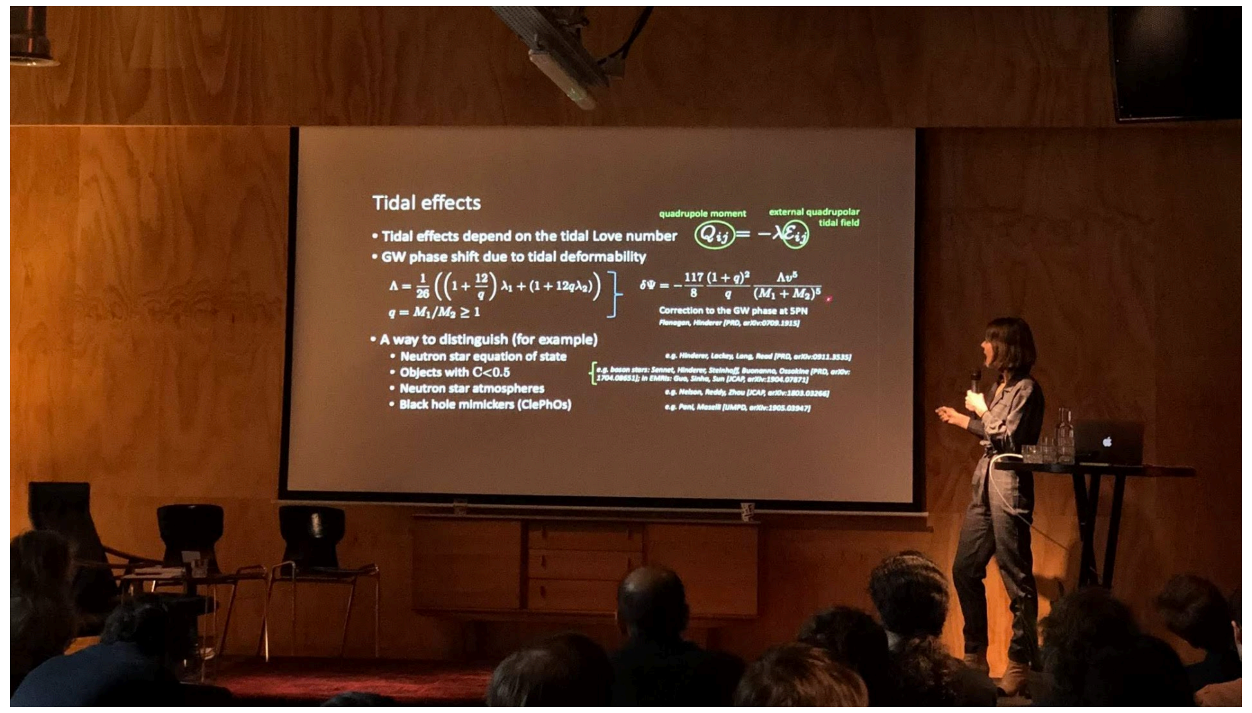
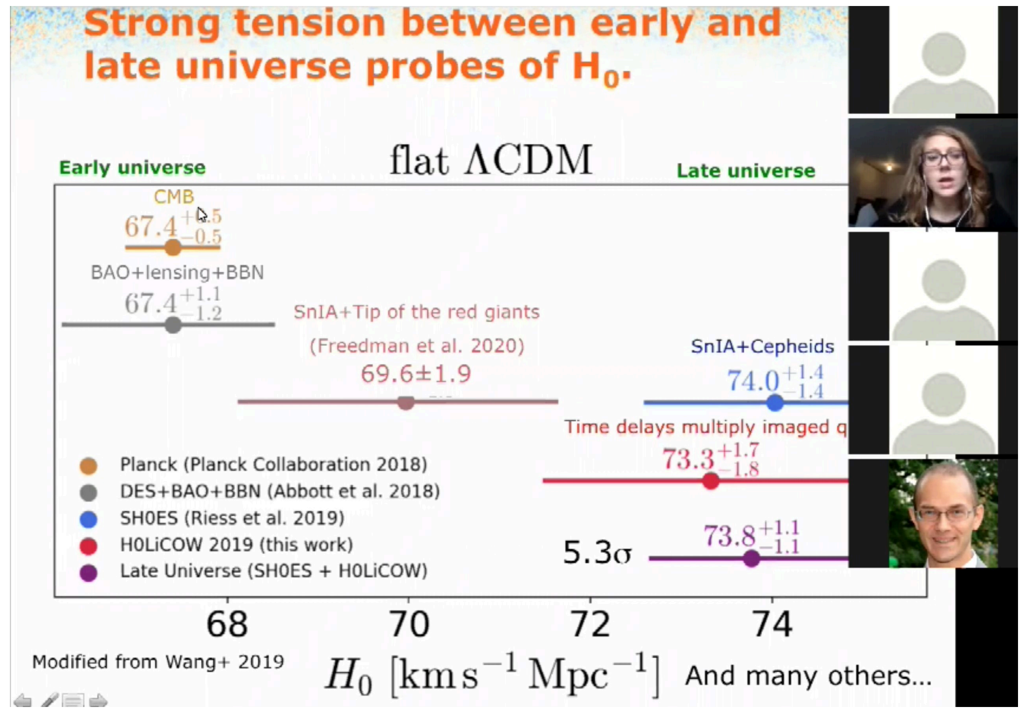
Theory

or *“Challenges and opportunities in theoretical astroparticle physics in view of upcoming multi-messenger observations”*







Gianfranco Bertone

Multi-Messenger Astrophysics Workshop (MMAW)
EGO, Italy 10/10/2022

EuCAPT Theory Community

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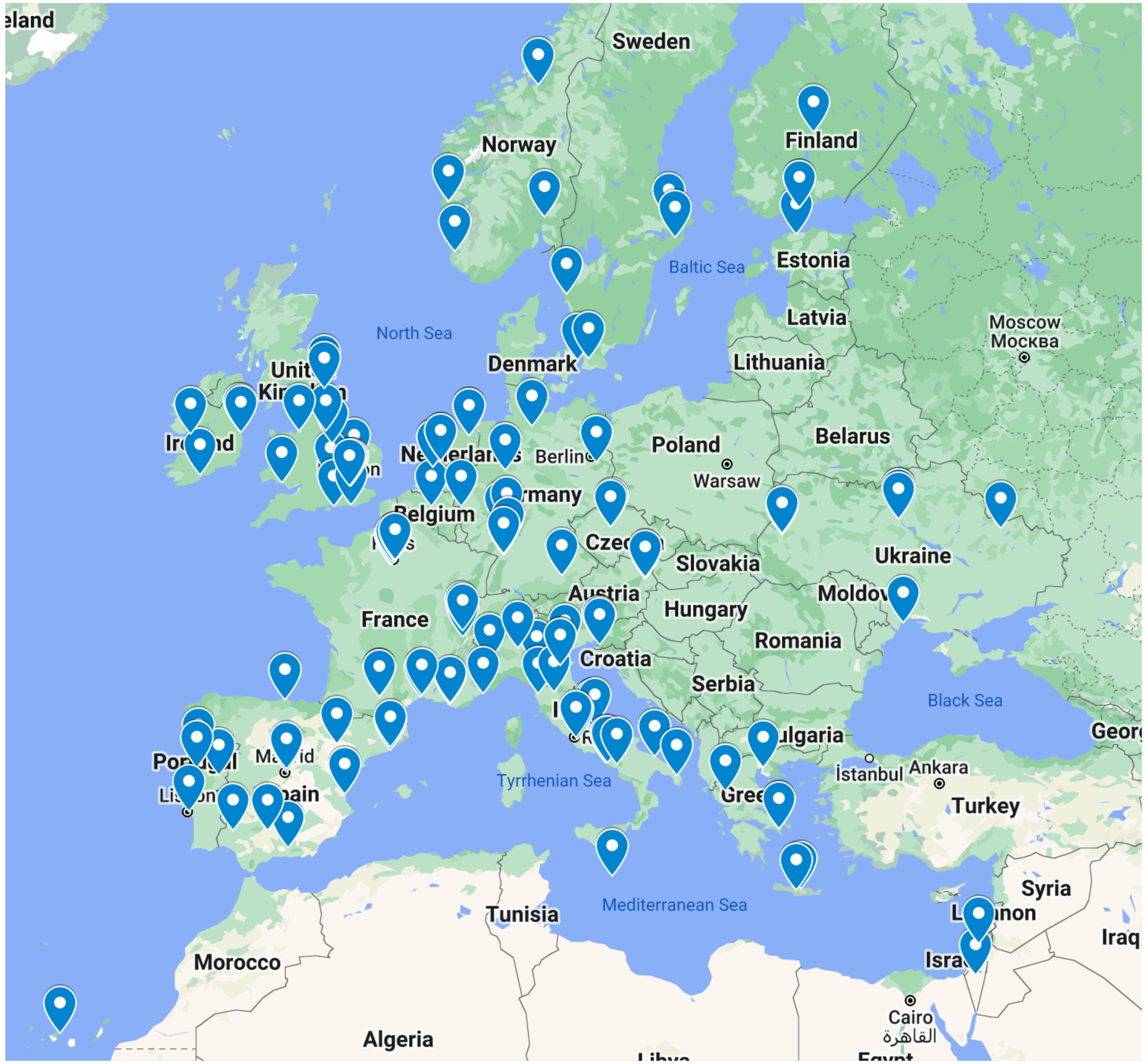

- European network of theorists in APP and Cosmology
- APPEC/CERN agreement in 2019
- Community as of 5 Oct:
  - 131 Institutions
  - 1690 registered members
- 2 Annual Symposia @ CERN
- 5 thematic workshops
- Travel Exchange programme
- Collaboration meetings
- Website/Newsletter
- Virtual events
- Council established last week!

and the **EuCAPT White Paper**

EuCAPT White Paper

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arXiv:2110.10074v1 [astro-ph.HE] 19 Oct 2021

EuCAPT White Paper

Opportunities and Challenges for Theoretical Astroparticle Physics in the Next Decade

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Abstract

Astroparticle physics is undergoing a profound transformation, due to a series of extraordinary new results, such as the discovery of high-energy cosmic neutrinos with IceCube, the direct detection of gravitational waves with LIGO and Virgo, and many others. This white paper is the result of a collaborative effort that involved hundreds of theoretical astroparticle physicists and cosmologists, under the coordination of the European Consortium for Astroparticle Theory (EuCAPT). Addressed to the whole astroparticle physics community, it explores upcoming theoretical opportunities and challenges for our field of research, with particular emphasis on the possible synergies among different subfields, and the prospects for solving the most fundamental open questions with multi-messenger observations.

https://arxiv.org/abs/2110.10074

- **Early universe**: Daniel Baumann and Laura Covi;
- **Dynamical spacetimes**: Rafael Porto and Philipp Moesta;
- **Nuclear Astrophysics**: Tetyana Galatyuk and Tanja Hinderer;
- **Cosmic accelerators**: Sera Markoff, James Matthews, and Enrico Ramirez Ruiz;
- **Traveling Messengers**: Daniele Gaggero and Kumiko Kotera;
- **Neutrino Properties**: Thomas Schwetz and Olga Mena;
- **Particles from stars**: Aldo Serenelli and Irene Tamborra;
- **Dark Matter**: Francesca Calore, David J. E. Marsh, and Christian Byrnes;
- **Dark Energy**: Alessandra Silvestri, and Julien Lesgourgues;
- **Astrostatistics**: Christoph Weniger and Roberto Trotta.

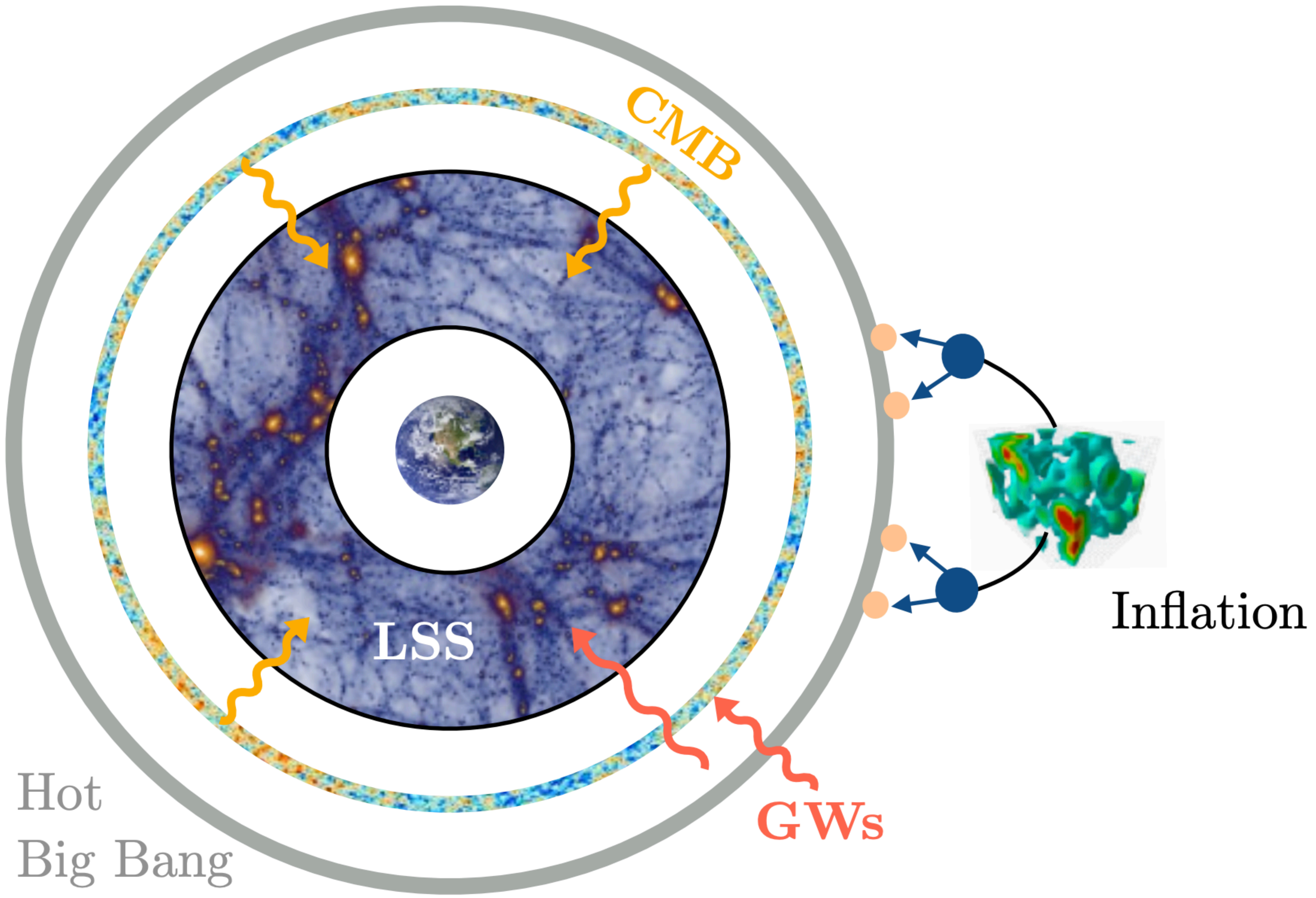
- 135 authors
- 400 endorsers
- 133 pages
- 1382 references

- ..I cannot possibly make justice in 25 mins
- high-level summary of key challenges/opportunities

Early Universe

ΛCDM model phenomenologically very successful, but raises many important questions, in particular about the physics of the early universe

- **Key questions:**
  - What happened in the 1st second?
  - What matter / what physical processes?
  - What created the initial fluctuations?
  - What created the baryon asymmetry?
- **Key challenges:**
  - systematic classification of inflationary predictions
  - calculations of non-Gaussian correlations
  - calculations of other probes of the early universe, including reheating, thermal relics, baryogenesis and phase transitions



Data: Photons (MWL), Neutrinos, GWs

Dynamical Spacetimes

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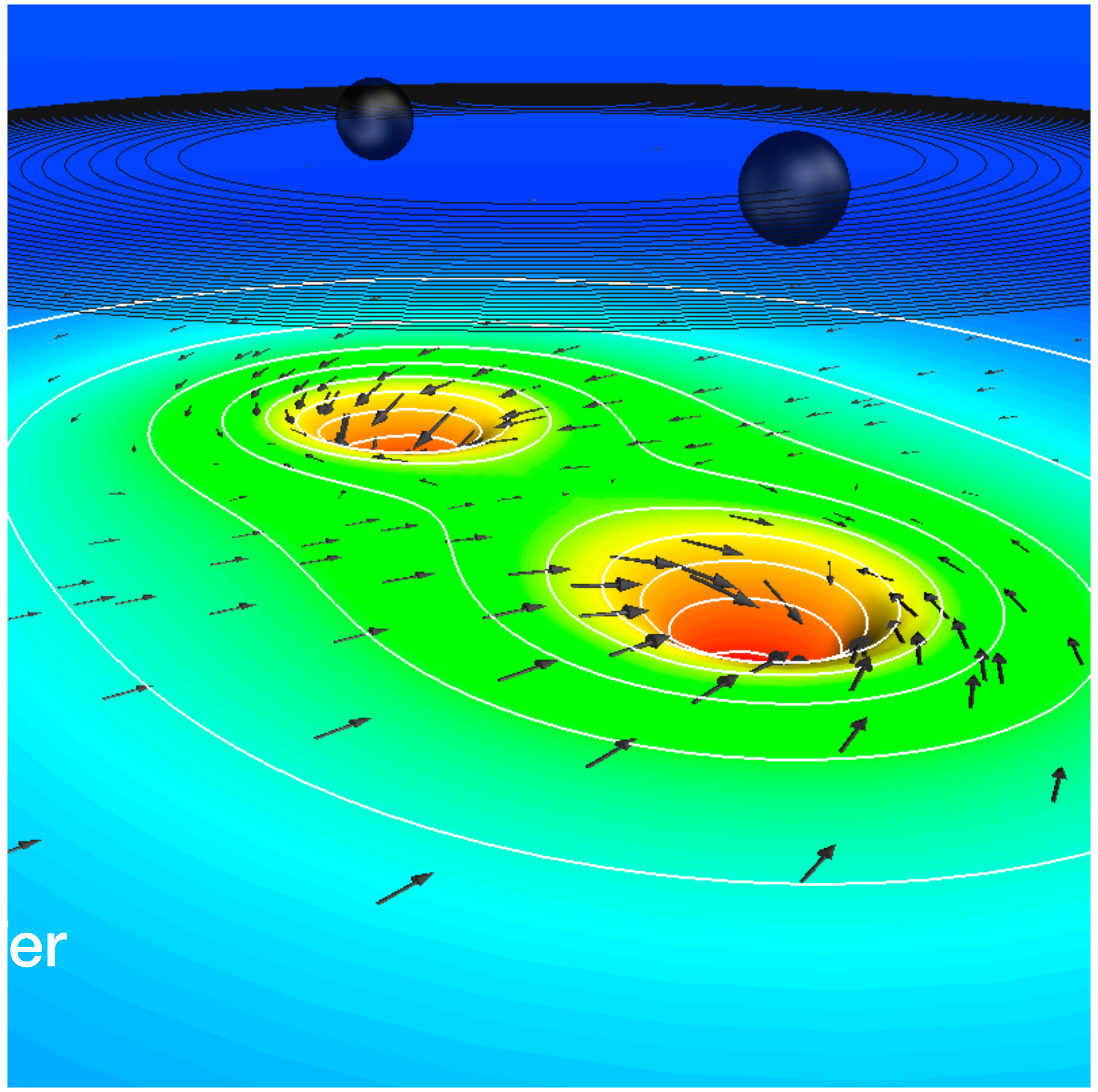
Future interferometers promise to solve long-standing problems in cosmology, astrophysics, and particle physics. High-precision theoretical predictions are crucial to enable new discoveries

- **Key questions:**
  - What is the nature of compact objects in binary systems?
  - Can we discover new physics in BH environments?
  - Does GR hold in the strong field regime?

- **Key challenges:**
  - reaching accuracy needed to properly interpret GW signals in future detectors
  - NR simulations computationally expensive/ significantly slower than perturbative approaches
  - implementing neutrino transport, B fields in full relativistic MHD simulations, to connect with multimessenger observations



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Nuclear Astrophysics

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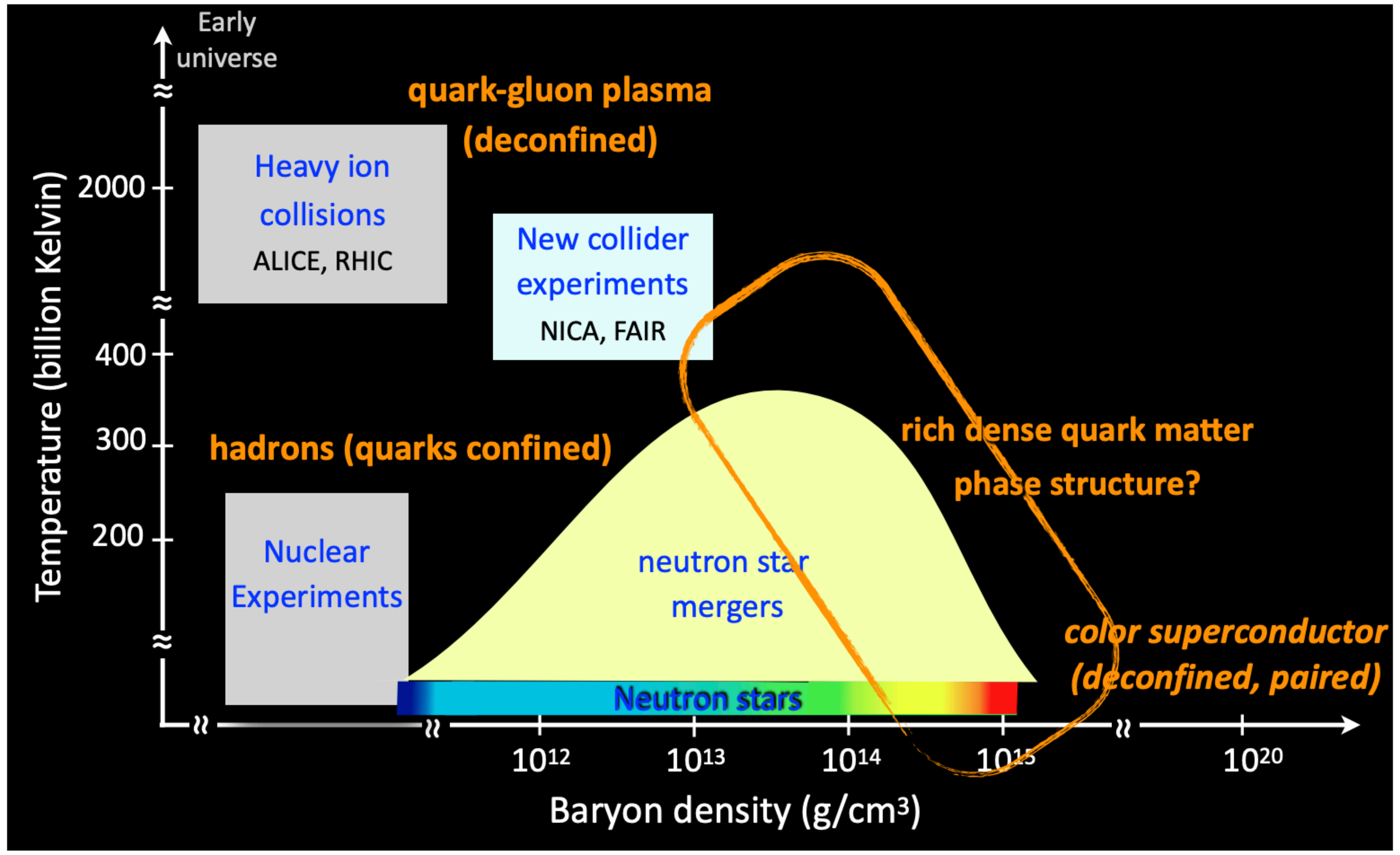
Nuclear astrophysics aims to understand the role of nuclear processes in astrophysical environments, and to probe nuclear astrophysics beyond the reach of terrestrial labs

- **Key questions:**
  - How does nuclear structure emerge from fundamental constituents?
  - What are the properties of nuclear matter in astrophysical environments?
  - What can we learn about QCD?
  - How are heavy elements formed?

- **Key challenges:**
  - Complexity/multi-scale/nonlinear dependence of observables
  - reduce uncertainties on properties of nuclides in unexplored regimes
  - dependence of lightcurves on physical processes and progenitor parameters



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Cosmic Accelerators

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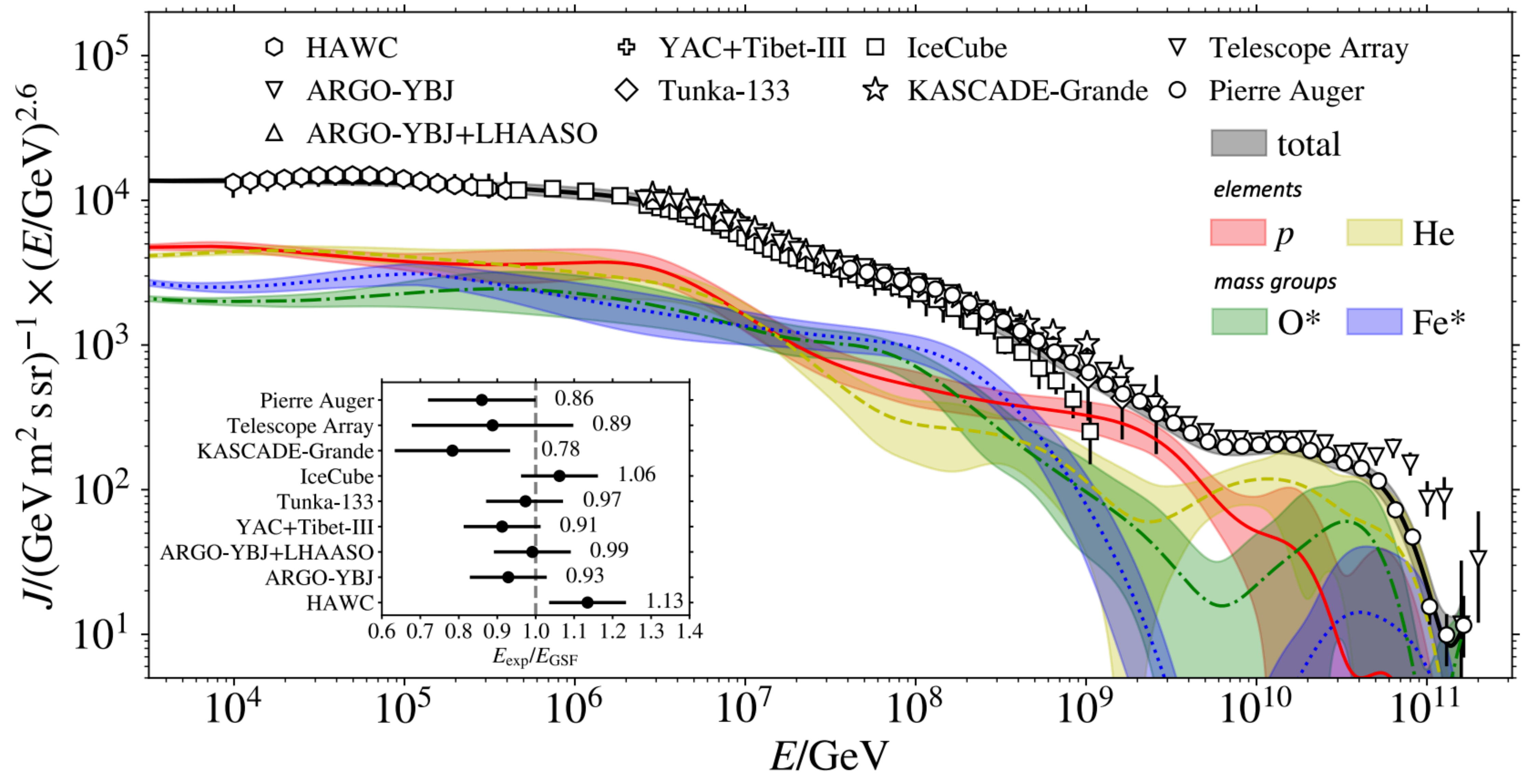
Unambiguously identifying cosmic accelerators remains the perennial challenge, as well as understanding particle acceleration, and sources accounting for total diffuse fluxes in all species

- **Key questions:**
  - What are PeVatrons?
  - Where and how CRs get accelerated to UHE?
  - How do BHs launch jets?
  - What are the sources of diffuse fluxes?

- **Key challenges/opportunities:**
  - predictions of MM and multi-wavelength (MWL) spectra require complex plasma physics
  - multi-scale simulations computationally prohibitive
  - community building is key, facilitating collaboration between scientists and institutions with different specialisations and crosspollination of ideas and methods



Data: Photons (MWL), CRs, Neutrinos, GWs

Traveling and Interacting Messengers

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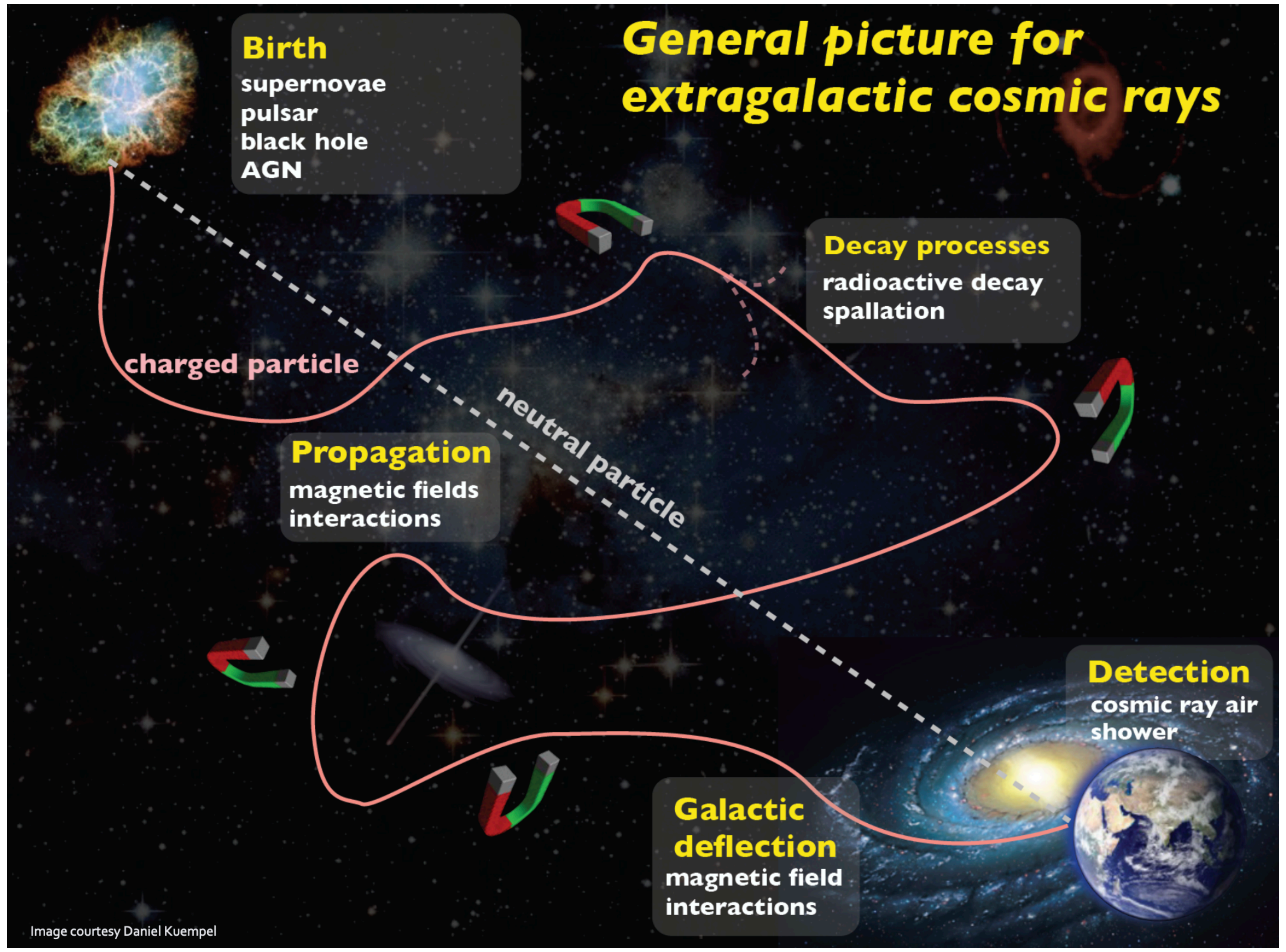
CRs travel from acceleration sites to us, interacting with the traversed media at various scales via micro-physics processes. These interactions leave imprints on astrophysical environments, and multi-messenger hints on their sources

- **Key questions:**
  - How do energetic charged particles interact with/ feedback onto with EM fields?
  - What are the plasma processes regulating propagation through turbulent media?
  - What is the mpact of cosmic rays on their environment?

- **Key challenges:**
  - Can we derive describe diffusion from first-principles?
  - Photodisintegration cross sections of nuclei poorly known
  - Capturing energy cascades/MM aspects in numerical simulations



Data: Photons (MWL), Neutrinos, CRs

Neutrino Properties

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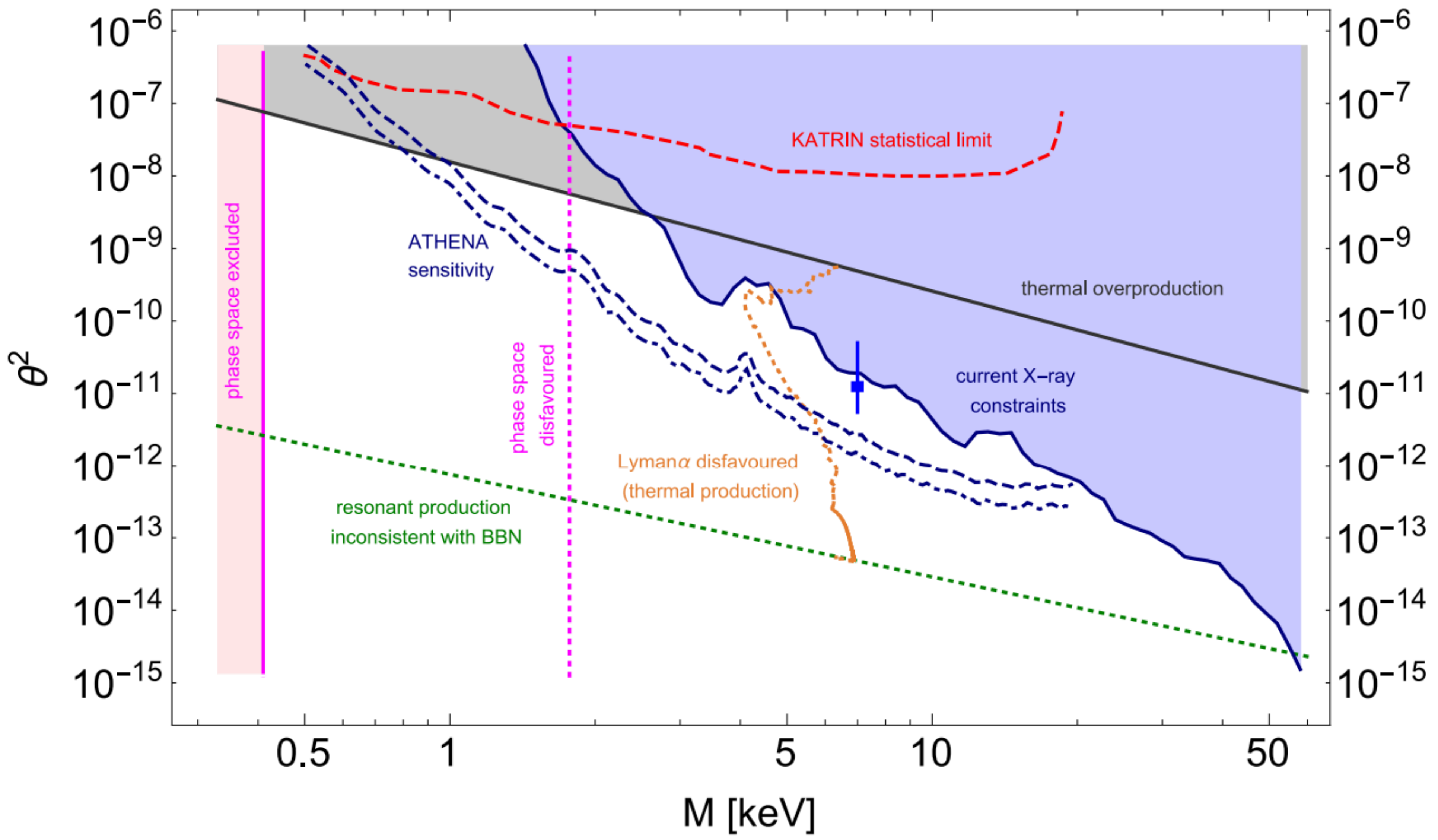
Cosmological surveys and other (astro)particle experiments aim to precisely measure the neutrino mass scale/ connect CP and L violation with the origin of matter / discover new physics

- **Key questions:**
  - Dirac or Majorana?
  - Are there sterile neutrinos?
  - Connections with dark matter? Dark energy? Leptogenesis?
  - Can we use HE astro neutrinos to test neutrino properties?

- **Key challenges/opportunities:**
  - Particle physicists are skeptical about cosmological neutrino mass determinations..
  - Can non-standard neutrino properties explain the H_0/σ_8 tensions?



Data: Photons (MWL), Neutrinos, GWs

Particles from stars

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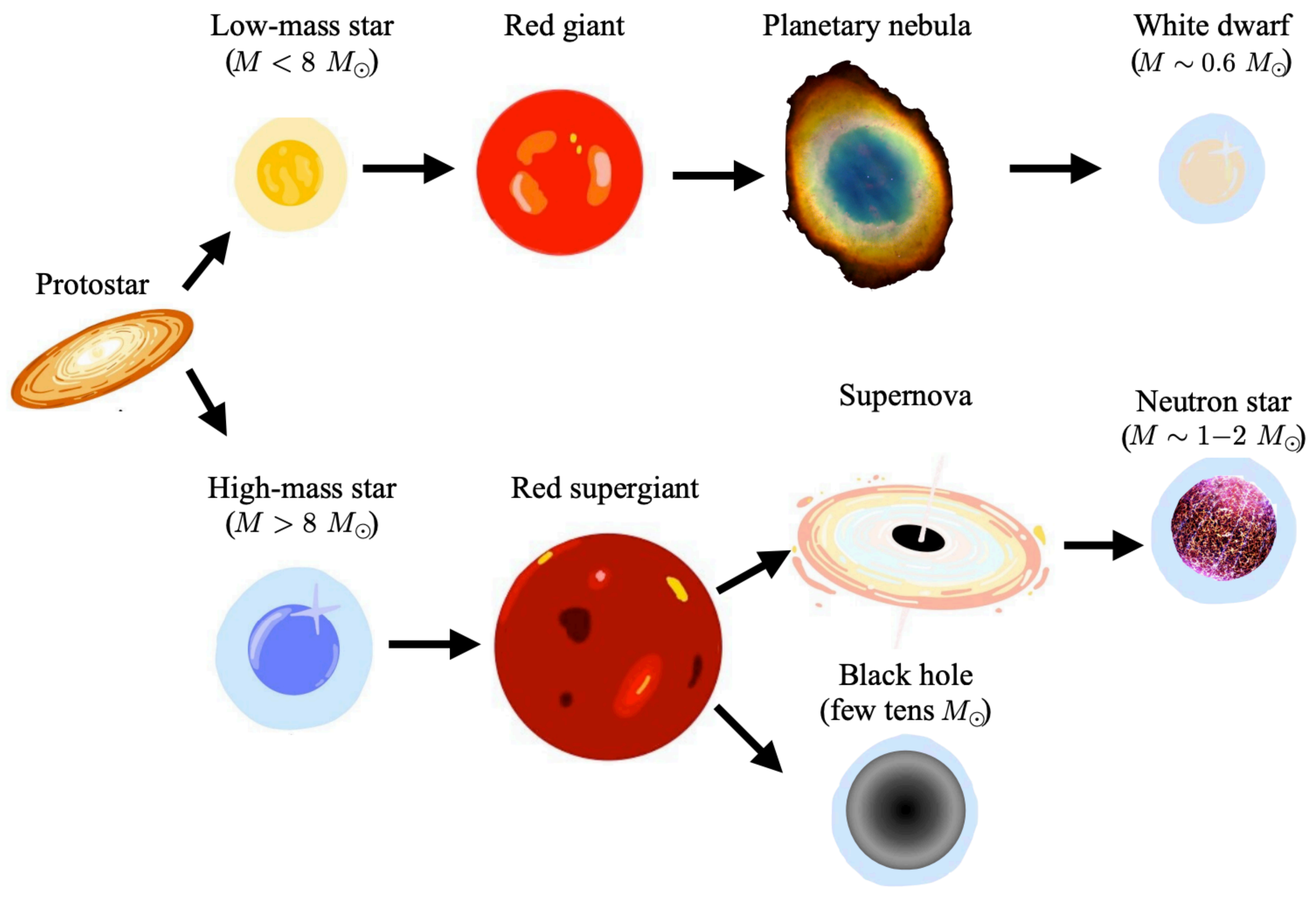
The sheer size of stars and the extreme conditions in stellar interiors make them excellent laboratories for particle physics, complementary in many cases to dedicated Earth-based experiments.

- **Key questions:**
  - What can be learn about new particles from stellar structure and evolution?
  - Can we probe dark matter with stellar physics?
  - Can we detect axions from the Sun?

- **Key challenges:**
  - Improved stellar evolution models throughout evolutionary phases and stellar masses are needed
  - ‘Holistic’ methods to capitalize on the upcoming wealth of multi-messenger data should be developed
  - including (neutrino/radiation/magneto) hydrodynamic + modeling of exotic physics needed to interpret data



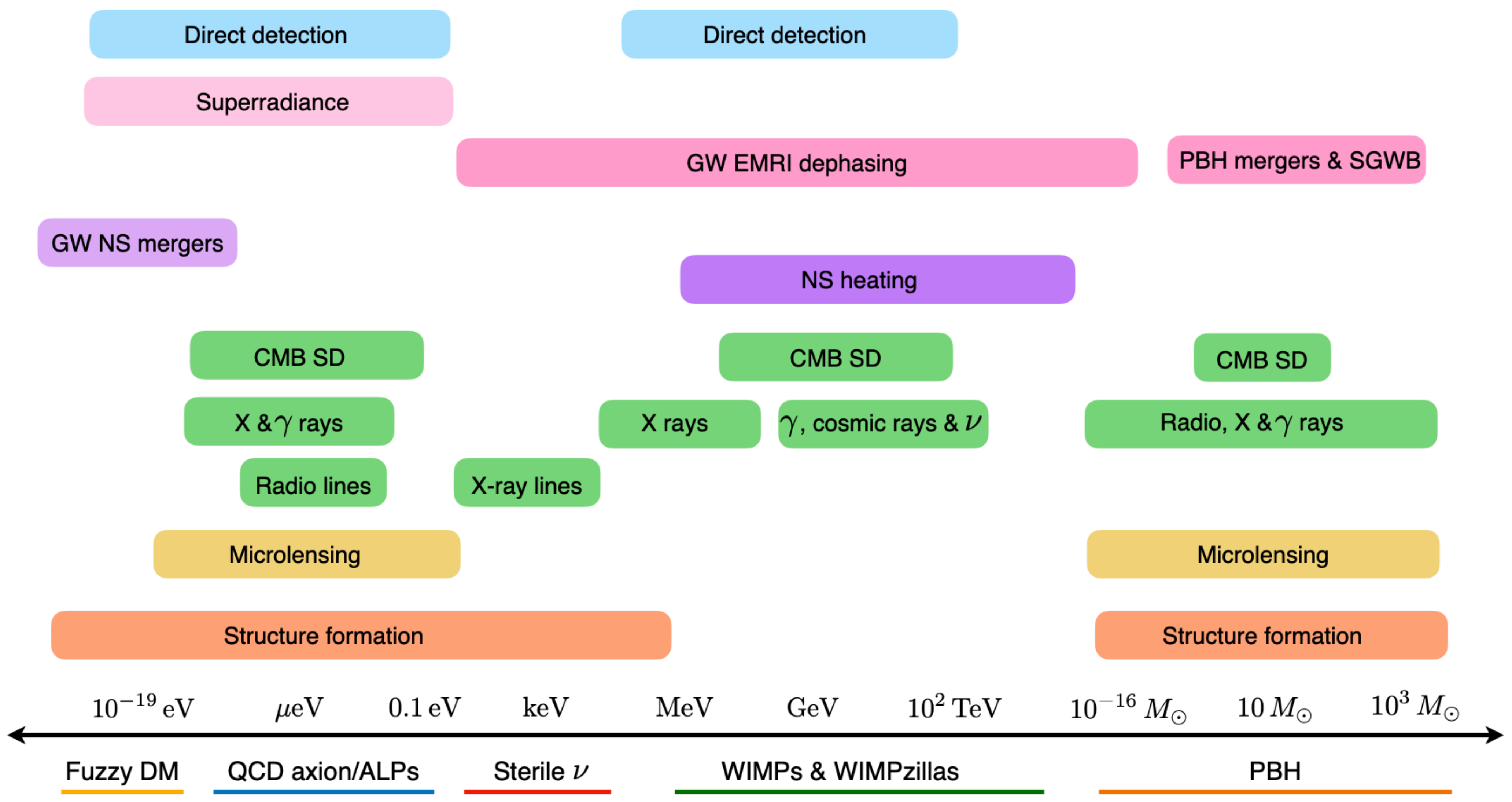
Data: Photons (MWL), Neutrinos, CRs

Dark matter

The physical nature of dark matter remains a mystery. Crucial to extend current searches to wide range of DM models, as well as to map out combinations of strategies yielding best chance of identifying DM.

- **Key questions:**
  - Is there astrophysical evidence to go beyond the cold and collisionless hypothesis?
  - If DM is multi-component, how would we know?
  - How is DM produced in the Early Universe/ connected to late Universe observables?

- **Key challenges:**
  - Can we find smoking-gun evidence from MM data?
  - Can we break degeneracies with baryons?
  - Vast DM theory parameter space. How to probe it?
  - What can we learn from GWs?



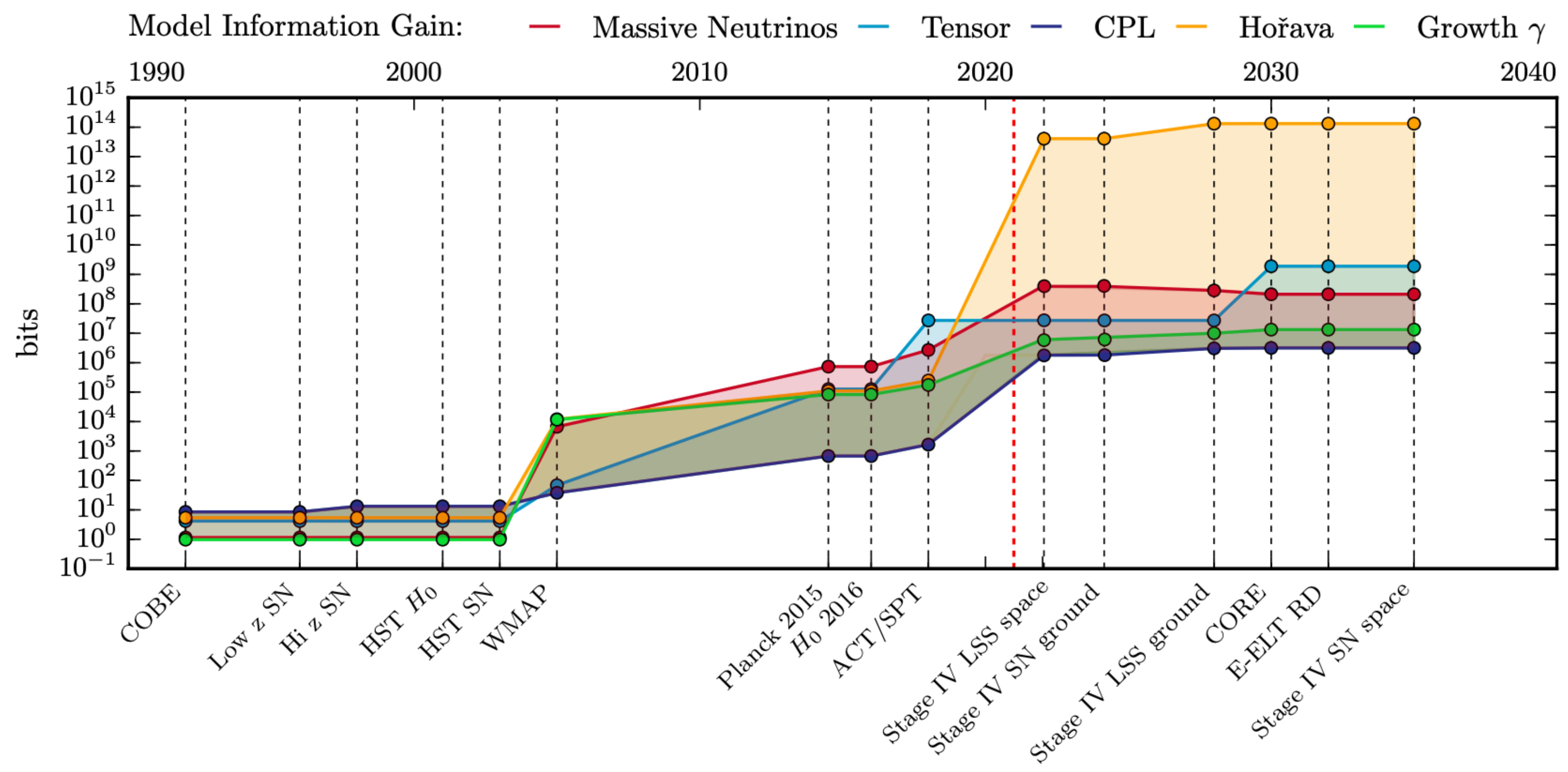
Data: Photons (MWL), Neutrinos, CRs, GWs

Dark energy

Past decade: constrained parameters of the standard cosmological model, and unveiled some tensions. Next decade: discerning among various extensions of standard cosmology

- **Key questions:**
  - Do we need to go beyond GR on large scales?
  - Are there screening mechanisms protecting modified gravity theories from small-scale constraints
  - What should we try to constrain with observations?

- **Key challenges:**
  - What if LCDM remains consistent with all data?
  - Is a parametrised approach sufficient to detect/ characterise cracks in LCDM?
  - Running/post-processing N-body simulations for a large number of modified gravity scenarios



Data: Photons (MWL), Neutrinos, CRs, GWs

Astrostatistics

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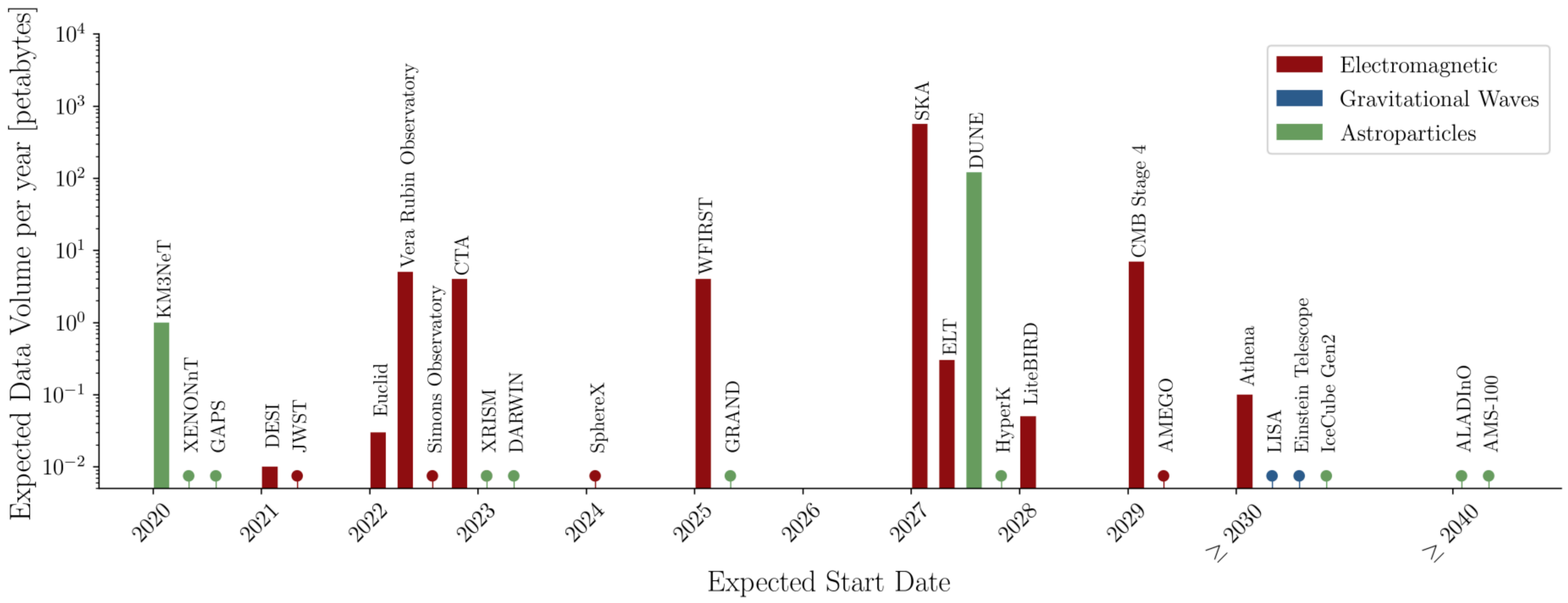
Astroparticle physics data rapidly increasing in volume and precision. Scientific return of upcoming observations is expected to be limited by efficiency and sophistication of statistical inference tools



- **Recommendations for theorists:**
  - Shift towards simulation-based inference + computational and educational infrastructure
  - Modern ML methods (e.g. variational inference) require differentiable physical simulators
  - Share simulation results in a way that allows simulation reuse

- **Recommendations for observers:**
  - release instrumental forward simulations together with data
  - provide detailed information about systematic uncertainties and all relevant correlations
  - jointly organise data and simulation challenges

Conclusions

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- We hope white paper will increase the awareness of theoretical challenges and opportunities, and help **prepare** for interpretation of upcoming data/**inform design** of future experimental probes

- Addressing fundamental questions will require **collaboration** of theorists with different backgrounds and skills, as well as with experimentalists, observers, data scientists, and computer scientists.

- Recommendations:

    - Support positions **beyond** geographic, thematic, or experimental **boundaries**

    - Provide adequate **computational resources** in Europe, avoid relying solely on infrastructure overseas

    - Build extensive **open-access repositories** for software, and services to enable open science

    - Explore **potential synergies** in technology, physics, organization and/or applications (e.g. JENAS, ESCAPE)

    - Support education and training in **machine learning** methods and astrostatistics

    - Ensure **diversity** in all initiatives + equal opportunities and access to scientific resources and funding