Overview of the (Medium and) High Energy (Physics) Theory Group at ASIoP

Meng-Ru Wu (吳孟儒)

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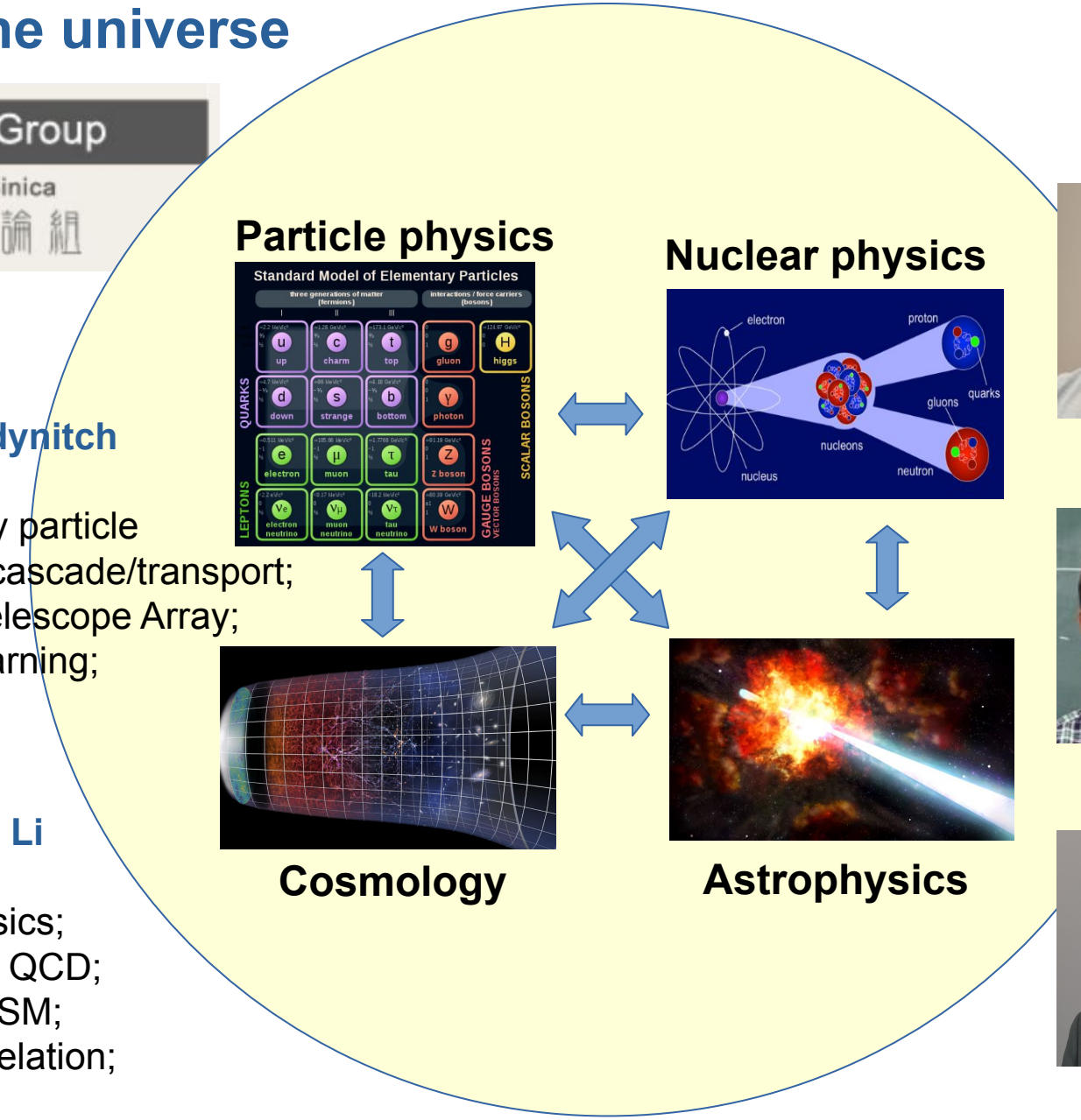
On behalf of the Medium and High Energy Physics Theory Group (HETG)
https://www.phys.sinica.edu.tw/~heptheory/index.php

Research Goal: Understanding the fundamental structure of matter and the evolution of the universe

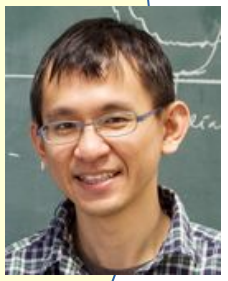
High Energy Theory Group
Institute of Physics, Academia Sinica
物理研究所高能理論組



Anatoli Fedynitch
(2021-)
High-energy particle interaction/cascade/transport;
IceCube; Telescope Array;
Machine learning;

Hsiang-nan Li
(2001-)
Hadron physics;
Perturbative QCD;
Beyond the SM;
Dispersion relation;

Kin-Wang Ng
(1992-)
Cosmology; CMB;
Gravitational waves;
Inflation; Primordial BH;
LIGO-Virgo-KAGRA;
Pulsar timing array;



Meng-Ru Wu
(2017-)
Neutrino astrophysics;
Collective neutrino oscillations;
Nucleosynthesis;
Dark sector in astrophysics;

Di-Lun Yang
(2021-)
Quantum transport theory;
Chiral & spin transport in astrophysics and in nuclear experiments;

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13 Postdoc fellows in our group [Taiwan (4), Germany (2), India (2), Israel, Japan, Russia, UK, Vietnam]

- **1 NSTC research scholar**: Yi-Peng Wu (cosmology).
- **3 HETG independent fellows**: Jakob Ehring (astrophysics), Yair Mulian (nuclear theory), Shu-Yu Ho (particle pheno).
- **9 fellows hosted by individual PI**:
  Soumya Bhattacharyya (neutrino), Madhurima Chakraborty (neutrino), Shu-Lin Cheng (inflation), Geraint Evans (QCD), Kozo Fujisue (cosmic rays), Karolin Hymon (IceCube), Yen-Hsun Lin (dark matter), Anton Prosekin (machine learning), Tran Van Que (particle pheno).

7 Adjunct fellows (6 retired from IoP):
Hai-Yang Cheng (hadron physics), Chi-Yee Cheung (quantum information),
Ting-Wai Chiu (Lattice QCD), Sai-Ping Li (statistical physics),
Hoi-Lai Yu (gravity), Tzu-Chiang Yuan (particle pheno), Wai Bong Yeung (gravity).

1 Distinguished Joint Fellow:
Ue-Li Pen (ASIAA director) [on BURSTT experiment for Fast Radio Bursts with A Fedynitch and KW Ng]

3 research assistants, 1 PhD students, and 4 master/undergrad students

Regular group activities:
Wednesday Journal Club, Thursday informal lunch arXiv chat, and Friday seminar

International collaborations, visitors, workshops, and visibility

- Official member of international experiments: **IceCube** and **Telescope Array** [A. Fedynitch].
- Long-term international theory collaborations:
  with **DESY, U Wurzburg, Dortmund U** (Germany), **ICRR** (Japan), **Alberta U** (Canada) [A Fedynitch];
  with **Zagreb U** (Croatia), **BNL** (USA), **Lanzhou U** (China) [HN Li];
  with **Tufts U** (USA), **APCTP** (Korea) [KW Ng];
  with **GSI & TU Munich** (Germany), **CU Geoscience** (China), **U Minnesota** (USA) [MR Wu];
  with **Keio U** (Japan), **USTC** (China), **Duke U** (USA) [DL Yang];

- Hosted 20-30 international visitors annually (23 in 2023 and 28 in 2024).

- Organized 1-3 international workshops/conferences in IoP
  (1 in 2023, 2 in 2024, projected 3-5 in 2025).

- Invited speakers at 30 international workshops/conferences outside TW in 2023 & 2024.

- International services:
  APCTP General Council Member [KW Ng (2017-present)].
  Editor of AAPPS Bulletin [MR Wu (2023-2026)].
  International advisory committee members of 4 workshops [A Fedynitch & MR Wu].

Recent Research Highlights

In 2023 & 2024, the group has ~ 70 research and review articles (3 PRL, 1 ApJS, 2 PPNP, 1 PRC-L, 3 PRD-L)
+ ~ 40 large collaboration papers (2 Science, 1 Nature Phys, 1 PRL, 1 ApJS, 2 ApJL; under IceCube)

What are the nature's most energetic accelerators?
-- new developments to uncover the astrophysical sources

[PI: A Fedynitch]

	Present	Next

Main theme
• Establishing group
• Popularize/let people know about the group
• Wrap up technical developments
• Focus on 3 main topics:
  • UHECR sources
  • Atmospheric neutrino modeling
  • IceCube Upgrade/Gen2
	UHECR
	• Start a **new effort from scratch** (GC SEED)
	• Create a **new data analysis technique** and obtain new data from Telescope Array
	• **Hire PDs**, Kozo Fujisue (TA) , refocus Anton Prosekin on Machine Learning
	• **Presented results** at main conf. UHECR 2024 (Anton & Kozo) in Argentina
		• **Measure and publish** UHECR spectrum
		• **Develop better ML** for UHECR mass measurement
		• Use a **new Bayesian method** to **search for sources** using our data obtained from TA (shown at UHECR 2024)

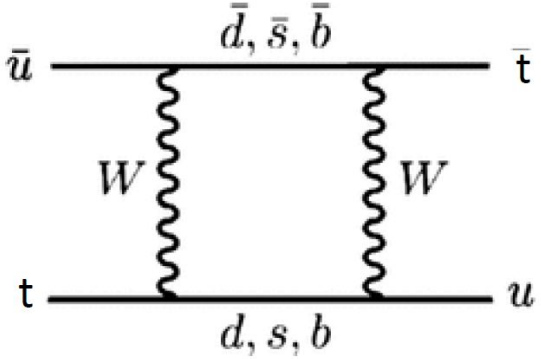
	Atm. neutrinos and CR pheno/theory • **Finalized** studying underground muons (1 ApJ and 1 PRD paper). Graduated PhD student at U. of Alberta (CA) • PRD: hadr. model SIBYLL* targeting muon puzzle	• Assemble technical works from past 3 years into **new flagship neutrino flux mo**del • **Target IceCube Upgrade/Hyper-K/DUNE/JUNO era**
IceCube 	• **Hired native IceCube** data-analysis postdoc, Karolin Hymon with atm. neutrinos as main topic • Contributed to coll. board, **publication committee** • 2 Science papers in the past 2 years, several PRLs • Future IceCube analyses **use my new flux model** • Personal contribution to IceCube Upgrade at the South Pole!	• Data analysis project with K. Hymon • Target **IceCube Upgrade physics** (few-GeV energy range) • **Considering Gen2 contribution** (Drill Control System Design) • Some Gen2 news expected in March

Dispersive determination of fourth generation quark masses

-- a potential extension of the Standard Model

[PI: HN Li]

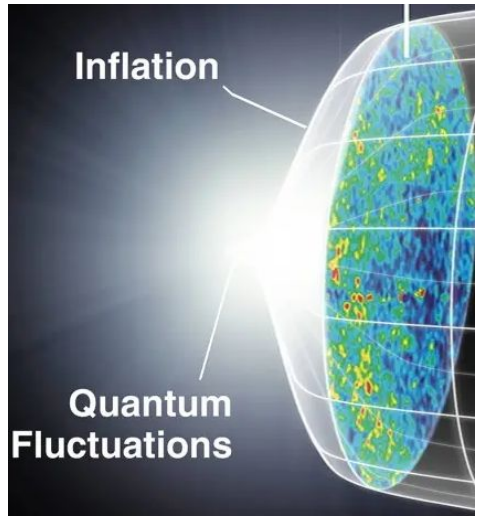
H.N. Li, Phys. Rev. D 109, 115024 (2024)



- solving the dispersion relations associated with the mixing between the neutral states $Q\bar{q}$ and $\bar{Q}q$, Q (q) being a heavy (light) quark
- determine the masses of the sequential **fourth generation quarks b' and t'** in the extension of the Standard Model from the solutions to the above dispersion relations
- the superheavy quarks with the masses **m_b' = (2.7 +- 0.1) TeV** and **m_t' = 200 TeV**, **forming bound states in a Yukawa potential**, barely contribute to Higgs boson production via gluon fusion and decay to photon pairs, and bypass current experimental constraints
- the **mass of the $\bar{b}$'b' ground state** was estimated to be about **3.2 TeV**, and it is **worthwhile to continue the search for b' quarks or $\bar{b}$'b' resonances at the LHC**

Beyond Slow-roll inflation?

-- primordial black holes, induced gravitational wave background, parity-violating four-point functions

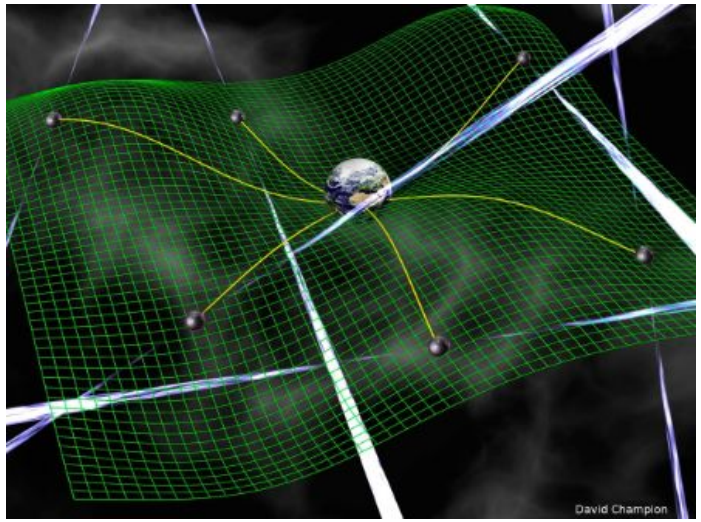


[PI: KW Ng; collaboration with Shu-Lin Cheng @ IOP, Da-Shin Lee @ NDHU, Hing-Tong Cho @ TKU]

S.-L. Cheng, D.-S. Lee, and K.-W. Ng, Phys. Lett. B 827 (2022) 136956; J. Cosmol. Astropart. Phys., 03 (2024) 008.
H.-T. Cho and K.-W. Ng, Class. Quantum Grav. 37, 165011 (2020); submitted to arXiv.

- Slow-roll inflation has been tested and confirmed by the Planck CMB data and large-scale-structure (LSS) surveys. CMB/LSS scales correspond to the first 7 e-foldings of inflation period. **What did happen after 7 e-folds to the end of inflation at about 60 e-folds**?
- We first pointed out that in ultra-slow-roll inflation models **large curvature perturbation seeding primordial black holes could back-react on the curvature perturbation at the CMB scales**. It was then followed by a debate about one-loop corrections in ultra-slow-roll inflation models.
- In **axion inflation**, the axion naturally couples to U(1) gauge field. We first studied the back reaction of the U(1) gauge field production during inflation. We first pointed out that the black hole binaries observed by LIGO-Virgo-KAGRA could be **primordial black holes** and that the **induced gravitational waves** associated with the primordial black holes could reach the detection sensitivity of **pulsar timing arrays**.
- Recently, it was detected in galaxy surveys that galaxies four-point functions have broken parity symmetry. We have put an effort to compute curvature of four-point functions in **axion inflation that are potential sources for cosmic large-scale parity violation**.

Stochastic Gravitational Wave Background by LIGO-Virgo-KAGRA and Pulsar Timing Arrays



On June 29 2023, NANOGrav 15-yrs +EPTA-InPTA + PPTA + CPTA confirmed the detection of a nanohertz stochastic GWB through pulsars time-delay correlation !

-- Gaussian GWB? Einstein GR? Anisotropic GWB? Circularly polarized GWB? Linearly polarized GWB?

[PI: KW Ng; collaboration with Reggie Bernardo, Stephen Appleby @ APCTP]

R. C. Bernardo and K.-W. Ng, Phys. Rev. D Letters, 107, L101502 (2023); 109, L101502 (2024).
R. C. Bernardo and K.-W. Ng, arXiv:2409.07955, invited chapter for "One Hundred and Ten Years of General Relativity -- From Genesis and Empirical Foundations to Gravitational Waves, Cosmology and Quantum Gravity"

Detector responses to stochastic gravitational wave background (Overlap Reduction Functions) by LIGO-Virgo-KAGRA, Einstein Telescope-Cosmic Explorer, LISA-Taiji, and pulsar timing arrays — to **invent new methods with public codes to accelerate data analysis and test gravity**

since 2021 - 5 PRD, 4 JCAP, 1 PLB, 2 PRDL, 1 A&A, 1 review article (World Scientific)

What is the role of neutrinos in supernova explosions?

-- toward solving the quantum kinetic transport of neutrinos in astrophysics

[PI: MR Wu; collaboration with NCHC & GSI @ Germany]

M. George, Z. Xiong, MRW, C.-Y. Lin, PRD 110 (2024) 123018
Z. Xiong, MRW, M. George, C.-Y. Lin, submitted to PRL (2403.17269)

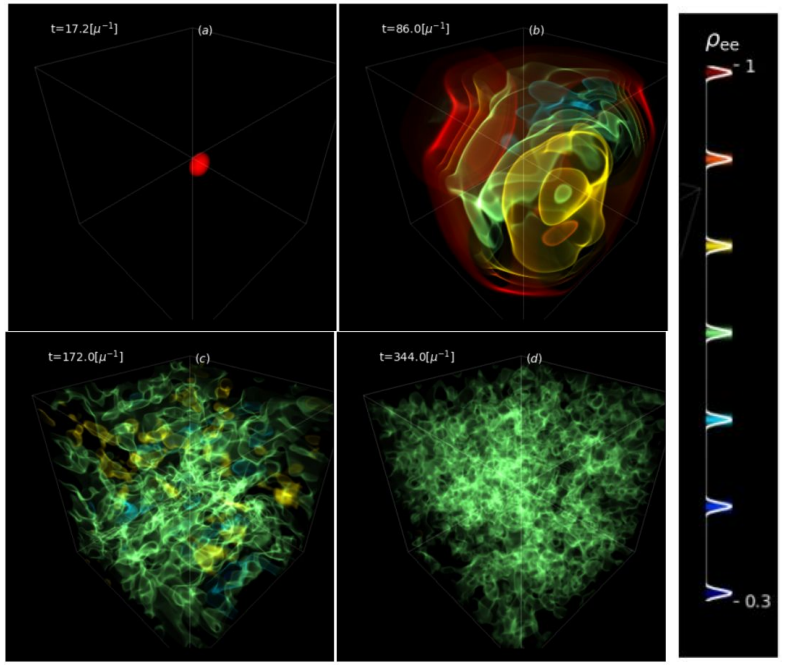
- Perform detailed multidimensional numerical simulations to solve the quantum kinetic transport equation of neutrinos in supernovae and neutron star mergers.

$$(\partial_t + v_r\partial_r + \tfrac{1-v_r^2}{r}\partial_{v_r})\varrho_\nu = -i[H_{\rm vac} + H_{\rm m} + H_{\nu\nu}, \varrho_\nu] + \mathcal{C}$$

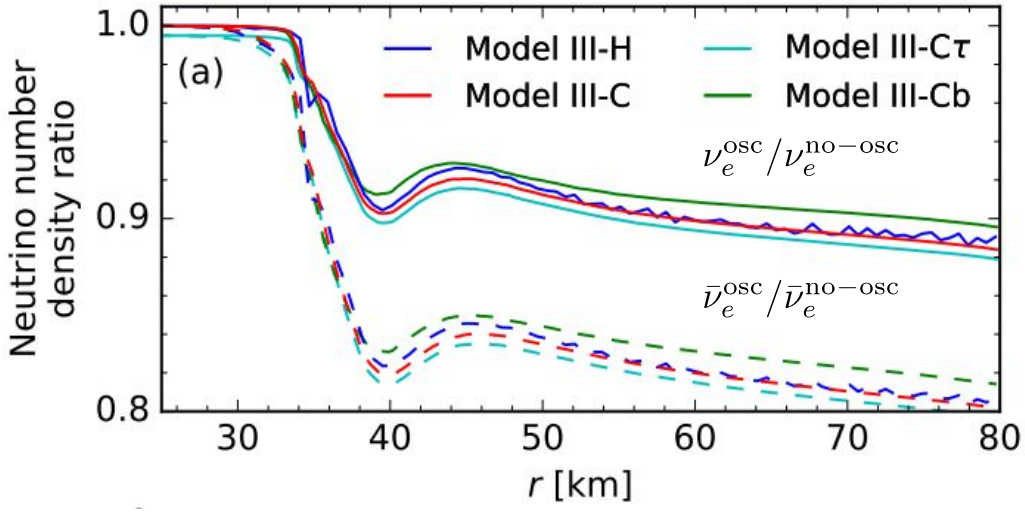
$$H_{\nu\nu}(\mathbf{x},\mathbf{p},t) = \frac{\sqrt{2}G_F}{(2\pi)^3}\int d^3q(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})[\varrho - \bar{\varrho}^*],$$

$$\varrho(t,\mathbf{x},\mathbf{p}) = \begin{bmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & f_{\nu_\tau} \end{bmatrix}$$

- Formulate an effective classical transport model to effectively incorporate quantum oscillations of neutrinos in classical transport.



[M. George, Z. Xiong, MRW, C.-Y. Lin, PRD 110 (2024) 123018]



[Z. Xiong, MRW, M. George, C.-Y. Lin 2403.17269]

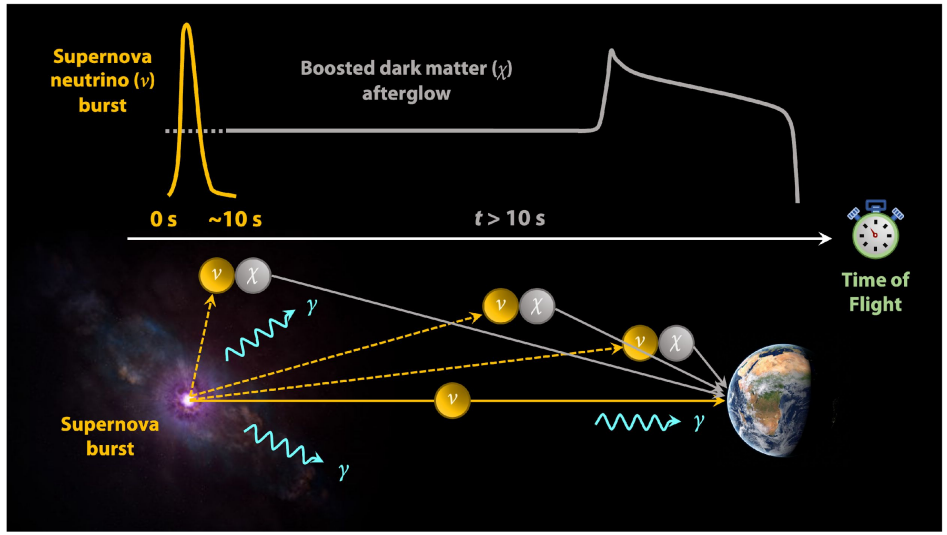
How to overcome the detection threshold for light dark matter?

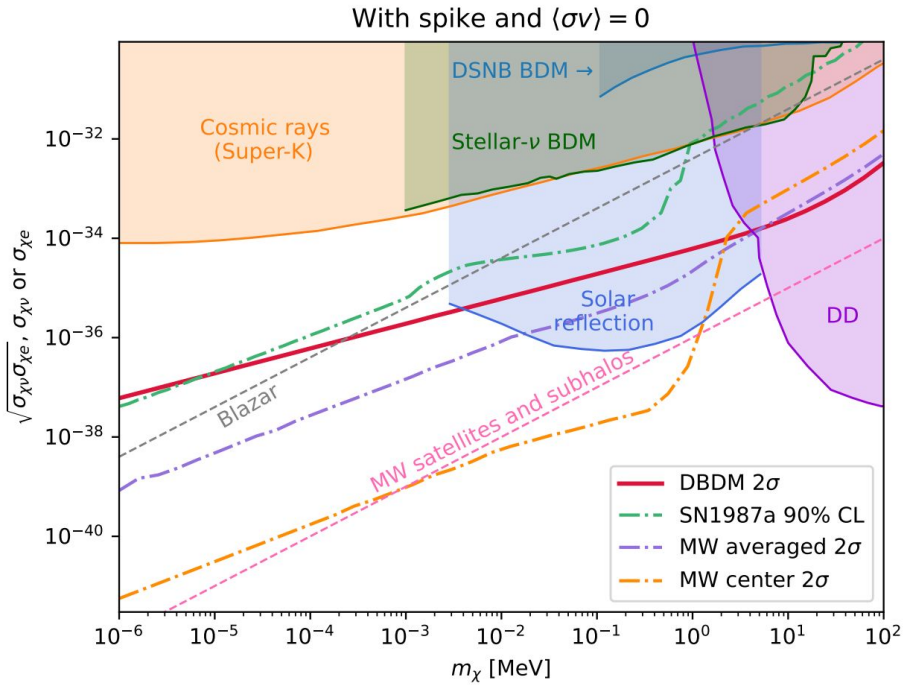
-- Probing light dark matter boosted by supernova neutrinos

[PI: MR Wu; led by postdoc fellow Yen-Hsun Lin]

Y.-H. Lin, W.-H. Wu, MRW, **H. T.-K. Wong**, PRL 130 (2023) 111002
Y.-H. Lin and MRW, PRL 133 (2024) 111004

- Light dark matter nearly at rest in galaxy's halo may be upscattered by energetic supernova neutrinos to leave detectable traces in large-size neutrino detectors.
- The associated signal carries temporal profiles that encodes the dark matter mass – analogy of "time-of-flight" measurement for particle mass.
- Both the upscattered component from the nearby galaxy (individual source) and from all galaxies at higher redshift (the diffuse component) can result in leading bound on dark matter interaction cross sections.





[Y.-H. Lin and MRW, PRL 133 (2024) 111004]

Spin transport in hot and dense QCD matter

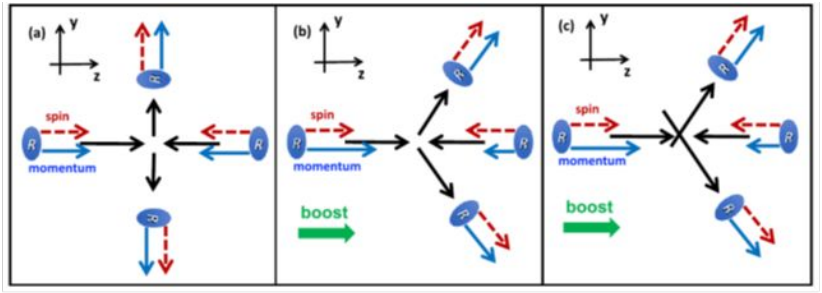
-- understanding dynamical spin polarization and alignment phenomena in relativistic heavy ion collisions

[PI: Di-Lun Yang; collaboration with USTC @ Duke]

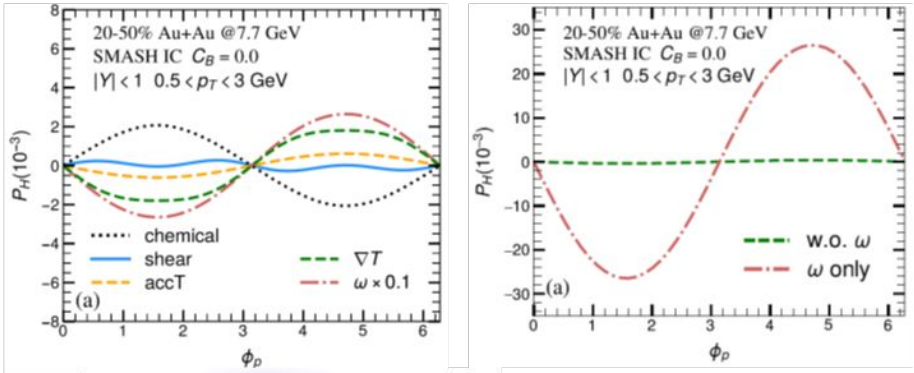
Y. Hidaka S. Pu, Q, Wang, DY, Prog. Part. Nucl. Phys. 127 (2022) 103989

S. Fang, S. Pu, DY, PRD 109, 034034 (2024)

Cong Yi, Xiang-Yu Wu, DY, Jian-Hua Gao, Shi Pu, Guang-You Qin, PRC 109, L011901 (2024)



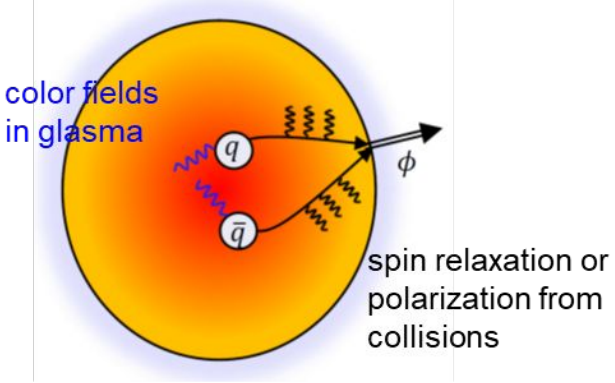
- Formulate quantum kinetic theory for spin transport of quarks to study non-equilibrium corrections on polarization spectra beyond thermal equilibrium.
- Perform hydrodynamic simulations for local and helicity polarization as a new probe and baseline for local vorticity in RHIC-BES energies.



B. Müller, DY, PRD 105, L011901 (2022)

A. Kumar, B. Müller, DY, PRD 108, 016020 (2023)

- Study how chromo-electromagnetic (color) fields from dense QCD matter affect the quark spin transport.
- Investigate the spin alignment of vector mesons induced by the spin correlation in the quark coalescence scenario from fluctuating color fields in the glasma state.



Chiral transport phenomena in dense astrophysical systems

-- exploring chiral effects from parity violation of the weak interaction upon lepton transport in core-collapse supernovae

[PI: Di-Lun Yang; collaboration with Keio]

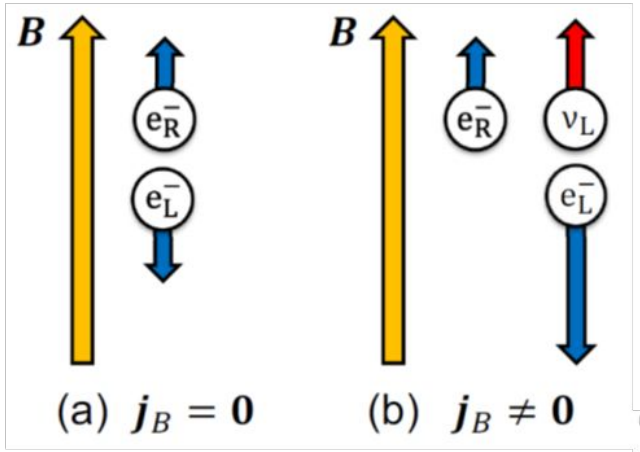
K. Kamada, N. Yamamoto, DY, Prog. Part. Nucl. Phys. 129 (2023) 104016

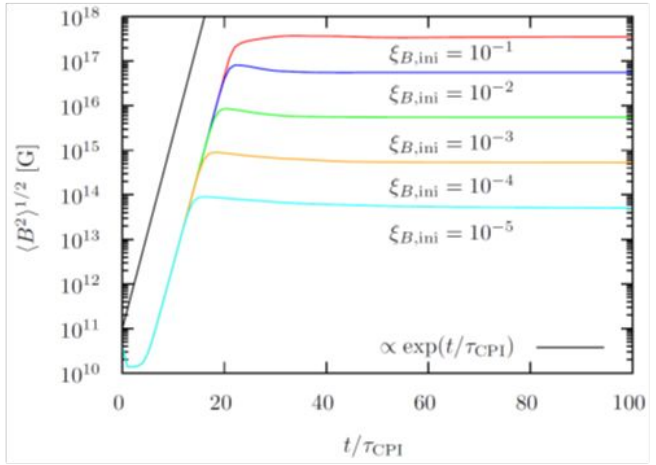
N. Yamamoto, DY, PRL 131, 012701 (2023)

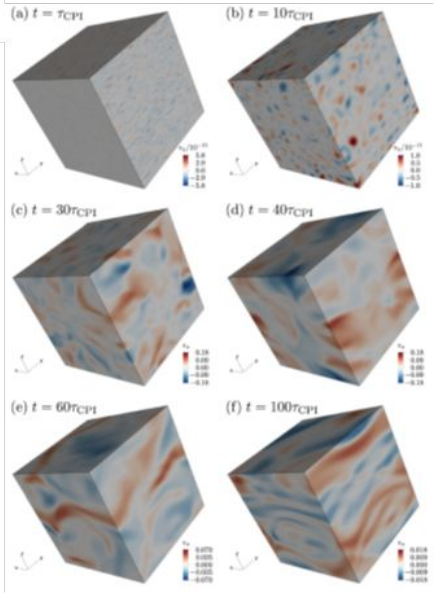
- Formulate the chiral radiation hydrodynamics to study the chiral effects especially induced by magnetic fields for the interplay between neutrino radiation and matter evolution in core-collapse supernovae.

- Derive the effective chiral magnetic effect led by non-equilibrium neutrino radiation from a novel power counting scheme to solve the chiral kinetic equation.

- Perform local chiral magneto-hydrodynamic simulations to understand the qualitative behaviors of the amplified magnetic fields from chiral plasma instability and inverse cascade due to the helicity conservation.







Synergy and Future Plan

Research projects as of now

- The theory group members have obtained a **good amount of individual grants** from various funding agencies beyond the typical NSTC grants:

  AS Career Development Award (前瞻計畫), **MR Wu**, 2020-2024.
  NSTC Excellent Young Scholars Research Grant (優青計畫), **MR Wu**, 2022-2026.
  AS Grand Challenge Seed Program (關鍵種子計畫), **A Fedynitch**, 2024-2025.
  NSTC Excellent Young Scholars Research Grant (優青計畫), **DL Yang**, 2024-2028.
  AS Investigator Project Grant (深耕計畫), **MR Wu**, 2025-2029.
  AS Career Development Award (前瞻計畫), **DL Yang**, 2025-2029.

- Key participants in other domestic cross-institution projects:

  AS Grand Challenge Seed Program (關鍵種子計畫), **A Fedynitch & KW Ng** (led by UL Pen @ ASIAA), 2025-2027.
  NCTS (國家理論中心) Center Scientist, **MR Wu** (2023-2025).

- Other domestic collaborations (no joint grants):

  KW Ng with Guo-Chin Liu, Hing-Tong Cho (TKU), Da-Shin Lee (NDHU), Wolung Lee (NTNU)
  MR Wu with Kuo-Chuan Pan (NTHU), Chun-Yu Lin (NCHC).
  DL Yang with Kuo-Chuan Pan (NTHU).

Planned synergetic focused directions

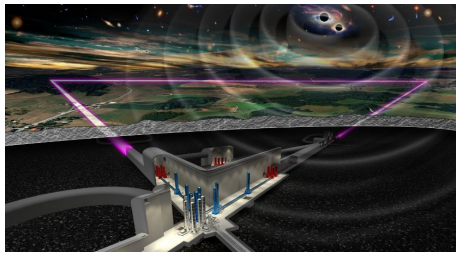
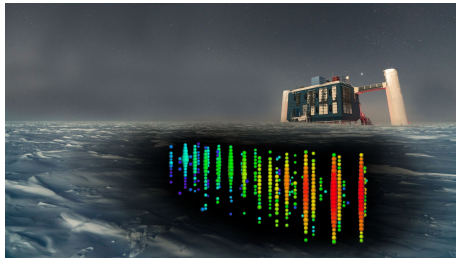
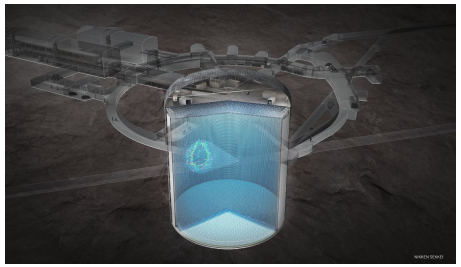
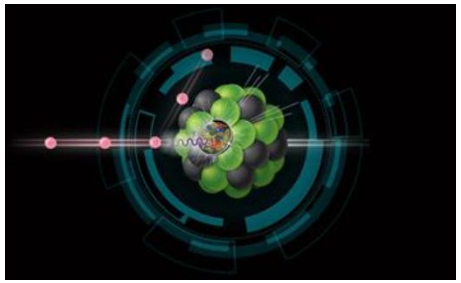
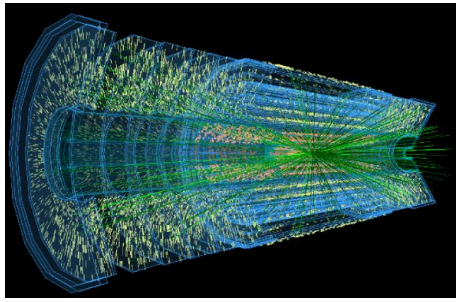
- **Projected coherent schemes** for the group's major research directions:

  Fundamental theory [HN Li + DL Yang + potential new recruit].
  Gravitational wave astronomy and cosmology [KW Ng + potential new recruit].
  Machine learning applications in theory and experiments [A Fedynitch + MR Wu + potential new recruit].
  Neutrino interaction and oscillations [A Fedynitch + MR Wu + DL Yang + potential new recruit].
  Nuclear theory relevant for high-energy nuclear collisions [DL Yang + potential new recruit].
  Quantum kinetic transport theory and computation [DL Yang + MR Wu].

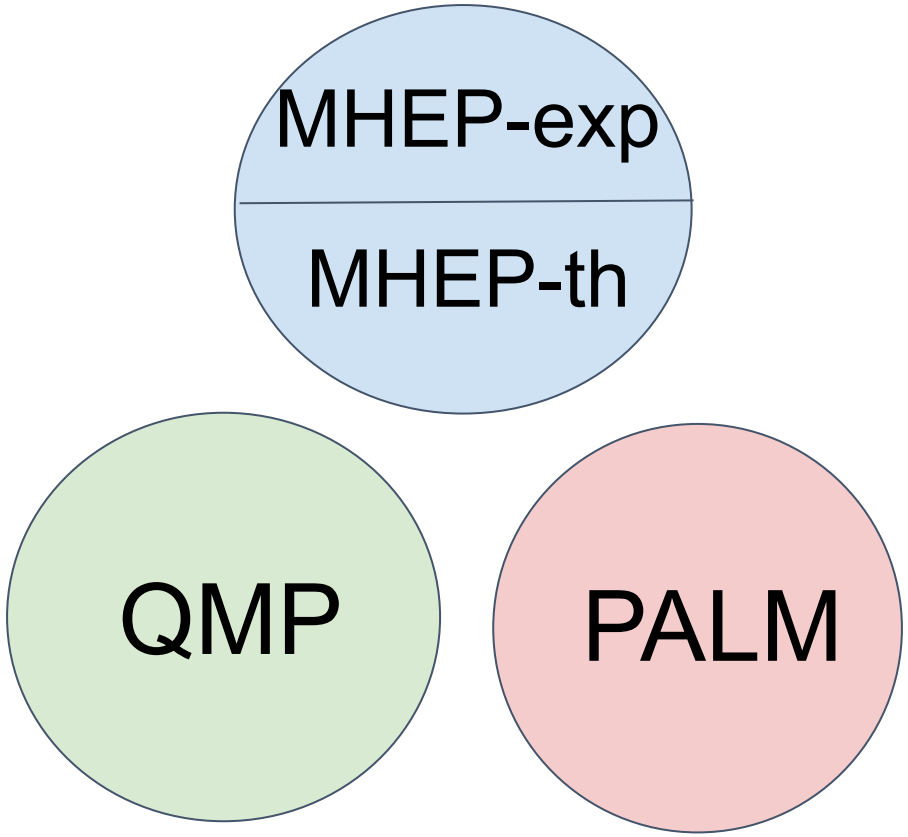
- We foresee that the group can be **ready to apply for synergetic programs involving multiple PIs in the next 5-10** years, with the successful recruitment of two excellent candidates in this coming year or two.

- **All these theory research directions will be tightly connected to the ongoing and upcoming major large scale experiments** in:
  Gravitational wave physics (LIGO-Virgo-KAGRA & upgrades, PTA & SKA).
  High-energy astroparticle physics (IceCube, Telescope Array & the related upgrades).
  Neutrino physics (Super-K, Hyper-K, DUNE, JUNO).
  Nuclear physics (RHIC, LHC, EIC).
  Particles physics (LHC & upgrades, Forward Physics Facilities).

➔ hope to broaden collaboration circles with theory colleagues outside ASIoP as well as experimentalists and observers within & beyond ASIoP

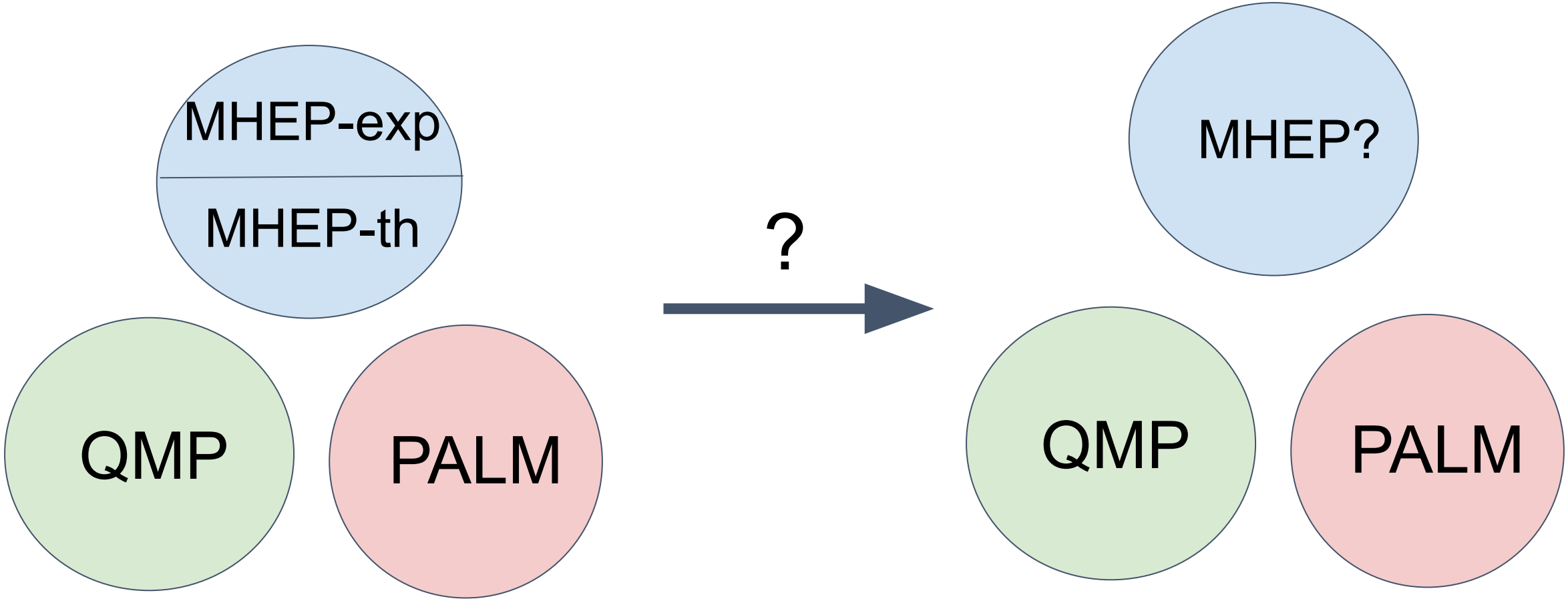
Future of the theory group?



*** Illustrative, not-to-scale

MHEP: Medium and High Energy Physics
QMP: Quantum Materials Physics
PALM: Physics of Active and Living Matter

Future of the theory group?



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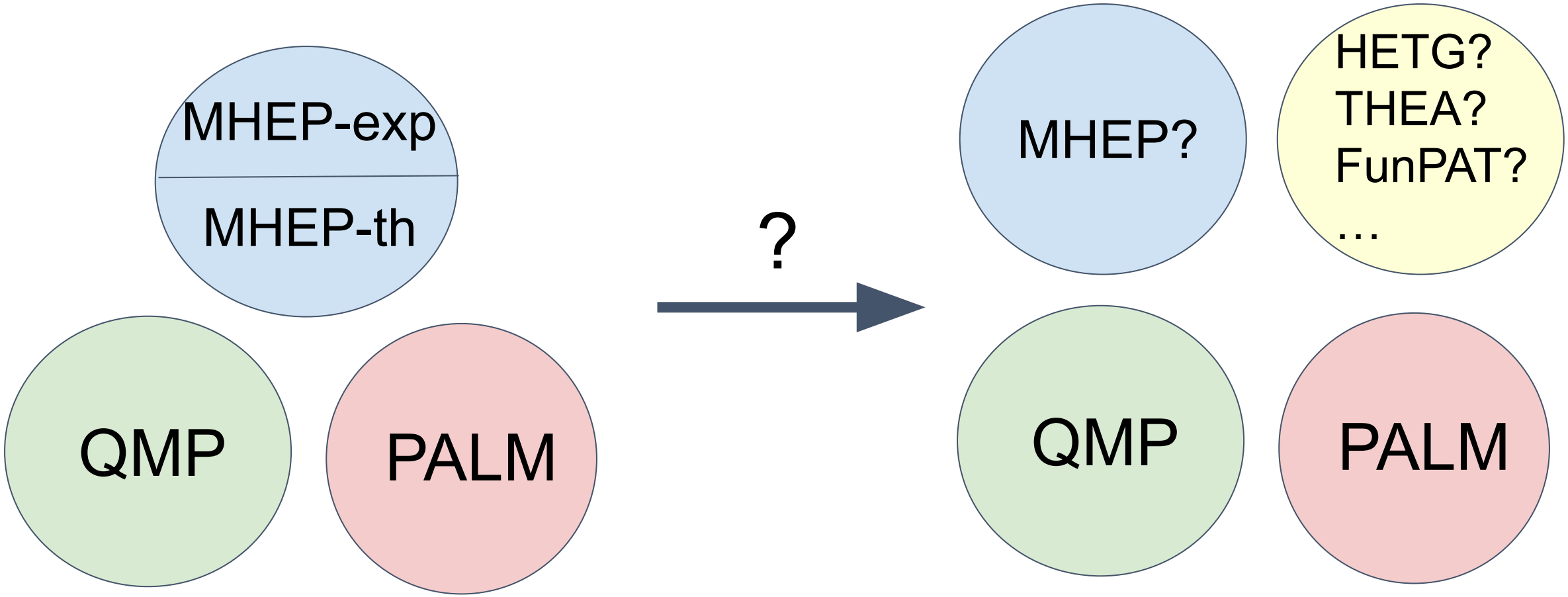

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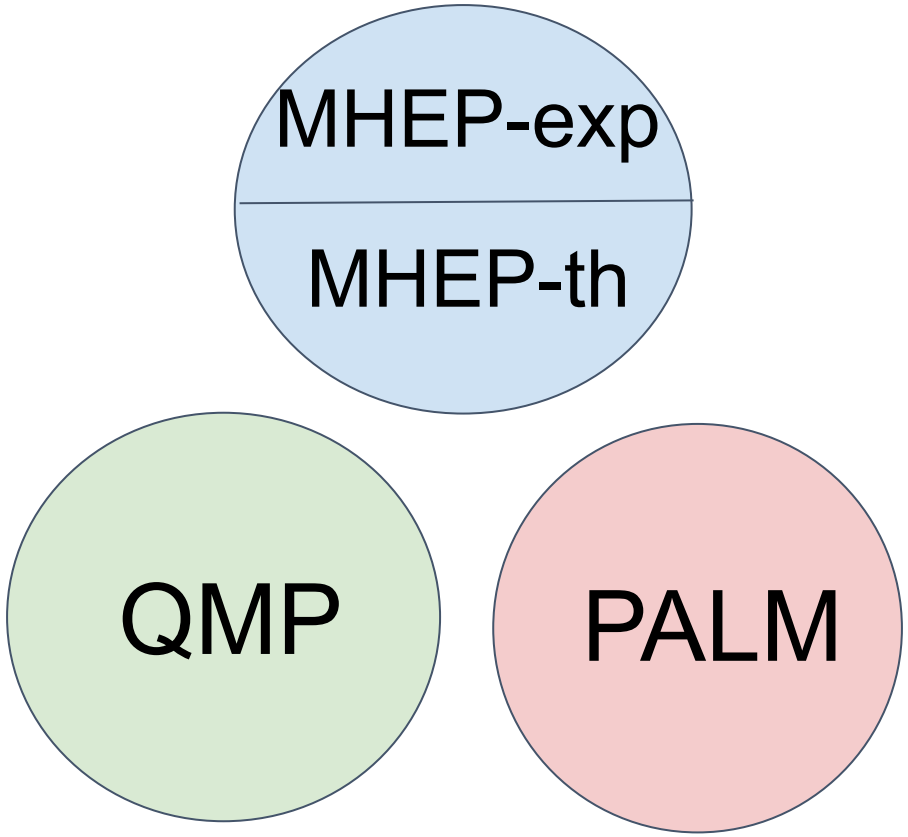
MHEP: Medium and High Energy Physics
QMP: Quantum Materials Physics
PALM: Physics of Active and Living Matter

HETG: High Energy Theory Group
THEA: Theoretical High Energy and Astrophysics
FunPAT: Fundamental Physics and Astrophysics Theory

Future of the theory group?



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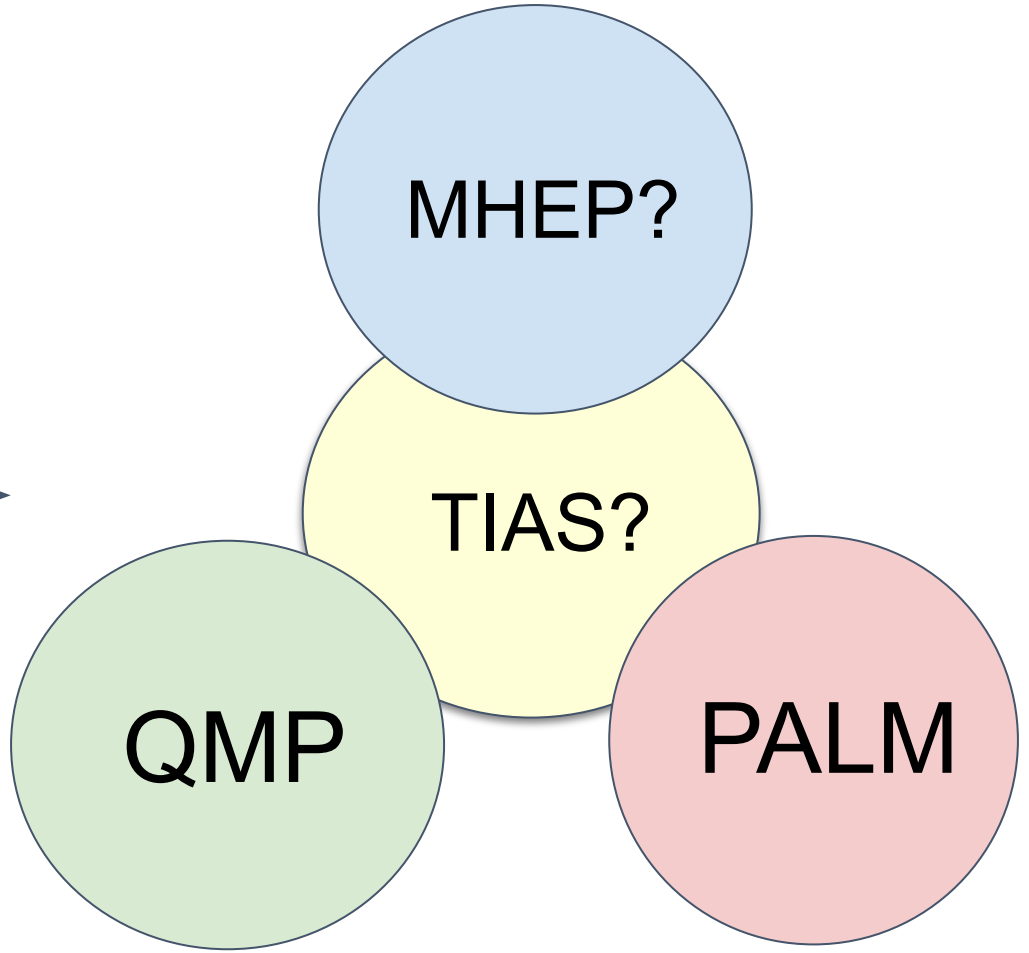

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MHEP: Medium and High Energy Physics
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TIAS: Theory Institute Academia Sinica or
Taiwan Institute for Advanced Study