Future Innovations in Gamma Rays SAG Executive Summary on Gamma-ray Science Objectives for the Next Two Decades

> **Gamma rays probe the most extreme phenomena in our Universe, from stellar death and birth of black holes on where they reside, how they are powered, and how they grow, to the most extreme cosmic particle accelerators challenging fundamental physical processes.**

Gamma rays span the highest energies of the electromagnetic spectrum, spanning ten orders of magnitude in energy from about 100 keV to 1 PeV ($10^5 - 10^{15}$ eV). NASA is uniquely suited for exploration of this extreme window, as direct detection of gamma rays below 10 GeV is only possible from space, and the Earth's atmosphere is opaque to gamma rays.

> **The United States pioneered space-based γ-ray astronomy in the 1960s and has led the field ever since. Without new NASA investment, this leadership will be ceded to China by the 2030s.**

In the past several decades, we have made extraordinary discoveries that transformed our understanding of the Universe with space-based gamma-ray observations. These discoveries are made possible from continual US investment in high energy missions and technology development for the past 50+ years. However, the MeV–GeV regime remains one of the *least explored* windows in observational astronomy, despite hosting some of the most consequential science for the coming decades: nuclear astrophysics & the origin of the heavy elements, fundamental physics & the nature of dark matter, compact objects and relativistic jets, and supermassive black holes. Here are the leading open topics uniquely address by gamma-ray observation and carry wide-reaching impact across multiple disciplines.

- Cosmic explosions – What are their origins? What is the nature of the explosion engine and its underlying physics? What gets left behind across the history of the Universe?
- Heavy elements in the Universe – How are they produced? What is the underlying nuclear physics behind their production? How are they distributed and transported?
- Supermassive black holes – How do they form and grow? What are their jets made of? How do particles get accelerated to relativistic speeds and interact?
- Fundamental Physics – How does light behave under strong magnetic fields?

To answer these questions, we need to continue US investment to advance gamma-ray instrumentation, theory, and computation that will also drive cross-sector innovations in nuclear physics, national security, and medical imaging.

Gamma-ray bursts and magnetar flares are produced under extreme conditions around neutron stars and black holes. Differentiating populations of these cosmic explosions are critical in understanding both the formation and evolution of neutron stars and black holes. To do this, scientists need well-studied events with sufficient localization to gain broad wavelength coverage. Although hundreds of gamma-ray bursts have been localized, the sample of events with well characterized associated supernovae remains low. Moreover, the number of extragalactic magnetar giant flares we detect today is just the tip-of-the-iceberg of a much larger population. Gamma rays are critical in discovering and quickly localizing these systems to drive broadband coverage of hundreds of events to test current models. To achieve this, **investment in sensitive gamma-ray burst monitors on astrophysics and planetary missions to expand and sustain the Interplanetary Network is essential for discovery and follow-up studies.**

The study of gamma rays from radioactive decay has play and will continue to play a critical role in probing supernova engines and their progenitors. This study of nuclear processes in heavy element production and dissemination has excellent synergy with the nuclear physics community and strong collaborations between gamma-ray and nuclear physics communities are growing. Currently there are limited observed systems with sufficient details. **Investment in gamma-ray detector technology for a high angular resolution spectrometer to provide sensitive supernovae observation out to the Virgo cluster could increase the number of well-studied systems by ten-fold.**

For a large group of gamma-ray science, advancement in the past three decades have stemmed from survey missions in the MeV to GeV regime. These include the most extreme accelerators within our Galaxy and the anti-matter production from remnants of supernovae and massive stars, the discovery of the largest structure in our Galaxy, and a yet-to-be explained gamma-ray excess at the Galactic center. External to our Galaxy, the study of supermassive black holes with active relativistic jets is crucial to understanding the jet physics relating to black hole growth and star formation history. To complete the picture of these objects and ties to fundamental physics, **continual investment in MeV instrumentation is needed to bridge the observational gap between X-ray and GeV gamma rays with sufficient sensitivity to connect the underlying physical processes.**

To realize the scientific goals laid out in this report in the coming decades, these are the necessary capabilities for transformative science:

1. **Large scale**: A sensitive MeV - GeV discovery and survey mission with large effective area ($\gtrsim 10$ m^2).
2. **Medium scale**: A nuclear spectrometer with high angular resolution and up to hundreds of keV.
3. **Transient monitoring and surveying**: Strategic infrastructure support for the Interplanetary Gamma-ray Burst Timing Network with distributed hosted payloads across missions beyond Earth's orbit.