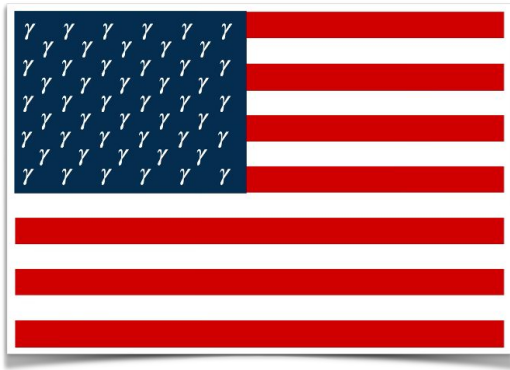




FLAG SAG Update

October 2, 2026

Co-chairs Henric Krawczynski and Liz Hays

Agenda

- Plan for the fall
- Call for feedback on preview draft
- Outline/construction of the draft
- Overview of key tables

Plan

Goal: deliver a draft with all planned primary content to GR SIG/PhysPAG in November.

October:

- Collect and incorporate feedback from preview/skeleton draft
- Find volunteers for 5 main science topic tables (**today**) to condense questions table content and firm up observational needs.
- Issue a revised draft mid-October
- Hold a discussion of that draft at the next FLAG SAG virtual meeting on October 30 in this time slot.

November: Address discussion in the draft to produce a final version of the primary content. This is when overall findings and conclusions and key tables and figures should be finalized and delivered to PhsPAG.

December: Complete remaining polishing in December. This may include appendix material where we may want to capture some details that might be useful to the potential study, for example on key performance metrics

January: Release report

- January 10: FLAG SAG splinter session at January AAS - Save the date!
- Post final report to arxiv

Call for feedback on preview draft

Henric and Liz will send out and post the preview/skeleton draft after this meeting.

Requesting in particular comments on

- **Structure, order, missing sections**
 - We've been asked to comment on technical readiness. How do we want to do that? Ideally this presents a roadmap to get a new mission in the pipeline and continue work towards more advanced capabilities we want.
- **Tables**
 - Need to refine goals and firm up numbers for observational needs.
 - Missing/redundant content?
 - Have one working group for each of the main 5 topics?
Need volunteers for each major topic to poll specialists, organize call, help draw conclusions.
 - Are there other tables that would be useful?
- **Figure suggestions**
 - What figures are needed to support key points of the report? Audience is broader community.
- **Findings need discussion and iteration within FLAG SAG**

The Future of Gamma-Ray Astronomy in Space

A Strategic Vision for the Years 2030 to 2050

Report of the Future Large Gamma-ray Mission Concepts Working Group (FLAG SAG)

Compiled by Elizabeth Hays (NASA Goddard Space Flight Center) and
Henric Krawczynski (Washington University in St. Louis)
for the FLAG and the contributors listed in [Appendix C](#)

Draft of September 2026

Abstract

Gamma rays allow us to study relativistic outflows and explosions and the most extreme particle accelerators in the Universe. Gamma rays below about 10 GeV can only be observed from space. The United States built this field, but the fleet that made the discoveries of the last two decades is reaching the end of its lifetime: INTEGRAL stopped its science operations in 2025, Swift is at the end of its orbital life, and Fermi has now been operating for 18 years. COSI, a Small Explorer that launches in 2027, restores part of the MeV line and polarization science but not the depth and sensitivity that the multi-messenger era needs. This report collects the input that the gamma-ray community gave to the Future Large Gamma-ray Mission Concepts working group in 2026, maps it to the open science questions, and lays out a plan for large (Probe and Flagship class) gamma-ray missions in the years 2030 to 2040. There is one obvious next gamma-ray mission: a wide field of view gamma-ray observatory as the survey and transient engine for multi-messenger astronomy offering sensitivity to follow up on both COSI and Fermi. Further down the road, this new mission could be complemented by a pointed telescope with focusing optics and high resolution spectrometers for nuclear lines and the 511 keV line.

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Methodology

Community input

Info from
FIGSAG Report,
eAstrogram, ...

Skeleton
FLAGSAG
report



Claude

Edit & Revise



Table 1: Missions that define the current capability in the keV to GeV band, and the missions in development. Dates are launch years; COSI, POLAR-2, HERD and VLAST dates are planned.

Mission	Band	Capability	Status
Fermi (NASA, 2008)	10 keV to 300 GeV	GeV all-sky survey (LAT, 2.4 sr, 0.8° at 1 GeV), keV to MeV burst monitor (GBM)	operating, 18 yr
Swift (NASA, 2004)	15 keV to 150 keV	coded mask burst imager (1.4 sr, arcminute), X-ray and UV follow-up within minutes	end of orbital life
INTEGRAL (ESA, 2002)	15 keV to 8 MeV	Ge spectrometer (SPI), coded mask imager (IBIS)	science ended Feb 2025
NuSTAR (NASA, 2012)	3 to 79 keV	focusing hard X-ray imaging, 1 arcminute	operating
IXPE (NASA, 2021)	2 to 8 keV	X-ray polarimetry	operating
AstroSat, Insight-HXMT, GECAM, SVOM, Einstein Probe	keV to MeV	burst detection, hard X-ray timing and polarimetry (CZTI, POLAR heritage)	operating
COSI (NASA SMEX, 2027)	0.2 to 5 MeV	Ge Compton telescope, 25% of the sky instantaneous, spectral resolution below 1%, polarimetry	in development
POLAR-2 (China, about 2027)	30 to 800 keV	dedicated GRB polarimeter on the Chinese space station	in development
HERD (China, late 2020s)	GeV to TeV	calorimeter with wide field gamma-ray monitoring	in development
VLAST (China, 2030s)	MeV to TeV	flagship scale pair telescope, acceptance about four times Fermi-LAT	in study
THESEUS (ESA M7 candidate)	0.3 keV to 10 MeV	lobster eye and coded mask imagers with an infrared telescope for high redshift GRBs	in study

Cosmic explosions

Question	Goals	Observational needs
What is the origin of cosmic explosions?	Provide prompt detections and locations of gamma-ray transients including neutron star mergers <i>See Astro 2020 Appendix B-Q2: What powers the diversity of explosive phenomena across the electromagnetic spectrum?</i>	Wide to all-sky instantaneous field of view; sub-arcmin to deg-scale localization; timing accuracy to 30 μ s with 10 μ s precision; keV-MeV energy range.
What is the nature of the explosion engine and its underlying physics?	Measure gamma-ray spectral and temporal structures <i>See Astro 2020 Appendix B-Q2: What powers the diversity of explosive phenomena across the electromagnetic spectrum?</i>	Wide to all-sky instantaneous field of view; timing accuracy to 30 μ s with 10 μ s precision; keV-MeV energy range.
	Neutron Star Mergers for Kilonova Studies	Wide to all-sky instantaneous field of view with sub-arcmin to deg-scale localization, timing accuracy to 30 μ s, with 10 μ s precision, keV-MeV energy range.
How has star formation changed over cosmic time?	GRB progenitors are the most massive stars and the GRB rate is sensitive to the initial mass function (IMF). Gamma rays can probe the production of GRBs to high redshift.	Wide to all-sky instantaneous field of view with sub-arcmin to deg-scale localization, keV-MeV energy range
How do supernova (SN) engines work? Critical in determining compact remnant formation (black holes and neutron stars), formation and dissemination of the elements.	Nearly direct probe of asymmetry. Gamma-ray observations of ^{56}Ni , ^{57}Ni , ^{44}Ti , ...	Large observation sample – sensitivity to detect SNe to Virgo cluster; time-resolved to probe element distribution, high spectral resolution ($\sim 1\%$) to measure ejecta velocity distribution and distinguish decay lines.

Questions are good.

Can we give sensitivity requirements for each of them?

Heavy elements

Question	Goals	Observational needs
How are heavy elements produced?	Measure the masses of ^{56}Ni , ^{57}Ni and ^{44}Ti made in thermonuclear and core-collapse supernovae from their decay lines (^{56}Co 847 and 1238 keV, ^{56}Ni 158 and 812 keV, ^{57}Co 122 and 136 keV, ^{44}Ti 68, 78 and 1157 keV). Line fluxes and line profiles give the yields and the velocities of the innermost ejecta. They tell the explosion type (deflagration, detonation, double detonation; single or double degenerate progenitor) and the strength of the engine. A sample of 3 to 10 events per class already advances the field, and the same data calibrate the optical light curves used for cosmology.	Sensitivity to broad lines (2 to 3% FWHM) of $3 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}$ or better at 847 keV in 10^6 s detects Type Ia supernovae out to 20 to 30 Mpc (Virgo), i.e. 1 to 3 events per year; $10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1}$ reaches core-collapse supernovae ($0.05 M_{\odot}$ of ^{56}Ni) out to 3 to 4 Mpc. Energy range 50 keV to 3 MeV; energy resolution of about 1% to measure ejecta velocities of a few 1000 km/s; repeated observations over the first 300 days with a cadence of days to weeks; a wide field of view or the ability to point within days of the explosion.
	Detect the decay of ^{44}Ti in young supernova remnants. ^{44}Ti is made at the base of the explosion, so its amount and spatial distribution test the engine directly (so far only Cas A and SN 1987A). Measure or limit ^{44}Ti in the remnants of Type Ia supernovae (Tycho, Kepler, G1.9+0.3), where the ^{44}Ti yield separates the explosion models.	Line sensitivity of 10^{-6} to $10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1}$ (1 yr) at 68, 78 and 1157 keV covers all Galactic remnants younger than about 500 yr and SN 1987A. Sub-arcminute imaging to map the ejecta of Cas A (5 arcmin across). Energy resolution better than 1% at 1157 keV, or better than 100 eV at 68 and 78 keV, for velocity maps at the 1000 km/s level.

(continued)

Question	Goals	Observational needs
	Classical novae: measure the ^{22}Na (1275 keV) and ^7Be (478 keV) decay lines and the early positron annihilation flash from ^{13}N and ^{18}F . These fix the nova yields, the white dwarf composition (CO or ONe) and the mixing during the outburst, and give the nova contribution to the Galactic ^{26}Al , ^{22}Na , ^7Li and positron budgets.	Line sensitivity of 10^{-6} to 10^{-5} $\text{ph cm}^{-2} \text{s}^{-1}$ at 478 and 1275 keV (10^6 s) for novae within 1 to 2 kpc (about one per year). The annihilation flash (up to 10^{-2} $\text{ph cm}^{-2} \text{s}^{-1}$ at 1 kpc) lasts a few hours and happens before the optical discovery, so an instantaneous wide field of view and full archival data are needed. Energy resolution of about 1%.
What is the underlying nuclear physics behind their production?	Use decay line fluxes and line ratios ($^{56}\text{Ni}/^{57}\text{Ni}$, $^{44}\text{Ti}/^{56}\text{Ni}$, $^{60}\text{Fe}/^{26}\text{Al}$ and the r-process isotopes) as direct measurements of the nuclear reaction flows in explosions and in massive star shell burning. The measured yields anchor the reaction rates and weak interaction rates used in the models and connect the observations to laboratory work at FRIB.	Same sensitivities as above, plus a Galactic survey in the ^{60}Fe (1173, 1332 keV) and ^{26}Al (1809 keV) lines with a line sensitivity of 10^{-7} to 10^{-6} $\text{ph cm}^{-2} \text{s}^{-1}$ per source region (1 yr) and about 1 degree angular resolution, so that the emission can be attributed to individual OB associations and remnants.
	Identify individual r-process isotopes through their decay lines in kilonova ejecta and in old merger remnants. The line pattern gives the electron fraction and the mass of the ejecta and tells whether the heaviest nuclei (actinides) are made.	Kilonova lines (50 keV to 5 MeV) peak 1 to 5 days after the merger and blend into a quasi-continuum, so a few percent energy resolution is enough, but the sensitivity must reach 10^{-8} to 10^{-7} $\text{ph cm}^{-2} \text{s}^{-1}$ in 10^6 s to detect a GW170817-like event beyond 10 Mpc. Long lived isotopes (e.g. ^{126}Sn at 415, 666 and 695 keV) from the last few Galactic mergers need 10^{-9} to 10^{-7} $\text{ph cm}^{-2} \text{s}^{-1}$ in 1 yr and sub-degree imaging.
How are they distributed and transported?	Map the Galaxy in the 1809 keV line of ^{26}Al and the 1173 and 1332 keV lines of ^{60}Fe with enough angular resolution to resolve the nearby star forming regions (Cygnus, Sco-Cen, Orion, Carina), and measure the Doppler shifts of the lines. The maps show how massive stars seed the interstellar medium with fresh nuclei over the last million years and how superbubbles carry them into the halo.	Wide field (10 to 1000 square degrees) survey of the Galactic plane; line sensitivity of 10^{-7} to 10^{-6} $\text{ph cm}^{-2} \text{s}^{-1}$ per beam (1 yr); angular resolution better than 1 degree; energy resolution of 0.2% or better (a few keV FWHM at 1.8 MeV) to measure the 100 to 300 km/s flows seen with INTEGRAL/SPI.

(continued)

Question	Goals	Observational needs
Where do the Galactic positrons come from, and how far do they travel before they annihilate?	Resolve the 511 keV emission of the bulge and the disk into its sources (^{26}Al , ^{44}Ti and ^{56}Co decay, novae, X-ray binaries, pulsars, or dark matter), measure the annihilation conditions (line width, positronium fraction) and the positron transport distance, and find point sources of annihilation radiation.	Imaging at the Doppler limit (about 1 degree at 511 keV) of the bulge and disk with a line sensitivity of about 10^{-5} $\text{ph cm}^{-2} \text{s}^{-1}$ per beam; arcminute imaging of point sources and of the Galactic center region with 10^{-6} to 10^{-5} $\text{ph cm}^{-2} \text{s}^{-1}$ (focusing optics or coded masks); energy resolution of 0.5% or better to measure the 2 to 3 keV line width and the positronium continuum.
	Measure the nuclear de-excitation lines of ^{12}C (4.44 MeV) and ^{16}O (6.13 MeV) produced by low energy cosmic rays hitting the interstellar gas. These lines are the only direct tracer of the sub-100 MeV cosmic rays that ionize and heat molecular clouds, and they show where freshly made nuclei mix with the gas.	Sensitivity of about 10^{-6} $\text{ph cm}^{-2} \text{s}^{-1}$ (10^7 s) for broad (few percent) lines at 4 to 7 MeV over the inner Galaxy and nearby star forming regions; degree scale imaging. The same capability measures the solar flare lines (2.223 MeV neutron capture, 4.4 and 6.1 MeV).
What are the production site(s) of r-process elements?	Determine whether neutron star mergers, collapsars, magnetorotational supernovae or magnetar giant flares make the r-process elements, and in which proportions. Gamma rays answer this directly: the decay lines identify the isotopes and their masses at each candidate site.	Gamma ray (and high energy X-rays, >30 keV) of kilonova observations provide definitive identification of r-process isotopes. Requirements: a 4π steradian monitor with an MeV line sensitivity of 10^{-8} to 10^{-7} $\text{ph cm}^{-2} \text{s}^{-1}$ (10^6 s) starting within a day of a gravitational wave trigger; a sensitivity of about 10^{-9} $\text{erg cm}^{-2} \text{s}^{-1}$ on hour timescales in the 0.1 to 3 MeV band for the delayed emission of magnetar giant flares (the 2004 flare of SGR 1806-20 showed such a component); pointed follow-up of nearby long GRBs and of the youngest Galactic merger remnants.

Supermassive black holes

Question	Goals	Observational needs
How do supermassive black holes form and grow?	Find the most massive black holes at $z > 4$ through their jets. For these objects the high energy peak of the jet emission falls in the MeV band, where no sensitive survey exists. Each detected blazar stands for about $2 \Gamma^2$ (hundreds) of misaligned jets, so an MeV census gives the space density of the first billion solar mass black holes and tells whether jets speed up their growth.	All-sky MeV survey with a continuum sensitivity of 10^{-12} $\text{erg cm}^{-2} \text{s}^{-1}$ (1 yr) in 0.3 to 30 MeV, and 10^{-13} for a full census; localization better than 0.5 degree for identifications; an energy resolution of 10% is enough; monitoring over years. An e-ASTROGAM class survey would detect 3000 to 4000 MeV sources in 3 years.
	Complete the census of obscured (Compton thick) accretion. Heavily absorbed AGN are brightest above 20 keV, and the sum of all accretion makes the cosmic hard X-ray and MeV background, whose MeV part is still unresolved. Measure the coronal cutoff energies, search for the 511 keV feature of pair dominated coronae, and measure the coronal geometry from polarization.	Sensitivity of 10^{-12} $\text{erg cm}^{-2} \text{s}^{-1}$ (1 yr) in 0.1 to 1 MeV for about 1000 AGN; arcminute hard X-ray imaging (coded mask or optics) to identify the counterparts; polarization MDP of about 10% for the brightest Seyferts (10^{-10} $\text{erg cm}^{-2} \text{s}^{-1}$ at 100 to 300 keV); absolute calibration good enough to measure the diffuse MeV background.

(continued)

Question	Goals	Observational needs
	Catch black holes as they switch on: jetted tidal disruption events and changing look AGN. Jetted tidal disruptions show how a jet forms when a dormant black hole suddenly accretes at a high rate, and they add lower mass black holes to the mass ladder. Their prompt emission is expected to peak in the MeV band.	Wide field monitoring with a sensitivity of 10^{-11} erg cm $^{-2}$ s $^{-1}$ per day in 0.05 to 10 MeV; localization better than 0.5 degree for X-ray and optical follow-up; light curves over months.
How do jets and winds from supermassive black holes feed energy and cosmic rays back into their host galaxies and clusters?	Image the GeV and MeV emission of radio galaxy lobes (Cen A, Fornax A), of AGN driven bubbles in nearby galaxies and of galaxy clusters to measure the cosmic ray and magnetic energy that jets deposit. Measure the cosmic ray content of star forming galaxies out to z of about 0.2, where evolution starts to matter. This is the gamma-ray view of black hole feedback.	Angular resolution better than 0.1 degree above 1 GeV and about 1 degree at 1 MeV; continuum sensitivity of 10^{-13} erg cm $^{-2}$ s $^{-1}$ (5 yr); all-sky survey so that dozens of radio galaxies and clusters are covered without pointing.
What are SMBH jets made of?	Decide between leptonic and hadronic jets. In leptonic models the MeV to GeV emission is inverse Compton scattering and is weakly polarized (below about 10% for external seed photons); in hadronic models it is proton synchrotron or cascade emission and can be polarized at the 40 to 70% level. Polarization measured within a single flare, and the MeV spectrum that connects the two spectral humps, settle the question for each source class (FSRQs, BL Lacs, radio galaxies).	Compton polarimetry in 0.2 to 5 MeV with an MDP of 5 to 10% in one day for a bright flare (10^{-9} erg cm $^{-2}$ s $^{-1}$) and 10% in a week for 10^{-10} erg cm $^{-2}$ s $^{-1}$, so that the polarization angle does not average out; pair polarimetry at 10 to 100 MeV with an MDP of 20 to 40% for the brightest sources; wide field of view so that flares are not missed.
	Test the hadronic content directly with neutrinos. Flaring blazars (TXS 0506+056) and the coronae of nearby Seyferts (NGC 1068) are the first neutrino sources. In Seyfert coronae the accompanying gamma rays cascade down into the MeV band, so MeV spectra are the electromagnetic side of the neutrino measurement. Search for the 511 keV annihilation feature of pair loaded jets.	All-sky monitoring with a daily sensitivity of about 10^{-11} erg cm $^{-2}$ s $^{-1}$ for coincidences with IceCube-Gen2 and KM3NeT alerts, with a latency below one hour; MeV sensitivity of 10^{-12} erg cm $^{-2}$ s $^{-1}$ (1 yr) to detect the predicted 10^{-11} erg cm $^{-2}$ s $^{-1}$ coronal emission of the nearest Seyferts; broad line sensitivity of about 10^{-5} ph cm $^{-2}$ s $^{-1}$ near 511 keV.

(continued)

Question	Goals	Observational needs
How do particles get accelerated to relativistic speeds and interact	Resolve the fastest variability. Minute scale GeV flares (3C 279) show emission zones much smaller than the light crossing time of the black hole horizon suggests. Fast flares with swings of the polarization angle point to magnetic reconnection, slower symmetric flares to shocks. Unbiased light curves of thousands of blazars at daily cadence, including their quiescent states, connect the flare statistics to the physics.	Effective area 10 to 30 times that of Fermi-LAT above 100 MeV so that a 10^{-5} ph cm $^{-2}$ s $^{-1}$ flare gives minute resolution light curves; continuous all-sky survey (no pointing bias); MeV coverage of 0.3 to 30 MeV with 10^{-12} erg cm $^{-2}$ s $^{-1}$ (1 week) to follow the low energy end of the electron spectrum; a mission lifetime of 10 years or overlapping missions.
	Use stellar mass black holes as scaled down laboratories. The MeV tails of Cyg X-1 and other black hole binaries are strongly polarized in the hard state (INTEGRAL: about 70% at 0.4 to 2 MeV), which points to synchrotron emission from the jet. Measure the polarization and the spectral shape as a function of accretion state for a sample of Galactic black holes, and study the pair content of the outflows (annihilation features in outbursts such as V404 Cyg).	MDP of 10% in 0.4 to 2 MeV within a day for a 10^{-9} erg cm $^{-2}$ s $^{-1}$ source (Cyg X-1 needed 2 Ms with INTEGRAL); sensitivity of 10^{-11} erg cm $^{-2}$ s $^{-1}$ per day to follow the outbursts of about 10 systems; energy range 0.1 to 10 MeV.
Supermassive Black Hole Evolution (during the jetted AGN phase); Particle acceleration in jets for energy & CRs	The nature of jet launching provides the jet composition. Jet composition is more uniquely probed (and less reliant on rare events) by MeV polarization. Blazar studies are usually multiwavelength endeavors that rely on survey data from Fermi.	High effective area instrumentation in the MeV regime, ideally a wide FoV survey to reduce pointing bias associated with flares. Polarization? Yes: an MDP of 5 to 10% in a day for a 10^{-9} erg cm $^{-2}$ s $^{-1}$ flare (0.2 to 5 MeV) and 10% in a week for 10^{-10} erg cm $^{-2}$ s $^{-1}$.

(continued)

Question	Goals	Observational needs
How do supermassive black holes form and merge? Are angular structures in the low frequency GW sky or individual sources?	Pulsars timed in the gamma rays are free of most systematics (e.g. ISM and solar wind) compared to radio PTAs. GPTA times different and many pulsars on the sky for high GW angular resolution.	high acceptance 0.1-5 GeV instrument with decent or good angular resolution and timing accuracy. Figure of merit: grasp (effective area times field of view) divided by the width of the point spread function. The baseline of Kerr et al. (2025) is 30 times the Fermi-LAT grasp (about $50 \text{ m}^2 \text{ sr}$ at 1 GeV), a PSF three times narrower (0.3 degree at 1 GeV), timing accuracy better than $30 \mu\text{s}$, and a 10 year all-sky survey in 0.1 to 10 GeV. This times about 3700 disk millisecond pulsars plus hundreds in the bulge, and reaches a strain amplitude of 10^{-15} at 1/yr in about a decade, enough to map the anisotropy of the background and to find individual sources.
	Find the electromagnetic counterparts of binary supermassive black holes. Periodic gamma-ray light curves with periods of 1 to 10 years are the expected signature of binaries in the final inspiral, and only a gamma-ray survey monitors thousands of jets continuously. Combined with the pulsar timing array this links individual nanohertz sources to galaxies.	Continuous all-sky GeV and MeV survey with a daily sensitivity of $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ and a total baseline of 20 years or more (Fermi plus its successor without a gap); no pointing needed.

Fundamental physics

Question	Goals	Observational needs
How does light behave under strong magnetic fields?	Photon splitting in astrophysical setting is best observed between 50 keV and 1 MeV, below pair production threshold where one photon can split into two in a strong magnetic field	Energy and magnetar rotational phase resolved polarization between 0.1-10 MeV. From the FIG SAG capability table: energy range 50 keV to 10 MeV; continuum sensitivity of $10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ in 1 to 3 yr; MDP better than 15% for the phase resolved pulsed emission of the brightest magnetars; an angular resolution better than 5 degrees is enough. A flux measurement in the 0.1 to 10 MeV band alone already separates an intrinsic cutoff from a QED attenuation edge.
Nature of dark matter	probe of critical MeV-GeV energy range where thermal WIMP signatures happen. Retain complete spectral and spatial information. Complement direct detection.	angular resolution $<0.05^\circ$: resolve dwarf galaxy substructure, precision morphological studies of Galactic center excess; energy resolution $<1\%$ for MeV lines [$<5\%$ GeV-TeV]; effective area $>30\times$ Fermi-LAT: Detect thermal relic cross-sections across full WIMP mass range, achieve 5 sigma discoveries in reasonable mission lifetimes.
	Axions/ALPs/dark photons/sterile neutrinos/PBHs: spectral line signatures in MeV scales	Poorly defined.

Other questions

Question	Goals	Observational needs	Reference
Cosmic rays and the interstellar medium: where are Galactic cosmic rays accelerated, and how do low energy cosmic rays shape the gas that forms stars?	Measure the pion bump near 70 MeV in supernova remnants and star forming regions to prove hadronic acceleration; trace the sub-100 MeV cosmic rays with nuclear de-excitation lines (4.4 and 6.1 MeV); map the MeV diffuse emission (inverse Compton from cosmic ray electrons) and the Fermi bubbles; use starburst galaxies as cosmic ray calorimeters.	Sensitivity of 10^{-12} erg cm $^{-2}$ s $^{-1}$ (1 yr) at 10 to 100 MeV, the least covered part of the spectrum; angular resolution better than 1 degree at 30 MeV and 0.1 degree at 1 GeV; line sensitivity of 10^{-6} ph cm $^{-2}$ s $^{-1}$ at 4 to 7 MeV.	Astro 2020 F-Q1, F-Q2, D-Q2; ASTRA objective 2 (energetic role of cosmic ray outflows); Enduring Quests
Neutron stars and magnetars as a population: how do pulsar magnetospheres radiate, what is the neutron star equation of state, and what makes fast radio bursts?	Phase resolved MeV spectroscopy and polarimetry of pulsars and magnetars (emission zones, rotation versus magnetic power); find the predicted MeV bright, GeV faint pulsars; localize magnetar giant flares as a population (their rate exceeds that of short GRBs below a fluence of 10^{-8} erg cm $^{-2}$); search for kHz QPOs in giant flares (equation of state); catch the high energy counterparts of fast radio bursts.	0.1 to 10 MeV; MDP below 10 to 20% in one year for faint pulsed sources; timing resolution better than 10 μ s; fluence sensitivity of 10^{-8} erg cm $^{-2}$ at 1 MeV; instantaneous all-sky coverage.	Astro 2020 B-Q1 (masses and spins of neutron stars), G-Q1; FIG SAG magnetar and pulsar themes
The intervening Universe: what are the extragalactic background light and the intergalactic magnetic field, and is Lorentz invariance exact?	Measure the attenuation of GeV spectra of distant blazars and GRBs by the extragalactic background light; search for pair halos and delayed emission that measure the intergalactic magnetic field; test Lorentz invariance with the arrival times and the polarization of GRB photons at high redshift.	0.1 to 100 GeV imaging with 0.1 degree resolution and 10^{-13} erg cm $^{-2}$ s $^{-1}$ sensitivity (5 yr); GRB polarimetry (MDP below 10%) and μ s timing for bursts at $z > 1$.	Astro 2020 C-Q3; Elizabeth marked MeV and GeV imaging for C-Q3 in the Astro 2020 sheet

(continued)

Question	Goals	Observational needs	Reference
Gravitational wave counterparts beyond binary neutron stars: what electromagnetic signals accompany massive black hole mergers (LISA) and the distant mergers seen by third generation ground detectors?	Provide prompt gamma-ray coverage of every gravitational wave event: the statistics of detections and non-detections out to z of about 1 measure the jet structure of short GRBs; search for prompt and delayed jet emission after LISA massive black hole mergers, which come with an advance warning of days.	Instantaneous 4 pi coverage (no Earth occultation), fluence sensitivity of 10^{-8} erg cm $^{-2}$ at 1 MeV, localization better than 1 degree within a minute, and a mission that operates through the 2030s and 2040s.	Astro 2020 C-Q4, B-Q2; LISA (launch mid 2030s), Cosmic Explorer and Einstein Telescope (2030s)
The Sun, stars and planets: how are particles accelerated in solar flares, and what do gamma rays tell us about stellar binaries and planetary surfaces?	Solar flare nuclear lines (2.223 MeV neutron capture, 4.4 and 6.1 MeV de-excitation, 511 keV) and pion decay emission measure the accelerated ions; GeV emission of novae and gamma-ray binaries probes shocks in binaries; gamma-ray spectrometers on planetary missions measure surface composition and double as burst monitors for the interplanetary network.	MeV line spectroscopy with about 1% resolution and a dynamic range that handles the brightest flares; GeV all-sky monitoring; hosted burst monitors on planetary missions.	Astro 2020 G-Q4 (space weather), G-Q2 (multiplicity), E-Q2; cross-division topic
Exotic physics from the next nearby supernova: are there axion-like particles, and do primordial black holes evaporate today?	Axion-like particles made in a collapsing stellar core convert to MeV gamma rays in the magnetic field of the progenitor or the Galaxy and arrive with the neutrino burst, before the optical supernova; the final evaporation of a primordial black hole makes a short GeV to TeV burst.	Continuous all-sky MeV coverage with a sensitivity to a 10 to 100 s transient at the 10^{-8} erg cm $^{-2}$ level; wide field GeV coverage with fast timing.	Astro 2020 C-Q2; survey input from J. Buckley (APT)
Positron astrophysics: where do the Galactic positrons come from?	Resolve the 511 keV emission into its sources and measure the annihilation conditions.	See the new row under Heavy Elements.	FIG SAG; Enduring Quests; Astro 2020 C-Q2 (dark matter), D-Q2

Table 7: Performance requirements by science case (based on the FIG SAG capability table [1], with additions from Section 3). Sensitivities are for the exposure in parentheses; MDP is the minimum detectable polarization at 99% confidence.

	Bursts and explosions	Nuclear transients	Remnants and point sources	Milky Way lines	Blazars, AGN, binaries	Pulsar timing array	Photon splitting	Dark matter
Field of view	all sky, instantaneous	wide field or prompt pointing	narrow ($< 10 \text{ deg}^2$)	wide (10 to 1000 deg^2)	all sky survey	all sky survey	pointed or survey	$> 2 \text{ sr}$, all sky
Energy range	keV to MeV prompt; MeV to GeV after-glow	50 keV to 5 MeV	50 keV to 2 MeV	50 keV to 10 MeV	0.1 MeV to 10 GeV	0.1 to 10 GeV	50 keV to 10 MeV	10 MeV to 10 TeV
Energy resolution	$< 5\%$	$\sim 1\%$ (few % for kilonovae)	0.1 to 1 keV (velocities); few keV for 511 keV point sources	$< 1\%$ (0.2% for kinematics)	10%	—	—	$< 1\%$ MeV, $< 5\%$ GeV
Angular resolution	sub-arcmin to degree localization	—	10 arcsec to 1 arcmin	$< 1^\circ$	$< 5^\circ$ MeV, $< 0.1^\circ$ GeV	$< 0.3^\circ$ at 1 GeV	$< 5^\circ$	$< 0.1^\circ$ at 1 GeV
Timing	$< 10 \mu\text{s}$ resolution, $< 30 \mu\text{s}$ accuracy	cadence of days	—	—	minutes to years, no gaps	$< 30 \mu\text{s}$	phase resolved	—
Grasp	—	—	—	—	$> 10\times$ LAT	$30\times$ LAT (50 $\text{m}^2 \text{ sr}$ at 1 GeV)	—	$30\times$ LAT
Polarization	MDP $< 10\%$ at 0.1 to 10 MeV	—	—	—	MDP 5 to 10% in a day (flares)	—	MDP $< 15\%$	MDP $< 10\%$
Continuum sensitivity	fluence $10^{-8} \text{ erg cm}^{-2}$ at 1 (erg $\text{cm}^{-2} \text{ s}^{-1}$)MeV	—	—	—	10^{-13} (1 wk flares; 1 yr survey)	10^{-13} (5 yr)	10^{-13} (1 to 3 yr)	—
Line sensitivity	discovery space (ph $\text{cm}^{-2} \text{ s}^{-1}$)	3×10^{-6} (SNe Ia to Virgo); 10^{-8} to 10^{-7} (kilonovae), 10^6 s	10^{-7} to 10^{-6} (1 yr); 10^{-8} for 511 keV point sources	10^{-7} to 10^{-6} per beam (1 yr)	discovery space	—	—	—

Table 8: The eight capabilities that the science questions need, the performance required, the current or funded state of the art, and the improvement needed. The labels C1 to C8 are used in Figure 1.

	Capability	Performance needed	State of the art	Step
C1	All-sky MeV transient monitoring	instantaneous coverage of most of the sky (4π goal), fluence sensitivity 10^{-8} erg cm $^{-2}$ at 1 MeV, localization below 1° within seconds, timing $< 10 \mu\text{s}$, alerts within 30 s	Fermi GBM (70% of the sky, degrees), Swift BAT (1.4 sr, arcminutes), SVOM, GECAM	$10\times$ in sensitivity, full sky, MeV coverage
C2	Wide field MeV to GeV imaging spectroscopy survey	0.1 MeV to 10 GeV, continuum sensitivity 10^{-12} (1 yr) to 10^{-13} erg cm $^{-2}$ s $^{-1}$ (5 yr) at 1 MeV, angular resolution 1 to 3° at 1 MeV, field of view > 2 sr	COMPTEL (1991 to 2000, $\sim 10^{-10}$), COSI (0.2 to 5 MeV, a few 10^{-11} in 2 yr)	10 to $100\times$ in sensitivity, MeV to GeV coverage
C3	MeV nuclear line spectroscopy over wide fields	$\Delta E/E \leq 1\%$ (0.2% for kinematics), line sensitivity 10^{-6} to 10^{-8} ph cm $^{-2}$ s $^{-1}$, 50 keV to 5 MeV, field of view > 1 sr	INTEGRAL SPI (3×10^{-5} in 10^6 s), COSI ($\sim 10^{-6}$ in 2 yr)	10 to $100\times$ in line sensitivity
C4	MeV and GeV polarimetry	MDP 5 to 10% in a day for 10^{-9} erg cm $^{-2}$ s $^{-1}$, 10% in a week for 10^{-10} ; MDP 20 to 40% at 10 to 100 MeV for the brightest sources	INTEGRAL (Crab, Cyg X-1, a few bursts), POLAR, AstroSat CZTI, COSI (bright bursts)	from single objects to samples
C5	Large grasp GeV survey with microsecond timing	10 to $30\times$ the Fermi-LAT acceptance (up to $50 \text{ m}^2 \text{ sr}$ at 1 GeV), PSF 0.1 to 0.3° at 1 GeV, timing accuracy $< 30 \mu\text{s}$, 10 yr baseline	Fermi-LAT (2.4 sr, 0.8° at 1 GeV), VLAST in study ($4\times$ LAT)	10 to $30\times$ in acceptance, $3\times$ in PSF
C6	Arcminute hard X-ray and soft gamma-ray imaging	20 keV to 1 MeV, 0.2° or better with 10° fields (coded masks), 1 arcminute with pointed optics, line sensitivity 10^{-5} ph cm $^{-2}$ s $^{-1}$	INTEGRAL IBIS (ended), Swift BAT (to 150 keV), NuSTAR (to 79 keV)	restore and extend to 1 MeV
C7	Pointed high resolution line spectroscopy	ΔE of 0.1 to 20 keV depending on the detector (0.1 to 1 keV for velocity measurements), arcsecond to arcminute imaging, 50 keV to 2 MeV, line sensitivity 10^{-6} to 10^{-8} ph cm $^{-2}$ s $^{-1}$	none (SPI: 2 keV, degrees; NuSTAR: 0.4 keV, arcminute, but only up to 79 keV)	new capability
C8	Rapid multiwavelength follow-up	arcminute or better positions within minutes, onboard infrared or optical telescope or coordinated fleet, autonomous operations	Swift (ending), SVOM	restore and extend to the infrared

Cosmic explosions

GRBs, magnetar flares, mergers, supernova engines

Heavy elements

nucleosynthesis lines, r-process sites, Galactic positrons

Black holes and jets

MeV blazars, jet composition, gamma-ray pulsar timing array

Fundamental physics

strong field QED in magnetars, dark matter

Additional topics

cosmic rays and the ISM, neutron star populations, the Sun

All-sky transient monitoring and rapid follow-up (C1, C8)

4π coverage, localization within seconds to minutes, follow-up telescopes

Wide field MeV to GeV survey (C2, C4, C5)

10^{-12} to 10^{-13} erg cm $^{-2}$ s $^{-1}$ at 1 MeV, polarimetry, 10 to 30 $\times$ the Fermi-LAT grasp

Wide field nuclear line spectroscopy (C3)

$\Delta E/E \leq 1\%$, line sensitivity 10^{-6} to 10^{-8} ph cm $^{-2}$ s $^{-1}$

Arcminute imaging and high resolution spectroscopy (C6, C7)

point sources: coded masks to 1 MeV, focusing optics with TES, Ge or CZT

Wide field MeV to GeV observatory: the next large mission

G1 Wide field, high resolution line spectroscopy

Ge pixel, liquid argon and CZT Compton telescopes

G2 Wide field, continuum, transients and polarization

Si trackers, scintillating fibers, gas TPCs, BGO occultation, pair telescopes

Transient infrastructure

G3 Hard X-ray imagers, burst missions and fleets

coded mask CZT imagers, burst missions with IR telescopes, small satellites, IPN

Pointed nuclear line telescope: further down the road

G4 Pointed telescopes with focusing optics

multilayer mirrors or Laue lenses; TES, Ge or CZT focal planes; formation flying

Gamma-ray Capabilities to Address High-Priority Astrophysical Questions

All-sky MeV Transient Monitoring					
Wide-field MeV to GeV Imaging Spectroscopic Surveys					
Wide-Field MeV Nuclear Line Spectroscopy					
Pointed High-resolution Line Spectroscopy					
MeV and GeV Polarimetry					
Large Grasp GeV Surveys with usec Timing					
Arcminute Hard X-ray and Soft Gamma-ray Imaging					
Rapid Multiwavelength Follow Up					
	Relativistic jets	Supermassive black holes	Cosmic explosions	Element formation & CR outflows	Fundamental physics

Draft capability summary table from ASTRA workshop needs critique and comment

Filled boxes indicate primary science applications discussed in the community survey inputs.

9 Findings and Recommendations

1. **Gamma-ray observatories enable key astrophysics studies that longer wavelength observatories cannot address.** The table of the FLAG group (Section 3) contains 28 goals in four themes and a set of additional topics, with observational requirements that are one to two orders of magnitude beyond the current observatories.
2. **A wide field of view gamma-ray observatory is the highest priority large mission.** Such a mission addresses the largest number of science questions, it is the mission that the multi-messenger facilities of the 2030s need, and the community has developed several technical approaches that each provide a large subset of the required capabilities. We recommend that two of the approaches be selected for increased funding through the strategic technology development program and that the other approaches continue to be developed through APRA.
3. **A pointed high resolution nuclear line telescope is a separate mission with a longer timeline to implementation.** Its science (511 keV point sources, ^{44}Ti maps, ejecta velocities) cannot be addressed in another way, but the optics still need maturation.
4. **Fermi and COSI should be operated as long as possible** to minimize a gap in all-sky monitoring which would cause a serious setback for gravitational wave and neutrino facilities.
5. **A coordinated technology program is required now.** Ideally, the technologies of Table 10 will be organized into a roadmap with a defined path to TRL 6 and will be funded through APRA and the SAT. Radiation hard SiPMs, silicon pixel sensors, liquid argon and germanium pixel detectors, CZT coded mask instruments, gamma-ray optics, TES microcalorimeter detectors, and platforms for long focal plane missions are all high priorities.
6. **Software is an important technology.** The event reconstruction, response generation and onboard analysis determine the sensitivity of Compton and pair telescopes. A funded software development plan that is shared across concepts would benefit the performance of all of the missions.
7. **The gamma-ray community should enter Astro2030 with a prioritized program.**
8. **International and interagency partnerships should be pursued for a NASA led wide field observatory.** International and interagency partners can provide instruments, follow-up telescopes, detectors and launch opportunities.

FLAG SAG Report Preview Draft Link and Feedback Form

Report preview link

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