宇宙の進化と素粒子模型

平成３０年度宇宙線研究所共同利用研究成果発表会

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国内旅費：10万円

2018 業績一部

1) Gravitational waves induced by scalar perturbations as probes of the small-scale primordial spectrum.
By Keisuke Inomata, Tomohiro Nakama.
[arXiv:1812.00674 [astro-ph.CO]].

2) Mixed Non-Gaussianity from Axion-Gauge Field Dynamics.
By Tomohiro Fujita, Ryo Namba, Ippei Obata.
[arXiv:1811.12371 [astro-ph.CO]].

3) Axion Search with Ring Cavity Experiment.
By Ippei Obata, Tomohiro Fujita, Yuta Michimura.
[arXiv:1811.12051 [physics.ins-det]].

4) Ultraviolet Completion of a Composite Asymmetric Dark Matter Model with a Dark Photon Portal.
By Masahiro Ibe, Ayuki Kamada, Shin Kobayashi, Takumi Kuwahara, Wakutaka Nakano.
[arXiv:1811.10232 [hep-ph]].

5) Chiral photons from chiral gravitational waves.
By Keisuke Inomata, Marc Kamionkowski.
[arXiv:1811.04959 [astro-ph.CO]].

6) Circular polarization of the cosmic microwave background from vector and tensor perturbations.
By Keisuke Inomata, Marc Kamionkowski.
[arXiv:1811.04957 [astro-ph.CO]].

7) Primordial Black Holes and the String Swampland.
By Masahiro Kawasaki, Volodymyr Takhistov.
[arXiv:1810.02547 [hep-th]].
10.1103/PhysRevD.98.123514.
Phys.Rev. D98 (2018) 123514.

8) The swampland conjecture and the Higgs expectation value.
By Koichi Hamaguchi, Masahiro Ibe, Takeo Moroi.
[arXiv:1810.02095 [hep-th]].
10.1007/JHEP12(2018)023.
JHEP 1812 (2018) 023.

9) Hunting for Statistical Anisotropy in Tensor Modes with B-mode Observations.
By Takashi Hiramatsu, Shuichiro Yokoyama, Tomohiro Fujita, Ippei Obata.
[arXiv:1808.08044 [astro-ph.CO]].
10.1103/PhysRevD.98.083522.
Phys.Rev. D98 (2018) no.8, 083522.

10) Footprint of Two-Form Field: Statistical Anisotropy in Primordial Gravitational Waves.
By Ippei Obata, Tomohiro Fujita.
[arXiv:1808.00548 [astro-ph.CO]].

11) Primordial Black Holes from Affleck-Dine Mechanism.
By Fuminori Hasegawa, Masahiro Kawasaki.
[arXiv:1807.00463 [astro-ph.CO]].

12) Long-term dynamics of cosmological axion strings.
By Masahiro Kawasaki, Toyokazu Sekiguchi, Masahide Yamaguchi, Jun'ichi Yokoyama.
[arXiv:1806.05566 [hep-ph]].
10.1093/ptep/pty098.
PTEP 2018 (2018) no.9, 091E01.

13) Big Bang Nucleosynthesis Constraint on Baryonic Isocurvature Perturbations.
By Keisuke Inomata, Masahiro Kawasaki, Alexander Kusenko, Louis Yang.
[arXiv:1806.00123 [astro-ph.CO]].
10.1088/1475-7516/2018/12/003.
JCAP 1812 (2018) no.12, 003.

14) Optical Ring Cavity Search for Axion Dark Matter.
By Ippei Obata, Tomohiro Fujita, Yuta Michimura.
[arXiv:1805.11753 [astro-ph.CO]].
10.1103/PhysRevLett.121.161301.
Phys.Rev.Lett. 121 (2018) no.16, 161301.

15) $B-L$ as a Gauged Peccei-Quinn Symmetry.
By Masahiro Ibe, Motoo Suzuki, Tsutomu T. Yanagida.
[arXiv:1805.10029 [hep-ph]].
10.1007/JHEP08(2018)049.
JHEP 1808 (2018) 049.

16) Exploring compensated isocurvature perturbations with CMB spectral distortion anisotropies.
By Taku Haga, Keisuke Inomata, Atsuhisa Ota, Andrea Ravenni.
[arXiv:1805.08773 [astro-ph.CO]].
10.1088/1475-7516/2018/08/036.
JCAP 1808 (2018) no.08, 036.

17) Formation of primordial black holes in an axionlike curvaton model.
By Kenta Ando, Masahiro Kawasaki, Hiromasa Nakatsuka.
[arXiv:1805.07757 [astro-ph.CO]].
10.1103/PhysRevD.98.083508.
Phys.Rev. D98 (2018) no.8, 083508.

18) Composite Asymmetric Dark Matter with a Dark Photon Portal.
By Masahiro Ibe, Ayuki Kamada, Shin Kobayashi, Wakutaka Nakano.
[arXiv:1805.06876 [hep-ph]].
10.1007/JHEP11(2018)203.
JHEP 1811 (2018) 203.

19) Gauged Peccei-Quinn symmetry — A case of simultaneous breaking of SUSY and PQ symmetry.
By Hajime Fukuda, Masahiro Ibe, Motoo Suzuki, Tsutomu T. Yanagida.
[arXiv:1803.00759 [hep-ph]].
10.1007/JHEP07(2018)128.
JHEP 1807 (2018) 128.

20) Primordial black holes and uncertainties in the choice of the window function.
By Kenta Ando, Keisuke Inomata, Masahiro Kawasaki.
[arXiv:1802.06393 [astro-ph.CO]].
10.1103/PhysRevD.97.103528.
Phys.Rev. D97 (2018) no.10, 103528.

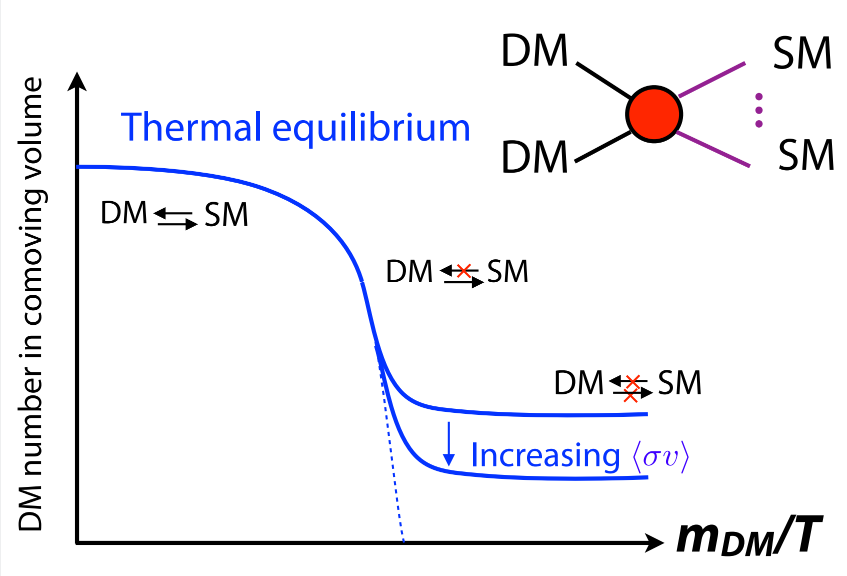
Asymmetric Dark Matter

[O(1)GeV Dark matter の無視できない有力候補]

By Masahiro Ibe, Ayuki Kamada, Shin Kobayashi, Wakutaka Nakano.
[arXiv:1805.06876 [hep-ph]] : JHEP 1811 (2018) 203.

By Masahiro Ibe, Ayuki Kamada, Shin Kobayashi, Takumi Kuwahara, Wakutaka Nakano.
[arXiv:1811.10232 [hep-ph]].

WIMP Miracle ?



- DM is in thermal equilibrium for $T > m_{DM}$.
- For $n_{DM} < T$, 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

✔ Abundance depends on the DM mass through $\langle \sigma v \rangle$.

DM abundance (for s-wave annihilation)

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

$$\langle \sigma v \rangle \sim \frac{g^2}{8\pi} \left(\frac{1}{\mathrm{TeV}} \right)^2$$

TeV scale physics !

✓ *Baryon-DM coincidence Problem…*

Baryon-DM coincidence ?

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

close with each other…

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

✓ 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…

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

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

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

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

✓ ***Asymmetric Dark Matter***

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

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

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, $M_R > 10^{10}$ ***GeV***)

✓ Dark Sector Shares ***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*

Leptogenesis

$T \sim M_R$

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

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

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

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

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

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

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

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

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

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

(Model dependent but O(1))

✔ *Composit Asymmetric Dark Matter*

✔ Implicit assumption

Annihilation of symmetric component of ***DM*** is very efficient !
→ ***DM*** has very large annihilation cross section like $\mathbf{p} + \bar{\mathbf{p}}$.

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

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

✔ Final states of the ***DM*** annihilation ?

Light degrees of freedom of dark sector. $p_D + \bar{p}_D \to \pi_D + \pi_D$

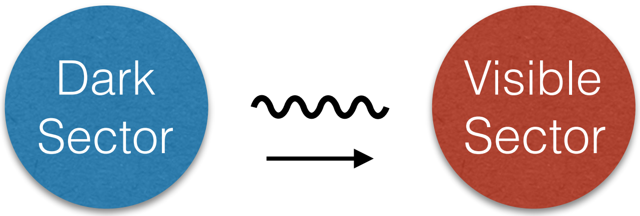
✔ Fate of the light degrees of freedom of dark sector ?

It seems OK that if they are massless….

→ too much contribution to dark radiation

(We assume strong dark dynamics which has sizable degrees freedom)

We need to have DARK STRONG DYNAMICS and a PORTAL to SM !



Composit Asymmetric Dark Matter

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

	$SU(3)_D$	$B-L$	$U(1)_D$
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 only need at least two-flavor to allow ***dark QED*** along with B-L .

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

Dark Matter = Dark baryons

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

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***

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

Composit Asymmetric Dark Matter

Fate of dark photon ?

Coupling to the ***QED*** through kinetic mixing

$$\mathcal{L}_{A'-A} = \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{\gamma'}^2 A'_\mu A'^\mu$$

→ ***QED*** charged particles (e.g. electron) couple to the dark photon !

$$\boldsymbol{L = \epsilon\, A'_\mu\, j_{QED}{}^\mu}$$

- Dark photon decays into SM fermions **[*dark Higgs mechanism*]**

$$2 \times m_e < m_{\gamma'} < m_{\pi'} < m_{\rm DM}$$

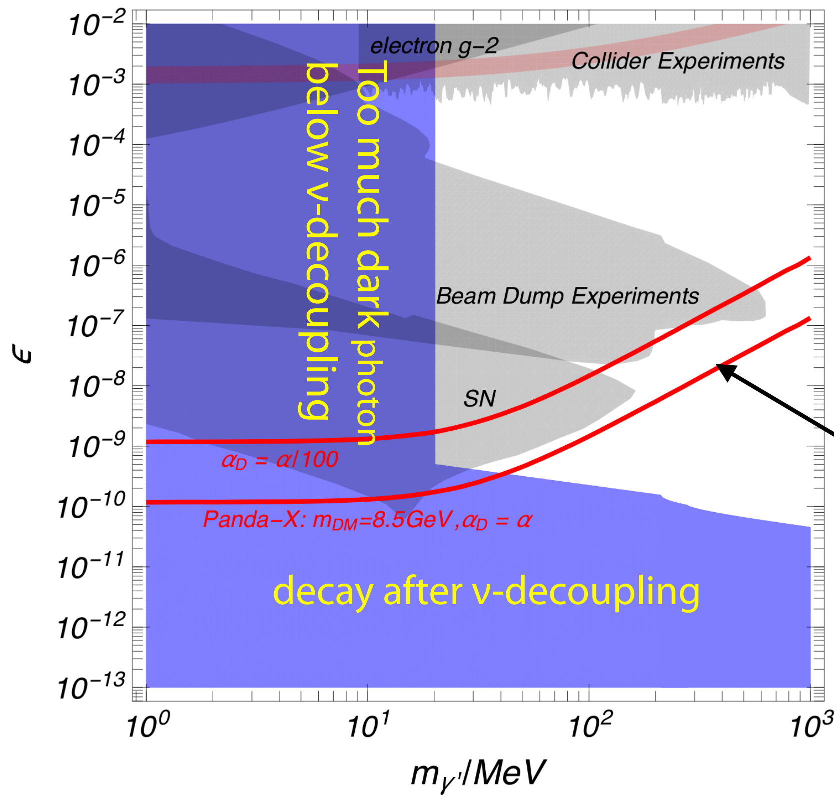
$$\Gamma_{\gamma'} = N_{\rm ch} \frac{1}{3} \epsilon^2 \alpha m_{\gamma'} \simeq 0.3\,{\rm s} \times N_{\rm ch} \left(\frac{\epsilon}{10^{-10}} \right)^2 \left(\frac{m_{\gamma'}}{100\,{\rm MeV}} \right)$$

If ϵ is too large → dark photon produced at beam dump experiments !

If ϵ is too small → fail to transfer entropy from the DM sector to the SM sector.

Composit Asymmetric Dark Matter

Constraints on dark photon ($N_F = 2$ —> $m_{DM} = 8.5$GeV)



Direct Detection Constraints (nuclear scattering)

Dark proton DM couples to the Nucleons !

$$\frac{\mathrm{d}\sigma_{XT}}{\mathrm{d}q^2} = \frac{4\pi\alpha_{\mathrm{em}}\alpha_X\epsilon_\gamma^2 Z^2}{(q^2+m_\phi^2)^2}\frac{1}{v^2}F_T^2(q^2)$$

✓ Summary

✓ *Asymmetric DM is very well motivated DM in view of the baryon-DM coincidence problem.*

✓ *Models seem to need a DARK PHOTON*

→ *Direct detection experiments aiming at O(1)GeV DM is very important !!*
(not only nuclear scattering but also electron scattering!)

✓ *Asymmetric DM in our model decays into the SM anti-neutrino.*

$$n_D \rightarrow \pi_D + \bar{\nu}$$

From SK constraint on the anti-neutrino : $\tau > 10^{20}$ sec.

[1411.4014. Fukuda, Matsumoto, Mukhopadhyay]

✓ *Dark pion decay could lead to O(100)MeV gamma-ray flux?*
(work in progress)