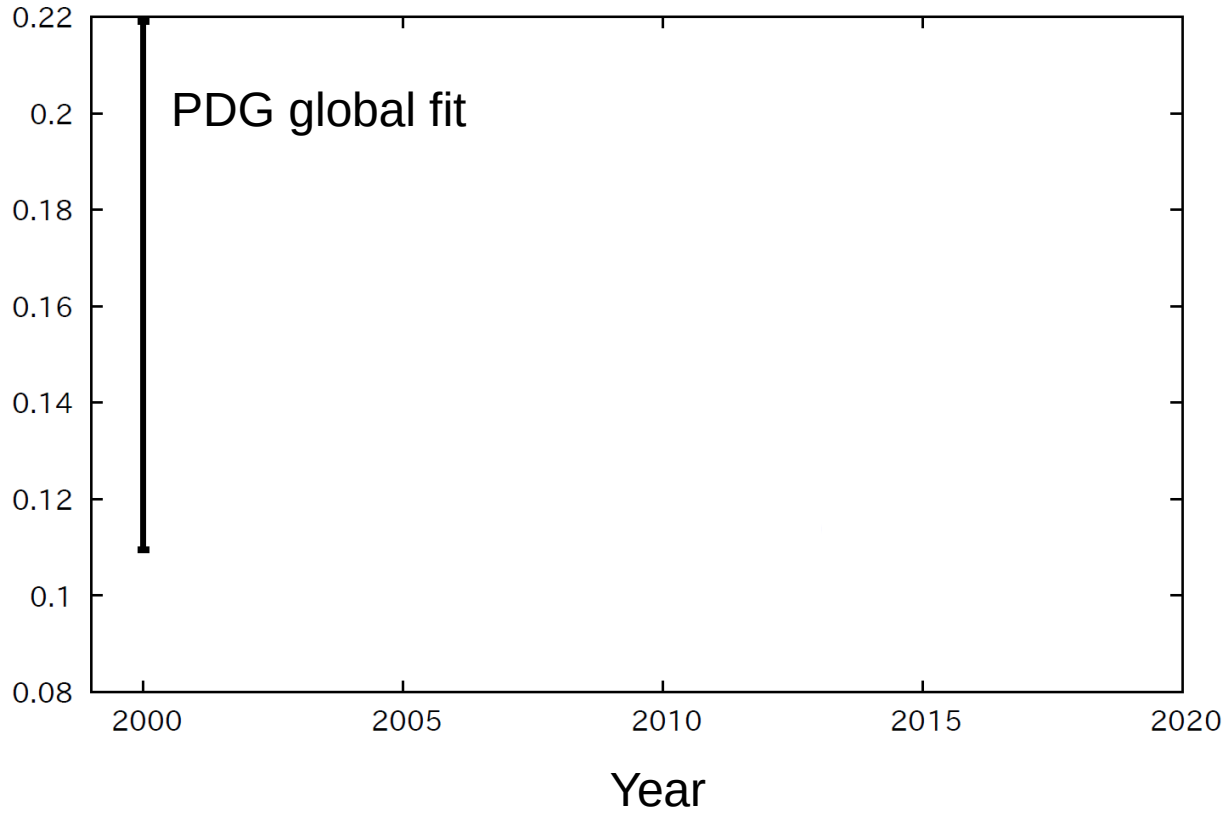
Advancements and Prospects in WIMP Dark Matter Detection

Satoshi Shirai (Kavli IPMU)

Precise DM Abundance

$\Omega_{\rm DM}^{\rm obs} h^2$



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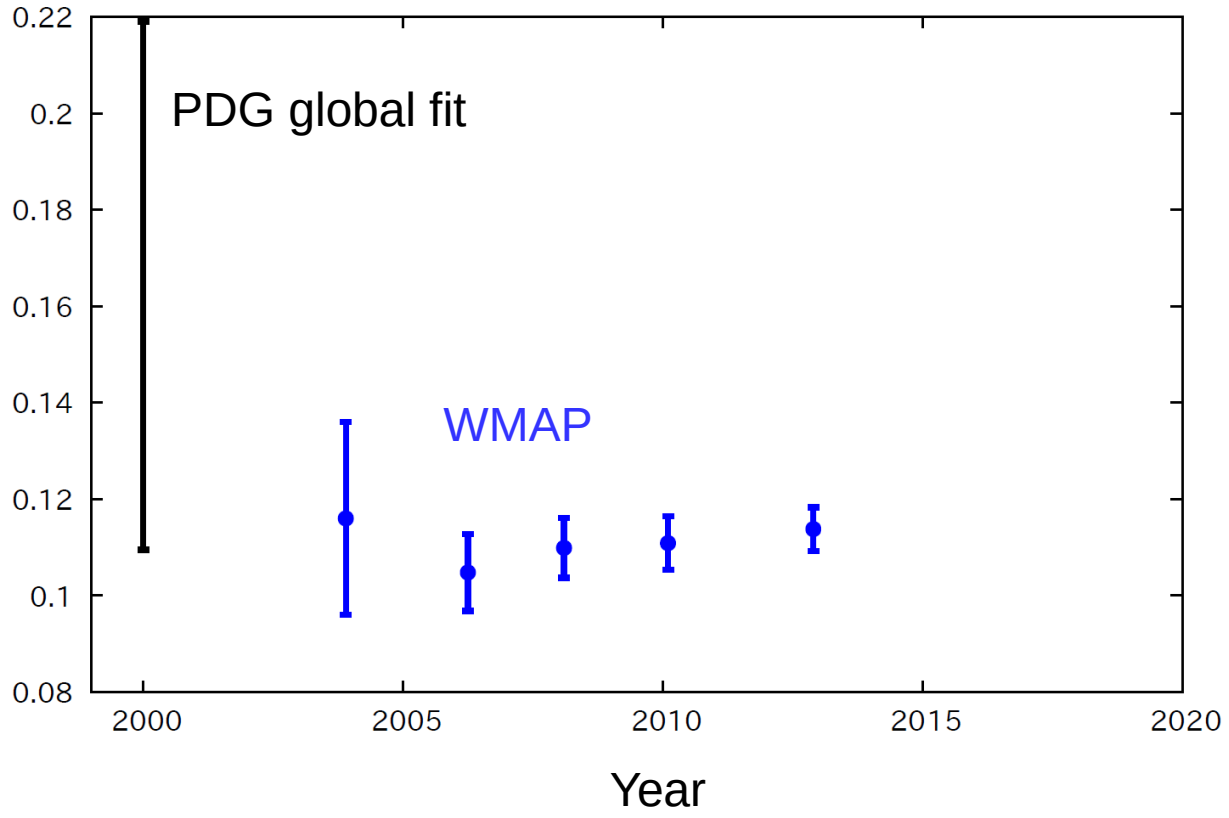

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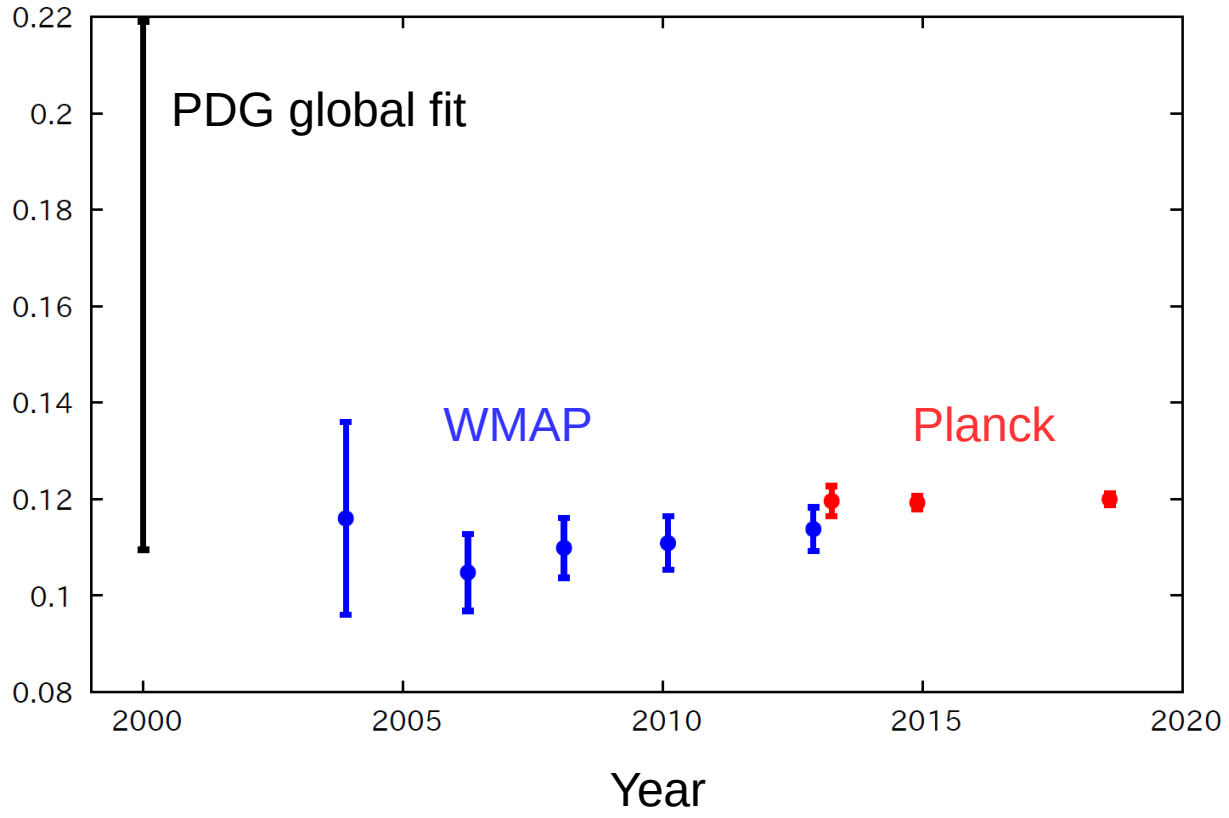

Precise DM Abundance

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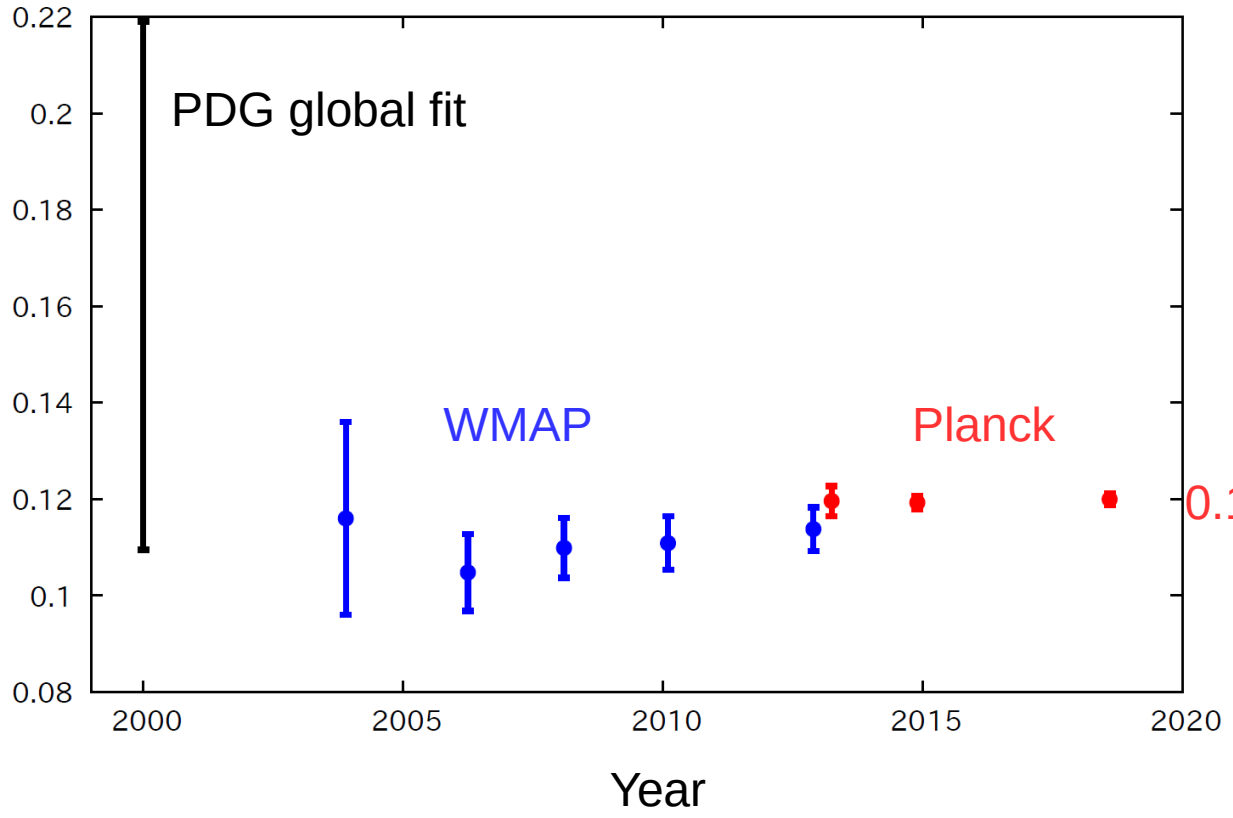

Precise DM Abundance

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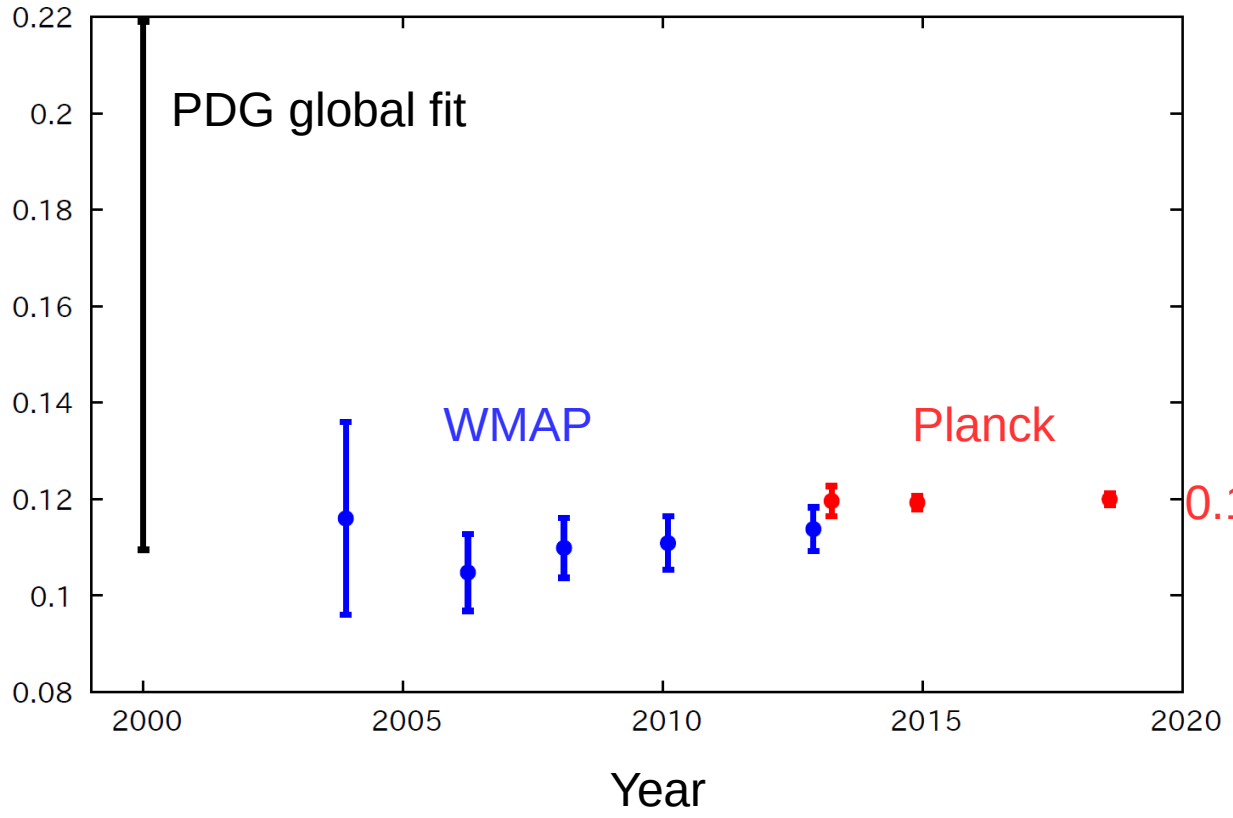


Q: What is Dark Matter?

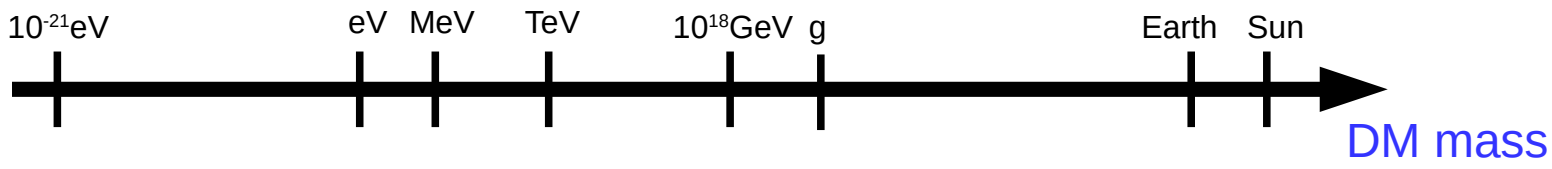
DM Should be...

- Stable.
- Weakly Interacting.
- Cold.
- Production mechanism.

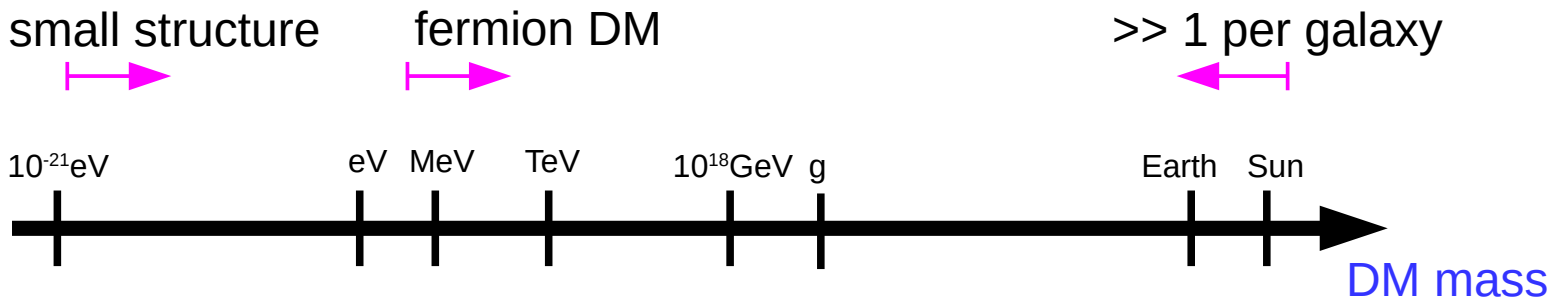
  20% of total energy of Universe

$$\Omega_{\mathrm{DM}} \sim 0.2$$

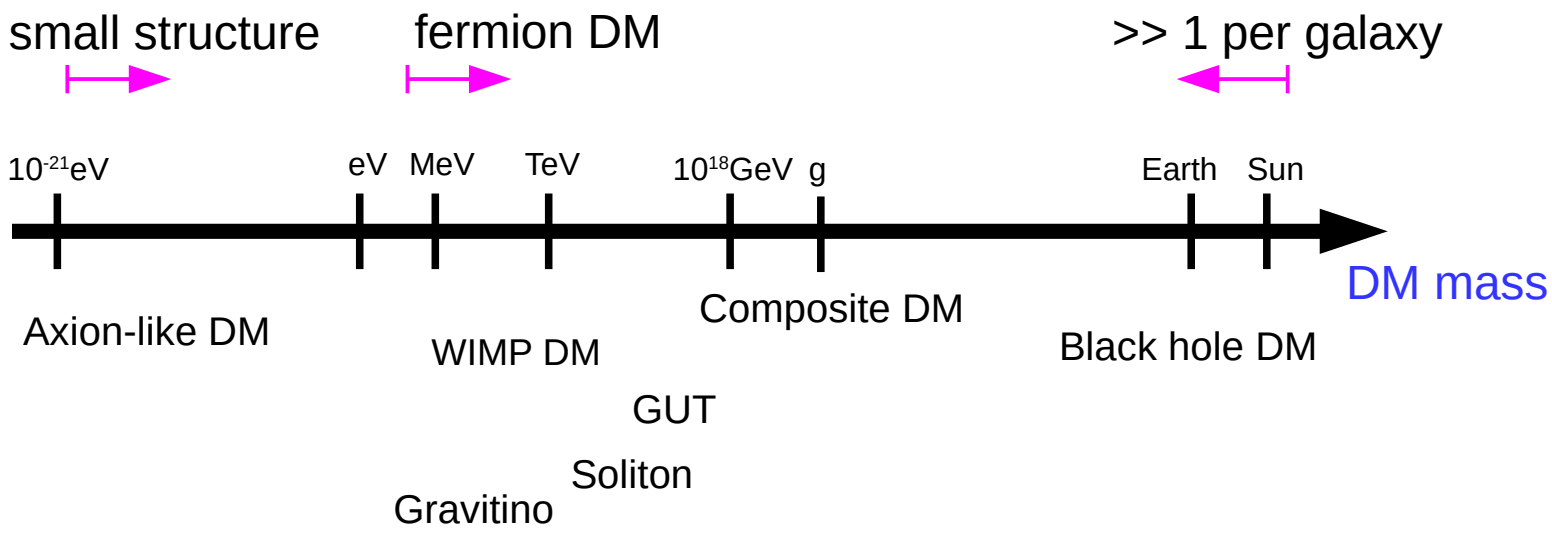
DM Landscape



DM Landscape



DM Landscape



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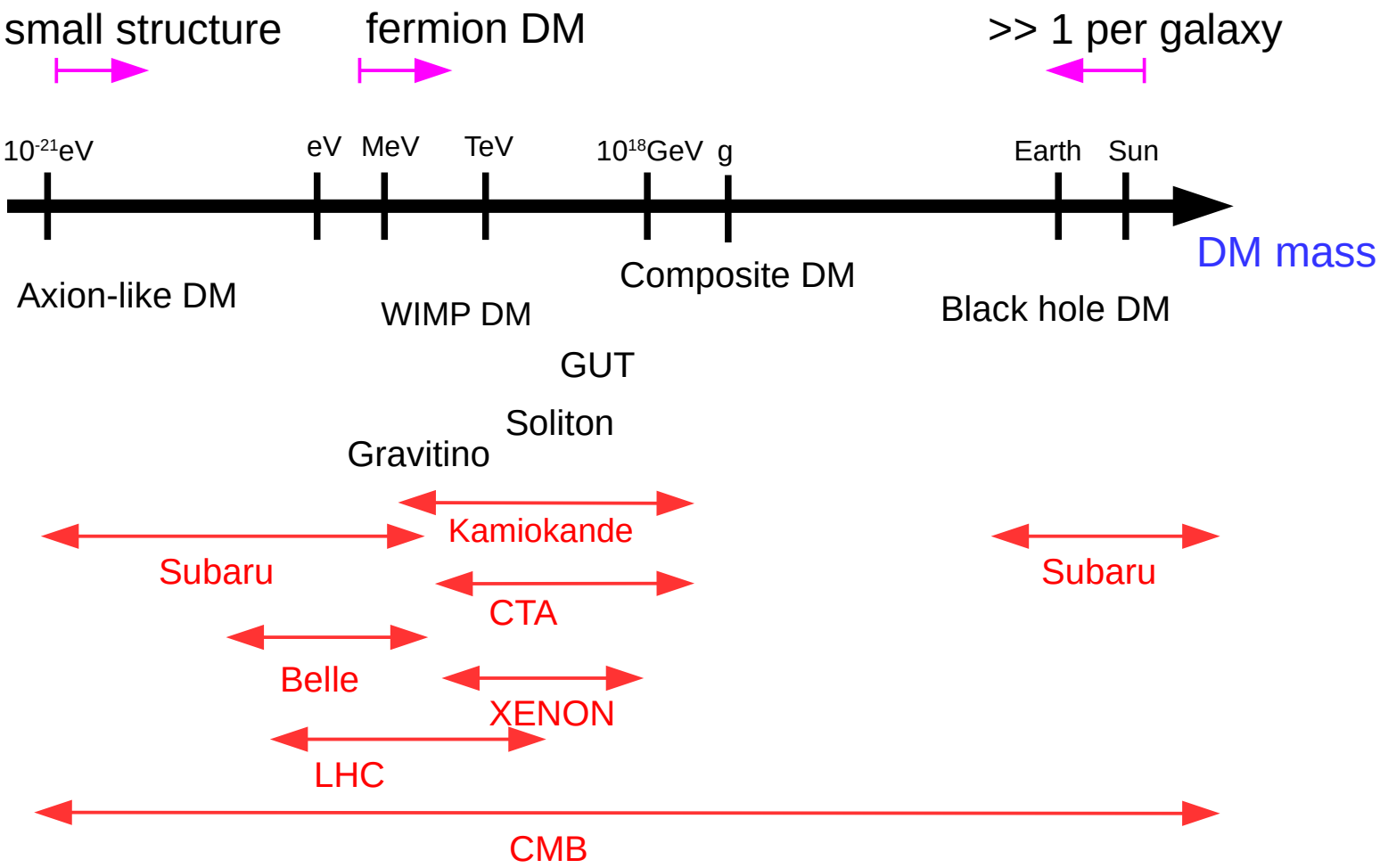

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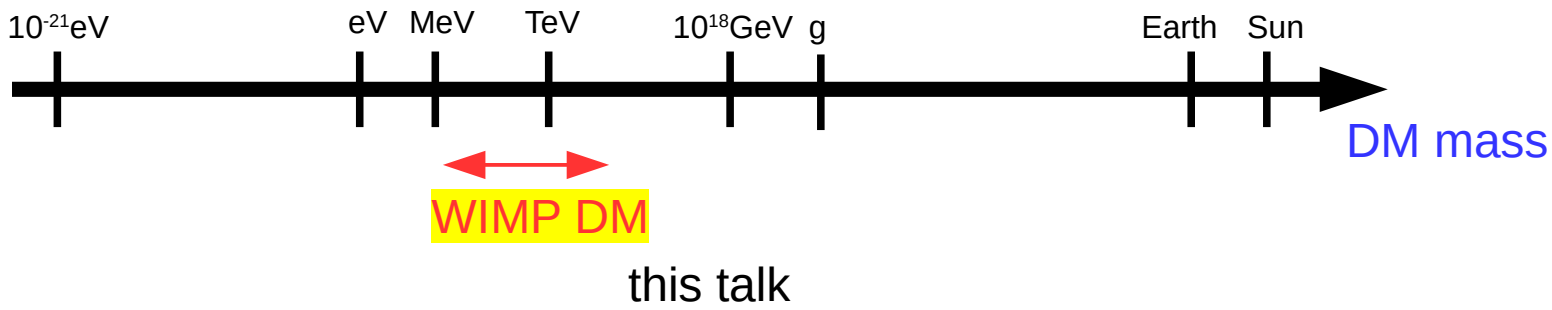


WIMP (Weakly Interacting Massive Particle):

MeV → 100 TeV scale.

New physics at weak scale likely includes WIMP candidates.

Contents

1. WIMP
   - Abundance, detection
   - WIMP with minimal setup

2. Higgs-portal
   - Scalar DM coupling to Higgs

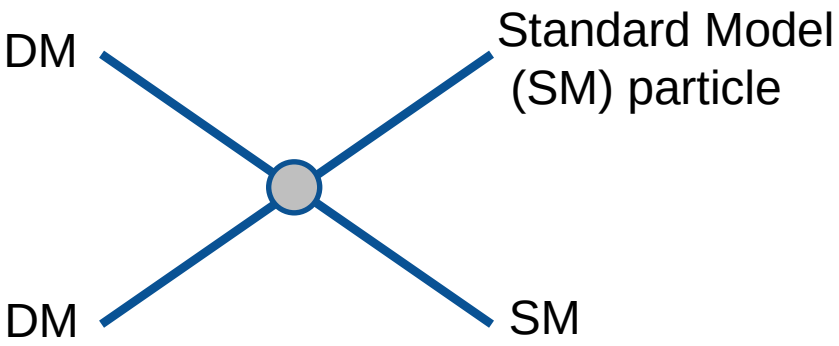
3. Gauge-portal
   - Gauge Interacting Fermion (Wino)

4. Summary

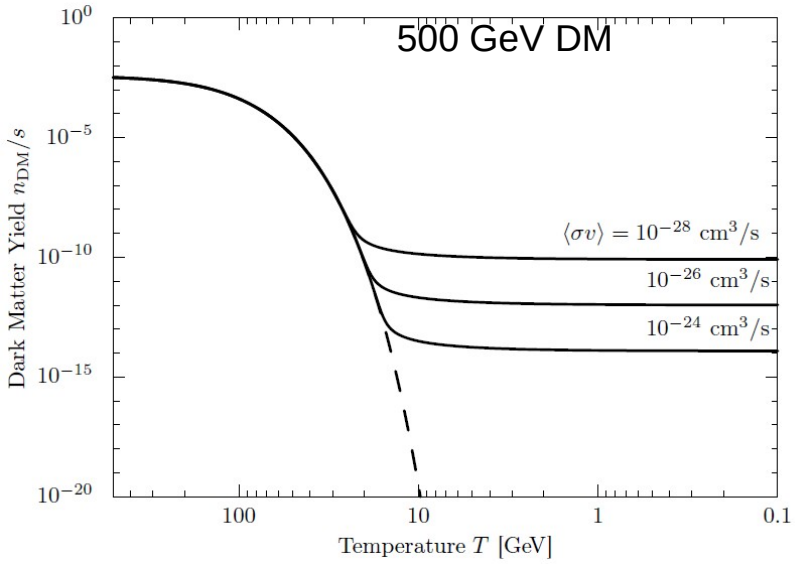
WIMP

WIMP Dark Matter

Weakly Interacting Massive Particle



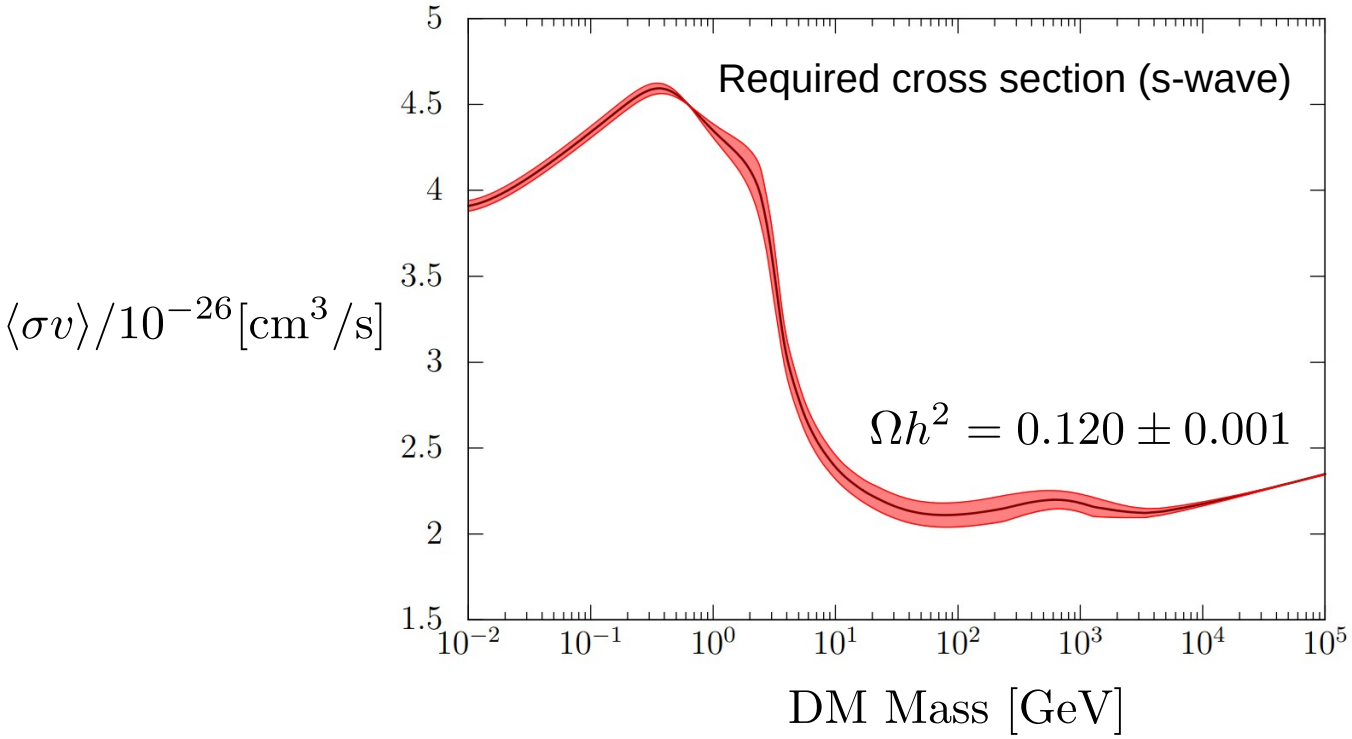
DM abundance



Time

WIMP Cross Section

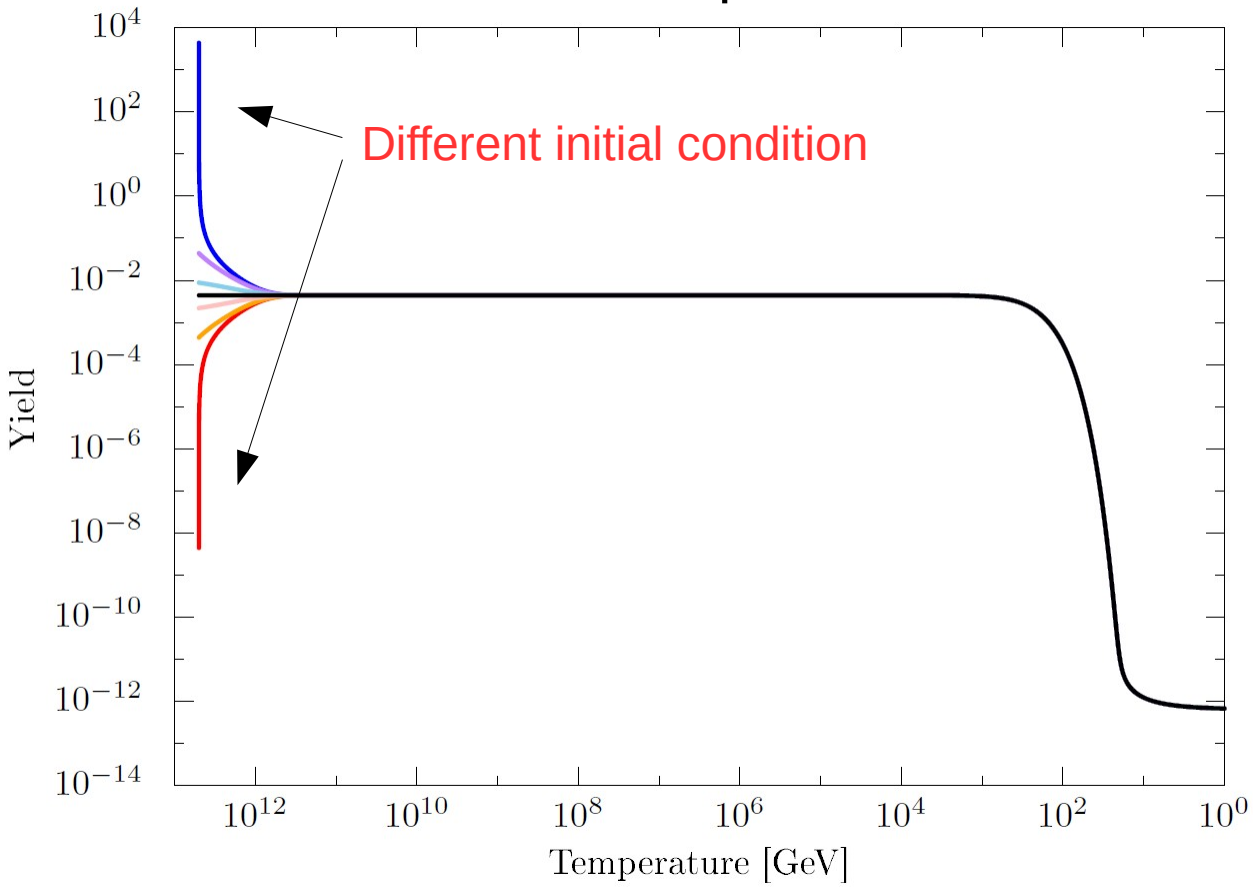
$$\Omega_{\rm DM} h^2 \simeq 0.1 \left(\frac{\langle \sigma v \rangle}{10^{-26}\ {\rm cm}^3/{\rm s}} \right)^{-1}$$



WIMP Dark Matter

DM Yield n/s

Independent on the initial condition.

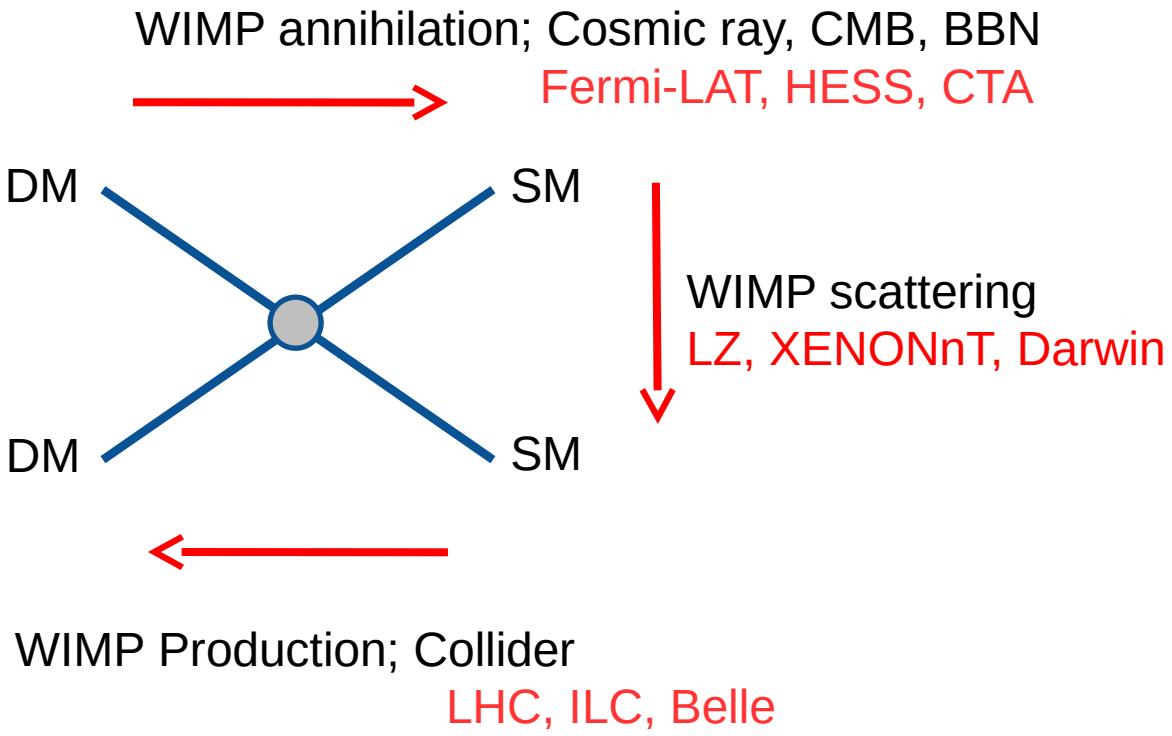


WIMP Advantage

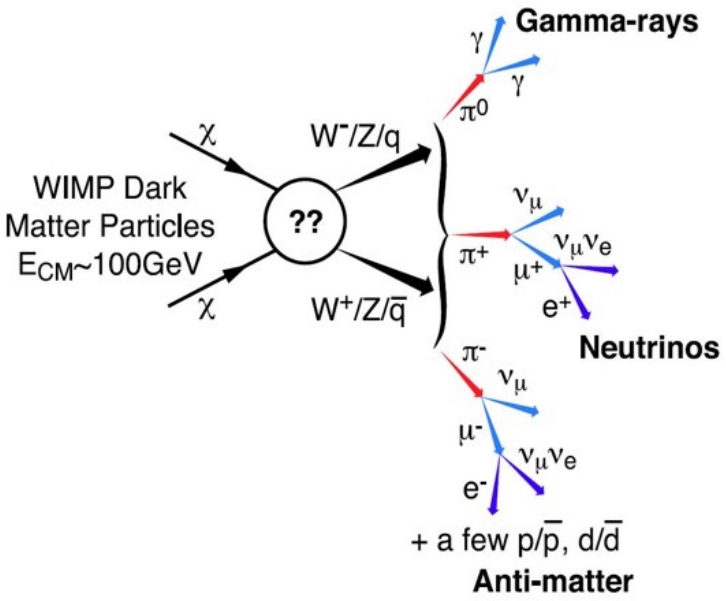
- Initial condition independence.
- Cross section can be calculated from IR input.

Verification through terrestrial experiments.

WIMP Detection



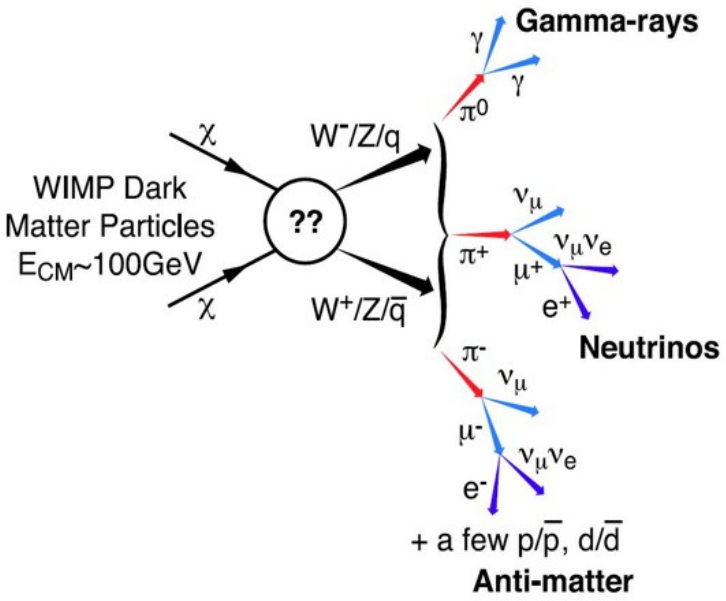
Indirect Detection



Cosmic-ray flux

$$\Psi(E) = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN_{\gamma,\mathrm{ann}}}{dE} \int ds \rho_\chi^2[\vec{r}(s)]$$

Indirect Detection



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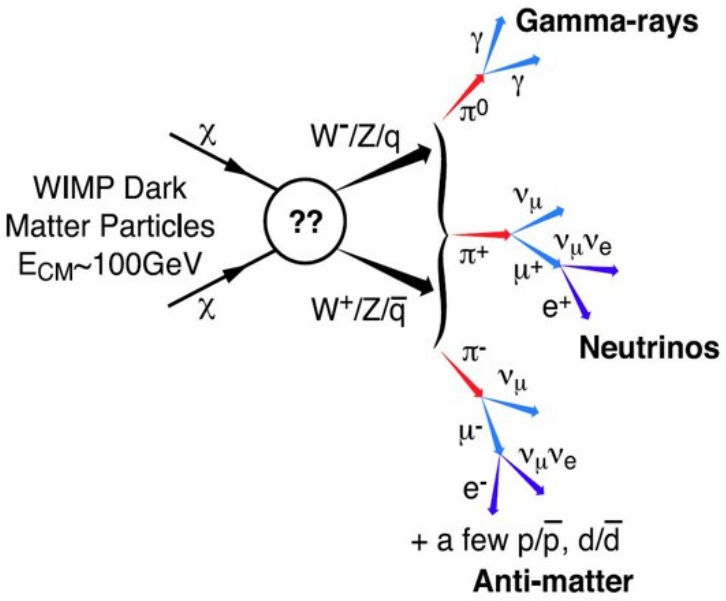
Particle physics

Astrophysics

$$\Omega_{\mathrm{DM}} \simeq 0.2 \left(\frac{\langle \sigma v \rangle}{10^{-26}\ \mathrm{cm}^3/\mathrm{s}} \right)^{-1}$$

Indirect Detection



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Particle physics Astrophysics

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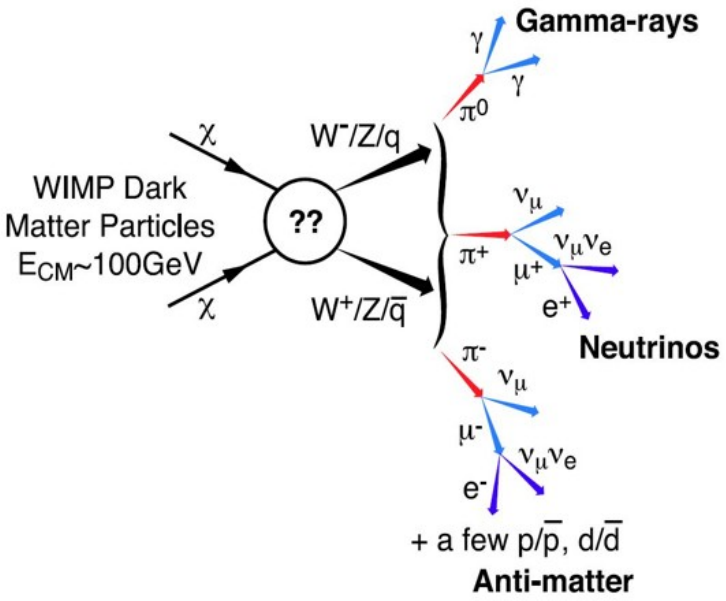
- DM lives everywhere:
  - Galactic center (GC)
  - Dwarf spheroidal galaxy (dSph)
  - Galaxy cluster
  - …

Indirect Detection



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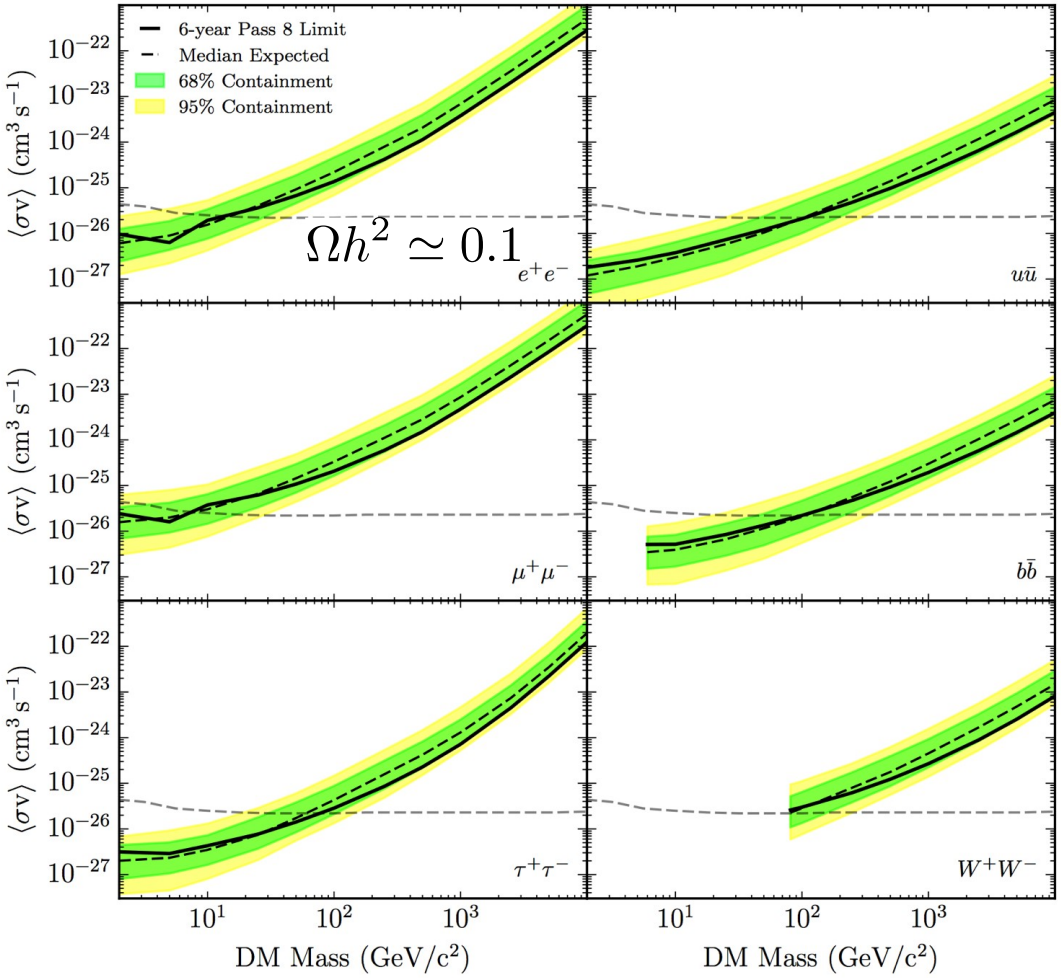
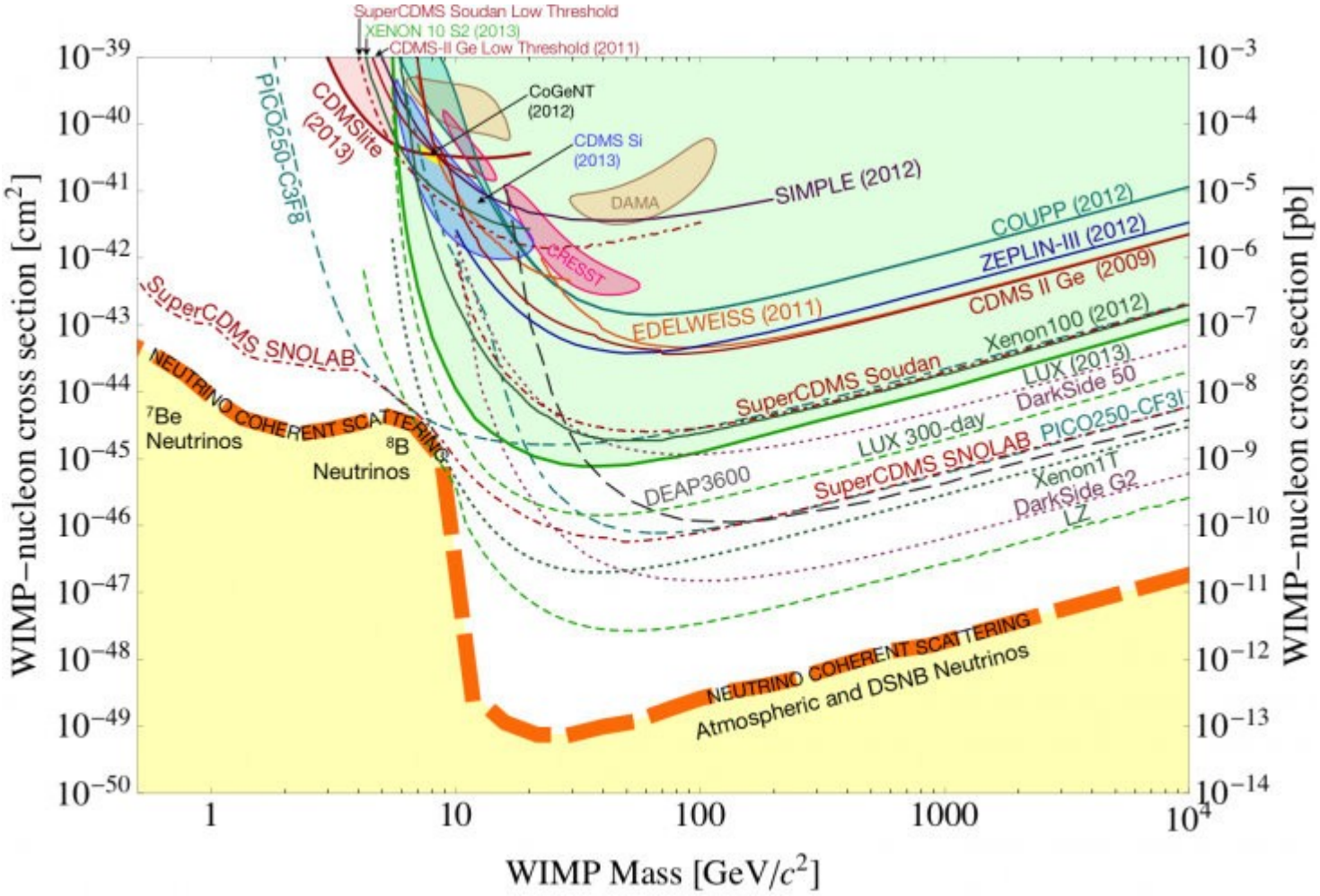
- DM lives everywhere:
  - Galactic center (GC)
  - Dwarf spheroidal galaxy (dSph)
  - Galaxy cluster
  - …
- Large astrophysical uncertainty.

Indirect Detection and Abundance

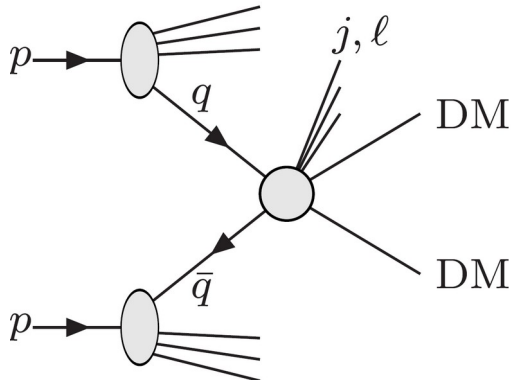
Constraint by Fermi-LAT



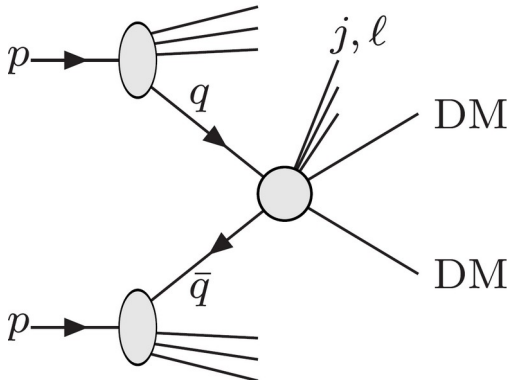
Direct Detection

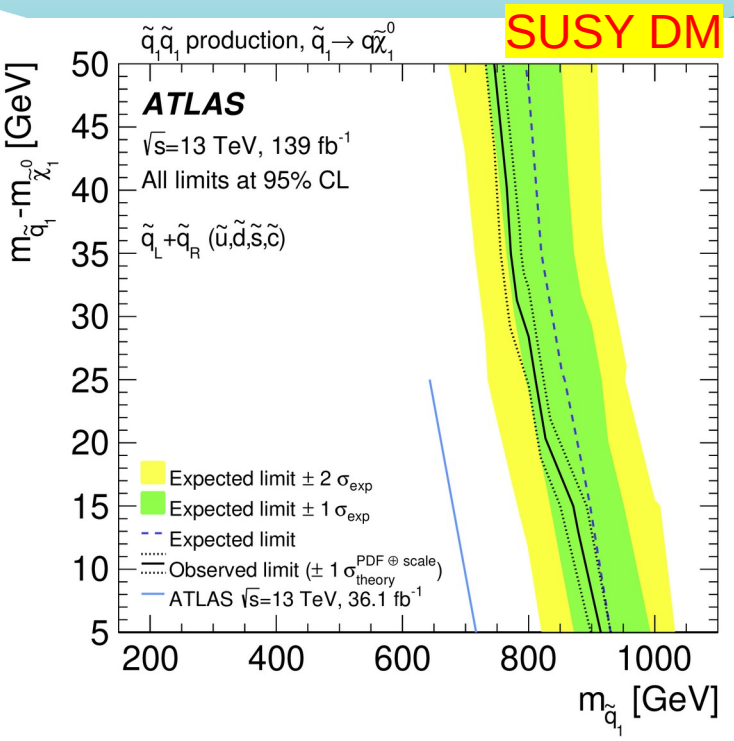


Collider

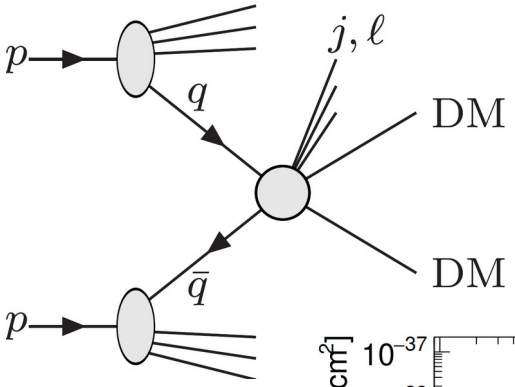


Collider

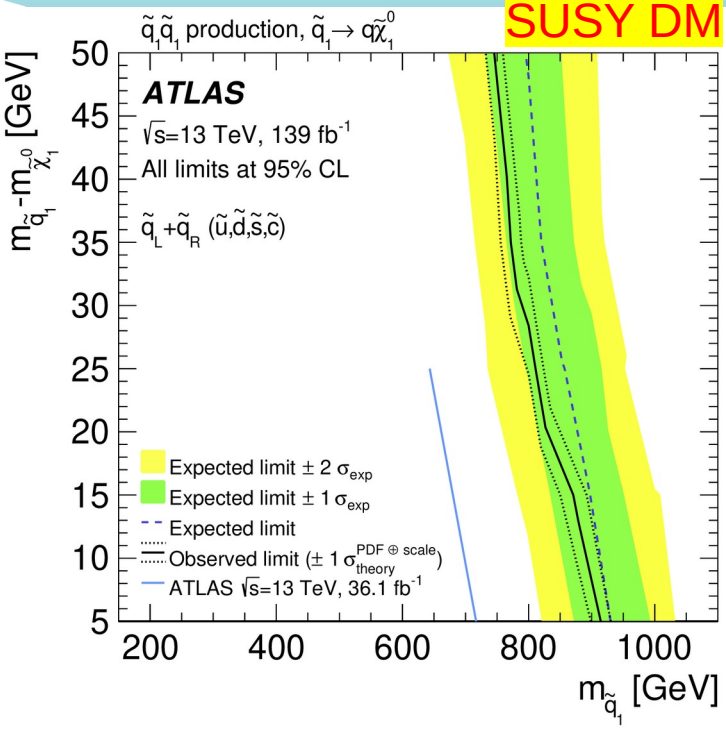

p
q
j, ℓ
DM
DM
q̄
p


SUSY DM
q̃1q̃1 production, q̃1→ qχ̃10
ATLAS
√s=13 TeV, 139 fb-1
All limits at 95% CL
q̃L+q̃R (ũ,d̃,s̃,c̃)
Expected limit ± 2 σexp
Expected limit ± 1 σexp
Expected limit
Observed limit (± 1 σtheoryPDF ⊕ scale)
ATLAS √s=13 TeV, 36.1 fb-1
mq̃1-mχ̃10 [GeV]
mq̃1 [GeV]
50
45
40
35
30
25
20
15
10
5
200
400
600
800
1000

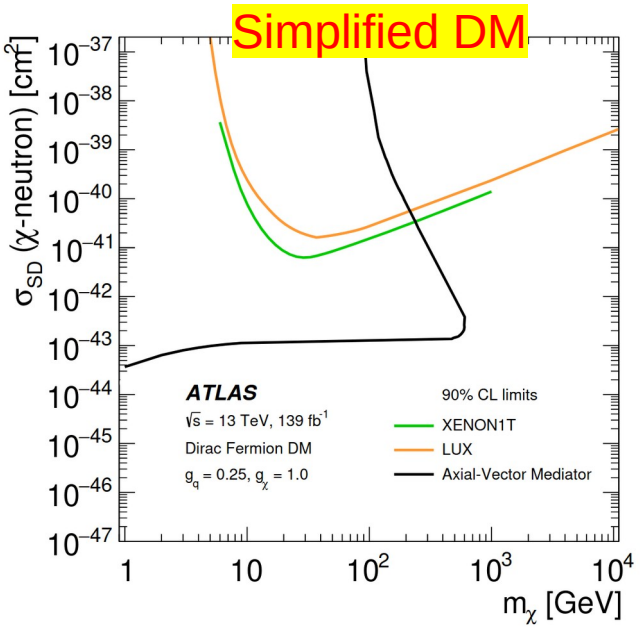
Collider



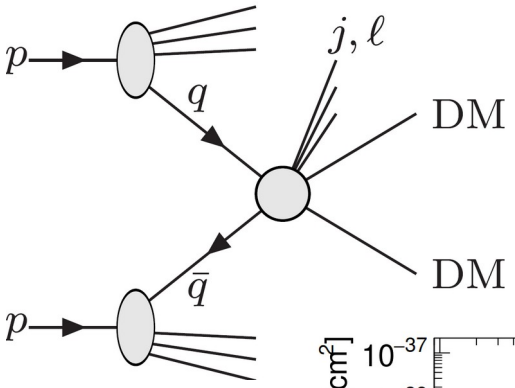
SUSY DM



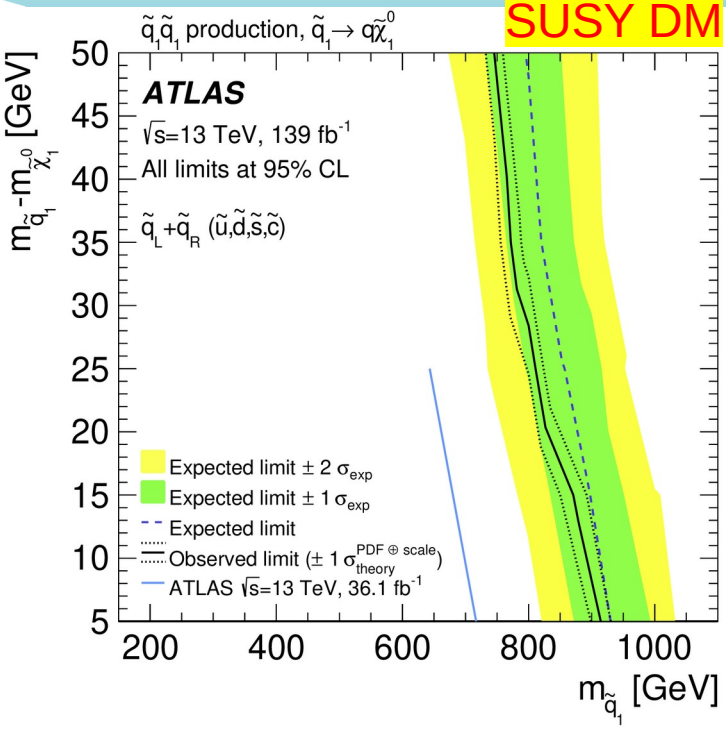
Simplified DM



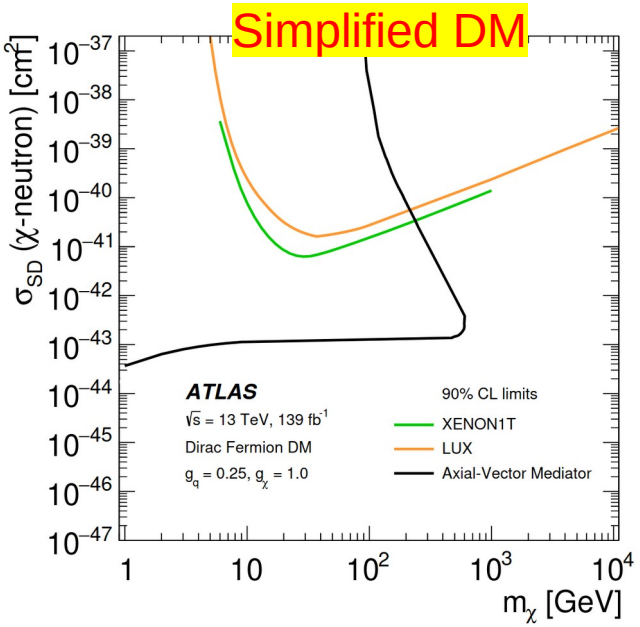
Collider



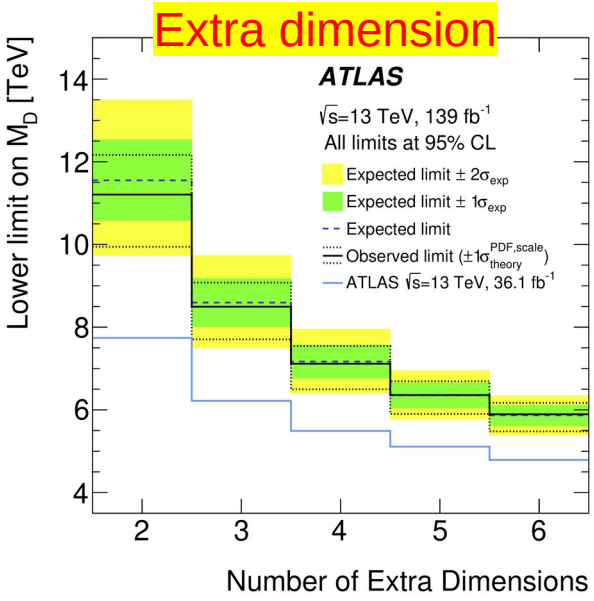
SUSY DM



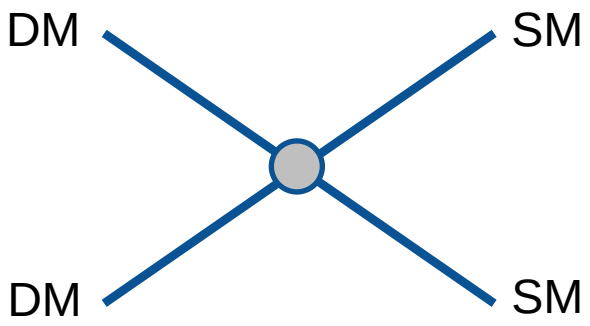
Simplified DM



Extra dimension

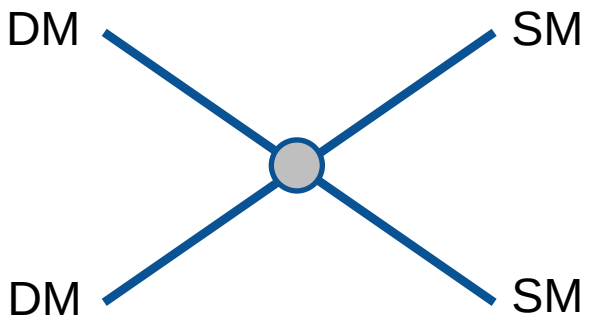


Coupling of DM and SM



Need to identify DM–SM for precise signal prediction.

Coupling of DM and SM



Need to identify DM–SM for precise signal prediction.

So many possibilities of DM-SM interactions….

- SUSY?
  - MSSM?, NMSSM?, ….
    AMSB?, SUGRA?
- Extra Dimension?
  - # of dimension, geometry of compactification,
- ….

Minimal WIMP Model

Add one DM particle, UV-complete (renormalizable theory).

Higgs Portal dark matter

- Scalar DM S coupling to Higgs. $\mathcal{L} = -\frac{m^2}{2}S^2 - \lambda S^2 H^\dagger H$

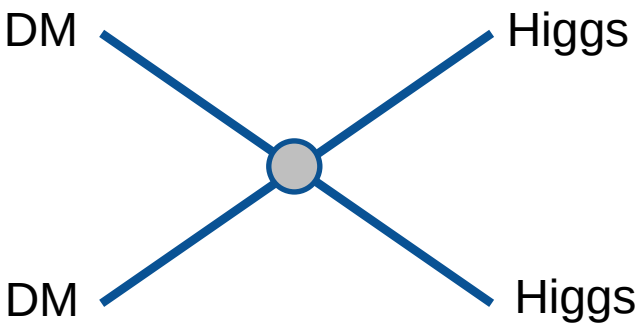
Gauge Portal dark matter

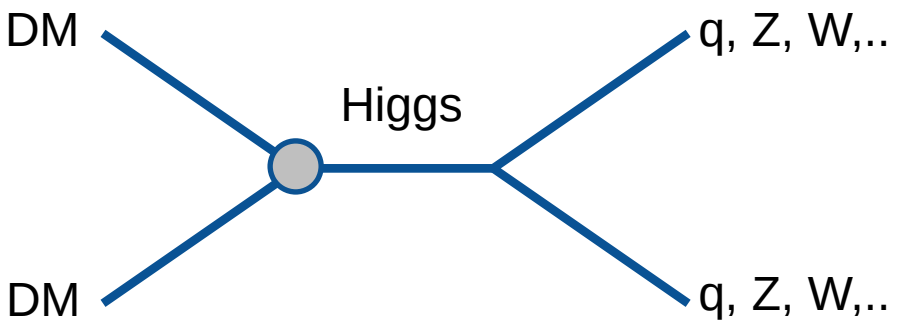
- Scalar or fermion DM charged weak interaction.
- Minimal choice of charge is triplet.
- Wino dark matter in SUSY model.

Higgs Portal DM

DM and Higgs

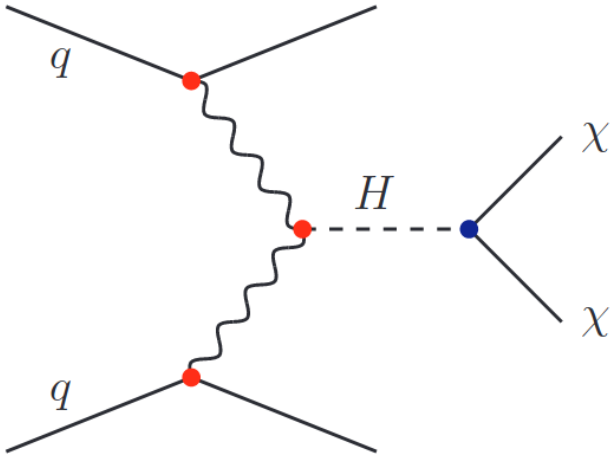
$$\mathcal{L} = -\frac{m^2}{2}S^2 - \lambda S^2 H^\dagger H$$





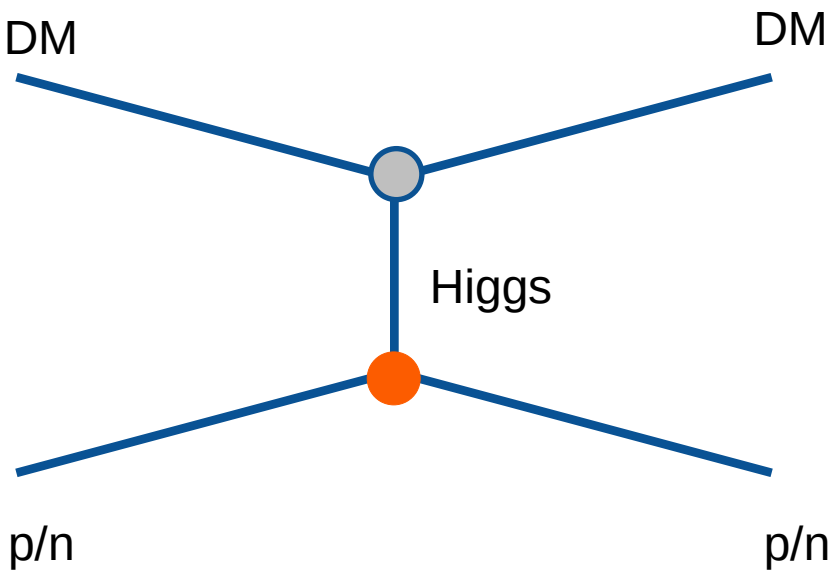
DM abundance, (in)direct, collider signature comes from one operator.

Higgs-portal at LHC

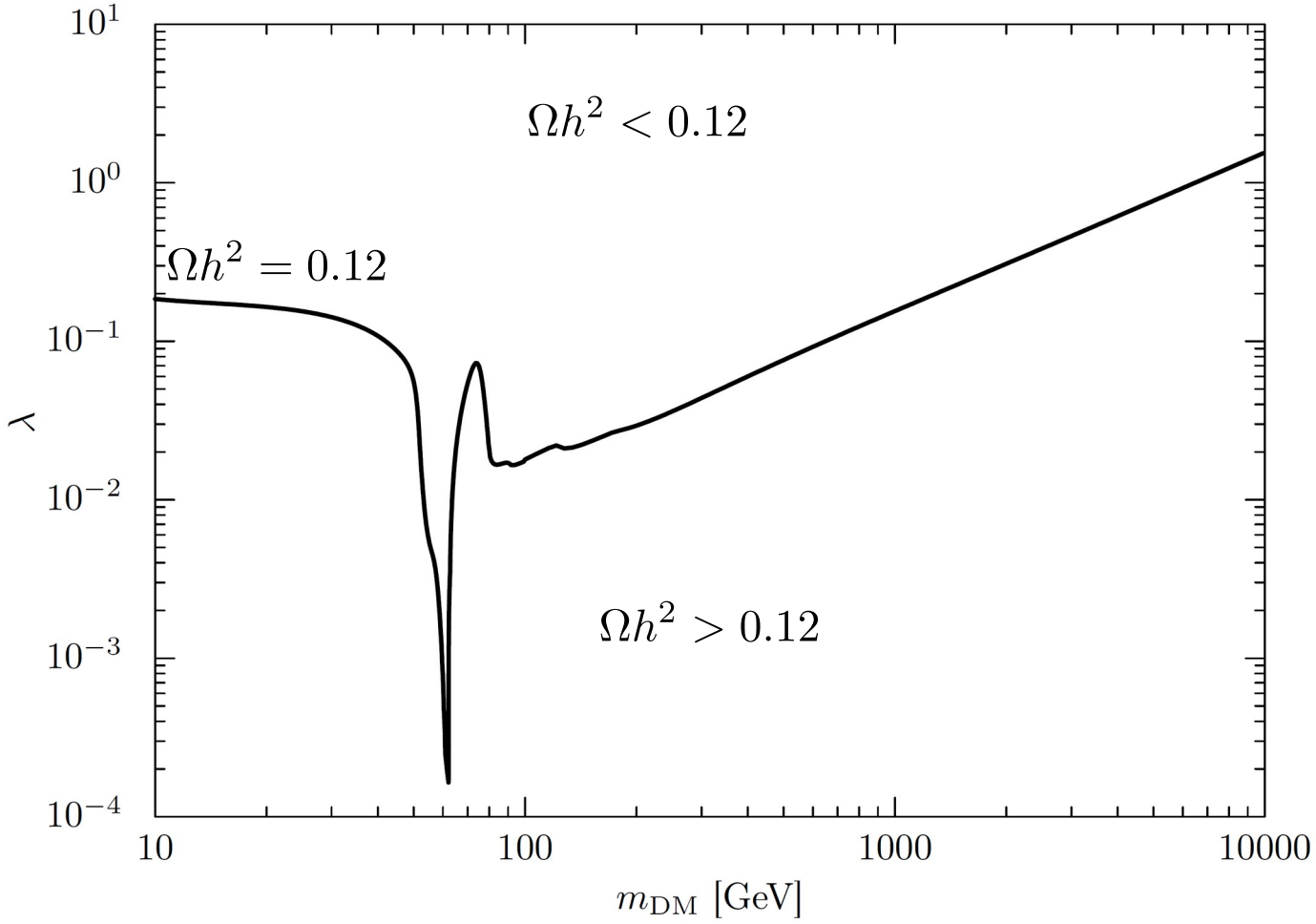


- Invisible Higgs decay constraints Br(H → DM DM):
  - < 0.11 (ATLAS), 0.15 (CMS)
  - < 0.06 (HL-LHC)
  - < 0.003 (ILC)
- Off-shell Higgs decay

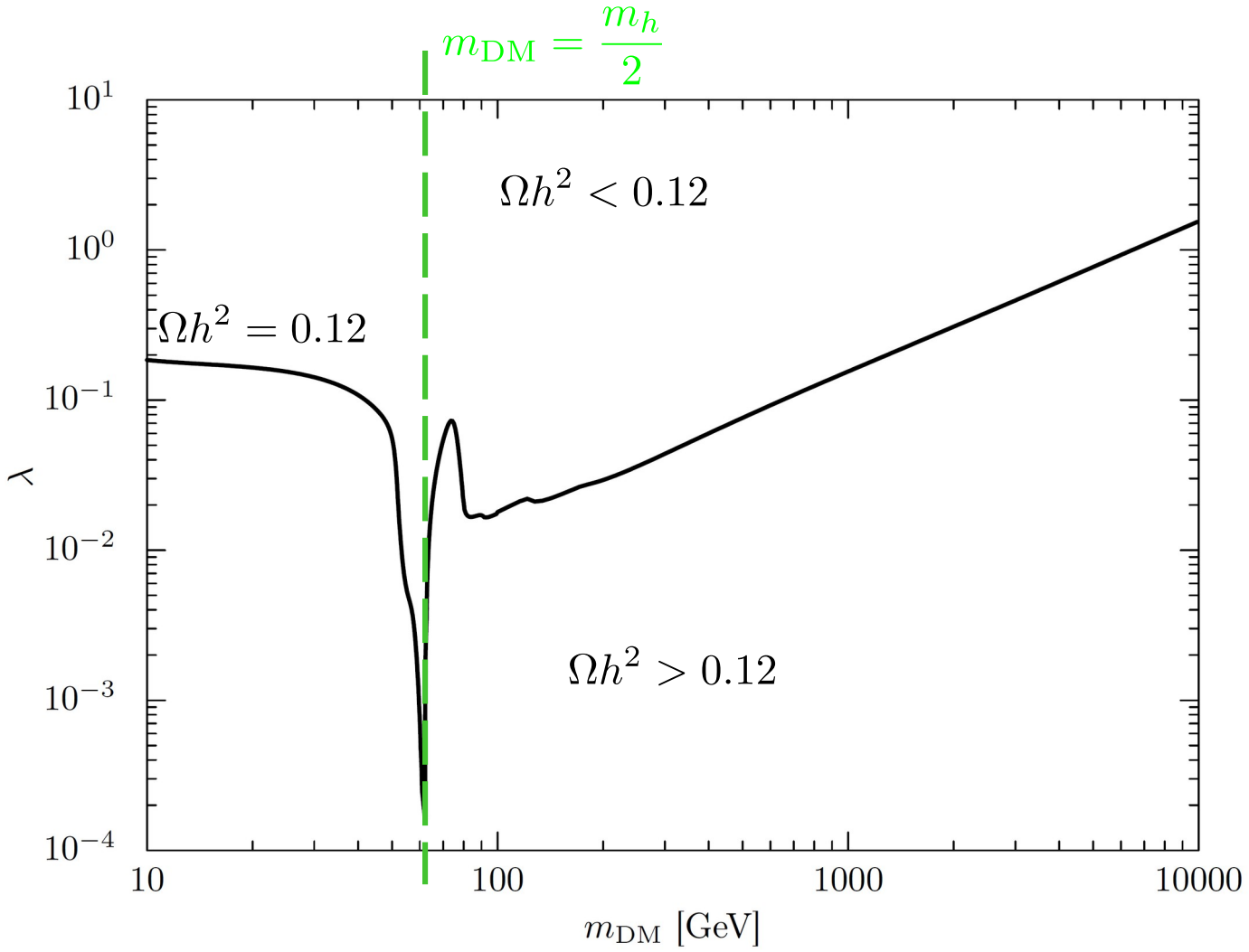
Direct Detection



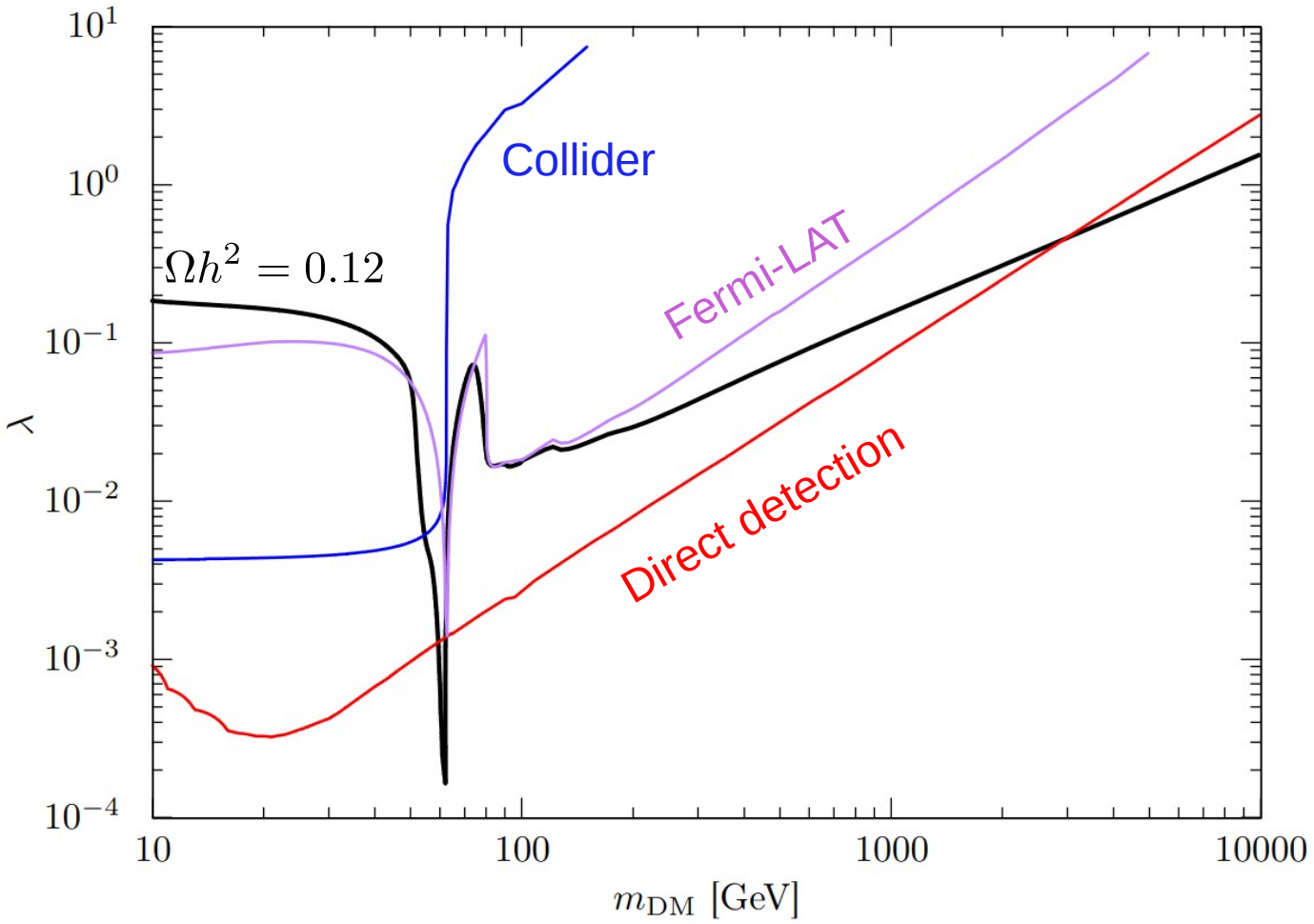
DM and Higgs


10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
λ
$\Omega h^2 < 0.12$
$\Omega h^2 = 0.12$
$\Omega h^2 > 0.12$
10
100
1000
10000
m_{DM} [GeV]

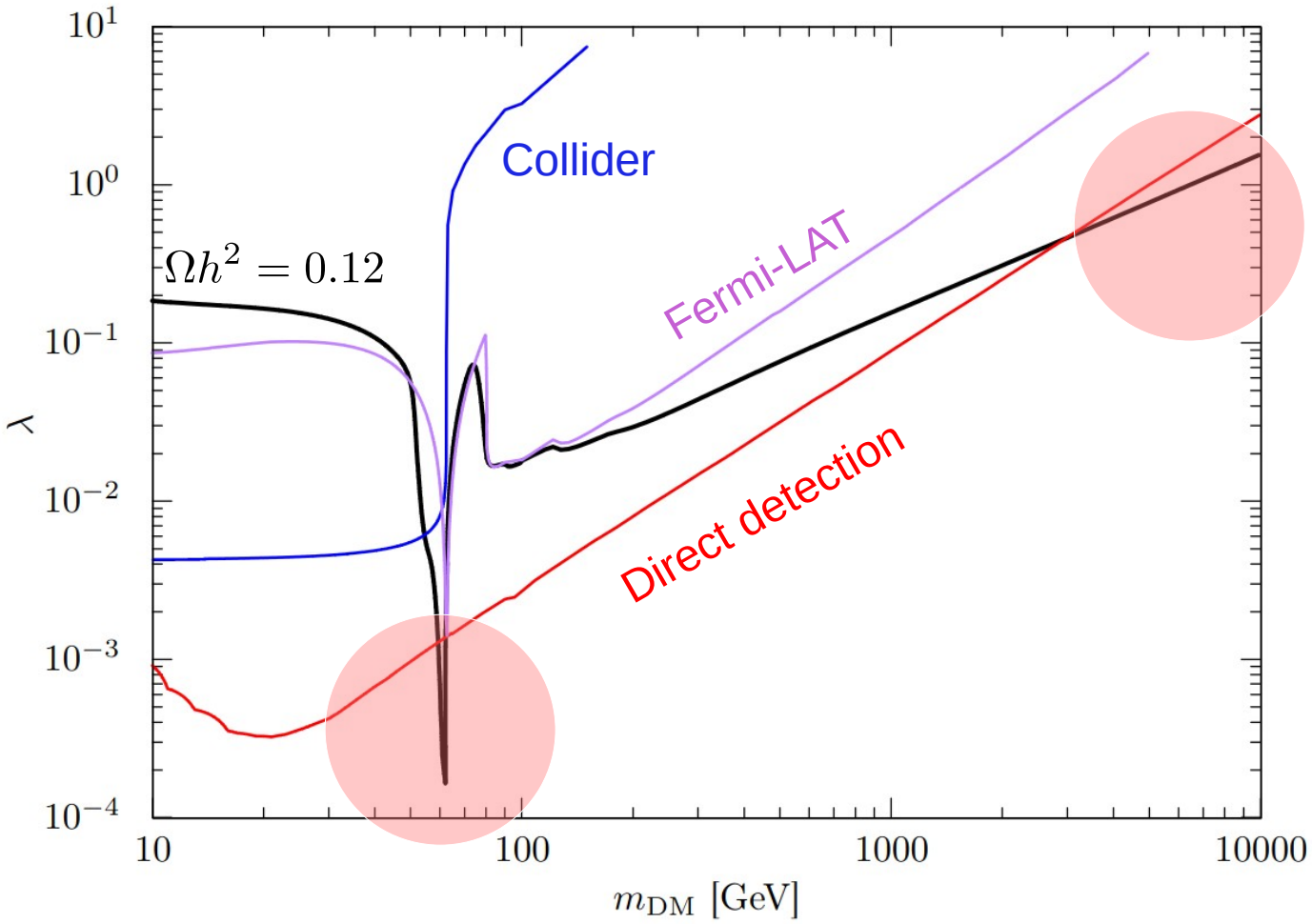
DM and Higgs


$m_{\rm DM} = \frac{m_h}{2}$
$\Omega h^2 < 0.12$
$\Omega h^2 = 0.12$
$\Omega h^2 > 0.12$
λ
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
100
1000
10000
$m_{\rm DM}$ [GeV]

DM and Higgs


10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
λ
$\Omega h^2 = 0.12$
Collider
Fermi-LAT
Direct detection
10
100
1000
10000
$m_{\rm DM}$ [GeV]

DM and Higgs


Collider
Fermi-LAT
Direct detection
$\Omega h^2 = 0.12$
λ
$m_{\rm DM}$ [GeV]
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
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10
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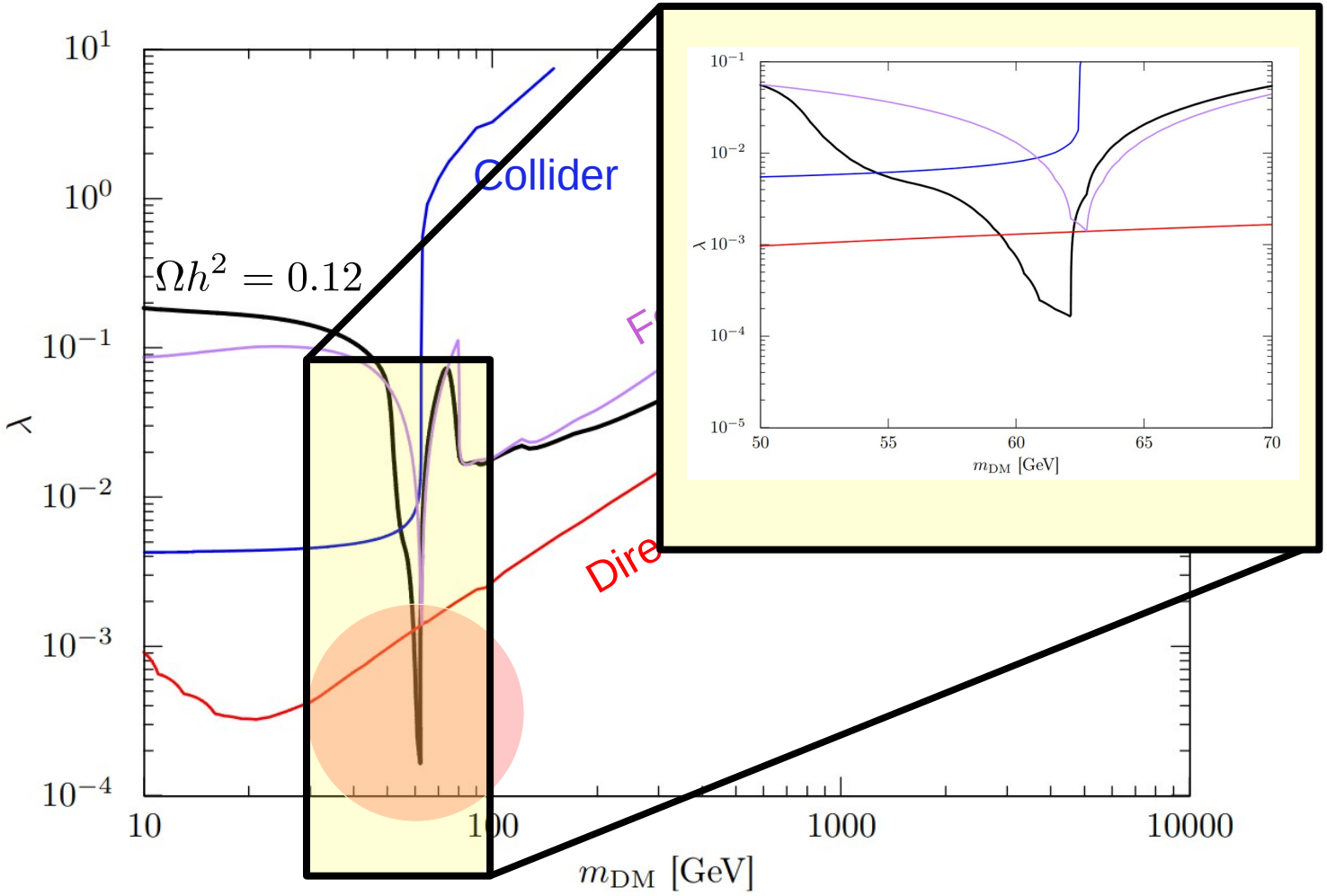
1000
10000

DM and Higgs


Collider
$\Omega h^2 = 0.12$
Dire
λ
$m_{\rm DM}$ [GeV]
10
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10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
50
55
60
65
70
$m_{\rm DM}$ [GeV]

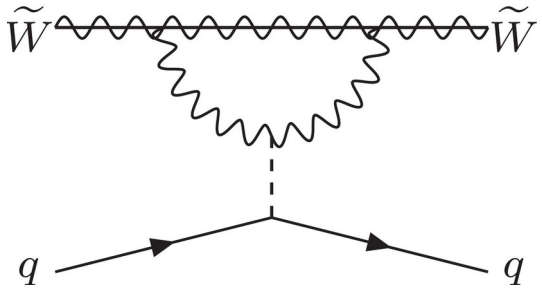
Gauge Portal DM (Wino)

What is Wino

- Majorana fermion $\widetilde{W}$
- Hypercharge Y=0
- $SU(2)_L$ triplet $\begin{pmatrix} \widetilde{W}^+ \\ \widetilde{W}^0 \\ \widetilde{W}^- \end{pmatrix}$
- Mass < 3 TeV

[Hisano, Matsumoto, Nagai, Saito & Senami, 06]

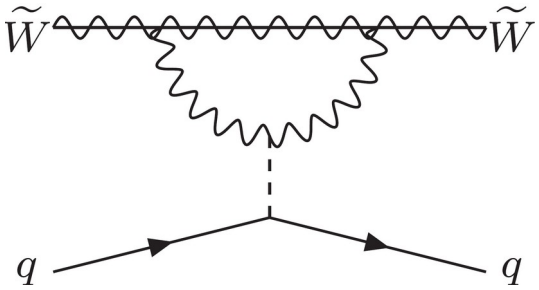
Wino Signal



Direct Detection

[Hisano, Ishiwata & Nagata, 12]

Wino Signal



Direct Detection

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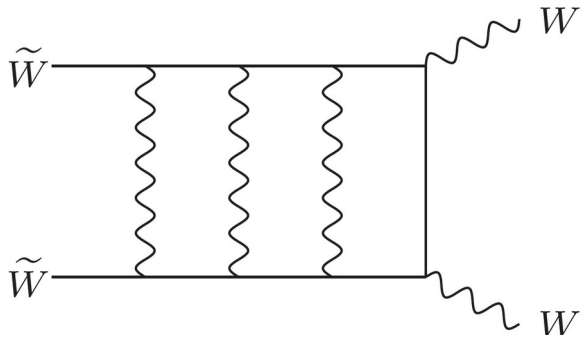
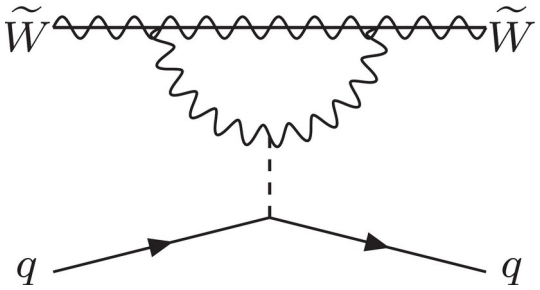


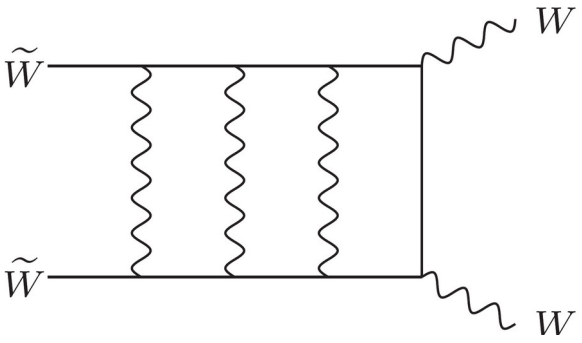
Indirect Detection

[Hisano, Matsumoto, Nojiri & Saito, 04]

Wino Signal



Direct Detection
[Hisano, Ishiwata & Nagata, 12]



Indirect Detection
[Hisano, Matsumoto, Nojiri & Saito, 04]

$\widetilde{W}\widetilde{W} \to \gamma V$

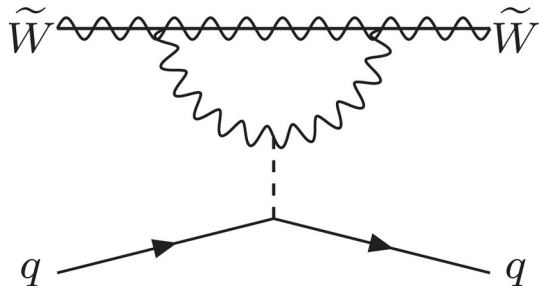
Line Photon

$\widetilde{W}\widetilde{W} \to WW$

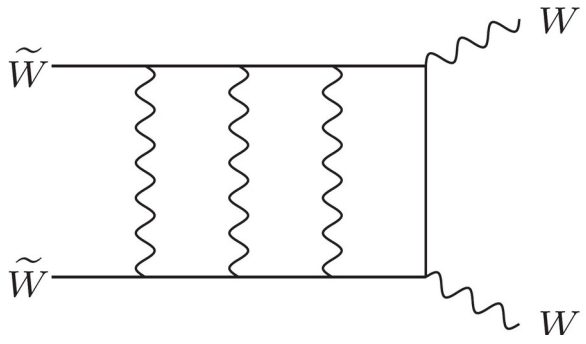
Continuum Photon

Anti-matter

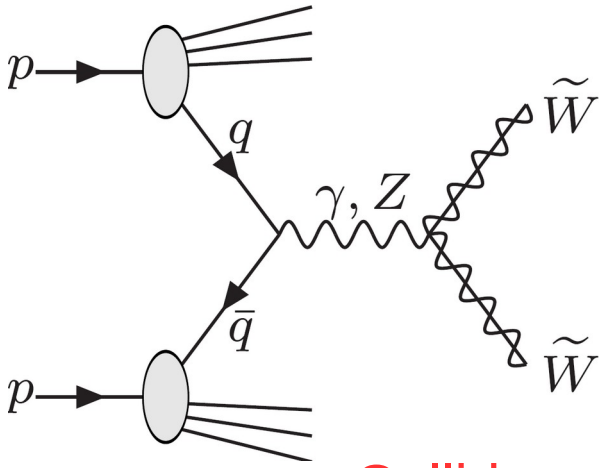
Wino Signal



Direct Detection
[Hisano, Ishiwata & Nagata, 12]



Indirect Detection
[Hisano, Matsumoto, Nojiri & Saito, 04]



Collider

$\widetilde{W}\widetilde{W} \to \gamma V$

Line Photon

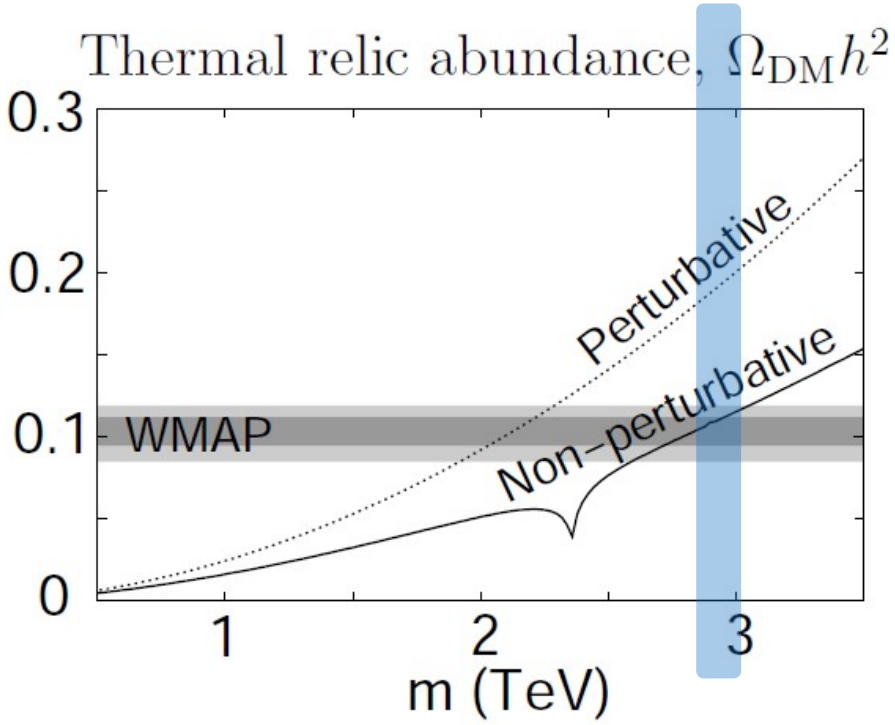
$\widetilde{W}\widetilde{W} \to WW$

Continuum Photon

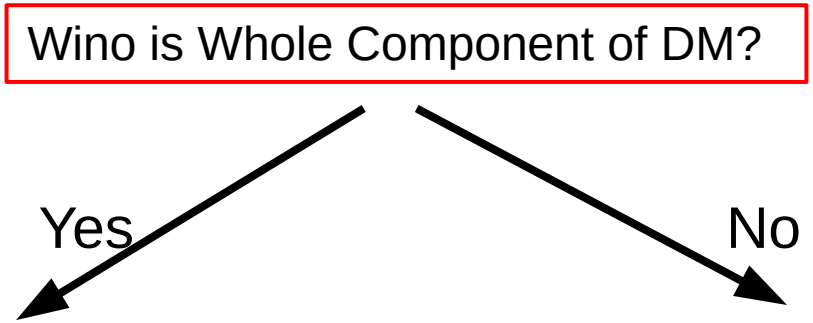
Anti-matter

Wino Thermal Abundance

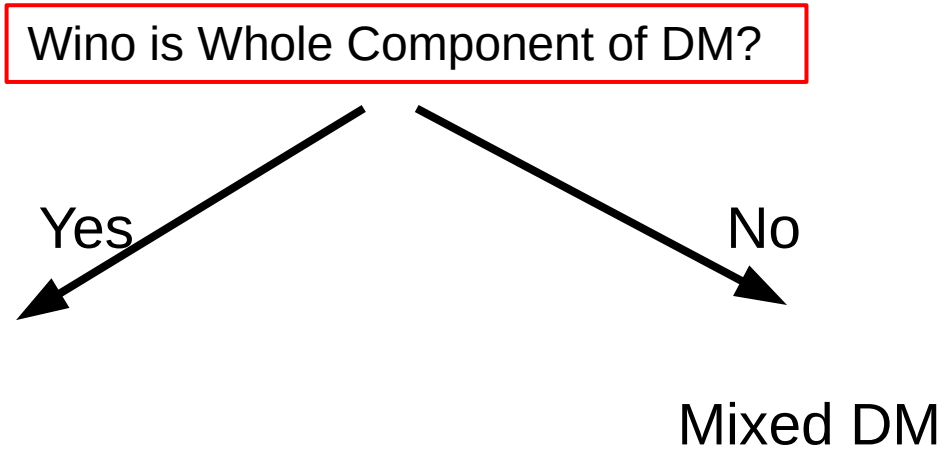
[Hisano,Matsumoto,Nagai,Seto,Senami,06]



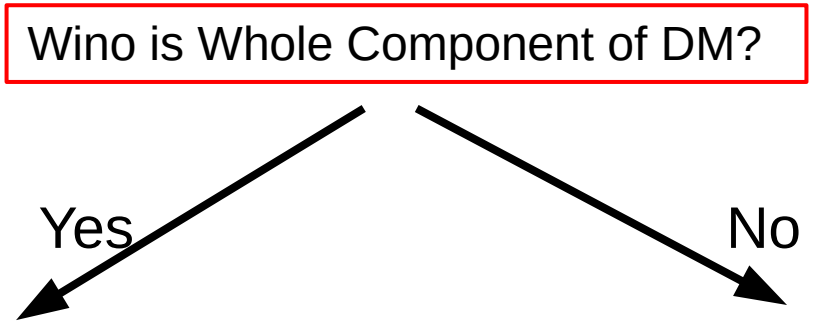
Wino Abundance



Wino Abundance



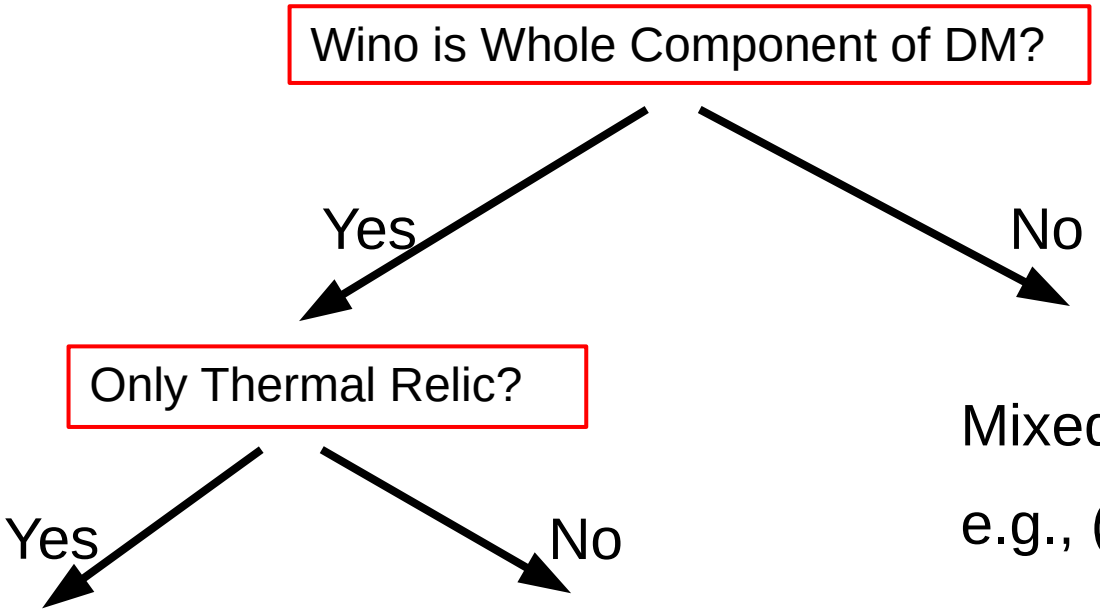
Wino Abundance



Mixed DM

e.g., (thermal) Wino + Axion

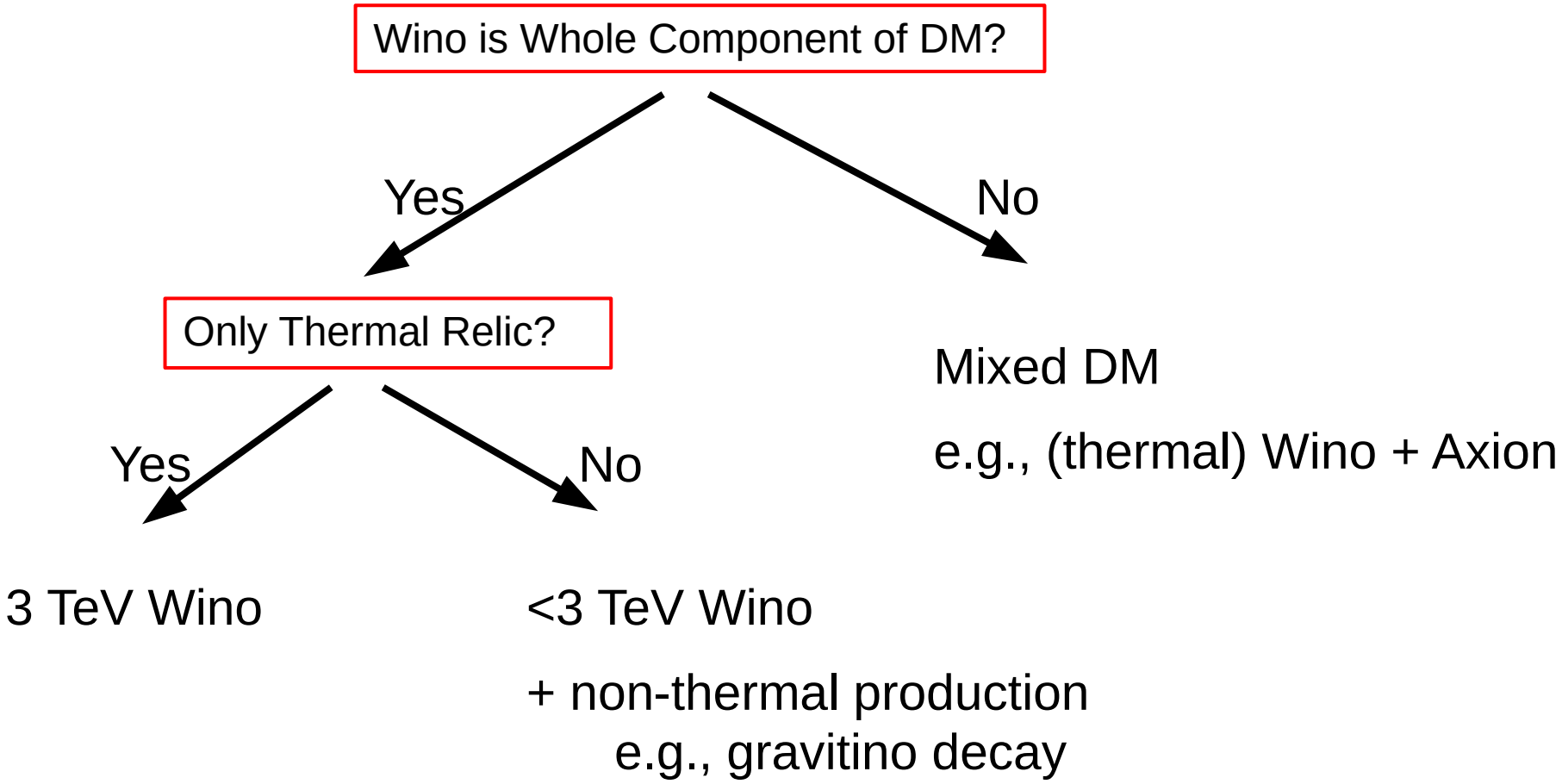
Wino Abundance



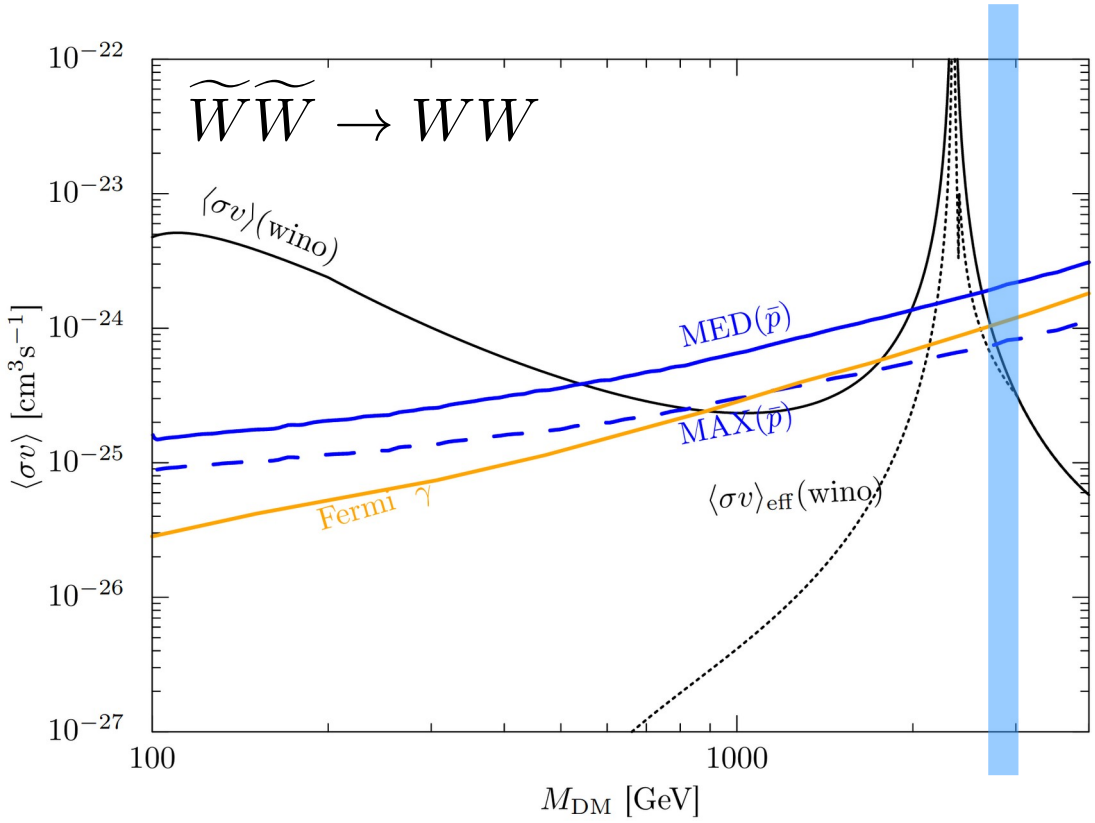
Mixed DM

e.g., (thermal) Wino + Axion

Wino Abundance



Cosmic Ray Signals



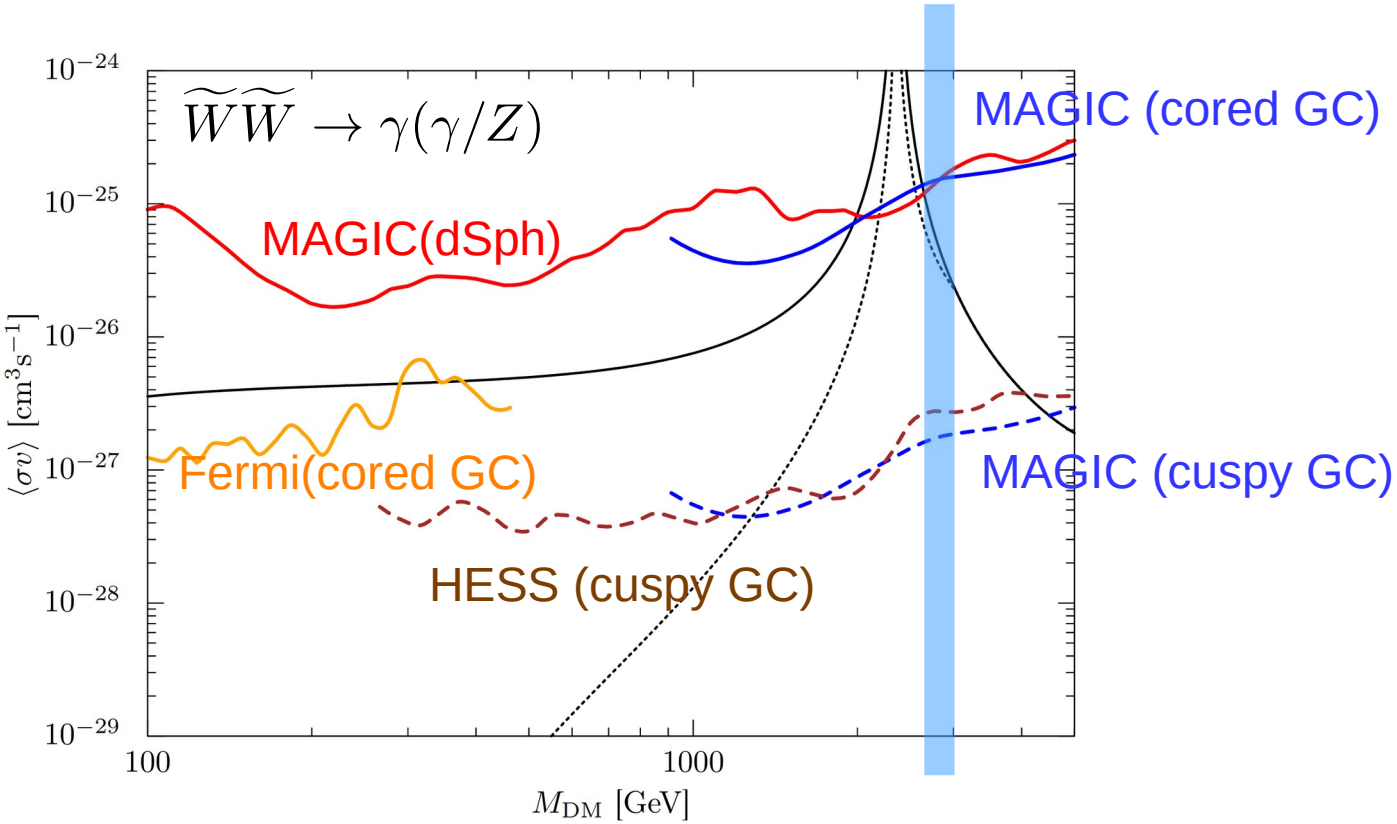
AMS02 antiproton

Fermi Gamma ray

$$\langle\sigma v\rangle_{\rm eff} = \left(\frac{\Omega_{\rm thermal}h^2}{\Omega_{\rm obs}h^2}\right)^2 \langle\sigma v\rangle$$

Large Uncertainty of Astrophysical model and DM density

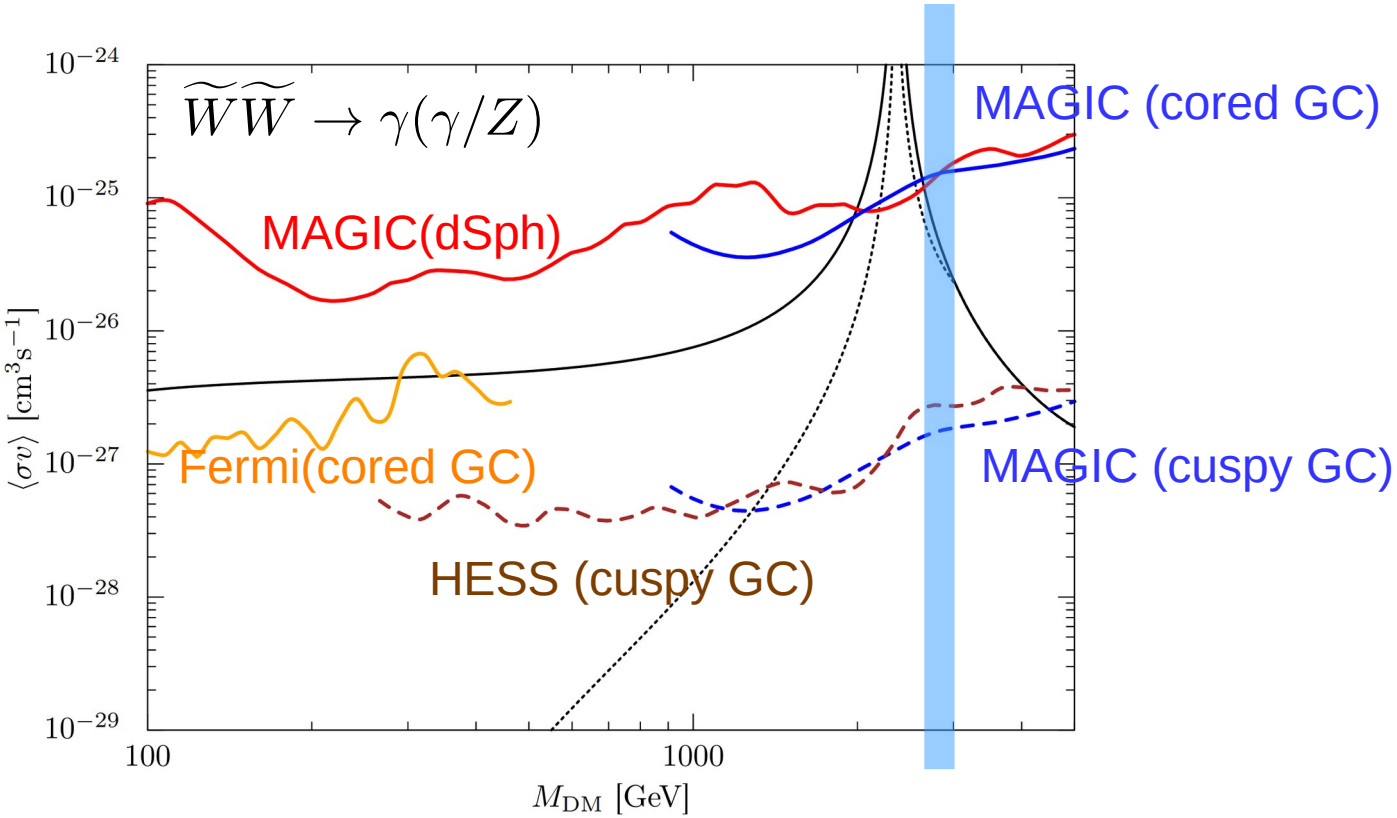
Line Search


$\widetilde{W}\widetilde{W} \to \gamma(\gamma/Z)$
MAGIC (cored GC)
MAGIC(dSph)
Fermi(cored GC)
MAGIC (cuspy GC)
HESS (cuspy GC)
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
$\langle\sigma v\rangle$ [cm^{3}s^{-1}]
100
1000
$M_{\rm DM}$ [GeV]

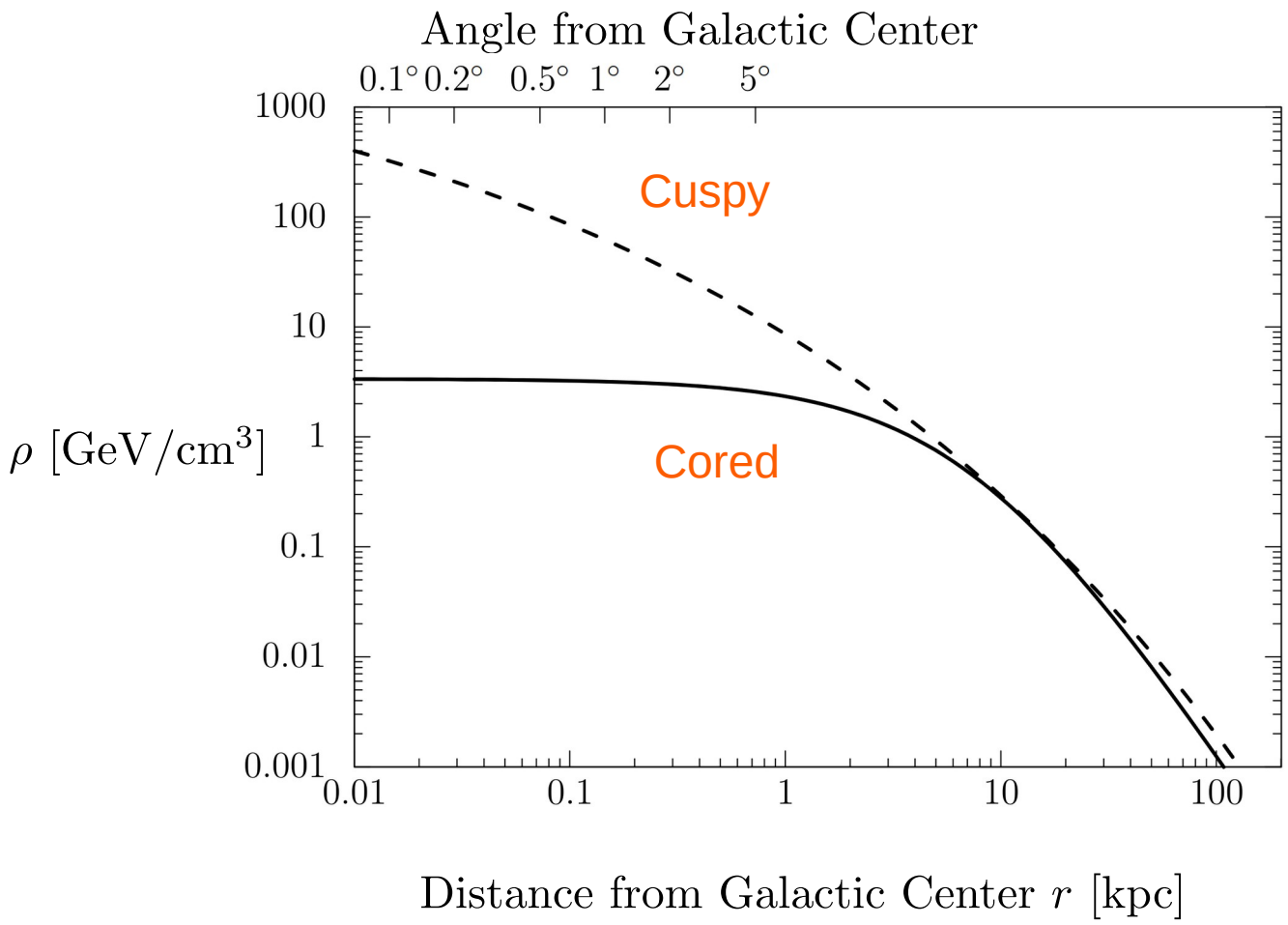
Line Search

From H.E.S.S. paper (1805.05741)

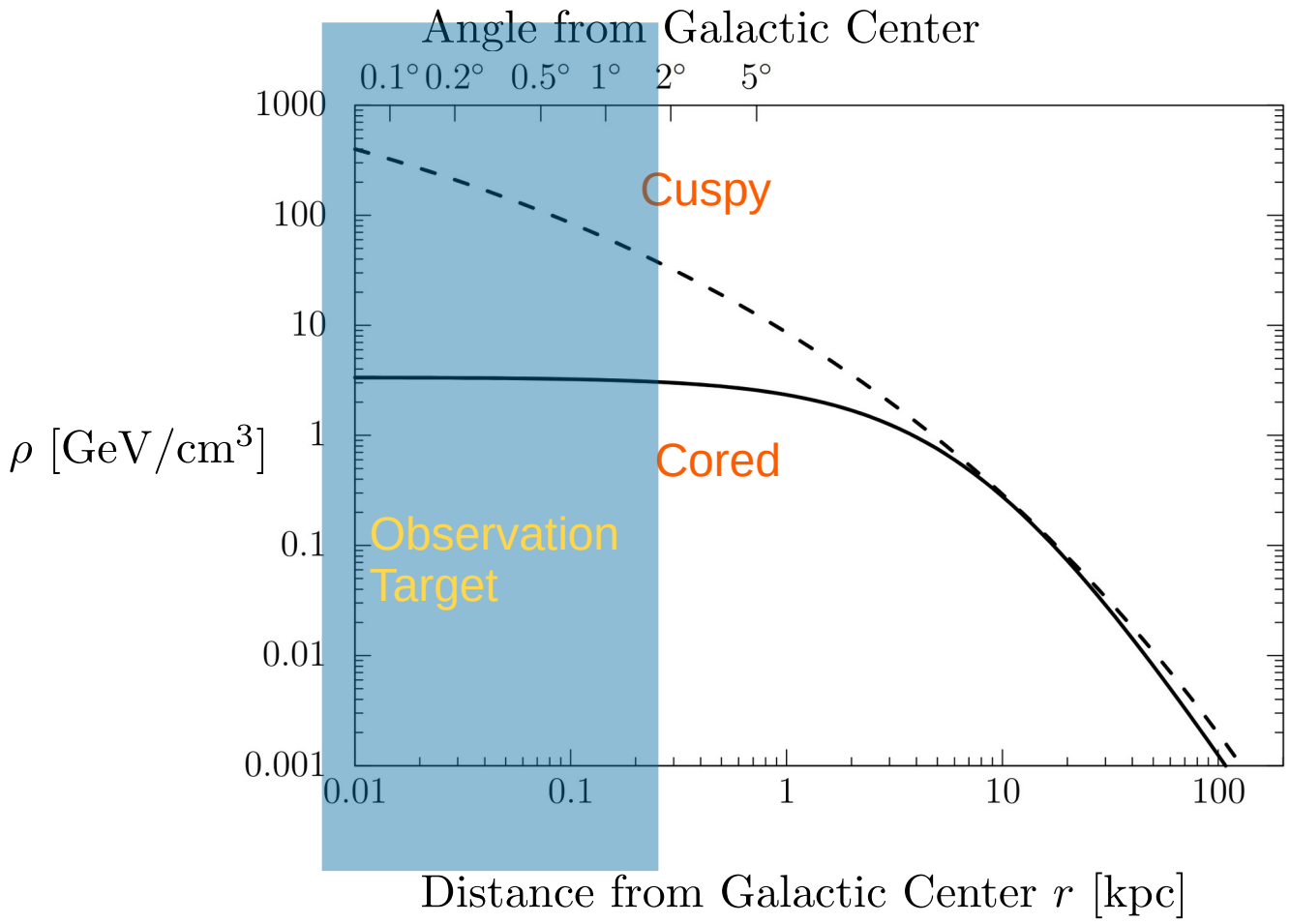
[3] Assuming a kpc-sized cored DM density distribution such as the Burkert profile would weaken the limits by about two-to-three orders of magnitude.



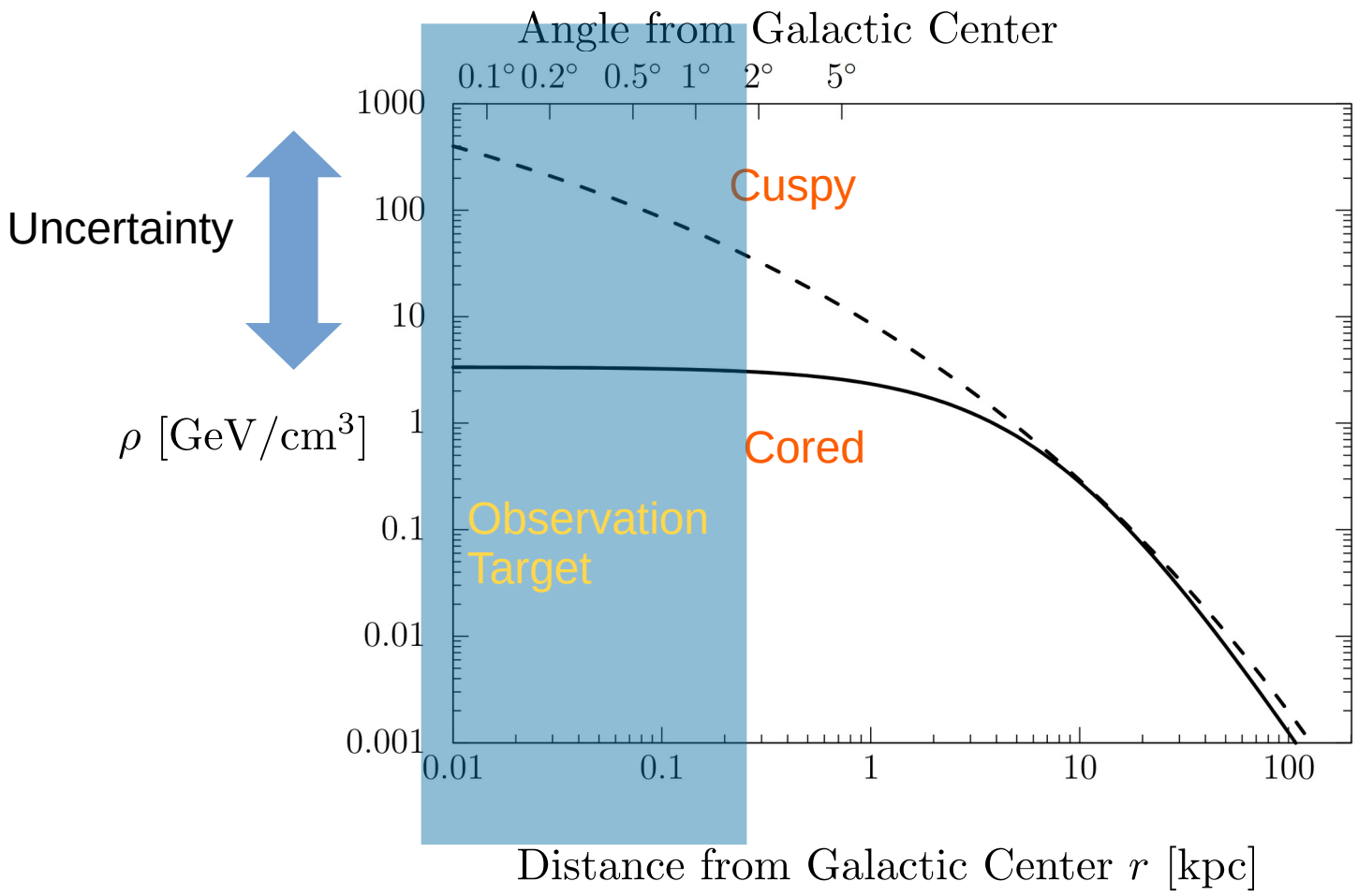
Dark Matter Density



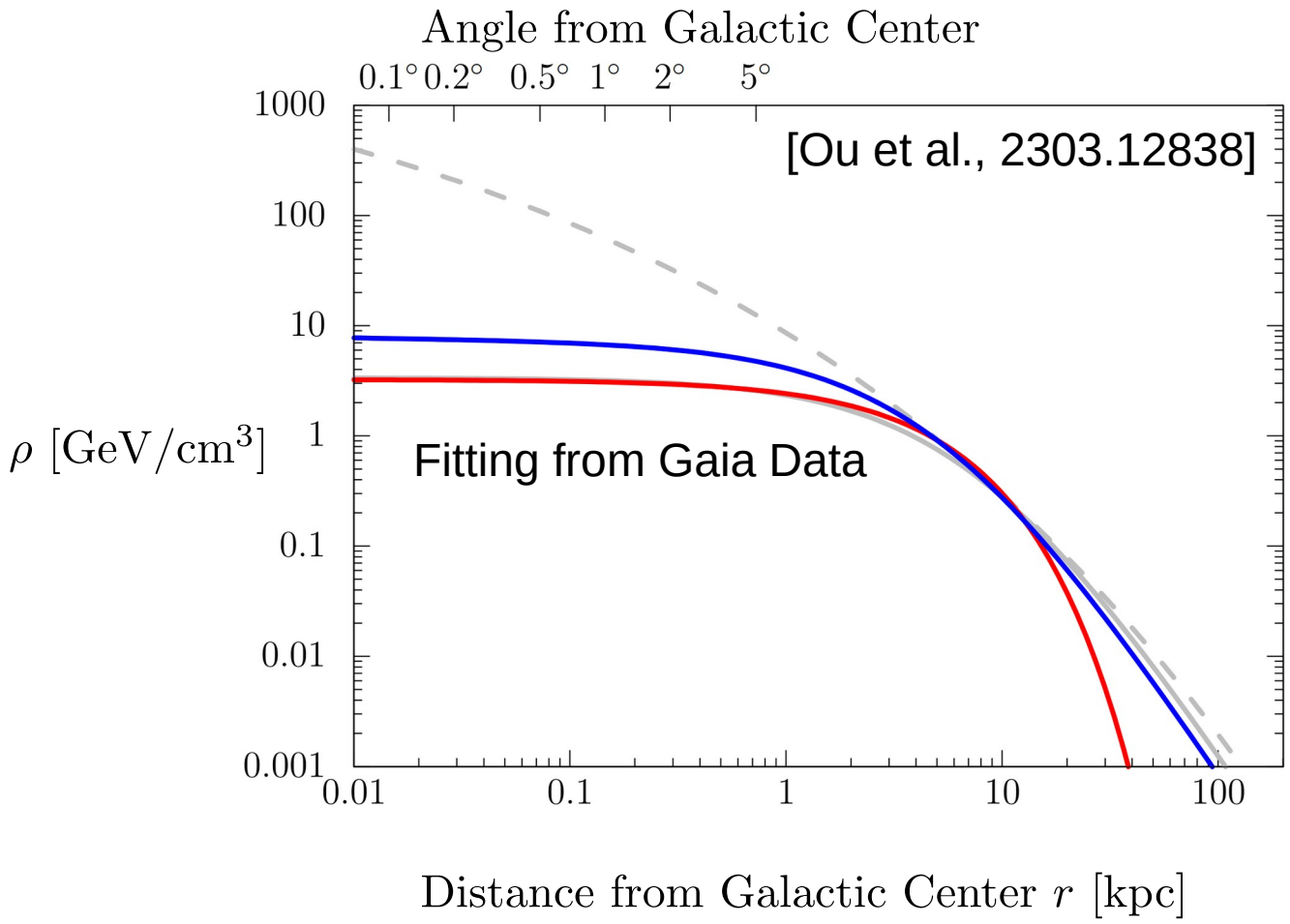
Dark Matter Density



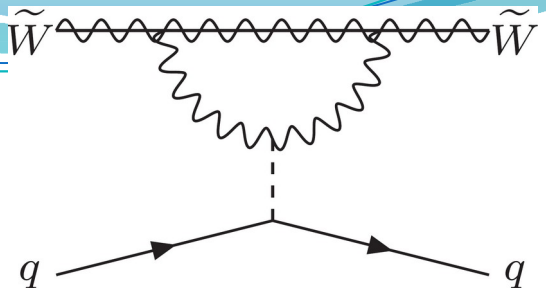
Dark Matter Density



Gaia Implication?



Direct Detection



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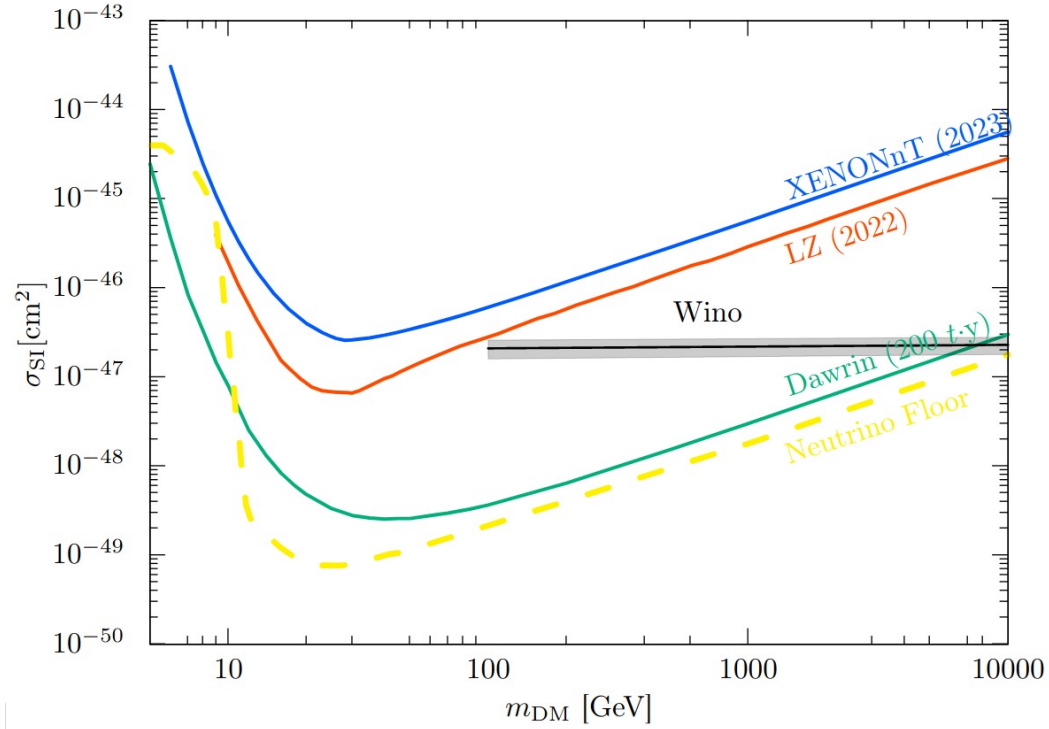
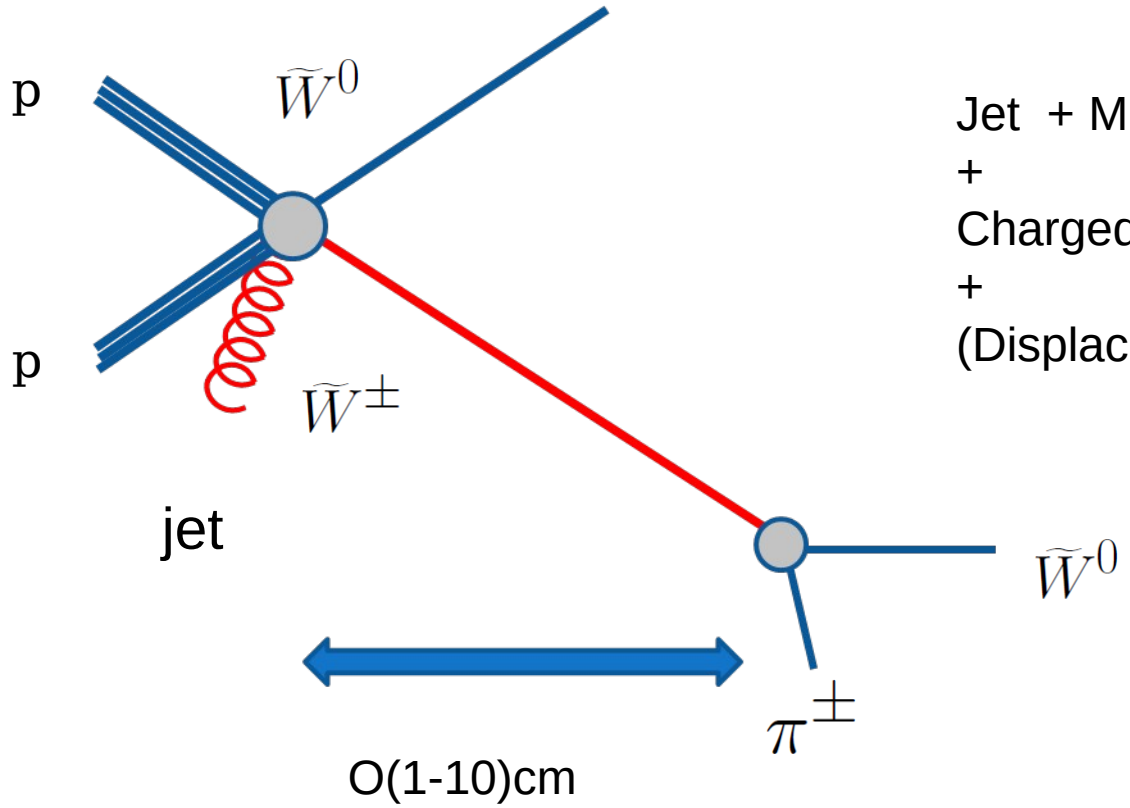


Direct LHC Signals

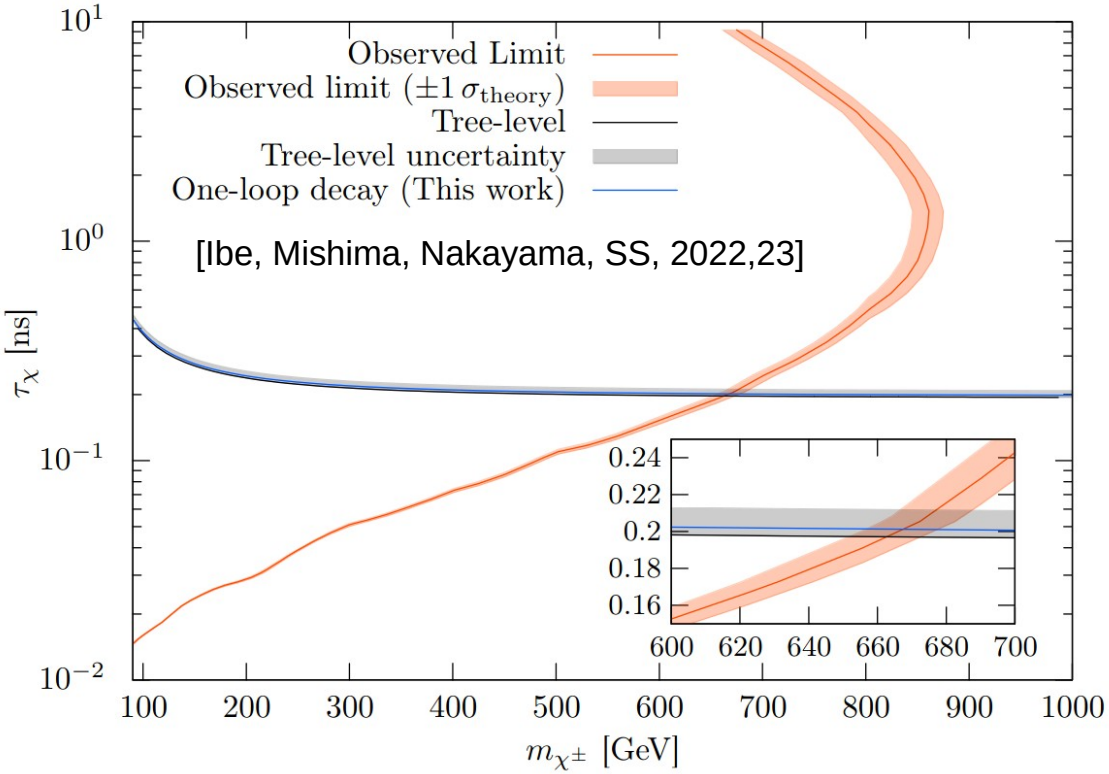


Jet + Missing energy
+
Charged track
+
(Displaced)Soft pion

ATLAS Search (2022)

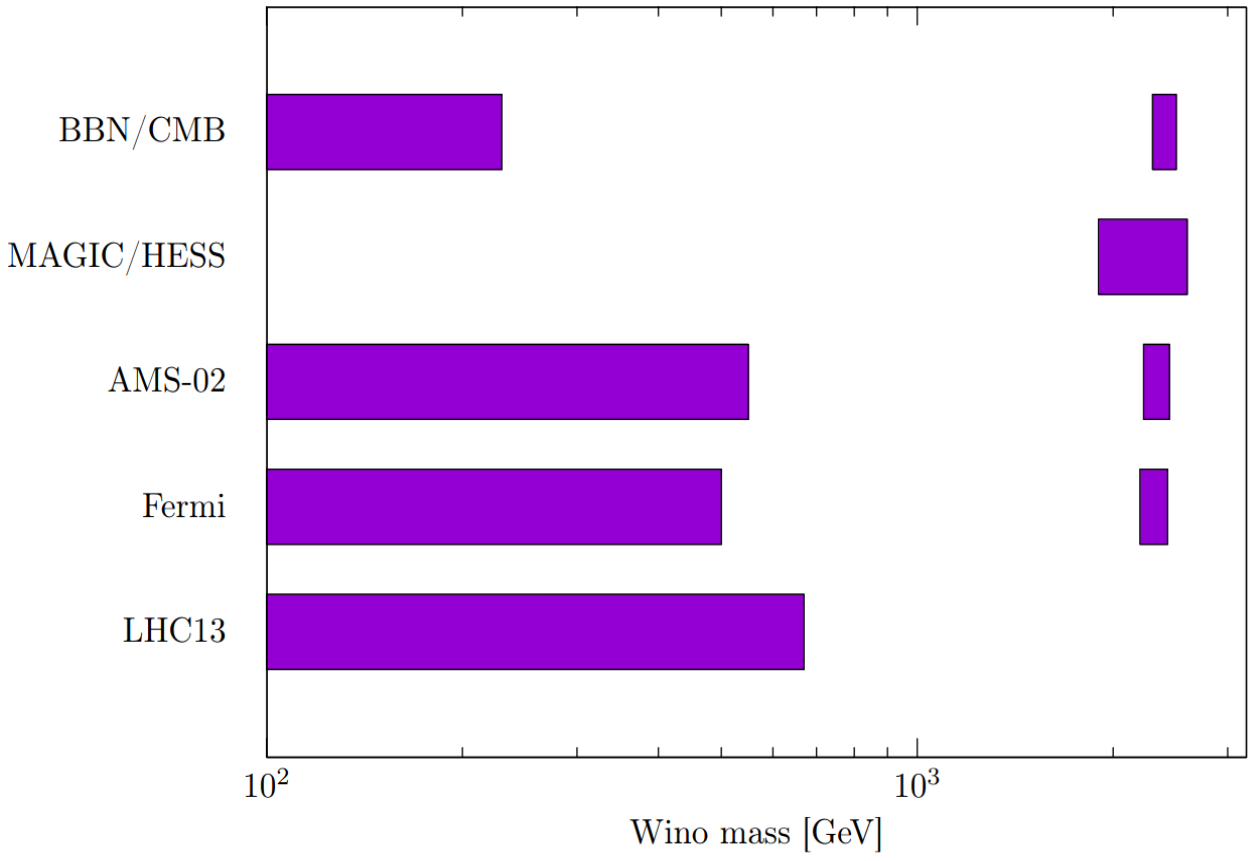
Theory: Two-loop mass difference + one-loop decay

[Ibe, Sato, Matsumoto, 2012]



> 670 GeV Wino

Wino Constraint



$$\Omega_{\widetilde{W}} h^2 = 0.12$$

Summary

- Minimal model is often good approximation of UV models.

- Cornering minimal model
  - Higgs-portal
    - LZ / XENONnT can exclude most of parameters.
    - ~100 x LZ can test all the parameters.
  - Gauge-portal (Wino)
    - CR can test high-mass region.
    - LHC can test low-mass region.
    - Theoretical estimation of thermal abundance is challenging.

- Synergy of multiple searches is essential for WIMP paradigm.

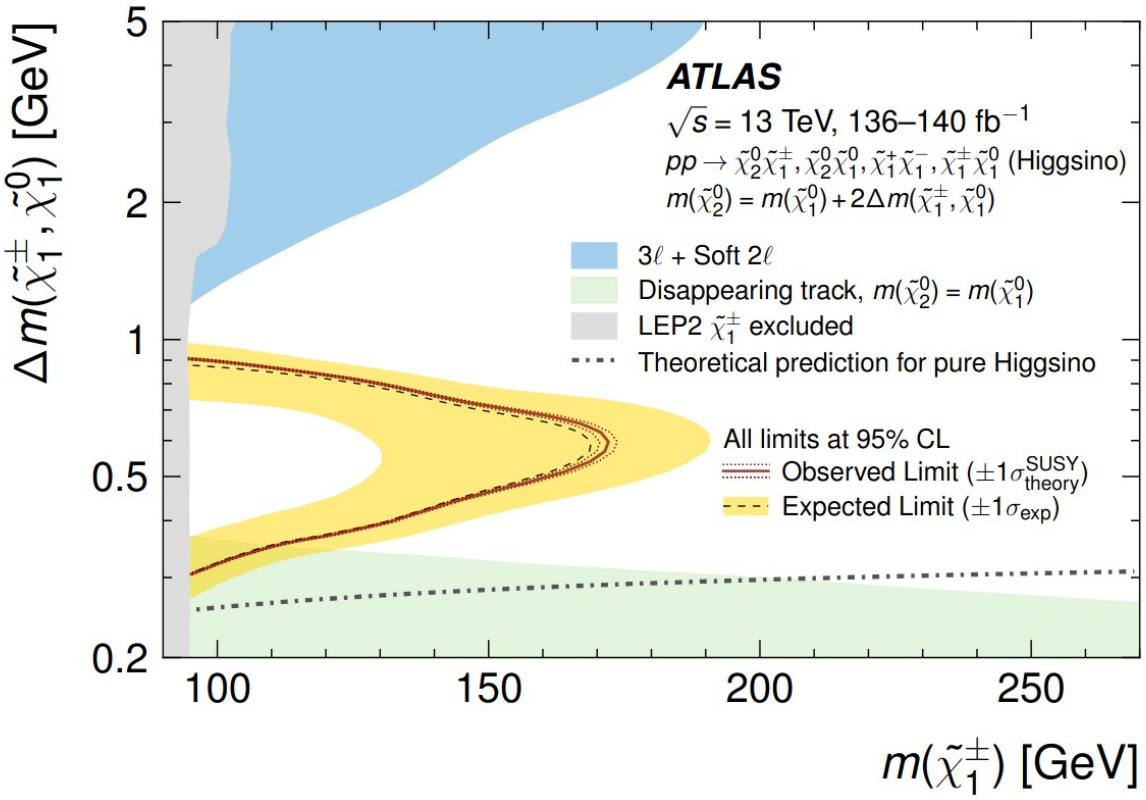
Minimal plus

- Non-pure gauge eigenstate.
  - Mixing with other particles, non-renormalizable interaction.
  - e.g., Higgsino.

- Higgs + Gauge portal.
  - Scalar DM with EW charge.
    - Can relax indirect constraint.

- Adding a mediator.
  - Annihilation into mediators, coannihilation,…
  - Direct DM-SM interaction can be tiny.
    - Direct DM search can be difficult.
    - Light DM is possible. (MeV-scale)
  - Mediator search.

Higgsino



New ideas and techniques needed!

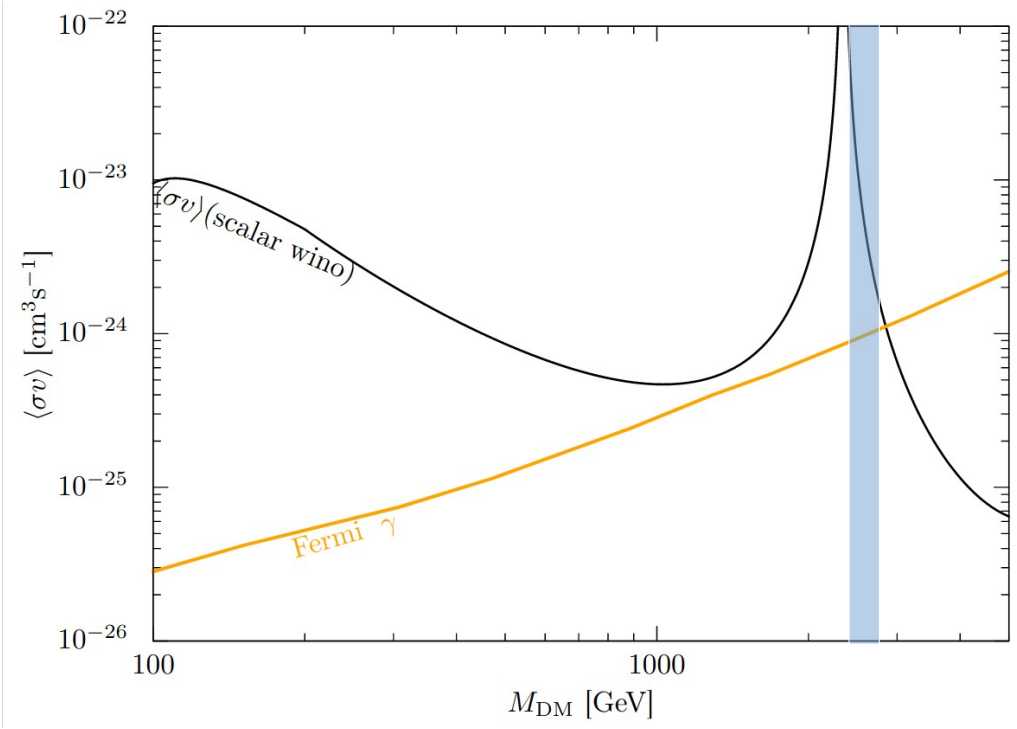
Scalar Triplet (Scalar Wino)

Scalar Triplet

- Real Scalar ϕ
- Hypercharge Y=0
- $SU(2)_L$ triplet $\begin{pmatrix} \phi^+ \\ \phi^0 \\ \phi^- \end{pmatrix}$

Scalar Wino

$\Omega h^2 = 0.12$



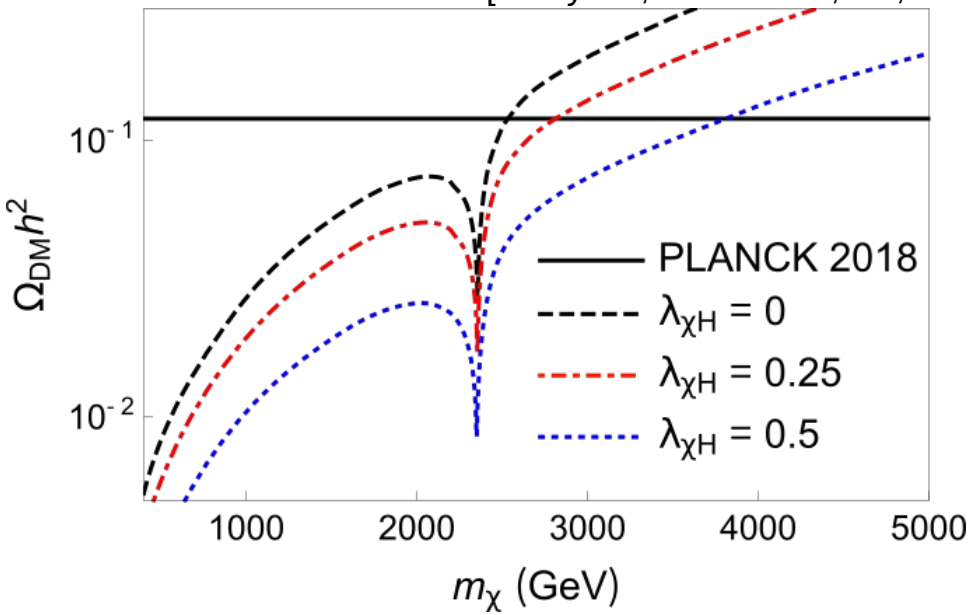
Scalar Wino has tension with indirect search.

Scalar Wino-Higgs Interaction

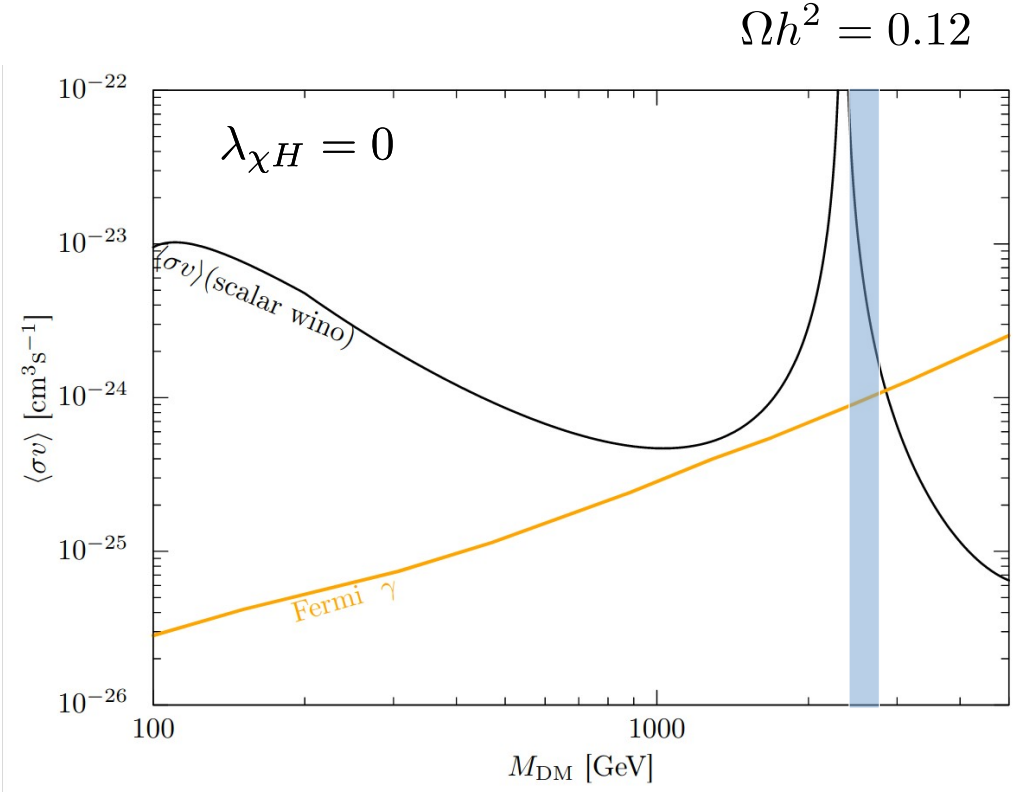
Scalar field can also couple to Higgs field.

$$\mathcal{L} = -\lambda_{\chi H}\phi_3^2 H^\dagger H$$

[Katayose, Matsumoto, SS, Watanabe, 2021]

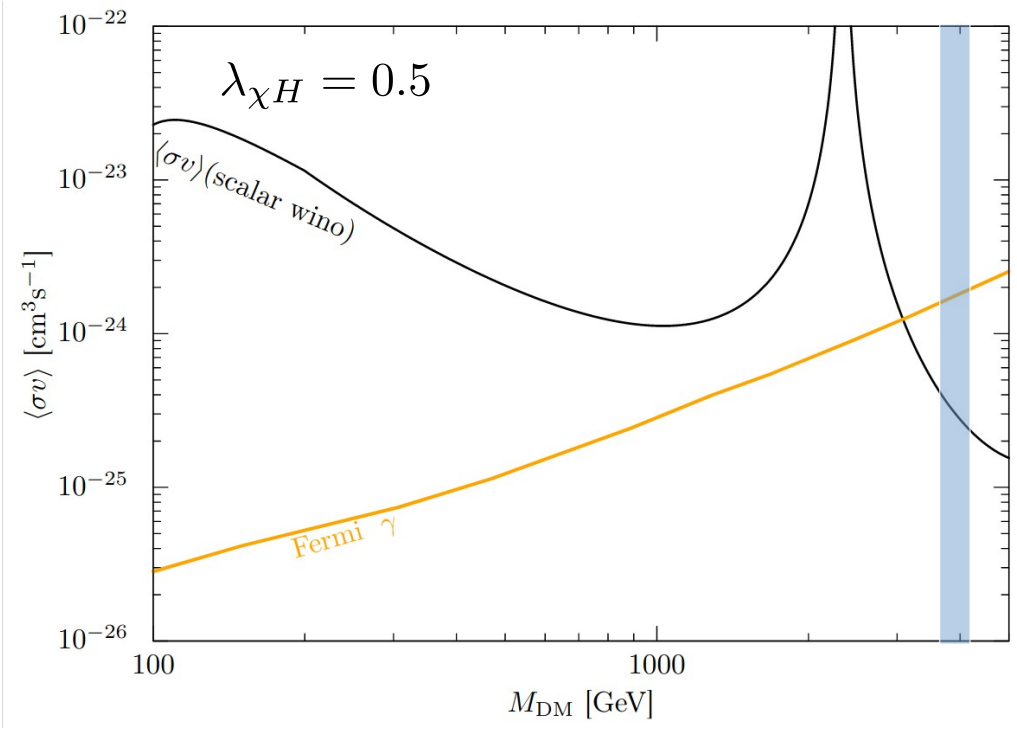


Scalar Wino


$\Omega h^2 = 0.12$
$\lambda_{\chi H} = 0$
$\langle\sigma v\rangle$(scalar wino)
Fermi γ
$\langle\sigma v\rangle$ [cm^{3}s^{-1}]
$M_{\rm DM}$ [GeV]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
100
1000

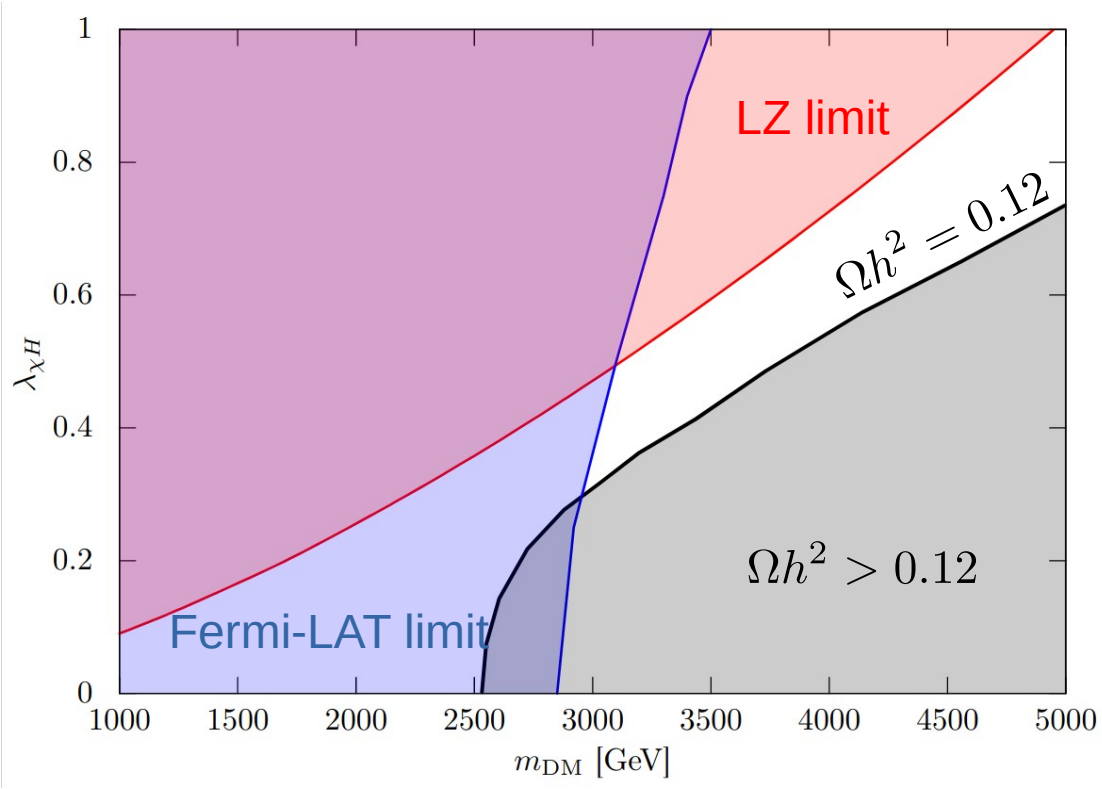
Scalar Wino+Higgs Interaction

$\Omega h^2 = 0.12$



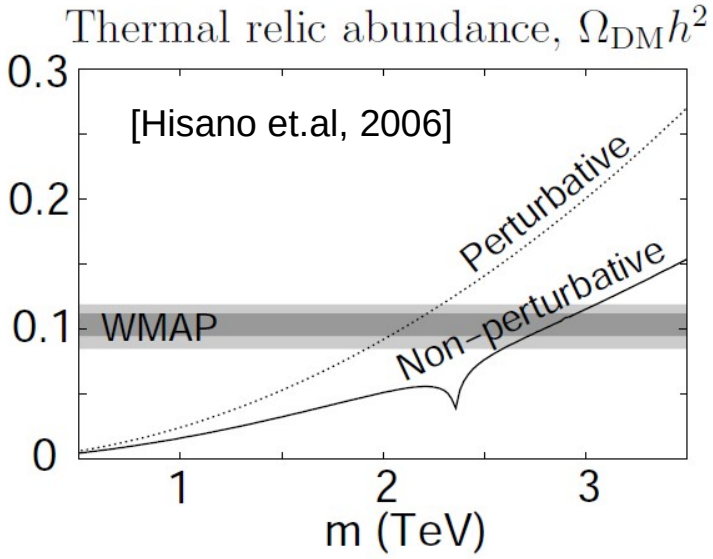
Evade Indirect constraint

Scalar Wino Parameter

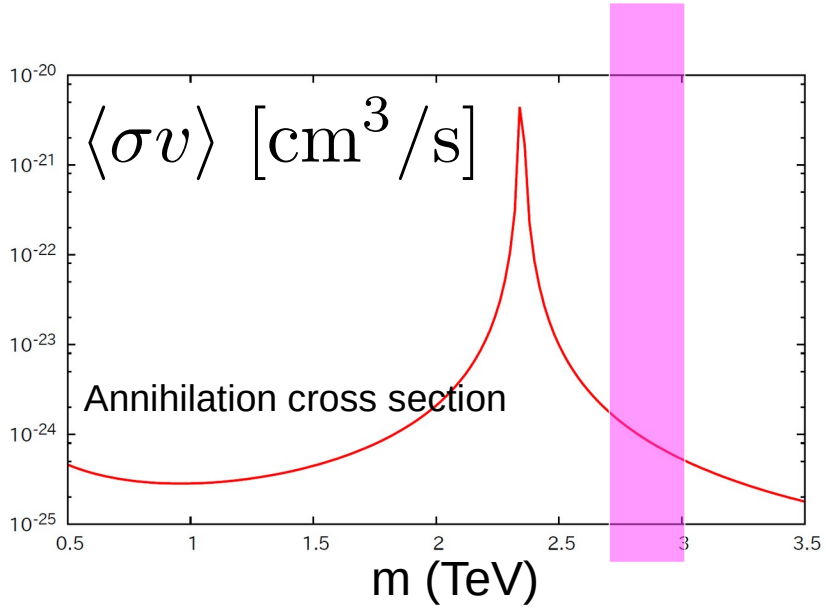


Abundance

$$\Omega h^2 \simeq 0.1$$



2.7 – 3 TeV wino looks good.



Largely depends on mass.

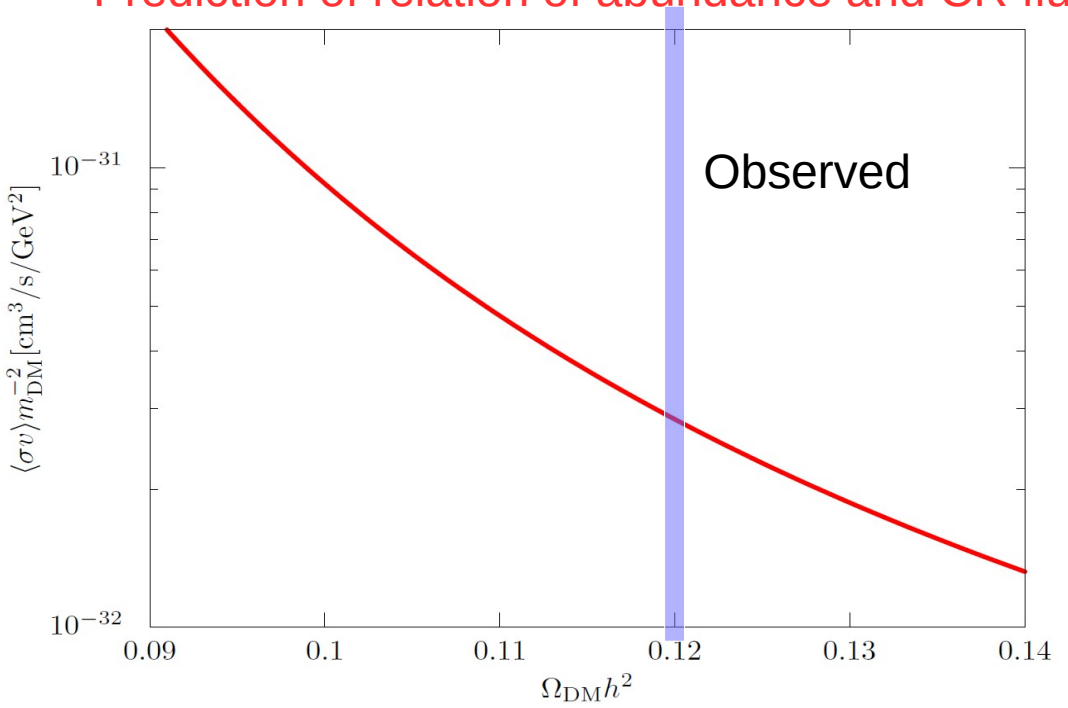
Precise Wino abundance estimation is still challenging.

- Phase transition effect
- NLO effect
- Sommerfeld / bound-state effect in thermal environment

Wino Case

$$\text{flux} \propto \frac{\langle \sigma v \rangle}{m_{\rm DM}^2}$$

Prediction of relation of abundance and CR flux



O(10)% uncertainty on abundance → O(100)% effect on flux