Particle models motivated by WIMP indirect search data

Osamu Seto

(Hokkai-Gakuen Univ.)

Refs : Phys. Rev. D **89** 043525 (2014)

Phys. Rev. D **90** 083523 (2014)

With: Nobuchika Okada (U. of Alabama)

in prep.

With: Arindam Das and Nobuchika Okada (U. of Alabama)

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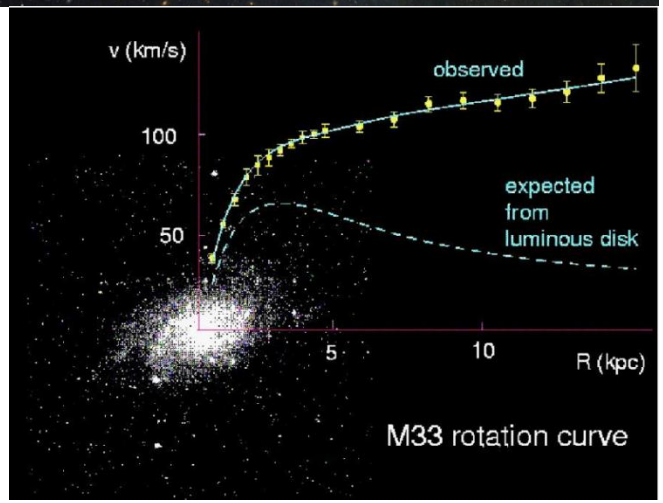
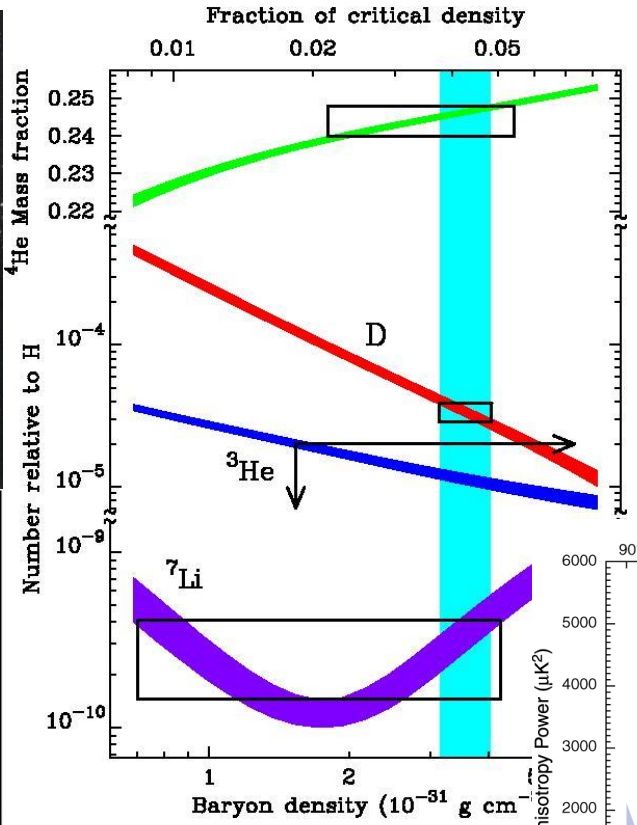
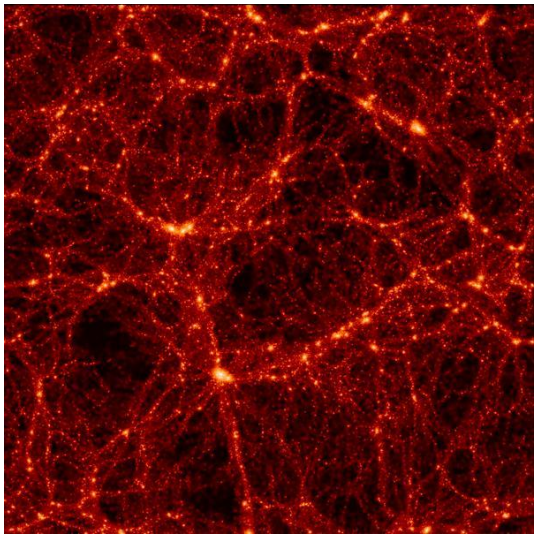
- Dark matter
- WIMP indirect detection
  (current status)
- Galactic center (GC) gamma ray excess
- GC excess from two Higgs doublet portal DM
- Summary

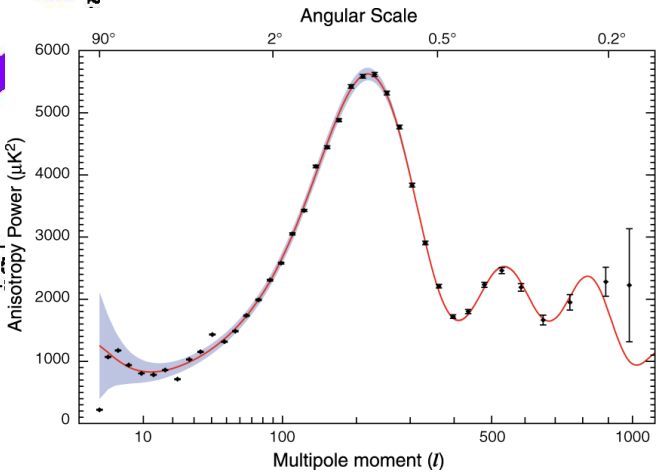
§ Dark matter

- Dark matter: convincing evidences





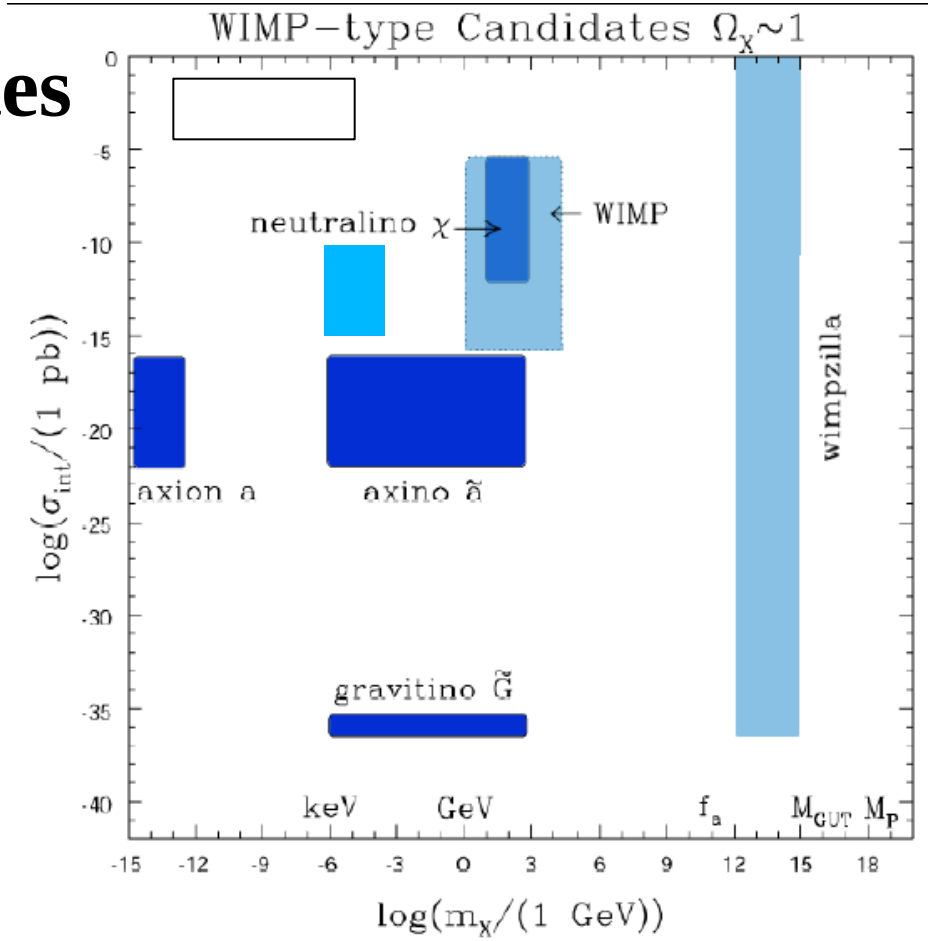




§ Dark matter candidates

Hypothetical candidates

- Sterile neutrino
- Axion
- WIMP
- Others

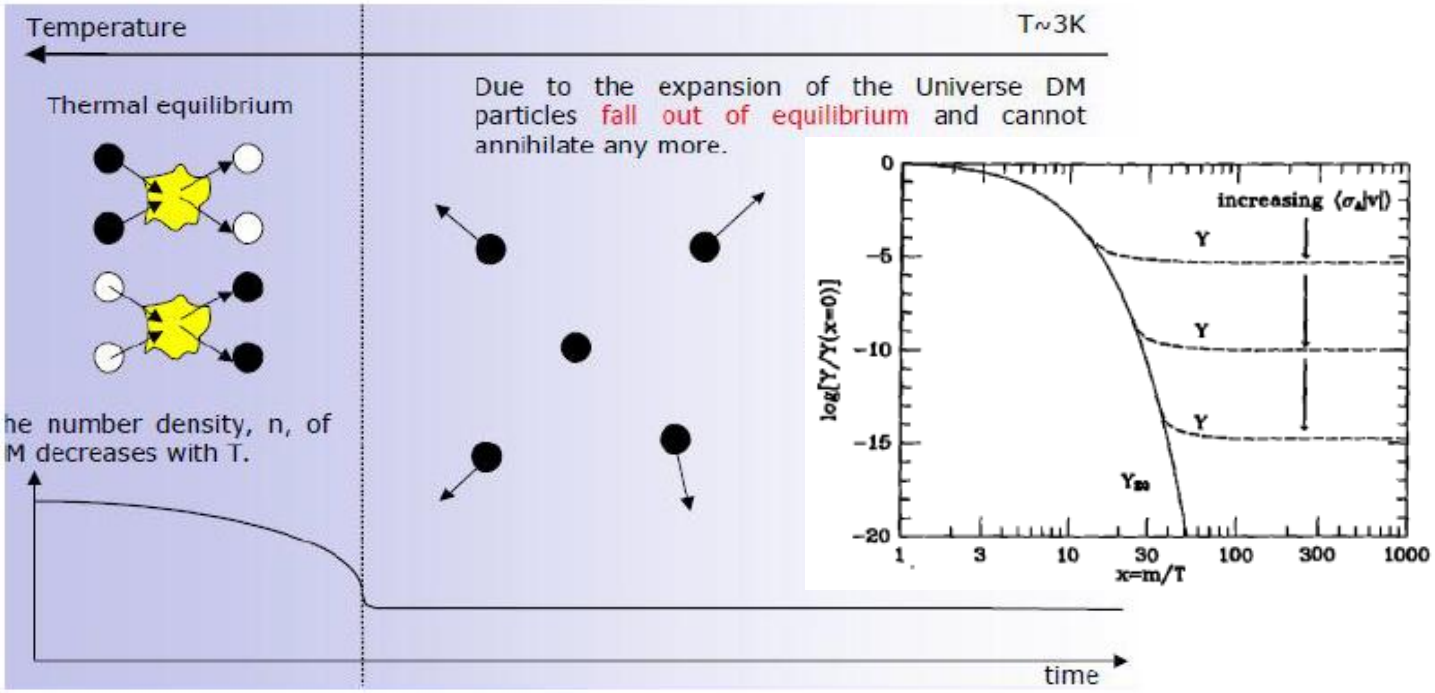


Those may co-exist, if stability reasons are different.

Thermal relic abundance of WIMP

Under ``standard'' cosmology

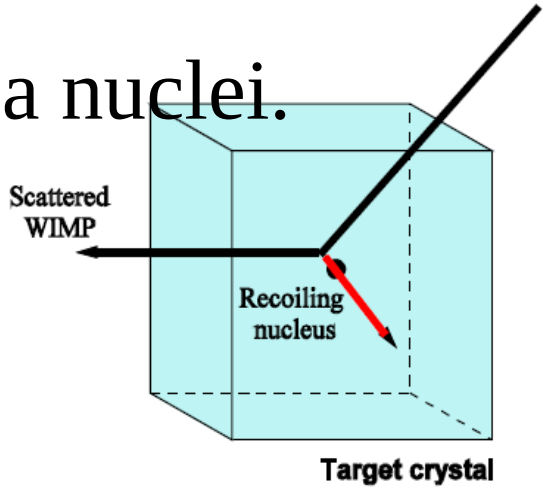
- Annihilation and thermal relic density



$$\Omega_{DM}h^2 \simeq 1\times 10^9 \frac{(m_{DM}/T_f)\mathrm{GeV}^{-1}}{\sqrt{g_*}M_{Pl}\langle\sigma v\rangle} =_{\text{typically}} \mathcal{O}(10^{-2}-1),$$ [Cerdeño's courtesy]

DM (WIMP) detection

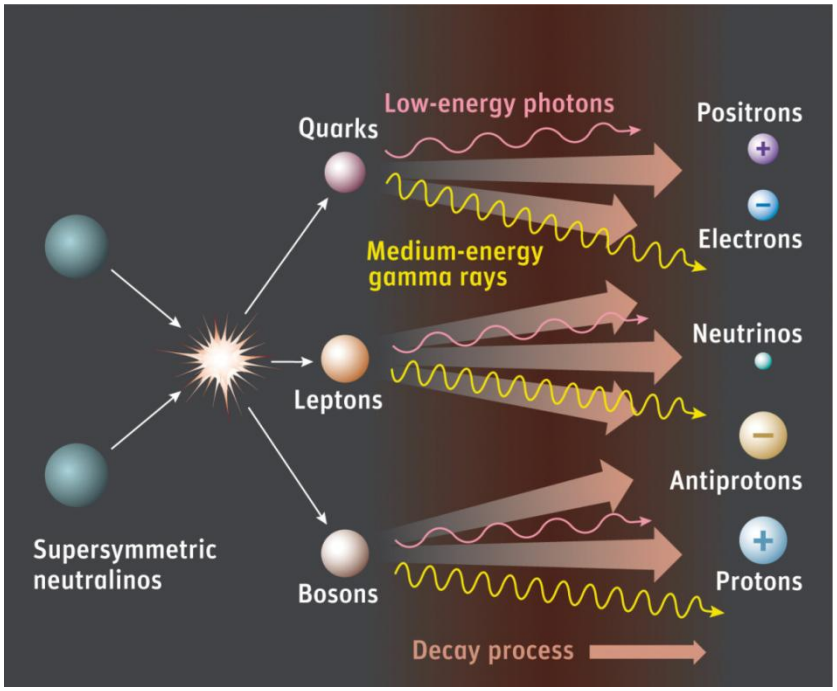
- Direct detection of WIMP
- WIMP would scatter off with a nuclei.



- Indirect detection
- WIMP annihilation (and non-WIMP DM decay) produces the extra component in cosmic rays.

§ DM indirect detection

- WIMP (non-WIMP) would self-annihilate (decay) today.
- Annihilation/decay final states produce an extra component in cosmic rays.



§ § DM indirect detection

- Annihilation/decay final states produce an extra component in cosmic rays.
- e.g.,

photon (diffuse or line)	Fermi-LAT, ...
neutrino	IceCube
electron / positron	PAMELA, AMS-02
other anti-particles	PAMELA, AMS-02

- Those would be observed as an excess over astrophysical background*.

Q``Do we know astrophysical part???''

§ § WIMP indirect detection

- photon (diffuse or line) or neutrino
- Flux

$$\Phi_i(\psi, E) = \sigma v \frac{dN_i}{dE} \frac{1}{4\pi m_{\rm DM}^2} \int_{\text{line of sight}} d\,s \rho^2\left(r(s,\psi)\right)$$

Cross section Spectrum number density^2

Astrophysical part

$$J(\psi) = \frac{1}{8.5\,\text{kpc}} \left(\frac{1}{0.3\,\text{GeV/cm}^3}\right)^2 \int_{\text{line of sight}} d\,s \rho^2\left(r(s,\psi)\right)$$

would come from the galactic center, dwarf galaxies.

§ § WIMP indirect detection

- Charged particle (e-, e+, antiproton etc.)
- Propagation equation

$$\frac{\partial}{\partial t}\frac{dn_{e^+}}{dE_{e^+}} = \vec{\nabla}\cdot\left[K(E_{e^+},\vec{x})\vec{\nabla}\frac{dn_{e^+}}{dE_{e^+}}\right] + \frac{\partial}{\partial E_{e^+}}\left[b(E_{e^+},\vec{x})\frac{dn_{e^+}}{dE_{e^+}}\right] + Q(E_{e^+},\vec{x})$$

Diffusion Energy loss Spectrum Source term

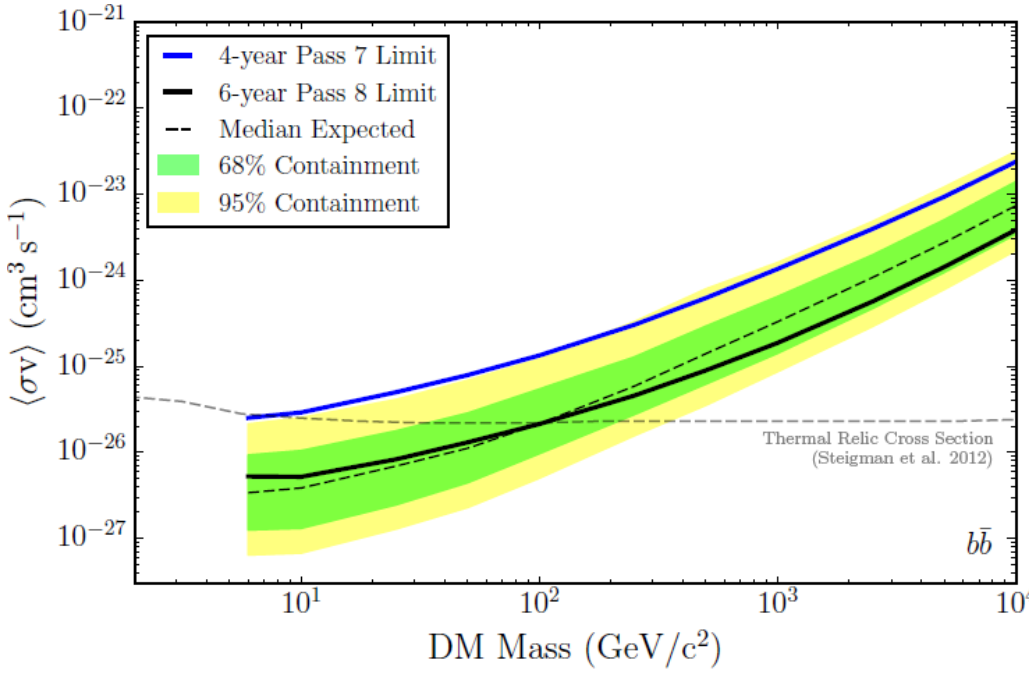
- The results strongly depend on propagation (diffusion) model and DM density profiles

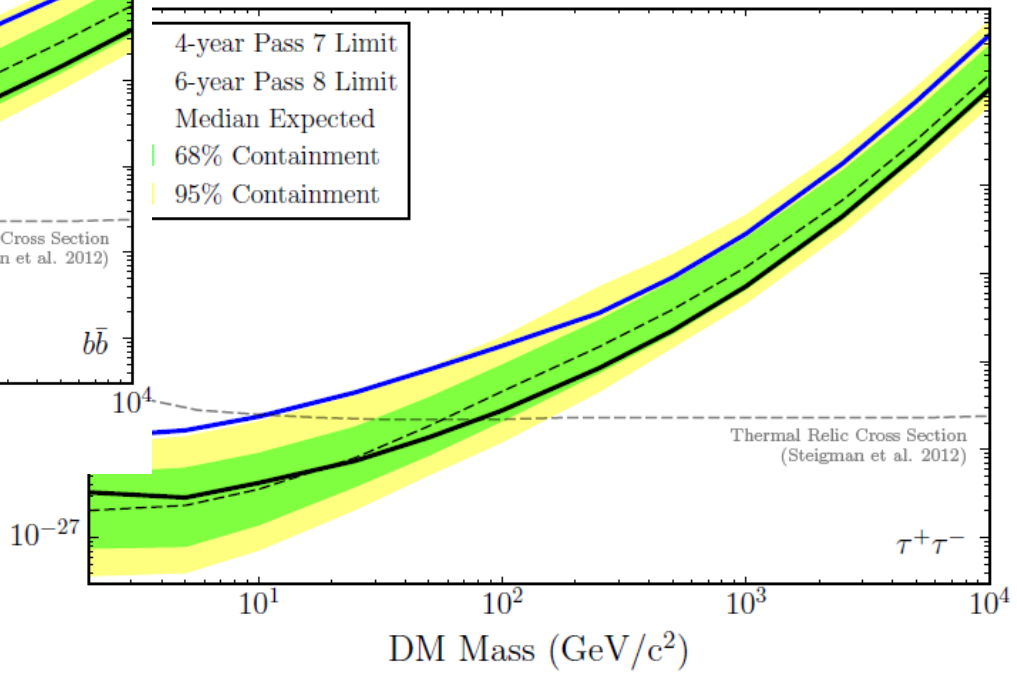
§ § indirect detection: status

- photon (diffuse or line)
- diffuse

dSph@Fermi-LAT

GC excess (later...)





§§ indirect detection: status

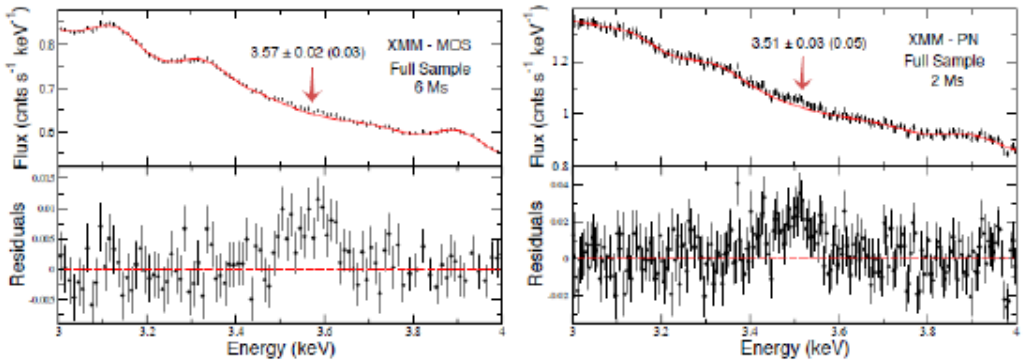
- photon (diffuse or line)
- Line signal(?)

130 GeV @ Fermi-LAT [claimed 2012 and denied 2013]

511 keV @ INTEGRAL [2003~]

sterile neutrino, Q-ball,...

3.5 keV @ XMM-NEWTON [2014~]



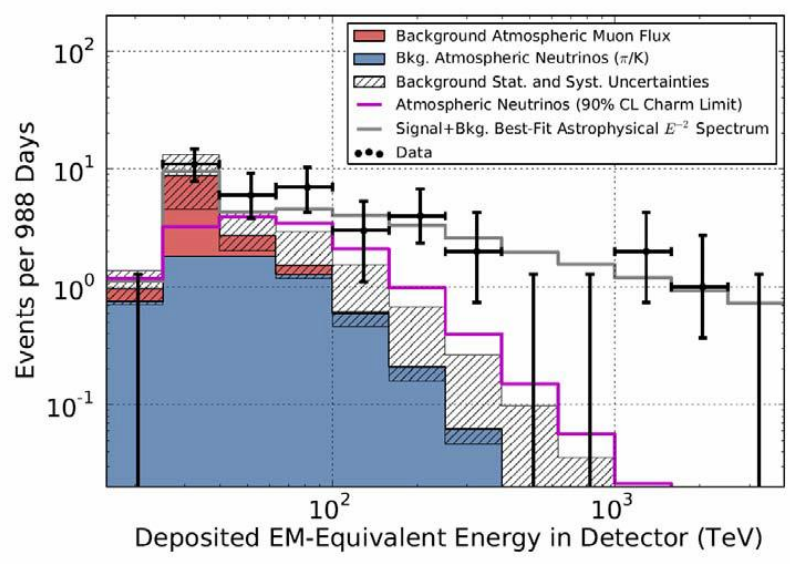
sterile neutrino, axion-like particle,

gravitino or axino with RpV, ...

§ § indirect detection: status

- neutrino

  a few PeV events @ IceCube [2013~]



DM annihilation is not available (too small flux)

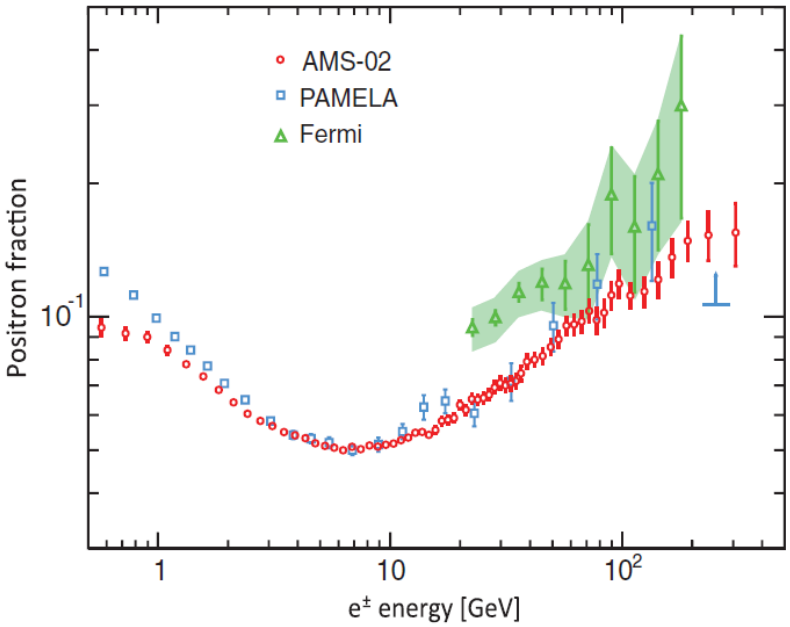
RH neutrino decay, Heavy A decay, ...

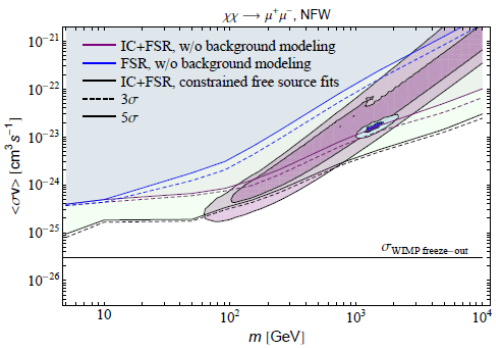
GRB, AGN, ...

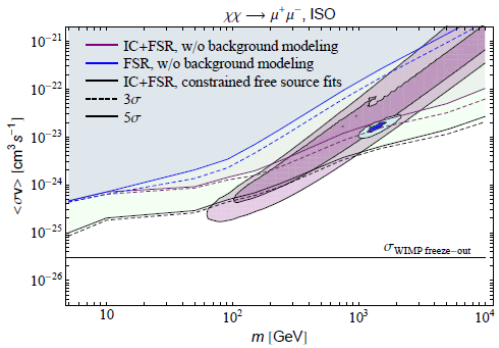
§ § indirect detection: status

- electron / positron

  positron excess @ PAMELA [2008~] and AMS-02







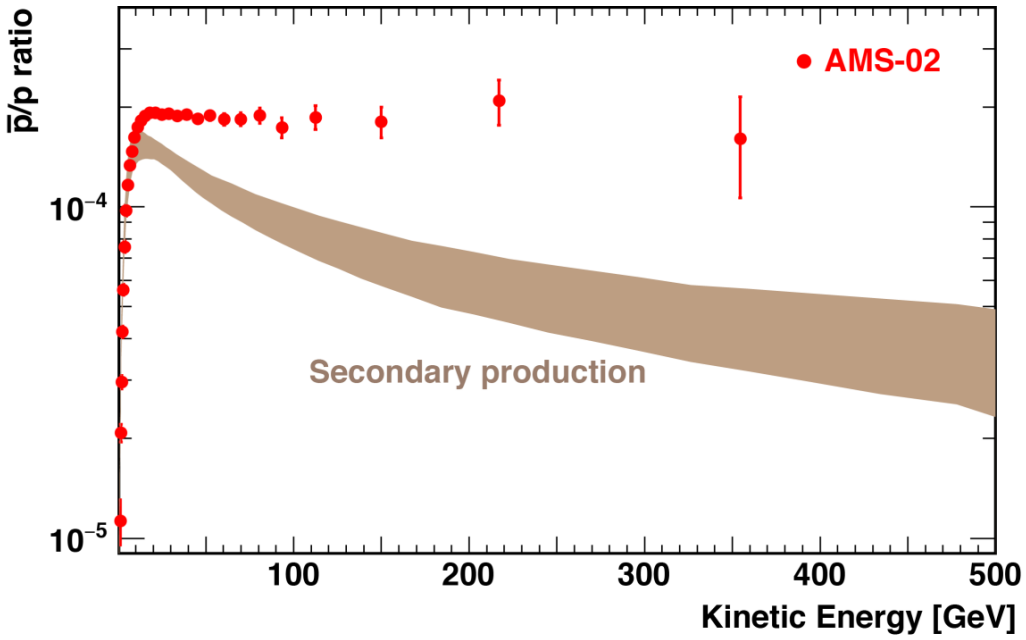
- DM annihilation interpretation is hardly consistent.
- DM decay is viable but getting constrained too [1501.05932]

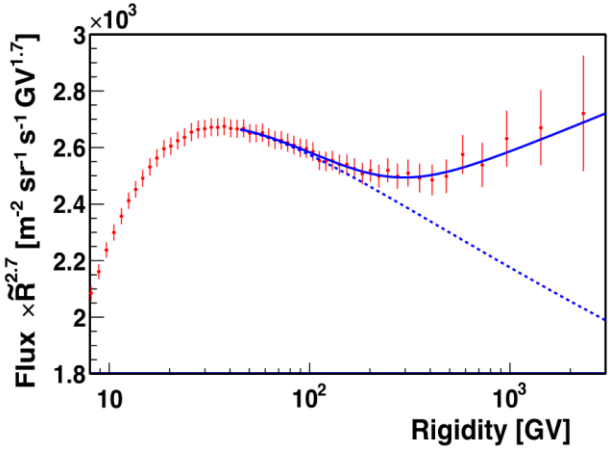
Whole astrophysical (secondary, pulsar) interpretation (1402.0321)

§ § indirect detection: status

- anti-particles (anti-proton)

New data from AMS-02 [AMS Days at CERN (15Apri 2015)]





A Strange feature: rise of helium too.

Being consistent with astrophysical (1504.04276, 1504.04604)

§ Galactic center (GC) gamma ray excess

§ Galactic center (GC) gamma ray excess

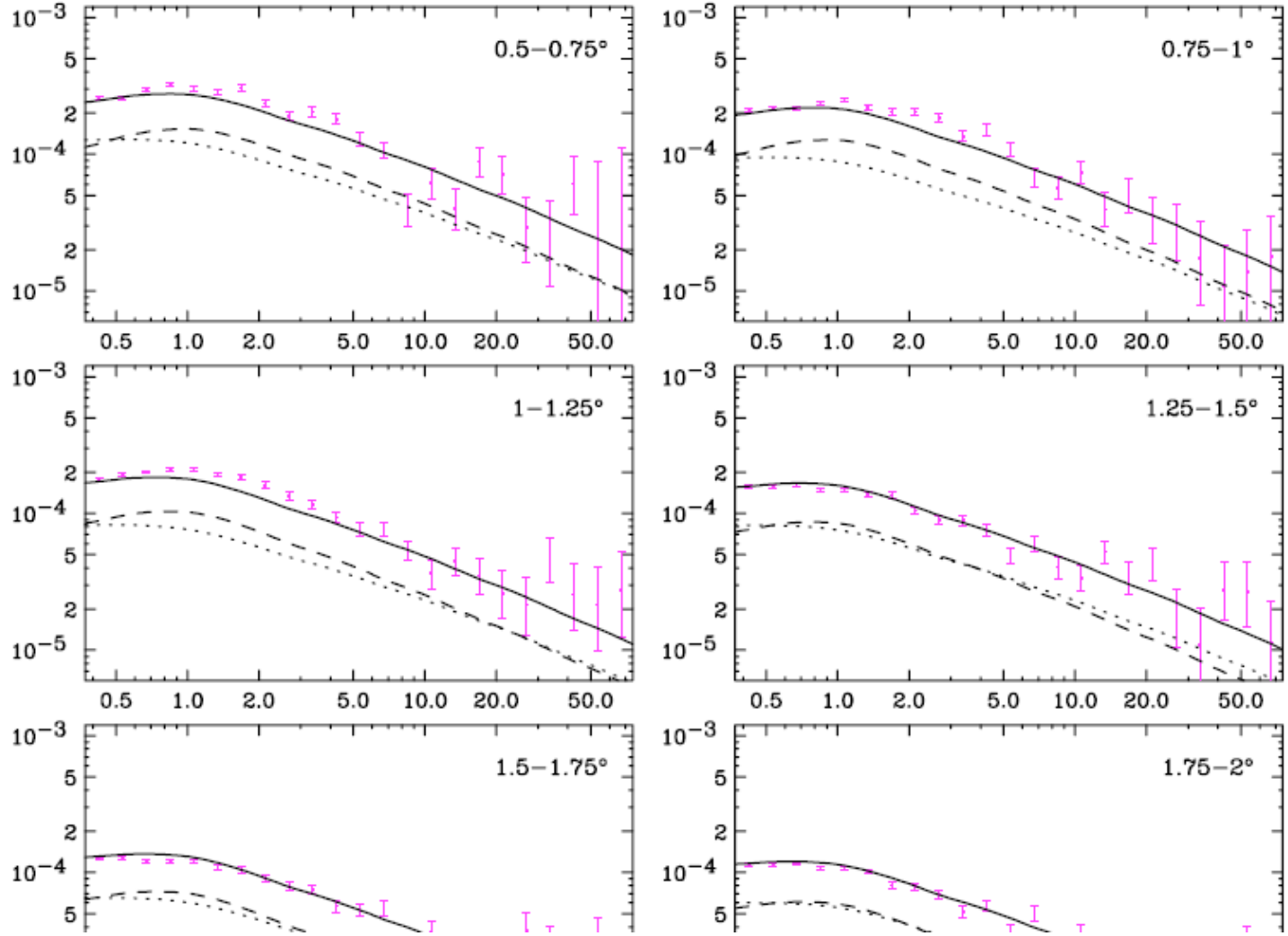
- Photons from GC [Hooper and Goodenough (2010)]

between 1.25° and 10° from the Galactic Center is well described by a the processes of decaying pions produced in cosmic ray collisions with gas, and the inverse Compton scattering of cosmic ray electrons in both the disk and bulge of the Inner Galaxy, along with gamma rays from known points sources in the region. The observed spectrum and morphology of the emission within approximately 1.25° ($\sim$ 175 parsecs) of the Galactic Center, in contrast, departs from the expectations for by these

...

which peaks at energies between 1-4 GeV (in E^2 units), can be well fit by a 7-10 GeV dark matter particle annihilating primarily to tau leptons with a cross section in the range of $\langle \sigma v \rangle = 4.6 \times 10^{-27}$ to 5.3×10^{-26} cm^3/s, depending on how the dark matter distribution is normalized. We also discuss

§ Galactic center (GC) gamma ray excess



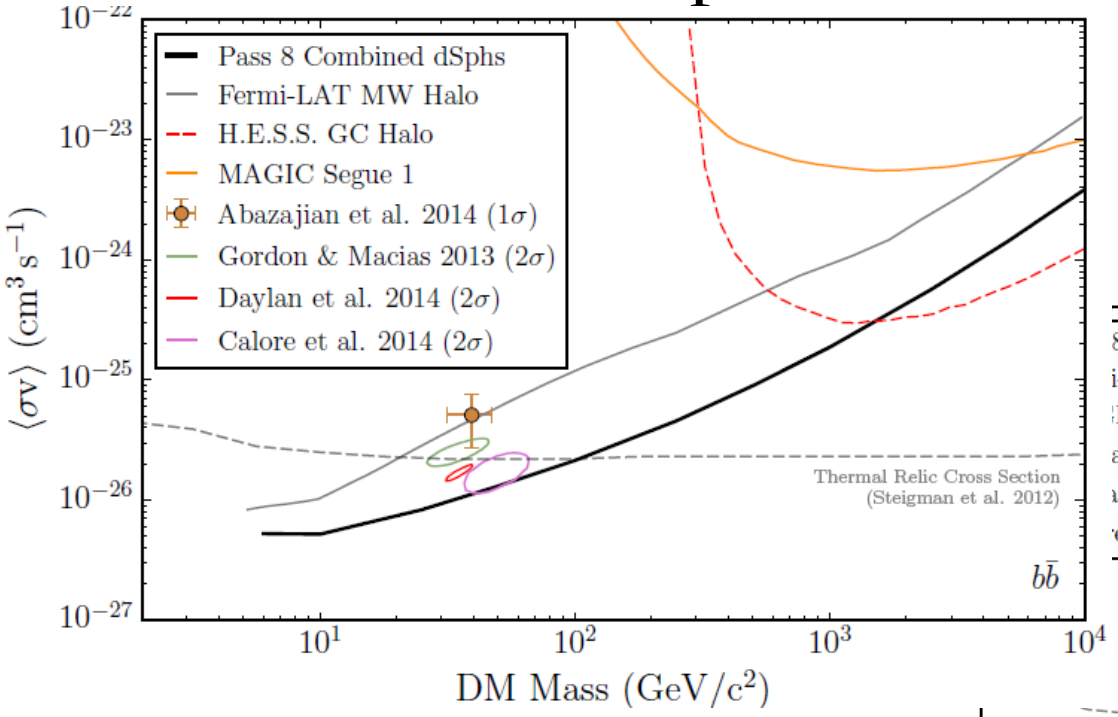
Good fit with?

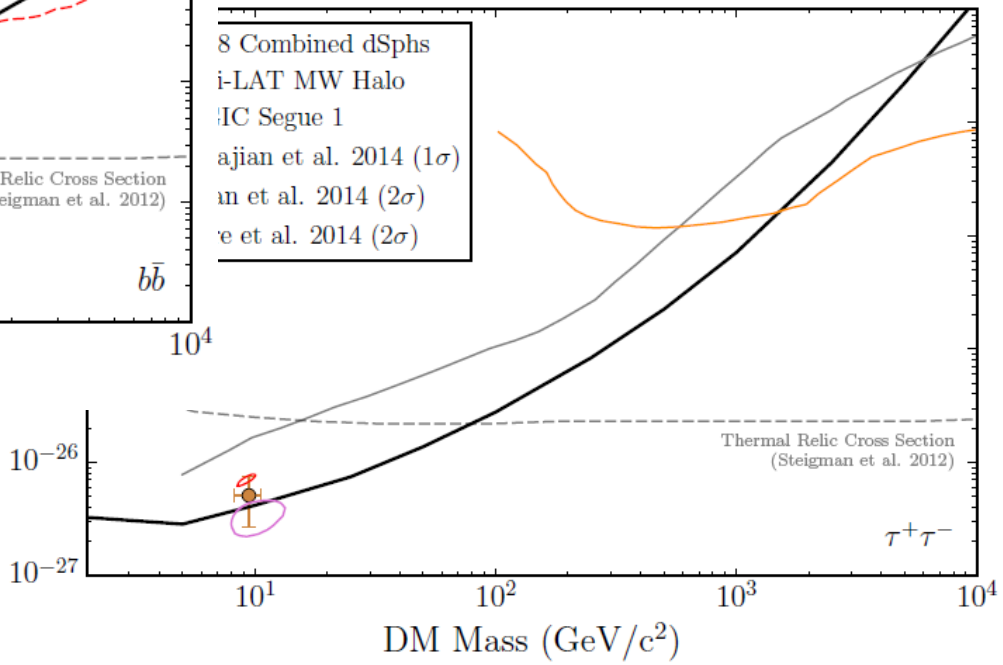
Analysis papers say

- GC [Goodenough and Hooper (2010)]
  7-10 GeV $\tau\ \tau$; (0.46 to 5.3)×10^-26 cm^3/s
- GC [Hooper and Linden (2011)]
  25-45GeV b b-bar or 7-12 GeV $\tau\ \tau$;
  ~ (0.6~0.7)×10^-26 cm^3/s
- GC [Abazajian and Kaplinghat (2012)]
  10GeV-1TeV b b-bar or 10-30 GeV $\tau\ \tau$
- …

§ § Galactic Center excess

Dark matter interpretation





the latest constraints

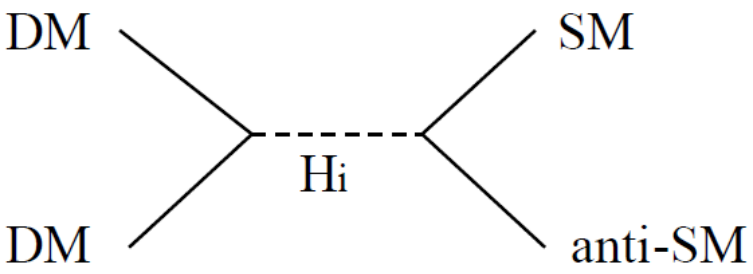
from dSph data [Fermi-LAT Coll. (1503.02641)]

§ GC excess from two Higgs doublet portal DM

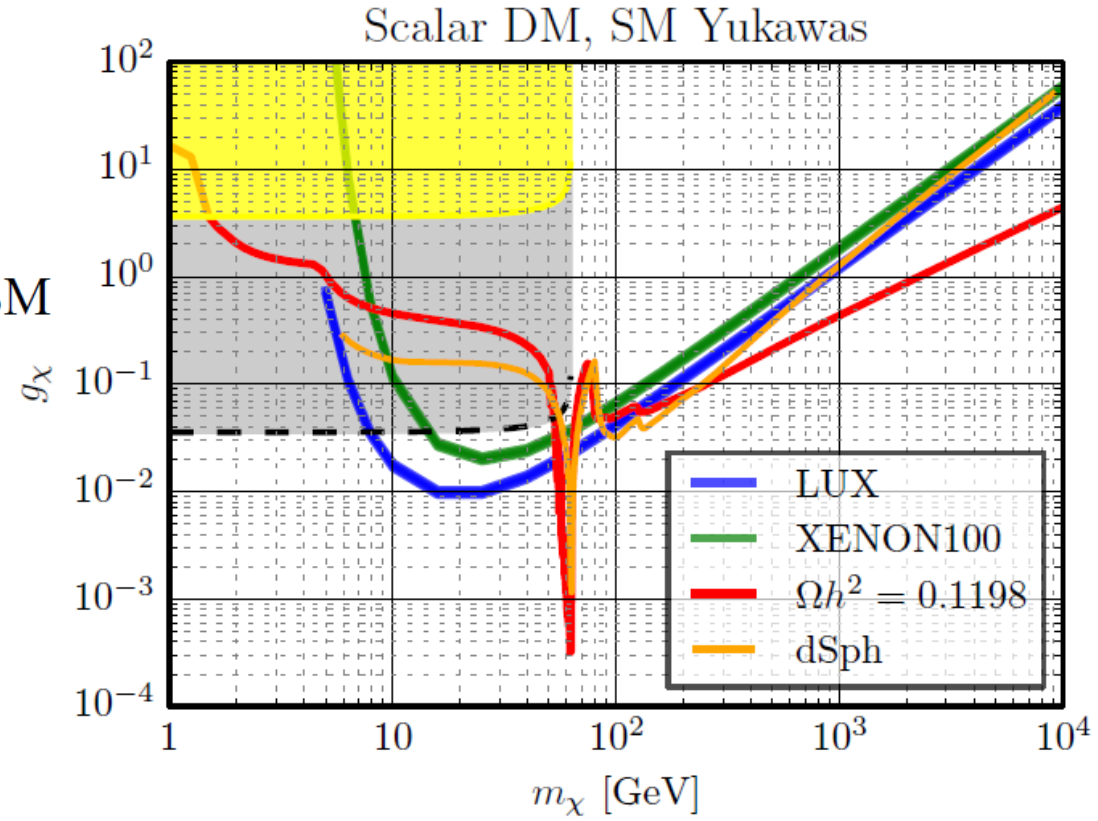
§ Higgs portal dark matter

McDonald (1994),Burgess et al, ...

$$\mathcal{L}_S = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial\phi)^2 - \frac{M_S^2}{2}\phi^2 - \frac{c_S}{2}|H|^2\phi^2 - \frac{d_S}{4!}\phi^4$$



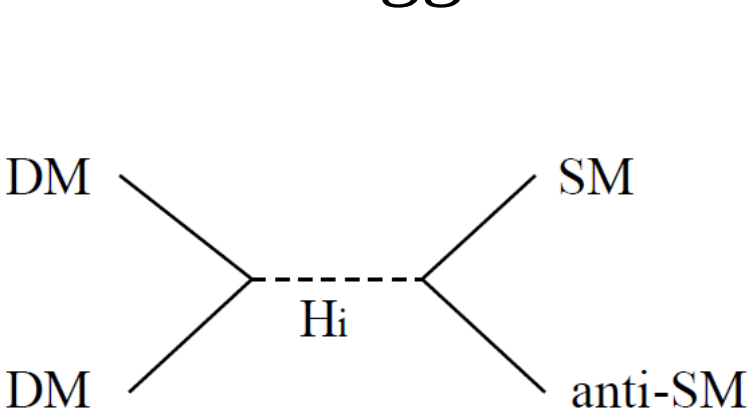
[Bishara et al 1504.04022]

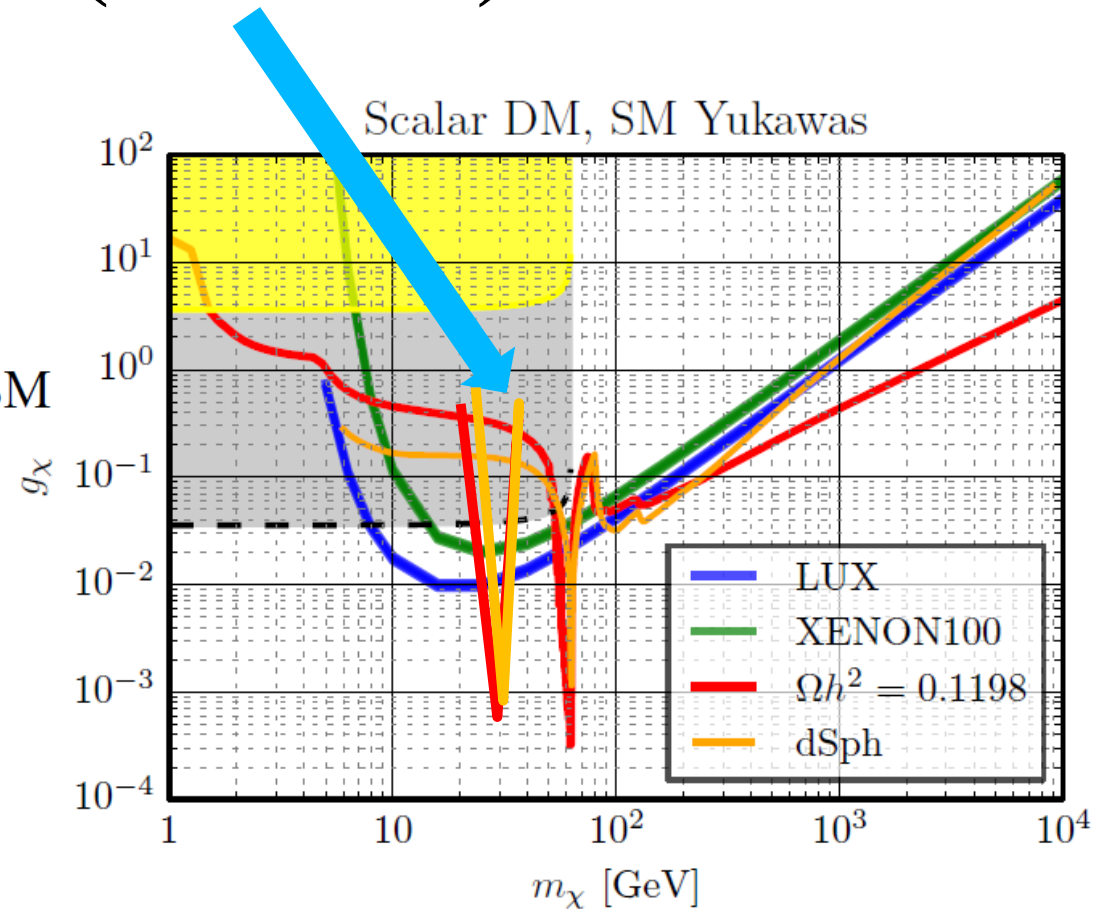


§ § How to realize desired DM mass and annihilation modes

- Two Higgs doublet model

Extra Higgs bosons (mH~2m$_{DM}$) contribution





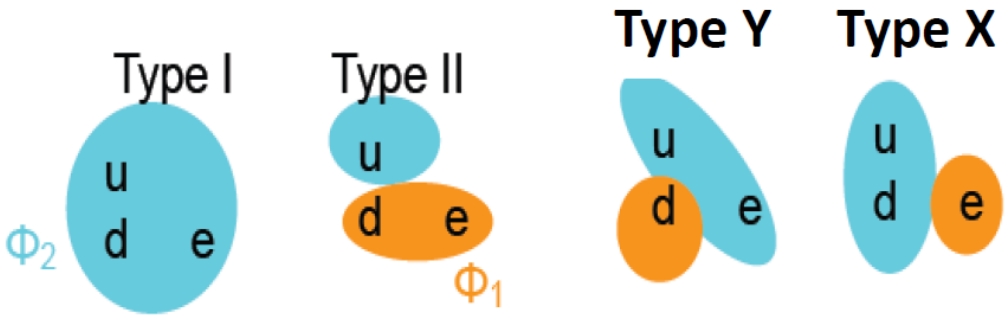
§ § How to realize desired DM mass and annihilation modes

Those DM properties are determined by **mediator**!

- Model

$$
\begin{aligned}
V \;=\; & -\mu_1^2|\Phi_1|^2 - \mu_2^2|\Phi_2|^2 - (\mu_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\
& +\lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \;+ \left\{\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right\} \\
& +\frac{1}{2}\mu_\phi^2\phi^2 + \lambda_\eta\phi^4 + (\sigma_1|\Phi_1|^2 + \sigma_2|\Phi_2|^2)\frac{\phi^2}{2}.
\end{aligned}
$$

$$
\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}
$$



§ § $\tau^+\tau^-$ annihilation case possible?

- ~10 GeV DM can kinematically annihilate into b-quark
- If large coupling to τ
- Favored σv is several times smaller than the canonical…
- If near resonance, significant p-wave, co-annihilation…

§ § $\tau^+\tau^-$ annihilation case possible?

- ~10 GeV DM can kinematically annihilate into b-quark
- If large coupling to τ
- Favored σv is several times smaller than the canonical…
- If near resonance

… another Higgs boson

in THDM

Type-X

(aka. lepton specific)

§§ $\tau^+\tau^-$ annihilating DM
: Type-X two Higgs portal DM

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§ § τ+τ- annihilation case possible? : Type-X two Higgs portal DM

studied for ν-mass [Aoki et al (2009)] and CDMS [Aoki et al (2010)]

- Higgs coupling

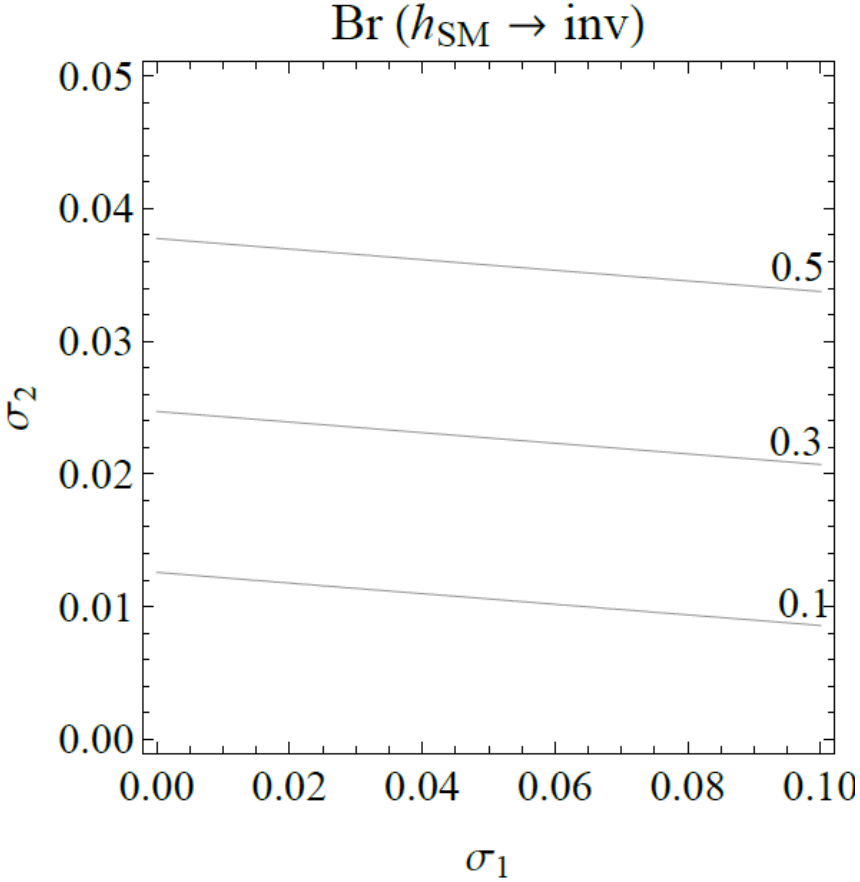
$$\mathcal{L}_\sigma \supset -\frac{\sigma_1 \cos\alpha\cos\beta + \sigma_2 \sin\alpha\sin\beta}{2} vH\phi^2 - \frac{-\sigma_1 \sin\alpha\cos\beta + \sigma_2 \cos\alpha\sin\beta}{2} vh\phi^2$$

- Amplitude

$$\overline{|\mathcal{M}(\phi\phi \to \tau\bar{\tau})|}^2 = \left| \frac{(-\sigma_1 \sin\alpha\cos\beta + \sigma_2 \cos\alpha\sin\beta)}{s - m_h^2 + i m_h \Gamma_h} \frac{\sin\alpha}{\cos\beta} - \frac{(\sigma_1 \cos\alpha\cos\beta + \sigma_2 \sin\alpha\sin\beta)}{s - m_H^2 + i m_H \Gamma_H} \frac{\cos\alpha}{\cos\beta} \right|^2 \times m_\tau^2 (s - 4m_\tau^2). \quad \text{(A9)}$$

§ § τ+τ- annihilation case possible? : Type-X two Higgs portal DM

- Invisible decay Br. of SM-like Higgs



$\sin(\beta-\alpha) = 1$

$m_h = 125$ GeV

$\tan\beta = 5$

$$\Gamma_h^{(\mathrm{inv})} = (-\sigma_1 \sin\alpha\cos\beta + \sigma_2 \cos\alpha \sin\beta)^2 \times \frac{v^2}{32\pi m_h}\sqrt{1-\frac{4m_\phi^2}{m_h^2}},$$

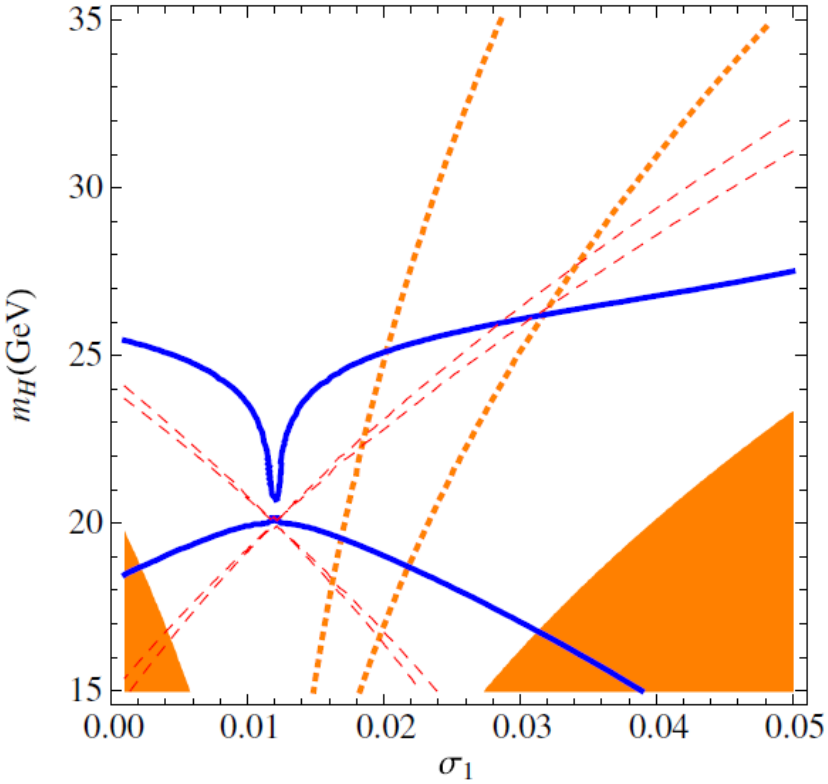
§ § τ+τ- annihilation case possible? : Type-X two Higgs portal DM

- DM calculation for 10 GeV DM
- (0.5~0.6)×10^-26 cm^3/s
- XENON100 and 1T

An example ; $\sigma_2 = 0.012$

↕

Br(h→inv) ≈ 10%



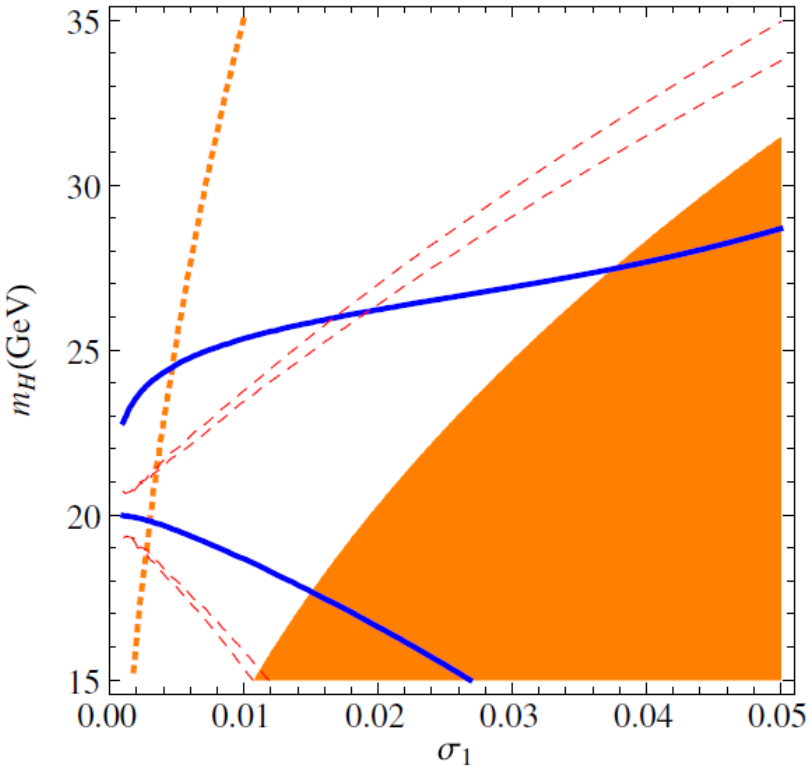
§ § τ+τ- annihilation case possible? : Type-X two Higgs portal DM

- DM calculation for 10 GeV DM
- (0.5~0.6)×10^-26 cm^3/s
- XENON100 and 1T

An example ; $\sigma_2 = 0.0$

↕

Br(h→inv) ≈ negligible



§ § b b-bar annihilating DM : Type-II two Higgs portal DM

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PHYSICAL REVIEW D **90,** 083523 (2014)

Galactic Center gamma ray excess from two Higgs doublet portal dark matter

Nobuchika Okada*

Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487, USA

Osamu Seto†

Department of Life Science and Technology, Hokkai-Gakuen University, Sapporo 062-8605, Japan

(Received 19 August 2014; published 21 October 2014)

We consider a simple extension of the type-II two-Higgs-doublet model by introducing a real scalar as a candidate for dark matter in the present Universe. The main annihilation mode of the dark matter particle

§ § b b-bar annihilating DM : Type-II two Higgs portal DM

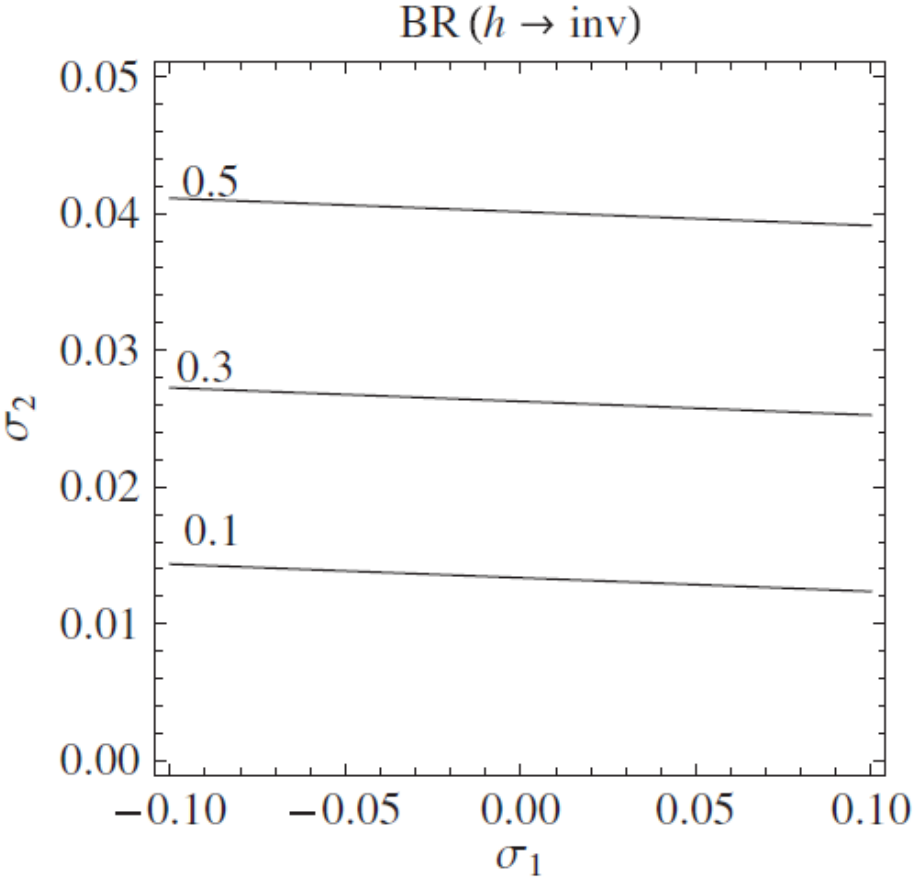
- Model
- Scalar potential is same
- Yukawa couplings

$$\mathcal{L}_Y^{\text{Quarks}} \supset \frac{m_{u^i}\sin\alpha}{v\sin\beta}H\bar{u}^i u^i + \frac{m_{u^i}\cos\alpha}{v\sin\beta}h\bar{u}^i u^i + \frac{m_{d^i}\cos\alpha}{v\cos\beta}H\bar{d}^i d^i - \frac{m_{d^i}\sin\alpha}{v\cos\beta}h\bar{d}^i d^i,$$

$$\mathcal{L}_Y^{\text{Leptons}} \supset \frac{m_{\ell^i}}{v}\frac{\cos\alpha}{\cos\beta}H\bar{\ell}^i\ell^i - \frac{m_{\ell^i}}{v}\frac{\sin\alpha}{\cos\beta}h\bar{\ell}^i\ell^i.$$

§ § b b-bar annihilating DM : Type-II two Higgs portal DM

- Invisible decay Br. of SM-like Higgs



$\sin(\beta-\alpha) = 1$

$m_h = 125$ GeV

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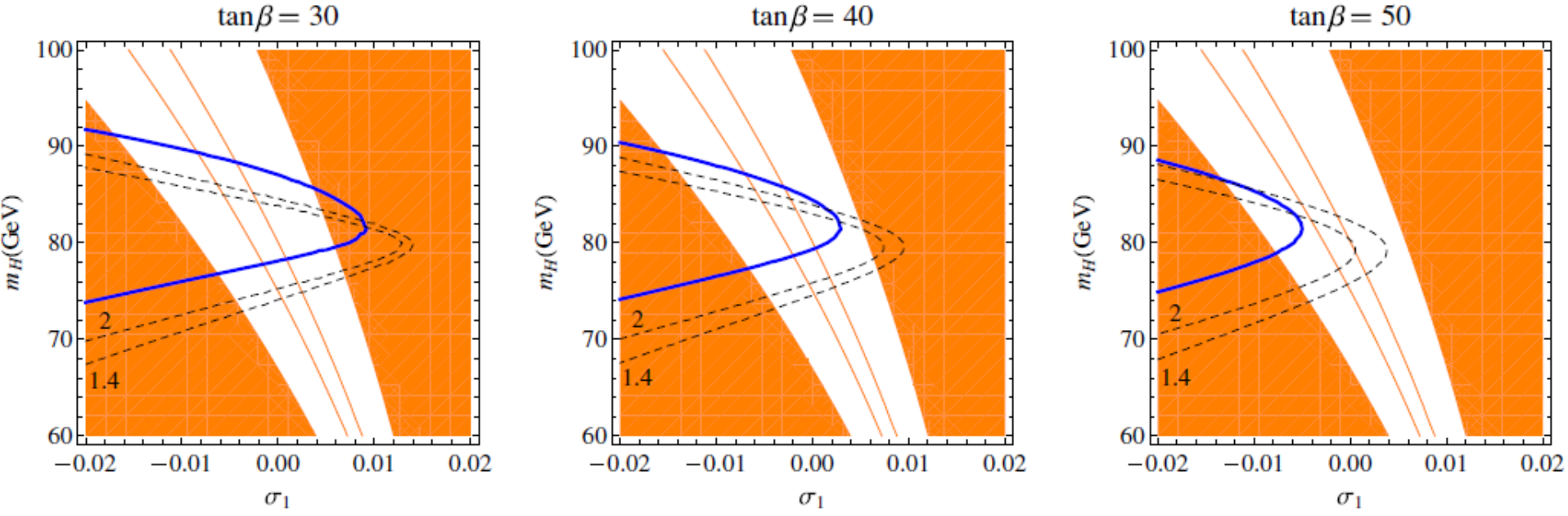
$$\Gamma_h^{(\mathrm{inv})} = (-\sigma_1 \sin\alpha\cos\beta + \sigma_2 \cos\alpha \sin\beta)^2 \times \frac{v^2}{32\pi m_h}\sqrt{1-\frac{4m_\phi^2}{m_h^2}},$$

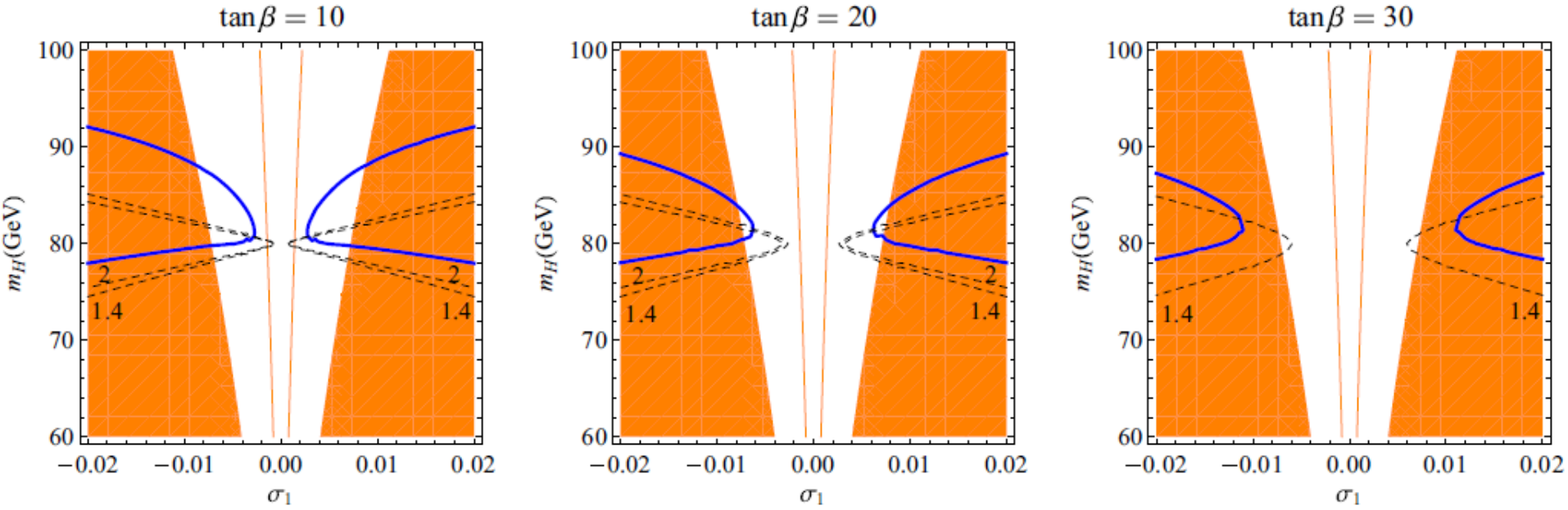
§ § b b-bar annihilating DM : Type-II two Higgs portal DM

- 40GeV DM, $\sigma_2 = 0.02 \Leftrightarrow$ Br(h→inv) ≈ 20%
- LUX and XENON1T



§ § b b-bar annihilating DM : Type-II two Higgs portal DM

- 40GeV DM, $\sigma_2 = 0 \Leftrightarrow$ Br(h→inv) ≈ negligible
- LUX and XENON1T



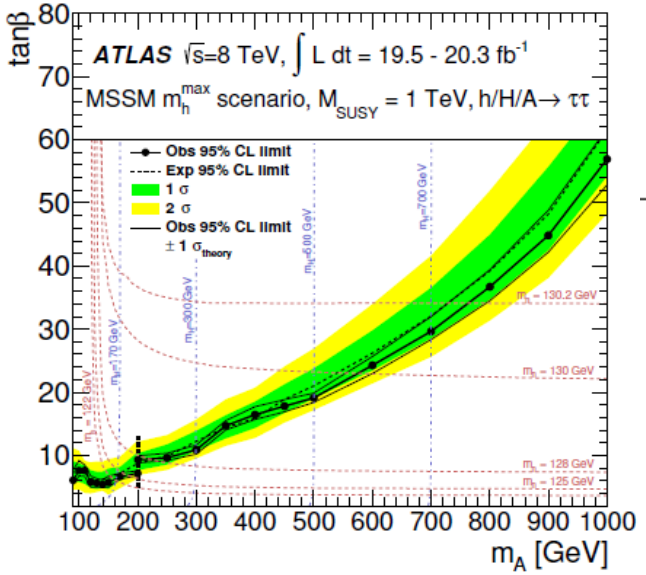
§ § b b-bar annihilating DM : Type-II two Higgs portal DM

- $\sigma_2 = 0.02 \Leftrightarrow$ Br(h→inv) ≈ 20%
  available @ large tanβ
- $\sigma_2 = 0 \Leftrightarrow$ Br(h→inv) ≈ negligible
  available @ small tanβ

- Correlation between Br(h→inv) and tanβ

§ § b b-bar annihilating DM : Type-II two Higgs portal DM: Sequel

- ``H → ττ constraint is stringent'' by Tsumura



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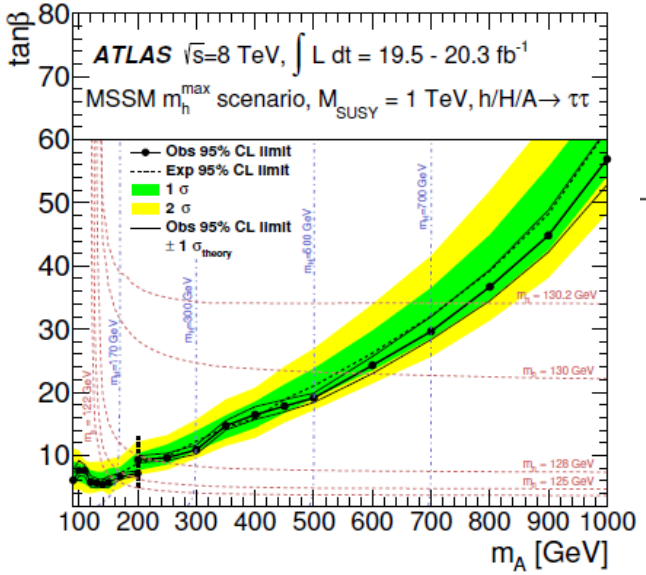
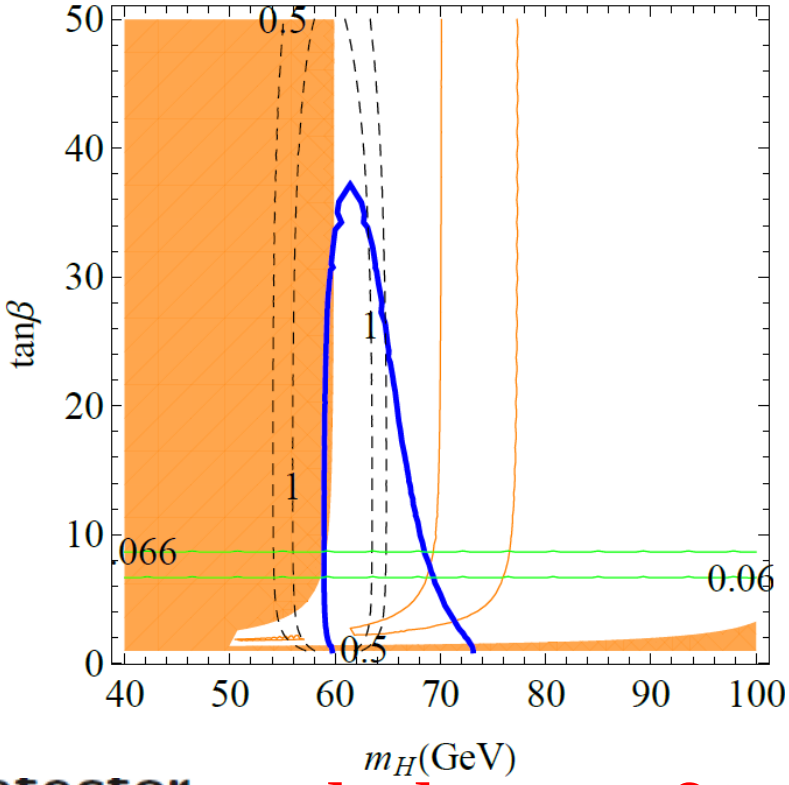
Search for neutral Higgs bosons of the minimal supersymmetric standard model in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

§ § b b-bar annihilating DM : Type-II two Higgs portal DM: Sequel

- ``H → ττ constraint is stringent'' by Tsumura



P



Search for neutral Higgs bosons

supersymmetric standard model

$\sqrt{s} = 8$ **TeV with the ATLAS detector**

only low tanβ?

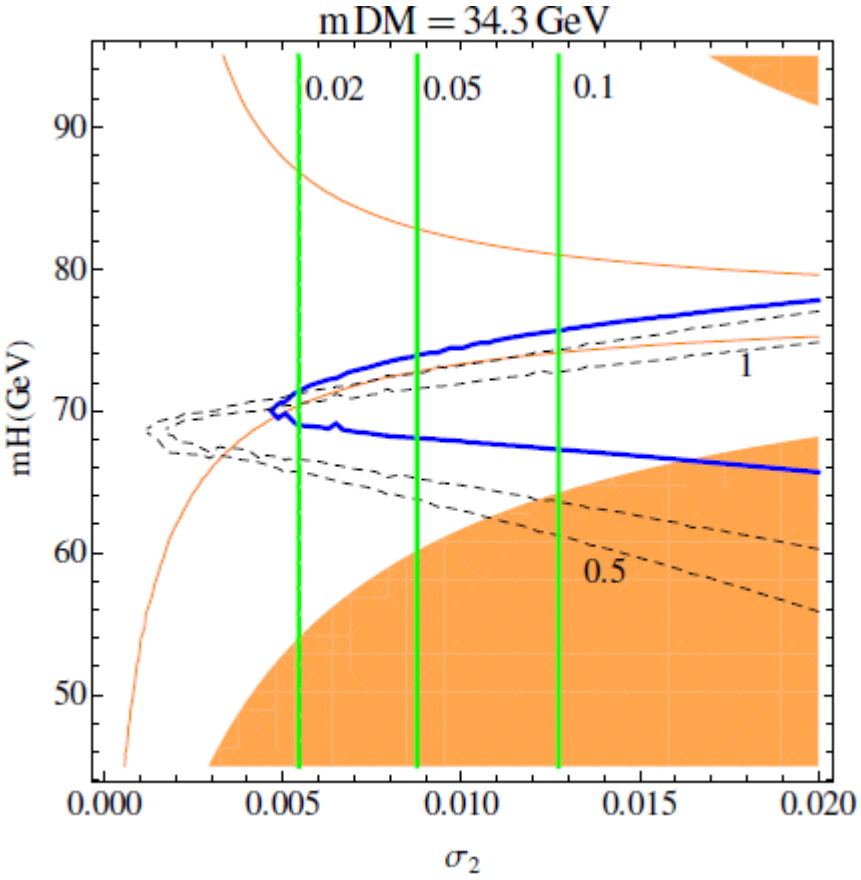
§ § b b-bar annihilating DM

: Type-Y two Higgs portal DM

in prep.

§ § b b-bar annihilating DM : Type-Y two Higgs portal DM

- DM and SM Higgs constraints and prospects



LUX and XENON1T

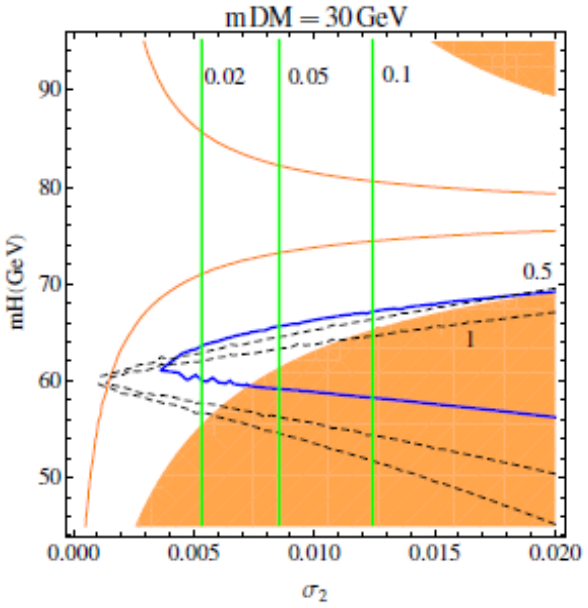
Ωh^2

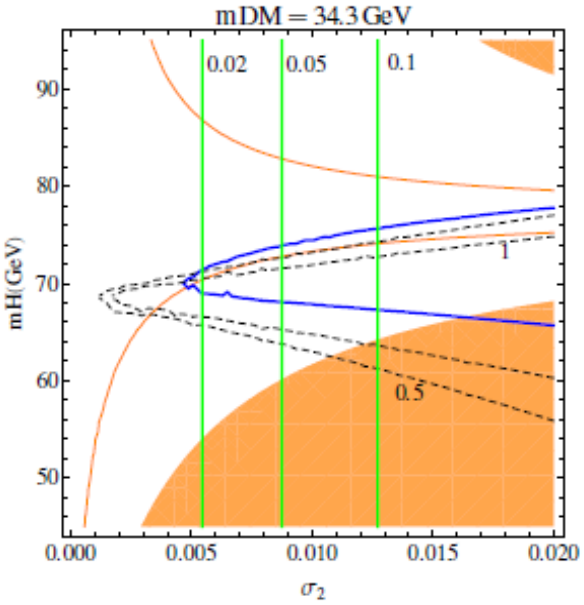
indirect in 10^{-26} cm^3/s

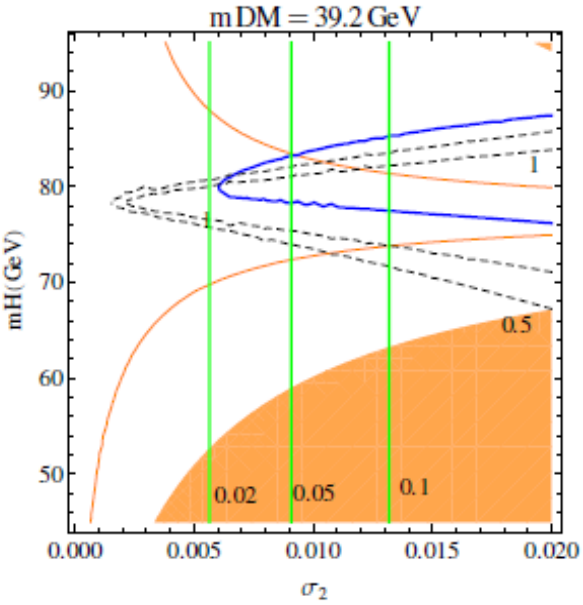
SM Higgs invisible

§ § b b-bar annihilating DM : Type-Y two Higgs portal DM

- DM and SM Higgs constraints and prospects



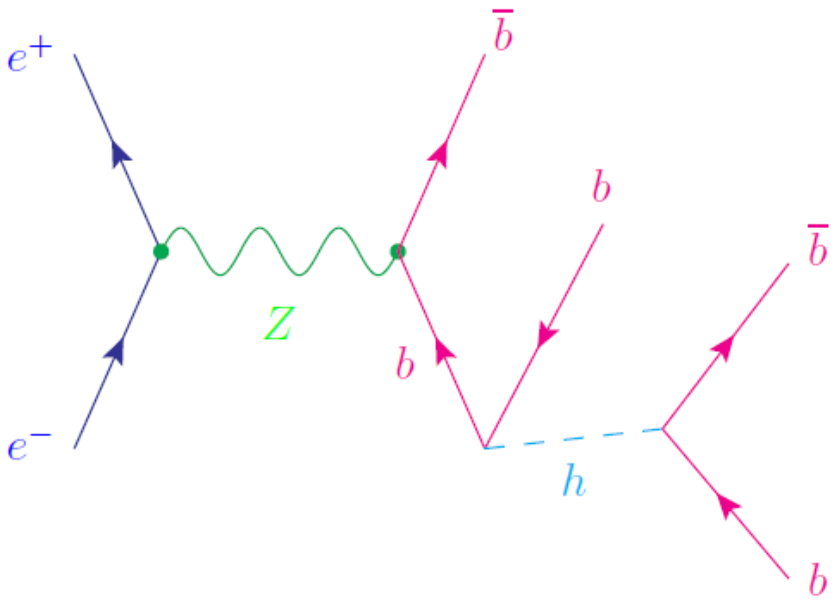




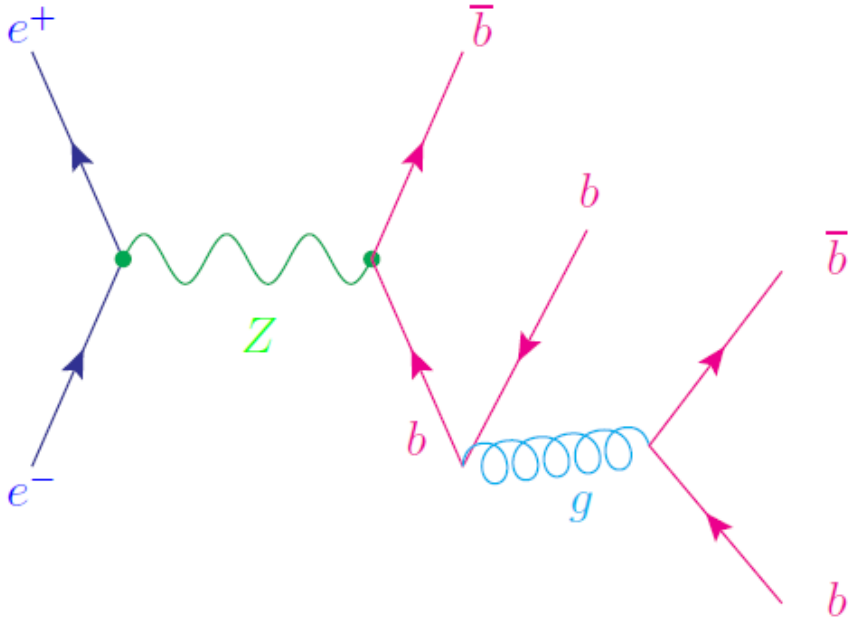
§ § b b-bar annihilating DM : Type-Y two Higgs portal DM

- Extra Higgs boson *H* discovery prospects @ ILC

H production

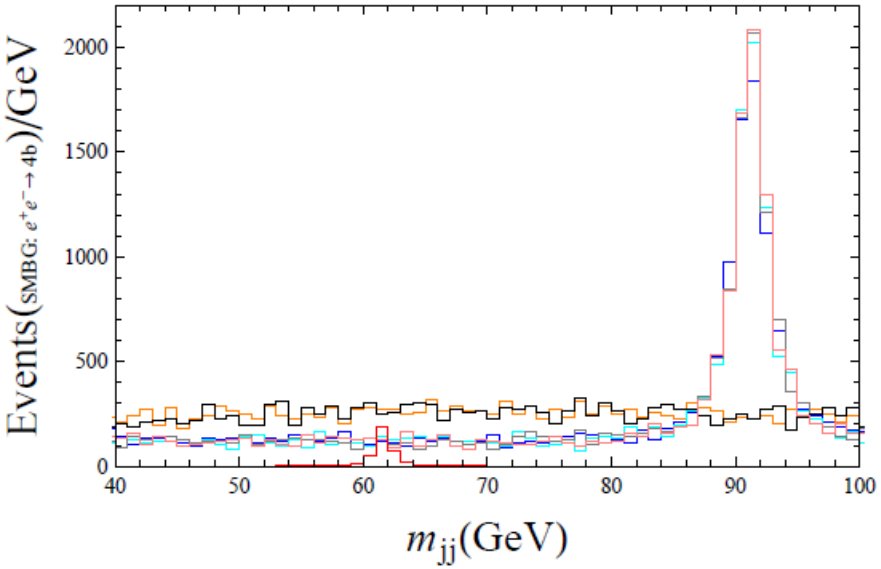


SM background

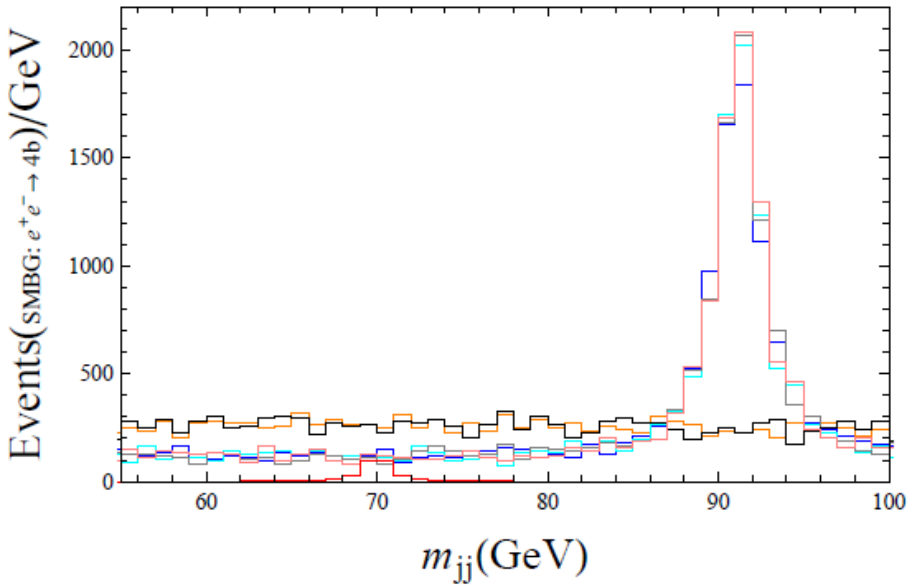


§ § b b-bar annihilating DM : Type-Y two Higgs portal DM

- Extra Higgs boson *H* discovery prospects @ ILC
- Event count for tanβ=20
- $\sqrt{s}$ = 250 GeV, $\mathcal{L}$ = 500/fb



mH ≅ 61.6 GeV



70 GeV

§ § b b-bar annihilating DM : Type-Y two Higgs portal DM

- Extra Higgs boson *H* discovery prospects @ ILC
- Significance

	$m_h(\mathrm{GeV})$	S
Case-a	61.6	4.4-σ
$\lvert m_{jj/bb} - m_h \rvert \leq 10$ GeV	70	3.4-σ
	80	2.5-σ
Case-b	61.6	5.8-σ
$\lvert m_{jj/bb} - m_h \rvert \leq 5$ GeV	70	4.4-σ
	80	3.3-σ

§ Summary

- Extra component in gamma ray flux from GC may be explained by Higgs portal scalar dark matter.

- Specific particle models have been proposed

1. Type-X THDM + 10 GeV DM ($\tau\tau$)
2. Type-II THDM + (30~40) GeV DM (bb)

 $H \rightarrow \tau\tau$ constraint

3. Type-Y THDM + (30~40) GeV DM (bb)