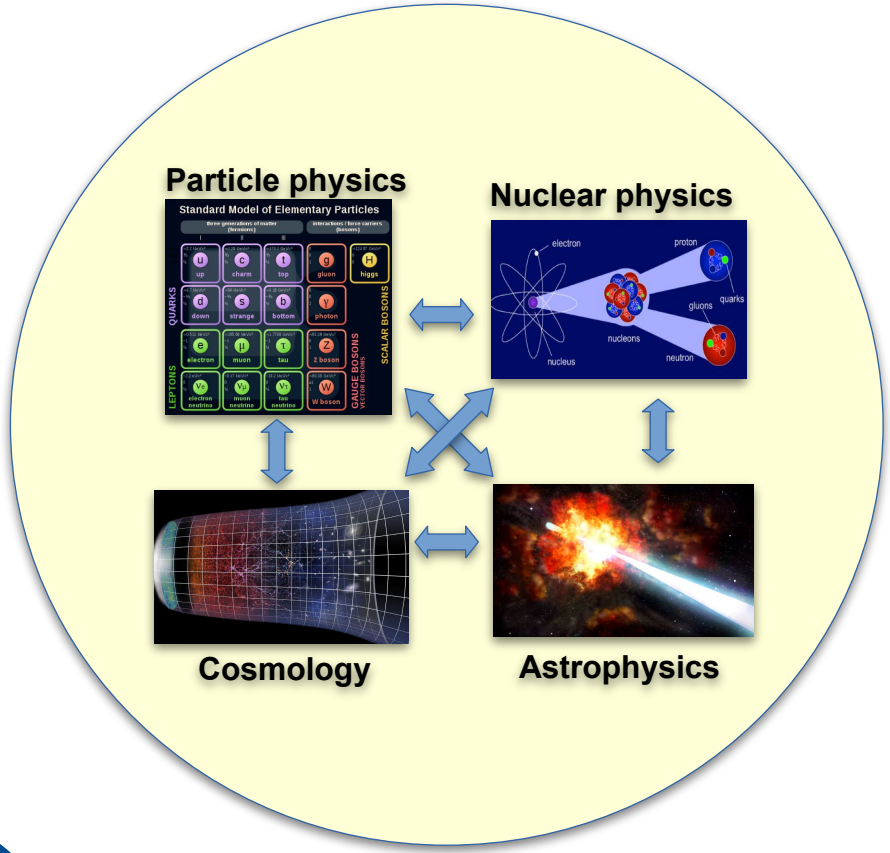
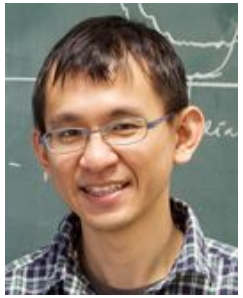
Report of the High Energy Theory Group (HETG)




Anatoli Fedynitch


Hsiang-nan Li


Kin-Wang Ng


Meng-Ru Wu


Di-Lun Yang

Meng-Ru Wu, on behalf of the HETG

IoP 2025 Retreat @ Xitou

Outline

- **Response to the 2025 AAC report**
- **HETG's grand challenge – a regional theory center**
- **Grand challenges from individual HETG members**

(Scan for detailed HETG information and achievement given in the HETG report for the 2025 AAC meeting)

- Size: 5 PIs + 4 adjunct fellows + 15 postdocs + 9 students
- Research output (2020-2025; quoted from June 2025):
  – 170+ published theory papers; 3,600+ citations (h-index 33);
  15 papers with 50+ citations; 3 papers with 100+ citations.
  – 3 invited review papers in PPNP & 1 in ARNPS.
- Numerous awards (domestic+regional) & competitive grants.
- **All 5 PIs are on the list of top 2% Scientists in the Stanford/Elsevier 2025 Single-Year List.**

Quotes from the 2025 AAC report

- "...The group's effort appears cohesive and all members of the group are able to communicate effectively with each other on scientific issues even if they do not regularly collaborate with each other…" 😀
- "The group as a whole has an excellent publication record…" 😀
- "...Envisioning the future retirements of the more senior group members, it is therefore expected that searches will be run to add new PIs…"
- "...Hires in any of these areas would overlap and strengthen the existing group. With professor Ng's retirement some priority might be given to cosmology to ensure it remains an active area in the IoP."
- "We are impressed with the thoughtfulness and detailed plans the theory group has provided." 😀

We will definitely search to add new PIs in coming years, and take into account AAC's suggestion regarding cosmology.

BIG Questions for HETG *– resolving fundamental problems from laboratory experiments to the Universe*

(A) Terrestrial Experiments (HN Li & DL Yang):

- Origin of the mass hierarchy and flavor structure in Standard Model – HN Li.
- CP violation in heavy meson and baryon experiments – HN Li.
- Transport of spin polarization and alignment in QCD matter – DL Yang.

(B) Multimessengers from Astrophysics and Cosmology (A Fedynitch, KW Ng, MR Wu, DL Yang):

- Origins of high-energy neutrinos and cosmic rays – A Fedynitch.
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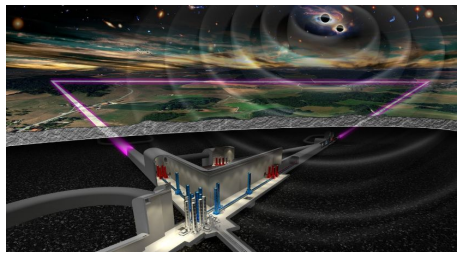
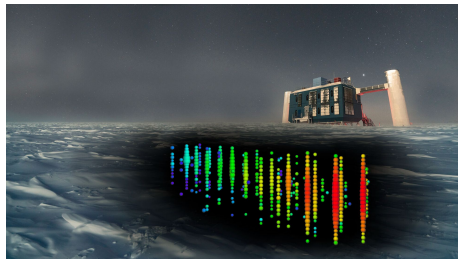
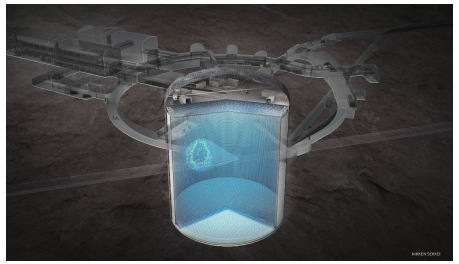
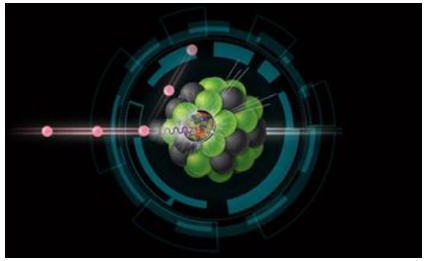
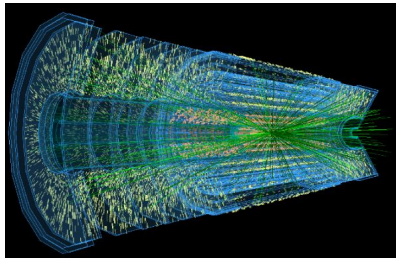

BIG Questions for HETG

for discovery of New Physics beyond the Standard Model
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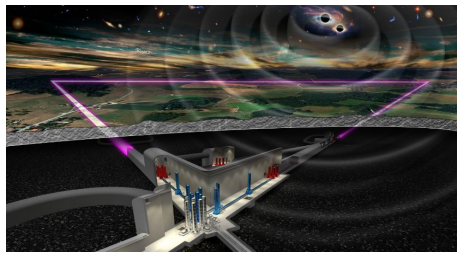
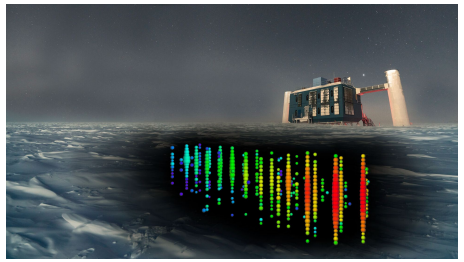
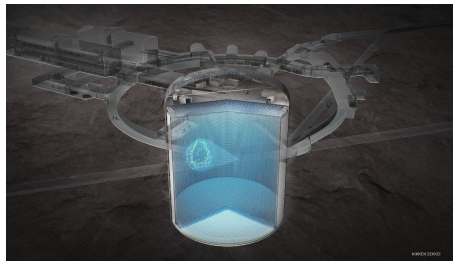
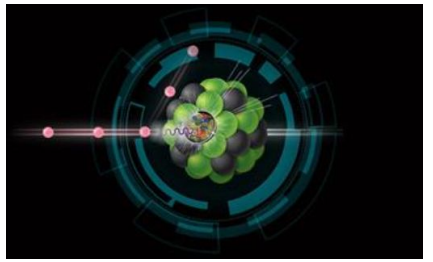
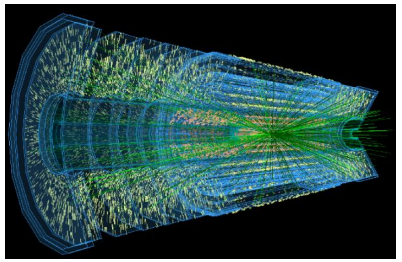






HETG's grand challenge

A regional theory center in nuclear and multimessenger physics

Science Goal: explore unknown physics at high energy, high density, and high redshift

– QCD matter & dense matter inside neutron stars and atomic nucleus

– Particle and nuclear interaction & transport in terrestrial colliders and extreme cosmic events

– Cosmic structure at high redshift

– Neutrinos, cosmic-rays, gravitational waves, and electromagnetic signals from extreme cosmic events and cosmos

– Observables in large-hadron collider, heavy-ion colliders and electron-ion collider

HETG's grand challenge – a regional theory center in nuclear and multimessenger physics

Mission & Vision:

➔ further enhance HETG's global scientific influence in major directions.

➔ become a **regional leading research center in related areas after 5-10 years**.

Is this possible? Very challenging but not impossible

Q: Why very challenging?

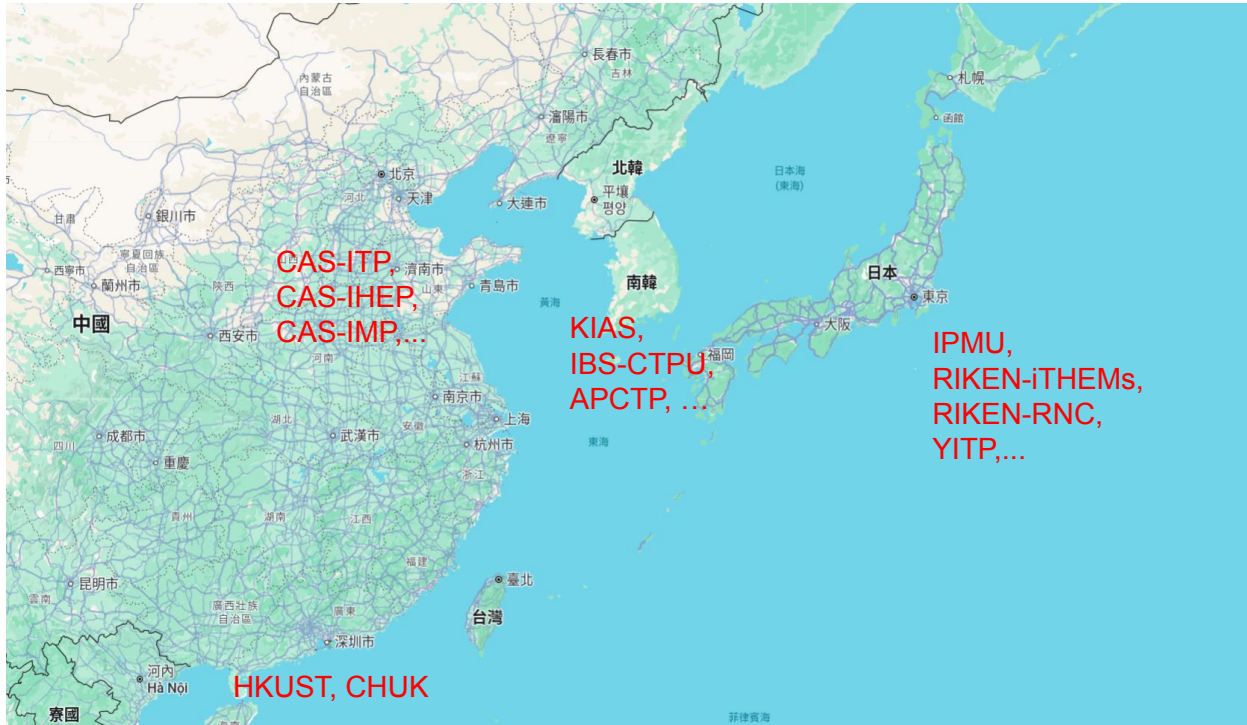
A: Limited money & manpower 😰

Q: Why not impossible?

A: Good base to build further on 🌟

Strategies & actions:

- Establishing a theory hub first
- Targeted faculty recruitment
- Enhancing international collaborations



NCTS Theory Hub @ IoP

IoP will be a Theory Hub of NCTS starting in 2026:
– Host a new nuclear theory thematic group [coordinated by DL Yang (+ HN Li, MR Wu, A Fedynitch)].
– Strengthen the HETG multimessenger direction [A Fedynitch + KW Ng + MR Wu + DL Yang].
– Support the high-energy phenomenology thematic group [coordinated by MR Wu (+ HN Li, KW Ng)].
– Support PALM theorists & complex system thematic group [HY Shih & T Hiraiwa].

- **Nuclear Physics Thematic Group**:
  – team up with domestic researchers from NTU, NYCU, NDHU, CYCU [a retreat in May 2026].
  – enhance collaboration with Korean & Japanese community [a TW-KR workshop in Sept 2026].
  – focus on heavy-ion collision, electron-ion collider, and nuclear astrophysics related topic.

- **Recruit two "Junior Research Fellows":**
  – one in nuclear physics and one in multimessenger.
  – multi-year (3+2 years) with competitive salary + research & travel funding.
  – rising researchers, expected to advance further to faculty level.

- **Visitor Program**: regularly inviting oversea speakers for HETG/NCTS Hub seminars.

Targeted faculty search & joint fellows

- Dr. **Hao-Jui Kuan** expected to join in early 2027.
  – Numerical relativity involving compact objects, **gravitational waves**, and gravity theory.
  – A big boost to the **multimessenger** program.
  – Complement with MRW, Di-Lun, & Kin-Wang's research directions.

- Recruit **2 to 3 more research fellows**, targeting the following areas:
  – Collider and accelerator theory for precision studies.
  – Dense matter nuclear physics.
  – High-energy astroparticle/astrophysical modeling.
  – High-redshift cosmology & gravitational physics.

- Processing a joint appointment for Dr. **Yang-Ting Chien** (Georgia State U).
  – 2 months at IoP in summer every year [starting 2026]
  – **heavy-ion physics** and effective field theory; enhances **nuclear theory** activity.
  – Expected to interact with Hsiang-nan & Di-Lun intensitvely.

Q: Should we consider "**5-year fixed-term junior fellow" position** (equipped with 1-2 postdocs + possibility to apply for NSTC grant)? [c.f., IBS & APCTP]
– pros 😀: enhances connections outside IoP + flexibility in terms of research directions.
– cons 😨: squeeze further the IoP budget if no external funding (next page…).

Enhancing International Collaborations

While the HETG are building around two coherent central topics, the success of HETG hinges on **international collaborations:**

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

- Host 20-30 international visitors annually **-> expect to increase to 30-40 / year**
- Organize ~ 2-3 international workshops/conferences at IoP **-> expect to increase to 3-5 / year**
- **Critical to extract young talents, increase collaborations, and enhance visibility.**

In the long-run:
– **establish partnerships** with other institutions/centers (e.g., AEI, GSI, NBI, IBS, YITP, RIKEN, …).
– hope to eventually **grow to a theory center** capable of bringing in external funding.

HETG member’s grand challenges

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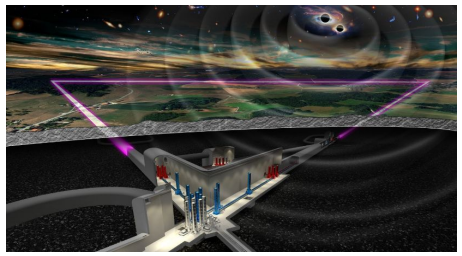
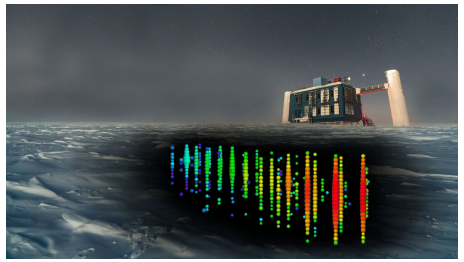
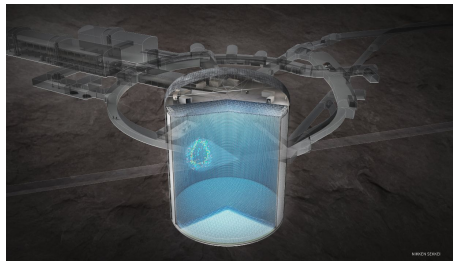
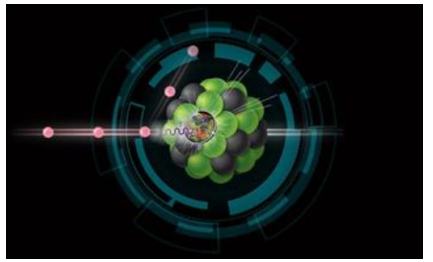
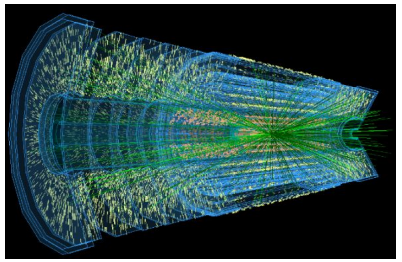






QCD matter in extreme conditions

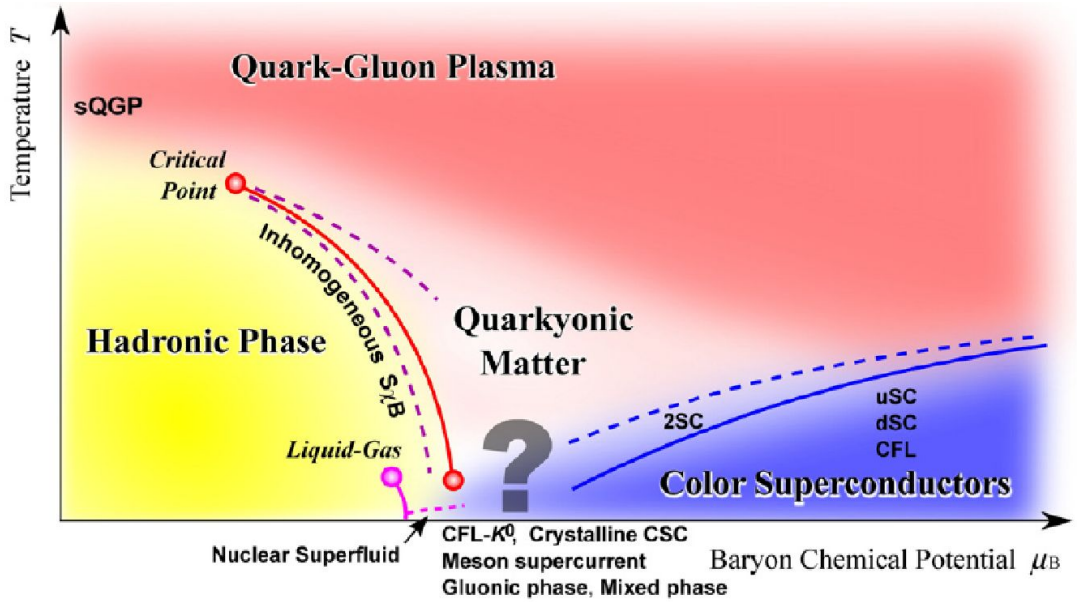
[PI: DL Yang]

- Hot and dense QCD or nuclear matter can be produced in nuclear-collision experiments or astrophysical systems. The QCD **phase diagram** and **transport properties** are long-sought problems.

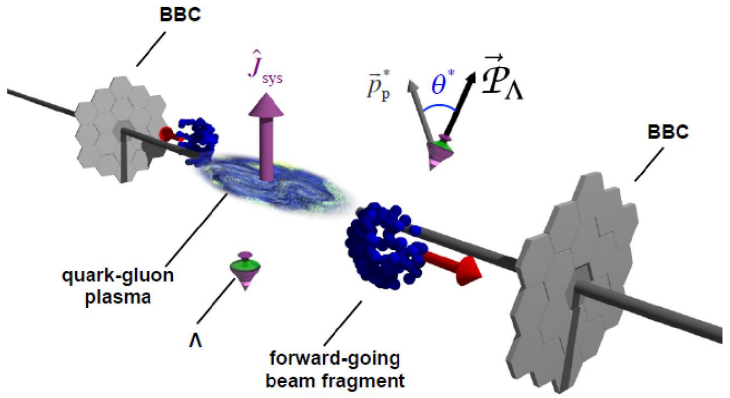
- Due to the complexity of QCD matter with many-body effects and the limitation of current experimental techniques, the study relies on **multi-observables** and **theoretical modeling** to extract the useful information.

- The goal is to utilize the transport theory constructed from quantum field theory to probe QCD matter through **new observables** such as the **spin or chiral transport phenomena** in heavy ion collisions or compact stars.

K. Fukushima, T. Hatsuda, Rep. Prog. Phys. 74 (2011) 014001



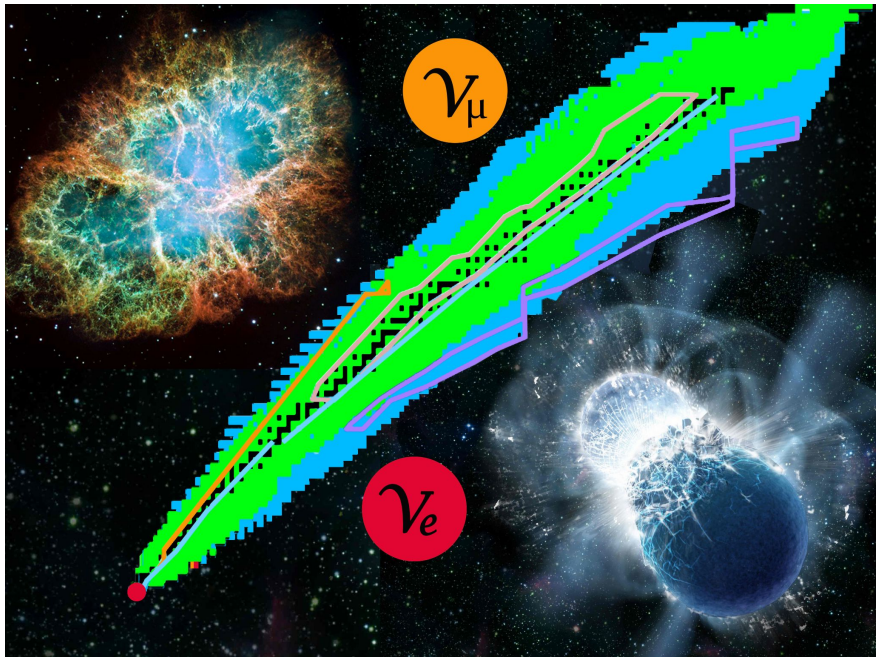
Global Λ polarization in HIC :



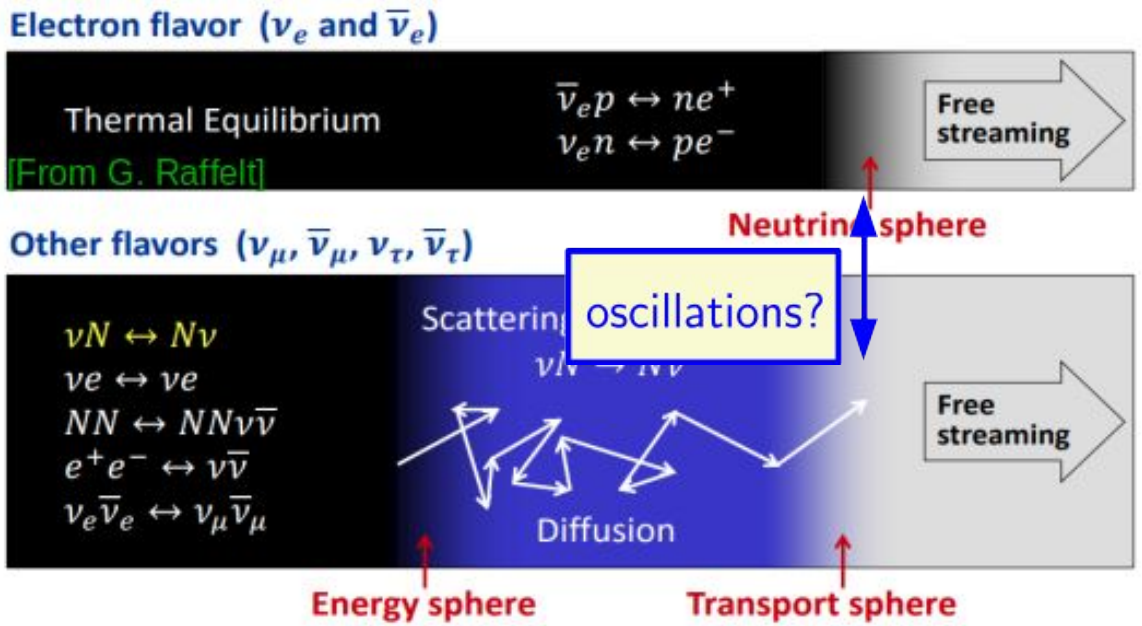
L. Adamczyk et al. (STAR), Nature 548, 62 (2017)

Neutrinos & the origin of heavy elements

[PI: MR Wu]



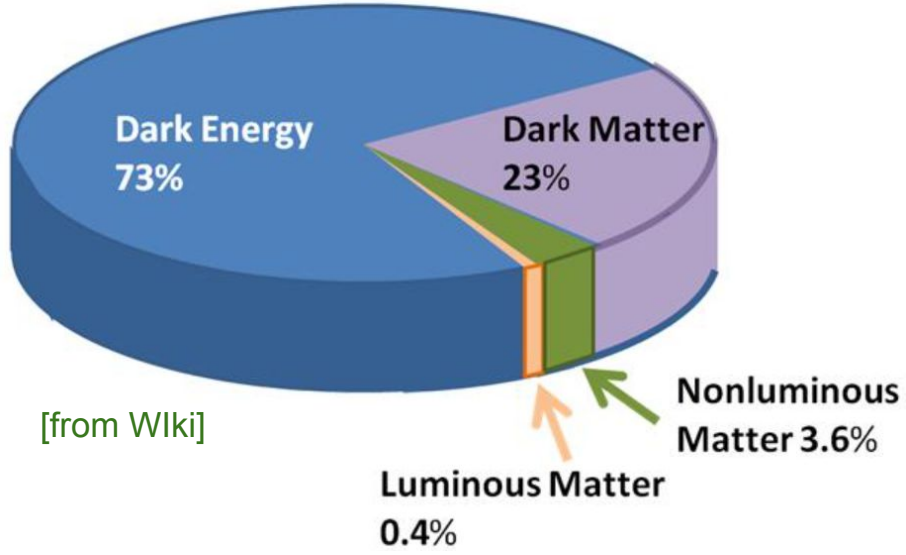
- Uncovering the origin(s) of nature's heavy elements is one of the holy grails in nuclear astrophysics – **supernovae**? **neutron star mergers**? …?
- **Neutrinos** are key to determine the **nucleosynthesis** conditions & important multimessenger probes of these phenomena.
- Important to understand **non-equilibrium quantum kinetic transport** (collisions + flavor oscillations) of neutrinos.
- Particularly challenging is their **"collective" flavor oscillations**, a multi-scale problem featuring similar properties as plasma turbulence.



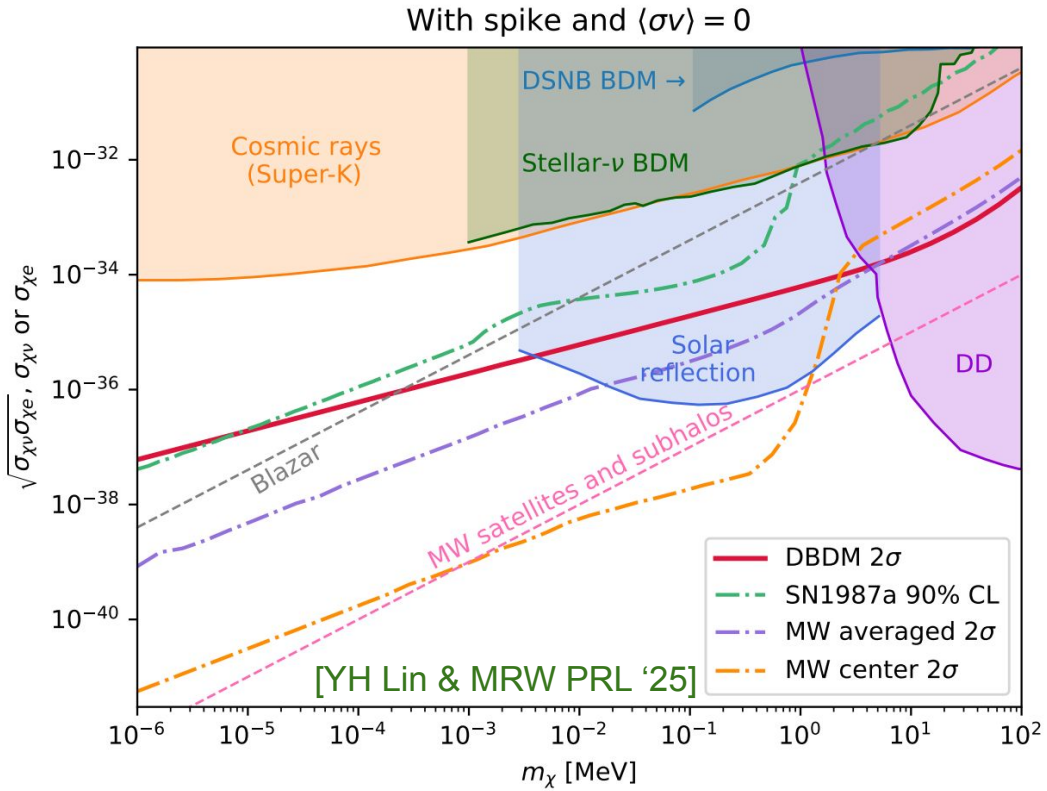
Astrophysical insights into dark matter

[PI: MR Wu]

- **Dark matter** consists of ¼ of present day's energy density in the whole universe. However, terrestrial experiments have yet been able to detected them.
- Various astrophysical phenomena provide complementary opportunities for dark matter hunting, widening the search window.
- Important to utilize **new astrophysical observables** to scrutinize traces of dark matter candidates.
- Equally important is to **improve theory modeling of astrophysical probes** – e.g., dark matter captures & thermalization in stellar bodies.



[from Wlki]



[YH Lin & MRW PRL '25]

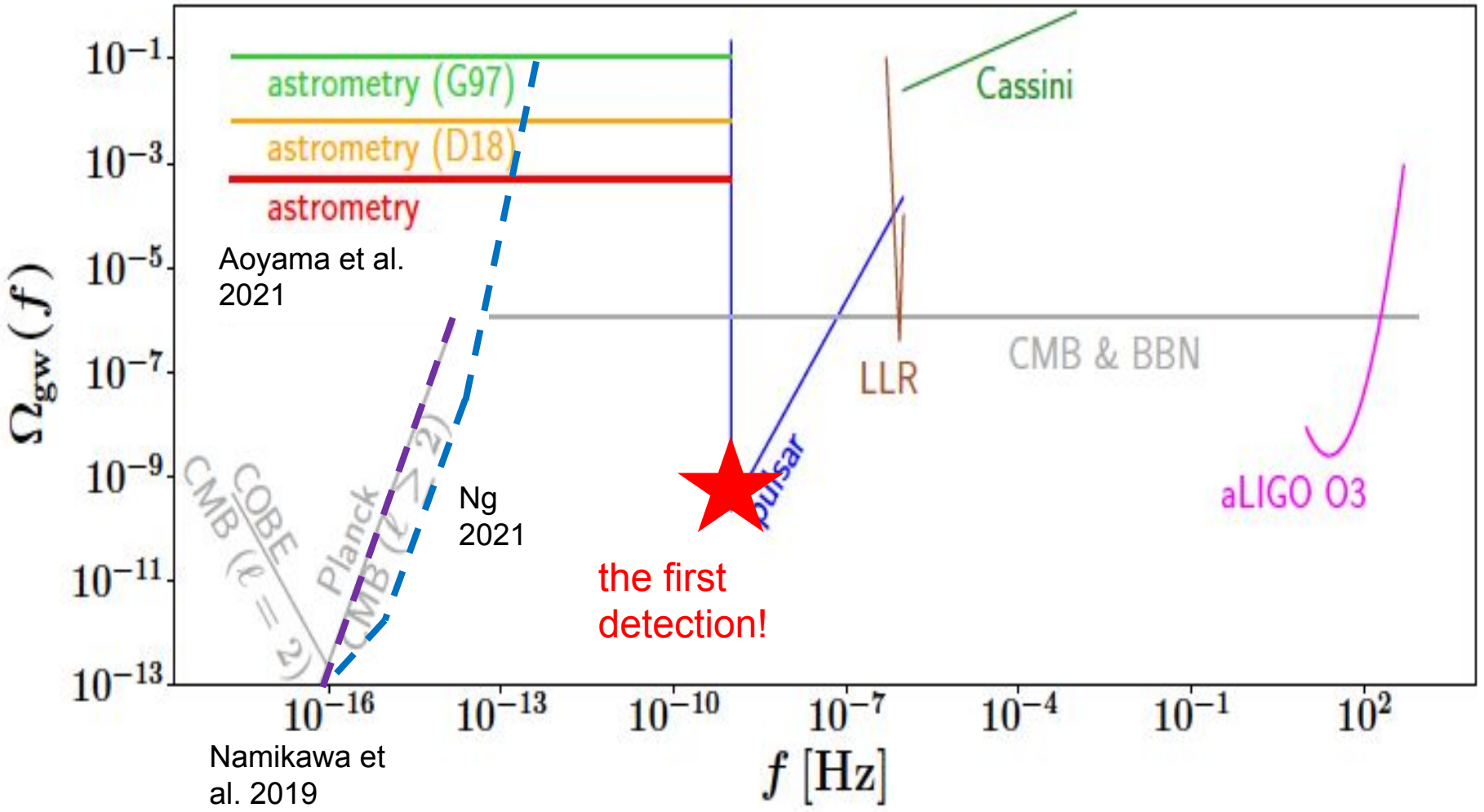
Initial conditions beyond slow-roll inflation

[PI: KW Ng]

- Recent CMB and LSS data have supported slow-roll inflation predictions for nearly scale-invariant and Gaussian primordial density fluctuations: Cosmological Standard Model.
- Large non-Gaussian primordial density fluctuations on small scales?
- They could be generated in later stage of inflation (too many references to list).
- They seed primordial black holes (PBHs) associated with gravitational waves (GWs).
- PBHs can be dark matter with say $m_{PBH}=1\text{-}10^{9}m_{\odot}$.
- PBHs may play an important role in forming first stars and galaxies in cosmic dawn and reionization epoch.
- This can be reconstructed by GW observation, CMB optical depth, 21 cm global signal and

Current upper bound on energy density of Gravitational Wave Background (GWB) and the first detection at nanohertz frequency

[PI: KW Ng]

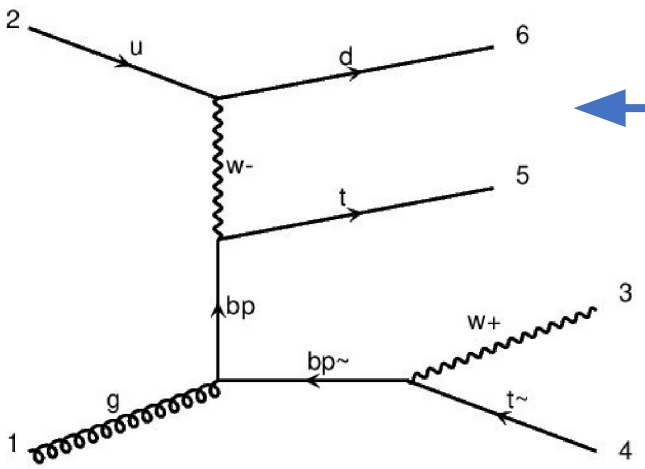


GWB encodes the evolutionary history of the Universe. GWB is a long-sought target in GW experiments, CMB measurements, pulsar timing arrays, and astrometric observation. The PTA experiments have recently detected a GWB at nanohertz. To develop efficient numerical codes for simulations of GW signals as well as data pipelines for parameter estimation are utmost important to advancing GWB observation and science output.

Flavor structure in Standard Model and its potential extension

[PI: HN Li]

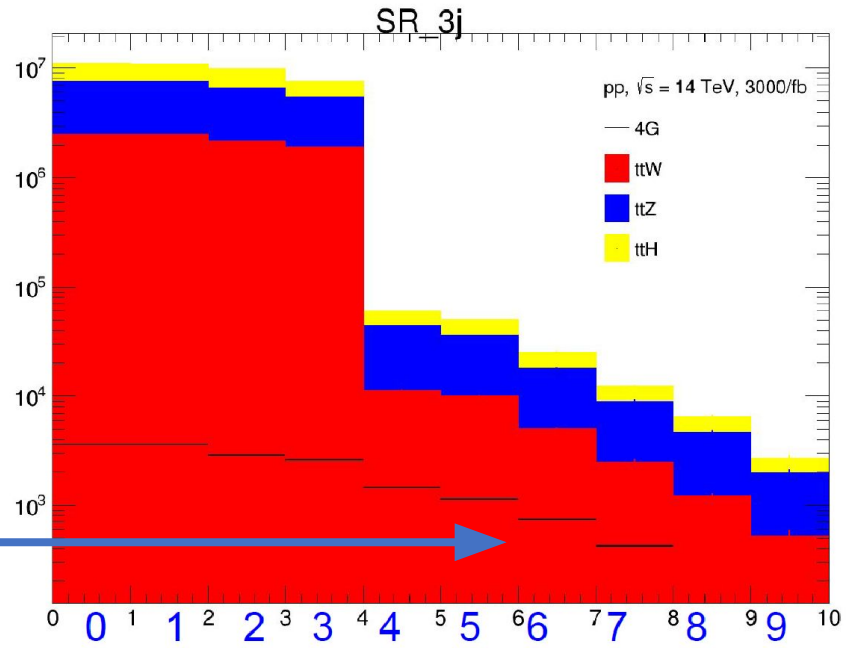
- Baryogenesis and dark matter demand new physics
- Dispersive analysis of SM flavor structure motivates 4th generation (SM4)
- Have shown SM4 satisfies all experimental, theoretical requirements
- Working with experimentalists on search for 4G fermions at LHC



single b' production
hadronic 3-jet channels
are promising
can reach 5 sigma by
end of Run4

5:SubLeading jet pT >500 GeV

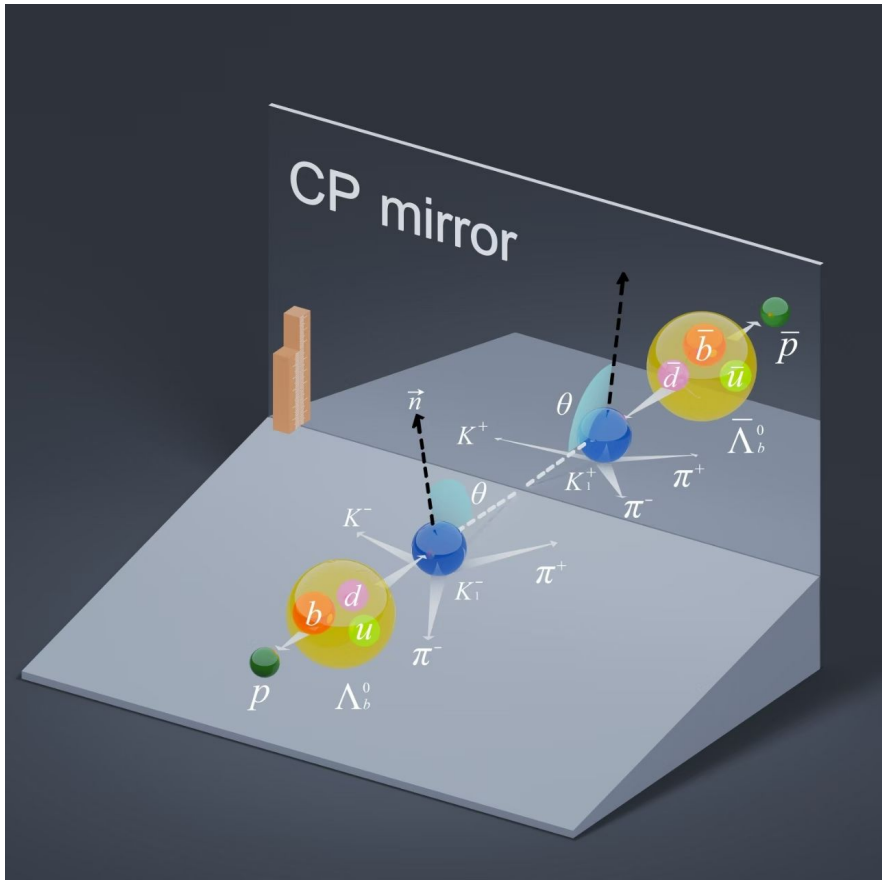
6:Leading jet pT >1200 GeV



CP violation in heavy baryon decays

[PI: HN Li]

- LHCb just announced 1st observation of CPV in bottom baryon decays
- Consistent with our predictions based on factorization theorem
- Milestone in understanding CPV mechanism in baryonic processes
- Pushing theoretical precision to higher orders and twists



Origin of high-energy cosmic particles

[PI: A Fedynitch]

- The **astrophysical sources** producing the ultra-high-energy cosmic-rays and the high-energy neutrinos remain illusive.

- Improving the theory modeling for the **interaction and propagation of high-energy cosmic rays** is necessary for cosmic-ray composition extraction and for reducing atmospheric background for high-energy neutrinos.

- **Data-driven** models + **machine-learning** based parameter extraction are currently being developed – key to help resolve this issues and some related puzzles.