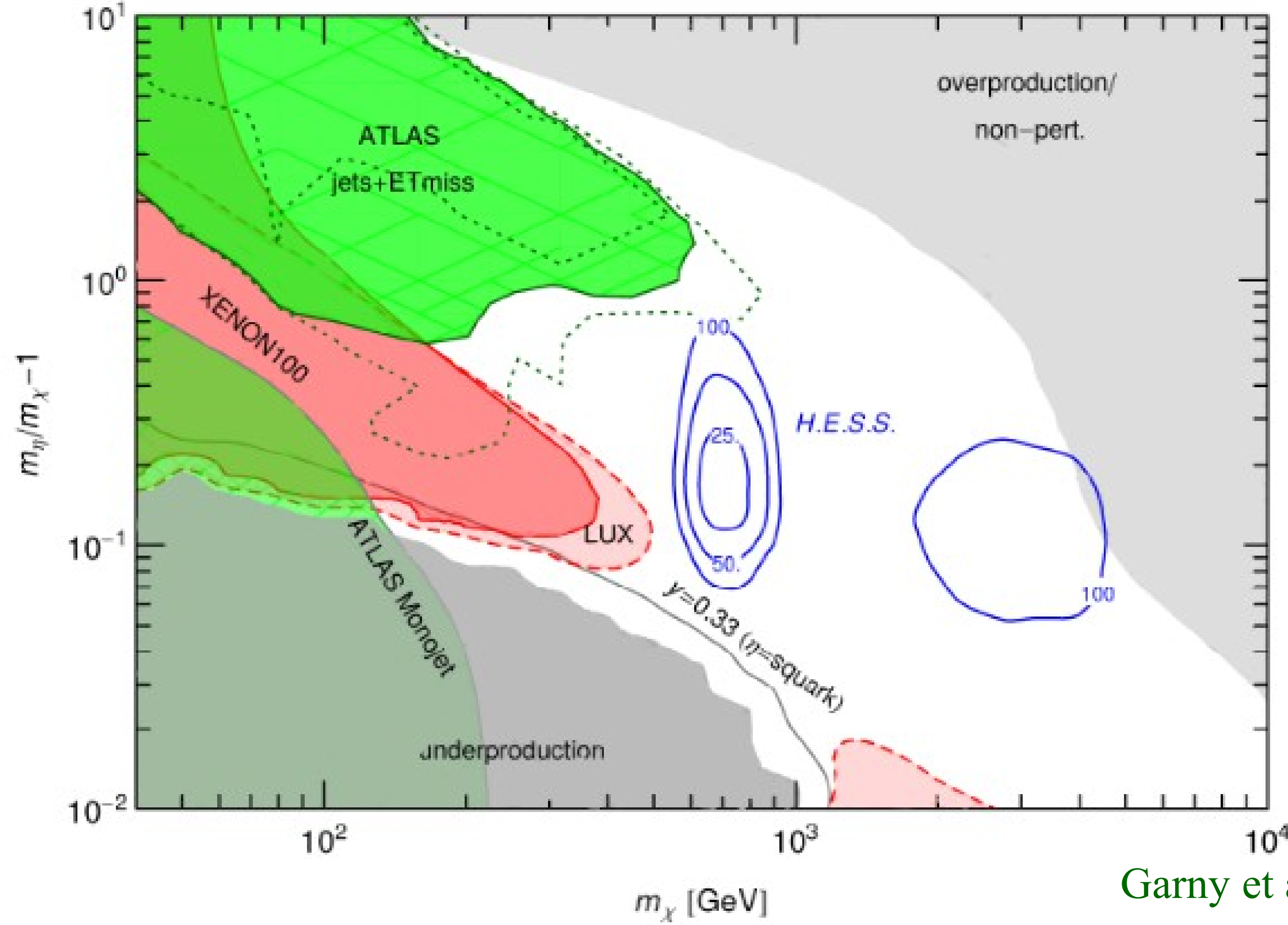




"Simplified models": tests

Complementarity of searches

DM coupling to RH up-quarks



Garny et al.'15

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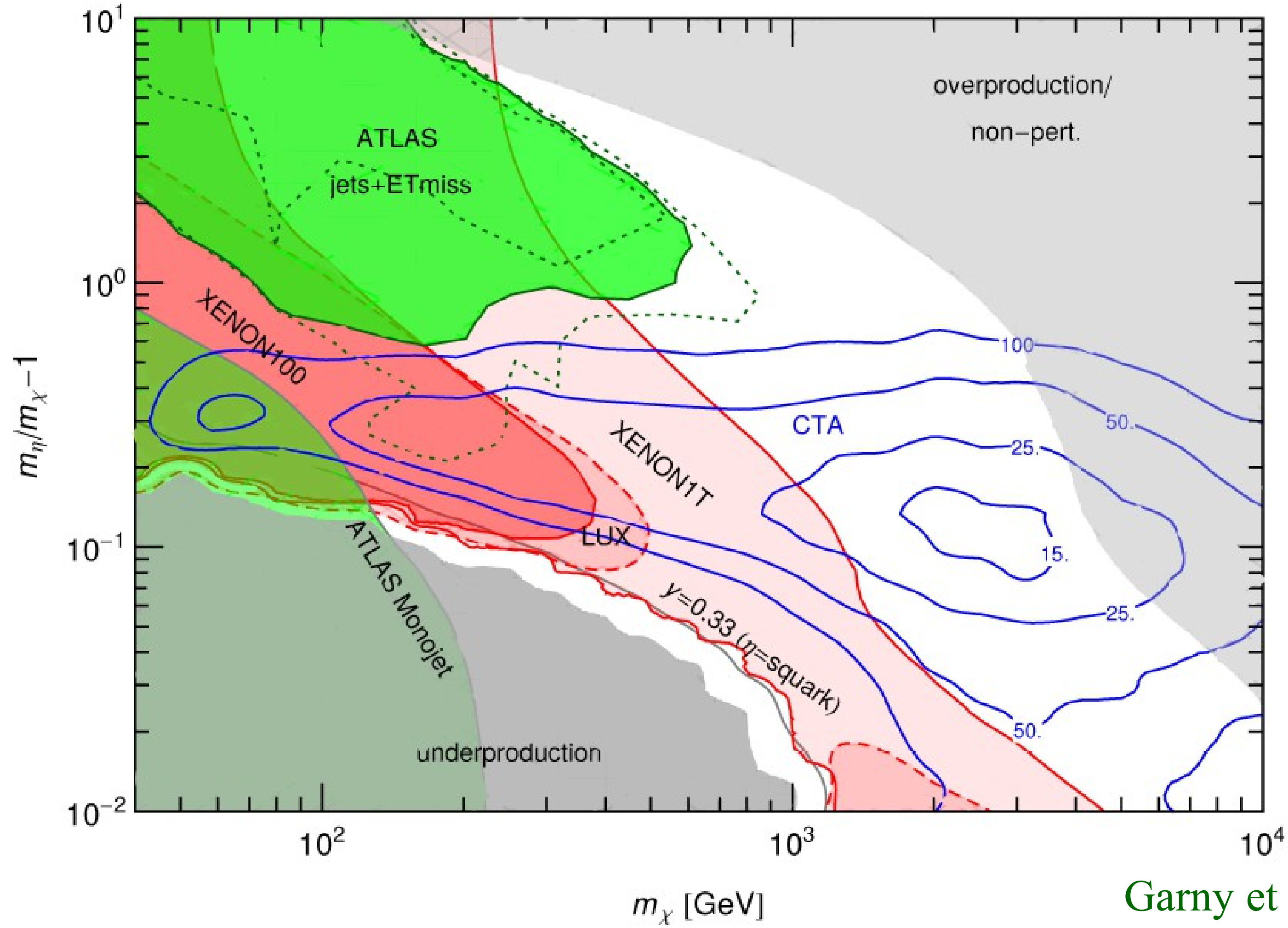

Garny et al.'15

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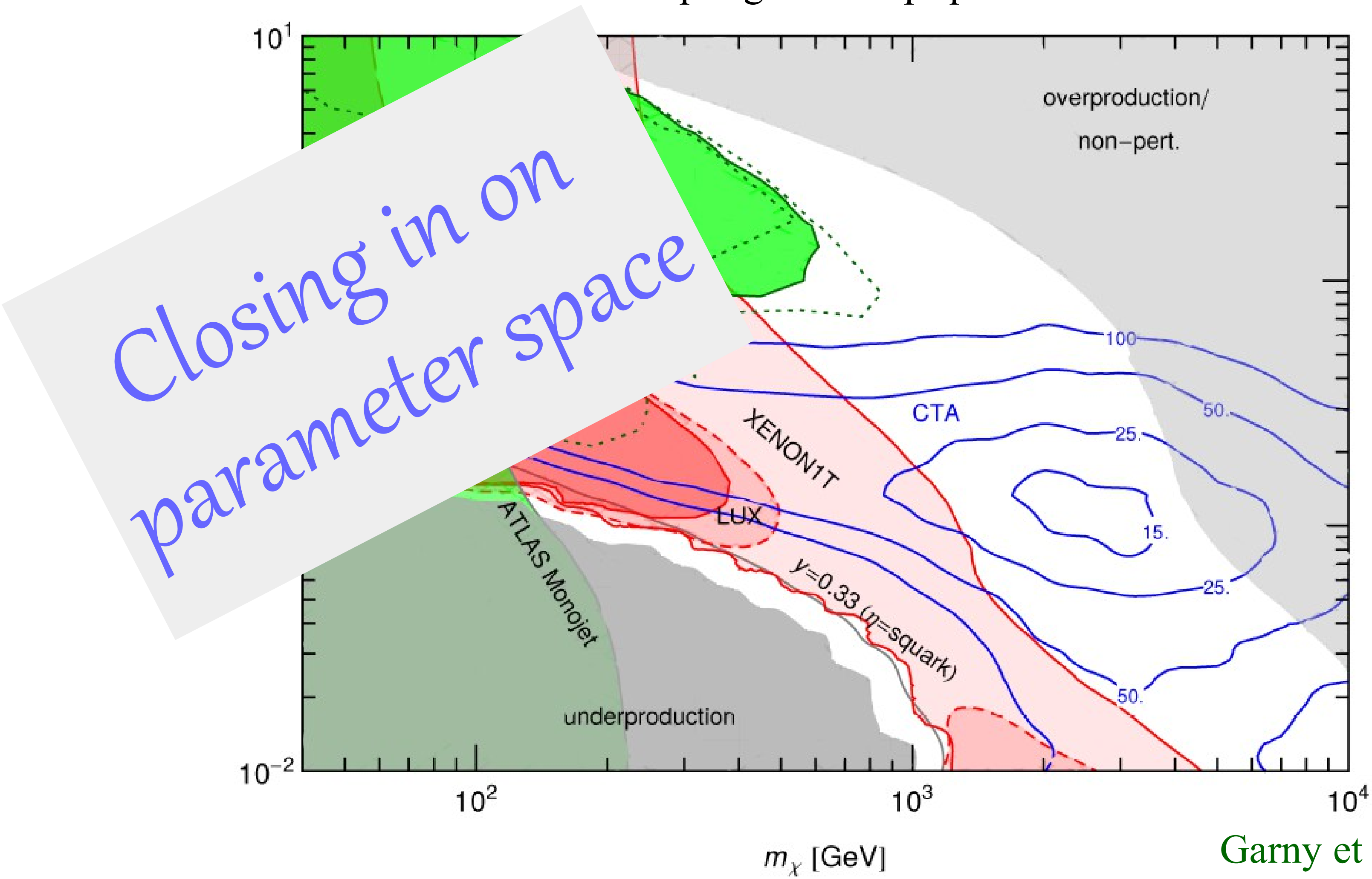

Garny et al.'15

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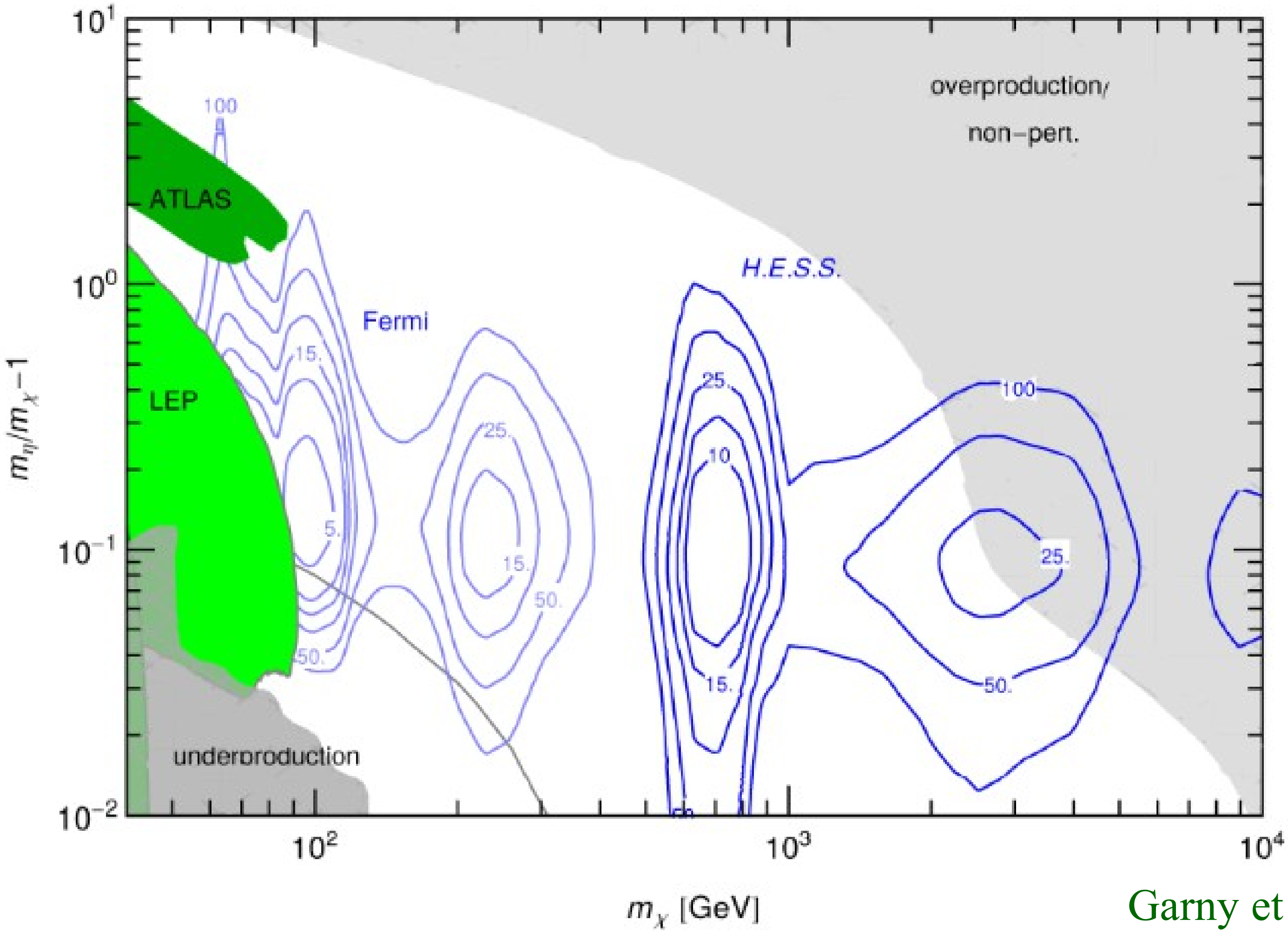
DM coupling to RH muons

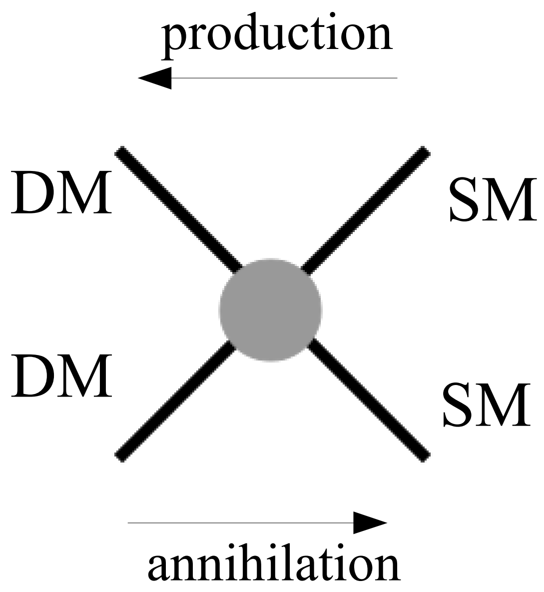


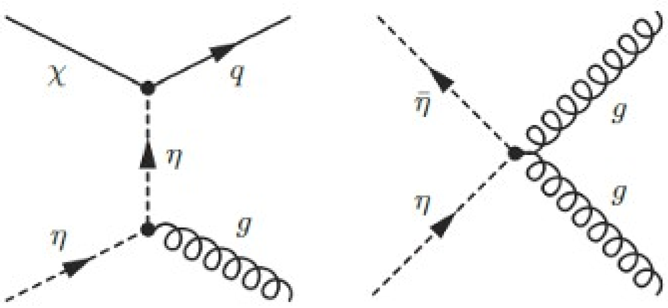
Garny et al.'15

“Simplified models”: take home lesson

The mediator plays a crucial role in the phenomenology, when its mass is close to the dark matter mass.

Thermal production





coannihilations

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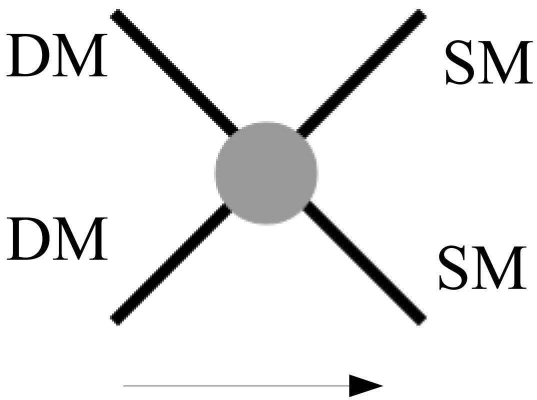
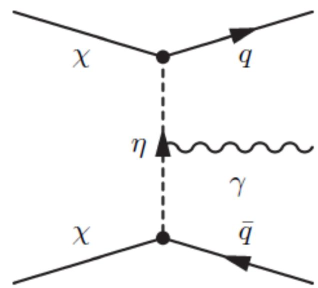
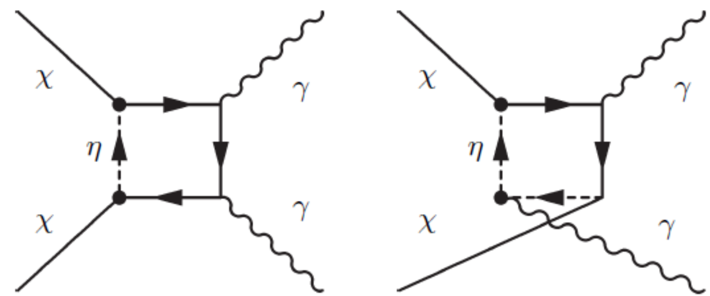
Indirect detection



annihilation



Internal Bremsstrahlung

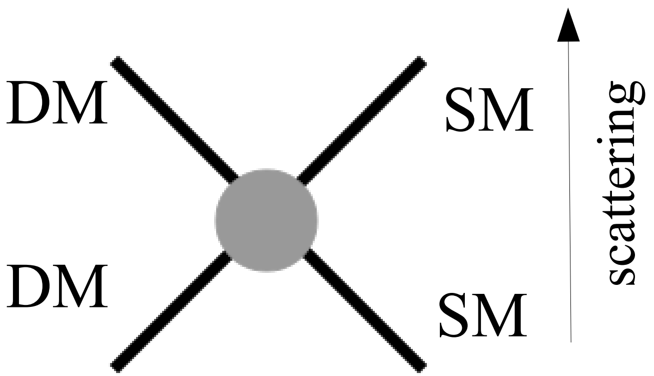


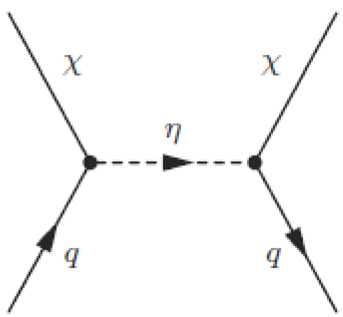
Loop annihilations

"Simplified models": take home lesson

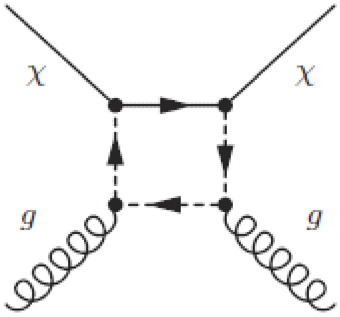
The mediator plays a crucial role in the phenomenology, when its mass is close to the dark matter mass.

Direct detection





resonance

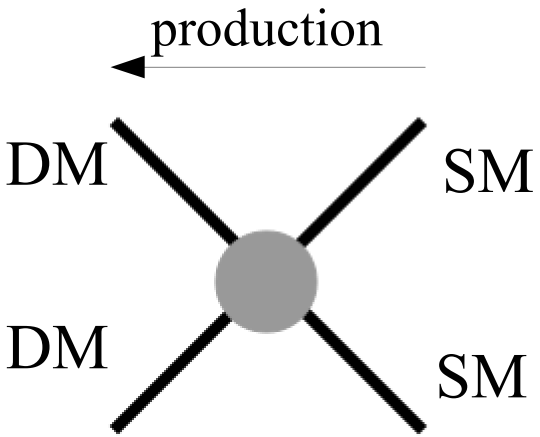


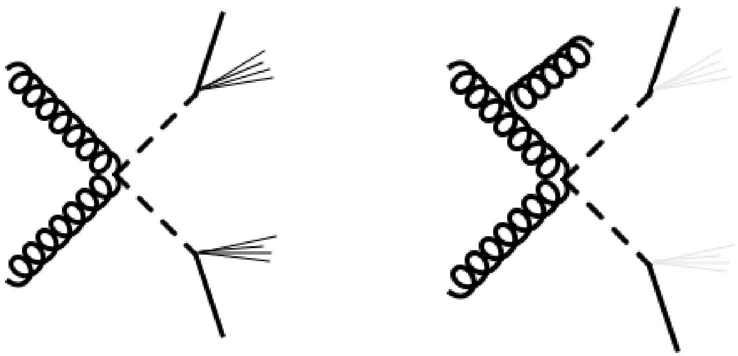
loops

"Simplified models": take home lesson

The mediator plays a crucial role in the phenomenology, when its mass is close to the dark matter mass.

Collider searches





Conclusions

- Simple particle physics frameworks contain a dark matter candidate with an abundance today which is in qualitative good agreement with observations. These models contain very few parameters and have some predictive power.

- Current experiments have achieved sufficient sensitivity to put tension on some of the simplest frameworks. From an optimistic point of view, discovery could be around the corner.