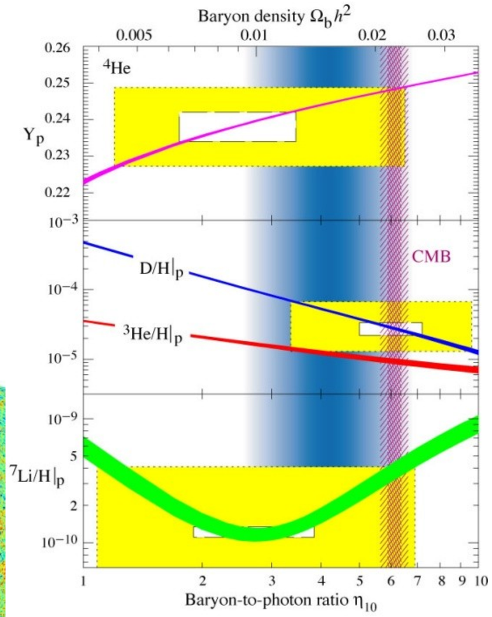
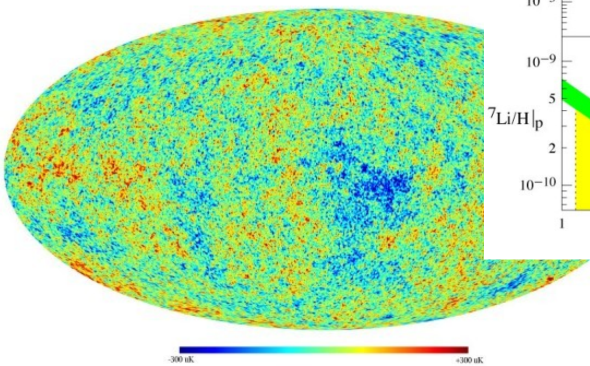
WIMP Phenomenology

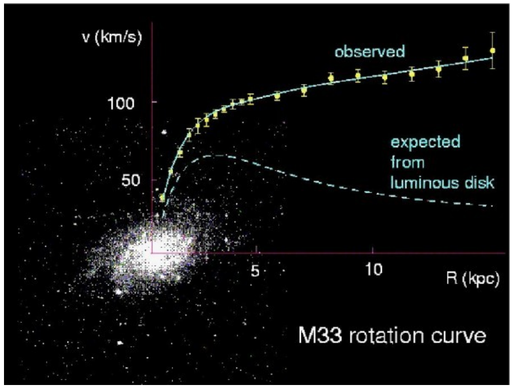
Satoshi Shirai (Kavli IPMU)

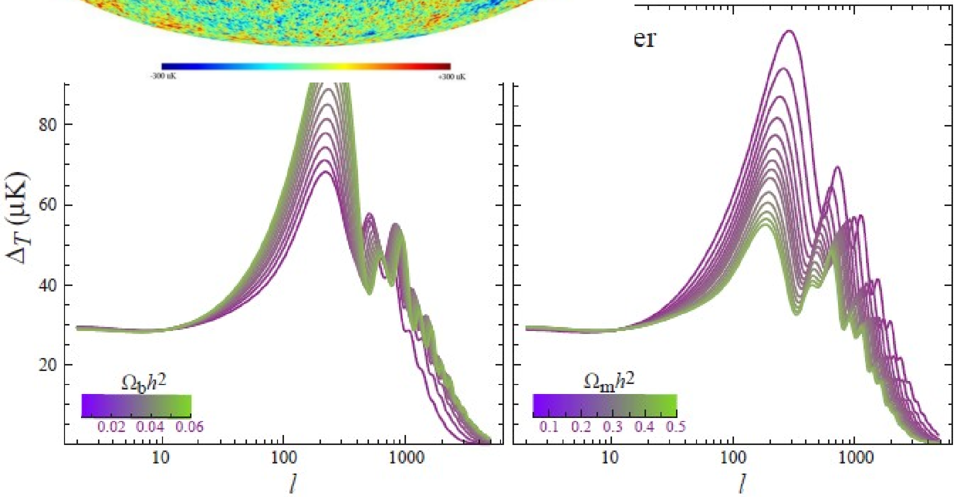
Dark Matter (DM)

So many evidences of Dark Matter (DM)



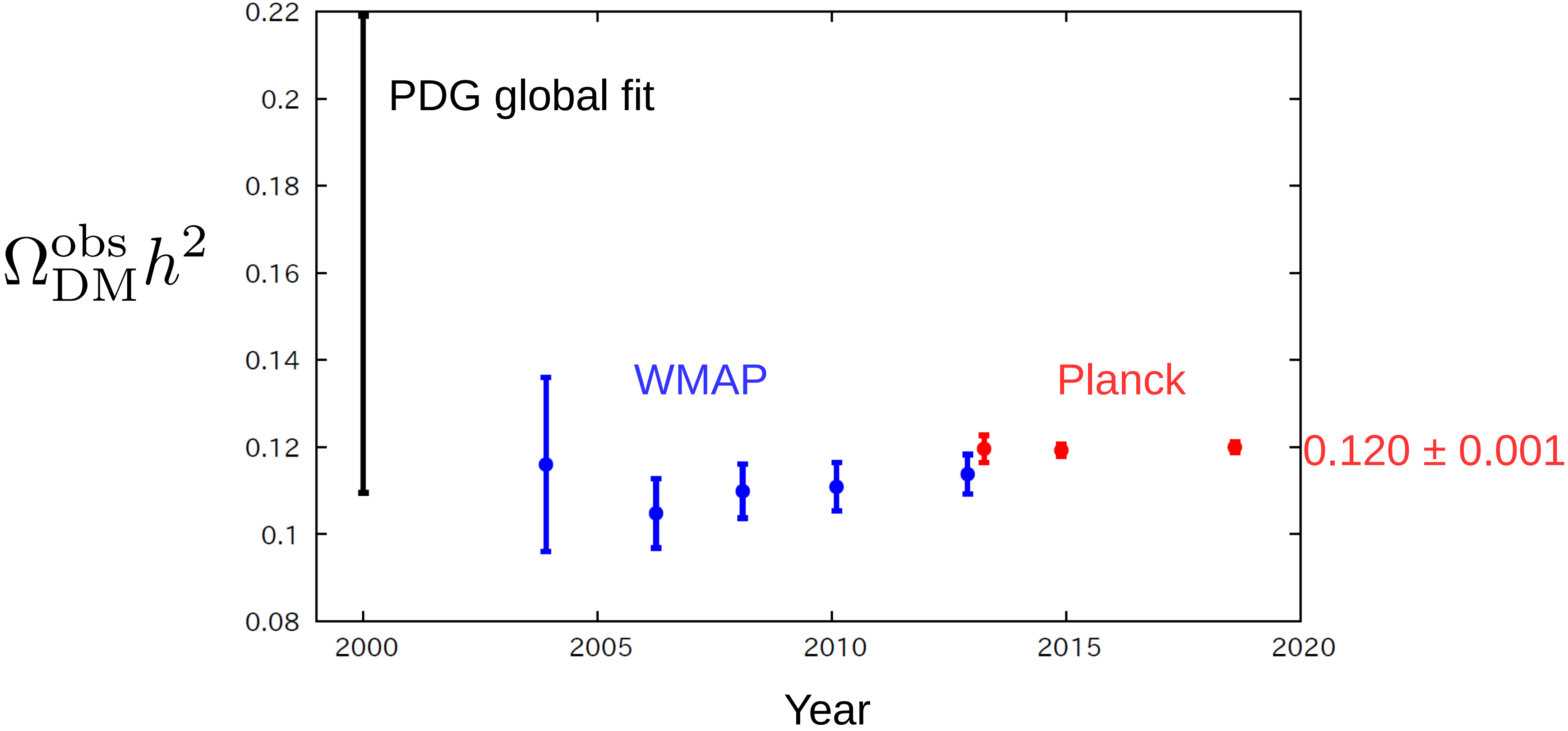






[astro-ph/0110414]

Precise DM Abundance



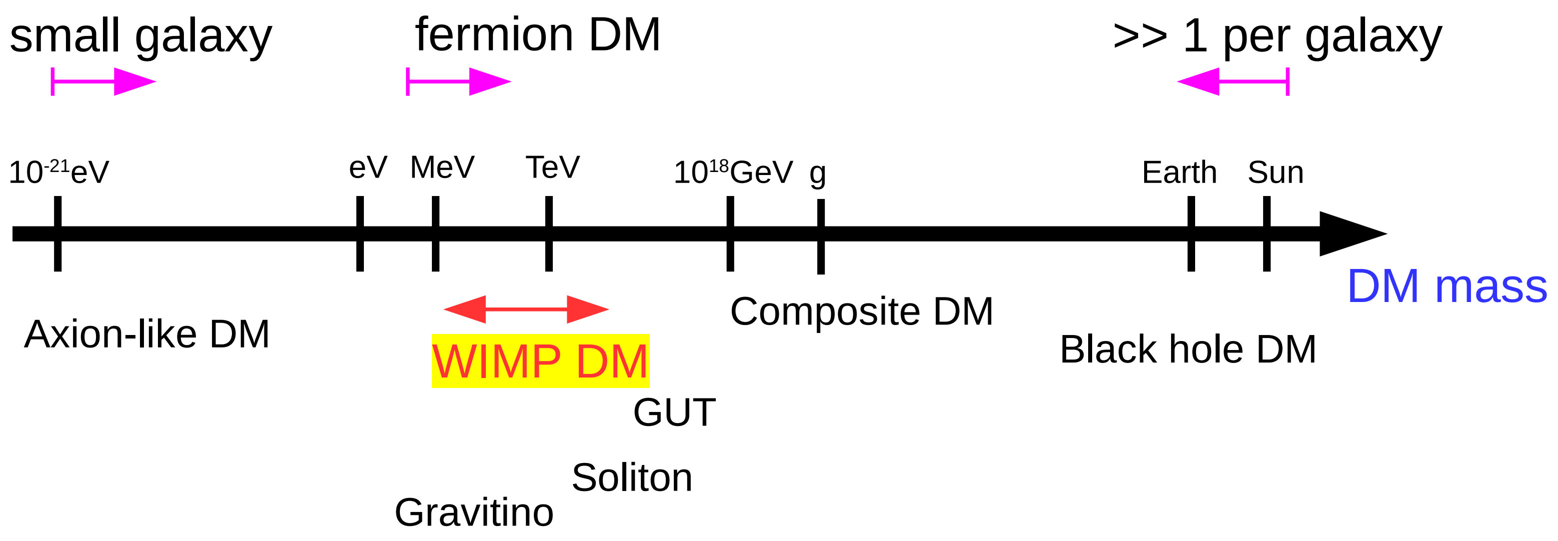
Q: What is Dark Matter?

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

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

2. Higgs-portal
   - Scalar DM coupling to Higgs

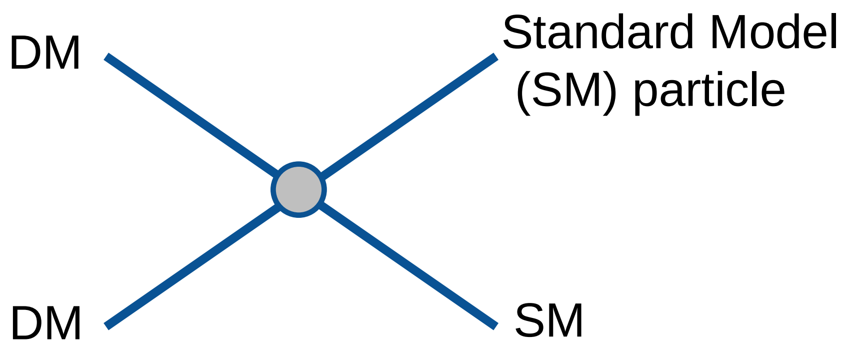
3. Gauge-portal
   - Fermion (Wino)
   - Scalar

4. Summary

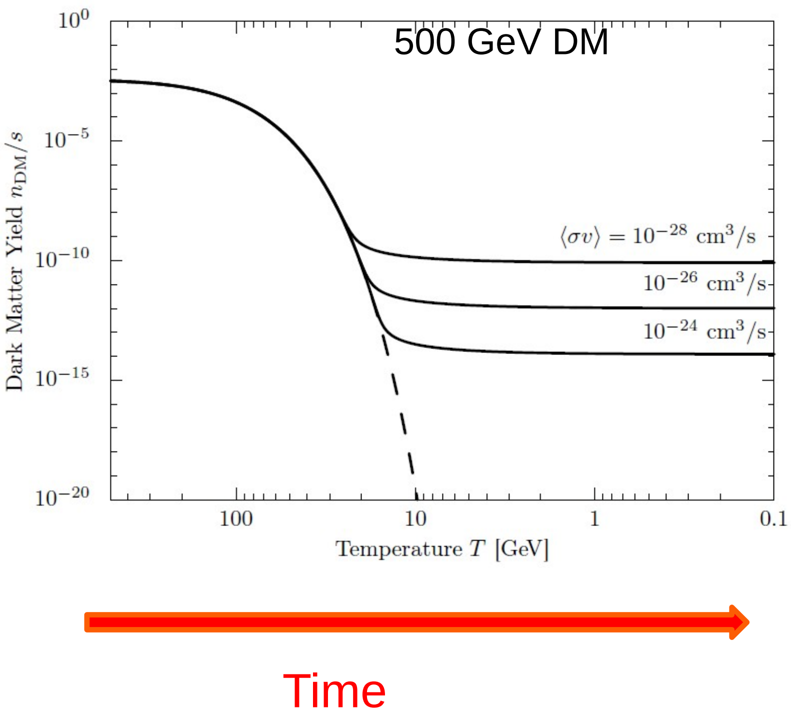
WIMP

WIMP Dark Matter

Weakly Interacting Massive Particle



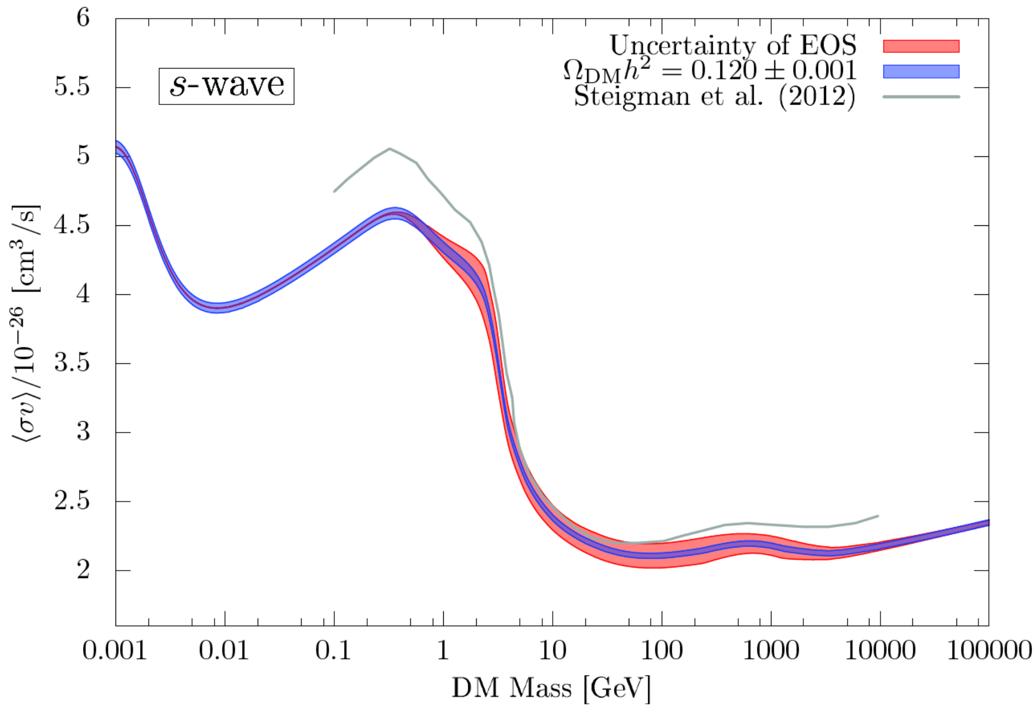
DM abundance



WIMP Cross Section

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

Required Cross section



WIMP Abundance

$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = -\langle\sigma v\rangle(n_{\rm DM}^2 - {n_{\rm DM,eq}}^2)$$

Hubble parameter

$\sim \exp(-m_{\rm DM}/T)$

High temperature:

$$\langle\sigma v\rangle n_{\rm DM,eq} \gg H \qquad n_{\rm DM} \to n_{\rm DM,eq}$$

Low temperature:

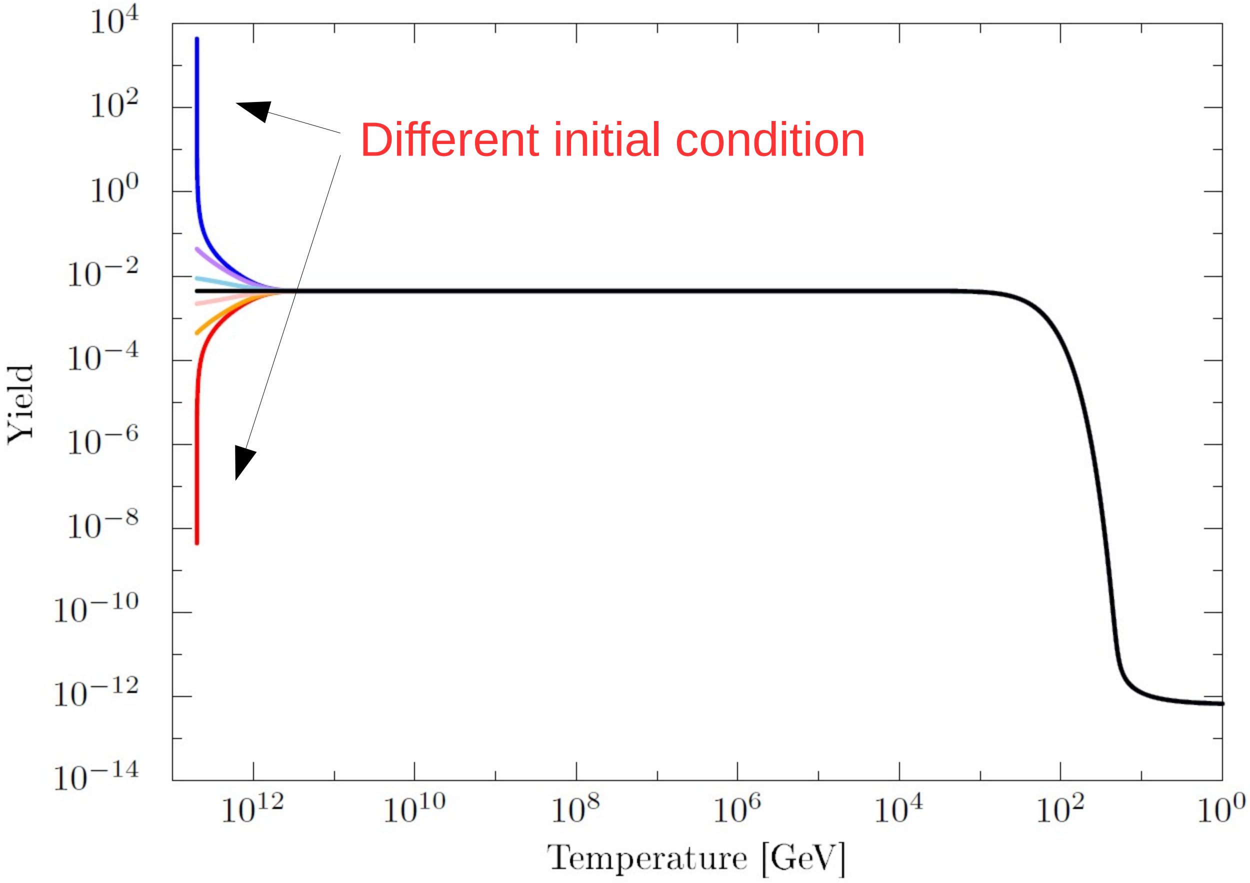
$$\langle\sigma v\rangle n_{\rm DM,eq} \lesssim H$$

Freeze-out

WIMP Dark Matter

DM Yield n/s

Independent on the initial condition.



WIMP Advantage

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

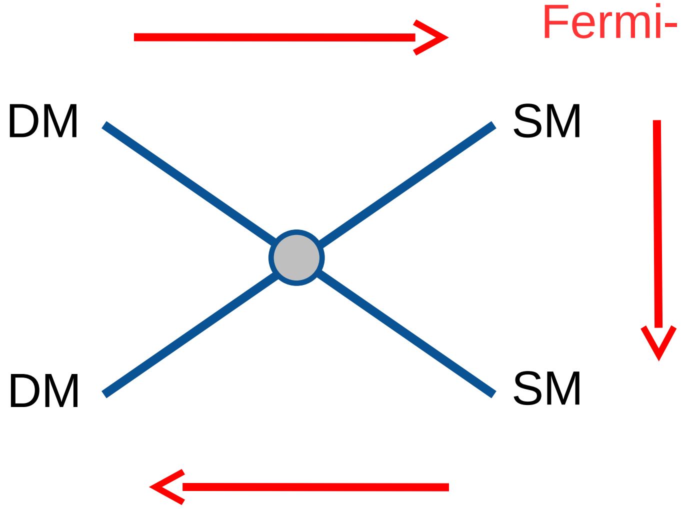
↓

Precise estimation of DM abundance is possible!

WIMP Detection

WIMP annihilation; Cosmic ray, CMB, BBN

Fermi-LAT, HESS, CTA



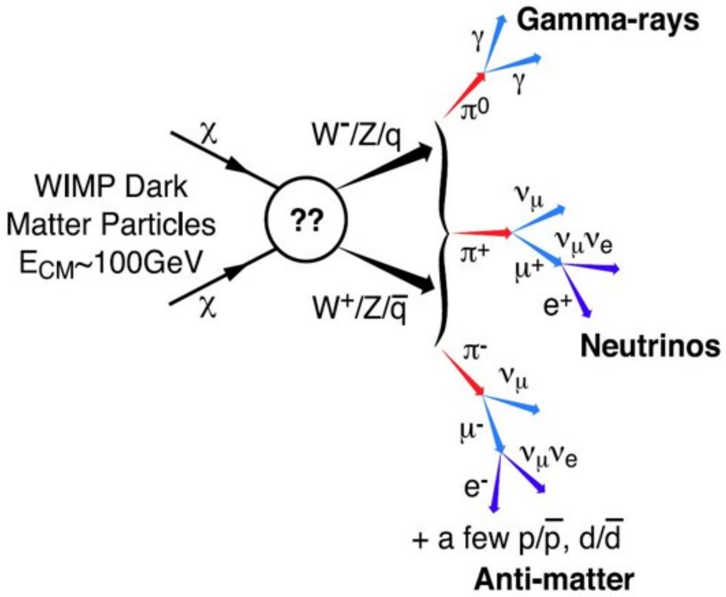
WIMP scattering

LZ, XENONnT, Darwin

WIMP Production; Collider

LHC, ILC, Belle

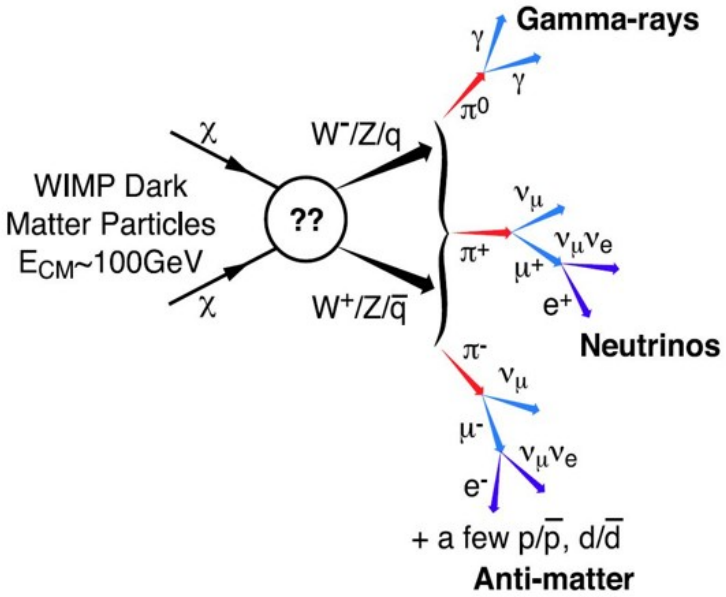
Indirect Detection



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

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

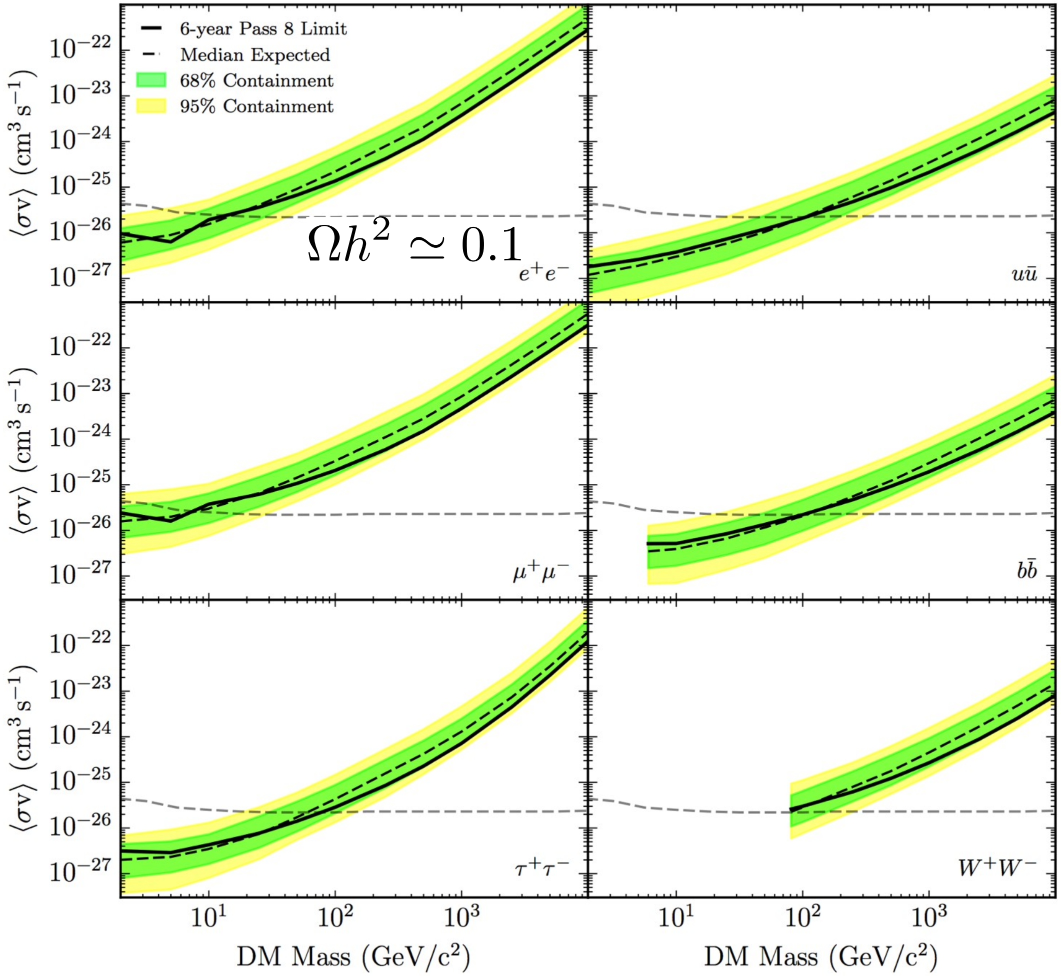
particle physics   Astrophysics

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

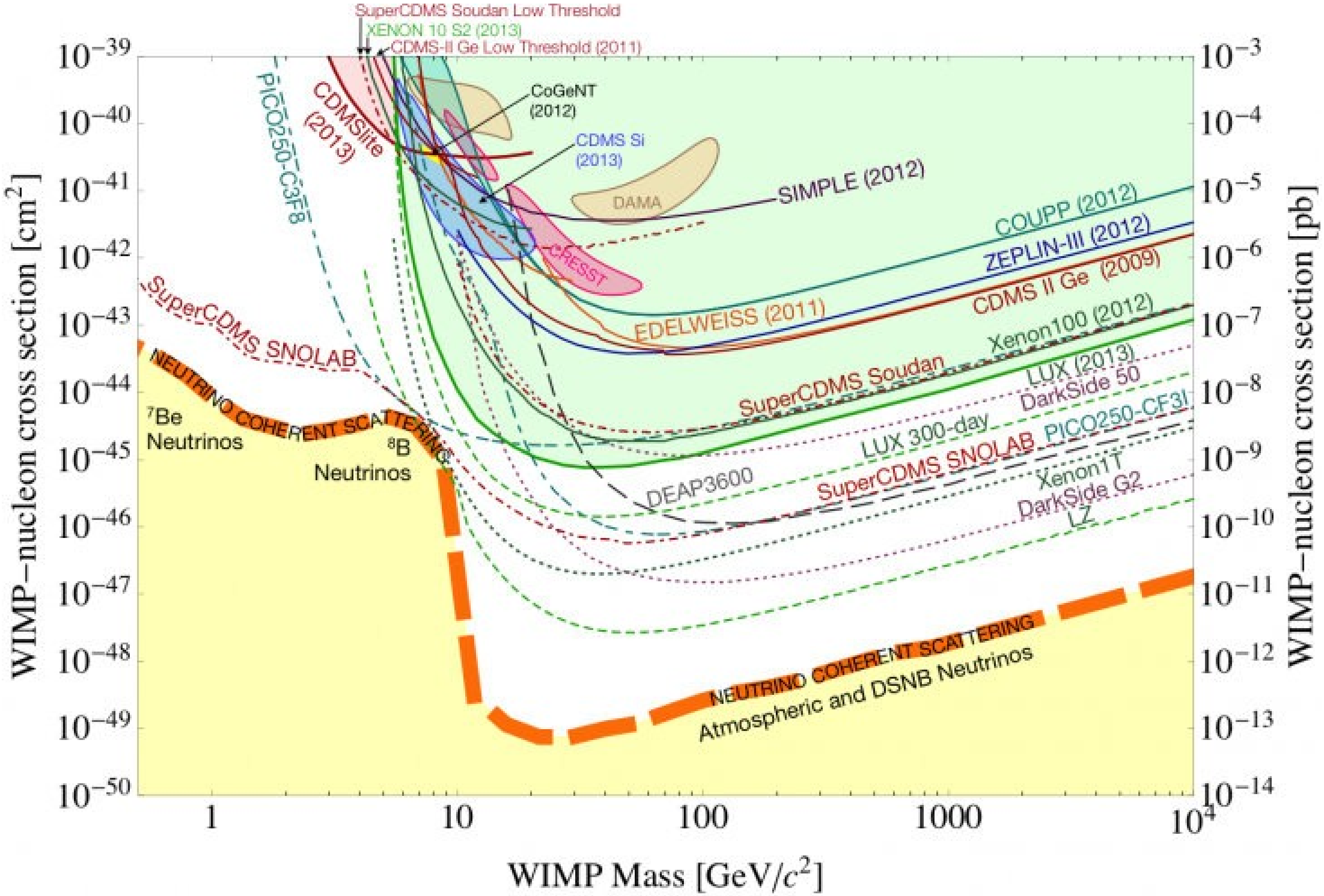
- DM lives everywhere:
  - Galactic center (GC)
  - Dwarf spheroidal galaxy (dSph)
  - Galaxy cluster
  - …
- Large astrophysical uncertainty.

Indirect Detection and Abundance

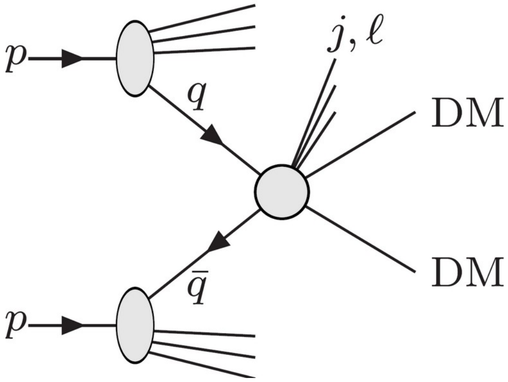
Constraint by Fermi-LAT



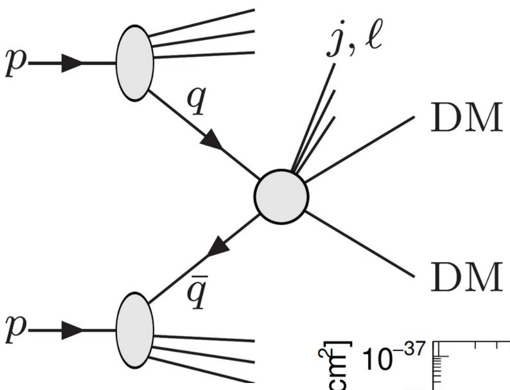
Direct Detection

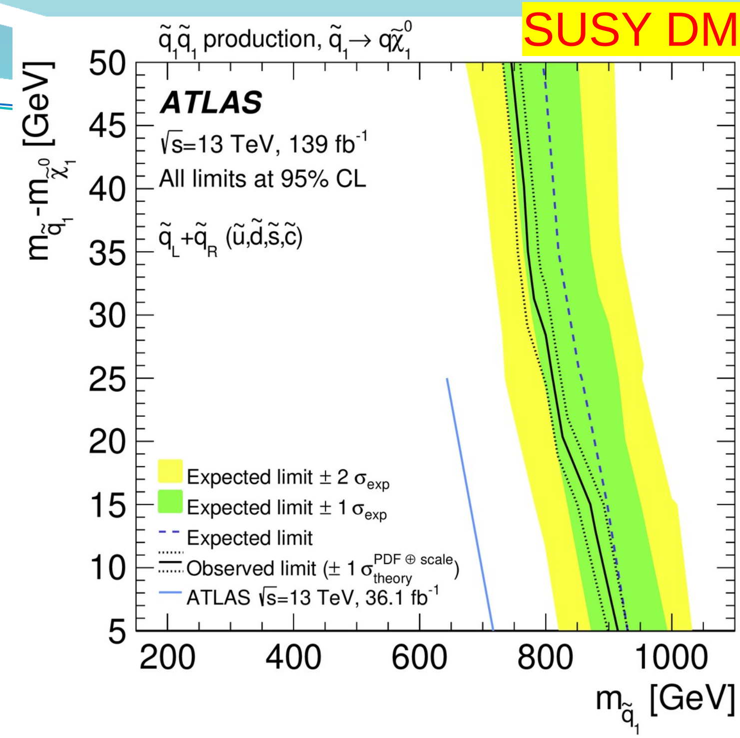


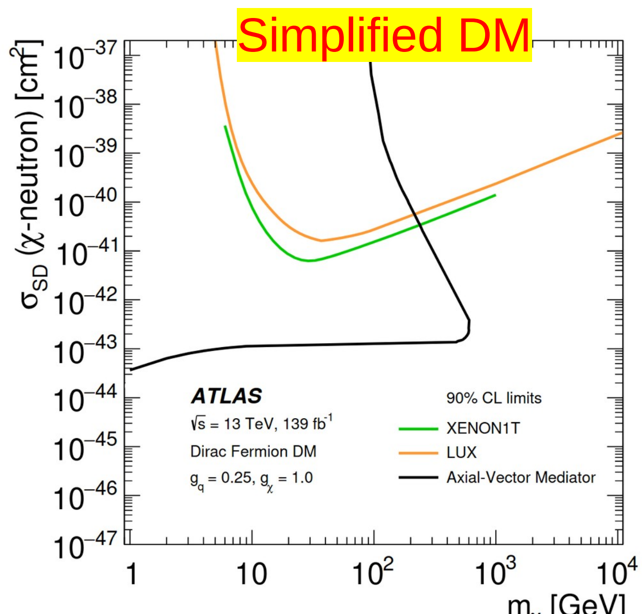
Collider

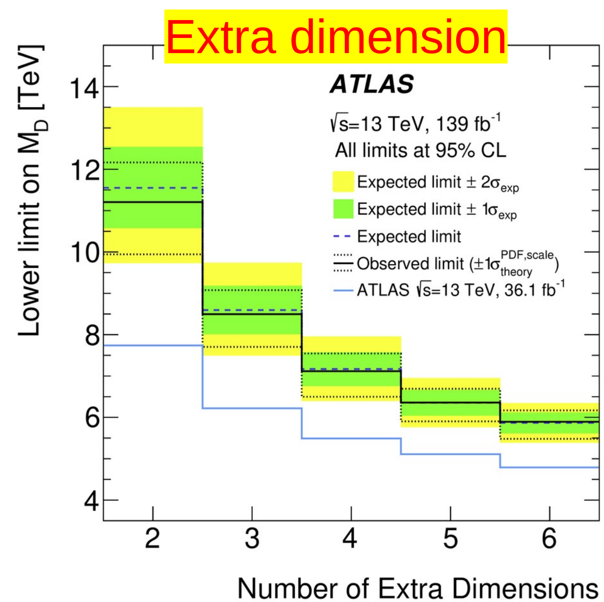


Collider

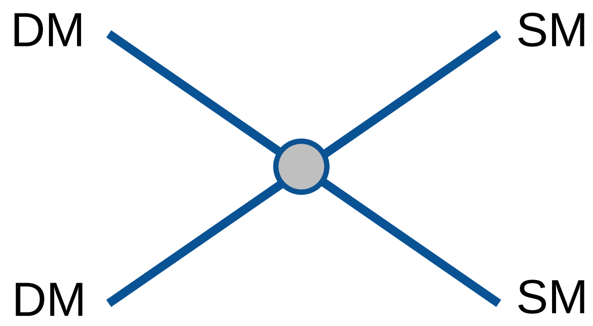

p
q
j, ℓ
DM
DM
q̄
p


SUSY DM
q̃₁q̃₁ production, q̃₁→ qχ̃⁰₁
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 σ theory PDF ⊕ scale)
ATLAS √s=13 TeV, 36.1 fb⁻¹
m q̃₁ - m χ̃⁰₁ [GeV]
m q̃₁ [GeV]
50
45
40
35
30
25
20
15
10
5
200
400
600
800
1000


Simplified DM
σSD (χ-neutron) [cm²]
mχ [GeV]
ATLAS
√s = 13 TeV, 139 fb⁻¹
Dirac Fermion DM
gq = 0.25, gχ = 1.0
90% CL limits
XENON1T
LUX
Axial-Vector Mediator
10⁻³⁷
10⁻³⁸
10⁻³⁹
10⁻⁴⁰
10⁻⁴¹
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
10⁻⁴⁶
10⁻⁴⁷
1
10
10²
10³
10⁴


Extra dimension
ATLAS
√s=13 TeV, 139 fb⁻¹
All limits at 95% CL
Expected limit ± 2σexp
Expected limit ± 1σexp
Expected limit
Observed limit (±1σ theory PDF,scale)
ATLAS √s=13 TeV, 36.1 fb⁻¹
Lower limit on MD [TeV]
Number of Extra Dimensions
14
12
10
8
6
4
2
3
4
5
6

Coupling of DM and SM



Need to identify DM–SM for precise signal prediction.

- 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.

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

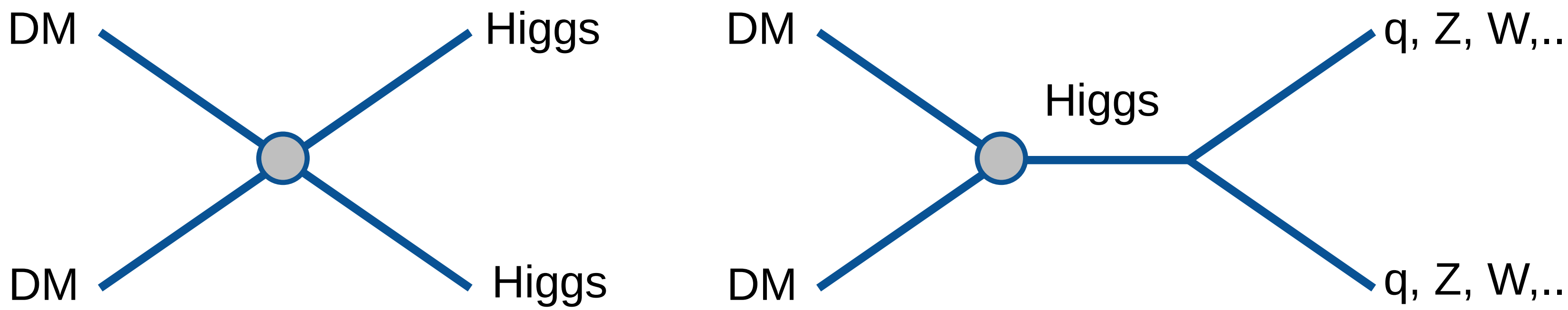
Gauge Portal dark matter

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

Higgs Portal DM

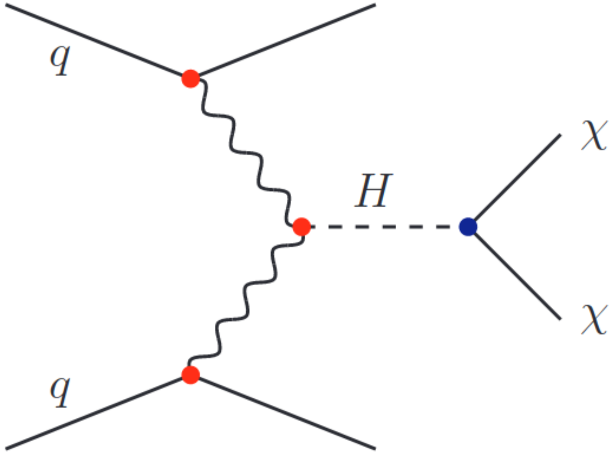
DM and Higgs

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



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

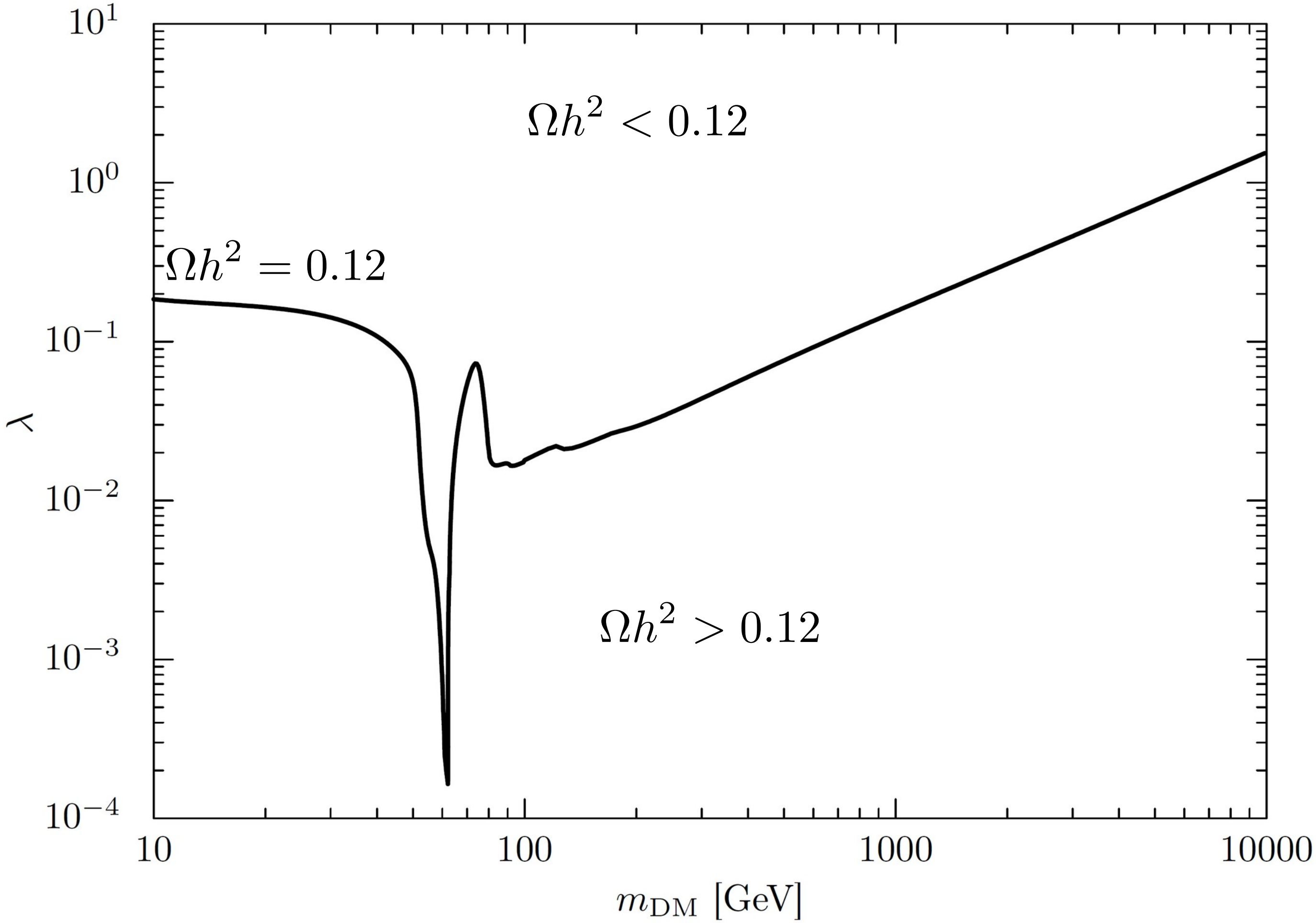
Higgs-portal at LHC



Invisible Higgs decay constraints Br(H → DM DM):

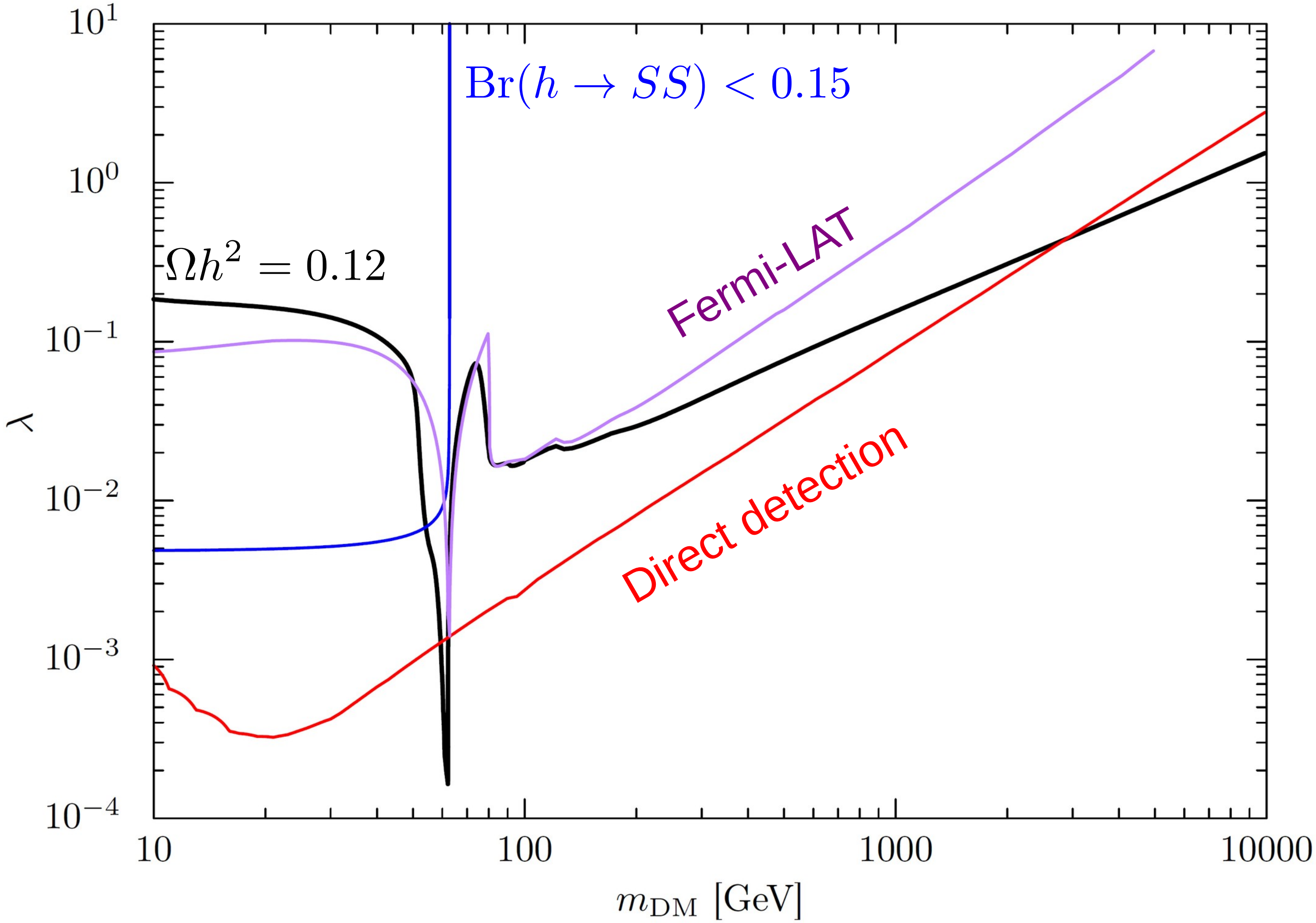
< 0.145 (ATLAS), 0.18 (CMS)
< 0.06 (HL-LHC)
< 0.003 (ILC)

DM and Higgs



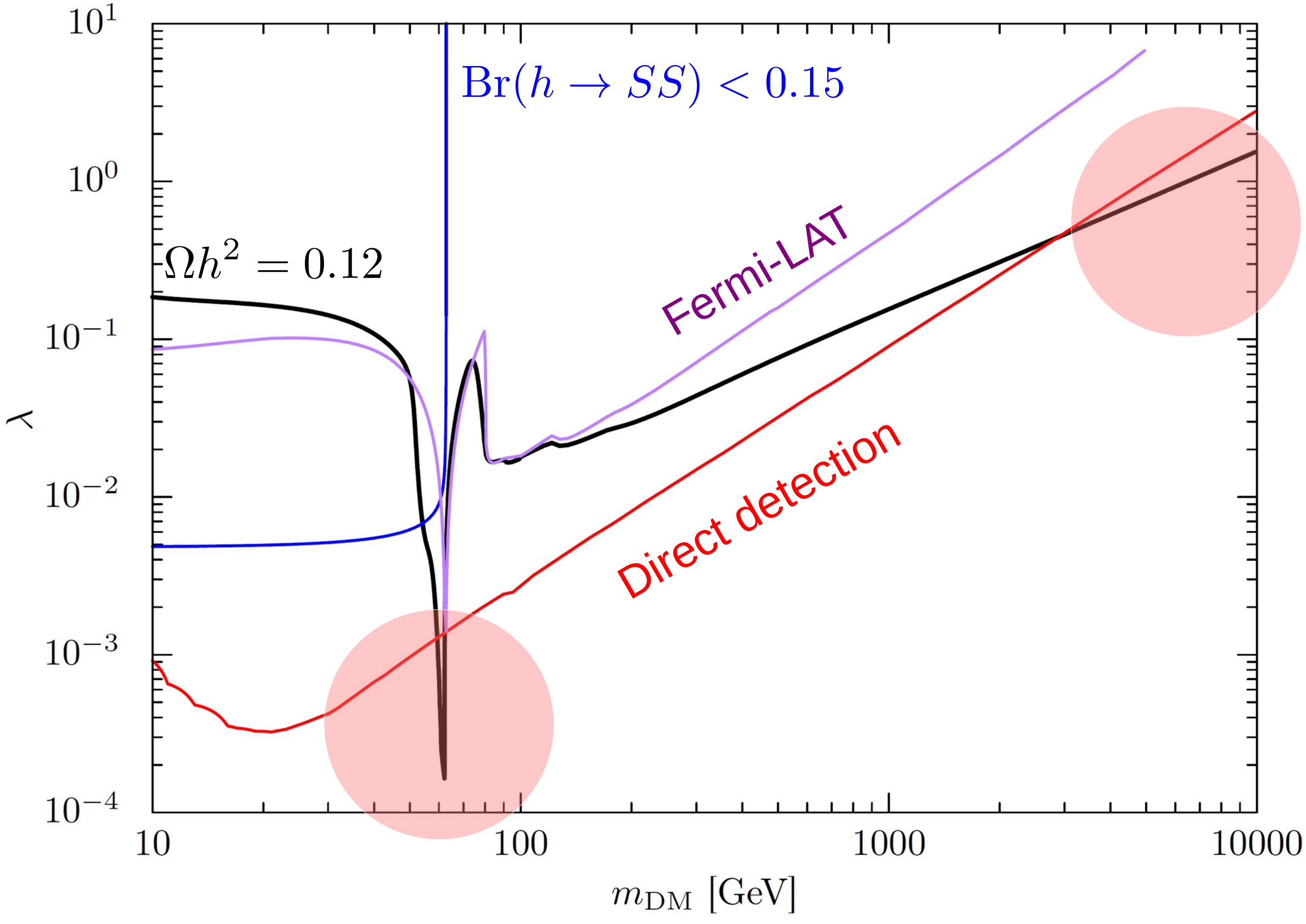
$\Omega h^2 < 0.12$
$\Omega h^2 = 0.12$
$\Omega h^2 > 0.12$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
λ
10
100
1000
10000
$m_{\rm DM}$ [GeV]

DM and Higgs



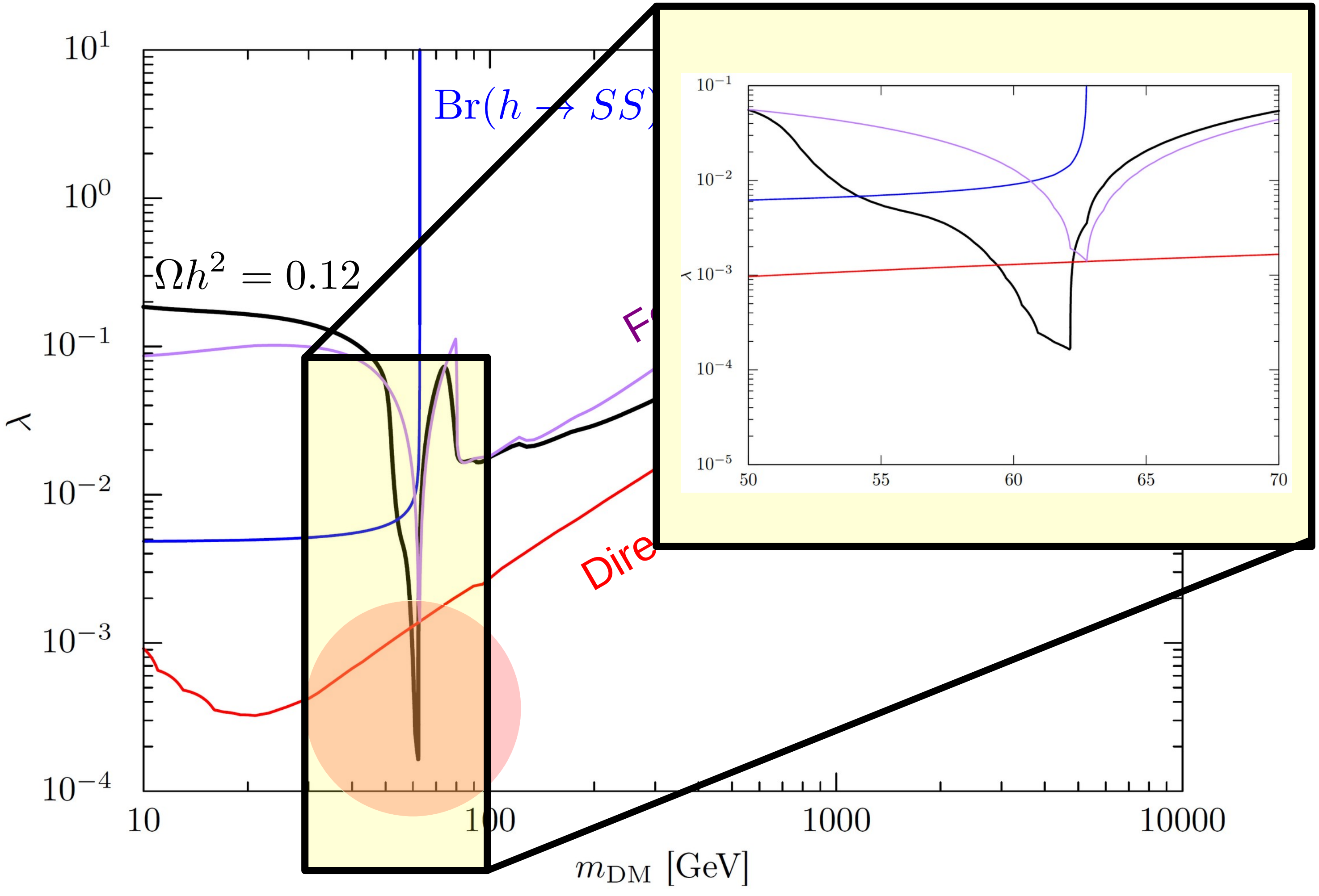
$\mathrm{Br}(h \to SS) < 0.15$
$\Omega h^2 = 0.12$
Fermi-LAT
Direct detection
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
λ
10
100
1000
10000
m_{DM} [GeV]

DM and Higgs



$\mathrm{Br}(h \to SS) < 0.15$
$\Omega h^2 = 0.12$
Fermi-LAT
Direct detection
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
λ
10
100
1000
10000
m_{DM} [GeV]

DM and Higgs



$\mathrm{Br}(h \to SS)$
$\Omega h^2 = 0.12$
Fe
Dire
λ
m_{DM} [GeV]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
100
1000
10000
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
50
55
60
65
70

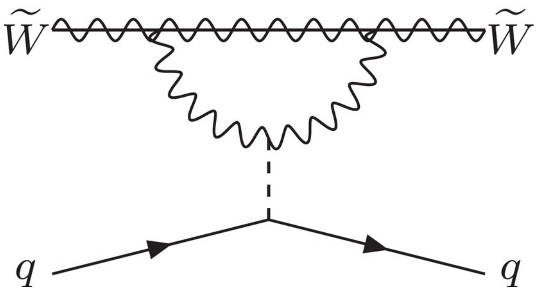
Gauge Portal DM (Wino)

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

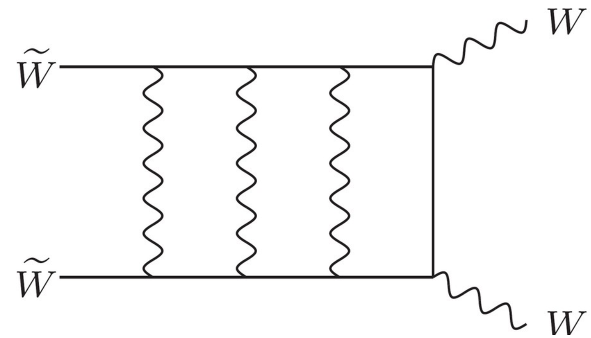
[Hisano, Matsumoto, Nagai, Saito & Senami, 06]

Wino Signal



Direct Detection

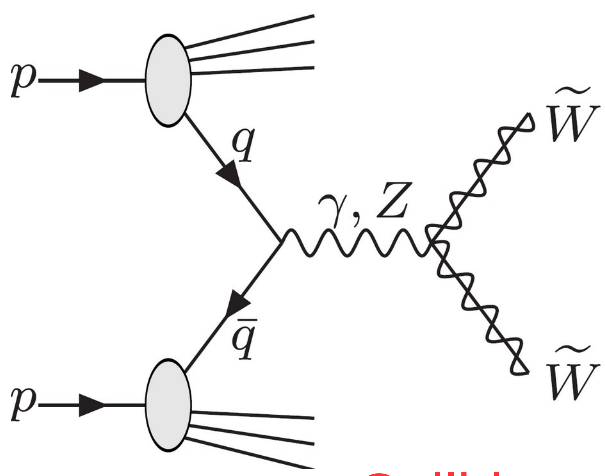
[Hisano, Ishiwata & Nagata, 12]



Indirect Detection

[Hisano, Matsumoto, Nojiri & Saito, 04]

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



Collider

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

Line Photon

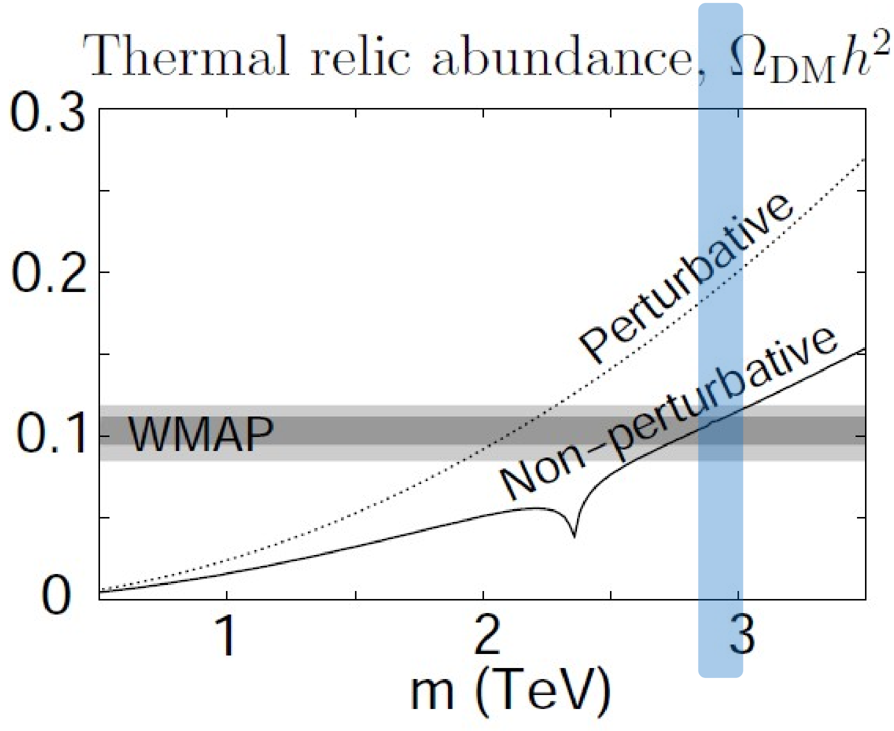
$$\widetilde{W}\widetilde{W} \to WW$$

Continuum Photon

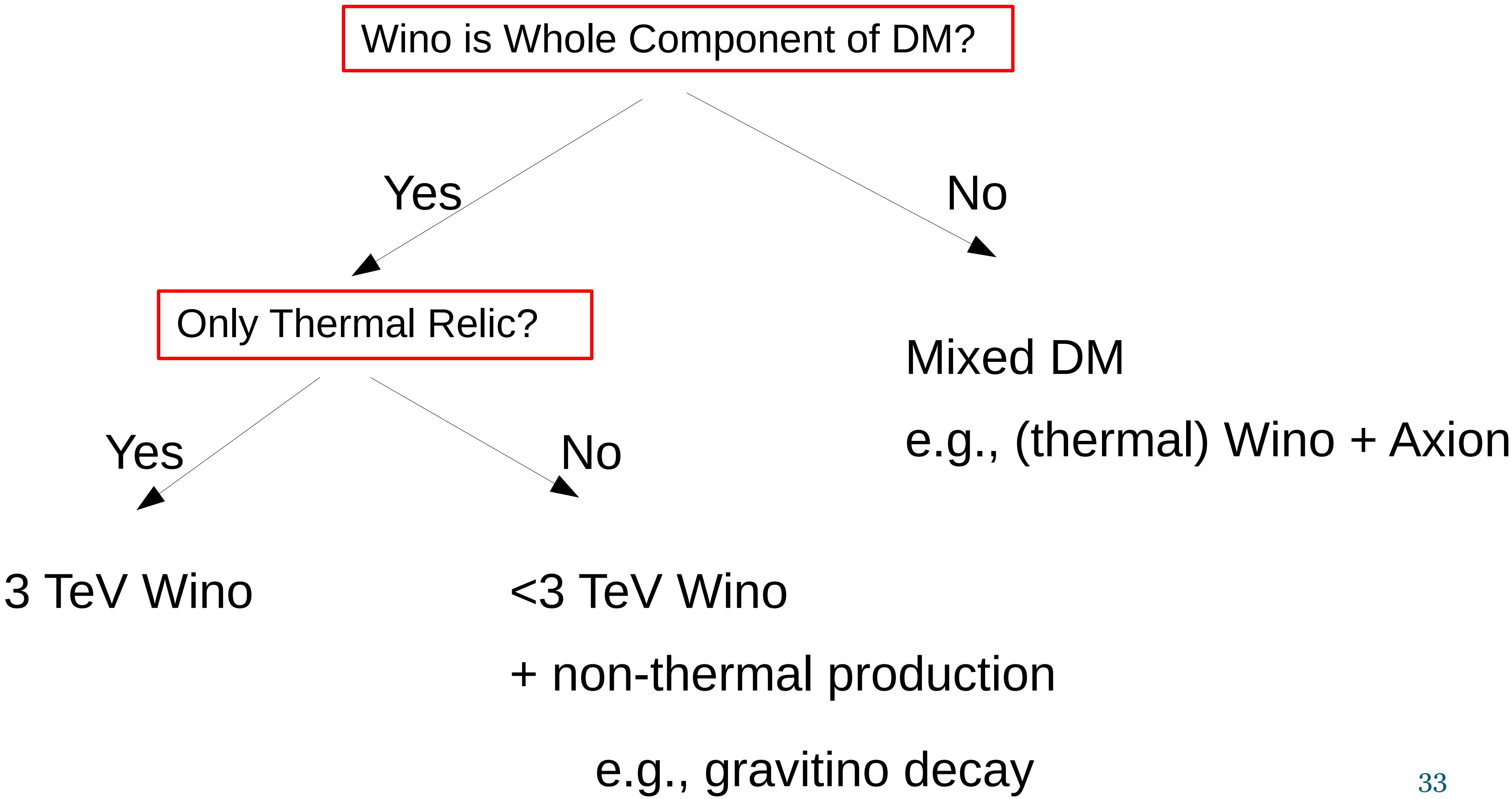
Anti-matter

Wino Thermal Abundance

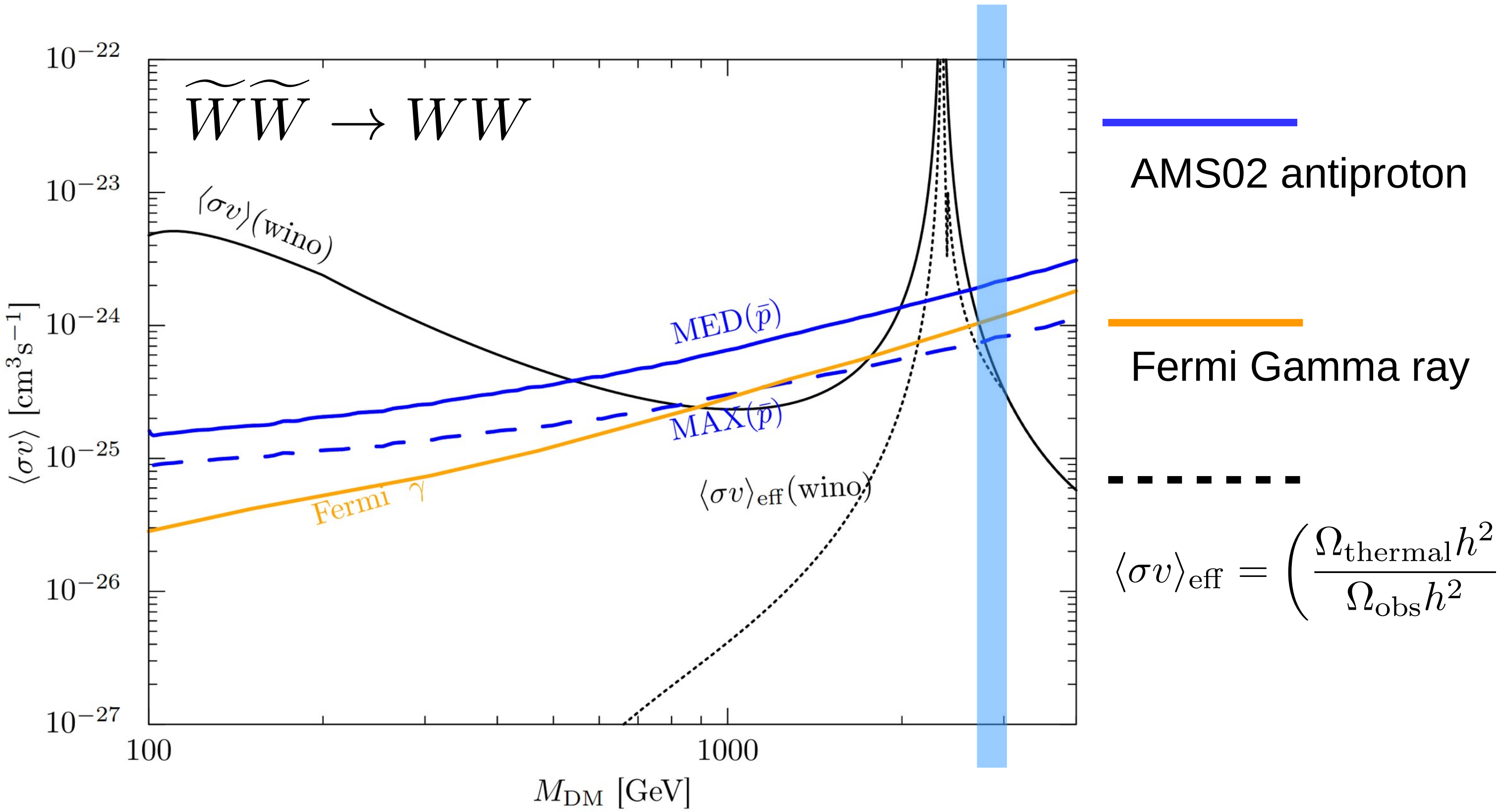
[Hisano,Matsumoto,Nagai,Seto,Senami,06]



Wino Abundance



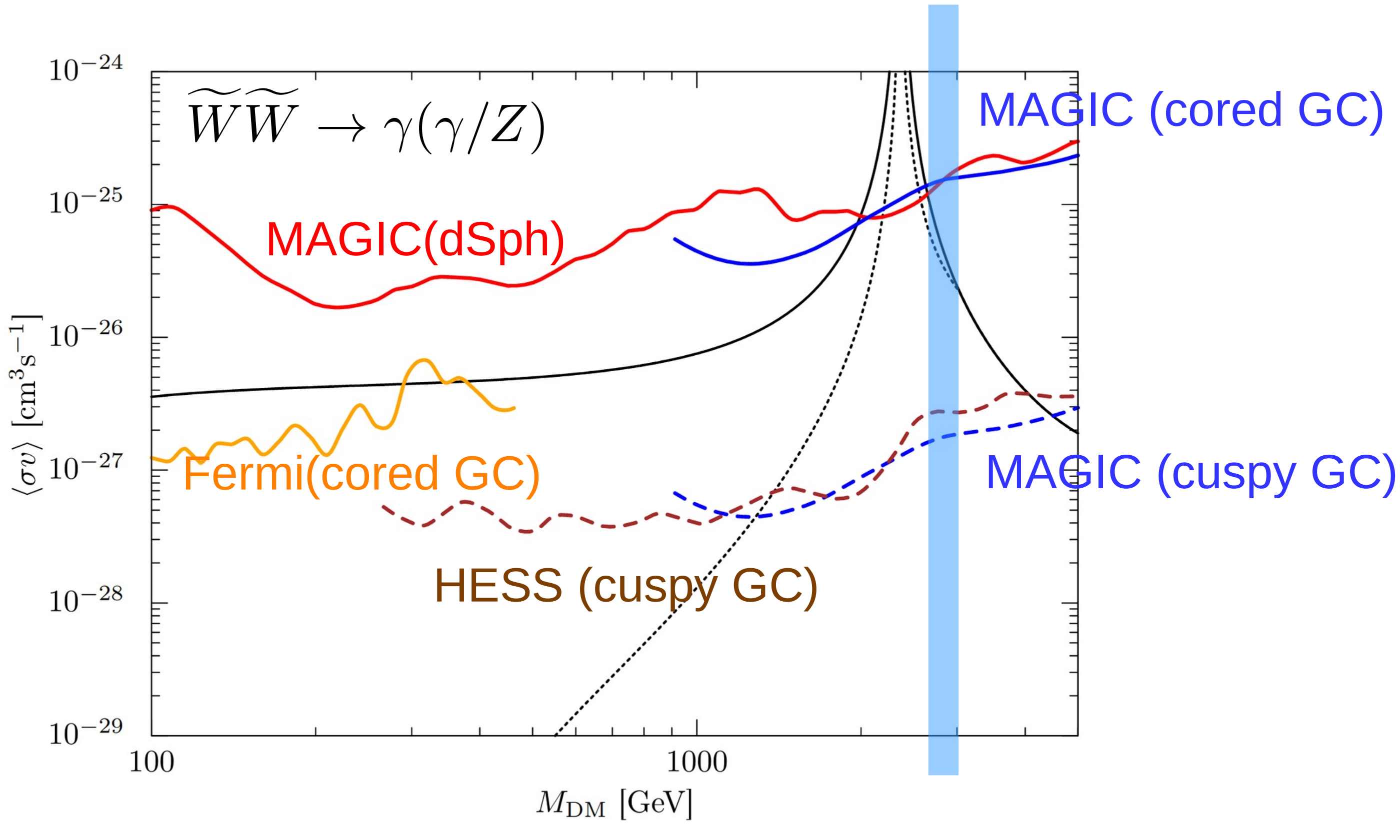
Cosmic Ray Signals



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

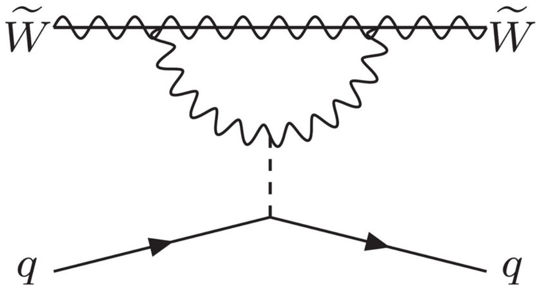
Large Uncertainty of Astrophysical model and DM density

Line Search

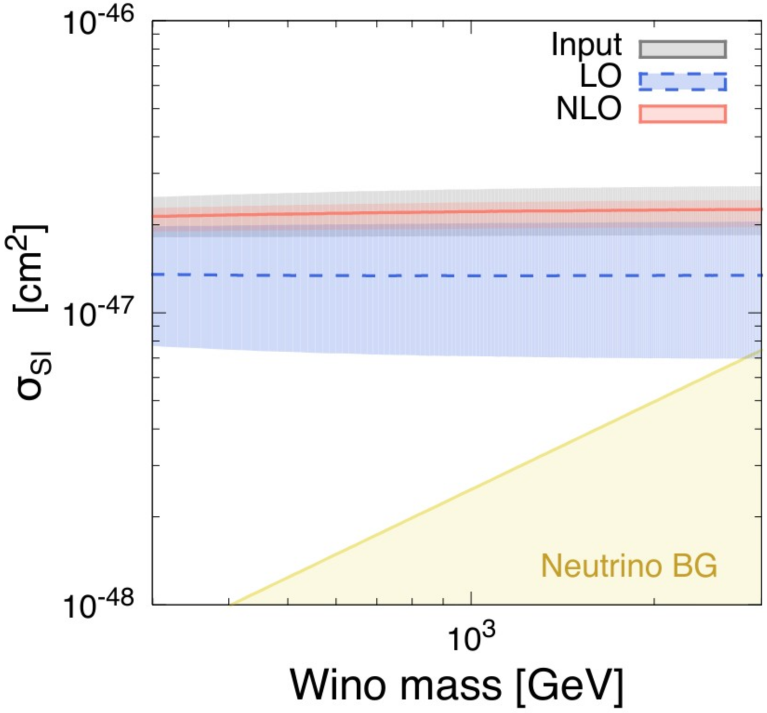


$\widetilde{W}\widetilde{W} \to \gamma(\gamma/Z)$
MAGIC (cored GC)
MAGIC(dSph)
Fermi(cored GC)
MAGIC (cuspy GC)
HESS (cuspy GC)
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
$\langle \sigma v \rangle$ [cm^{3}s^{-1}]
100
1000
$M_{\rm DM}$ [GeV]

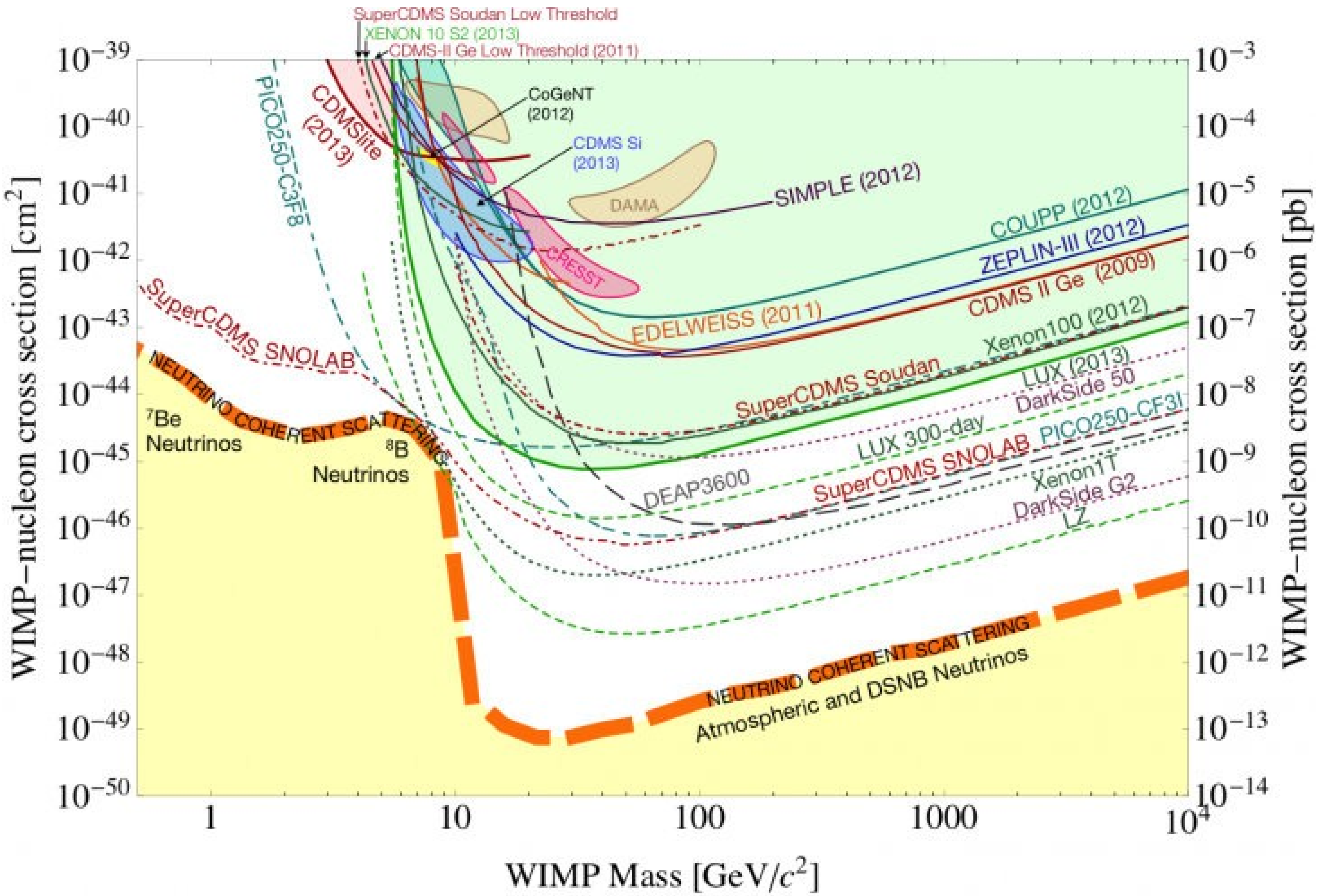
Direct Detection



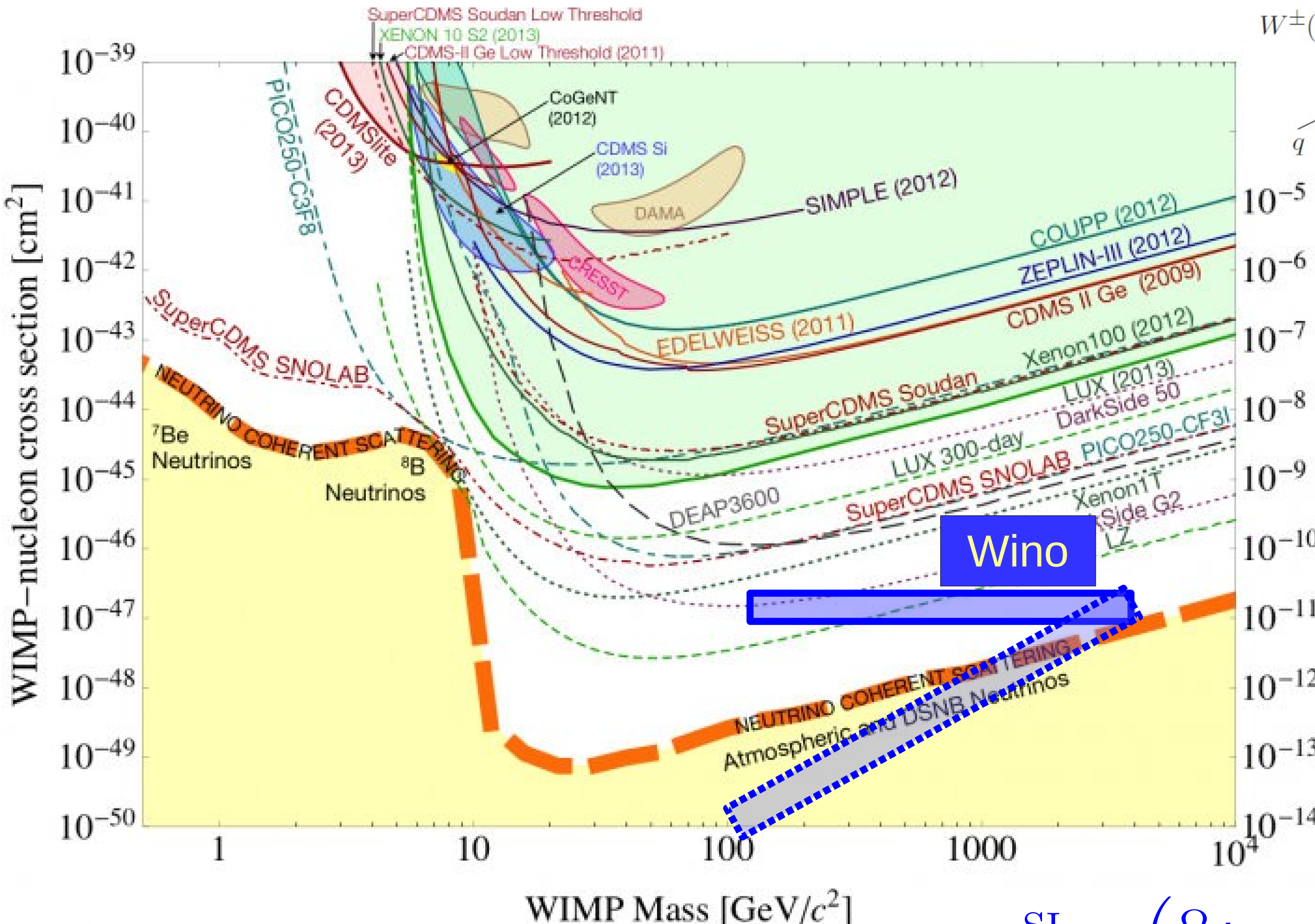
Hisano, Ishiwata, Nagata 15

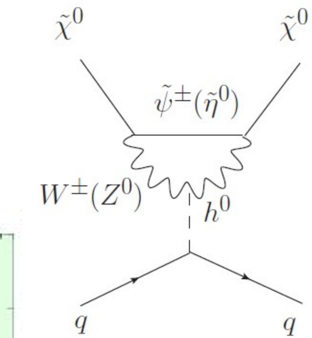


Direct Detection



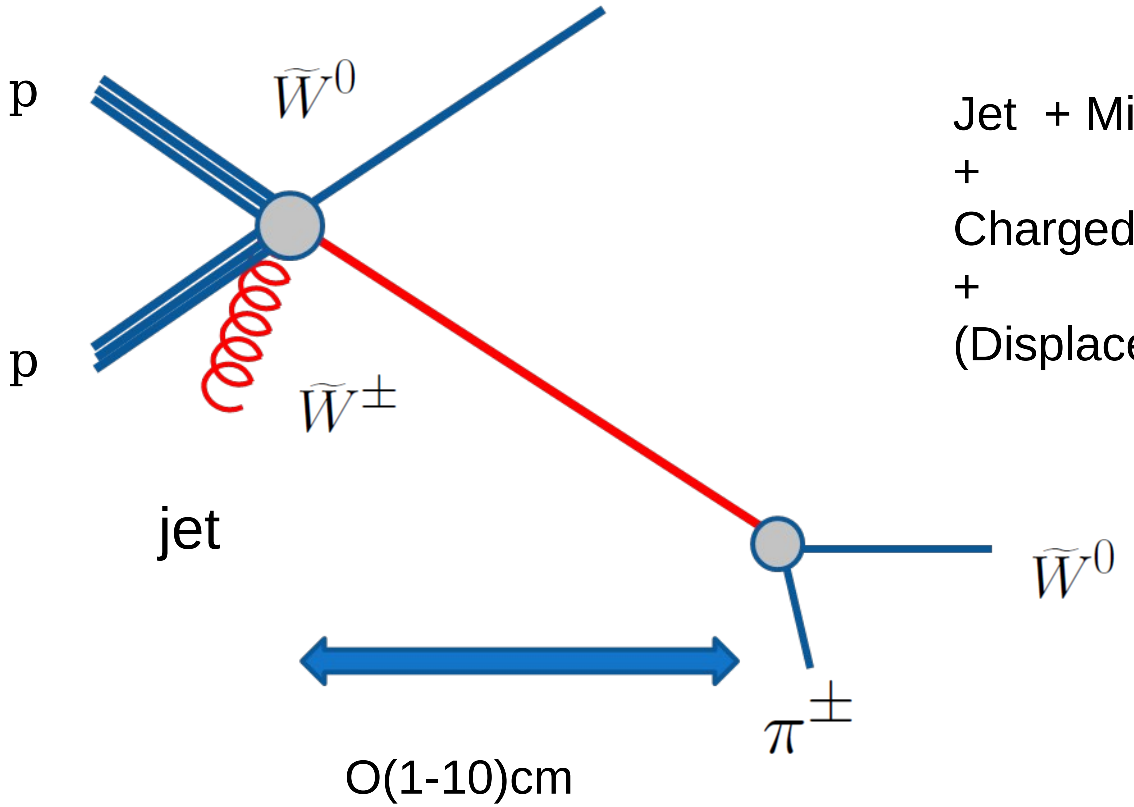
Direct Detection





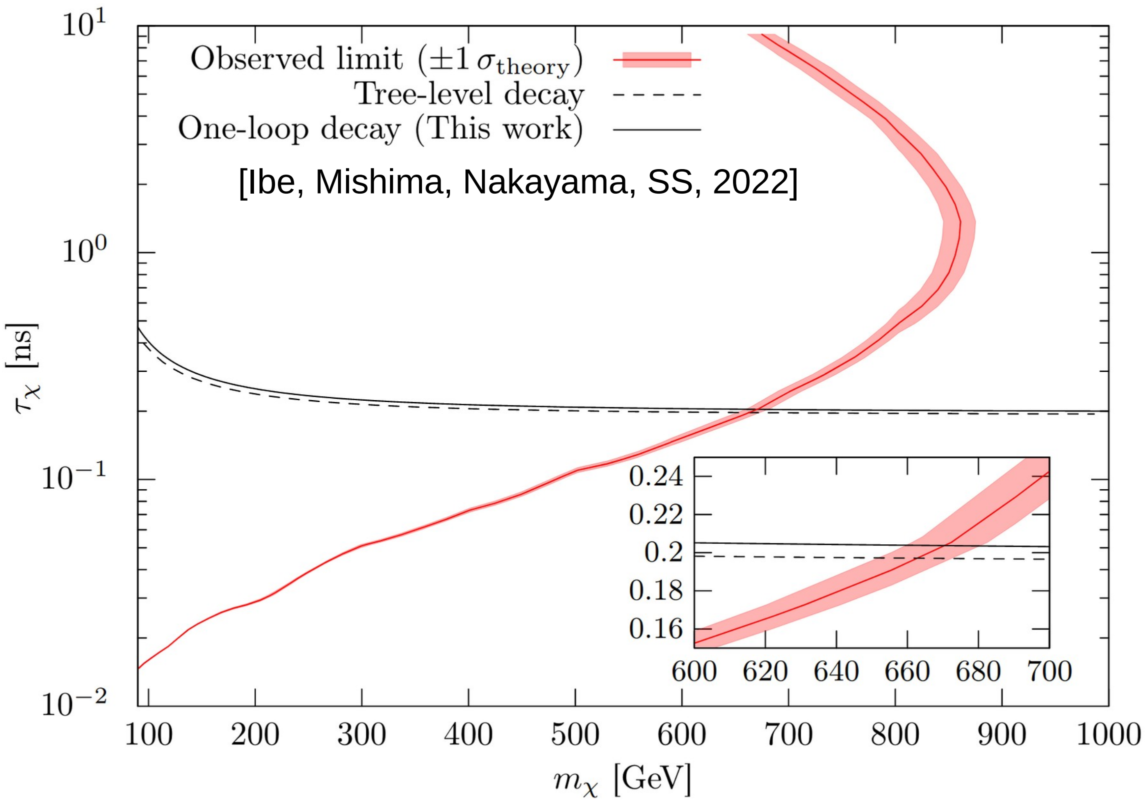
$$\sigma^{\rm SI}_{\rm eff} = \left(\frac{\Omega_{\rm thermal}h^2}{\Omega_{\rm obs}h^2}\right)\sigma^{\rm SI}$$

Direct LHC Signals



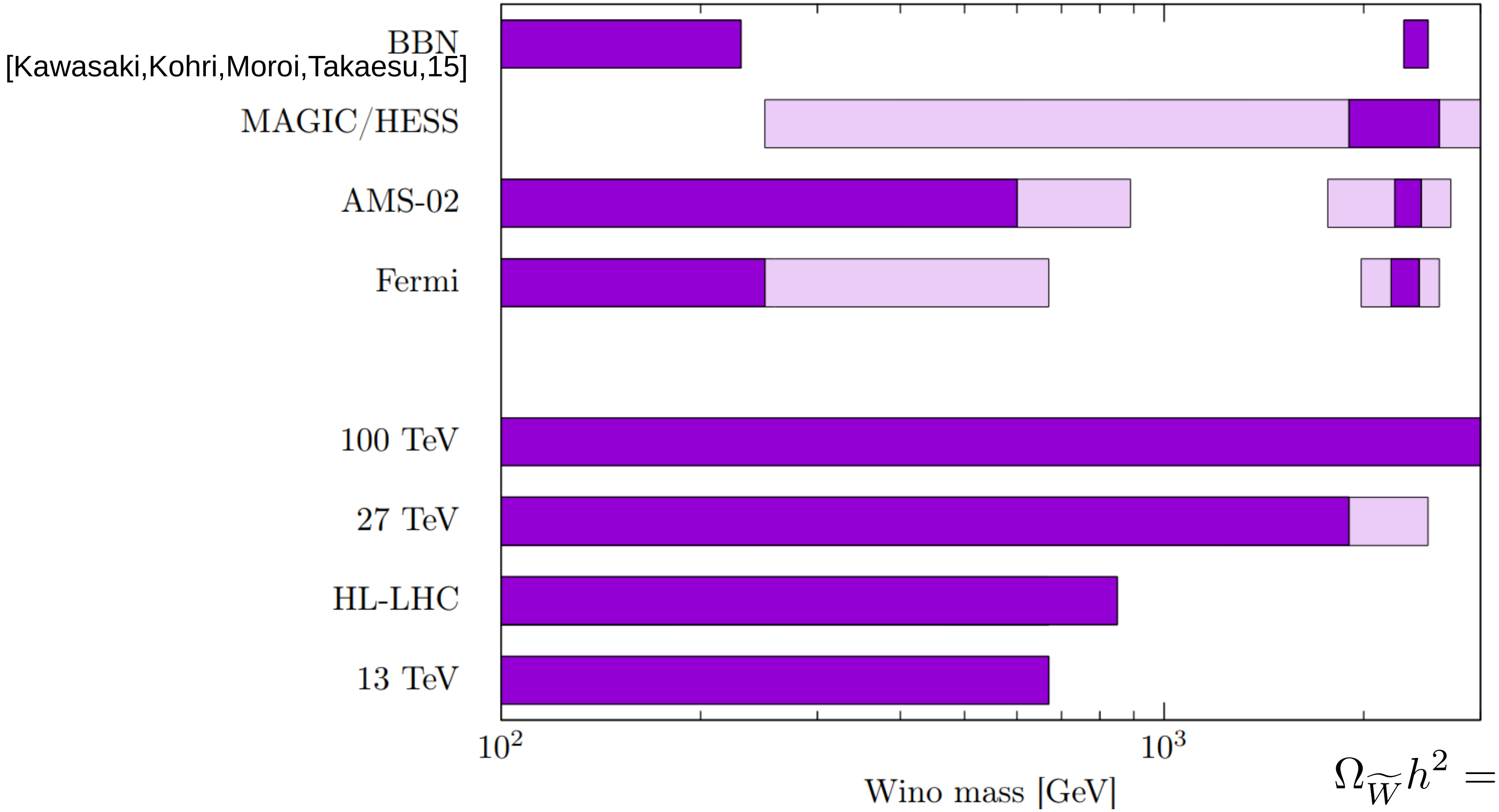
Jet + Missing energy
+
Charged track
+
(Displaced)Soft pion

ATLAS Search (2022)



> 670 GeV Wino

Wino Constraint/Prospect



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

Scalar Triplet (Scalar Wino)

Scalar Triplet

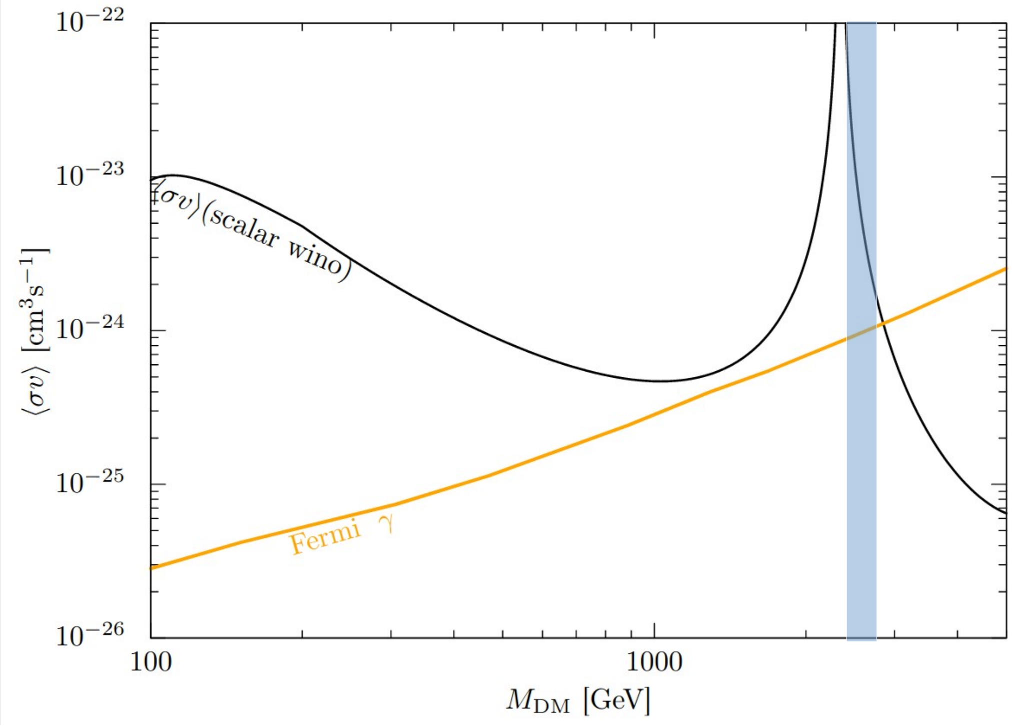
- Real Scalar ϕ

- Hypercharge Y=0

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

Scalar Wino

$\Omega h^2 = 0.12$



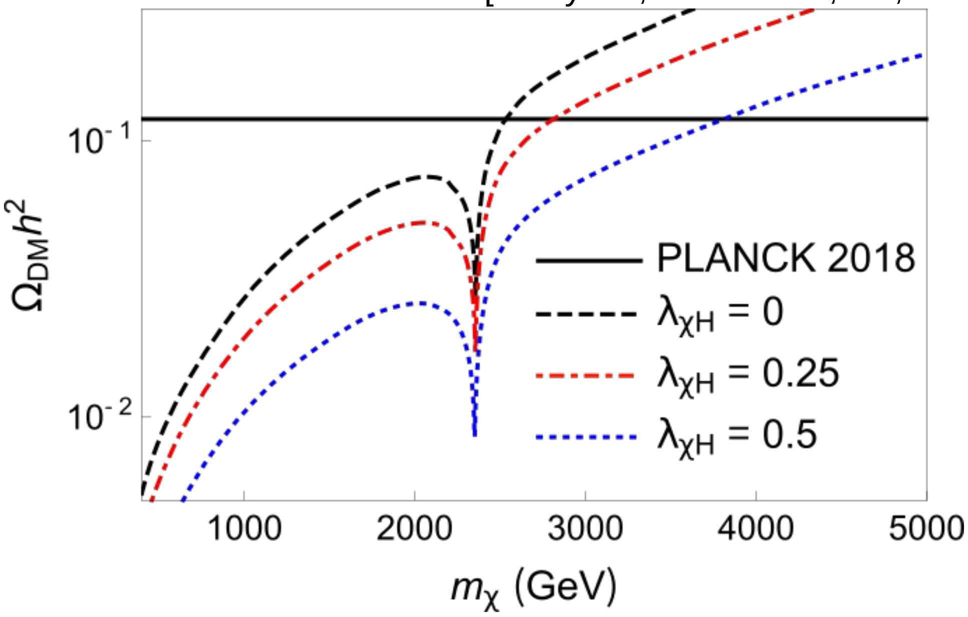
Scalar Wino has tension with indirect search.

Scalar Wino-Higgs Interaction

Scalar field can also couple to Higgs field.

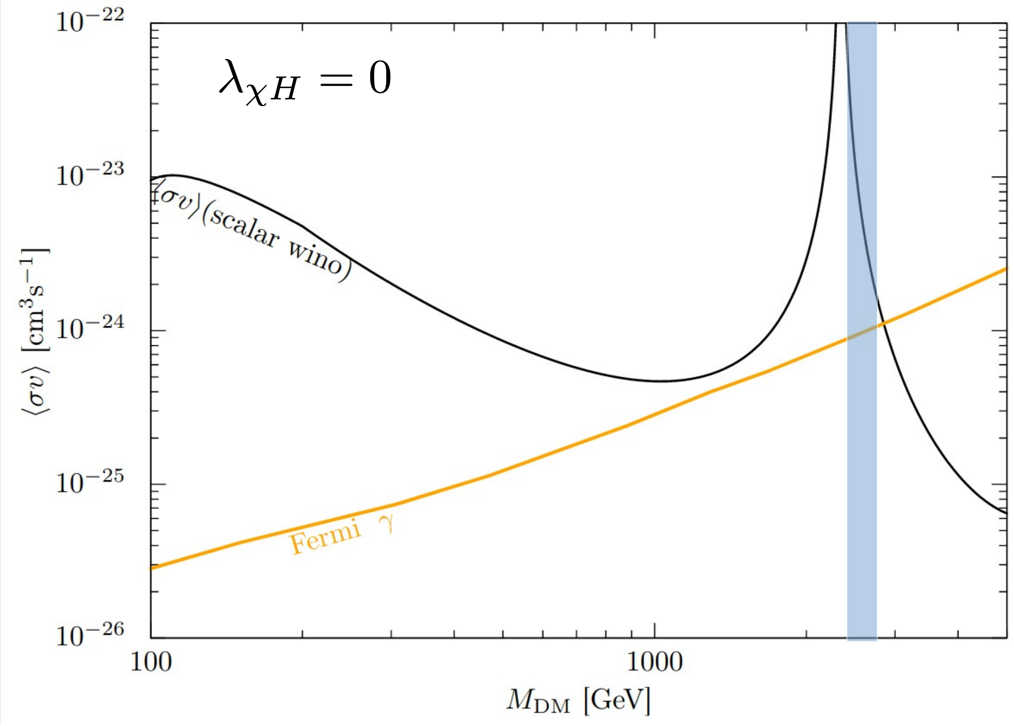
$$\mathcal{L} = -\lambda_{\chi H}\phi_3^2 H^\dagger H$$

[Katayose, Matsumoto, SS, Watanabe, 2021]



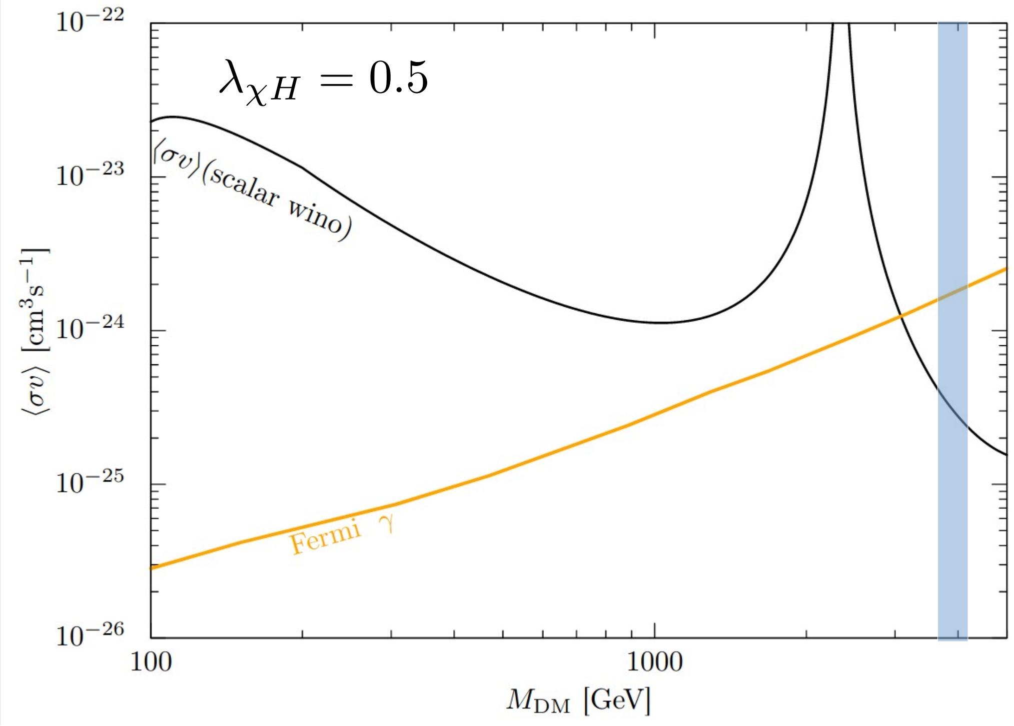
Scalar Wino

$\Omega h^2 = 0.12$



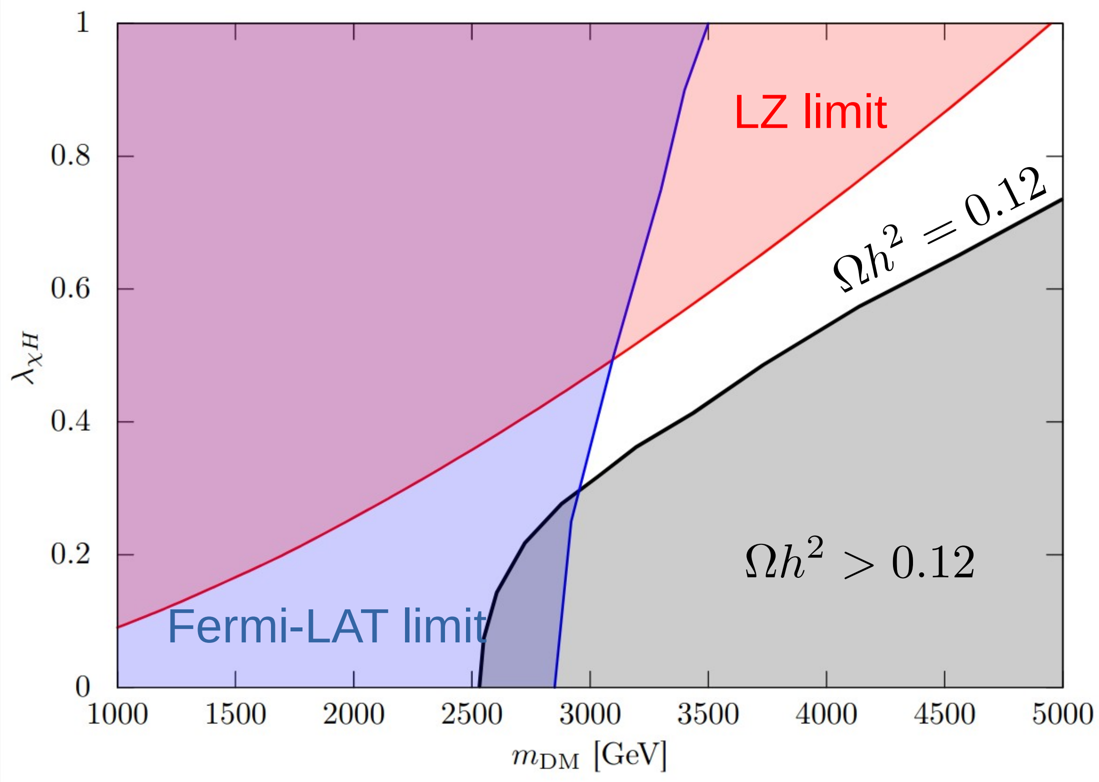
Scalar Wino+Higgs Interaction

$\Omega h^2 = 0.12$



Evade Indirect constraint

Scalar Wino Parameter



Summary

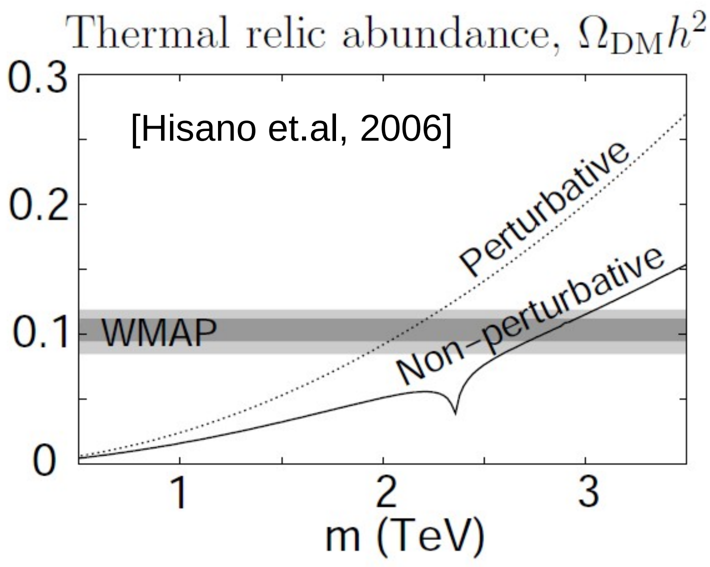
- Minimal model is often good approximation of UV models.

- 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.

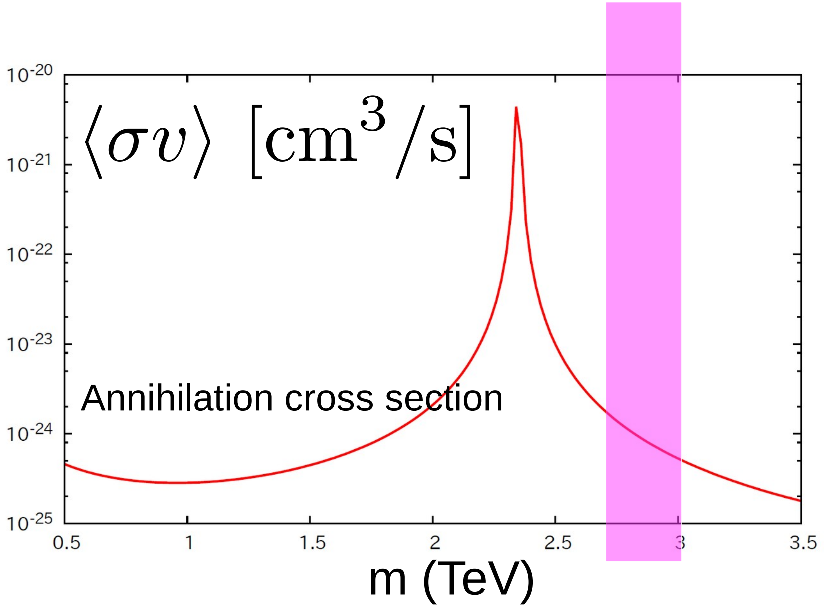
- Synergy of multiple searches is essential for WIMP paradigm.

Abundance

$\Omega h^2 \simeq 0.1$



2.7 – 3 TeV wino looks good.



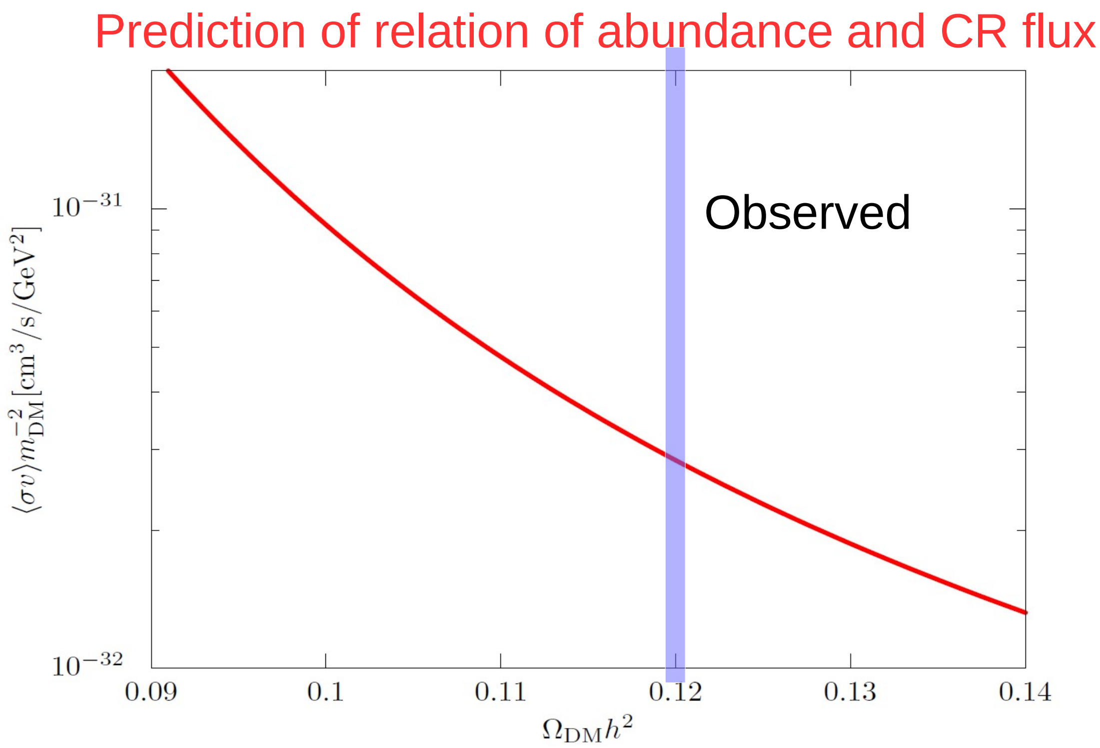
Largely depends on mass.

Precise Wino abundance estimation is still challenging.

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

Wino Case

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



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