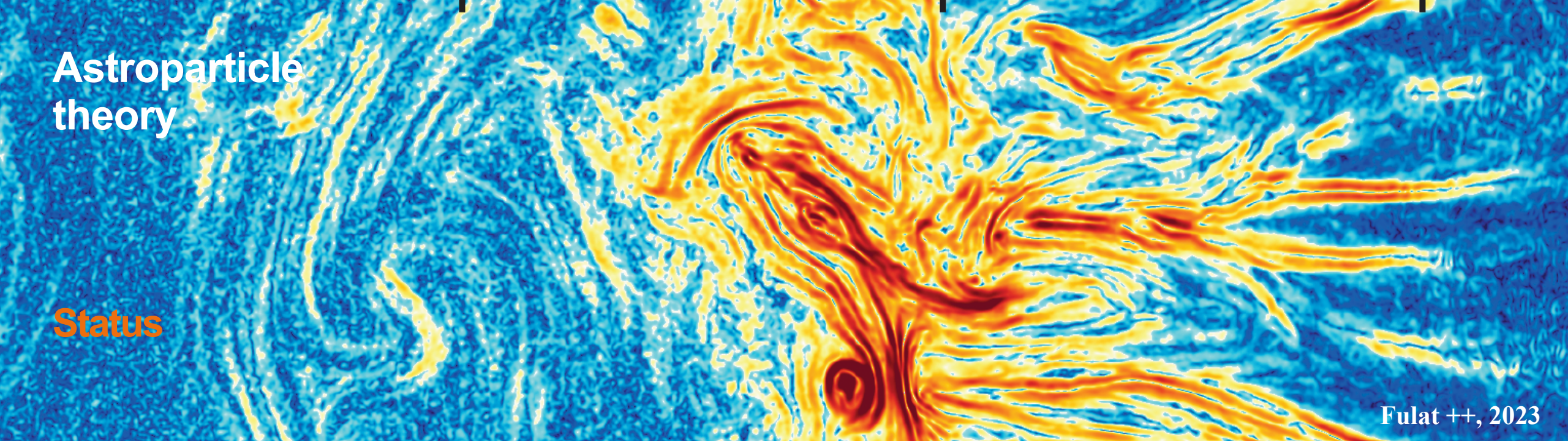


Thomas Schwetz-Mangold (KIT), Winter Walter (DESY) and Michael Klasen (WWU Münster)

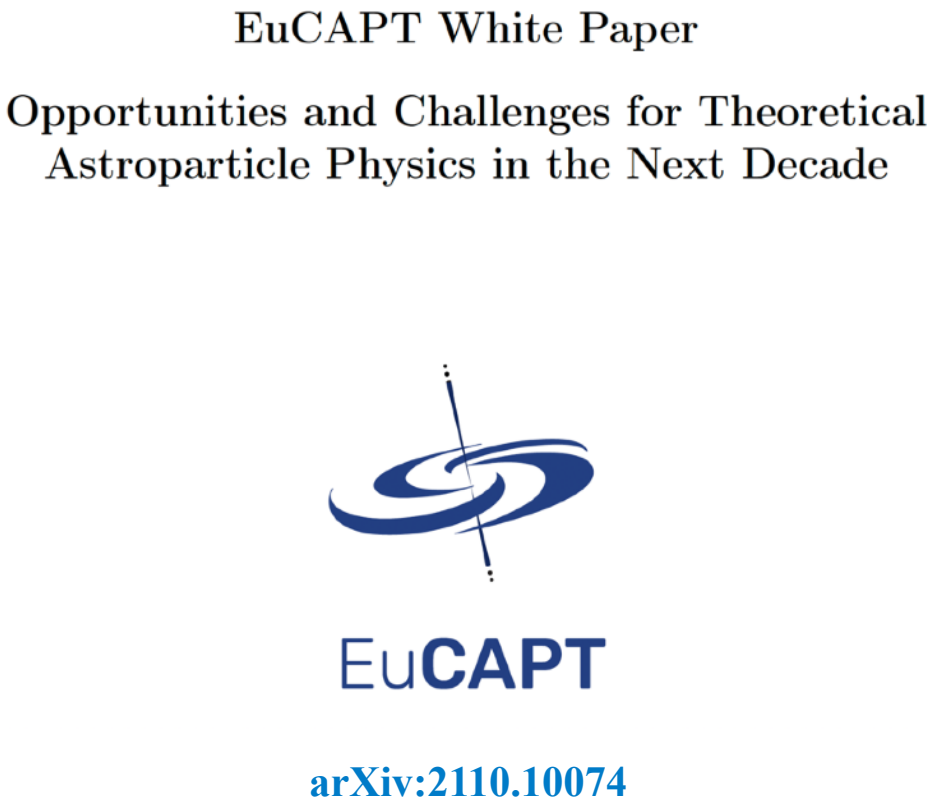
Astroparticle Physics in Germany — Long-Term Strategy 2024

Karlsruhe, 17. 10. 2024

Contents

- Introduction to Theory approach:
  adapting EuCAPT white paper to German AP theory landscape
- Topics of theoretical astroparticle physics (walk-through)
- Theory-community input so-far and a proposal for how to integrate theory into the main document
- Community input required:
  Plans and challenges for the next decade for AP theory?
  What resources do we need for AP theory?
- Open questions/discussion

The European Consortium for Astroparticle Theory — EuCAPT



- EuCAPT goals:
  - to increase the exchange of ideas and knowledge;
  - to coordinate scientific and training activities;
  - to help scientists attract adequate resources for their projects;
  - to promote a stimulating, fair and open environment in which young scientists can thrive.

  https:///www.eucapt.org

- **White paper on perspective for next decade published in 2021**
- No equivalent initiative/program in Germany

⇒ use EuCAPT White Paper as starting point and adapt to German AP theory landscape

Starting point: EuCAPT white paper

Topics with critical German participation

Topics EuCAPT white paper:	Related experimental topics KAT
• Early Universe	
• Dynamical Spacetimes →	• Gravitational waves
• Nuclear Astrophysics →	• Nuclear astrophysics
• Cosmic Accelerators →	• Cosmic rays, gamma-rays, neutrino astronomy
• Traveling and Interacting Messengers →	• Cosmic rays, [gamma-rays, neutrino astronomy]
• Neutrino Properties →	• Neutrino properties
• Particles from stars	• Low-energy neutrino astrophysics, nuclear astroph.
• Dark Matter →	• Dark matter
• Dark Energy	
• Astrostatistics	

Starting point: EuCAPT white paper

Topics with critical German participation

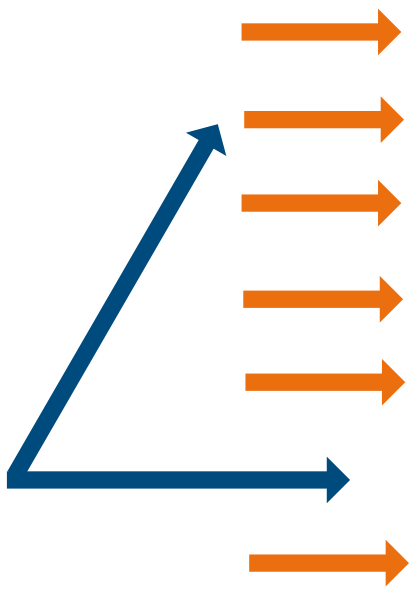
Topics EuCAPT white paper:

- Early Universe
- Dynamical Spacetimes
- Nuclear Astrophysics
- Cosmic Accelerators
- Traveling and Interacting Messengers
- Neutrino Properties
- Particles from stars
- Dark Matter
- Dark Energy
- Astrostatistics

KAT theory

KAT theory

KAT theory?



Related experimental topics KAT

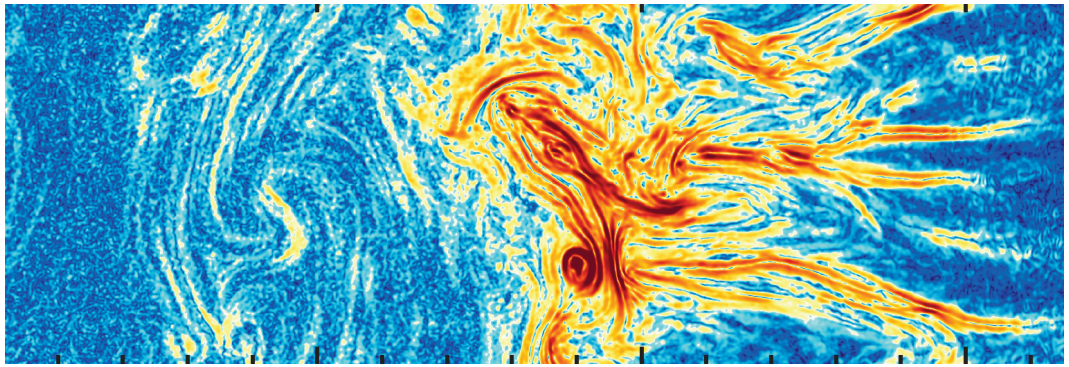
- Gravitational waves
- Nuclear astrophysics
- Cosmic rays, gamma-rays, neutrino astronomy
- Cosmic rays, [gamma-rays, neutrino astronomy]
- Neutrino properties
- Low-energy neutrino astrophysics, nuclear astroph.
- Dark matter

Current strategy:
Merge “particles from stars” with nuclear astrophysics.
Merge ”Early Universe” and ”Dark Energy” into “Evolution of the Universe”

Cosmic accelerators

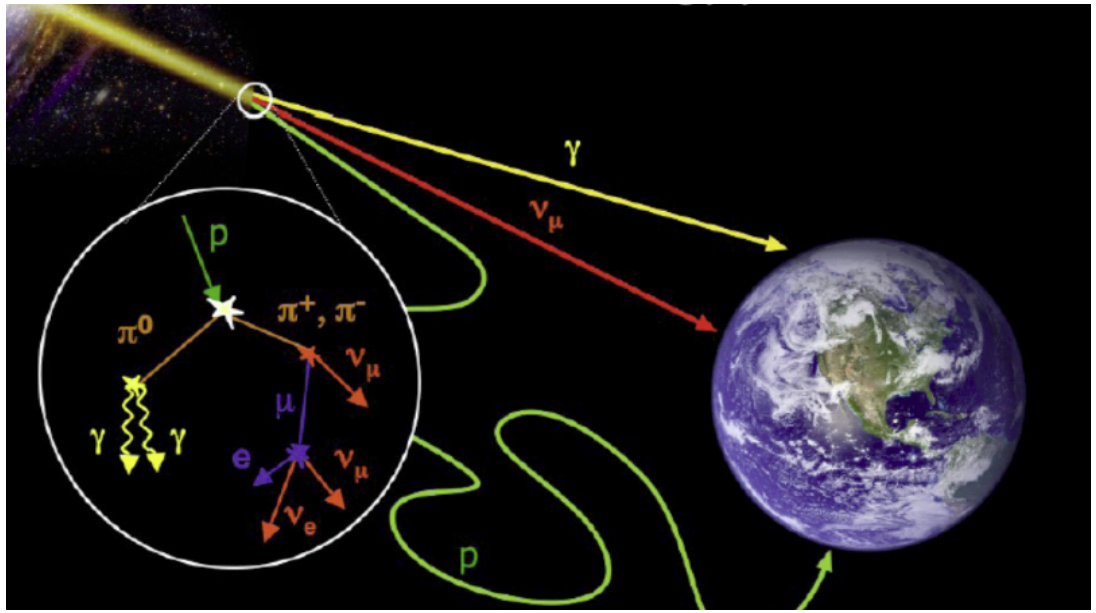
- Key observations requiring new theoretical frameworks:
  - Pevatrons in the Galaxy: Supernovae and Beyond
  - Relativistic jets from supermassive black holes
  - Gamma-Ray Bursts
  - Diffuse contributions
- Closely related to **multi-messenger astrophysics**, interdisciplinary
- Calculations span extremely large/different scales; very different methods

Fulat et al, 2023



Traveling messengers

- Microphysics of cosmic-ray transport, impact on composition measurements, e.g. CRPropa, PriNCE
- Role of electromagnetic cascades from transport
- Role of magnetic fields

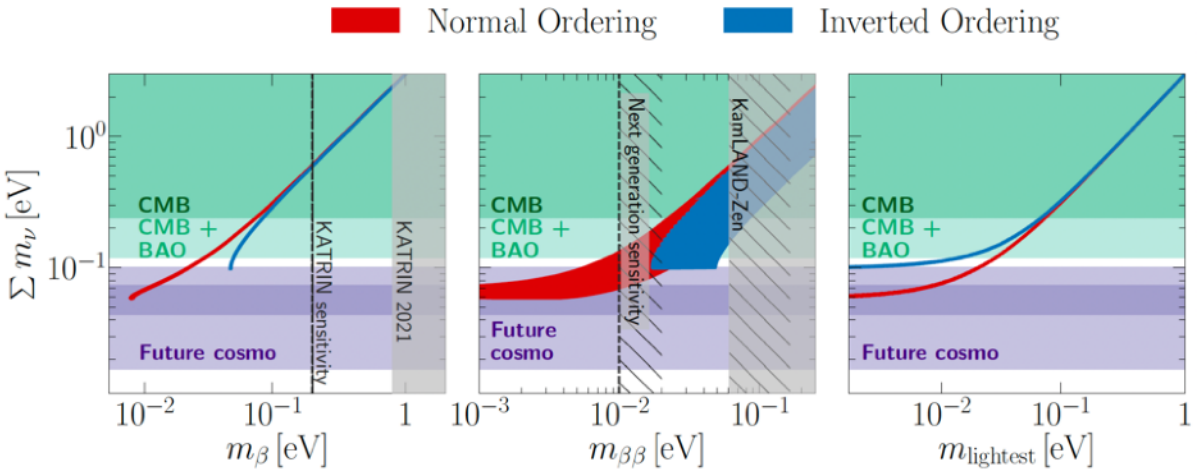


- Connection with fundamental physics, interactions in atmosphere

EuCAPT white paper, arXiv:2110.10074, adapted to German perspective

Neutrino properties

- Origin of mass, mass ordering, mixings
- Dirac or Majorana? Role of $0\nu\beta\beta$?
- Do sterile neutrinos exist?
- Is there a theory of flavor?
- What are the interaction properties?
- Role in leptogenesis, CP violation
- Beyond the Standard Model

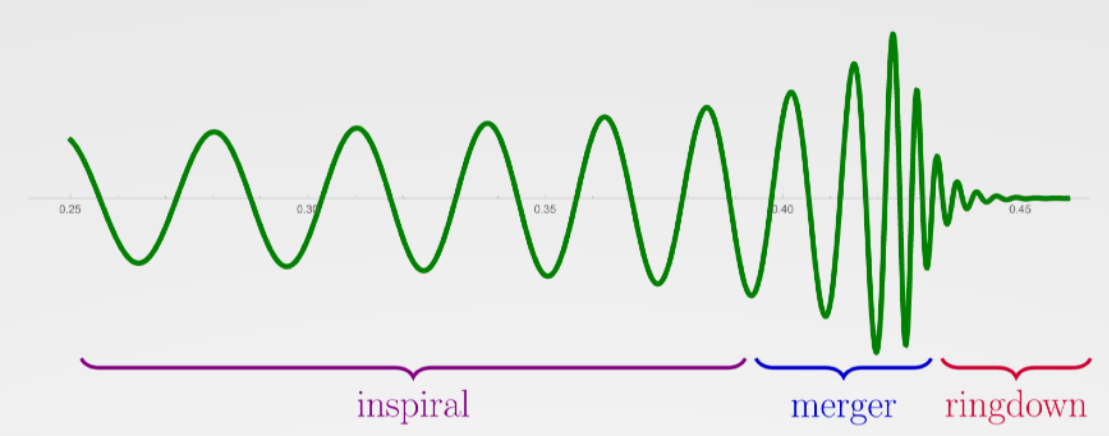


Dynamical spacetimes

1. Nature of compact objects
2. Laboratory for dark matter and general relativity e.g. *quantum gravity*

Tools:

- Perturbative computations
- Numerical relativity



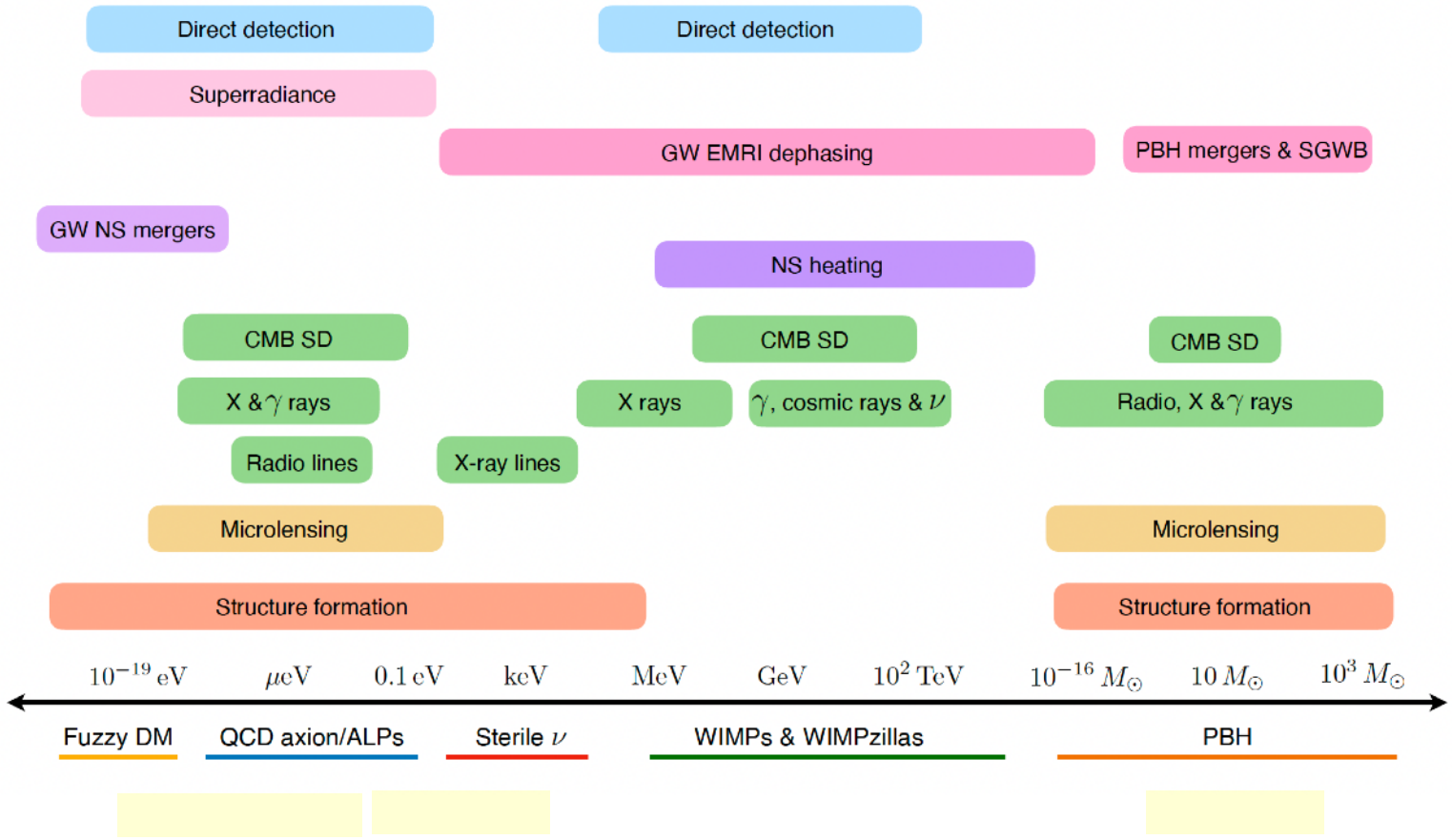
G. Kälin

EuCAPT white paper, arXiv:2110.10074

Dark matter

Key questions:

- Production in early universe?
- Formation of large-scale structures?
- Which candidates are viable, and how can these be explored
- Complementarity of different searches
- Are there ”extra ingredients”, e.g. self-interactions, interesting mediators,… ?
- How to integrate DM into the Standard Model of particle physics



EuCAPT white paper, arXiv:2110.10074; adopted to German perspective

Nuclear astrophysics

Connect these two topics!

Key objectives (theory):

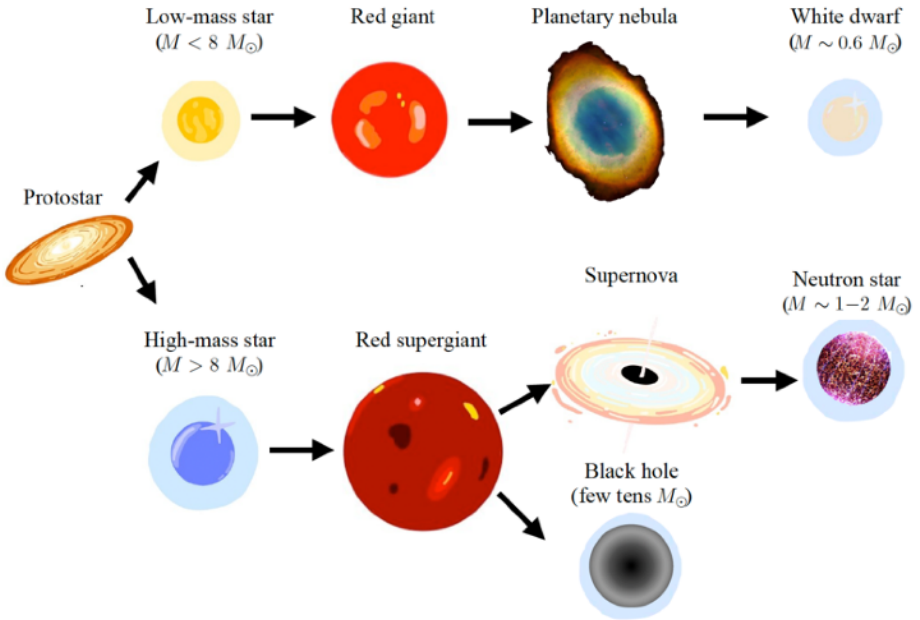
- Predict nucleosynthetic yields
- Multi-messenger picture: gravitational waves, electromagnetic radiation, neutrinos
- Simulation of dynamical systems
- Role of neutrinos and axion-like particles, and their properties
- Key role connecting laboratory advances with astrophysical phenomena

Challenges:

- Large parameter spaces, complexity, many disciplines
- Computational resources
- Ambition to serve as an umbrella for coherent interpretation of multi-messenger signals

Particles from stars

- Sun/stars
- Evolved stars, white dwarfs
- Accretion disks, outflows from black holes
- Transients, supernovae
- Neutron stars, black holes
- Compact object mergers



EuCAPT white paper, arXiv:2110.10074; adopted to German perspective

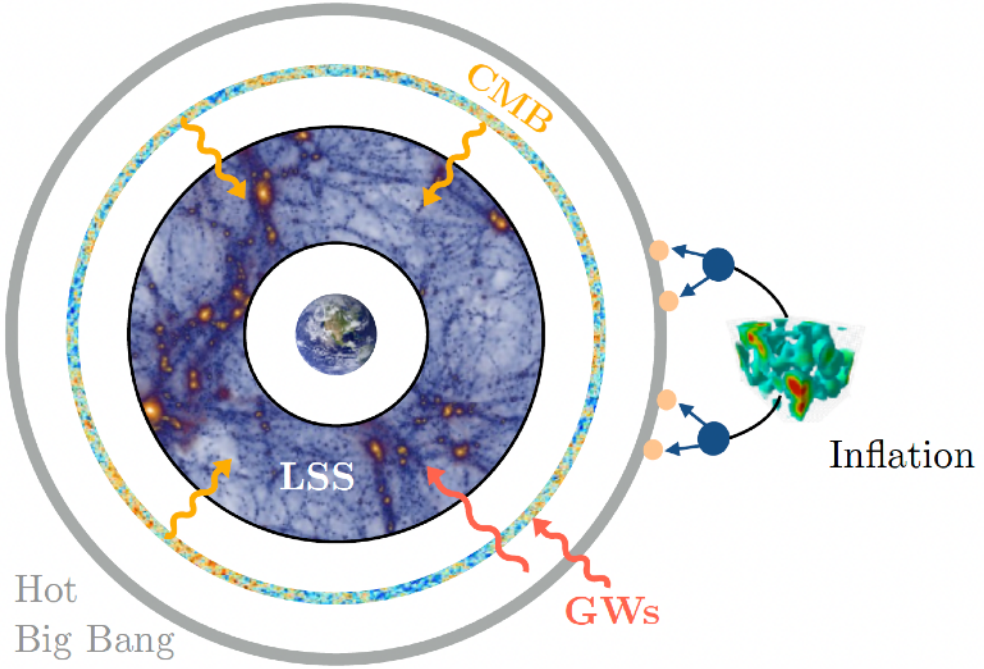
Dark energy

- cosmological constant problem, origin of dark energy density
- Effective approaches
- Theoretical constrains
- Observational prospects

Early universe

- Physics of inflation, reheating, primordial tensor perturbations?
- Thermal relics from the big bang
- Baryogenesis and leptogenesis
- Phase transitions

No direct experimental counterpart in KAT. Merge into “Evolution of the Universe”



EuCAPT white paper, arXiv:2110.10074, slightly adjusted

Community input - Status

- Theory input solicited from experts in their field especially in areas not represented well by the editorial board or other topics:
  - "half a page for each topic on the key science questions and 1-2 paragraphs and the research focus of the German theory community"
  - "half a page for each topic on plans and challenges for the next decade"
- Idea: Complement expertise available in other topics, **do not forget important areas pursued by the German community**
- Result: Substantial overlap with key science questions/input from experimental groups
- However: some overarching/cross-topic subjects (e.g. cosmic accelerators), and subjects without experimental counterparts (e.g. Evolution of the Universe)

- **Cosmic accelerators**
  (Andrew Taylor, Walter Winter)
- **Traveling and interacting messengers**
  (Günter Sigl, also overlap with "cosmic rays")
- **Dark matter**
  (Joachim Kopp)
- **Neutrino properties**
  (to be covered by Thomas Schwetz-Mangold)
- **Nuclear astrophysics**
  (Andreas Bauswein, Gabriel Martínez-Pinedo)
- **Gravitational wave physics**
  (sufficient input Harald Lück?)
- **Evolution of the Universe**
  (Early Universe, Dark Energy etc; Laura Covi)

KAT theory, and its way into the main document

Proposal:

- Integrate **topic-specific activities** into the corresponding **experimental subsections** (avoid repetition of science goals)

- have a **dedicated theory section** focusing on:
  - **overarching cross-topics** (e.g., multi-messenger astronomy, search for beyond-Standard Model across different phenomena)
  - **topics with no direct experimental counterpart** (early universe cosmology, dark energy, „Evolution of the Universe“)
  - **global embedding** and **links to neighbouring fields** (particle physics, beyond-Standard Model, cosmology, astronomy)

(first proposal is available in the circulated draft)

Crucial role of AP theory for connecting to neighbouring fields

3 examples:

- **Particle physics and beyond-Standard Model physics:**
  Dark Matter, neutrino mass, collider searches for new physics, long-lived particle searches at accelerators, axion searches, theory developments in extensions of the SM,
  thermal quantum field theory: applications in heavy ion physics, early universe, astrophysics

- **Cosmology:** importance of surveys (e.g., GAIA, EUCLID), 21cm observations, CMB missions
  neutrino mass, (ultra-light) dark matter, light new physics, long-lived particles, baryogenesis, cosmic inflation

- **Gravitational waves**
  cross links of ground-based GW searches to space-based (LISA) and pulsar-timing arrays
  stochastic GWs, phase transitions in the early universe (particle physics, neutrino mass, DM,…)

Plans and challenges for the next decade for AP theory?

Community feedback required!

Examples:

- Provide „theory support“ for planned experiments and observatories (physics motivation, phenomenology, simulations,….)
- Follow and contribute to developments in neighbouring fields (particle physics, cosmology) and cross-link to AP
- Change in „culture“: sustainable computing, software publication, open access, AI support, …
- ….

Are there theory-specific challenges?

What resources do we need for AP theory?

Community feedback required!

Examples:

- **Personell funding:** Sufficient size of theory groups at all levels (what does that mean?)
- Access to high-performance and parallel **computing**
- Financial support for **travel, equipment, publication charges**
- Support of **software development, maintenance, publication,** FAIR data principles
- Incentives for "modern" topics, such as sustainable computing, software publication, open access, training in the non-academic sector, outreach, AI support, …
- Additional resources for explorative phenomenological studies which could lead to new experiment classes?
- …

Can we / should we quantify our needs in terms of Euro?

Recommendations — proposal

Community feedback required!

- Importance of **„experiment-close“ theory and phenomenology**
- Support **astroparticle theory** in its own right:
  - genuine astroparticle theory and phenomenology
  - integration in the global physics context
    links to neighbouring fields (e.g., particle physics, cosmology)
- Dedicated funding for (theory-related) **computing**

Q: should/can we give specific funding recommendations (in Euro)?

Open issues / discussion

Please provide input:

- comments on our approach to integrate AP Theory into the document
- comments on strategy and challenges
- comments on recommendations and quantifying resources
- are we missing something?

please send your comments to:

walter.winter@desy.de, michael.klasen@uni-muenster.de, schwetz@kit.edu