Over View on Dark Matter Models and Neutrino Signals

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Masahiro Ibe (ICRR)

✓ Dark Matter ?

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

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

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

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

- 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 $\Delta x \Delta p > 1$)

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

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

[*e.g. Phys.Rev.D91,023519 Martinez-Medina, Robles, Matos*]

✔ 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 $\Delta v \sim 10$ km/s , $R \sim 1$kpc

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

$$\rightarrow m_{DM} > 2keV \text{ (Tremaine-Gunn Bound)}$$

Mass Range ?

Upper Limit

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

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

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

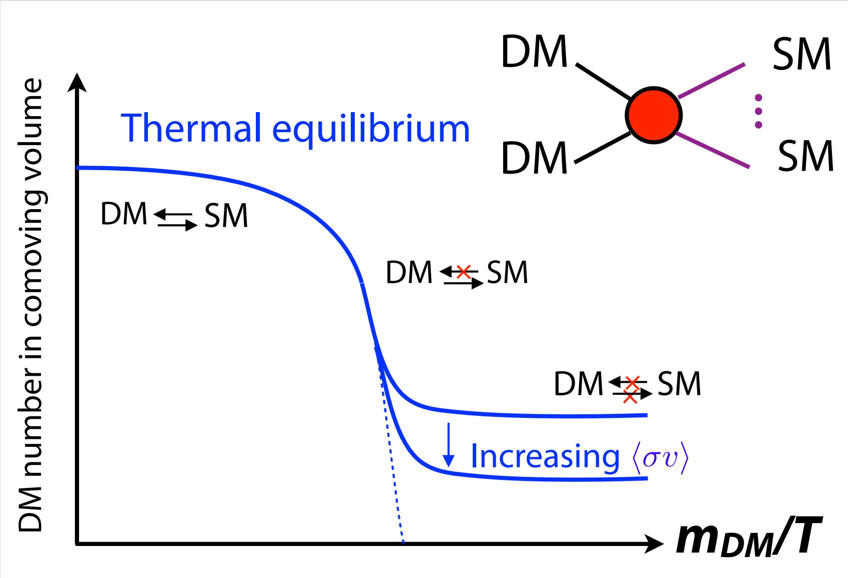
$$m_{DM} < 10^3M_{\odot} \sim 10^{60}GeV$$

Model Independent Mass Range

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

WIMP

WIMP abundance



- DM is in thermal equilibrium for $\boldsymbol{T > m_{DM}}$.
- For $\boldsymbol{m_{DM} < T}$, DM is no more created
- DM is still annihilating for $\boldsymbol{m_{DM} < T}$ 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 : $\boldsymbol{T_F \sim m_{DM}/20}$

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

$$\boldsymbol{n_{DM} \sim H/\langle\sigma v\rangle \text{ at } T_F}$$

WIMP abundance

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

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

ρ_{DM}/s is constant in time

In the WIMP scenario

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

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)

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

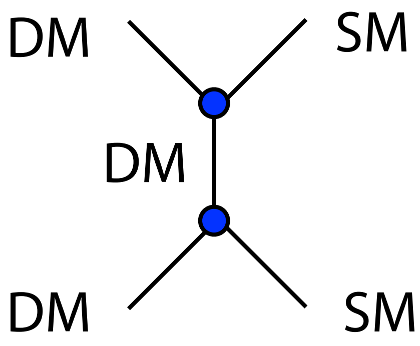
✓ Abundance depends on the DM mass only through ***$\langle\sigma v\rangle$!***

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 :



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

- 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

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

- 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

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

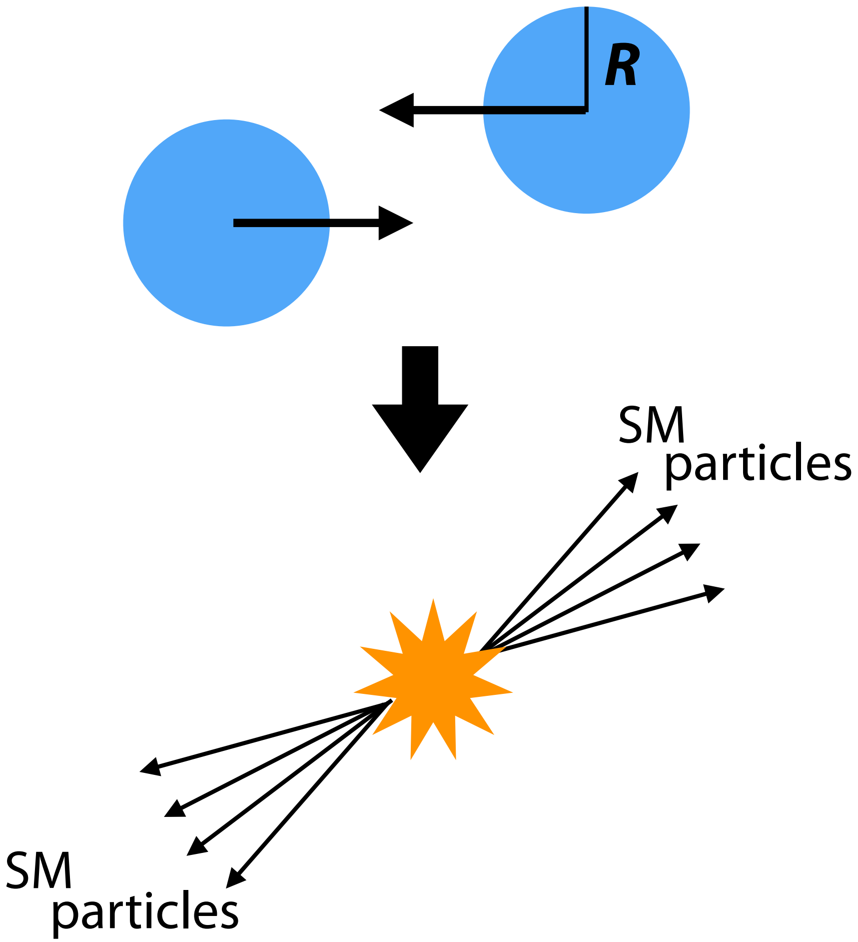
(spineless case for simplicity)

→ $\boldsymbol{M_{DM} < 300\ \mathrm{TeV}}$

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, $\boldsymbol{\sigma \sim \pi R^2}$? (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

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)*

If n_{DM} is also given by the baryon asymmetry, i.e. $n_{DM} = \eta \times n_\gamma$,

$$\Omega_B / \Omega_{DM} = O(1)$$

is naturally explained for $m_{DM} \sim m_{p,n}$ **[e.g. 1990 Barr Chivukula, Farhi] .**

→ ***Asymmetric Dark Matter***

Concrete Set Up **[1805.0687 Kamada, Kobayashi, Nakano MI]**

✓ ***Baryogenesis = Leptogenesis***

$$\mathcal{L}_{N\text{-SM}} = \frac{1}{2} M_R \bar{N}_R \bar{N}_R + y_N H L \bar{N}_R + \text{h.c.}$$

(N_R : right-handed neutrino, $M_R > 10^{10}\,\mathrm{GeV}$)

✓ Dark Sector Shares the ***B-L*** symmetry with the ***SM*** via

$$\mathcal{L}_{B-L\,\text{portal}} = \frac{1}{M_*^n} \mathcal{O}_D \mathcal{O}_{\text{SM}} + \text{h.c.}$$

O_{SM} : Neutral (other than B-L) consisting of SM fields.

O_{DM} : Neutral (other than B-L) consisting of DM fields.

✓ *Asymmetric Dark Matter (ADM)*

$T \sim M_R$

Leptogenesis

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

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

$T_D \sim M_* (M_*/M_{PL})^{1/(2n-1)}$

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

$T_{EW} \sim 100\,\mathrm{GeV}$

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

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

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

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

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

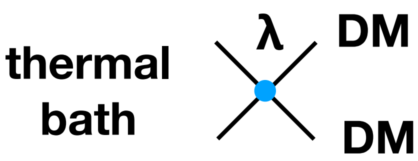
In ADM model, DM abundance is determined by m_{DM} for a given B asymmetry!

Feebly Interacting Massive Particle (FIMP)

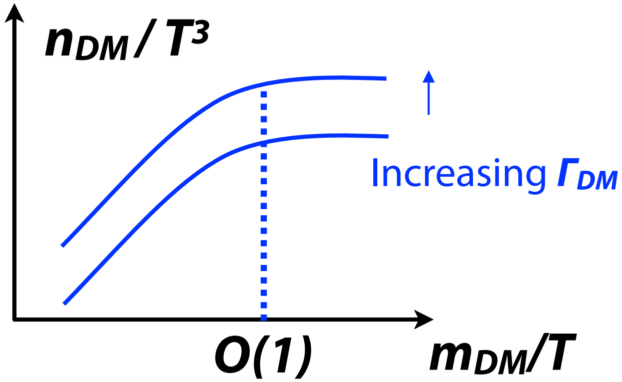
✔ *FIMP*

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]

Tiny coupling of $O(10^{-13})$ reproduces the observed dark matter density !

Sterile Neutrino Dark Matter

✔ Sterile Neutrino Dark Matter

Add a sterile neutrino $\boldsymbol{\nu_s}$ neutrino mixing with active neutrinos $\boldsymbol{\nu_a}$:

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

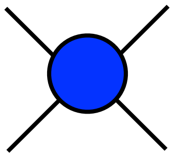
$m_s \gg$ ***active neutrino masses***

$\mu \propto$ [***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



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

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

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

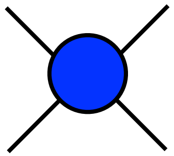
$$V(T\,,\mu_L) \sim -100\, G_F{}^2\, T^4 p + G_F\, T^3 \underbrace{\eta_L}_{\text{Lepton asymmetry below the EWSB scale}}$$

[1807.07938 Boyarsky et. al.]

Sterile Neutrino Dark Matter

- The sterile neutrinos are mainly produced via the neutrino oscillation

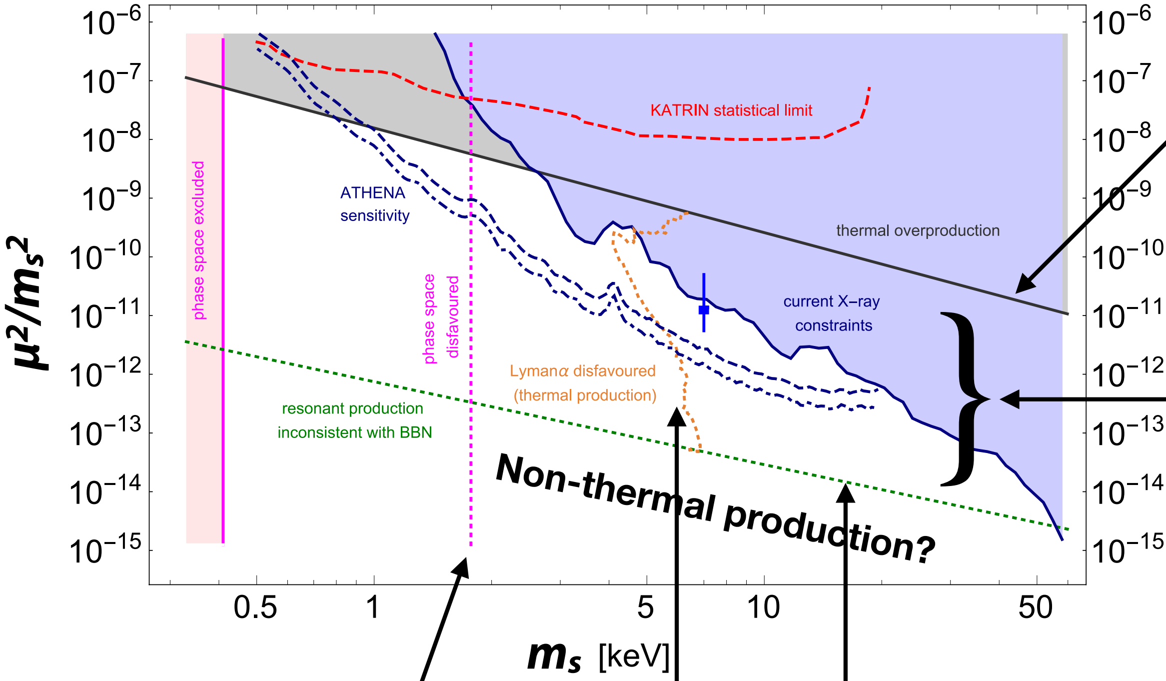
thermal bath



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

Production rate

Fig from [1807.07938 Boyarsky et. al.]



Non-thermal production?

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

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

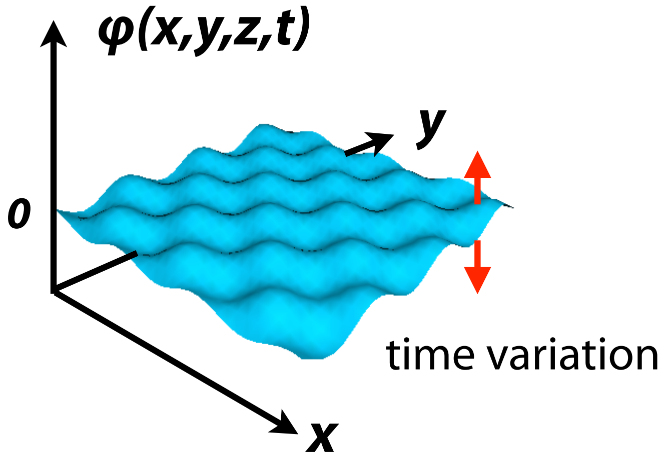
Tremaine-Gunn bound

Warm dark matter constraint

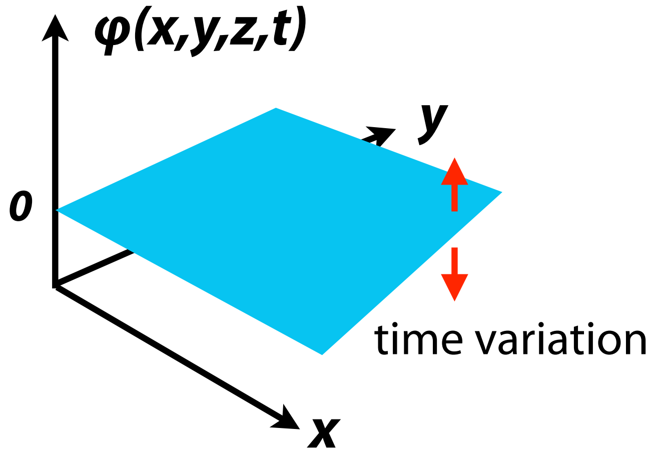
***$\eta_L \sim 10^{-3}$*:** The upper limit on η_L in νMSM model due to the late time decay of $N_{2,3}$
['05 Asaka, Shaposhnikov]

Axion and scalar field Dark Matter

✓ *Scala Field Dark Matter = Coherent oscillation of the scalar field*

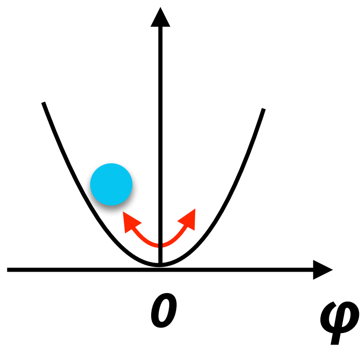


spatial fluctuation
→ DM momentum



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

$$\ddot{\varphi} + \underline{3H\dot{\varphi}} = -m_{DM}^2\varphi$$

Hubble friction

- 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)

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

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

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

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

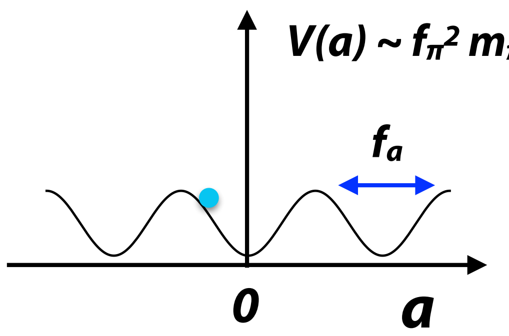
$$\mathcal{L}_{\rm eff} = \frac{g_s^2}{32\pi^2}\boxed{\left(\theta - \frac{6a}{f_a}\right) G^{a\mu\nu}\tilde{G}^a_{\mu\nu}} \leftarrow \textbf{gluons}$$

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

$f_a \gg 10^2\,\mathrm{GeV}$ ~ 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

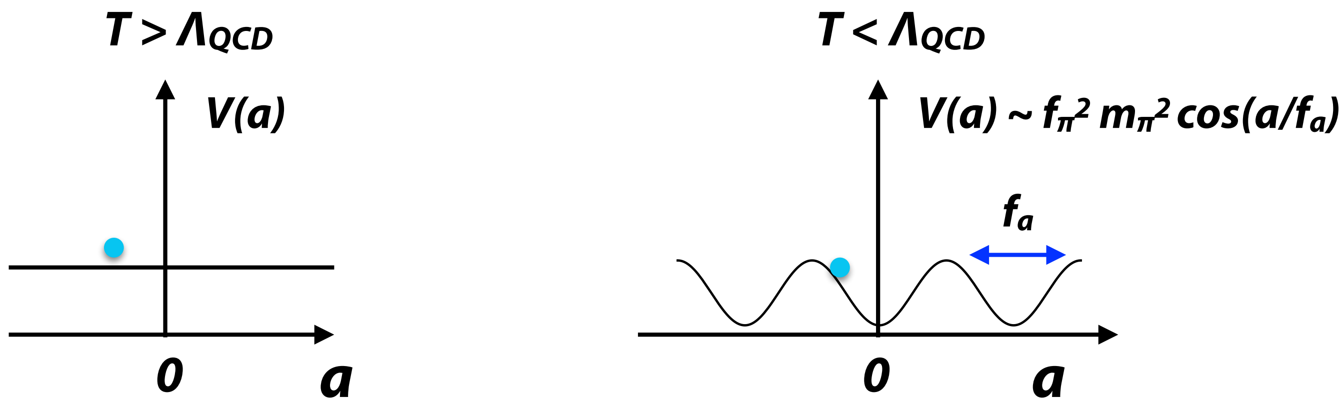
$$m_a \sim \frac{f_\pi m_\pi}{f_a}$$

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

Axion Dark Matter

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

→ $T_{osc} \sim O(1)$ GeV



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

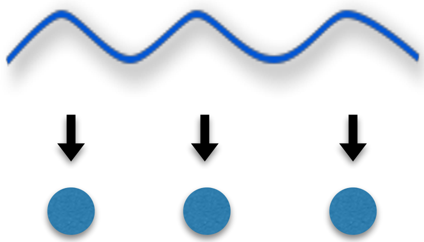
$f_a \sim 10^{12}$ GeV ***($m_a \sim 10\,\mu$eV)***

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

Primordial Black Hole

✓ <u>*Primordial Black Hole*</u>

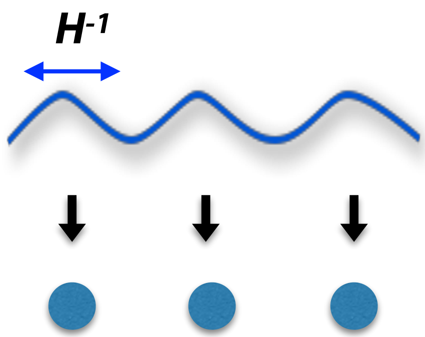
The density fluctuations of $\boldsymbol{\delta = (\rho - \rho_{average})/\rho_{average} = O(1)}$ collapse.



$\boldsymbol{\delta = O(1)}$

Collapsed objects

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



$\boldsymbol{\delta = O(1)}$

Collapsed objects : Mass ~ $4\pi/3\ \rho\ H^{-3}$

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

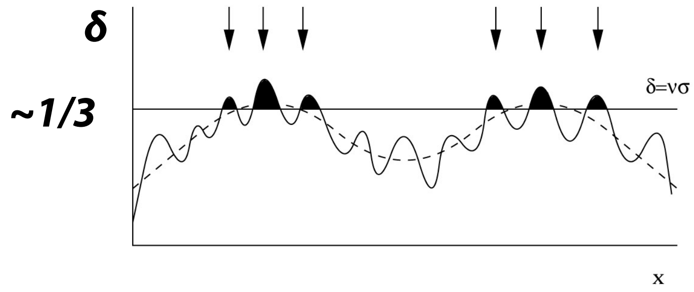
$\boldsymbol{\delta = O(1)}$ of a spatial size $\boldsymbol{\sim H^{-1}}$ → Black Hole

Primordial Black Hole

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

$$M_{BH} \sim 4\pi/3\, \rho\, H^{-3} \sim 0.066 M_\odot \left(\frac{\mathrm{GeV}}{T}\right)^2$$

- Energy fraction at the formation



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

Energy fraction at the formation

$$\beta_*(M_*) = \int_{1/3}^{1} \frac{d\delta}{\sqrt{2\pi}\bar{\delta}(M_*)} \exp\left(-\frac{\delta^2}{2\bar{\delta}^2(M_*)}\right) \simeq \bar{\delta}(M_*) \exp\left(-\frac{1}{18\bar{\delta}^2(M_*)}\right),$$

Abundance

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

$$\Omega_{DM} \sim 0.3 \rightarrow \beta_* \sim 10^{-6} \rightarrow \delta(M) \sim 0.07$$

[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

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

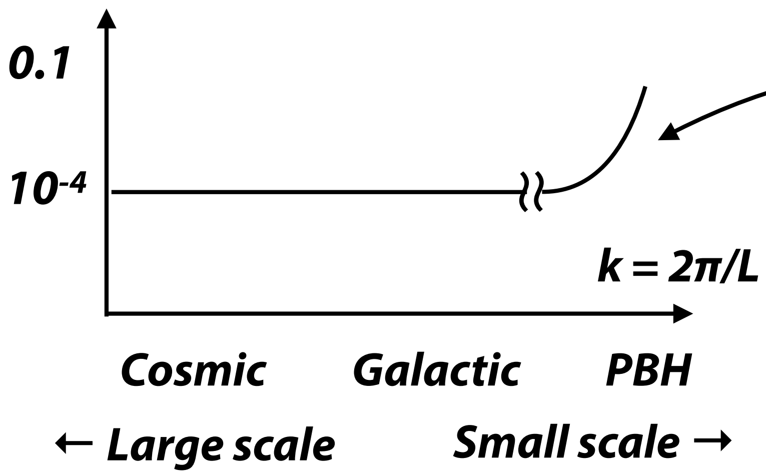
at H^{-1} ~ CMB, galaxy cluster sizes…

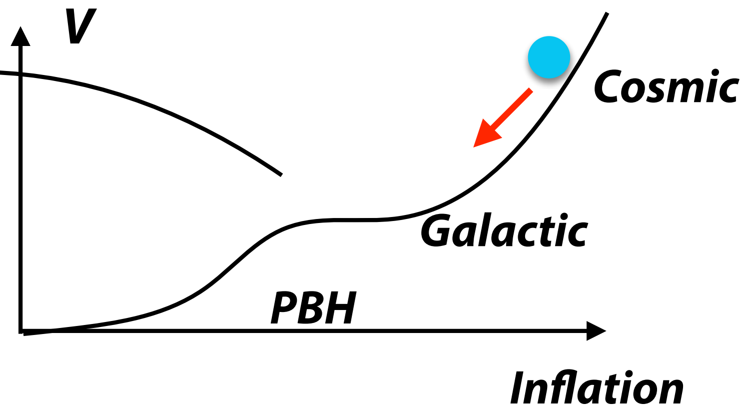
We prepare large fluctuation at very small structure scale !

$$\delta(\text{PBH}) \sim 0.1 \qquad \text{at } H^{-1} << \text{CMB, galaxy cluster sizes}$$

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

initial condition of $\delta(k)$





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

✓ *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	*> 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	$> 10^{-22}eV$
Aixion DM	Very light & Weak Coupling	Axion decay constant	*~ μeV*
PBH DM	Heavy Enough Black Hole	Density fluctuation Mass	$10^{-(12\text{-}14)}M_\odot$

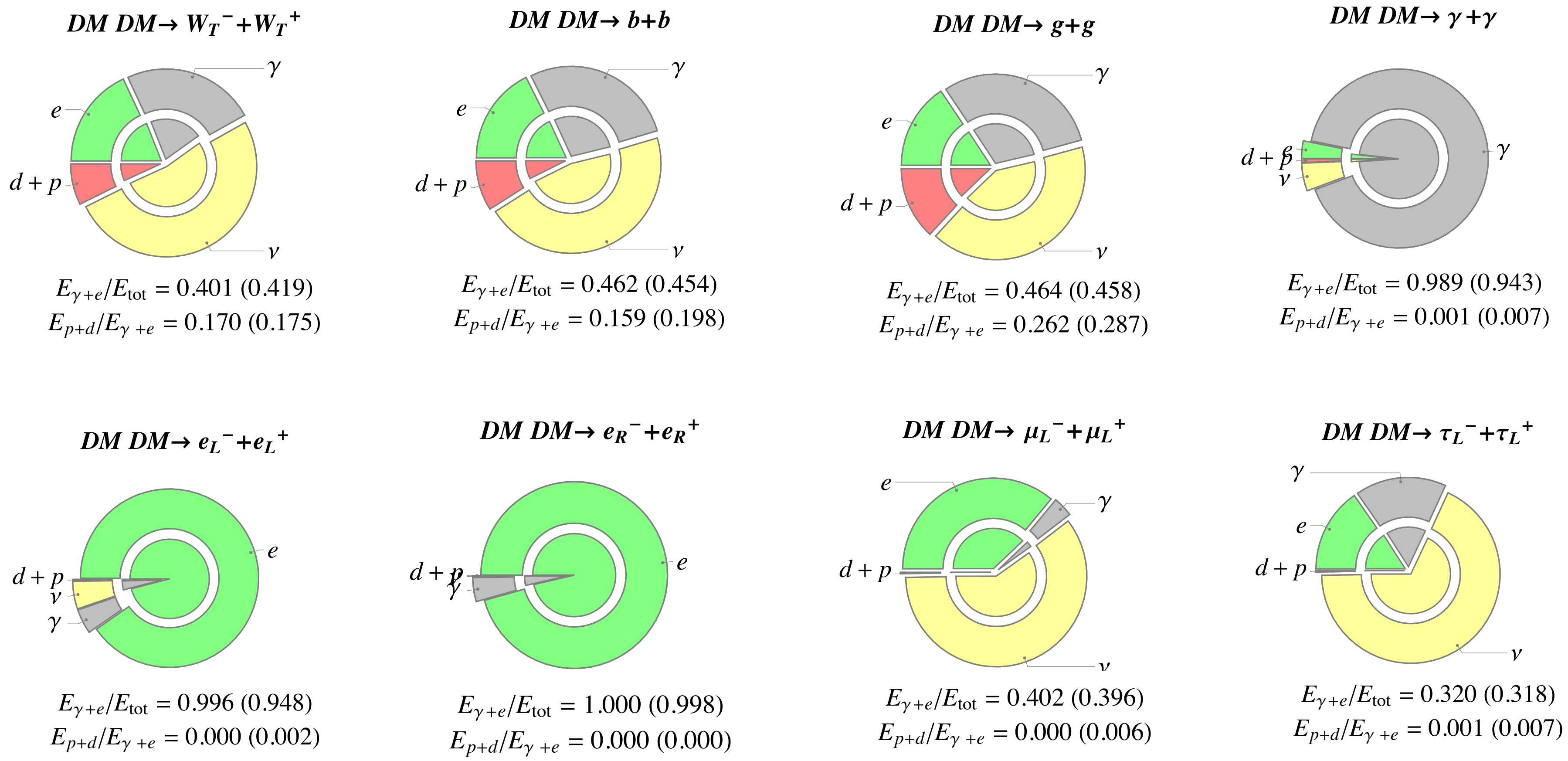
Dark Matter self-Interaction of *σ/m ~ barn/GeV ~* cm^2/g leaves visible impacts on the structure of (dwarf) galaxies.

Neutrino Signals ?

Neutrino Signals in WIMP scenario

- The WIMP annihilates into the Standard Model Particles
- The final states of the annihilation often involve lots of neutrinos !

<u>PIE charts of the energy fraction of the final states</u>



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

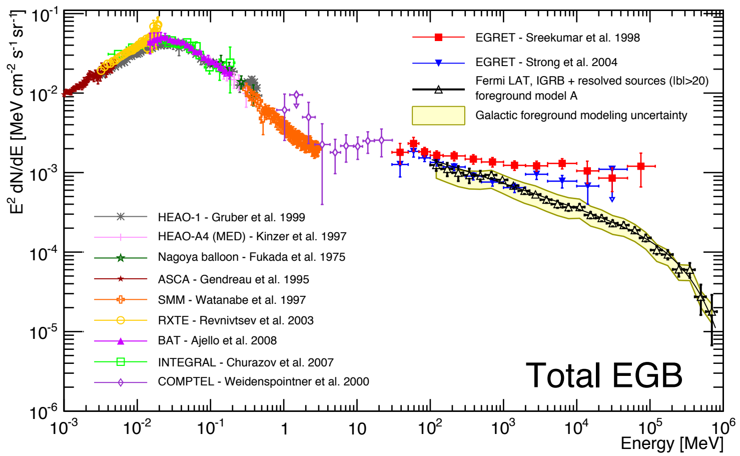
[PPPC 4 DM ID : Cirelli et. al.]

Neutrino Signals in WIMP scenario

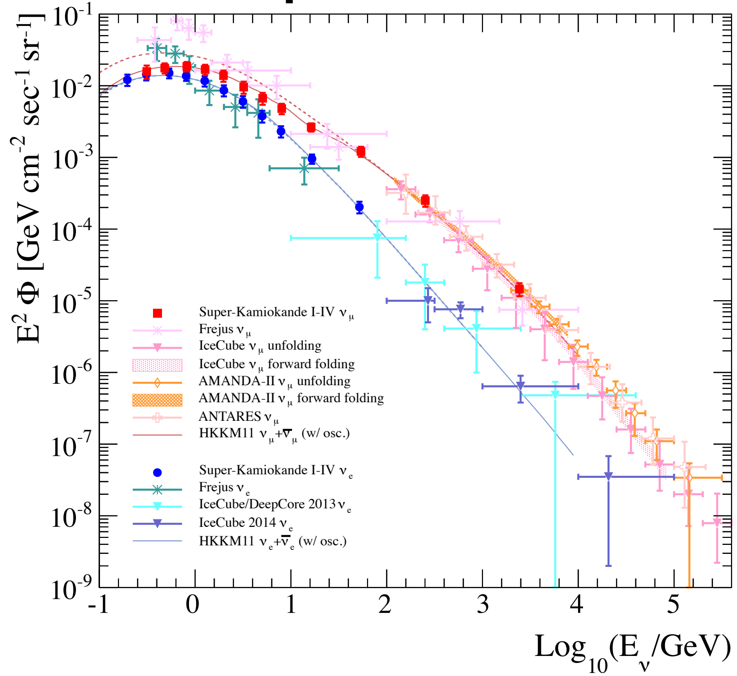
- The WIMP annihilates into the Standard Model Particles
- The final states of the annihilation often involve lots of neutrinos !
- The neutrino signals require larger detectors compared with other channels.
- The large atmospheric neutrino background compared with e.g. γ-ray signals.

[(isotropic ***γ***-ray) / (atmospheric ***ν***) ***~ 10^-4^*** at ***E ~ 1TeV***]

Isotropic γ-ray [1410.3696]



atmospheric ν [1510.08127]



Neutrino Signals in WIMP scenario

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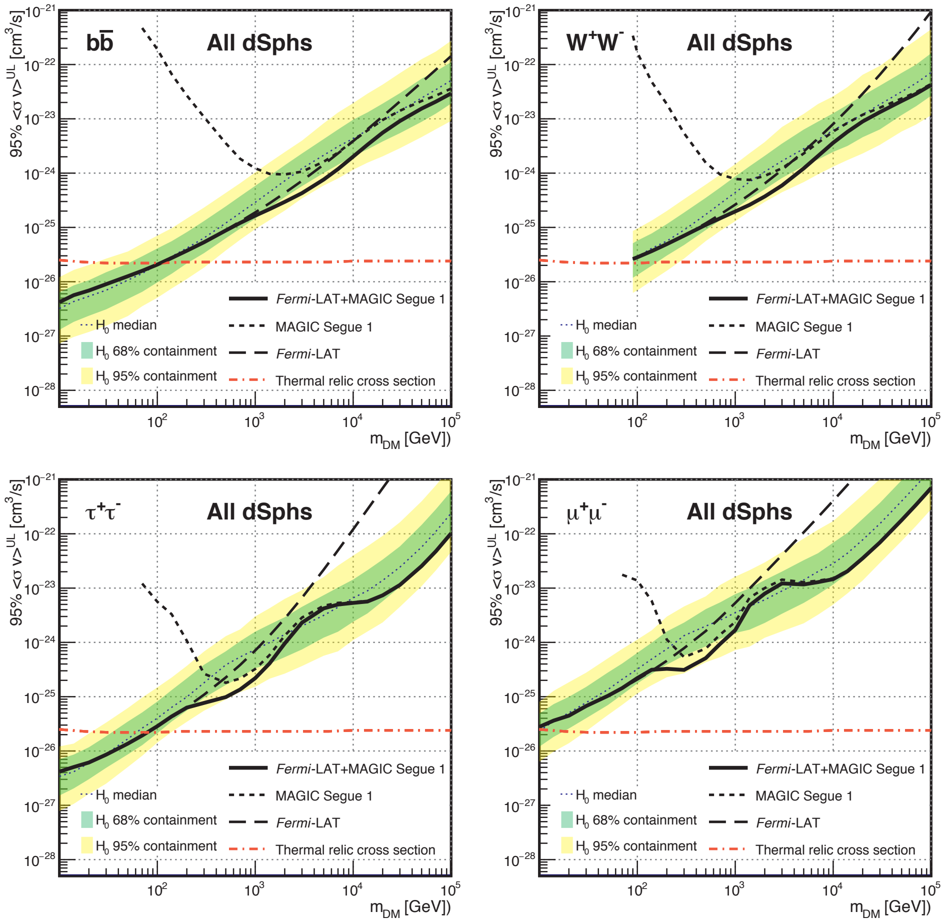
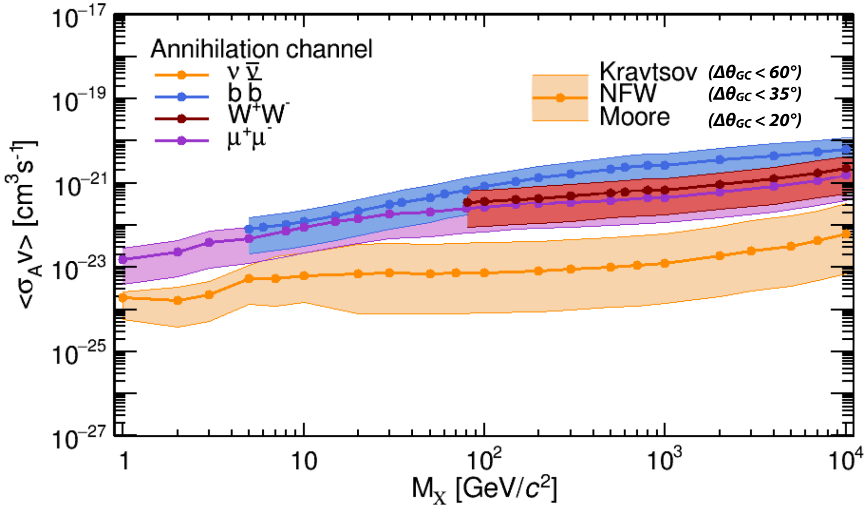
γ-ray from dSphs [1601.06590]



constraints from ν flux

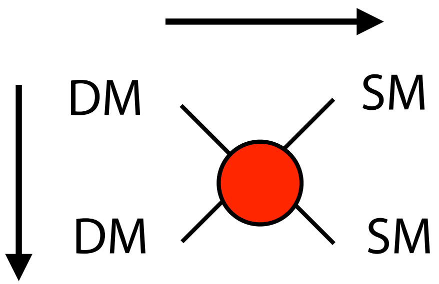


[18 Frankiewicz]

The neutrino signals are not very promising to test the WIMP models for ***m_{DM} < 10 TeV*** …

Neutrino Signals in WIMP scenario

- The neutrino signals from the center of the SUN !
- Dark Matter are captured by the SUN via scattering with the Nuclei in the SUN.



Accumulated DM annihilates into the SM at the core of the SUN.

→ Only ***ν*** can reach the Earth !

- Total number of DM in the SUN $\boldsymbol{N_{DM}}$:

$$\frac{dN_{\rm DM}}{dt} = \Gamma_{\rm capt} - C_{\rm ann} N_{\rm DM}^2$$

$$\longrightarrow \quad N_{DM} = \sqrt{\frac{\Gamma_{\rm capt}}{C_{\rm ann}}} \tanh\left(t\sqrt{\Gamma_{\rm capt} C_{\rm ann}} \right)$$

Neutrino Signals in WIMP scenario

$$N_{DM} = \sqrt{\frac{\Gamma_{\rm capt}}{C_{\rm ann}}} \tanh\left(t\sqrt{\Gamma_{\rm capt} C_{\rm ann}}\right)$$

Capture rate at the SUN

Mostly through He, O, Fe

Mostly through H

$$\Gamma_{\rm capt} \simeq \frac{5.90 \cdot 10^{26}}{\rm sec} \left(\frac{\rho_{\rm DM}}{0.3\,\frac{\rm GeV}{\rm cm^3}}\right) \left(\frac{100\,{\rm GeV}}{M_{\rm DM}}\right)^2 \left(\frac{270\,\frac{\rm km}{\rm sec}}{v_0^{\rm eff}}\right)^3 \frac{\sigma_{\rm SD} + 1200\,\sigma_{\rm SI}}{\rm pb}.$$

[Cirelli, PPPC ν]

σ_{SI}, σ_{SD} **:** spin independent and dependent DM-nucleon cross section

Annihilation rate at the SUN

$$C_{\rm ann} = \langle \sigma v \rangle \left(\frac{G_N\, M_{\rm DM}\, \rho_\odot}{3\, T_\odot}\right)^{3/2} \simeq \frac{2 \cdot 10^{-51}}{\rm sec} \left(\frac{\sigma}{1\,{\rm pb}}\right) \left(\frac{v}{300\,{\rm km/s}}\right) \left(\frac{m_{\rm DM}}{\rm TeV}\right)^{3/2}$$

$\rho_\odot$ = 151 g/cm³ **:** the core mass density of the SUN

$T_\odot$ = 15.5 K **:** the core temperature of the SUN

σ **:** annihilation cross section of dark matter

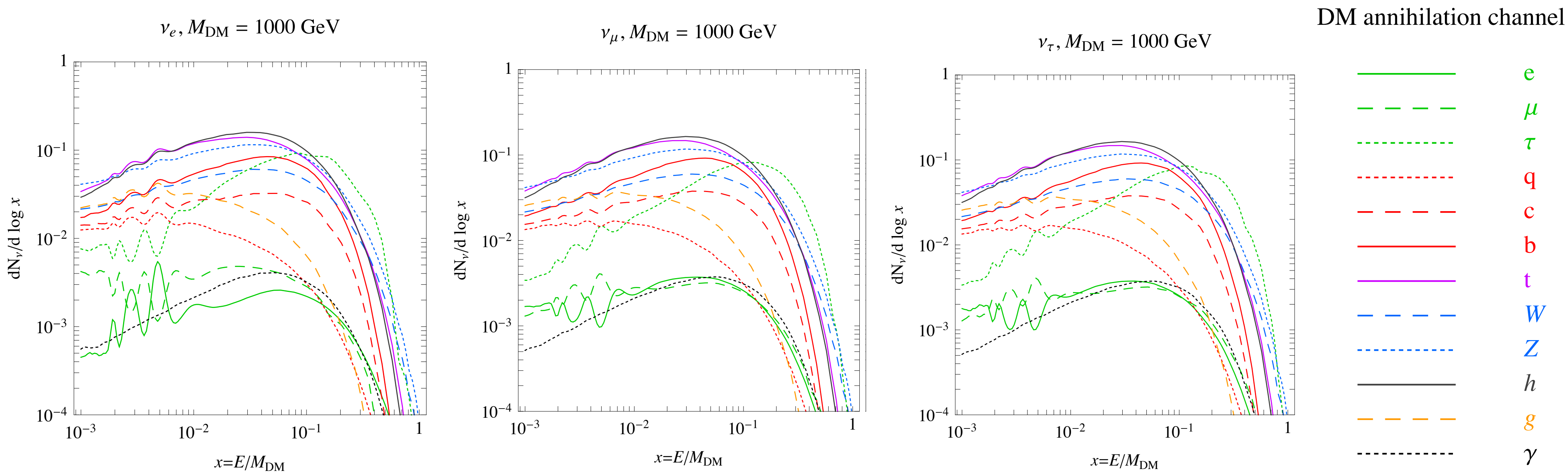
Neutrino Signals in WIMP scenario

- For the age of the SUN **~ 4.5 Gyr, $t\sqrt{\Gamma_{capt} C_{ann}} \gg 1$** for **$\sigma_{WIMP}$ ~ 1 pb** .

$$N_{DM} \sim \sqrt{\frac{\Gamma_{\rm capt}}{C_{\rm ann}}} \qquad\qquad \Gamma_{\rm ann} = \frac{1}{2} C_{\rm ann} N_{\rm DM}^2 \sim \frac{1}{2}\Gamma_{\rm capt}$$

- Flux from DM annihilation in the SUN

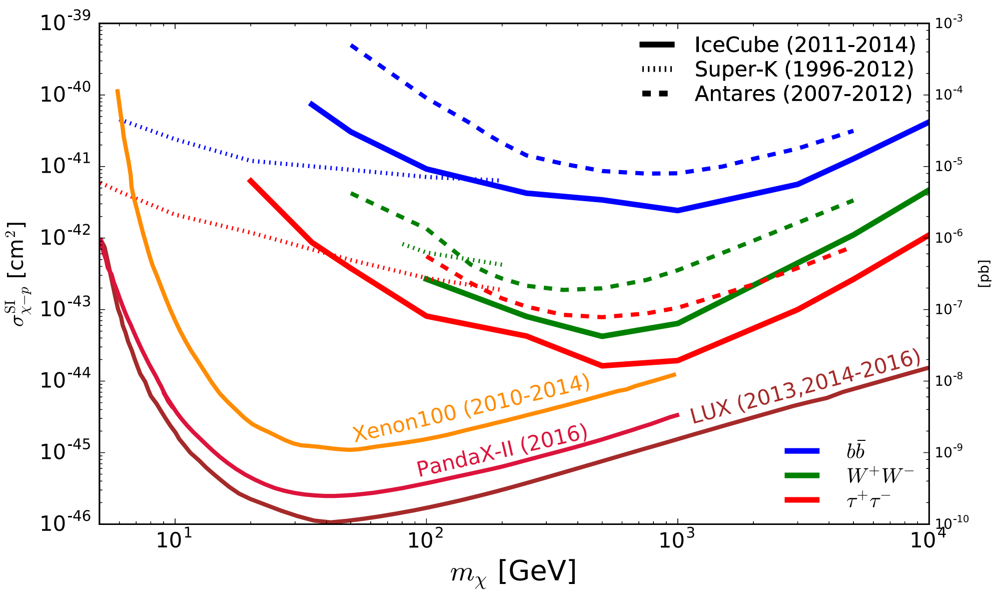
$$F \sim 10^{-29}/cm^2 \times \Gamma_{capt}$$

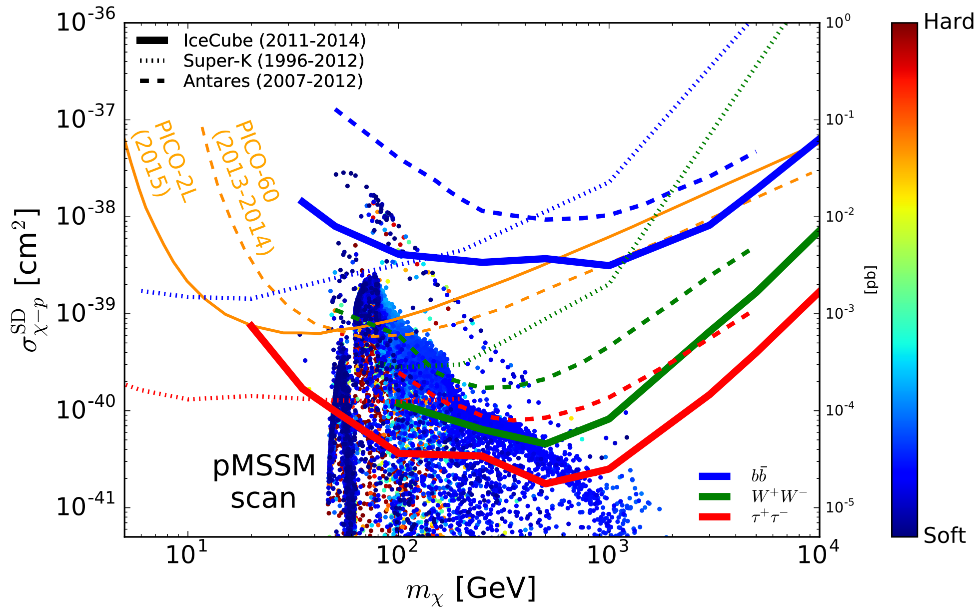


EX) ν spectrum at the detection per one annihilation (crossing vertically the Earth) **[Cirelli, PPPC ν]**

Neutrino Signals in WIMP scenario

90%CL limits on the Nucelon-DM scattering cross section from the DM annihilation in the SUN [Icecube 1612.05949]





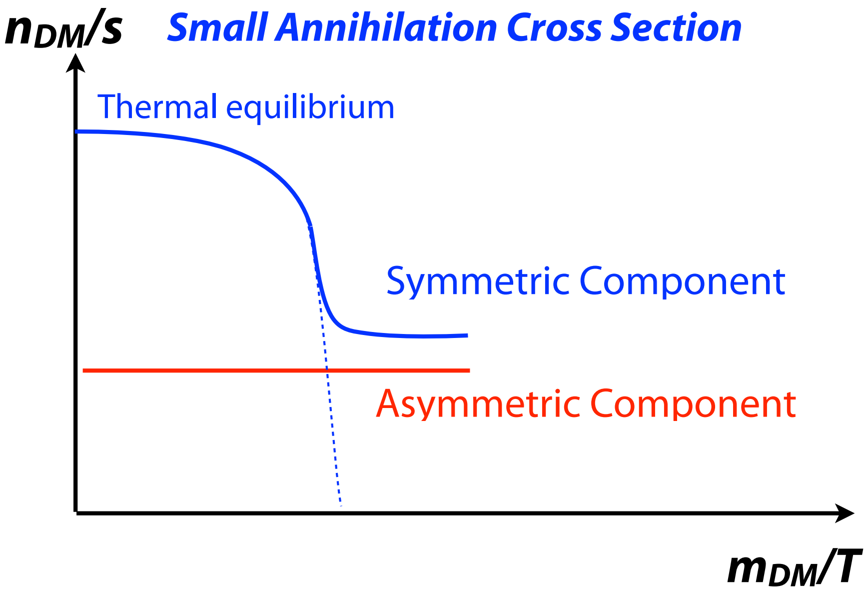
532 days of lifetime, Eν > 100GeV IceCube, Eν > 10GeV DeepCore up-going muon tracks by ν_μ's.

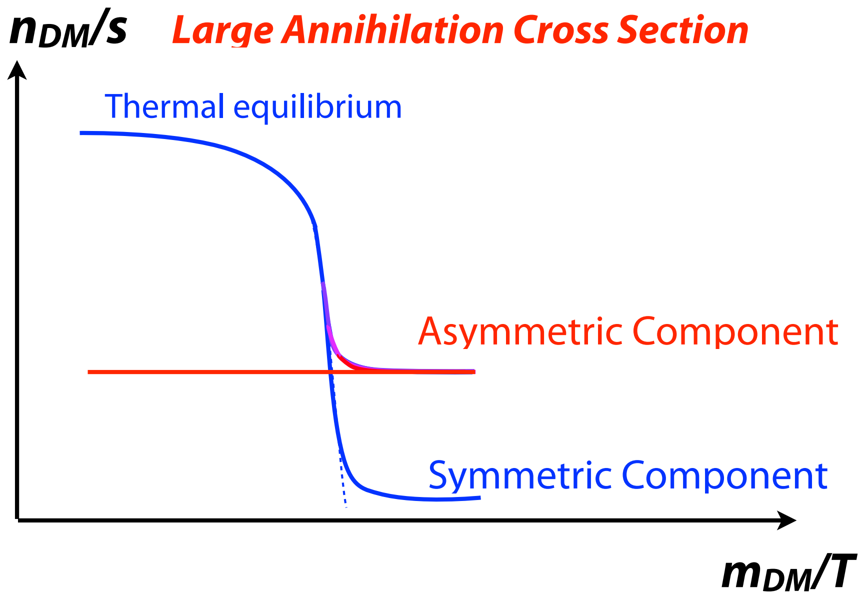
Assuming the WIMP cross section ***σ ~ 1pb***, the DM capture and the DM annihilation has come to an equilibrium, and the neutrino flux puts constraints not on the annihilation cross section but on the Nucelon-DM scattering cross section.

The ν signals from the SUN play crucial roles to search for dark matter with the spin-dependent nucleon-DM scattering!

✓ *Neutrino Signals in ADM scenario*

✓ ADM models require a large annihilation cross section





Annihilation of the symmetric component of ***DM*** should be very efficient !

→ This is achieved ***DM*** is a composite state of dark strong dynamics !

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

Composite ADM model is highly motivated !

✓ *Neutrino Signals in ADM scenario*

✓ ***The simplest model = Mirror Copy of QCD (= dark QCD) with dark QED.***

[1805.0687 Kamada, Kobayashi, Nakano MI]

	$\mathrm{SU}(3)_D$	$B-L$	$\mathrm{U}(1)_D$
Q_1	$\mathbf{3}$	q_{B-L}	$2/3$
$\bar{Q}_1$	$\bar{\mathbf{3}}$	$-q_{B-L}$	-$2/3$
Q_2	$\mathbf{3}$	q_{B-L}	-$1/3$
$\bar{Q}_2$	$\bar{\mathbf{3}}$	$-q_{B-L}$	$1/3$

We need at least two-flavors to allow ***dark QED*** along with B-L .

Dark QCD eventually exhibits confinement at O(1-10) GeV.

Dark Matter = Dark protons and Dark neutrons !

$$p' \propto Q_1 Q_1 Q_2 \,, \quad \bar{p}' \propto \bar{Q}_1 \bar{Q}_1 \bar{Q}_2 \,, \quad n' \propto Q_1 Q_2 Q_2 \,, \quad \bar{n}' \propto \bar{Q}_1 \bar{Q}_2 \bar{Q}_2 \,.$$

Dark baryons annihilates into ***Dark pions***

$$\pi'^0 \propto Q_1 \bar{Q}_1 - Q_2 \bar{Q}_2 \,, \quad \pi'^+ \propto Q_1 \bar{Q}_2 \,, \quad \pi'^- \propto Q_2 \bar{Q}_1$$

Dark pions annihilate/decay into ***dark photons***

$(A_{SM}/A_{DM}) = 237/(22N_F) \rightarrow m_{DM} = 8\mathrm{GeV}\,(2/N_F)$

[1411.4014 Fukuda, Matsumoto, Mukhopadhyay]

Neutrino Signals in ADM scenario

- Dark Sector Shares ***B-L*** symmetry with the ***SM*** via

$$\mathcal{L}_{B-L\,\mathrm{portal}} = \frac{1}{M_*^n}\mathcal{O}_D\mathcal{O}_{\mathrm{SM}} + \mathrm{h.c.}$$

$$= \frac{1}{M_*^3}\underbrace{(\bar{Q}_1\bar{Q}_2\bar{Q}_2)}LH$$

Dark neutron operator

- Dark Neutron decays into anti-neutrinos !

[Dark neutron] → [dark neutral pion] + ν̄

$$\tau \sim 10^{24}\,\mathrm{sec}\left(\frac{M_*}{10^9\,\mathrm{GeV}}\right)^6\left(\frac{10\,\mathrm{GeV}}{m_{\mathrm{DM}}}\right)^5$$

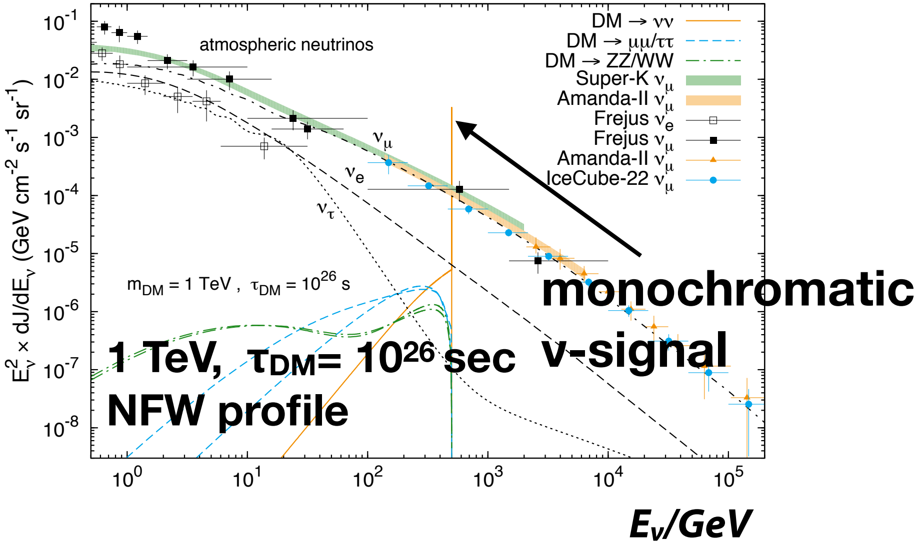
The main mode is given by **<*H*>** = ***v*** .

[1411.4014 Fukuda, Matsumoto, Mukhopadhyay]

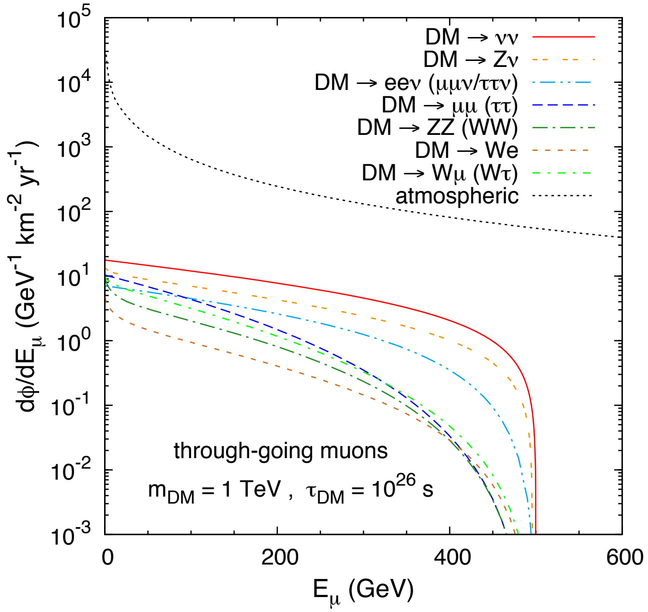
Composite ADM leads to a monochromatic anti-neutrino signal !

✔ *Neutrino Signals in ADM scenario*

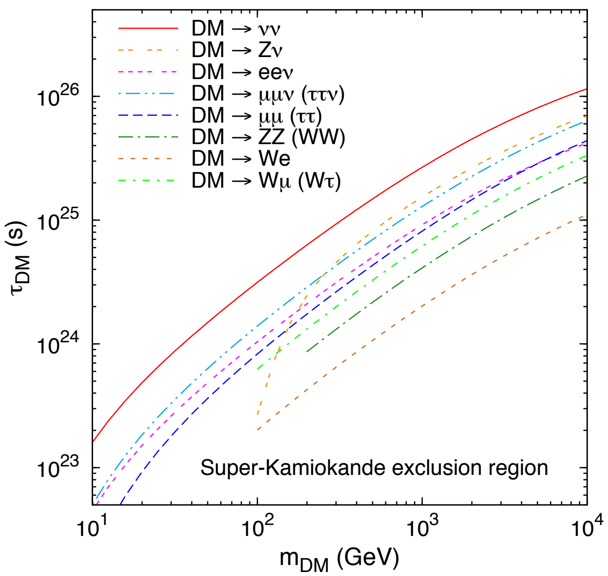
full-sky averaged neutrino flux



Through going muon spectrum



Constraint on the dark matter lifetime



SK, 1679.6 live days, $\Delta\theta_{GC} = 30°$

['09 Covi, Grefe, Ibarra, Tran]

τ_{DM}(DM → X + ν) > 10^{23} sec **for** ***m_{DM} ~ 10GeV***.

(SK 90%CL constraints on the neutrino flux)

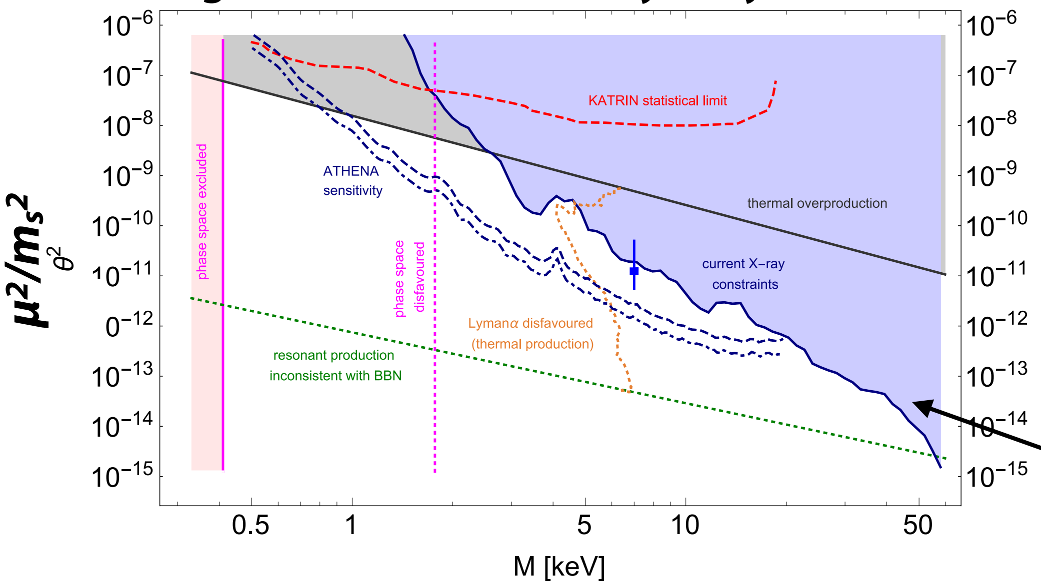
$M_* > 10^{8\text{-}8.5}$ GeV

~ Lower limits on the right-handed neutrino mass in the leptogenesis (theoretically $M_* < M_R$).

In the ADM models, anti-neutrino signals in O(1)GeV play important role !

✔ *Sterile Neutrino*

Fig from [1807.07938 Boyarsky et. al.]



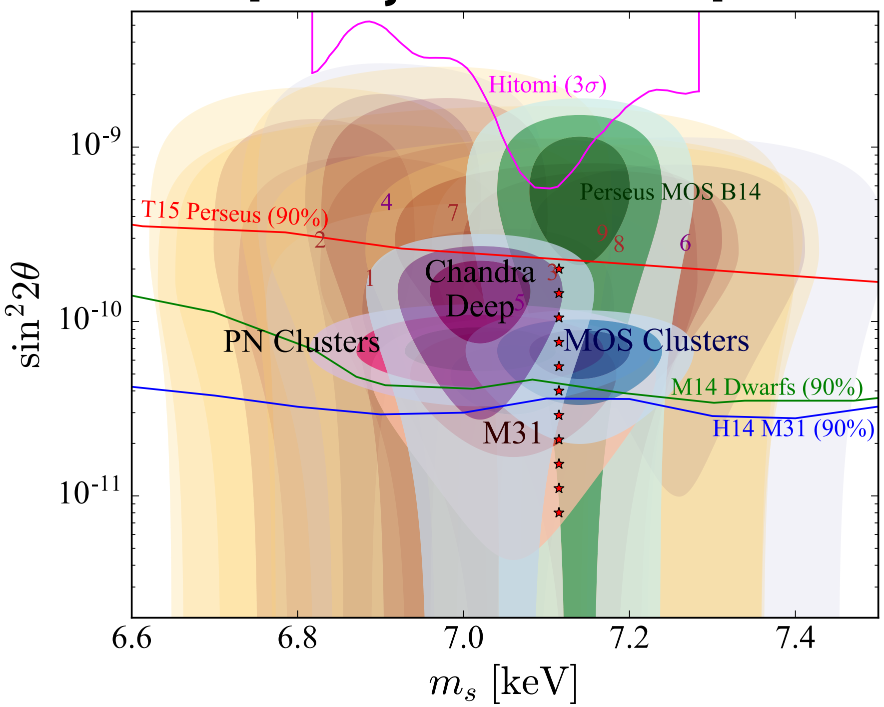
✔ Sterile Neutrino lifetime

$$\tau_{\nu_s \to 3\nu} \simeq 1.5 \times 10^{14} \text{sec} \left(\frac{m_s}{10\text{keV}}\right)^5 \times \theta^2$$

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

Constraints from Non-observation of X-ray

[Abazajian 1705.01837]



✔ ***3.5keV X***-ray line signal ?

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

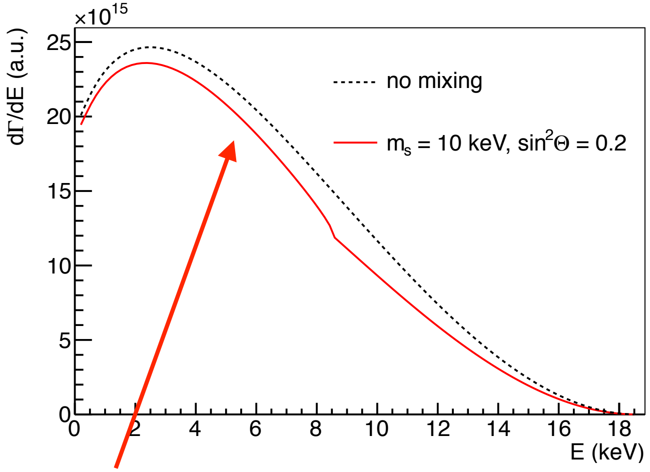
Sterile DM @ (7keV, θ² ~ 10⁻¹⁰) ?

Situation is still controversial…

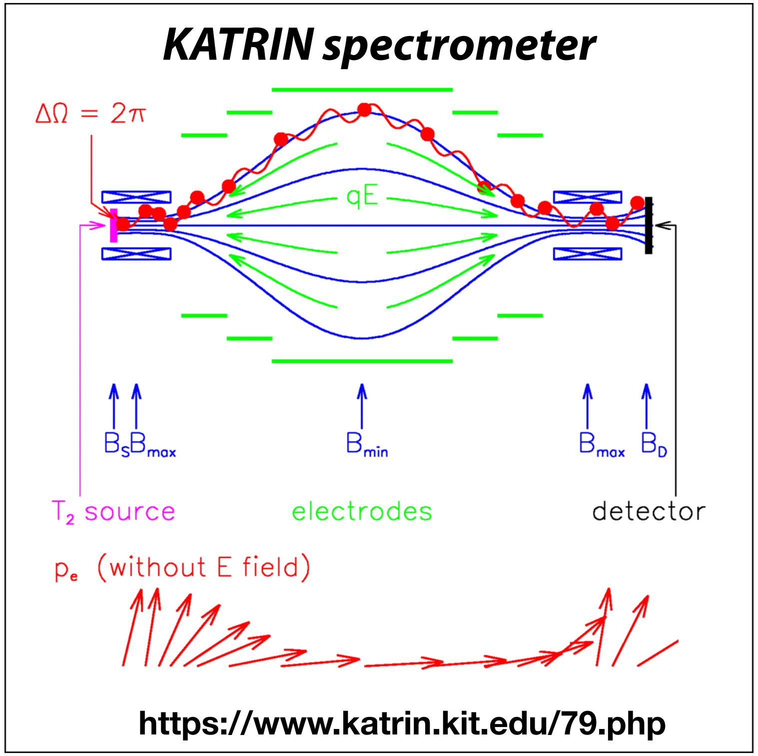
Future X-ray telescopes with high energy resolution will confirm/refute.

Sterile Neutrino

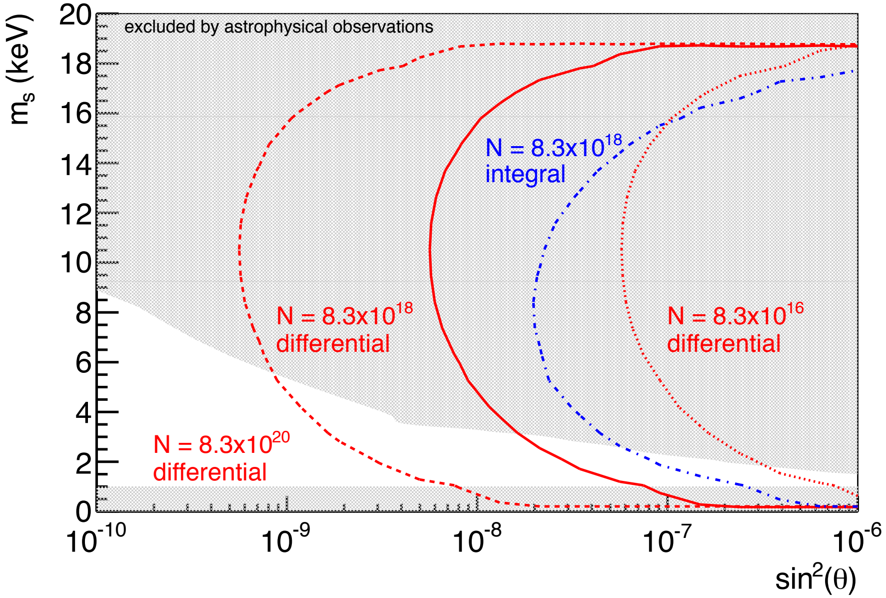
keV ν_s search by tritium β-decay



$$\frac{d\Gamma}{dE} = \cos^2\theta \frac{d\Gamma}{dE}(m_{\rm light}) + \sin^2\theta \frac{d\Gamma}{dE}(m_s)$$



[Mertens *et al* JCAP02(2015)020]



An upgraded KATRIN detector with $N = 8.3 \times 10^{18}$ β-decays (Full KATRIN source strength)

$\theta^2 \sim 10^{-7}$ can be tested

For (Full KATRIN source strength) x 100

$\theta^2 \sim 10^{-9}$ can be reachable?

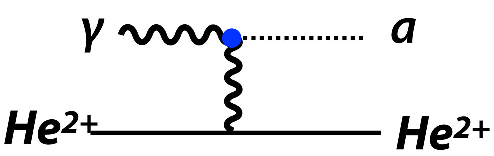
Further improvement by using TOF of e?

Constraints on Axion (No neutrino…)

- Axion mass : $m_a \sim \frac{f_\pi m_\pi}{f_a}$ **$f_\pi = 93MeV, m_\pi = 135MeV$**
- 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

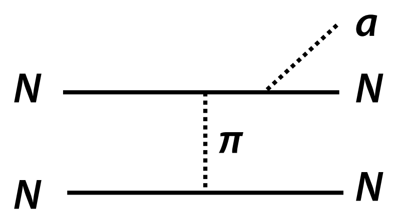


$E_{loss} > 10\, g^{-1}\, erg\, s^{-1}$ ($T_{HB\ core} \sim 10keV$)

[arXiv:1110.2895]

$f_a > 10^7 GeV$

Supernovae Constraint (1987a)



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

[arXiv:1008.0636]

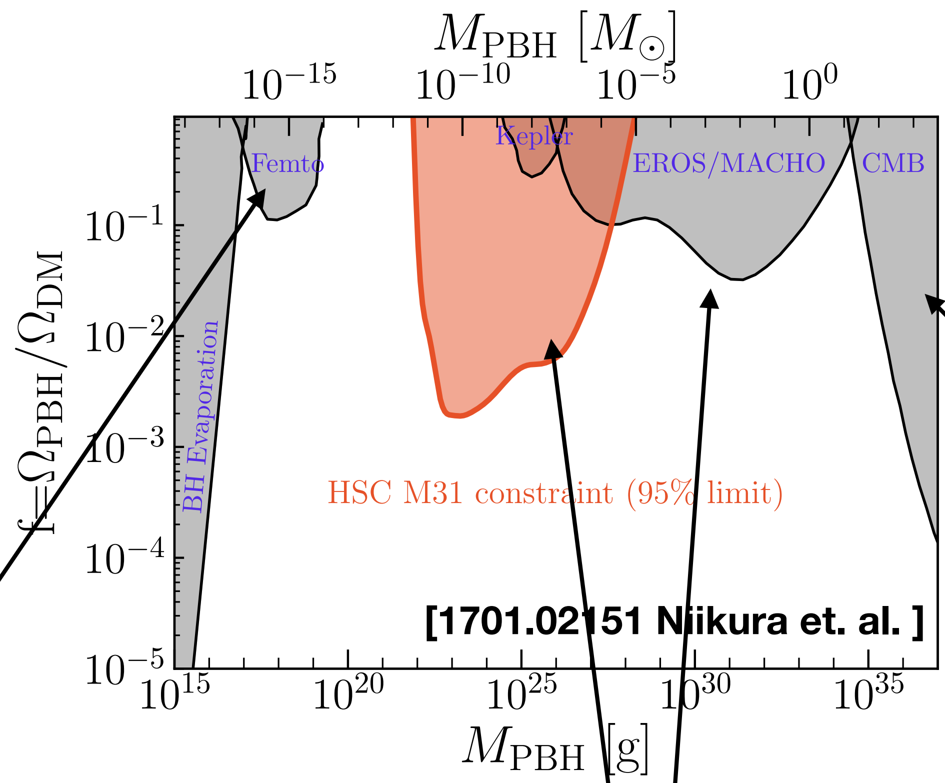
($T_{SN} \sim 30MeV$, mean free path > 10km)

$f_a > 10^8 GeV$

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

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

✔ *Constraints on Primordial Black Hole (No neutrino…)*



Gas accretion onto PBH affects CMB.

Constraints from femtolensing

[PBH modulates energy spectrum of the gamma-ray burst]

Constraints from microlensing

[PBH magnifies star lights]

Allowed mass range of PBH dark matter : $M_{DM} = 10^{-(14\text{-}12)} M_\odot$

✔ Summary

	Stability	Abundance	Mass Range	ν signals ?
WIMP	**Symmetry**	**Annihilation cross section**	***10MeV - 300TeV (or Beyond)***	***annihilation in the SUN***
ADM	**Symmetry**	**Baryon asymmetry Mass**	***O(1)GeV***	***dark neutron decay into ν***
FIMP	**Very Weak Coupling**	**Interaction strength**	***> O(1)keV*** (?)	Model dependent
Sterile ν	**Very Weak Coupling / Approximate**	**Mass / mixing angle Lepton asymmetry**	***2keV - O(100)keV***	***β-decay spectrum ?***
Fuzzy DM	**Very light & Weak Coupling**	**Initial amplitude Mass**	$> 10^{-22}$eV	?
Aixion DM	**Very light & Weak Coupling**	**Axion decay constant**	***~ μeV***	?
PBH DM	**Heavy Enough Black Hole**	**Density fluctuation Mass**	$10^{-(14-12)} M_\odot$	?

✓ *Summary*

- There are lots of dark matter candidates.
- Neutrino singles are important channels to narrow down the candidates for dark matter !
- With the advent of larger neutrino detectors, the neutrino signals become more important.
- Other channels such as charged cosmic rays, γ-rays, optical lights, radio signals, gravitational waves, and direct detection experiments etc are also important.

Let us unveil the nature of dark matter by using everything in our power !

Back Up

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

(Spineless case for simplicity)

Since we are interested in rather strongly interacting case, we may assume that the reaction rates are dominated by 2-body interactions.

Unitarity : $S^\dagger S = 1$

$$S = 1 + iT_{el} + i\,T_R \rightarrow \; \langle i \,|\, T_{el}^\dagger T_{el} \,|i\rangle + \langle i \,|\, T_R^\dagger T_R \,|\, i \rangle = 2\,\mathrm{Im} \langle i \,|\, T_{el} \,|\, i \rangle$$

$$\langle f \,|\, T \,|\, i \rangle \; = \; 2\pi^4\,\delta^4(p_f - p_i)\,M_{f\,i}$$

$$\Sigma_f \langle i \,|\, T_f^\dagger T_f \,|\, i \rangle \; = \; \sigma_{tot}\, v_{rel}\, n_1 n_2 \;x\; 2\pi^4\,\delta^4(0)$$

$$\rightarrow \; \sigma_{tot}\, v_{rel} = 2 / s \;\; x\,\mathrm{Im}\, M^{(el)}{}_{i\,i} \quad (n_1 = n_2 = s^{1/2})$$

<u>***Unitarity Limit on WIMP mass***</u> ***(1990 Griest & Kamionkowski)***

(Spineless case for simplicity)

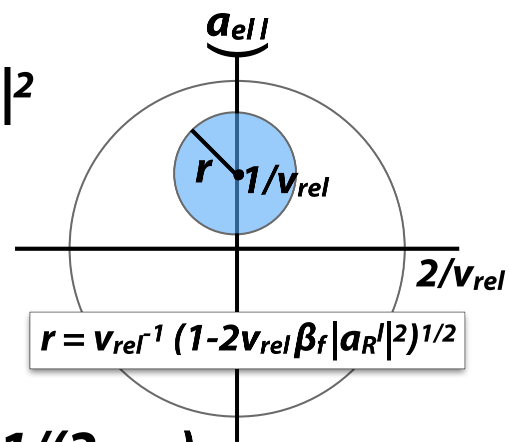
Since we are interested in rather strongly interacting case, we may assume that the reaction rates are dominated by 2-body interactions.

Partial wave decomposition :

$$M_{fi} = 16\pi\, \Sigma_l\, (2l + 1)\, a_l\, P_l\, (\cos\theta)$$

$$\rightarrow \quad \sigma_{el}\, v_{rel} = \Sigma_l\, \sigma_{el}{}^l\, v_{rel} = 16\pi\, v_{rel} / s \times \Sigma_l\, (2l + 1)\, |a_{el\, l}|^2$$

$$\sigma_R\, v_{rel} = \Sigma_l\, \sigma_R{}^l\, v_{rel} = 32\pi\, \beta_f / s \times \Sigma_l\, (2l + 1)\, |a_{R\, l}|^2$$



By using $\sigma_{el}{}^l < \sigma_{tot}{}^l$,

$$v_{rel} / 2 \times |\, a_{el\, l}|^2 + \beta_f |\, a_{R\, l}\, |^2 < Im\; a_{el\, l} \;\rightarrow\; \beta_f\, |\, a_{R\, l}|^2 \;<\; 1/(2v_{rel})$$

Unitarity limit on reaction cross section :

$$\sigma_R\, v_{rel} < 16\, \pi\, \Sigma_l\, (2l{+}1) /(\, s\, v_{rel})$$