Implications of DM Indirect Detection for Neutralino DM

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Photon flux from dark matter annihilations

particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE_\gamma} \int_{ROI} \frac{dJ}{d\Omega} d\Omega,$$

astrophysics

$$J = \int_{ROI} ds\, d\Omega\, \rho(r)^2,$$

$\frac{dN_\gamma}{dE_\gamma}$: gamma ray spectrum produced per annihilation

largest uncertainty usually comes from J factor

Constraints from Milky Way Dwarf Galaxies

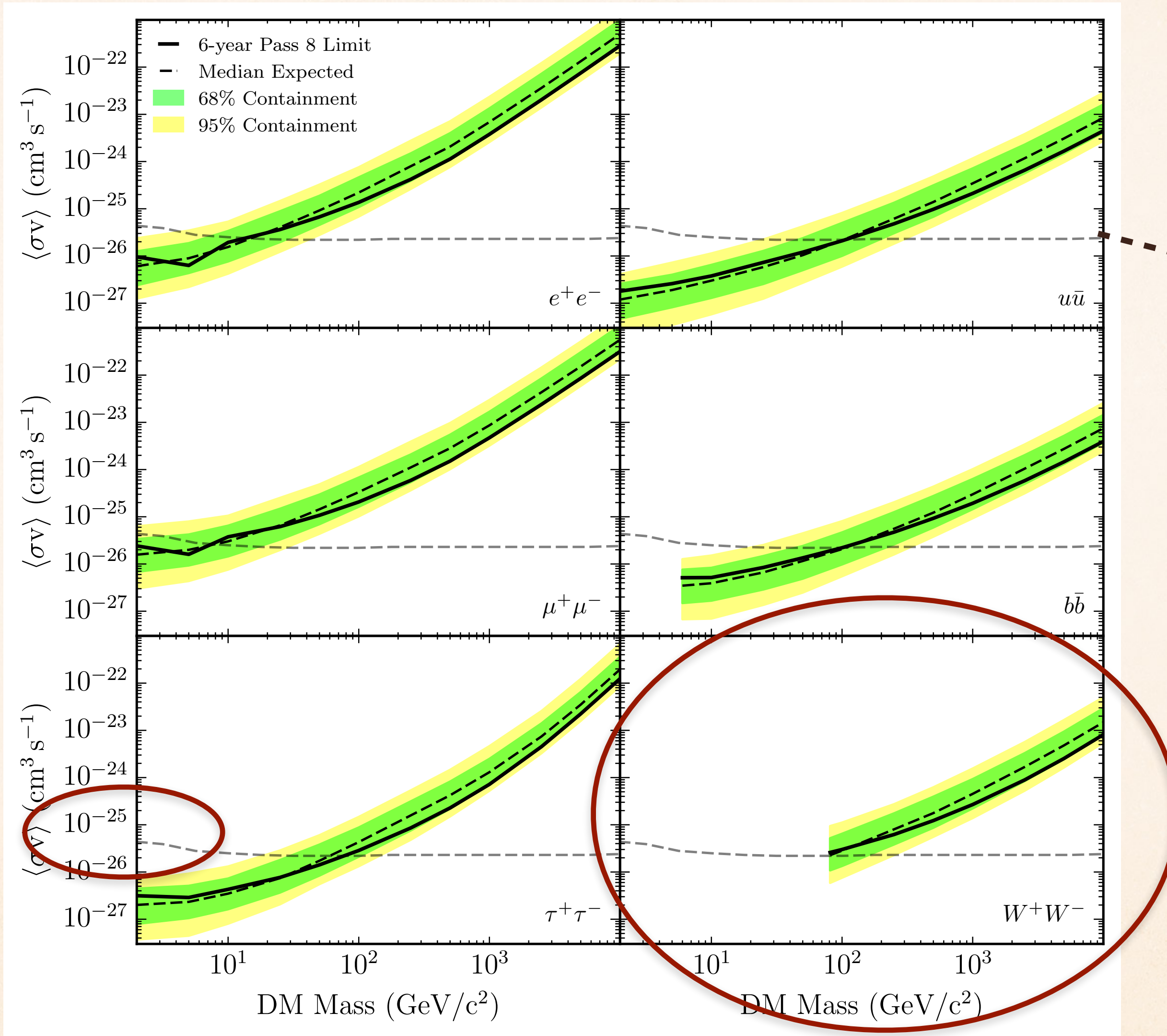


FIG. 8. DM annihilation cross-section constraints derived from the combined 15-dSph analysis for various channels.

thermal relic

most relevant for neutralino DM

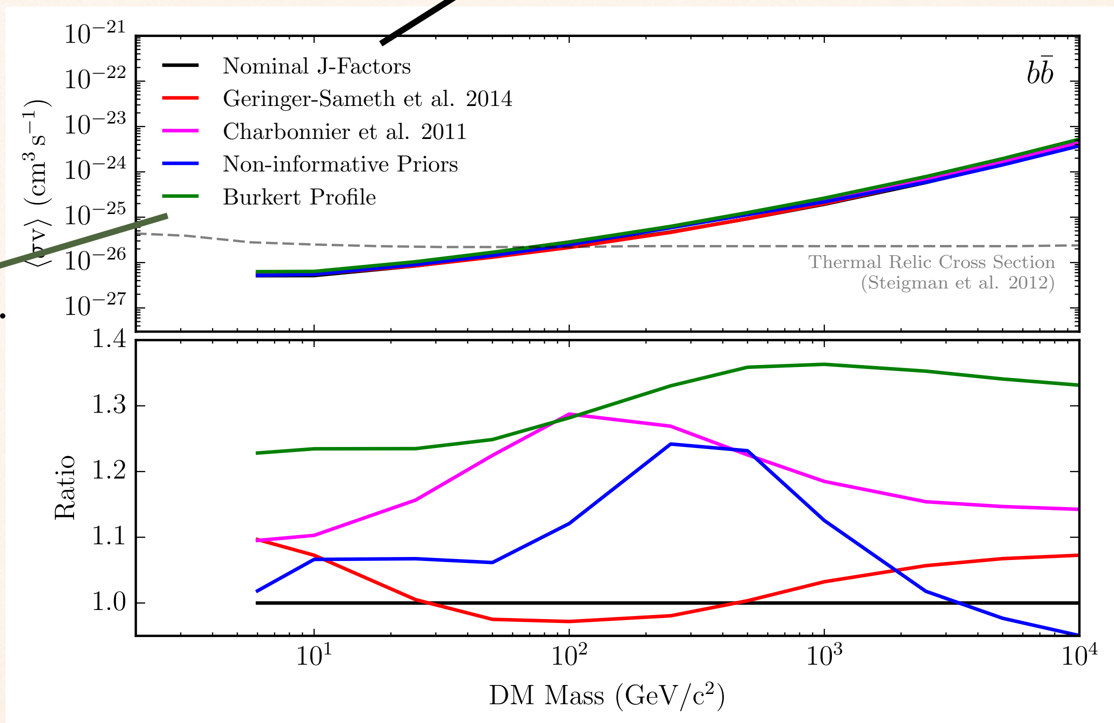
Fermi-LAT collaboration 2015

Effect of uncertainties of J factor

$$\rho_{\rm DM}(r) = \frac{\rho_0 r_s^3}{r(r_s+r)^2}, \quad \text{NFW cuspy}$$

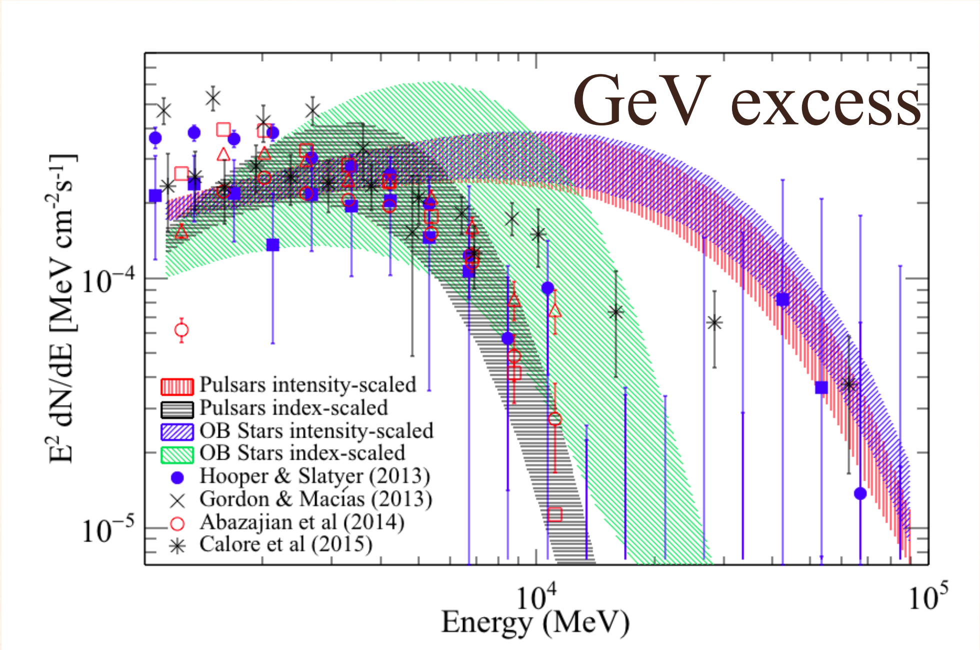
$$\rho_{\rm DM}(r) = \frac{\rho_0 r_s^3}{(r_s+r)(r_s^2+r^2)}.$$

Burkert core



Galactic Center: photon continuum

Differential residual flux spectrum



Fermi-LAT, 1511.02938

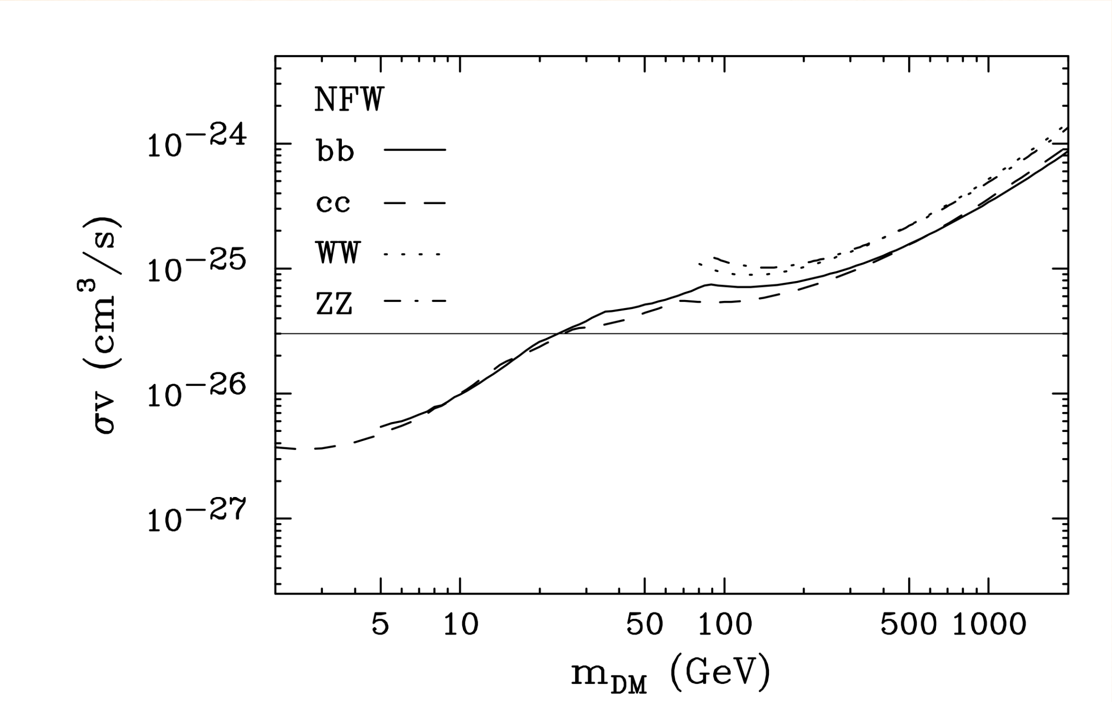
Explanations:

astrophysics: unresolved point sources, i.e, millisecond pulsar

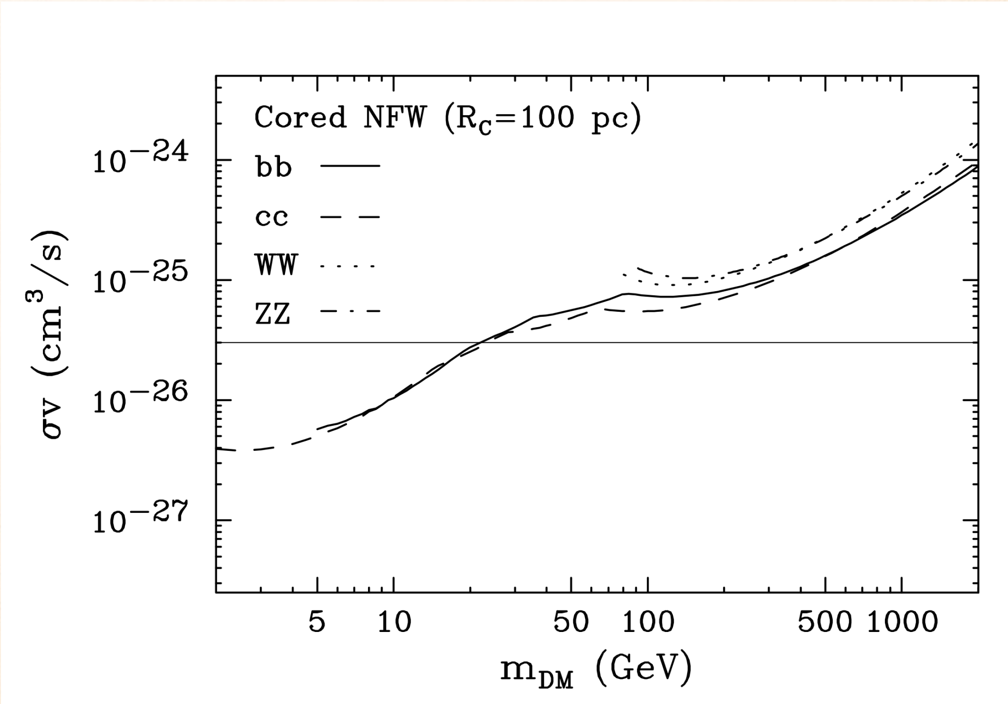
Bartels, Krishnanmurthy and Weniger; Lee, Lisanti, Safdi, Slatyer and Xue 2015

DM: e.g, higgsino (as a fraction of DM) or other simple WIMP models

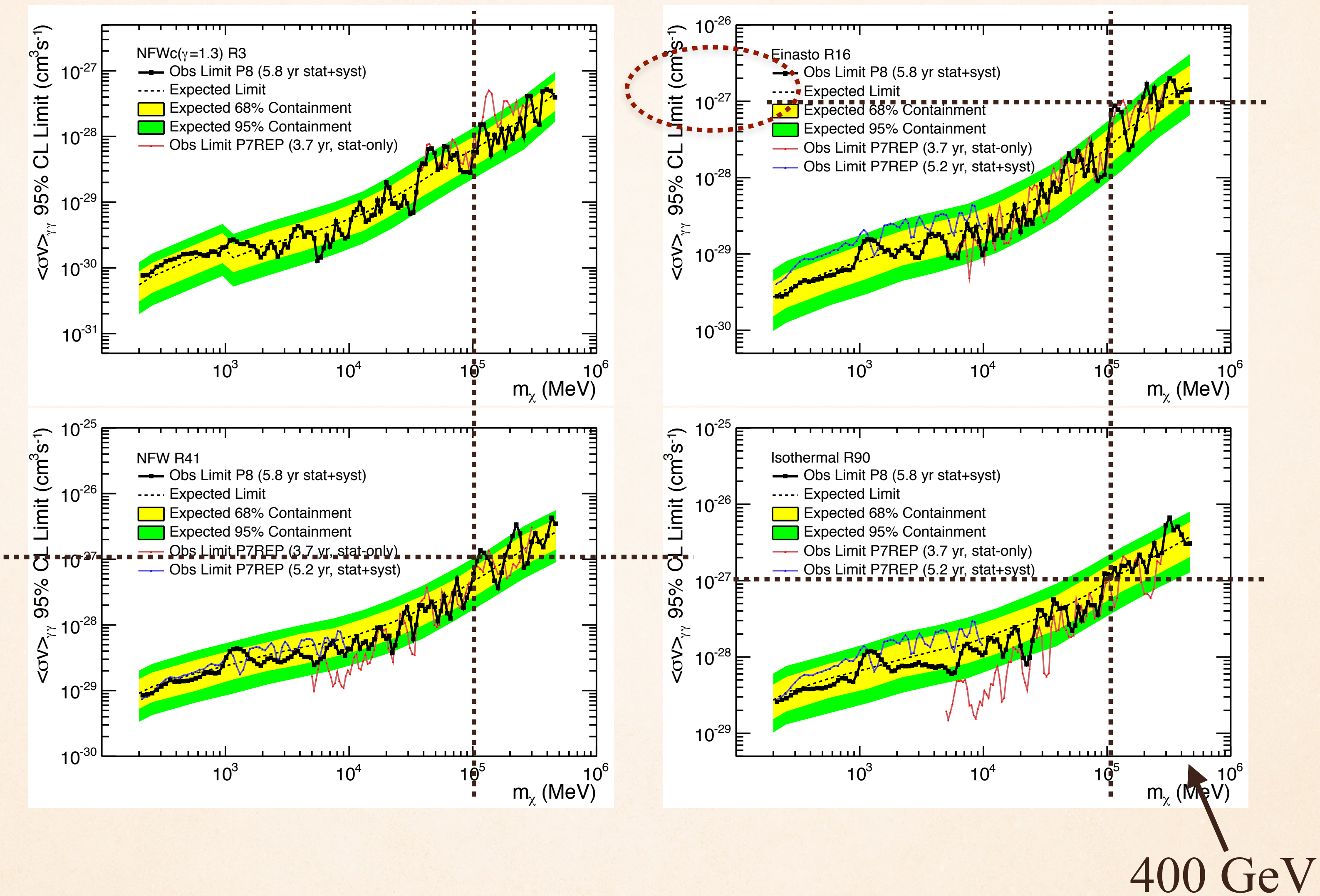
Agrawal, Batell, Fox, Harnik 2014



constraints from GC (subtract bg; 4-year pass 7 data)
Hooper, Kelso, Queiroz 1209.3015

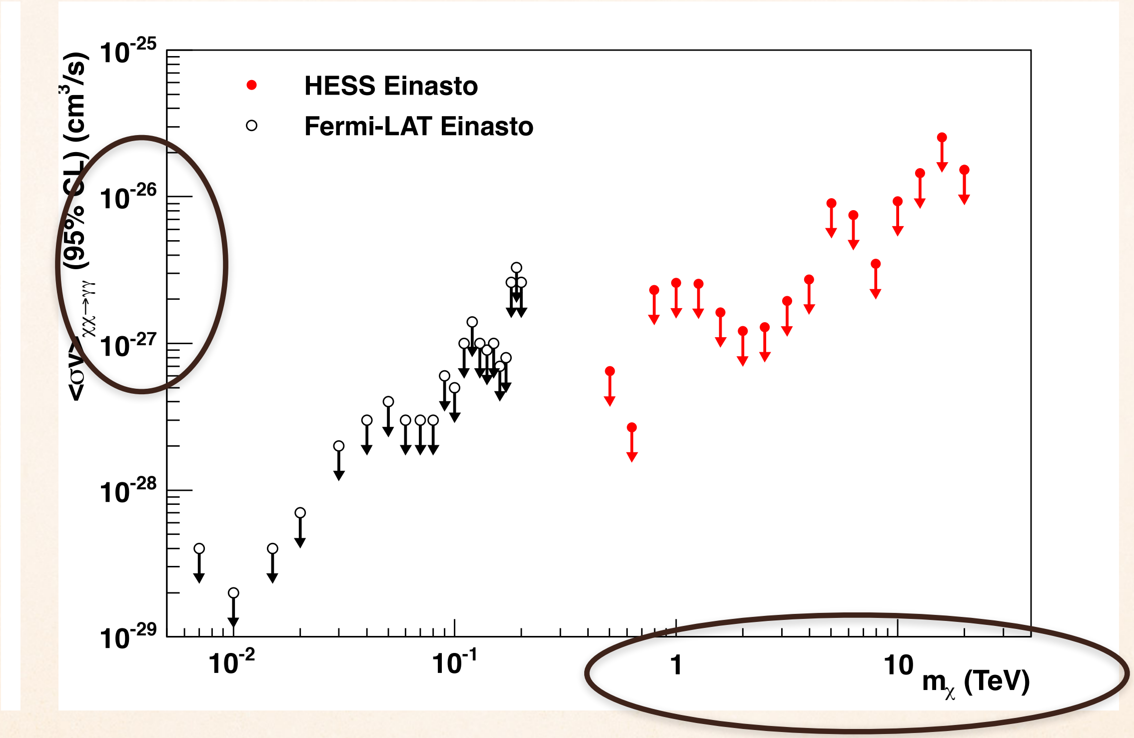


Line search from galactic center



Fermi-LAT, 1506.00013

HESS line search: 1301.1173



Neutralino DM provides classic benchmarks of WIMP scenario.

Neutralino DM exhausts the simplest possibilities of electroweak symmetry representations:

Bino: electroweak singlet;
Higgsino: electroweak doublet;
Wino: electroweak triplet;

Direct detection:

mixing between bino (wino) and higgsino: direct detection through Higgs exchange (leading order)

$$M_\chi = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'v\cos\beta & \frac{1}{2}g'v\sin\beta \\ 0 & M_2 & \frac{1}{2}gv\cos\beta & -\frac{1}{2}gv\sin\beta \\ -\frac{1}{2}g'v\cos\beta & \frac{1}{2}gv\cos\beta & 0 & -\mu \\ \frac{1}{2}g'v\sin\beta & -\frac{1}{2}g'v\cos\beta & -\mu & 0. \end{pmatrix}.$$

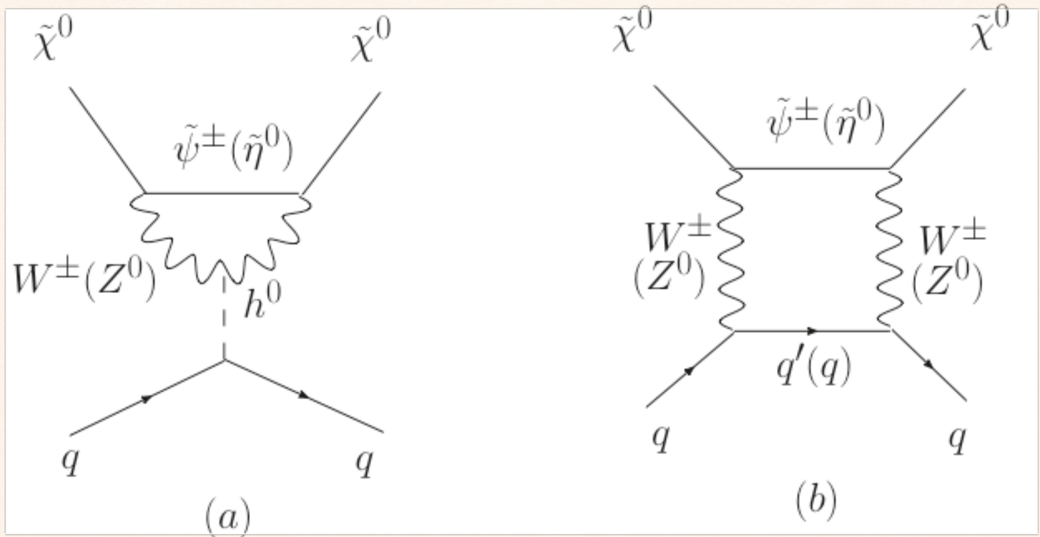
$$\mathcal{L}_{h\chi\chi} = \frac{1}{2}m_{\chi_i}(v+h)\chi_i\chi_i$$
$$= \frac{1}{2}m_{\chi_i}(v)\chi_i\chi_i + \frac{1}{2}\frac{\partial m_{\chi_i}(v)}{\partial v}h\chi_i\chi_i + \mathcal{O}(h^2),$$

$$= 0$$

spin-independent blind spots :
$$m_{\chi_1} = M_1, M_2, -\mu, \text{ and } m_{\chi_1} + \mu\sin 2\beta = 0$$
$$m_{\chi_1} = M_1 = M_2,$$

Hall, Ruderman, Pinner, 1211.4873;
heavy Higgs effects: Huang and Wagner 1404.0392

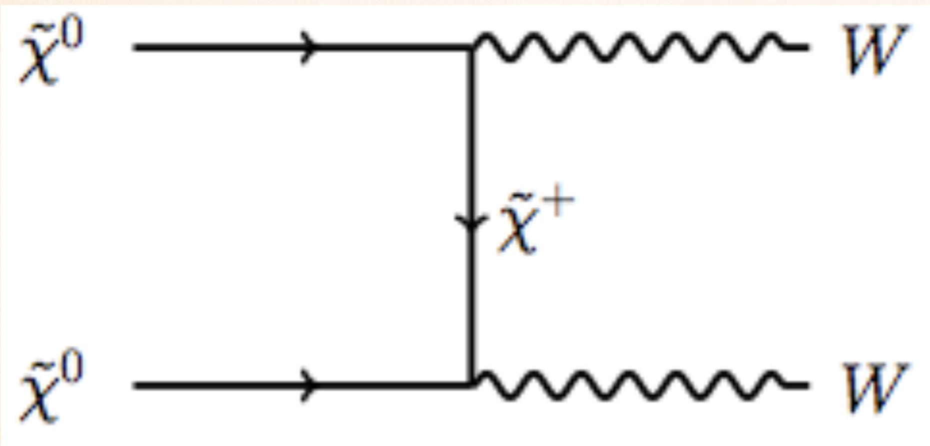
Direct detection is also insensitive to cases with very small mixing. For example, pure wino (decouple bino and higgsino); pure higgsino (decouple wino and bino).



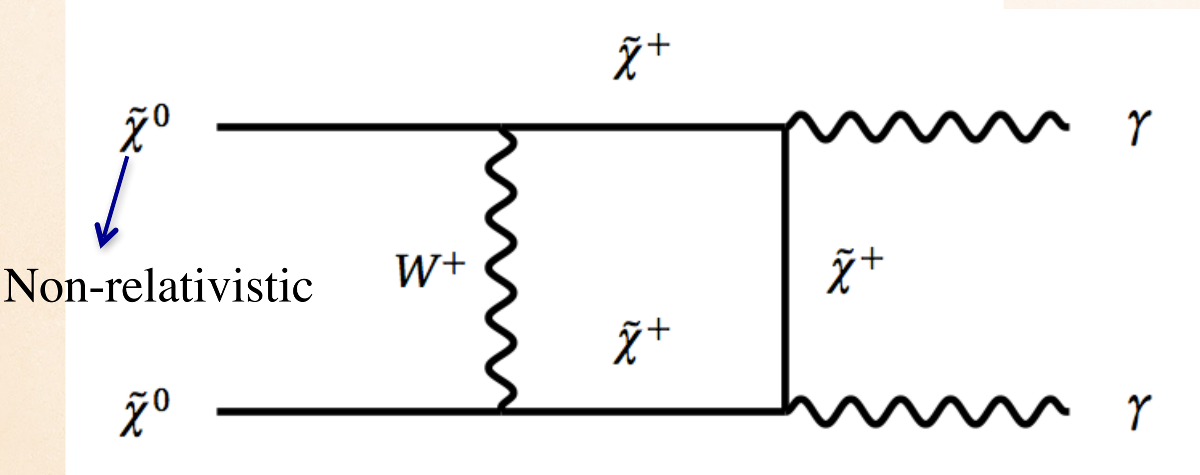
$$\sigma_n \sim 10^{-47}\text{cm}^2$$

Hisano, Ishiwata, Nagata,and Takesako; Hill, Solon 2011

Indirect detection (sensitive to the gauge interaction): search for excesses in the photon continuum spectrum or a line-like feature in a dark matter dense region, e.g., galactic center or dwarf galaxies.



Continuum photons



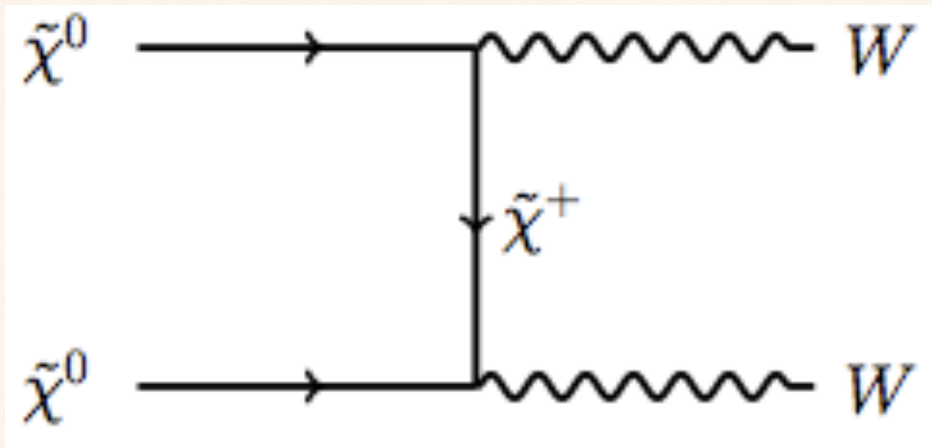
Photon line

$$E_\gamma = m_{\tilde{\chi}_0}$$

also photon+Z final state

$$\delta m = \frac{m_Z^2}{4 m_{\tilde{\chi}^0}} \approx 10\,\text{GeV}\left(\frac{200\text{GeV}}{m_{\tilde{\chi}^0}}\right)^2 .$$

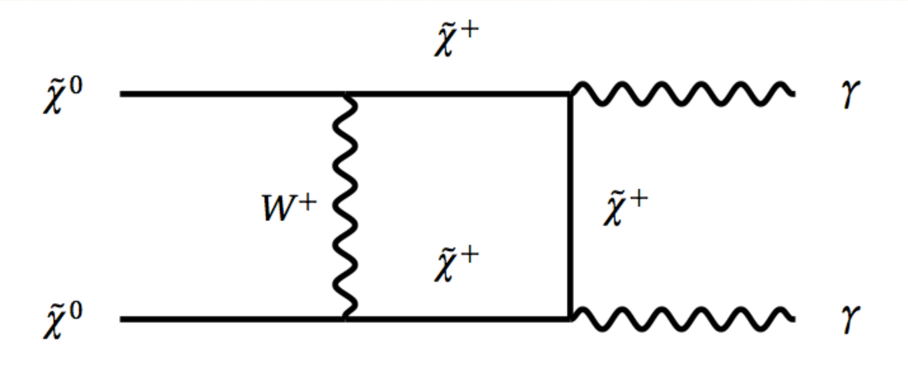
Tree-level process



$$\langle \sigma v \rangle \approx \frac{g_2^4}{8\pi}\frac{1}{m_\chi^2} \approx 4 \times 10^{-24}\mathrm{cm}^3/\mathrm{s}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^2$$

Dwarf/GC continuum: a few $10^{-26}\,\mathrm{cm}^3/s - 10^{-25}\,\mathrm{cm}^3/s$

One-loop processes: perturbative



$$\langle \sigma v \rangle_{\tilde{\chi}^0 \tilde{\chi}^0 \to \gamma\gamma} \approx \frac{4\alpha^4 \pi}{m_W^2 \sin^4 \theta_W} \approx 1.6 \times 10^{-27}\,\mathrm{cm}^3/s \quad (\tilde{\chi}^0 = \tilde{W}^0),$$

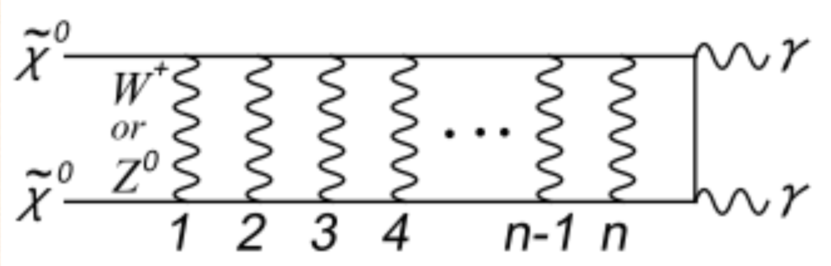
$$\approx \frac{\alpha^4 \pi}{4 m_W^2 \sin^4 \theta_W} \approx 10^{-28}\,\mathrm{cm}^3/s \quad (\tilde{\chi}^0 = \tilde{H}^0),$$

$$\langle \sigma v \rangle_{\tilde{\chi}^0 \tilde{\chi}^0 \to Z\gamma} \approx \frac{8\alpha^4 \pi \cos^2 \theta_W}{m_W^2 \sin^6 \theta_W} \approx 1.1 \times 10^{-26}\,\mathrm{cm}^3/s \quad (\tilde{\chi}^0 = \tilde{W}^0),$$

$$\approx \frac{\alpha^4 \pi \left(\sin^2 \theta_W - 0.5\right)^2}{2 m_W^2 \sin^6 \theta_W \cos^2 \theta_W} \approx 8.0 \times 10^{-29}\,\mathrm{cm}^3/s \quad (\tilde{\chi}^0 = \tilde{H}^0).$$

Line search: $10^{-27}\,\mathrm{cm}^3/s$

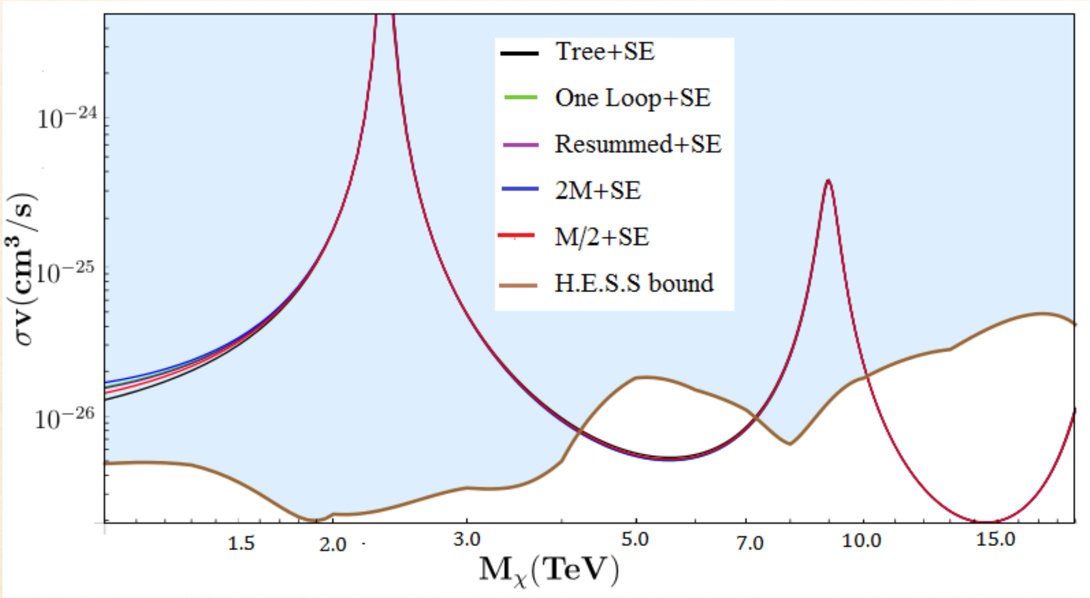
Heavy wino (above TeV): Sommerfeld enhancement



$$\alpha_2 m_{\tilde{\chi}^0} > m_W$$

Electroweak Sudakov double-logs

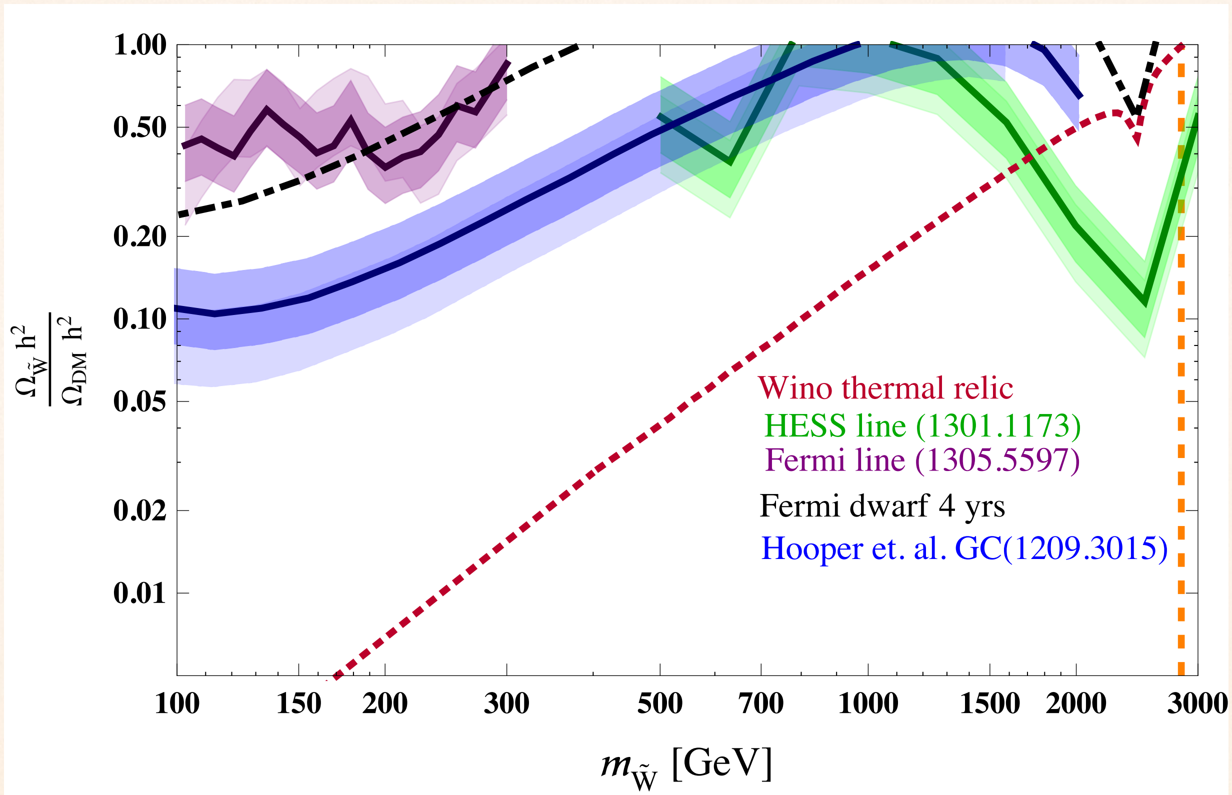
$$\alpha_W \log(\frac{M_\chi^2}{M_W^2})^2$$



Baumgart, Rothstein and Vaidya 1412.8698;

Ovanesyan, Slatyer and Stewart 1409.8294;

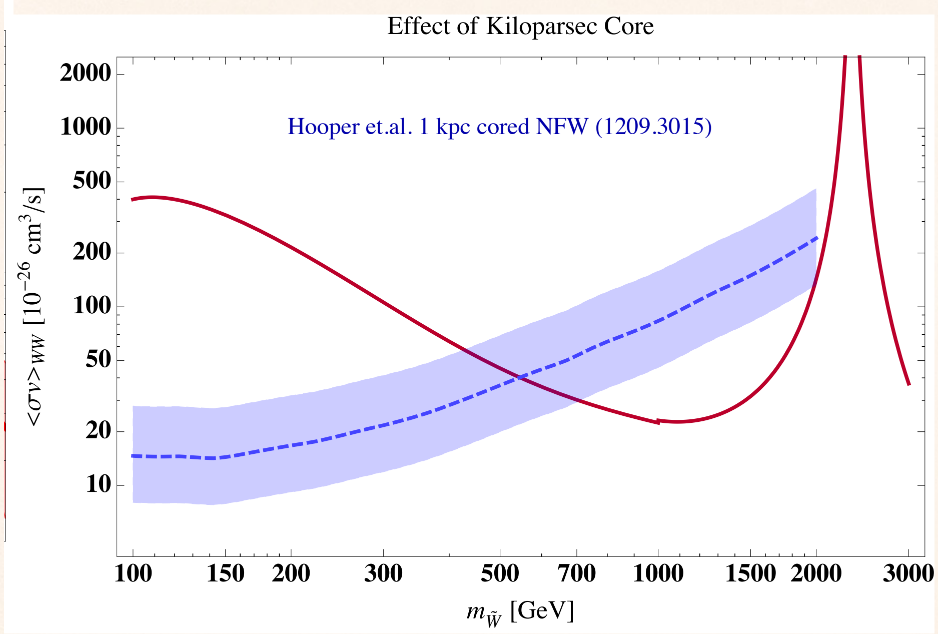
Light wino (a few hundred GeV range):
working perfectly with Moroi-Randall scenario;



Fan, Reece 1307.4400;

(see also Cohen, Lisanti, Pierce, Slatyer 1307.4082)

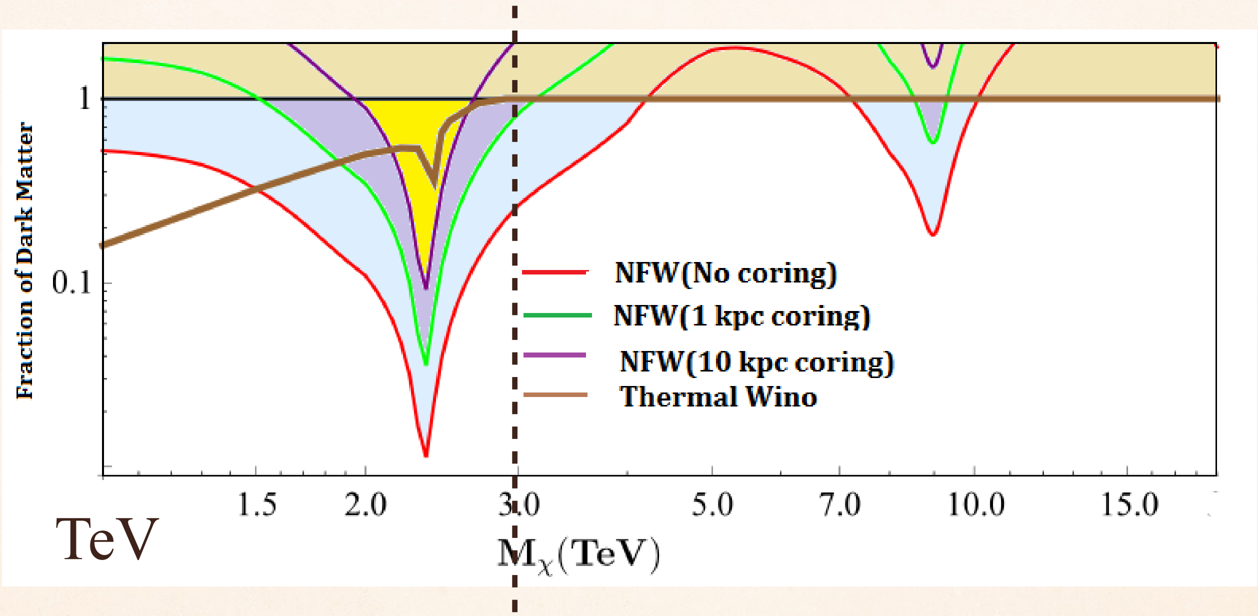
Light wino: excluded even when one considers cored profile (1kpc core)



Fan, Reece 1307.4400

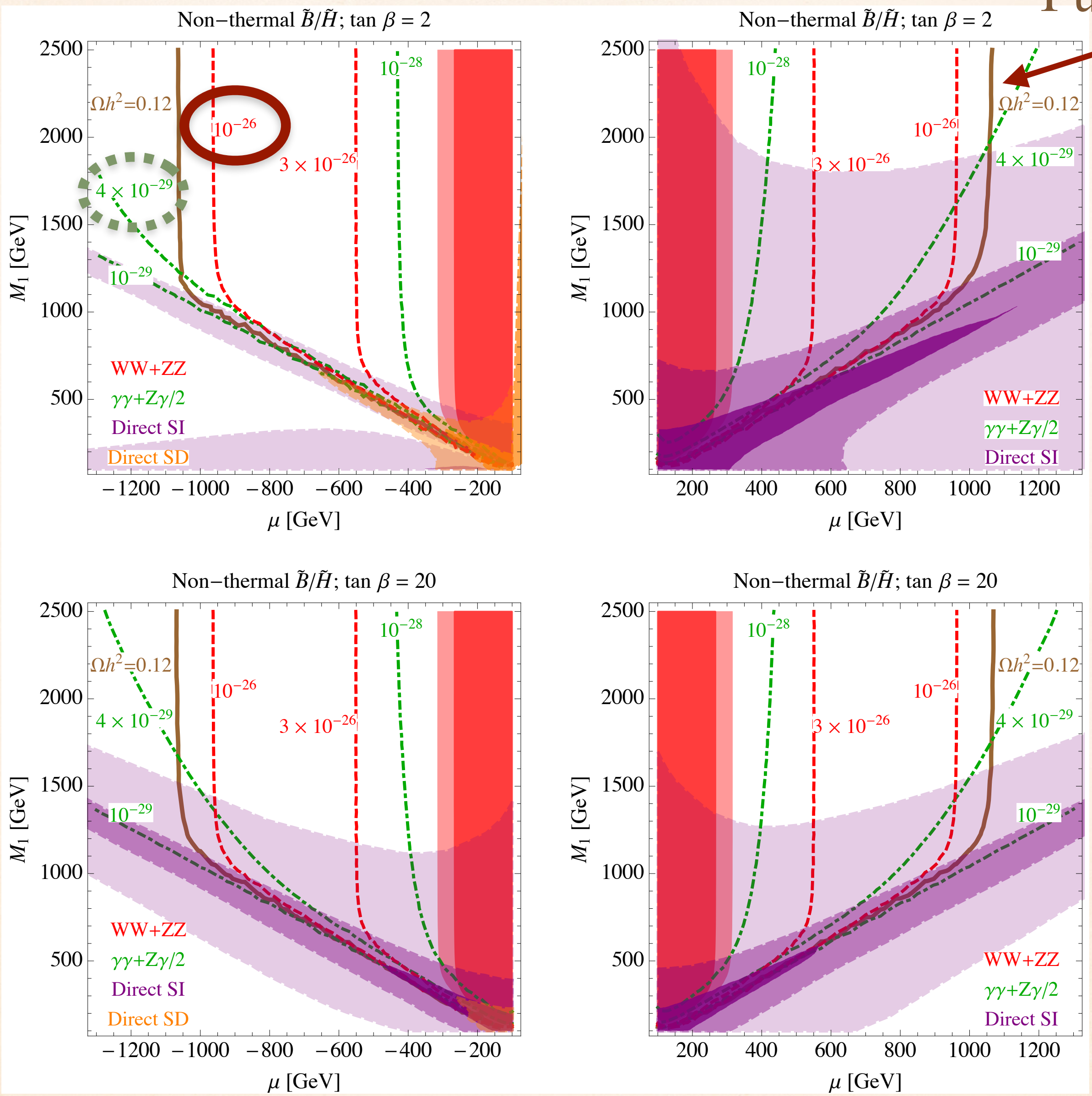
Heavy wino DM

Thermal scenario is excluded even when one considers an NFW profile with a 4 kpc core



Baumgart, Rothstein and Vaidya 1412.8698

Higgsino(with bino mixture) DM



Pure higgsino DM with mass at a TeV

Hall, Ruderman, Pinner, 1211.4873

Fan, Reece 1307.4400

A bit about non-thermal scenario

Non-thermal scenario arises generally in high-scale SUSY.

You cannot get whatever you want with a non-thermal scenario. In the wino case, there are already highly non-trivial constraints on non-thermal scenarios from indirect detection.

In high-scale SUSY, DM non-thermal histories are inherent.

SUSY theories always contain very weakly-coupled particles such as gravitinos and moduli.
Their masses are determined by the SUSY breaking scale.
In high-scale SUSY, they are heavy and have long life-times.
Their decays before BBN will automatically lead to non-thermal production of DM particles.

The requirement that the DM relic abundance resulting from gravitino decays does not overclose the Universe and satisfies the indirect detection constraints demand the reheating temperature to be below $10^9 - 10^{10}$ GeV in mini-split scenario with gravitinos around PeV scale.

If one takes into account of gravitinos from inflaton decays, the upper bound on the reheating temperature will get even stronger.

This puts a non-trivial interaction on inflation and reheating scenario.

For example, in large-field inflation $c\frac{\phi F\tilde{F}}{M_p}$

$$\Gamma_\phi = \frac{c m_\phi^3}{M_p^2}, \quad T_R \approx 5 \times 10^9\,\mathrm{GeV}\sqrt{c}\left(\frac{m_\phi}{10^{13}\,\mathrm{GeV}}\right)^{3/2},$$

Fan, Jain, Ozsoy, 2014

Light wino DM fits perfectly into the moduli scenario (before the indirect detect constraint):

Light winos have a small thermal relic abundance

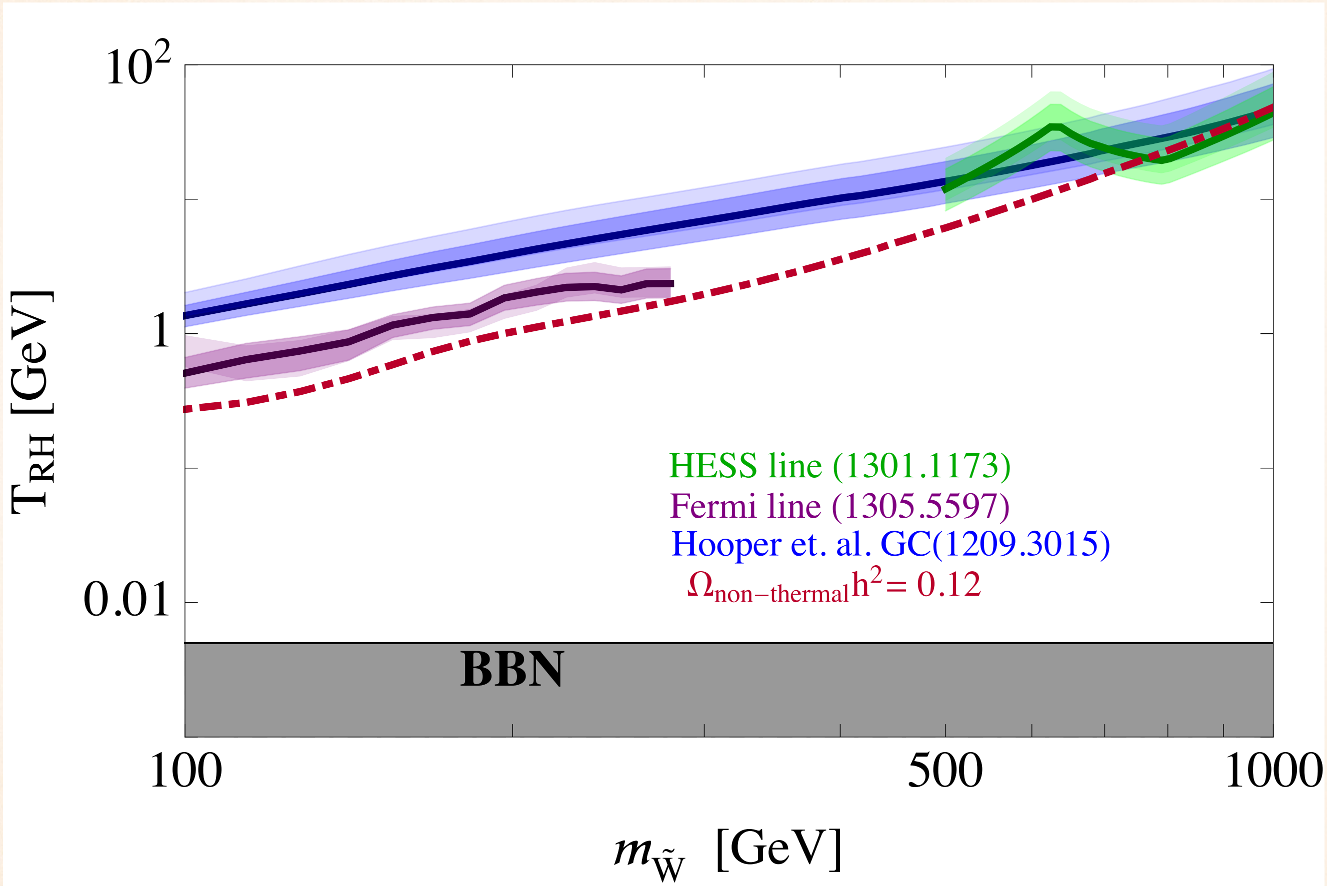
Moduli arise ubiquitously in string compactifications.
Moduli mass ~ gravitino mass, and their relic abundance could dominate the early Universe and lead to a late-time matter domination phase.

Moduli decays produce sufficient winos which will annihilate efficiently
Moroi, Randall 1999

$$H \sim \Gamma_\phi \sim n\langle\sigma v\rangle \qquad \phi : \text{modulus}$$

$$\Omega^{\rm non-thermal} h^2 \sim \frac{T_{\rm freezeout}}{T_{\rm RH}} \Omega^{\rm thermal} h^2$$

Translate the bound on wino relic abundance as a lower bound on T_{RH}

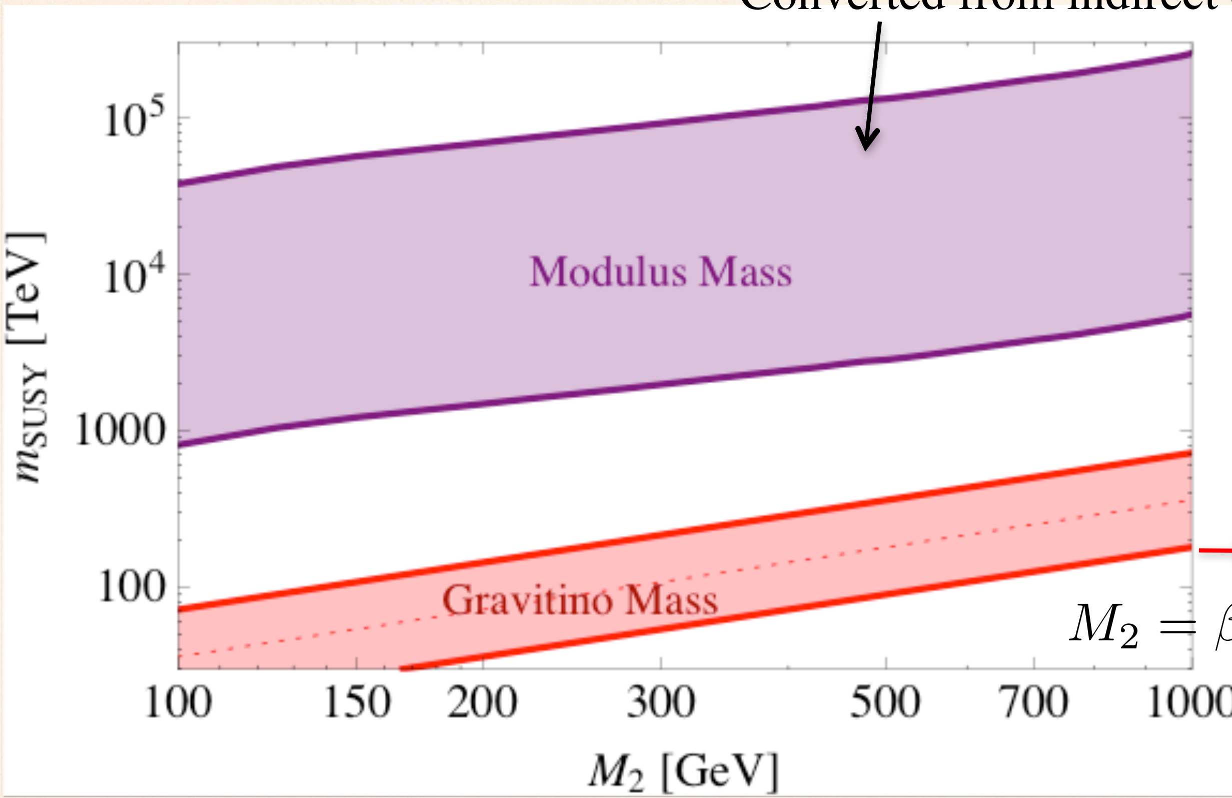


The reheating temperature has to be above 1 GeV!

Fan, Reece 2013

Implication for SUSY breaking scale

Converted from indirect detection constraints



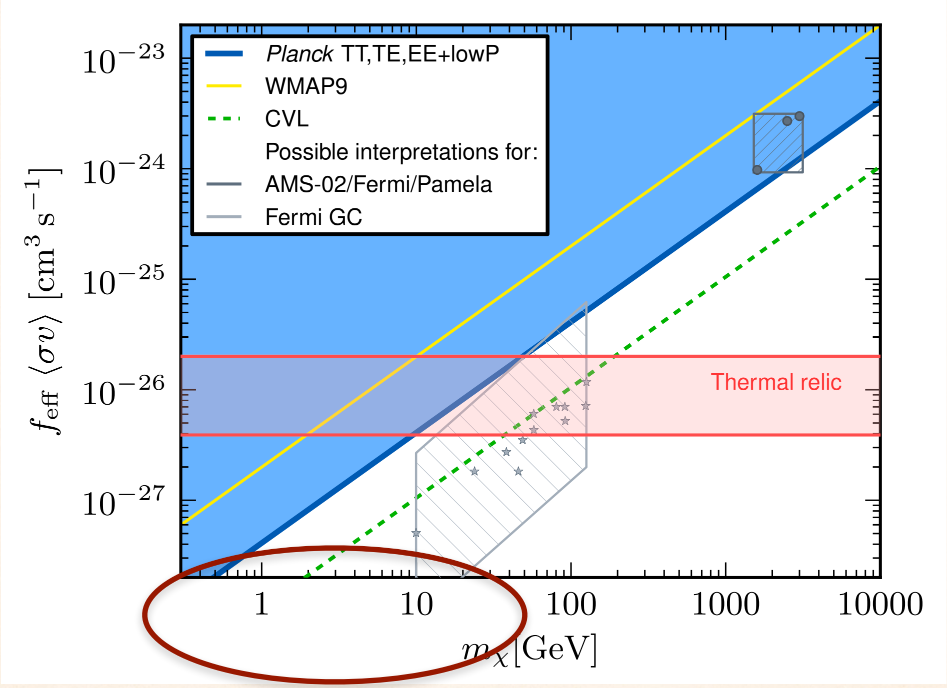
anomaly mediation

$$M_2 = \beta(g)/g m_{3/2} \approx m_{3/2}/360$$

The moduli mass scale compatible with data has to be an order of magnitude or more above $m_{3/2}$

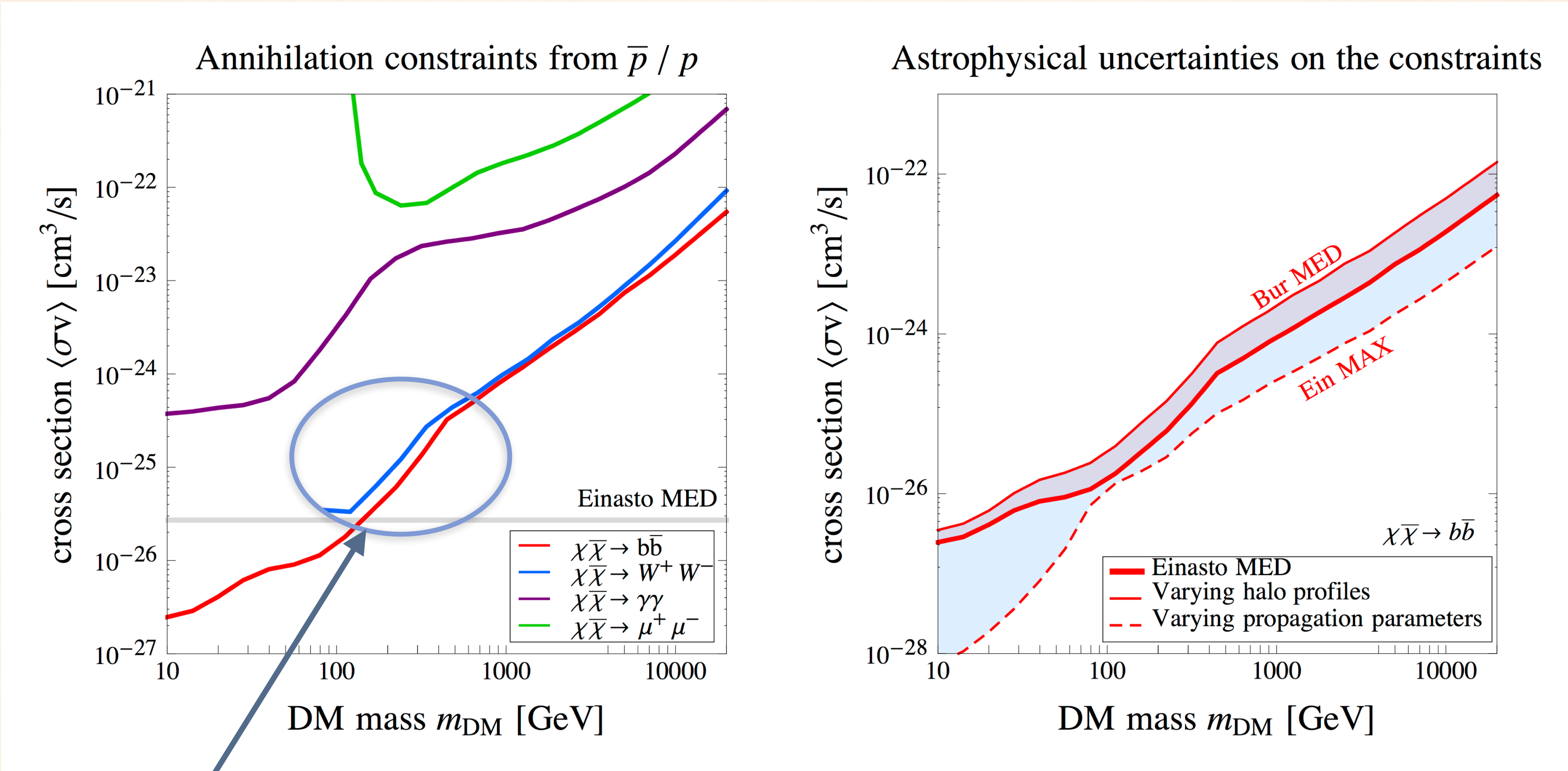
- A serious problem is the moduli-induced gravitino problem. The decays of gravitino produced from moduli decays can cause problem for BBN and over-production of winos at late times.
- Possible ways out: go beyond MSSM, consider an additional dark sector and make winos decays into the dark sector   Blinov, Kozaczuk, Menon, Morrissey 2014; Kane, Kumar, Nelson and Zheng 2015

CMB: energy injection from DM constraints can alter the recombination history, leading to changes in the temperature and polarization power spectra of CMB



Planck: 1502.01589

AMS anti-proton data



comparable to gamma ray constraints

Giesen et al 1504.04276

Summary and discussions

Mixed scenario: indirect, direct detection and collider are complementary.

Wino DM have been strongly constrained by indirect detection: excluded or milky way DM density distribution has a large core (with core size above kpc).

Thermal higgsino DM (the simplest counterexample that thermal WIMP is going to be excluded soon) will be difficult to be ruled out:

How much improvement of sensitivity one could get from CTA or Gamma400 in both continuum and line searches?

In general, any better current and future experimental probe of thermal higgsino? In addition to the all the probes that have been discussed, one could also hope to look for it through its radiative effect. For example, triple gauge coupling (Fan, Reece, Wang 1412.3107) or running of electroweak gauge coupling (Alves, Galloway, Ruderman, Walsh 1410.6810).

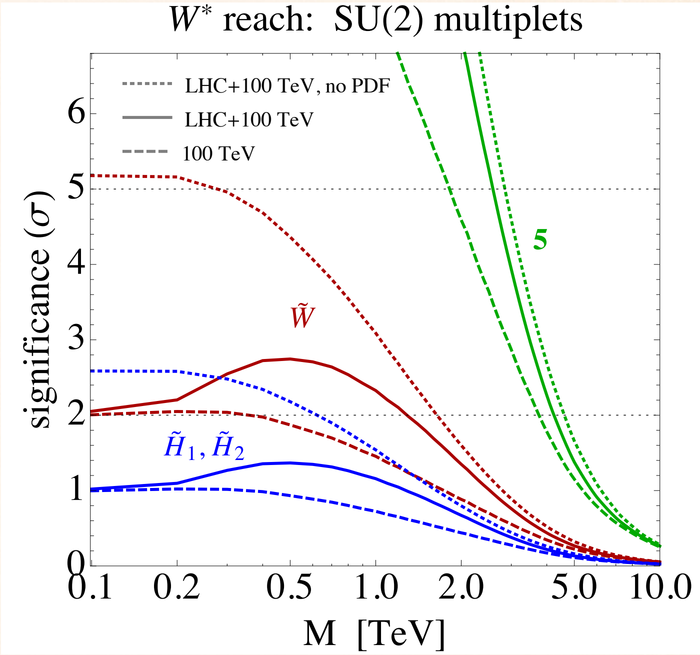
lepton collider

$$c_{WWW} = \frac{g^2}{2880\pi^2} \sum_{\text{rep } R, \text{ mass } M} (-1)^F \frac{T(R)}{M^2},$$

ILC: $|\lambda_{\gamma,Z}| \lesssim 6 \times 10^{-4}$

$\sqrt{s} = 500 \text{ TeV} \quad 500 \text{ fb}^{-1}$

hadron collider



High luminosity?
diboson channel?

Thank you!

Backup

Higgs portal: Silveira and Zee 1985; McDonald 1994; Burgess, Pospelov and ter Veldhuis 2001; Patt and Wilczek 2006…..

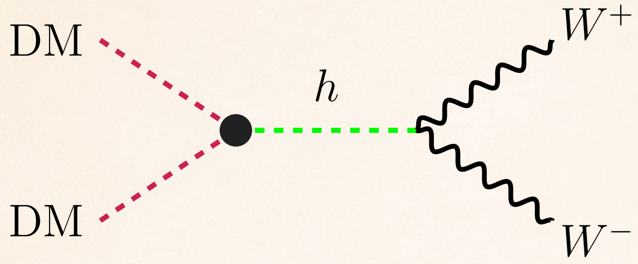
Higgs provides an entirely new gateway to physics beyond the SM thanks to the low dimension of the operator $|H|^2$

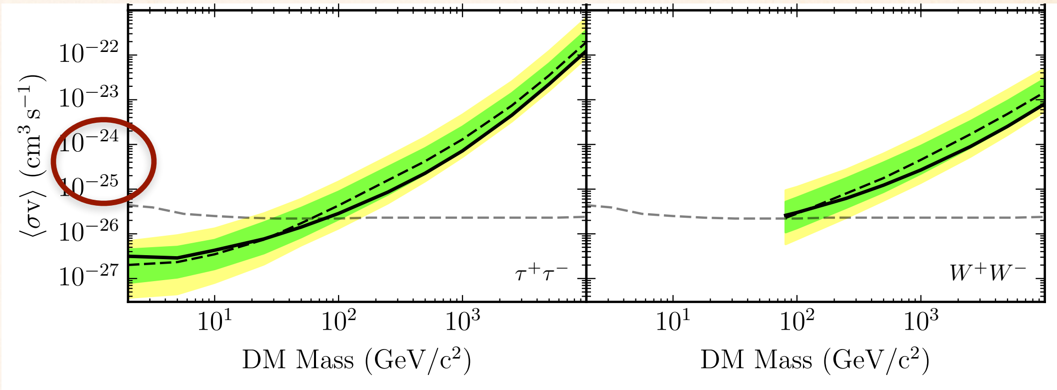
$$|H|^2\mathcal{O}$$

operator of dark sector:
simplest possibility $\mathcal{O}:\phi^2, \quad |\phi|^2$

Indirect detection:

Milky Way dwarf galaxies:
Fermi-LAT 2015

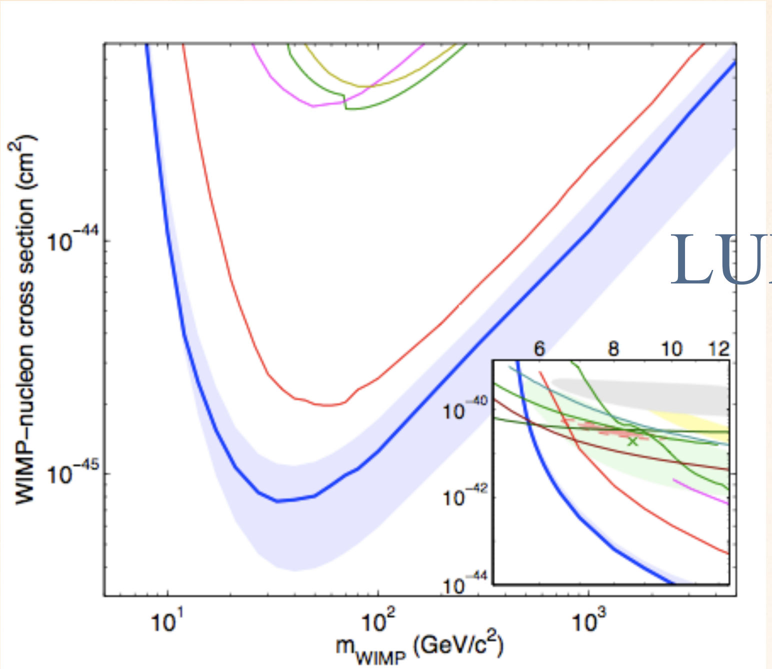




$$\langle \sigma v \rangle = \sum_{i=W,Z} n_i \frac{|\lambda_{\phi H}|^2}{2\pi m_\phi^2} \sqrt{1-\frac{m_i^2}{m_\phi^2}} \frac{m_i^4}{\left(4m_\phi^2 - m_h^2\right)^2} \left(2 + \frac{(2m_\phi^2 - m_i^2)^2}{m_i^4}\right)$$

$$= \left|\frac{\lambda_{\phi H}}{0.038}\right|^2 3 \times 10^{-26}\,\mathrm{cm^3 s^{-1}} \quad m_\phi = 100\,\mathrm{GeV}$$

Fan, Reece 1301.2597



LUX

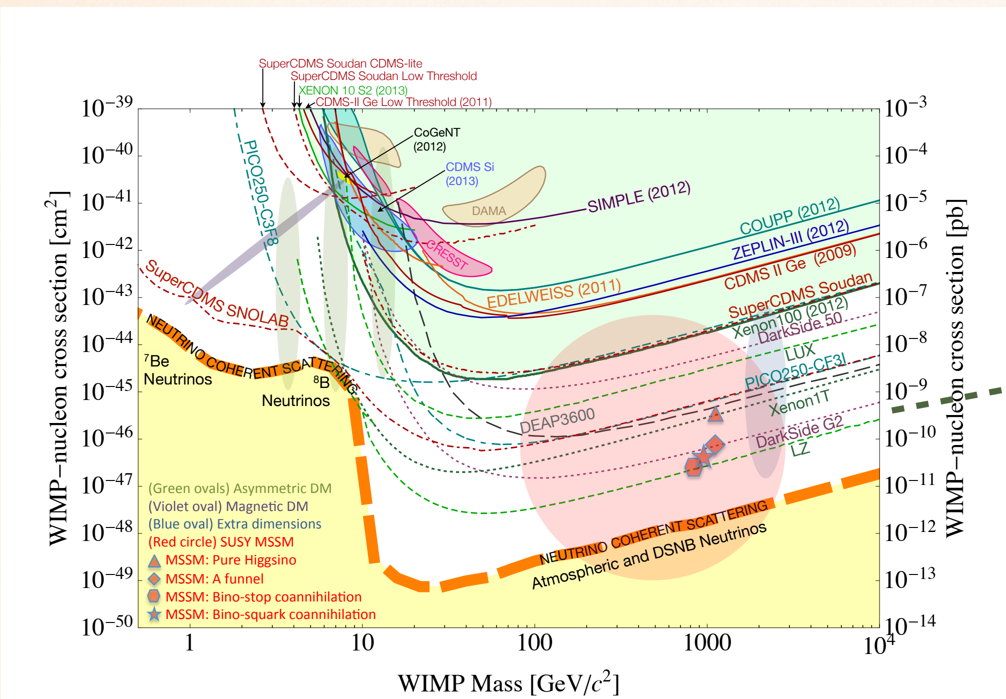
$$\sigma_{SI} = \frac{|\lambda_{\phi H}|^2 m_n^4 f^2}{\pi m_h^4 m_\phi^2}$$

$$= \left(\frac{\lambda_{\phi H}}{0.02}\right)^2 \left(\frac{100\,\text{GeV}}{m_\phi}\right)^2 1.4 \times 10^{-45}\text{cm}^2,$$

$$m_\phi = 500\,\text{GeV} \quad \lambda_{\phi H} \approx 0.2$$

$$m_\phi = 10\,\text{GeV} \quad \lambda_{\phi H} \approx 0.005$$

EWSB contributes a small mass to the DM



Future: LZ

$$\lambda_{\phi H} \sim (0.002 - 0.02)$$

$$m_\phi = (100 - 500)\,\text{GeV}$$