A01: Light dark matter

Feb. 6. 2020 @
“What is dark matter? - Comprehensive study of the huge discovery space in dark matter"

Fuminobu Takahashi (Tohoku)

Why (ultra)light dark matter?

Equivalence principle?

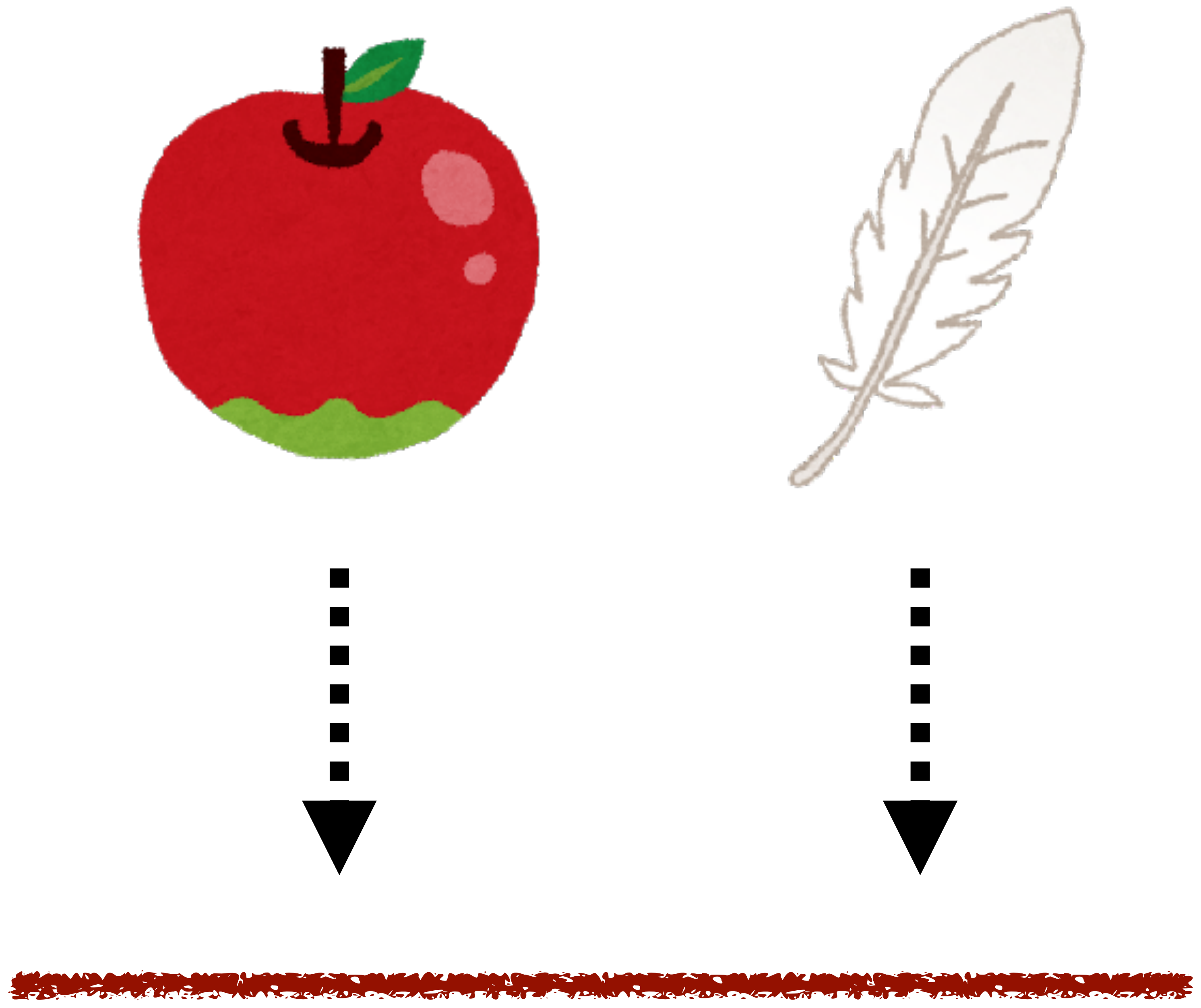
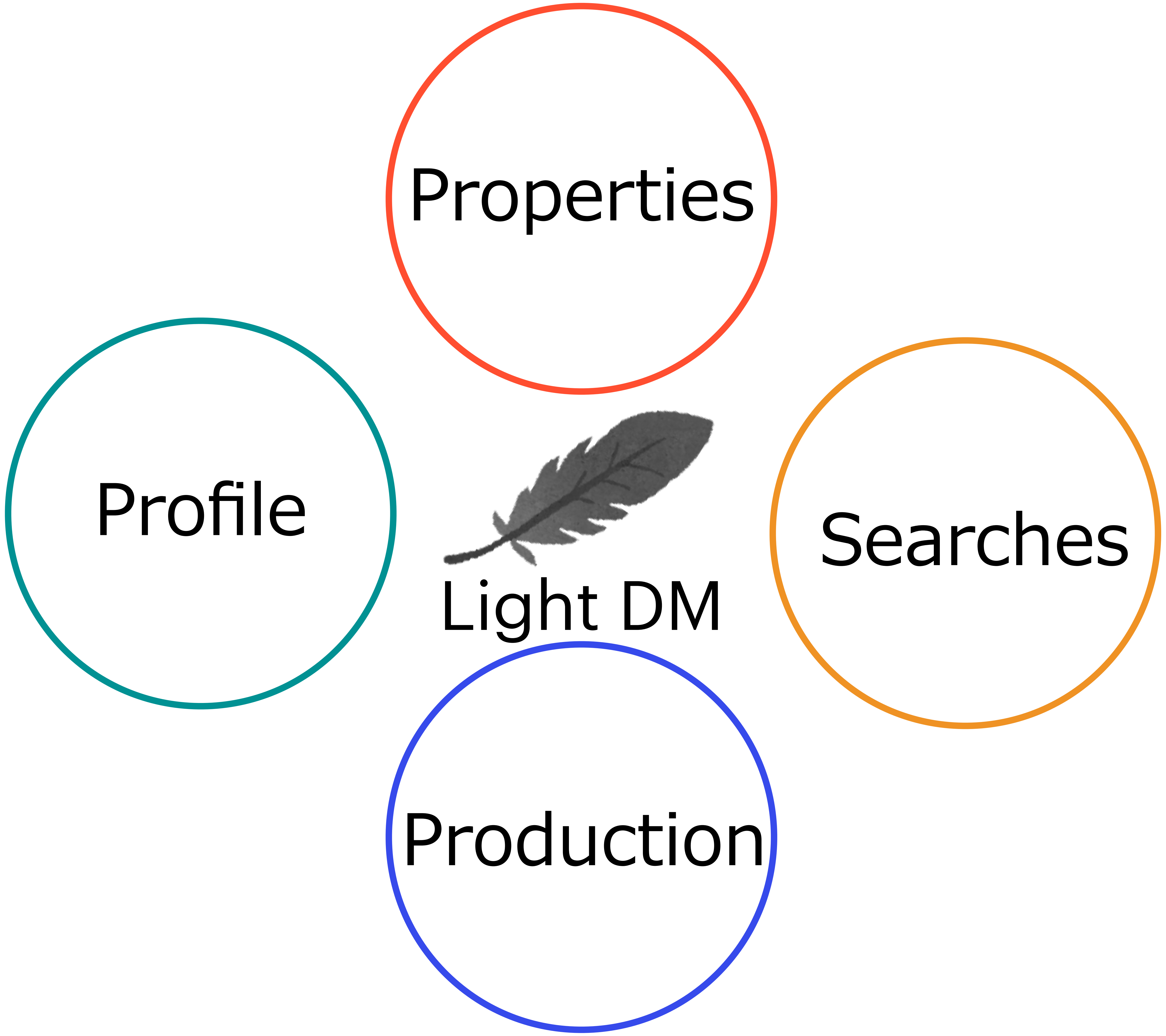
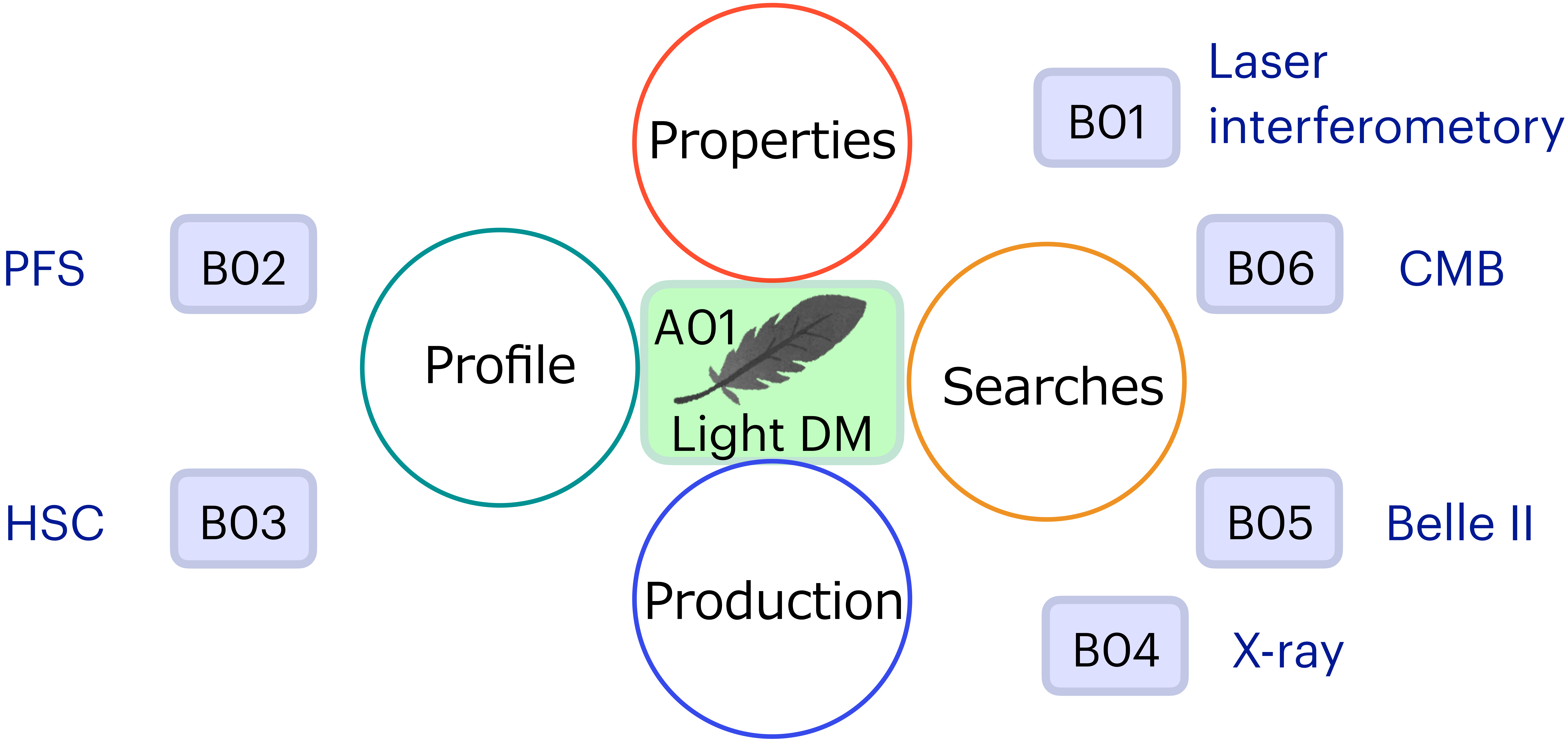


Illustration by James Edwin McConnell (1903-1995) depicting Galileo's demonstration of the principle of equivalence from a top the tower of Pisa in 1591. J.-E. McCONNELL/LOOK AND LEARN/BRIDGEMAN IMAGES

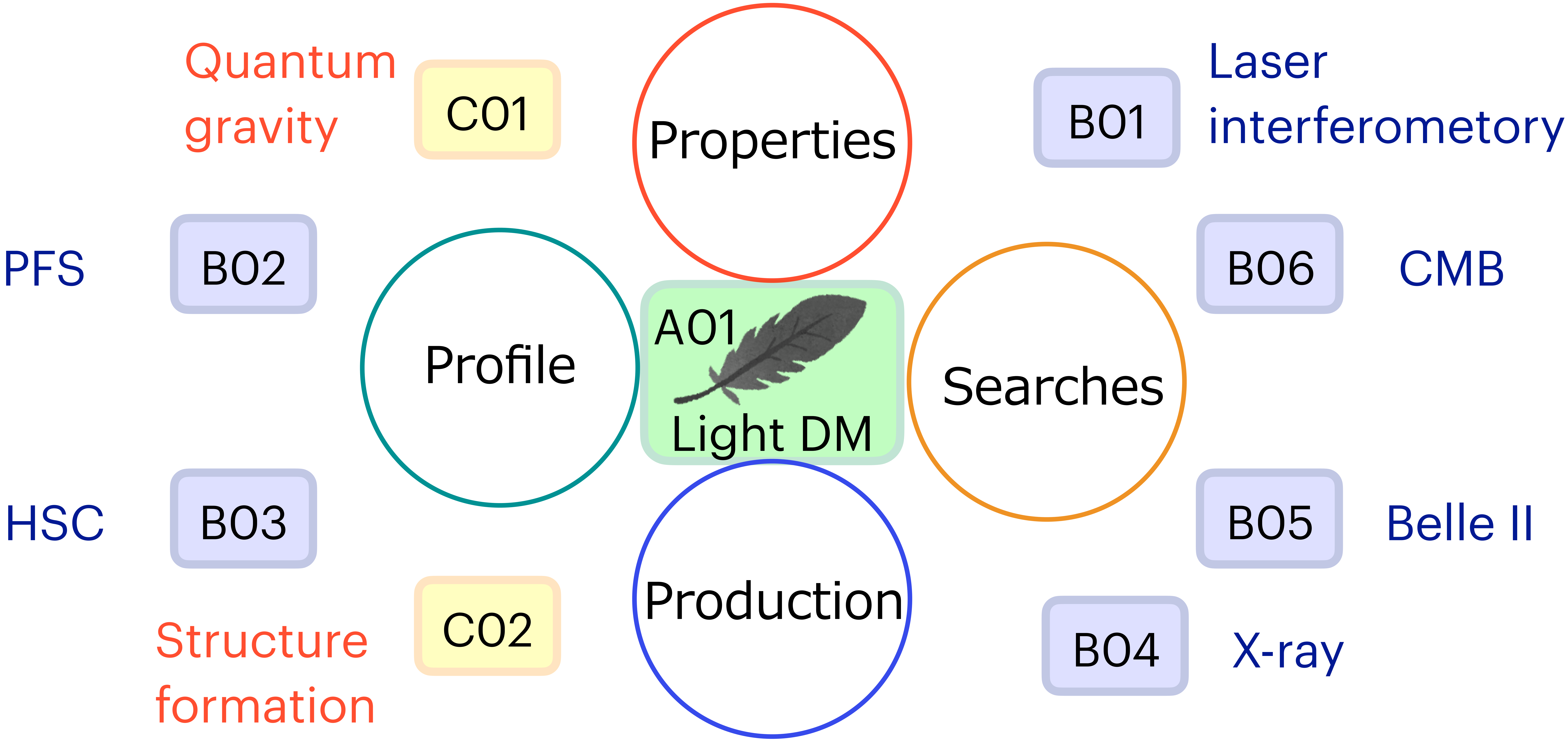
In fact, the lightness of DM mass changes all the aspects of DM physics!



In fact, the lightness of DM mass changes all the aspects of DM physics!

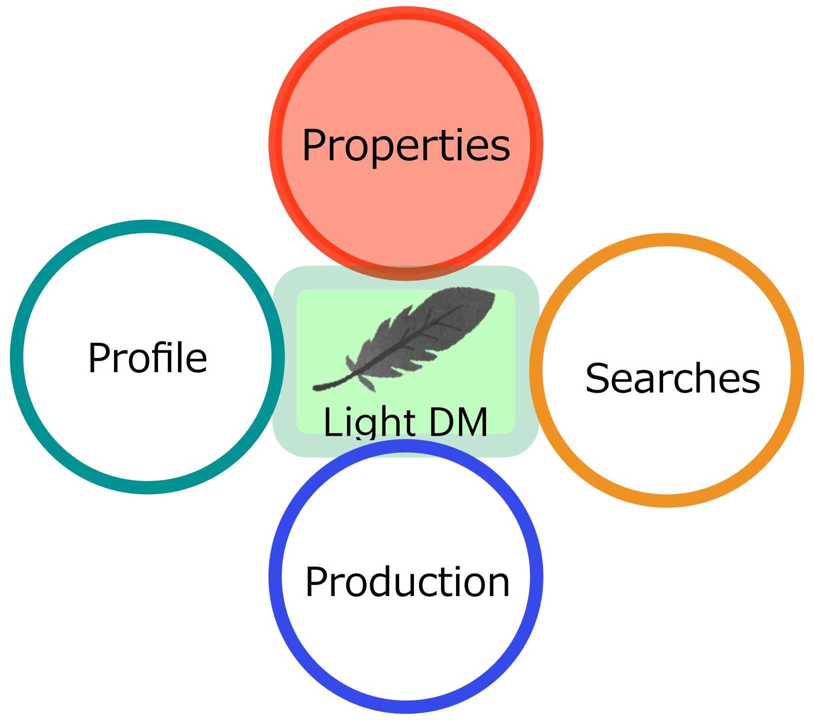


In fact, the lightness of DM mass changes all the aspects of DM physics!



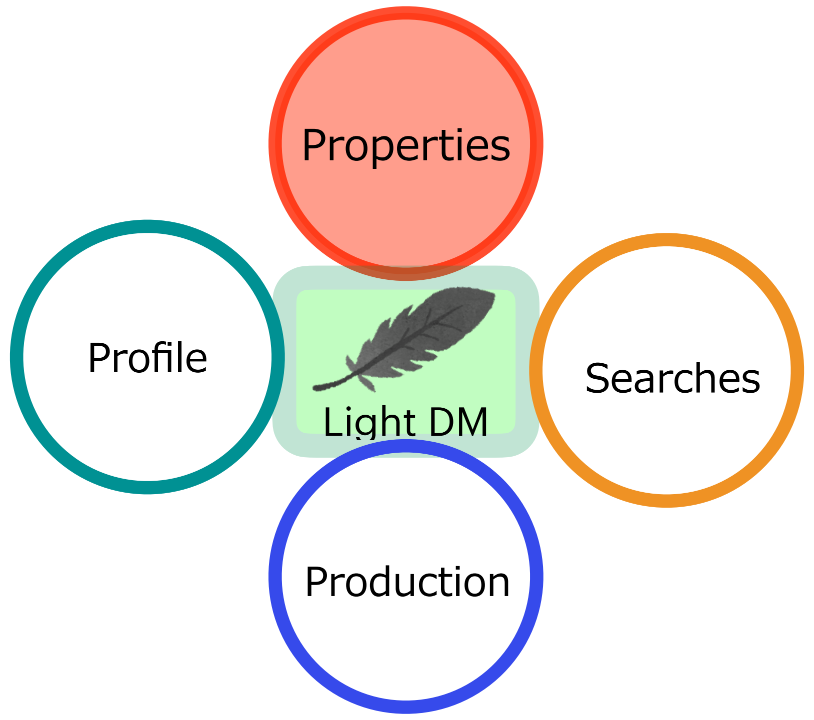
In fact, the lightness of DM mass changes all the aspects of DM physics!

Properties of dark matter



- Long-lived
- Non-relativistic (cold)
- (Almost) electrically neutral

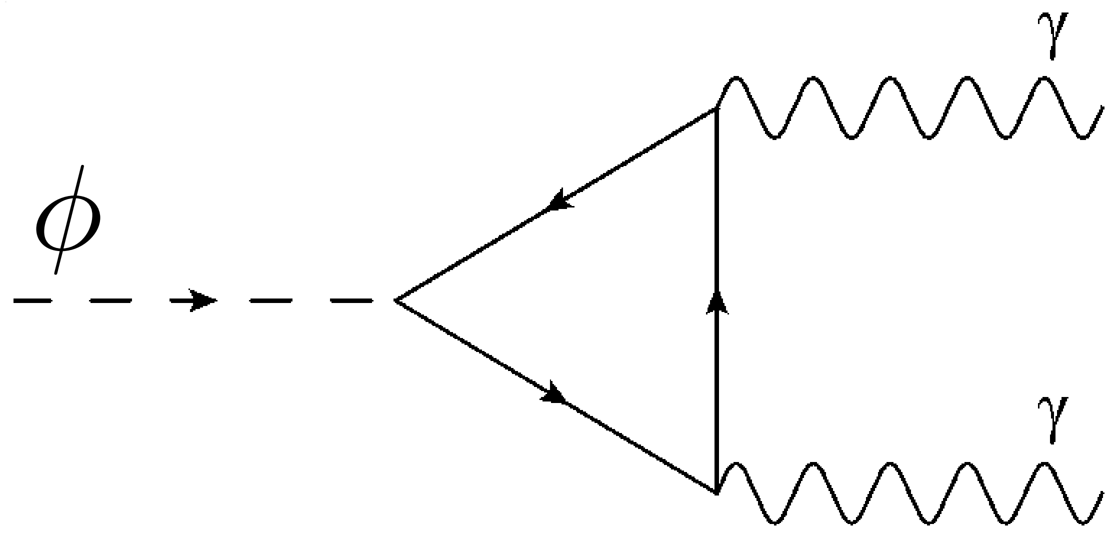
Properties of dark matter



- Long-lived

Light DM can naturally be long-lived

e.g. axion decays into two photons

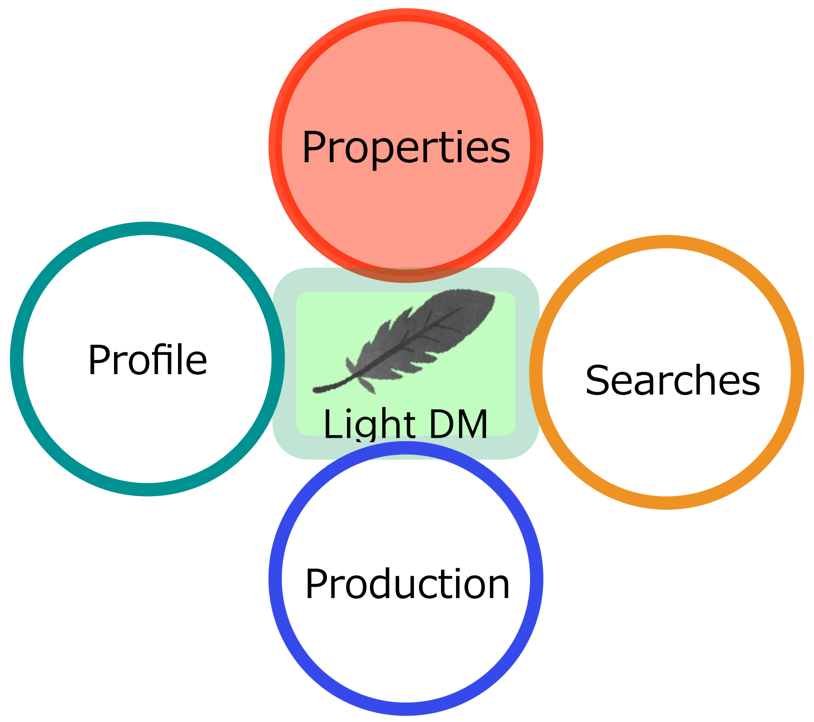


$$\mathcal{L}_{\phi\gamma} = -c_\gamma \frac{\alpha}{4\pi}\frac{\phi}{f_\phi} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$= -\frac{1}{4} g_{\phi\gamma\gamma} \phi F_{\mu\nu}\tilde{F}^{\mu\nu},$$

$$\Gamma(\phi \to \gamma\gamma) = \frac{g^2_{\phi\gamma}}{64\pi} m^3_\phi$$

B04 (X-ray), C01 (Quantum gravity), also B05 (Belle II)

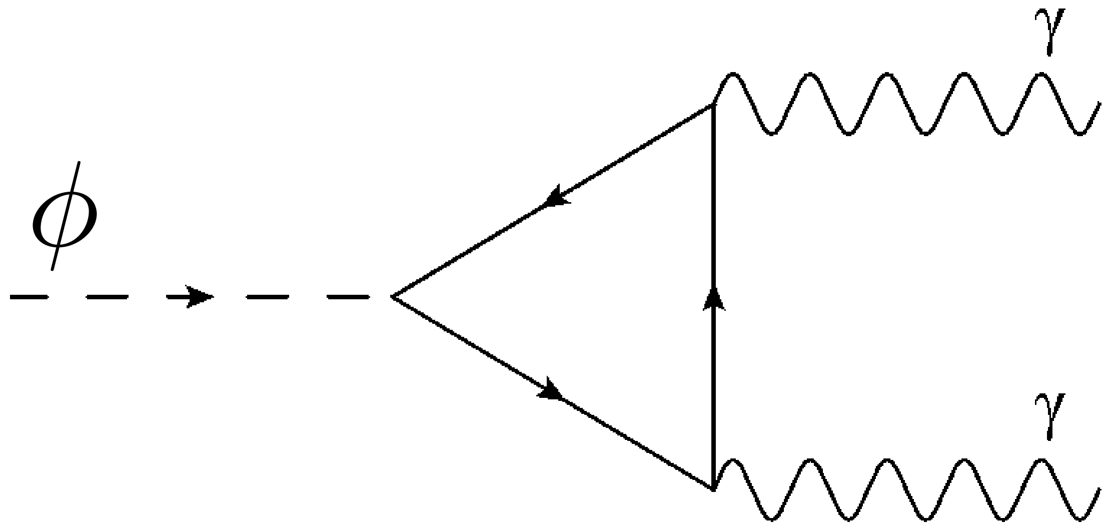


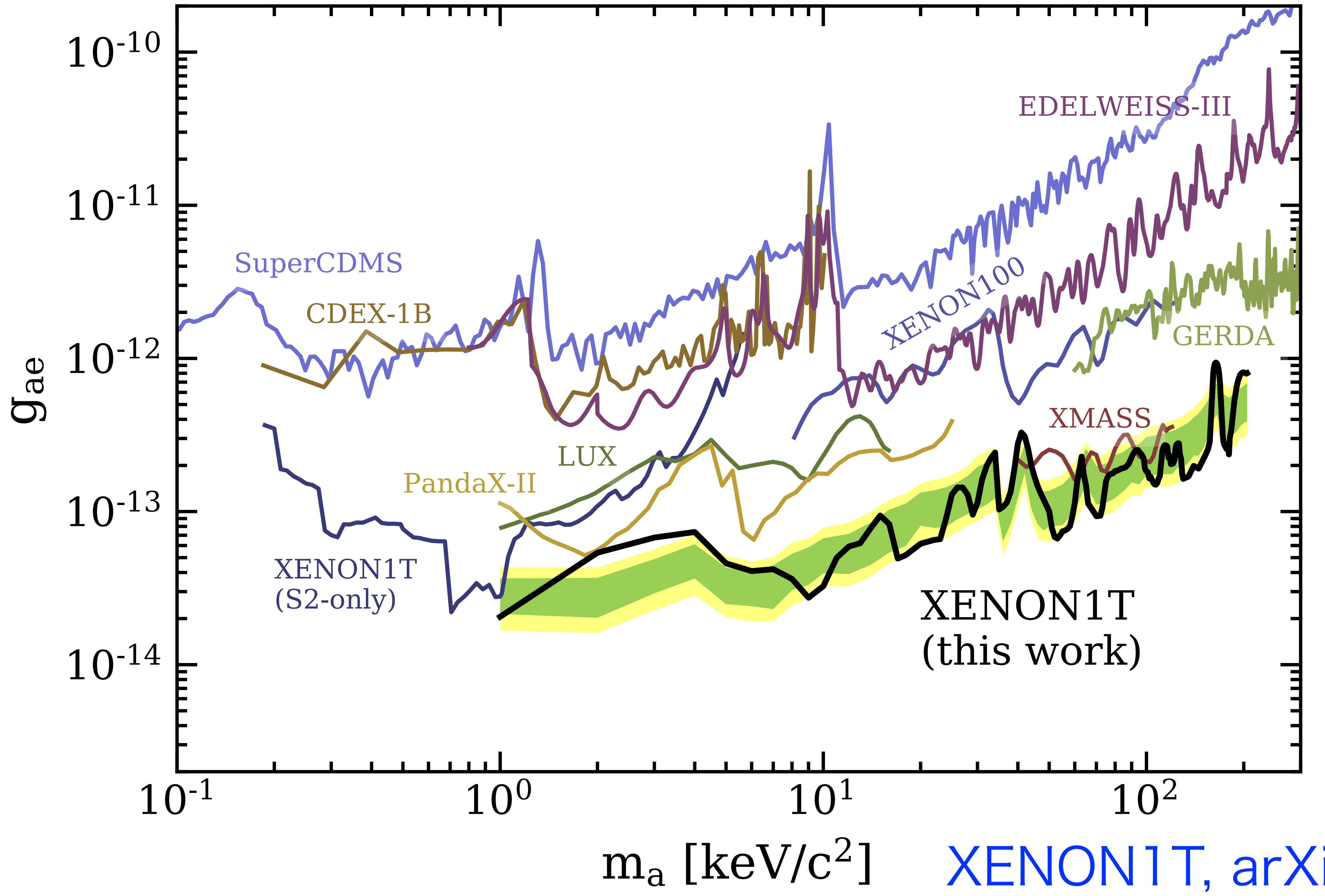
Properties of dark matter

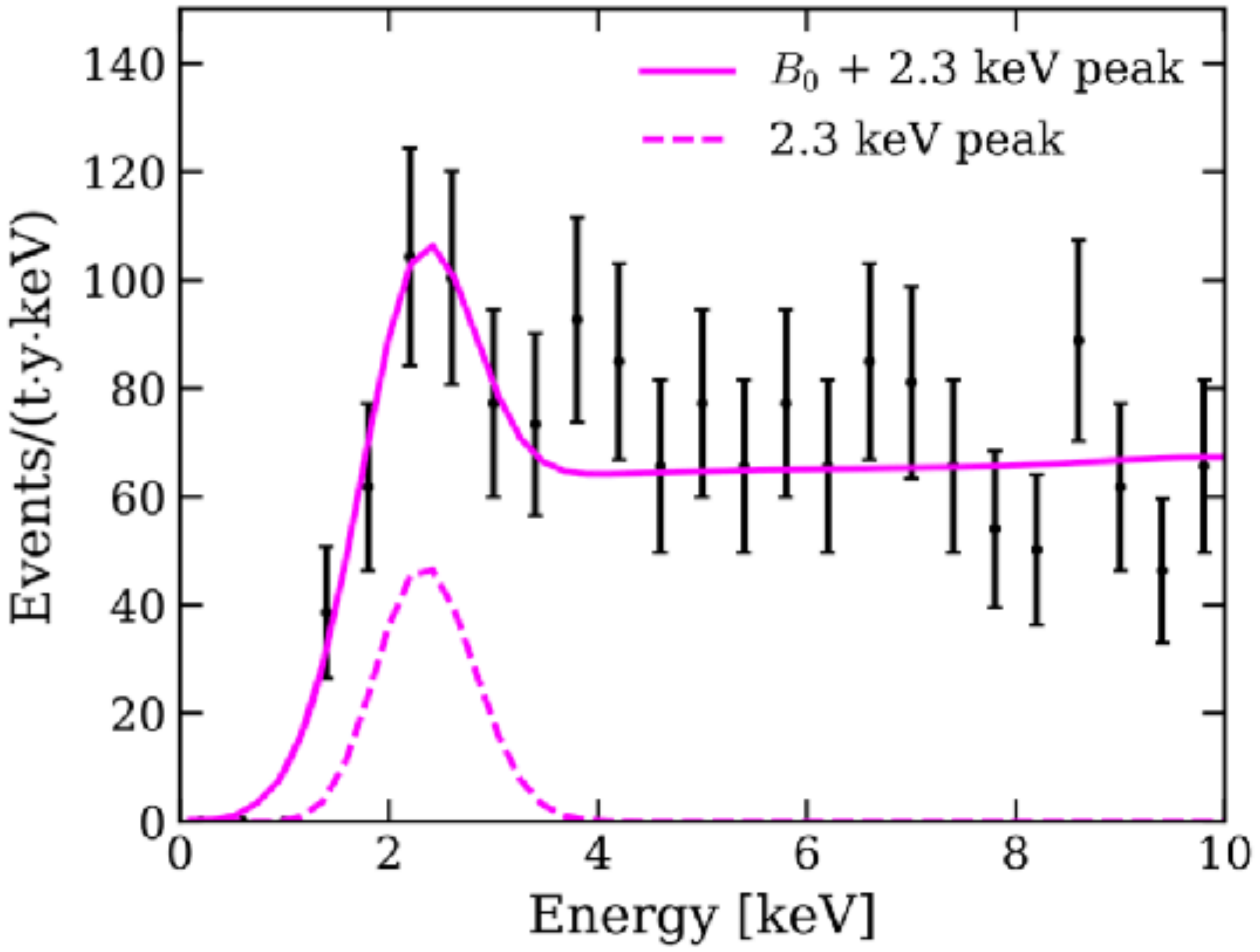
- Long-lived

Light DM can naturally be long-lived

e.g. axion decays into two photons







XENON1T, arXiv:2006.09721

$$\mathcal{L}_{\phi\gamma} = -c_\gamma \frac{\alpha}{4\pi}\frac{\phi}{f_\phi} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

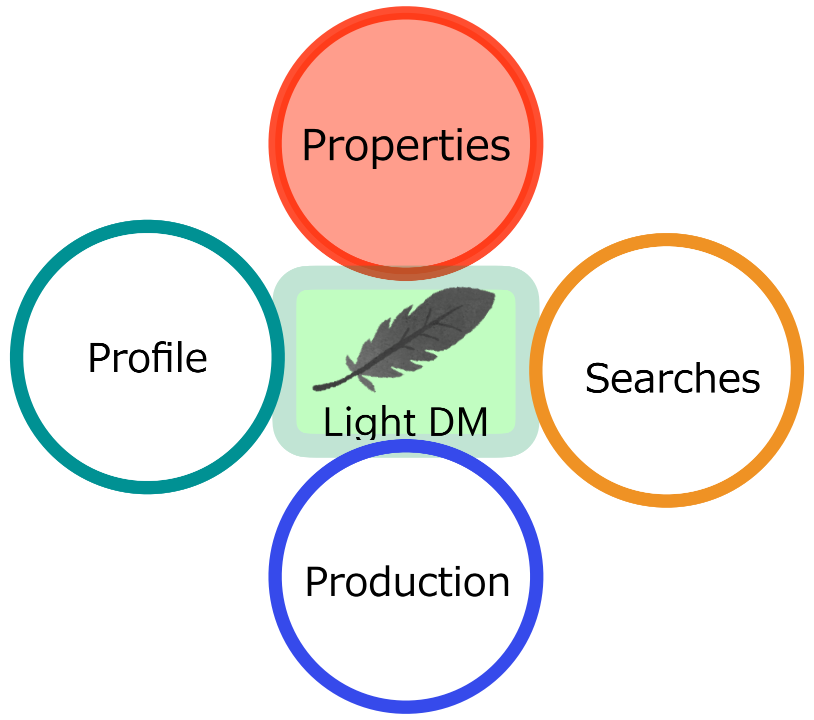
$$= -\frac{1}{4} g_{\phi\gamma\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu},$$

$$\Gamma(\phi \to \gamma\gamma) = \frac{g_{\phi\gamma}^2}{64\pi} m_\phi^3$$

B04 (X-ray), C01 (Quantum gravity), also B05 (Belle II)

KeV-scale bosonic DM (axion, hidden photon)?

Properties of dark matter



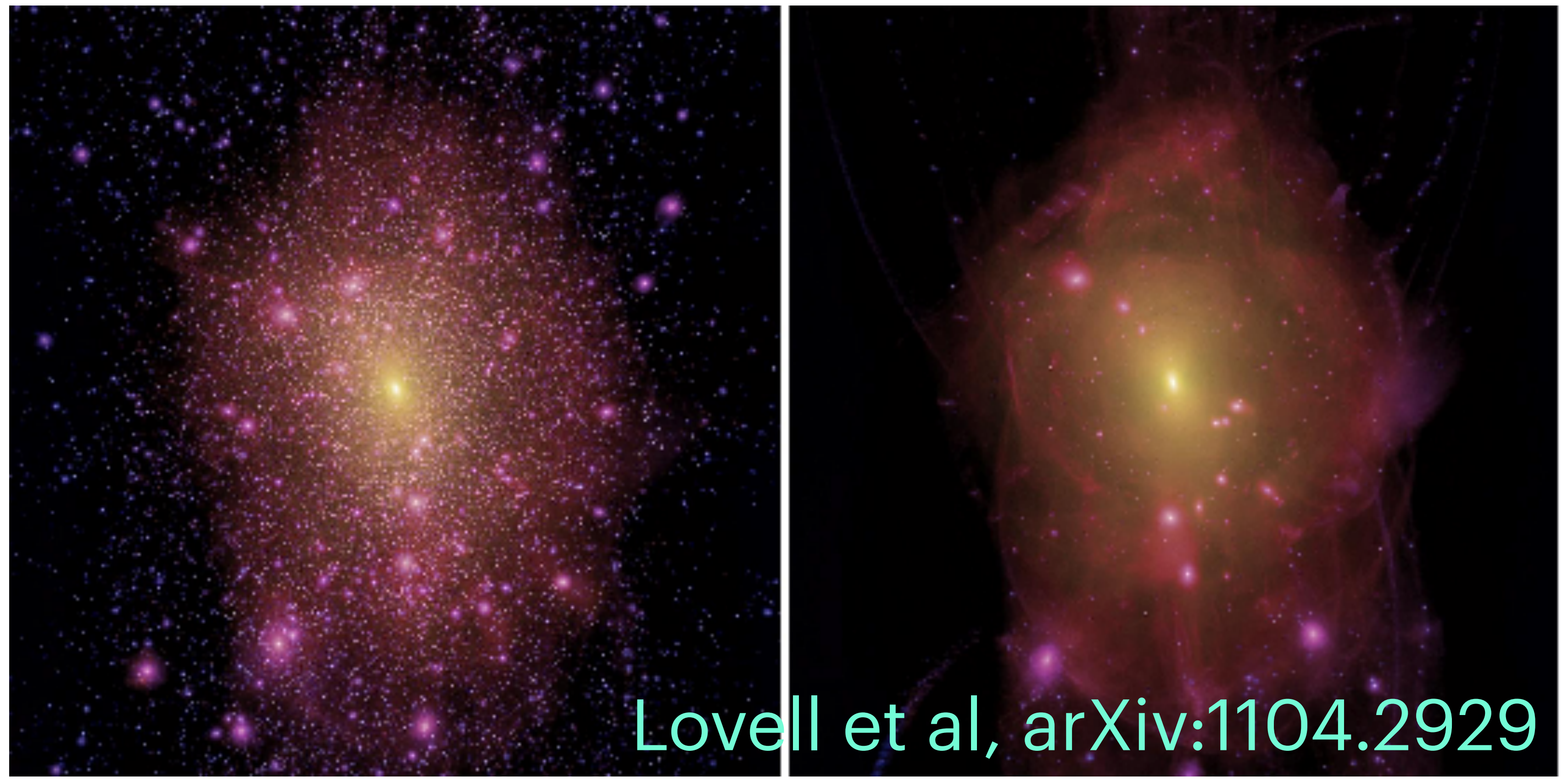
- Long-lived

  Light DM can naturally be long-lived

- Non-relativistic (cold)

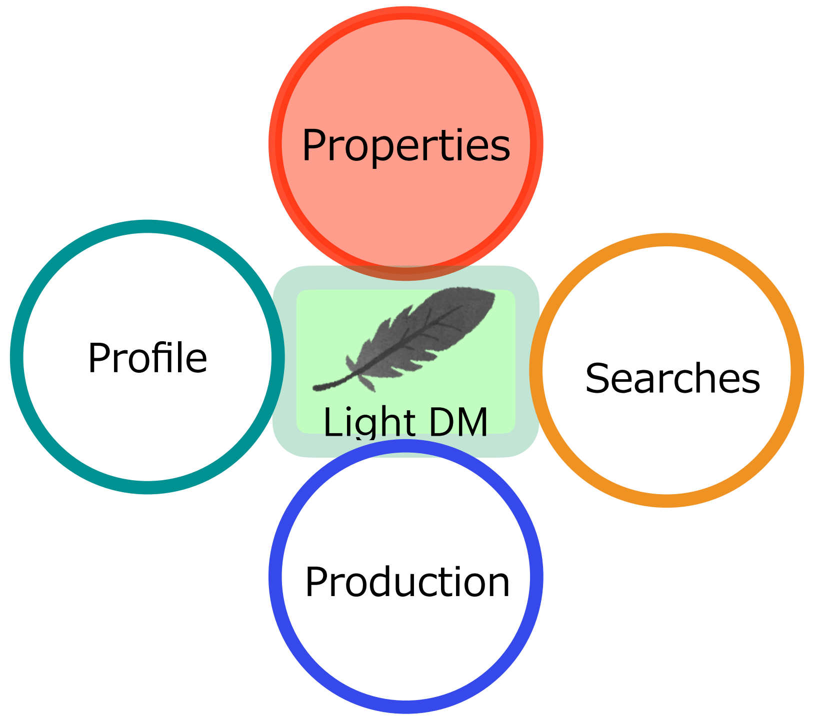
  Light DM can also be warm/hot DM

$$m_{\rm DM} \gtrsim \mathcal{O}(1)\,{\rm keV}$$



B02 (PFS), B03 (HSC)
C02 (Structure formation)

Properties of dark matter



- Long-lived

  Light DM can naturally be long-lived

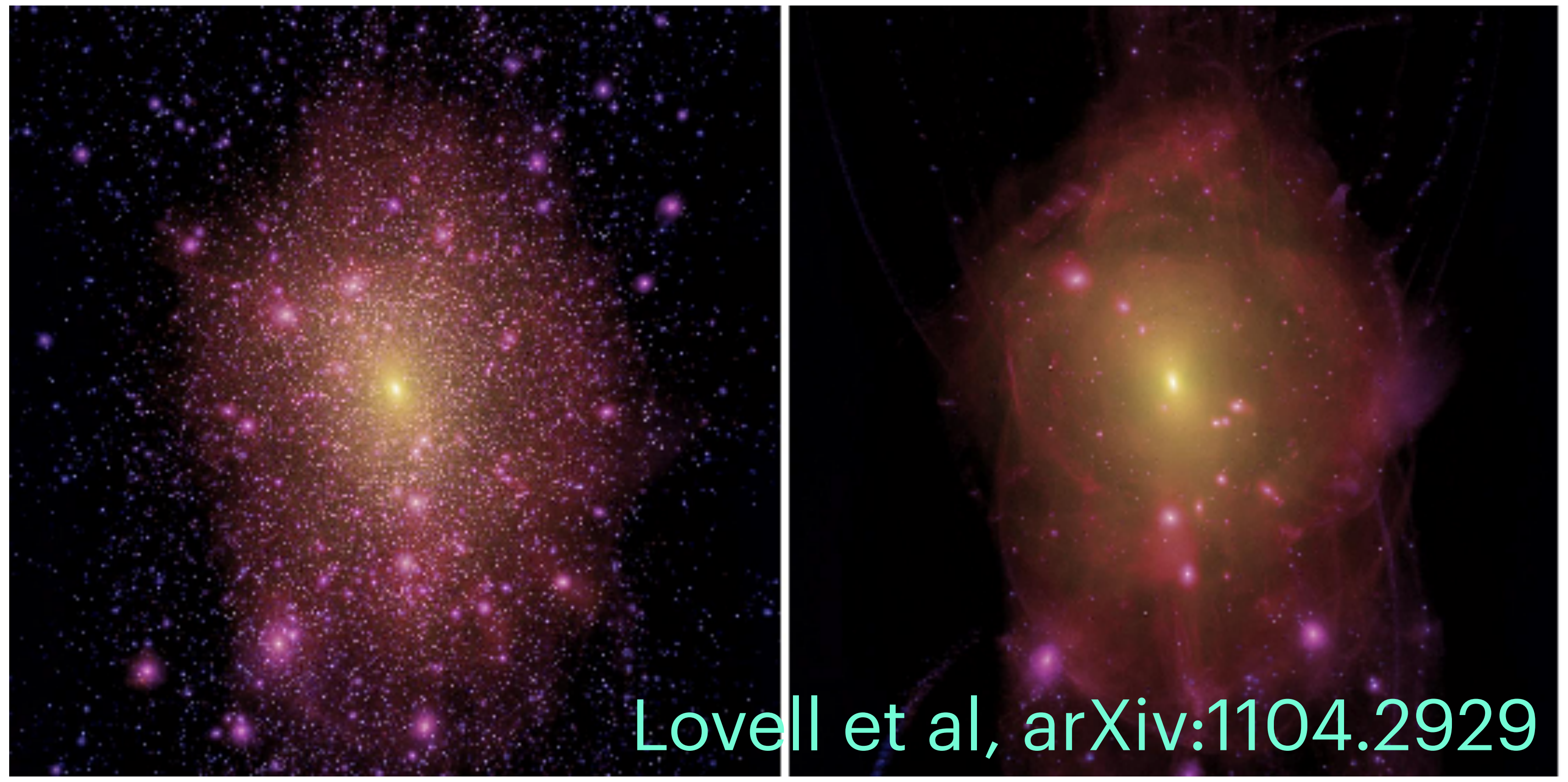
- Non-relativistic (cold)

  Light DM can also be warm/hot DM

$$m_{\rm DM} \gtrsim \mathcal{O}(1)\,{\rm keV}$$

if thermally produced.

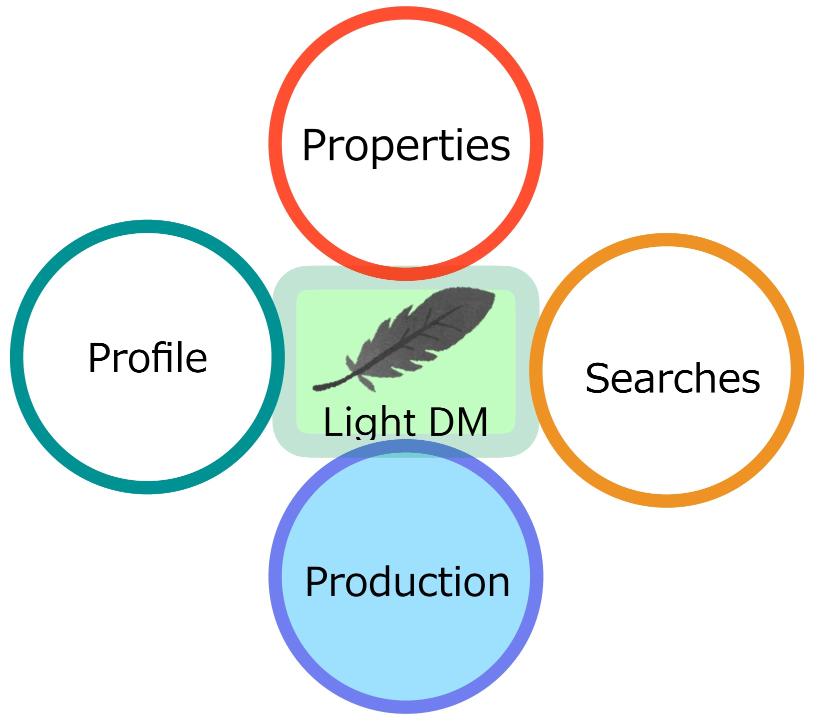
The bound depends on the production mechanism.



Lovell et al, arXiv:1104.2929

B02 (PFS), B03 (HSC)

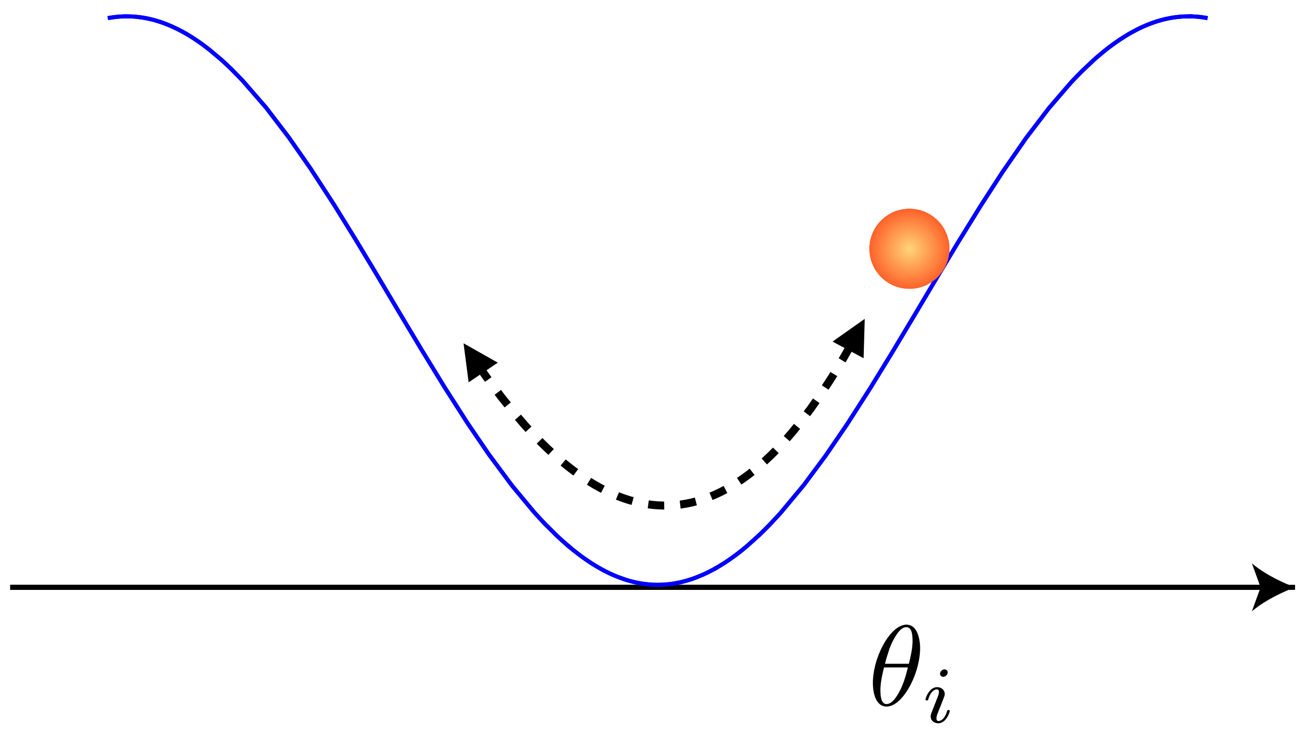
C02 (Structure formation)



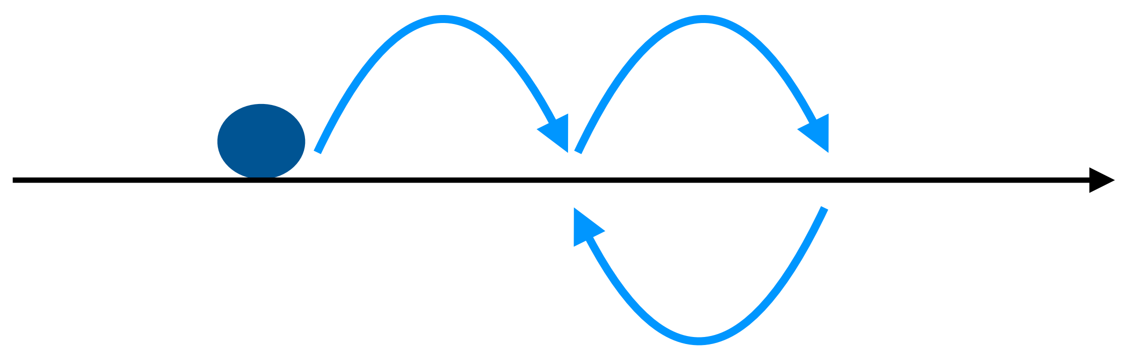
Production of dark matter

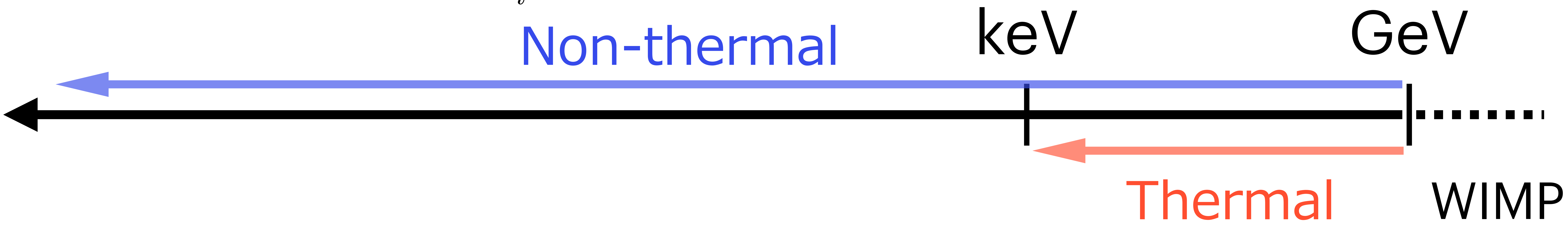
- Thermal production (for $m_{\rm DM} \gtrsim {\rm keV}$)
- Non-thermal production required for $m_{\rm DM} \lesssim {\rm keV}$

e.g.) • The misalignment mechanism

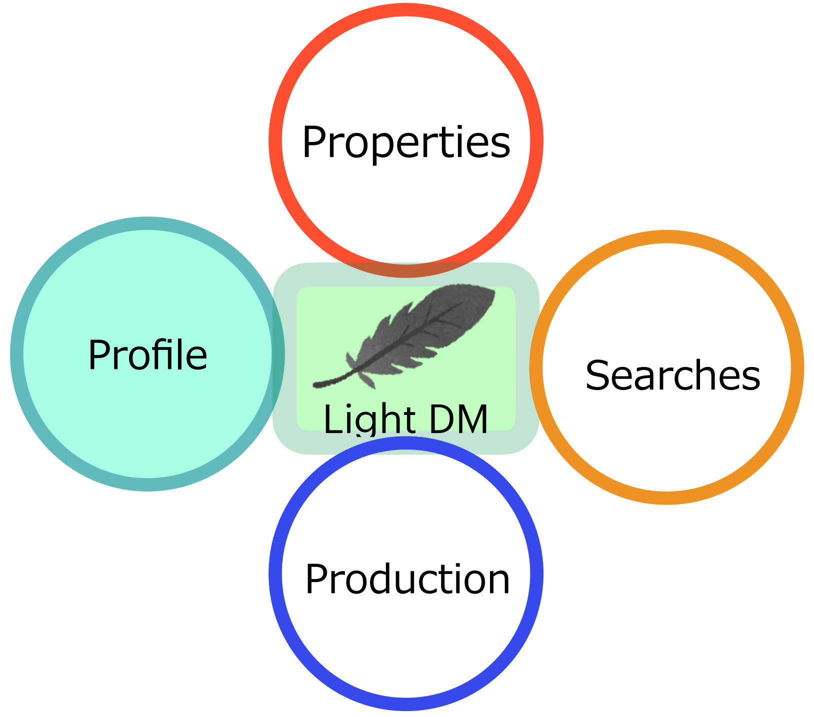


• Gravitational production for e.g. hidden photon

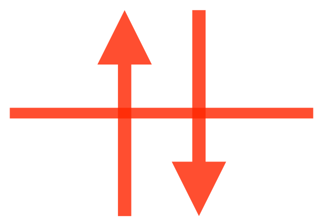




Profile of dark matter



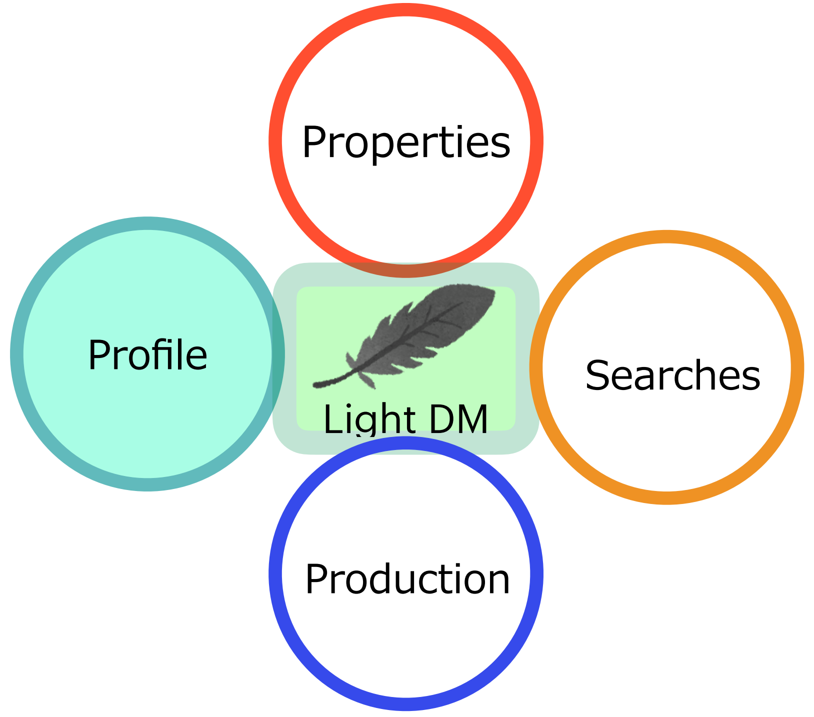
Mass is important even if one considers only gravitational interactions. It’s Quantum Mechanics.

- Pauli exclusion principle 

  DM cannot be fermionic if $m_{\rm DM} \lesssim \mathcal{O}(100)\,{\rm eV}$ since the phase space is limited by the Pauli blocking.

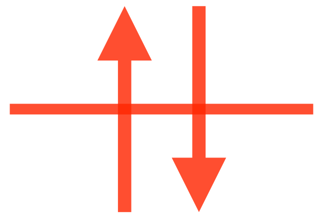
dwarf spheroidal galaxy

Profile of dark matter



Mass is important even if one considers only gravitational interactions. It's Quantum Mechanics.

- Pauli exclusion principle



DM cannot be fermionic if $m_{\rm DM} \lesssim \mathcal{O}(100)\,{\rm eV}$ since the phase space is limited by the Pauli blocking.

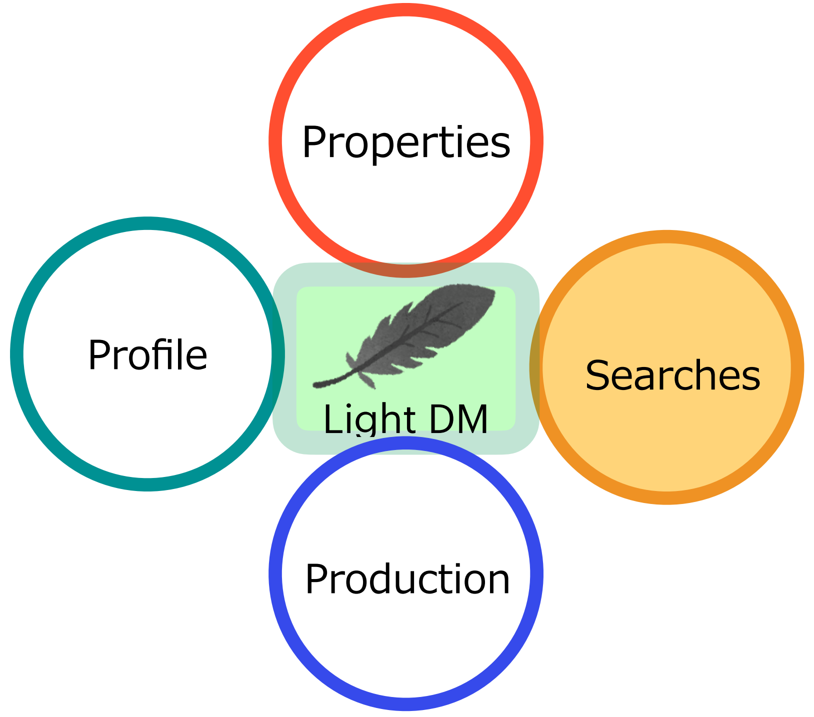
dwarf spheroidal galaxy

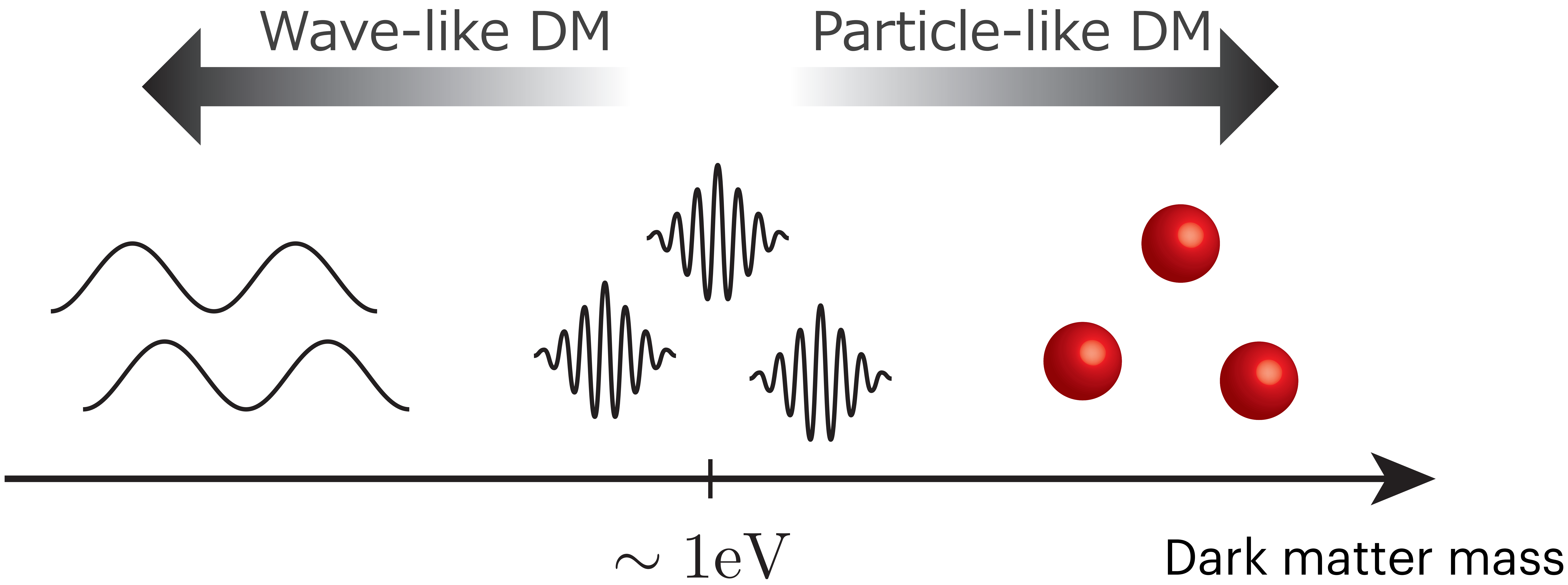
- Uncertainty principle

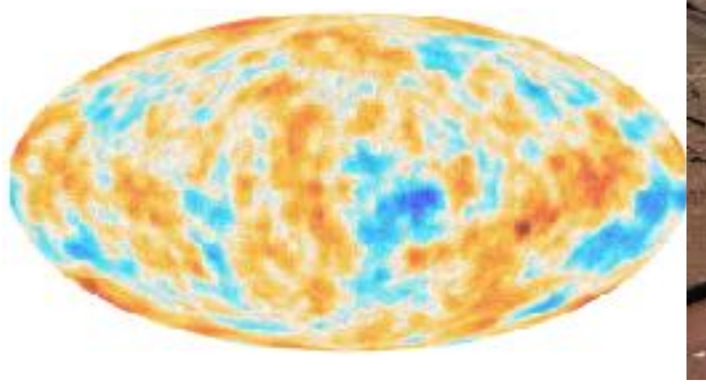
For bosonic DM with $m_{\rm DM} \lesssim \mathcal{O}(1)\,{\rm eV}$, many particles exist in its de Broglie wavelength λ_{dB} and they behave like wave. For $m_{\rm DM} \sim 10^{-22}\,{\rm eV}$, the Jeans scale ~ λ_{dB} ~ O(kpc). → Cored profile

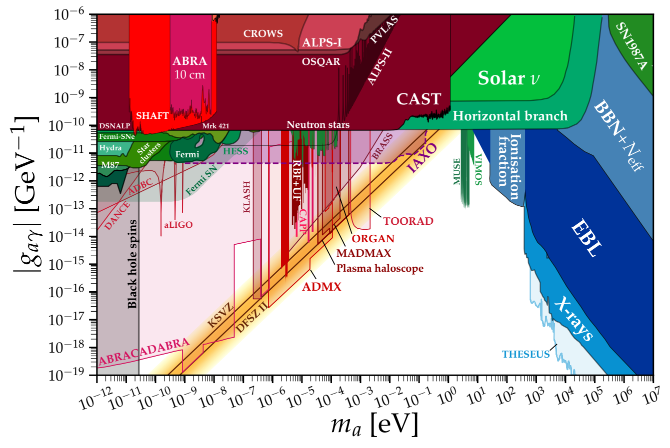
"Fuzzy DM"

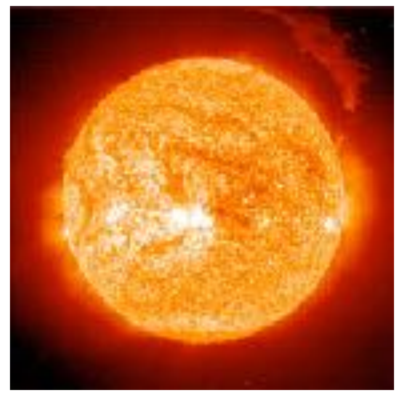
Searches for light DM



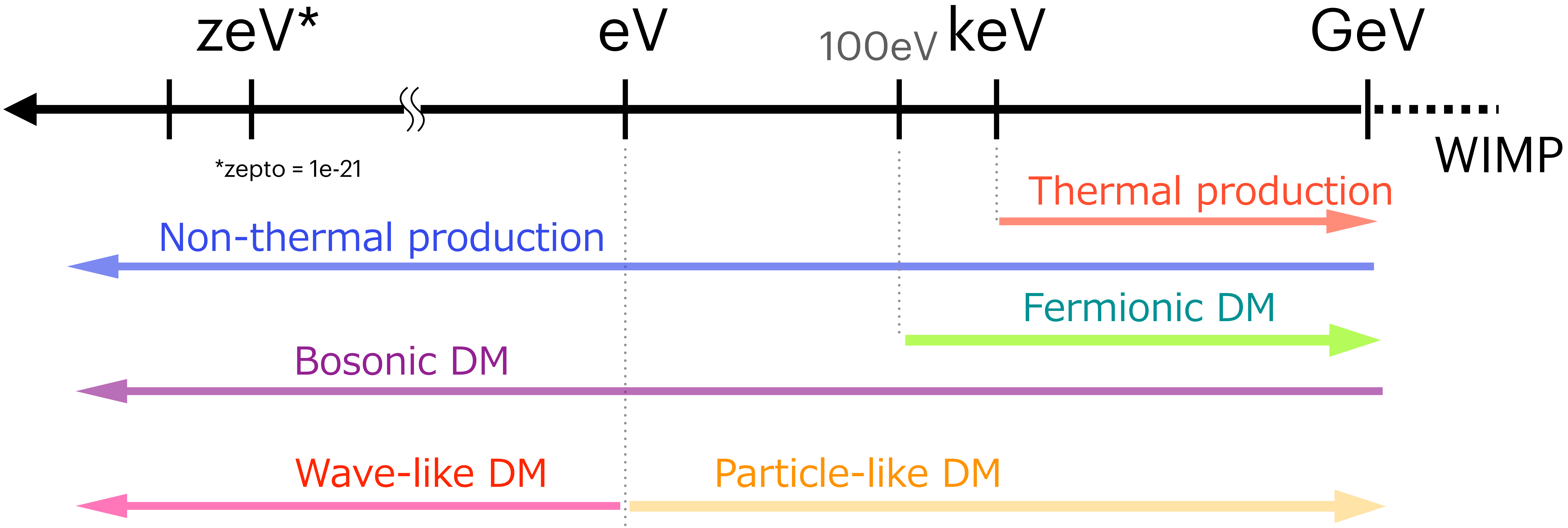








Mass scale of light dark matter



Mass scale of light dark matter

Members

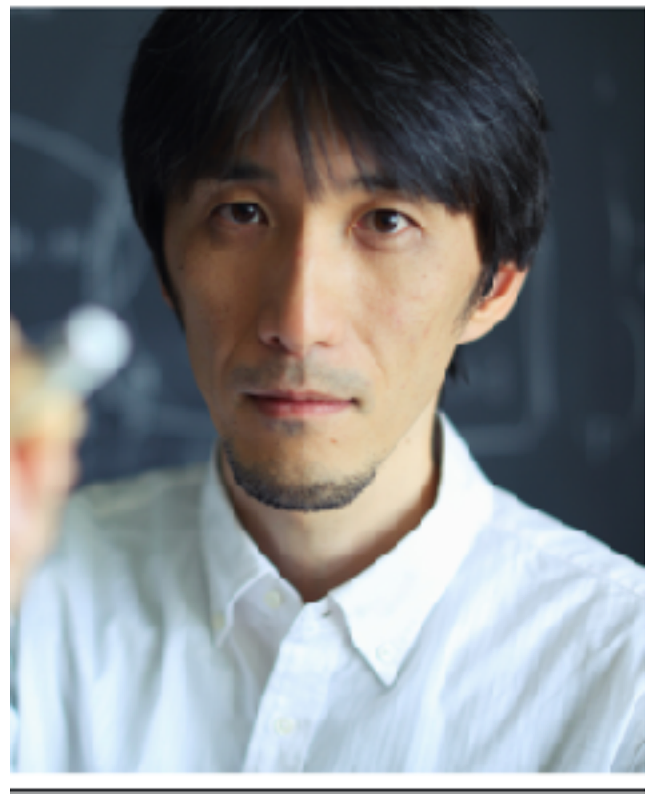
Fuminobu Takahashi (Tohoku)

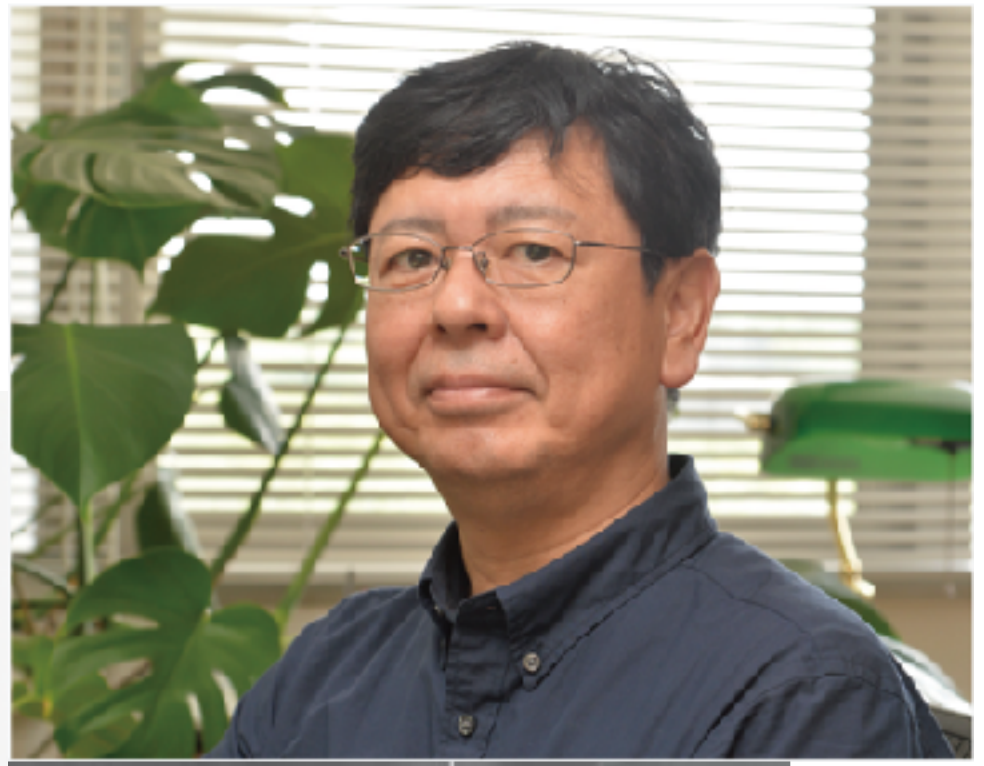
Masahiro Kawasaki (ICRR)

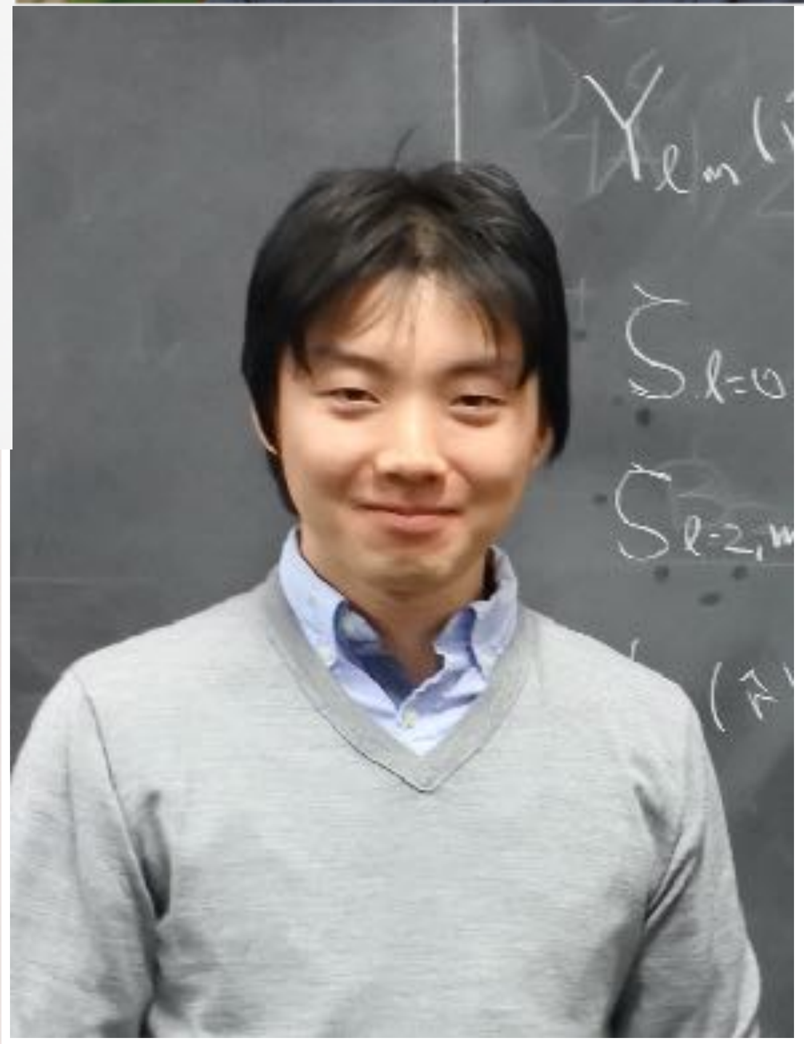
Naoya Kitajima (Tohoku)

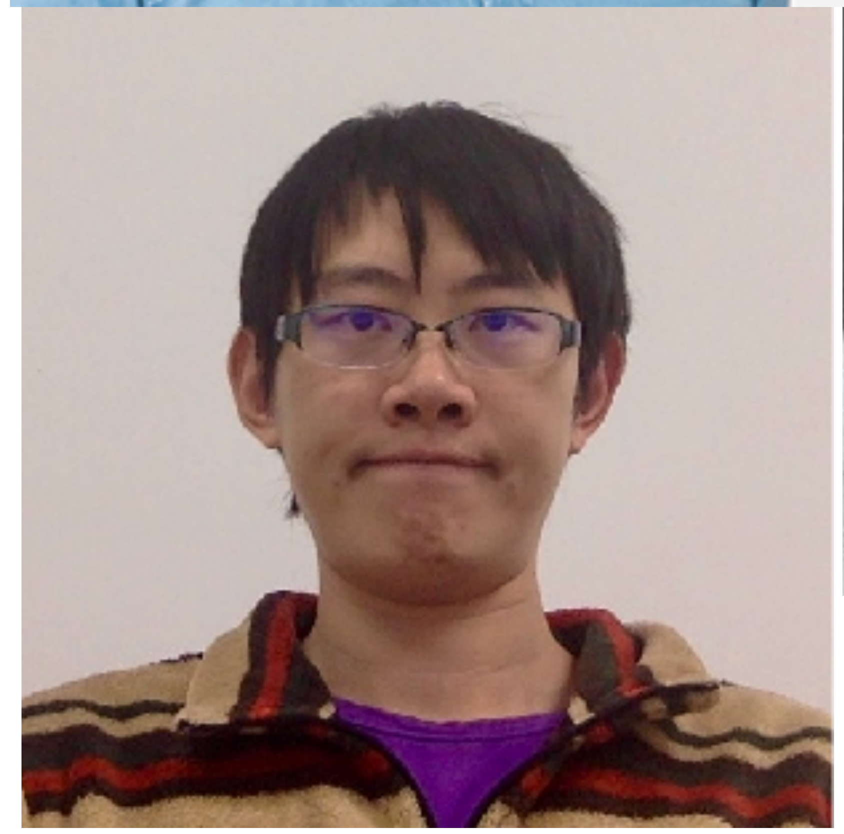
Masaki Yamada (Tohoku)

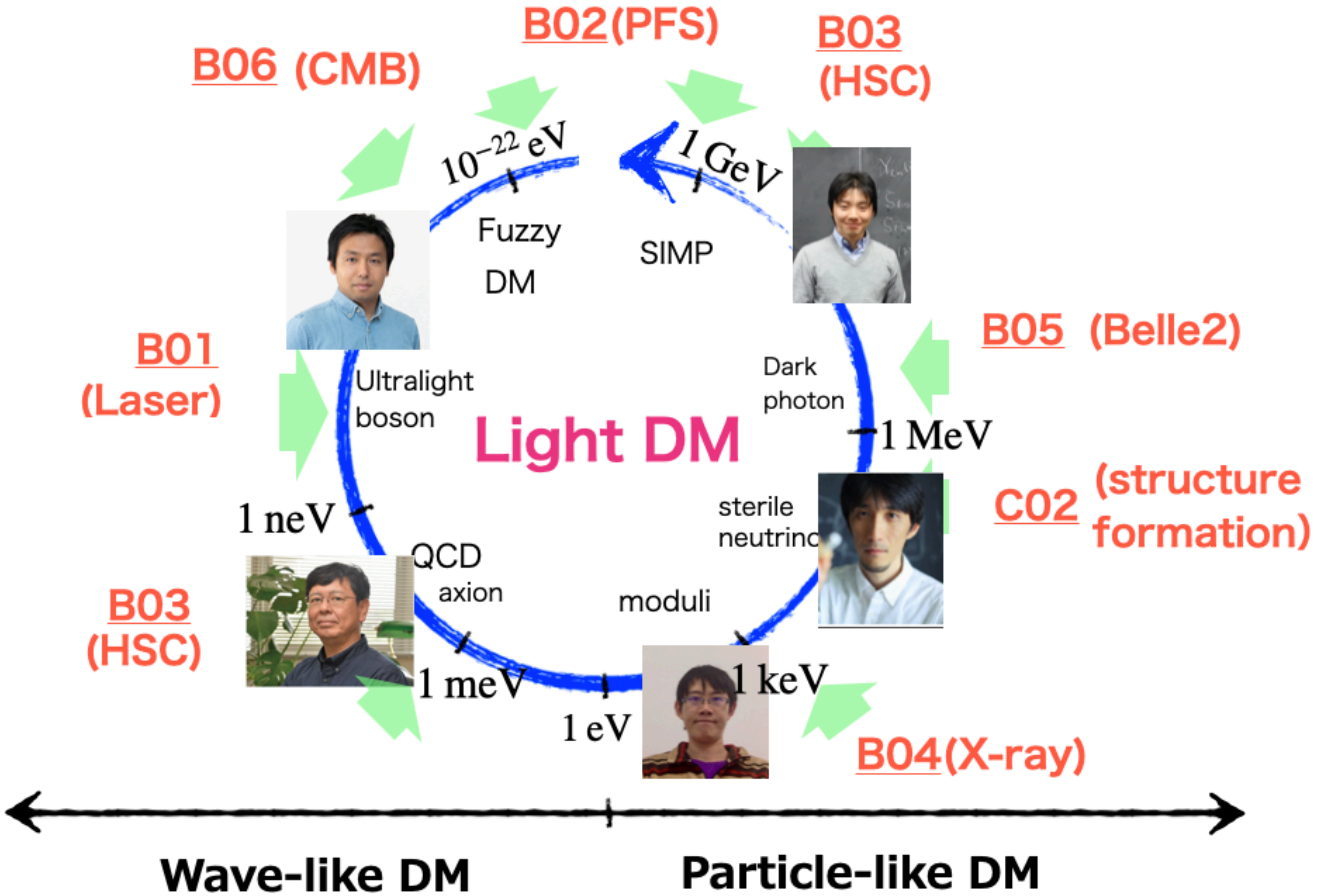
Wen Yin (Univ. of Tokyo)



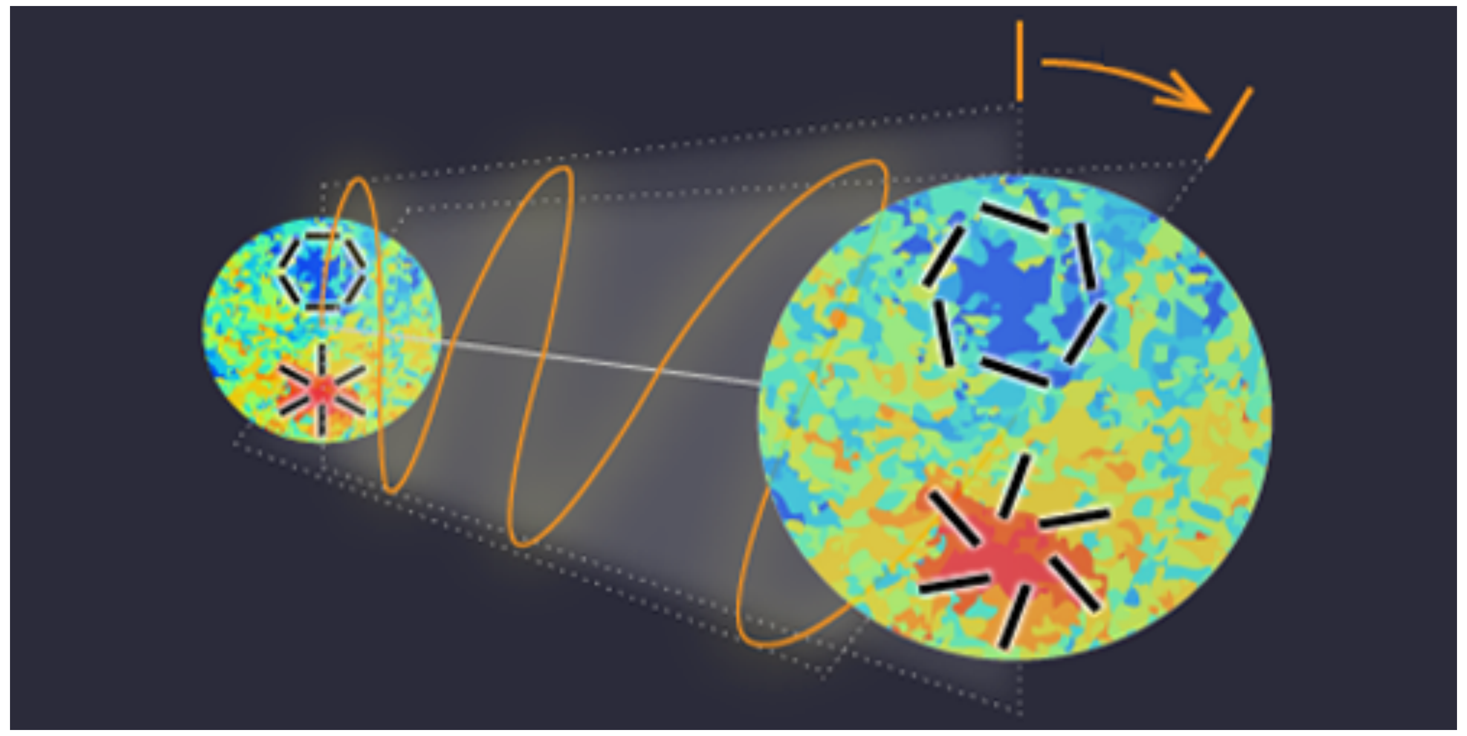







B02(PFS)
B06 (CMB)
B03
(HSC)
10^{-22} eV
1 GeV
Fuzzy
DM
SIMP
B05 (Belle2)
B01
(Laser)
Ultralight
boson
Dark
photon
1 MeV
Light DM
C02
(structure
formation)
1 neV
sterile
neutrino
QCD
axion
moduli
B03
(HSC)
1 meV
1 keV
1 eV
B04(X-ray)
Wave-like DM
Particle-like DM

CMB constraints on the CB



https://physics.aps.org/articles/v13/s149

Minami, Komatsu, Phys. Rev. Lett. **125**, 221301

Isotropic CB

$$\beta = \frac{1}{4\pi}\int d\Omega\,\Phi(\Omega) = 0.35 \pm 0.14\ \mathrm{deg}$$

from Planck 18 pol. data

based on a new method that uses both the CMB and Galactic foreground to distinguish between CB (β) and detector orientation miscalibration (α).

Minami et al, PTEP 2019 083E02 , Minami PTEP 2020 063E01, Minami and Komatsu PTEP 2020 103E02

cf. The reported isotropic CB in the past:

$$\alpha + \beta = \begin{cases} -0.36 \pm 1.24\,\mathrm{deg} & \mathrm{WMAP} \\ 0.31 \pm 0.05\,\mathrm{deg} & \mathrm{Planck} \\ -0.61 \pm 0.22\,\mathrm{deg} & \mathrm{POLARBEAR} \\ 0.63 \pm 0.04\,\mathrm{deg} & \mathrm{SPTpol} \\ 0.12 \pm 0.06\,\mathrm{deg} & \mathrm{ACT} \\ 0.09 \pm 0.09\,\mathrm{deg} & \mathrm{ACT} \end{cases}$$

$$\sigma_{\mathrm{syst}}(\alpha) = \begin{cases} 1.5\,\mathrm{deg} & \mathrm{WMAP} \\ 0.28\,\mathrm{deg} & \mathrm{Planck} \end{cases}$$

Implications for ALP

$$\mathcal{L}_{\phi\gamma} = -c_\gamma \frac{\alpha}{4\pi}\frac{\phi}{f_\phi} F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{1}{4} g_{\phi\gamma\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu},$$

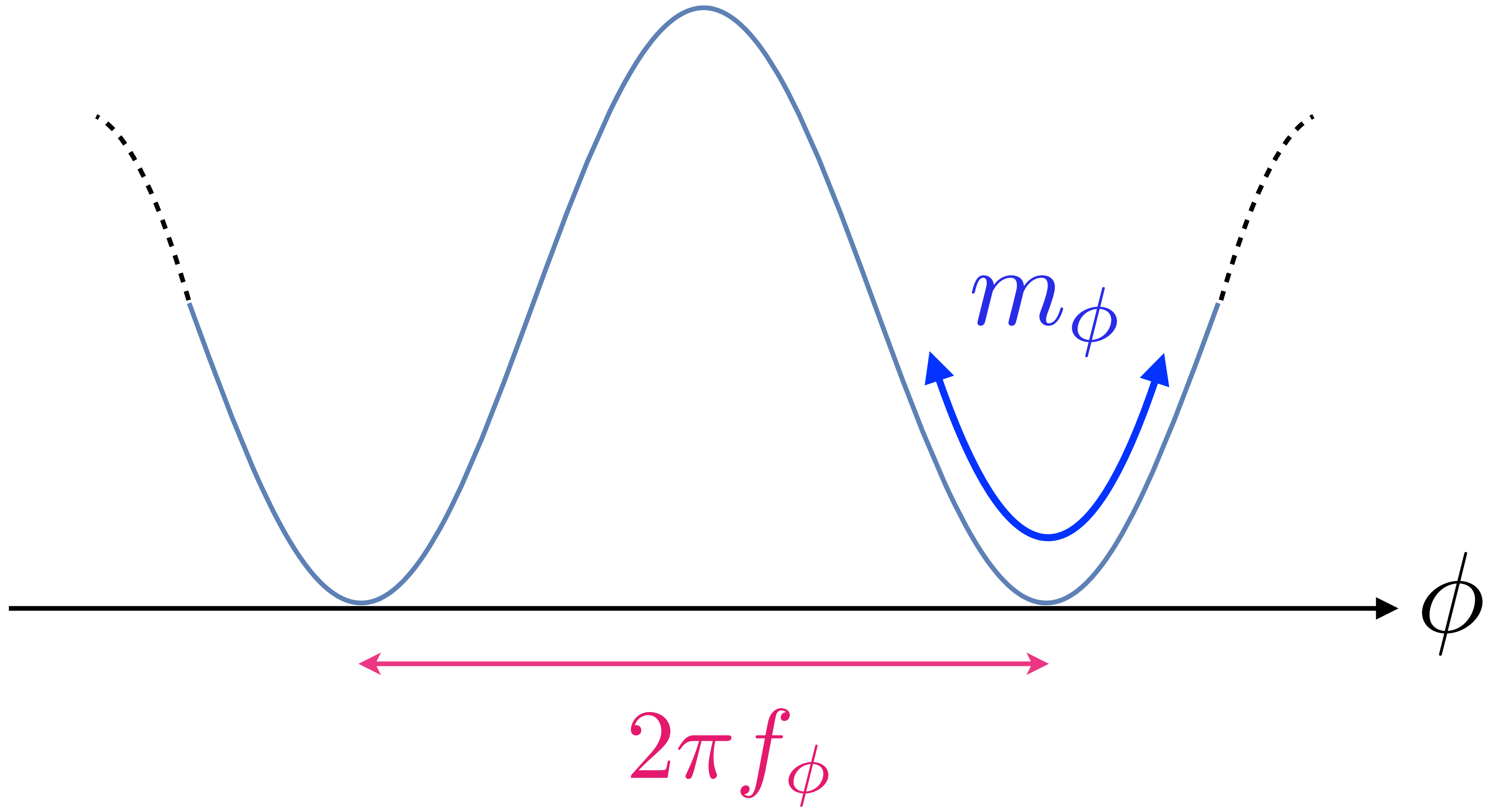
- The hint of the isotropic CB: $\beta = \frac{1}{4\pi}\int d\Omega\, \Phi(\Omega) = 0.35 \pm 0.14\ \mathrm{deg}$
- The ALP prediction: $\Phi(\Omega) \simeq 0.42 c_\gamma \left(\frac{\phi_{\mathrm{today}} - \phi_{\mathrm{LSS}}(\Omega)}{2\pi f_\phi}\right)\ \mathrm{deg}$

The ALP must have moved by $\Delta\phi = \mathcal{O}(\pi f_\phi)$ for $c_\gamma = O(1)$ after recombination

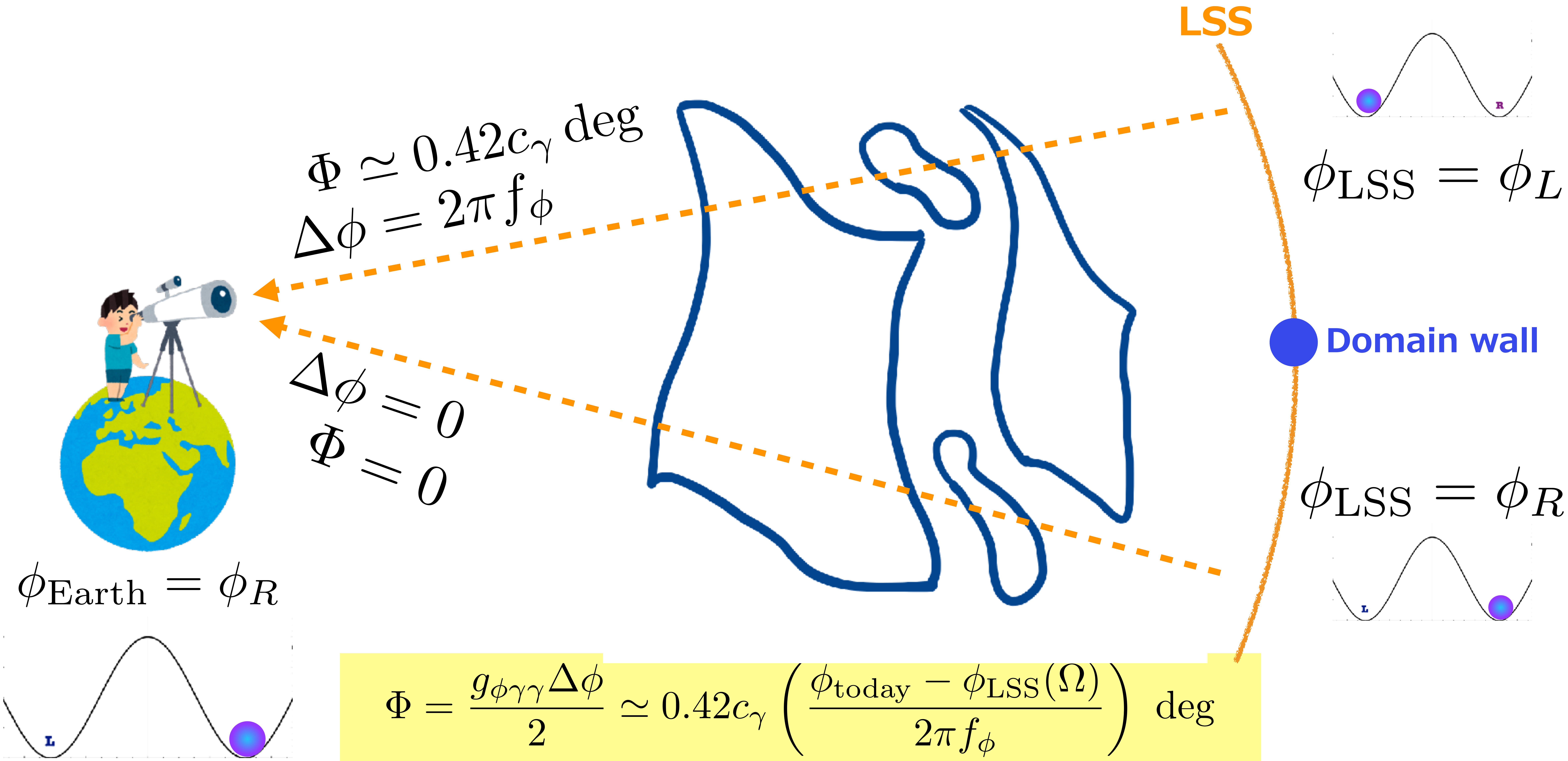
The interpretation in terms of a homogeneous ALP was studied in e.g. Fujita et al 2011.11894

★ We study the ALP domain wall connecting the two adjacent vacua separated by $\Delta\phi = 2\pi f_\phi$.

FT and Yin 2012.11576

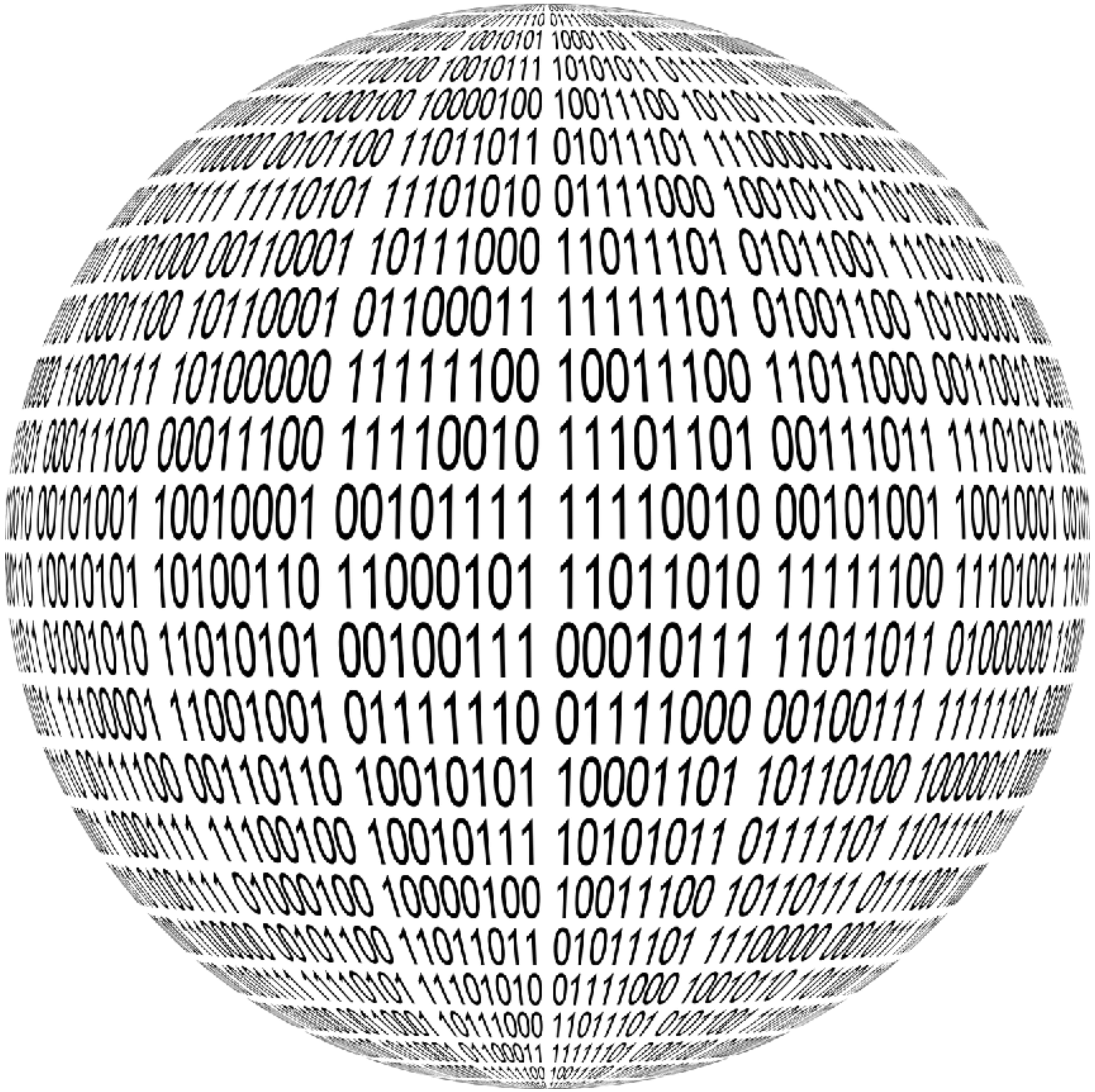


KiloByte CB from ALP domain walls



$$\Phi = \frac{g_{\phi\gamma\gamma}\Delta\phi}{2} \simeq 0.42 c_\gamma \left(\frac{\phi_{\rm today} - \phi_{\rm LSS}(\Omega)}{2\pi f_\phi} \right) \text{deg}$$

There will be $O(10^{3-4})$ domains on the LSS, and the CMB polarization from each domain is either not rotated at all or rotated by a fixed angle, $\Phi \simeq 0.42 c_\gamma \, \mathrm{deg}$.



$$= 2^N, \quad N = O(10^{3-4})$$

"KiloByte Cosmic Birefringence"
(KBCB)

Predictions of KiloByte Cosmic Birefringence

Isotropic CB

$$\beta_{\rm KBCB} \simeq 0.21\, c_\gamma \ \ \deg \cdot$$

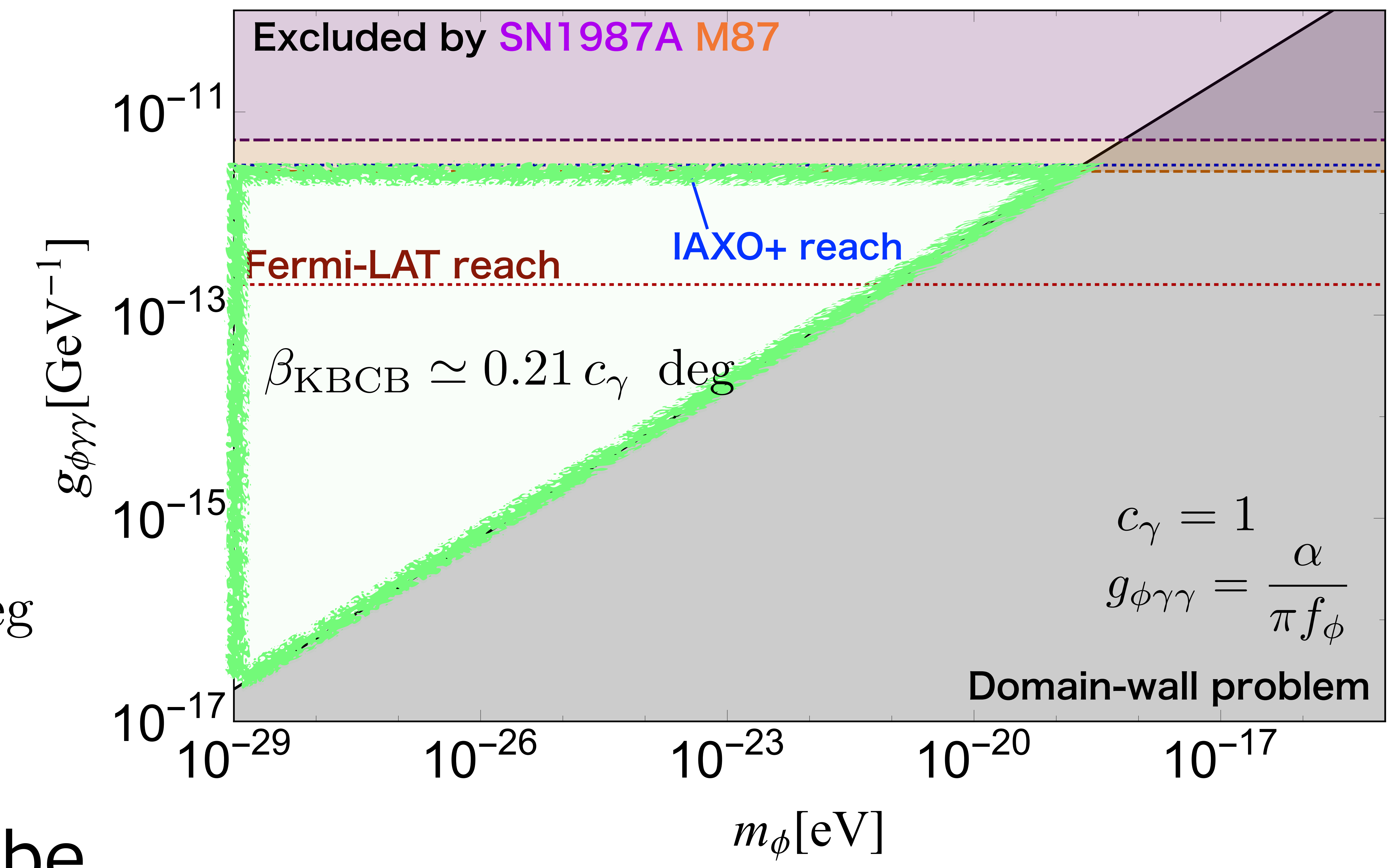
independent of m_ϕ and f_ϕ .

Recall $\Phi = \frac{g_{\phi\gamma\gamma}\Delta\phi}{2} \simeq 0.42 c_\gamma \left(\frac{\phi_{\rm today} - \phi_{\rm LSS}(\Omega)}{2\pi f_\phi}\right) \deg$

cf. $\beta_{\rm obs} = 0.35 \pm 0.14 \deg .$ can be

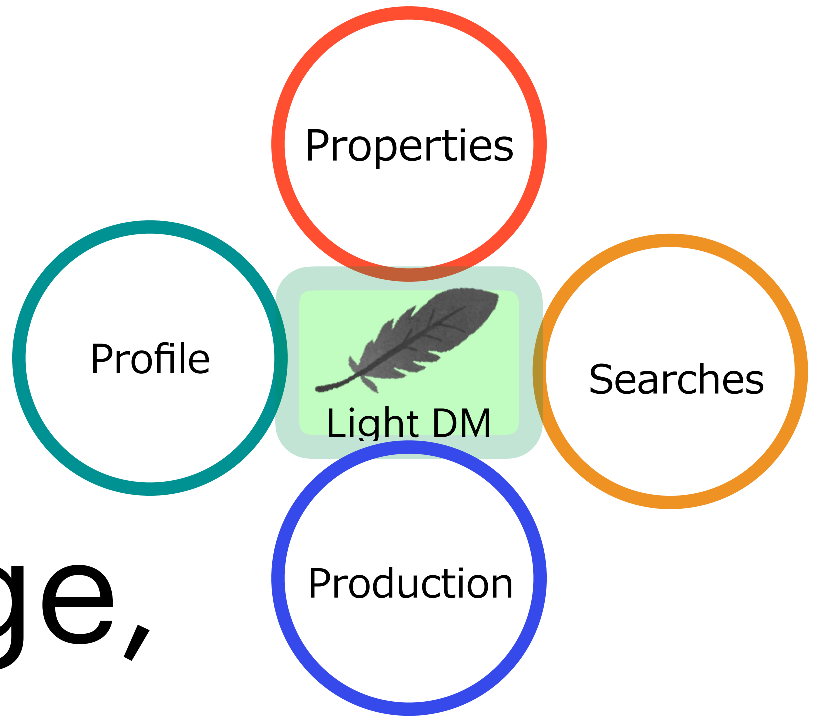
Minami, Komatsu, Phys. Rev. Lett. **125**, 221301

explained for $c_\gamma = O(1)$.



The predicted isotropic CB is the same over the viable parameter space (green triangle).

Summary



There are many light DM candidates in this vast mass range, and we will clarify their production, evolution, and experimental implications to get closer to the nature of light DM.