WIMP dark matter

Tomohiro Abe
Tokyo University of Science

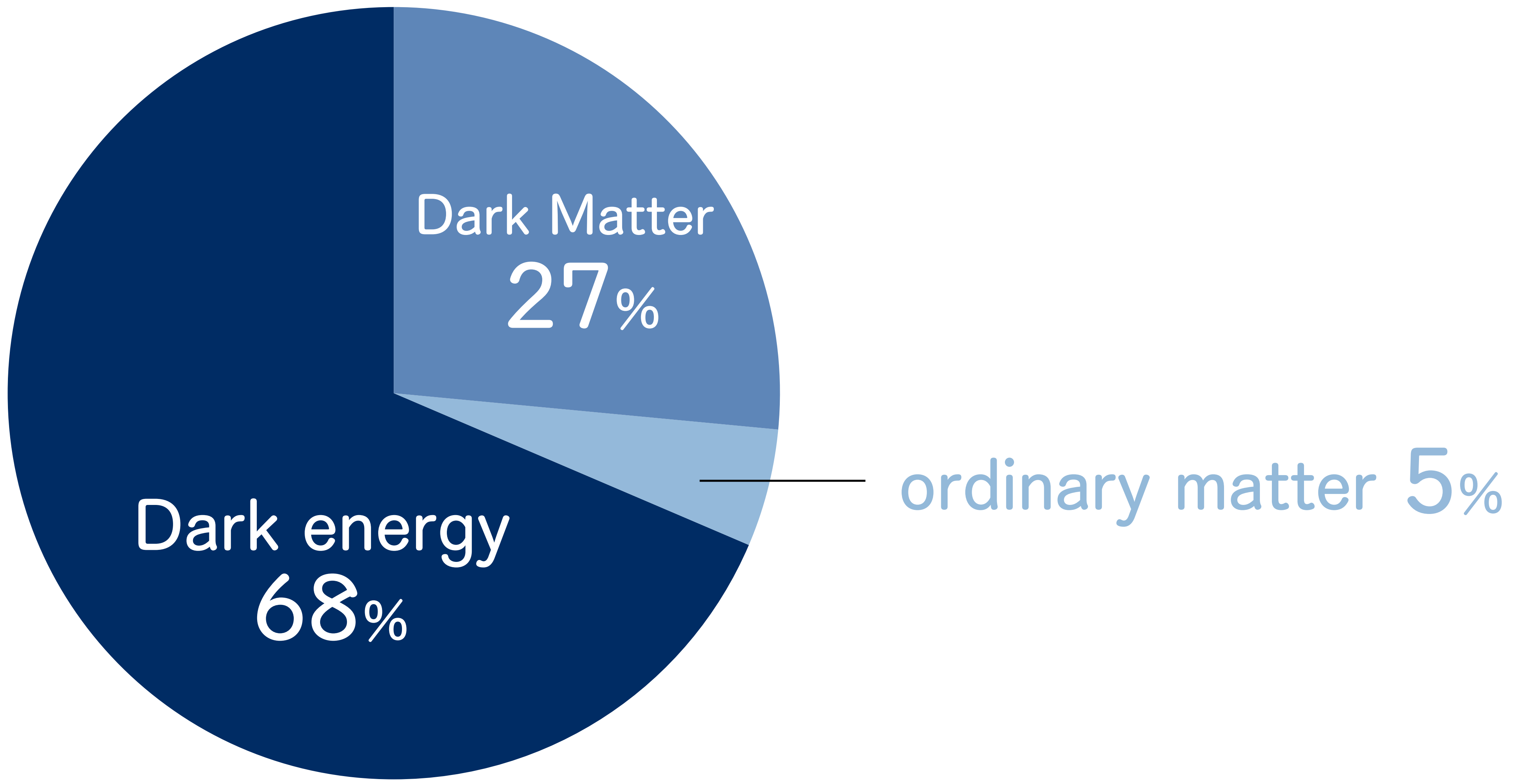
東京理科大学
TOKYO UNIVERSITY OF SCIENCE

創域理工学部
Faculty of Science and Technology

Dark Matter

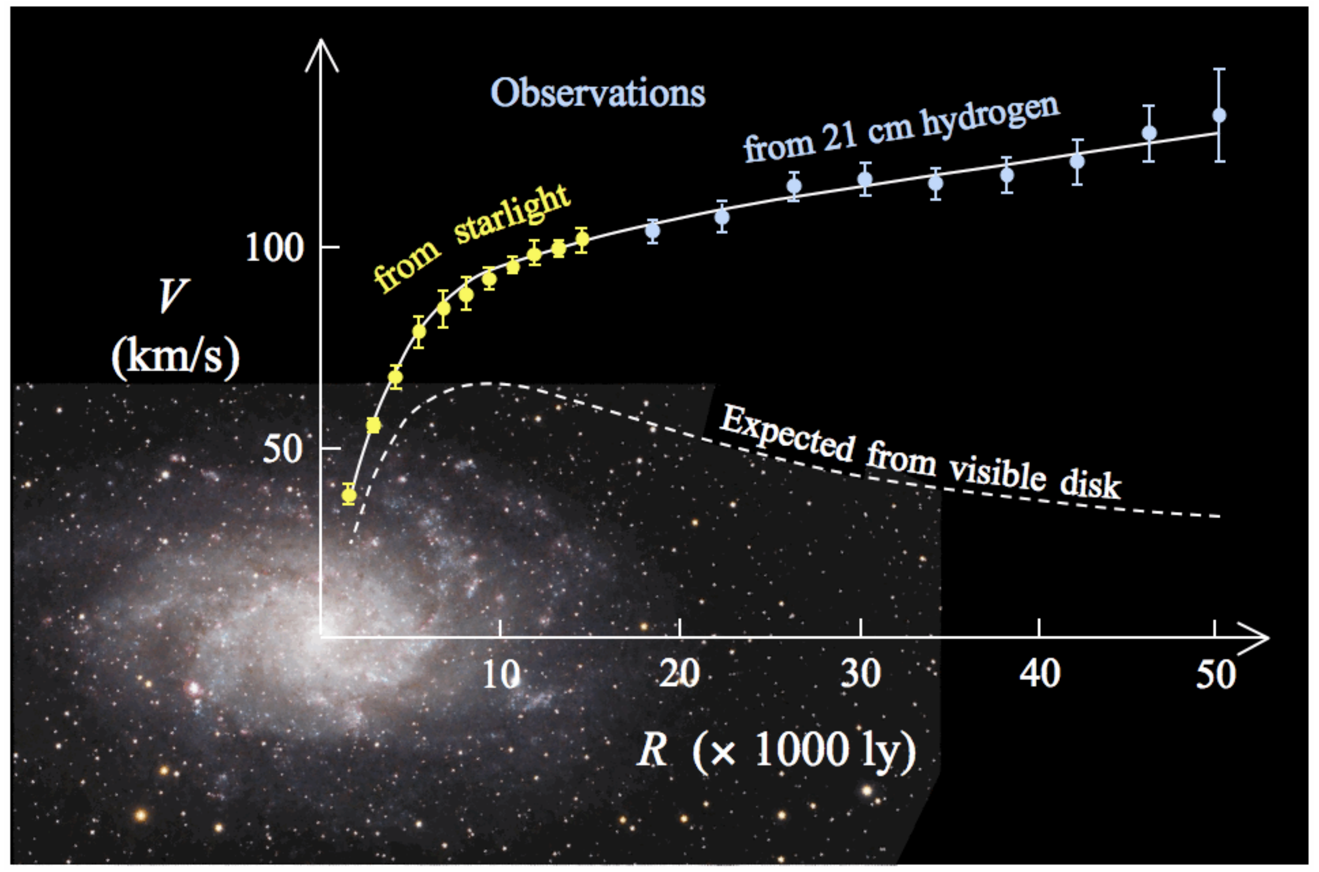
Dark Matter (DM)

- is unknown matter in our universe
- occupies ~ 27% of the energy of the universe
- $\Omega h^2 = 0.120 \pm 0.001$ [Planck 2018]
- interacts gravitationally
- has (almost) no electromagnetic interaction



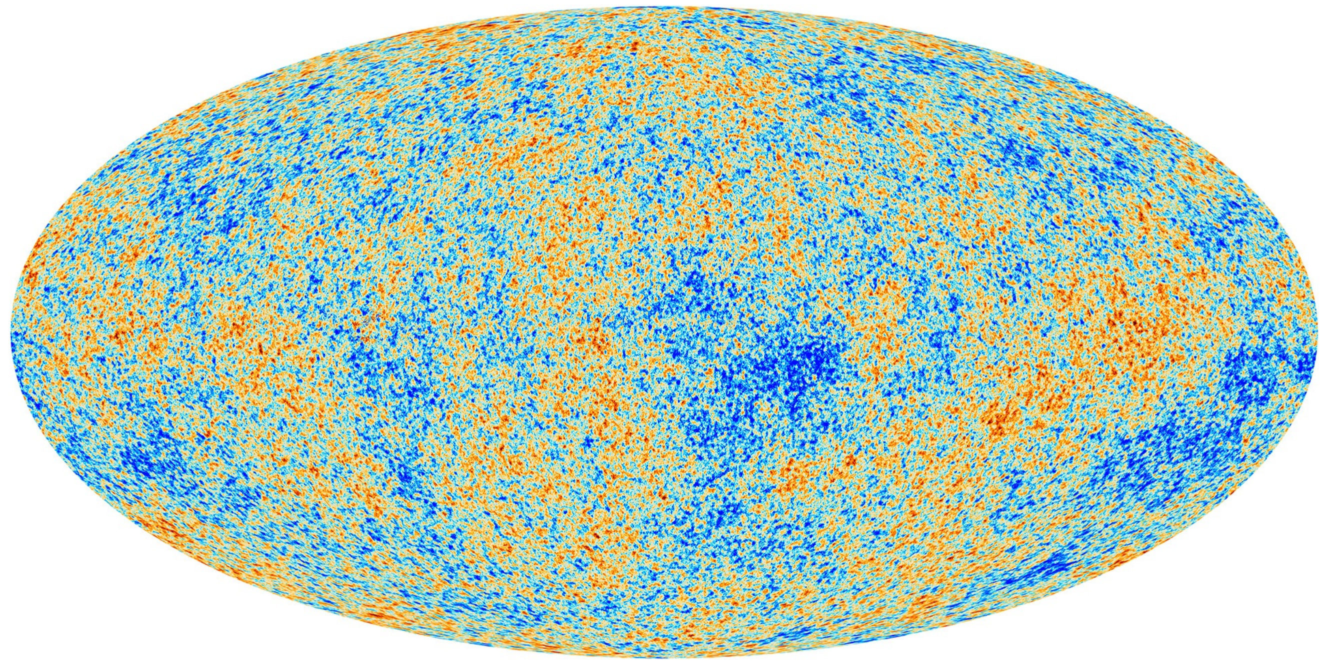
Dark matter evidence

rotation curve



bullet cluster

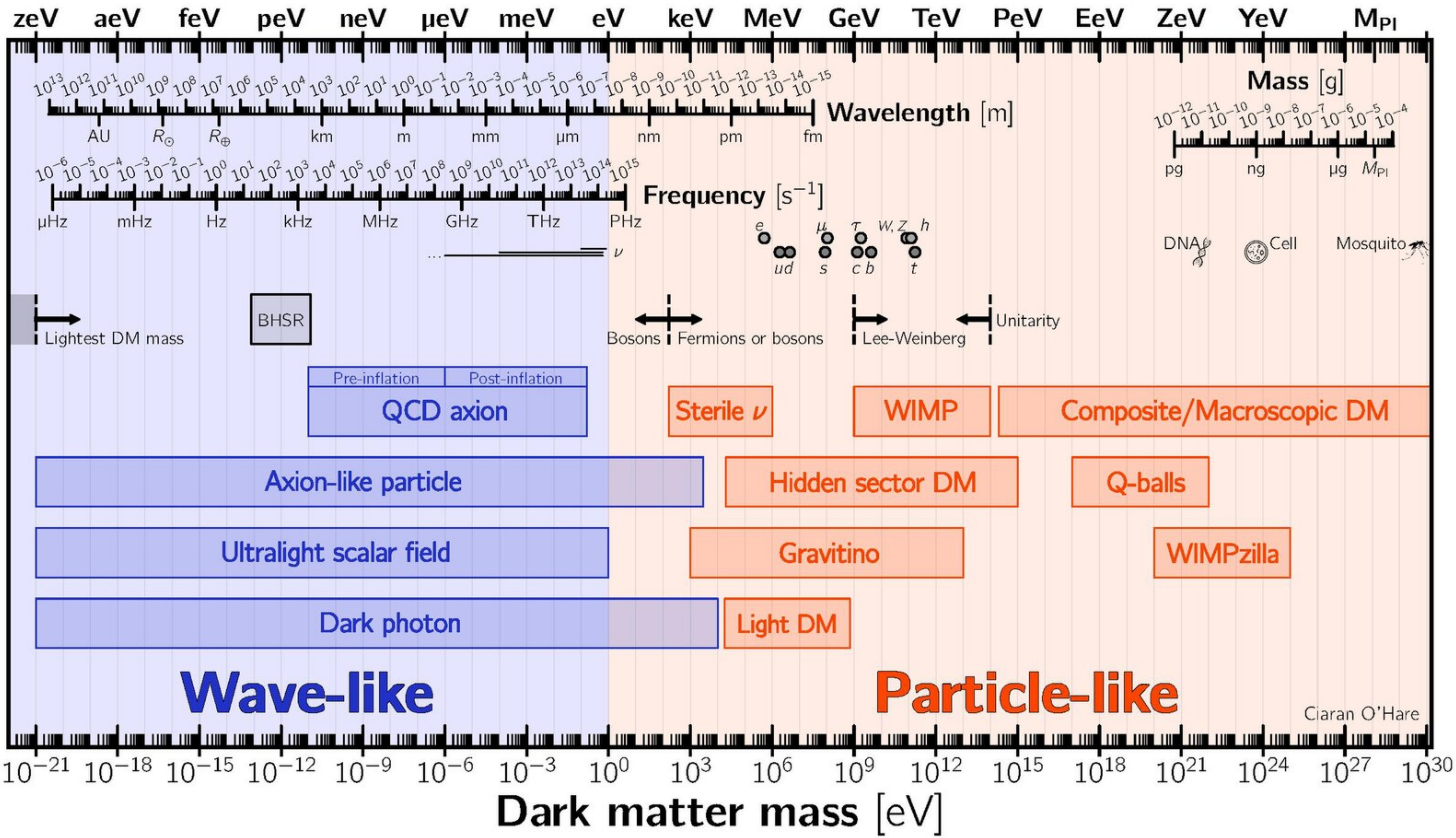
CMB



and more …

- many evidence
- no candidate in known particles
- what is the dark matter candidate?

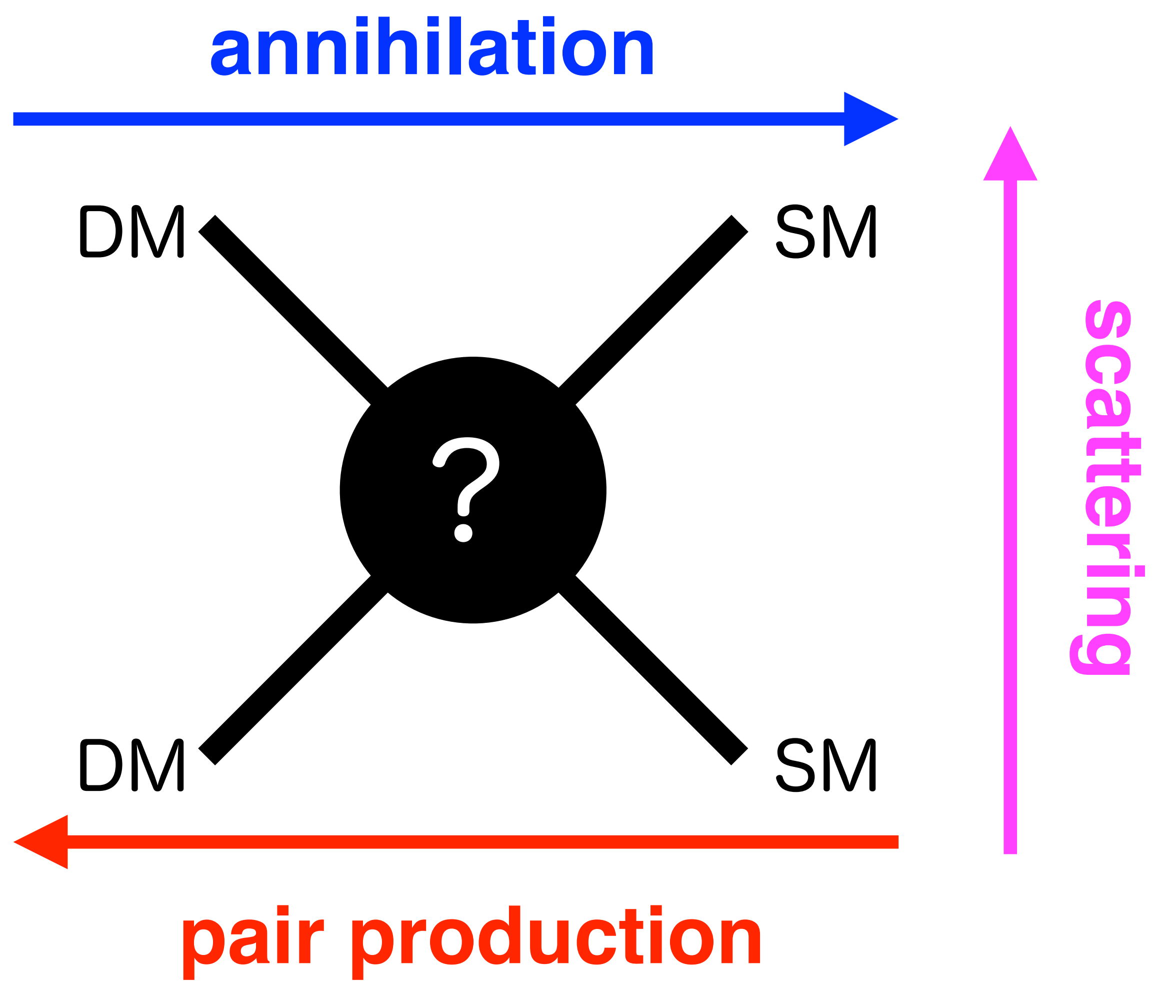
Many Dark Matter Scenarios



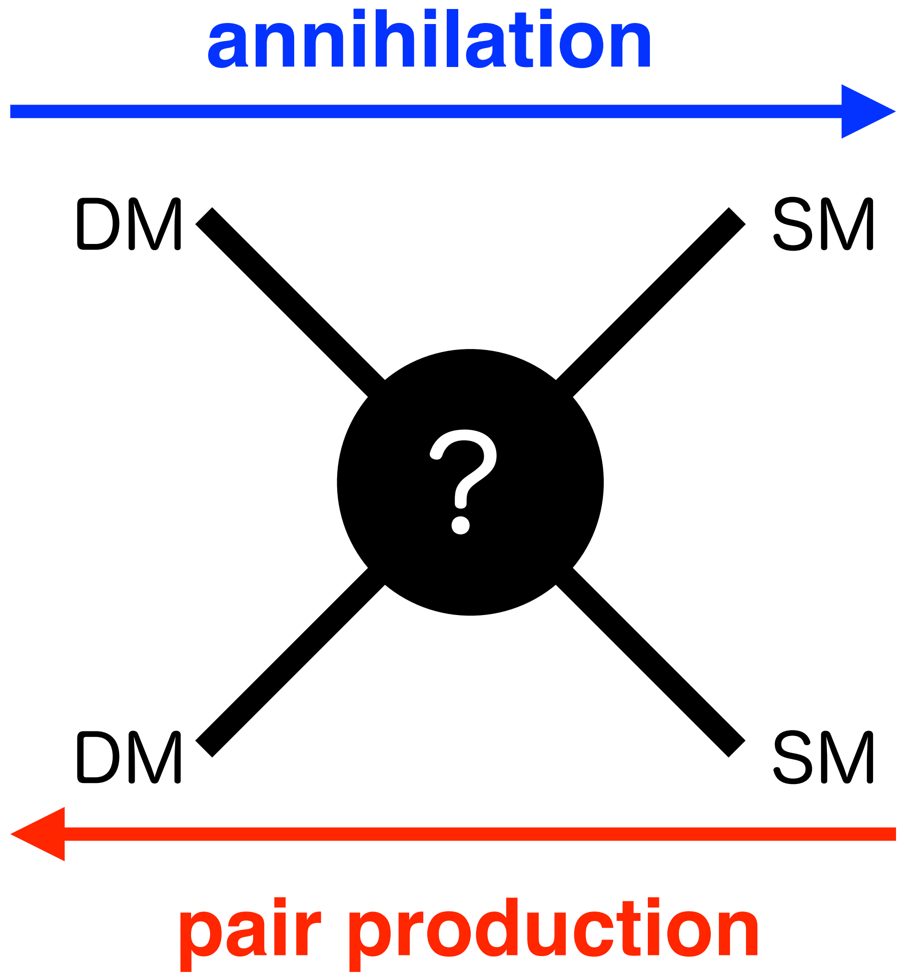
WIMP (or thermal DM)

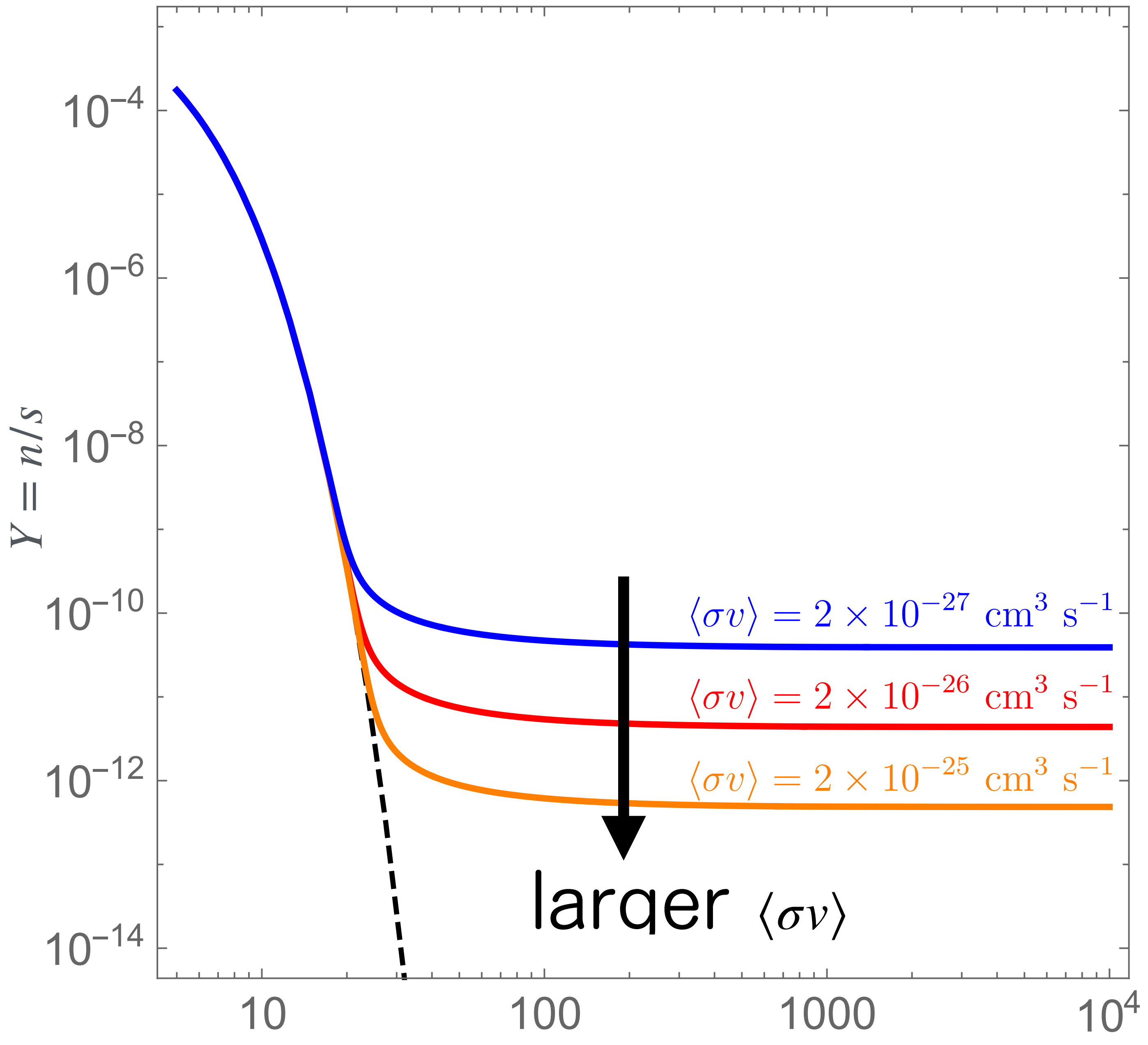
WIMP (Weakly Interacting Massive Particle)

- has short-range interactions with the SM particles (or new particles in the thermal bath in the early universe)
- correlation among various processes
- is predicted in many motivated models in particle physics (MSSM, exDim, …)



Freeze-out mechanism





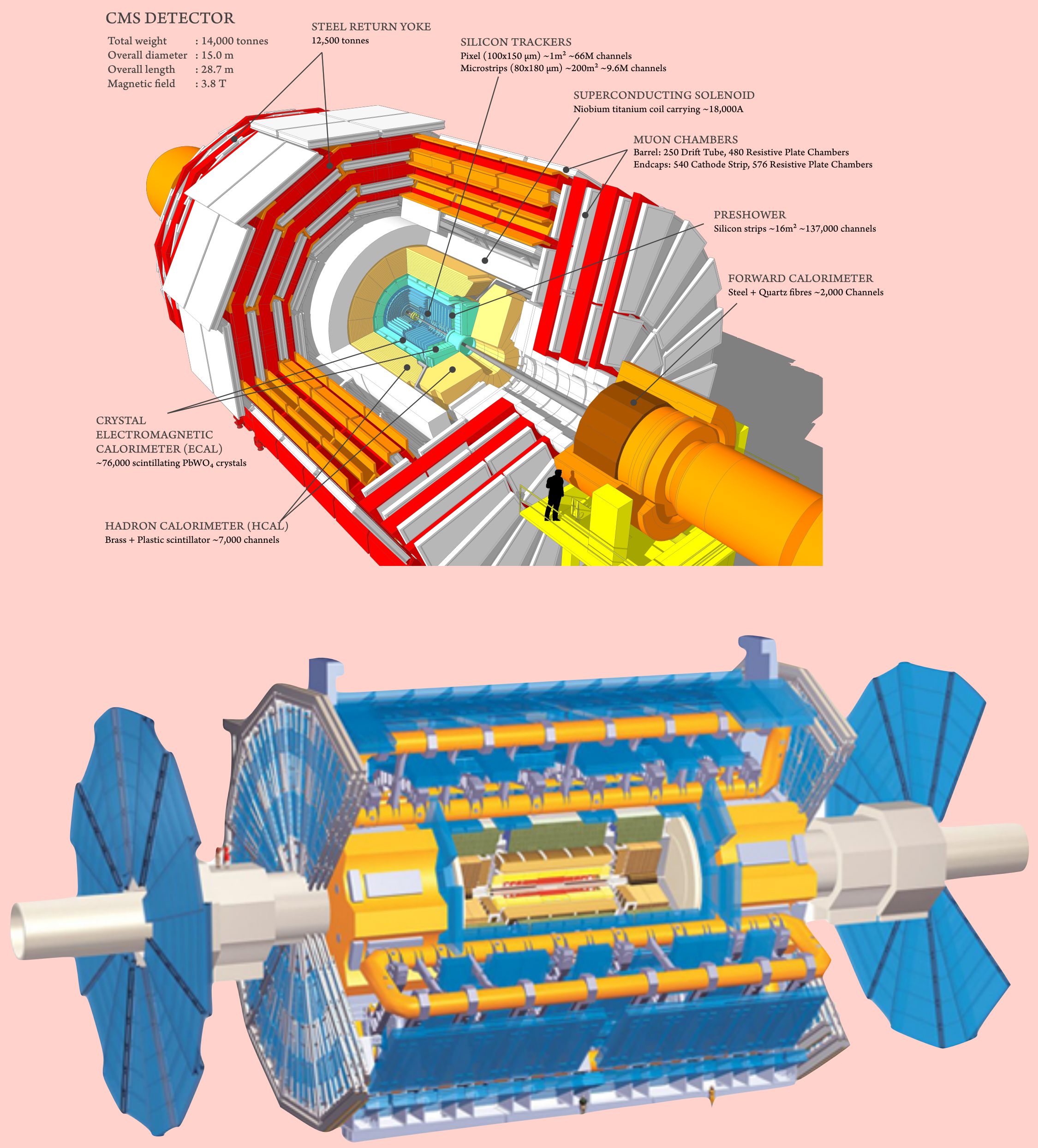
- DM was in thermal equilibrium in the early universe
- production and annihilation of DM stop as the universe expands
- the relic is the DM in the universe today
- number density is obtained by solving the Boltzmann equation

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{\rm eq}^2 \right)$$

- Ωh^2 is determined by DM annihilation cross section $\langle \sigma v \rangle$
- $\Omega h^2 = 0.12$ is obtained if $\langle \sigma v \rangle \simeq 2 \times 10^{-26}$ cm^3 s^{-1} $\simeq 1$ pb c

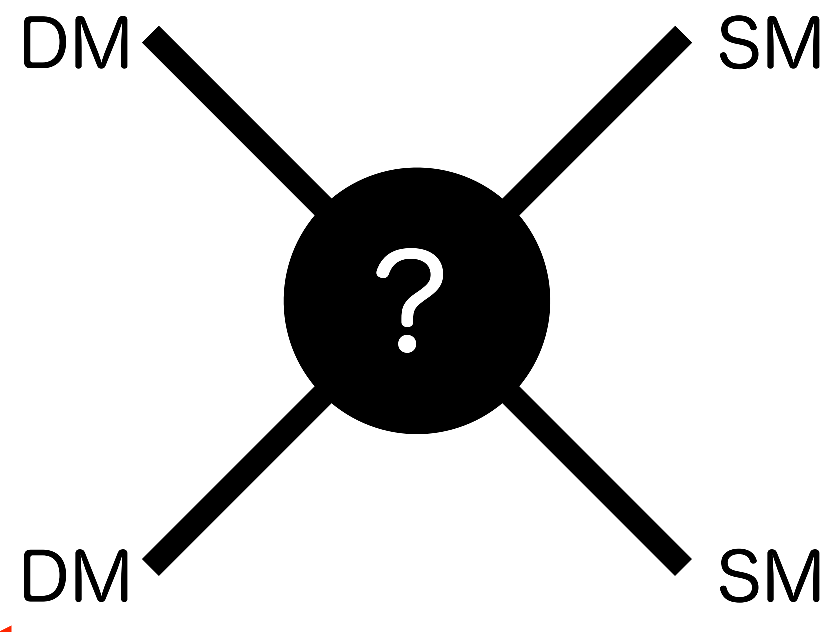
DM DM $\leftrightarrow$ SM SM

- freeze-out mechanism requires annihilation $\langle \sigma v \rangle \simeq 1\ \mathrm{pb\ c}$
- we can expect
  - indirect detection
  - production in collider experiments

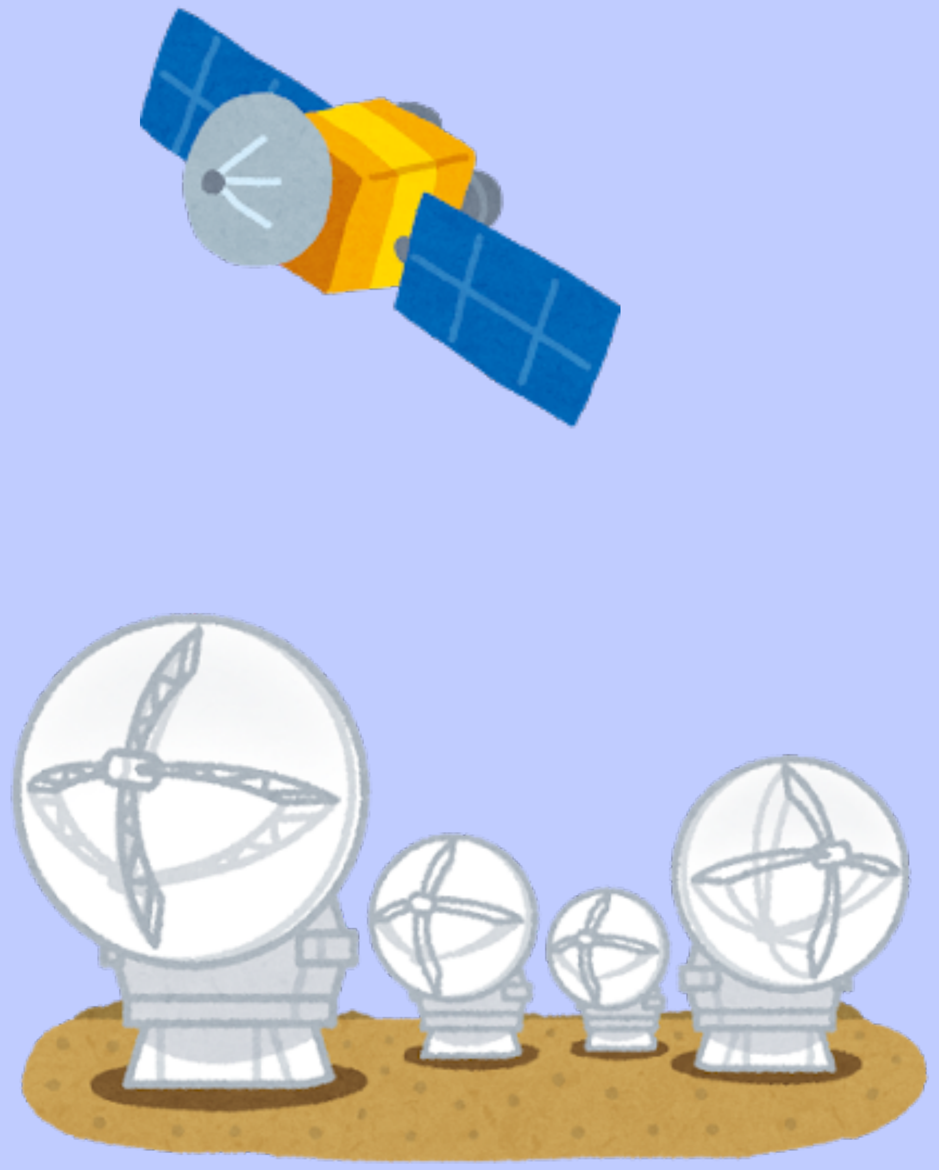


[talk by Shion Chen]

annihilation (indirect detection)

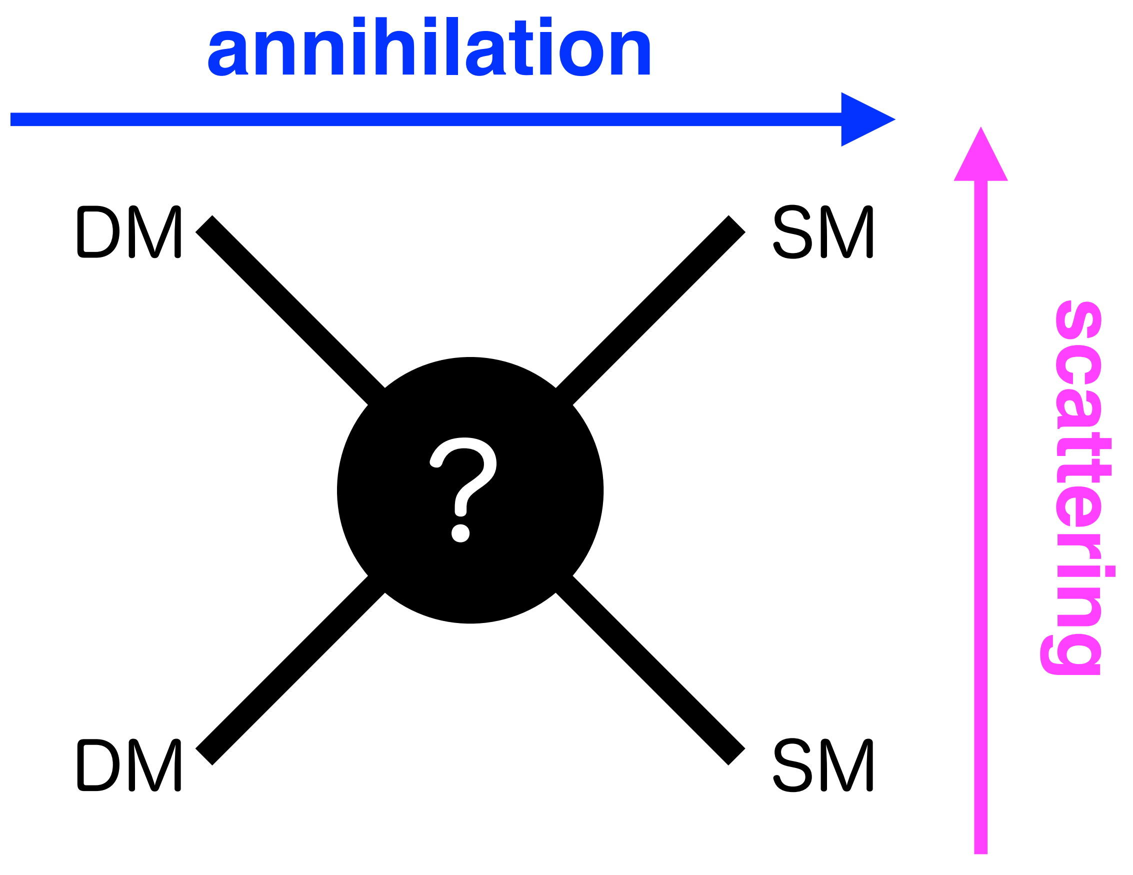


pair production (collider experiments)



[talks by Tomohiro Inada and Kohei Hayashi]

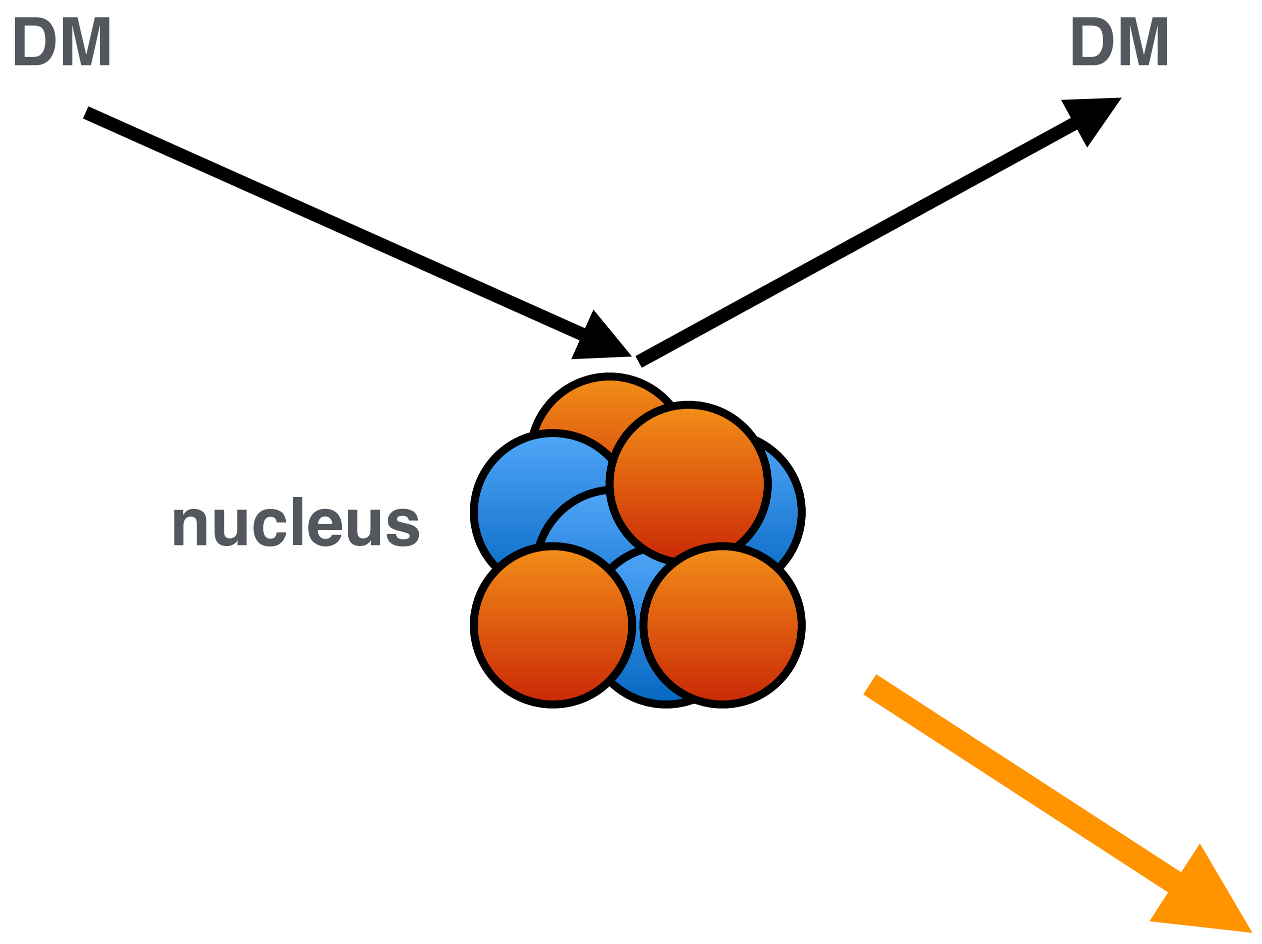
DM SM $\leftrightarrow$ DM SM



annihilation (DM DM $\rightarrow$ SM SM) $(\sigma v)_{\text{ann.}} \propto \frac{\lambda^2}{m_{\text{DM}}^2}$

naive expectation by crossing symmetry

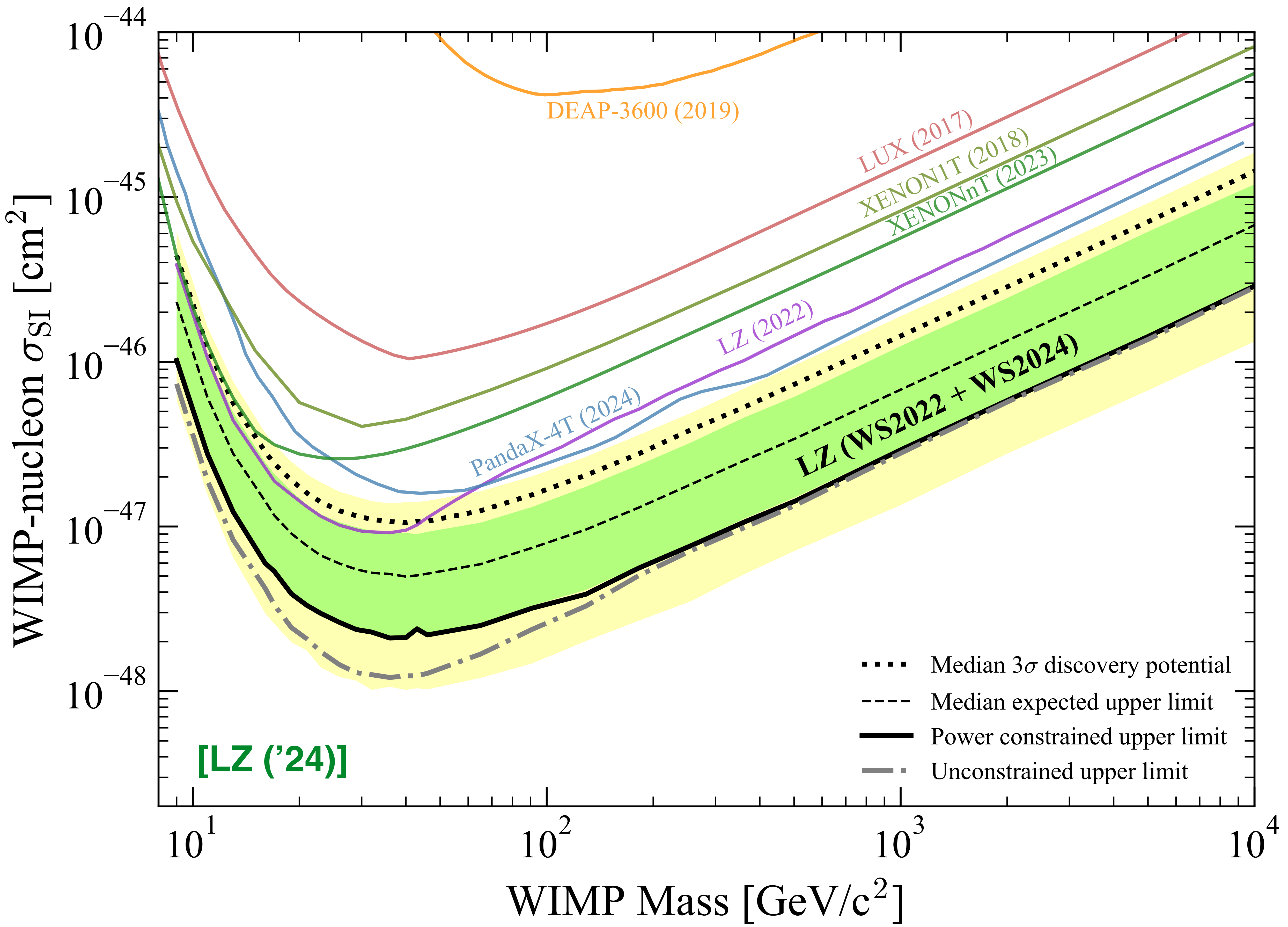
scattering (DM SM $\rightarrow$ DM SM) $\sigma_{\text{scat.}} \propto \frac{\lambda^2}{m_{\text{DM}}^2}$



Direct detection experiments aim to detect DM-nucleon, DM-electron scattering

[talks by Masatoshi Kobayashi and Takashi Asada]

No significant signals (yet!)



- The direct detection experiments give upper bounds on the DM-SM scattering cross-section
- the LZ experiment gives the stringent bound ($\sigma < 3 \times 10^{-48}$ cm² for m_{DM} = 100 GeV)
- strong constrains for WIMP
- Let me show an example model to get feeling how strong the constraint is

Direct detection experiments exclude simple DM models

e.g SM + a gauge singlet scalar DM

[Silveria et.al. ('85), McDonald ('94), Burgess ('01)]

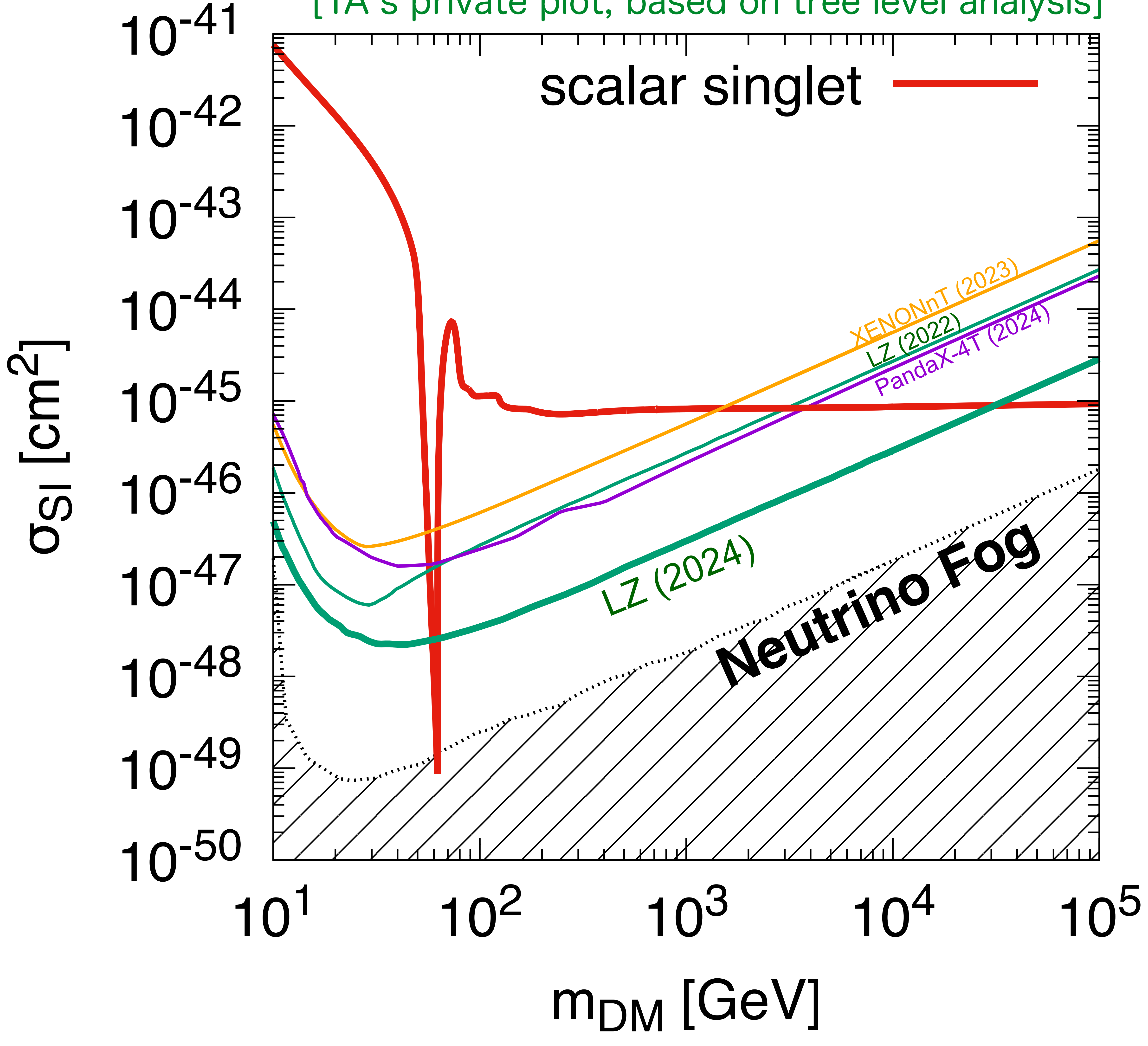
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{\mu_S^2}{2}S^2 - \frac{\lambda_S}{24}S^4 - \frac{\lambda_{hS}}{2}S^2 H^\dagger H$$

- S : DM candidate
- H : SM Higgs doublet

- the only coupling connect SM and DM sectors
- determined to obtain $\Omega h^2 = 0.12$
- $\sigma_{\rm SI} \propto \lambda_{hS}^2$
- let' see the current status from direct detection exp. (see next slide)

typical result with direct detection experiment

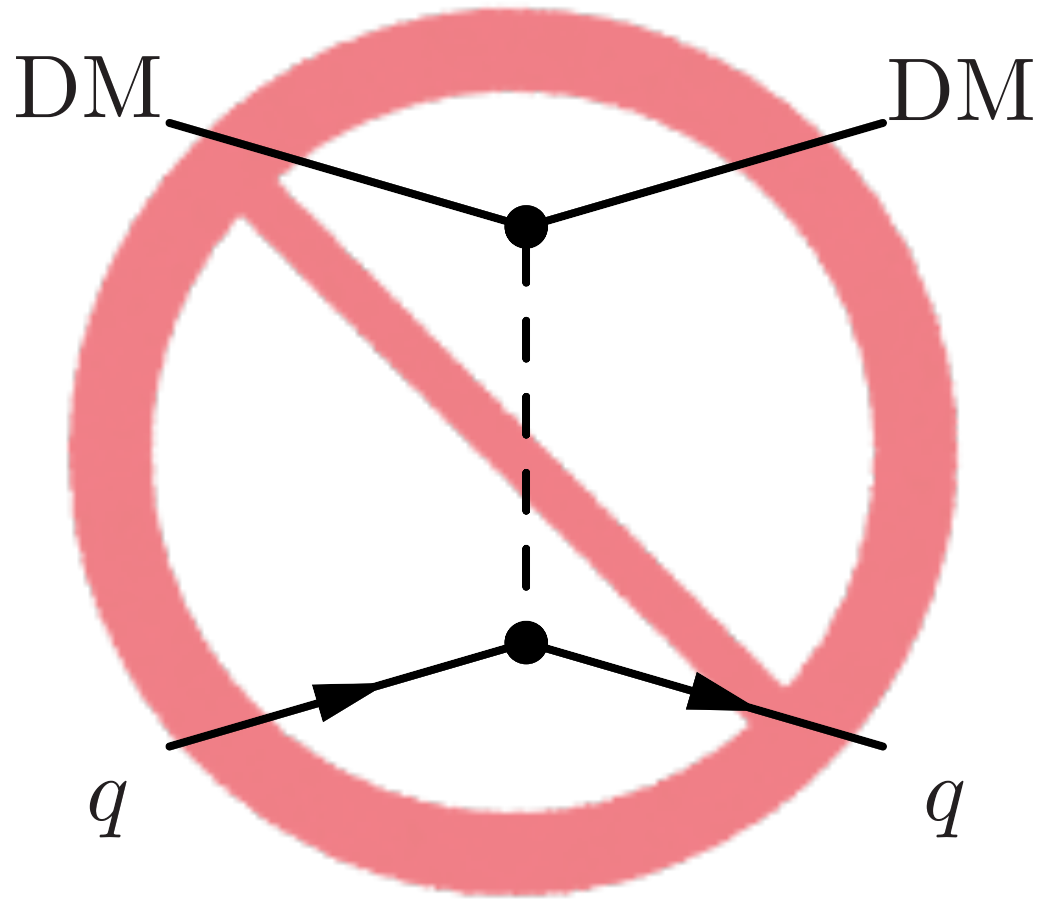
[TA's private plot, based on tree level analysis]

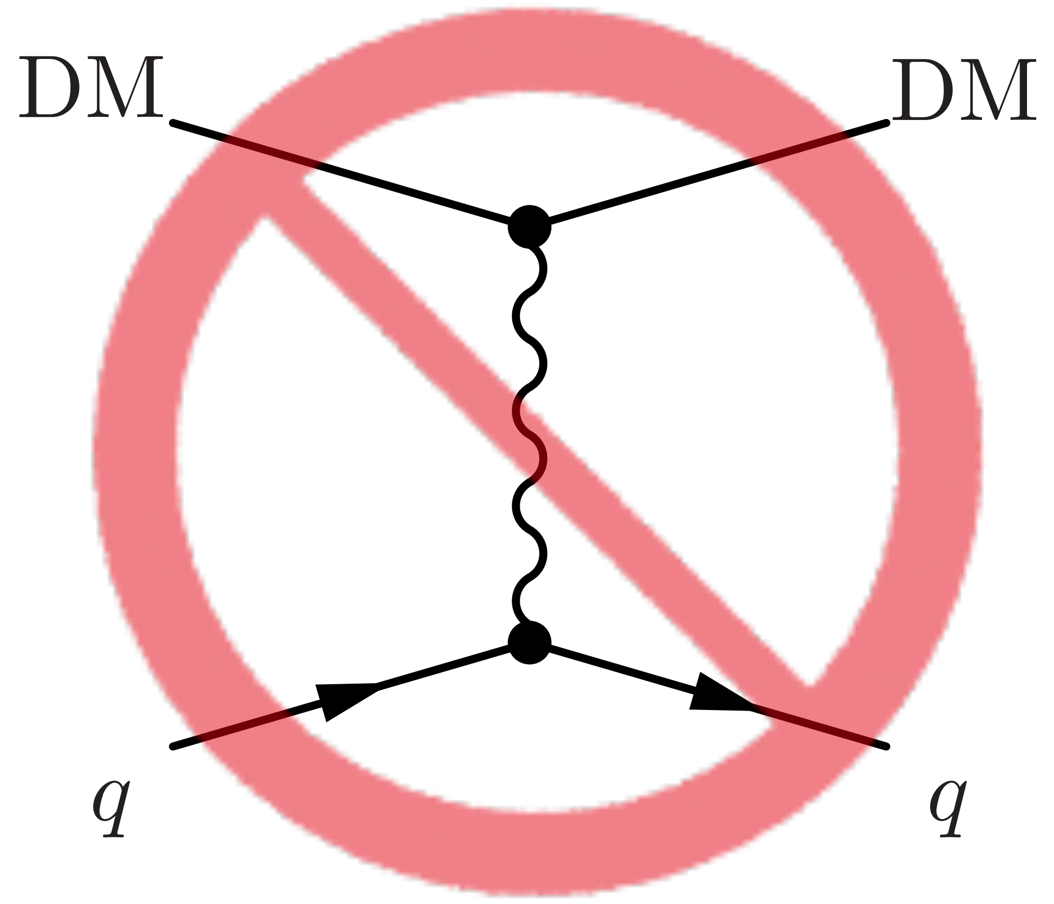


[see also Bharadwaj+ (2412.13301) for loop crrections]

- the coupling is determined to obtain $\Omega h^2 = 0.12$
- almost excluded for m_{DM} < O(10) TeV
- (see also Bharadwaj+ (2412.13301) for loop crrections)
- other typical simple models are similarly excluded

This result implies that σ_{SI} should be zero at the tree level

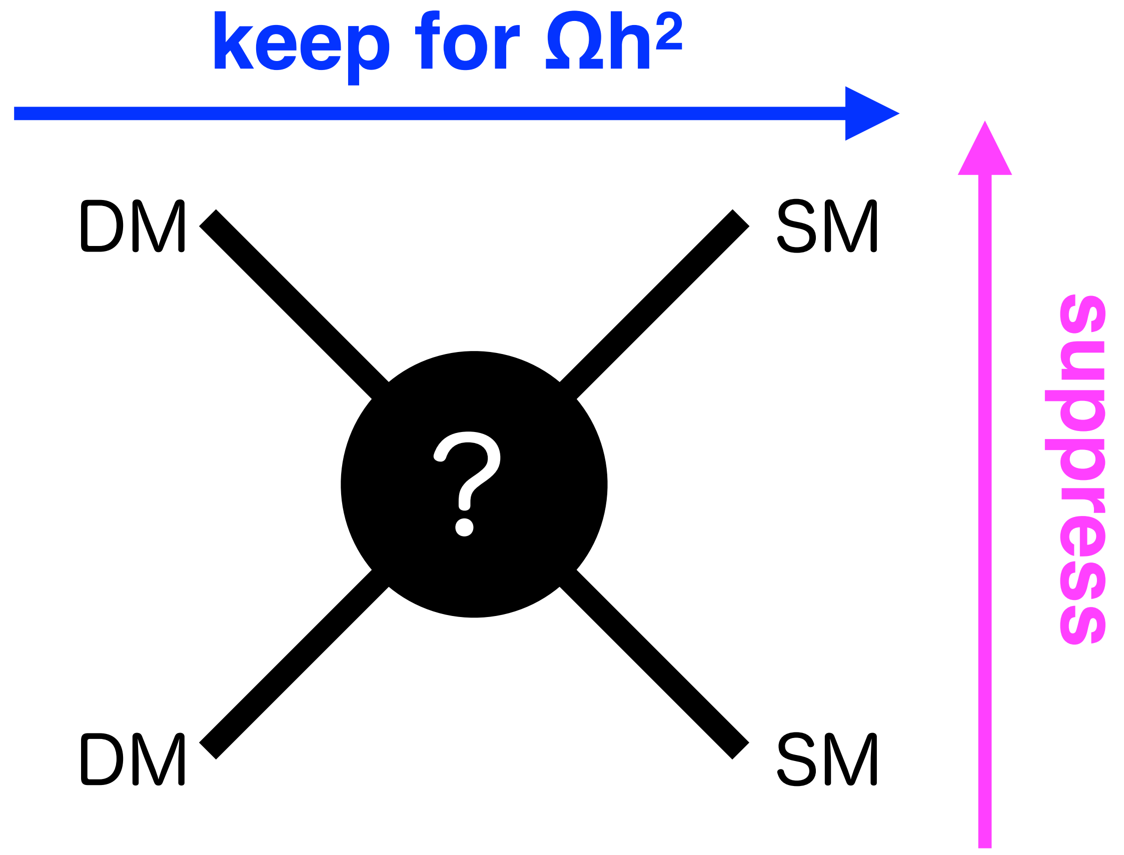




current status of WIMP

need to break the naive expectation from the crossing symmetry

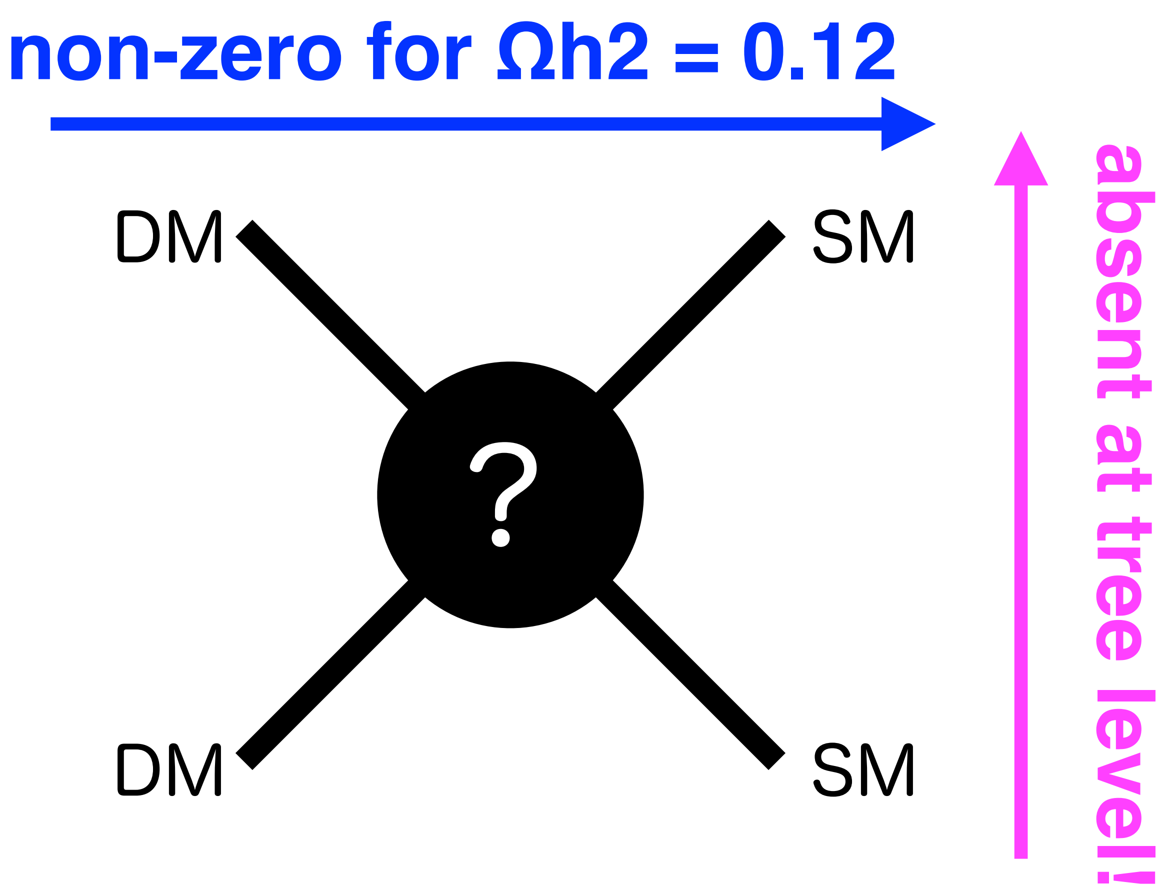
$$(\sigma v)_{\text{ann.}} \propto \frac{\lambda^2}{m_{\text{DM}}^2} \xrightarrow[\text{from crossing symmetry}]{\text{naive expectation}} \sigma_{\text{scat.}} \propto \cancel{\frac{\lambda^2}{m_{\text{DM}}^2}}$$



How to suppress σ_{scat} while keeping σ_{ann}?

1) find models without DM-nucleon elastic scattering
   - forbid DM-DM-Z, DM-DM-h couplings
2) find models suppressing DM-nucleon elastic
   - momentum dependent amplitude
3) and other ideas (multi-component DM, secluded DM, inelastic DM, …)

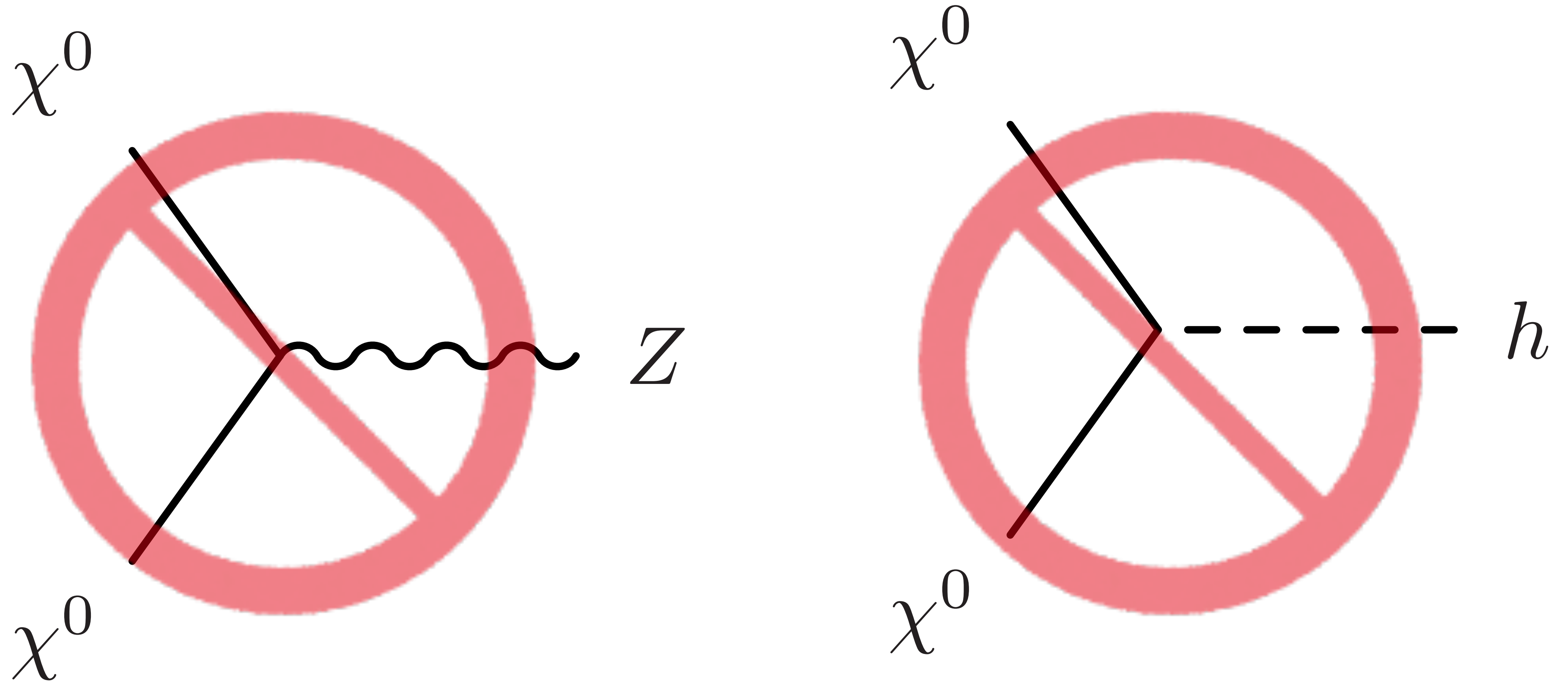
Models without DM-quark elastic scattering



Electroweakly interacting DM (eWIMP)

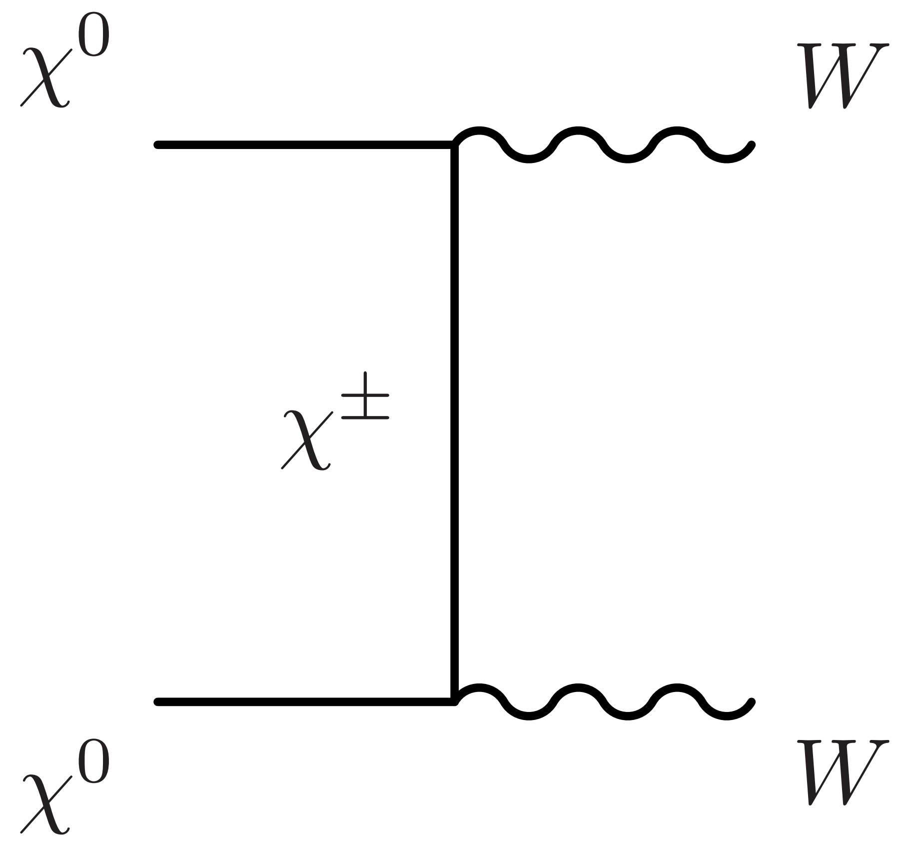
- SU(2)L multiplet ($\chi^0, \chi^\pm, \cdots$)
- the neutral component χ^0 is DM
- (e.g.) Higgsino, Wino, minimal DM, spin-1, ⋯

$\chi^0\chi^0 Z$ and $\chi^0\chi^0 h$ couplings are absent at tree level



→ No DM-nucleon scattering at tree level

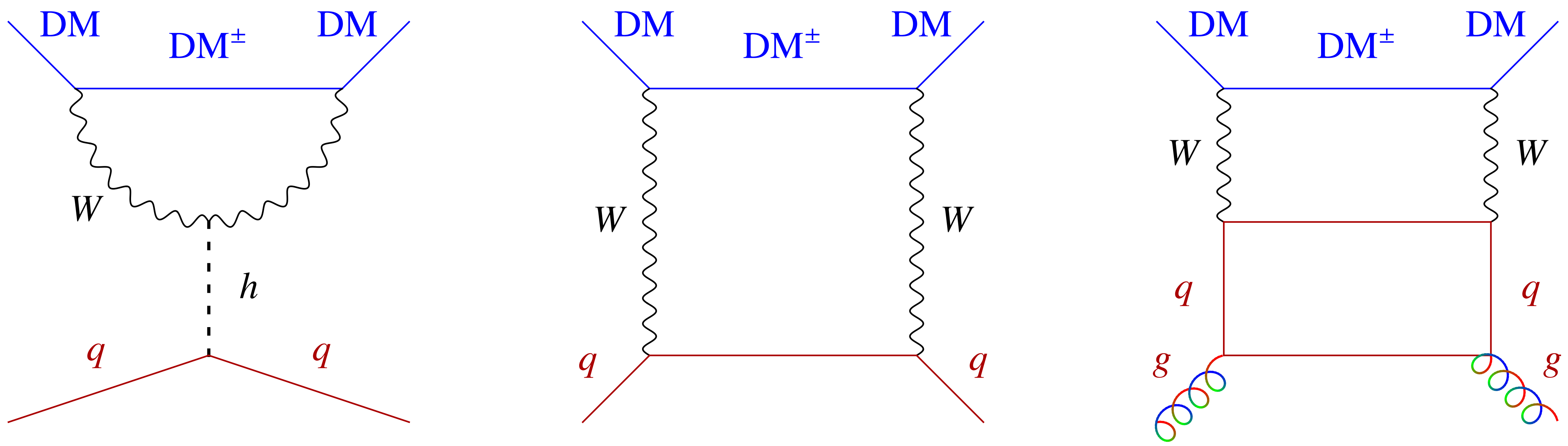
$\Omega h^2 = 0.12$ is explained by $\chi^0\chi^0 \to WW, \cdots$

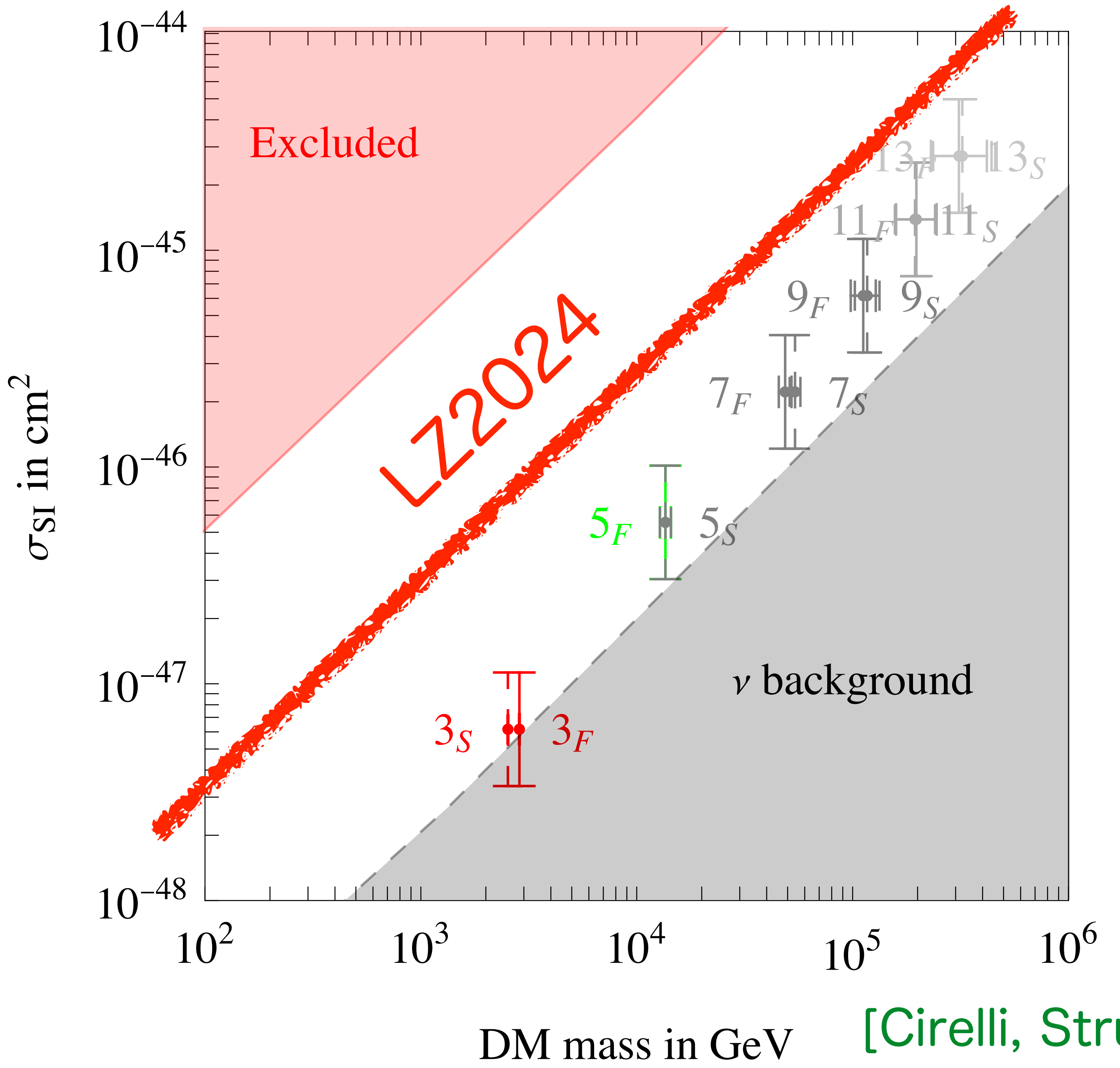


→ keep annihilation for $\Omega h^2 = 0.12$

eWIMP and direct and indirect detections

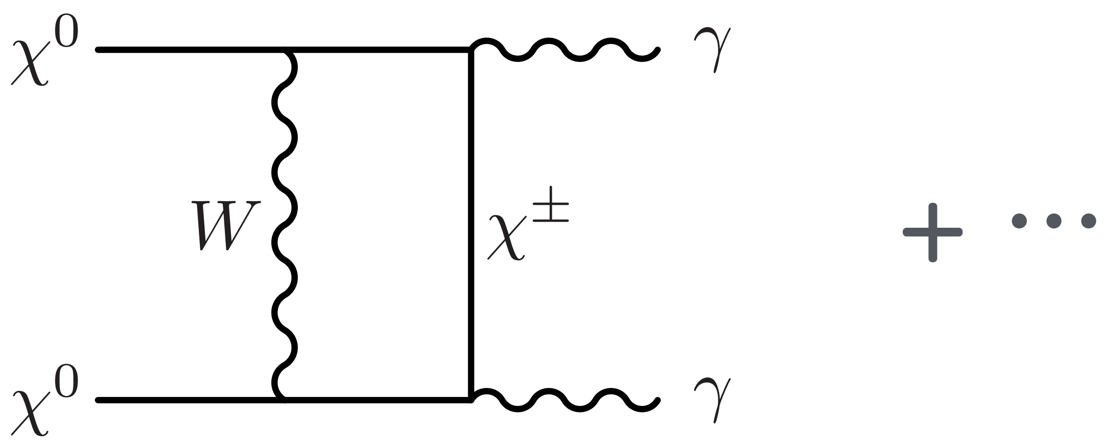
σ_{SI} is induced at loop level [Hisano, Ishiwata, Nagata ('15)]



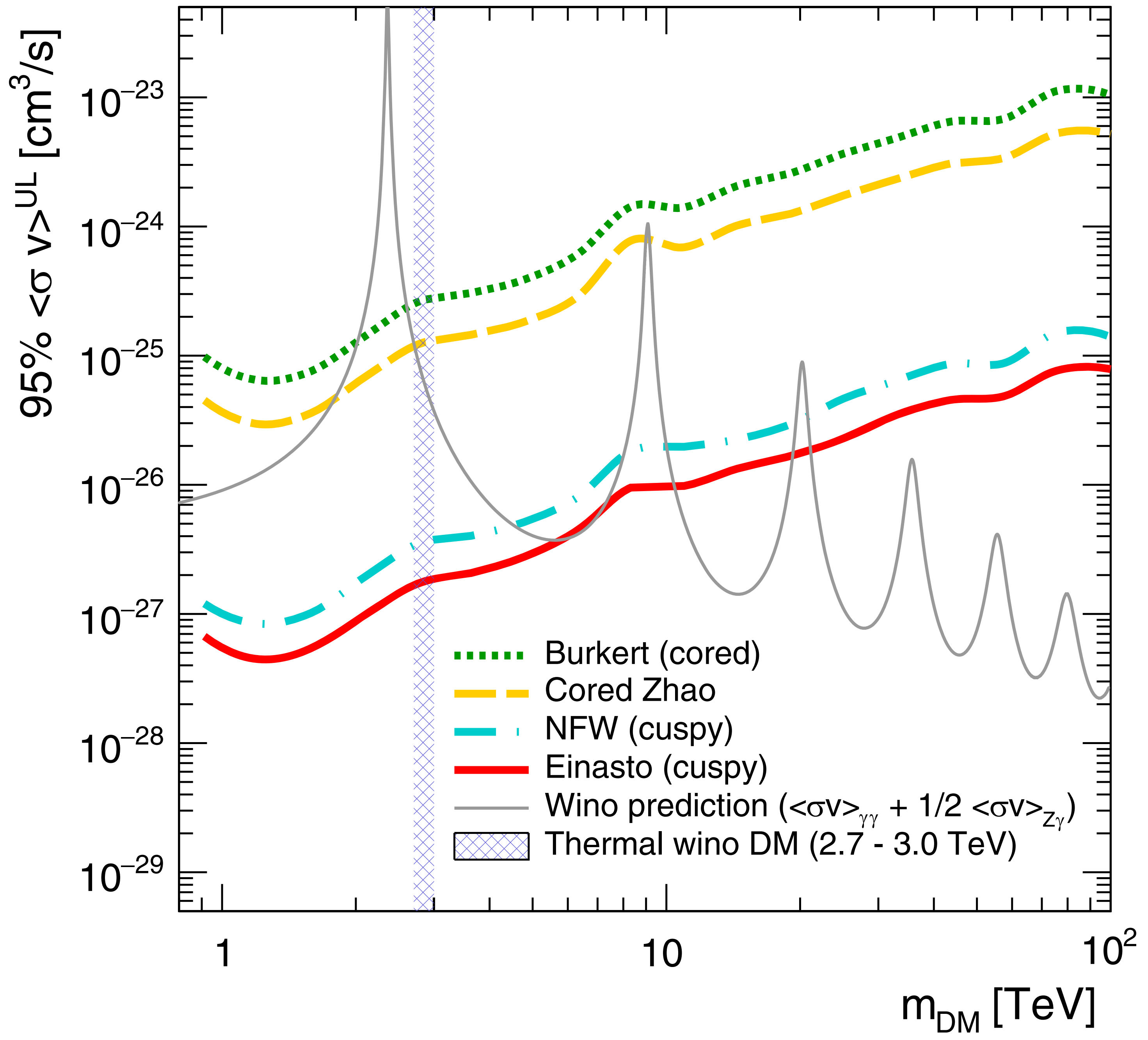


[Cirelli, Strumia, Zupan 2406.01705)]

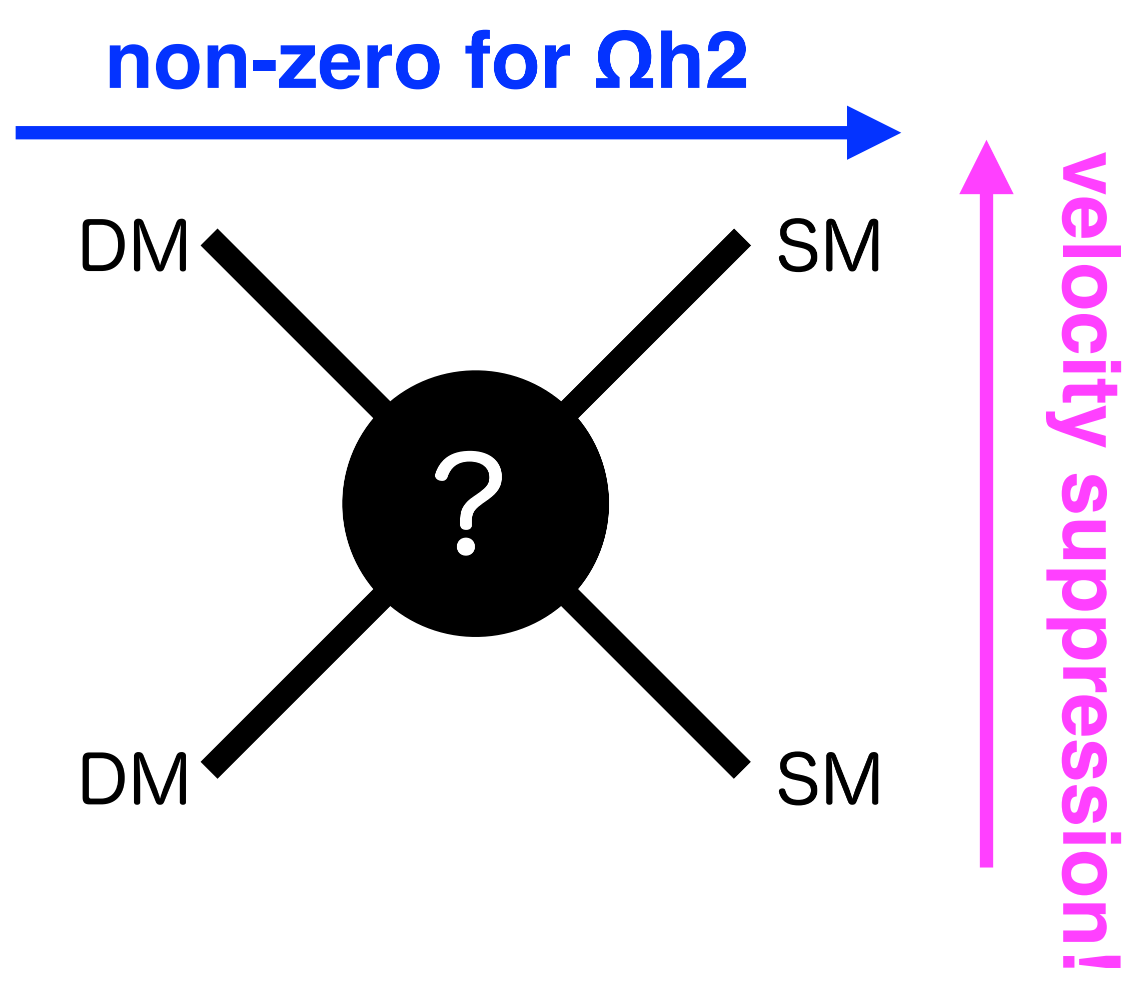
indirect detection (gamma-ray)



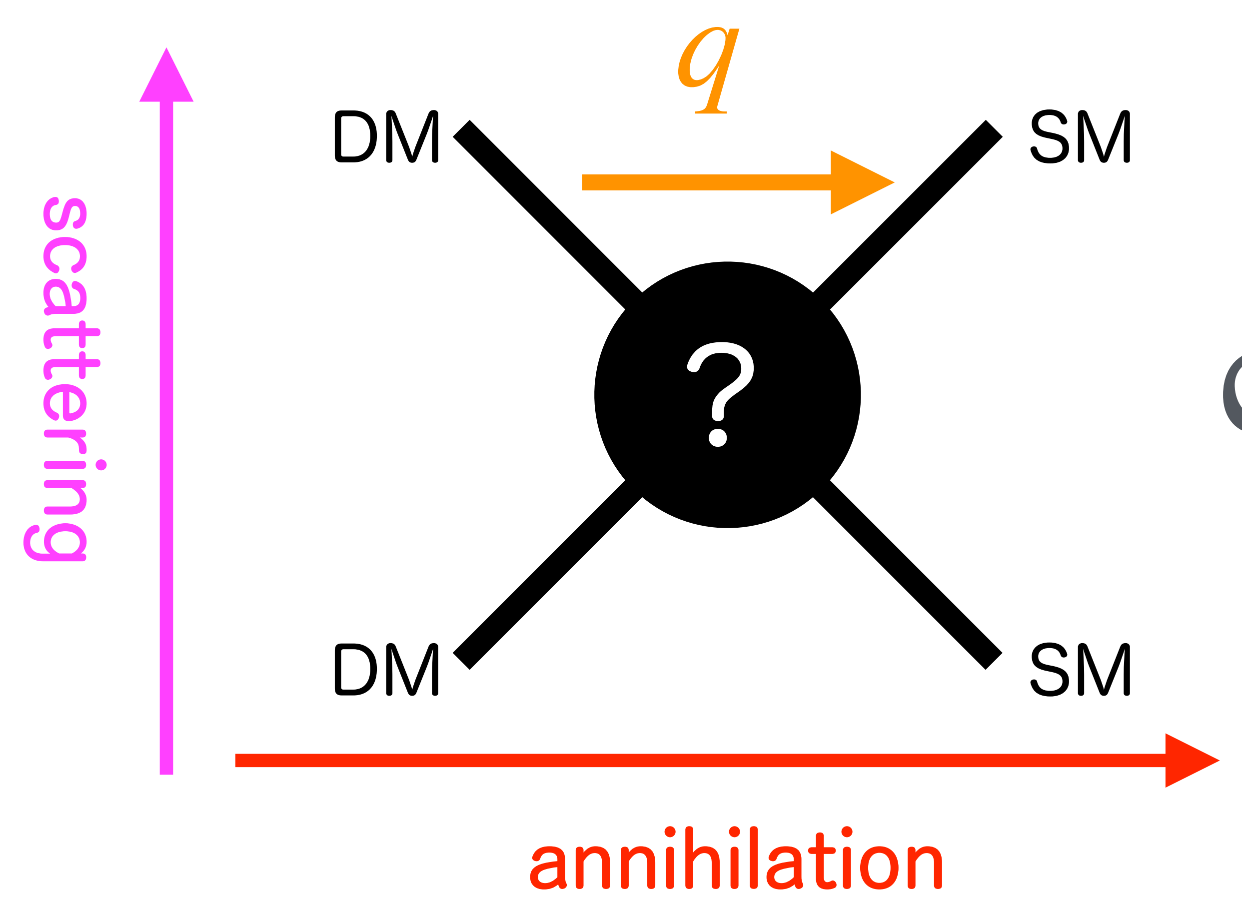
[MAGIC collaboration (PRL 130. 061002)]



spin-1/2 DM Models with momentum-suppressed DM-quark elastic scattering



Amplitude depending on momentum transfer



$\propto q^n$

- $q \simeq$ m$_{\rm DM}$ @annihilation
- $q \simeq 0$ @direct detection

$\to$ if $n > 0$, $\sigma_{\rm scat.} \simeq 0$ while $\langle \sigma v \rangle_{\rm ann.}$ is kept

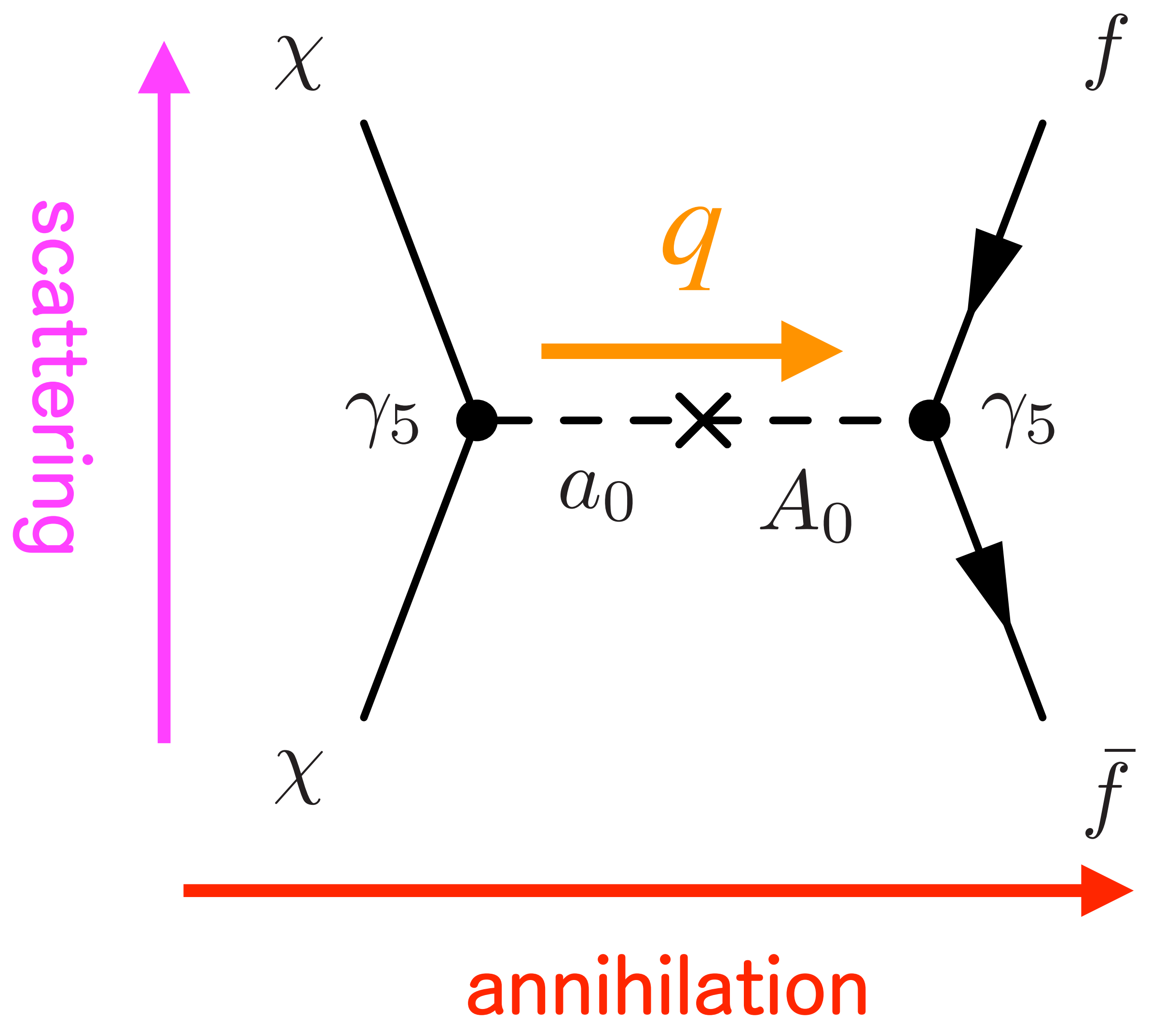
(n = 0 for the previous examples)

If amplitude depends on momentum transfer from DM sector to visible sector, we can suppress the scattering amplitude in direct detection while keeping the annihilation process

example models for the momentum dependent scattering amplitude

THDM + a [Ipek, McKeen, Nelson ('14), Baek, Ko, Li ('17); Ghorbani ('15), TA Fujiwara Hisano ('19), TA Fujiwara Hisano Shoji ('20), ⋯]

- gauge singlet spin-1/2 DM χ coupling to a gauge singlet CP-odd scalar a_0 : $\bar{\chi}\gamma^5\chi a_0$
- the Higgs sector is extended to the two-Higgs doublet model (THDM)
- THDM contains another CP-odd state A_0 coupling to the SM
- mixing of a_0 and A_0 connect the dark and visible sector



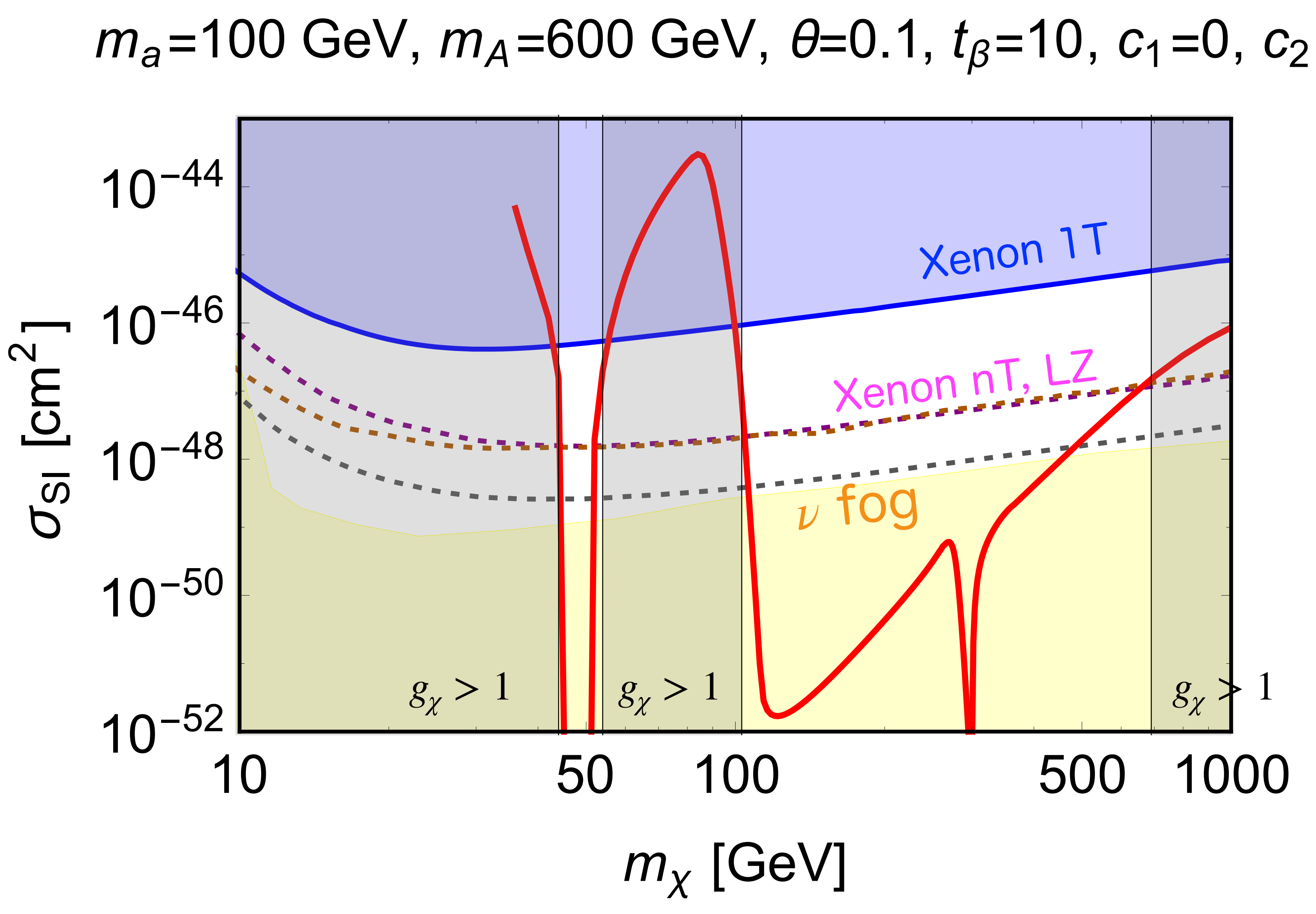
$$\propto \begin{cases} \bar{v}(p)\gamma^5 u(p) \simeq m_{\rm DM} & \text{(annihilation)} \\ \bar{u}(p)\gamma^5 u(p) \simeq \vec{q}\cdot\vec{\sigma} & \text{(scattering)} \end{cases}$$

momentum dependence suppresses $\sigma_{\rm SI}$ while keeping $\langle\sigma v\rangle_{\rm ann.}$!

Phenomenology of THDM+a

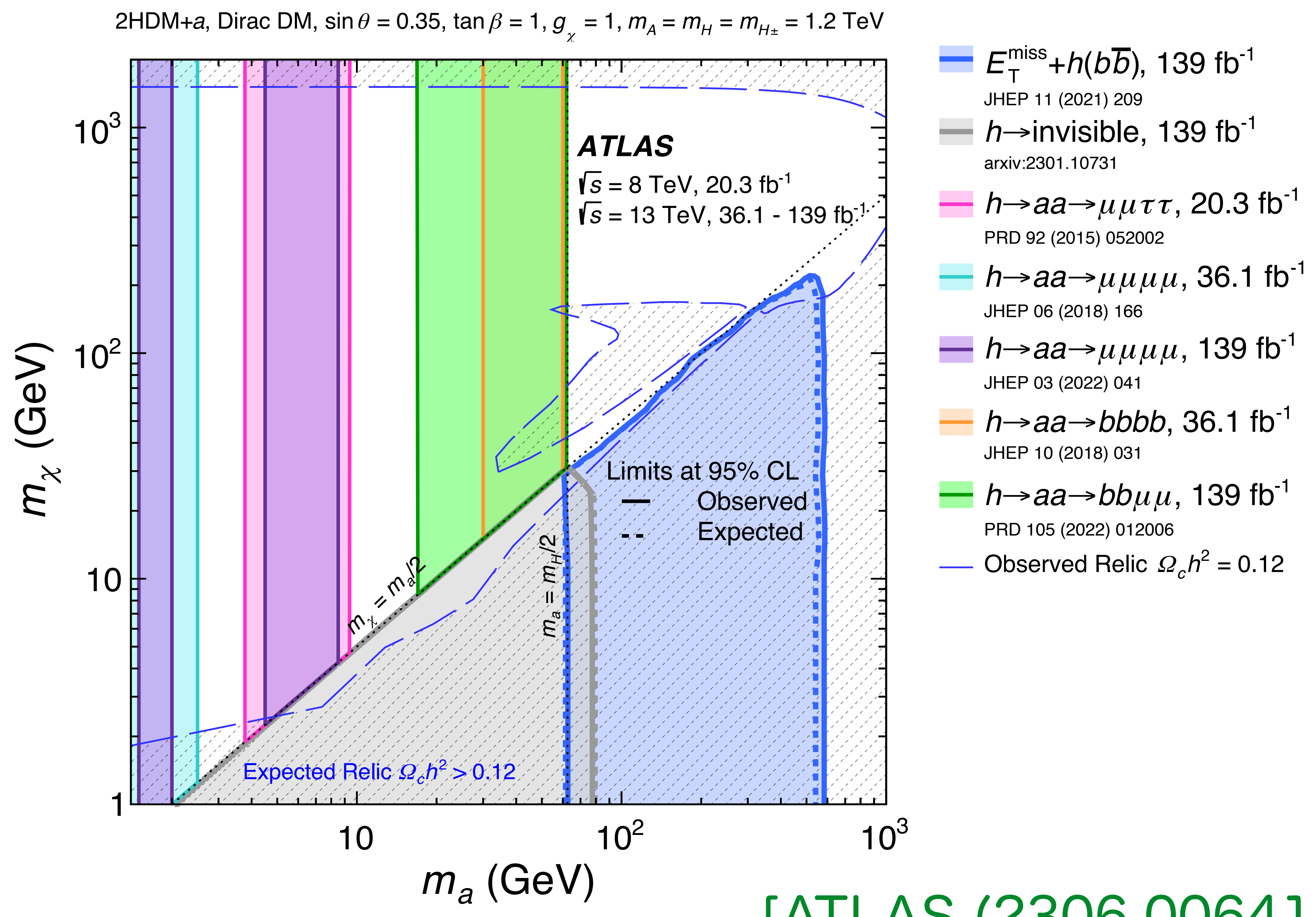
highly depends on the model parameters

σ_{SI} can be above the ν fog at loop level



[TA Fujiwara Hisano ('19)]

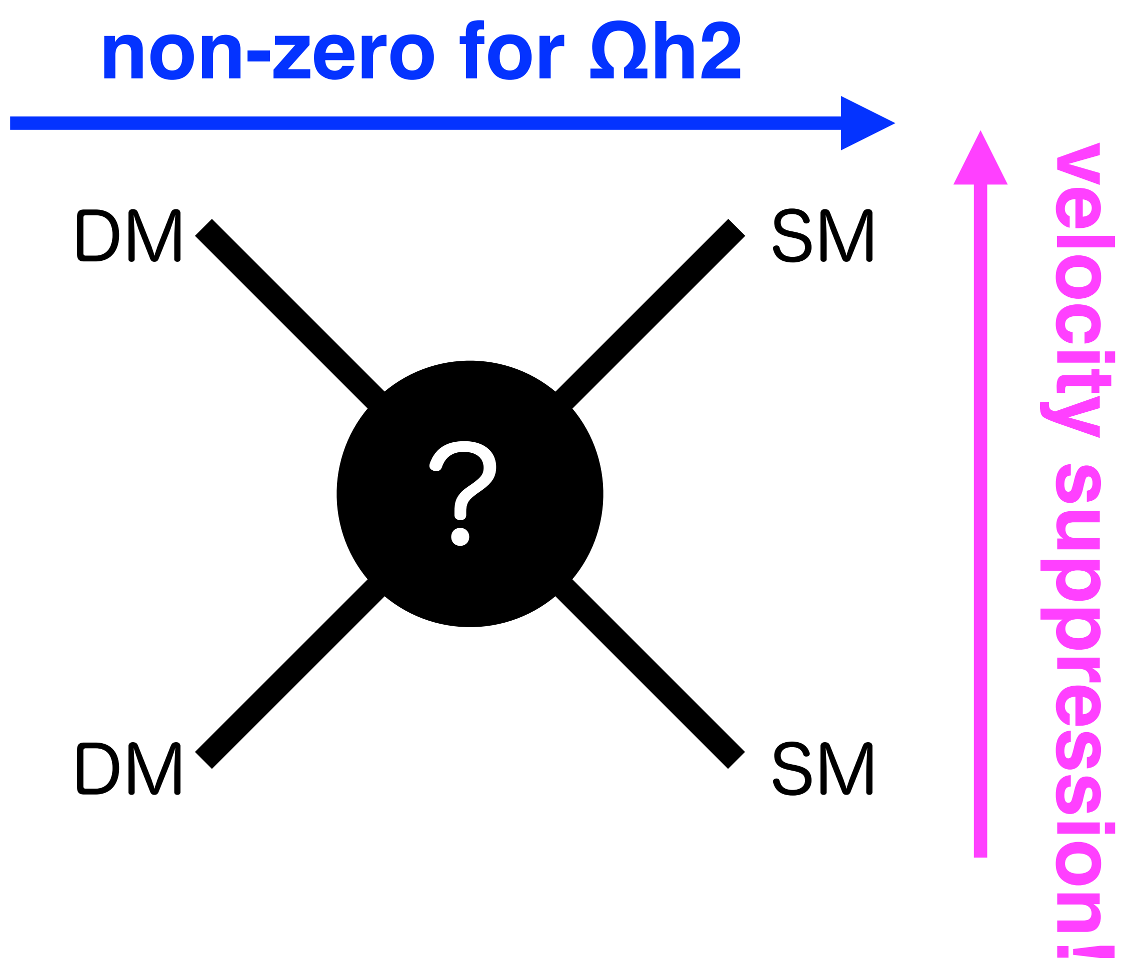
collider searches constrain parameter space



[ATLAS (2306.00641)]

- gravitational waves from 1st order phase transition [Arcadi+ (2212.14788)]
- see also [LHC DM working group (https://lpcc.web.cern.ch/content/dark-matter-wg-documents)]

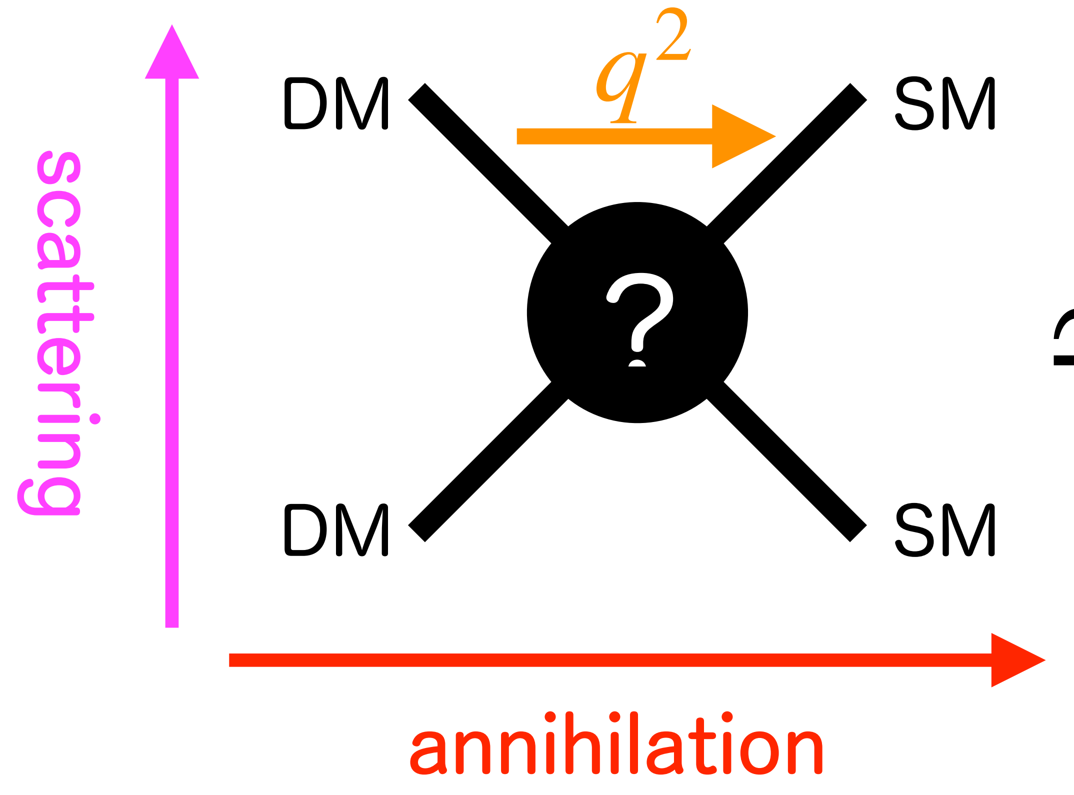
spin-0 DM Models with momentum-suppressed DM-quark elastic scattering



pseudo-Nambu-Goldstone (pNG) DM

pseudo-Nambu-Goldstone (pNG) DM [Gross, Lebedev, Toma ('17)]

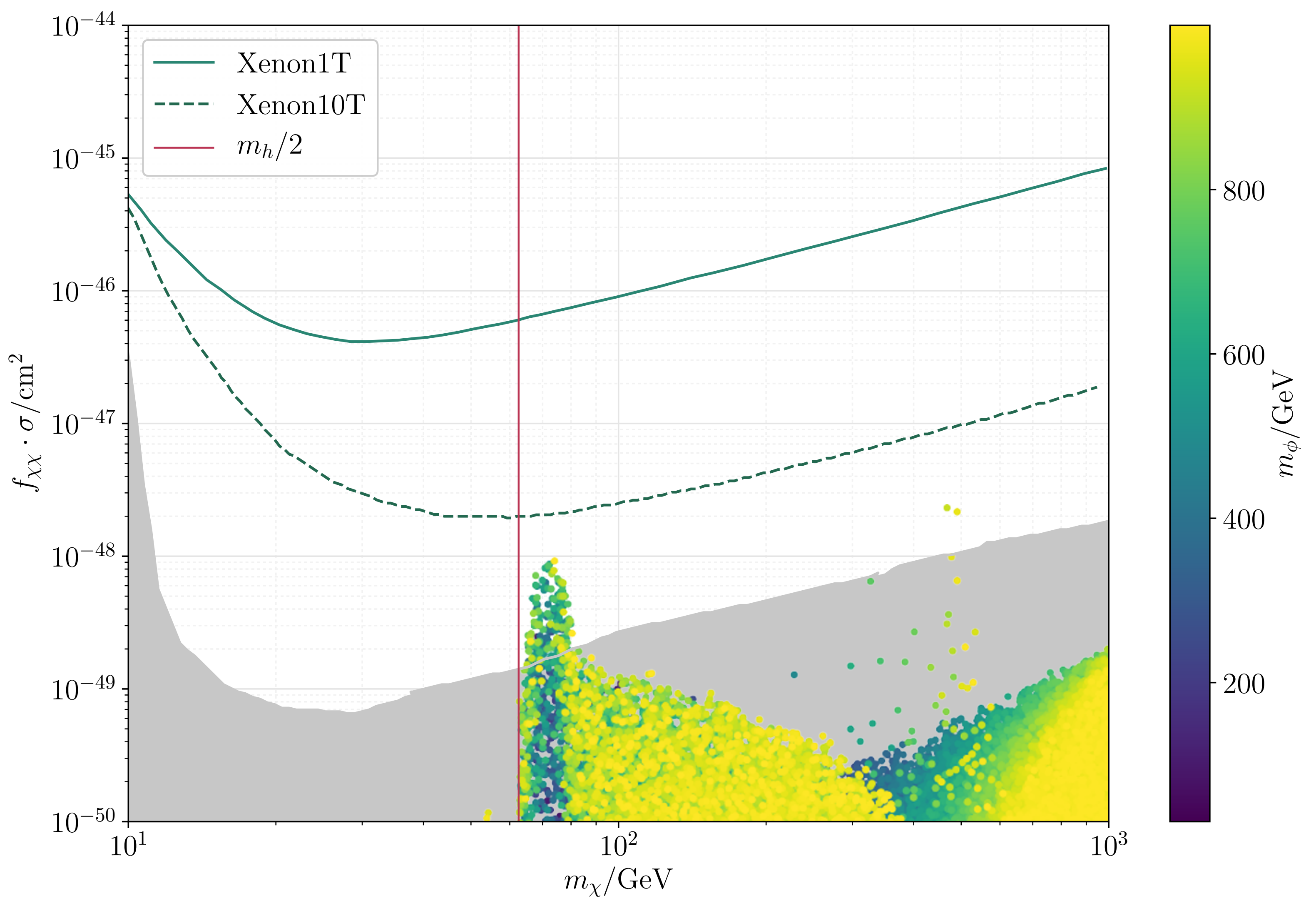
- arise from spontaneous symmetry breaking of global symmetry
- utilize the NG boson low energy theorem: amplitude depends on momentum squared



$\simeq q^2$

➡ $\sigma_{\rm SI}$ = 0 at tree level while keeping $\langle \sigma v \rangle$

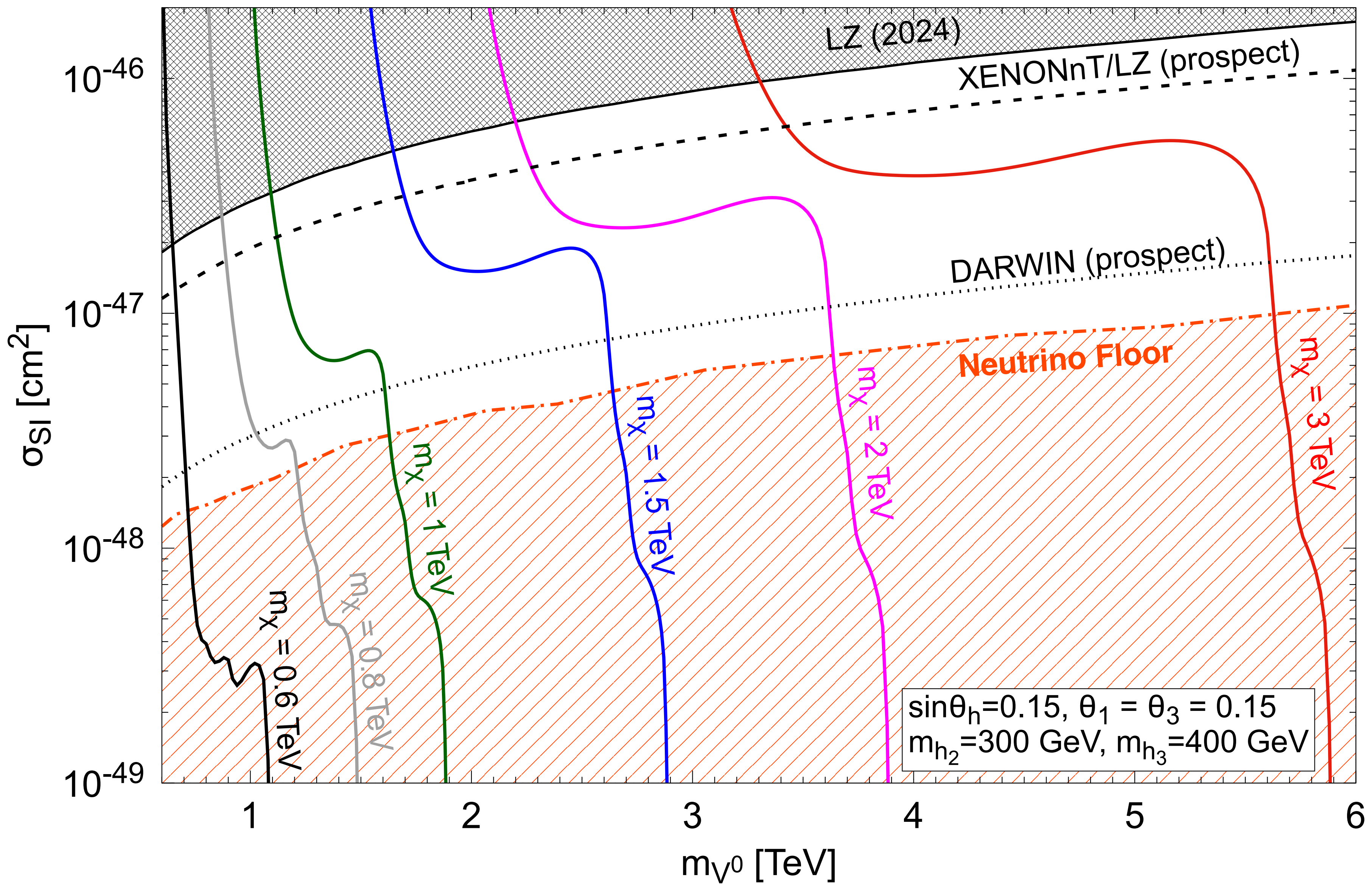
$\sigma_{\rm SI}$ is tiny even at the loop level



[Ishiwata+ ('18), Azevedo+ ('19), Glaus+ ('20)]

$\sigma_{\rm SI}$ can be above the ν-fog in two-component models (pNG + WIMP)

[TA Ichiki (2411.15755)]



Summary

current status of WIMP

- the direct detection experiments give strong constraint
- need to suppress the DM-nucleon elastic scattering
- simple models are excluded

WIMP is not dead!

- there are many models predicting tiny σ_{SI}
- wino, Higgsino, minimal DM, THDM+a, PNG DM, …
- it is important to see the correlation among various observables (direct detection, indirect detection, collider, …) to figure out the right WIMP model