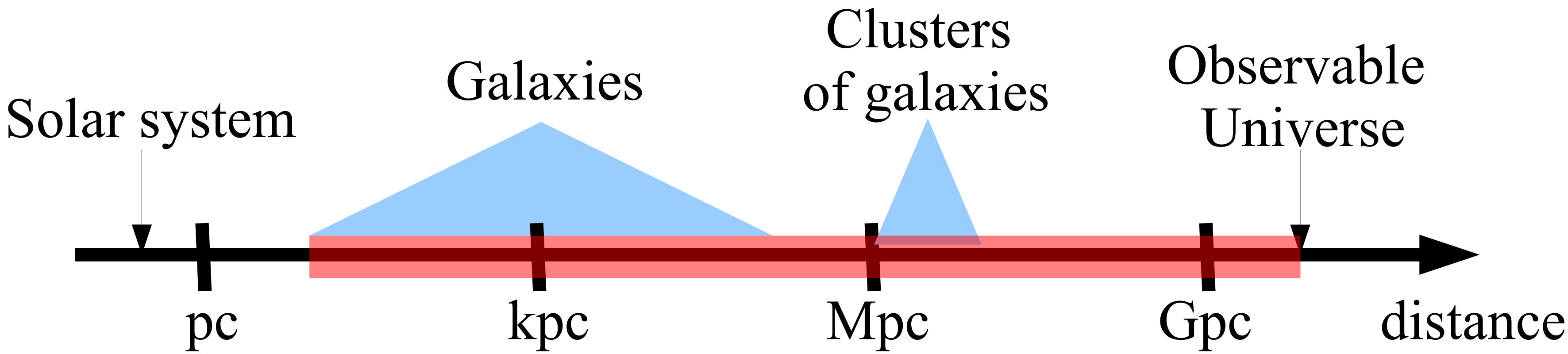
# Dark matter at LHC and beyond

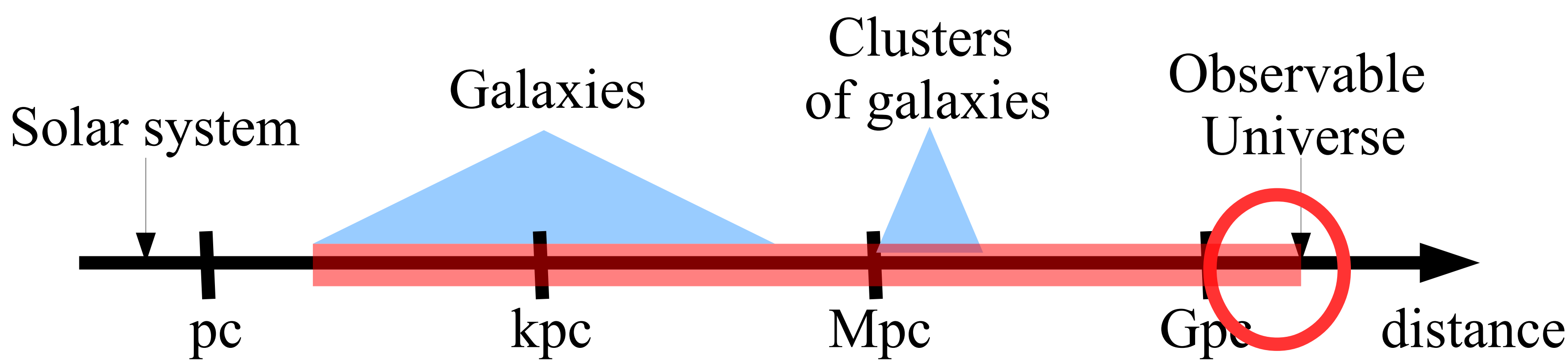
Alejandro Ibarra

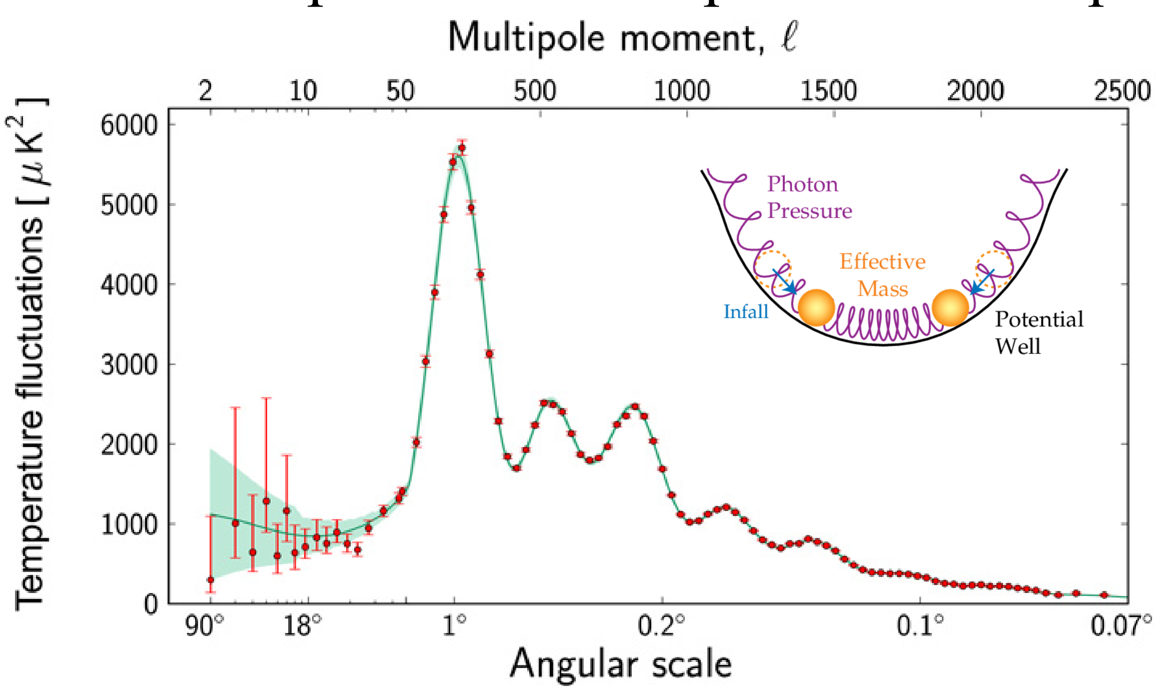
ICTP, Trieste
May 2019

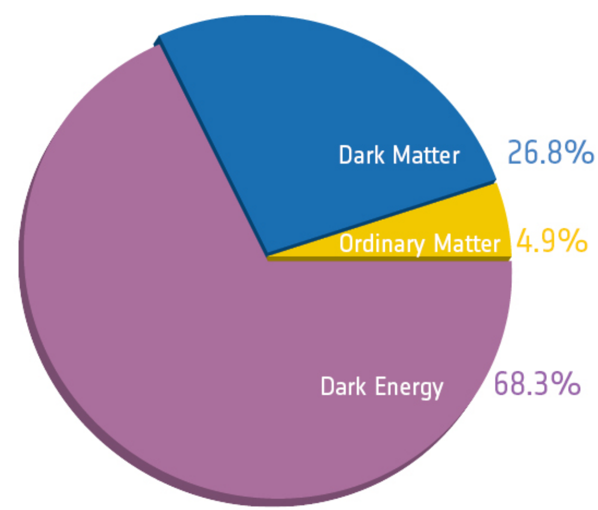
# There is evidence for dark matter in a wide range of distance scales



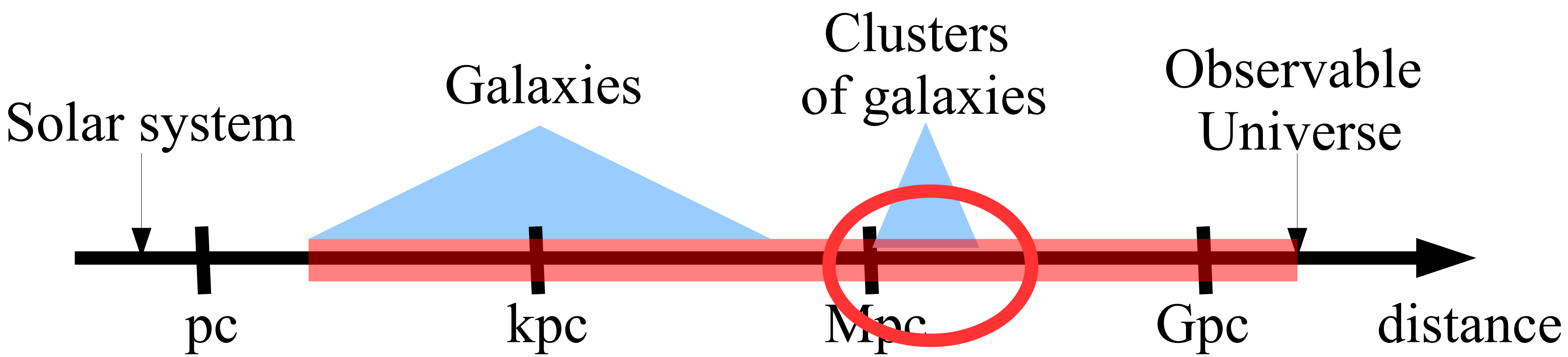
# There is evidence for dark matter in a wide range of distance scales

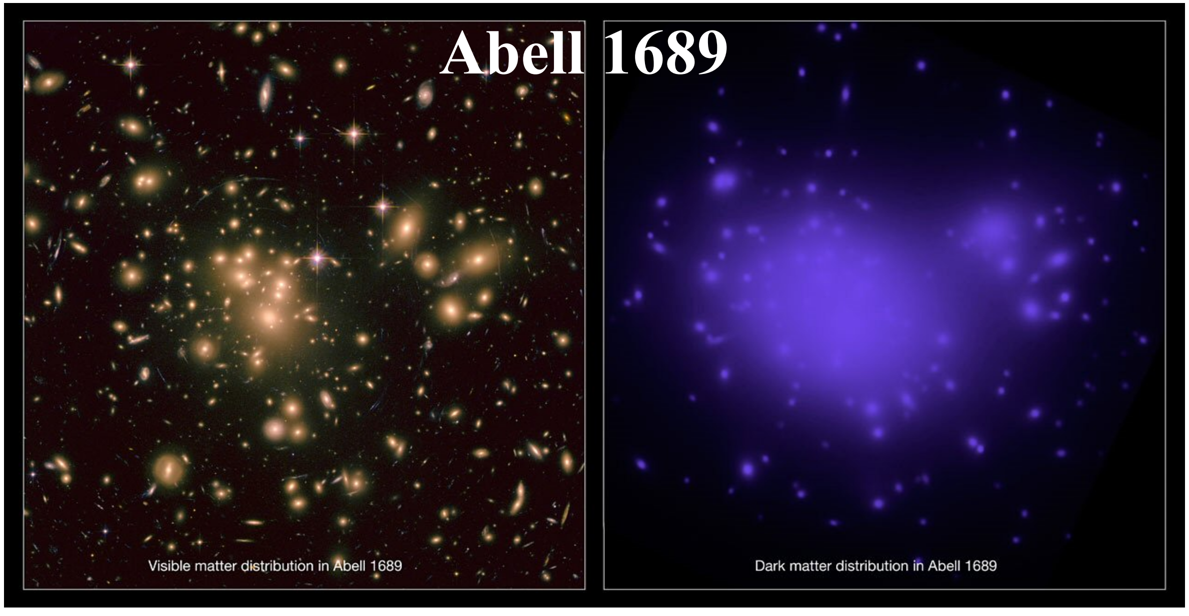


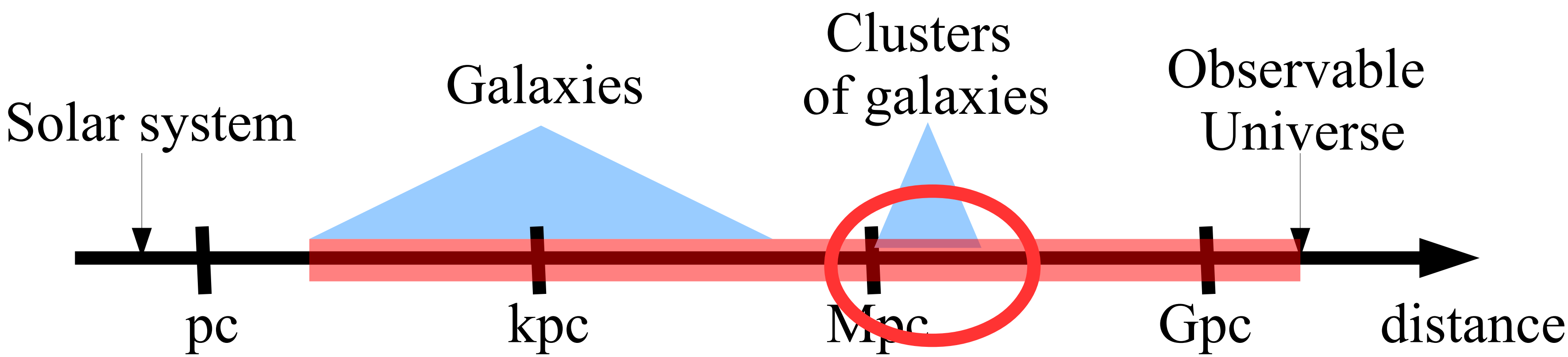



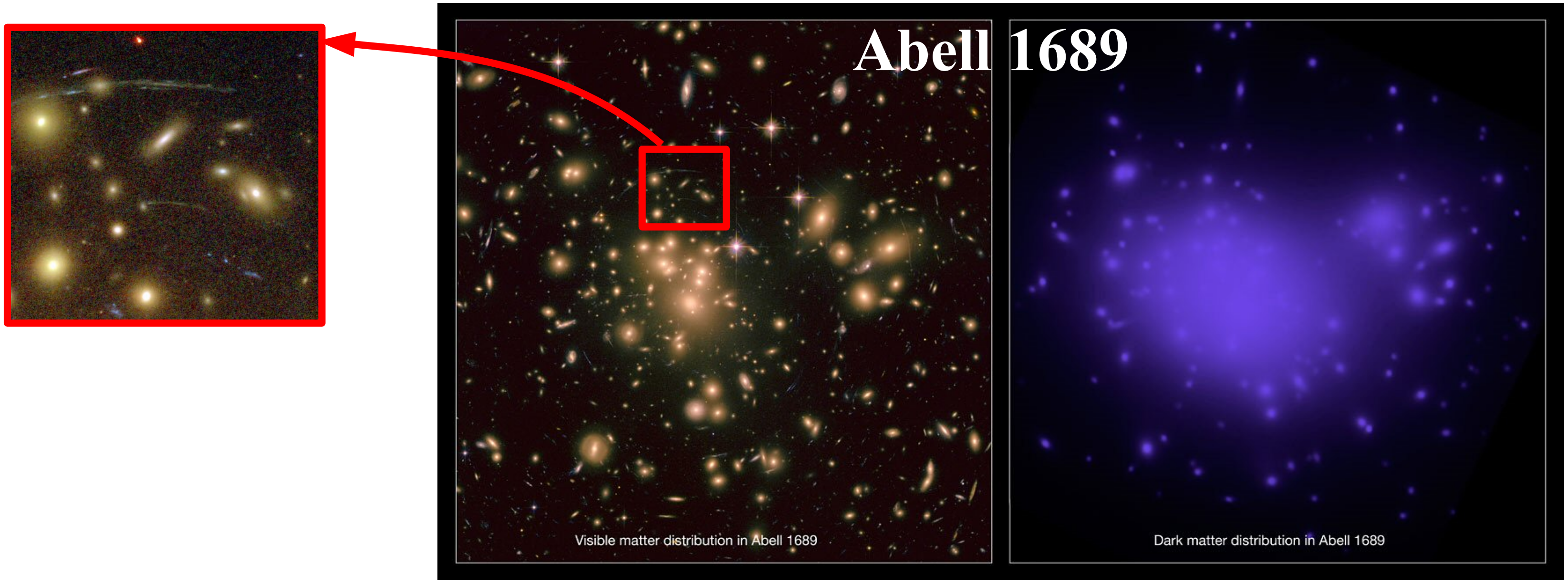
# There is evidence for dark matter in a wide range of distance scales



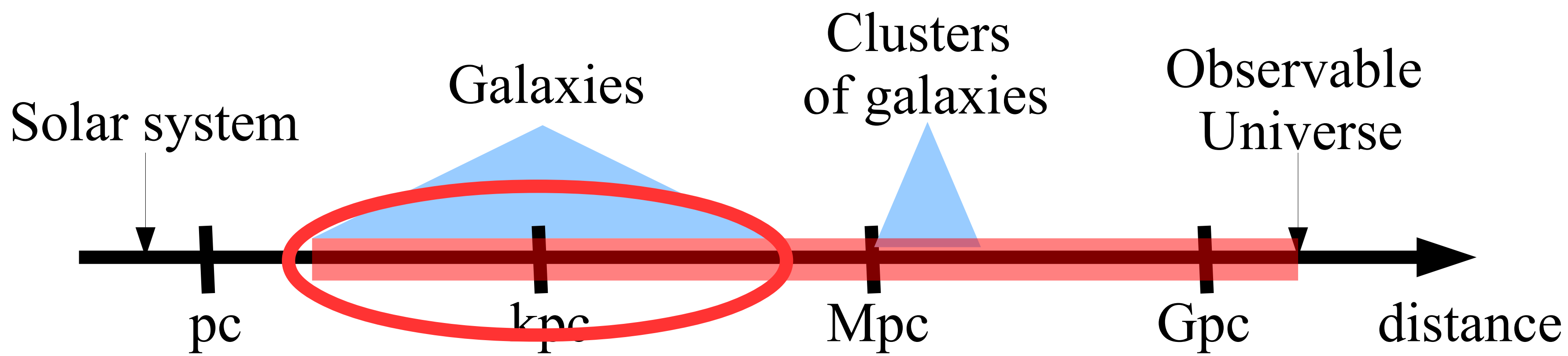



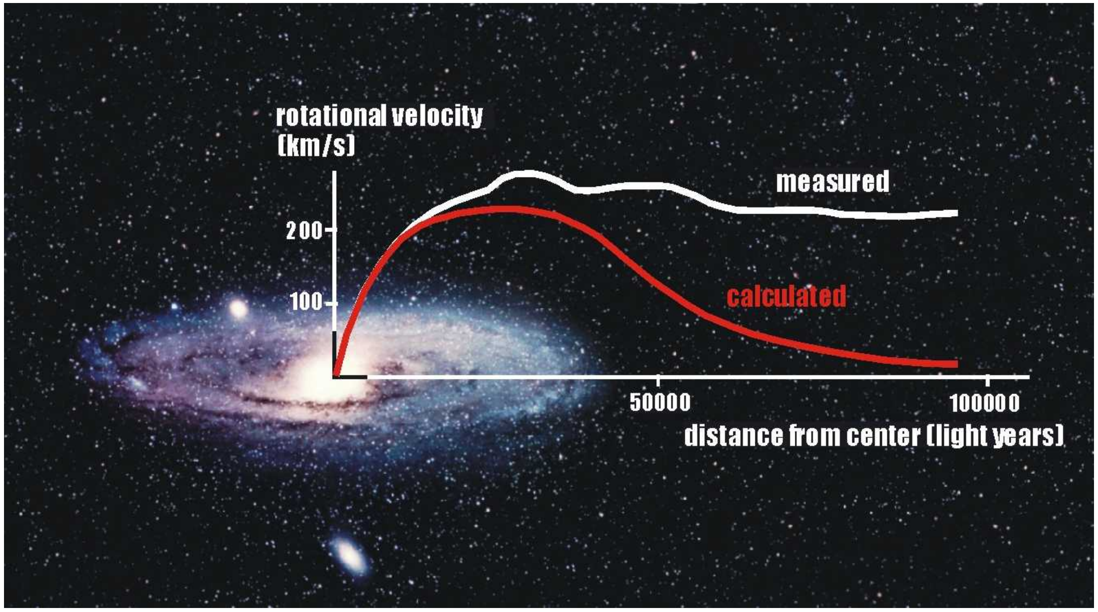
# There is evidence for dark matter in a wide range of distance scales



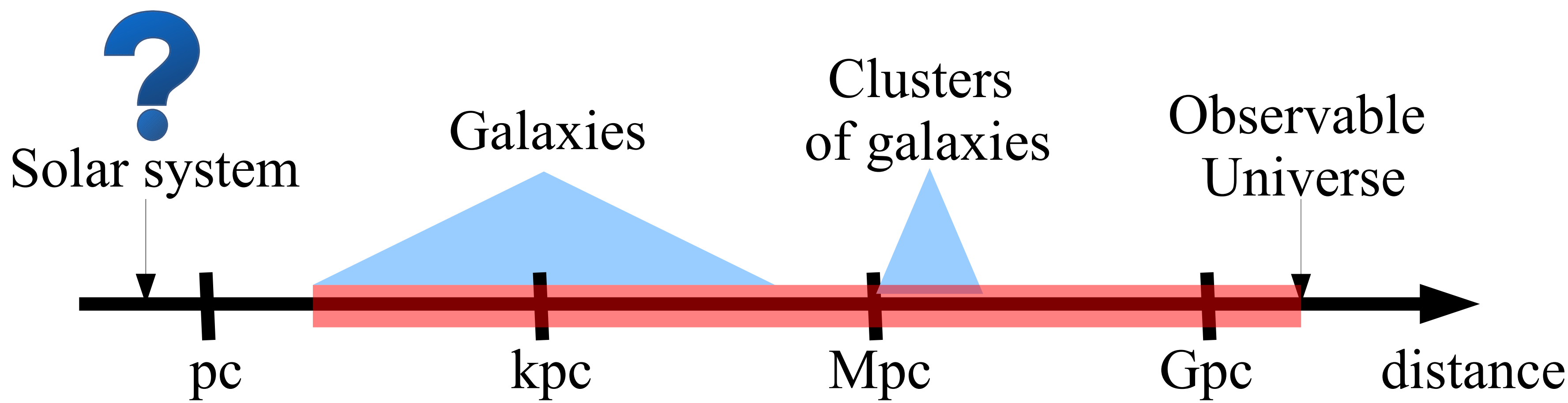



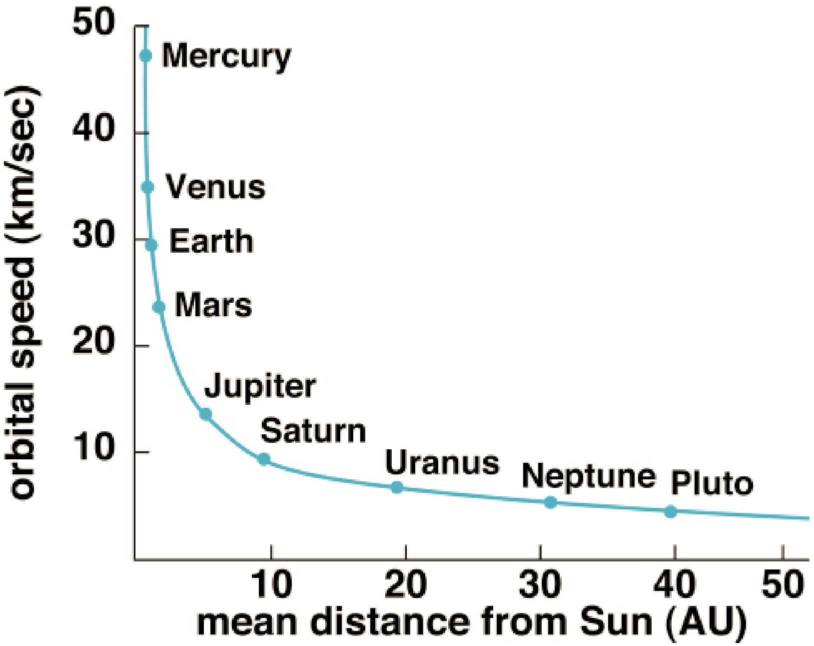
# There is evidence for dark matter in a wide range of distance scales



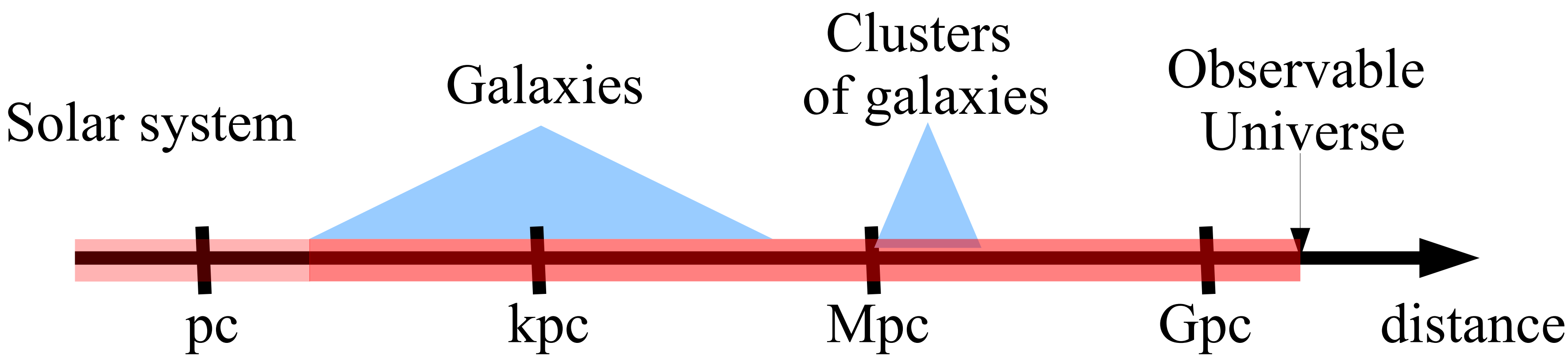



# There is evidence for dark matter in a wide range of distance scales

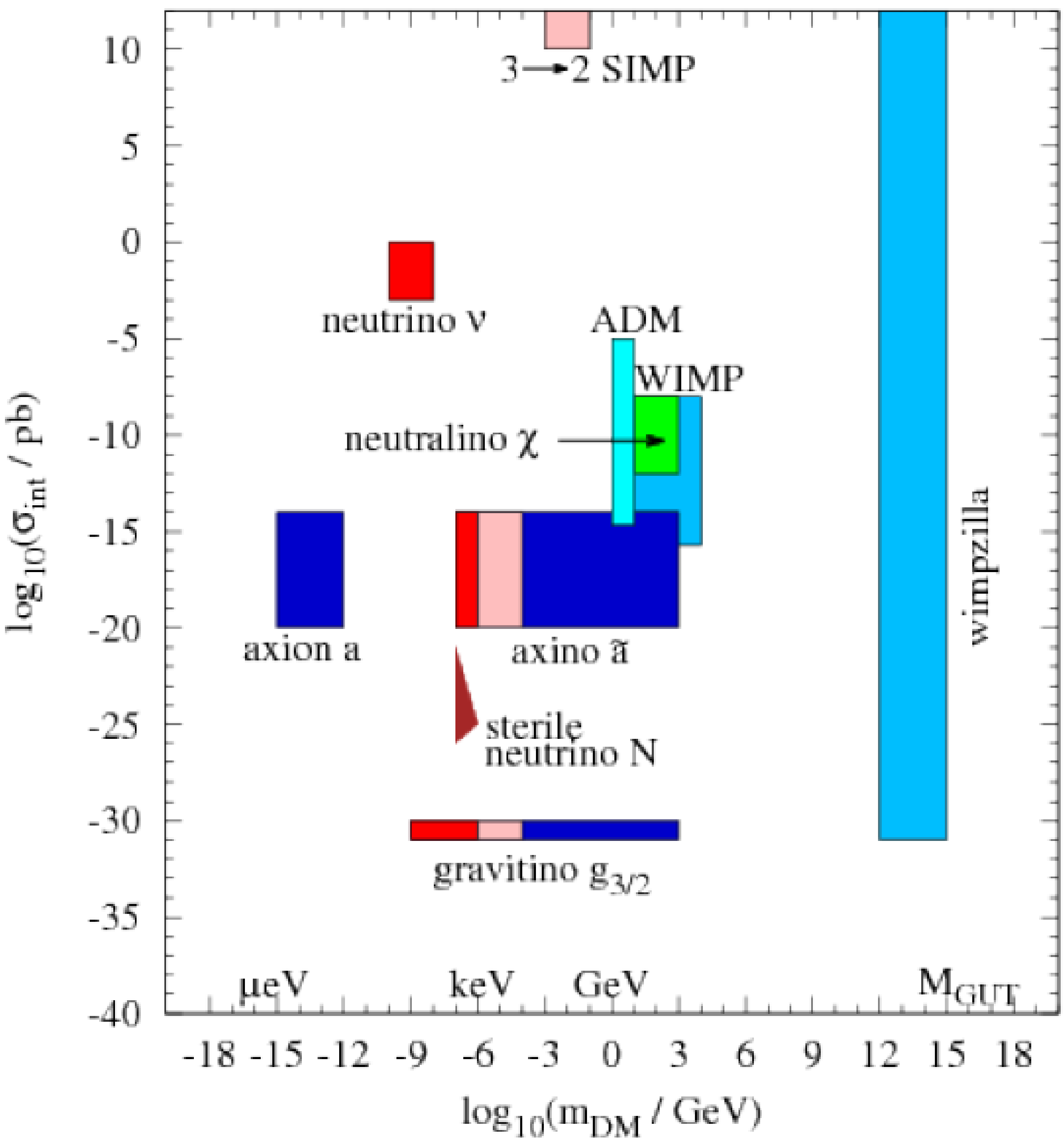


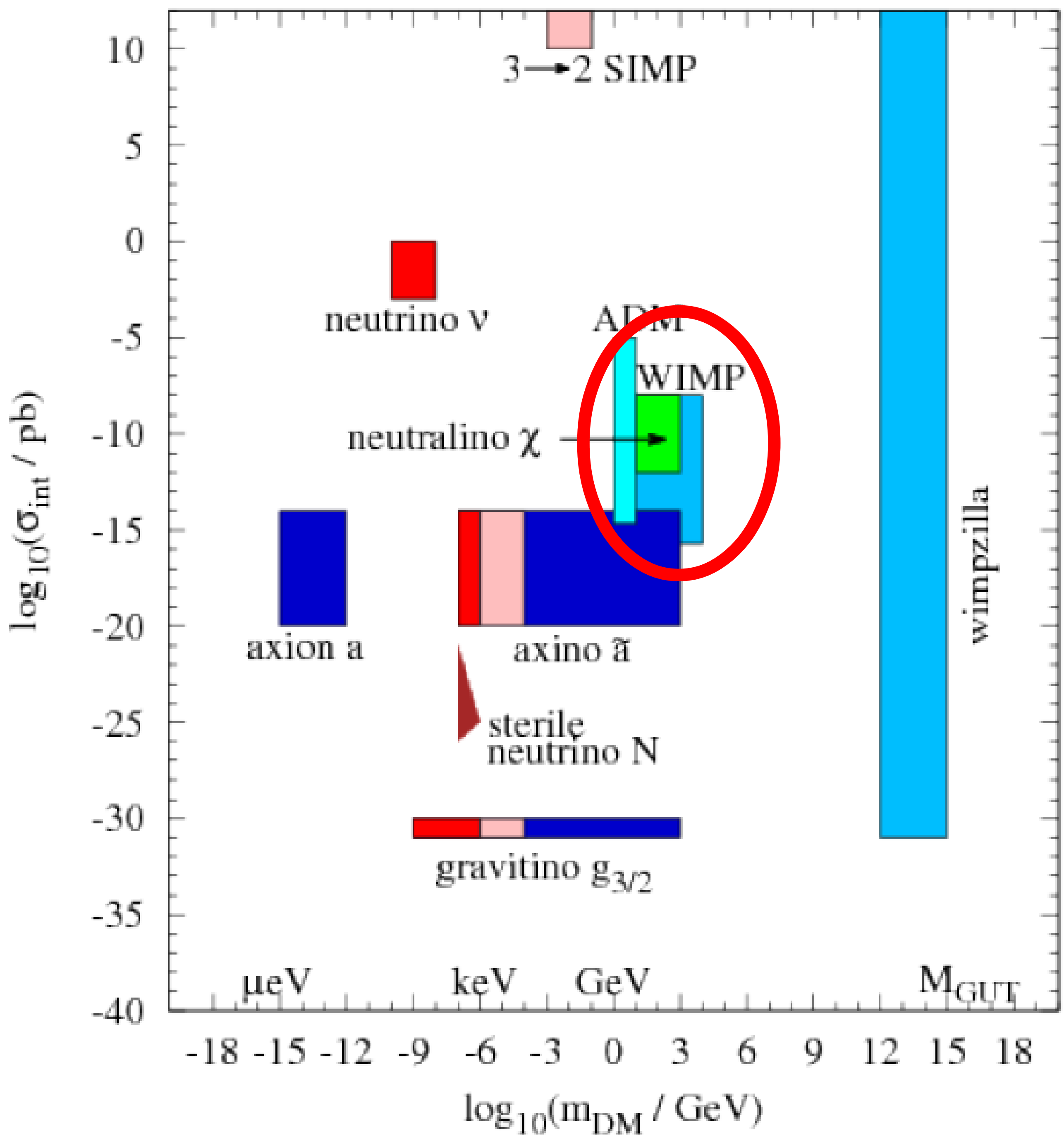
# There is evidence for dark matter in a wide range of distance scales



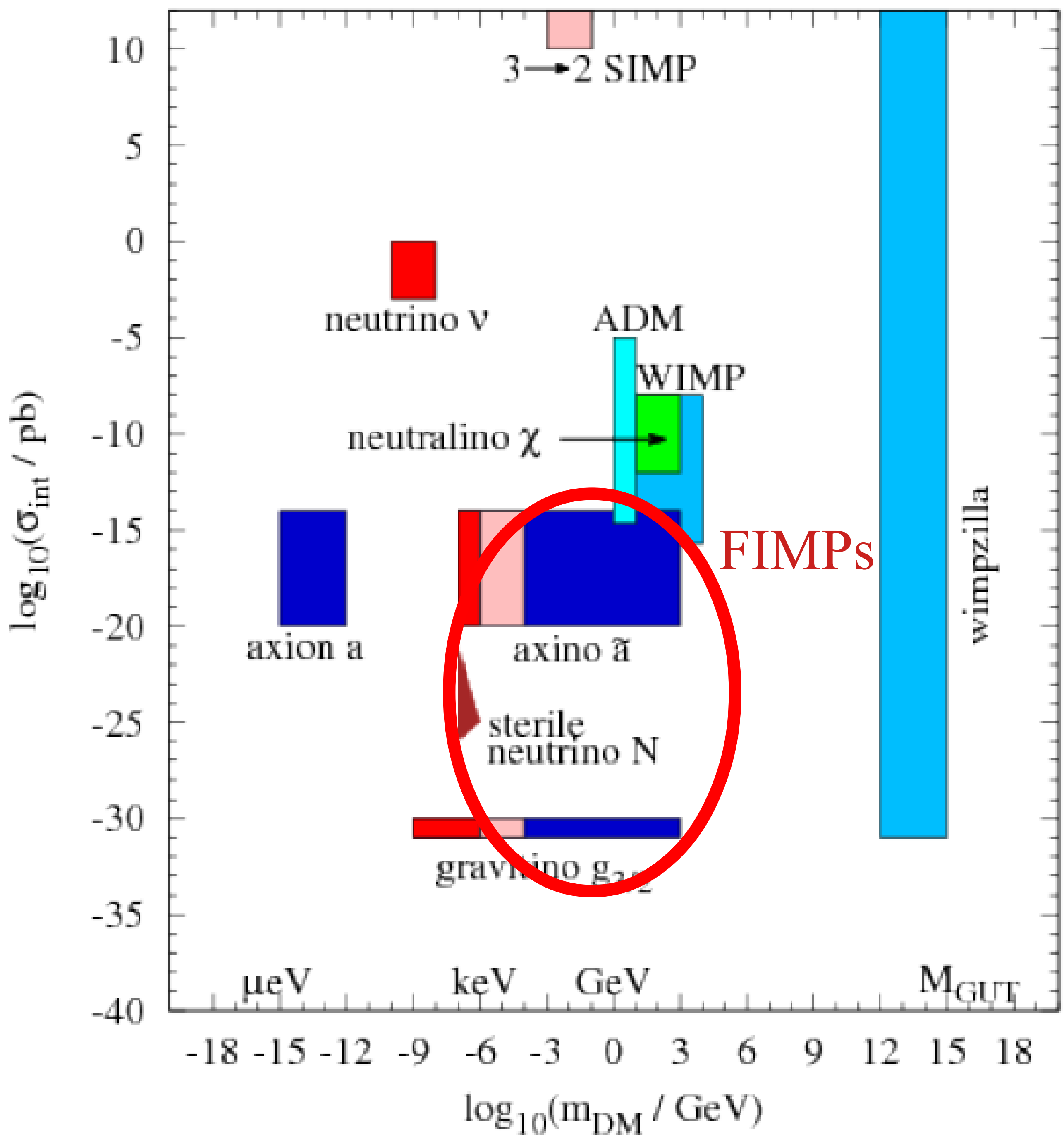

Assumption,
but well motivated



3→2 SIMP
neutrino ν
ADM
WIMP
neutralino χ
wimpzilla
axion a
axino ã
sterile neutrino N
gravitino $g_{3/2}$
μeV
keV
GeV
$M_{GUT}$
$\log_{10}(\sigma_{int}$ / pb)
$\log_{10}(m_{DM}$ / GeV)
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-18
-15
-12
-9
-6
-3
0
3
6
9
12
15
18



3→2 SIMP
neutrino ν
ADM
WIMP
neutralino χ
axion a
axino ã
sterile neutrino N
gravitino $g_{3/2}$
wimpzilla
μeV
keV
GeV
$M_{GUT}$
$\log_{10}(\sigma_{int} / pb)$
$\log_{10}(m_{DM} / GeV)$
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-18 -15 -12 -9 -6 -3 0 3 6 9 12 15 18



3→2 SIMP
neutrino ν
ADM
WIMP
neutralino χ
FIMPs
wimpzilla
axion a
axino ã
sterile
neutrino N
gravitino $g_{3/2}$
μeV
keV
GeV
$M_{GUT}$
$\log_{10}(\sigma_{int}$ / pb)
$\log_{10}(m_{DM}$ / GeV)
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-18 -15 -12 -9 -6 -3 0 3 6 9 12 15 18

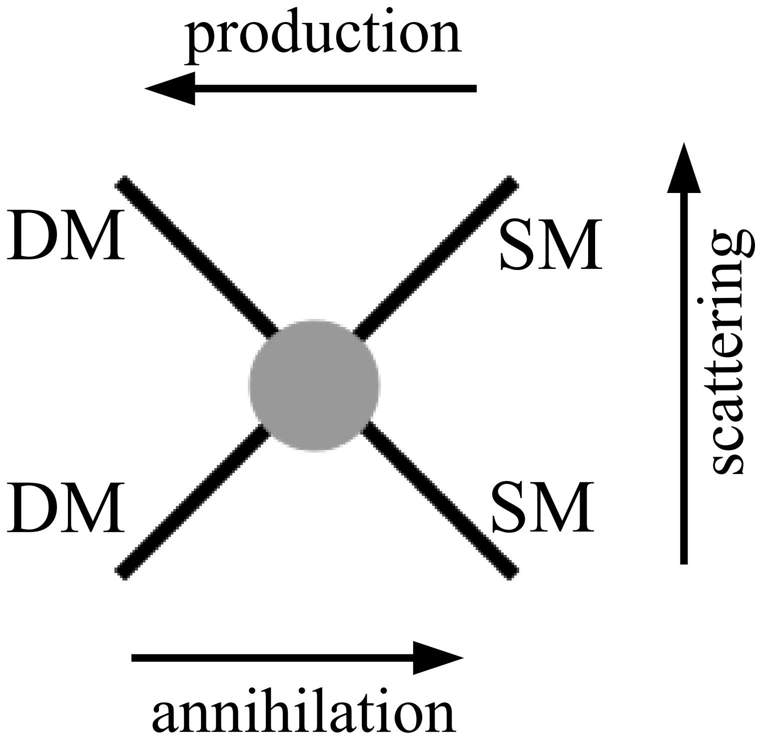
# WIMPs at colliders

## The freeze-out mechanism

Assumption 1:

Dark matter particles are stable on cosmological timescales.

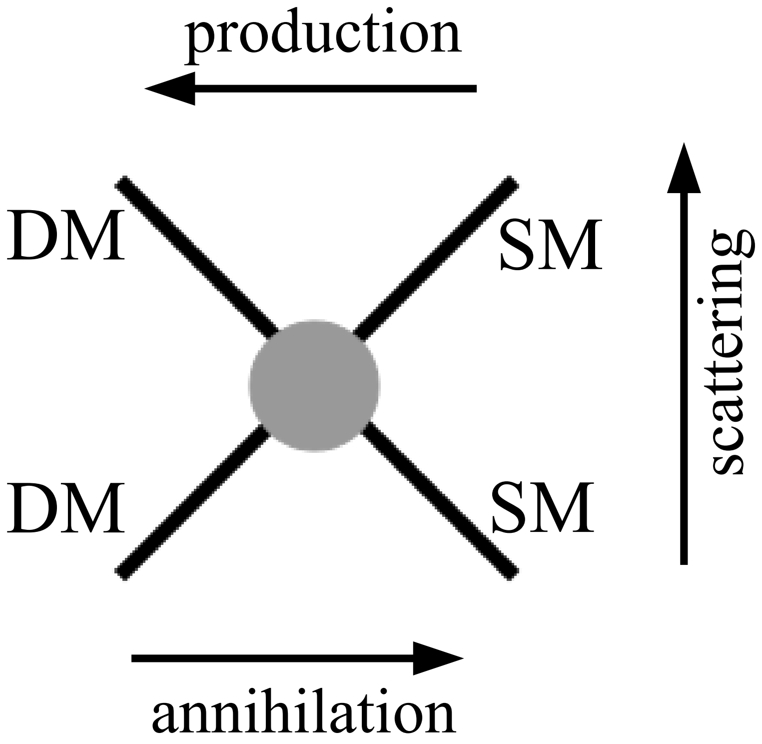
# The freeze-out mechanism




<u>Assumption 2:</u>

Dark matter particles interact in pairs with the Standard Model particles.

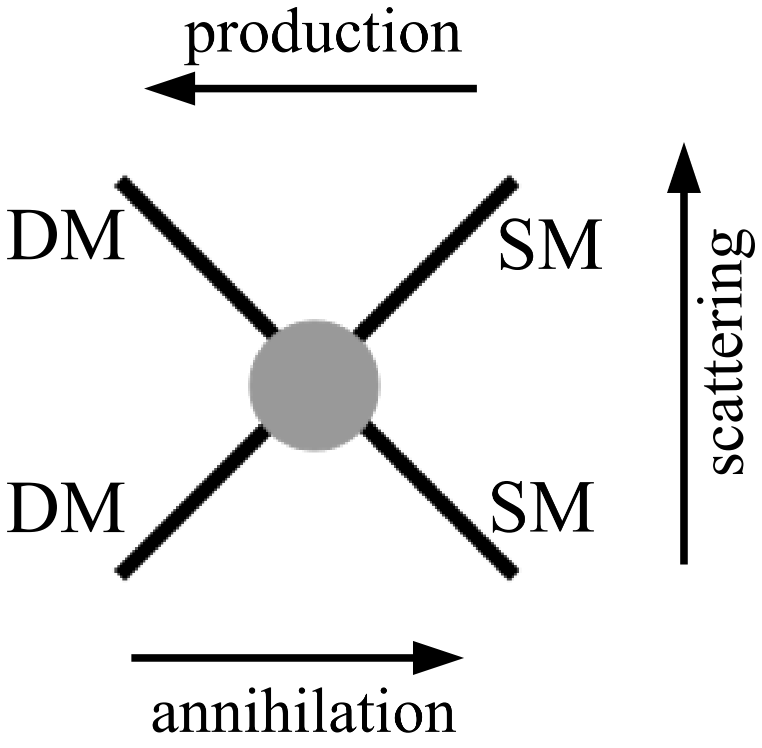
# The freeze-out mechanism




Assumption 3:

The WIMP interaction strength is *large enough* to keep the DM particles in thermal equilibrium with the SM plasma at very high temperatures

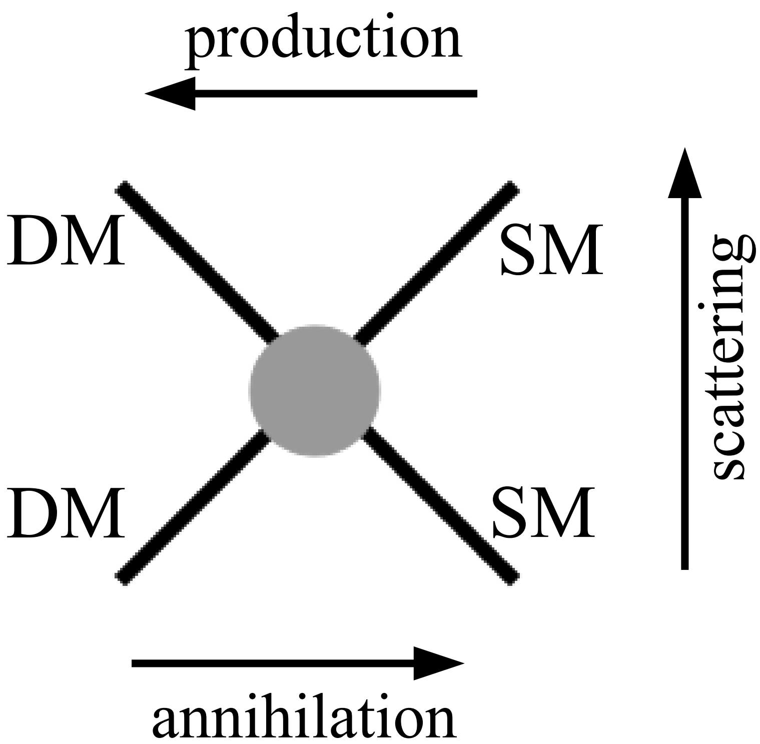
# The freeze-out mechanism

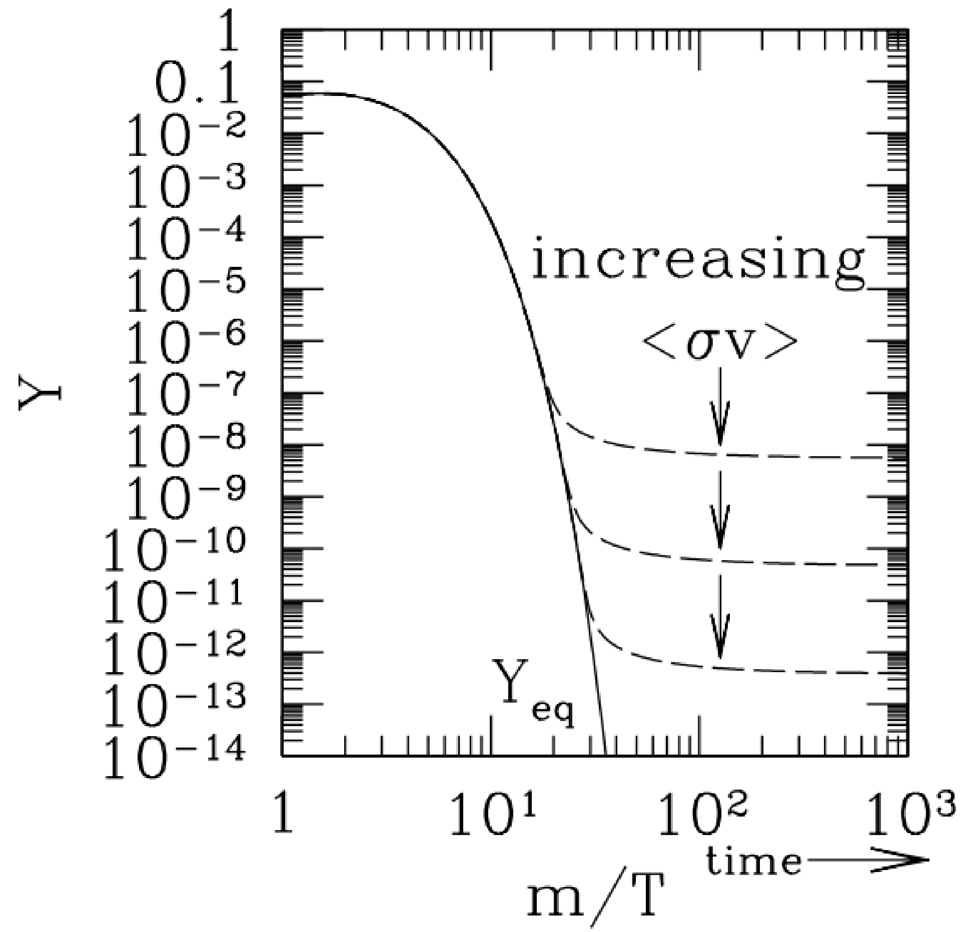



**Assumption 4:**

The WIMP interaction strength is *small enough* to allow DM particles to chemically decouple from the SM plasma sufficiently early.

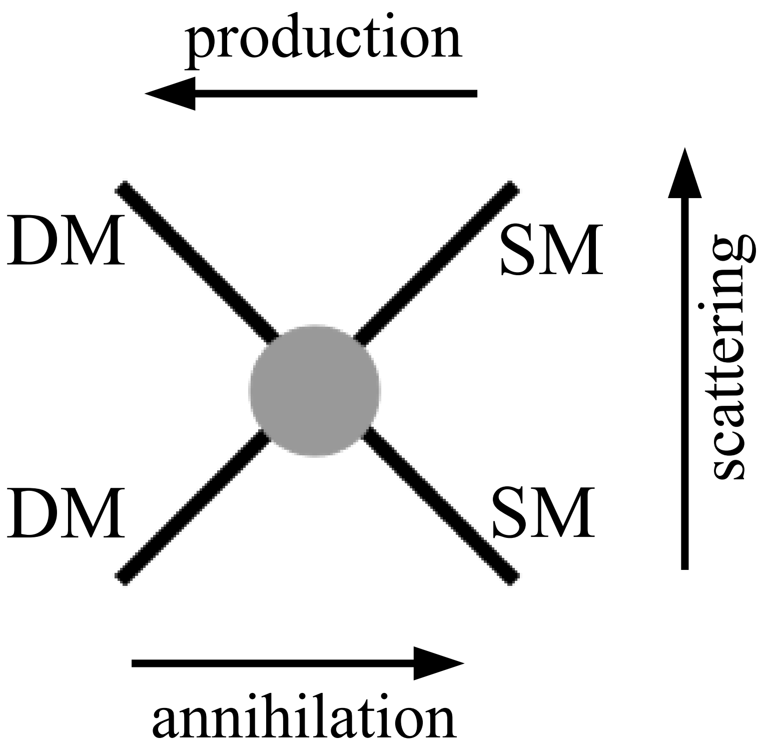
# The freeze-out mechanism

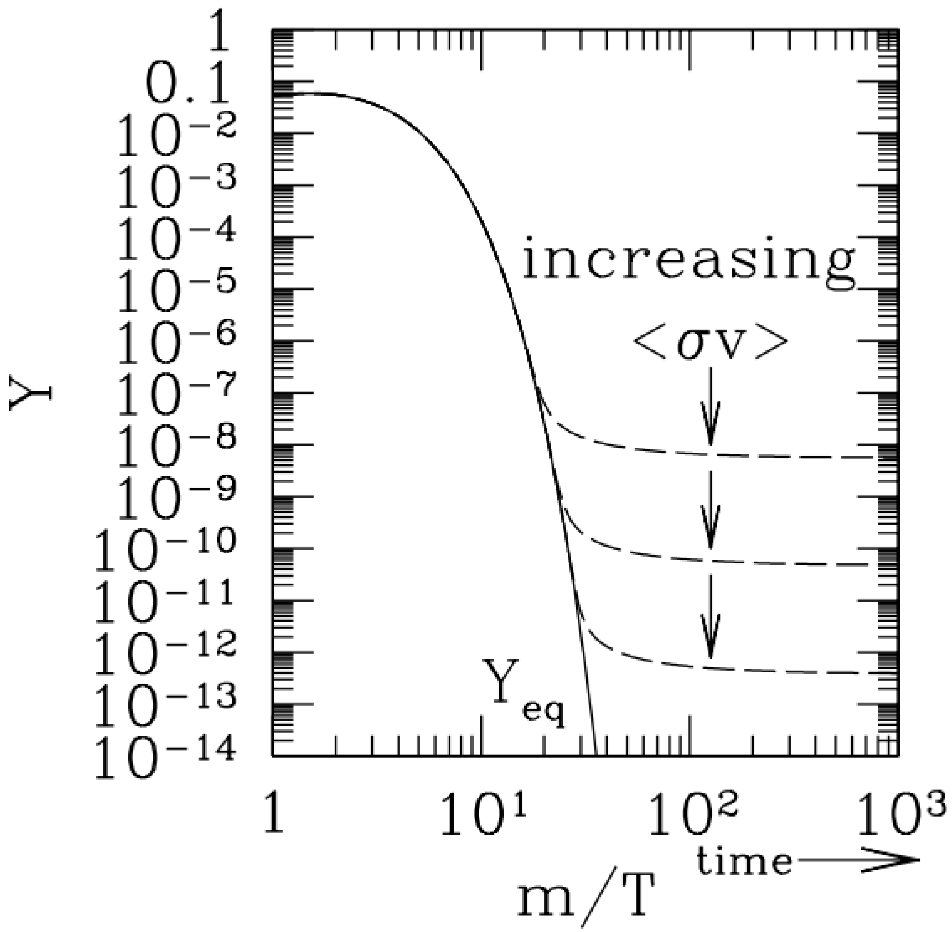



$$\text{Fraction of the total energy of the Universe in the form of DM} \simeq \frac{6 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

# The freeze-out mechanism

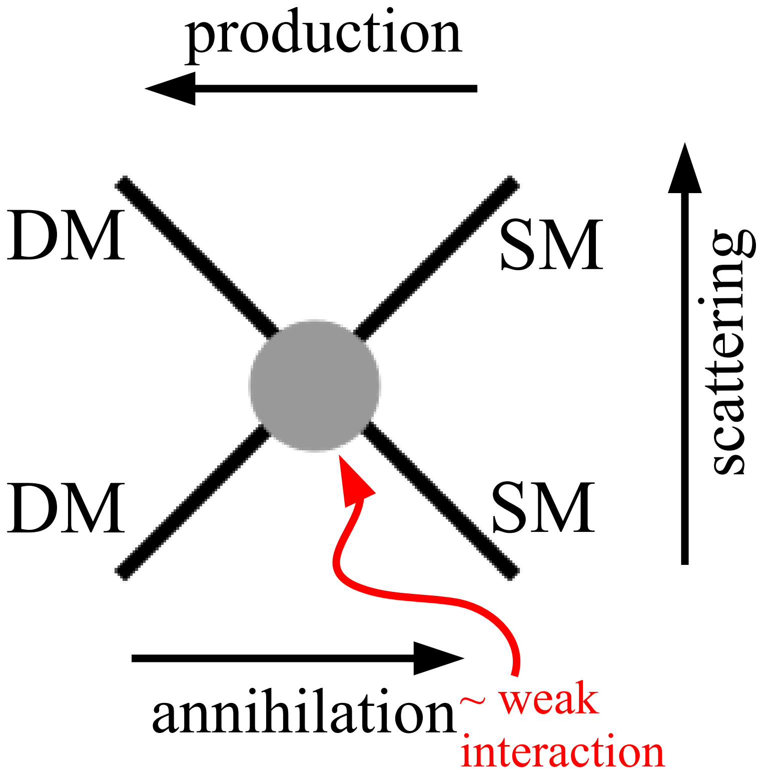


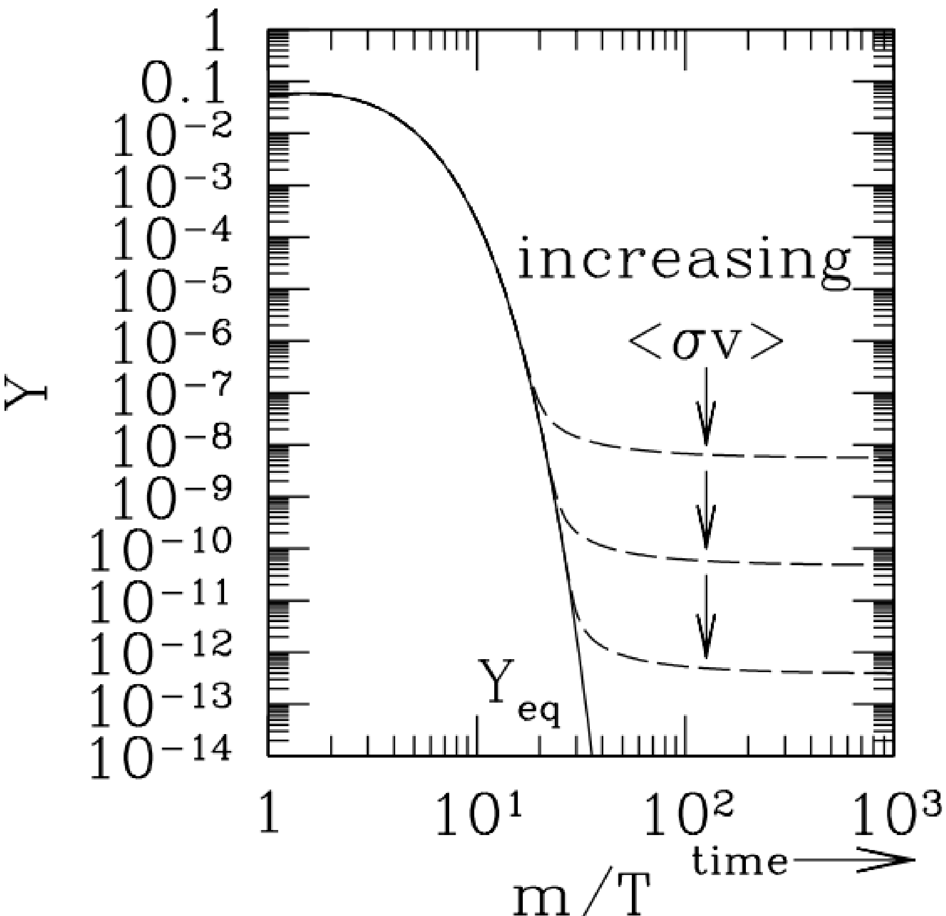




Correct DM abundance (25% of the total energy of the Universe), if

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

# The freeze-out mechanism



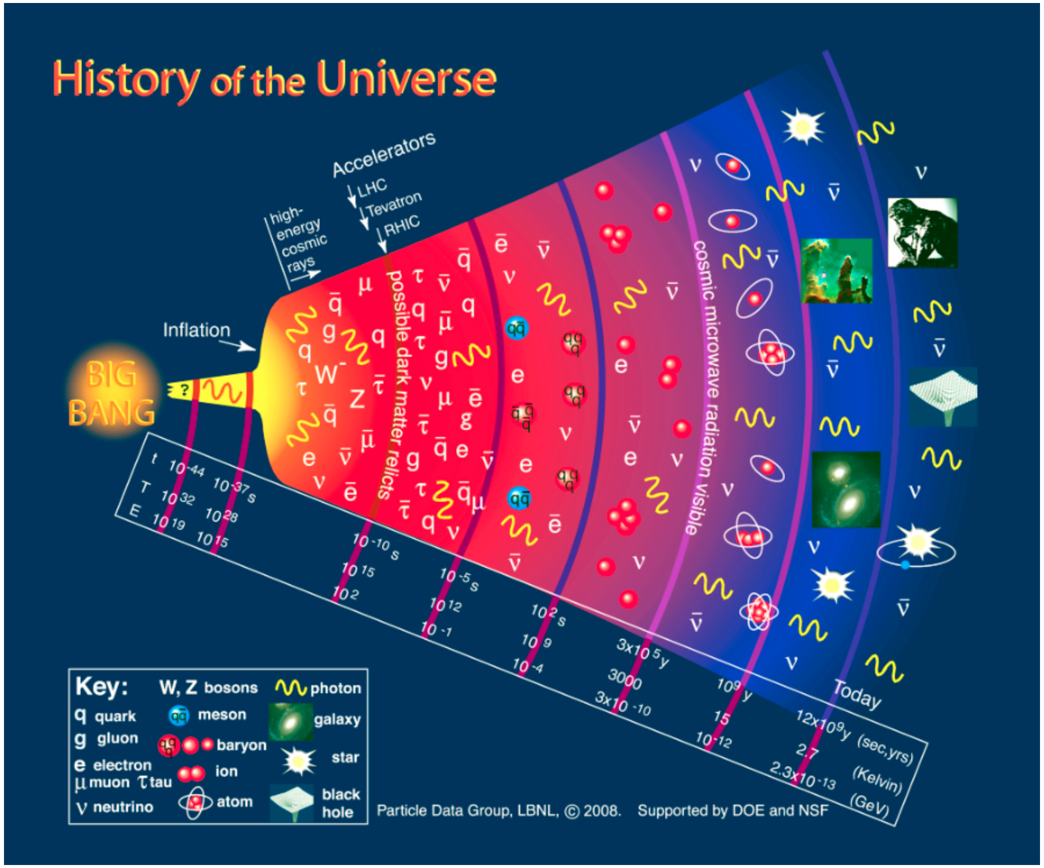




Correct DM abundance (25% of the total energy of the Universe), if

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1} = 1\,\mathrm{pb} \cdot c$$

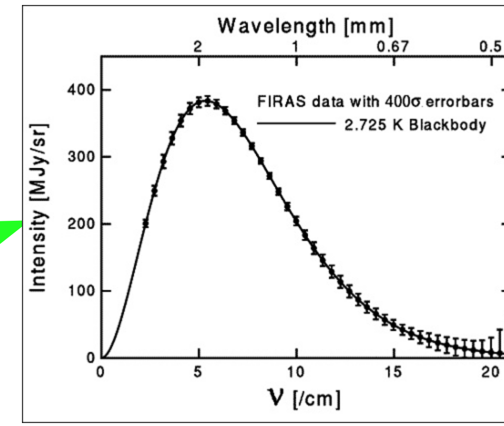
## Very attractive framework:

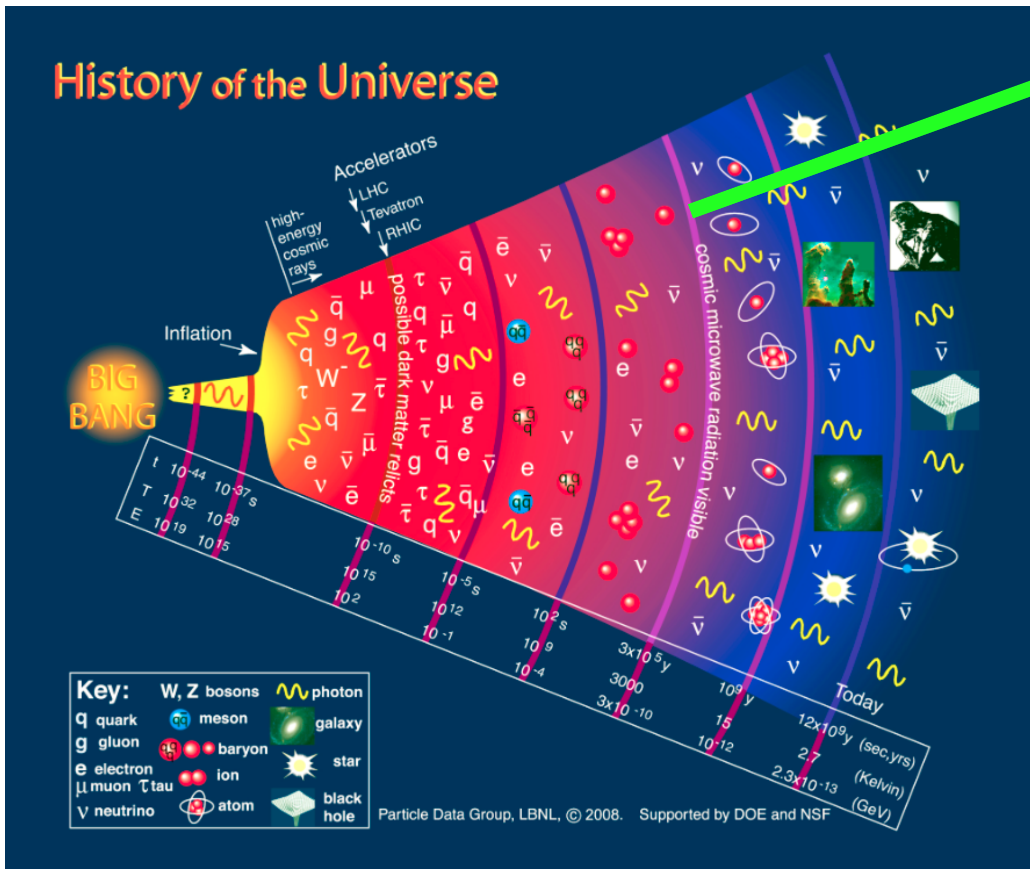
1) Relatively few speculations from particle physics and from cosmology. Thermal freeze-out lies at the core of other (tested) phenomena in the early Universe



# Very attractive framework:

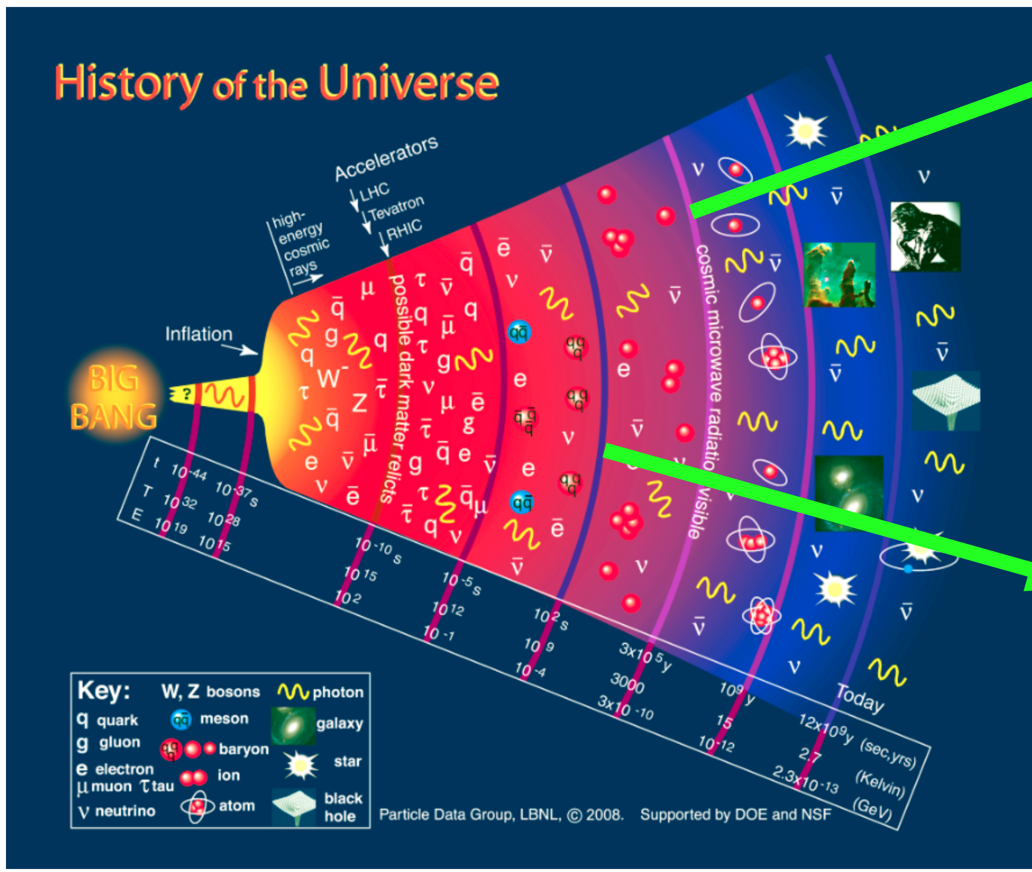
1) Relatively few speculations from particle physics and from cosmology. Thermal freeze-out lies at the core of other (tested) phenomena in the early Universe

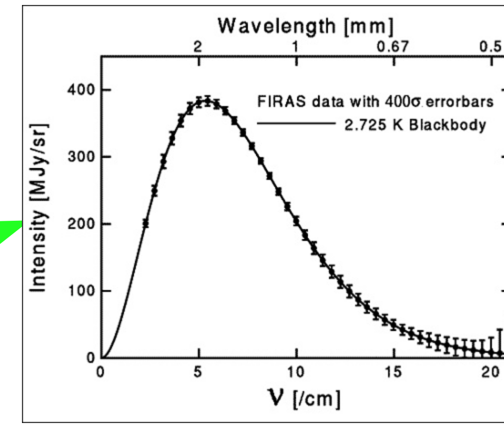


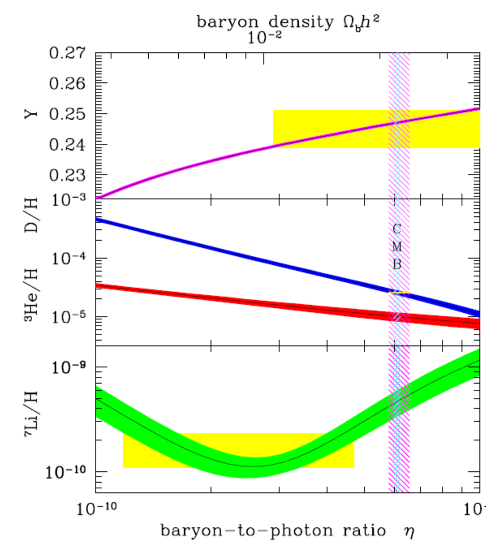



# Very attractive framework:

1) Relatively few speculations from particle physics and from cosmology. Thermal freeze-out lies at the core of other (tested) phenomena in the early Universe

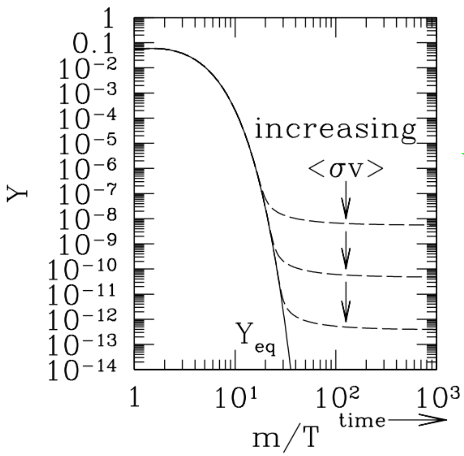


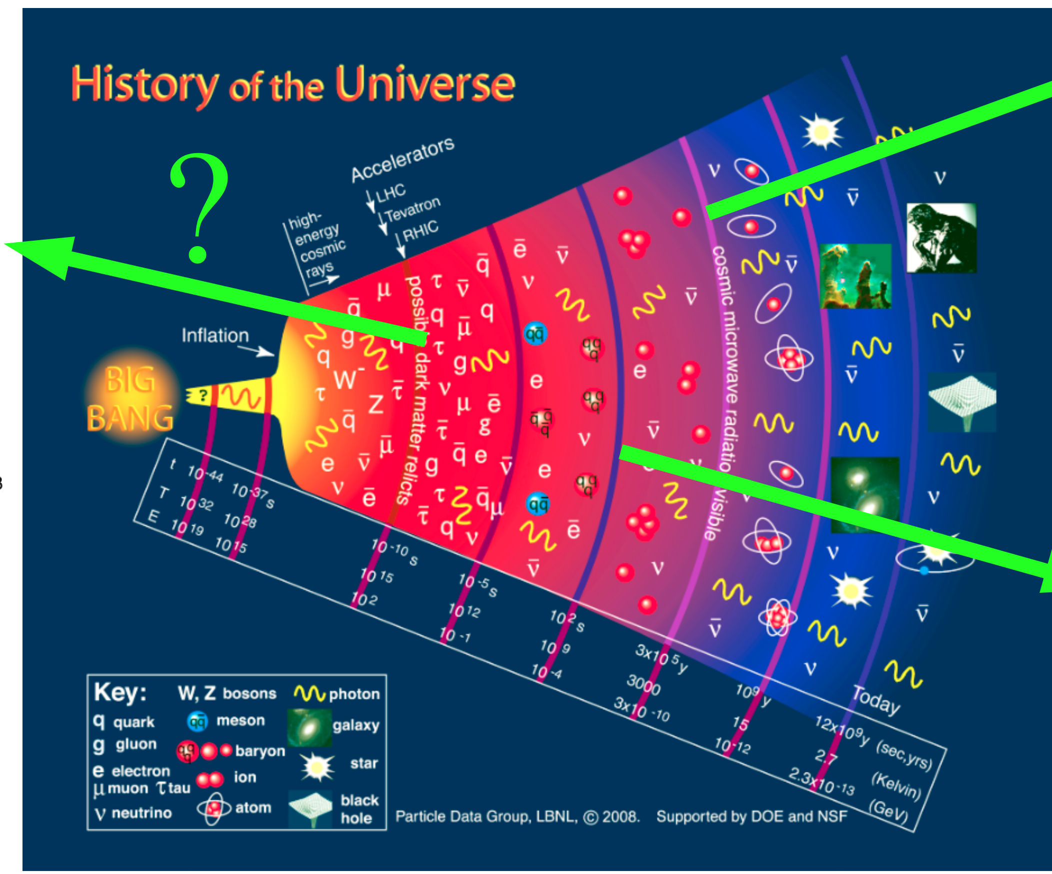



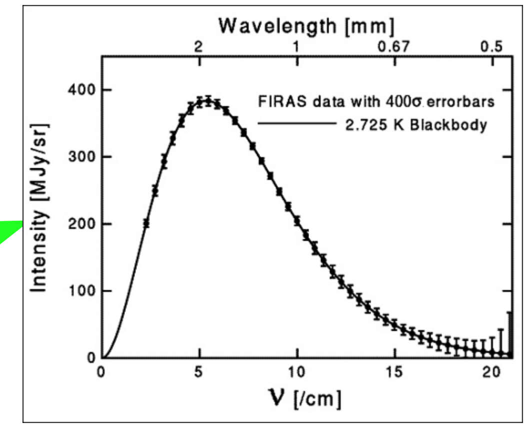



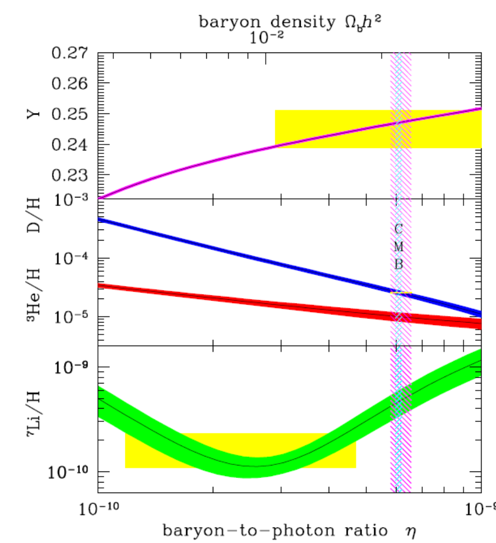
# Very attractive framework:

1) Relatively few speculations from particle physics and from cosmology. Thermal freeze-out lies at the core of other (tested) phenomena in the early Universe



## Very attractive framework:

1) Relatively few speculations from particle physics and from cosmology. Thermal freeze-out lies at the core of other (tested) phenomena in the early Universe

2) Potentially testable

$$\text{cross section} \sim \frac{\text{coupling}^{\text{power}}}{\text{mass}^2}$$

$\sigma \sim 1$ pb, for coupling $\sim 0.01 - 0.1$ and mass $\sim 1$ GeV – 1 TeV

## Very attractive framework:

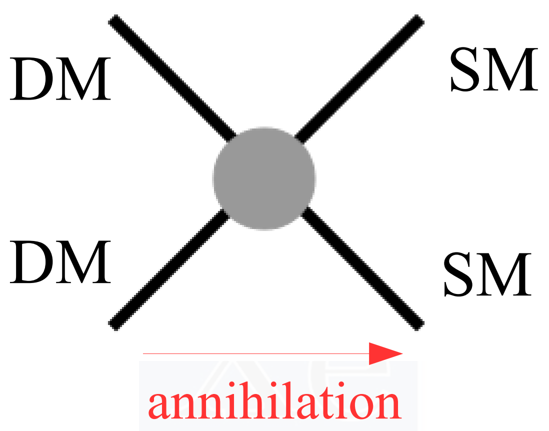
1) Relatively few speculations from particle physics and from cosmology. Thermal freeze-out lies at the core of other (tested) phenomena in the early Universe

2) Potentially testable

## Very attractive framework:

1) Relatively few speculations from particle physics and from cosmology. Thermal freeze-out lies at the core of other (tested) phenomena in the early Universe

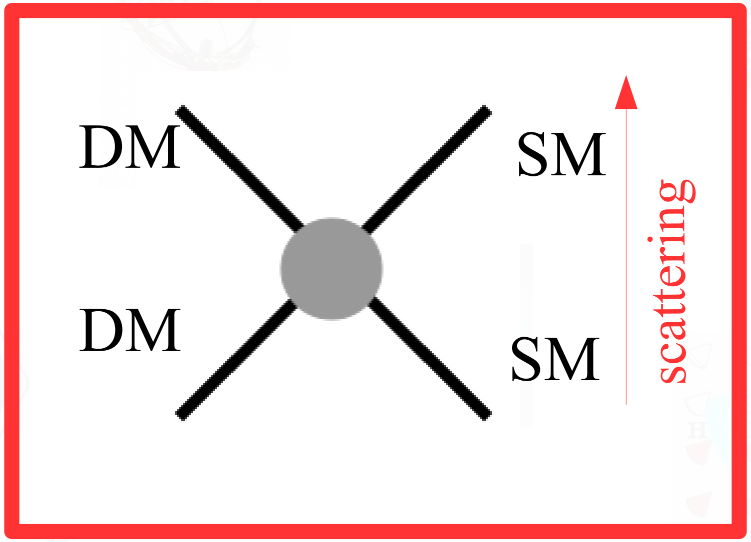
2) Potentially testable



## Very attractive framework:

1) Relatively few speculations from particle physics and from cosmology. Thermal freeze-out lies at the core of other (tested) phenomena in the early Universe

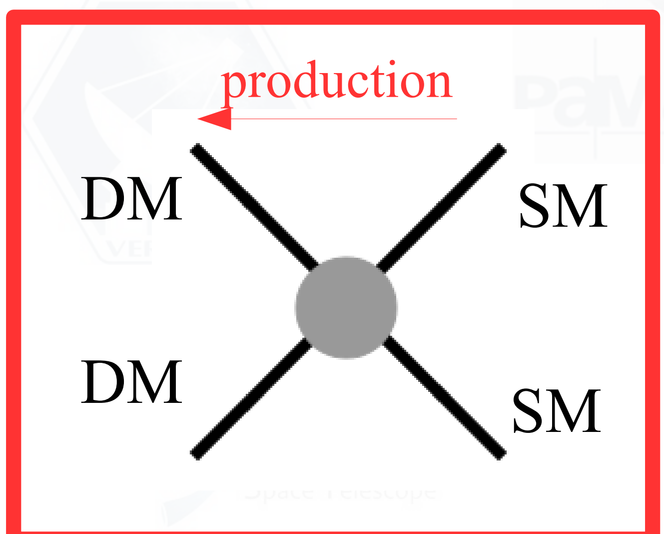
2) Potentially testable



## Very attractive framework:

1) Relatively few speculations from particle physics and from cosmology. Thermal freeze-out lies at the core of other (tested) phenomena in the early Universe

2) Potentially testable



# Searching for WIMP dark matter at the LHC

Differential cross-section for the final state of interest Y

$$d\sigma(p(P_1) + p(P_2) \to Y + X) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{i_1,i_2} f_{i_1}(x_1)\, f_{i_2}(x_2) d\sigma(i_1(x_1 P_1) + i_2(x_2 P_2) \to Y)$$

# Searching for WIMP dark matter at the LHC

Differential cross-section for the final state of interest Y

$$d\sigma(p(P_1)+p(P_2)\to Y+X) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{i_1,i_2} f_{i_1}(x_1) f_{i_2}(x_2) d\sigma(i_1(x_1P_1)+i_2(x_2P_2)\to Y)$$

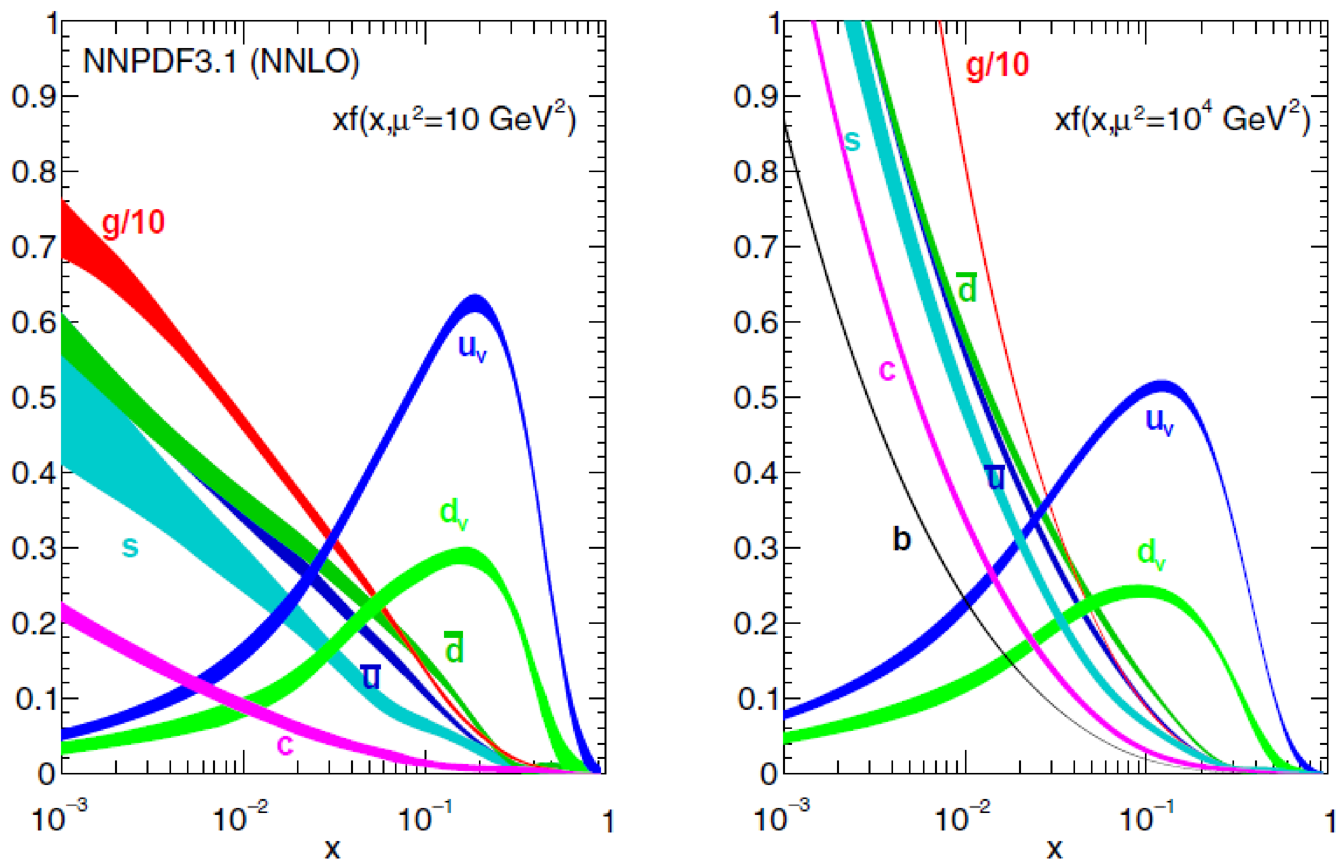
Fraction of the momenta of the proton carried by the parton $i$

# Searching for WIMP dark matter at the LHC

Differential cross-section for the final state of interest Y

$$d\sigma(p(P_1)+p(P_2)\to Y+X) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{i_1,i_2} f_{i_1}(x_1) f_{i_2}(x_2) d\sigma(i_1(x_1P_1)+i_2(x_2P_2)\to Y)$$

Parton distribution functions



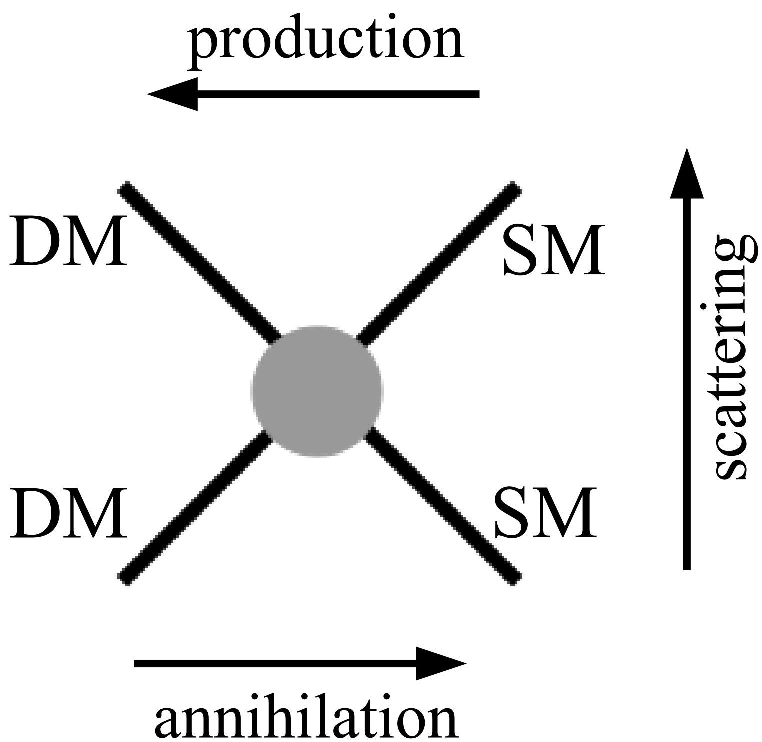

Ball et al'17

# Searching for WIMP dark matter at the LHC

Differential cross-section for the final state of interest Y

$$d\sigma(p(P_1)+p(P_2)\to Y+X) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{i_1,i_2} f_{i_1}(x_1)\, f_{i_2}(x_2)\, d\sigma(i_1(x_1P_1)+i_2(x_2P_2)\to Y)$$

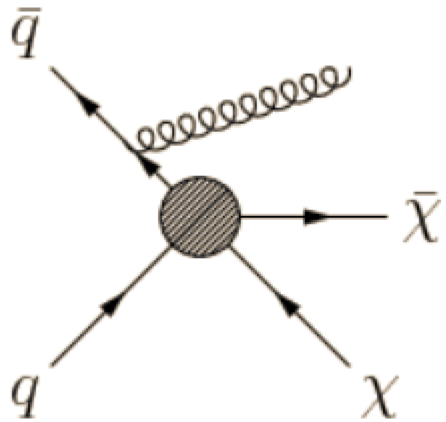
Cross-section for the partonic process




| Name | Initial state | Type | Operator |
|---|---|---|---|
| C1 | $qq$ | scalar | $\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$ |
| C5 | $gg$ | scalar | $\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$ |
| D1 | $qq$ | scalar | $\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$ |
| D5 | $qq$ | vector | $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ |
| D8 | $qq$ | axial-vector | $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$ |
| D9 | $qq$ | tensor | $\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ |
| D11 | $gg$ | scalar | $\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$ |

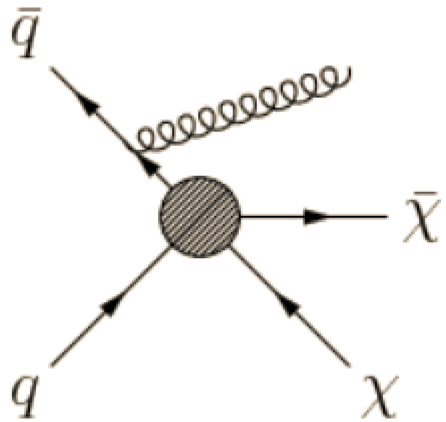
# Searching for WIMP dark matter at the LHC

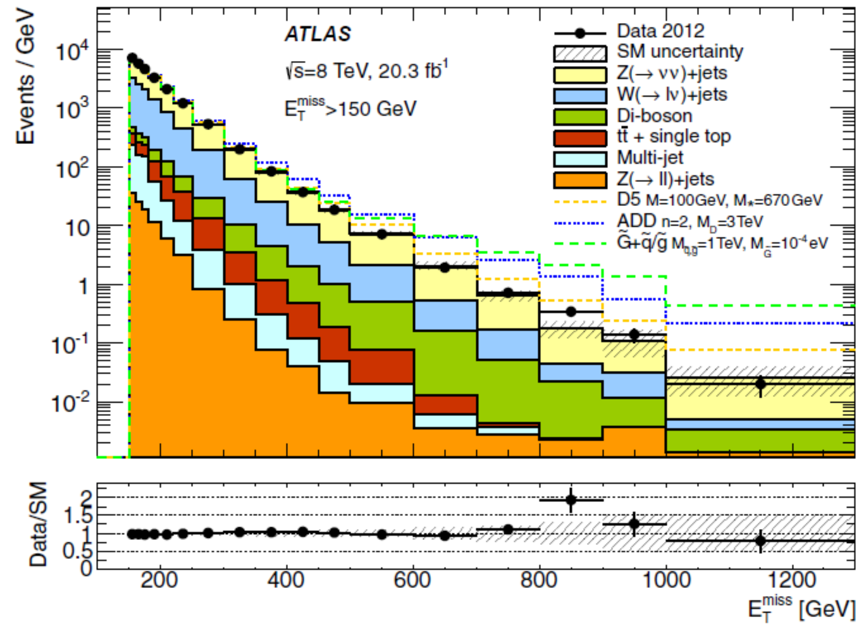
Monojet + missing $E_T$



# Searching for WIMP dark matter at the LHC

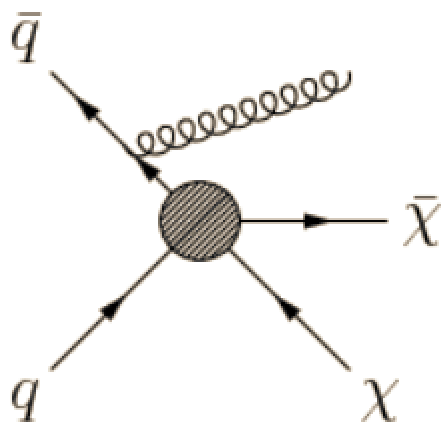
Monojet + missing $E_T$

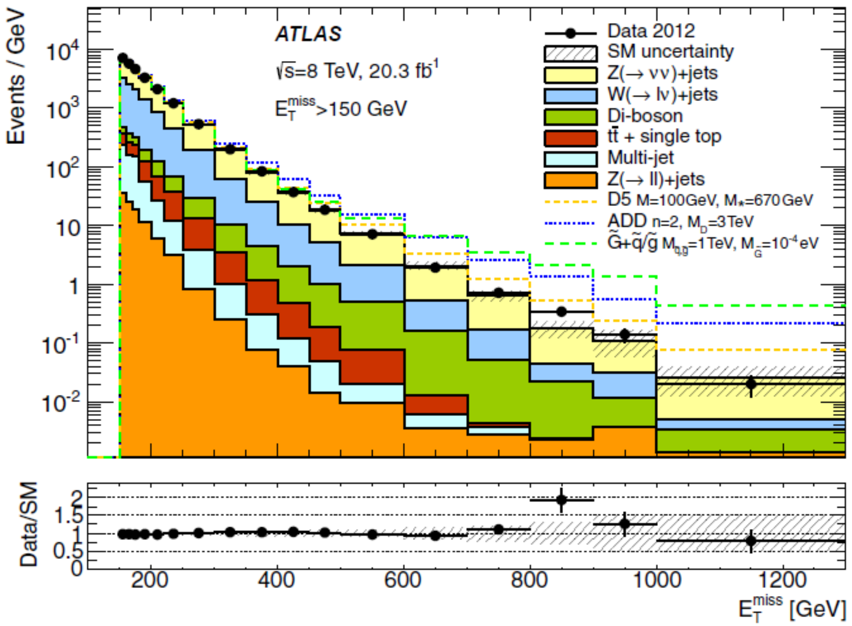


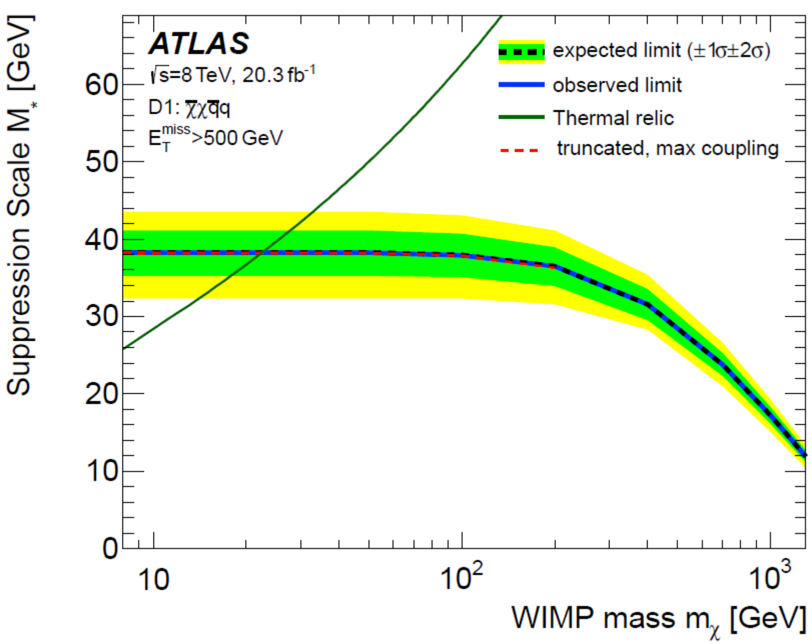



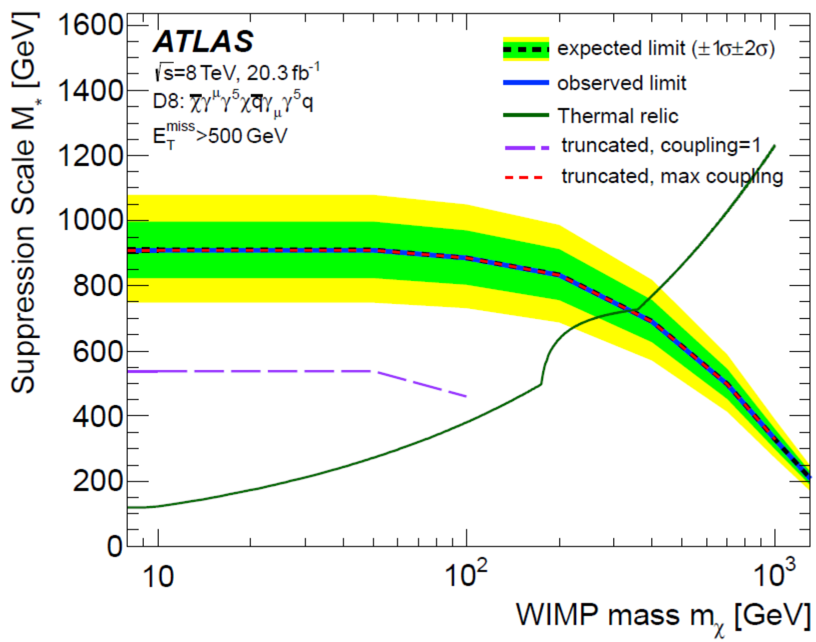
# Searching for WIMP dark matter at the LHC

Monojet + missing $E_T$

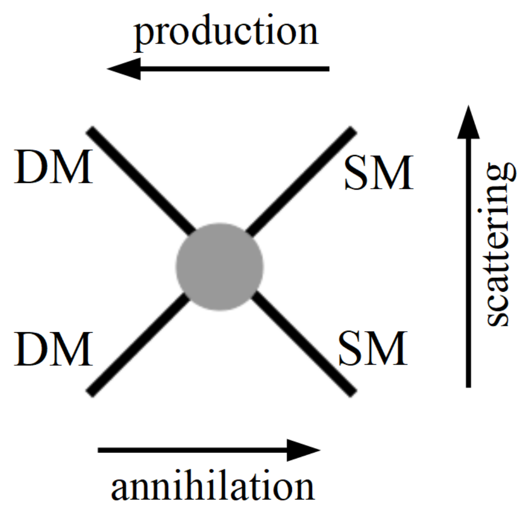


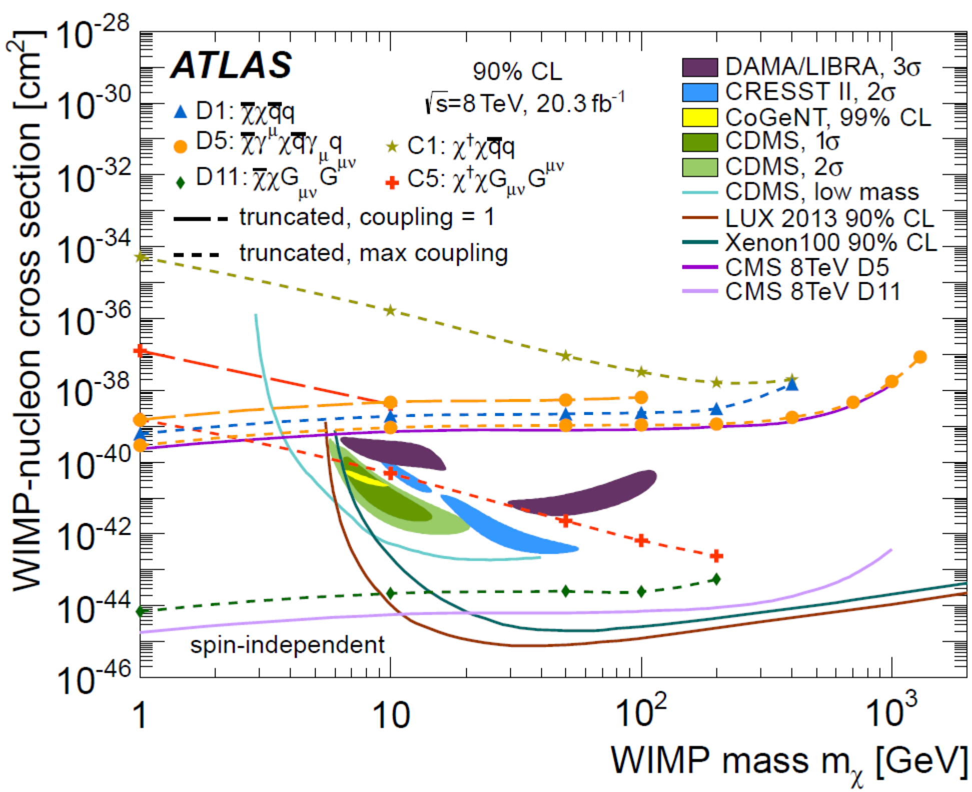



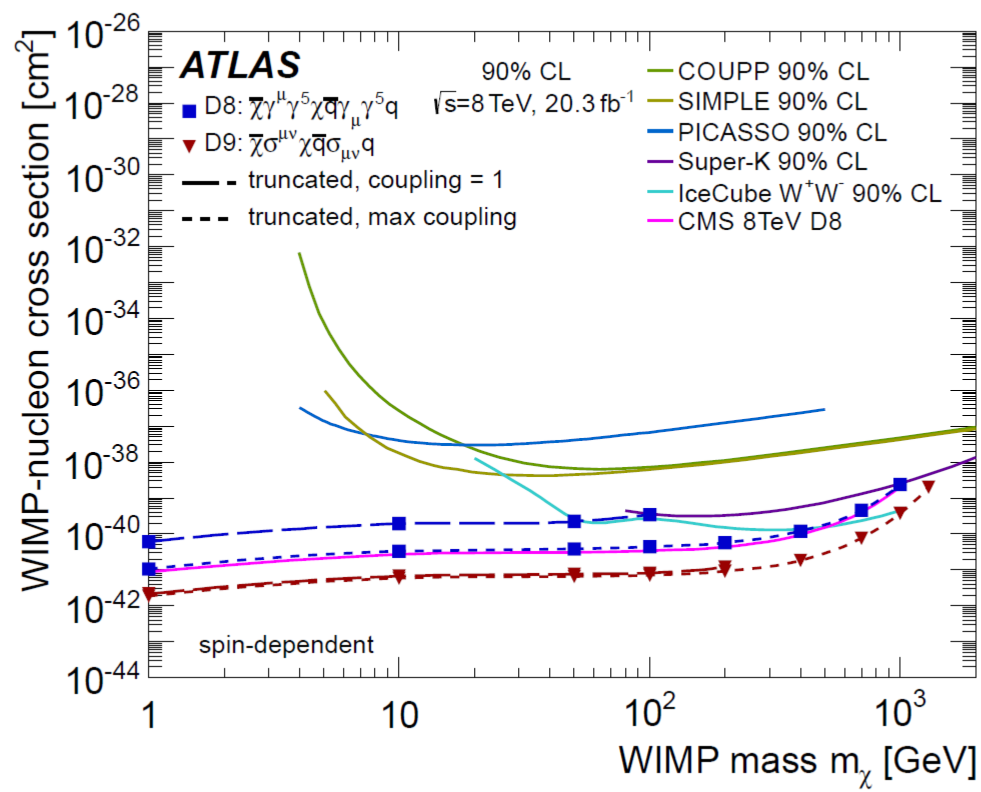



# Comparison to direct detection experiments




| Name | Initial state | Type | Operator |
|---|---|---|---|
| C1 | $qq$ | scalar | $\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$ |
| C5 | $gg$ | scalar | $\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$ |
| D1 | $qq$ | scalar | $\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$ |
| D5 | $qq$ | vector | $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ |
| D8 | $qq$ | axial-vector | $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$ |
| D9 | $qq$ | tensor | $\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ |
| D11 | $gg$ | scalar | $\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$ |



# Astrophysical uncertainties in DD experiments

- The energy and luminosity of a collider is known (information from colliders very robust)
- Dark matter direct search experiments, on the other hand, suffer from astrophysical uncertainties

Differential rate of DM-induced scatterings

$$\frac{dR}{dE_R} = \frac{\rho_{\rm loc}}{m_A m_{\rm DM}} \int_{v \geq v_{\rm min}(E_R)} {\rm d}^3 v \, v f(\vec{v} + \vec{v}_{\rm obs}(t)) \, \frac{{\rm d}\sigma}{{\rm d}E_R}$$

# Astrophysical uncertainties in DD experiments

- The energy and luminosity of a collider is known (information from colliders very robust)

- Dark matter direct search experiments, on the other hand, suffer from astrophysical uncertainties

Differential rate of DM-induced scatterings

$$\frac{dR}{dE_R} = \frac{\rho_{\rm loc}}{m_A m_{\rm DM}} \int_{v \geq v_{\rm min}(E_R)} {\rm d}^3 v \, v \, f(\vec{v} + \vec{v}_{\rm obs}(t)) \, \frac{{\rm d}\sigma}{{\rm d}E_R}$$

# Astrophysical uncertainties in DD experiments

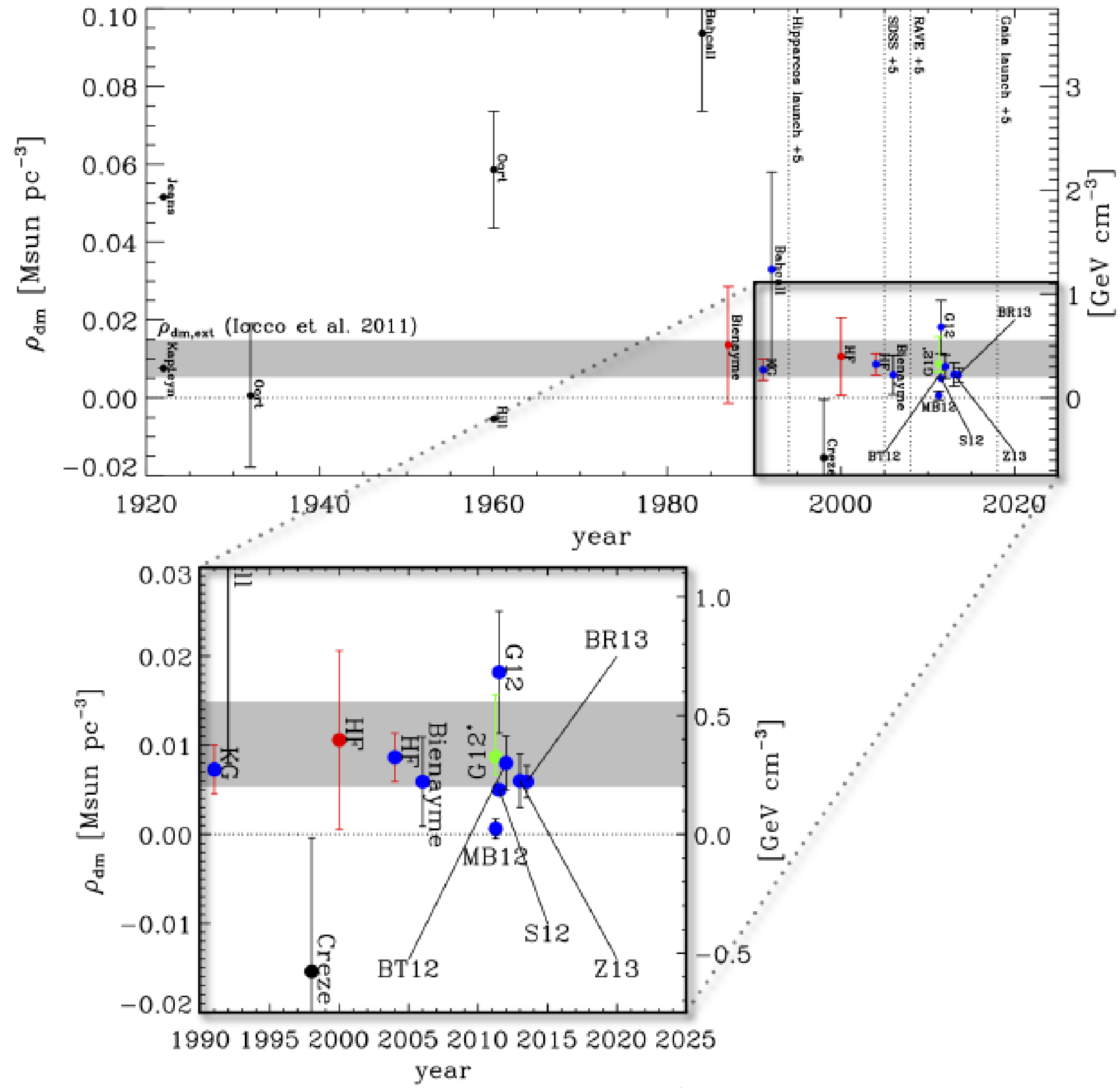
- Local dark matter density?

  - "local measurements":

    From vertical kinematics of stars near (~1 kpc) the Sun

  - "global measurements":

    From extrapolations of $\rho(r)$ determined from rotation curves at large $r$, to the position of the Solar System.




Read '14

# Astrophysical uncertainties in DD experiments

- Local dark matter velocity distribution?

  Completely unknown. Rely on theoretical considerations

  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.

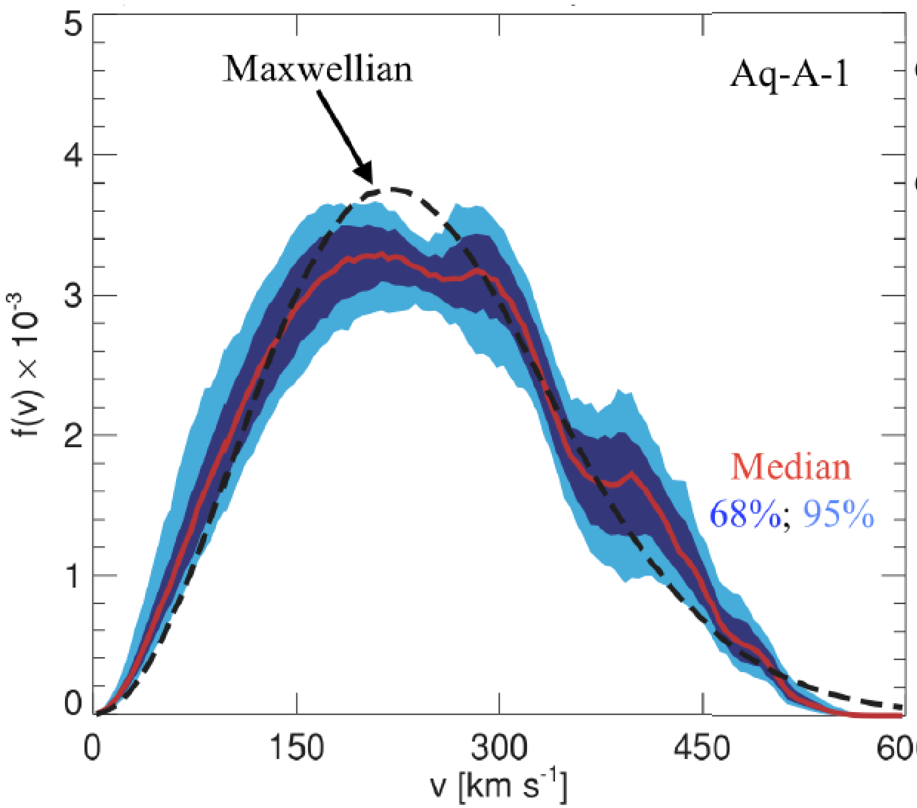
$$\rho(r) \sim \frac{1}{r^2} \longrightarrow f(v) \sim \exp(-v^2/v_0^2)$$

# Astrophysical uncertainties in DD experiments

- Local dark matter velocity distribution?

  Completely unknown. Rely on theoretical considerations

  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.
  - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann



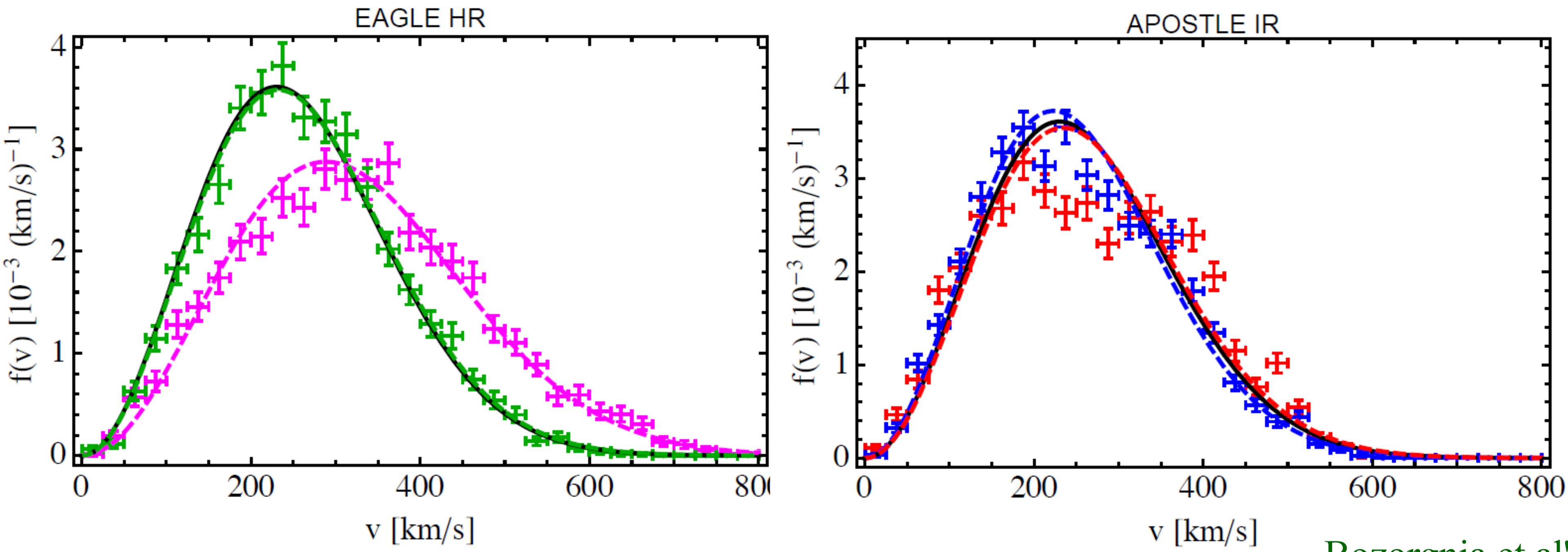

Vogelsberger et al. 2009

# Astrophysical uncertainties in DD experiments

- Local dark matter velocity distribution?

  Completely unknown. Rely on theoretical considerations

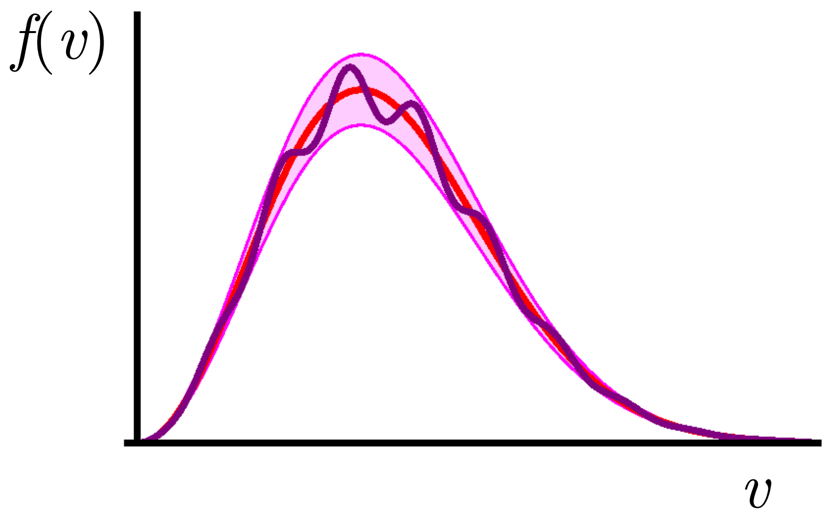
  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.
  - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann
  - Hydrodynamical simulations (DM+baryons). Inconclusive at the moment.

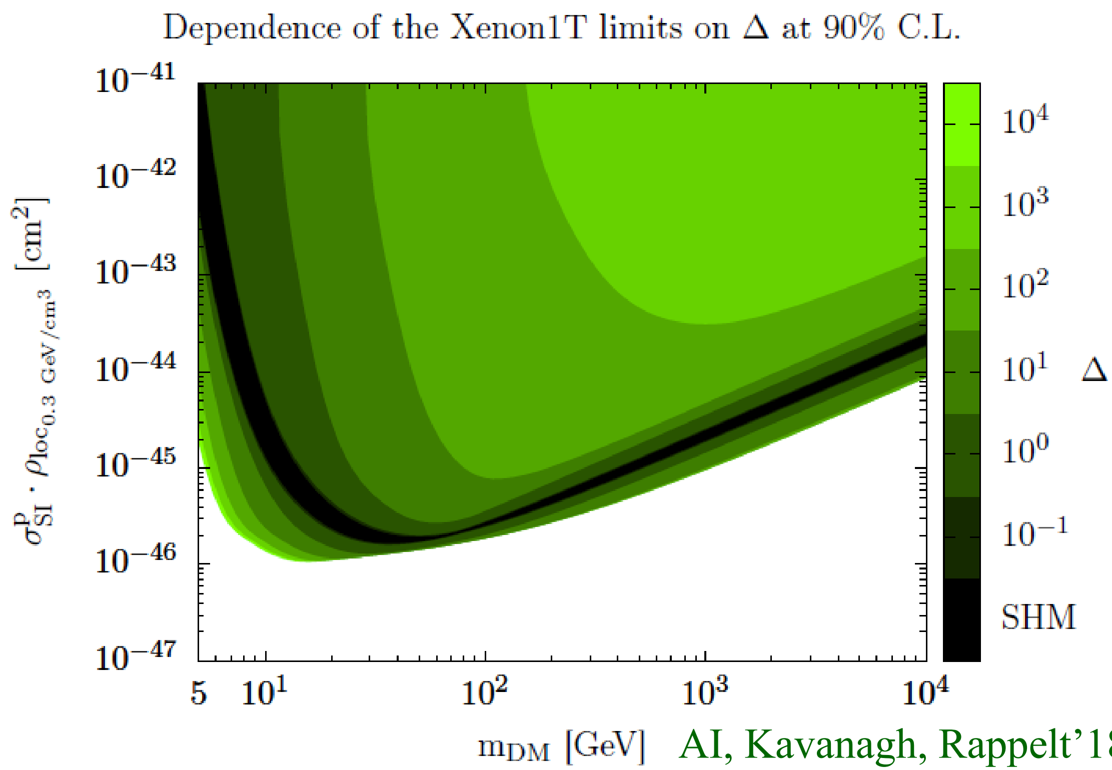



Bozorgnia et al'16

# Astrophysical uncertainties in DD experiments

Consider "distortions" of the Maxwell-Boltzmann distribution



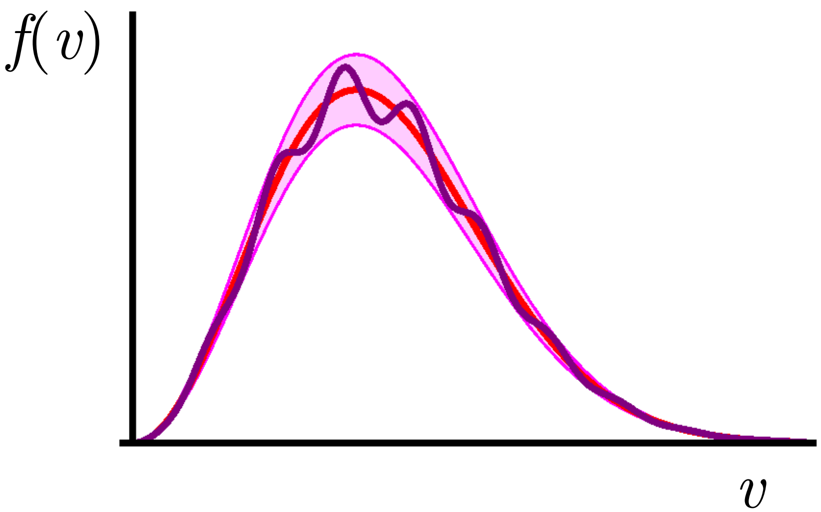



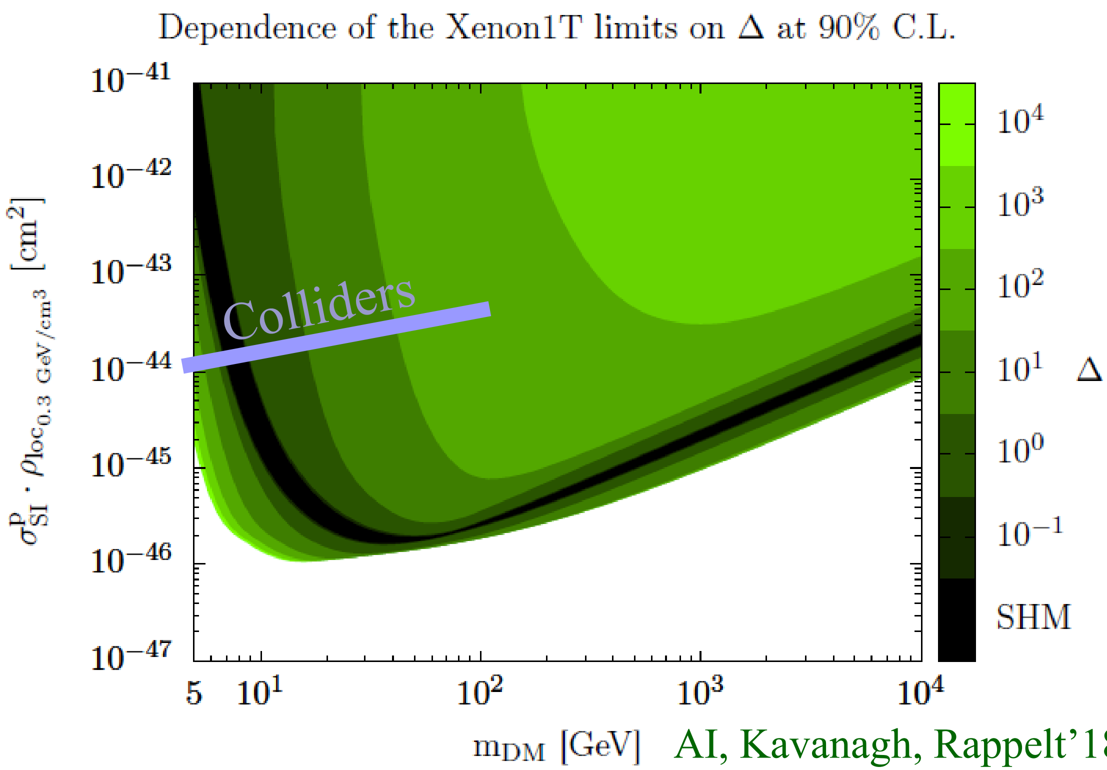

AI, Kavanagh, Rappelt'18

$$\left| \frac{f(\vec{v}) - f_{\rm MB}(\vec{v})}{f_{\rm MB}(\vec{v})} \right| \leq \Delta$$

# Astrophysical uncertainties in DD experiments

Consider "distortions" of the Maxwell-Boltzmann distribution




AI, Kavanagh, Rappelt'18

$$\left|\frac{f(\vec{v}) - f_{\rm MB}(\vec{v})}{f_{\rm MB}(\vec{v})}\right| \leq \Delta$$

# Some caveats in collider DM searches

1- The particle produced is invisible, but not necessarily dark matter. (Not cosmologically long-lived? Only a subdominant DM component? But anyway new physics, not discoverable at direct detection experiment.)

Consider an invisible particle decaying into visible particles

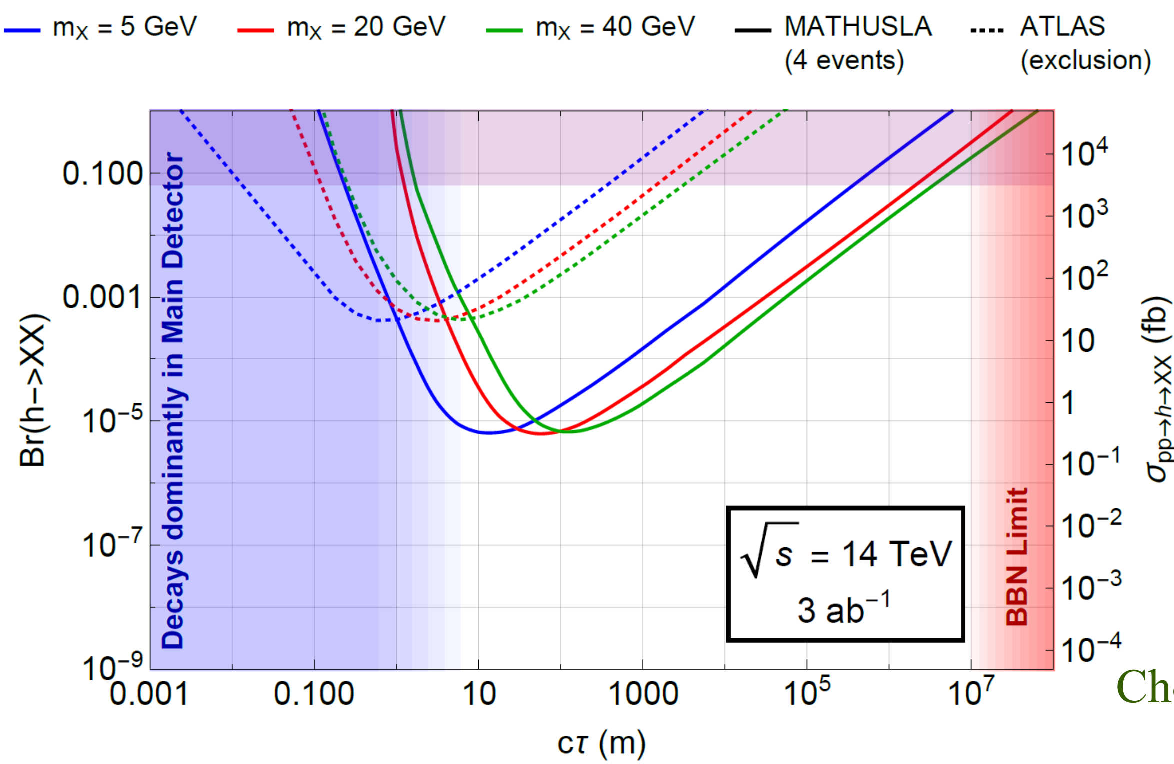
- If short lifetime, the visible particles can be observed at the detector
- If very long lifetime, the invisible particle leaves the detector, but the decay products may leave an imprint in BBN, CMB or cosmic rays.
- A "blind spot" for intermediate lifetimes.

# Some caveats in collider DM searches

1- The particle produced is invisible, but not necessarily dark matter. (Not cosmologically long-lived? Only a subdominant DM component? But anyway new physics, not discoverable at direct detection experiment.)

Consider an invisible particle decaying into visible particles

- If short lifetime, the visible particles can be observed at the detector
- If very long lifetime, the invisible particle leaves the detector, but the decay products may leave an imprint in BBN, CMB or cosmic rays.
- A "blind spot" for intermediate lifetimes.



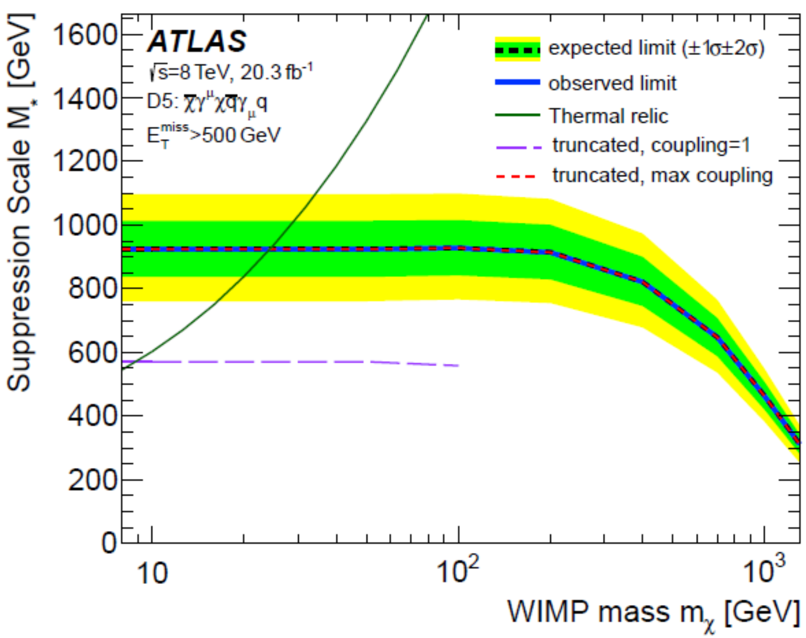

Also FASER, CODEX-b...

Chou, Curtin, Lubatti'16

# Some caveats in collider DM searches

1- The particle produced is invisible, but not necessarily dark matter. (Not cosmologically long-lived? Only a subdominant DM component? But anyway new physics, not discoverable at direct detection experiment.)

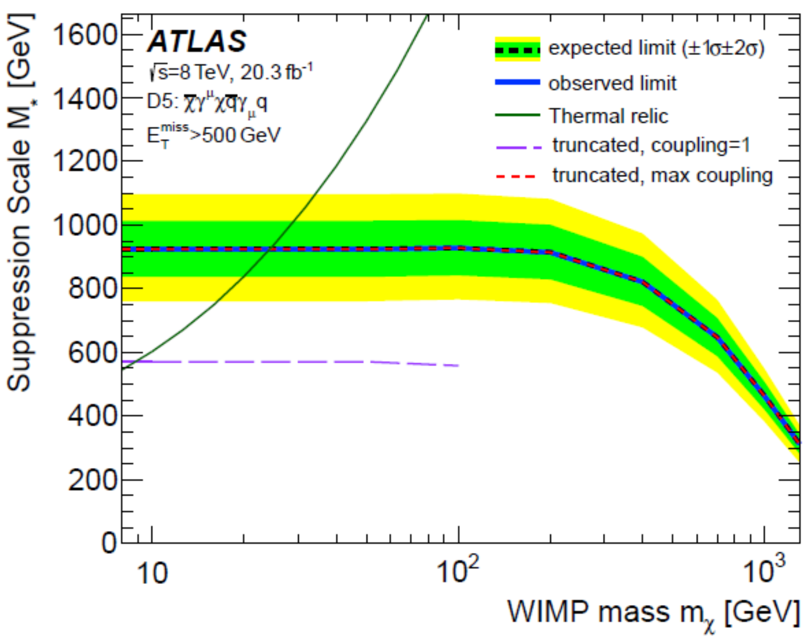
Ideally, the DM parameters may be determined at a collider and used to calculate their abundance. Interplay colliders ↔ cosmology.

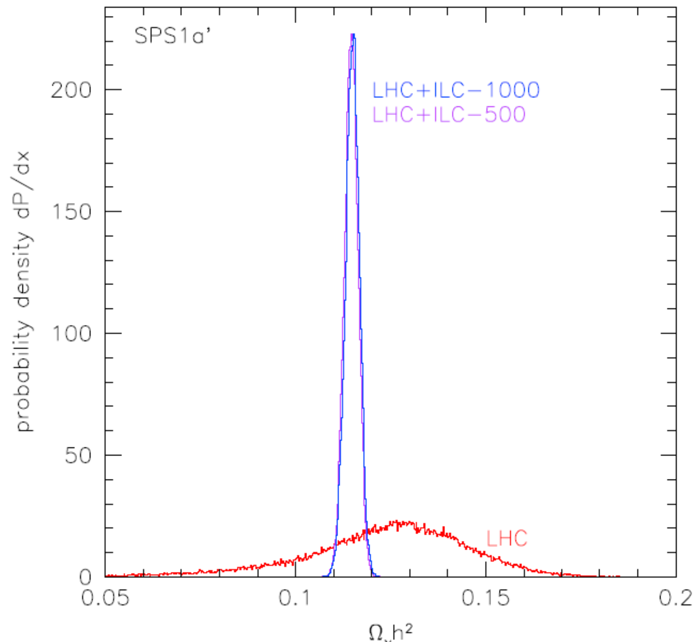


# Some caveats in collider DM searches

1- The particle produced is invisible, but not necessarily dark matter. (Not cosmologically long-lived? Only a subdominant DM component? But anyway new physics, not discoverable at direct detection experiment.)

Ideally, the DM parameters may be determined at a collider and used to calculate their abundance. Interplay colliders ↔ cosmology.



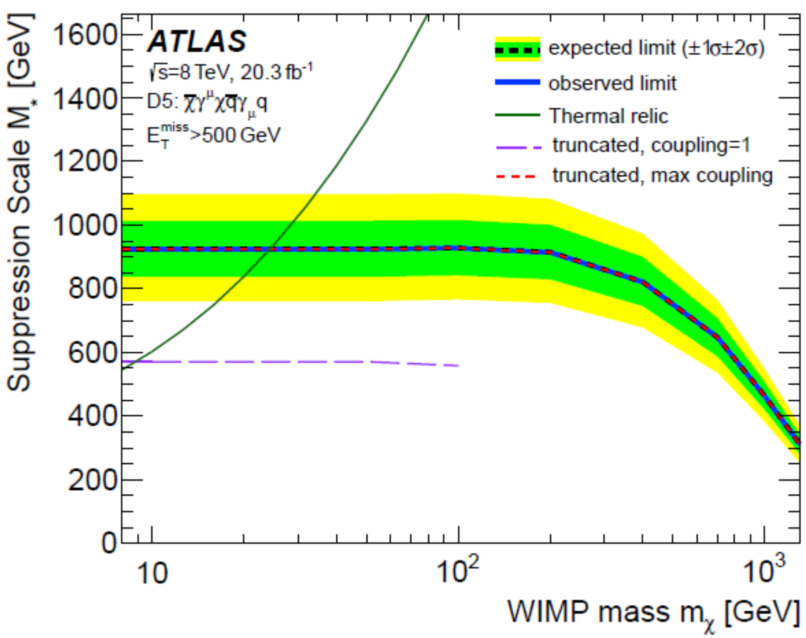



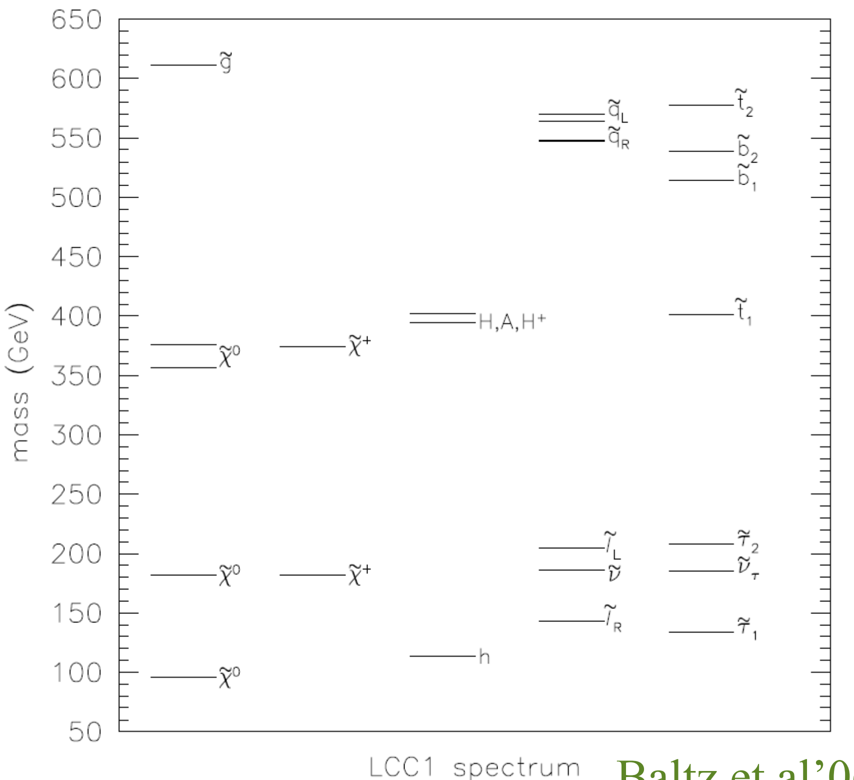

Baltz et al'06

# Some caveats in collider DM searches

1- The particle produced is invisible, but not necessarily dark matter. (Not cosmologically long-lived? Only a subdominant DM component? But anyway new physics, not discoverable at direct detection experiment.)

Ideally, the DM parameters may be determined at a collider and used to calculate their abundance. Interplay colliders ↔ cosmology.



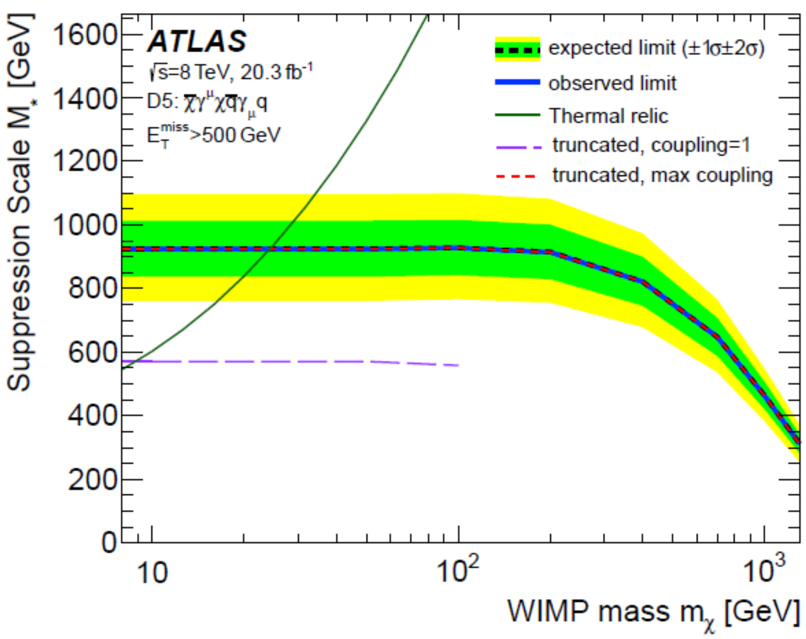



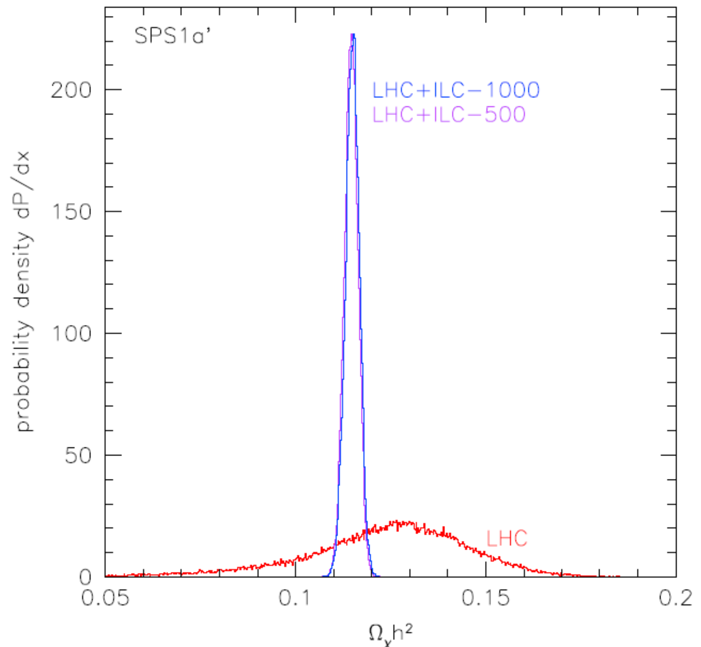

Baltz et al'06

# Some caveats in collider DM searches

1- The particle produced is invisible, but not necessarily dark matter. (Not cosmologically long-lived? Only a subdominant DM component? But anyway new physics, not discoverable at direct detection experiment.)

Ideally, the DM parameters may be determined at a collider and used to calculate their abundance. Interplay colliders ↔ cosmology.




Baltz et al'06

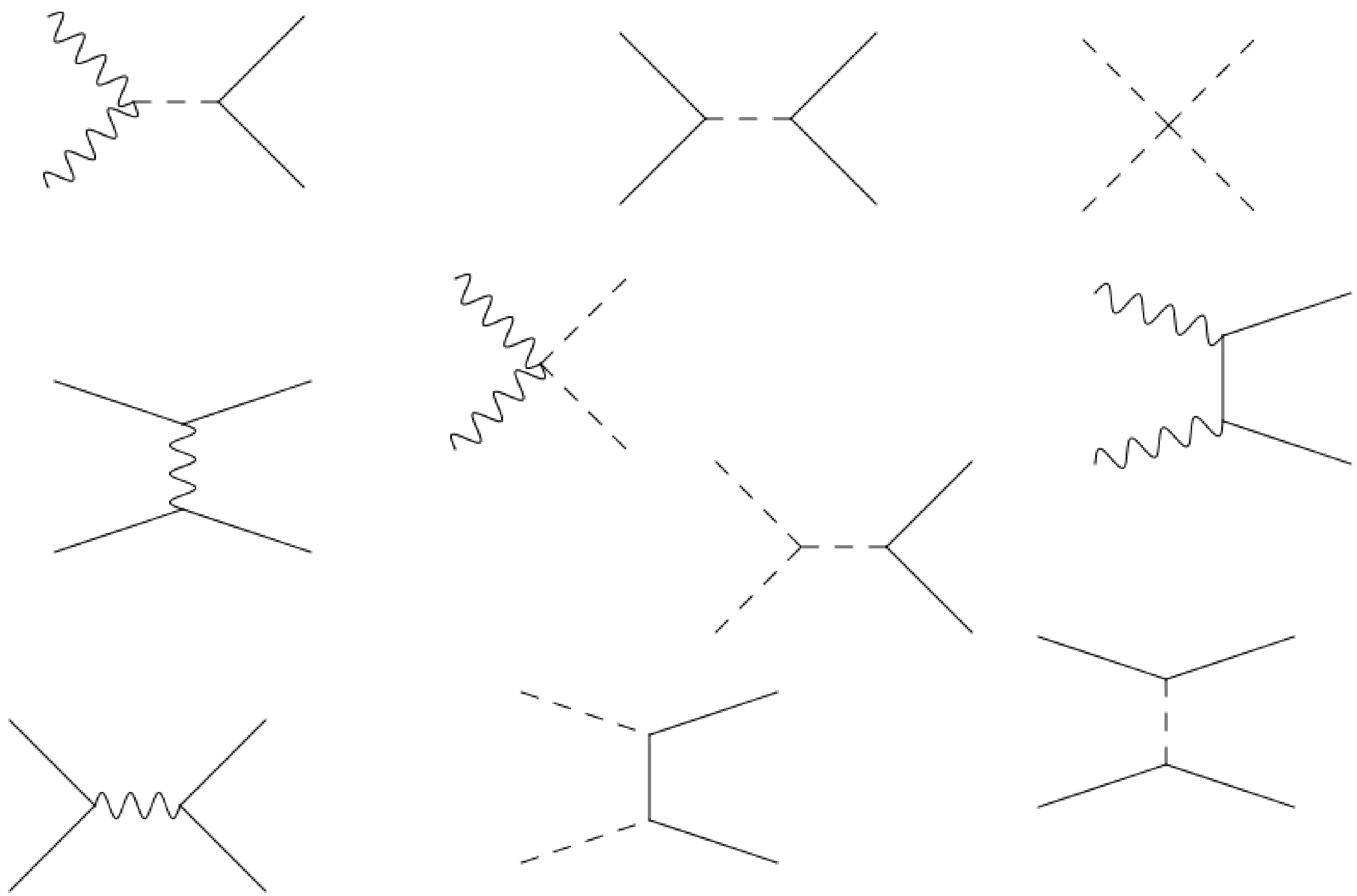
# Some caveats in collider DM searches

2- The effective theory approach may be not sufficient or be simply incorrect. (analysis more model dependent, but collider experiments offer extra information about the dark sector couplings/particles).

# Some caveats in collider DM searches

2- The effective theory approach may be not sufficient or be simply incorrect. (analysis more model dependent, but collider experiments offer extra information about the dark sector couplings/particles).

Many possible realizations of the effective interaction



# Some caveats in collider DM searches

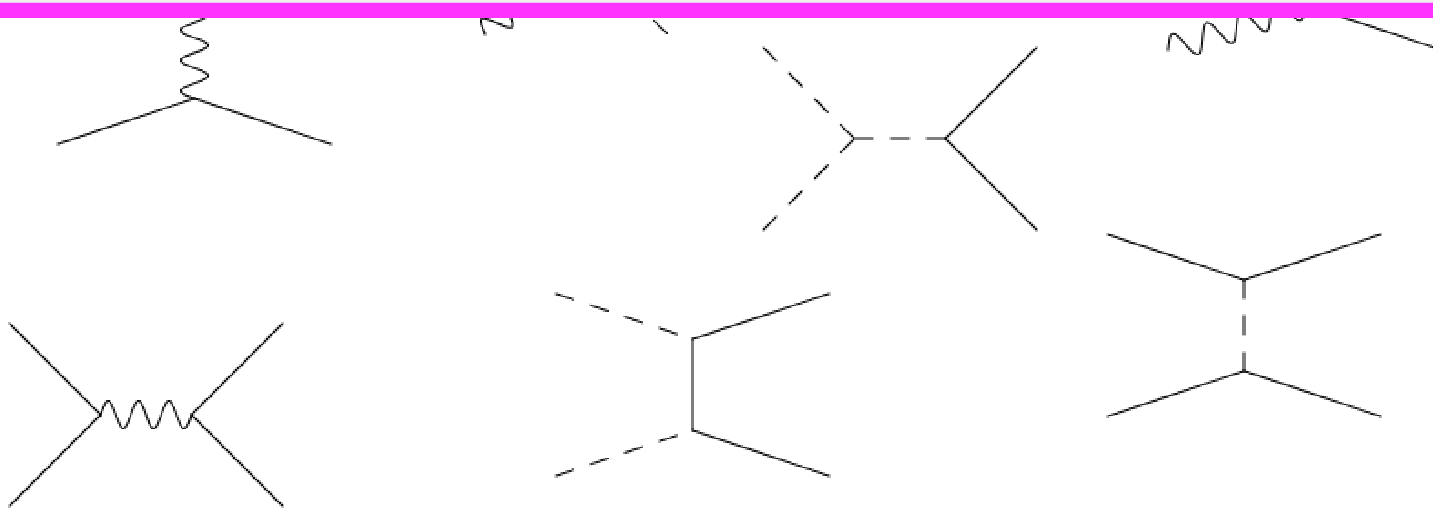
2- The effective theory approach may be not sufficient or be simply incorrect. (analysis more model dependent, but collider experiments offer extra information about the dark sector couplings/particles).

Many possible realizations of the effective interaction

Which dark matter particle?

Which mediator (if any)?

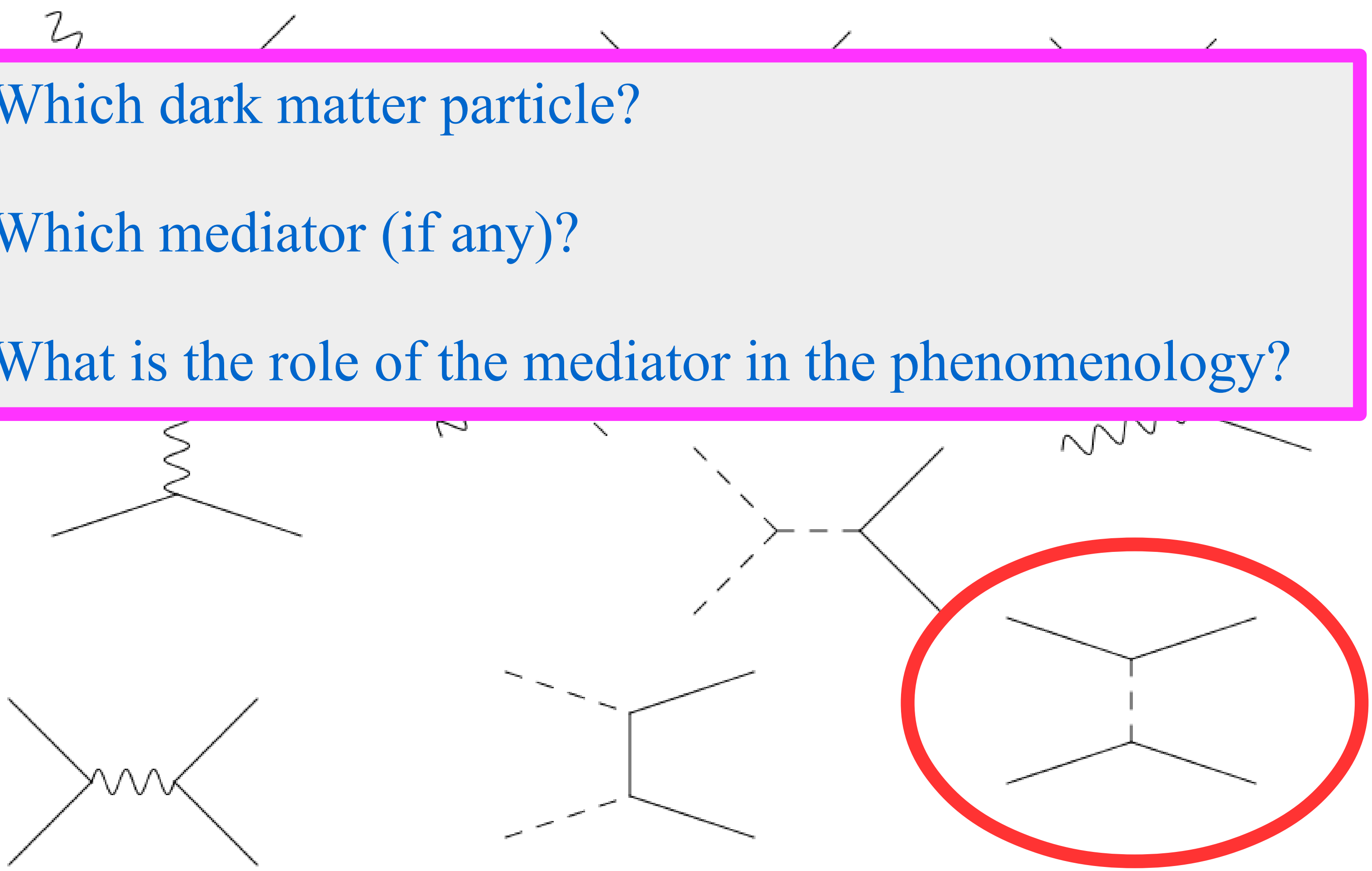
What is the role of the mediator in the phenomenology?



# Some caveats in collider DM searches

2- The effective theory approach may be not sufficient or be simply incorrect.
(analysis more model dependent, but collider experiments offer extra information about the dark sector couplings/particles).

Many possible realizations of the effective interaction



Which dark matter particle?

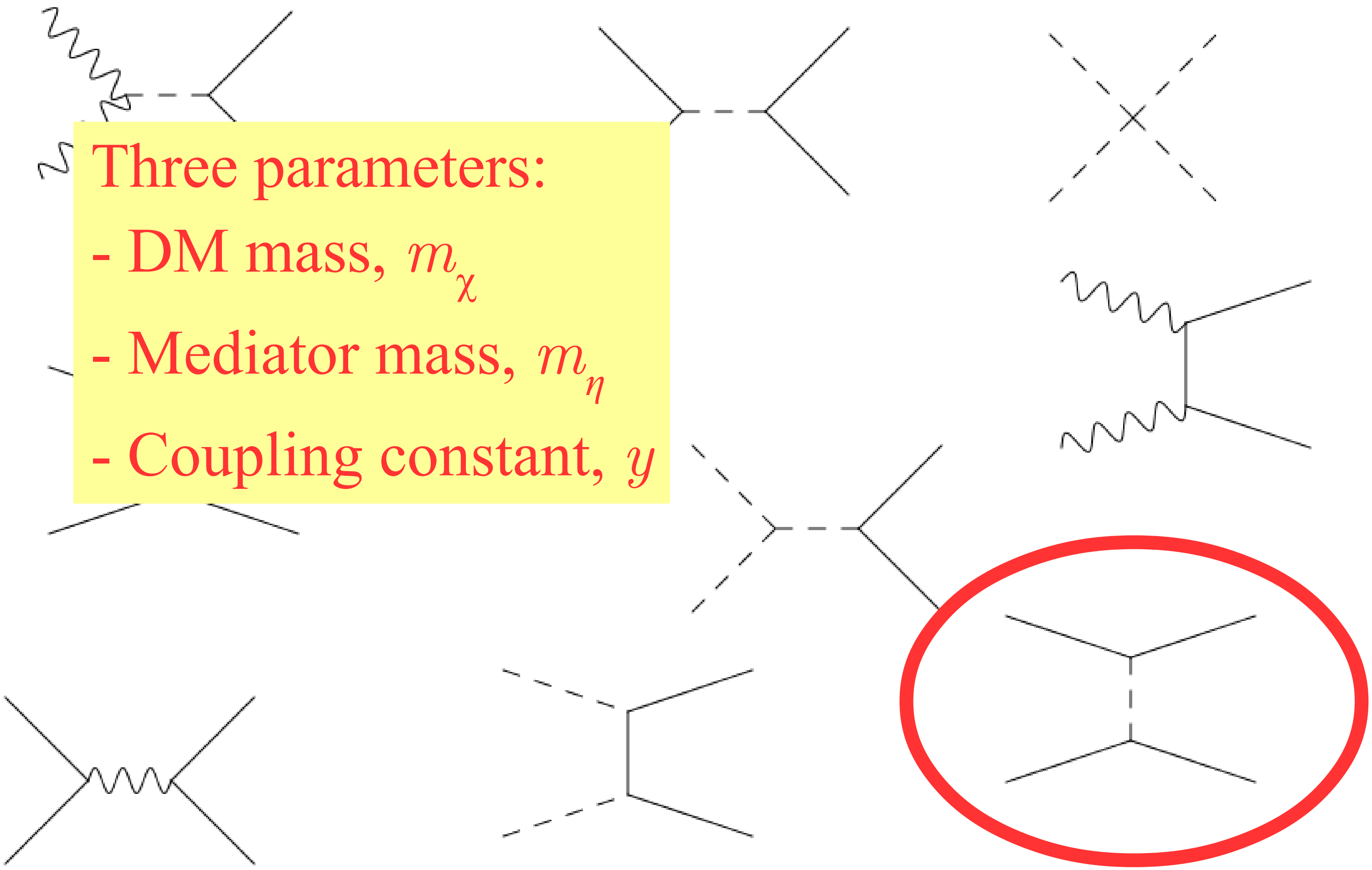
Which mediator (if any)?

What is the role of the mediator in the phenomenology?

# Some caveats in collider DM searches

2- The effective theory approach may be not sufficient or be simply incorrect. (analysis more model dependent, but collider experiments offer extra information about the dark sector couplings/particles).

Many possible realizations of the effective interaction



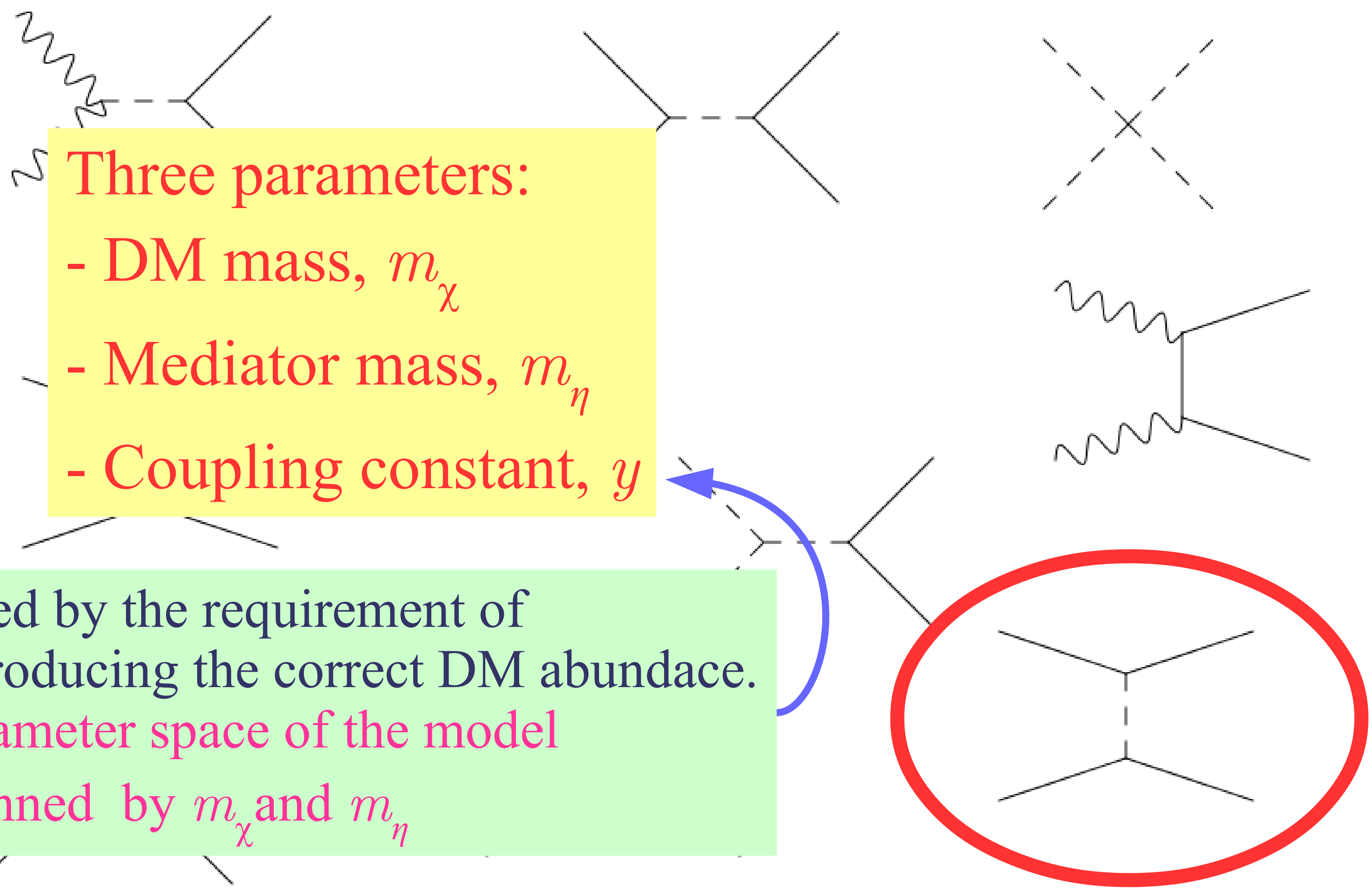
Three parameters:

- DM mass, $m_\chi$
- Mediator mass, $m_\eta$
- Coupling constant, $y$

# Some caveats in collider DM searches

2- The effective theory approach may be not sufficient or be simply incorrect. (analysis more model dependent, but collider experiments offer extra information about the dark sector couplings/particles).

Many possible realizations of the effective interaction

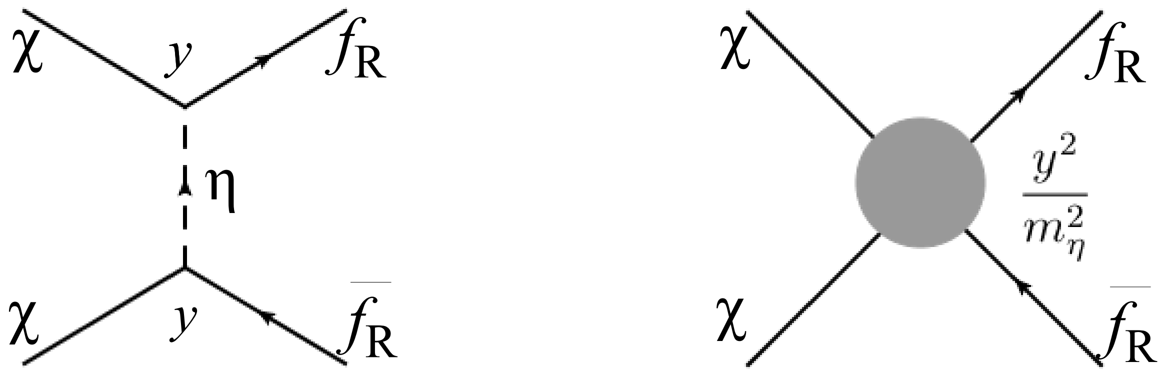


Three parameters:
- DM mass, $m_\chi$
- Mediator mass, $m_\eta$
- Coupling constant, $y$

Fixed by the requirement of reproducing the correct DM abundace.
Parameter space of the model spanned by $m_\chi$ and $m_\eta$

# Majorana DM with t-channel scalar mediator

For $m_\eta \gg m_\chi$, the interaction can be described by a contact term.

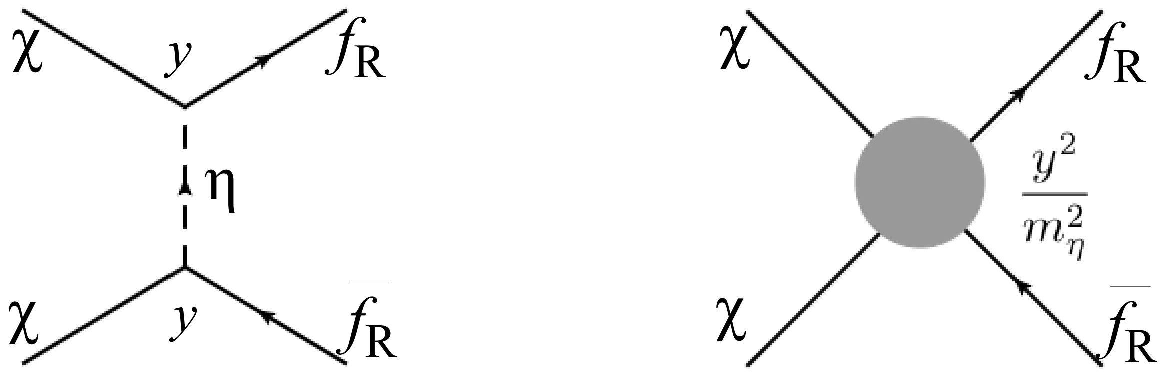



$$\Omega_\chi h^2 \simeq \frac{0.12}{N_c}\left(\frac{1.85}{y}\right)^4\left(\frac{m_\eta}{500\,\mathrm{GeV}}\right)^4\left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^{-2}$$

For every dark matter mass, there is always a choice of the coupling and the mediator mass that reproduces the observed DM abundance.

# Majorana DM with t-channel scalar mediator

For $m_\eta \gg m_\chi$, the interaction can be described by a contact term.




$$\Omega_\chi h^2 \simeq \frac{0.12}{N_c}\left(\frac{1.85}{y}\right)^4\left(\frac{m_\eta}{500\,\mathrm{GeV}}\right)^4\left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^{-2}$$

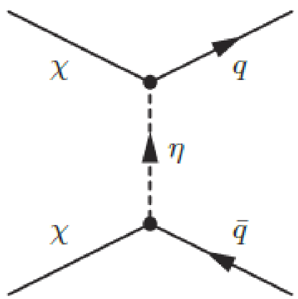
For every dark matter mass, there is always a choice of the coupling and the mediator mass that reproduces the observed DM abundance.

The phenomenology is completely modified when the mediator is light

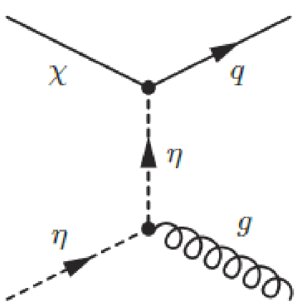
# Majorana DM with t-channel scalar mediator

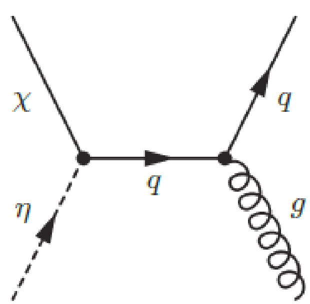
If the mediator and the dark matter have comparable masses, the mediator is present in the thermal plasma during the epoch of freeze-out.

New channels deplete the number of dark matter particles, via "coannihilations", and lower the dark matter relic abundance. Griest, Seckel '91

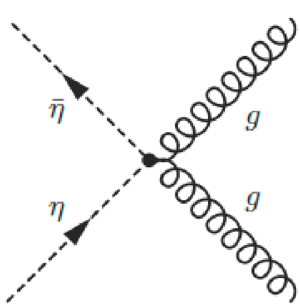


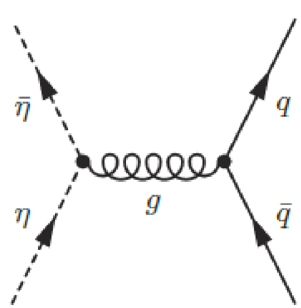

$\sim y^4$




$\sim y^2 g^2$



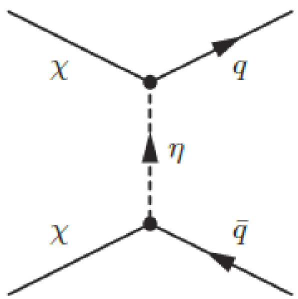




$\sim g^4$

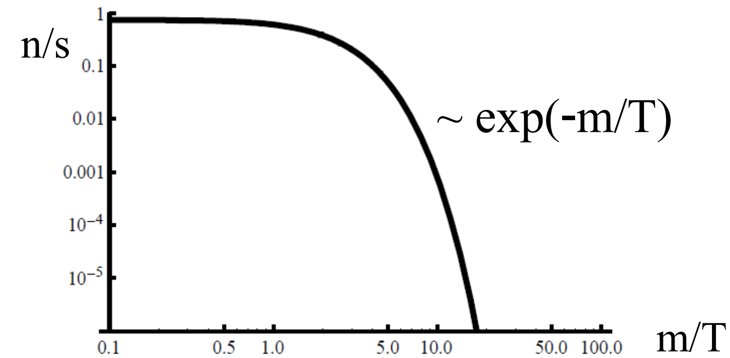
# Majorana DM with t-channel scalar mediator

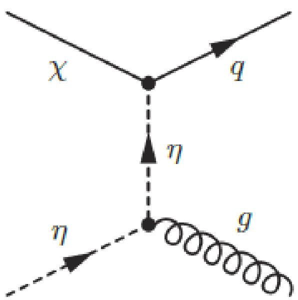
If the mediator and the dark matter have comparable masses, the mediator is present in the thermal plasma during the epoch of freeze-out.

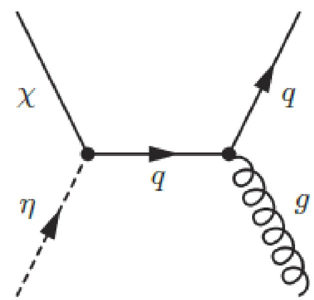
New channels deplete the number of dark matter particles, via “coannihilations”, and lower the dark matter relic abundance. Griest, Seckel '91




$\sim y^4$

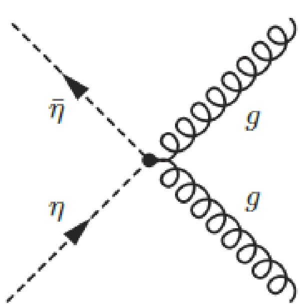


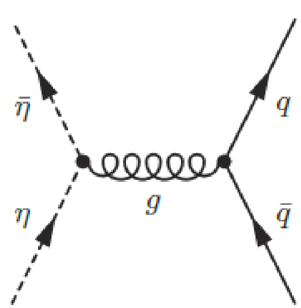




$\sim y^2 g^2$ Rate compared to $\chi\chi\to q\bar{q}$ suppressed by

$$\frac{g^2}{y^2}\, e^{-\frac{(m_\eta - m_\chi)}{T}}$$

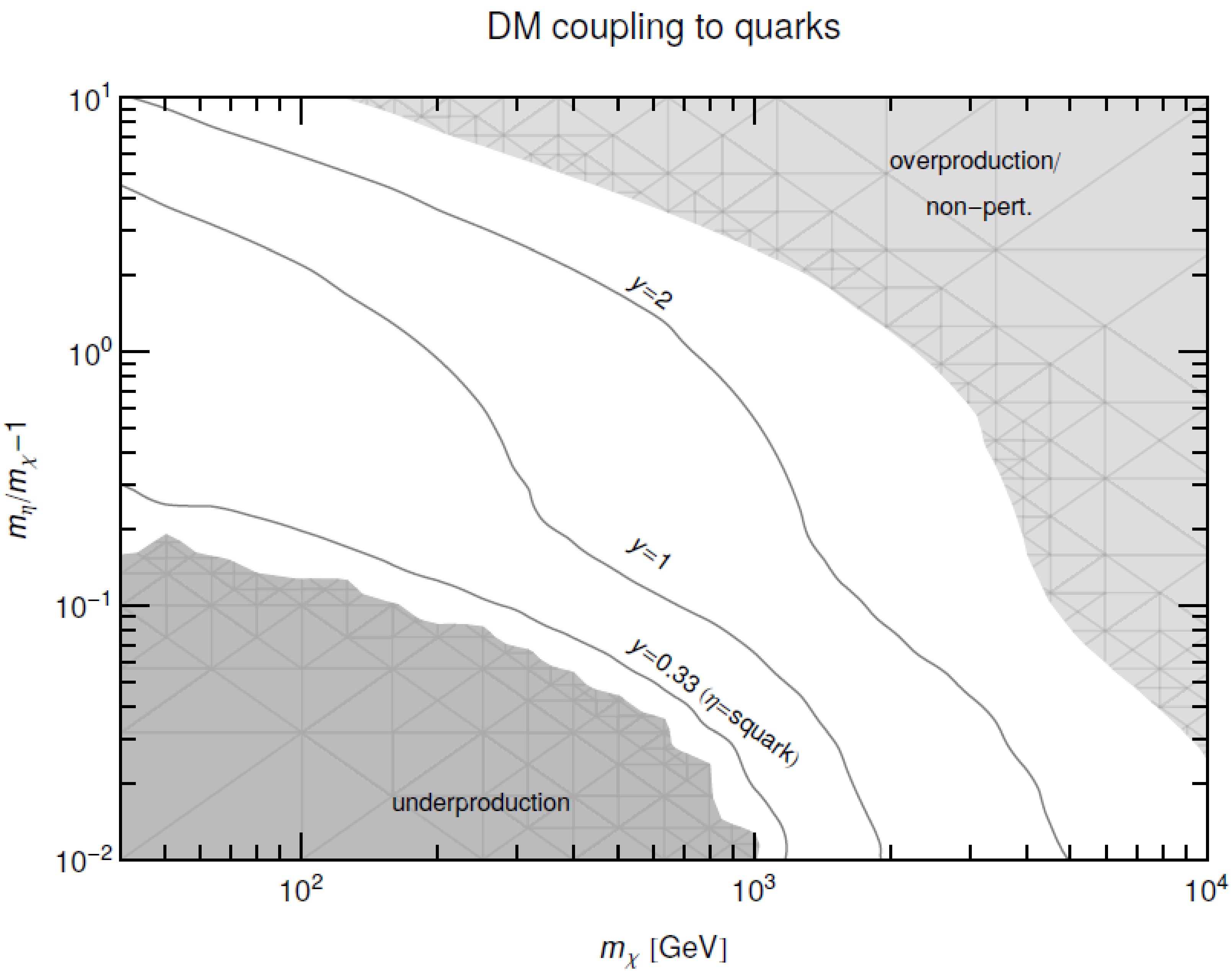


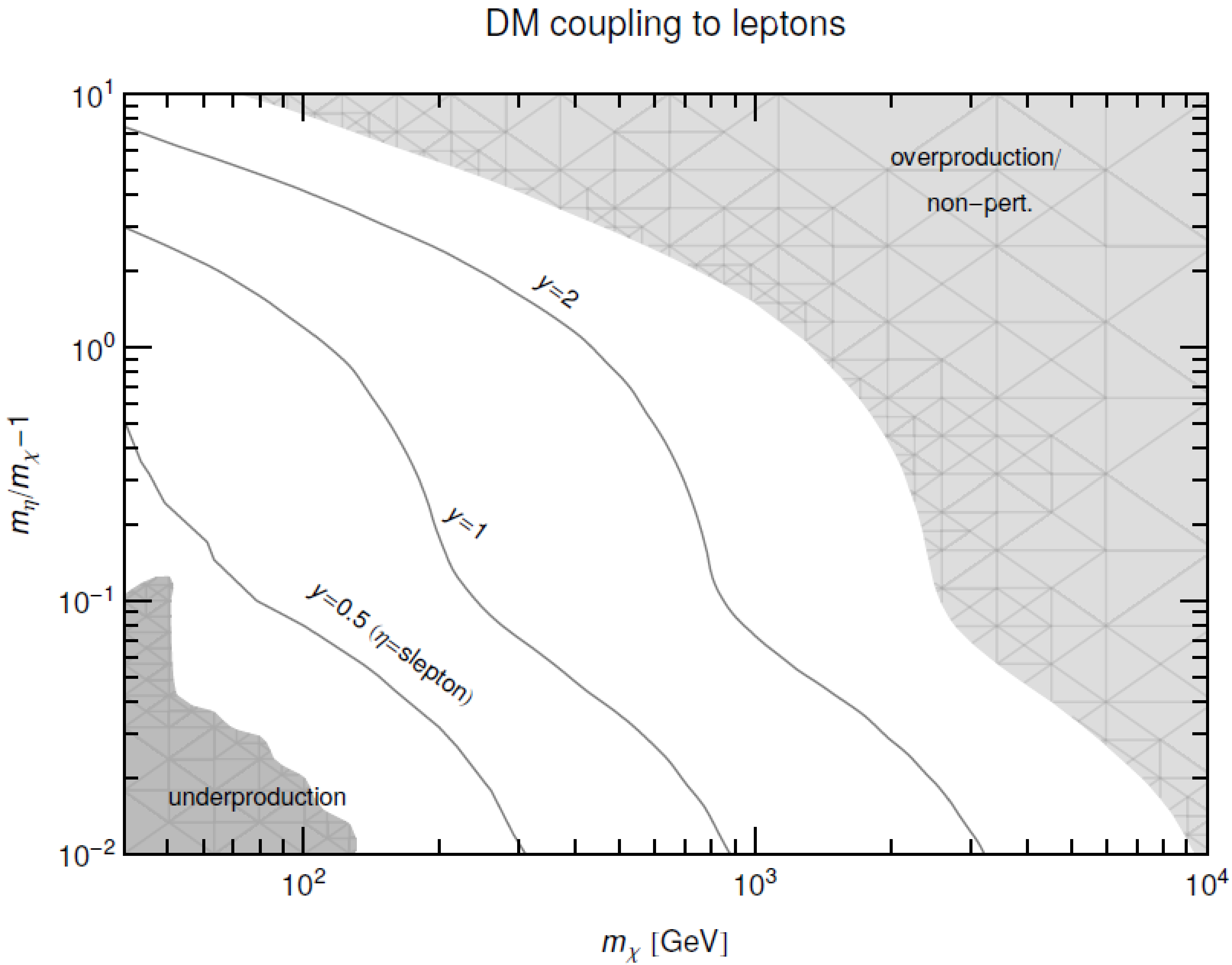

$\sim g^4$ Rate compared to $\chi\chi\to q\bar{q}$ suppressed by

$$\frac{g^4}{y^4}\, e^{-\frac{2(m_\eta - m_\chi)}{T}}$$

# Majorana DM with t-channel scalar mediator



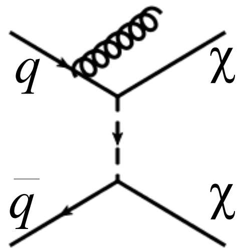
# Majorana DM with t-channel scalar mediator



# Collider signals

Three different regimes

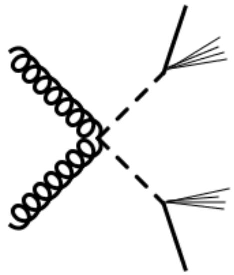
- $m_\eta \gg m_\chi$. The scalar mediator cannot be produced at the colliders; only the DM.




The signal consists on a monojet/monophoton/mono-W/Z boson plus missing transverse momentum.

- $m_\eta = O(m_\chi)$. The scalar mediator might be produced at the colliders and then decays into the DM plus a quark/lepton.

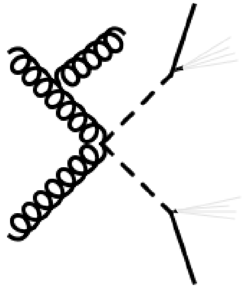
e.g



The signal consists of missing transverse momentum plus two jets/two leptons.

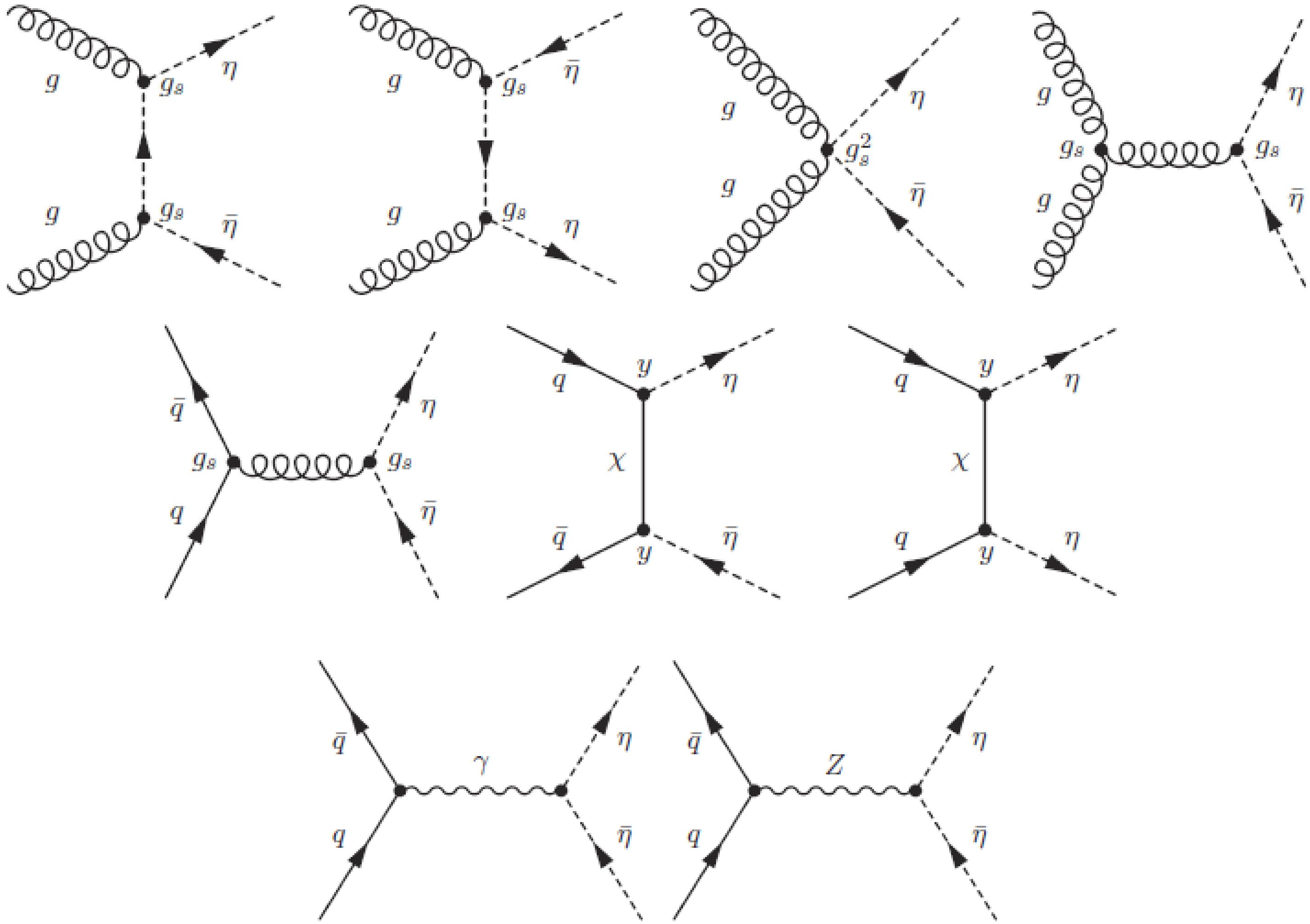
- $m_\eta \simeq m_\chi$. The scalar mediator might be produced at the colliders and then decays into the DM plus a quark/lepton. However, the jets and leptons are too soft to be detected.

e.g

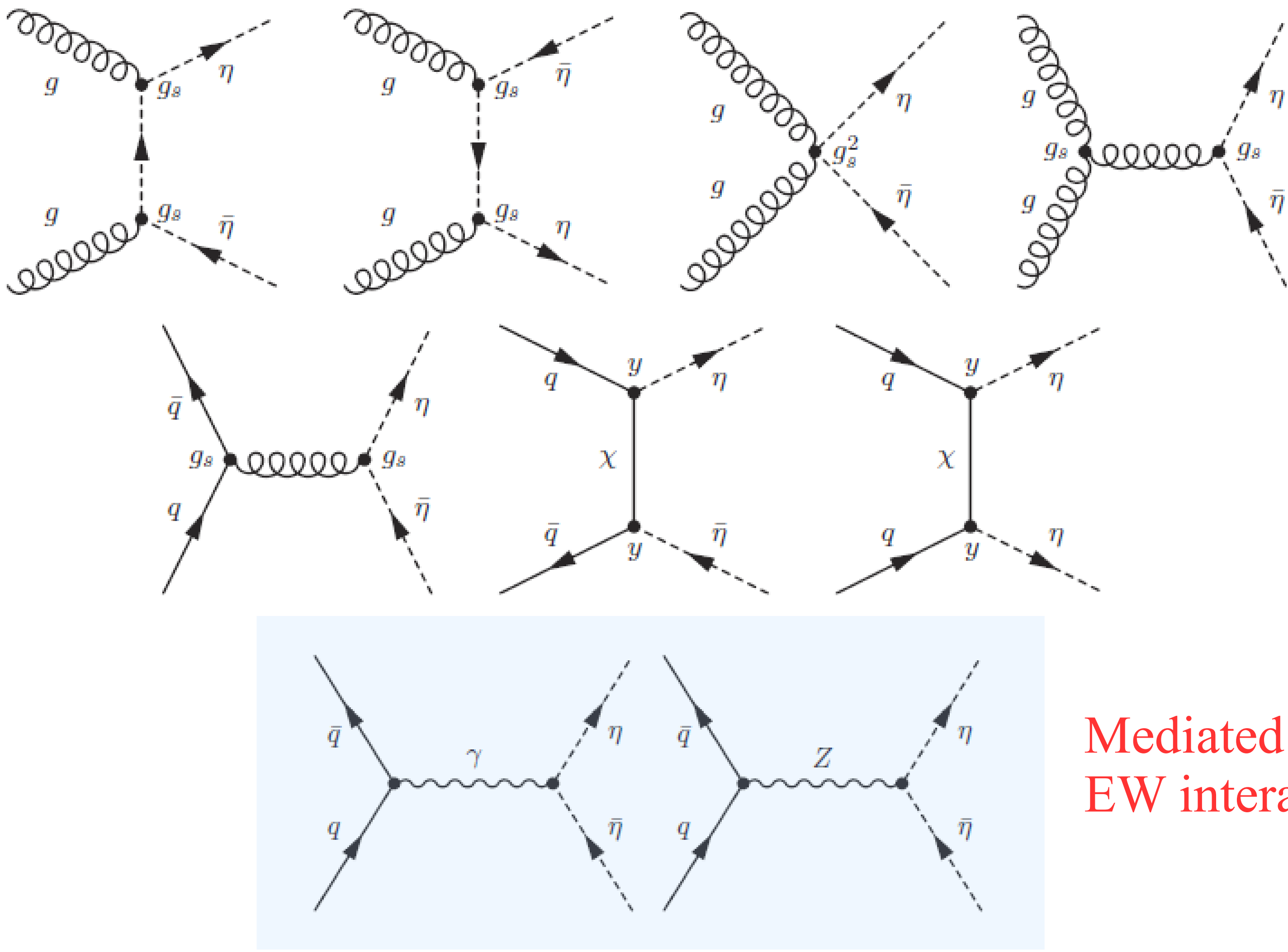


The signal consists on a monojet/monophoton/mono-W/Z boson plus missing transverse momentum.

# Production of scalar mediators

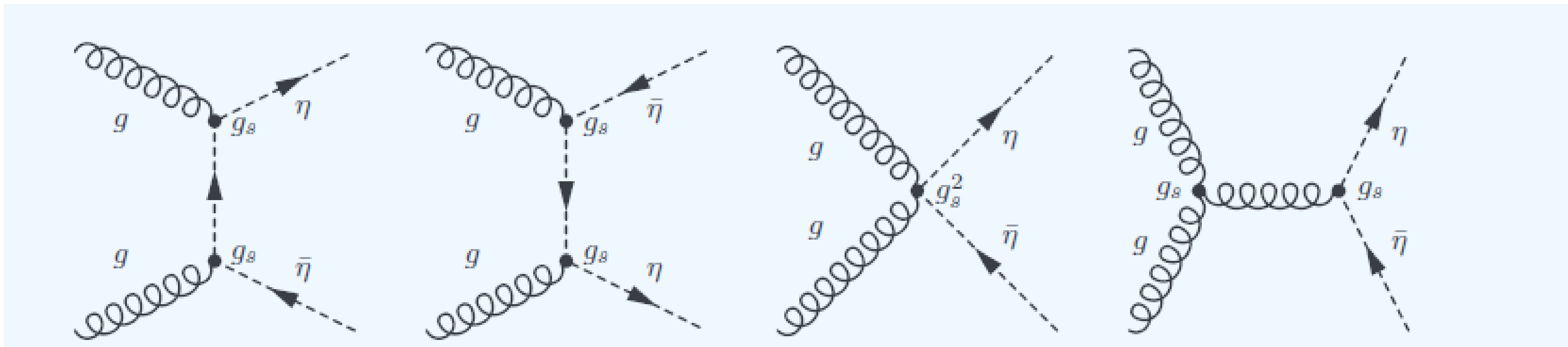


# Production of scalar mediators

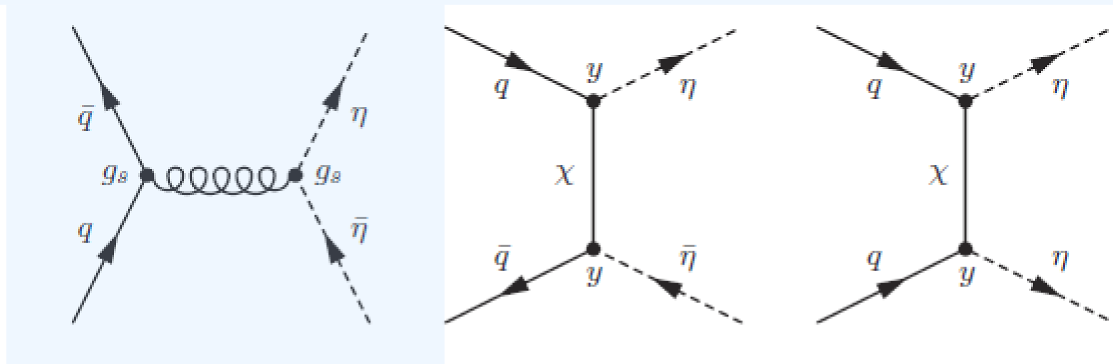


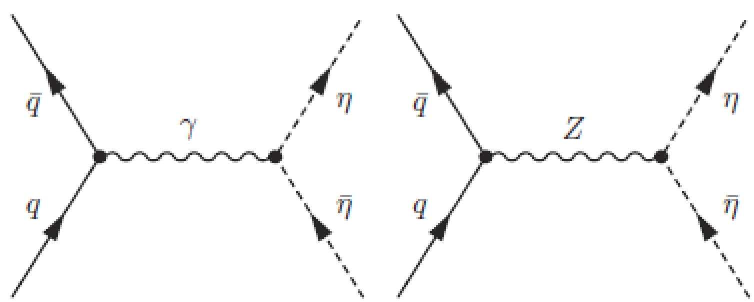

Mediated by EW interactions

# Production of scalar mediators

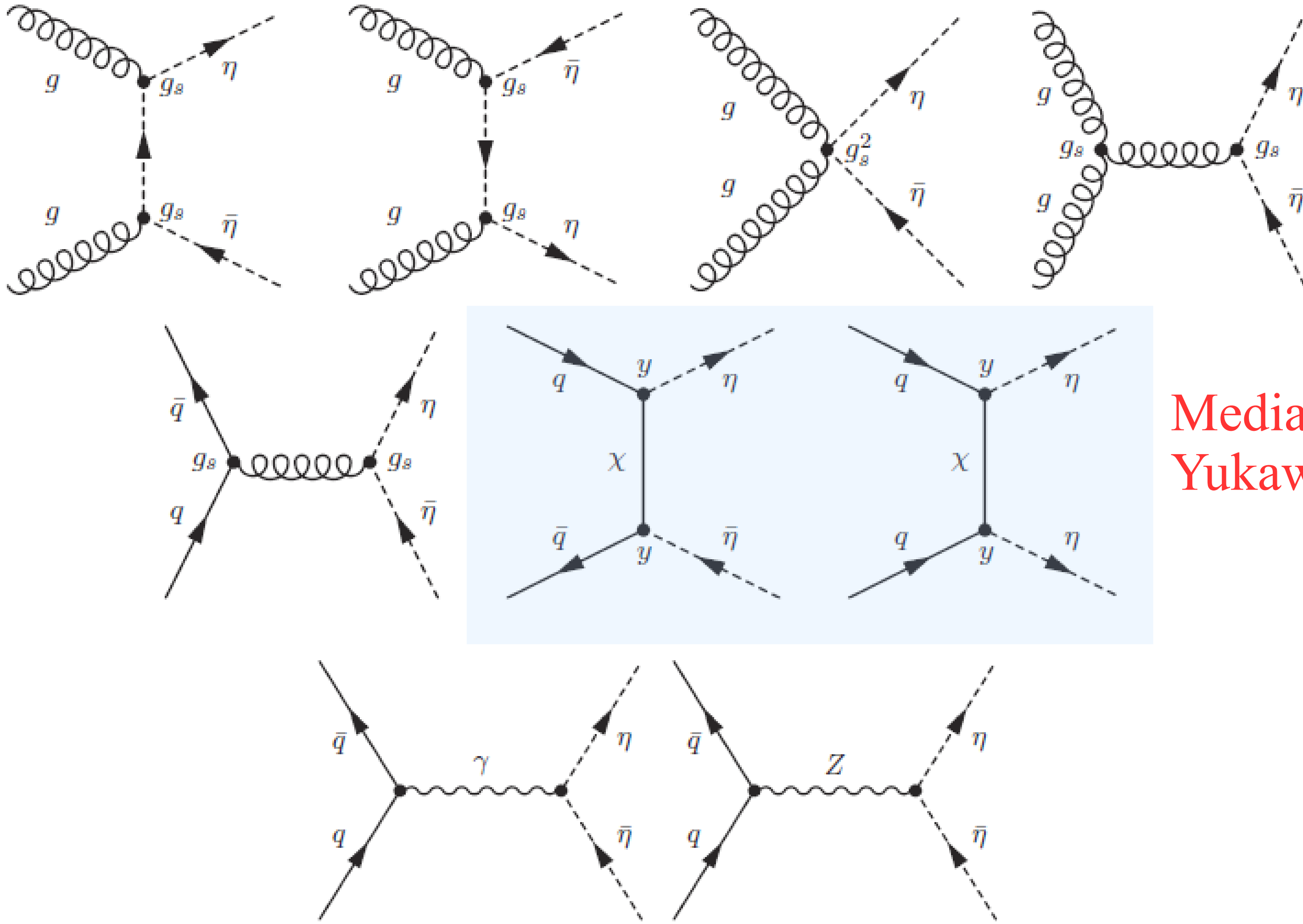



Mediated by the strong interaction



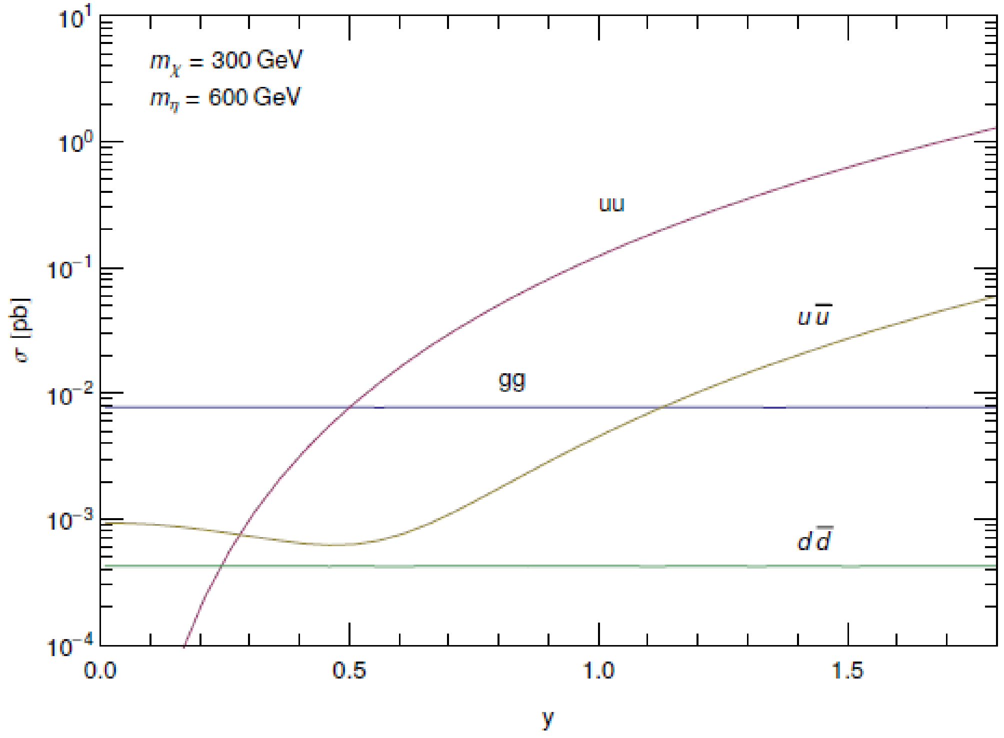
# Production of scalar mediators



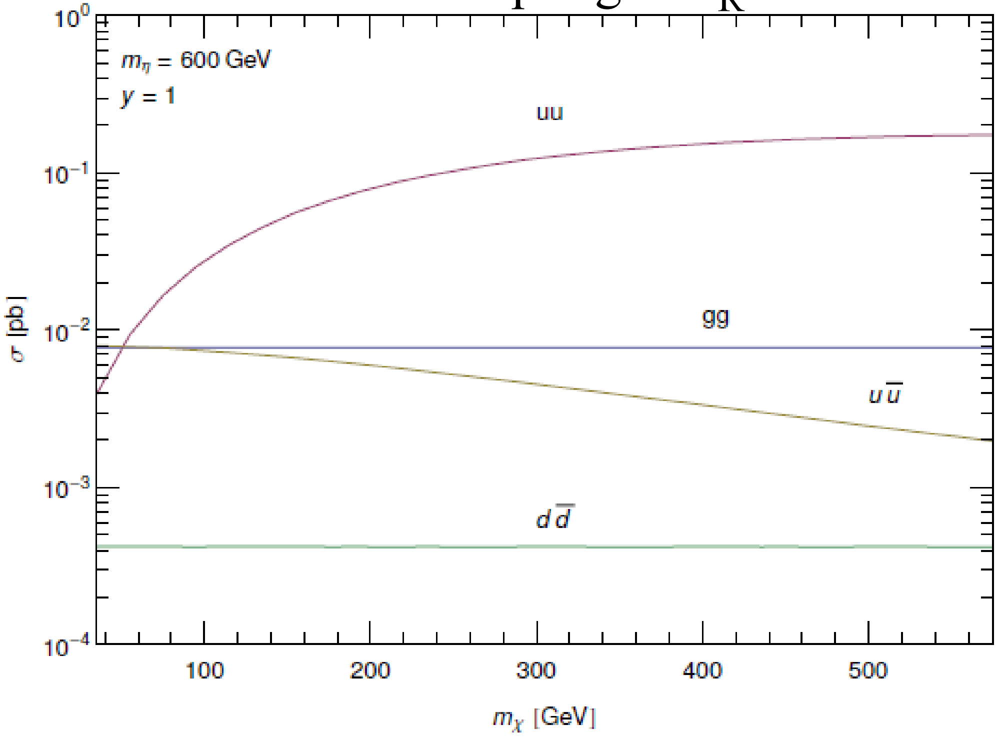

Mediated by a
Yukawa interaction

# Production of scalar mediators

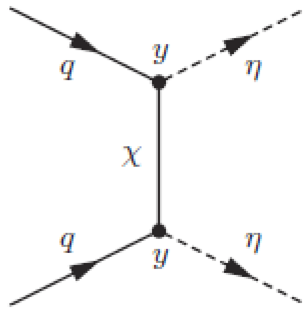
DM coupling to $u_R$




DM coupling to $u_R$

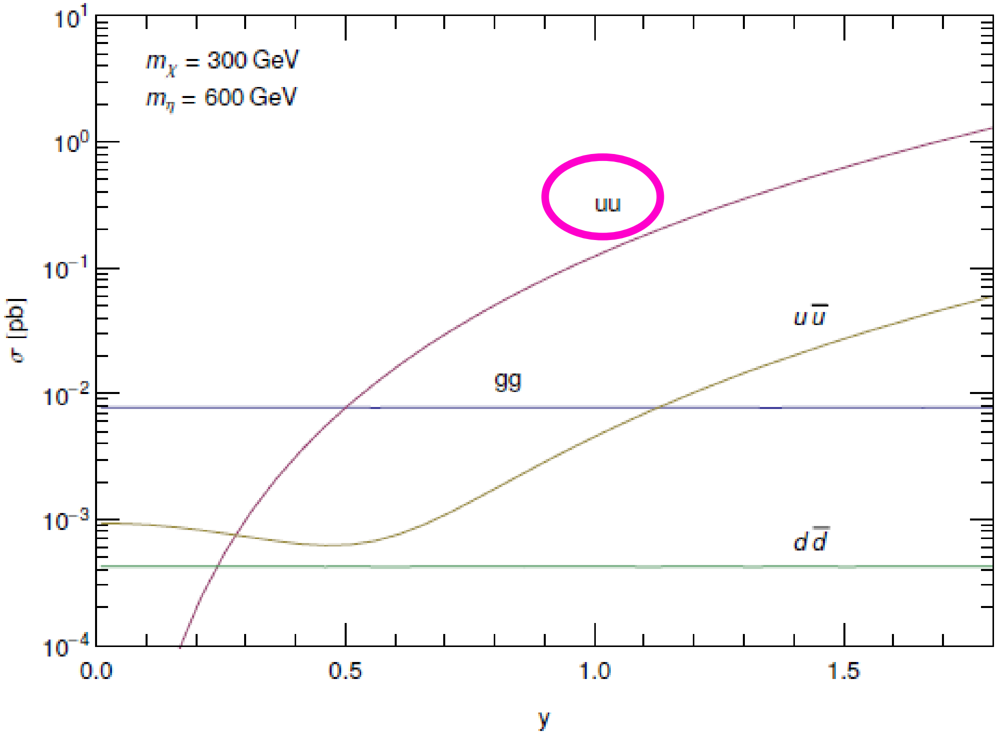


# Production of scalar mediators

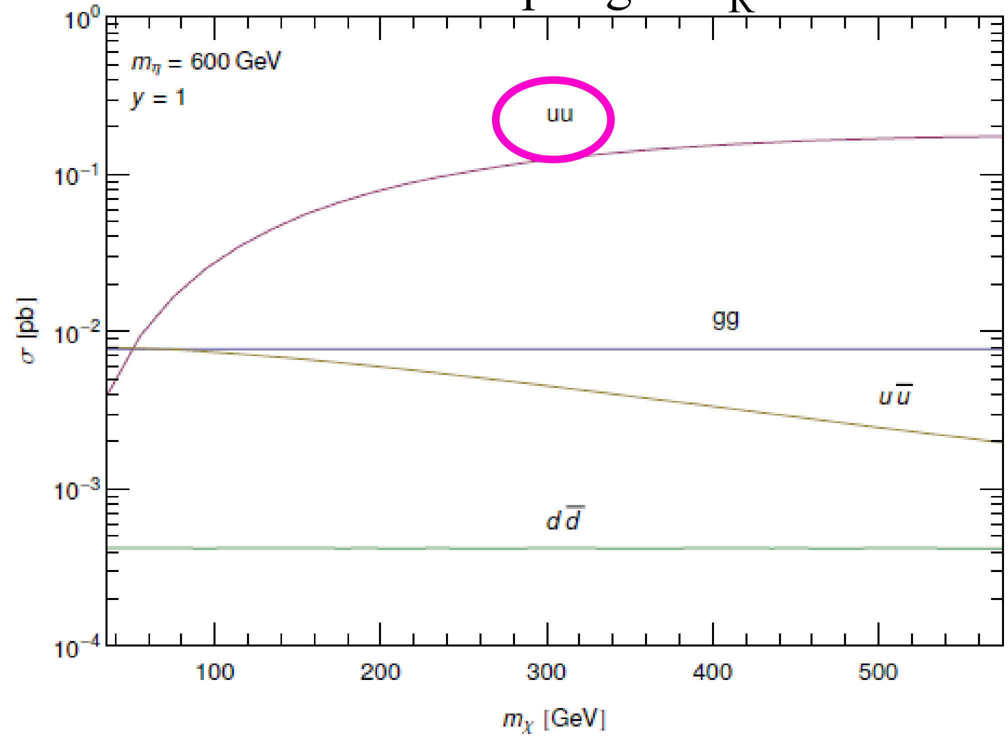



Exists only for χ Majorana.
Cross section enhanced for large $m_\chi$.
Relevant for thermal DM, since y=O(1)

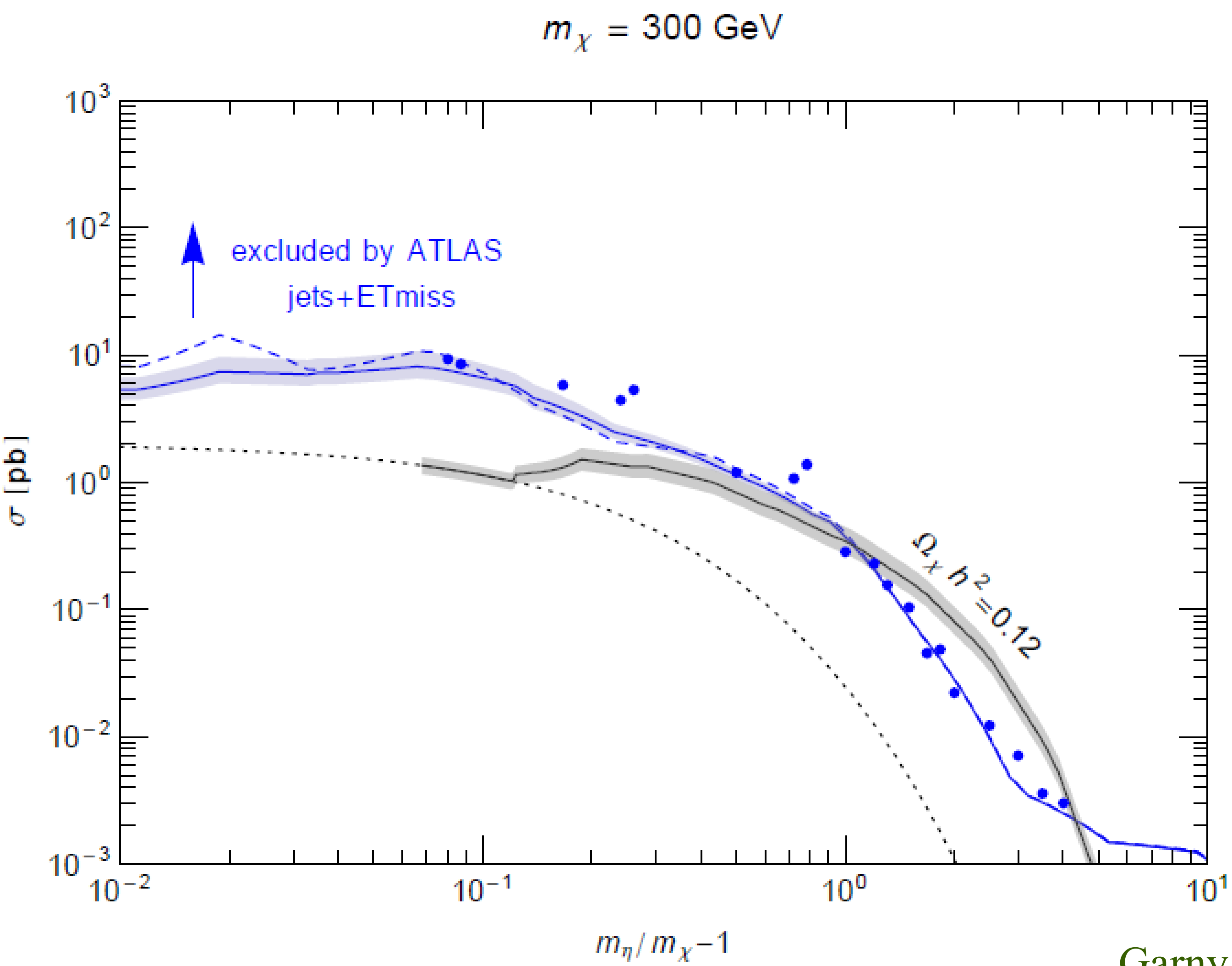
DM coupling to $u_R$



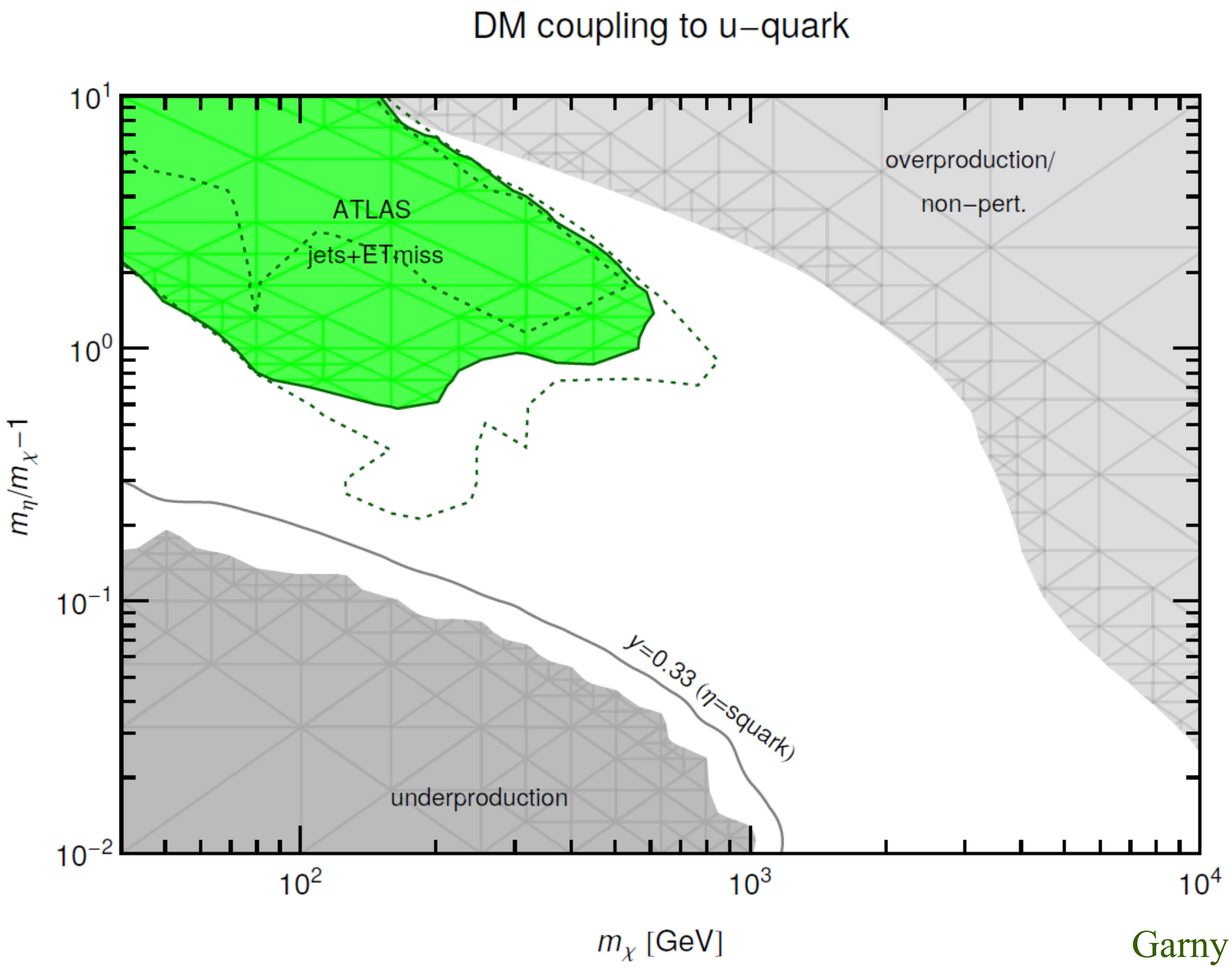

DM coupling to $u_R$



# Limits from colliders

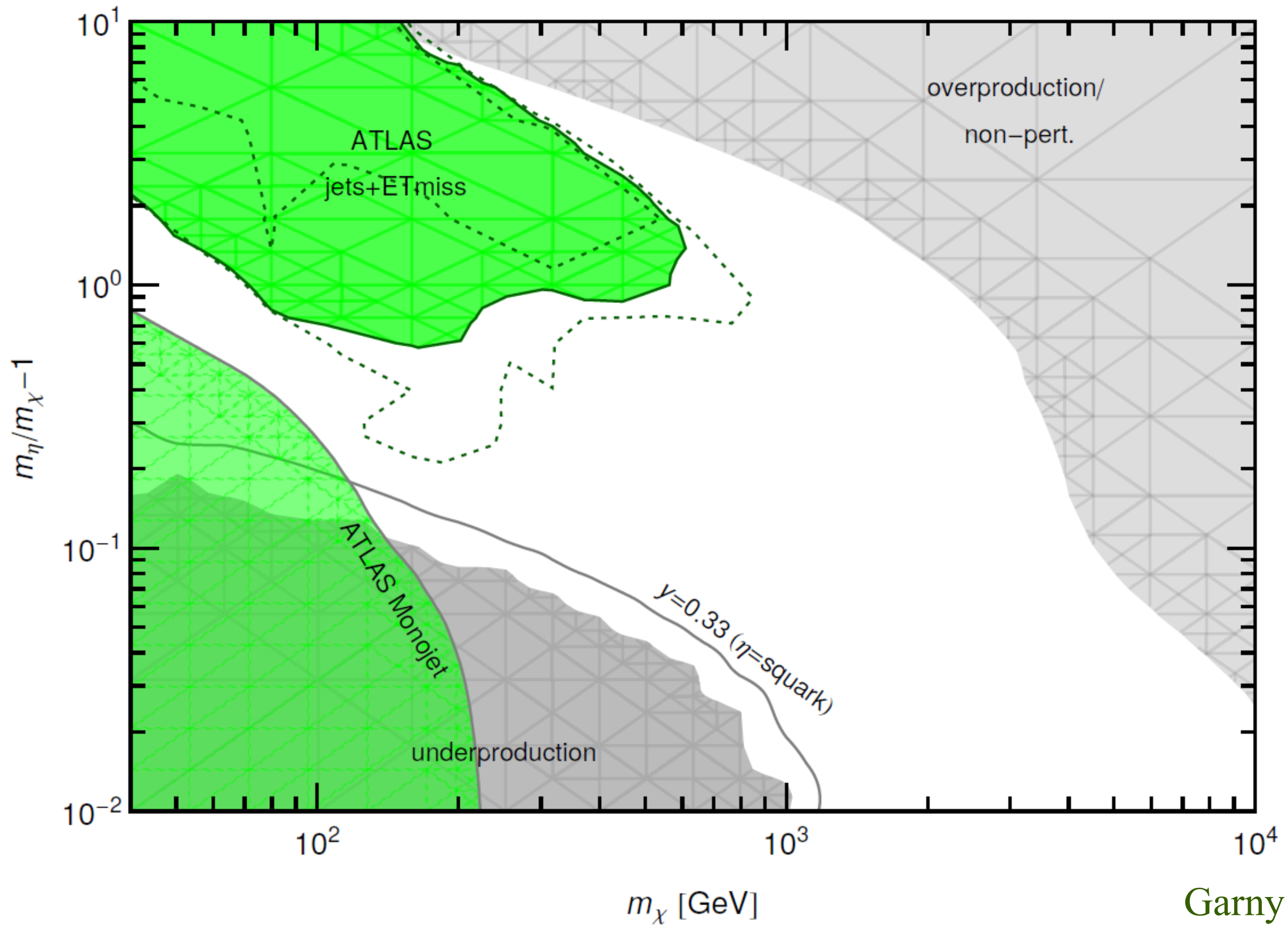



Garny et al'14




Garny et al'14

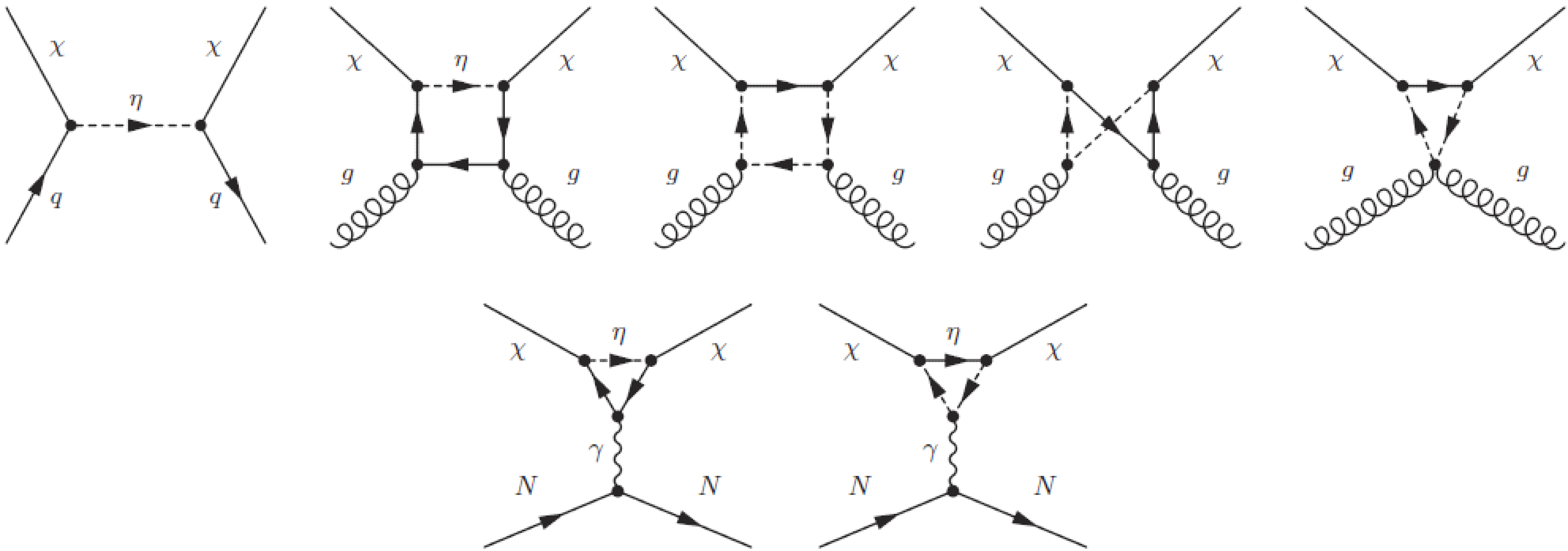
## DM coupling to u−quark




Garny et al'14

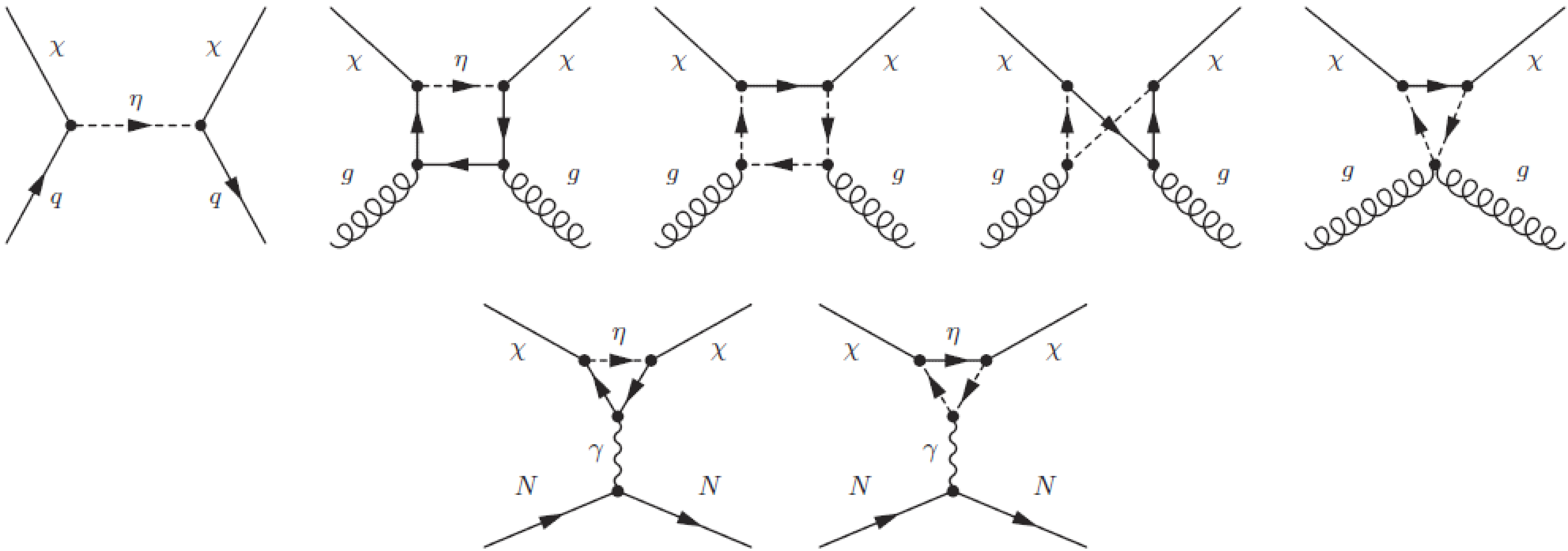
# Interplay with direct detection experiments

Various diagrams contribute to the scattering of a dark matter particle with a nucleon:



# Interplay with direct detection experiments

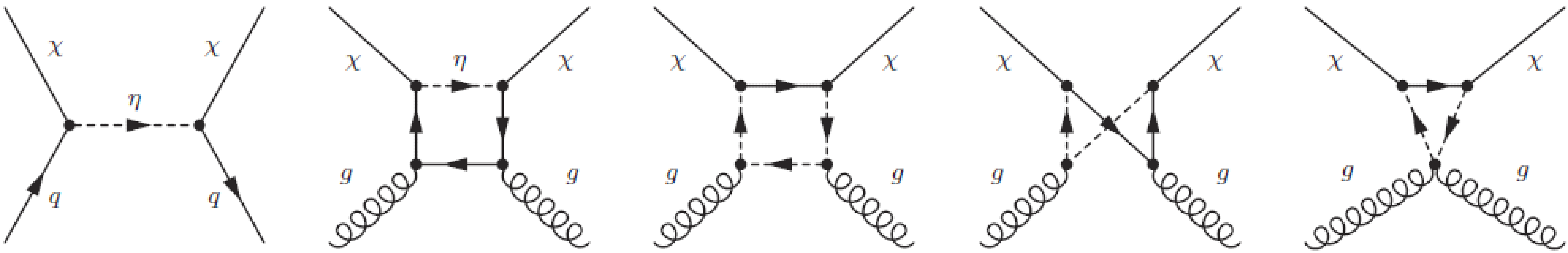
Various diagrams contribute to the scattering of a dark matter particle with a nucleon:



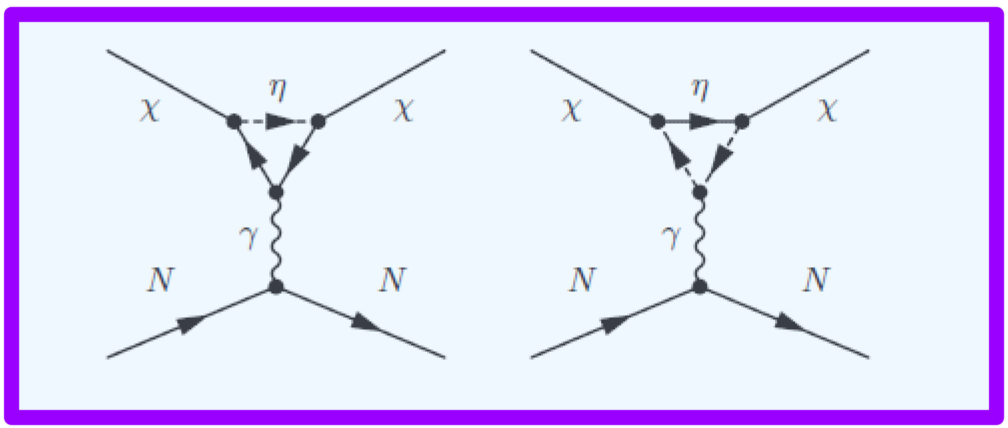

The interaction DM-nucleon exists *for any* $\mathcal{L}_{\rm int}^{\rm fermion} = -y\bar{\chi} f_R \eta + {\rm h.c.}$

# Interplay with direct detection experiments

Various diagrams contribute to the scattering of a dark matter particle with a nucleon:



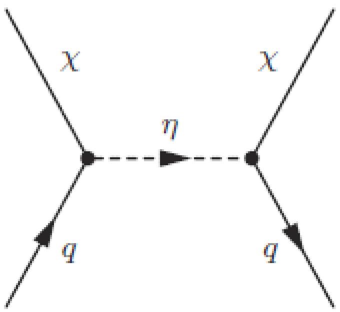

Dark matter coupling to leptons.



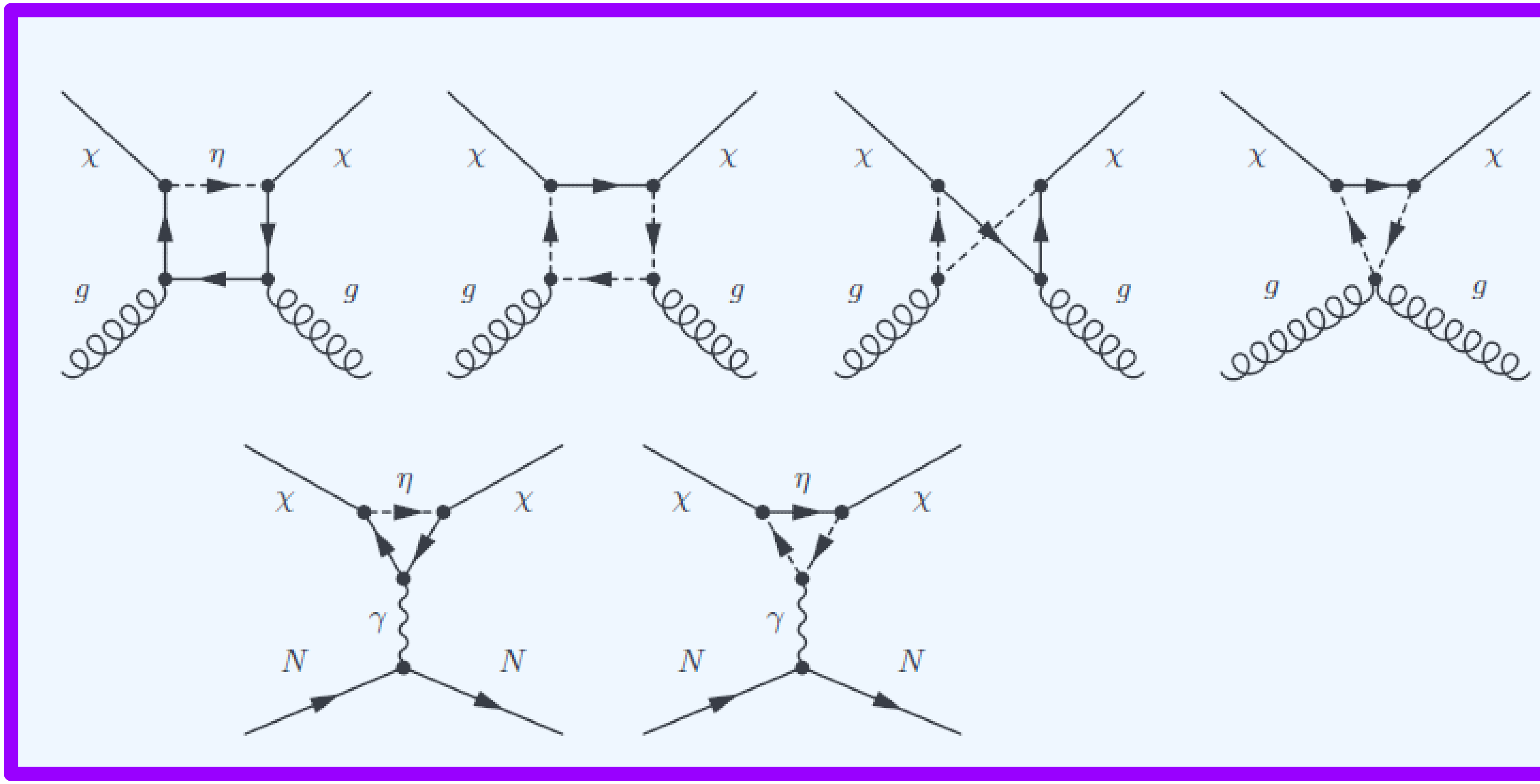

The interaction DM-nucleon exists *for any* $\mathcal{L}_{\rm int}^{\rm fermion} = -y\bar{\chi} f_R \eta + \text{h.c.}$

# Interplay with direct detection experiments

Various diagrams contribute to the scattering of a dark matter particle with a nucleon:



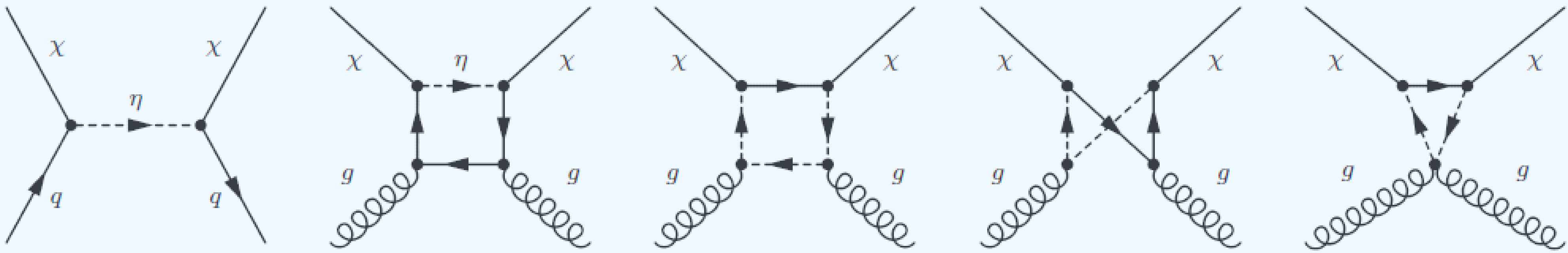

DM coupling
to heavy quarks



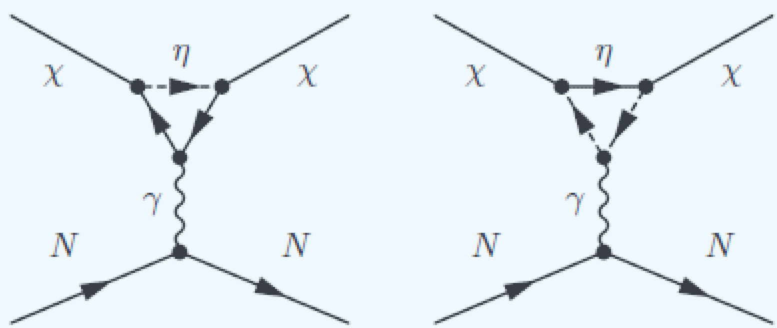

The interaction DM-nucleon exists *for any* $\mathcal{L}_{\rm int}^{\rm fermion} = -y\bar{\chi} f_R \eta + {\rm h.c.}$

# Interplay with direct detection experiments

Various diagrams contribute to the scattering of a dark matter particle with a nucleon:



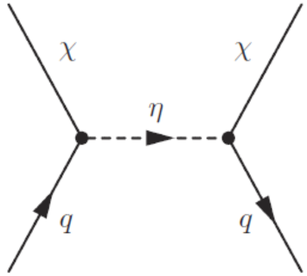

DM coupling
to light quarks




The interaction DM-nucleon exists *for any* $\mathcal{L}_{\rm int}^{\rm fermion} = -y\bar{\chi} f_R \eta + {\rm h.c.}$

# DM coupling to light quarks: spin independent interaction

Tree level:

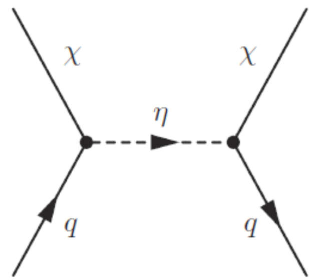



$$\mathcal{L}_{\mathrm{eff,tree}}^{\mathrm{SI}} = -\frac{y^2}{2(m_\eta^2 - (m_\chi + m_q)^2)^2} (\bar{\chi}\gamma^\mu D_\nu \chi)(\bar{q}_R \gamma_\mu D_\nu q_R - (D_\nu \bar{q}_R)\gamma_\mu q_R)$$

Dim. 8 operator. Singular when $m_\eta \to m_\chi + m_q$

# DM coupling to light quarks: spin independent interaction

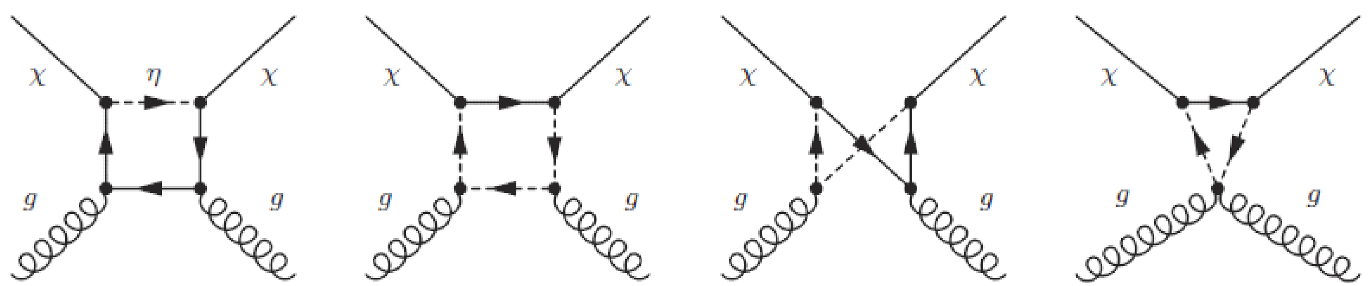
Tree level:




$$\mathcal{L}^{\rm SI}_{\rm eff,tree} = -\frac{y^2}{2(m_\eta^2 - (m_\chi + m_q)^2)^2}(\bar{\chi}\gamma^\mu D_\nu \chi)(\bar{q}_R \gamma_\mu D_\nu q_R - (D_\nu \bar{q}_R)\gamma_\mu q_R)$$

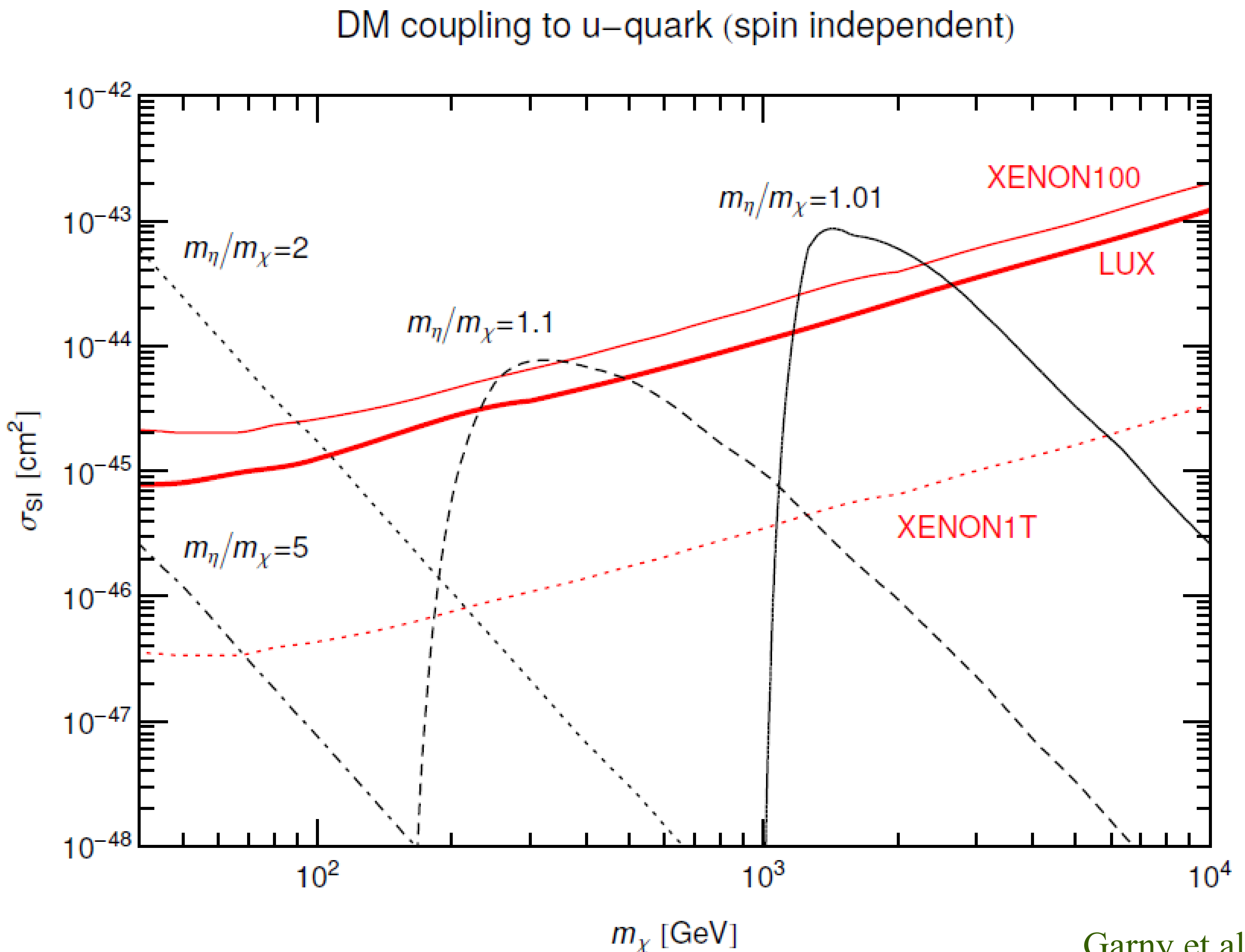
Dim. 8 operator. Singular when $m_\eta \to m_\chi + m_q$

One loop:




Dim. 7 operator (but loop suppressed). Regular when $m_\eta \to m_\chi + m_q$

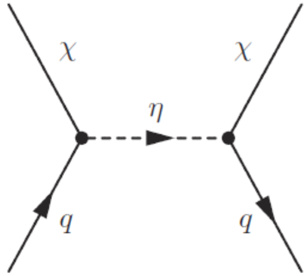
# DM coupling to quarks: spin independent interaction




Garny et al'14

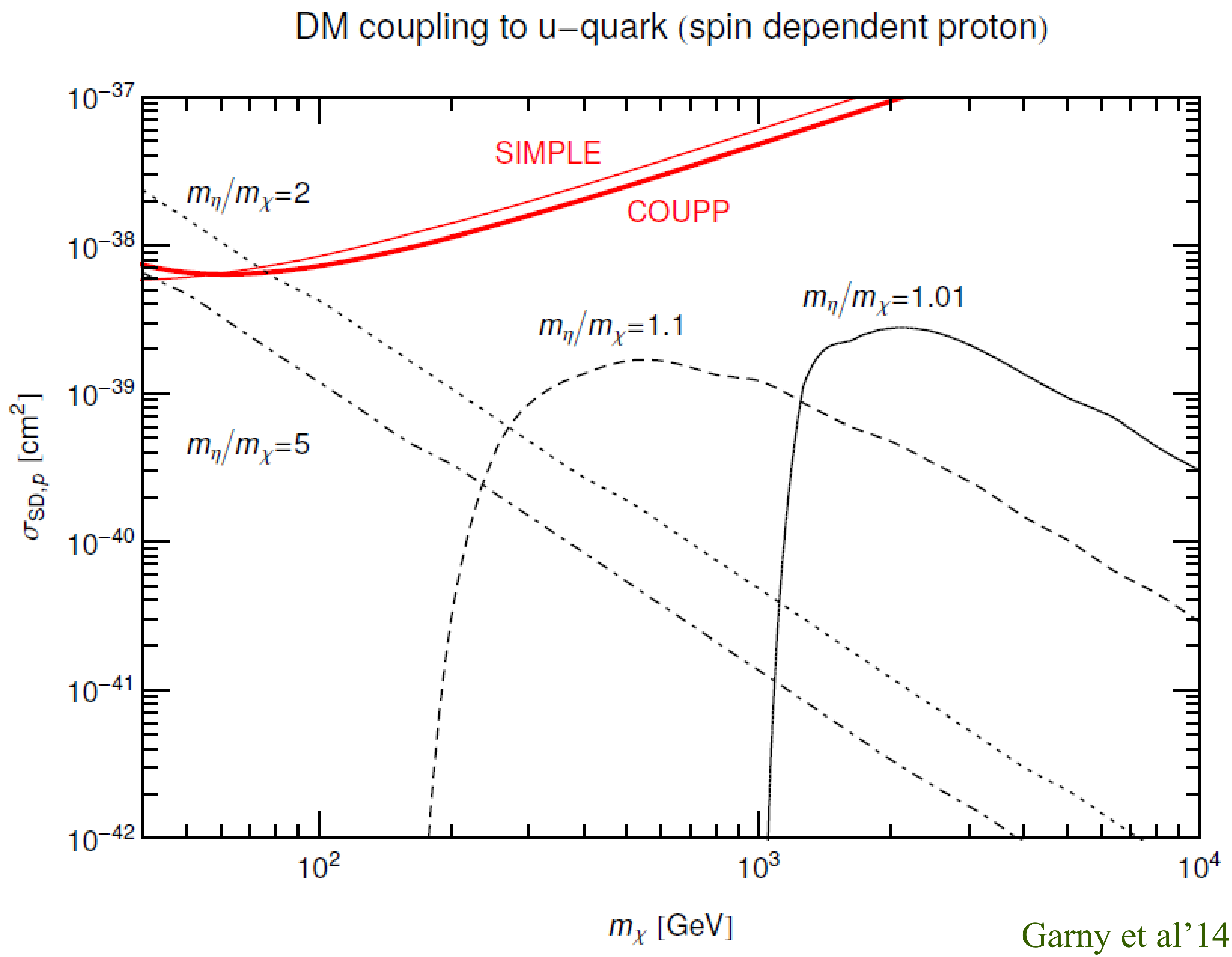
# DM coupling to quarks: spin dependent interaction

Tree level:




$$\mathcal{L}^{\rm SD}_{\rm eff,tree} = -\frac{y^2}{2(m_\eta^2-(m_\chi+m_q)^2)}\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}_R\gamma_\mu\gamma_5 q_R$$

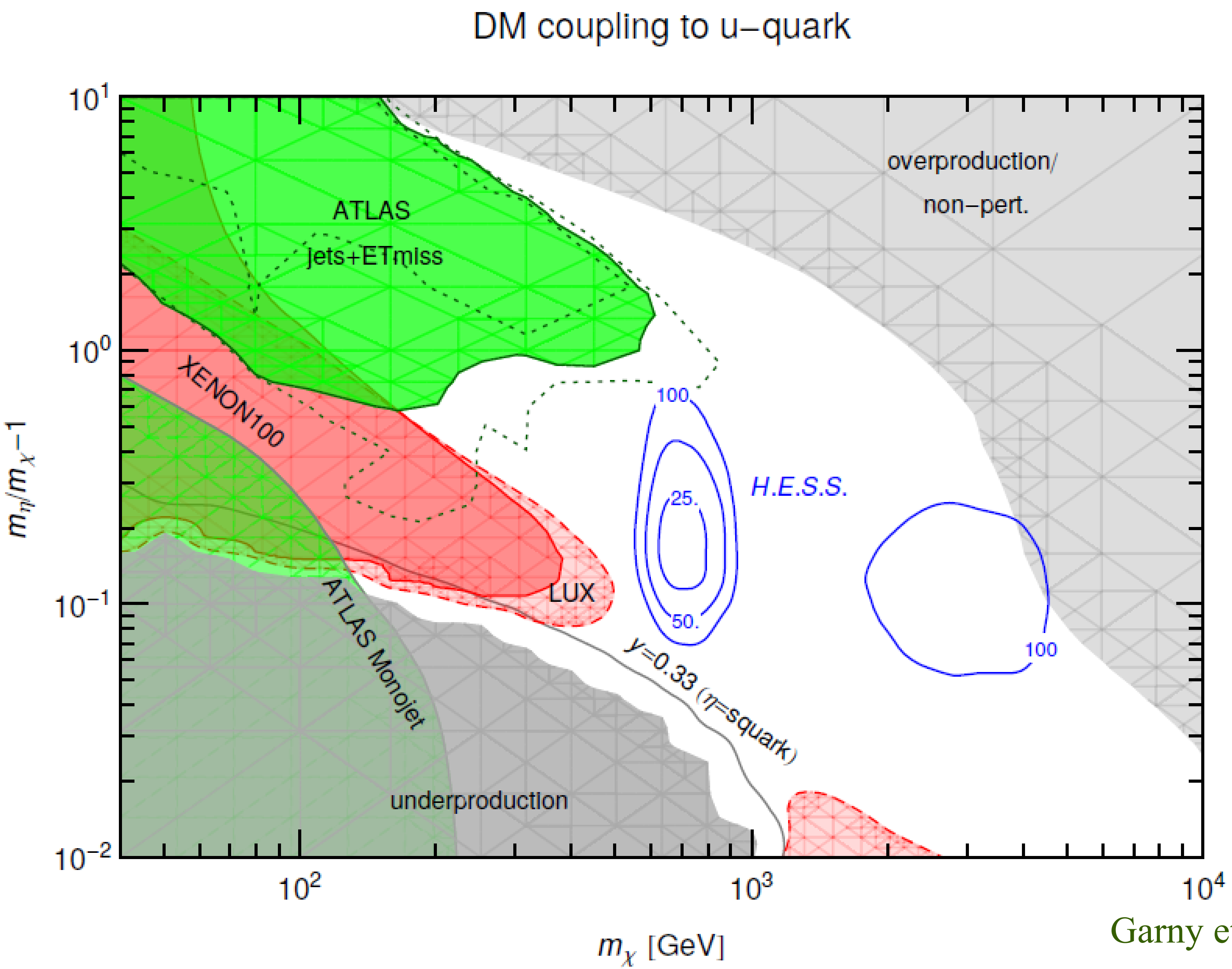
Dim. 6 operator. Singular when $m_\eta \to m_\chi + m_q$




Garny et al'14

# Interplay with direct detection experiments

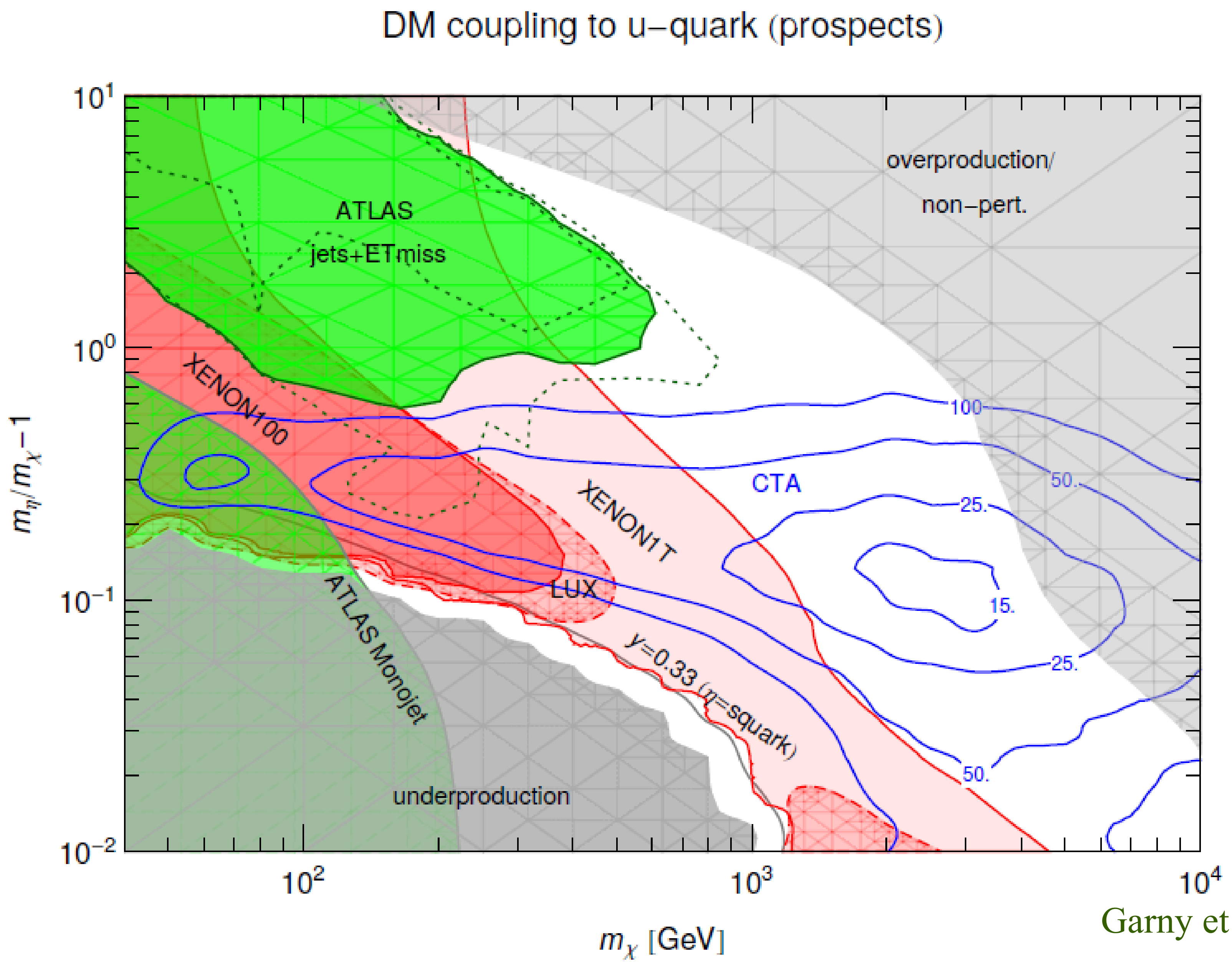
Impact for dark matter produced via thermal freeze-out




Garny et al'14

# Interplay with direct detection experiments

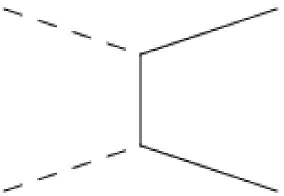
Impact for dark matter produced via thermal freeze-out

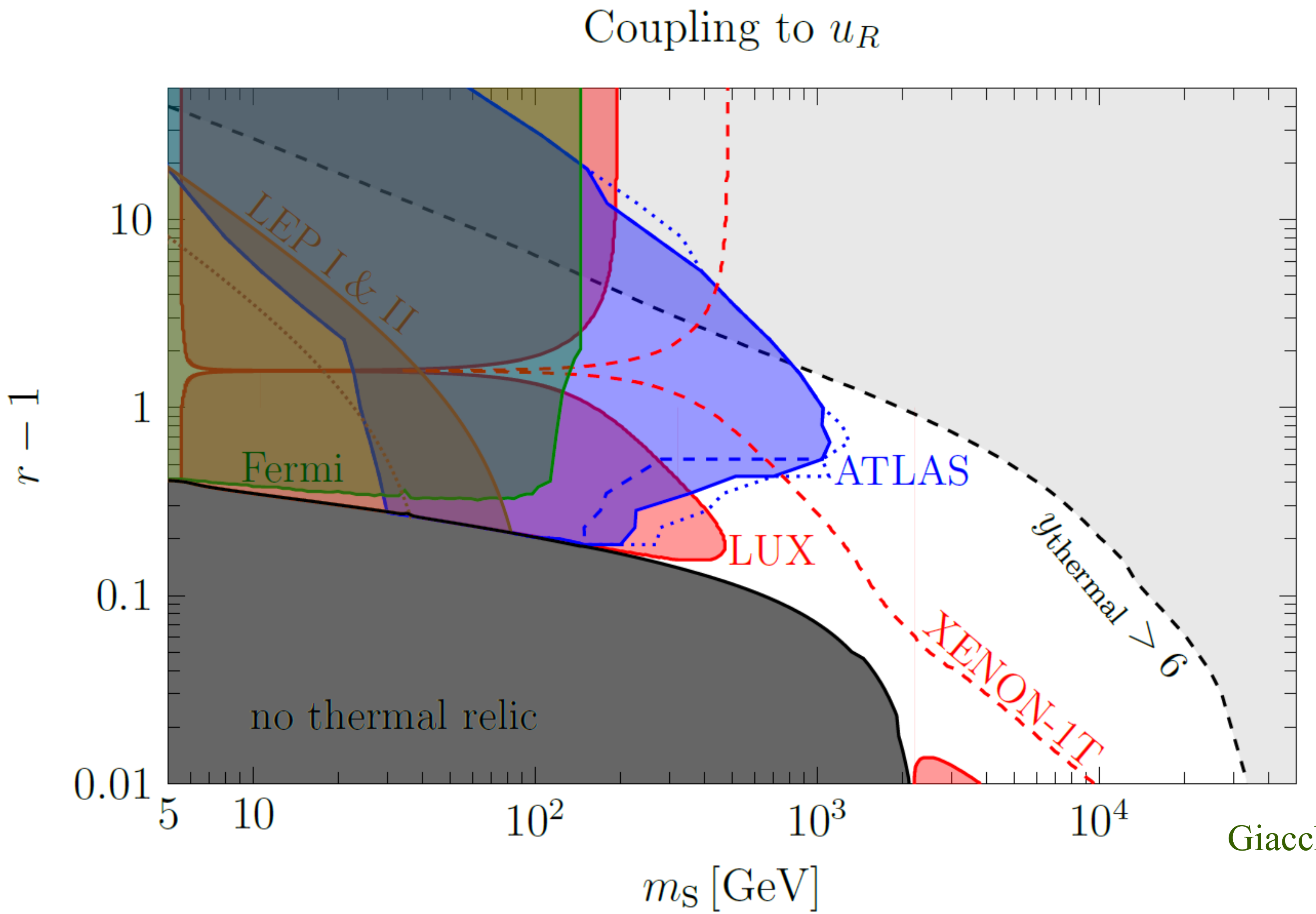



Garny et al'14

# Interplay with direct detection experiments

Scalar dark matter with fermion mediator

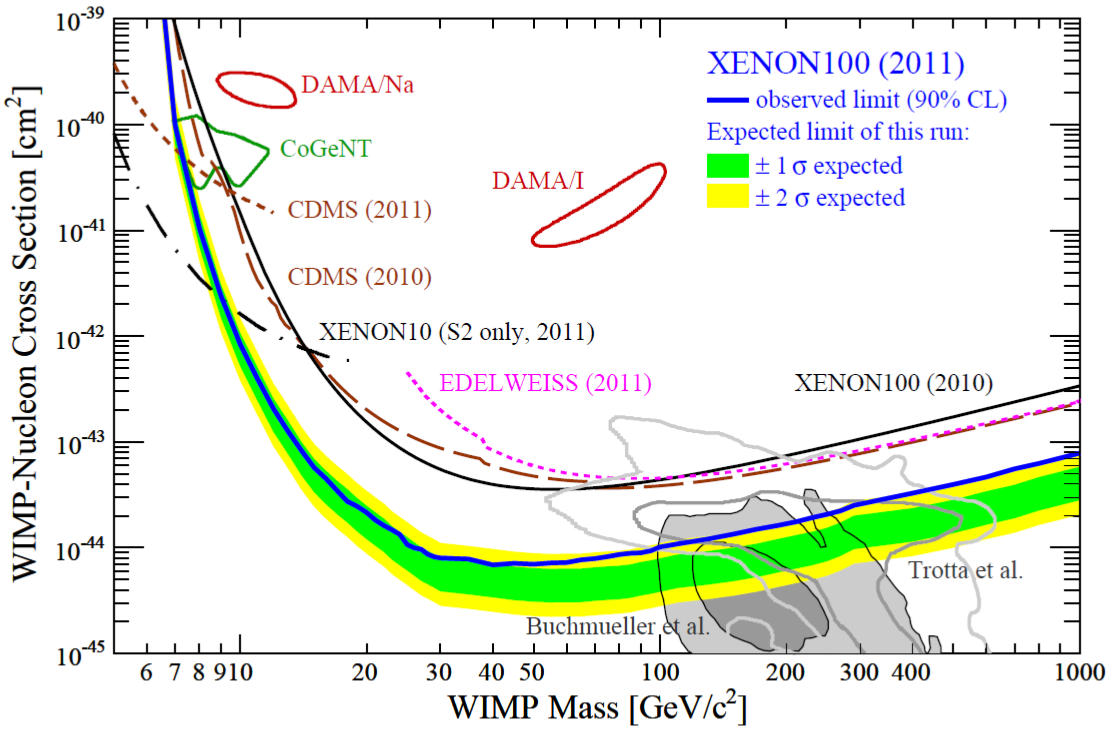





Giacchino et al'15

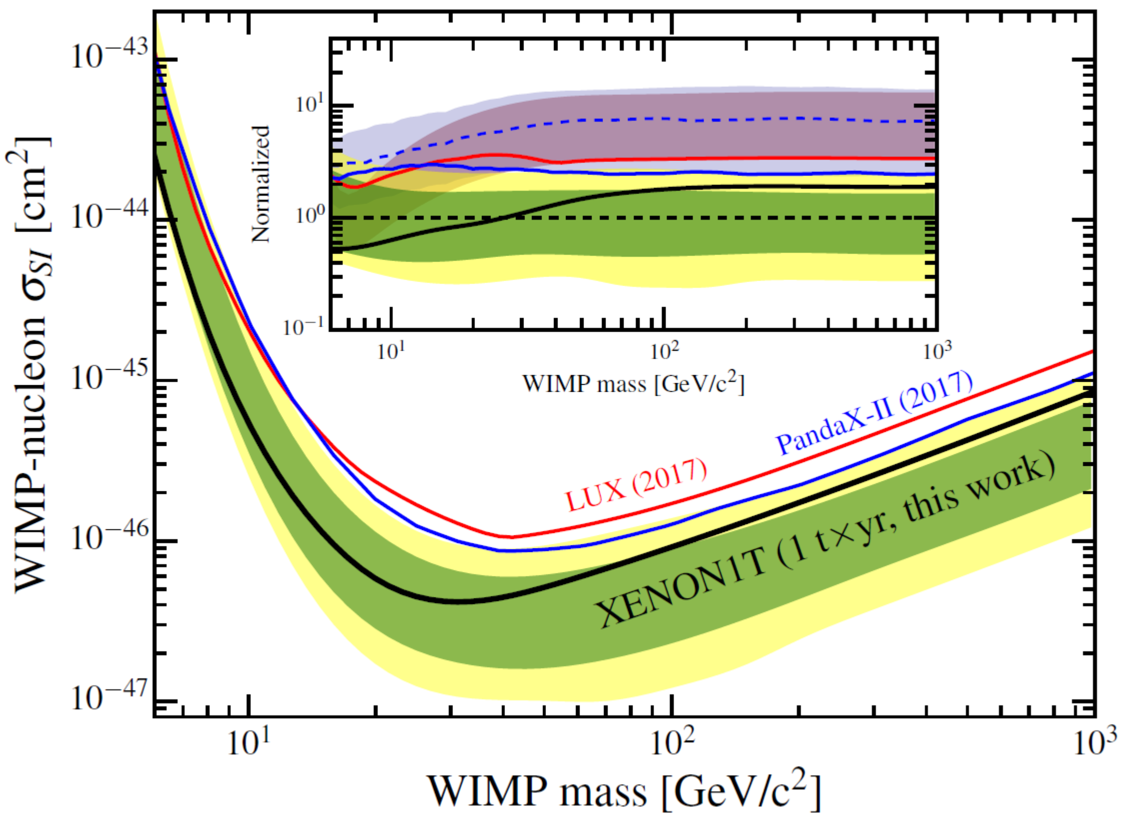
# Collider searches vs. direct detection

- Very fast progress in direct detection experiments.



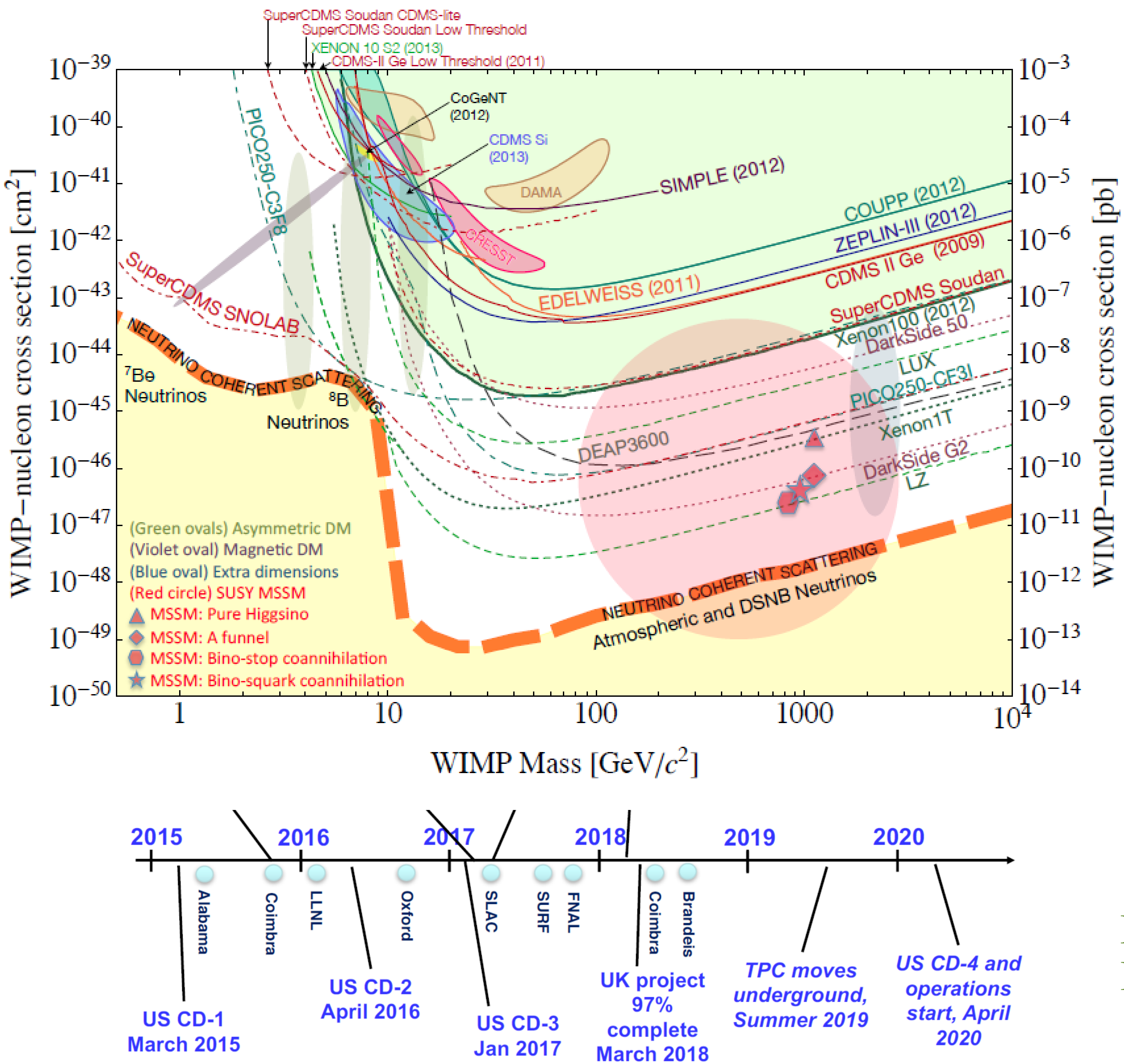
# Collider searches vs. direct detection

- Very fast progress in direct detection experiments.



# Collider searches vs. direct detection

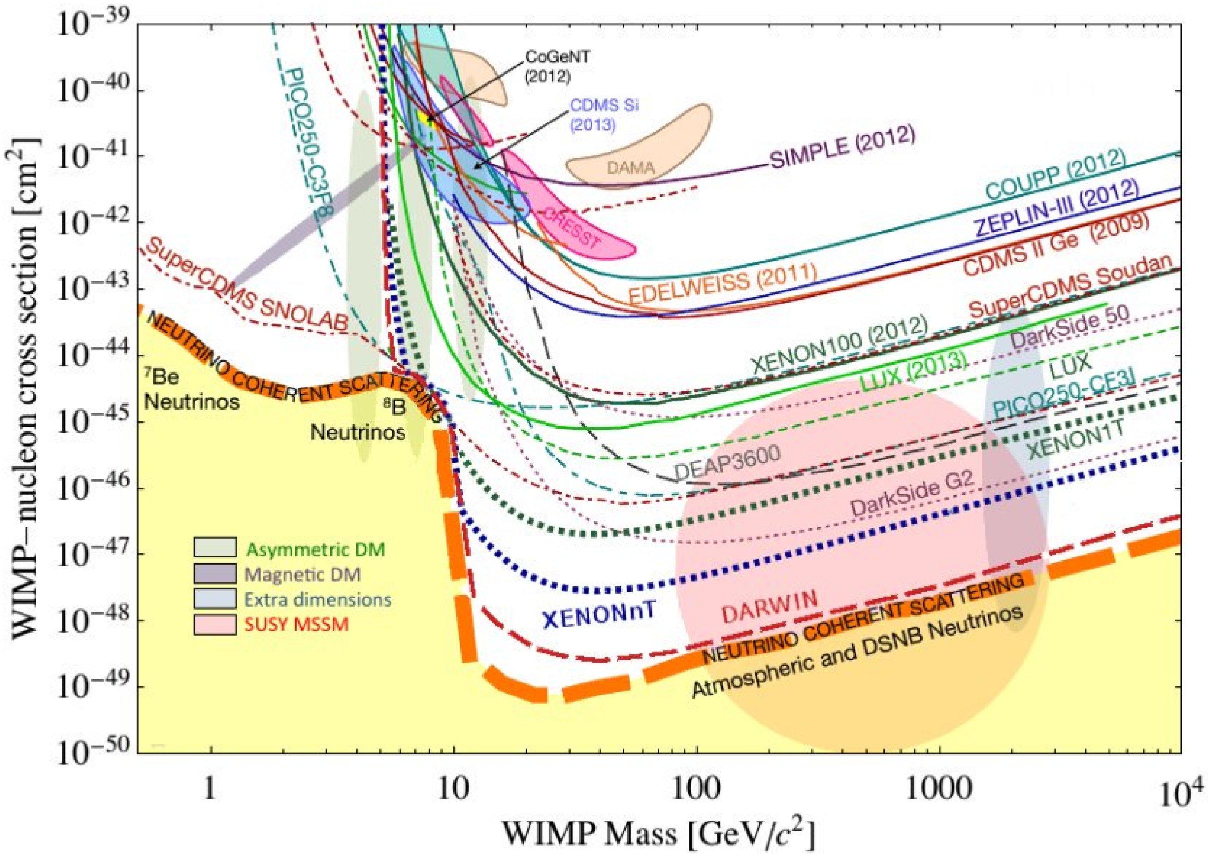
- Very fast progress in direct detection experiments.




LZ coll.
IDM'18

# Collider searches vs. direct detection

- Very fast progress in direct detection experiments.

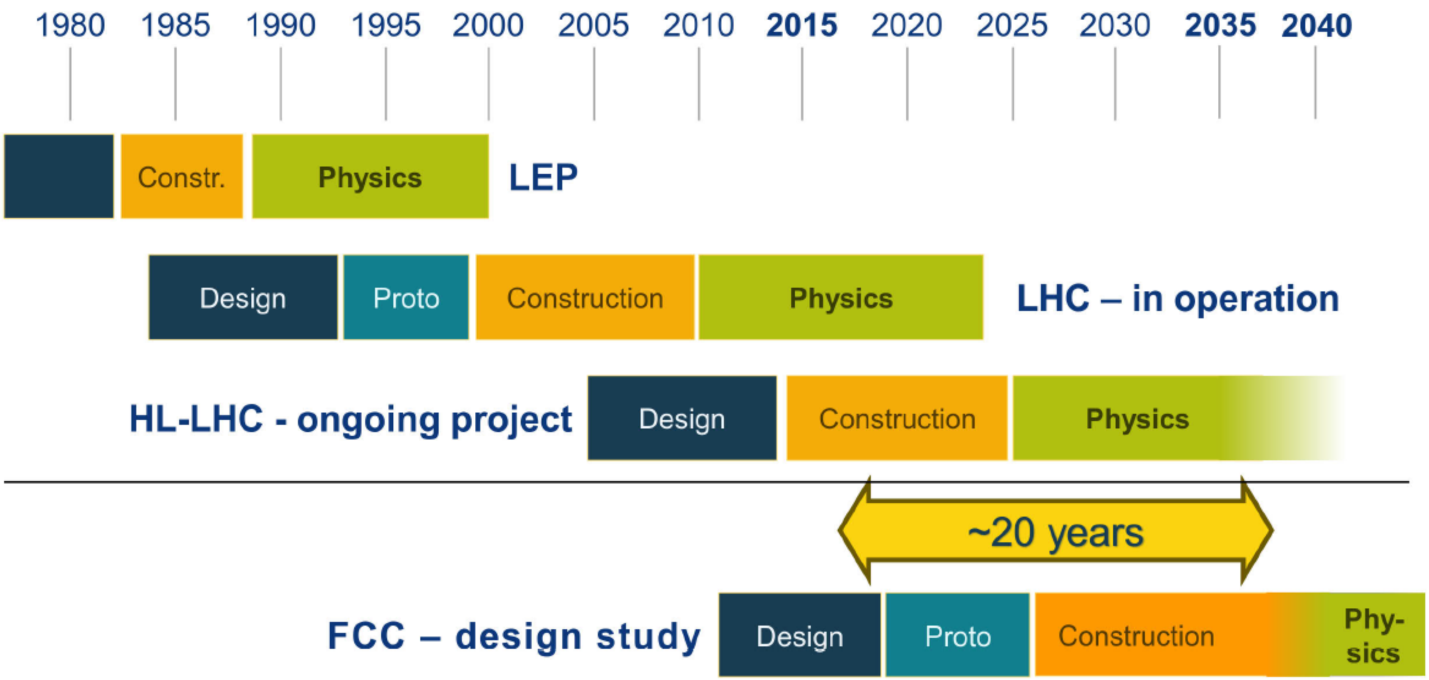



"A first science run could start by 2023"

"DARWIN: towards the ultimate dark matter detector", arXiv:1606.07001

# Collider searches vs. direct detection

• Very fast progress in direct detection experiments. Not so fast in collider searches...



# Collider searches vs. direct detection

- Yet, collider experiments are an invaluable tool probe WIMP dark matter (and new physics in general)

    1) The data are available for analysis.

# Collider searches vs. direct detection

- Yet, collider experiments are an invaluable tool probe WIMP dark matter (and new physics in general)

  1) The data are available for analysis.
  2) The energy and luminosity of the collider are known (no astrophysical uncertainties)

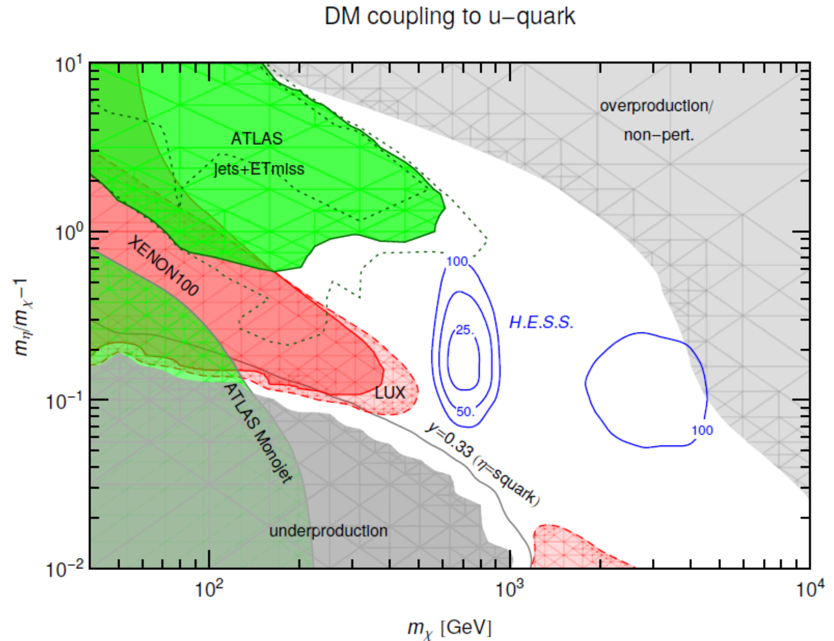
# Collider searches vs. direct detection

- Yet, collider experiments are an invaluable tool probe WIMP dark matter (and new physics in general)
    1) The data are available for analysis.
    2) The energy and luminosity of the collider are known (no astrophysical uncertainties)
    3) May provide information about the dark sector (mediators, couplings…). The DM abundance could (in principle) be reconstructed, providing a test of WIMP production

# Collider searches vs. direct detection

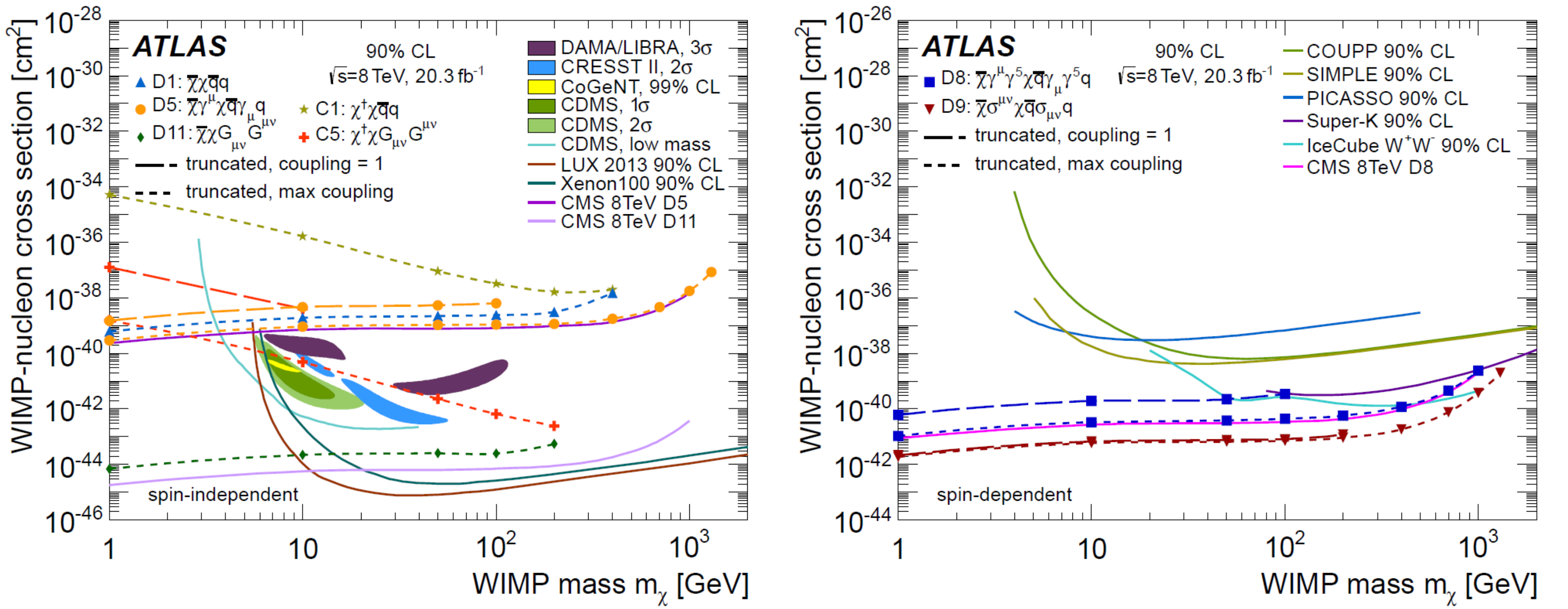
- Yet, collider experiments are an invaluable tool probe WIMP dark matter (and new physics in general)

    1) The data are available for analysis.
    2) The energy and luminosity of the collider are known (no astrophysical uncertainties)
    3) May provide information about the dark sector (mediators, couplings…). The DM abundance could (in principle) be reconstructed, providing a test of WIMP production.
    4) In some scenarios, collider searches probe regions of the parameter space difficult to probe with direct detection (or indirect detection) experiments. Also, they can test possible signals in other experiments.



# Collider searches vs. direct detection

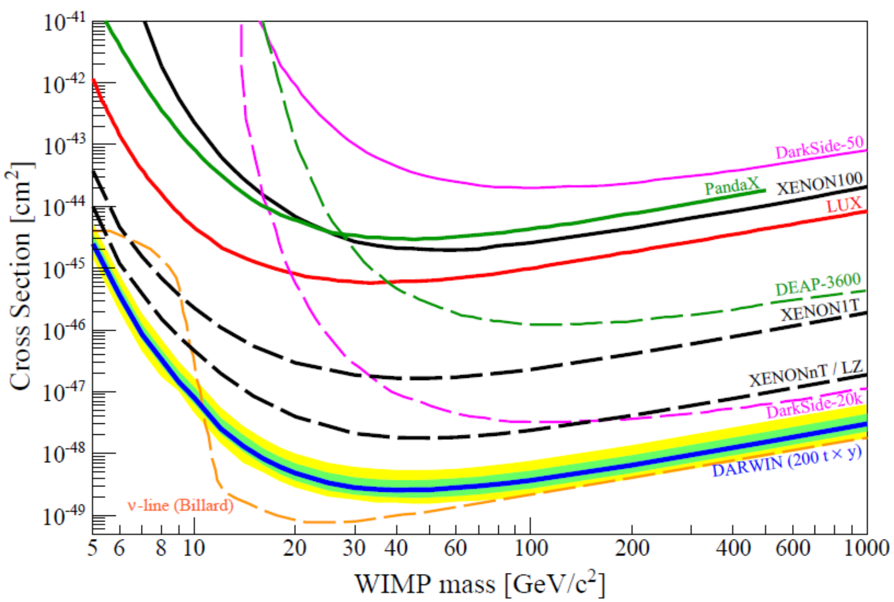
5) Collider experiments provide the best sensitivity to light WIMPs...

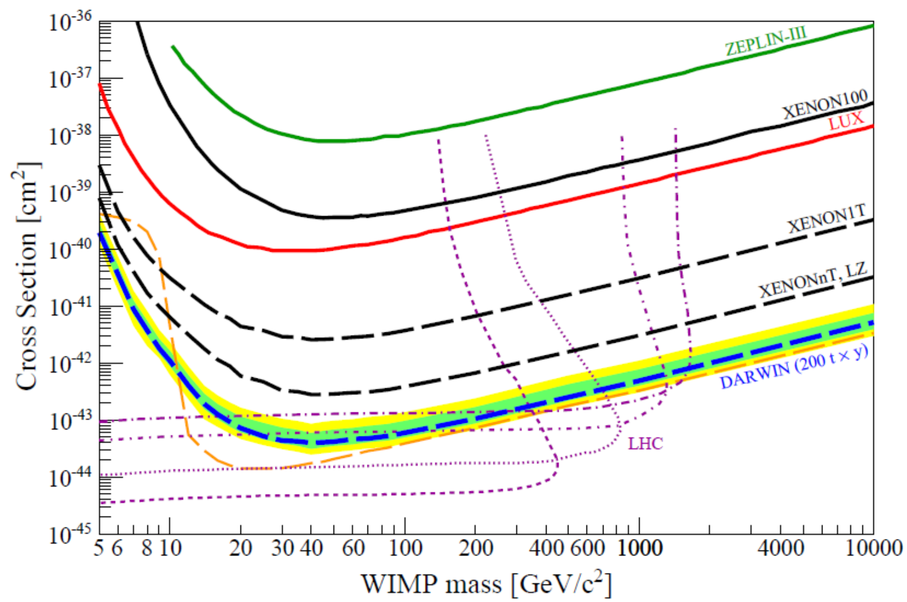


# Collider searches vs. direct detection

5) Collider experiments provide the best sensitivity to light WIMPs...

6) … and in some scenarios, even better sensitivity than the "ultimate" dark matter detectors.



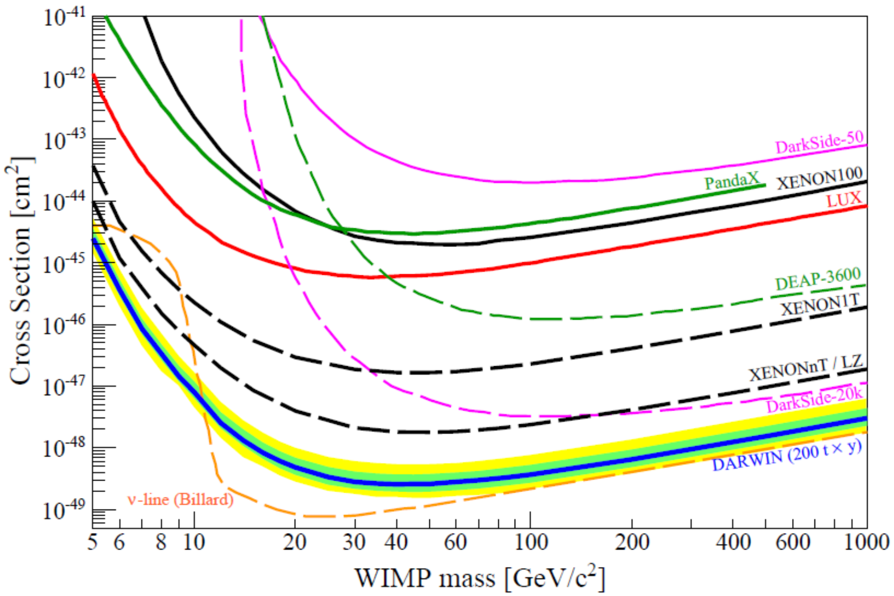

arXiv:1606.07001

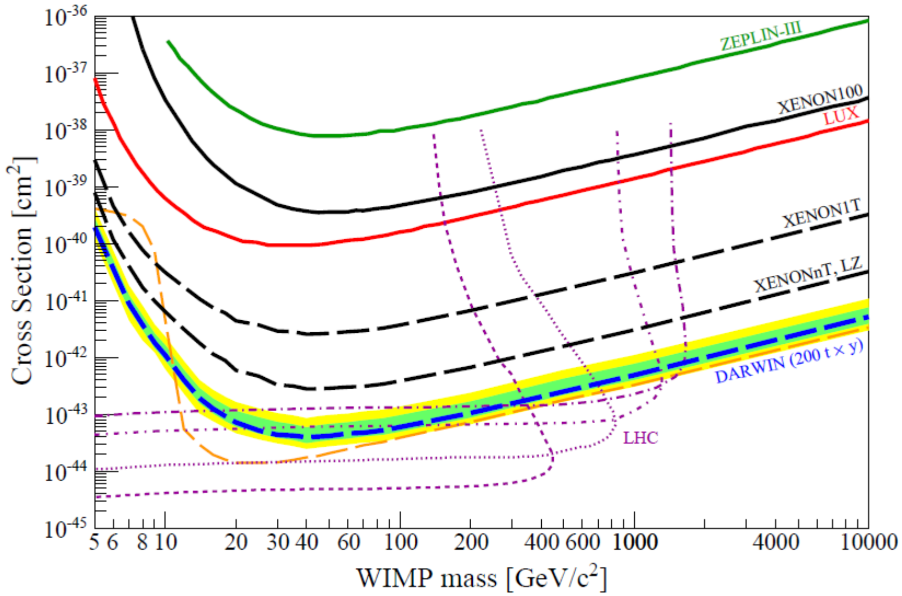
# Collider searches vs. direct detection

5) Collider experiments provide the best sensitivity to light WIMPs...

6) … and in some scenarios, even better sensitivity than the "ultimate" dark matter detectors.

7) … even reaching beyond the "neutrino floor"



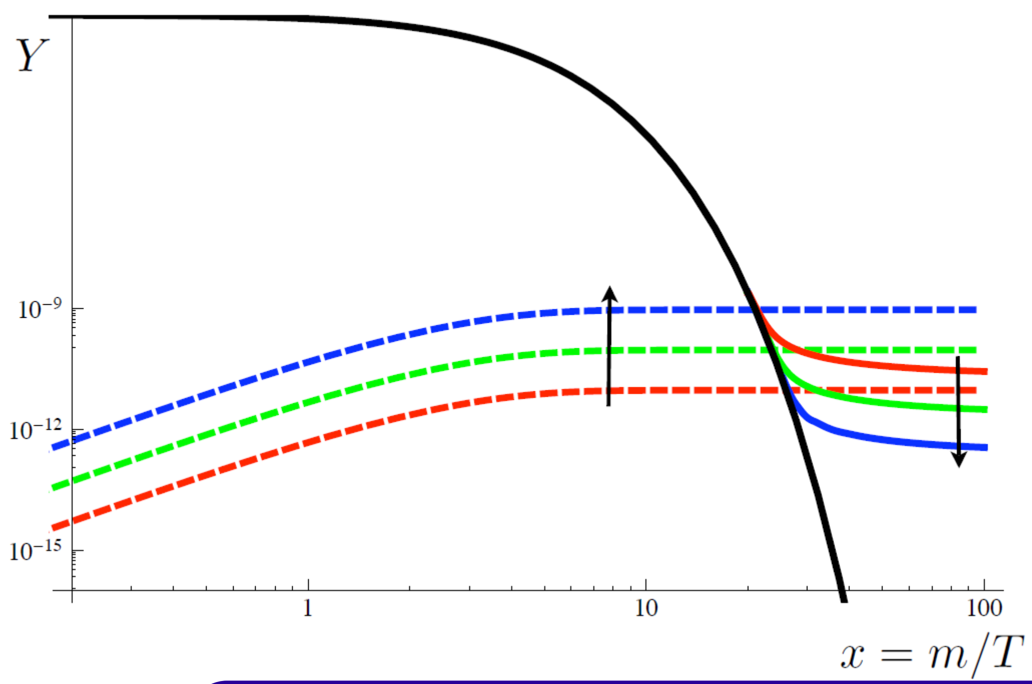

arXiv:1606.07001

# FIMPs at colliders

# The freeze-in mechanism

Feebly interacting massive particles have very weak couplings to the Standard Model particles and were always out of thermal equilibrium.

Yet, they are produced via scatterings/decays in the primeval plasma. (e.g. $h\rightarrow \chi\chi$, or $\eta^{+}\rightarrow l^{+}\chi$). Very slow processes due to the small coupling.




Their number density can only increase, until the plasma is too diluted to allow collisions or the mother particles have disappeared

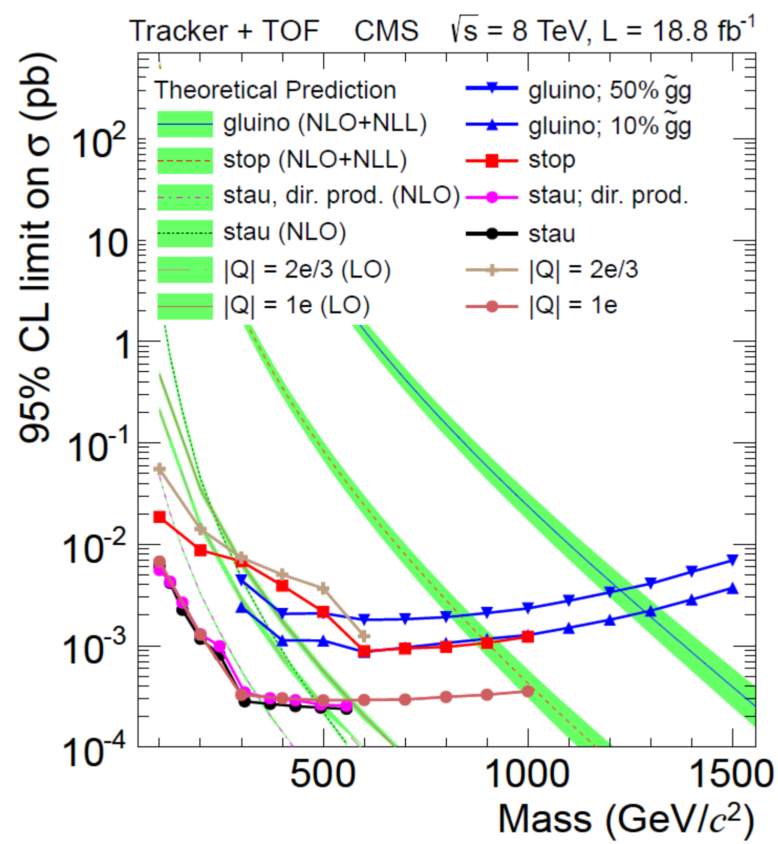
$$\Omega_\chi h^2 \simeq 0.12 \left(\frac{m_\chi}{10\,\mathrm{keV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_S}\right)\left(\frac{y}{2\times 10^{-9}}\right)^2$$

# Searching for FIMP dark matter at the LHC

Consider a FIMP that is produced via decays of a charged scalar particle.

$$c\tau \sim 8.3 \text{ m} \left(\frac{m_\chi}{10\,\text{keV}}\right)\left(\frac{100\,\text{GeV}}{m_\eta^+}\right)$$

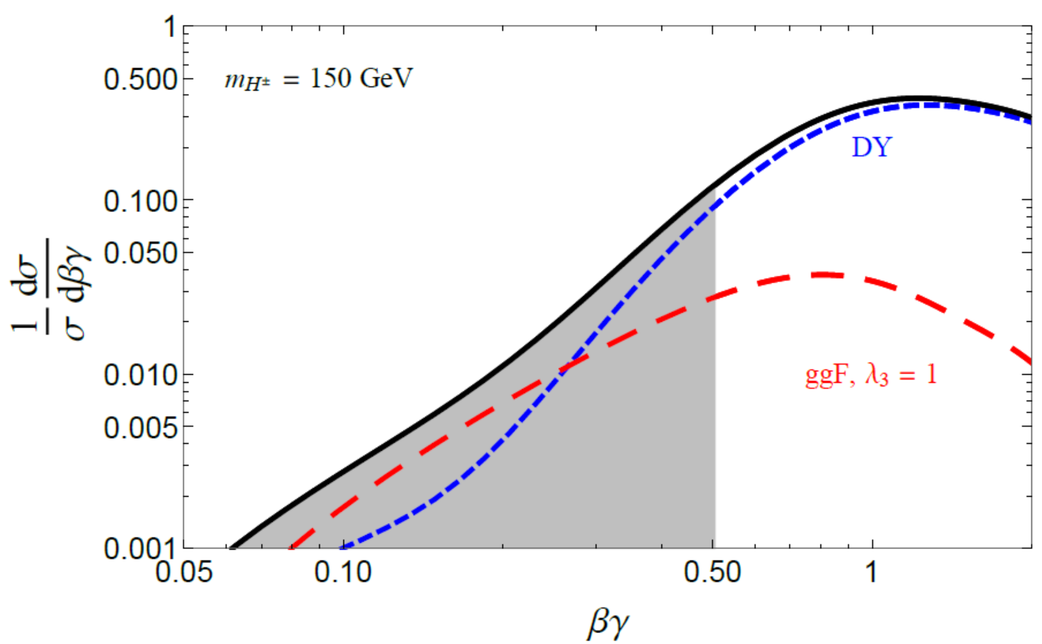
→ Long-lived charged particle.



# Searching for FIMP dark matter at the LHC

Consider a FIMP that is produced via decays of a charged scalar particle.

$$c\tau \sim 8.3\ \mathrm{m} \left(\frac{m_\chi}{10\,\mathrm{keV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_\eta^+}\right)$$




A fraction of the charged scalars gets trapped in the detector, and decays at late times.

# Conclusions

- Dark matter in the form of Weakly Interacting Massive Particles is among the best motivated scenarios for Physics beyond the Standard Model. Bonus: it is testable, now, in various ways.
- The LHC is complementary in many ways to direct and indirect WIMP searches. It's free of astrophysics uncertainties and may provide deeper insights on the dark sector.
- Moreover, in some scenarios the LHC constitutes the best probe to WIMP dark matter (e.g. light WIMPs). High discovery potential. The role of colliders will increase if direct detection experiments reach the neutrino floor without observing signals.
- The LHC can also probe non-WIMP dark matter scenarios, e.g. FIMPs.