Dark matter overview and a novel proposal of using paleo detector

TOKYO METROPOLITAN UNIVERSITY
東京都立大学

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@MDnuDM

2025/5/22

Plan

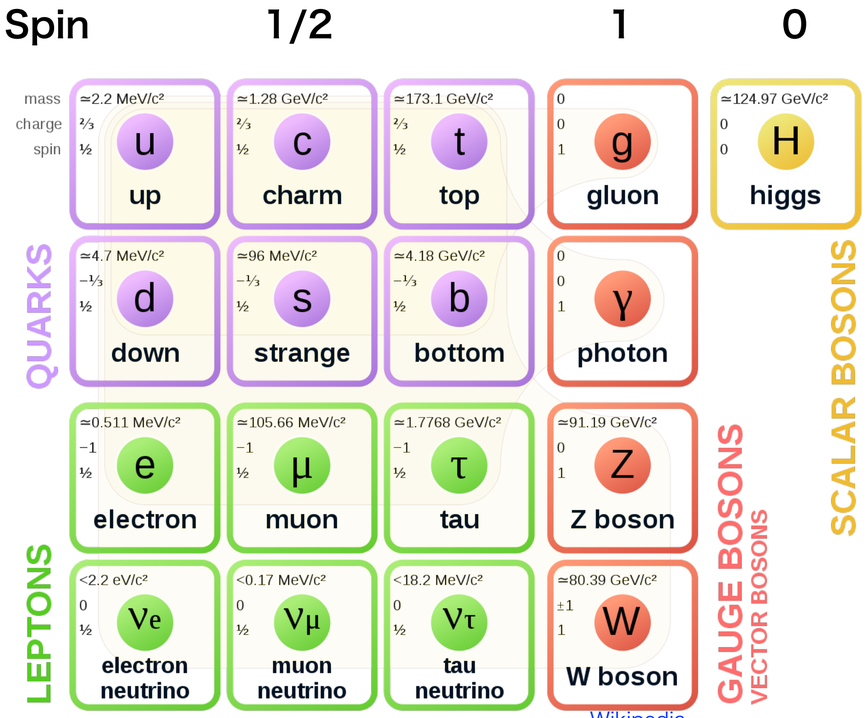
- 1. DM overview
  —a particle theorist point of view—
- 2. Searching for cosmic walls with Paleo detector
- 3. Conclusions

- 1. DM overview
  —a particle theorist point of view—

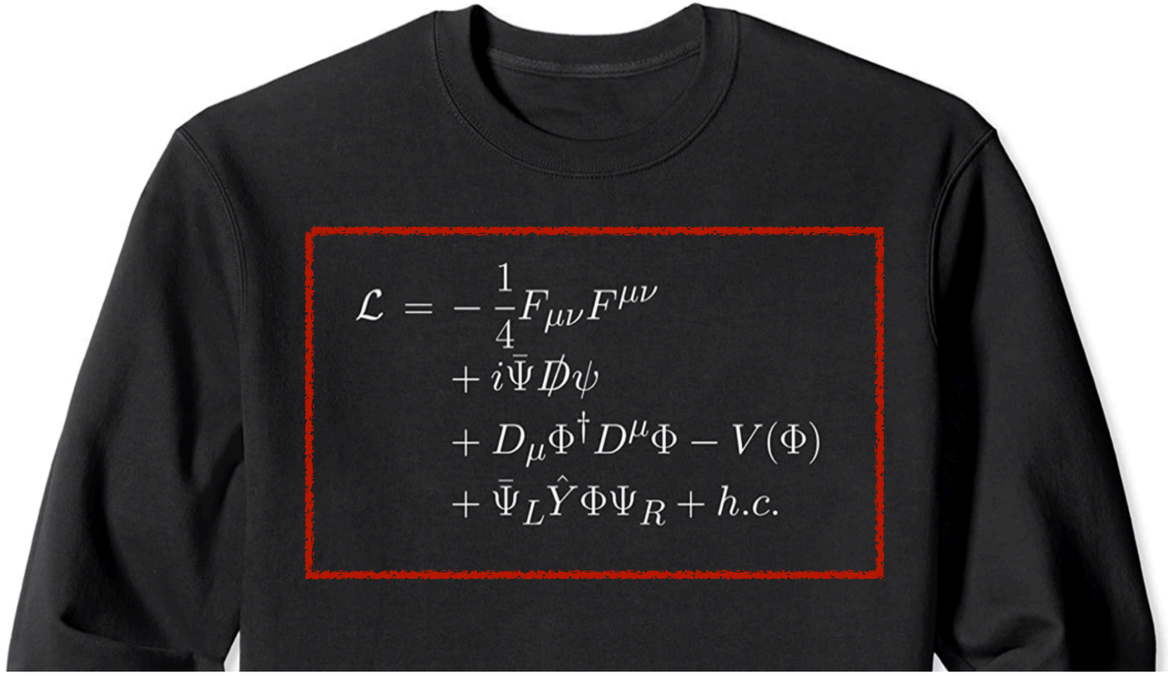
Particle theory：Particle property(mass、spin、coupling)＝fundamental law of physics

Standard model (SM)=

Particle property(spin, mass, coupling) ＋ QFT



Wikipedia

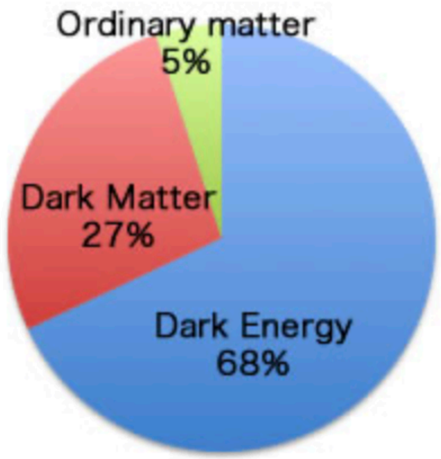


https://www.amazon.co.jp

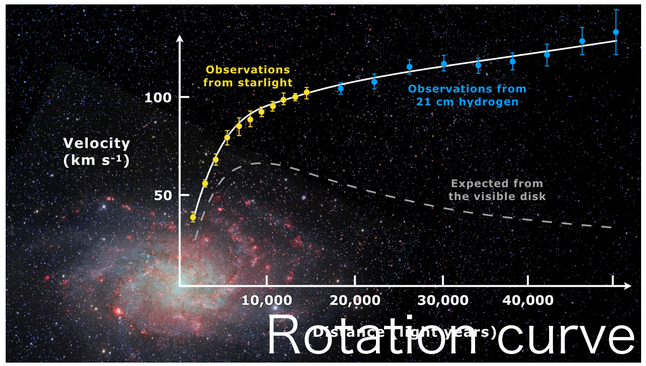
Standard model of particle theory can explain most things in nature with very good precision, when our calculations are well justified.

Dark matter (DM), long-standing mystery

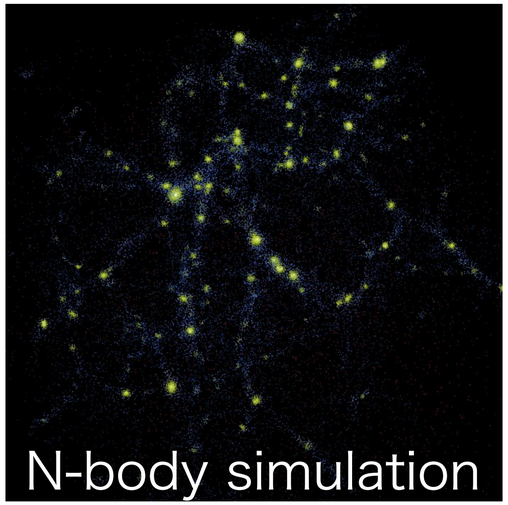
What is DM? **Longevity**, Neutral, Cold, $\rho_{\rm DM}/s \sim$ **eV**



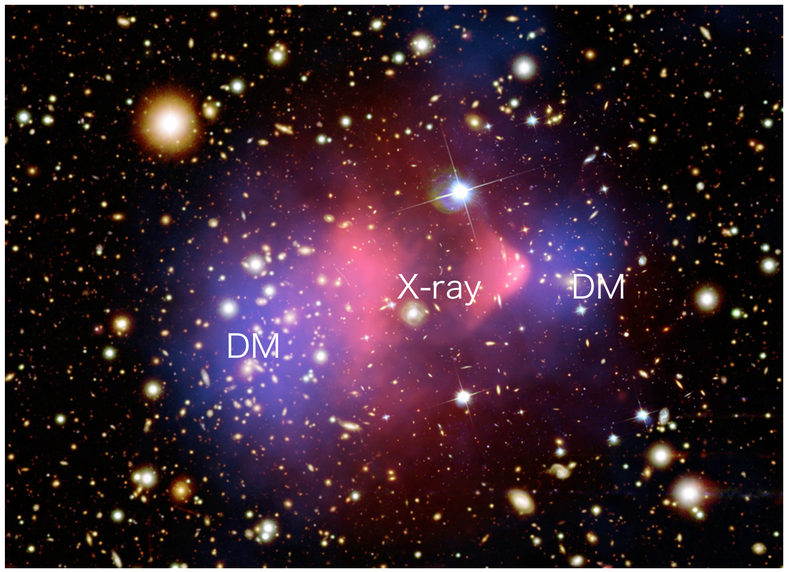
CMB data



Rotation curve



N-body simulation



Bullet cluster

- What is DM?

Q: Is DM neutrino？

Neutrino's status

-Constraint from Tritium β decay

$$T_2 \rightarrow {}^3HeT^+ + e^- + \bar{\nu}_e$$

The KATRIN Collaboration. 2022

neutrino mass $\lesssim 1\mathrm{eV}$

-Neutrinoless double β decay

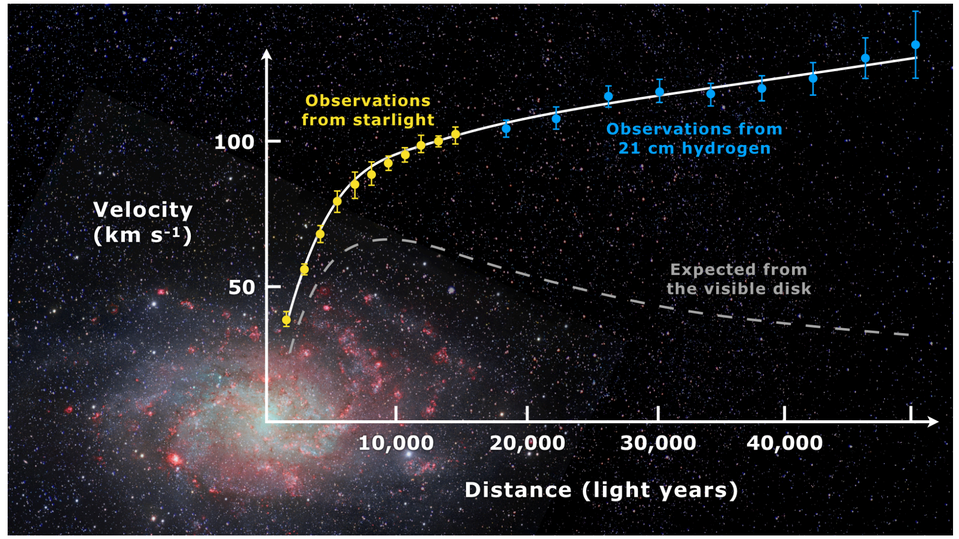
KamLAND-Zen Collaboration,
Phys.Rev.Lett. 130 (2023) 5, 051801

(Majorana)Neutrino mass $\lesssim 0.1\mathrm{eV}$

Neutrino mass $\lesssim 1\mathrm{eV}$

If neutrino is the DM

Pauli Exclusion Principle



∵Neutrino cannot be too many in the galaxy

(Tremaine & Gunn 1979).

Neutrino mass $\gtrsim 100\mathrm{eV}$

This is also a constraint for generic fermionic DM

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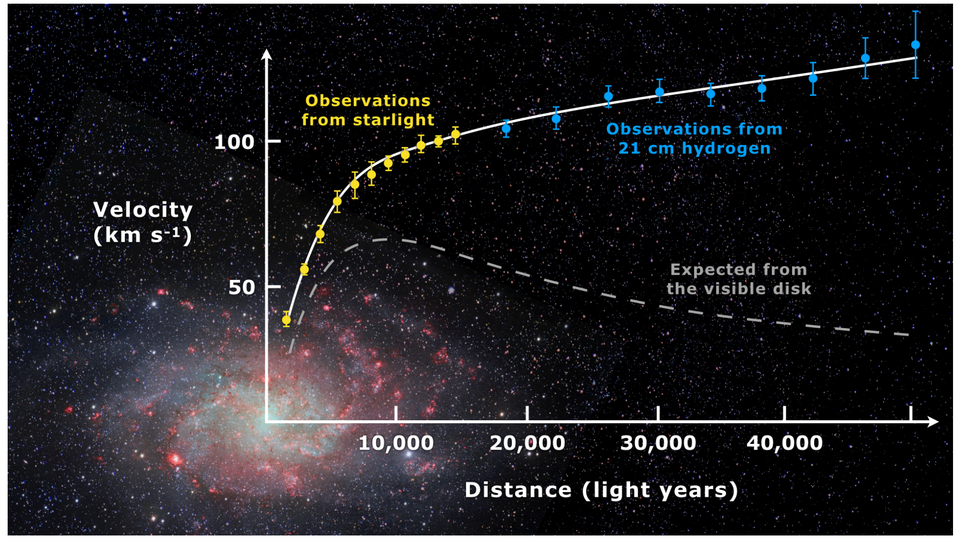

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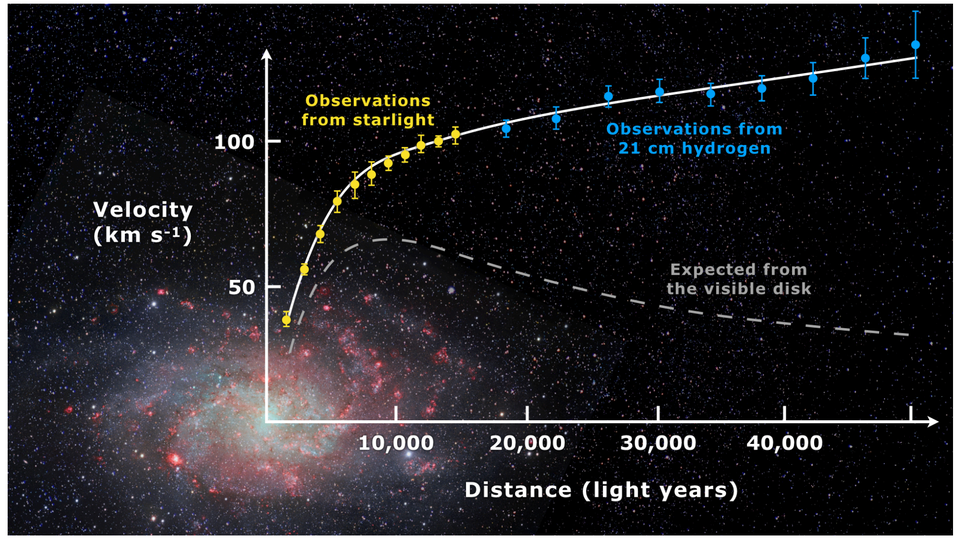

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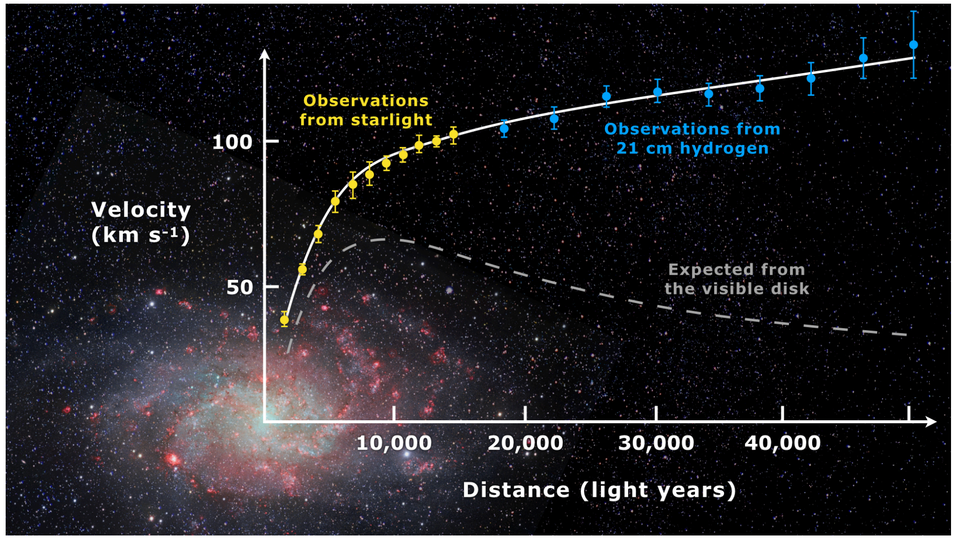

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Q: Is DM neutrino？

No-Go This no-go theorem does not rely early cosmology and thus super robust.

- Just `hot dark matter' does not mean an exclusion. See WY 2301.08735.

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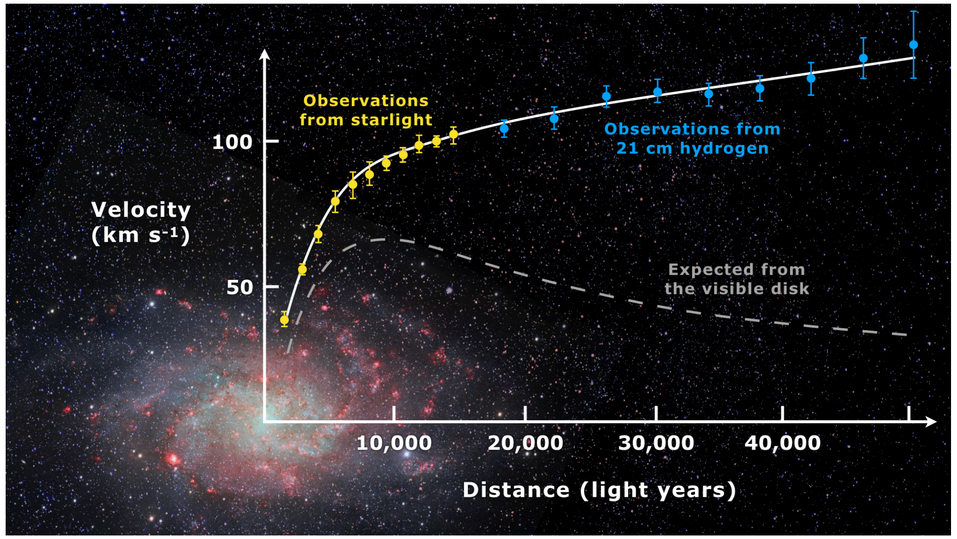

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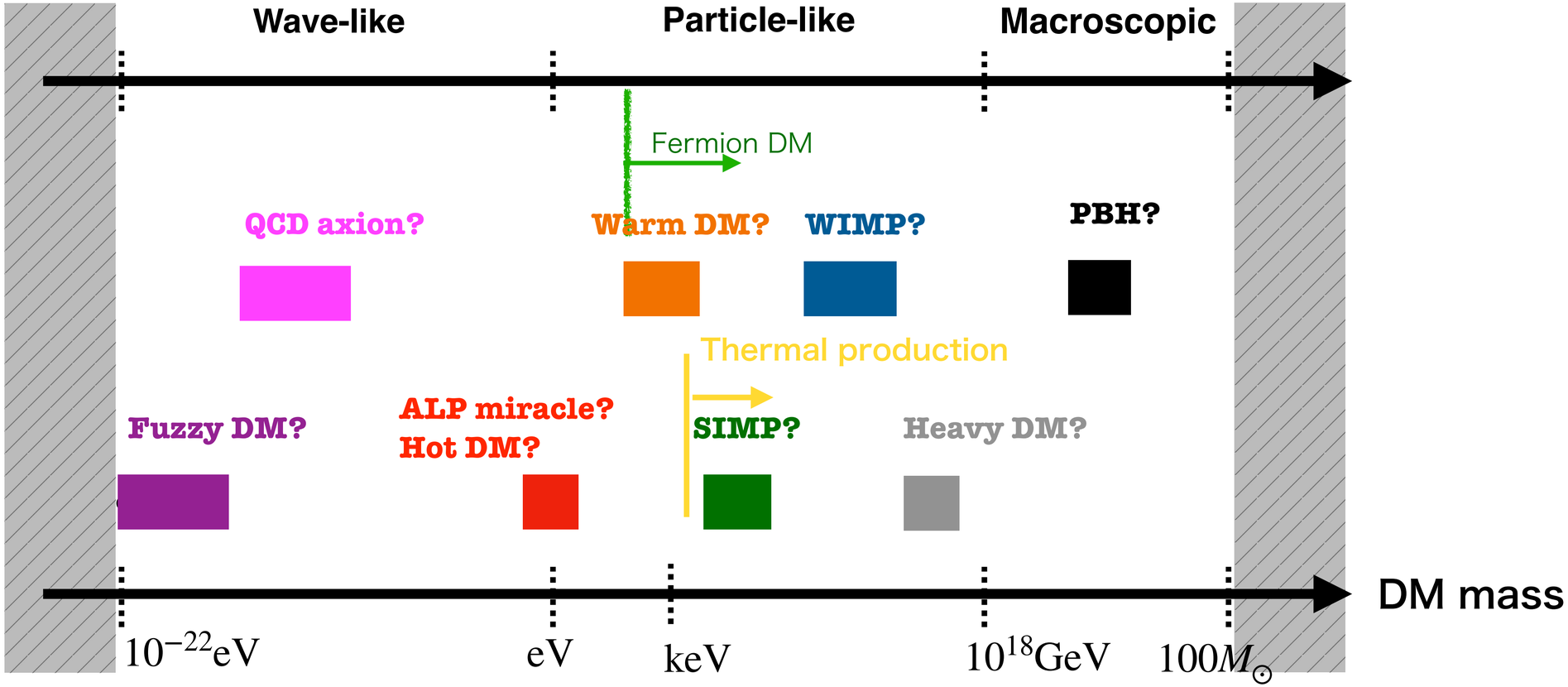
DM is BSM

What is DM? Long lived, Neutral, Cold, $\rho_{\rm DM}/s \sim$ eV

We do not know the particle property at all.



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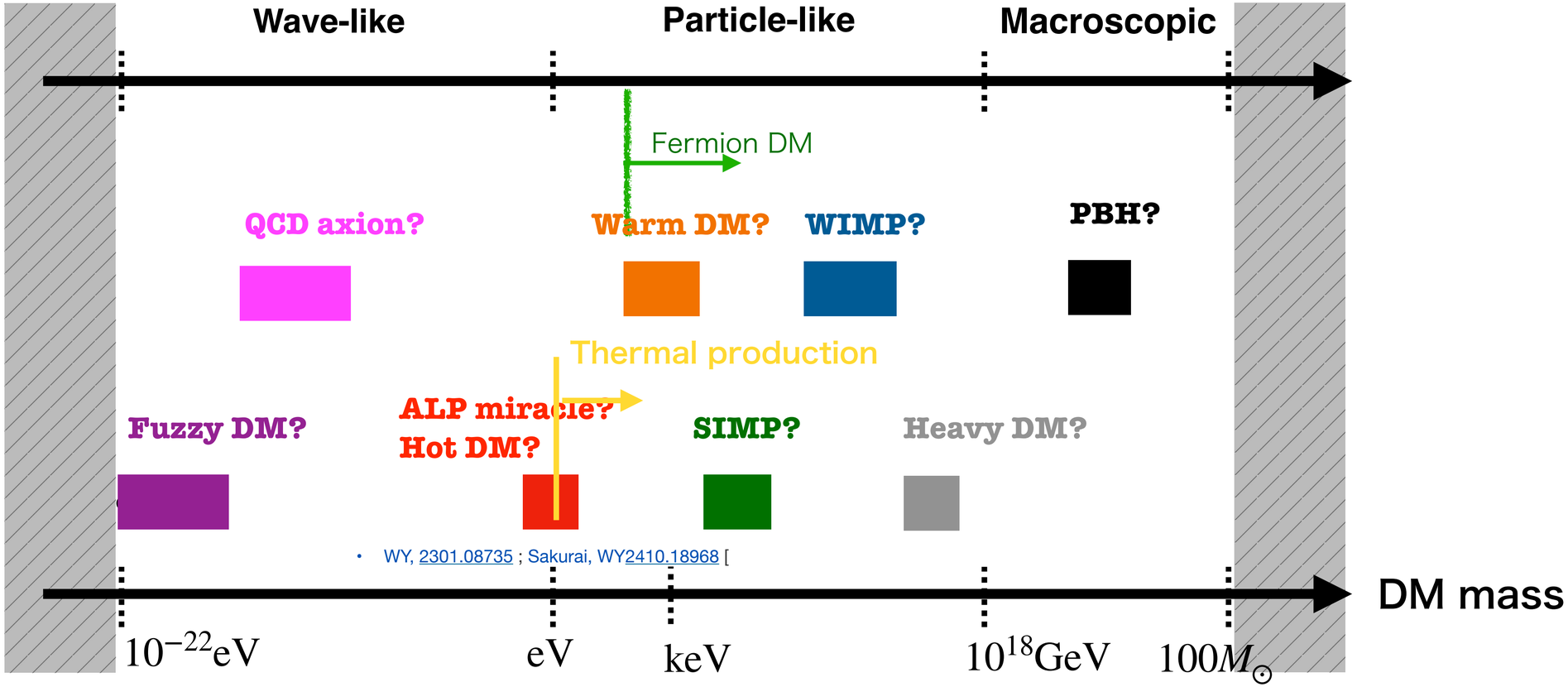

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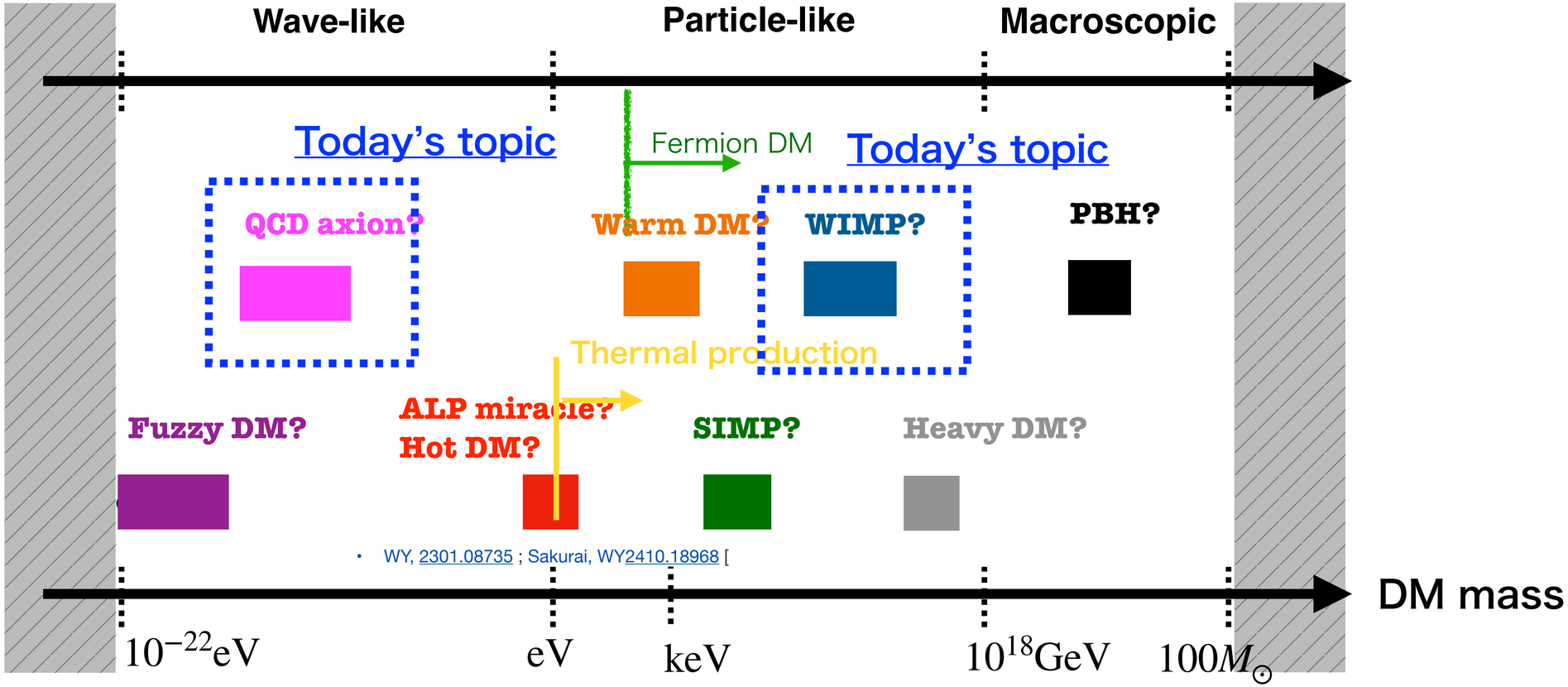
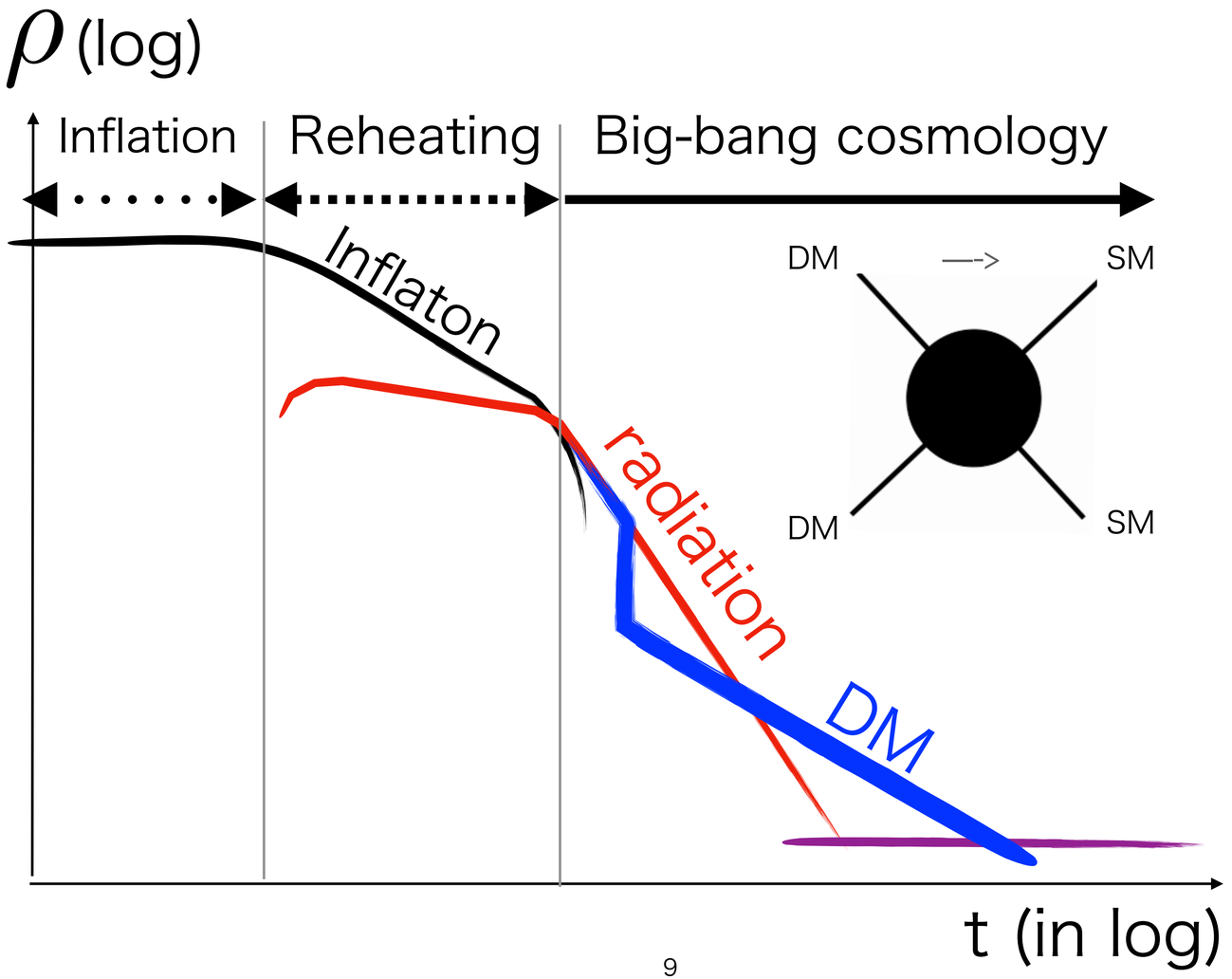


Weakly Interacting Massive Particle(WIMP)

- A new symmetry for stability.



$$\rho_{DM}/s = m_{\mathrm{DM}} n_{\mathrm{DM}}/s \sim eV$$

$$n_{DM}/s \quad \searrow \qquad m_{DM} \quad \nearrow$$

WIMP has been popularly studied over 40years.

$$\Omega_{\mathrm{DM}} \sim 30\,\% \frac{\langle v_{\mathrm{rel}}\sigma\rangle^{-1}}{(20\mathrm{TeV})^2}$$

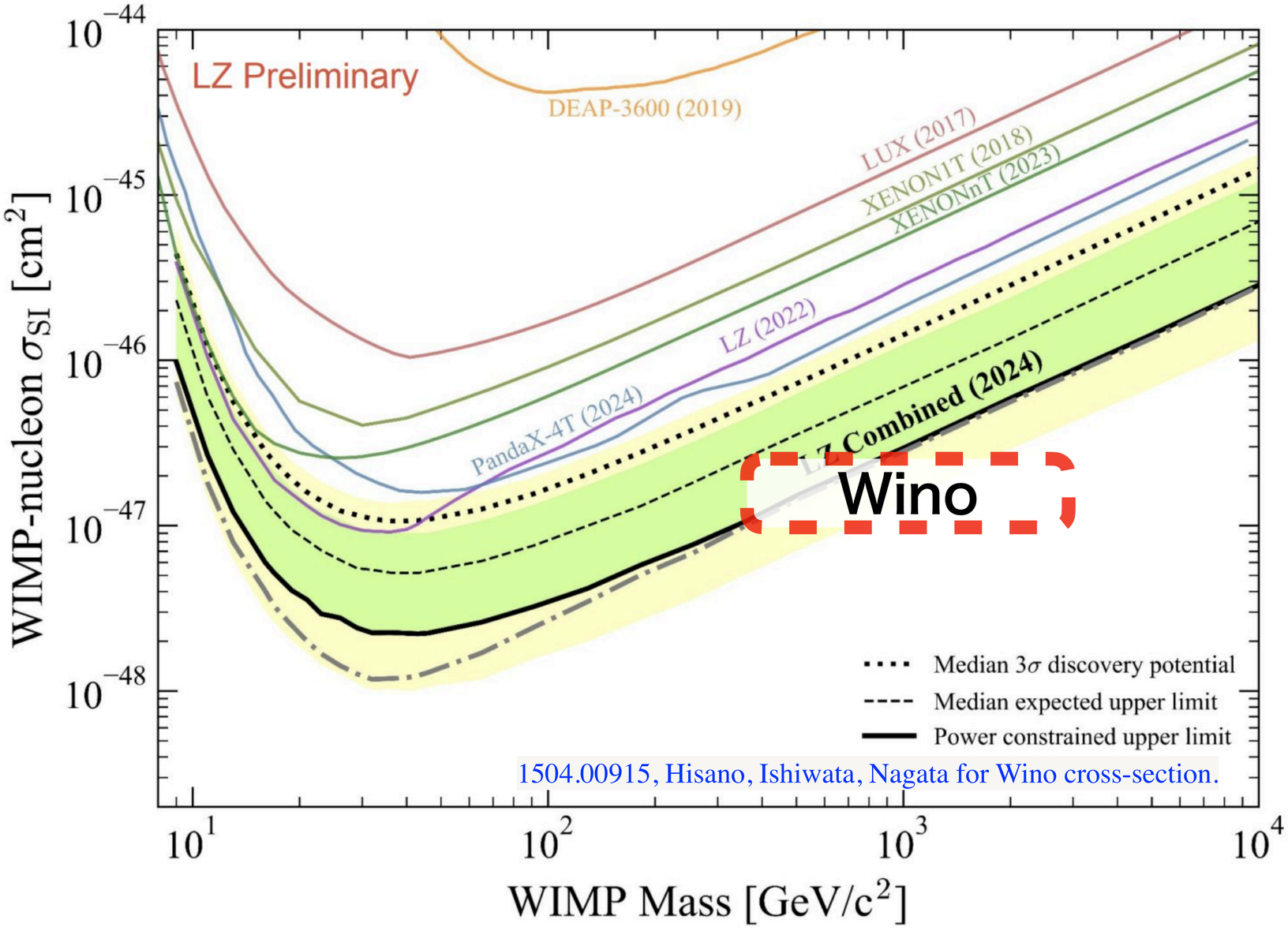
$$\sigma \sim 10^{-36} cm^2$$

- Many extensions of the standard model, supersymmetric extension, extra dimension, composite Higgs, etc., predict particles with this crosssection.

Example of the possibility: Wino DM

- Wino is a superpartner of SU(2) gauge boson. Triplet Majorana fermion.
- A cosmologically-safe model with Yukawa coupling unification.

Giudice, Luty, Murayama, Rattazzi, 1999;
See also Randall, Sundrum, 1999;
WY, Yokozaki, 1607.05705,



1504.00915, Hisano, Ishiwata, Nagata for Wino cross-section.

Weekly interacting slim particle (WISP)

- Lightness for stability

Axion, dark photon, light dilaton (see also sterile neutrinos)

Asked chatGPT to draw a illustration of WISP and WIMP

Asked chatGPT to draw a illustration of WISP and WIMP
in the context of dark matter.

Axion (Axion-like particle)

- explains the dark matter, the inflation, and/or strong CP, etc.
- appears as a remnant of extra dimension, or as a pseudo-Nambu-Goldstone boson.
- mass is generated with some non-perturbative effects and scales exponentially.

e.g. Daido, Takahashi, WY 1702.03284; Narita, Takahashi, WY, 2308.12154; Takahashi WY 2301.10757 etc for ``and".

QCD axion and strong CP problem

Strong CP phase sources the nucleon EDM, the non-observation of which strictly constrains the strong CP phase $|\theta| < 10^{-10}$.

$$\mathscr{L} = \mathscr{L}_{\rm SM}|_{\theta_{\rm CP}=0}$$
$$-\frac{\theta g_s^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}G_{\mu\nu}G_{\delta\epsilon}$$
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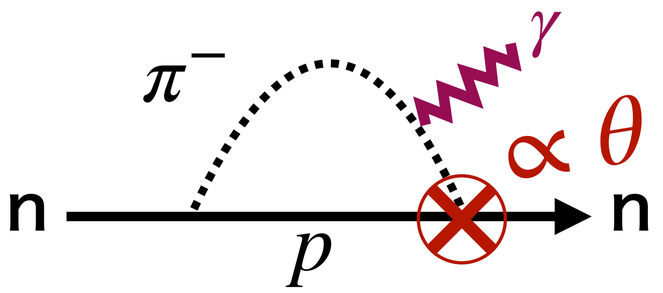
standard model

CPV: $\dfrac{\theta g_s^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}G_{\mu\nu}G_{\delta\epsilon}$

θ changes QCD potential:

$$-\mathscr{L} \supset \frac{\theta g_s^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}G_{\mu\nu}G_{\delta\epsilon} \leftrightarrow m_u\bar{u}e^{i\gamma_5\theta}u \to m_u\cos[\theta]\langle\bar{u}u\rangle$$

EDM:



Non-observation of neutron EDM

→Strong CP problem: $|\theta| \lesssim 10^{-10}$

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QCD Axion model

$$-\frac{f_a^2}{2}(\partial_\mu\theta)^2$$

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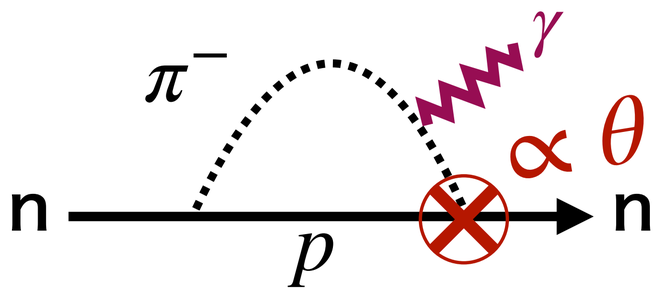

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QCD axion and strong CP problem

Peccei, Quinn, 77; Weinberg, 78; Wilczek, 78;

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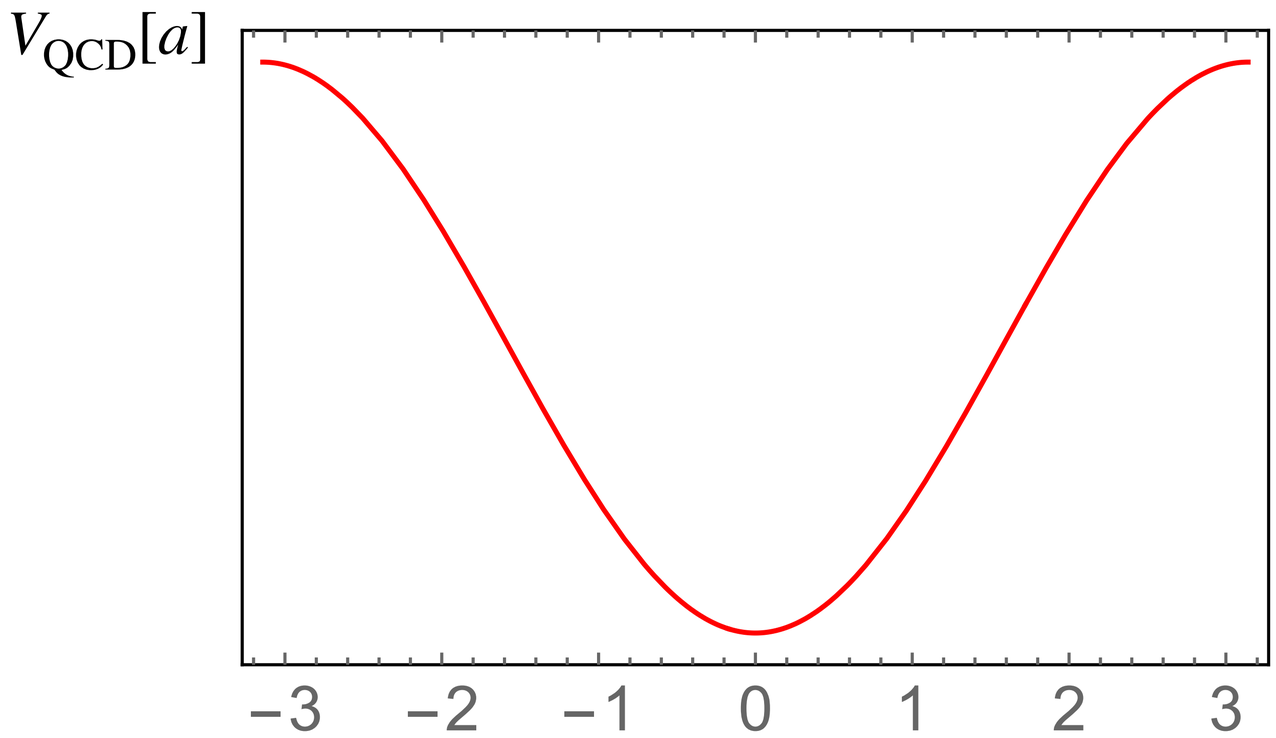

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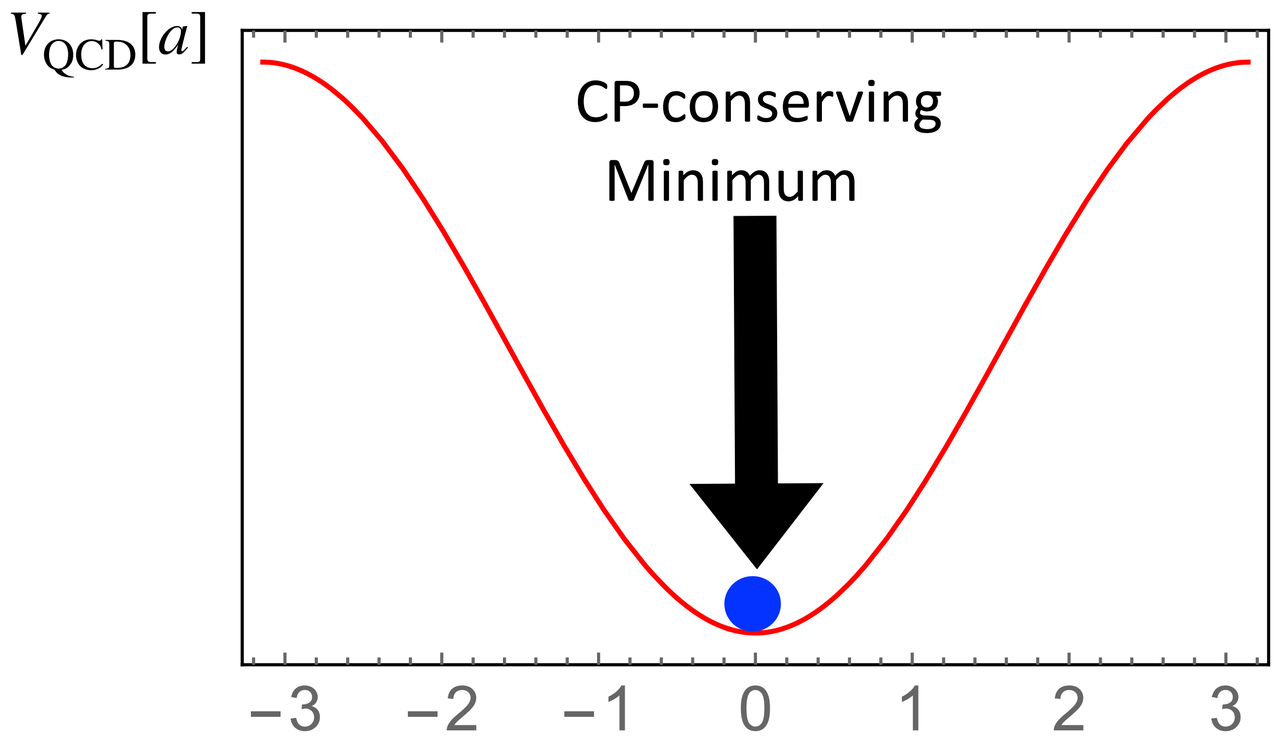
QCD Axion model

$$m_a \simeq \frac{(80\text{MeV})^2}{f_a}$$



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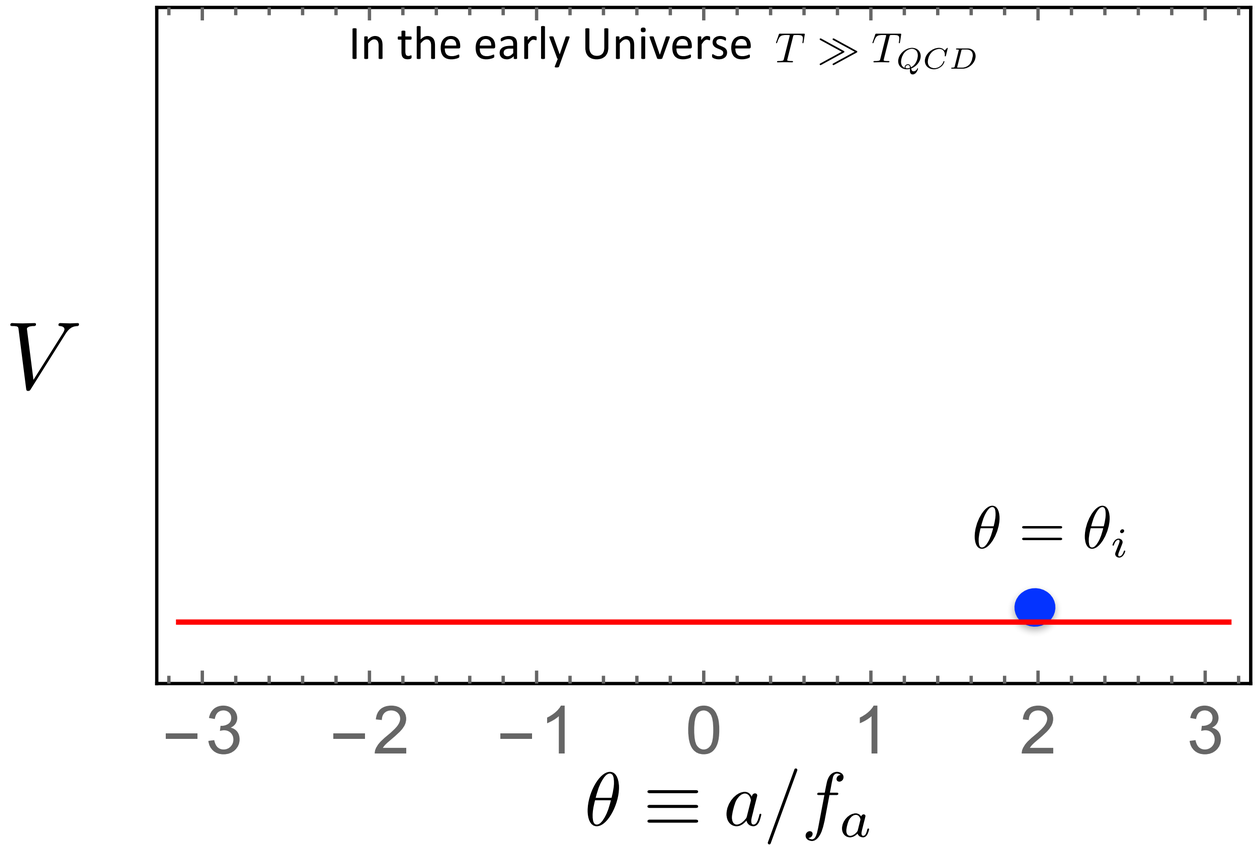
Quality problem

- Why does axion the very flat potential when we turn off the QCD interaction?

A built-in mechanism and the prediction

Mis(re)alignment mechanism: Preskill et al, 1983; Abbott, Sikivie, 1983; Dine, Fishler, 1983;



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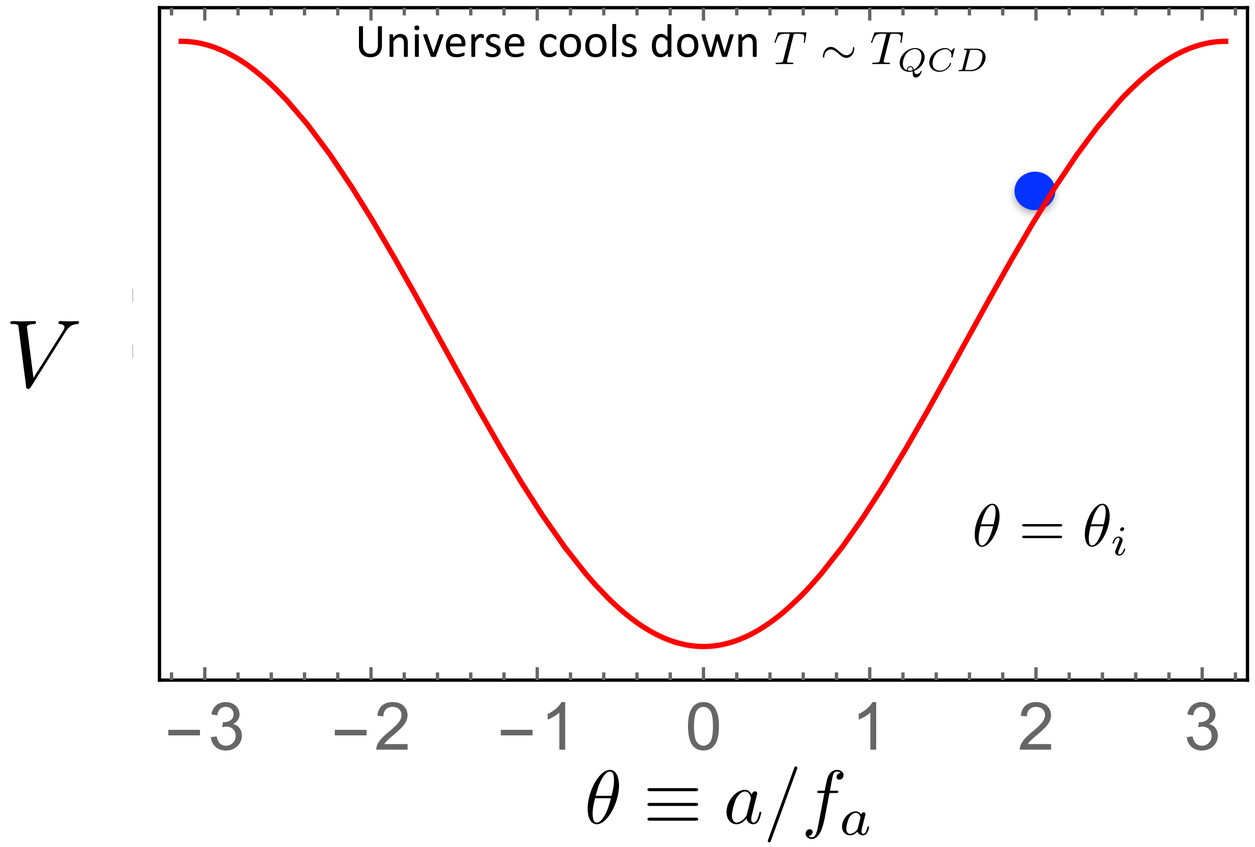

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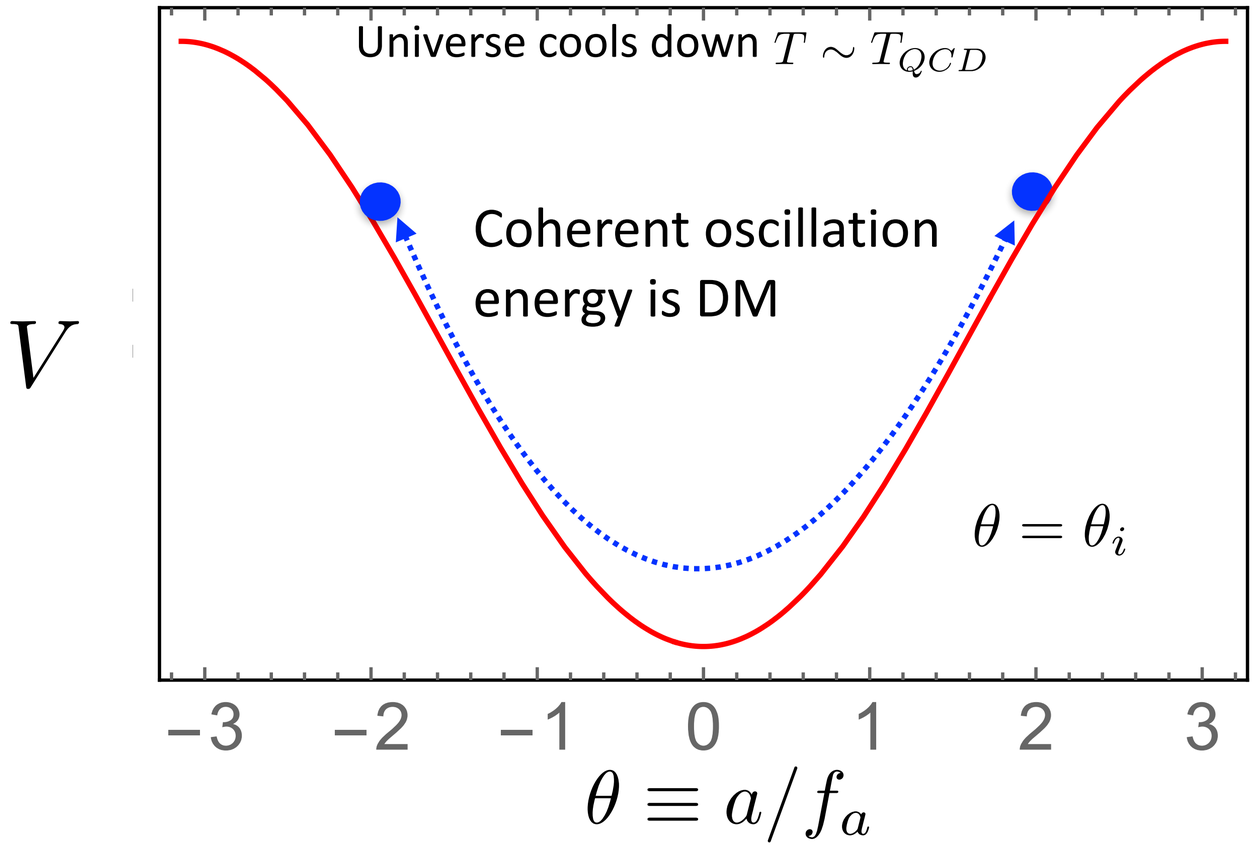

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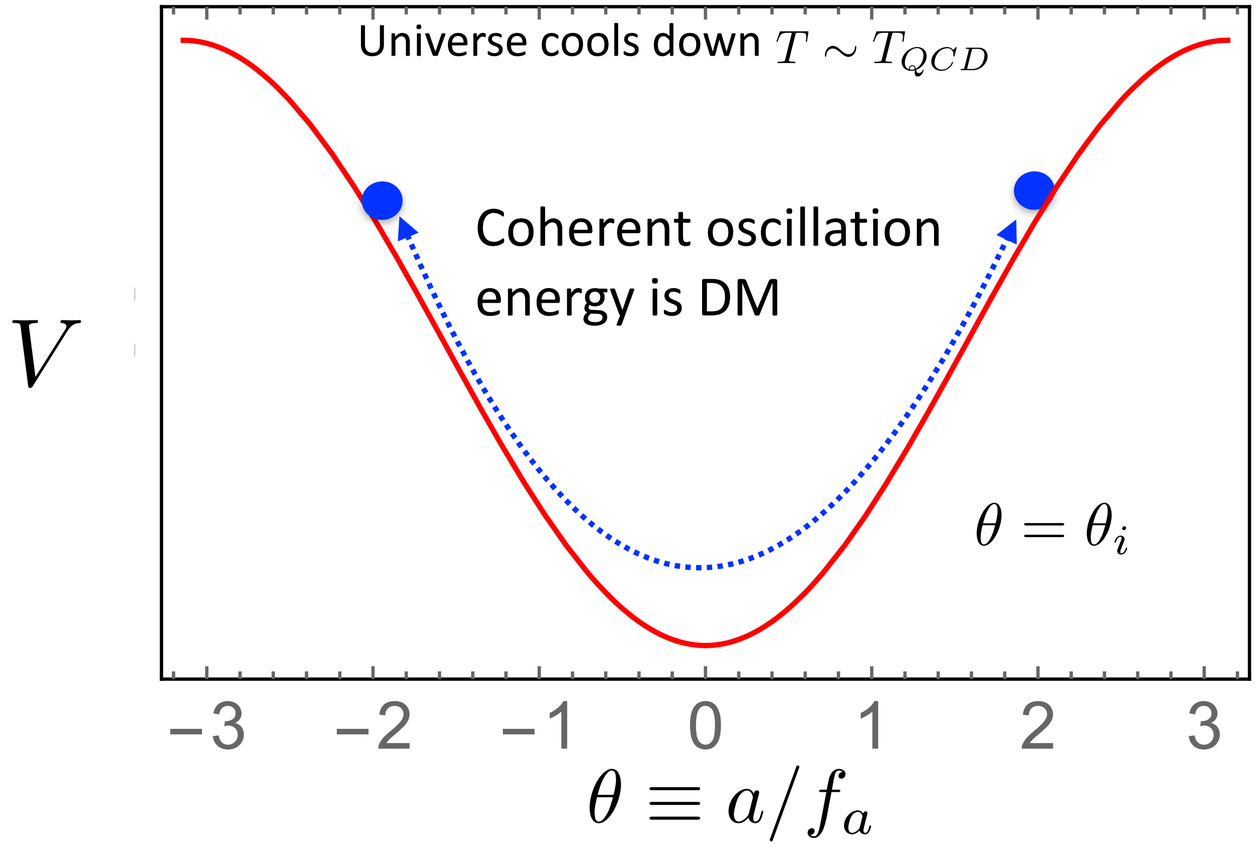
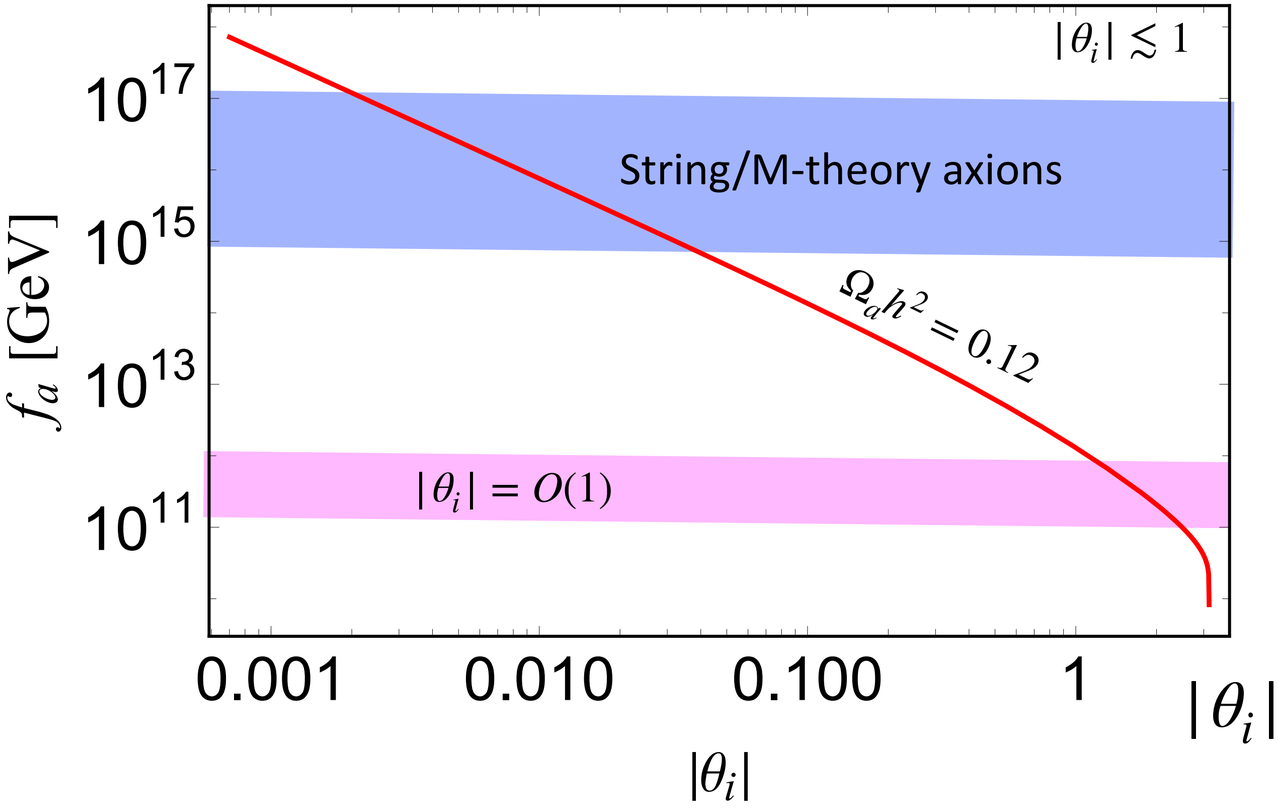


The axion abundance



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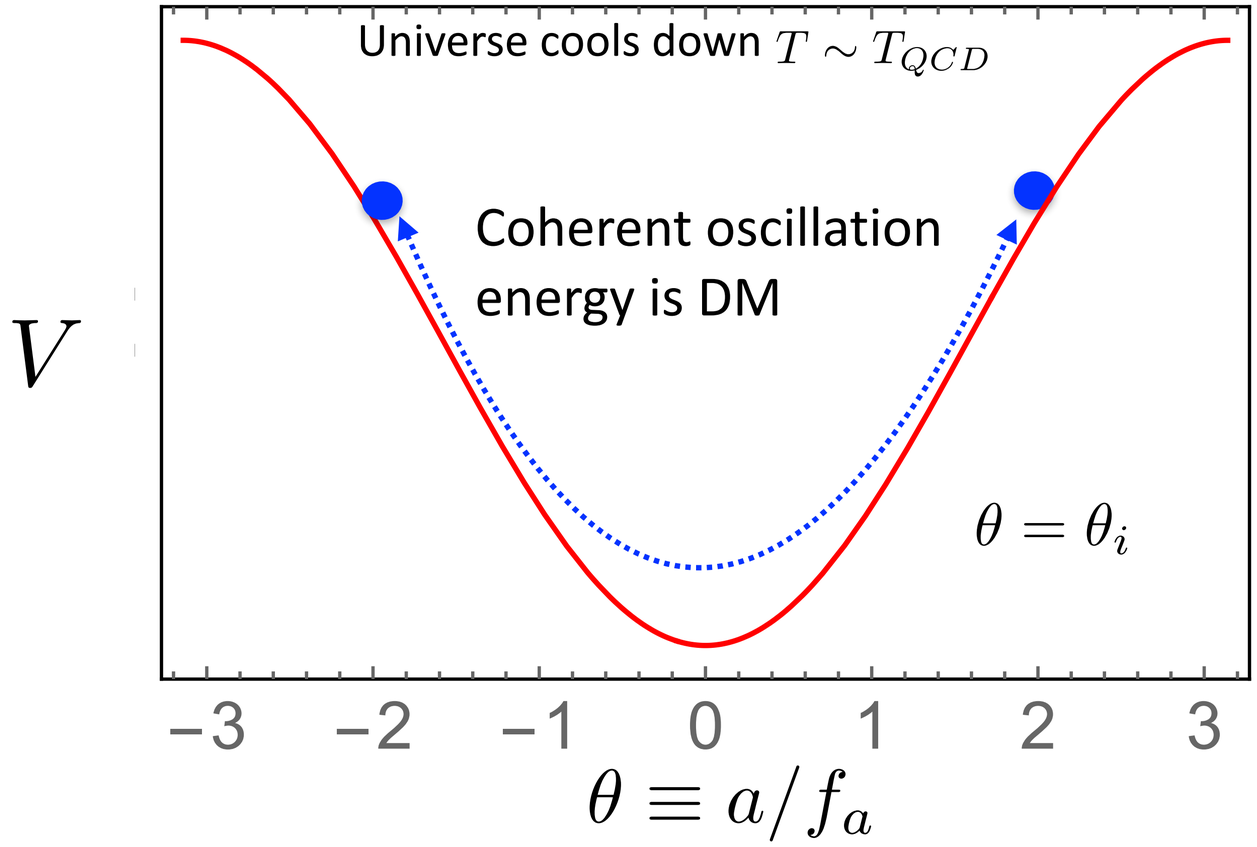

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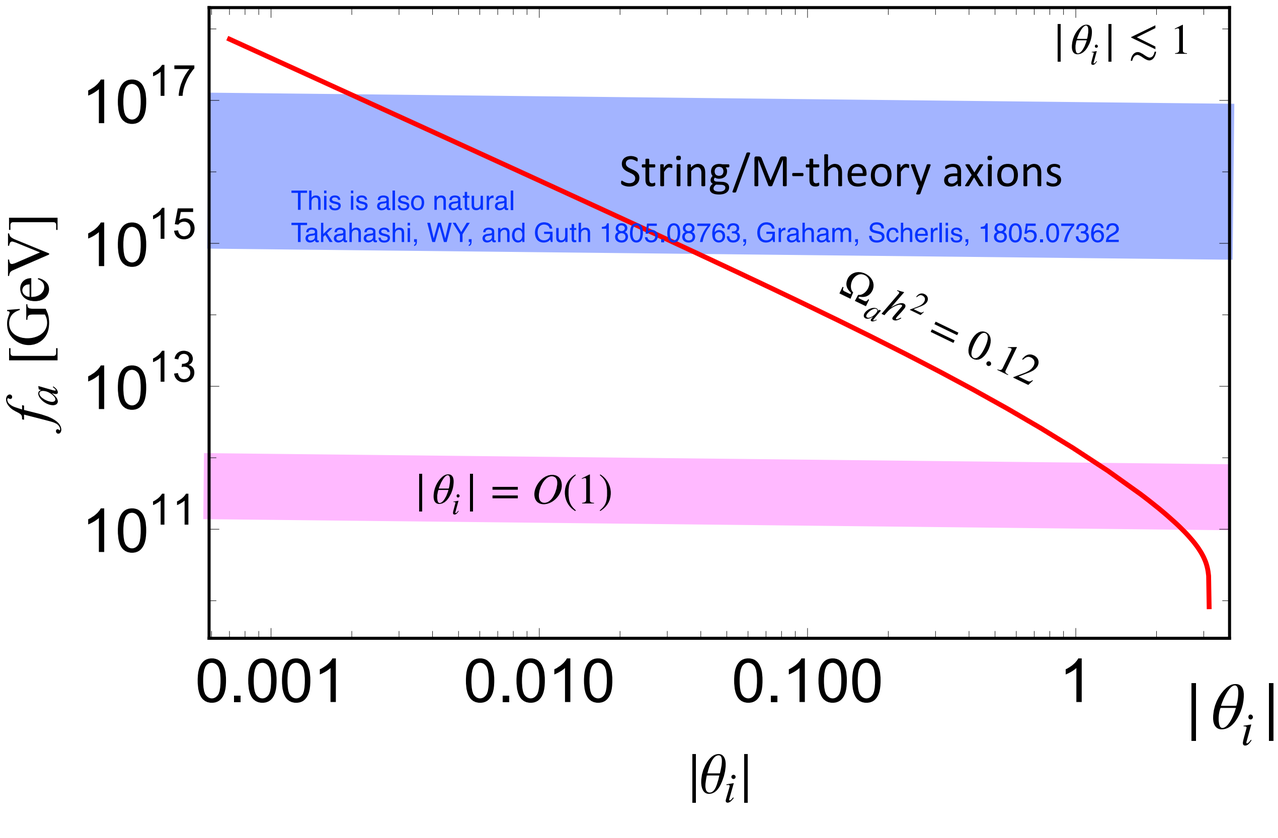

Axion couplings

Original Lagrangian

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$$-\frac{f_a^2}{2}(\partial_\mu\theta)^2$$

Effective Lagrangian in confining phase

$$\delta\mathscr{L}^{EFT,a}_{\rm int} \simeq$$
$$-\frac{\alpha}{4\pi}\frac{c_\gamma}{f_a}a\epsilon^{\mu\nu\delta\epsilon}F^{(\gamma)}_{\mu\nu}F^{(\gamma)}_{\delta\epsilon}$$
$$-g^p_\Psi a\bar{\Psi}\gamma_5\Psi$$
$$-g_d a F_{\mu\nu}\bar{N}\sigma_{\mu\nu}\gamma_5 N$$
$$-g^s_N a\bar{N}N$$
$$-V_{\rm QCD}[a]$$

$\rightarrow$

EFT with background EM fields and (non-relativistic) fermions

$$-g_{a\gamma\gamma}a\mathbf{E}\cdot\mathbf{B}$$
$$-g_\Psi\vec{\partial}a\cdot\vec{\sigma}_\Psi$$
$$-g_d a\mathbf{E}\cdot\sigma_N$$
$$-a g^s_N\frac{\rho_{\rm N}}{m_N}$$
$$-\frac{(80MeV)^4}{2f_a^2}a^2$$

Also exist for non-QCD axion

Special for **QCD** axion

How do we know if it is QCD axion?

Original Lagrangian

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Effective Lagrangian in confining phase	EFT with background EM fields and (non-relativistic) fermions	
$-\frac{\alpha}{4\pi}\frac{c_\gamma}{f_a}a\epsilon^{\mu\nu\delta\epsilon}F^{(\gamma)}_{\mu\nu}F^{(\gamma)}_{\delta\epsilon}$	$-g_{a\gamma\gamma}a\mathbf{E}\cdot\mathbf{B}$	Also exist for non-QCD axion
$-g^p_\Psi a\bar\Psi\gamma_5\Psi$	$-g_\Psi\vec\partial a\cdot\vec\sigma_\Psi$	Also exist for non-QCD axion
$-g_d aF_{\mu\nu}\bar N\sigma_{\mu\nu}\gamma_5 N$	$\rightarrow\quad -g_d a\mathbf{E}\cdot\sigma_N$	Special for **QCD** axion
$-g^s_N a\bar N N$	$-ag^s_N\frac{\rho_{\rm N}}{m_N}$	Special for **QCD** axion
$-V_{\rm QCD}[a]$	$-\frac{(80MeV)^4}{2f_a^2}a^2$	Special for **QCD** axion

$$\delta\mathscr{L}^{EFT,a}_{\rm int}\simeq$$

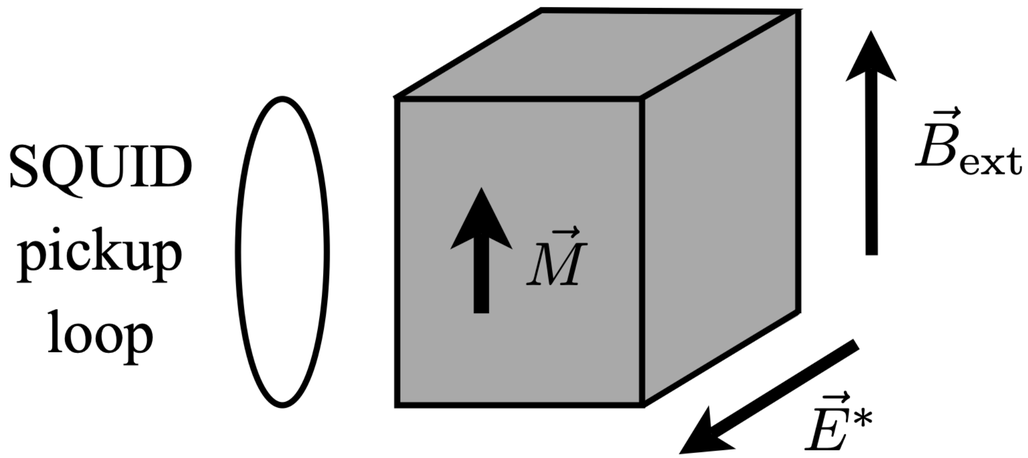
Probing Oscillating Nucleon EDM: CASPEr-electric

Budker, et al, 1306.6089

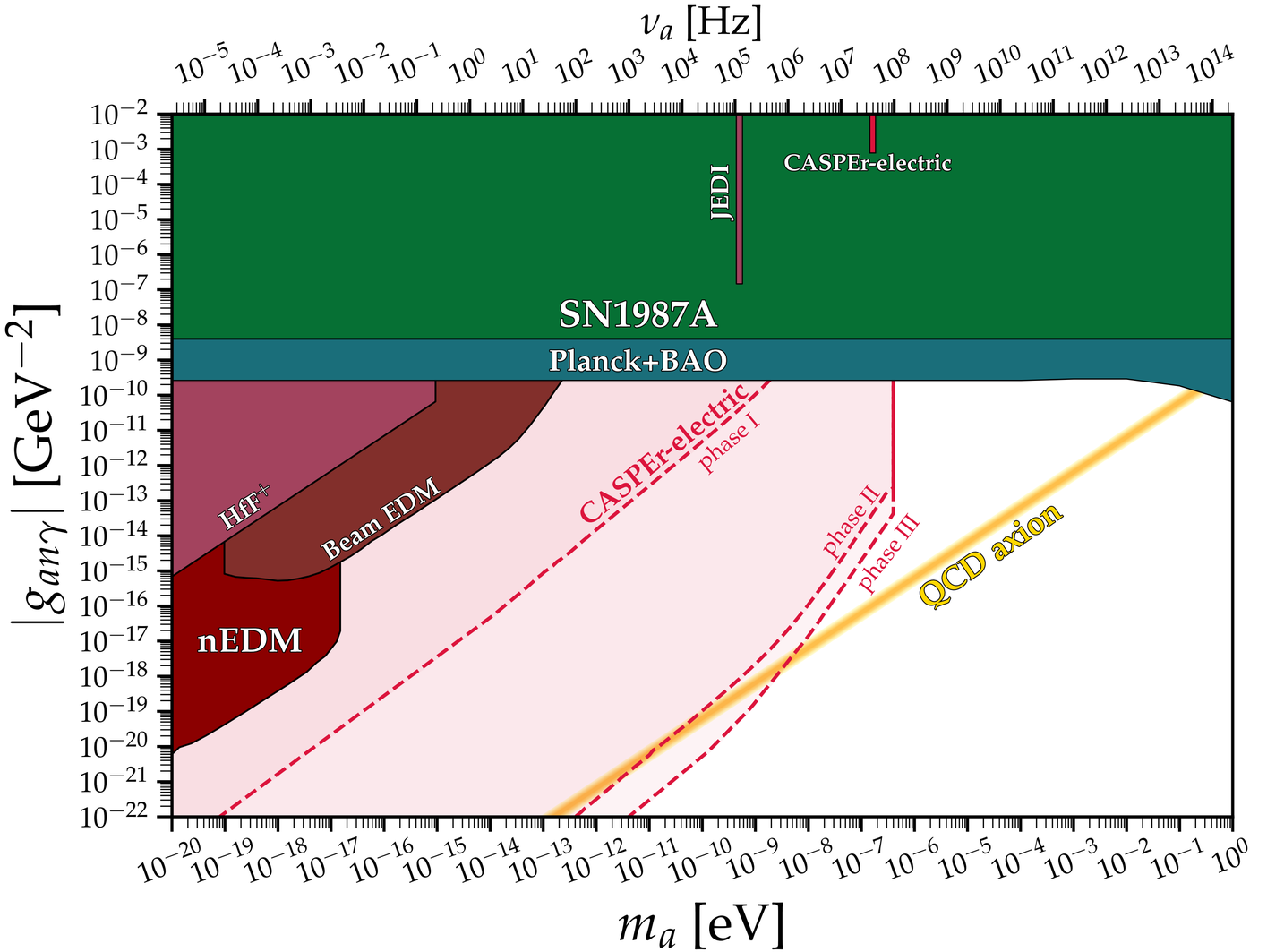
Scanning $\vec{B}_{\rm exp}$ to find the m_a with $\vec{M}$ precession frequency = axion oscillation frequency

$$\mathscr{L}_{\rm eff} \supset g_{an\gamma} a F_\gamma^{\mu\nu} \bar{N} \sigma_{\mu\nu} \gamma_5 N$$

$$+ \quad a = \frac{\sqrt{2\rho_{\rm DM}}}{m_a} \cos[m_a t]$$



a la, NMR



Very heavy dark matter beyond particle

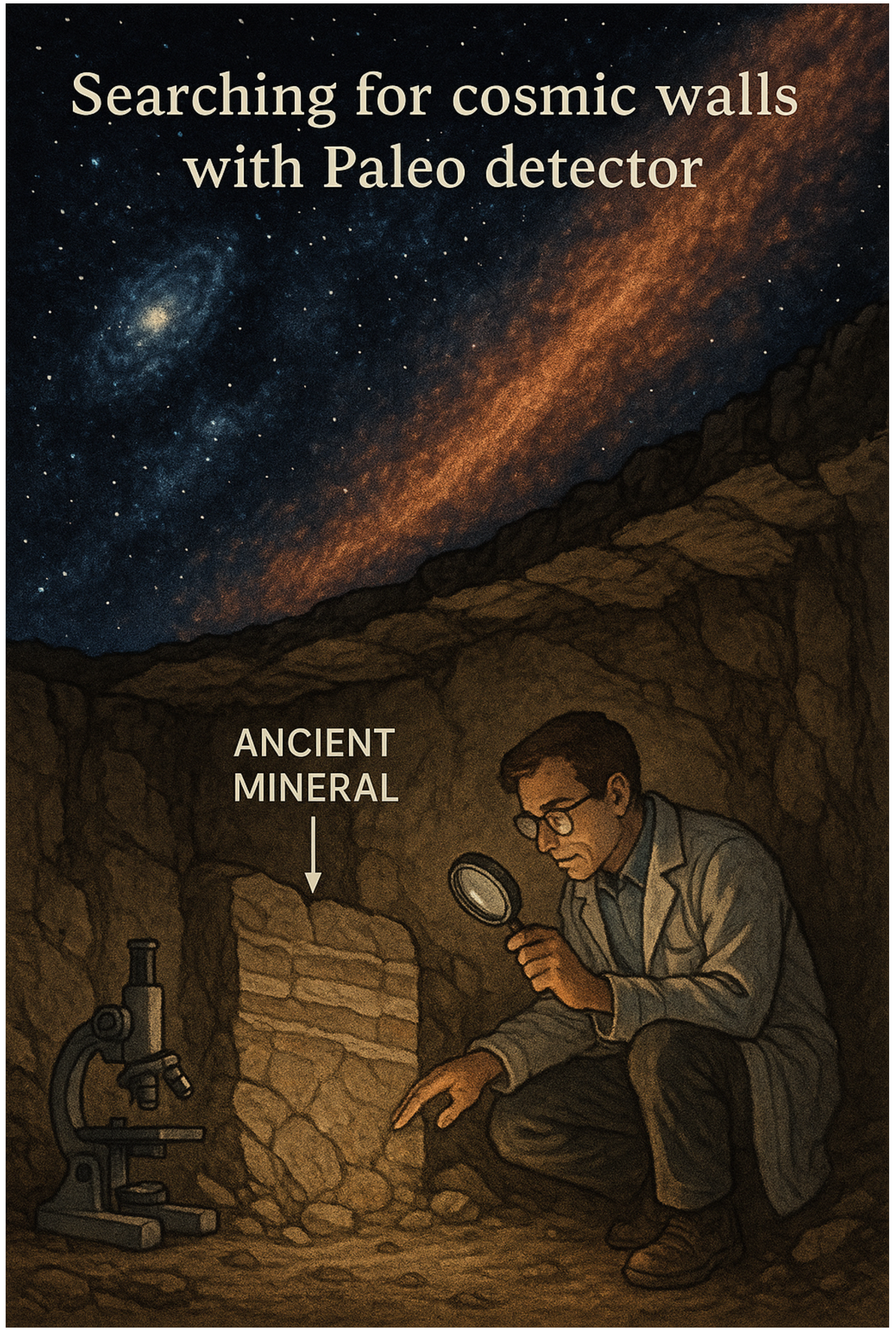
Stability by other reasons

Primordial blackholes,
quark nuggets, Q-balls,
topological defects (my focus)
etc.

- 2. Searching for cosmic walls with Paleo detector

  - WY,2505.15764

Strictly speaking, cosmic walls belong to a wide sense of dark matter.
It cannot explain the total dark matter.



Cosmic walls

Production mechanism of cosmic walls

- Z_2 phase transition Kibble:1976sj,Vilenkin:1984ib,Vilenkin:2000jqa
- Axions with large inflationary fluctuations Gonzalez:2022mcx,Kitajima:2023kzu
- Negative Higgs portal to Z_2 Yin:2024pri

} **Domain wall.**

- **See WY,2505.15764**

- First order phase transition etc

Bubble wall

- **This talk**

How to meet the walls?

- **Domain wall**: always O(1) per Hubble horizons
- **Bubble wall**: Passing through any point but only instantly.
- Meeting cosmic walls today is **extremely rare.**

Efficient search of Walls is mostly via indirect detection

- Gravitational effects, detected!? Zeldovich:1974uw,Vilenkin:1984ib NANOGrav:2023gor,Kitajima:2023cek,
- CMB Birefringence, detected!? Takahashi:2020tqv,Lee:2025yvn

See also GNOME direct detection experiment of special domain wall scenarios (number $\gg$ O(1) per horizon)

Masia-Roig:2019hsy,GNOME:2023rpz,Pospelov:2012mt

My proposal

- **Paleo-detector can directly detect the cosmic walls who pass through the Earth only O(1) time/Gyr.**

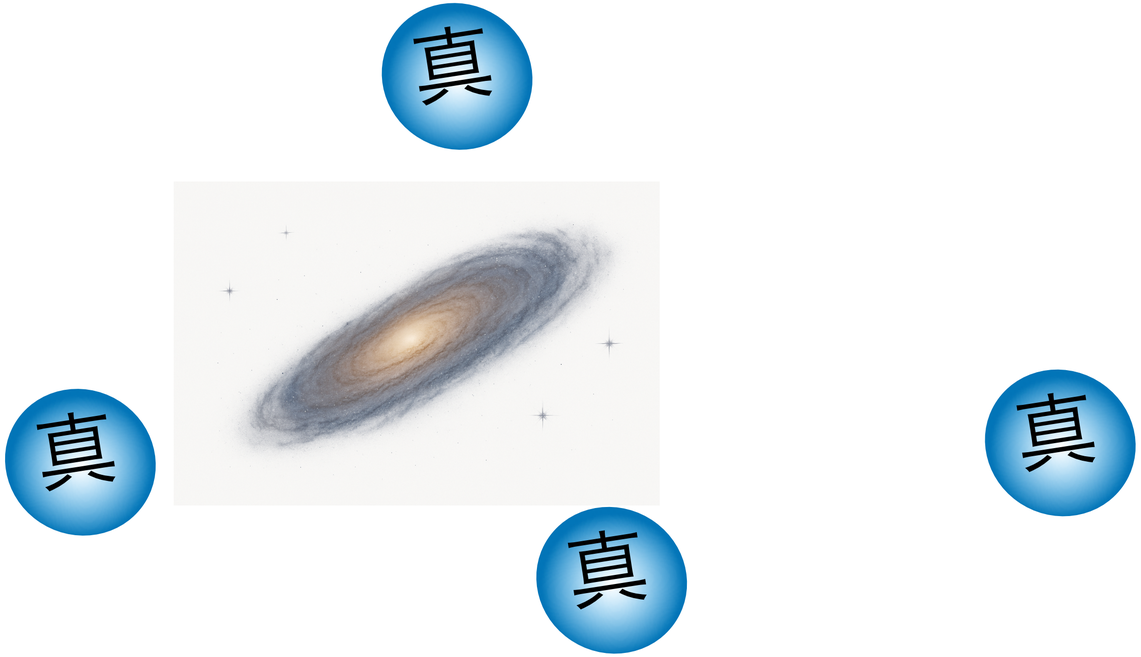
This is perhaps the only way for the direct detection of wall.

Late-time 1st-order phase transition

False vacuum

(疑真空)

$< \phi > = 0$

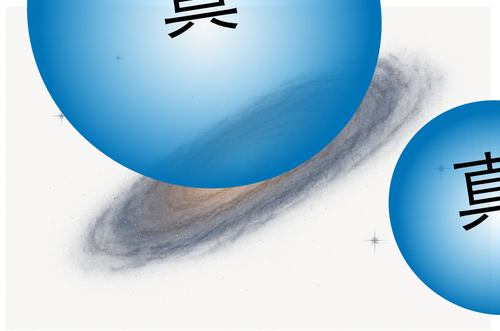


Late-time 1st-order phase transition

False vacuum

(疑真空)

$< \phi > = 0$



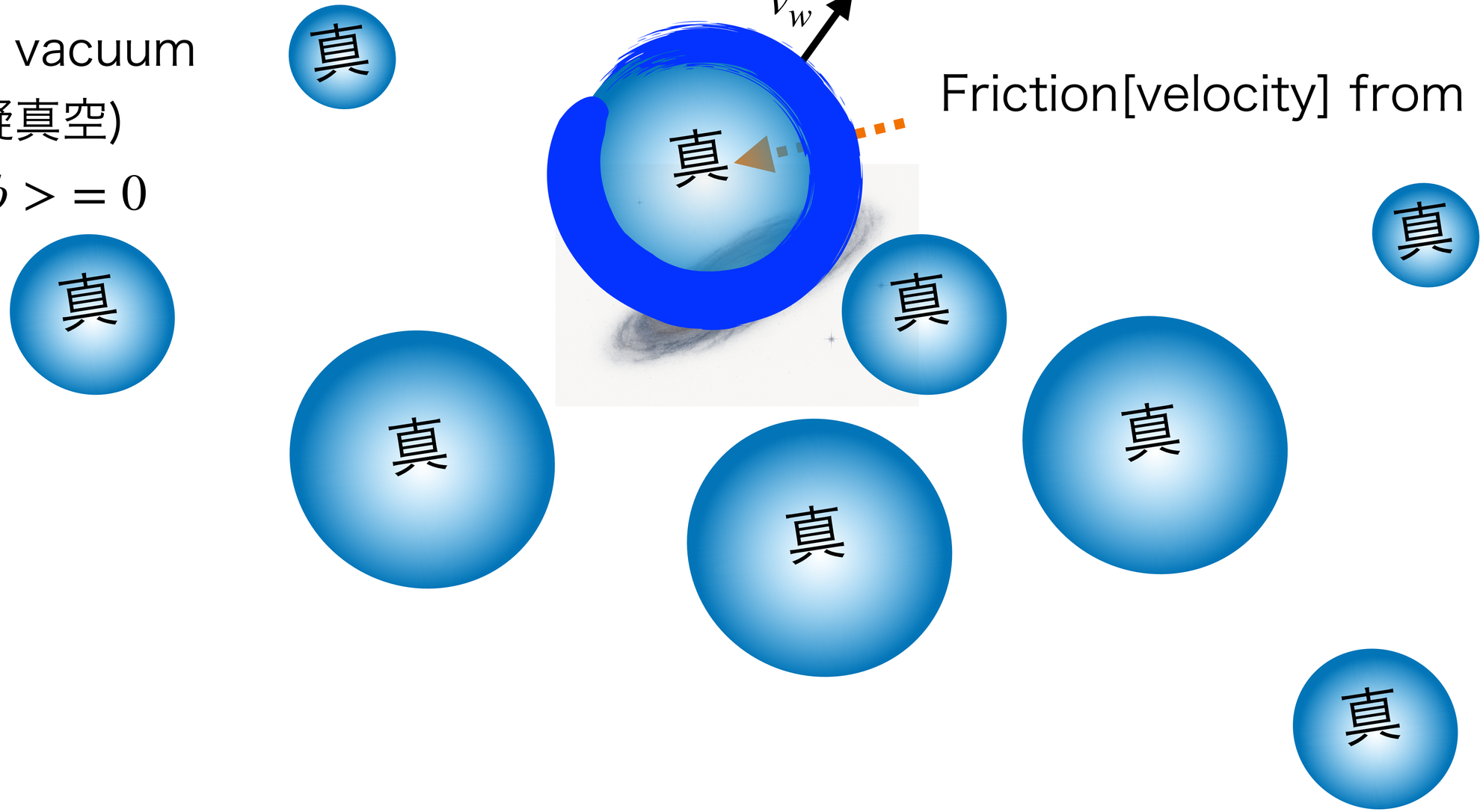
Wall reaches a typical velocity, v_w

Pressure: $\Delta V = V_{\text{false}} - V_{true}$

v_w

False vacuum
(疑真空)
$< \phi > = 0$

Friction[velocity] from plasma



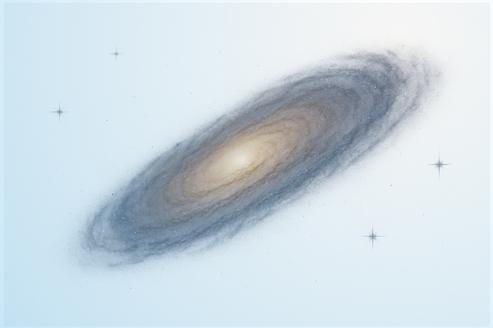
Universe filled with true vacuum

True vacuum

(真真空)

$< \phi > = v$

真

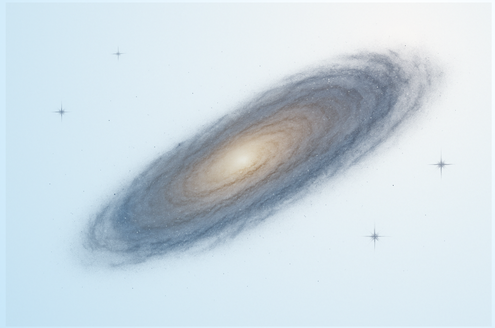


$< \phi > = v$

Universe filled with true vacuum

True vacuum
(真真空)
$< \phi > = v$

真



$< \phi > = v$

The bubble wall goes through Milky_Way/ Solar_system/Earth by just 1 ($\neq 0$) time.

"Domain wall problem":

$$tension \sim m_\phi v^2 < \mathrm{MeV}^3$$

Perturbativity:

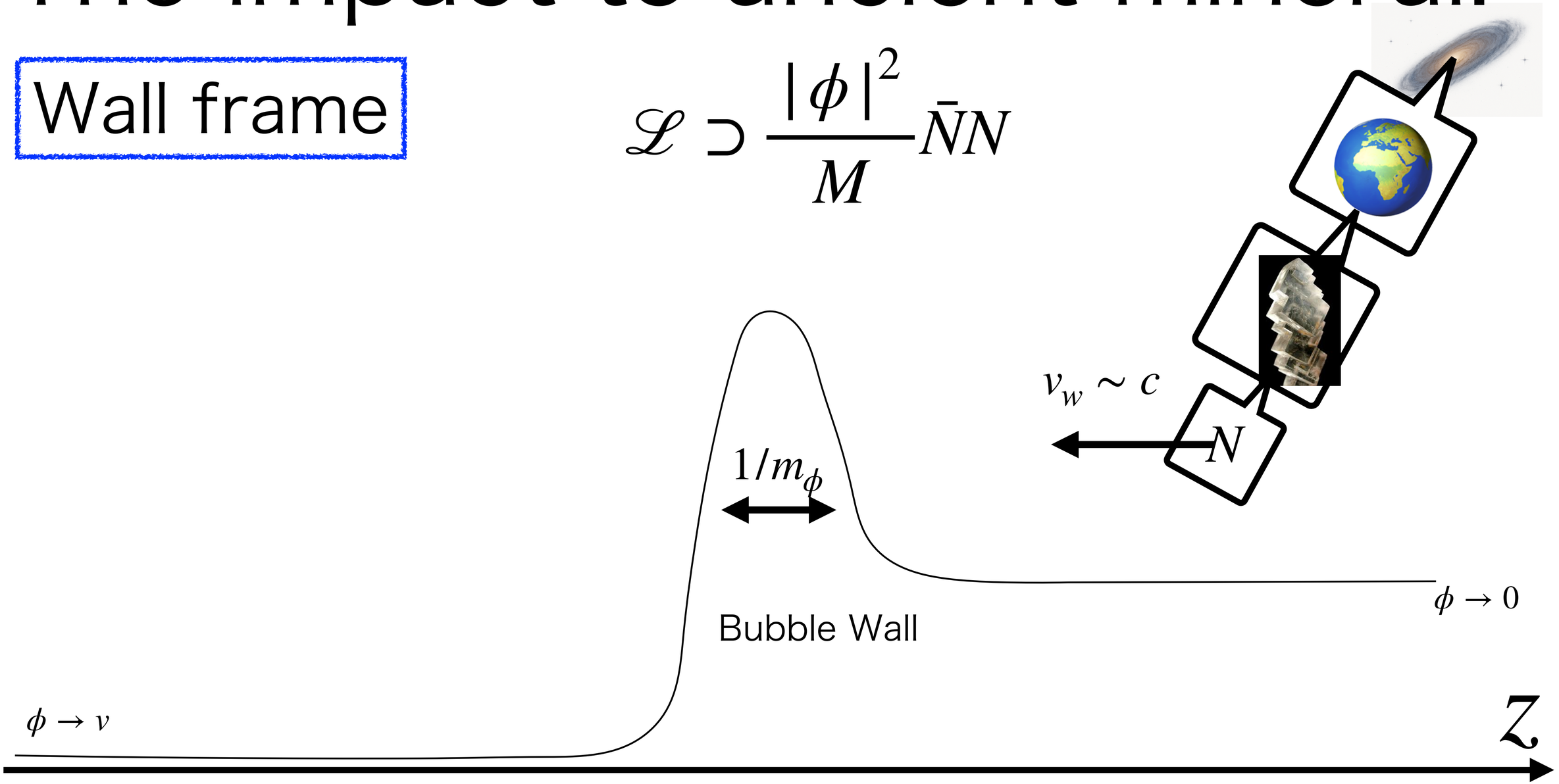
$$m_\phi \lesssim v$$

$$\Rightarrow \quad m_\phi \lesssim MeV$$

The impact to ancient mineral.

Wall frame

$$\mathscr{L} \supset \frac{|\phi|^2}{M}\bar{N}N$$

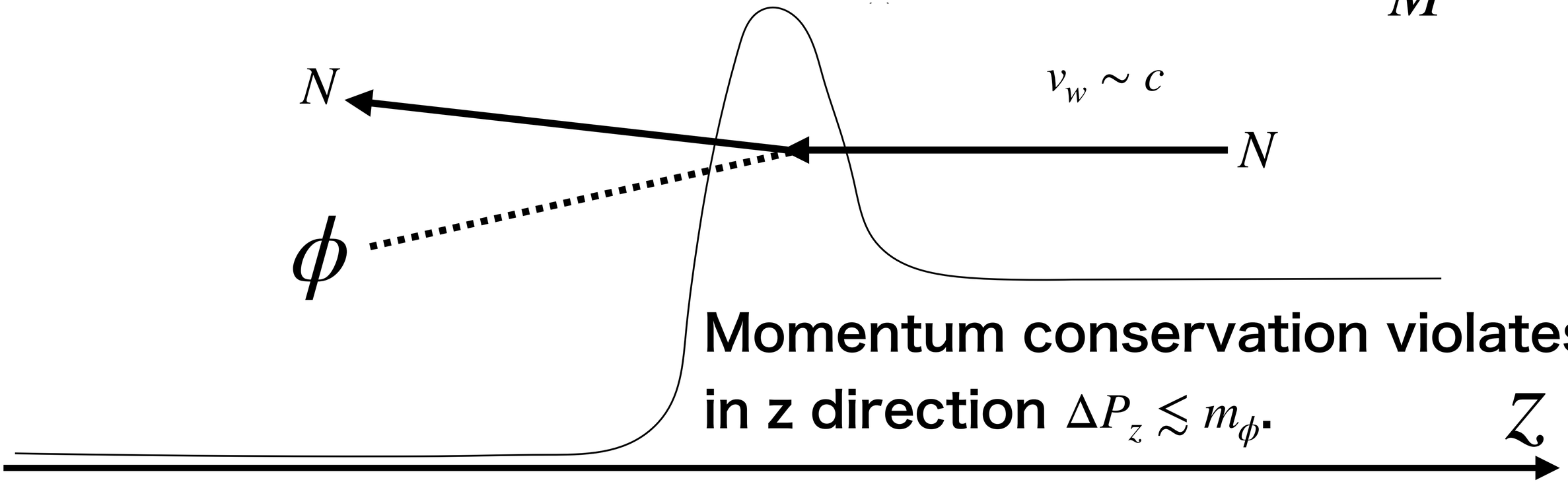


One can estimate the dynamics with WKB $\because$ $m_\phi \lesssim MeV \ll \mathrm{GeV} \lesssim k_z$

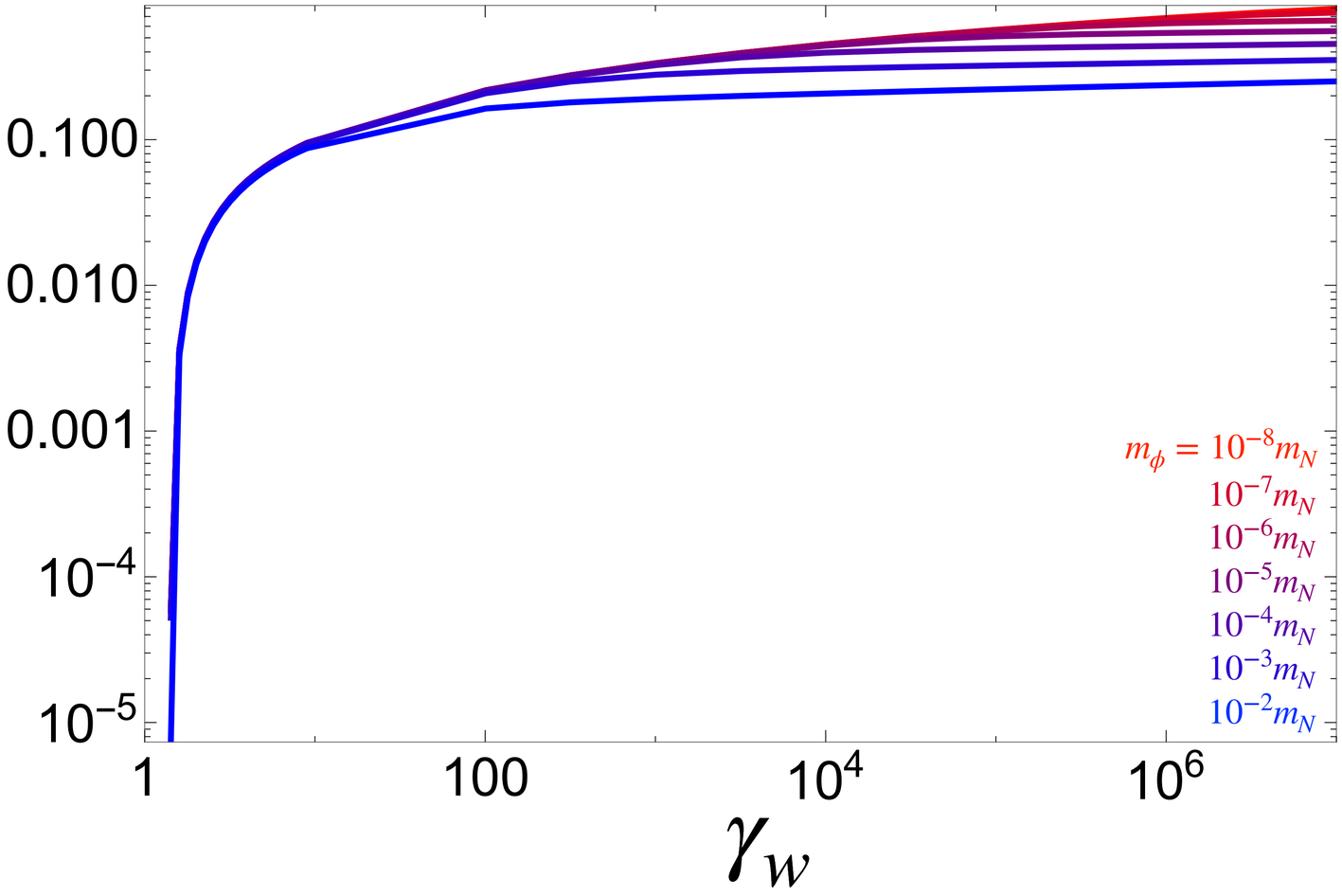
See Azatov, Nagels, Vanvlasselaer and WY, 2406.12554
for a similar calculation in the context of dark matter production.

$$P_{N\to N\phi} = \frac{1}{2}\sum_{spins}\int \frac{d^3p_x f d^3p_\phi}{(2\pi)^3 2p_f^0 2p_\phi^0 2p_i^0}\delta^3(p_f+p_\phi-p_i)\left|\int dz e^{i\Delta p_z z} f'(\langle\phi(z)\rangle)\right|^2 |\mathcal{M}|^2$$

$$\mathscr{L} \supset f(\phi)\bar{N}N = \frac{|\phi|^2}{M}\bar{N}N$$



Sensitive to very small coupling!

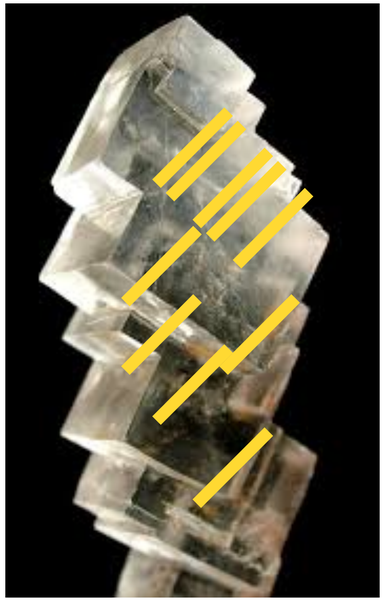


Reaction happens

$$P_{N\to N\phi} \times N \sim 10 \left(\frac{v}{\mathrm{MeV}}\right)^2 \left(\frac{10^8 \mathrm{GeV}}{M}\right)^2 \frac{N}{10^{24}}$$

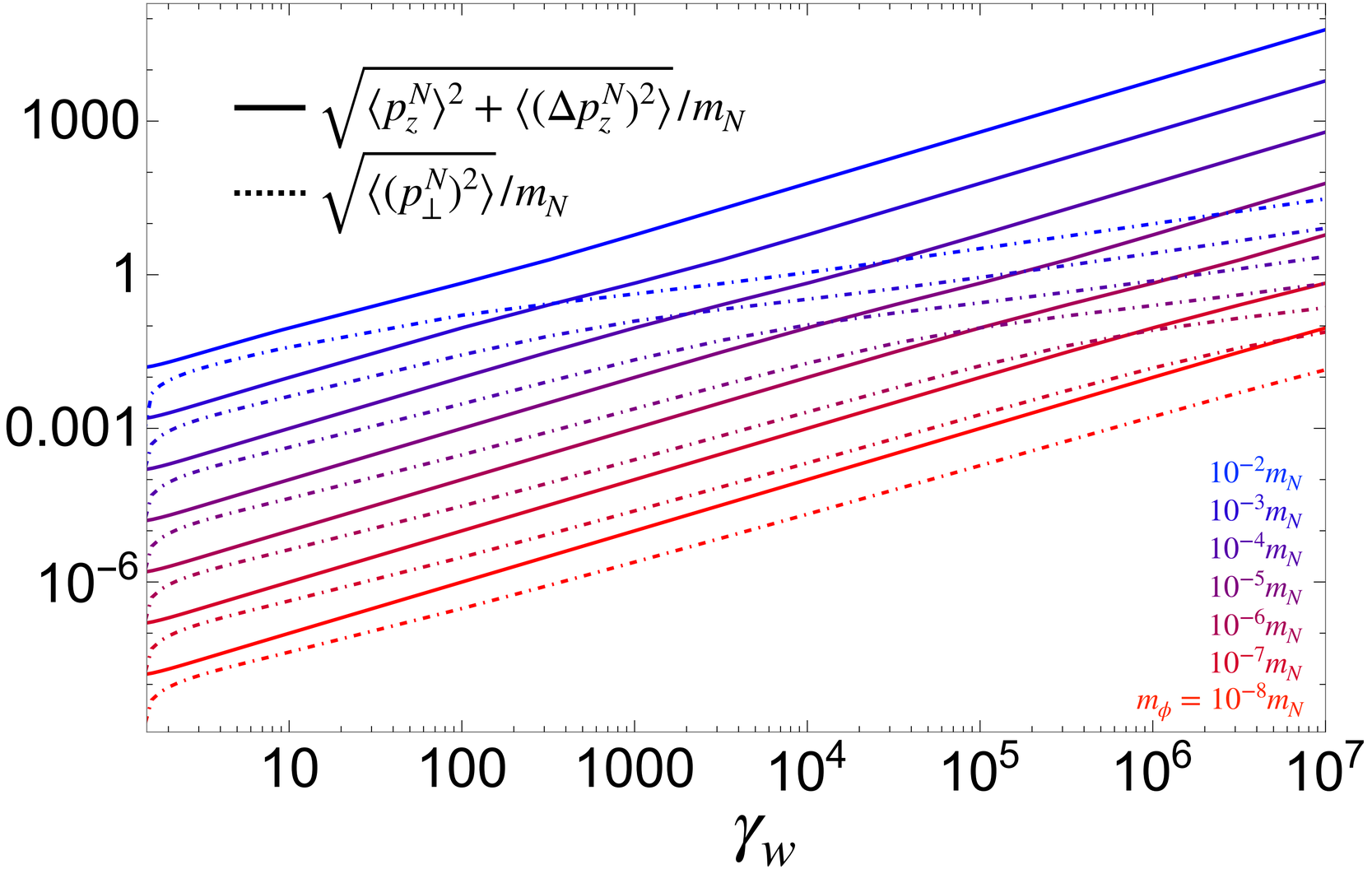
e.g. Signals

(for the ones longer than certain age)

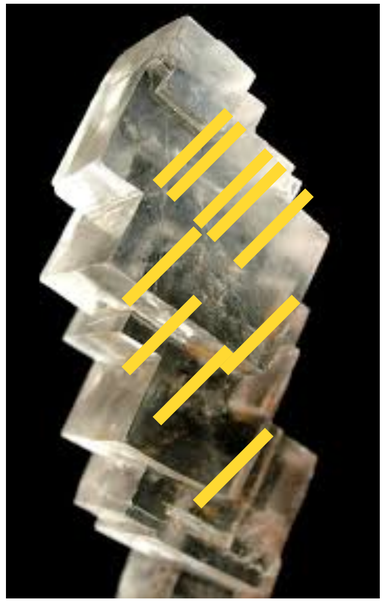


3D track distribution measure the wall velocity?

$$\Delta p_z \sim m_\phi \gamma_w$$

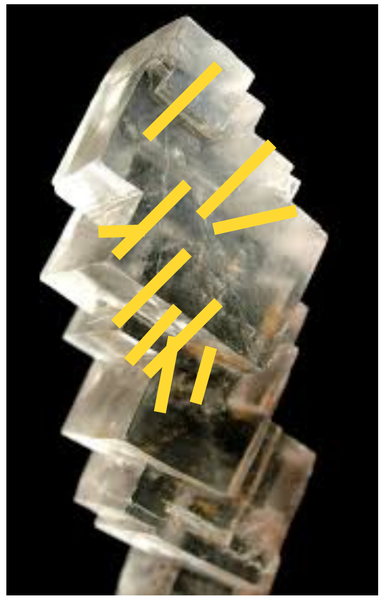


$\gamma_w \lesssim 2$ or $\gamma > 10$



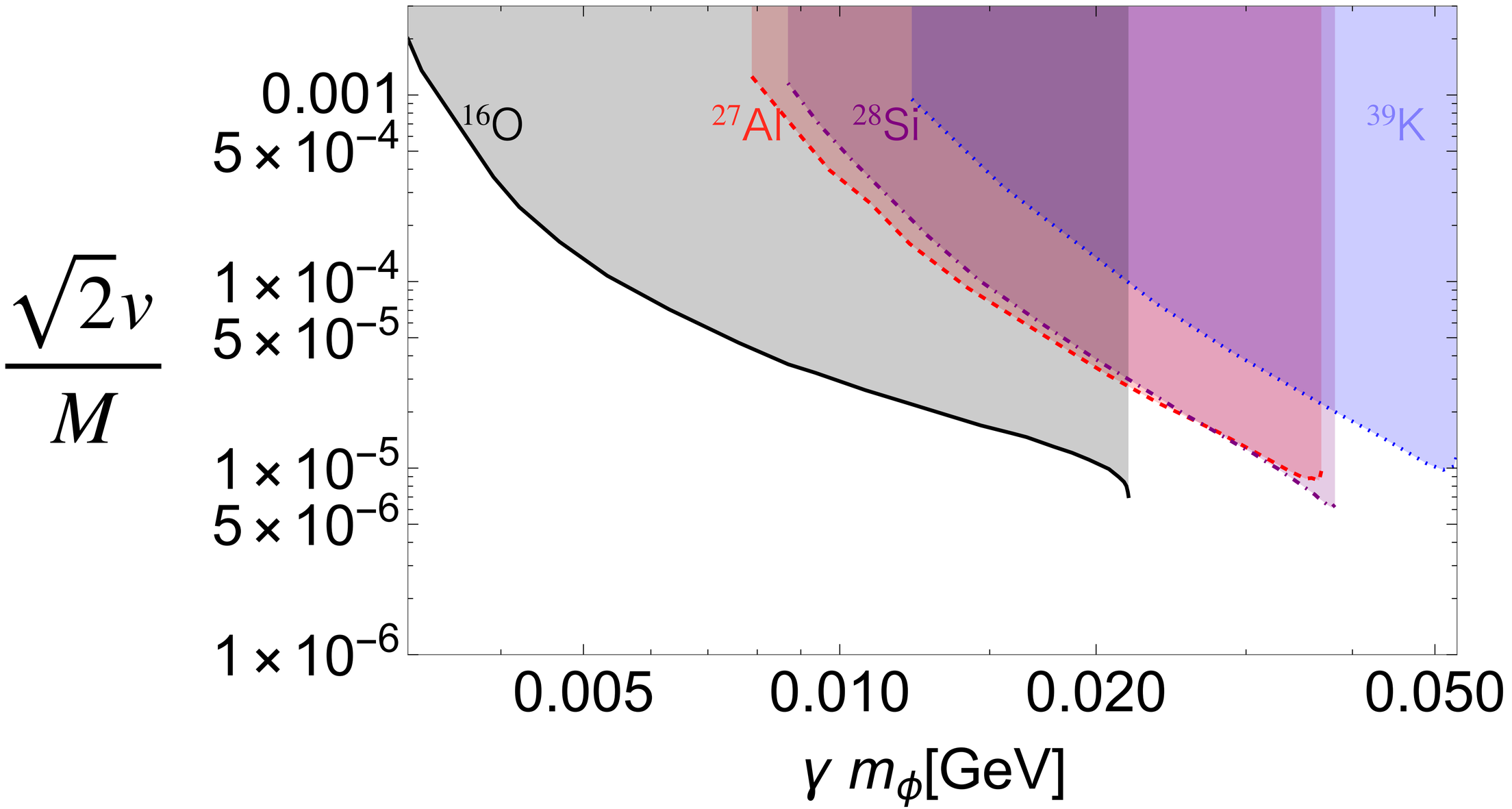
Mostly **perpendicular** to the wall

$\gamma \sim 2 - 10$



More random

Limit translated from the WIMP search result in Snowden-Ifft:1995zgn



Conclusions:

DM particle property remains puzzle.

- Many theoretical models and experimental technologies are proposed according to the particle theory.

- Paleo-detector can be unique to directly detect the cosmic walls that pass through Earth only O(1) time per Universe.
  - WY, 2505.15764

- The perhaps the first direct detection limit was derived.