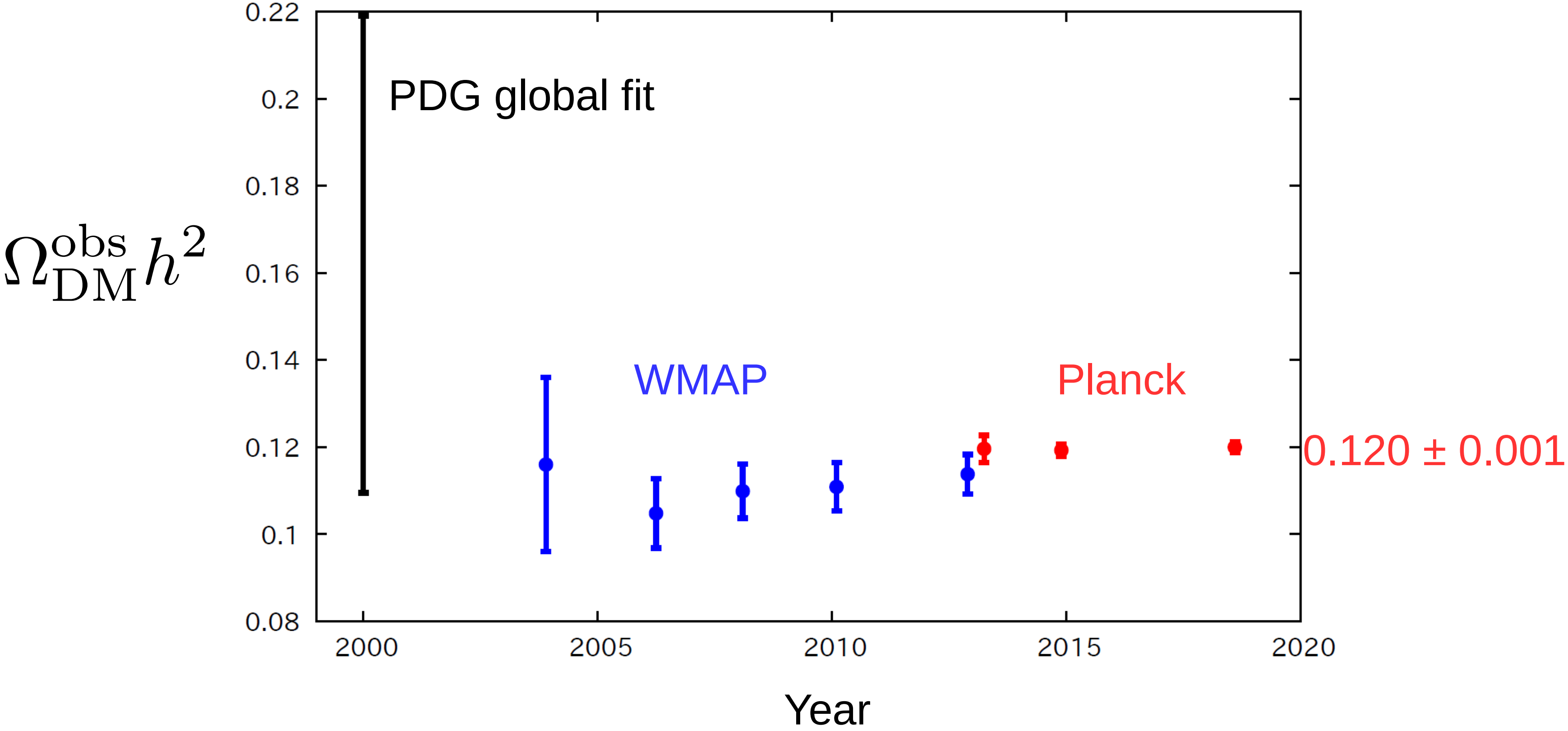
Status of WIMP Dark Matter

Satoshi Shirai (Kavli IPMU)

Precise DM Abundance



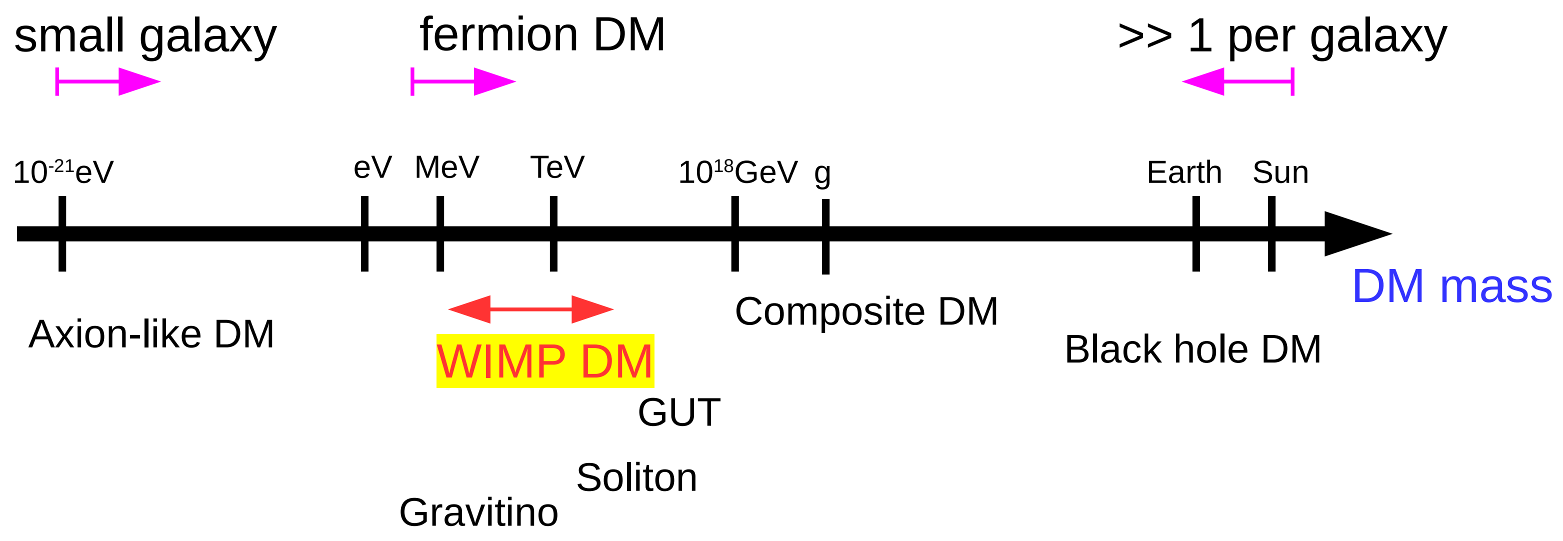
Q: What is Dark Matter?

DM Should be...

- Stable.
- Weakly Interacting.
- Cold.
- Production mechanism.
  20% of total energy of Universe

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

DM Landscape



WIMP (Weakly Interacting Massive Particle):

MeV → 100 TeV scale.

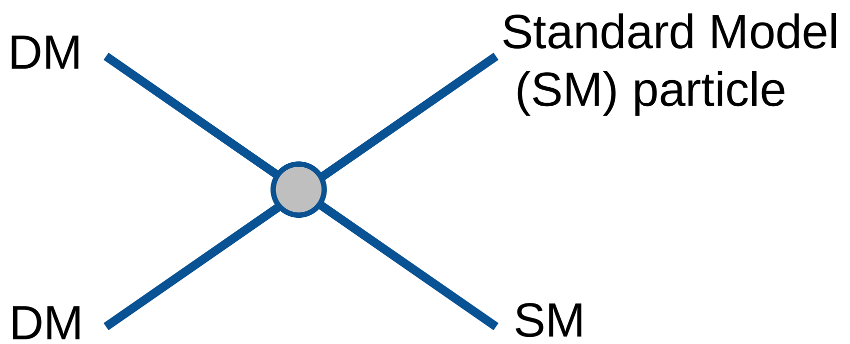
New physics at weak scale likely includes WIMP candidates.

Contents

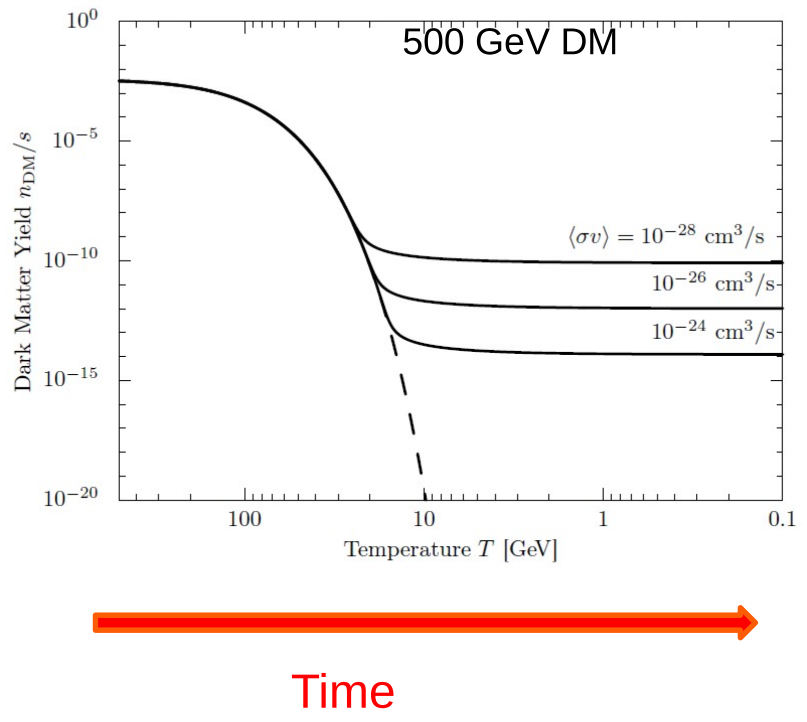
WIMP

WIMP Dark Matter

Weakly Interacting Massive Particle



DM abundance

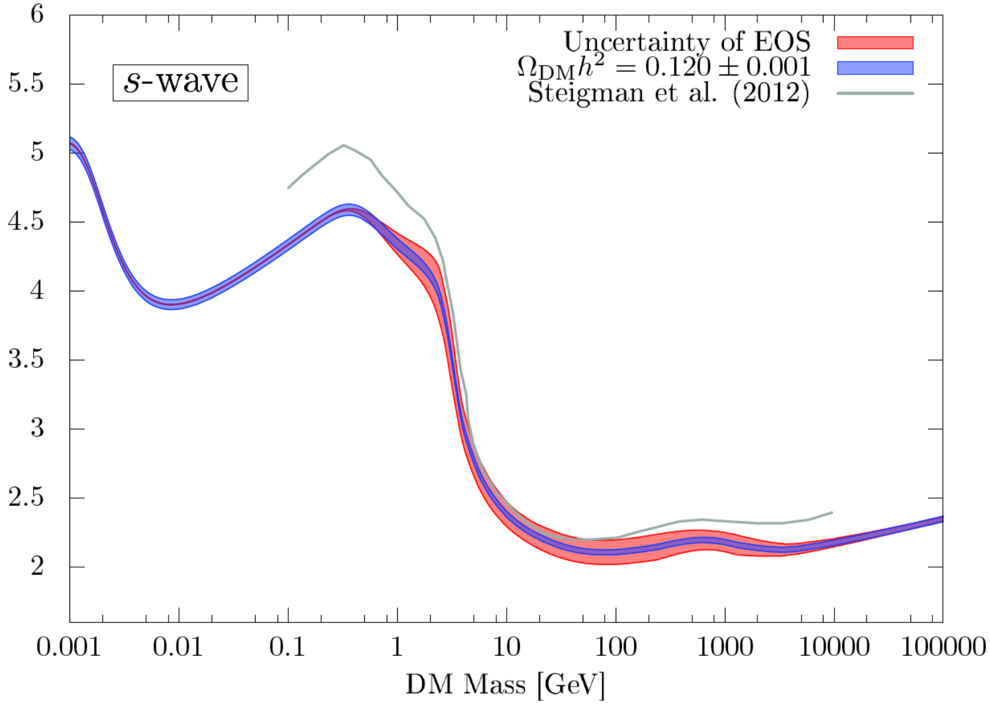


WIMP Cross Section

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

$\langle \sigma v \rangle / 10^{-26} [{\rm cm^3/s}]$

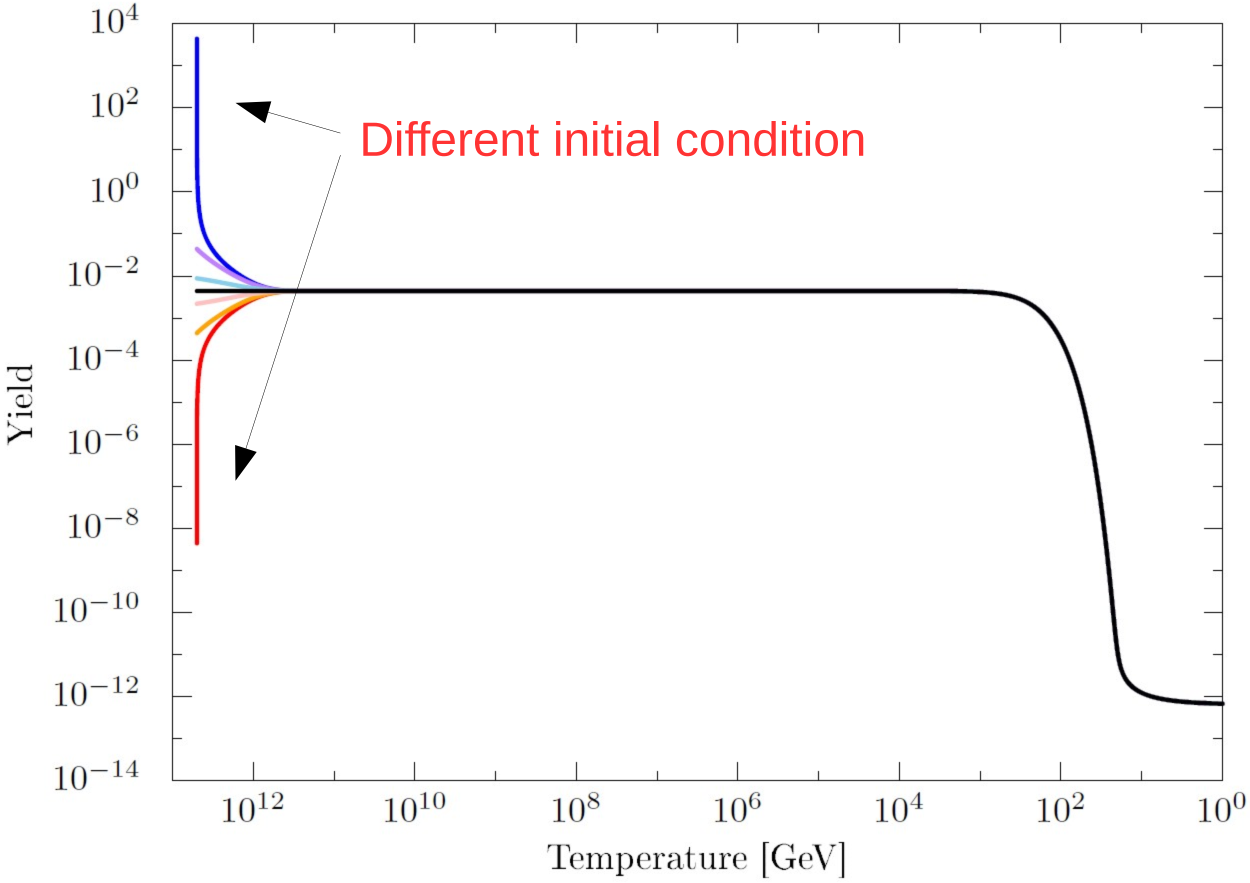
Required Cross section



WIMP Dark Matter

DM Yield n/s

Independent on the initial condition.



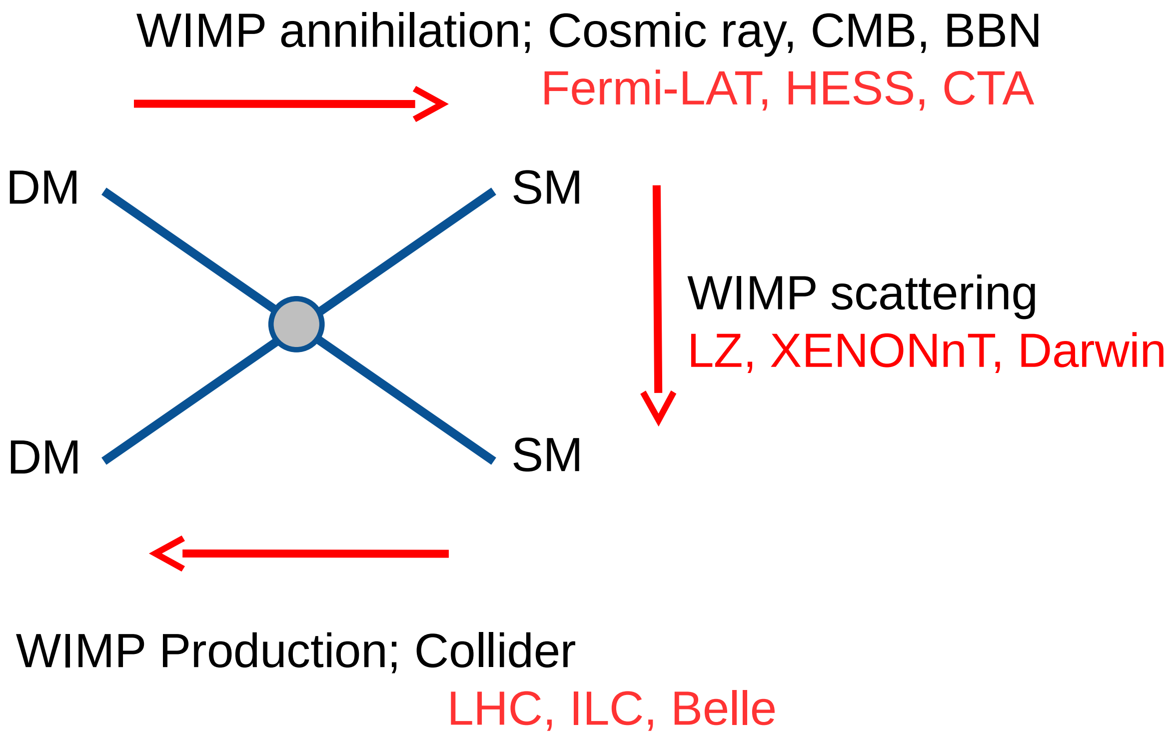
WIMP Advantage

- Initial condition independence.
- Cross section can be calculated.

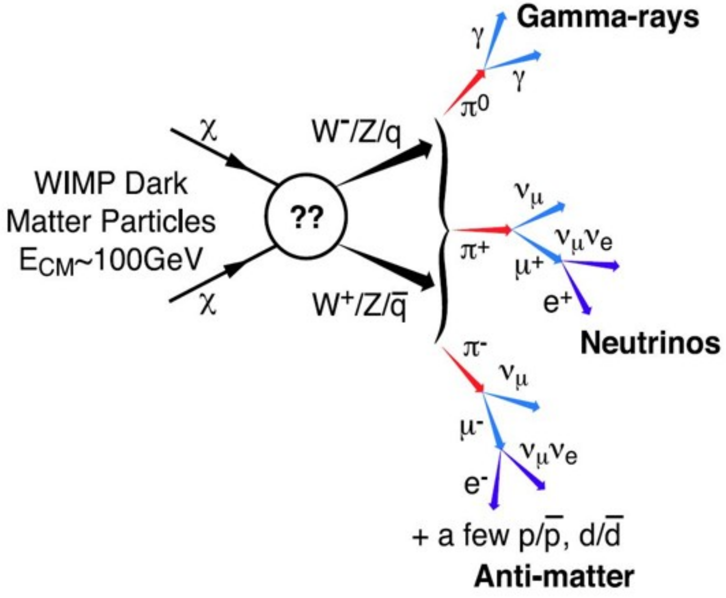
↓

Precise estimation of DM abundance is possible!

WIMP Detection



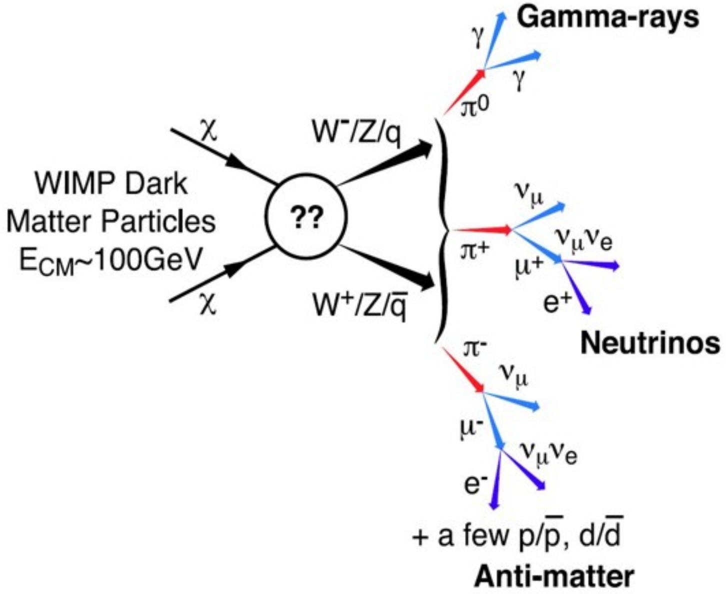
Indirect Detection



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



Cosmic-ray flux

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

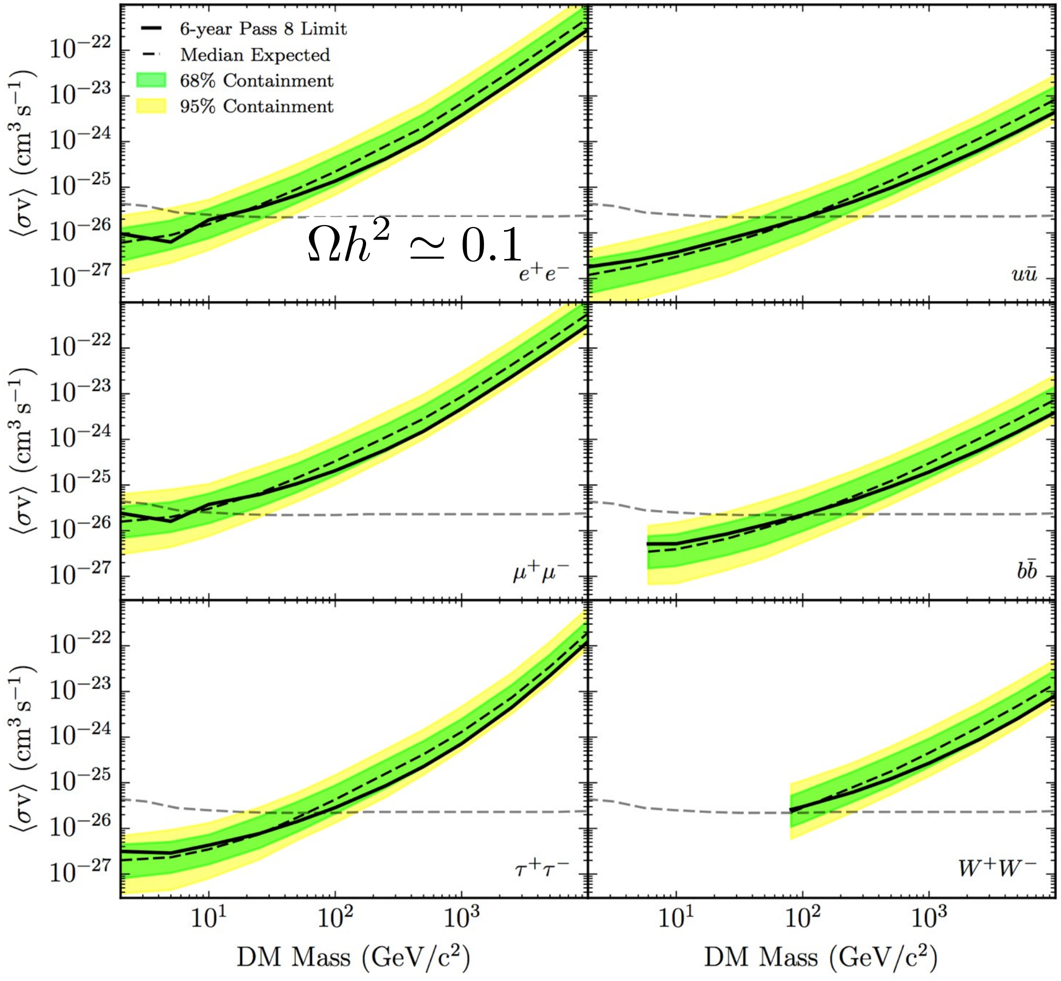
Particle physics   Astrophysics

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

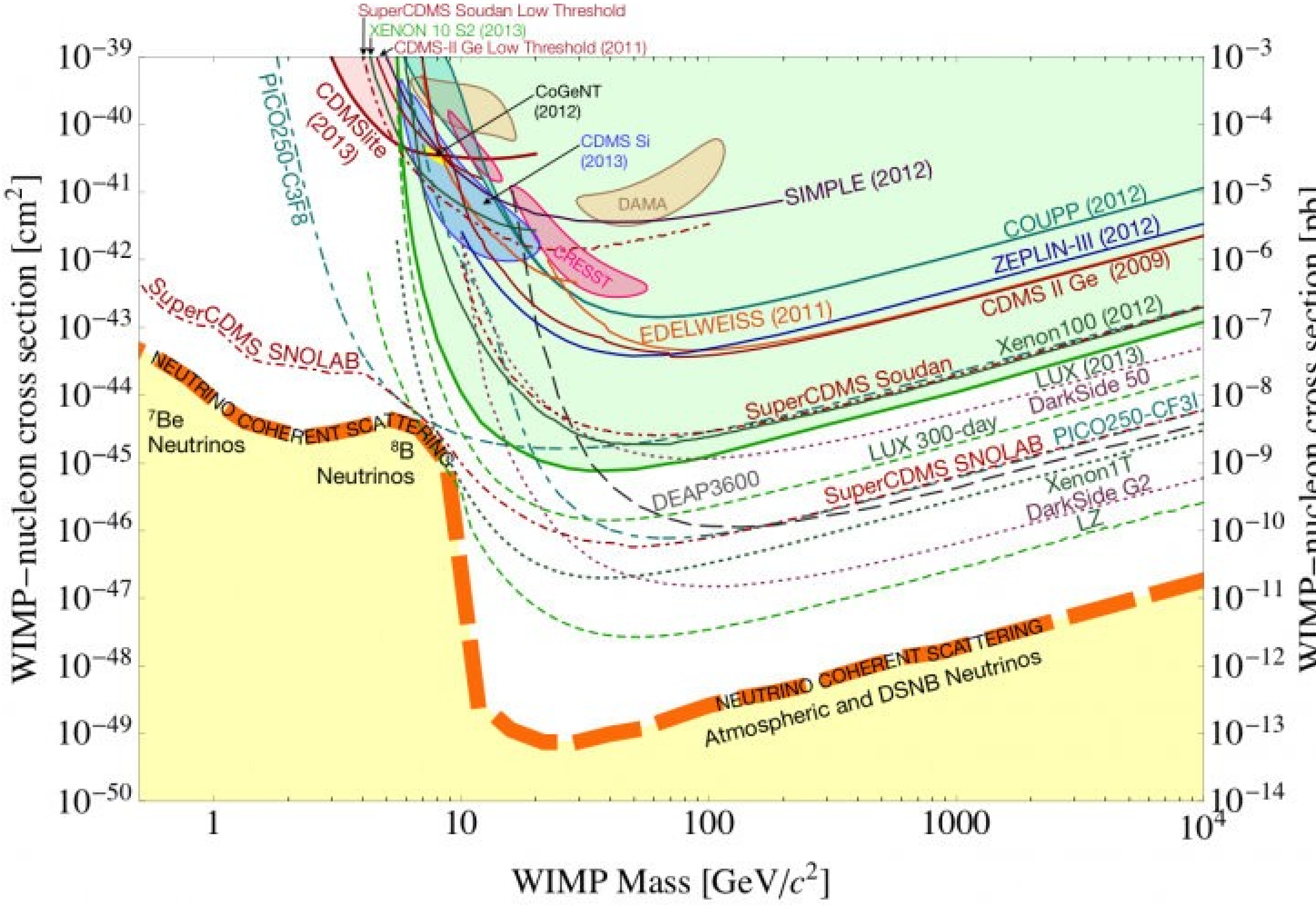
- DM lives everywhere:
  - Galactic center (GC)
  - Dwarf spheroidal galaxy (dSph)
  - Galaxy cluster
  - …
- Large astrophysical uncertainty.

Indirect Detection and Abundance

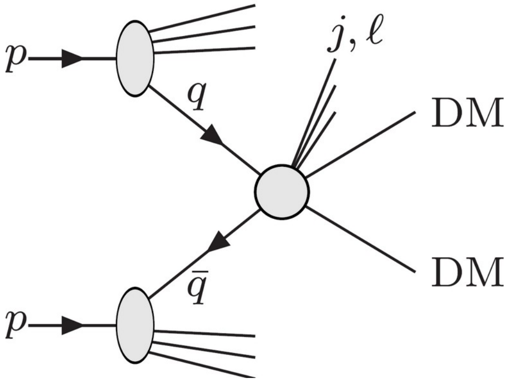
Constraint by Fermi-LAT



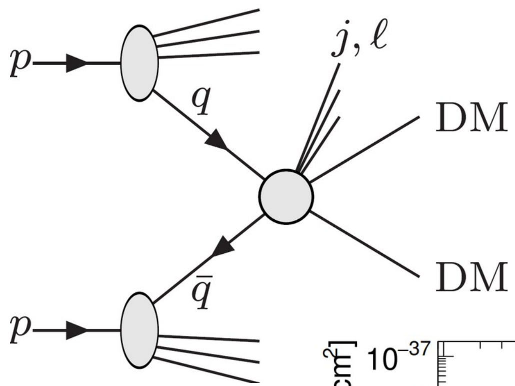
Direct Detection



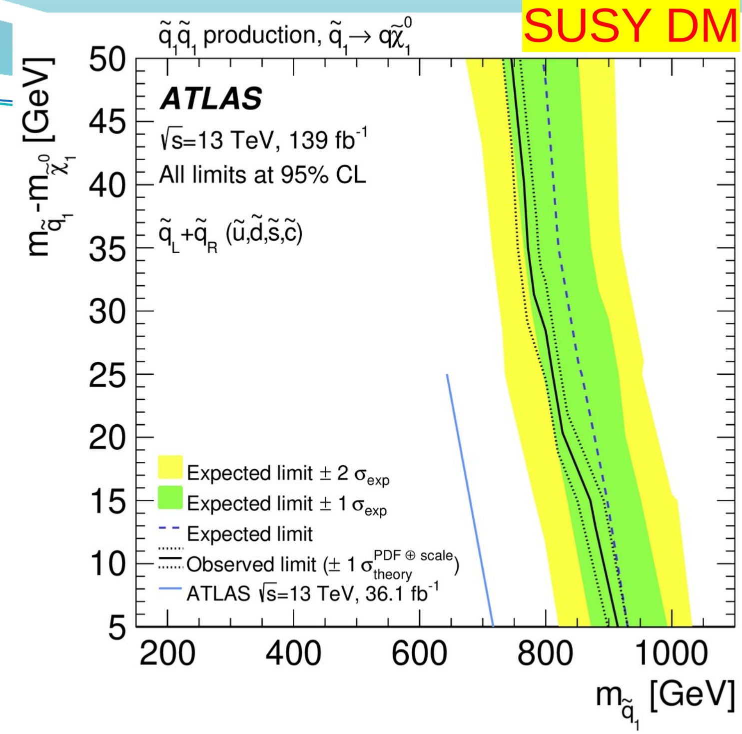
Collider



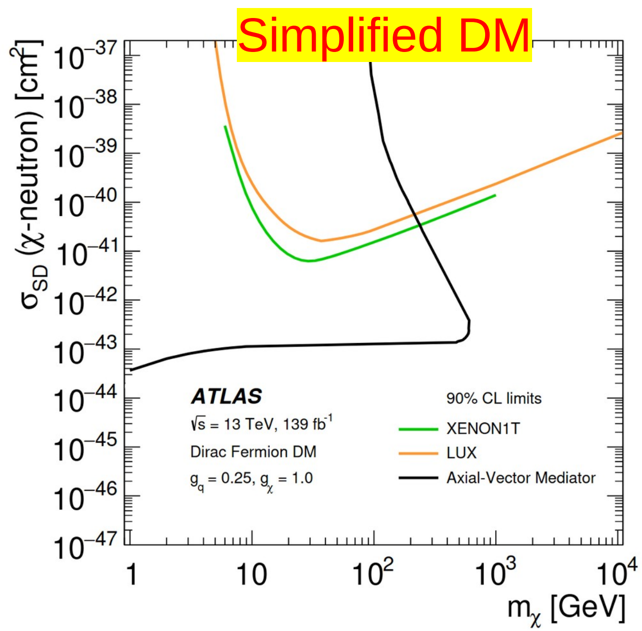
Collider



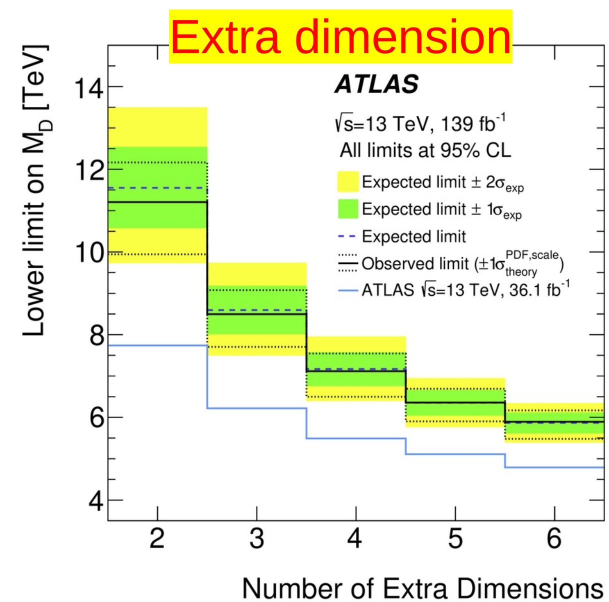
p
q
j, ℓ
DM
DM
$\bar{q}$
p



SUSY DM
$\tilde{q}_1\tilde{q}_1$ production, $\tilde{q}_1 \rightarrow q\tilde{\chi}_1^0$
ATLAS
$\sqrt{s}$=13 TeV, 139 fb^{-1}
All limits at 95% CL
$\tilde{q}_L+\tilde{q}_R$ ($\tilde{u},\tilde{d},\tilde{s},\tilde{c}$)
Expected limit ± 2 σ_{exp}
Expected limit ± 1 σ_{exp}
Expected limit
Observed limit (± 1 $\sigma_{theory}^{PDF \oplus scale}$)
ATLAS $\sqrt{s}$=13 TeV, 36.1 fb^{-1}
$m_{\tilde{q}_1} - m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{q}_1}$ [GeV]

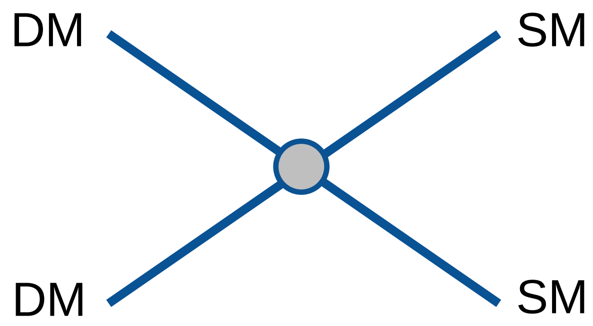


Simplified DM
ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Dirac Fermion DM
g_q = 0.25, g_χ = 1.0
90% CL limits
XENON1T
LUX
Axial-Vector Mediator
σ_{SD} (χ-neutron) [cm^2]
m_χ [GeV]



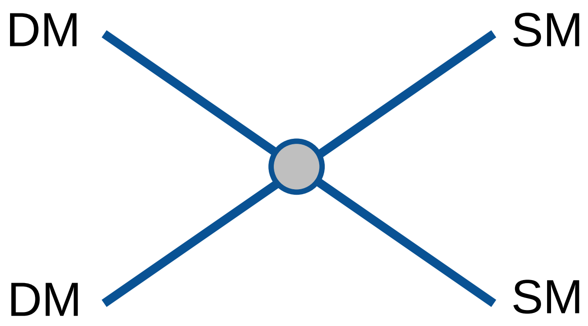
Extra dimension
ATLAS
$\sqrt{s}$=13 TeV, 139 fb^{-1}
All limits at 95% CL
Expected limit ± 2σ_{exp}
Expected limit ± 1σ_{exp}
Expected limit
Observed limit (±1$\sigma_{theory}^{PDF,scale}$)
ATLAS $\sqrt{s}$=13 TeV, 36.1 fb^{-1}
Lower limit on M_D [TeV]
Number of Extra Dimensions

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

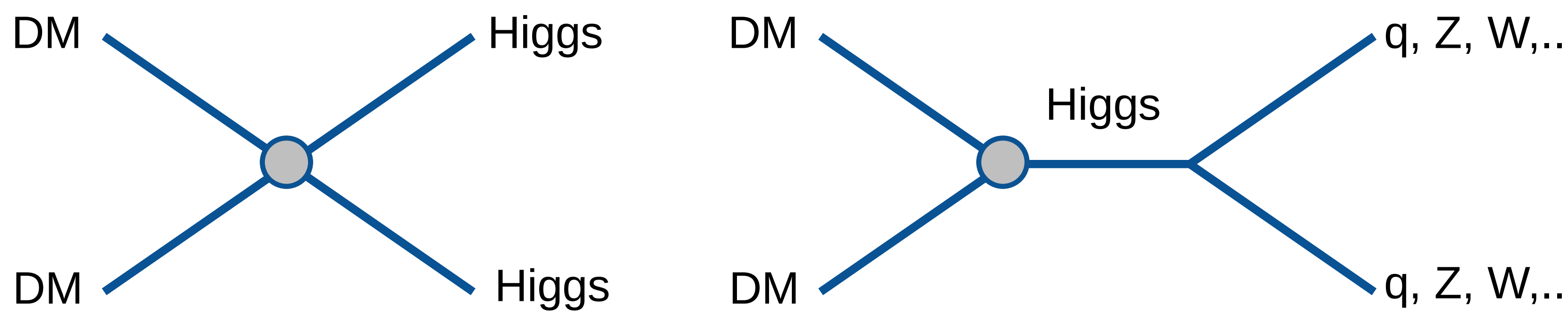
Gauge Portal dark matter

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

Higgs Portal DM

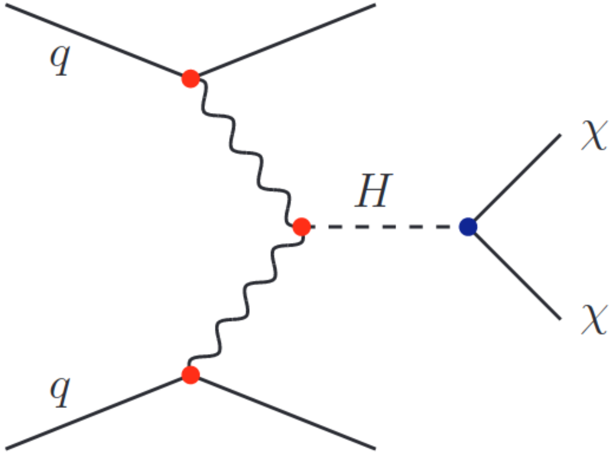
DM and Higgs

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



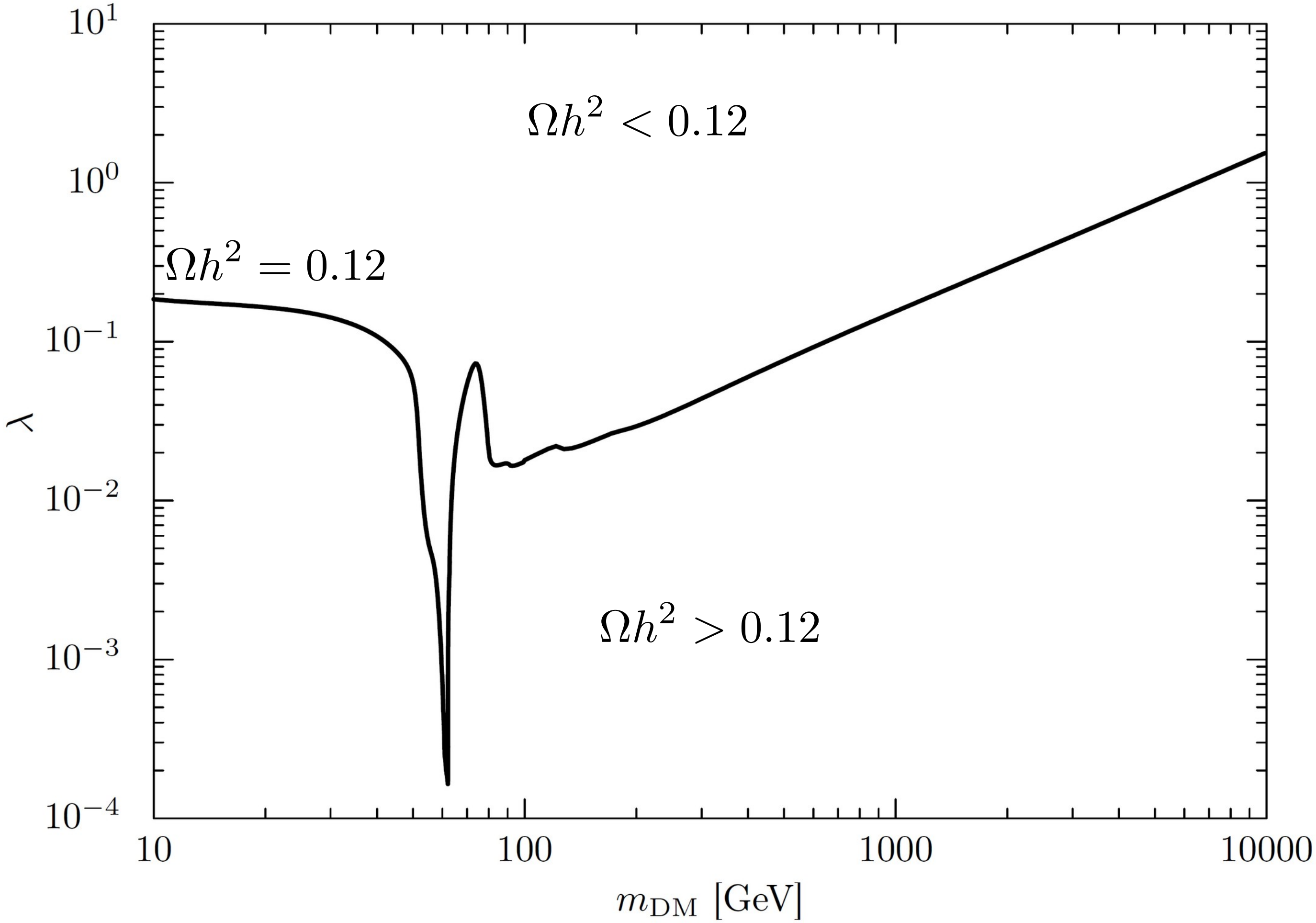
DM abundance, (in)direct, collider signature comes from one operator.

Higgs-portal at LHC



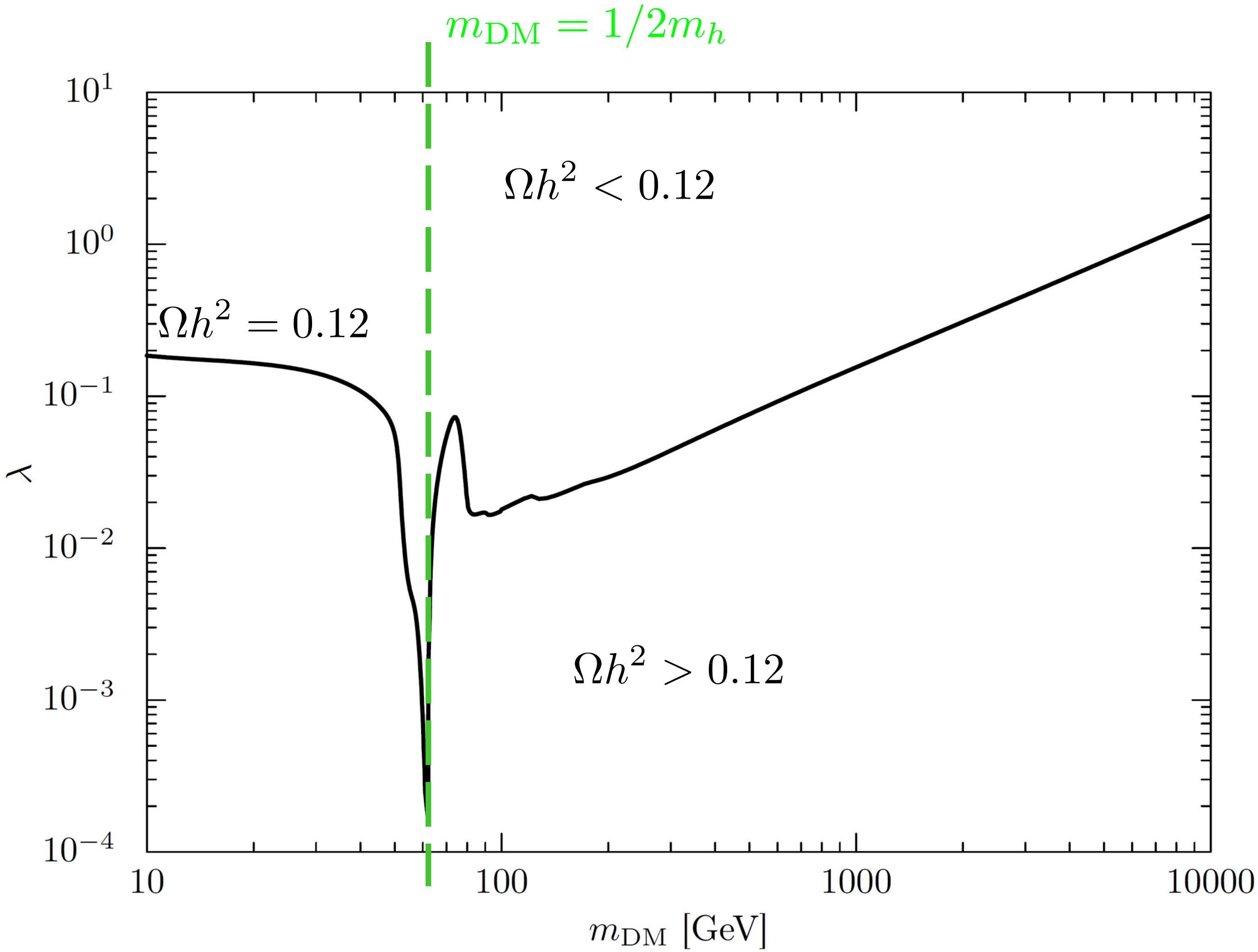
- Invisible Higgs decay constraints Br(H → DM DM):
  - < 0.11 (ATLAS), 0.15 (CMS)
  - < 0.06 (HL-LHC)
  - < 0.003 (ILC)
- Off-shell Higgs decay

DM and Higgs



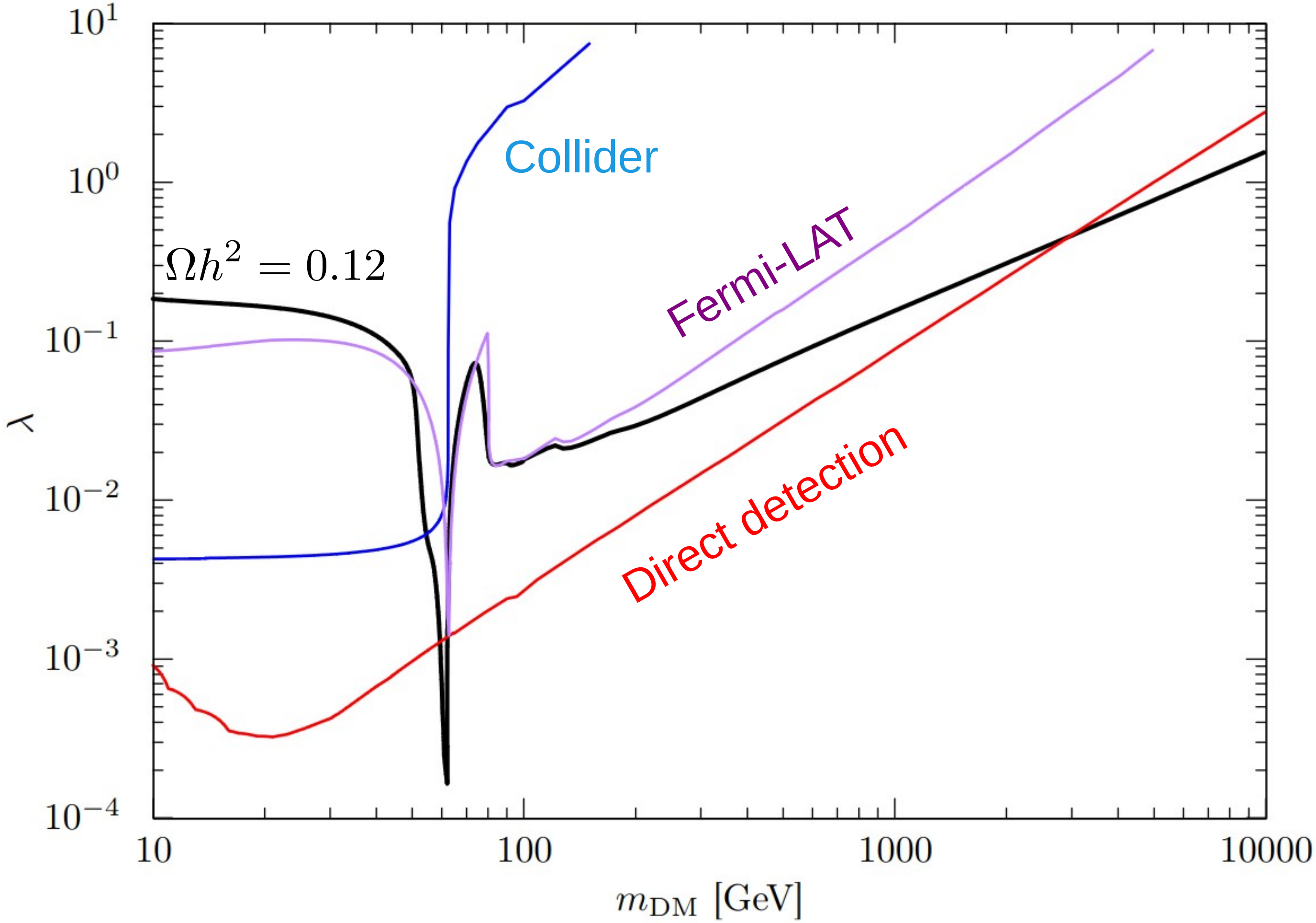
$\Omega h^2 < 0.12$
$\Omega h^2 = 0.12$
$\Omega h^2 > 0.12$
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
λ
10
100
1000
10000
$m_{\rm DM}$ [GeV]

DM and Higgs



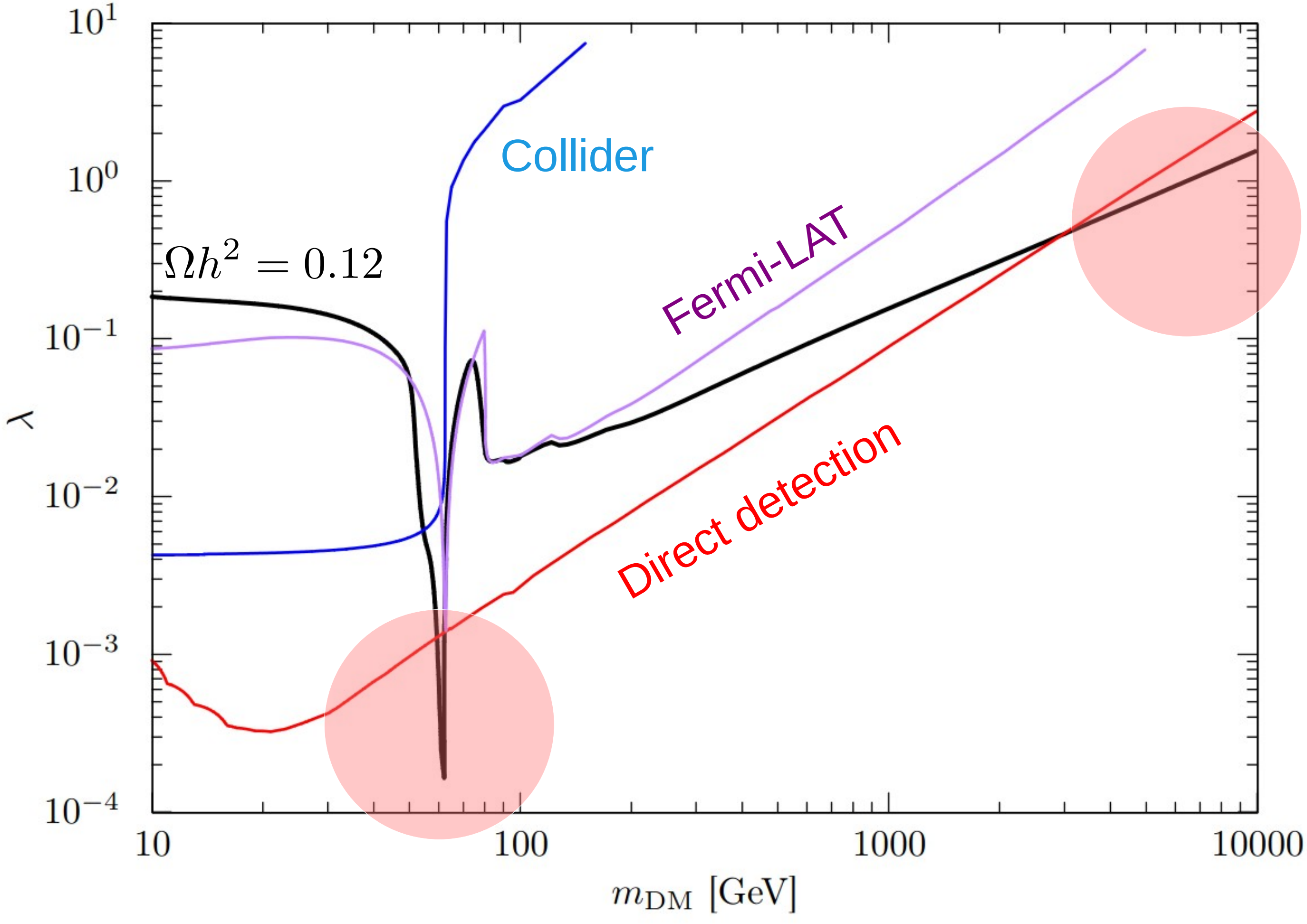
$m_{\rm DM} = 1/2 m_h$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
λ
$\Omega h^2 < 0.12$
$\Omega h^2 = 0.12$
$\Omega h^2 > 0.12$
10
100
1000
10000
$m_{\rm DM}$ [GeV]

DM and Higgs



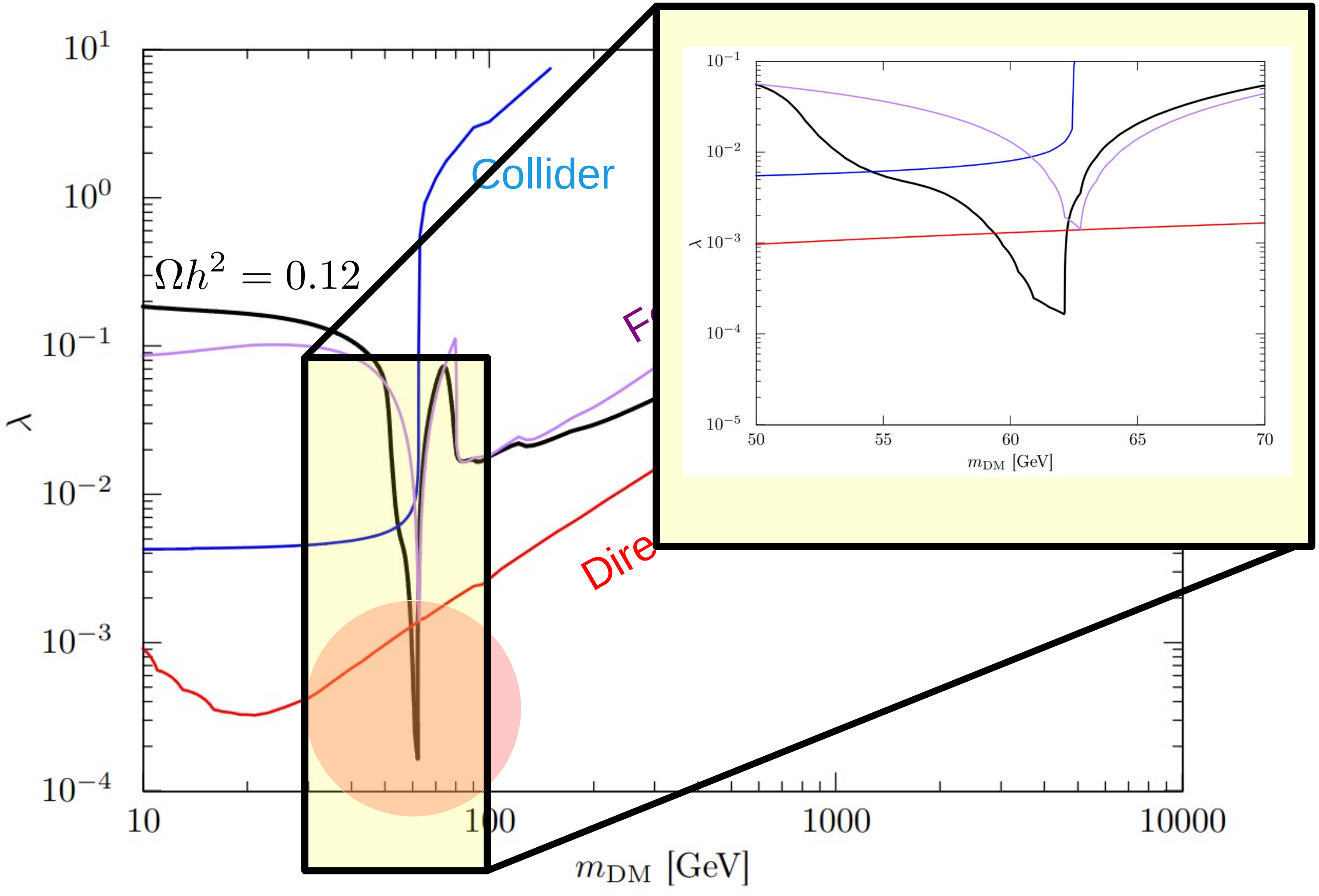
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
λ
$\Omega h^2 = 0.12$
Collider
Fermi-LAT
Direct detection
10
100
1000
10000
$m_{\rm DM}$ [GeV]

DM and Higgs



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

DM and Higgs



10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
λ
$\Omega h^2 = 0.12$
Collider
Dire
10
100
1000
10000
$m_{\rm DM}$ [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
50
55
60
65
70

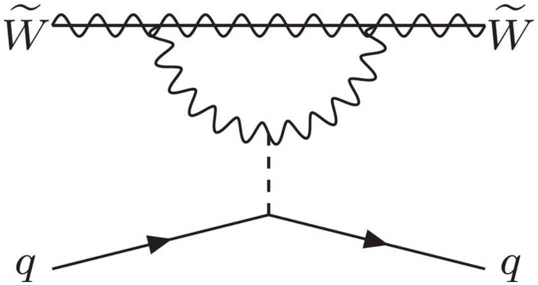
Gauge Portal DM (Wino)

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

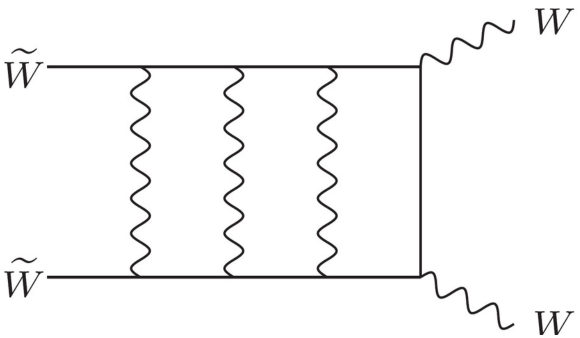
[Hisano, Matsumoto, Nagai, Saito & Senami, 06]

Wino Signal



Direct Detection

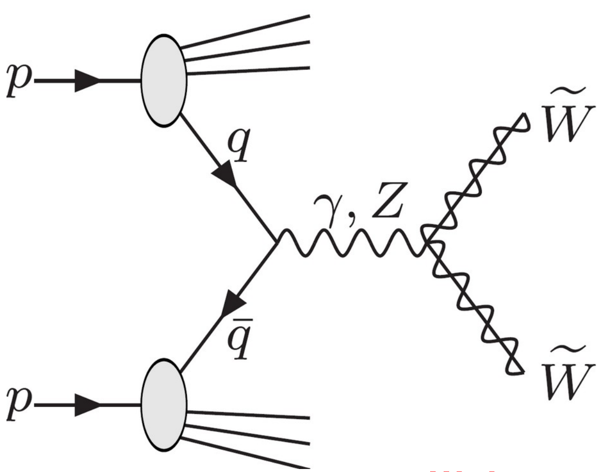
[Hisano, Ishiwata & Nagata, 12]



Indirect Detection

[Hisano, Matsumoto, Nojiri & Saito, 04]

Wino-Nucleon XS ~ 10^{-47} cm^2



Collider

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

Line Photon

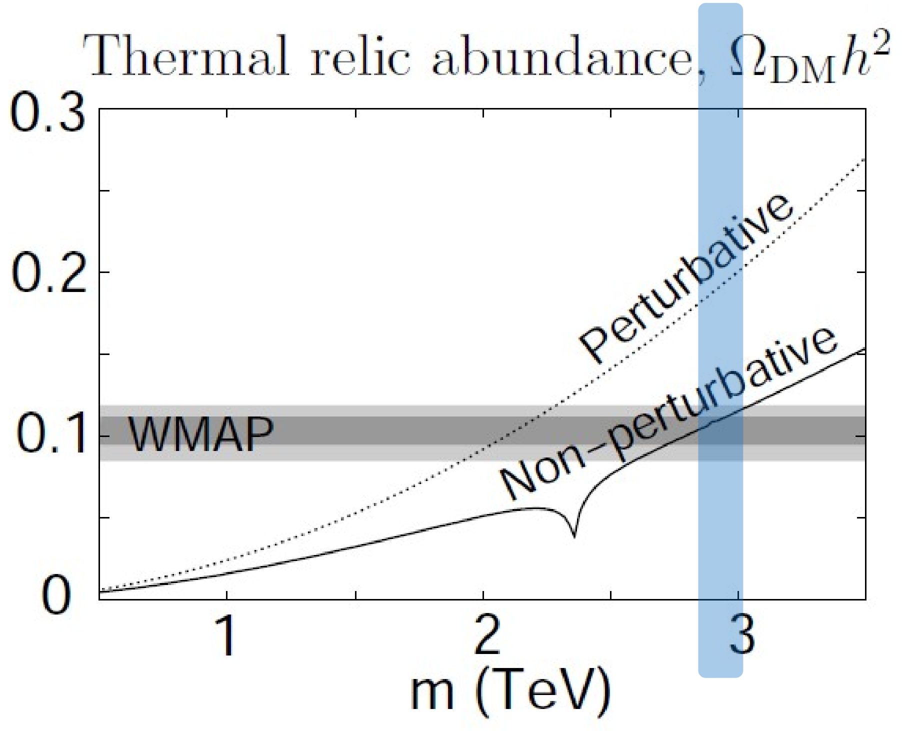
$$\widetilde{W}\widetilde{W} \to WW$$

Continuum Photon

Anti-matter

Wino Thermal Abundance

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

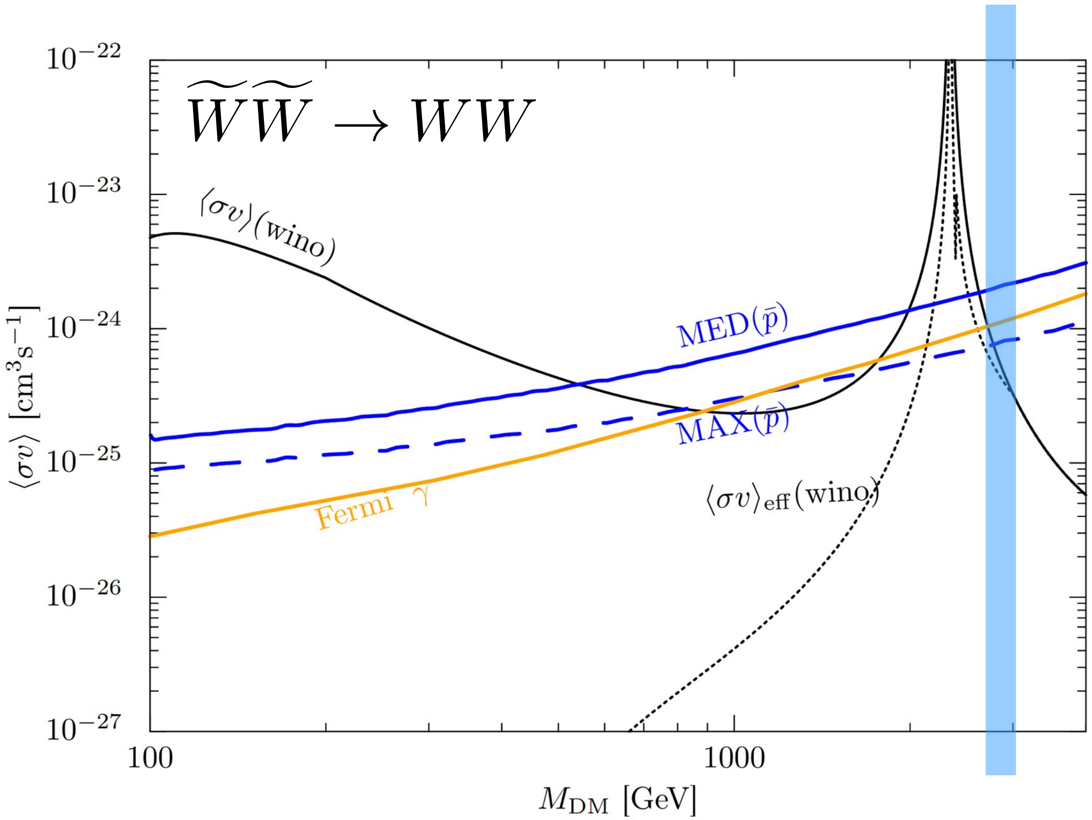


Wino Abundance

Wino is Whole Component of DM?

- Yes → Only Thermal Relic?
  - Yes → 3 TeV Wino
  - No → <3 TeV Wino + non-thermal production
    - e.g., gravitino decay
- No → Mixed DM
  - e.g., (thermal) Wino + Axion

Cosmic Ray Signals



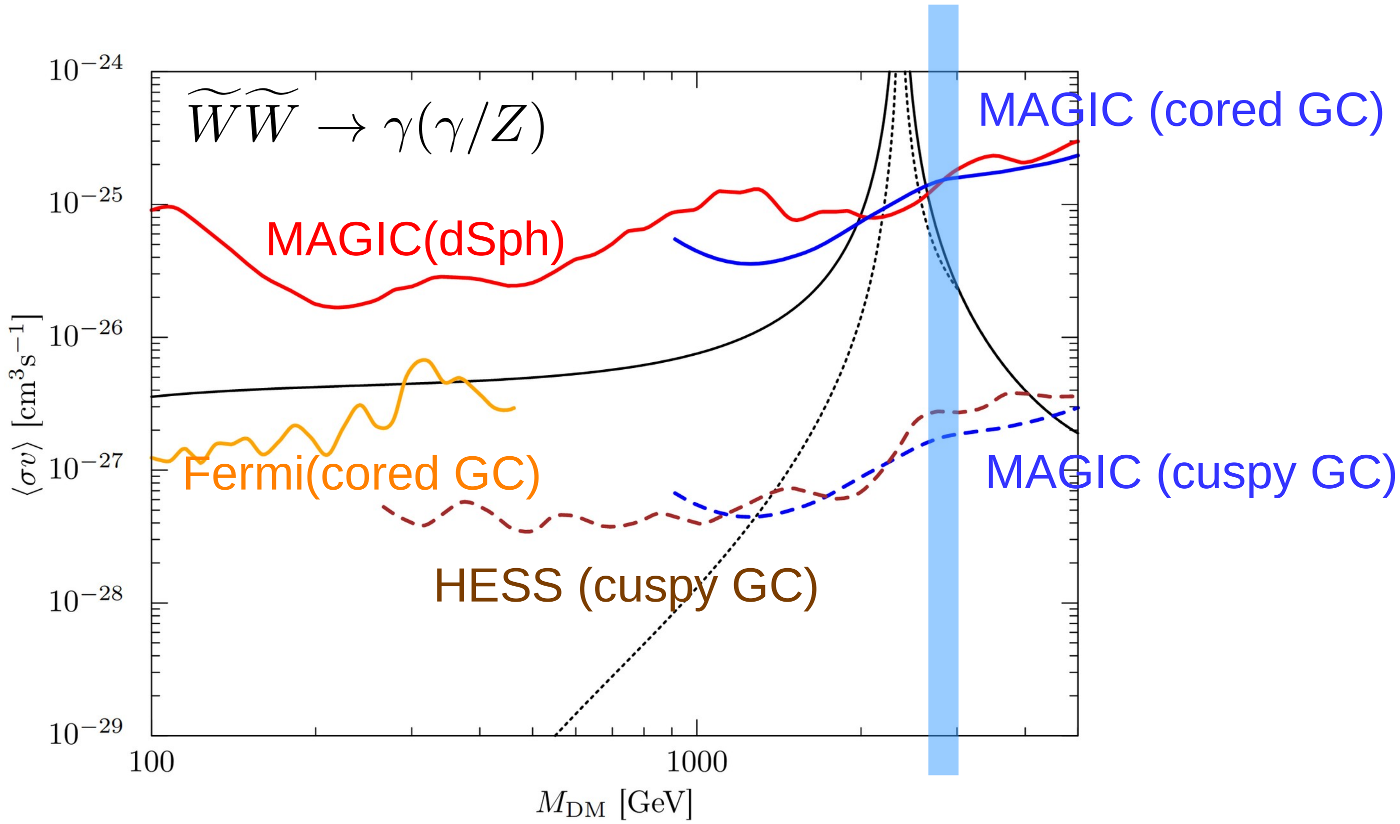
AMS02 antiproton

Fermi Gamma ray

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

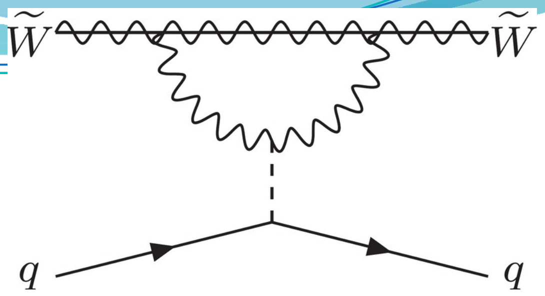
Large Uncertainty of Astrophysical model and DM density

Line Search

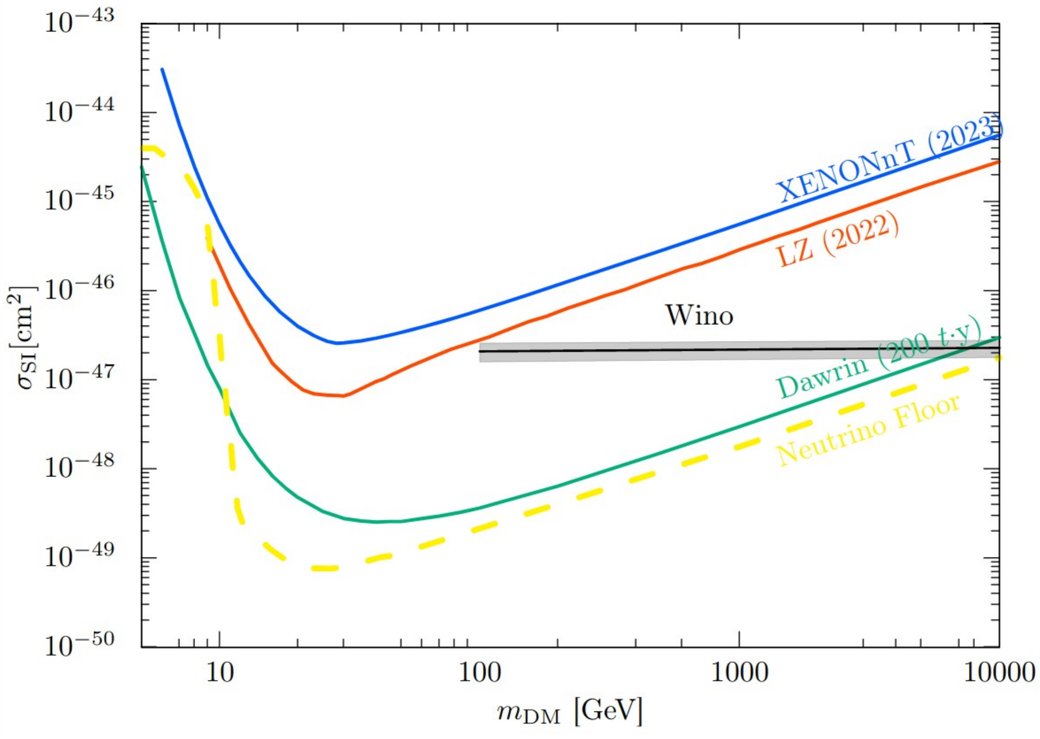


$\widetilde{W}\widetilde{W} \to \gamma(\gamma/Z)$
MAGIC (cored GC)
MAGIC(dSph)
Fermi(cored GC)
MAGIC (cuspy GC)
HESS (cuspy GC)
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
$\langle \sigma v \rangle$ [cm^{3}s^{-1}]
100
1000
$M_{\rm DM}$ [GeV]

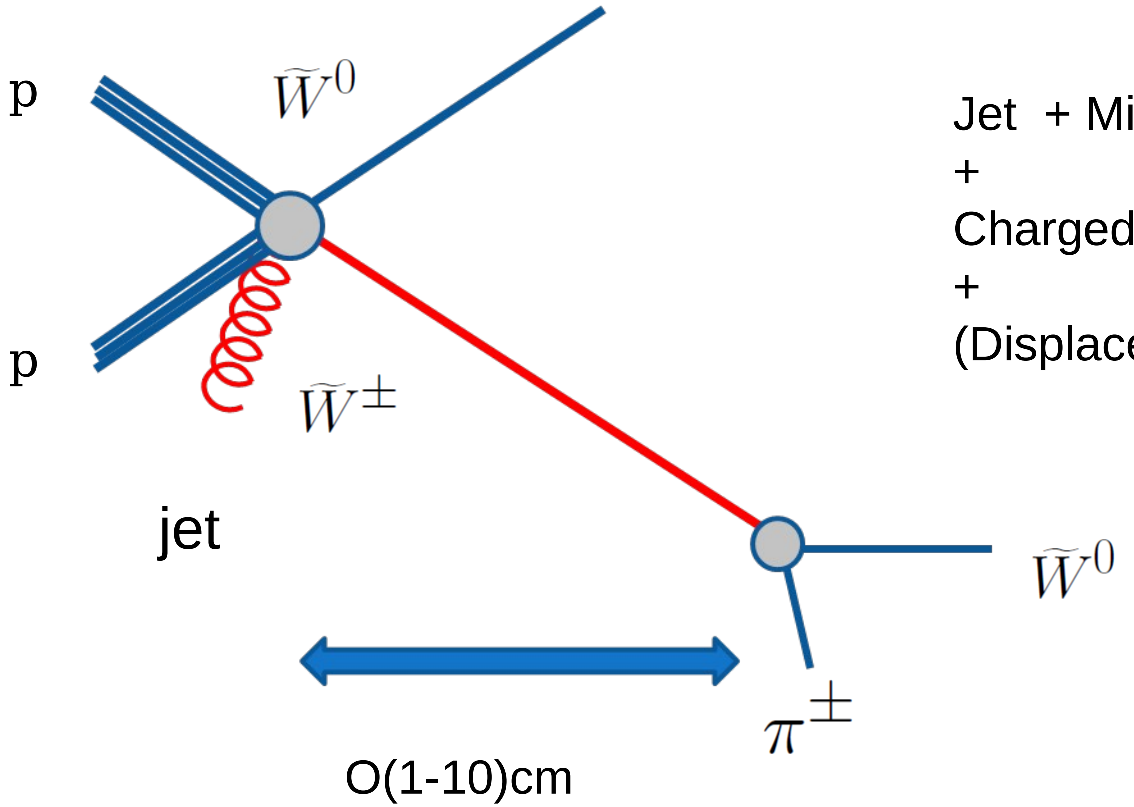
Direct Detection



Hisano, Ishiwata, Nagata 15

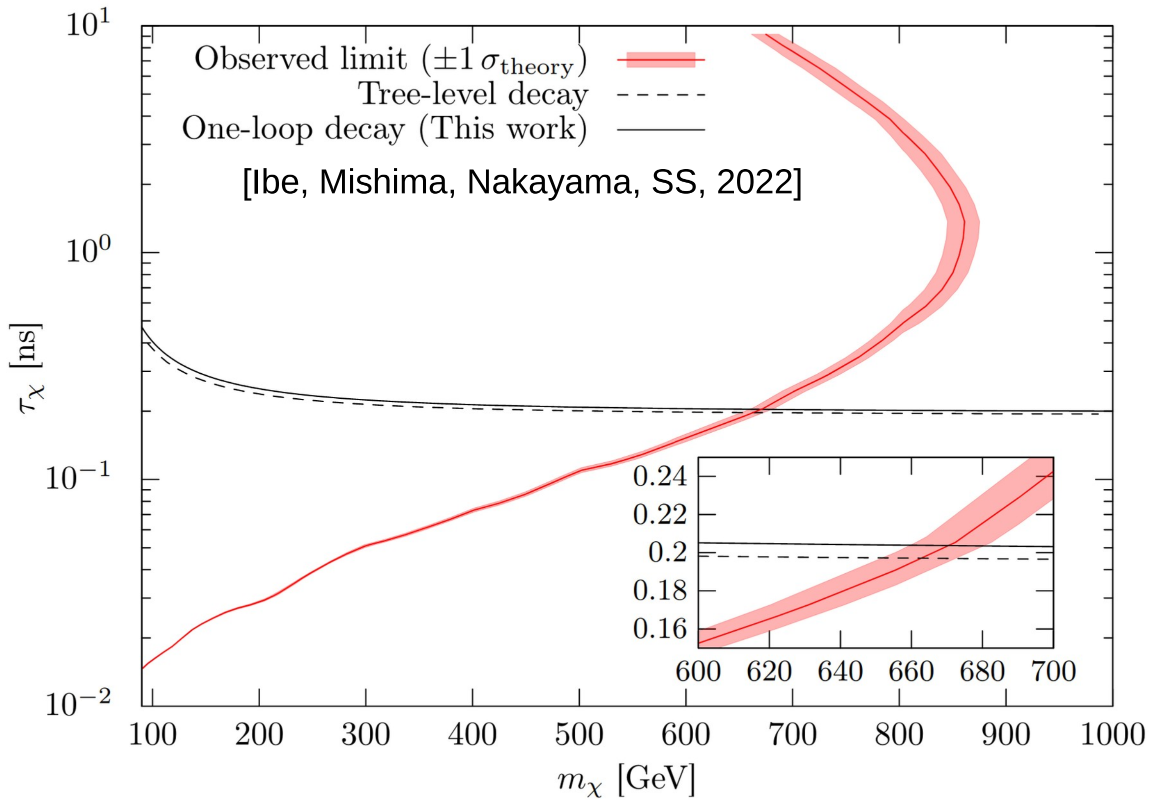


Direct LHC Signals



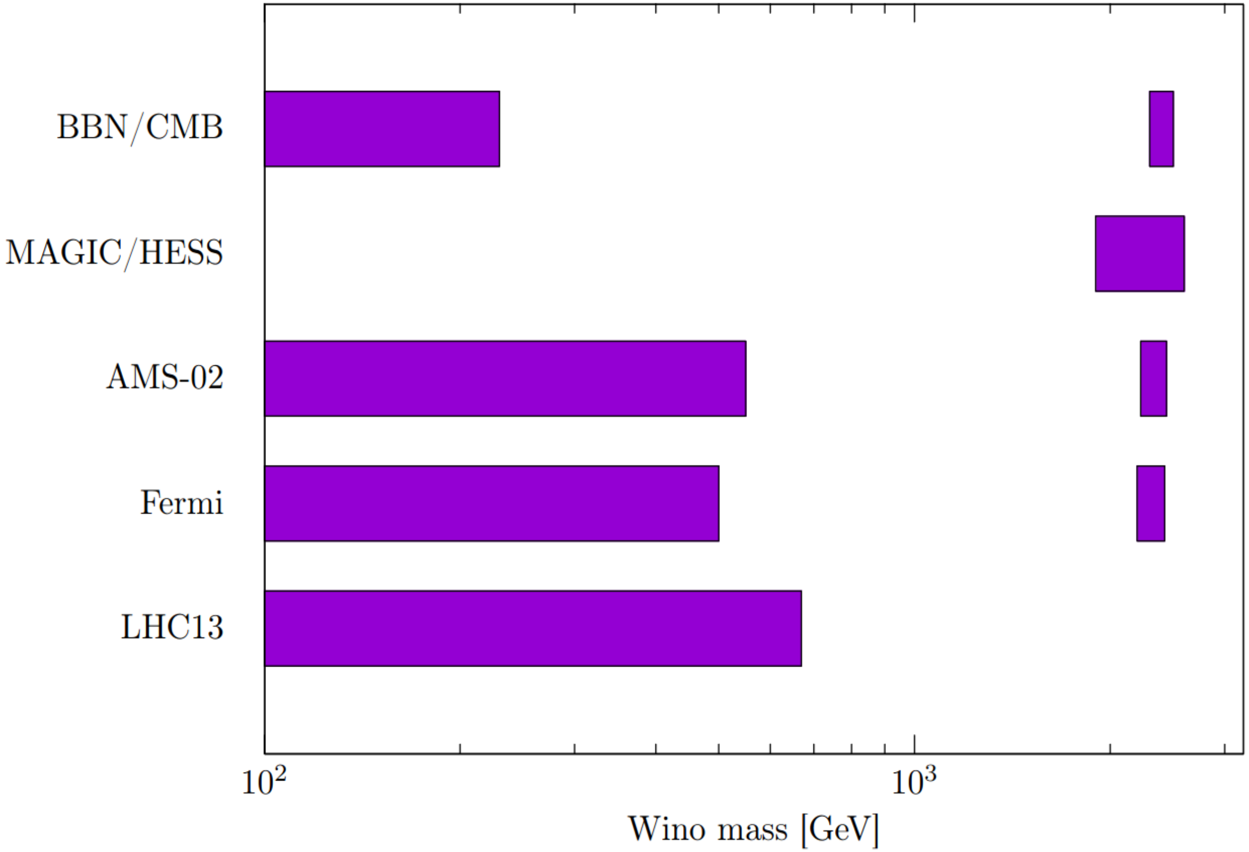
Jet + Missing energy
+
Charged track
+
(Displaced)Soft pion

ATLAS Search (2022)



> 670 GeV Wino

Wino Constraint/Prospect



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

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

- 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.

- ….

Scalar Triplet (Scalar Wino)

Scalar Triplet

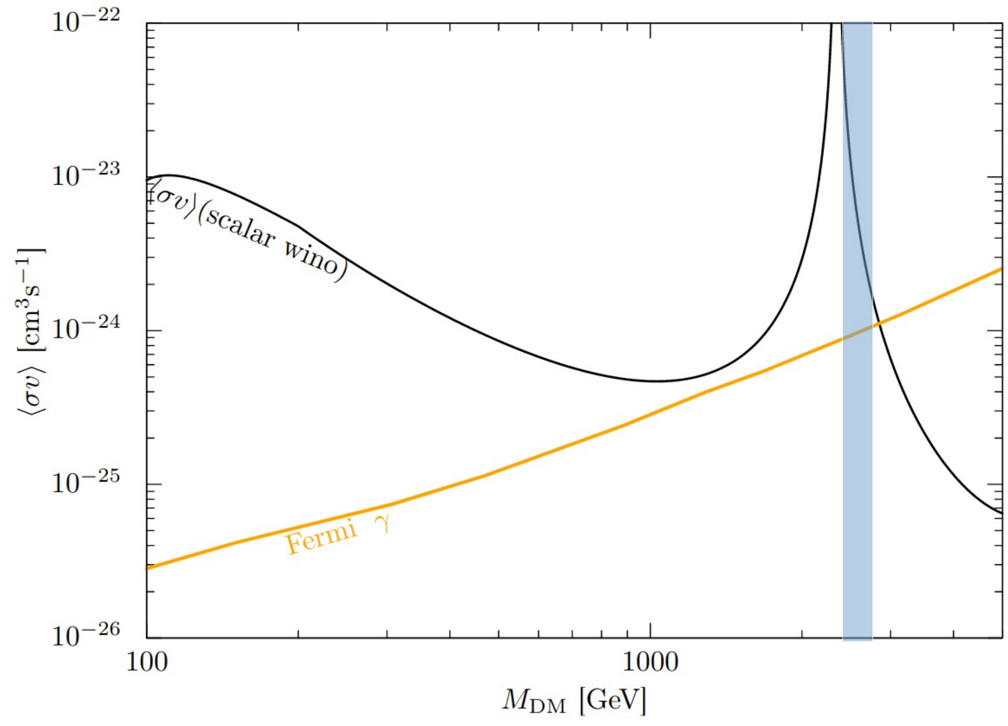
- Real Scalar ϕ

- Hypercharge Y=0

- $SU(2)_L$ triplet $\begin{pmatrix} \phi^+ \\ \phi^0 \\ \phi^- \end{pmatrix}$

Scalar Wino

$\Omega h^2 = 0.12$



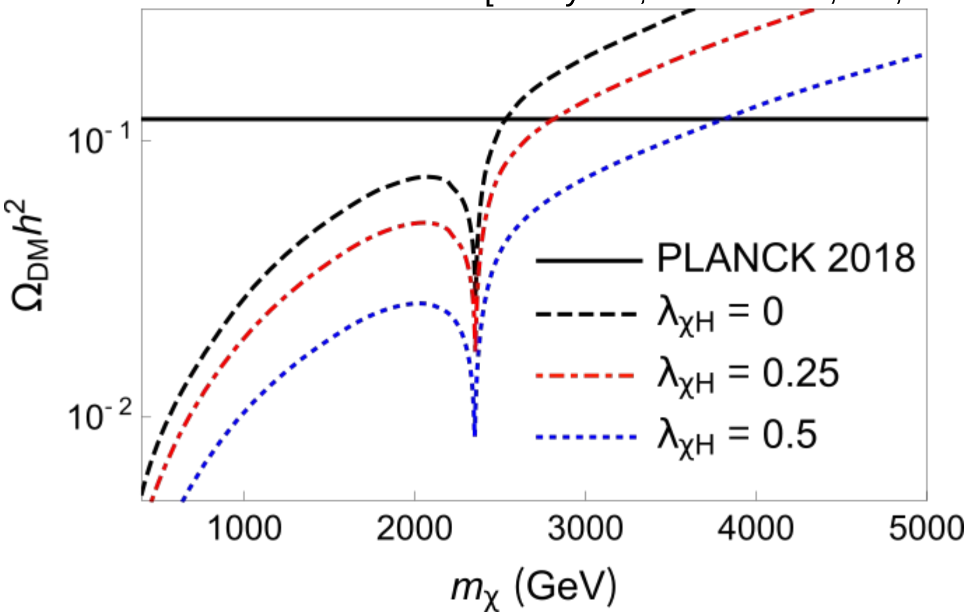
Scalar Wino has tension with indirect search.

Scalar Wino-Higgs Interaction

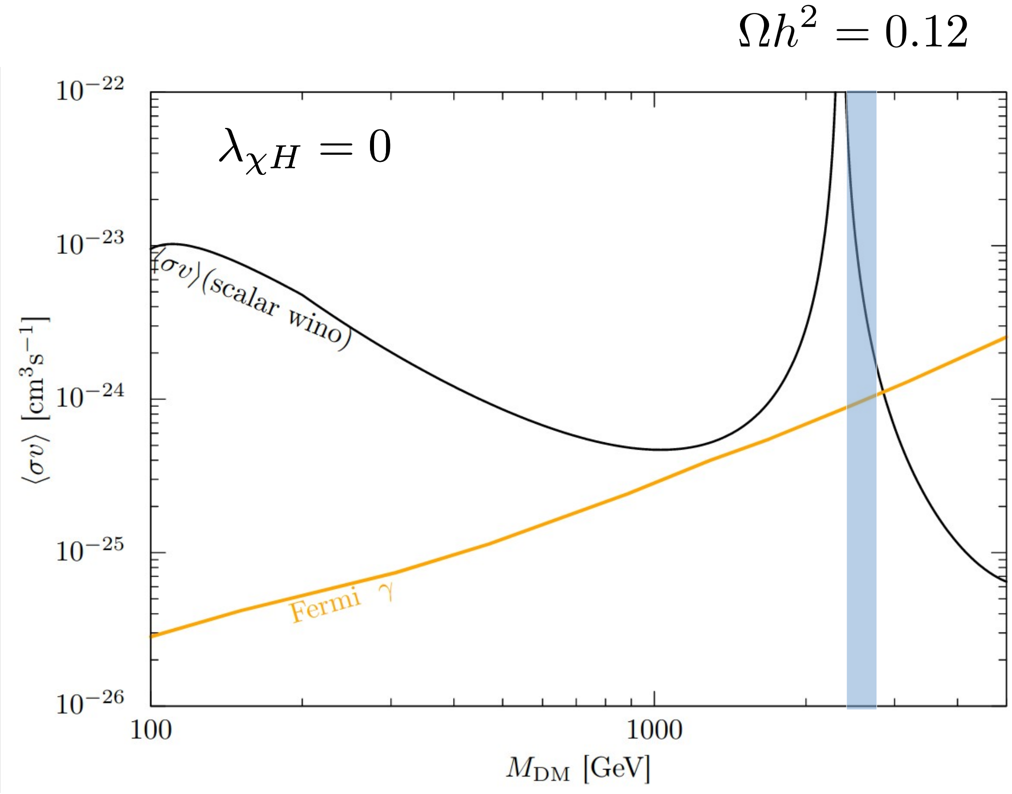
Scalar field can also couple to Higgs field.

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

[Katayose, Matsumoto, SS, Watanabe, 2021]



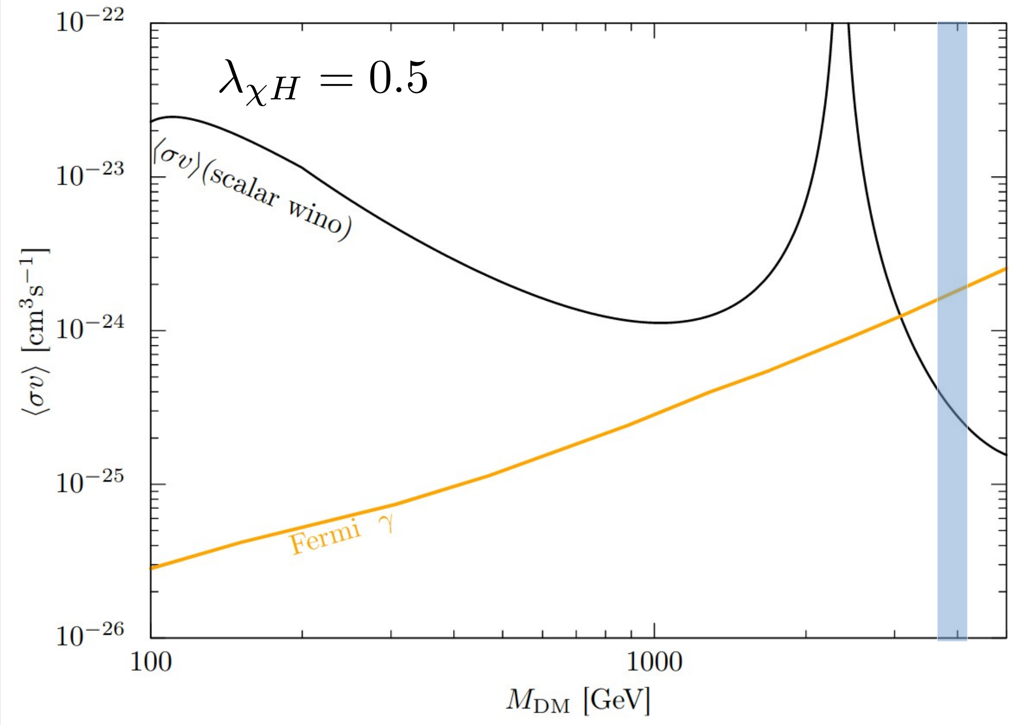
Scalar Wino



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

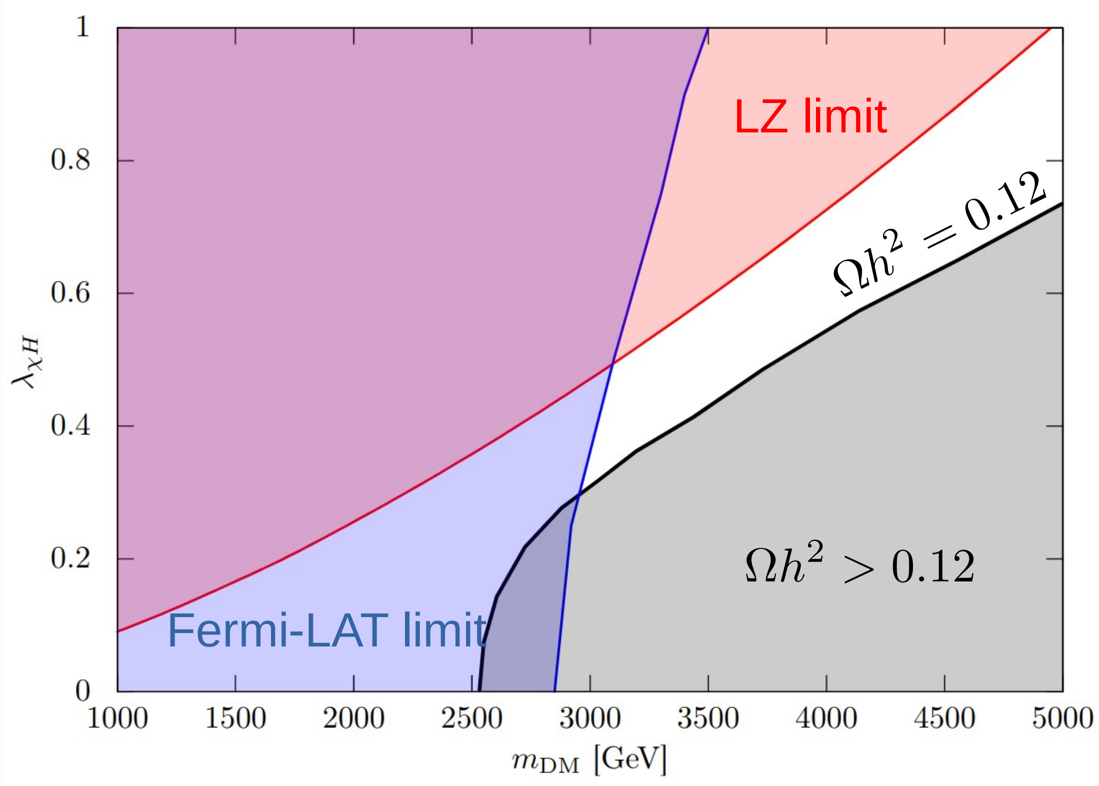
Scalar Wino+Higgs Interaction

$\Omega h^2 = 0.12$



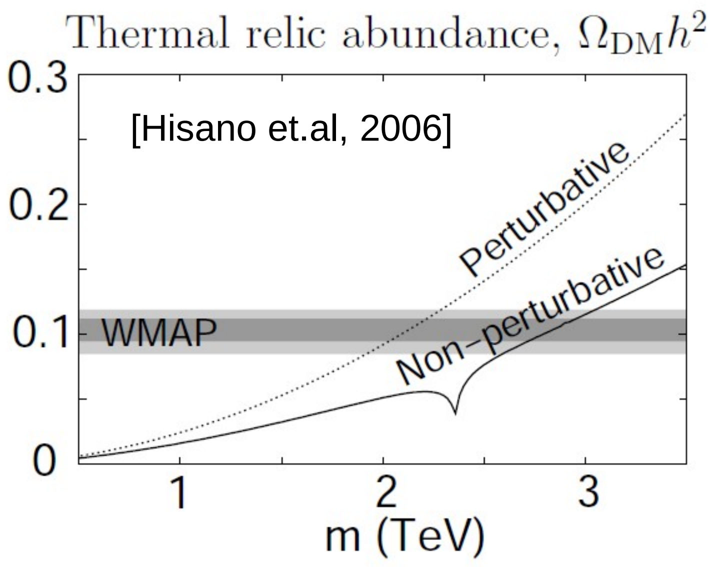
Evade Indirect constraint

Scalar Wino Parameter

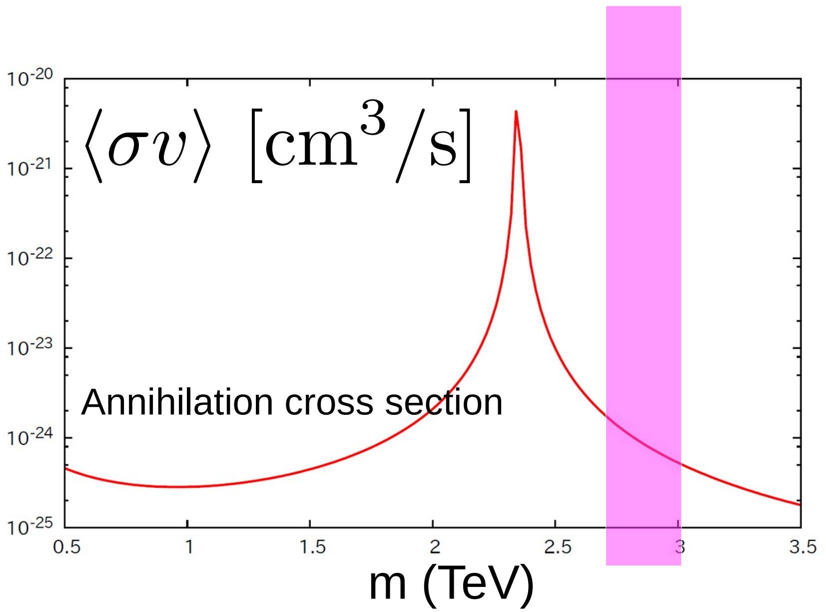


Abundance

$\Omega h^2 \simeq 0.1$



2.7 – 3 TeV wino looks good.



Largely depends on mass.

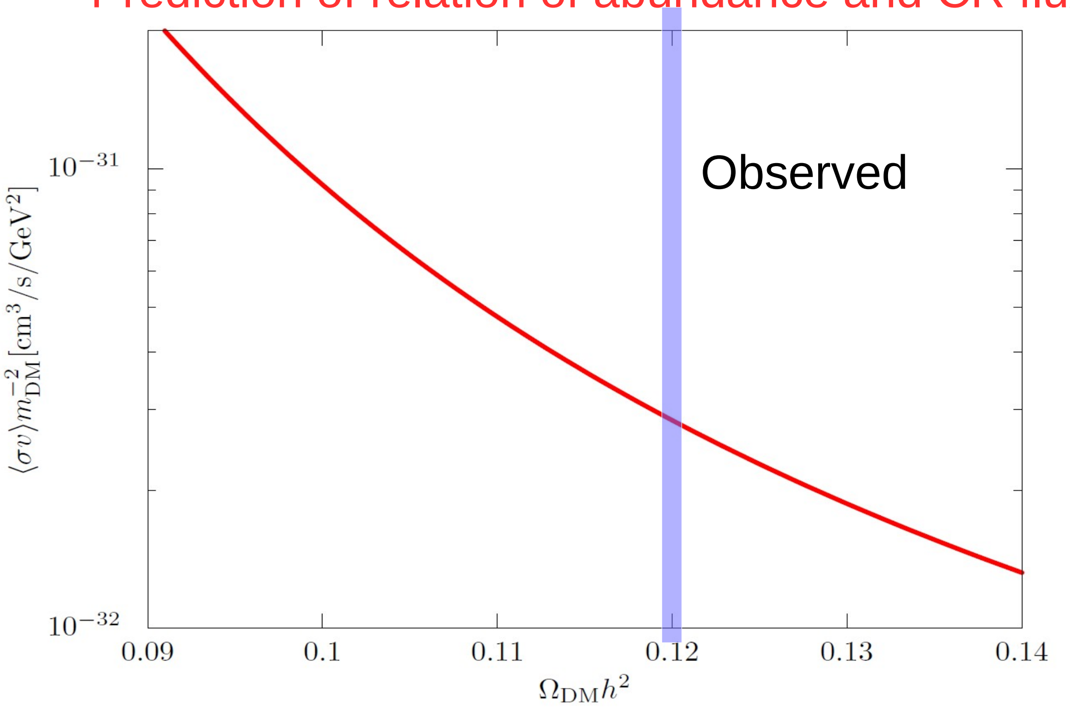
Precise Wino abundance estimation is still challenging.

- 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