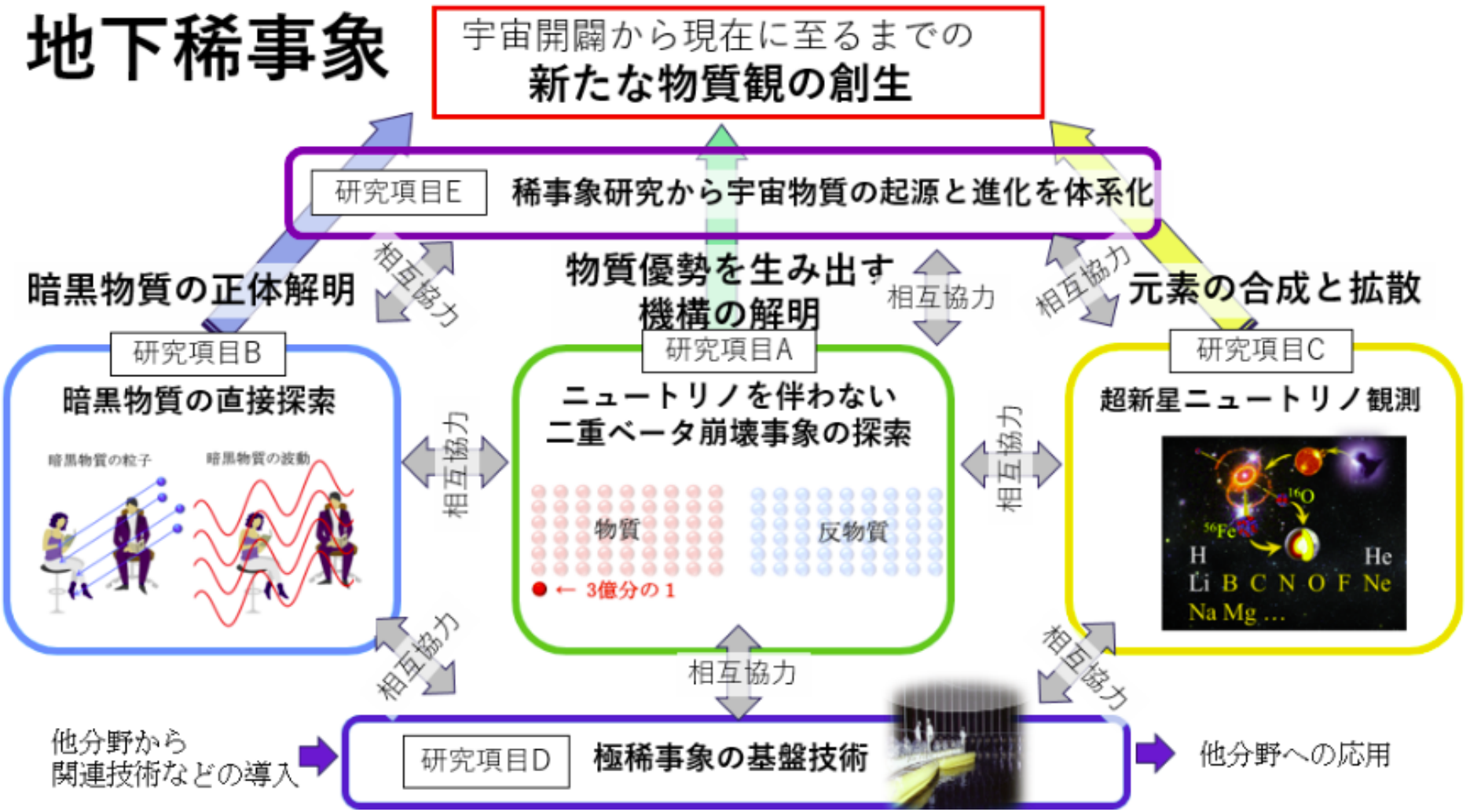
物質の起源と
初期宇宙の進化を
解き明かす理論研究

佐藤 亮介

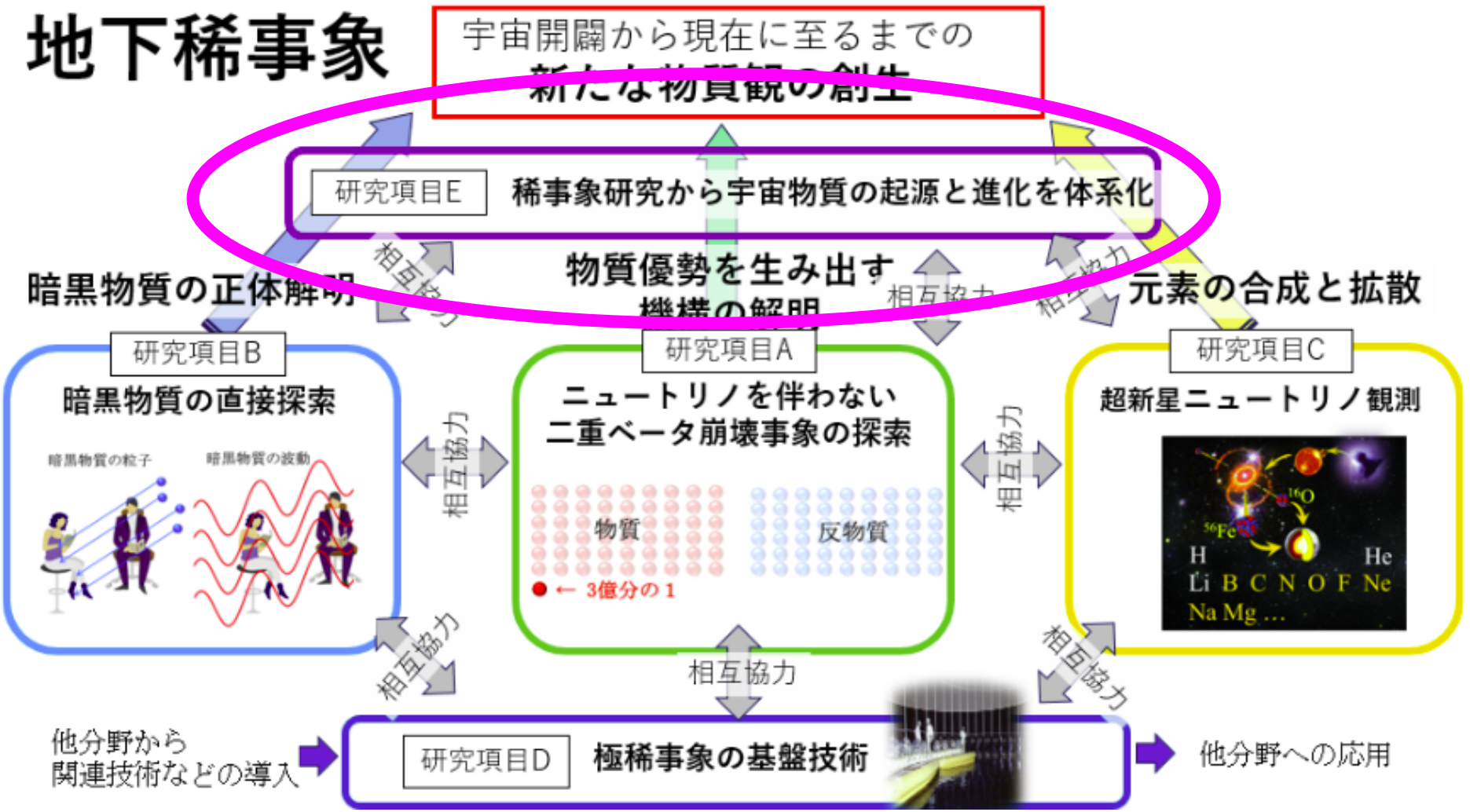
大阪大学
THE UNIVERSITY OF OSAKA

2025. 6. 26 @ 極稀事象で探る宇宙物質の起源と進化 領域研究会

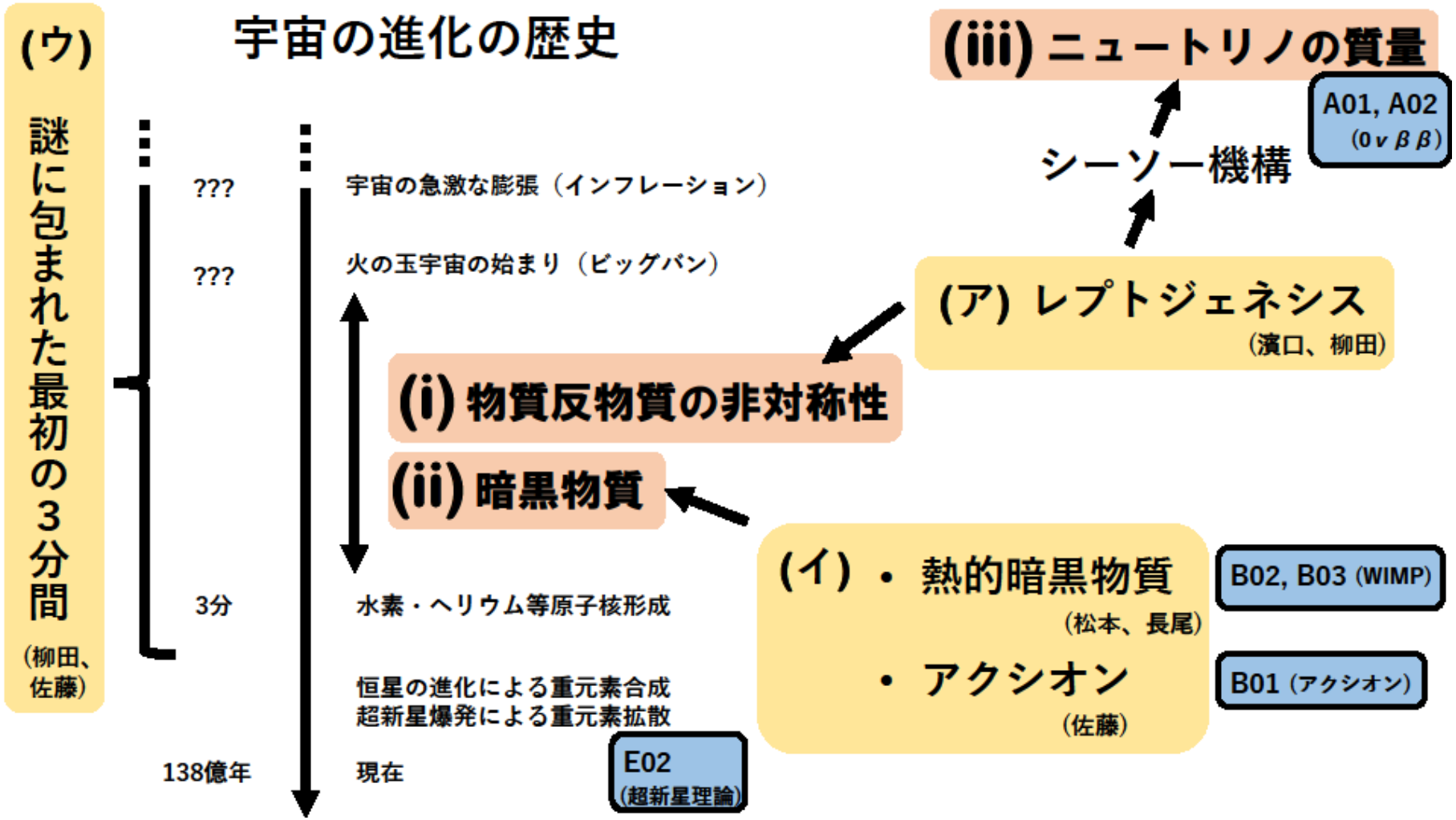
理論班の役割（E01班、 E02班）



理論班の役割（E01班、 E02班）

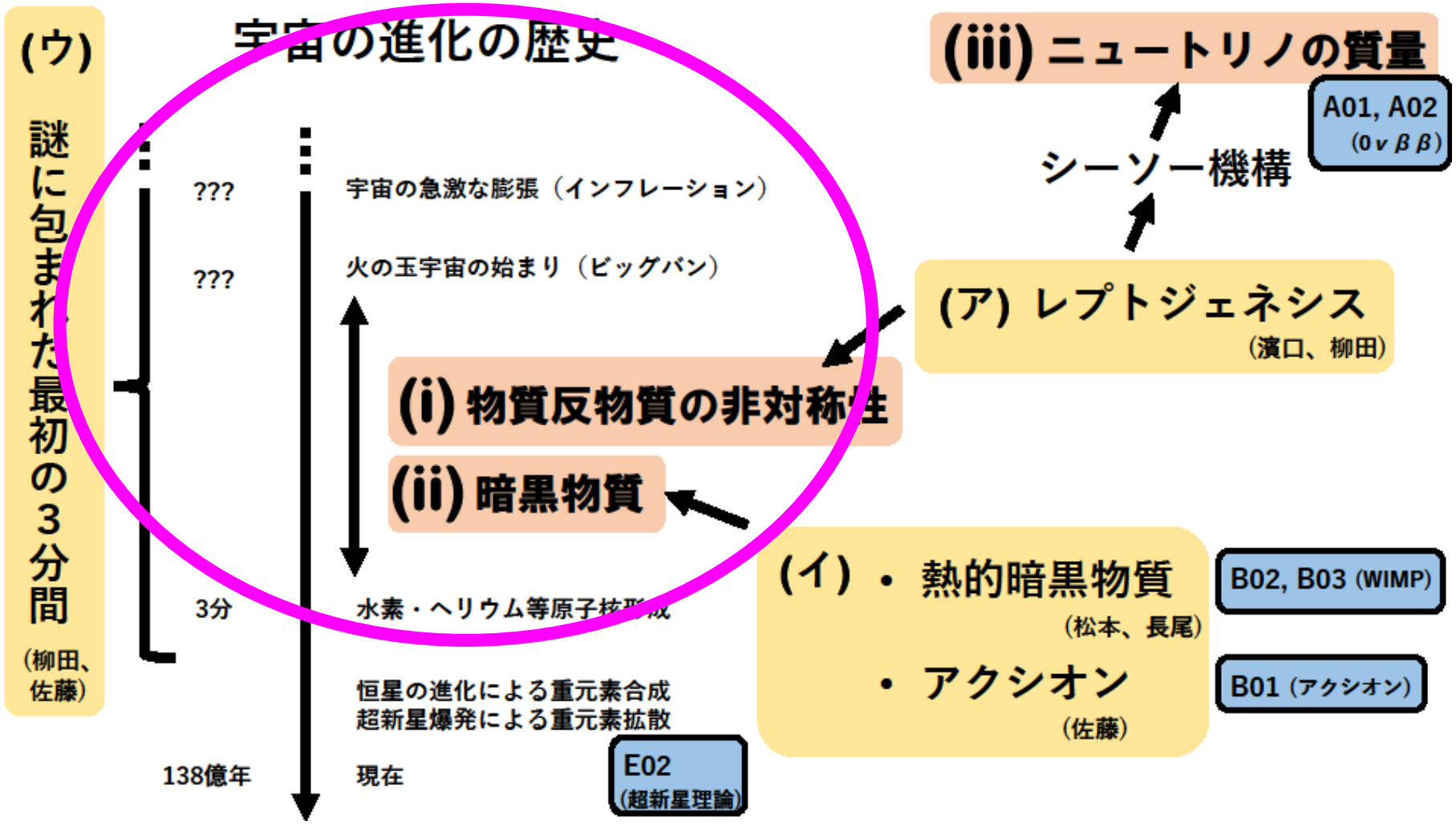


E01班の役割


(ウ)
謎に包まれた最初の3分間
(柳田、佐藤)
宇宙の進化の歴史
???
???
3分
138億年
宇宙の急激な膨張（インフレーション）
火の玉宇宙の始まり（ビッグバン）
水素・ヘリウム等原子核形成
恒星の進化による重元素合成
超新星爆発による重元素拡散
現在
E02
(超新星理論)
(i) 物質反物質の非対称性
(ii) 暗黒物質
(iii) ニュートリノの質量
A01, A02
(0νββ)
シーソー機構
(ア) レプトジェネシス
(濱口、柳田)
(イ)
• 熱的暗黒物質
(松本、長尾)
• アクシオン
(佐藤)
B02, B03 (WIMP)
B01 (アクシオン)

E01班の役割

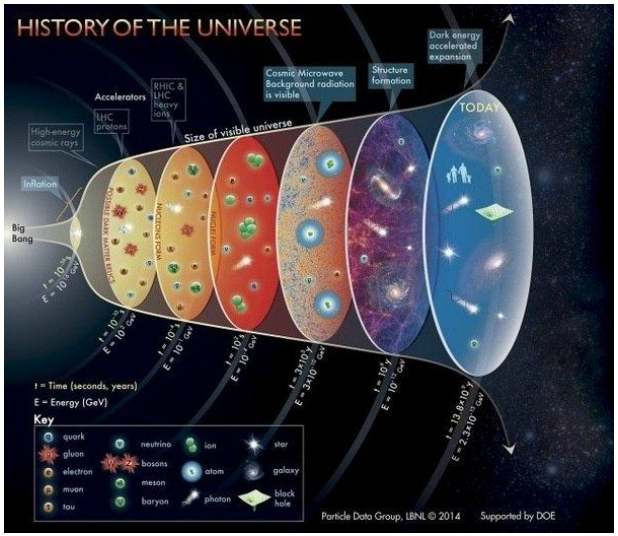
宇宙の歴史の初期の問題にアタックする

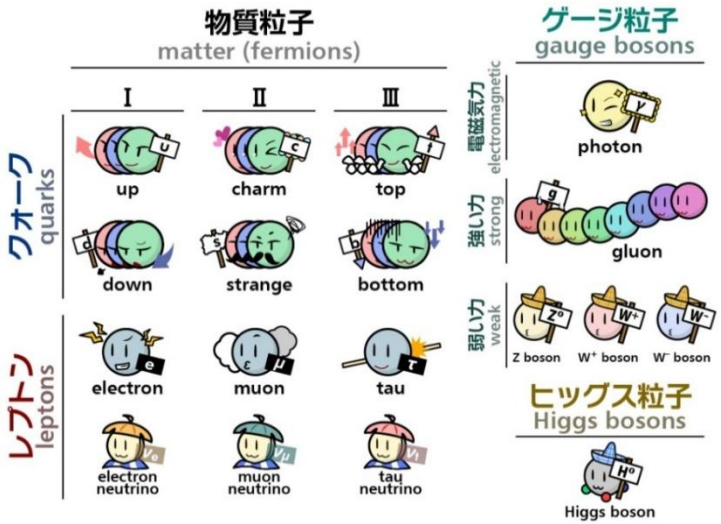


初期宇宙と素粒子

高温の初期宇宙（ビッグバン宇宙論）　→　すべてが素粒子レベルでバラバラ

宇宙の始まりを知るには素粒子が大事





1. **ニュートリノの質量の起源**は何か？
2. **暗黒物質の正体**は何か？なぜこの宇宙に存在するのか？
3. **物質と反物質の非対称性**はどのようにして生まれたのか？

標準模型では解けない重要な問題　→　**標準模型を超える物理**が必要！

Beyond the Standard Model

E01班のメンバー

（代表）佐藤亮介		大阪大学	統括・アクシオン
（分担）濱口幸一		東京大学	反物質消失の理論
（分担）松本重貴		東京大学IPMU	暗黒物質理論
（分担）長尾桂子		岡山理科大学	暗黒物質理論
（分担）柳田勉		東京大学IPMU	素粒子模型構築

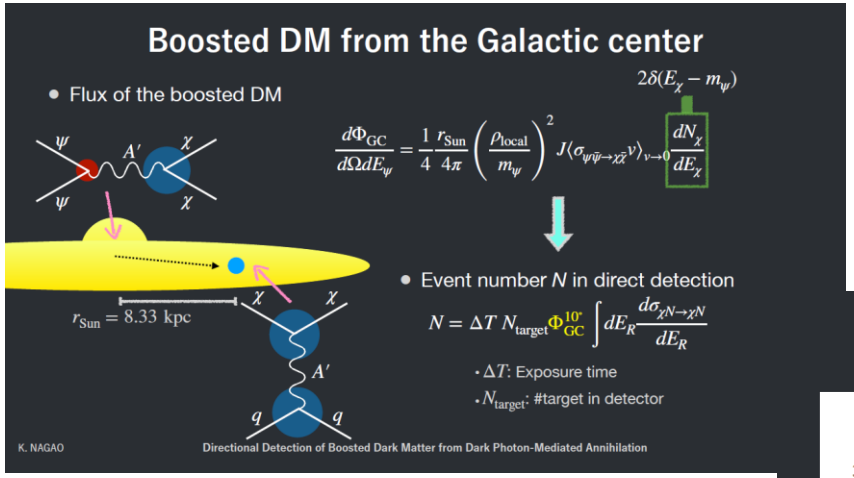
最近のE01班の研究（2024年4月～2025年6月）

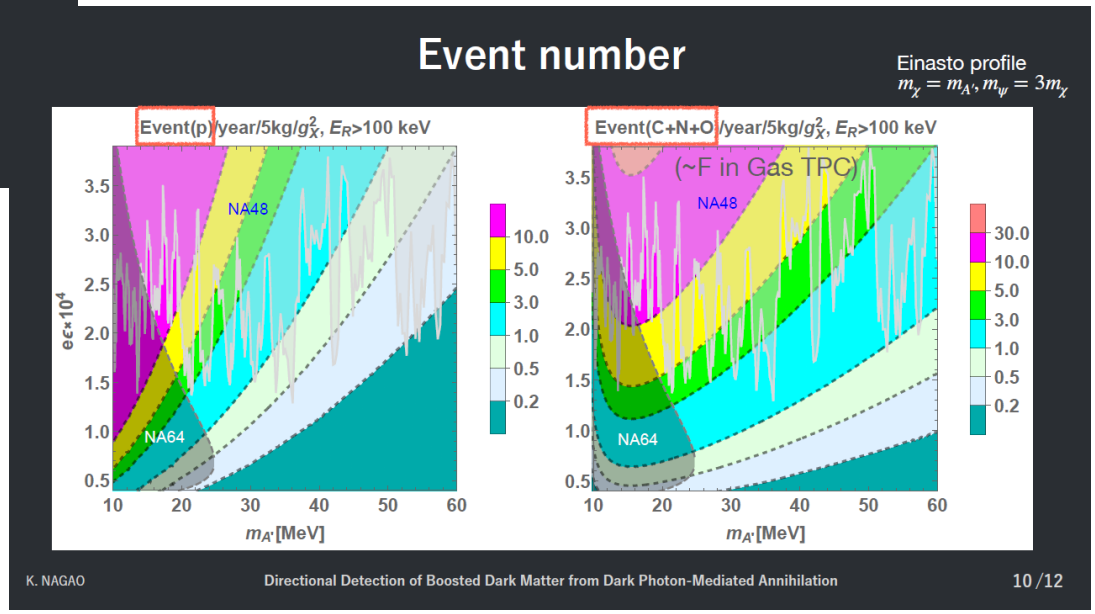
2404.03963, “Composite dark matter with forbidden annihilation”, T. Abe, R. Sato, T. Yamanaka
2404.06793, “Mediator decay through mixing with degenerate spectrum”, A. Kamada, T. Kuwahara, S. Matsumoto, Y. Watanabe, Y. Watanabe
2405.16222, “Proposal for a quantum mechanical test of gravity at millimeter scale”, Y. Cheng, J. Lin, J. Sheng, T. T. Yanagida
2406.19083, “Axion Detection Experiments Can Probe Majoron Models”, Q. Liang, X. P. Diaz, T. T. Yanagida
2407.11892, “A Generic Analysis of Nucleon Decay Branching Fractions in Flipped SU(5) Grand Unification”, K. Hamaguchi, S. Hor, N. Nagata, H. Takahashi
2407.18300, “Do neutrinos bend? Consequences of an ultralight gauge field as dark matter”, L. Visineli, T. T. Yanagida, M. Zantedeschi
2408.08355, “Model implementations of axion dark matter from kinetic misalignment“, C. Eroncel, R. Sato, G. Servant, P. Sorensen
2408.12146, “Three-zero texture of quark-mass matrices as a solution to the strong CP problem”, Q. Liang, R. Okabe, T. T. Yanagida
2408.12155, “Gauge U(1)B-L dark matter above the e-e+ threshold”, T. Hayashi, S. Matsumoto, Y. Watanabe, T. T. Yanagida
2409.06365, “Induced gravitational waves probing primordial black hole dark matter with the memory burden effect”, K. Kohri, T. Terada, T. T. Yanagida
2409.08747, “Exploring chirality structure in nucleon decay”, K. Hamaguchi, S. Hor, N. Nagata, H. Takahashi
2409.09950, “Detecting meV-Scale Dark Matter via Coherent Scattering with an Asymmetric Torsion Balance”,
P. Luo, S. Matsumoto, J. Sheng, C-Y. Xing, L. Zhu, Z-J. Zhuge
2410.01224, “Prediction of the CP Phase deltaCP in the Neutrino Oscillation and an Axion-less Solution to the Strong CP Problem”, M. Tanimoto, T. T. Yanagida
2410.12554, “Féeton (B − L gauge boson) dark matter testable in future direct detection experiments”, Y. Cheng, J. Sheng, T. T. Yanagida
2410.18168, “Regulating Sommerfeld resonances for multi-state systems and higher partial waves”, A. Parikh, R. Sato, T. R. Slatyer
2411.03452, “Dark matter in the high-scale seesaw leptogenesis paradigm”, J. Herrero-Garcia, G. Landini, T. T. Yanagida
2411.07713, “Wormhole-induced ALP dark matter”, D. Y. Cheong, K. Hamaguchi, Y. Kanazawa, S. M. Lee, N. Nagata
2411.10149, “Directional direct detection of MeV scale boosted dark matter in two component dark matter scenario via dark photon interaction”,
K. I. Nagao, T. Naka, T. Nomura
2501.17226, “A universal bound on the duration of a kination era”, C. Eroncel, Y. Gouttennoire, R. Sato, G. Servant, P. Simakachorn
2502.10093, “Insights on the Scale of Leptogenesis from Neutrino Masses and Neutrinoless Double-Beta Decay”,
A. Granelli, K. Hamaguchi, M. E. Ramirez-Quezada, K. Shimada, J. Wada
2502.16437, “Superconducting Cloud Chamber”, B. Gao, J. Sheng, T. T. Yanagida
2502.18931, “Axion Emission from Proton Cooper Pairs in Neutron Stars”, K. Hamaguchi, N. Nagata, J. Zhang
2503.04880, “A New Source for (QCD) Axion Dark Matter Production: Curvature-Induced”, C. Eroncel, Y. Gouttennoire, R. Sato, G. Servant, P. Simakachorn
2503.08780, “Long-lived Light Mediators in a Higgs Portal Model at the FCC-ee”, B. Bhattacherjee, C. Bose, H. K. Dreiner, N. Ghosh, S. Matsumoto
2503.18648, “No-scale Brans-Dicke Gravity -- ultralight scalar boson & heavy inflaton”, M. Hong, K. Mukaida, T. T. Yanagida
2503.21875, “Proposal for a shared transverse LLP detector for FCC-ee and FCC-hh and a forward LLP detector for FCC-hh”,
B. Bhattacherjee, C. Bose, H. K. Dreiner, N. Ghosh, S. Matsumoto, S. Mukherjee, R. Sengupta, A. Sharma
2504.06599, “Axionless Solution to the Strong CP Problem -- two-zeros textures of the quark and lepton mass matrices and neutrino CP violation --”,
M. Tanimoto, T. T. Yanagida
2504.11810, “Light WIMPs and MeV Gamma-ray Detection with COSI”, Y. Watanabe, S. Matsumoto, C. M. Karwin, T. Melia, M. Nergo
2504.17638, “Testing Quintessence Axion Dark Energy with Recent Cosmological Results”, W. Lin, L. Visinelli, T. T. Yanagida
2505.00763, “JFlow: Model-Independent Spherical Jeans Analysis using Equivariant Continuous Normalizing Flows”,
S. H. Lim, K. Hayashi, S. Horigome, S. Matsumoto, M. M. Nojiri
2505.05142, “Non-invertible symmetry as an axion-less solution to the strong CP problem”, Q. Liang, T. T. Yanagida
2506.01543, “Dynamical dark energy in the no-scale Brans-Dicke gravity”, M. Hong, K. Mukaida, T. T. Yanagida
2506.07009, “Indirect Detection of Dark Matter Around a Supermassive Black Hole with High Energy-Resolution Gamma-Ray Telescopes”,
Y. Watanabe, A. Kusenko, S. Matsumoto
2506.07763, “Torsion Balance Experiments Enable Direct Detection of Sub-eV Dark Matter”, S. Matsumoto, J. Sheng, C-Y. Xing, L. Zhu

最近のE01班の研究

B03班との連携！

“Directional direct detection of MeV scale boosted dark matter in two component dark matter scenario via dark photon interaction”
<u>K. I. Nagao</u>, T. Naka, T. Nomura, JCAP 04 (2025) 030, arXiv:2411.10149





[HPNP2025の長尾さんのスライドより抜粋]

最近のE01班の研究

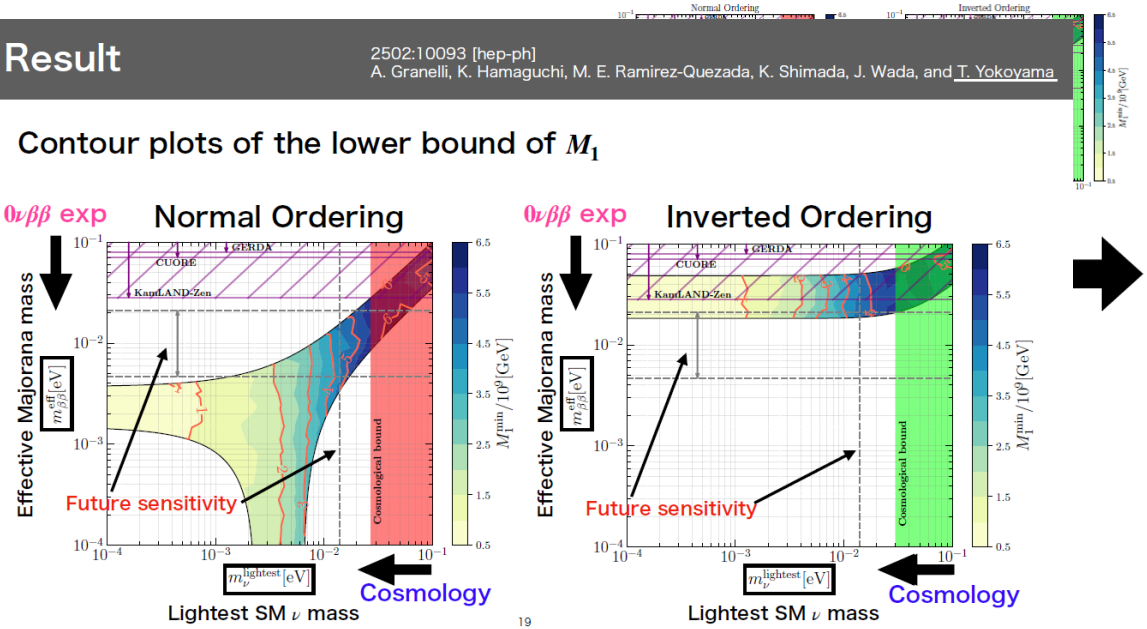
"Insights on the Scale of Leptogenesis from Neutrino Masses and Neutrinoless Double-Beta Decay"
A. Granelli, K. Hamaguchi, M. E. Ramirez-Quezada, K. Shimada, J. Wada, T. Yokoyama
arXiv:2502.10093

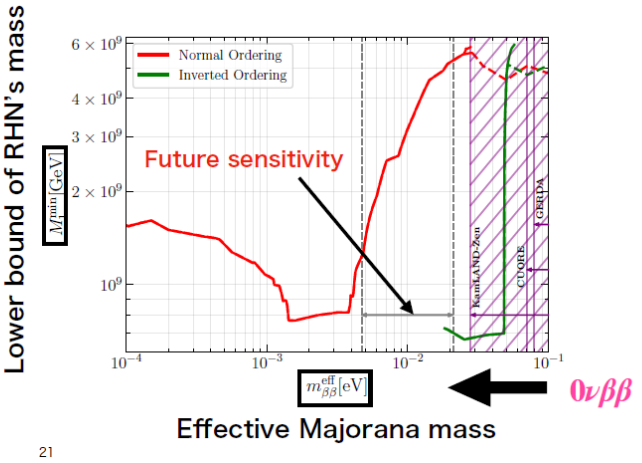
Result 2502:10093 [hep-ph]
A. Granelli, K. Hamaguchi, M. E. Ramirez-Quezada, K. Shimada, J. Wada, and T. Yokoyama

Projection of the contour plots on the vertical axis.

Result 2502:10093 [hep-ph]
A. Granelli, K. Hamaguchi, M. E. Ramirez-Quezada, K. Shimada, J. Wada, and T. Yokoyama

Contour plots of the lower bound of M_1





[KEK-PH 2025の横山さんのスライドより抜粋] **※今回の研究会の横山さんのポスターも参照してください。**

最近のE01班の研究

“Axion Detection Experiments Can Probe Majoron Models”
Q. Liang, X. P. Diaz, T. T. Yanagida, Phys. Rev. Lett. 134 (2025) 15, 151803, arXiv:2406.19083

Majoron as DM candidate

- This gives the anomaly coupling as

$$\mathcal{L}_{\rm anom.} = 3\frac{\alpha_{\rm em}}{4\pi}\frac{J}{F_J}F_{\mu\nu}\widetilde{F}^{\mu\nu} = \frac{g_{J\gamma\gamma}}{4}JF_{\mu\nu}\widetilde{F}^{\mu\nu}$$

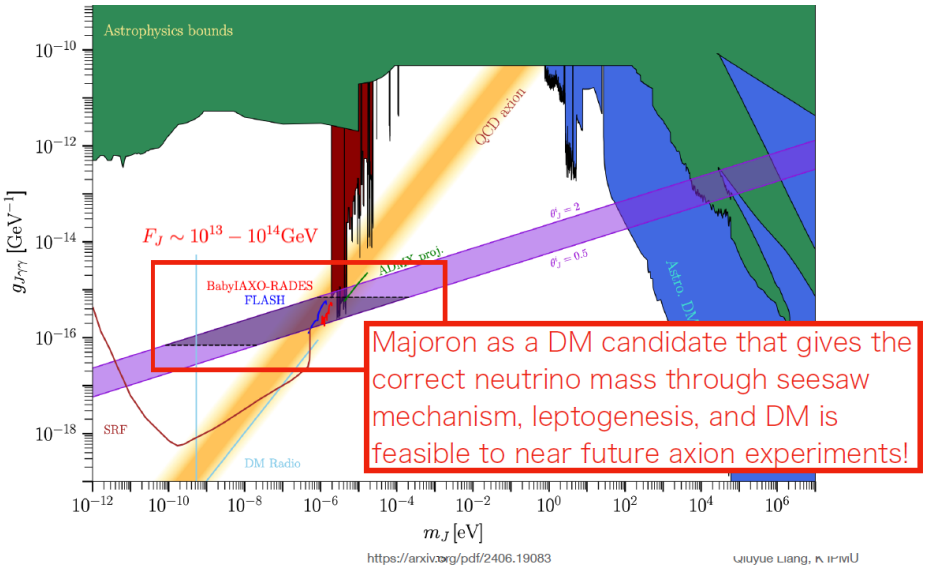
- We ``prompt'' majoron to an axion-like-particle candidate that can be produced through misalignment mechanism, which relates the DM abundance with mass, decay constant and initial angle of majoron:

$$\Omega_J h^2 \simeq 0.12\left(\frac{m_J}{\mu\text{eV}}\right)^{1/2}\left(\frac{F_J\theta_J^i}{1.9\times10^{13}\,\text{GeV}}\right)^2$$

- We further obtain the relation between mass and anomalous coupling

$$m_J \simeq \left(\frac{\pi}{3\alpha_{\rm em}\theta_J^i}\frac{g_{J\gamma\gamma}}{1.9\times10^{-13}\text{GeV}}\right)^4\mu\text{eV}$$

10 Qiuyue Liang, K IPMU



Majoron as a DM candidate that gives the correct neutrino mass through seesaw mechanism, leptogenesis, and DM is feasible to near future axion experiments!

https://arxiv.org/pdf/2406.19083 Qiuyue Liang, K IPMU

[The Frontier of Particle PhysicsのQiuyue Liangさんのスライドより抜粋]

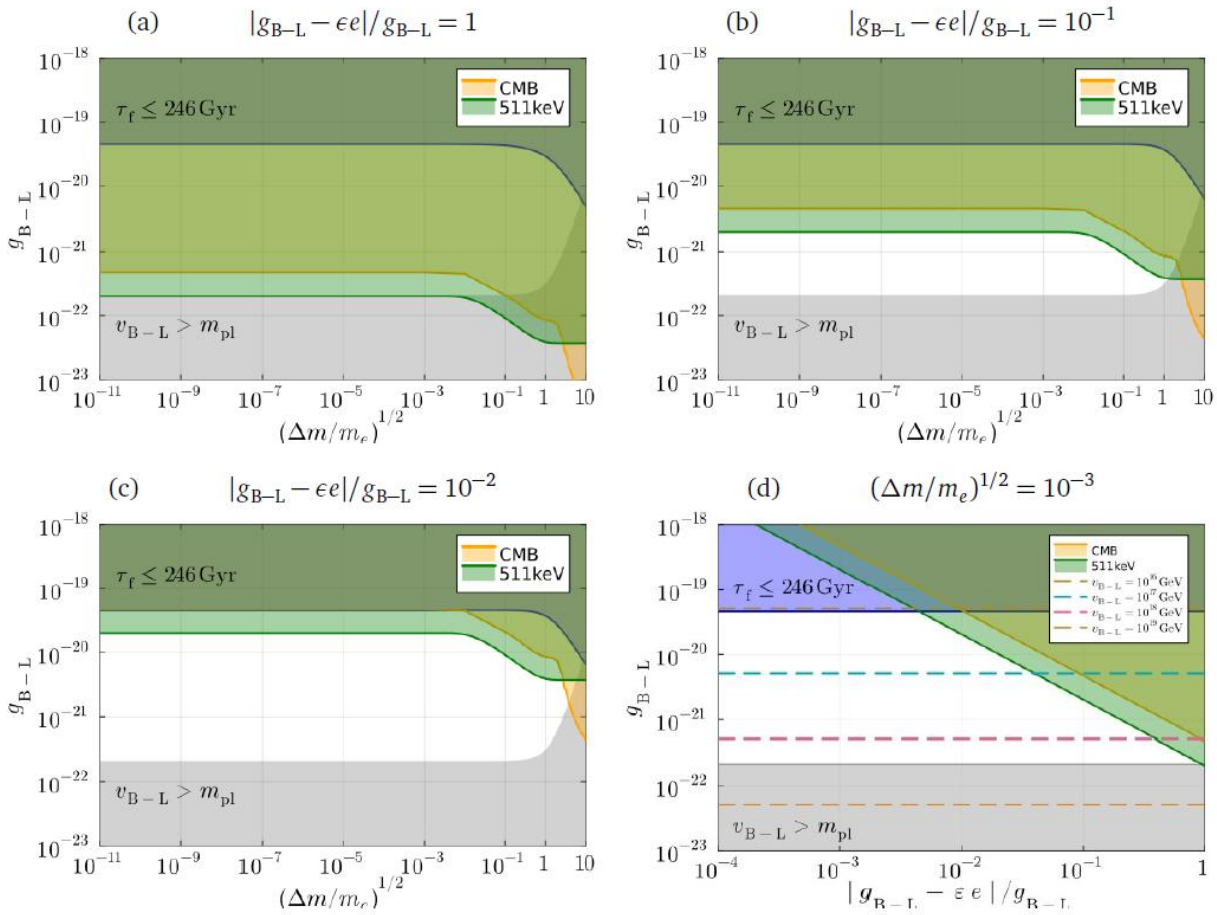
最近のE01班の研究

“Gauge U(1)B-L dark matter above the e-e+ threshold”

T. Hayashi, S. Matsumoto, Y. Watanabe, T. T. Yanagida, Phys. Rev. D 111 (2025) 5, 055012, arXiv:2408.12155

$$\mathcal{L}_{\mathrm{B-L}} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4}V^{\mu\nu}V_{\mu\nu} + |D_\mu \Phi|^2 + \sum_{i=1}^{3} \bar{N}_i\, i\gamma^\mu D_\mu N_i + V(\Phi, H)$$

$$+ g_{\mathrm{B-L}} V_\mu J^\mu_{\mathrm{B-L}} - \frac{\xi}{2} B_{\mu\nu} V^{\mu\nu} - \sum_{i,j=1}^{3} \left[y^{(\nu)}_{ij} \bar{L}_i H^c N_j + \frac{1}{2} y^{(N)}_{ij} \bar{N}^c_i N_j \Phi + h.c. \right],$$



[2408.12155より抜粋]

最近のE01班の研究

"Regulating Sommerfeld resonances for multi-state systems and higher partial waves"
A. Parikh, R. Sato, T. R. Slatyer, arXiv:2410.18168

S-matrix

We obtain S-matrix for each ℓ as

$$S_\ell \simeq \underbrace{\exp\left(2i\delta_\ell^{(L)}(p)\right)}_{\text{Phase-shift by long-range force}} \times \underbrace{\frac{k_{\ell,0}+z_\ell(p)-ip^{2\ell+1}C_\ell^2(p)}{k_{\ell,0}+z_\ell(p)+ip^{2\ell+1}C_\ell^2(p)}}_{\text{Relevant part for annihilation}}$$

Annihilation cross section :

Unitarity bound ✓

$$\sigma_{ann,\ell} = \frac{\pi}{p^2}(2\ell+1)(1-|S_\ell|^2) < \frac{(2\ell+1)\pi}{p^2}$$

$$= 4\pi(2\ell+1)p^{2\ell-1}\,\mathrm{Im}\left[-\frac{1}{k_{\ell,0}}\right] \times C_\ell^2 \times \left|1+\frac{z_\ell+ip^{2\ell+1}C_\ell^2}{k_{\ell,0}}\right|^{-2}$$

Annihilation cross section w/o long-range force | Conventional Sommerfeld factor | Correction factor

[27 / 33]

Unitarity bound vs. zero-energy resonance

Annihilation cross section on zero-energy resonance

$$|\psi_{\text{long}}|^2 \propto p^{-2} \text{ (for s-wave)} \Rightarrow \sigma_{ann,s} = \frac{1}{v}\times|\psi_{long}|^2\times(\sigma v)_0 \propto \frac{1}{p^3}$$

violates unitarity bound at small p

Partial wave expansion in two body scattering

$$E\psi = -\frac{1}{2\mu}\nabla^2\psi + V(x)\psi$$

$$\text{with } \psi \to e^{ipz} + f(\theta)\frac{e^{ikr}}{r} = \sum_\ell P_\ell(\cos\theta)\frac{S_\ell e^{ipr}-(-1)^\ell e^{-ipr}}{2ipr}$$

Annihilation cross section

$$\sigma_{ann} = \frac{\pi}{p^2}\sum_\ell(2\ell+1)(1-|S_\ell|^2) \Rightarrow \sigma_{ann,s} \le \frac{\pi}{p^2}$$

[19 / 33]

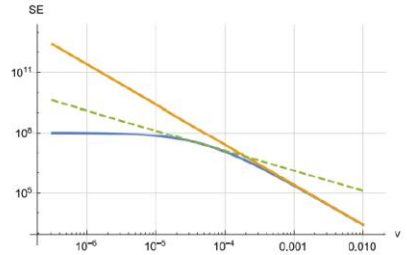
Examples

[Blum, Sato, Slatyer (2016)]

Hulthen potential : $V(r) = -\frac{\alpha m_* e^{-m_* r}}{1-e^{-m_* r}}$ (Good approximation of $V(r) = -\frac{\alpha e^{-mr}}{r}, m_* = \frac{\pi^2}{6}m$)

$$\alpha = 1, \quad \sigma v = \frac{1}{32\pi M^2}, \quad \sigma_{sc} = \frac{\mu^2}{4\pi}(\sigma v)^2$$

$m_* = 0.0625M$ ⇒



Yellow : usual formula
Blue : our formula
Green dotted : Unitarity bound

[30 / 33]

[The Frontier of Particle Physicsの佐藤のスライドより抜粋]