Overview on Dark Matter Models

11/9/2020
Masahiro Ibe (ICRR)

Dark Matter ?

- DM makes up ***27%*** of total energy and ***85%*** of matter

$\Omega_{DM} h^2 \sim 0.14$ $\quad\quad$ $\Omega_B h^2 \sim 0.022$ $\quad\quad$ $0.0006 < \Omega_\nu h^2 < 0.0013$

(Planck 2018 : $\Omega_X = \rho_X / 3 M_{PL}^2 H_0^2$, $H_0 = 100h$ ***km/s/Mpc,*** $h \sim 0.7$***)***

- Neutral (does not couple to photon)

- Cold (small velocity dispersion at matter radiation equality)

  Neutrinos have a large velocity dispersion and erases structures smaller than ~***10Mpc*** and hence are ***HOT***.

- Stable or very long lived

  The lifetime should be much loner than the age of the universe, ***10^{17} sec***

  (detailed constraints depend on the daughter particles)

There are Many Candidates ...

✓ ***Stability (not exclusively categorized)***

- ✓ Stability by Symmetry

  The lightest particle charged under a new symmetry is stable.

  New Symmetry ↔ New Dark Matter Candidates

  ex) Weakly Interacting Massive Particle (WIMP)

  ex) Asymmetry Dark Matter (ADM)

- ✓ Stability due to very weak coupling

  A new particle which couples to other particle very very weakly can have a long lifetime.

  ex) Feebly Interacting Massive Particle (FIMP)

  ex) Sterile Neutrino Dark Matter

✓ ***Stability (not exclusively categorized)***

✓ Very Light Particle

$$[\textit{Decay Rate}] \propto m_{DM}^{n} \quad (n>0)$$

→ Very light particles have long lifetimes.

ex) Axion Dark Matter : $m_{DM} < O(1\text{-}10)\ \mu eV$

ex) Fuzzy Dark Matter : $m_{DM} < 10^{-21}\ eV$

✓ Very Heavy Particle

Point-like particles heavier than M_{PL} are Black Holes !

$$l_{compton} \sim m_{DM}^{-1} < m_{DM}/M_{PL}^{2} \sim \textit{Schwartzchild Radius}$$

They only evaporate by Hawking radiation

$$T_{BH} \sim M_{PL}^{2}/m_{DM} \rightarrow \tau_{BH} \sim m_{DM}/T_{BH}^{4} R_{BH}^{2}$$

$$\tau \gg [\textit{age of the universe}] \rightarrow m_{DM} \gg 10^{38}\ GeV \sim 10^{-19} M_{\odot}$$

ex) Primordial Black Hole (PBH)

✓ *Mass Range ?*

✓ Lower Limit (Uncertainty principle $\Delta x \Delta p > 1$)

$$\begin{cases} \Delta p = m_{DM}\,\Delta v \\ \text{Dwarf Spheroidal Galaxy (dSphs)} : \Delta x \sim 1\ \text{kpc}\,,\ \Delta v \sim 10\ \text{km/s} \end{cases}$$

$$m_{DM} > 6 \times 10^{-22}\text{eV}$$

[e.g. 1906.11848 Safarzadeh, Spargel]

✓ Lower Limit (Fermi's exclusion principle)

For a fermionic dark matter localized spatially, there is an upper limit on the number of dark matter from the Fermi's exclusion principle.

$$N_{max} = \frac{4\pi}{3} R^3 \int \frac{d^3\,p}{(2\pi)^3}\theta(p_F - p) \sim \frac{4\pi}{3} R^3\, p_F^3 \qquad p_F \sim m_{DM}(\Delta v^2)^{1/2}$$

For a dwarf galaxy $\Delta v \sim 10\ \text{km/s}$, $R \sim 1\text{kpc}$

$$N = M_{Halo}/m_{DM} < \frac{4\pi}{3} R^3\, p_F^3$$

$$\rightarrow m_{DM} > 2\text{keV}$$ **[1712.04597, *Wang et.al.*]**

✓ ***Mass Range ?***

✓ Upper Limit

DM mass should be much smaller than the mass of the dSphs

$$m_{DM} \ll 10^{10} M_\odot \sim 10^{67}\mathrm{GeV}$$

PBH DM with mDM > $10^{3} M_\odot$ is constrained from the CMB constrraint caused by accretion onto the PBHs:

$$m_{DM} < 10^{3} M_\odot \sim 10^{60}\mathrm{GeV}$$

Model Independent Mass Range

$$10^{-22}\,\mathrm{eV}\ \ (2\mathrm{keV}) < m_{DM} < 10^{60}\mathrm{GeV}$$

✓ *How many DM goes through us ?*

$$n_{\rm DM} \simeq \frac{0.004}{\rm cm^3}\left(\frac{100\,{\rm GeV}}{m_{\rm DM}}\right)$$

$$\mathscr{F}_{\rm DM} \simeq \frac{9.2\times 10^4}{\rm cm^2\,s}\left(\frac{100\,{\rm GeV}}{m_{\rm DM}}\right)\left(\frac{v_{\rm DM}}{230\,{\rm km/s}}\right)$$

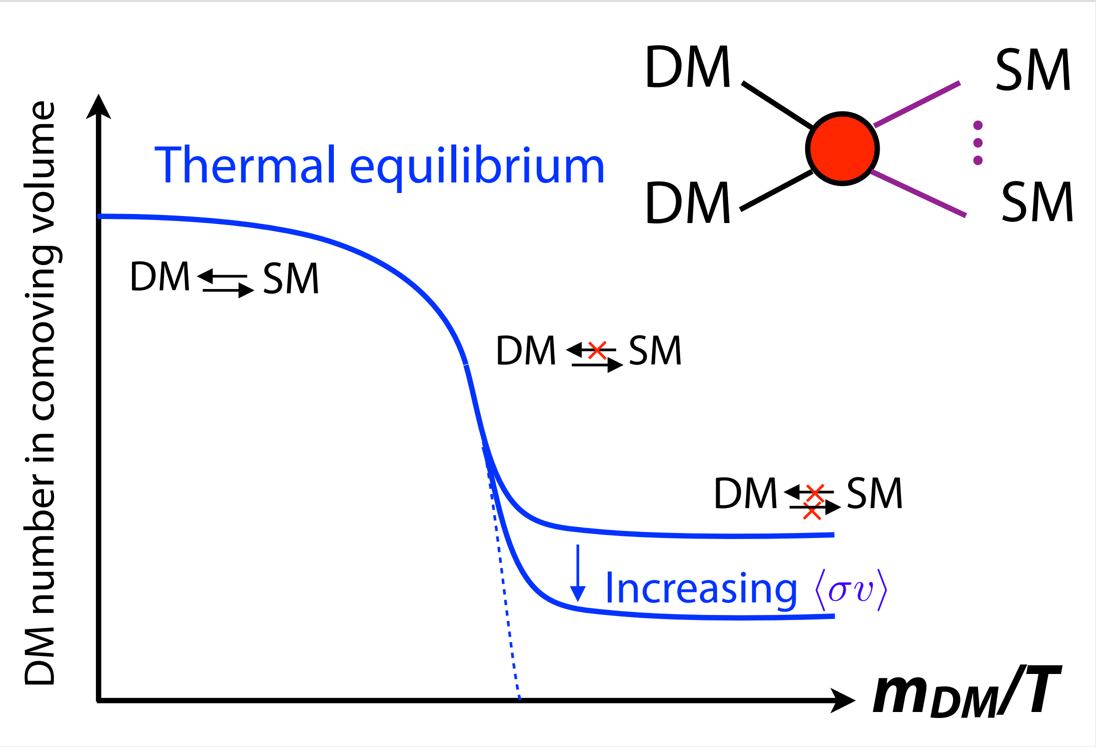
$$n_{\rm DM} \simeq \frac{0.0001}{\rm pc^3}\left(\frac{1\,M_\odot}{m_{\rm DM}}\right)$$

$$\mathscr{F}_{\rm DM} \simeq \frac{2.6\times 10^{-45}}{\rm cm^2\,yr}\left(\frac{1\,M_\odot}{m_{\rm DM}}\right)\left(\frac{v_{\rm DM}}{230\,{\rm km/s}}\right)$$

$$M_\odot \simeq 1.116\times 10^{57}\,{\rm GeV} \qquad M_\odot/{\rm pc}^3 \simeq 37.99\,{\rm GeV/cm^3}$$

WIMP

WIMP abundance



- DM is in thermal equilibrium for ***T* > *m*** $T > m_{DM}$.
- For $m_{DM} < T$, DM is no more created
- DM is still annihilating for $m_{DM} < T$ for a while...
- DM is also diluted by the cosmic expansion
- DM cannot find each other and stop annihilating at some point
- DM number in comoving volume is frozen

Boltzmann Equation :

$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = -\langle\sigma v\rangle(n_{\rm DM}^2 - n_{\rm eq}^2) \qquad n_{eq} \propto e^{-m_{DM}/T}$$

✓ Number density (per comoving) is fixed when :

DM cannot be produced from thermal bath : $T_F \sim m_{DM}/20$

DM cannot find its partner for annihilation any more : $<\sigma v>\ n_{DM} < H$

$$n_{DM} \sim H/<\sigma v> \text{ at } T_F$$

✓ WIMP abundance

$$\rho_{DM}/s = m_{DM}\, n_{DM}/s$$

$$\begin{cases} s \propto T^3 \propto a^{-3} & \text{: entropy density} \\ n_{DM} \propto a^{-3} & \end{cases}$$

$$\rho_{DM}/s \text{ is constant in time}$$

After freeze out (= mean free path > the size of the Universe ($\sim H^{-1}$))

$$\rho_{DM}/s = m_{DM} H/\langle\sigma v\rangle s \sim 20/\langle\sigma v\rangle M_{PL}$$

is constant in time.

$$\Omega_{DM} h^2 \sim 0.1 \leftrightarrow \rho_{DM}/s \sim 10^{-10}\,\mathrm{GeV}$$

DM abundance (for s-wave annihilation)

$$\Omega_{DM} h^2 \simeq 0.1 \times \left(\frac{10^{-9}\,\mathrm{GeV}^{-2}}{\langle\sigma v\rangle} \right)$$

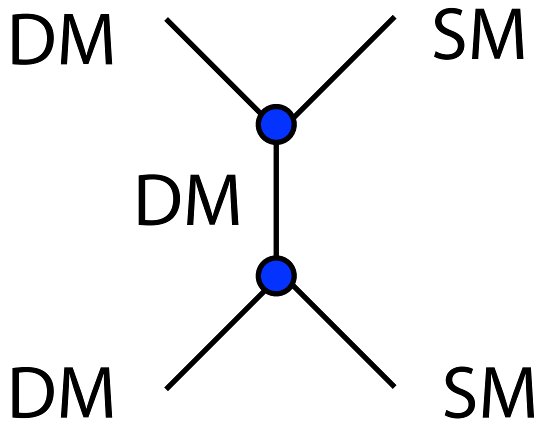
✓ Abundance depends on the DM mass only through ***$\langle\sigma v\rangle$!***

✓ *WIMP Miracle !*

DM abundance (for s-wave annihilation)

$$\Omega_{DM}h^2 \simeq 0.1 \times \left(\frac{10^{-9}\,\mathrm{GeV}^{-2}}{\langle\sigma v\rangle}\right)$$

- ✓ Typical Annihilation Cross section :



$$\boldsymbol{\langle\sigma v\rangle \sim \frac{\pi\,\alpha^2}{m_{DM}^2}}$$

- ✓ Observed Dark Matter Density can be explained for

$m_{DM} \sim O(100)\mathrm{GeV} - O(1)\ \mathrm{TeV}$ and $\alpha \sim 10^{-2}$

→ *WIMP is interrelated to Big Picture of the Beyond the Standard Model !*

✓ *Mass Range of WIMP*

✓ *Lower Limit on WIMP mass*

Dark matter freezes-out from the thermal bath at around

$$T_F \sim M_{DM}/O(10)$$

for $\langle\sigma v\rangle \sim 10^{-9}\mathrm{GeV}^{-2}$.

Freeze-out should complete before the neutrino decoupling and BBN

$$M_{DM} > O(10)\mathrm{MeV}$$

- ✓ If $m_{DM} < O(1)\mathrm{MeV}$, H is larger for a given T , and (n/p) becomes larger
  → ${}^4He$ abundance is increased compared with Hydrogen abundance.

- ✓ If freeze-out after the neutrino decoupling at $T \sim 1\mathrm{MeV}$, the DM annihilation increases or decreases effective number of the neutrino depending on the branching ratio.

✓ Mass Range of WIMP

✓ Upper Limit on WIMP mass

The heavier the DM is, the larger couplings are required.

$$\langle\sigma v\rangle \sim \frac{\pi\,\alpha^2}{m_{DM}^2} \sim 10^{-9}\mathrm{GeV}^{-2}$$

→ Unitarity Limit on WIMP mass (1990 Griest & Kamionkowski)

Each partial wave cross section is limited from above

$$\sigma_\ell v_{\rm rel} \leq \frac{16\pi(2\ell+1)}{s\, v_{\rm rel}}$$

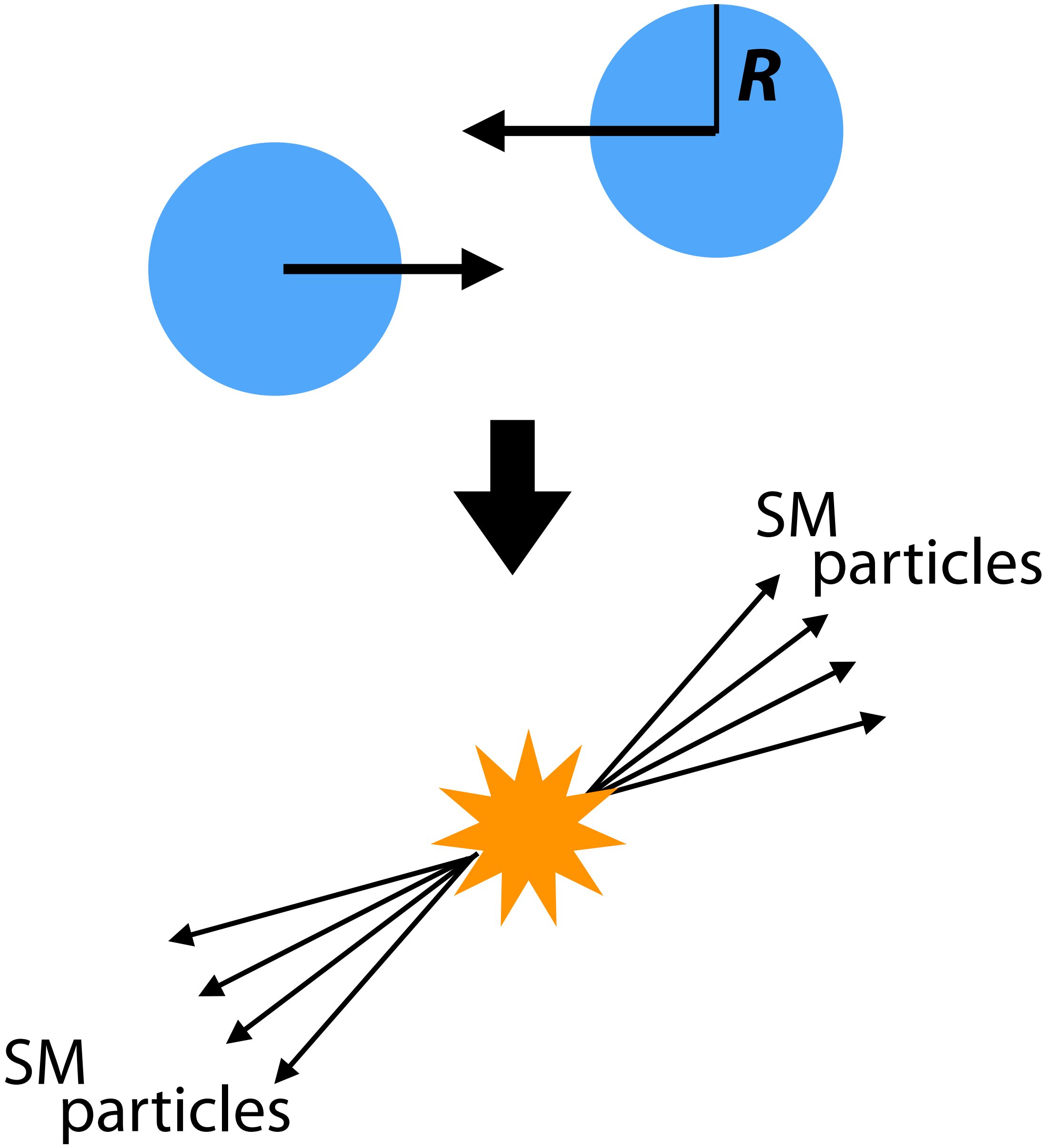
(spineless case for simplicity)

→ $M_{DM} < 300$ **TeV**

WIMP mass range : O(10)MeV < M_{WIMP} < 300TeV

✓ *Thermal WIMP beyond the unitarity limit ?*

- ✓ What if dark matter annihilates as ***extended objets*** with geometric cross sections, ***$\sigma \sim \pi R^2$*** ? (1990 Griest & Kamionkowski)



$L_{MAX} \sim M_{DM}\, v\, R$

$$\sum_{\ell=0}^{L_{\rm MAX}} \sigma_\ell < \sum_{\ell=0}^{L_{\rm MAX}} \frac{4\pi(2\ell+1)}{M_{DM}^2 v^2}$$

$$\sim \frac{4\pi L_{\rm MAX}^2}{M_{DM}^2 v^2} = 4\pi R^2$$

consistent with unitarity limit !

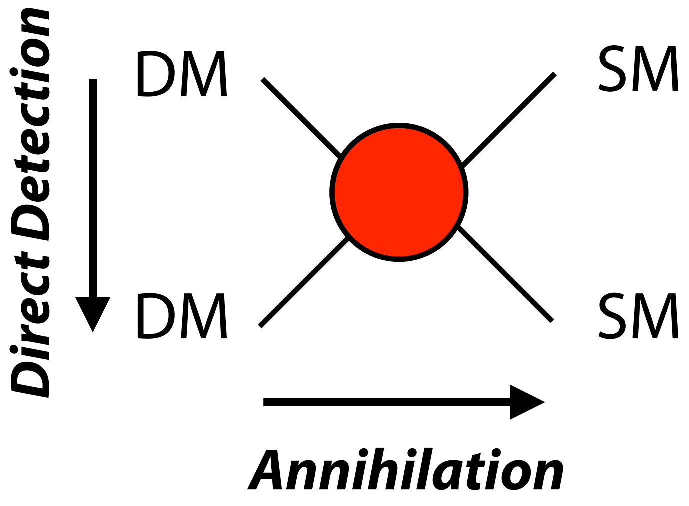
For ***$R \gg 1/(M_{DM}\, v)$***, we may have thermal relic dark matter much heavier than ***O(100)TeV !***

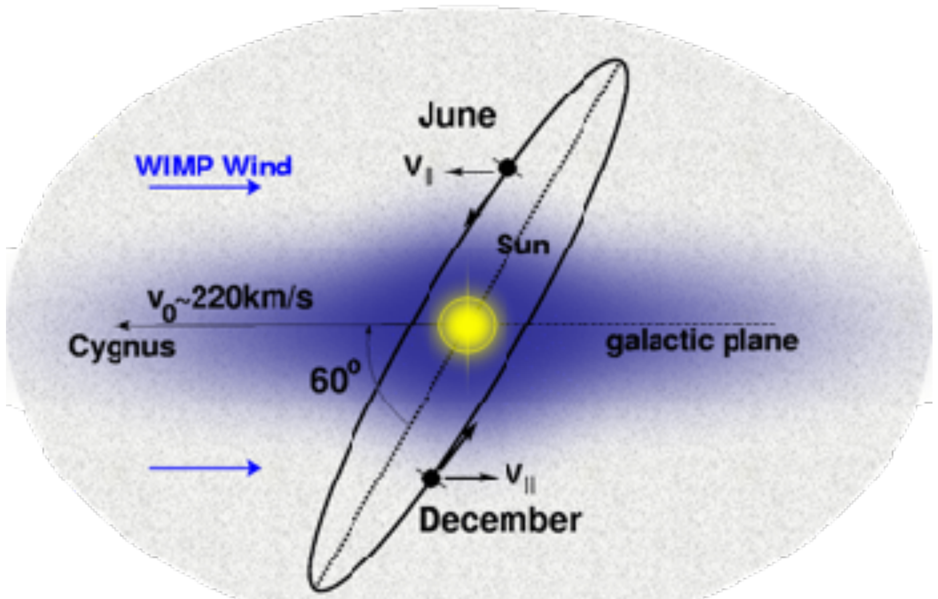
Model Building is complicated though…

see e.g. Harigaya, MI, Kaneta, Nakano, Suzuki JHEP 1608 (2016) 151

Direct WIMP Detection

By design, the WIMP is likely to be detected by direct detection!





https://www.hep.shef.ac.uk/research/dm/intro.php

solar velocity : ***(0, 220 , 0) + (10 , 13 , 7) km/s***

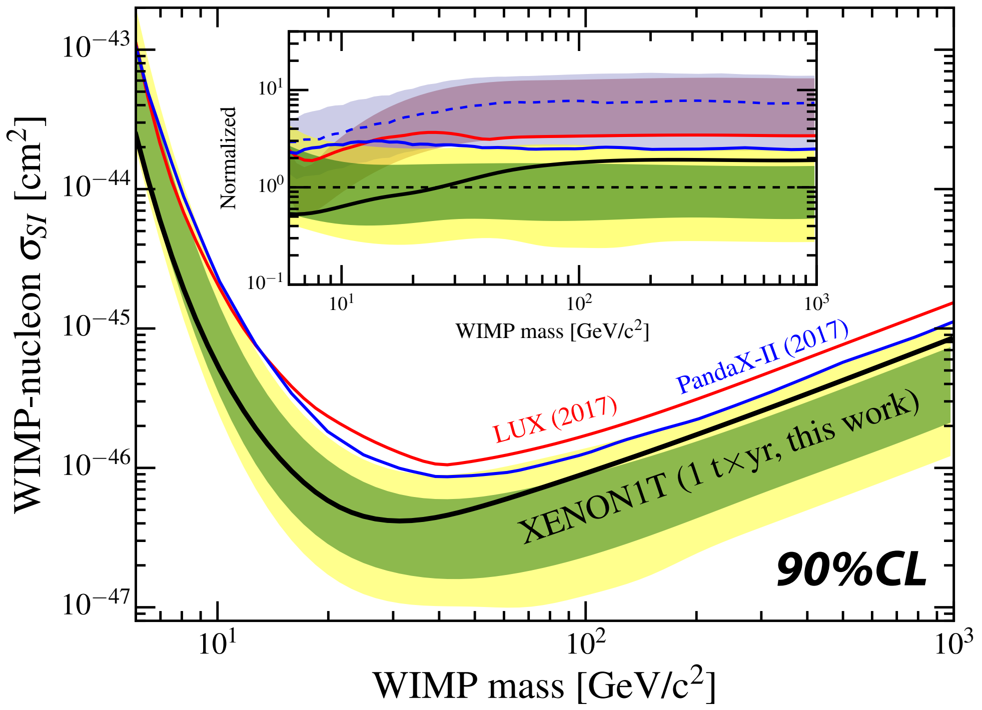
earth velocity : ***30 km/s***

$$n_{\mathrm{DM}} \simeq \frac{0.004}{\mathrm{cm}^3}\left(\frac{100\,\mathrm{GeV}}{m_{\mathrm{DM}}}\right)$$

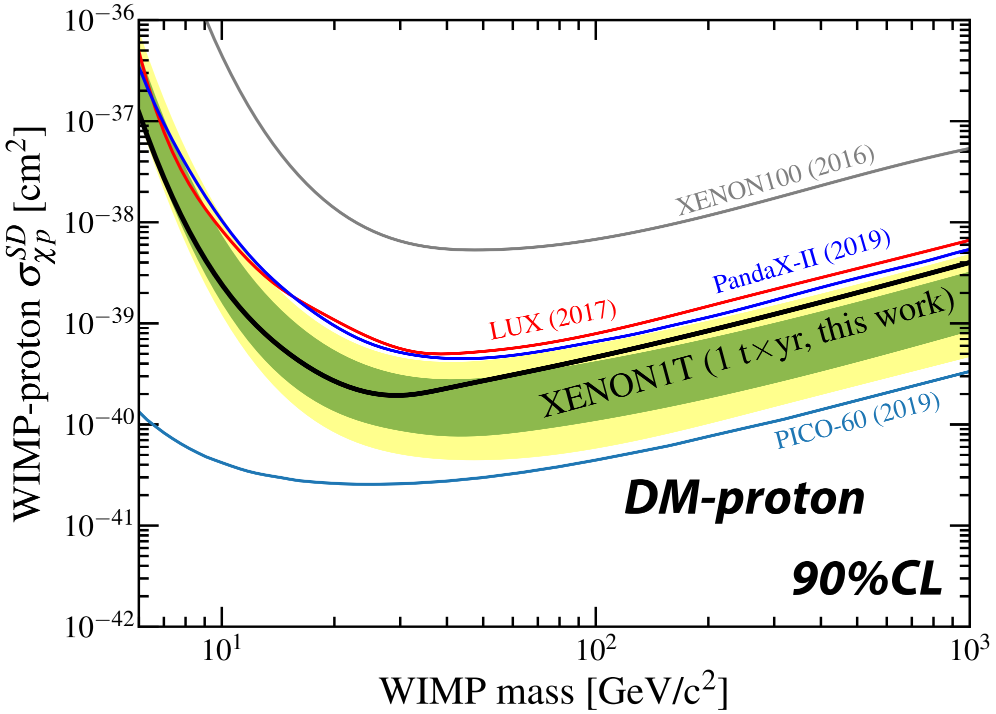
$$\mathscr{F}_{\mathrm{DM}} \simeq \frac{9.2\times 10^4}{\mathrm{cm}^2\,\mathrm{s}}\left(\frac{100\,\mathrm{GeV}}{m_{\mathrm{DM}}}\right)\left(\frac{v_{\mathrm{DM}}}{230\,\mathrm{km/s}}\right)$$

Current Status

Spin Independent : 1805.12562



Spin dependent : 1902.03234



DM-neutron constraint is about 30 times more stringent.

Examples (nucleon - Majorana Dark Matter : χ)

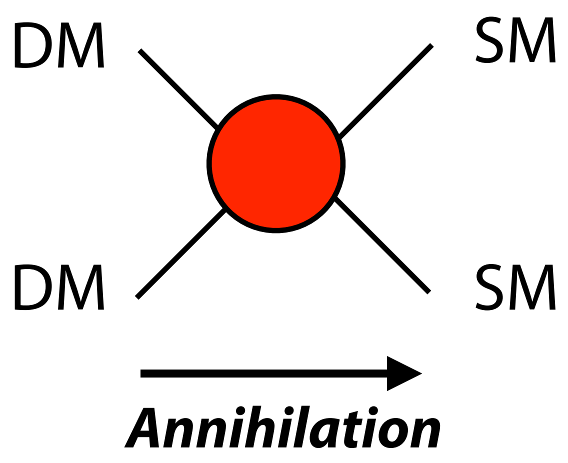
$$\mathcal{L}_{\rm int} = \frac{c_{h\chi\chi}}{2}\, h(\chi\chi + \chi^\dagger\chi^\dagger) \;\rightarrow\; \mathcal{L}_{\rm int} \propto {\rm DM}^2 \times \bar\psi_n \psi_n \;\rightarrow\; \sigma_{\rm SI} = 8\times 10^{-45}\ {\rm cm}^2 \left(\frac{c_{h\chi\chi}}{0.1}\right)^2$$

$$\mathcal{L}_{\rm int} = c_{Z\chi\chi}\, \chi^\dagger \bar\sigma^\mu \chi Z_\mu \;\rightarrow\; \mathcal{L}_{\rm int} \propto ({\rm DM}^2)_\mu \times \bar\psi_n \gamma_5 \gamma^\mu \psi_n \;\rightarrow\; \sigma_{\rm SD} = 3\times 10^{-39}\ {\rm cm}^2 \left(\frac{c_{Z\chi\chi}}{0.1}\right)^2$$

Examples (neutron - Dirac Dark Matter : χ)

$$\mathcal{L}_{\rm int} = c^D_{Z\chi\chi} \bar\chi \gamma^\mu \chi Z_\mu \;\rightarrow\; \mathcal{L}_{\rm int} \propto ({\rm DM}^2)_\mu \times \bar\psi_n \gamma^\mu \psi_n \;\rightarrow\; \sigma_{\rm SI} = 6.8\times 10^{-41} {\rm cm}^2 \left(\frac{c^D_{Z\chi\chi}}{0.1}\right)^2$$

Indirect WIMP Detection



The WIMP annihilates into the Standard Model Particles

PIE charts of the energy fraction of the final states

inner chart : 200GeV DM
outer chart : 5TeV DM

[PPPC 4 DM ID : Cirelli et. al.]

✓ *Indirect WIMP Detection*

The charged cosmic-ray (proton, electron) signals

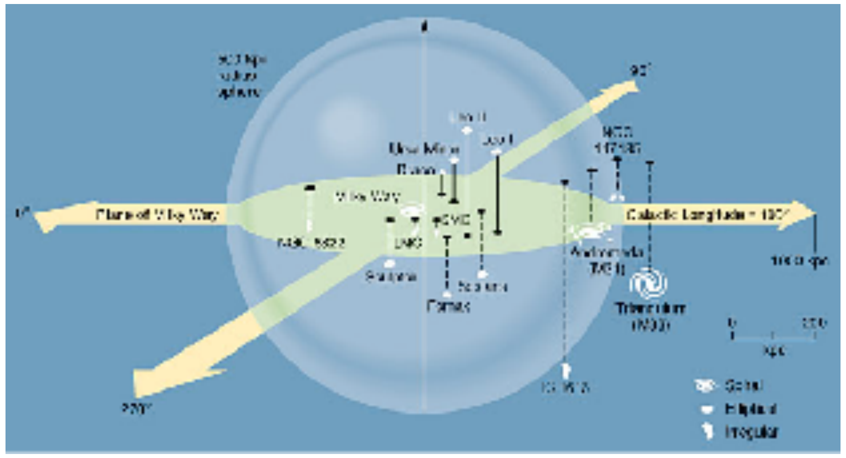
- ✓ less sensitive to DM profile in the Milky Way (CR is bend by the magnetic field)
- ✓ background uncertainties due to the propagation model

The gamma-ray signals

- ✓ propagation straightforward
- ✓ sensitive to DM profile in the Milky Way
- ✓ The galactic center of the Milky Way has lots of gamma-ray sources

The gamma-ray signals from the dwarf spheroidal galaxies are the most reliable

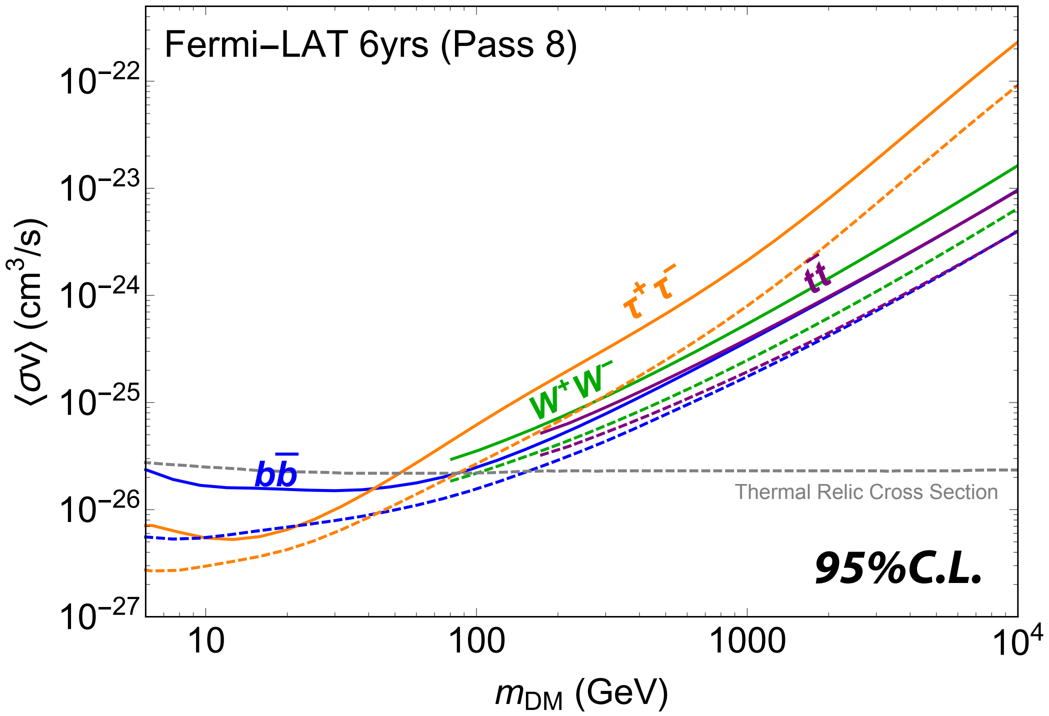
http://astronomy.nmsu.edu/tharriso/ast110/class24.html



$$\mathscr{F} \propto \frac{\langle\sigma v\rangle}{m_{\rm DM}^2}\times J \qquad J=\int_{\Delta\Omega}\int_{\rm los} d\ell d\Omega\ \rho^2(\ell,\Omega)$$

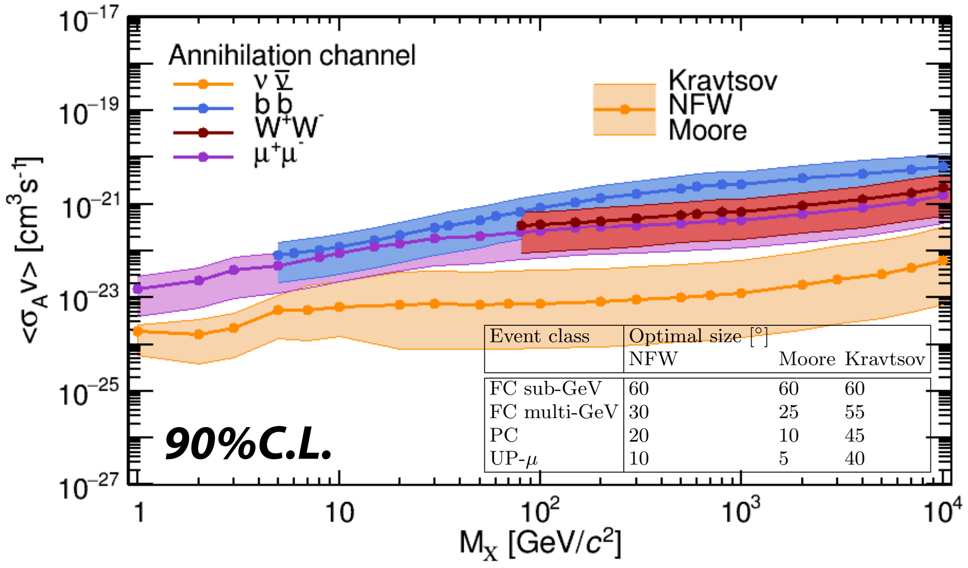
$$J_{\rm dwarf}\sim 10^{18\text{-}20}\,{\rm GeV^2cm^{-5}}$$

['16 Hayashi, Ishikawa, Matsumoto, MI, Ishigaki, Sugai]



Neutrino Signals in WIMP scenario

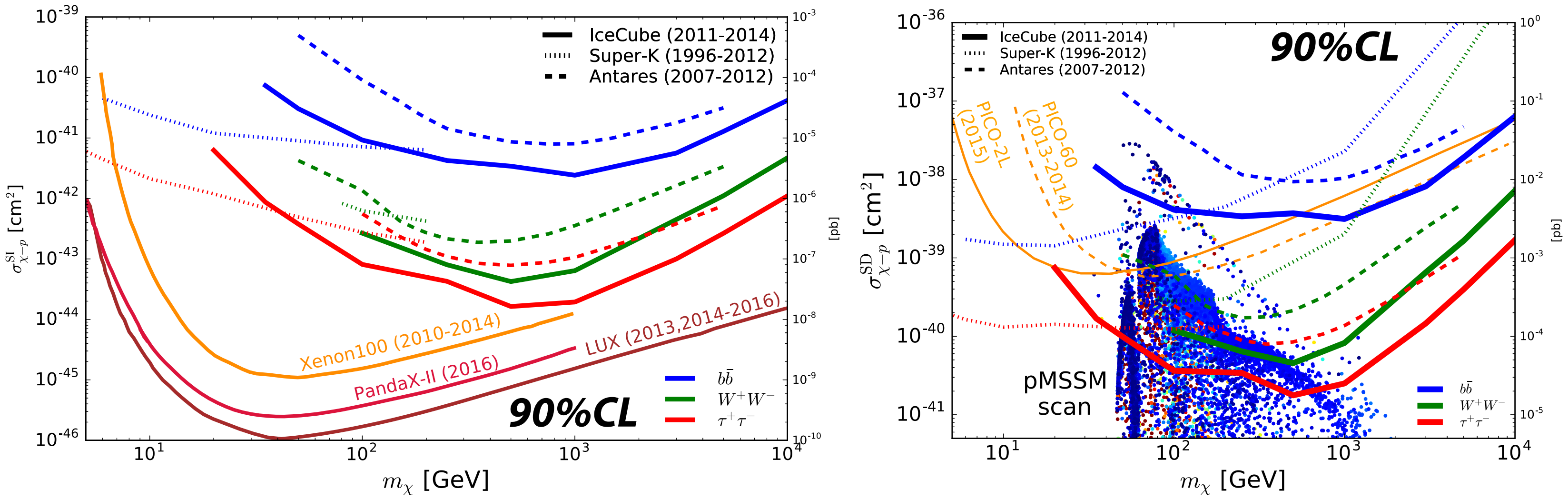
constraints on ν flux from GC



Event class	Optimal size [°] NFW	Moore	Kravtsov
FC sub-GeV	60	60	60
FC multi-GeV	30	25	55
PC	20	10	45
UP-μ	10	5	40

[SK : 2005.05109] (see also [IceCube : 2003.06614])

ν flux from DM trapped in the SUN (sensitive to nucleon-DM cross section)



[Icecube : 1612.05949]

- Constraints on $\sigma_{ann}v$ by the ν flux from GC are weaker than the gamma-ray search.
- Constraints on $\sigma_{DM\text{-}N}{}^{SD}$ from the ν flux from the DM trapped in the SUN can be comparable with the direct detection experiments.

$$\Gamma_{\rm capt} \simeq \frac{5.90\cdot 10^{26}}{\rm sec}\left(\frac{\rho_{\rm DM}}{0.3\,\frac{\rm GeV}{\rm cm^3}}\right)\left(\frac{100\,{\rm GeV}}{M_{\rm DM}}\right)^2\left(\frac{270\,\frac{\rm km}{\rm sec}}{v_0^{\rm eff}}\right)^3\frac{\overset{\overset{\textit{H \& N}}{\downarrow}}{\sigma_{\rm SD}}+\overset{\overset{\textit{Heavy Element} \,\propto\, A^5}{\downarrow}}{1200}\,\sigma_{\rm SI}}{\rm pb}.$$

$$C_{\rm ann}=\langle\sigma v\rangle\left(\frac{G_N\,M_{\rm DM}\,\rho_\odot}{3\,T_\odot}\right)^{3/2}\simeq\frac{2\cdot10^{-51}}{\rm sec}\left(\frac{\sigma}{1\,\rm pb}\right)\left(\frac{v}{300\,\rm km/s}\right)\left(\frac{m_{\rm DM}}{\rm TeV}\right)^{3/2}$$

[Cirelli, PPPC 4 DMν]

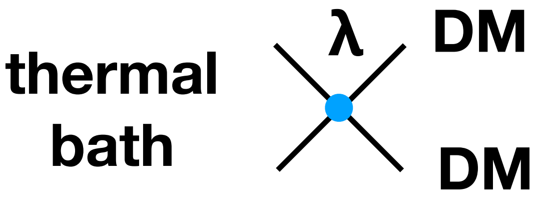
$$N_{DM}=\sqrt{\frac{\Gamma_{\rm capt}}{C_{\rm ann}}}\tanh\left(t\sqrt{\Gamma_{\rm capt}C_{\rm ann}}\right)\xrightarrow[t\,\gg\,\sqrt{\Gamma_{\rm capt}C_{\rm ann}}]{\sigma_{\rm scat}\,\sim\,1\,\rm pb}N_{DM}\sim\sqrt{\frac{\Gamma_{\rm capt}}{C_{\rm ann}}}\qquad\underline{\Gamma_{\rm ann}=\frac{1}{2}C_{\rm ann}N_{\rm DM}^2\sim\frac{1}{2}\Gamma_{\rm capt}}$$

Feebly Interacting Massive Particle (FIMP)

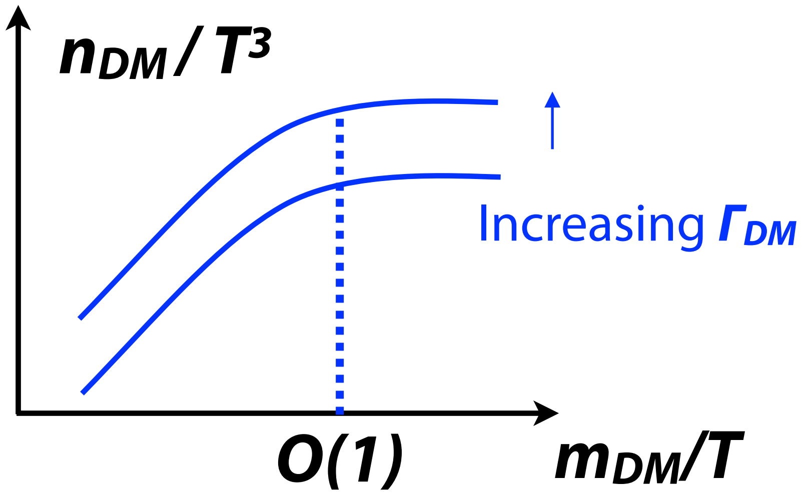
✓ *Freeze-in FIMP*

Assume DM has feeble interactions to the thermal bath through dimensionless coupling.

ex)



$$\langle\sigma v\rangle \sim \lambda^2 / T^2$$



✓ The abundance of the FIMP is given by

$$\dot{n}_{DM} + 3H\, n_{DM} = \langle\sigma v\rangle\, n_{th}{}^2$$

Initial condition @ $T \gg m_{DM}$: $n_{DM} = 0$

✓ DM abundance is fixed at $m_{DM}/T = O(1)$

(Freeze-in mechanism)

DM abundance : $Y = n_{DM} / s \sim \lambda^2 (M_{PL}/m_{DM})$

$$m_{DM} Y \sim 10^{-10}\mathrm{GeV} \;\rightarrow\; \Omega_{DM}\, h^2 \sim 0.1\, (\lambda / 10^{-13})^2$$

[09 Hall, Jedamzik, March-Russell, West]

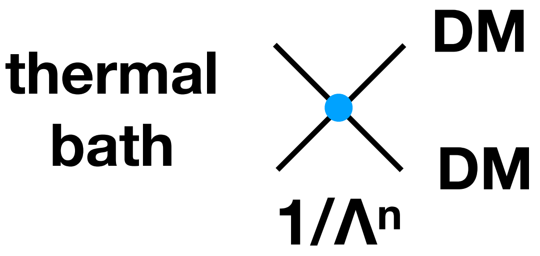
Variety of models have been proposed.

Since it has feebly interaction, it is difficult to test the scenario as it is…

✓ *FIMP production through higher dimensional interaction.*

Assume DM has feeble interactions to the thermal bath through
higher dimensional interaction.

ex)



$\Gamma_{prod} \sim T^{2n+1}/\Lambda^{2n}$ (case n + 4 dim operator)

✓ The FIMP production is dominated at the highest temperature:

$$n_{DM} \sim \Gamma_{prod} \times n_{rad} \times H^{-1} \quad @\, T \sim T_R$$

DM abundance can be explained by appropriate reheating temperature.

$$\Omega_{DM}\, h^2 \sim 0.1 \quad \rightarrow m_{DM} Y \sim 10^{-10}\mathrm{GeV}$$

$$T_R \sim 10^{-\frac{10}{2n-1}} \times 10^{18}\,\mathrm{GeV} \left(\frac{\Lambda}{M_{\mathrm{Pl}}}\right)^{\frac{2n}{2n-1}} \left(\frac{\mathrm{GeV}}{m_{\mathrm{DM}}}\right)^{\frac{1}{2n-1}}$$

Ex) light gravitino is an example with n = 1

FIMP Search ?

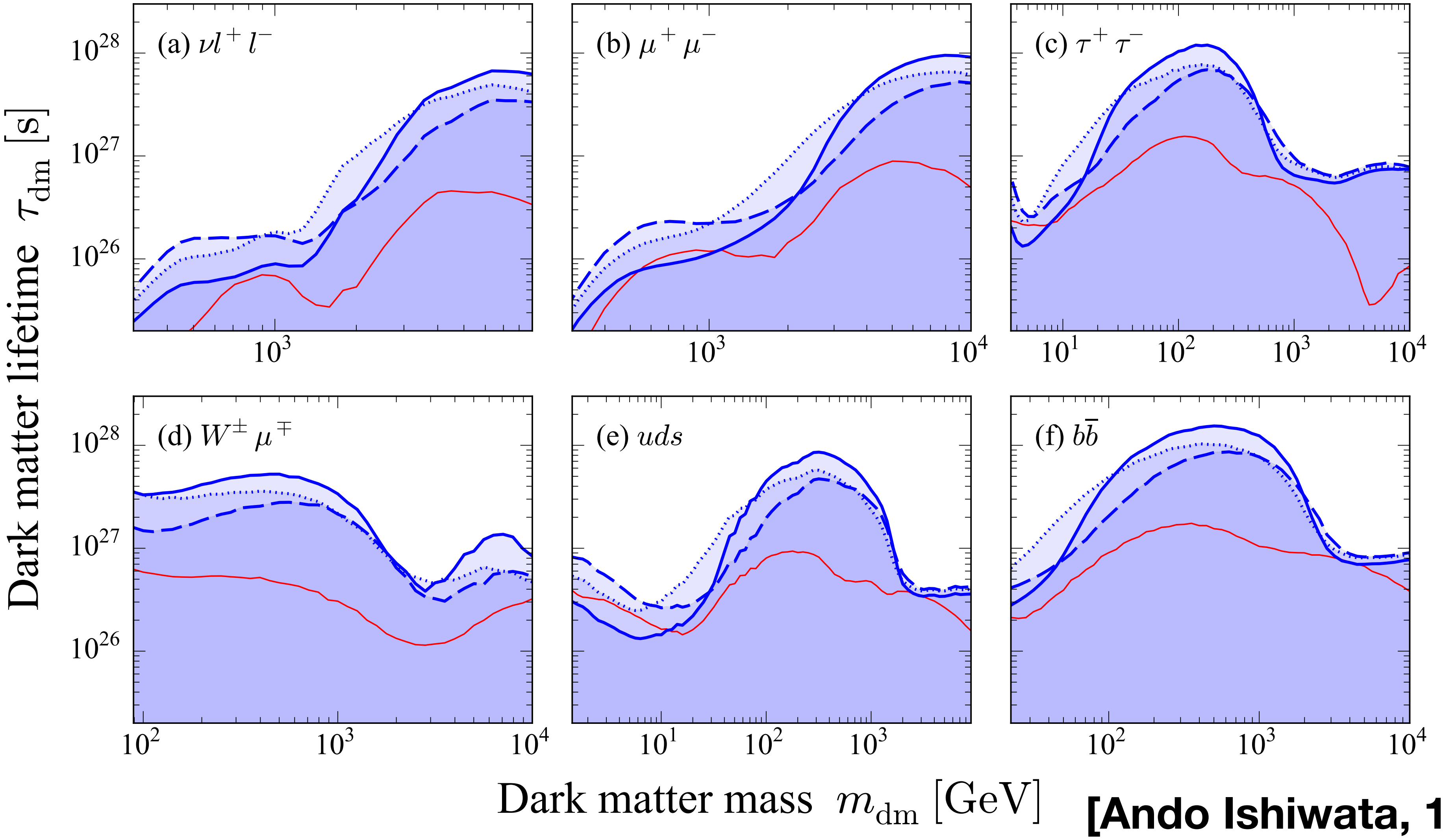
- ✓ By definition, the FIMP is difficult to be tested.
- ✓ Mass Range is wider than WIMP.
- ✓ No universal channel for the FIMP detection.

  (Most channels rely on model dependent additional particles…)

We can test the FIMP if it decays (though it is not necessary).

The following constraints are applicable to the decaying WIMPs.

Constraints from the extragalactic gamma-ray background (Fermi-LAT)



[Ando Ishiwata, 1502.02007]

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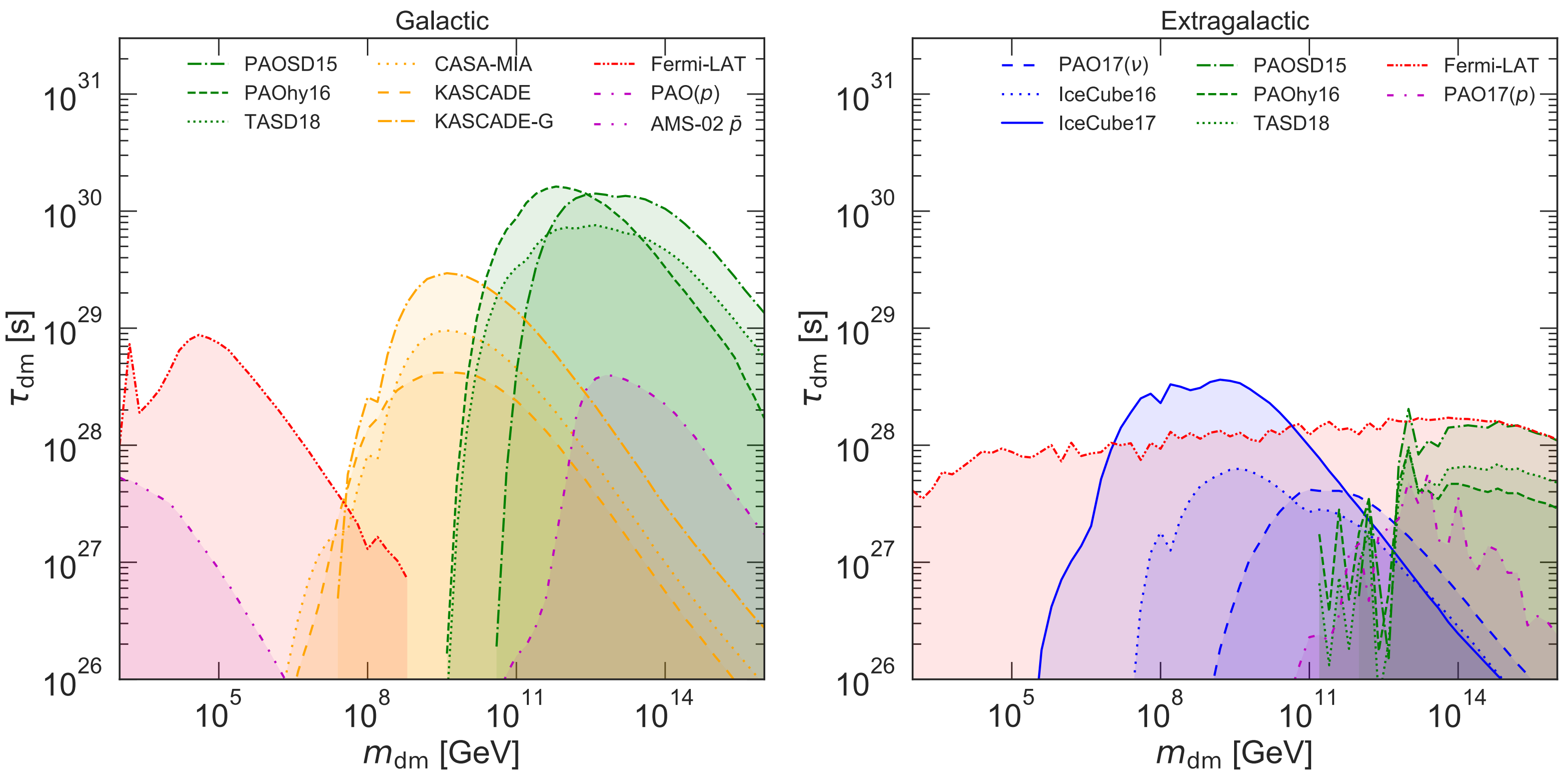
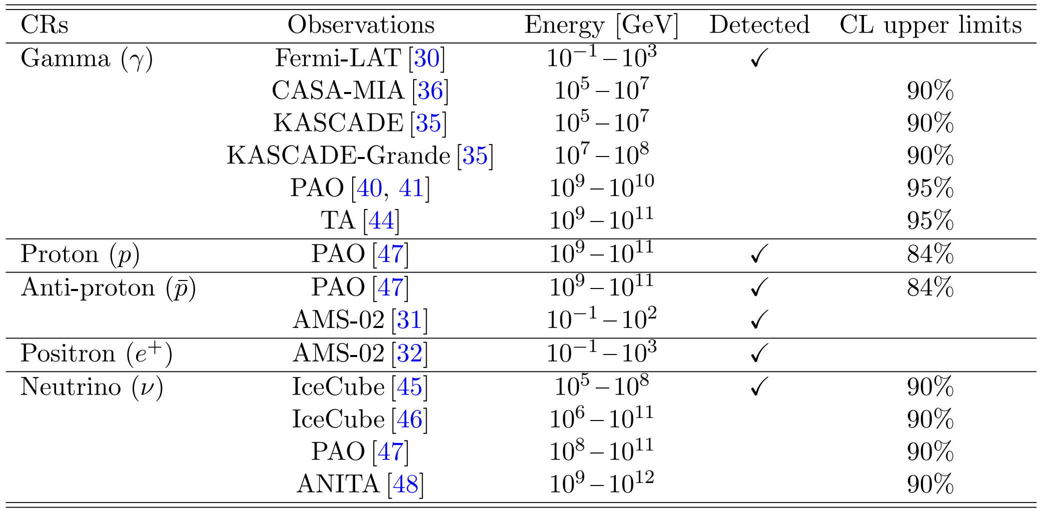
Constraints multi-messenger astrophysical data (100% DM→b b*)





CRs	Observations	Energy [GeV]	Detected	CL upper limits
Gamma (γ)	Fermi-LAT [30]	$10^{-1}-10^{3}$	✓	
	CASA-MIA [36]	$10^{5}-10^{7}$		90%
	KASCADE [35]	$10^{5}-10^{7}$		90%
	KASCADE-Grande [35]	$10^{7}-10^{8}$		90%
	PAO [40, 41]	$10^{9}-10^{10}$		95%
	TA [44]	$10^{9}-10^{11}$		95%
Proton (p)	PAO [47]	$10^{9}-10^{11}$	✓	84%
Anti-proton ($\bar{p}$)	PAO [47]	$10^{9}-10^{11}$	✓	84%
	AMS-02 [31]	$10^{-1}-10^{2}$	✓	
Positron (e^{+})	AMS-02 [32]	$10^{-1}-10^{3}$	✓	
Neutrino (ν)	IceCube [45]	$10^{5}-10^{8}$	✓	90%
	IceCube [46]	$10^{6}-10^{11}$		90%
	PAO [47]	$10^{8}-10^{11}$		90%
	ANITA [48]	$10^{9}-10^{12}$		90%

[Ishiwata, Macias, Ando, Aritomo : 1907.11671]

DM lifetime > 10^{26} sec for various decay modes

Asymmetric Dark Matter (ADM)

✓ *Asymmetric Dark Matter (ADM)*

Baryon-DM coincidence ?

$$\Omega_{DM} : \Omega_b \;=\; 5 : 1$$

close with each other…

ex) neutrino-DM : $\Omega_{DM} : \Omega_\nu(\Sigma m_\nu = 0.06\mathrm{eV}) \;=\; 200 : 1$

- ✓ DM mass density is given by

$$\Omega_{DM} \propto m_{DM}\, n_{DM}$$

→ m_{DM} is independent of $m_{p,n}$. n_{DM} should be adjusted appropriately.

- ✓ If it were not for Baryogenesis, baryon should have annihilated…

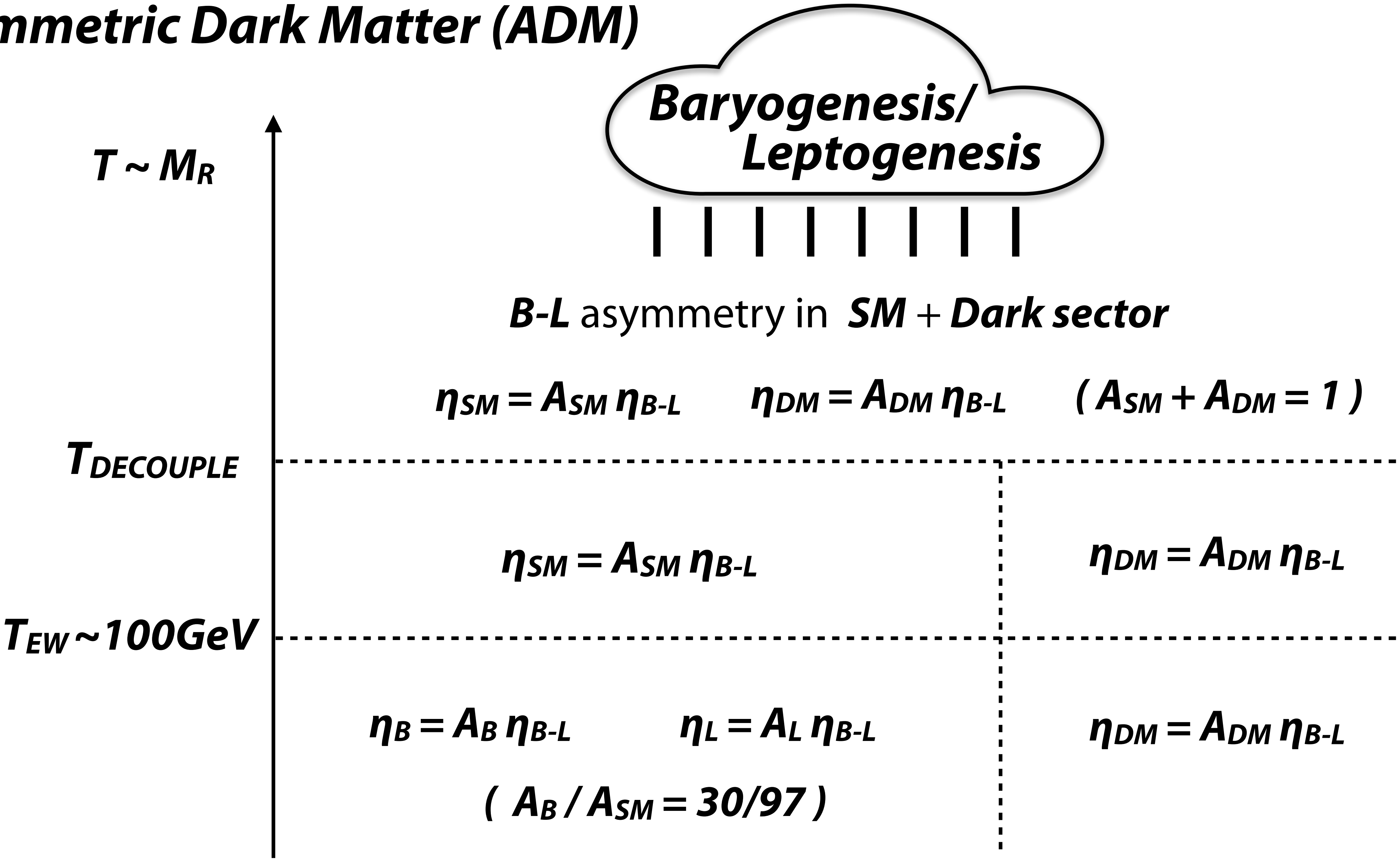
$$\Omega_{DM} : \Omega_b(\text{no-asymmetry}) = 1 : 10^{-11}$$

$$\Omega_b\,(\text{with asymmetry}) = 0.02\,(\eta / 10^{-9})$$

$$\eta = (n_B - n_{\bar{B}})/n_\gamma$$

Baryon-DM coincidence = conspiracy between n_{DM} and Baryogenesis ?

✓ Asymmetric Dark Matter (ADM)



Baryogenesis/ Leptogenesis

$T \sim M_R$

B-L asymmetry in ***SM*** + ***Dark sector***

$\eta_{SM} = A_{SM}\,\eta_{B\text{-}L}$ $\quad$ $\eta_{DM} = A_{DM}\,\eta_{B\text{-}L}$ $\quad$ $(A_{SM} + A_{DM} = 1)$

$T_{DECOUPLE}$

$\eta_{SM} = A_{SM}\,\eta_{B\text{-}L}$ $\quad$ $\eta_{DM} = A_{DM}\,\eta_{B\text{-}L}$

$T_{EW} \sim 100\text{GeV}$

$\eta_B = A_B\,\eta_{B\text{-}L}$ $\quad$ $\eta_L = A_L\,\eta_{B\text{-}L}$ $\quad$ $\eta_{DM} = A_{DM}\,\eta_{B\text{-}L}$

$(A_B / A_{SM} = 30/97)$

$$n_B = \eta_B\, n_\gamma \rightarrow n_{DM} = (A_{DM}/A_B)\, n_B = (A_{DM}/A_{SM})\,(A_{SM}/A_B)\, n_B$$

$$\Omega_{DM} = (m_{DM}/m_p)\,(A_{DM}/A_{SM})\,(A_{SM}/A_B)\,\Omega_B$$

$$m_{DM} = 5\, m_p\,(30/97)\,\underline{(A_{SM}/A_{DM})}\times(\Omega_{DM}/5\Omega_B)$$

ADM mass is typically O(1-10) GeV

Asymmetric Dark Matter Search ?

✓ ADM seems not annihilate in the present Universe (due to charge conservation)

✓ Direct detection depends on models…

In most models, the asymmetry is shared between the DM and the SM sectors.

→ the DM and the SM sectors were likely in the thermal equilibrium

In the ADM sector, the symmetric components disappear through a large annihilation cross section…into what ?

***O(1)* GeV** DM cannot couple the SM particle strongly…

ADM annihilates into lighter particles in the DARK SECTOR.

Fate of the lighter dark sector particles ? They should decay into the SM particles.

✓ There should be some PORTAL to the SM (though model dependent).

ADM also exhibits DM - anti DM oscillation

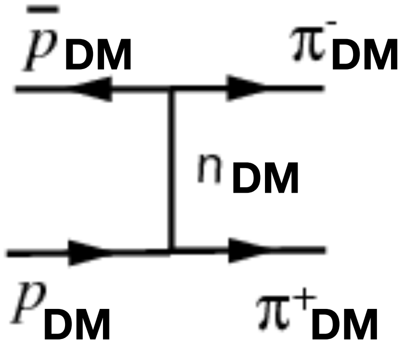
→ tiny fraction of DM is converted to the anti-DM

✓ DM annihilation may occur in the present Universe

Ex). A model with dark QCD & dark QED [1805.0687 Kamada, Kobayashi, Nakano MI]

DM = dark proton & dark neutron

✓ ***DM*** annihilation cross section is large !



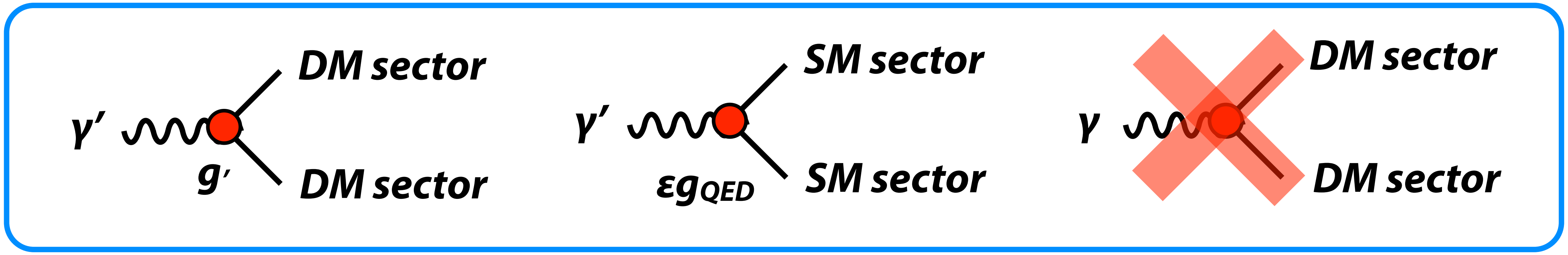
$\sigma v \sim 4\pi / m_{DM}^2$

✓ ***Dark QED*** can mix with ***QED*** through the kinetic mixing.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \underset{\textbf{kinetic mixing}}{\underline{\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}}} + \frac{1}{2}m'^2_A A'_\mu A'^\mu$$

$F_{\mu\nu}$: QED photon ***$F'_{\mu\nu}$: dark QED photon*** ***ε : mixing parameter << 1***

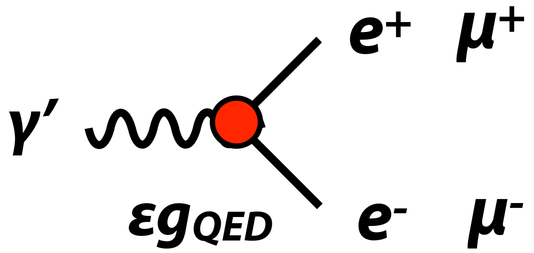
The massive ***dark photon*** couples to ***QED*** current with ***$\varepsilon\, g_{QED}$***.



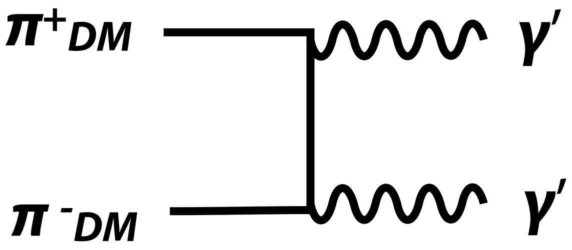
Ex). A model with dark QCD & dark QED [1805.0687 Kamada, Kobayashi, Nakano MI]

DM = dark proton & dark neutron

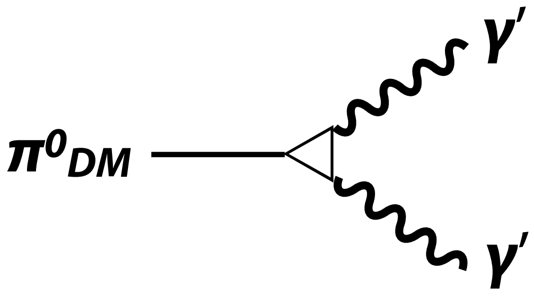
✓ ***Dark photon*** decays into $e^+ + e^-$ ($\mu^+ + \mu^-$) ($2m_e < m_{\gamma'}$)



✓ ***Dark pions*** annihilate/decay into ***dark photons*** ($m_{\gamma'} < m_{\pi'} < m_{N'}$)



$\sigma v \sim \pi \alpha'^2 / m_{\pi'}^2$



$\Gamma \sim \alpha'^2 / 64\pi^3 \times m_{\pi'}^3 / f_\pi^2$

(*charged pion can also decay if dark Higgs VEV has QED′ charge 1*)

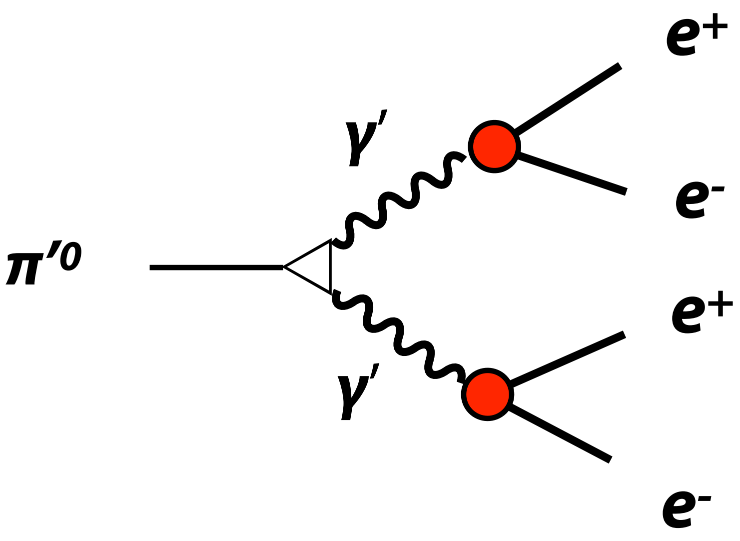
These processes are important to transfer excessive entropy in the DM sector to the SM sector

Ex). A model with dark QCD & dark QED [1805.0687 Kamada, Kobayashi, Nakano MI]

- ✓ Tiny Majorana mass induces pair annihilation of ADM at late times !

average number of pions ~ 5

- ✓ Dark neutral pion decays into two pairs of $e^- + e^+$



Typical electron energy :

$E_e \sim 2m_{DM}/5/4$

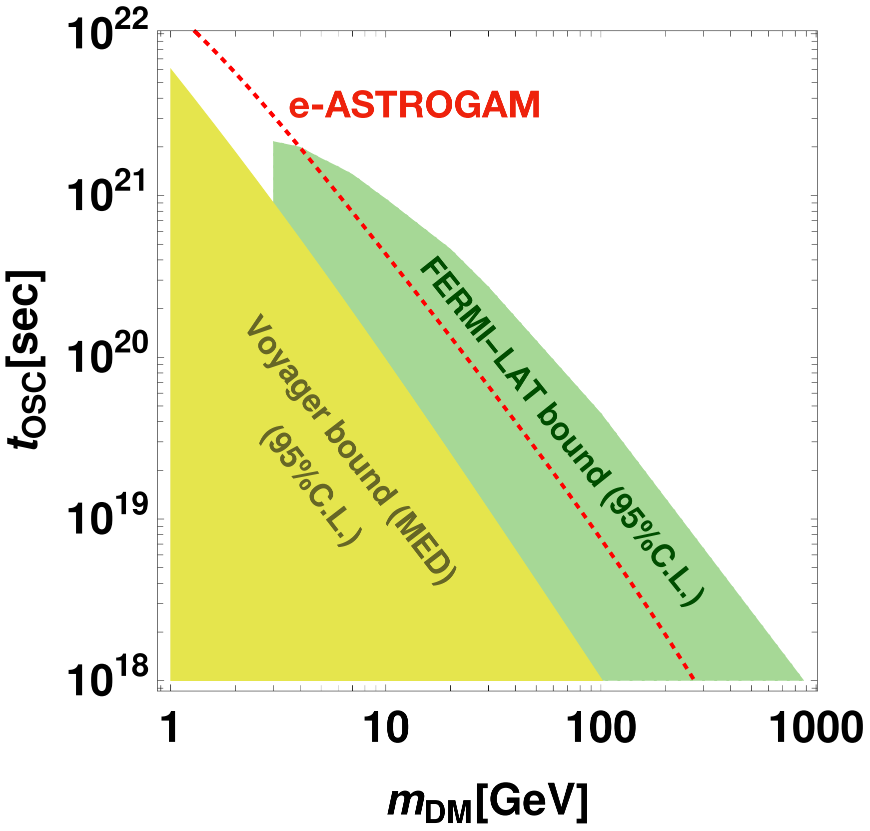
$\sim O(10)$ MeV - $O(1)$ GeV

too soft to be detected…

→ Final state radiation and electron CR can be tested in the

Ex). A model with dark QCD & dark QED [1805.0687 Kamada, Kobayashi, Nakano MI]

[MI, Kobayashi, Nagai, Nakano 1907.11464]



In the model of 1805,0687, the Majorana mass of ***n' = oscillation time scale of the n' and n'*** is given by

$$t_{\rm osc} \simeq 3.3\times10^{21}\,{\rm sec}\left(\frac{\Lambda'_{\rm QCD}}{2\,{\rm GeV}}\right)^{-6}\left(\frac{\tilde{M}_C}{3\times10^{9}\,{\rm GeV}}\right)^{4}\left(\frac{M_R}{10^{9}\,{\rm GeV}}\right)$$

Some portion of the model parameters can be tested by the MeV-gamma ray and the electron/positron CR !

Sterile Neutrino Dark Matter

Sterile Neutrino Dark Matter

Add a sterile neutrino ν_s neutrino mixing with active neutrinos ν_a:

$$L = \underbrace{\mu \, \nu_a \nu_s}_{\text{mixing mass}} + m_s \nu_s \nu_s / 2 + h.c.$$

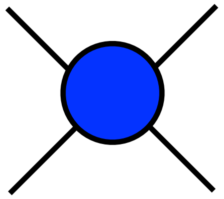
$m_s \gg$ ***active neutrino masses***

$\mu \propto$ [***Higgs expectation value***]

ν_s does not contribute to the active neutrino mass : $\mu^2/m_s \ll m_\nu$

- The sterile neutrinos are mainly produced via the neutrino oscillation

thermal bath



$$\nu_a \xrightarrow{\text{oscillation}} \begin{cases} \nu_a & : 1 - P_{a\to s} \\ \nu_s & : P_{a\to s} \end{cases}$$

$$P_{a\to s} = \sin^2 2\theta_{eff} \sin^2(m_s{}^2/T\, t) \sim (\sin^2 2\theta_{eff})/2$$

$$\sin^2 2\theta_{eff} \sim \frac{\mu^6}{\mu^6 + m_s{}^2(\mu^2 - 2V(T, \eta_L)p)^2} \qquad (\theta_s \sim \mu/m_s)$$

$$V(T, \mu_L) \sim -100\, G_F{}^2 T^4 p + G_F T^3 \underline{\eta_L}$$

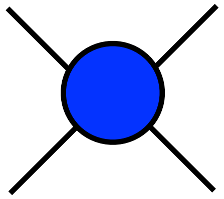
Lepton asymmetry below the EWSB scale

[1807.07938 Boyarsky et. al.]

✓ *Sterile Neutrino Dark Matter*

✓ The sterile neutrinos are mainly produced via the neutrino oscillation

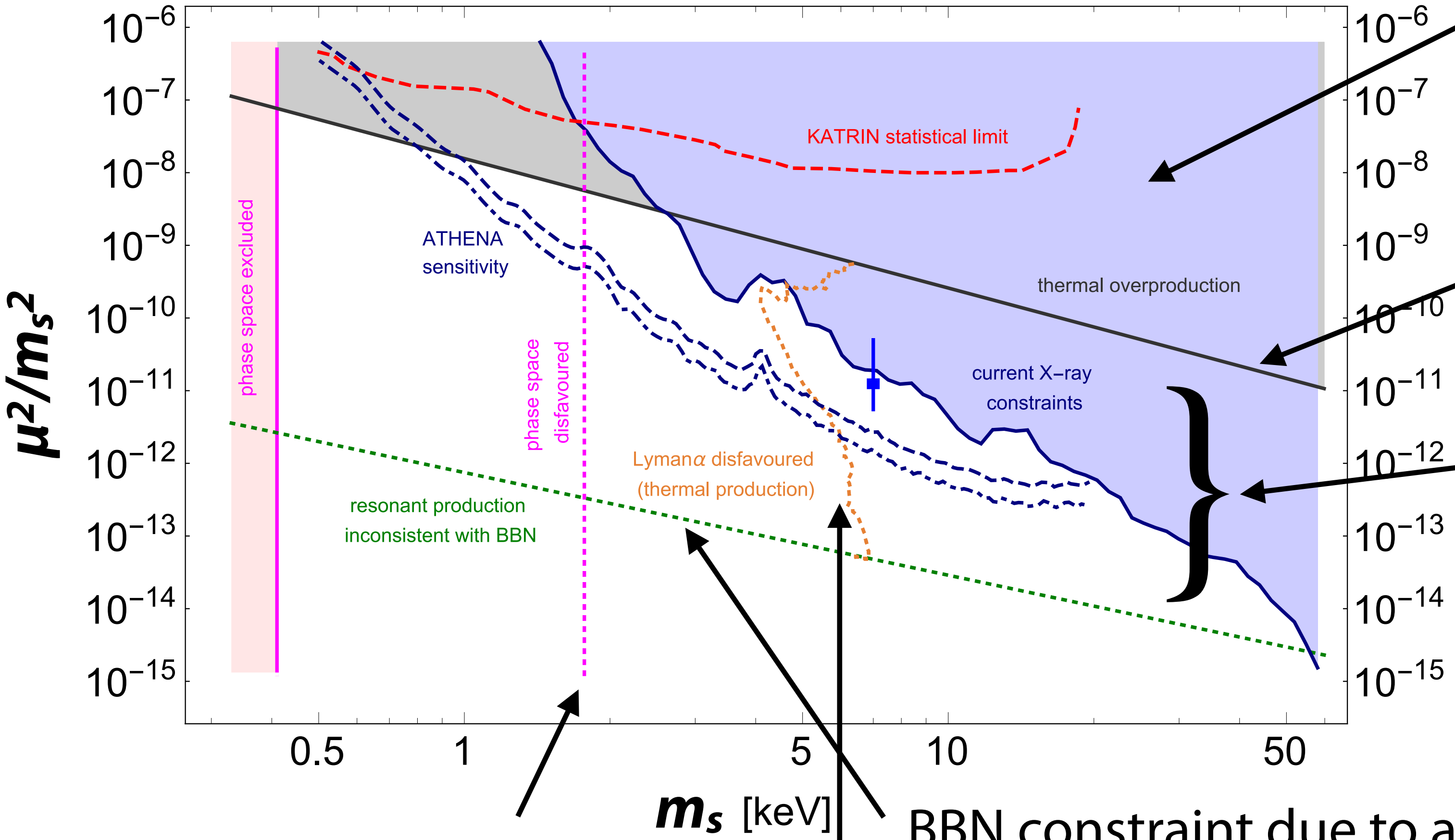
thermal bath



$$\nu_a \xrightarrow{\text{oscillation}} \begin{cases} \nu_a & : 1 - P_{a\to s} \\ \nu_s & : P_{a\to s} \end{cases} \quad \times \quad \Gamma_s \sim G_F T^5 \sin^2 2\theta_s$$

Production rate

Fig from [1807.07938 Boyarsky et. al.]



$\nu_s \to \nu_a$ + X-ray constraint

$\eta_L \ll 10^{-6}$ $\Omega_{DM}h^2 \sim 0.1$
(non-resonant production)
['93 Dodelson, Widrow]

$\eta_L > 10^{-6}$ $\Omega_{DM}h^2 \sim 0.1$
(resonant production)
['99 Shi, Fuller]

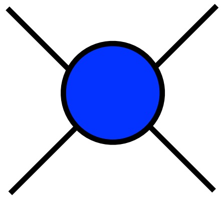
Phase-space constraint
[dSphs : 1712.04597, *Wang et.al.*]

BBN constraint due to a large η_L
(There are controversies. See e.g. **[2005.03039 *Bodeker & Klaus*]**)

Warm dark matter constraint
Lyman alpha Forest
[BOSS, 1706.03118, *Baur et.al.*]

Sterile Neutrino Dark Matter

- The sterile neutrinos are mainly produced via the neutrino oscillation

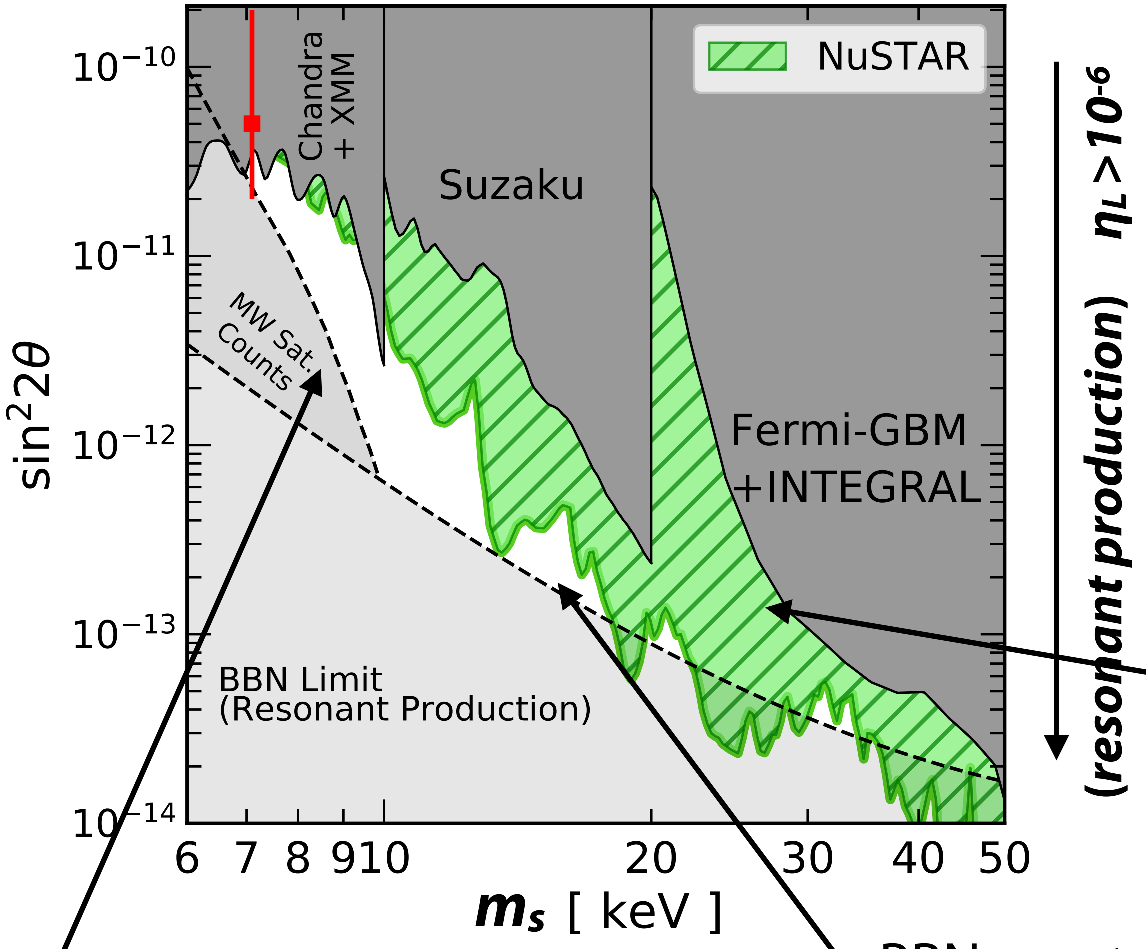


thermal bath

Production rate

$$\nu_a \xrightarrow{\text{oscillation}} \begin{cases} \nu_a & : 1 - P_{a\to s} \\ \nu_s & : P_{a\to s} \end{cases} \times \quad \Gamma_s \sim G_F T^5 \sin^2 2\theta_s$$

[1908.09037 Roach et.al.]



$\eta_L \ll 10^{-6}$ $\Omega_{DM}h^2 \sim 0.1$
(non-resonant production)
['93 Dodelson, Widrow]

$\eta_L > 10^{-6}$ $\Omega_{DM}h^2 \sim 0.1$
(resonant production)
['99 Shi, Fuller]

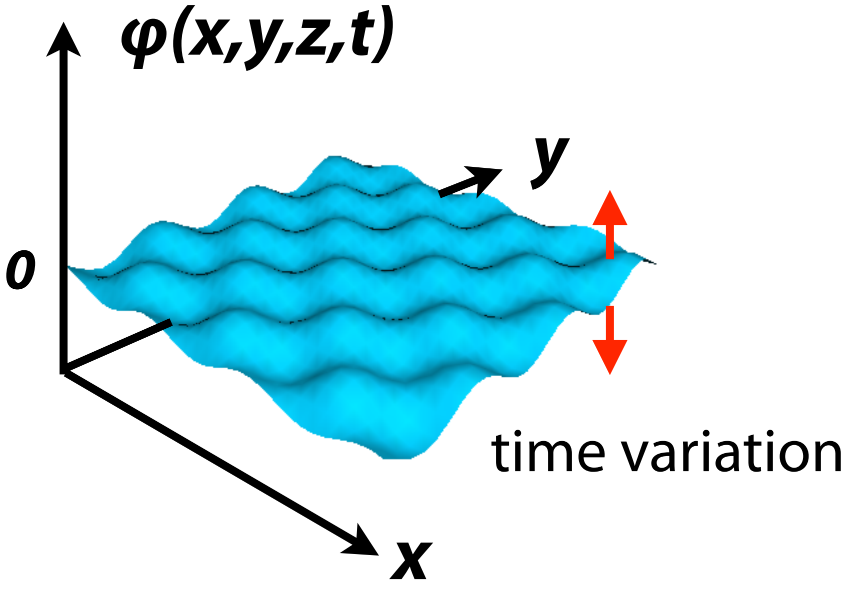
$\nu_s \to \nu_a$ + X-ray constraint

BBN constraint due to a large η_L
(There are controversies. See e.g. **[2005.03039 *Bodeker & Klaus*]**)

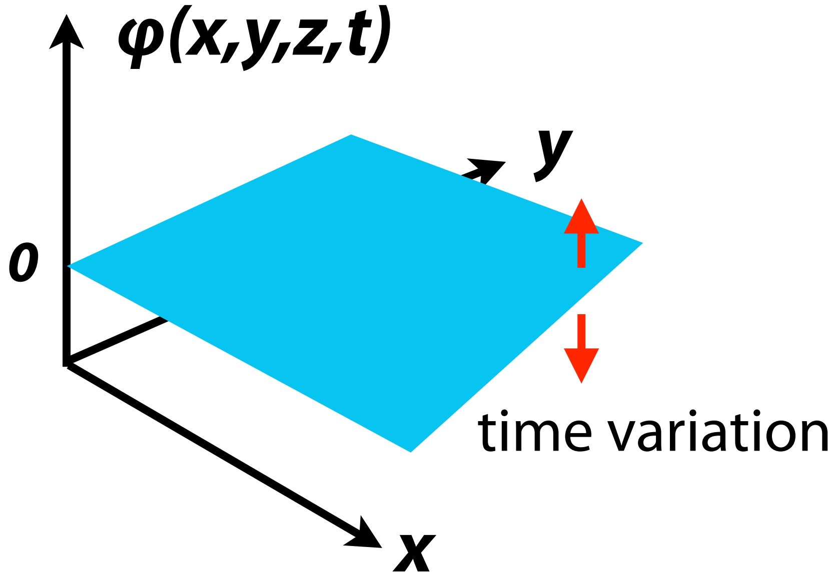
MW subhalo count constraint (**$N_{subhalo}$=47**)
[1701.07874, *Cherry & Horiuchi*]

Scalar field Dark Matter and Axion

✓ Scala Field Dark Matter = Coherent oscillation of a scalar field

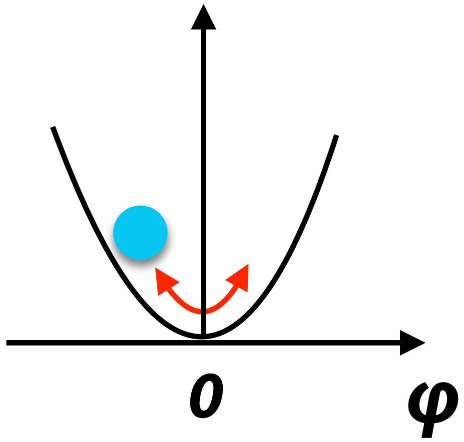


spatial fluctuation
→ DM momentum



coherent oscillation
→ DM with v = 0 and cold

$$V(\varphi) = m_{DM}^2\varphi^2/2$$



DM energy density is set by the amplitude of the oscillation

$$\rho_{DM} = m_{DM}^2 |\varphi_0|^2$$

where the oscillation starts at a cosmic temperature T_{osc} .

✓ *Scala Field Dark Matter*

✓ DM Equation of motion

$$\ddot{\varphi} + \underbrace{3\,H\,\dot{\varphi}}_{\text{Hubble friction}} = -\,m_{DM}^2\,\varphi$$

✓ DM starts coherent oscillation at

$$H \sim T^2/M_{PL} \sim m_{DM} \quad \rightarrow T_{osc} \sim (\,m_{DM}\,M_{PL}\,)^{1/2}$$

$$T_{osc} \sim 0.3\ \mathrm{keV}\,(m_{DM}/10^{-22}\,\mathrm{eV})^{1/2}$$

✓ Initial condition with $\varphi_0 \neq 0$ is set during inflation (misalignment mechanism)

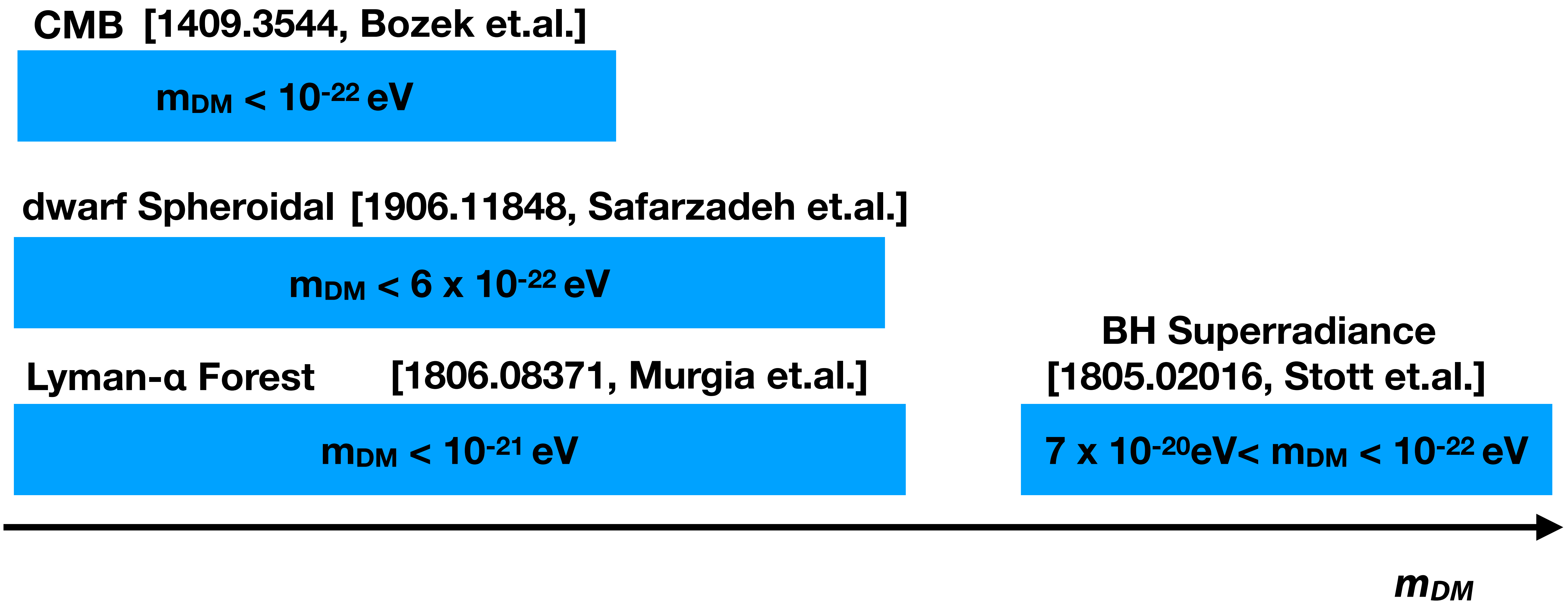
$$\rho_{DM}/s \sim m_{DM}^2\,\varphi_0^2/T_{osc}^3 \sim 10^{-9}\,\mathrm{GeV}\left(\frac{m_{\mathrm{DM}}}{10^{-22}\mathrm{eV}}\right)^{1/2}\left(\frac{\phi_0}{10^{17}\,\mathrm{GeV}}\right)^2$$

$$\Omega_{DM}\,h^2 \sim 0.1 \quad \leftrightarrow \quad \varphi_0 \sim 10^{17.5}\,\mathrm{GeV}\,(10^{-22}\,\mathrm{eV}/m_{DM})^{1/4}$$

Fuzzy Dark Matter **[00 Hu, Barkana, Gruzinov]**

Scala Field Dark Matter

Mass range (blue boxes have been excluded)



CMB [1409.3544, Bozek et.al.]

$m_{DM} < 10^{-22}$ eV

dwarf Spheroidal [1906.11848, Safarzadeh et.al.]

$m_{DM} < 6 \times 10^{-22}$ eV

Lyman-α Forest [1806.08371, Murgia et.al.]

$m_{DM} < 10^{-21}$ eV

BH Superradiance [1805.02016, Stott et.al.]

$7 \times 10^{-20}\,\mathrm{eV} < m_{DM} < 10^{-22}$ eV

$m_{DM} \sim 10^{-21}$ eV may solve the small scale problems (if they exist)

✓ ***Axion Dark Matter***

- ✓ Axion couples to the **θ**-term of QCD to solve the strong CP problem.

Axion : pseudo scalar field ***a***

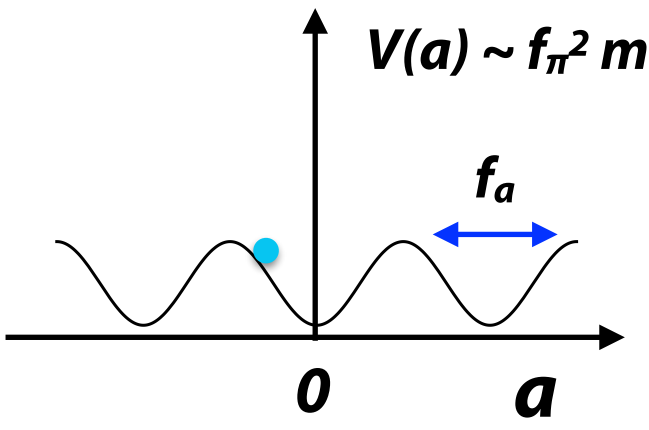
Arrange models so that the axion couples to gluons via

$$\mathcal{L}_{\rm eff} = \frac{g_s^2}{32\pi^2}\boxed{\left(\theta - \frac{6a}{f_a}\right) G^{a\mu\nu}\tilde{G}^a_{\mu\nu}} \longleftarrow \textbf{gluons}$$

- ✓ The axion is a goldstone boson (like **π^0**) associated with spontaneous breaking of the Peccei-Quinn symmetry, and hence, almost massless !

$$f_a \gg 10^2\,\mathrm{GeV} \sim \text{PQ breaking scale}$$

- ✓ The axion obtains a scalar potential due to the strong dynamics of QCD



$$V(a) \sim f_\pi^2\, m_\pi^2 \cos(a/f_a)$$

Axion mass

$$m_a \sim \frac{f_\pi m_\pi}{f_a}$$

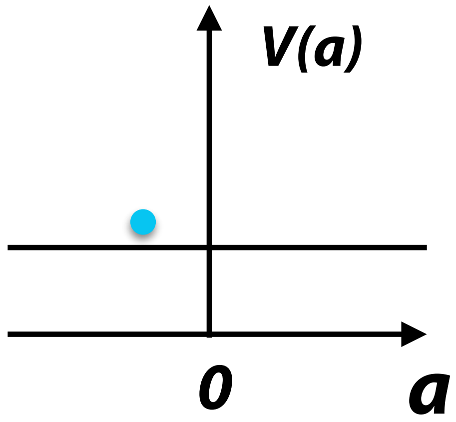
$$f_\pi = 93\,\mathrm{MeV},\ m_\pi = 135\,\mathrm{MeV}$$

Axion Dark Matter

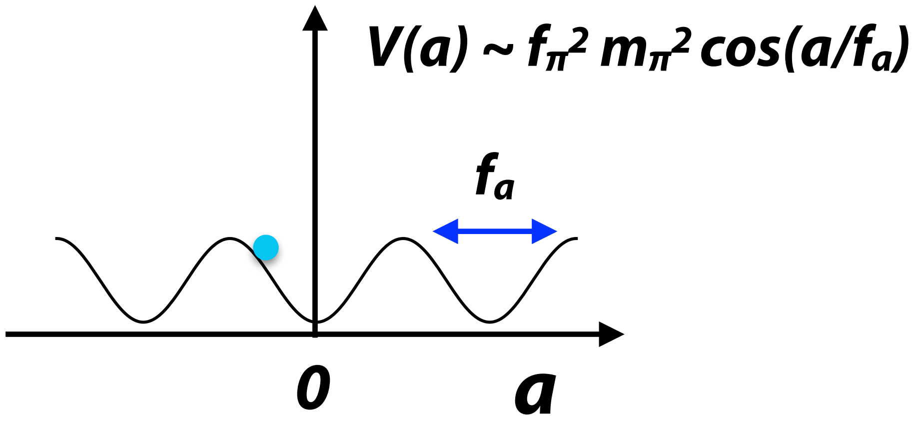
✓ Axion obtains its potential at ***$T < O(1)$GeV.***

→ ***$T_{osc} \sim O(1)$ GeV***

$T > \Lambda_{QCD}$



$T < \Lambda_{QCD}$



Typically, the initial amplitude : ***$a_0 = O(f_a)$.***

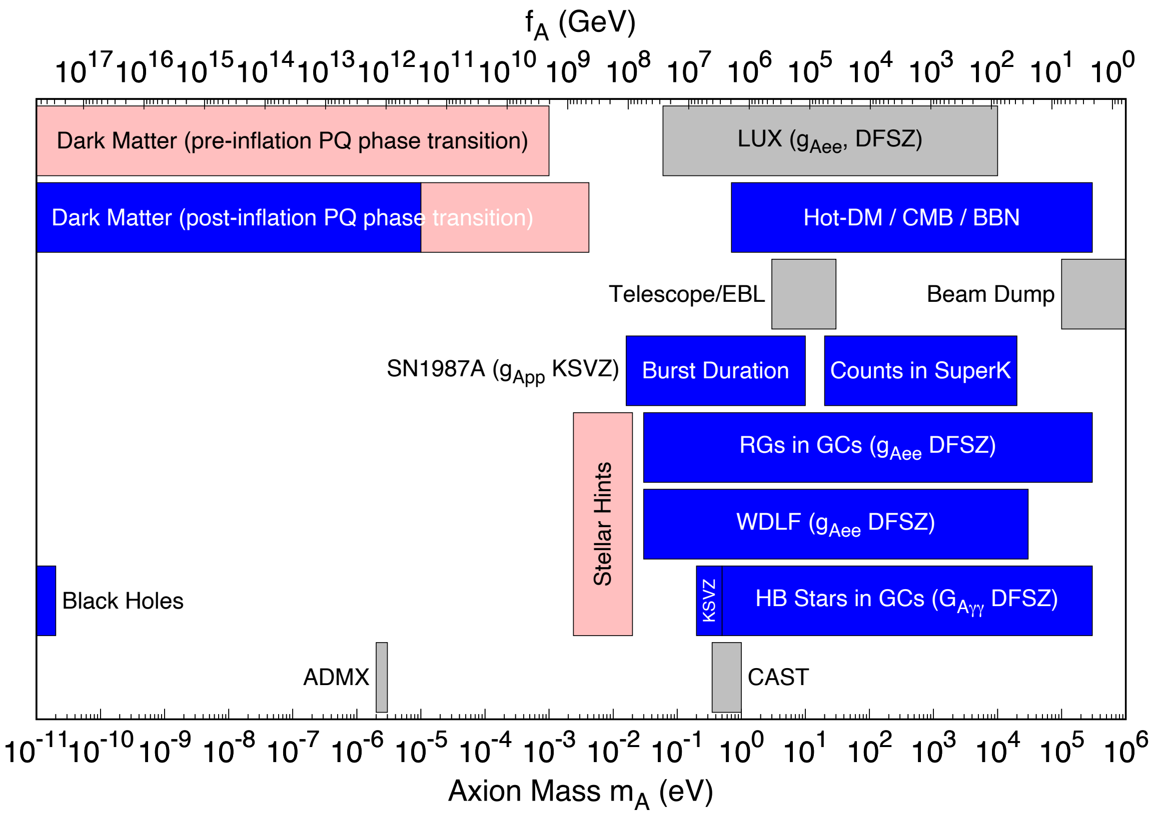
$$\Omega_a h^2 \simeq 0.2 \times \left(\frac{a_0}{f_a}\right)^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19} \left(\frac{\Lambda_{QCD}}{400\,\mathrm{MeV}}\right)$$ ['86 Turner]

✓ ***Dark Matter Density can be naturally explained for***

$f_a \sim 10^{12}$ GeV ***($m_a \sim 10\,\mu$eV)***

(For a larger ***f_a***, we need ***$a_0/f_a \ll 1$***)

Axion Summary

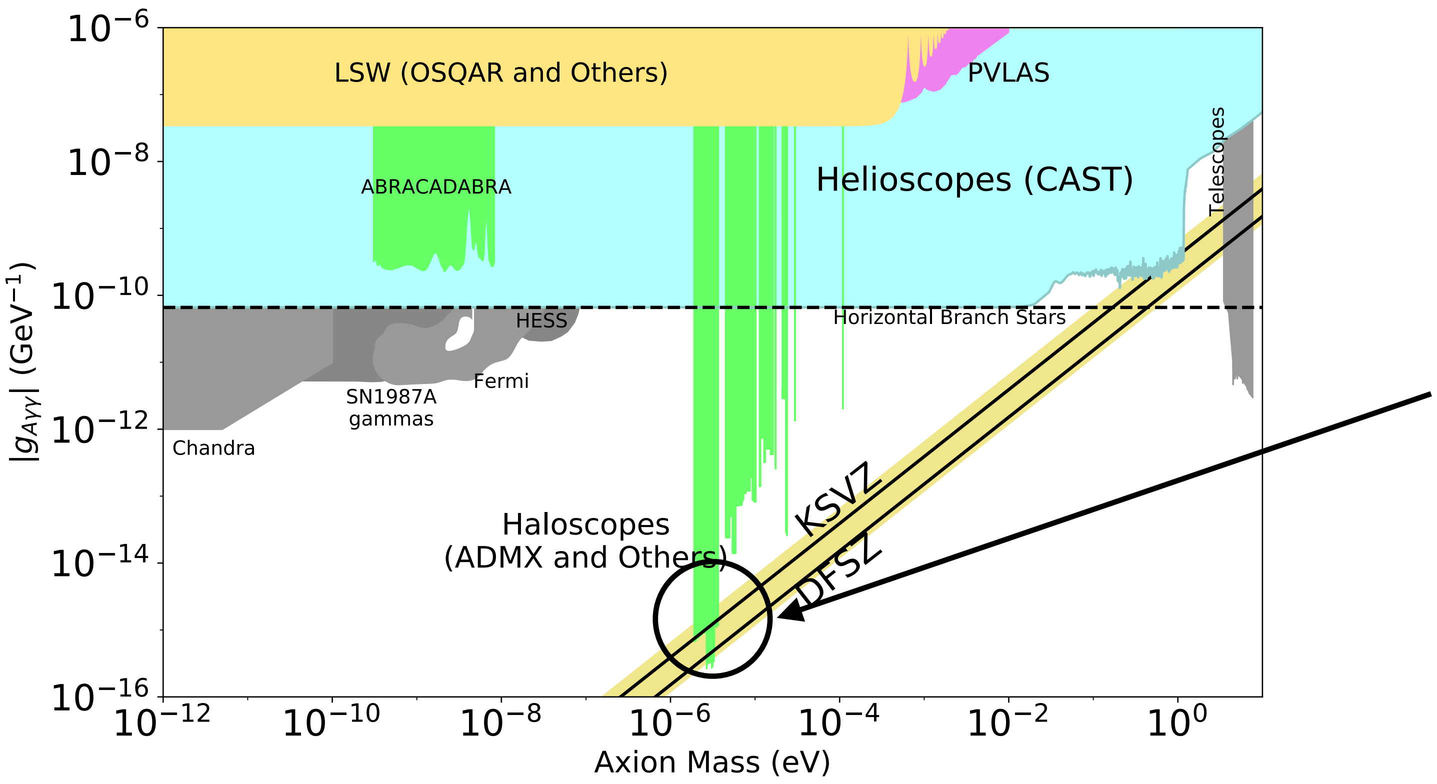


Axion-Fermion coupling

$$\mathscr{L}_A = g_{Aff}\, a \bar{f} \gamma_5 f$$

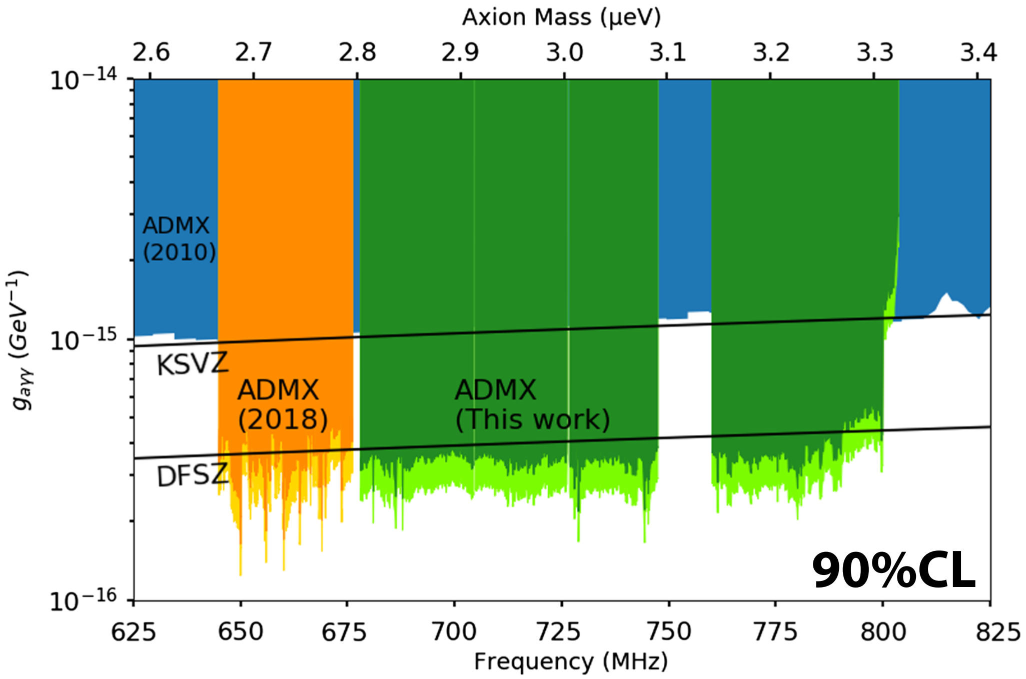
Axion-photon coupling

$$\mathcal{L}_{A\gamma\gamma} = -\frac{g_{A\gamma\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} \phi_A$$



[From Particle Data Group]

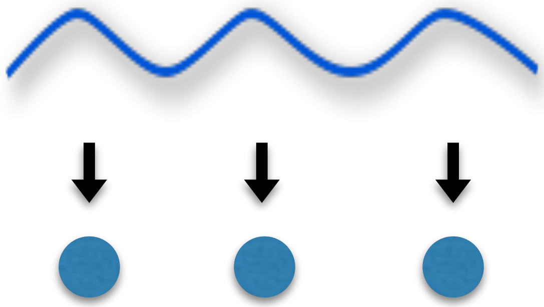
[ADMX 1910.08638]



Primordial Black Hole

Primordial Black Hole

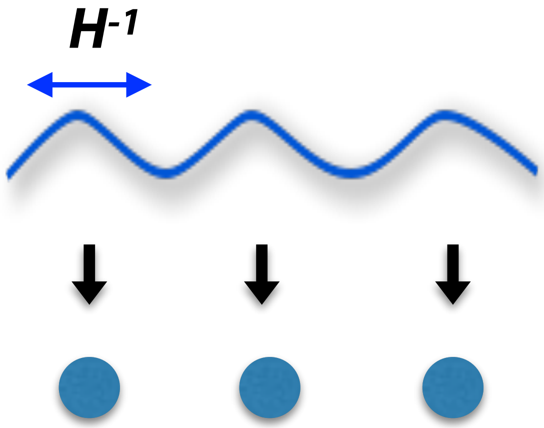
The density fluctuations of $\delta = (\rho - \rho_{average})/\rho_{average} = O(1)$ collapse.



$\delta = O(1)$

Collapsed objects

When the spatial size of the over-dense region is about the Horizon scale $\sim H^{-1}$



$\delta = O(1)$

Collapsed objects : Mass ~ 4π/3 ρ H^{-3}

Schwarzschild Radius of : 2 G_N Mass ~ H^{-1} ~ Object Size !

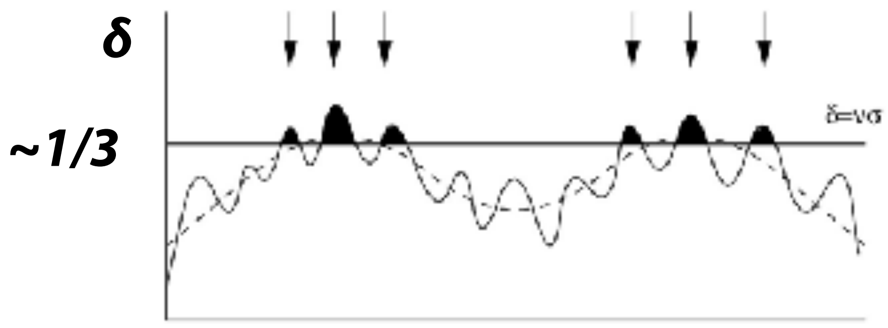
$\delta = O(1)$ of a spatial size $\sim H^{-1}$ → Black Hole

✓ ***Primordial Black Hole***

✓ Mass of the PBH formed at $H \sim T^2/M_{PL}$

$$M_{BH} \sim 4\pi/3\,\gamma\,\rho\,H^{-3} \sim 0.01 M_\odot \times (\mathrm{GeV}/T)^2 \qquad (\text{correction factor } \gamma\sim0.2)$$

✓ Energy fraction at the formation



https://ned.ipac.caltech.edu/level5/Sept03/Peacock/Peacock6_2.html

Variance of the fluctuation

Energy fraction at the formation

$$\beta(M_{\rm PBH}) = \gamma \int_{\delta_{\rm th}}^{1} \frac{d\delta}{\sqrt{2\pi}\sigma_{M_{\rm PBH}}} \exp\left[-\frac{\delta^2}{2\sigma^2_{M_{\rm PBH}}}\right] \approx \frac{\gamma}{\sqrt{2\pi}\nu_{\rm th}} \exp\left[-\frac{\nu^2_{\rm th}}{2}\right] \qquad \left(\nu^2_{\rm th} = \delta^2_{\rm th}/\sigma^2_{M_{\rm PBH}}\right)$$

Abundance

$$\Omega_{DM} \sim (1+z_{production})\,\beta\,\Omega_\gamma \sim 10^5 \beta(\,T/GeV\,) \sim 10^5 \beta_*(\,0.066M_\odot/M_{BH}\,)^{1/2}$$

$$\Omega_{DM} \sim 0.3 \rightarrow \beta_* \sim 10^{-6} \rightarrow \sigma(M) \sim O(10^{-1}\text{-}10^{-2})$$

[For details, see. e.g. 1801.05235, Sasaki, Suyama, Tanaka, Yokoyama]

✓ ***Primordial Black Hole***

At the large scales, the fluctuations are fixed to reproduce the CMB anisotropy

$$\sigma(\mathrm{CMB,\ galaxy\ cluster}) \sim 4(\Delta T/T)_{\mathrm{CMB}} \sim 10^{-4}$$

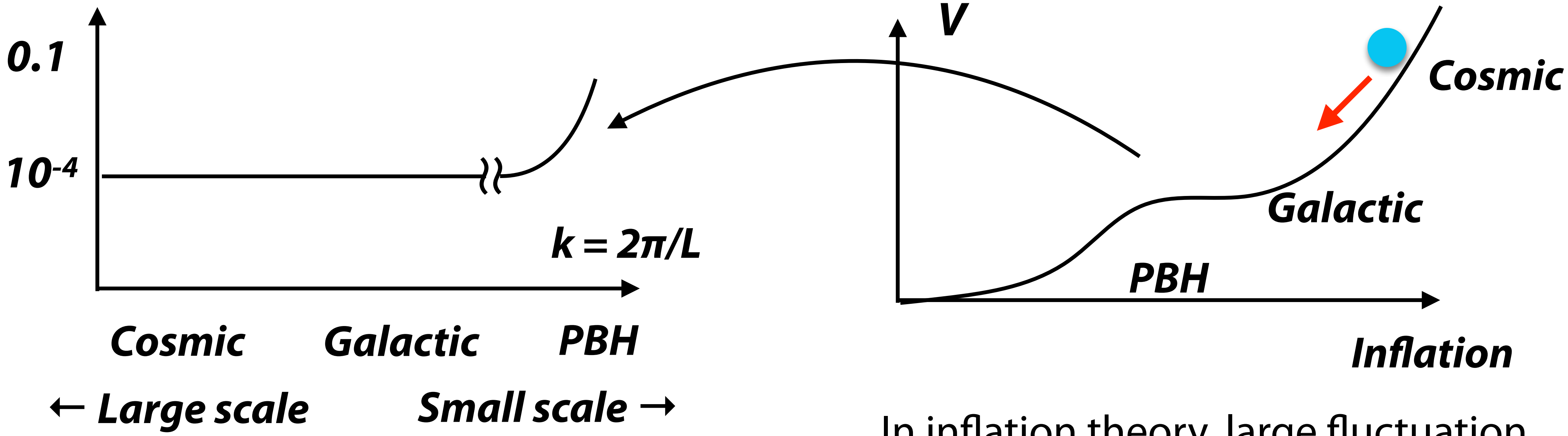
at H^{-1} ~ CMB, galaxy cluster sizes…

We prepare large fluctuation at very small structure scale !

$$\sigma(\mathrm{PBH}) \sim 0.1 \qquad \mathrm{at}\ H^{-1} \ll \mathrm{CMB,\ galaxy\ cluster\ sizes}$$

['67 Zel'dovich&Novikov, '71 Hawking]

initial condition of δ(k)

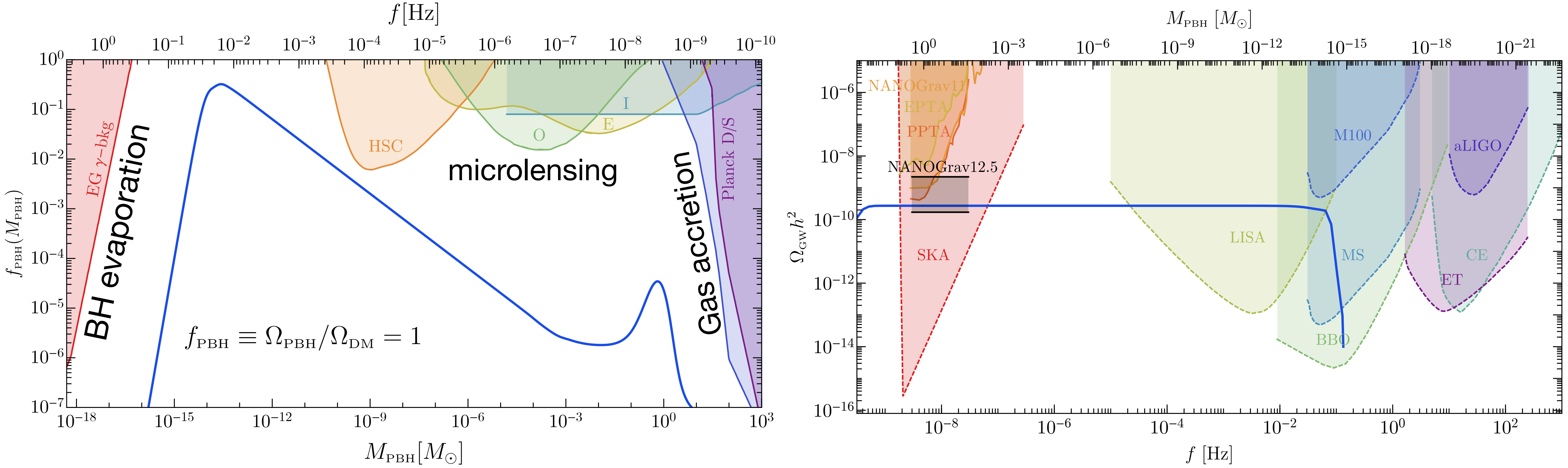


In inflation theory, large fluctuation is achieved for flat potential !

✓ ***Primordial Black Hole***

PBH can explain the total DM density.

[Luca, Franciolini, Riotto 2009.08268.]



PBH constraints

Gravitational wave signals

FIG. 1. *Left:* Mass function resulting from a flat power spectrum such that it peaks at $\simeq 10^{-14} M_\odot$, with $A_\zeta \simeq 5.8 \cdot 10^{-3}$ and $k_s = 10^9 k_l \simeq 1.6$ Hz, and PBHs comprise the totality of DM, i.e. $f_{\rm PBH} = 1$. In the tail of the population, around $M_\odot$, one can notice the bump in the PBH production due to the decrease of the threshold by QCD epoch equation of state [23, 46]. Shown are the most stringent constraints in the mass range of phenomenological interest coming from the Hawking evaporation producing extra-galactic gamma-ray (EGγ-bkg) [47], microlensing searches by Subaru HSC [48, 49], MACHO/EROS [50, 51], Ogle [52] and Icarus [53], and those coming from CMB distortions by spherical or disk accretion (Planck S and Planck D, respectively) [54, 55]. See Ref. [4] for a comprehensive review on constraints on the PBH abundance. Notice that there are no stringent constraints in the PBH mass range of interest [56, 57]. *Right:* The abundance of GWs according to our scenario. In black the 95% C.I. from the NANOGrav 12.5 yrs experiment is shown. For more details about the projected sensitivities see the main text.

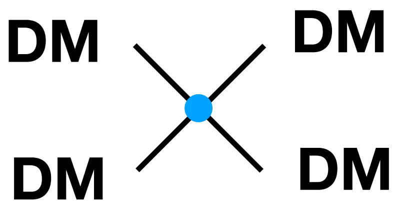
✓ *Dark Matter Models*

	Stability	**Abundance**	**Mass Range**
WIMP	**Symmetry**	**Annihilation cross section**	***10MeV - 300TeV (or Beyond)***
ADM	**Symmetry**	**Baryon asymmetry / Mass**	***O(1)GeV***
FIMP	**Very Weak Coupling**	**Interaction strength / mass / reheating T**	***> O(1)keV***
Sterile ν	**Very Weak Coupling / Approximate Symmetry**	**Mass / mixing angle / lepton asymmetry**	***2keV ~ 100keV***
Fuzzy DM	**Very light & Weak Coupling**	**Initial amplitude / mass**	$> 10^{-21}\mathrm{eV}$
Aixion DM	**Very light & Weak Coupling**	**Axion decay constant**	***~ μeV***
PBH DM	**Heavy Enough Black Hole**	**Density fluctuation / mass**	$10^{-(12-14)}M_\odot$

Dark Matter self-Interaction of $\sigma/m \sim barn/GeV \sim cm^2/g$ leaves visible impacts on the structure of (dwarf) galaxies.

Self Interacting Massive Particle SIMP

✓ SIMP



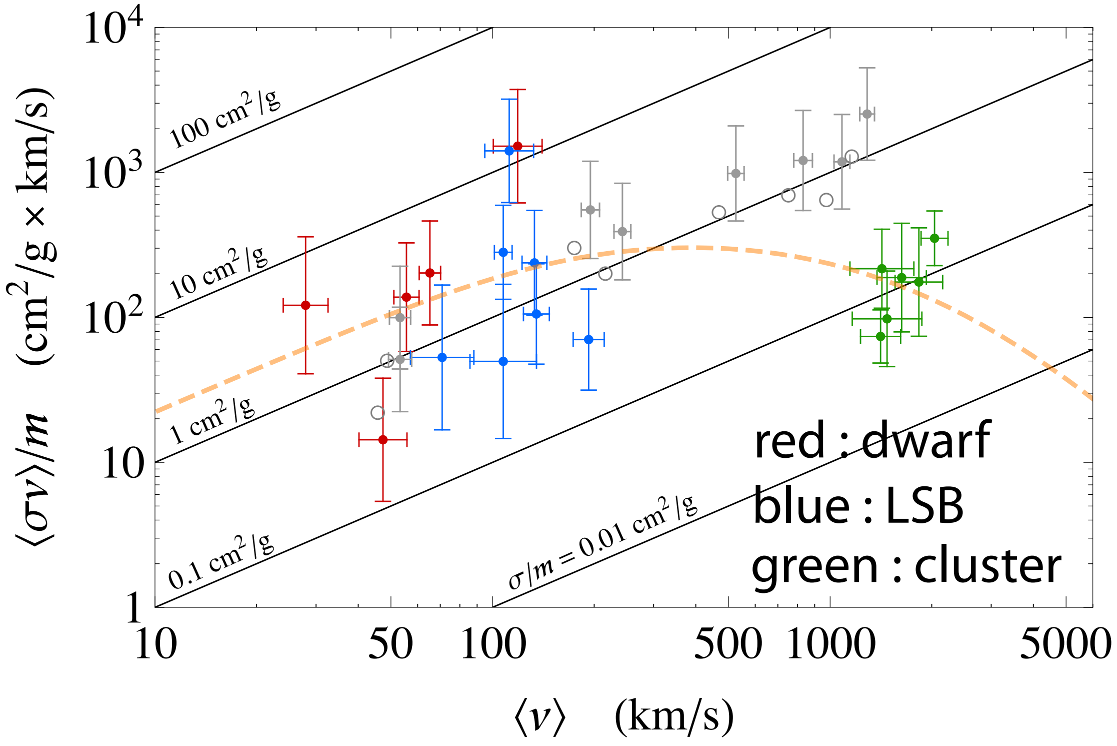
DM self interaction affects the DM profile in dwarf galaxies.

ex) For a DM density ~ ***10GeV/cm³*** @ ***r ~ 100pc***

[Mean free path] $\sim \dfrac{1}{\sigma_{\rm self} n_{DM}} \sim \mathcal{O}(10)\,{\rm kpc}$

for $\dfrac{\sigma_{\rm self}}{m_{\rm DM}} = \dfrac{\mathcal{O}(1)\,{\rm cm}^2}{g}$ $\rho_{\rm DM} = \mathcal{O}(1)\,{\rm GeV/cm}^3$

[1508.03339, Kaplinghat, Tullin, Yu]



A phenomenological DM halo profile :

Iso-thermal inner core + NFW

due to the self-interaction

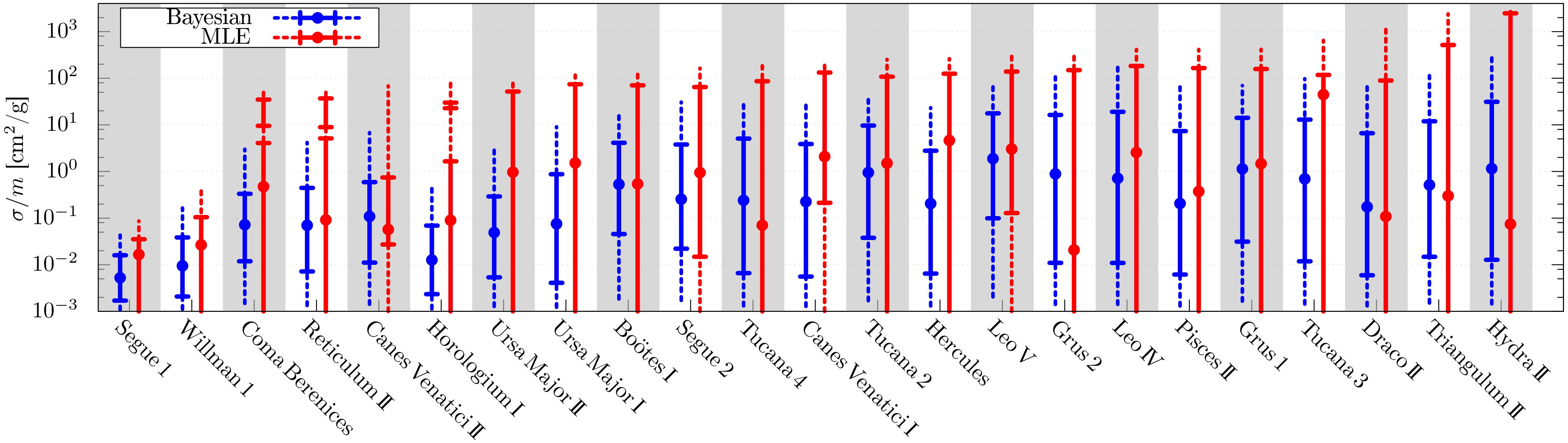
$\sigma_{\rm self} = \mathcal{O}(1)\,{\rm cm}^2$ well explains the dwarf irregular and low surface brightness galaxies.

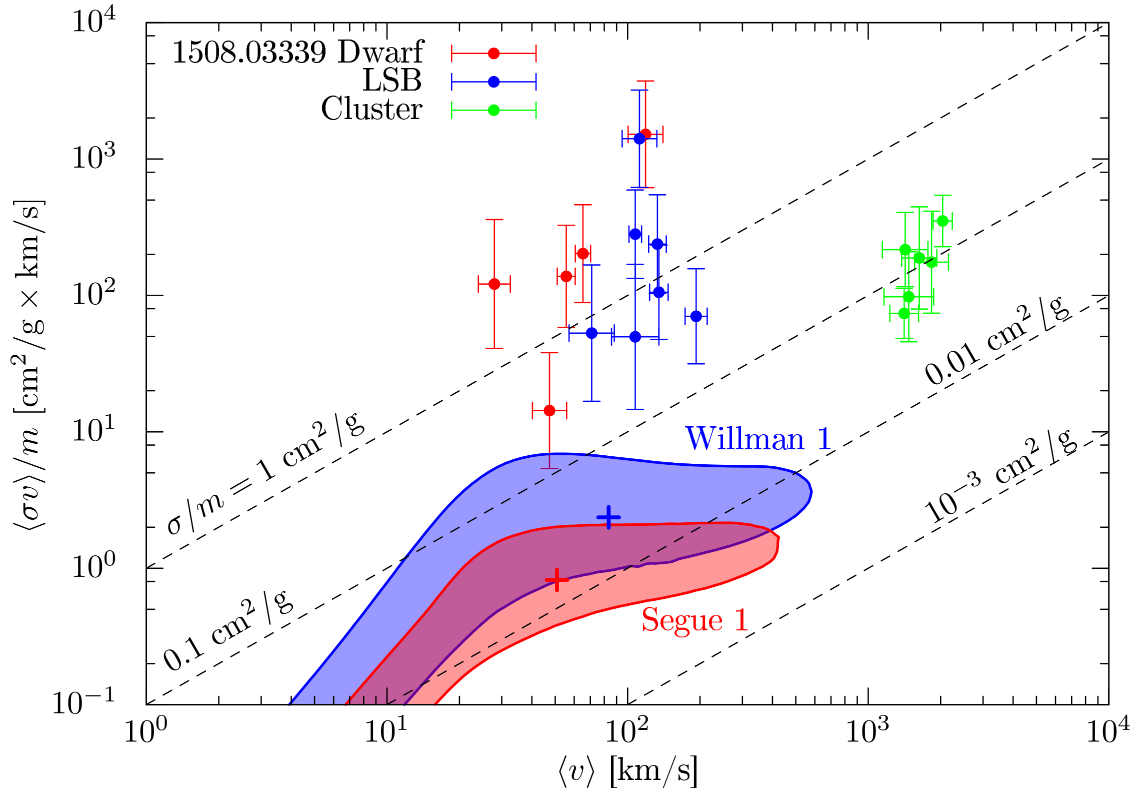
[1508.03339, Kaplinghat, Tullin, Yu]

✓ ***SIMP***

How about ultra-faint dwarf spheroidal (UFD)?

No UFDs favor self-interaction ***[2008.02529, Hayashi, MI, Kobayashi, Nakayama, Shirai]***





Segue1/Willman1 put stringent constraint if we use the same phenomenological model.

Our result does not exclude SIDM, but exclude

Iso-thermal inner core + NFW

due to the self-interaction

profile.

For further study, we need numerical simulation for the DM profile for given $\sigma_{\rm self}/m$.

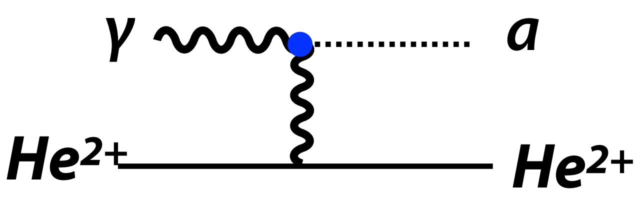
Backup

✓ Constraints on Axion (No neutrino…)

- ✓ Axion mass : $m_a \sim \frac{f_\pi m_\pi}{f_a}$ **$f_\pi = 93\text{MeV}, m_\pi = 135\text{MeV}$**
- ✓ Axion coupling to **γ** $\mathcal{L} \sim \frac{\alpha}{4\pi}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$
- ✓ Axion mixes with **π^0** with a mixing angle **$\sim f_\pi/f_a$**

Constraint from Horizontal Branch

The axion enhances the energy loss rate of the stars in Horizontal Branch of globular clusters via the Primakoff conversion

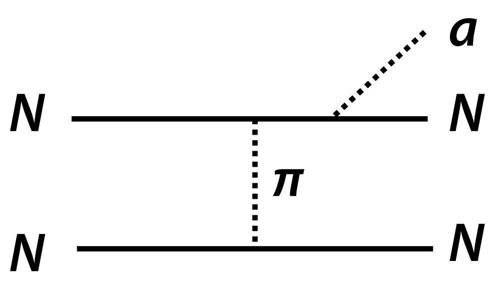


$E_{loss} > 10\ g^{-1}\ \text{erg}\ s^{-1}$ ($T_{\text{HB core}} \sim 10\text{keV}$)

[arXiv:1110.2895]

$f_a > 10^7\text{GeV}$

Supernovae Constraint (1987a)



$E_{\text{loss by axion}} < E_{\text{loss by neutrino}}$

[arXiv:1008.0636]

($T_{SN} \sim 30\text{MeV}$, mean free path > 10km)

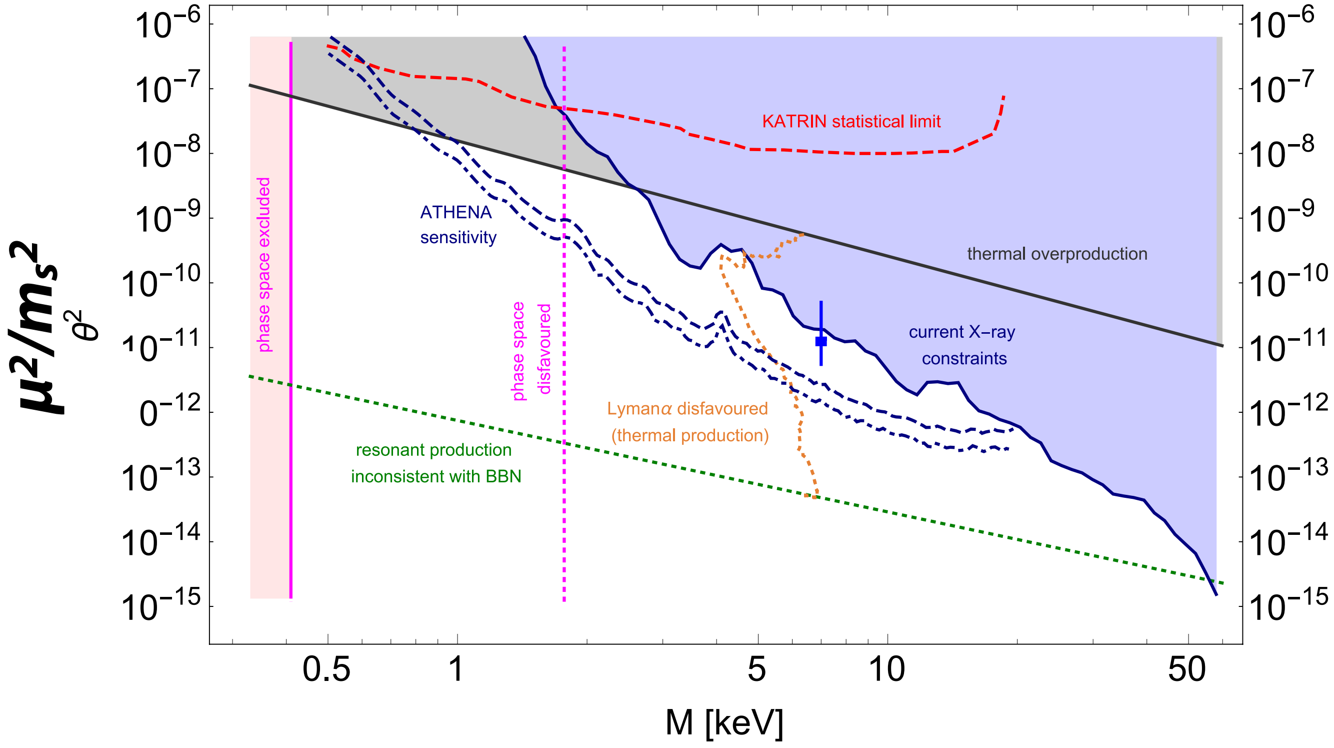
$f_a > 10^8\text{GeV}$

These constraints are consistent with observed dark matter density which favors **$f_a \sim 10^{12}\text{GeV}$**

$$\Omega_a h^2 \simeq 0.2 \times \left(\frac{a_0}{f_a}\right)^2 \left(\frac{f_a}{10^{12}\,\text{GeV}}\right)^{1.19} \left(\frac{\Lambda_{QCD}}{400\,\text{MeV}}\right)$$

✓ *Sterile Neutrino*

Fig from [1807.07938 Boyarsky et. al.]

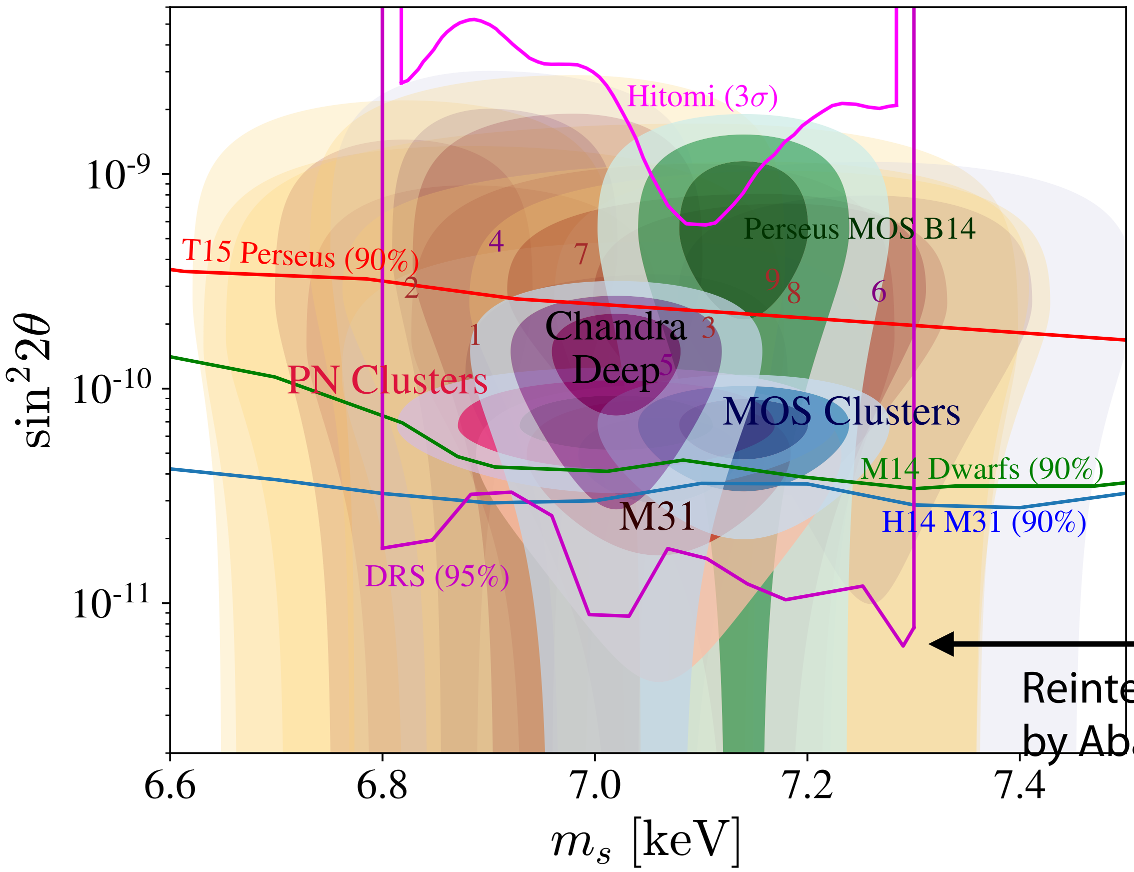


✓ Sterile Neutrino lifetime

$$\tau_{\nu_s\to3\nu}\simeq 1.5\times10^{14}\text{sec}\left(\frac{m_s}{10\text{keV}}\right)^5\times\theta^2$$

$$\tau_{\nu_s\to\nu\gamma}\simeq 1.8\times10^{16}\text{sec}\left(\frac{m_s}{10\text{keV}}\right)^5\times\theta^2$$

[Abazajian 2004.06170]



Reinterpreted by Abazajian

✓ ***3.5keV X***-ray line signal ?

XMM-Newton & Chandra observed ***3.5 keV X***-ray signals

Sterile DM @ (7keV, θ² ~ 10⁻¹⁰) ?

✓ New limit from XMM-Newton 117 cluster survey (3σ limit on flux)

$$\sin^2 2\theta < 4.4\times10^{-11}$$

[2006.13955, *Bhargava et.al.*]

✓ The blank-sky observation put a stringent limit.

[1812.06976, *Dessert et.al.*]

✓ *WIMP example*

✓ *Wino DM*

SU(2) triplet fermion (←same charges with W&Z boson !)

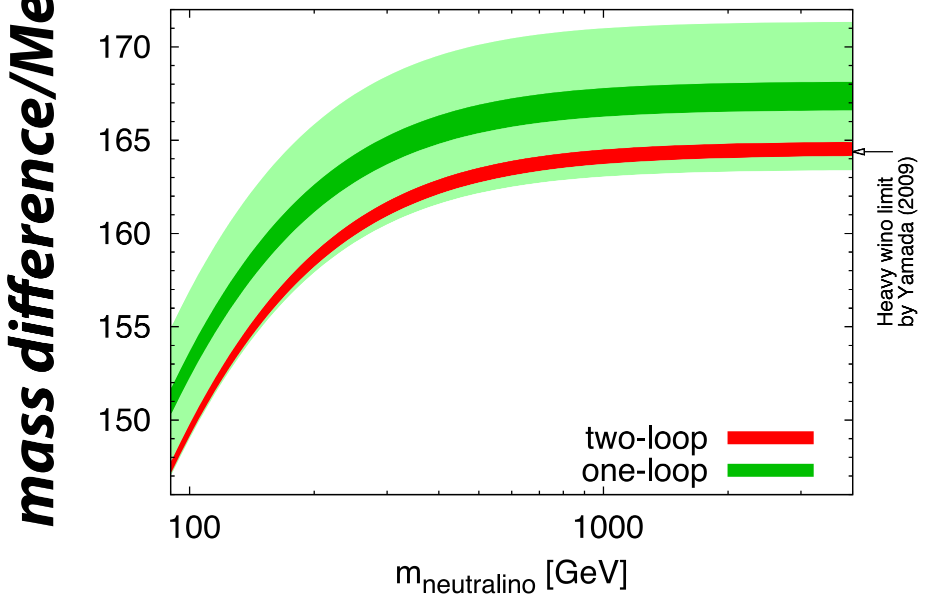
$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{\tilde{\chi}}^0\left(i\not\partial - M_2\right)\tilde{\chi}^0 + \bar{\tilde{\chi}}^-\left(i\not\partial - M_2\right)\tilde{\chi}^- \\ &\quad -g\left(\bar{\tilde{\chi}}^0\not W^\dagger\tilde{\chi}^- + h.c.\right) + g\bar{\tilde{\chi}}^-\left(c_W\not Z + s_W\not A\right)\tilde{\chi}^-\end{aligned}$$

All the interactions are determined by gauge interactions.

Free parameter = Mass !

(This is nothing but the PURE WINO LSP in supersymmetry)

Triplet fermion = Charged component + Neutral component



['12 Ibe,Mastumoto,Sato]

Decay mode : ***$\chi^\pm \rightarrow \chi^0 + \pi^\pm$: $\tau_{\rm wino} = O(10^{-10})$ sec.***

Disappearing track search at LHC

$m_{\rm wino} > 460$ GeV (13TeV&36fb^{-1}ATLAS)

($m_{\rm wino} \sim 850$ GeV (14TeV&3000fb^{-1}))

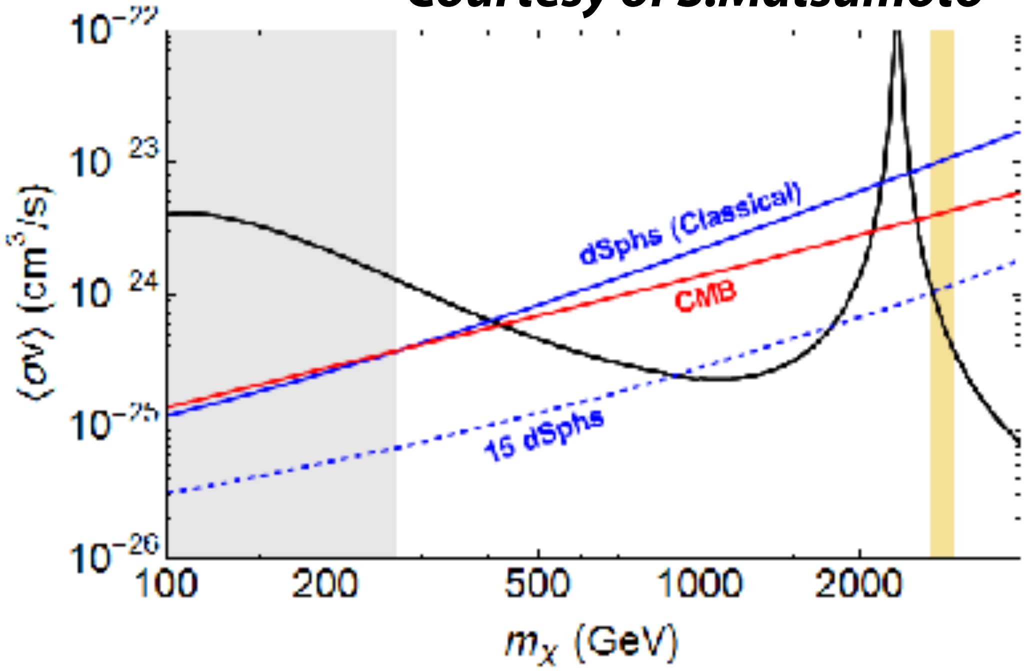
ATL-PHYS-PUB-2018-031

✓ *WIMP example*

✓ *Wino DM*

- ✓ Indirect search by gamma-ray from dwarf Spheroidal galaxies are promising !

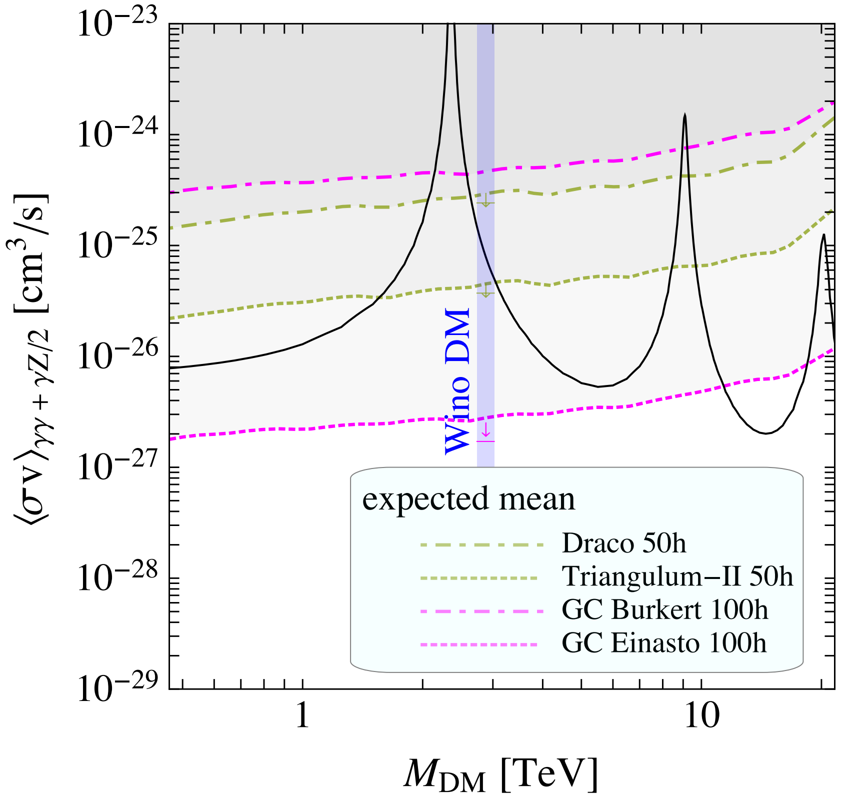
Courtesy of S.Matsumoto



Fermi-LAT 6 years data excluded the triplet dark matter in

$m_{triplet} < 400$ GeV (classical dSphs)

[For recent J-factor estimation '16 Hayashi, Ichikawa, Matsumoto, MI, Ishigaki, Sugai]



- ✓ Future prospect at CTA

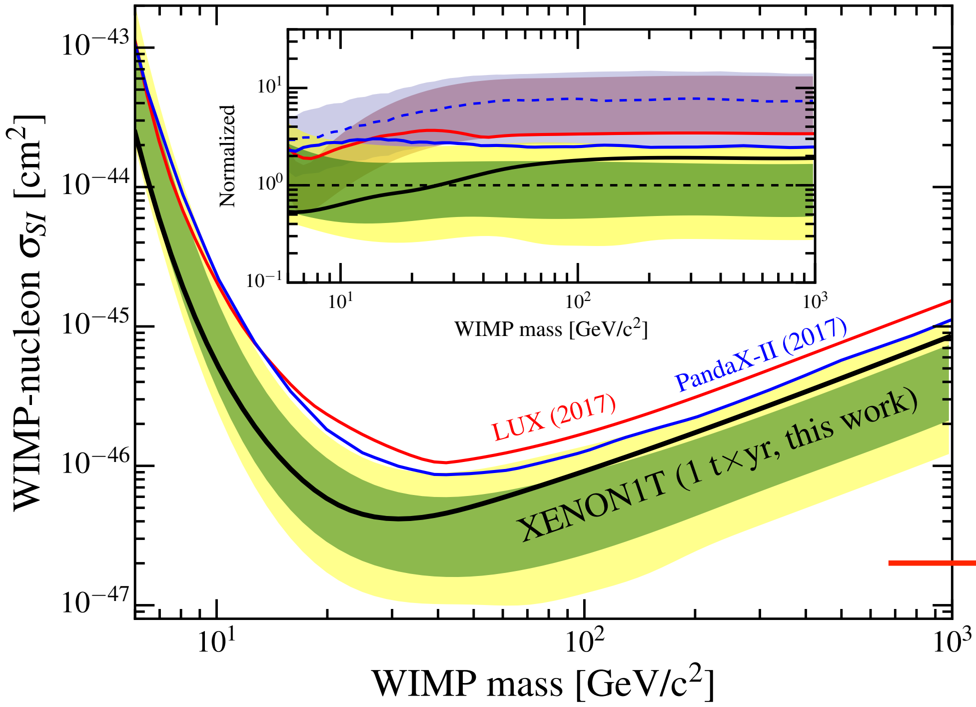
Dwarf looks better target than the galactic center by taking the DM profile of the galactic center into account!

['16 Lefranca, Moulina, Panci, Sala, Silk]

✓ *WIMP example*

✓ *Wino DM*

Wino Dark Matter Search (direct detections, $\chi N \rightarrow \chi N$)



Coupling to H and Z are highly suppressed for ***μ_H=O(10-100) TeV*** at the tree-level.

Wino-Nucleon @ higher loop level

$\sigma_{p\text{-}N}$ = (10^{-47})cm^2

(much smaller than the current reach...)

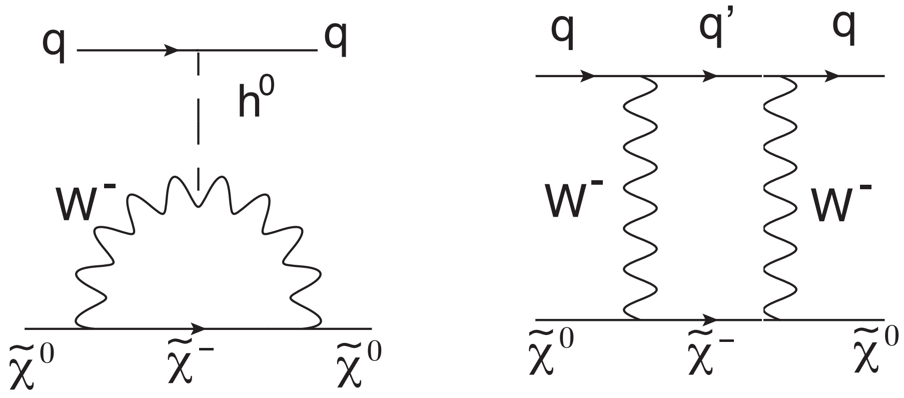
['10 Hisano, Ishiwata, Nagata]

DM mass :

Wino Mass $\lesssim$ 3TeV

= 3TeV : Thermal abundance

< 3TeV : Gravitino Decay



One-loop diagrams which contribute to the Wino-nucleon scatterings.

✓ Darwin (multi-ton Argon/Xe detector) will reach down to 10^{-47}cm^2 for WIMP mass below 300GeV.

✓ The irreducible background from atmospher neutrinos at about 10^{-48}cm^2. [arxiv:1003.5530]