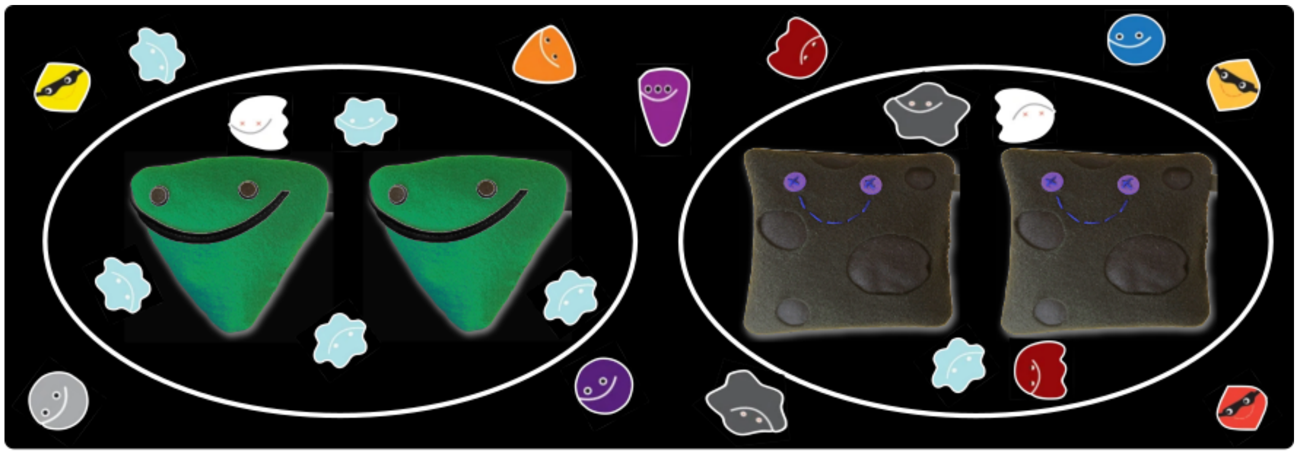
Electroweak-Interacting dark matter - Window to BSM@TeV -



Junji Hisano (KMI, Nagoya)

Workshop "Quarkonia meet Dark Matter”

15-18 June 2021, Kavli IPMU, Kashiwa, Japan

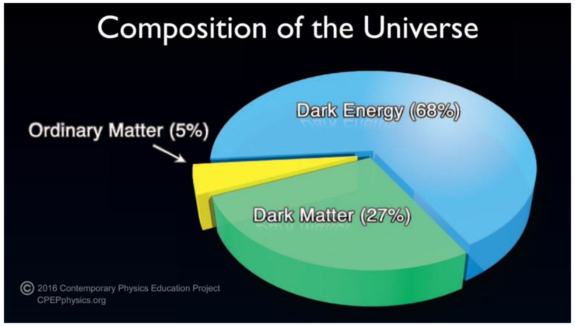
Agenda

- Introduction
- Wino/Higgsino DM in SUSY SM
- Pair annihilation of Heavy EW-int. DM
- Line gamma rays from GC of Wino/Higgsino
- Direct Detection of Wino/Higgsino
- Electroweakly-interacting vector DM
- Summary

Introduction

Nature of Dark Matter is still a big mystery.

- New DM particles
- New symmetries
- New interactions
-

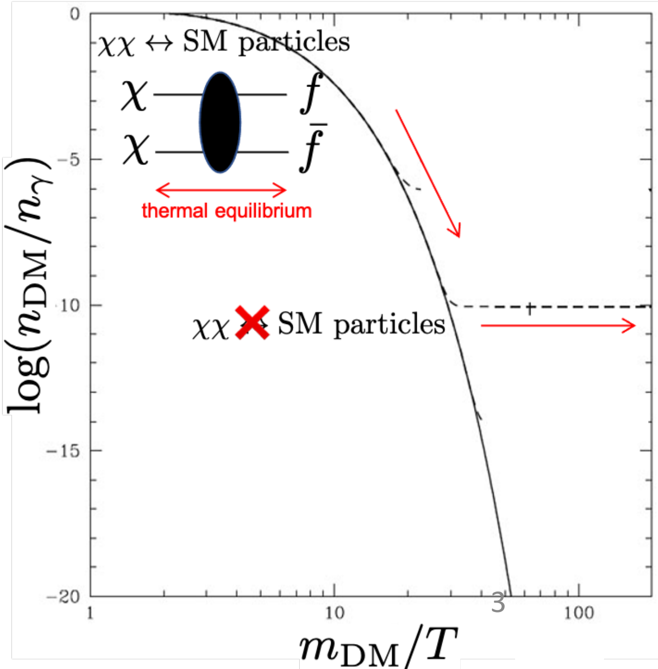


Weakly-Interacting Massive particles (WIMPs)

Thermal relic abundance hypothesis

$$\Omega_{\rm DM}h^2 \simeq 0.1 \times \frac{3\times 10^{-26}{\rm cm}^3/{\rm sec}}{\langle \sigma_{\rm ann} v\rangle}$$

The mass is typically O(100)GeV to O(1)TeV.

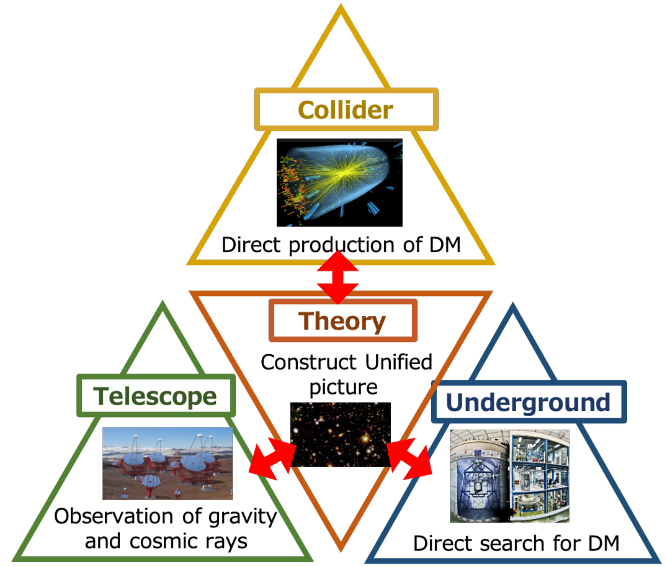


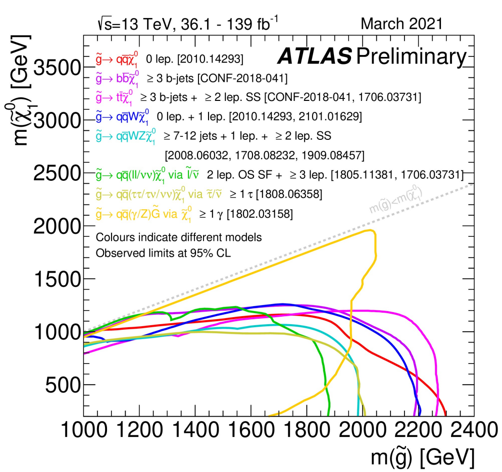
Introduction

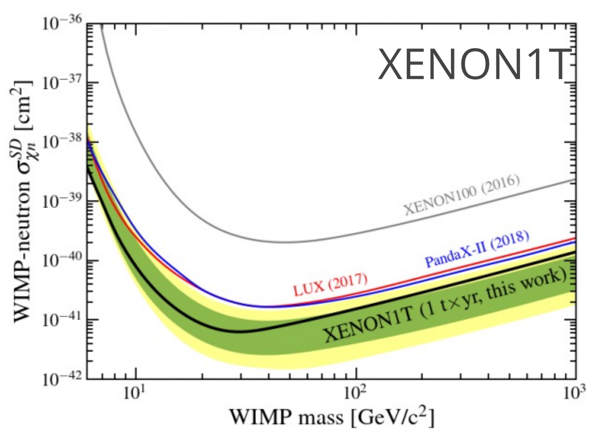
WIMP DM are being searched for

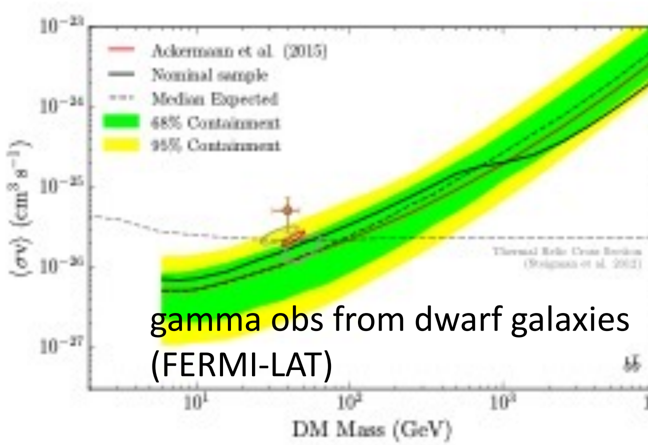
1) Direct production at LHC
2) Direct detection in underground
3) Indirect detection by observing gamma rays from universe.

However, null results are fund.









Electroweak-Interacting DM

BSM Models with electroweakly charged stable particles

$$\sigma v \sim \frac{\pi \alpha_2^2}{m^2} = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s} \times \left(\frac{2\ \mathrm{TeV}}{m} \right)^2$$

- Supersymmetric standard model (SUSY SM)
  Wino (I=1, S=1/2), Higgsino (I=1/2, S=1/2)
- Extra-dimensional models
  Kaluza-Klain weak gauge bosons (I=1, S=1)
- Neutrino mass models
  - Scotogenic models
- Extended Higgs sector models
  - Inert Higgs models
- Minimal dark matter models
  - automatically stable fermion (I=2, S=1/2)
- …………

Wino/Higgsino DM in SUSY SM

SUSY SM before LHC

Energy scale

SUSY GUTs ~ 10^{16} GeV

SUSY SM @ < O(1) TeV

Standard model

Motivation of Low-scale SUSY (<~1TeV):

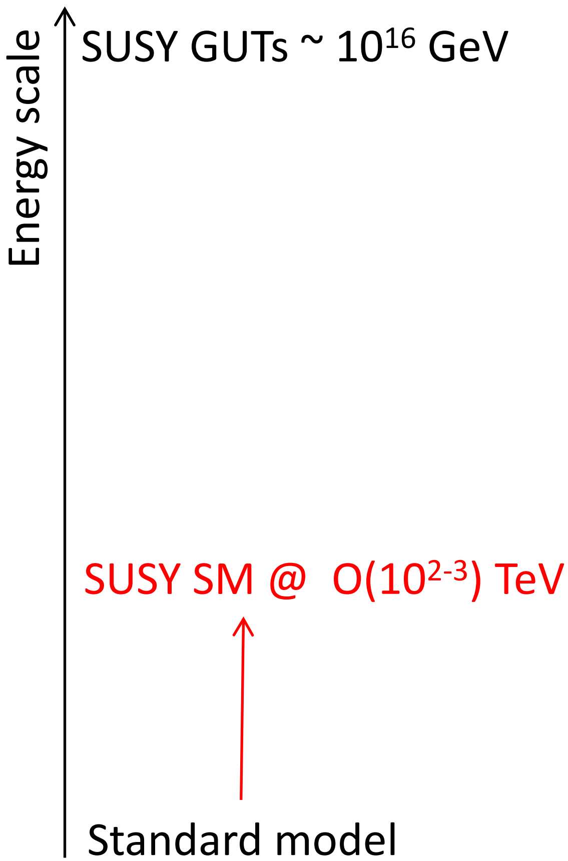
- Hierarchy problem
- WIMP dark matter (R parity)
- Gauge coupling unification (SUSY GUTs)

Shortcoming of SUSY :

- FCNC and CP problems
- Gravitino problem in nucleosynthesis
- D=5 proton decay in SUSY GUTs
- 125GeV Higgs mass (after 2012)

Wino/Higgsino DM in SUSY SM

SUSY SM after LHC



Motivation of mini-split SUSY (~O($10^{2\text{-}3}$) TeV).

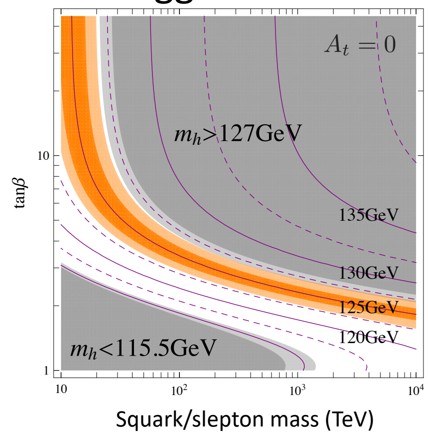
- Solution of following problems
  - FCNC and CP problems
  - Gravitino problem in nucleosynthsis
  - D=5 proton decay in SUSY GUTs
  - 125GeV Higgs mass
- Easy model building of SUSY breaking by anomaly mediation
- WIMP dark matter (R parity)
  Wino/Higgsino
- Improved gauge coupling unification

Phenomenologically successful model ! (Except for Naturalness)

Wino/Higgsino DM in SUSY SM

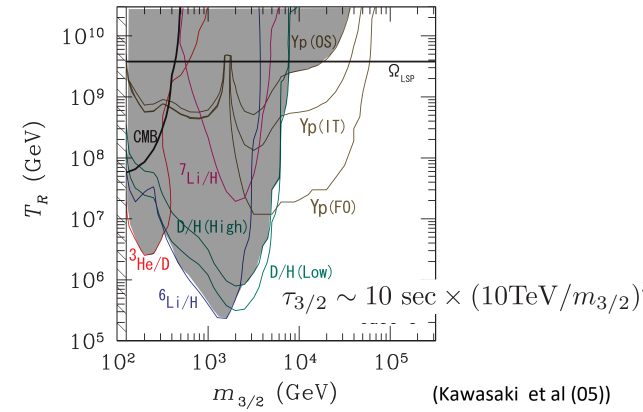
List of strong constraints on SUSY SM

Higgs mass



(Ibe, Matsumoto, Yanagida (12))

Gravitino problem in BBN



(Kawasaki et al (05))

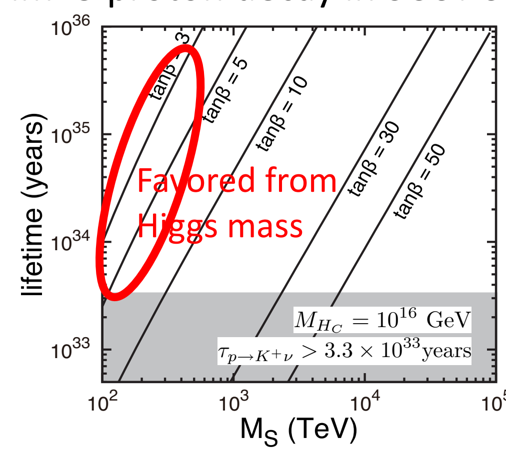
K^0–$\overline{K}^0$ mixing constraints

$$m_{\tilde{q}} > 10\text{TeV} \times \sqrt{\left|\text{Re}\left(\frac{m^d_{12,LL/RR}}{m^2_{\tilde{q}}}\right)^2\right|}$$

$$m_{\tilde{q}} > 200\text{TeV} \times \sqrt{\left|\text{Re}\left(\frac{m^d_{12,LL}}{m^2_{\tilde{q}}}\frac{m^d_{12,RR}}{m^2_{\tilde{q}}}\right)\right|}$$

If CP phases are O(1), squark masses should be ten times larger than above.

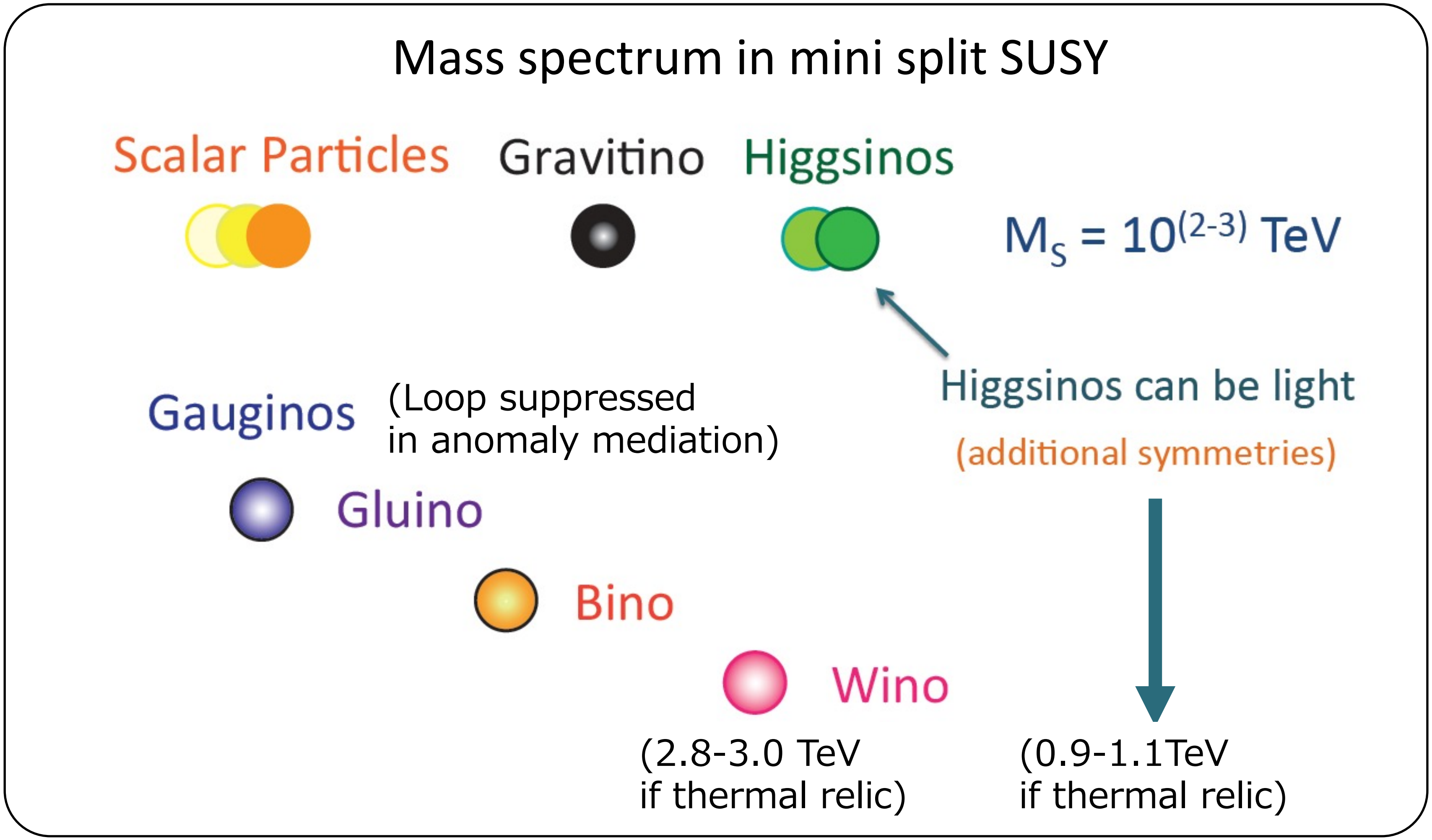
Dim=5 proton decay in SUSY SU(5) GUT



(JH, Kobayashi et al (13))

mini-split SUSY (~O($10^{2\text{-}3}$) TeV) solve those problems.

Wino/Higgsino DM in SUSY SM



How to test this model?

Wino/Higgsino DM is a window to access the model.

Wino/Higgsino DM in SUSY SM

Wino
(I=1, Y=0, S=1/2)
Partners of weak bosons

$$\chi^0,\ \chi^\pm$$

$$\Delta m_+ = 166\mathrm{MeV} + O(\frac{v^4}{M^3})$$

(EW radiative correction)

Higgsino
(I=1/2, Y=$\pm$1/2, S=1/2)
Partners of Higgs bosons

$$\chi^0,\ \chi^{0\prime},\ \chi^\pm$$

$$\Delta m_+ = 340\mathrm{MeV} + O(\frac{v^2}{M})$$

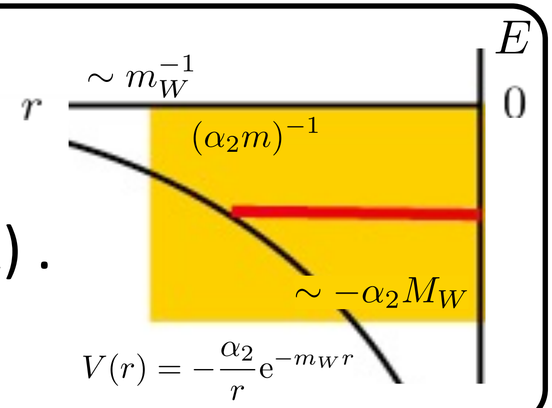
(EW radiative correction)

$$\Delta m_0 = O(\frac{v^2}{M})$$

(Pseudo Dirac fermion)

Pair annihilation of Heavy EW-int. DM

X sections are affected by Sommerfeld effect
when $\alpha_2 m \gtrsim m_W$ (long range force) and $v \lesssim \alpha_2$ (NR) .

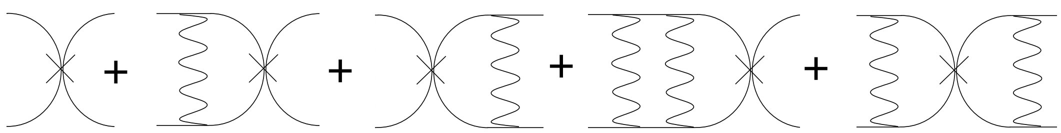


NR eff. Lagrangian for neutral 2-bodies states of winos ($\mathbf{\Phi}(\mathbf{r}) = (\phi_C(\mathbf{r}),\ \phi_N(\mathbf{r}))$)

$$\mathcal{L} = \frac{1}{2}\mathbf{\Phi}^T(\mathbf{r})\left(\left(E + \frac{\nabla^2}{m}\right)\mathbf{1} - \mathbf{V}(r) + 2i\mathbf{\Gamma}\delta^3(\mathbf{r})\right)\mathbf{\Phi}(\mathbf{r})$$

$$\mathbf{V}(r) = \begin{pmatrix} 2\delta m - \frac{\alpha}{r} - \alpha_2 c_W^2 \frac{e^{-m_Z r}}{r} & -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} \\ -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} & 0 \end{pmatrix} \qquad \mathbf{\Gamma} = \frac{\pi \alpha_2^2}{m^2}\begin{pmatrix} \frac{3}{2} & \frac{1}{2\sqrt{2}} \\ \frac{1}{2\sqrt{2}} & 1 \end{pmatrix}$$

Optical theorem:

$\sigma v \propto \mathrm{Im}$


$\propto \sum_{a,b} \mathbf{\Gamma}_{ab} d_{ia} d_{ib}^{\star}$

Pair annihilation of Heavy EW-int. DM

X sections are affected by Sommerfeld effect

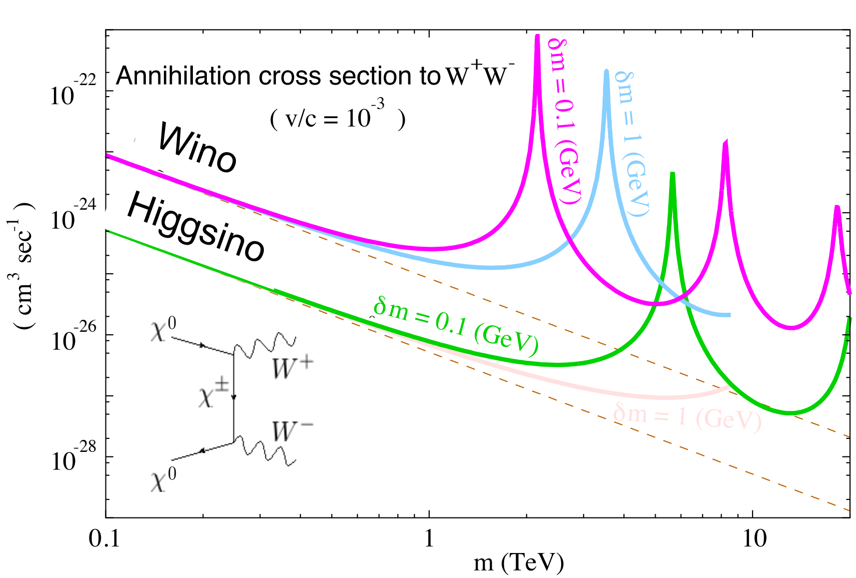
1) enhancement of x sections, such as $e^+e^- \to 2\gamma$

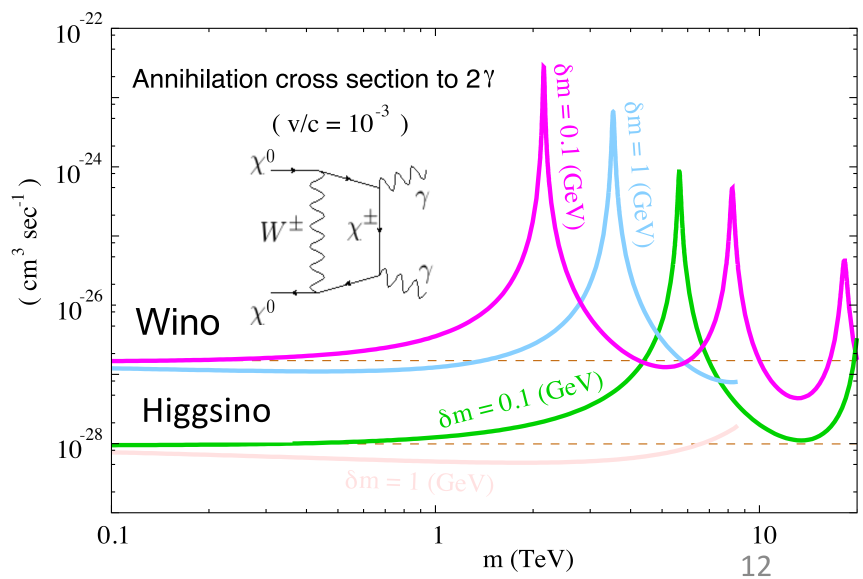
Peaks correspond to zero-energy bound states.

2) enhancement of x section to two gammas, relatively to $W^+ W^-$

$$\sigma v(2\chi^0 \to 2\gamma) \propto \alpha^2 \alpha_2^2 \Rightarrow \alpha^2$$

Sudakov double log resummantion modifies x sections by O(1).

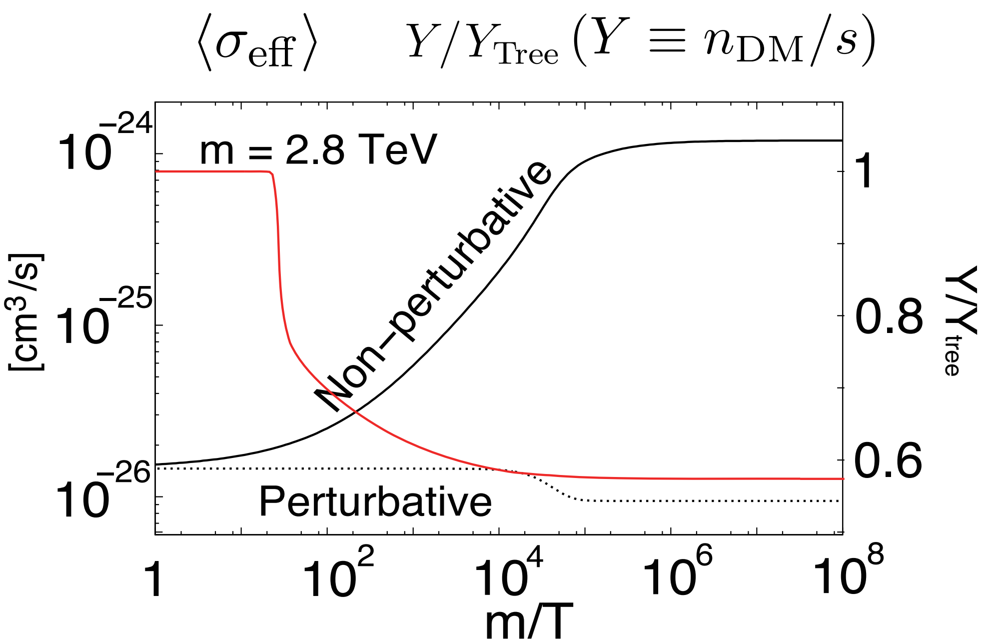


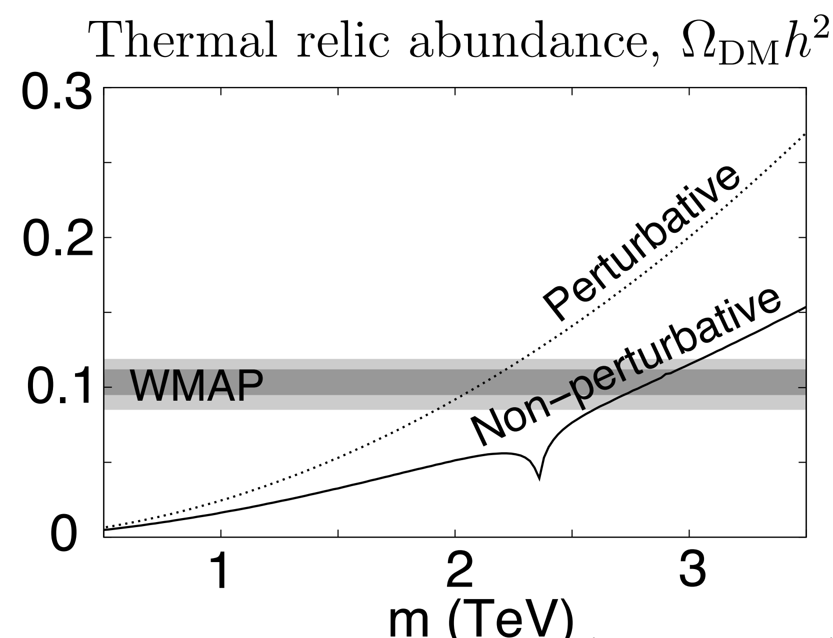


(JH, Matsumoto, Nojiri (04))

Thermal relic abundance of Wino/Higgsino

- The Sommerfeld effect modifies the thermal relic abundance of wino, though the effect is limited. The preferred value is m~3TeV.





(JH, Matsumoto et al (07))

- Abundance of Higgsino is not changed (m~1TeV).
- More precise evaluation is important to test the models.
  - NLO potential (Beneke et al 20).
  - Bound state effects (topic of this workshop) ?

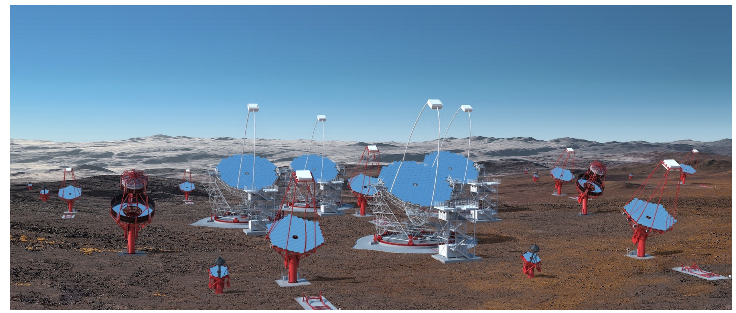
Line gamma rays from GC of Wino/Higgsino

Line gamma ray observation from Galactic Center: a smoking gun of DM

$$\chi^0\chi^0 \to \gamma\gamma,\ \gamma Z^0 \quad (E_\gamma \simeq m)$$

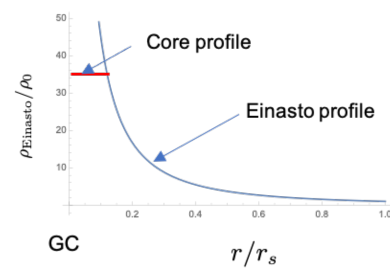
H.E.S.S.

Cherenkov Telescope Array (CTA)



Gamma ray flux:

$$\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma v \rangle_{\rm line}}{8\pi m_{\rm DM}^2}\frac{dN_\gamma}{dE} \times \int_{\rm ROI} d\Omega \int ds\, \rho_{\rm DM}^2$$



DM density profile around GC

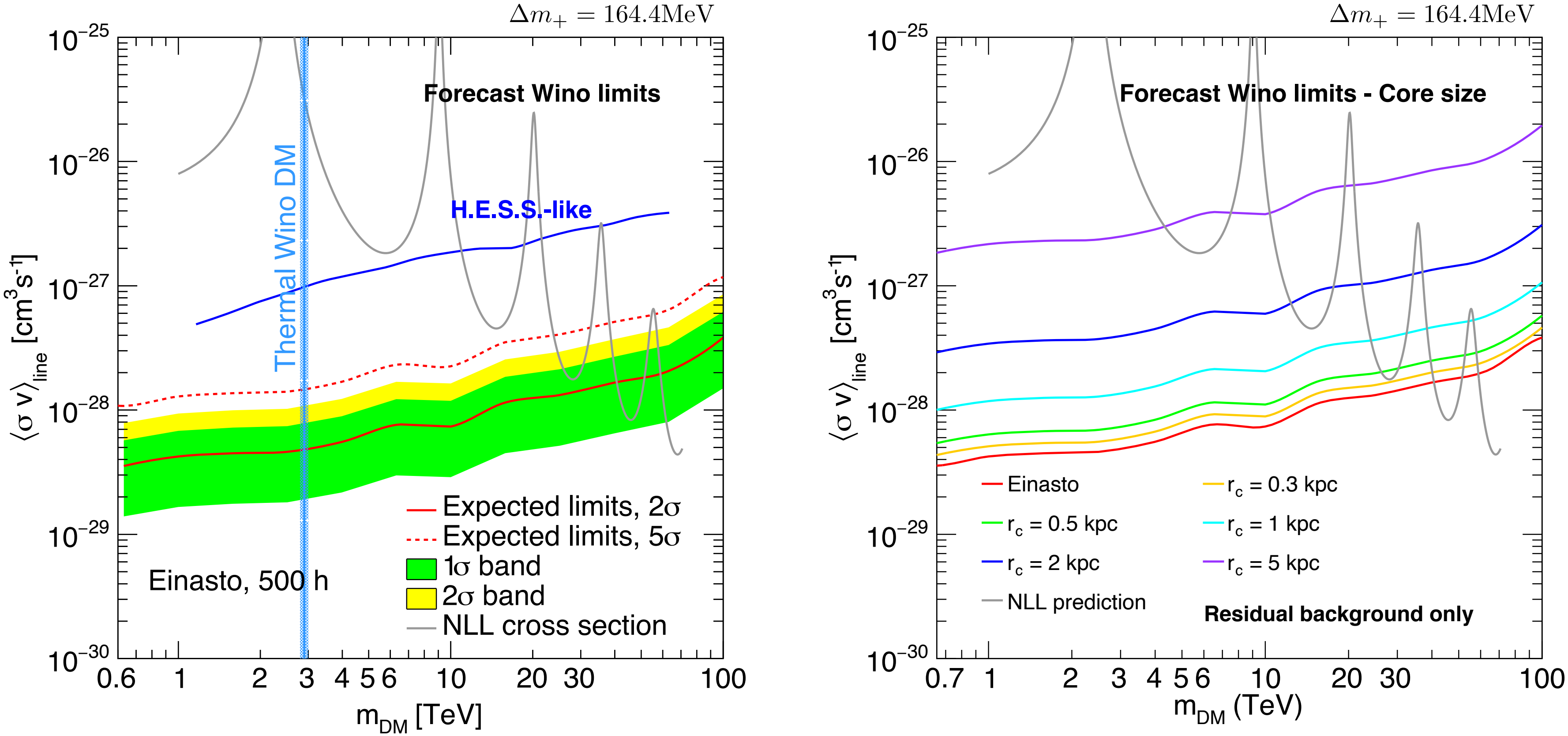
Einasto profile : $\rho_{\rm Einasto} = \rho_0 \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - 1\right)\right]$

Core profile : $\rho_{\rm DM}(r_{\rm c}) = \rho_{\rm Einasto}(r_{\rm c})$ ($r < r_{\rm c}$), $\rho_{\rm Einasto}(r)$ ($r > r_{\rm c}$)

Line gamma rays from GC of Wino/Higgsino

CTA Prospect for Wino DM (Rinchiuso, Slatyer, et al (20))

(Resummation of Sudalov double log, continuum emission, endpoint photons, energy resolution of CTA are included.)

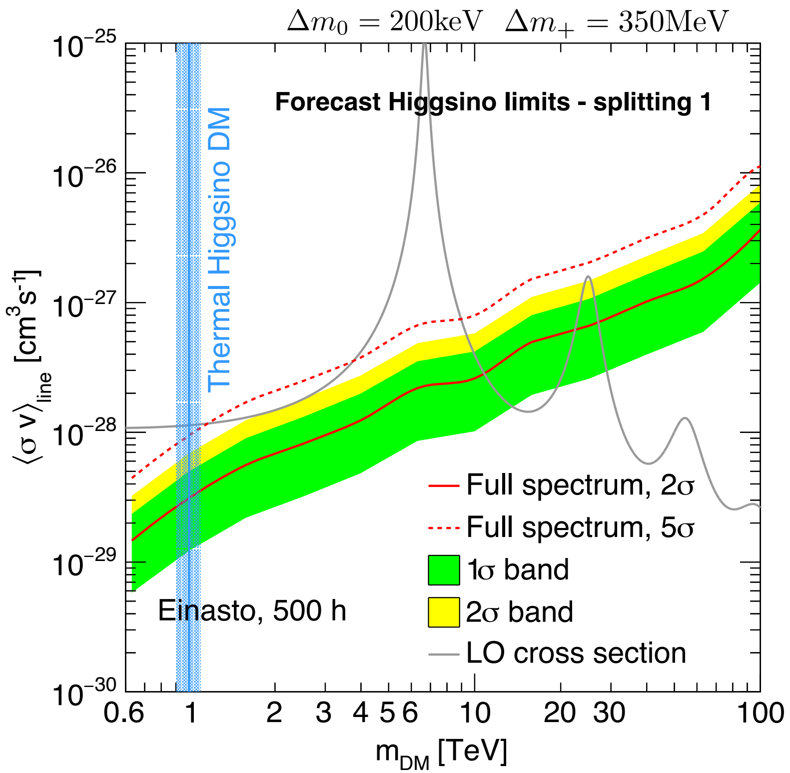


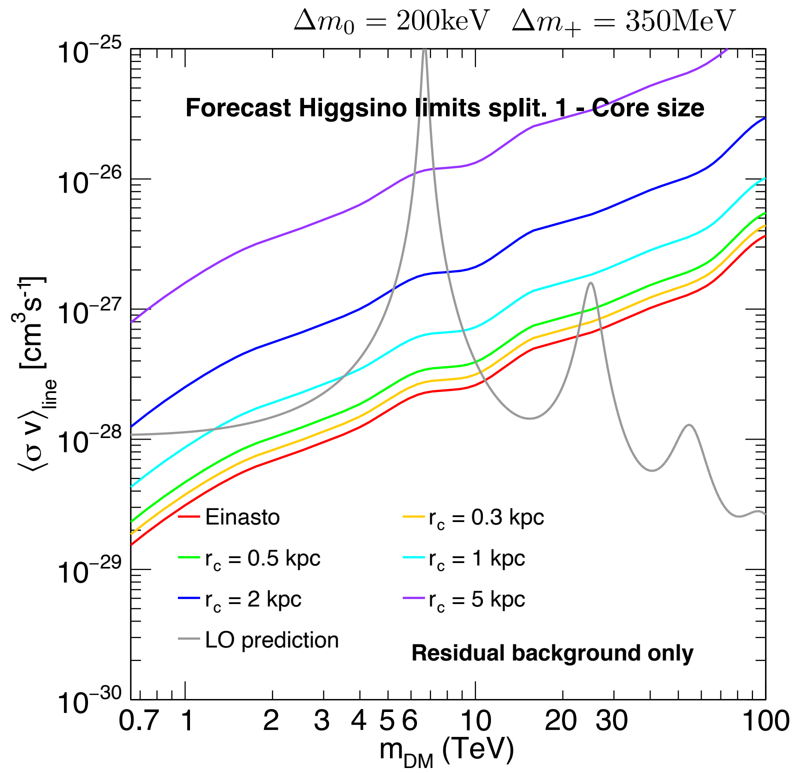
The precise evaluation of thermal relic abondance is important since the x section to line gamma is quite sensitive to wino mass.

Line gamma rays from GC of Wino/Higgsino

CTA Prospects for Higgsino DM (Rinchiuso, Slatyer, et al (20))

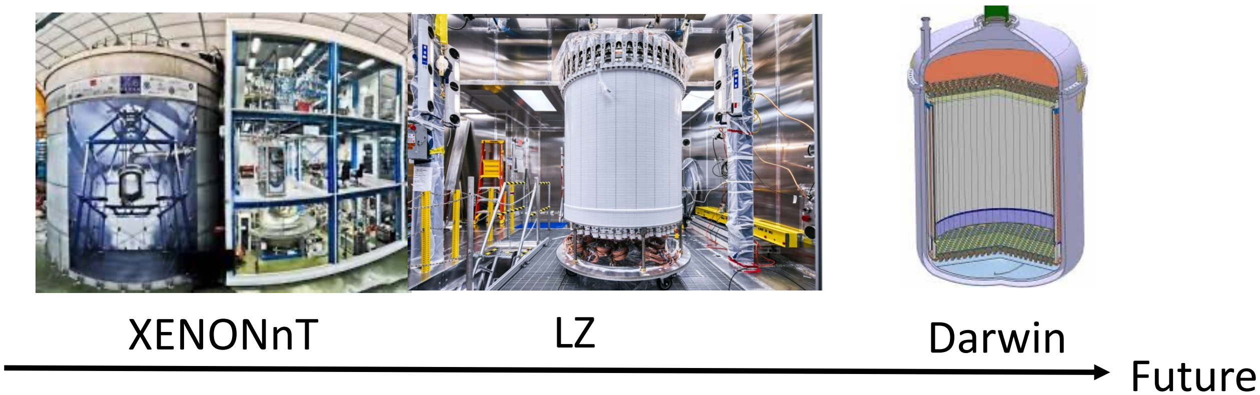
(Resummation of Sudalov double log is not included. The O(1) correction is missing.)





Higgsino DM would be also testable, depending on the core size.

Direct Detection of Wino/Higgsino

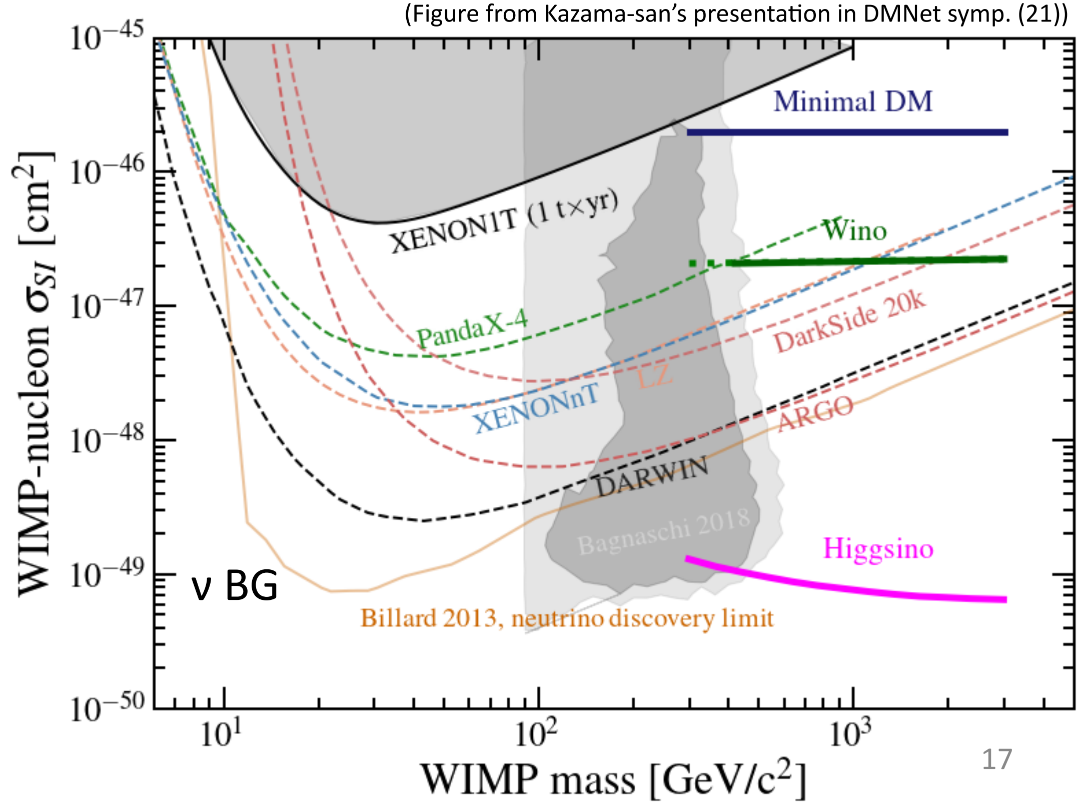


Experiments are sensitive to Spin-indep. DM-nucleon elastic scattering.

$$f\chi\chi\bar{N}N$$

In near future, experiments will reach close to neutrino BG.

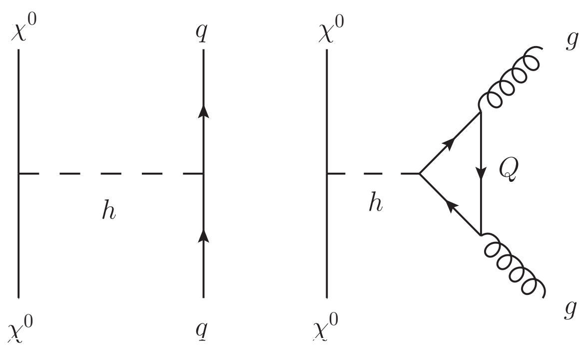
(Figure from Kazama-san's presentation in DMNet symp. (21))



Direct Detection of Wino/Higgsino

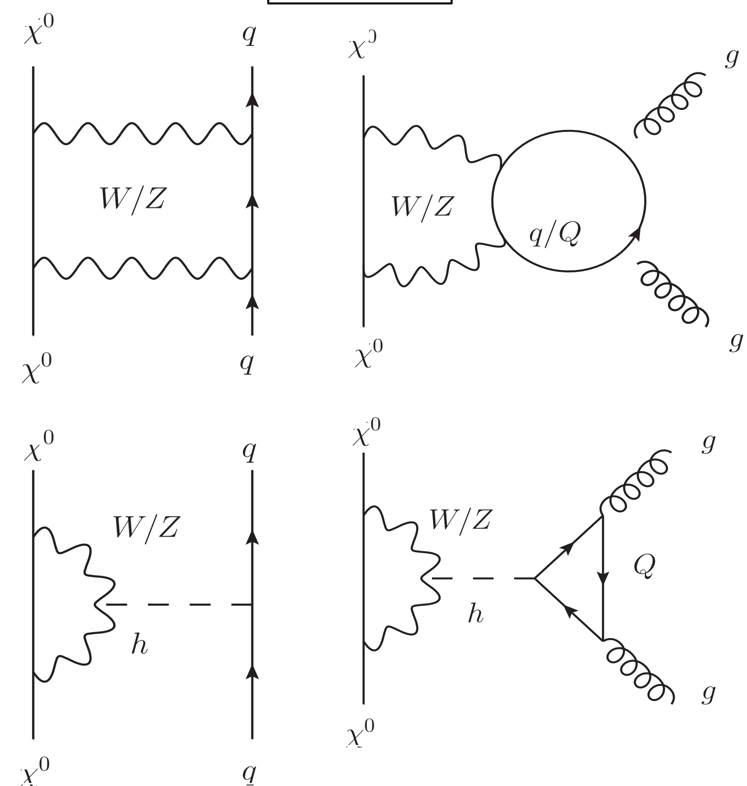
Spin-independent DM-nucleon elastic scattering (scalar coupling)

TREE



Leading, but suppressed by Gaugino-Higgsino mixing.

LOOP

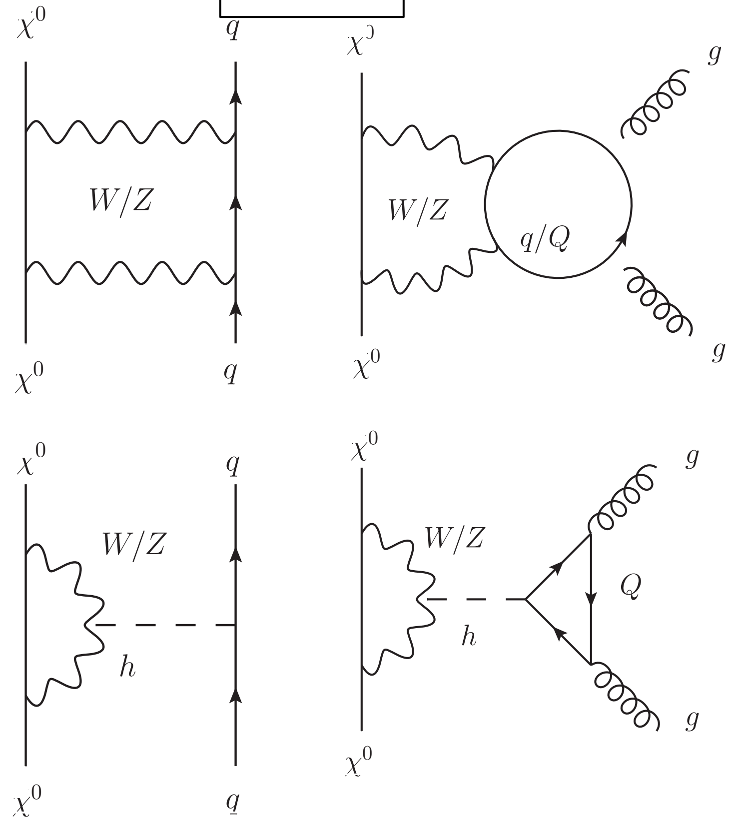


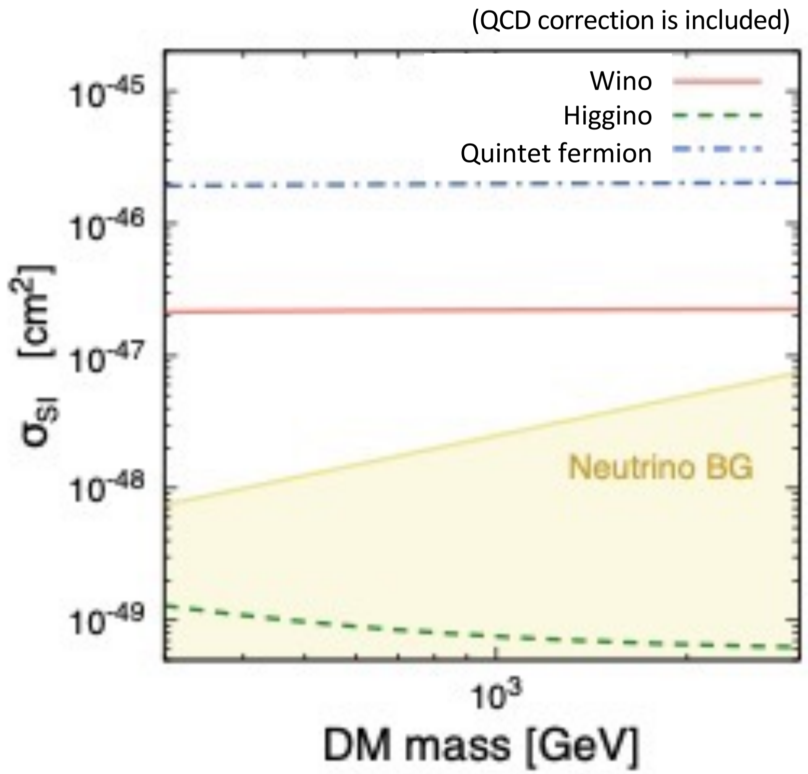
Subleading, but not suppressed by Gaugino-Higgsino mixing. The x section is suppressed by weak boson mass squared.

Direct Detection of Wino/Higgsino

Spin-independent DM-nucleon elastic scattering (scalar coupling)

LOOP



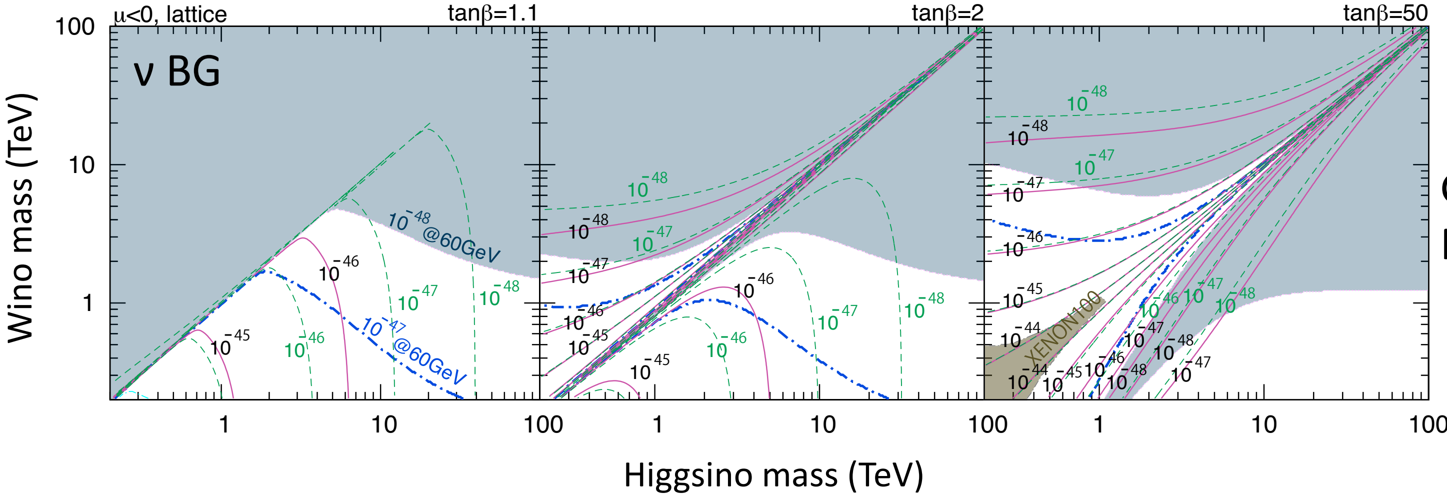


(JH, Ishiwata, Nagata (15))

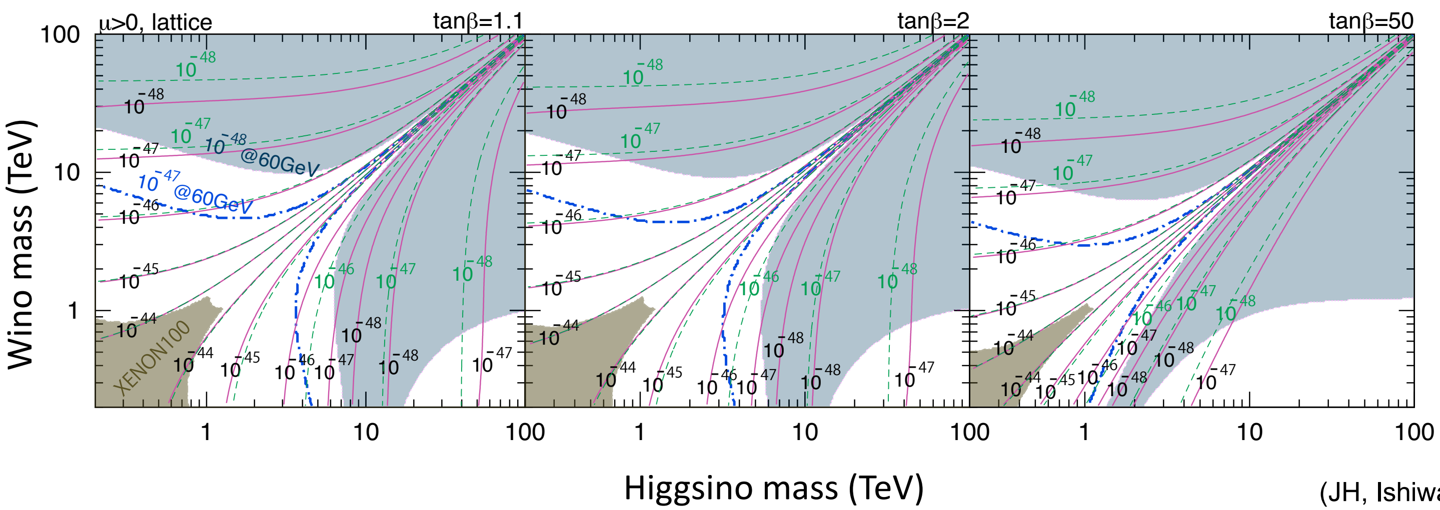
X section of wino is above the neutrino BG, and wino DM can be tested.
The determination of abundance is important to test wino DM again.

Direct Detection of Wino/Higgsino

Spin-independent DM-nucleon elastic scattering (scalar coupling)



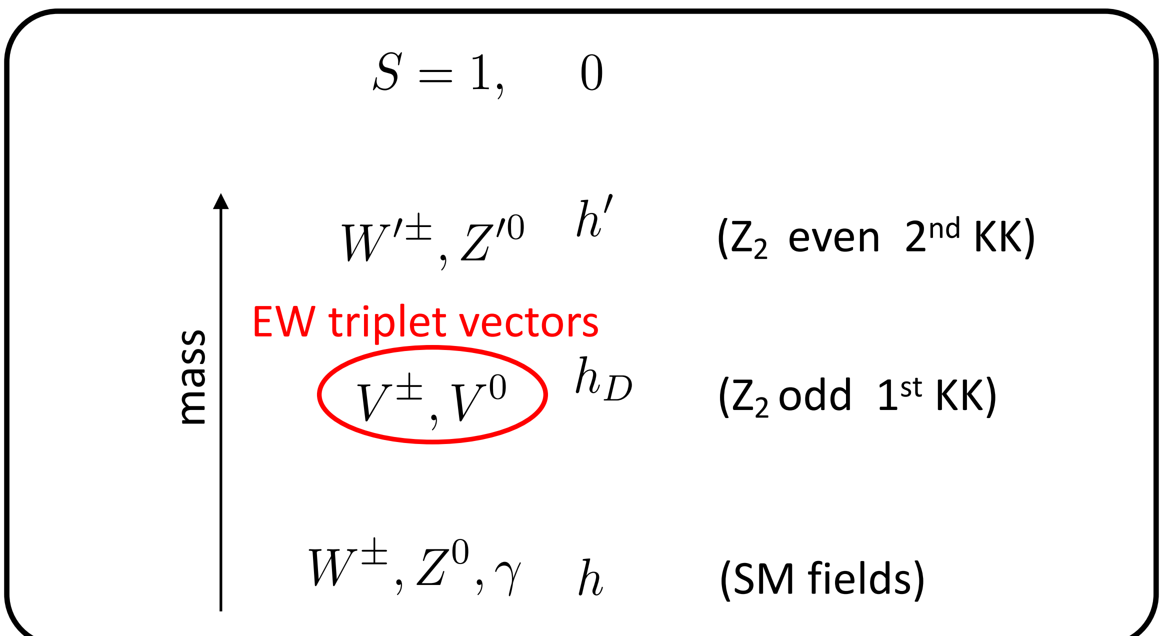
Green: TREE
Purple: TREE +LOOP



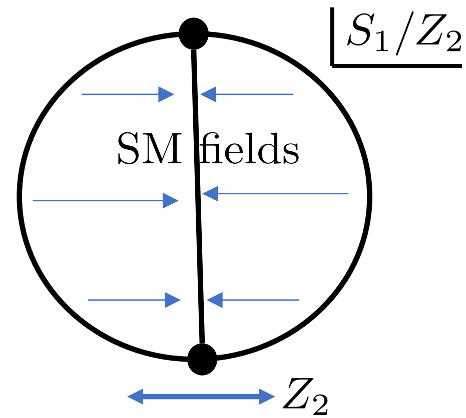
(JH, Ishiwata, Nagata (12))

Electroweakly-interacting vector DM

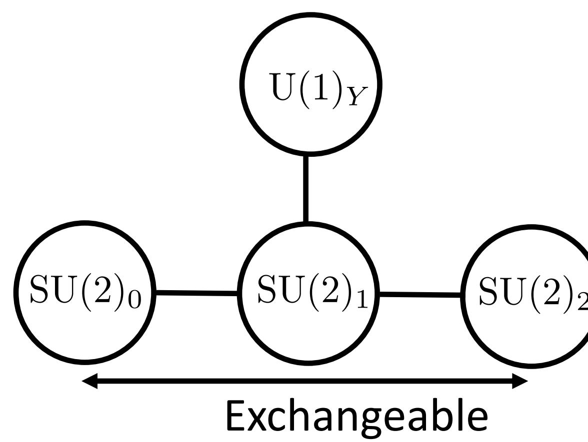
- Extra-dimensional models predict vector DM, i.e., Kaluza-Klain gauge bosons.
- Renorm. model for EWly-interacting vector DM,
  $\mathrm{SU}(2)_0 \times \mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2 \times \mathrm{U}(1)_Y \to \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
  Symmetry for $\mathrm{SU}(2)_0 \leftrightarrow \mathrm{SU}(2)_2$ predicts stable massive EW triplet vectors. (Abe, JH, Matsushita, Fujiwara (20))



Extra-dim models



Minimal model



Electroweakly-interacting vector DM

The model has rich phenomenology

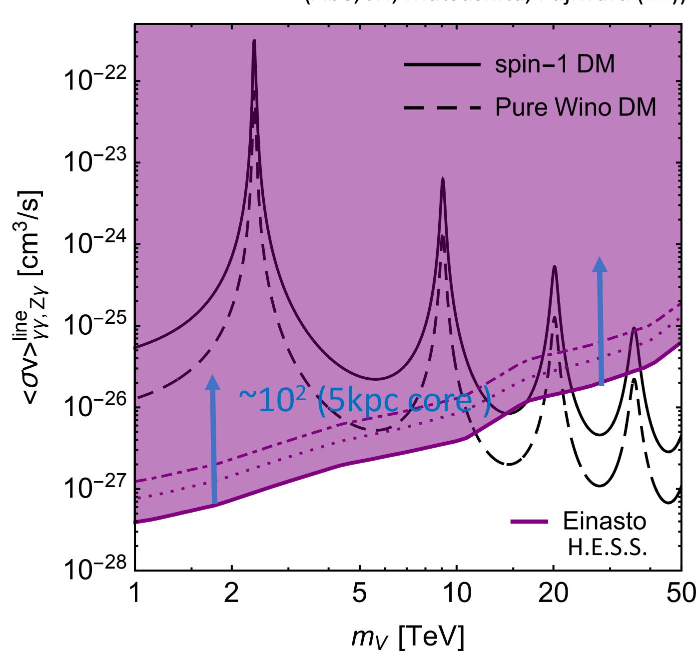
- Thermal relic abundance (perturbative calculation)

$$3\text{TeV} \lesssim m \lesssim 19\text{TeV} \;(V_0 V_0 \to W'^{\pm} W^{\mp})$$

- Direct detection comes from $h - h'$ mixing, and the XENONnT will cover almost of allowed region.

(Abe, JH, Matsushita, Fujiwara (21))

- The Sommerfeld enhancement for x sections for $\gamma\gamma$ and γZ^0 is the same as wino's, while the x section are 38/9 times larger due to total spin 0 and 2.



- $\gamma Z'^0$ final state contributes to line gamma rays if $m < m_{Z'} < 2m$. This may be discriminated from $\gamma\gamma$ and γZ^0 with CTA energy resolution. ($\delta E_\gamma = m_{Z'}^2/4m$)

(Please visit Fujiwara-san's poster presentation.)

Summary

Electroweakly-interacting dark matter is fit with the current experimental results, and it will be tested in near future experiments, such as CTA and XENONnT/LZ/Darwin.

The dark matter mass is one of important parameters to test the models. The thermal relic abundance is desirable to be precisely evaluated.

We do not discuss future prospects of

- Electron EDM
- Long-lived particle searches at LHC/future colliders

They are also important to test the models.

FIN.

JSPS core-to-core program "DMNet"

PI's in KMI

Y. Itow XENON | Y.Nakahama LHC ALTAS | T. Iijima Belle-II (PI) | H. Tajima CTA | K. Ichiki Cosmlogy | H. Miyatake Cosmlogy | J. Hisano Particle Physics | S. Nojiri Particle Physics

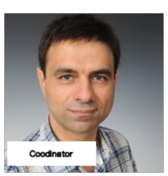
Max Planck Institute for Nuclear Physics

Hub of astroparticle and particle physics in Eurioe

J.HINTON
CTA

M.LINDNER
XENON
(Co-PI)

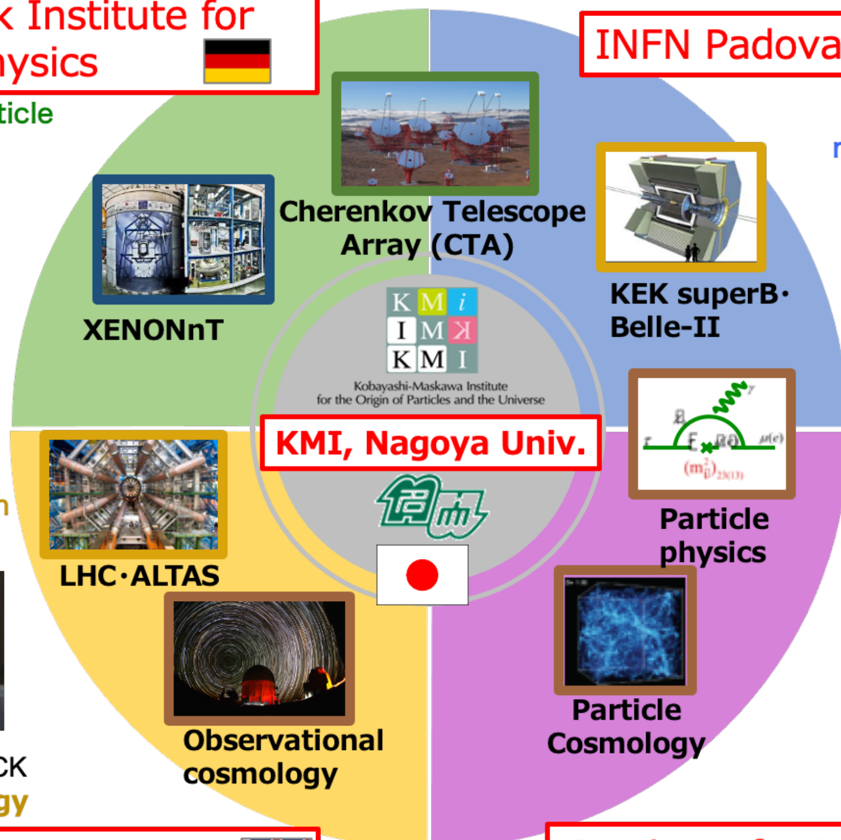
Hub of LHC and cosmology in Europe



C.LEONIDOPOULOS
LHC·ALTAS

J.PEACOCK
Cosmology

The University of Edinburgh



INFN Padova

Hub of particle physics, gamma rays obs. and B physics in Europe

E.Torassa
Belle-II

Hub of particle physics in Asia

K.CHOI
Theory of Particle Physics

Institute for Basic Science