Future Innovations of Gamma rays Science Analysis Group

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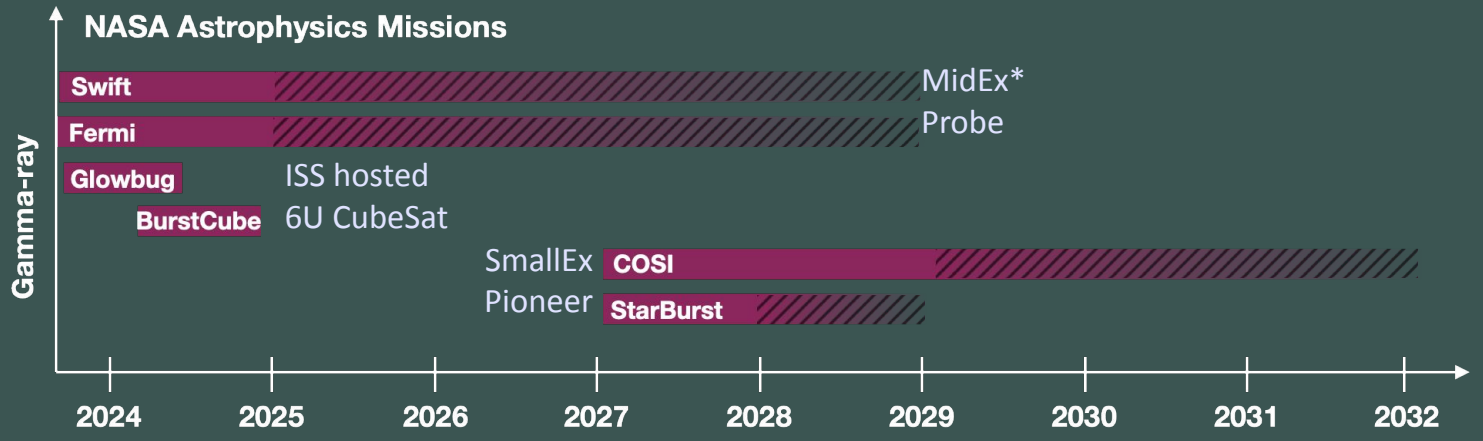
Gamma-ray Astronomy

Revolutionizing Astrophysics through continuous observations

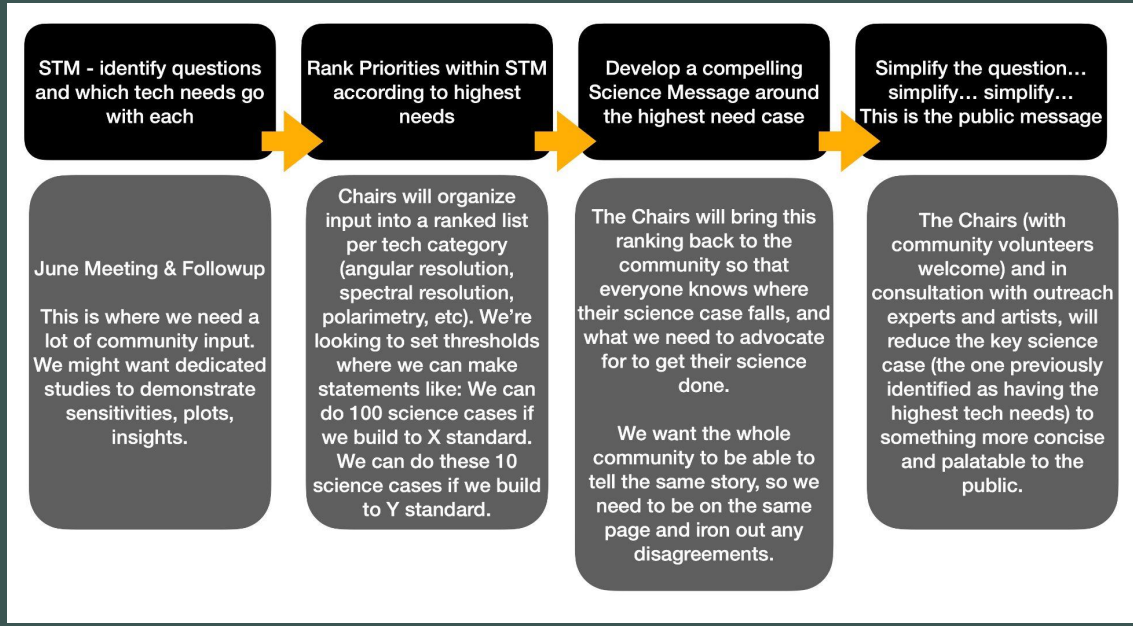
- Discoveries: new classes of transients and flares (GRBs, magnetars, novae, AGNs, multimessenger), large-scale/extended structures (Fermi Bubble), CR acceleration sites (SNR), particle interactions and accelerations (pulsars, jets etc.), constraints on DM.
- Issue: current major missions are all in their decade+ extended operational. Only smaller-scale missions have been funded.
- Action: Reassess current and future priorities for a gamma-ray vision towards 2040.



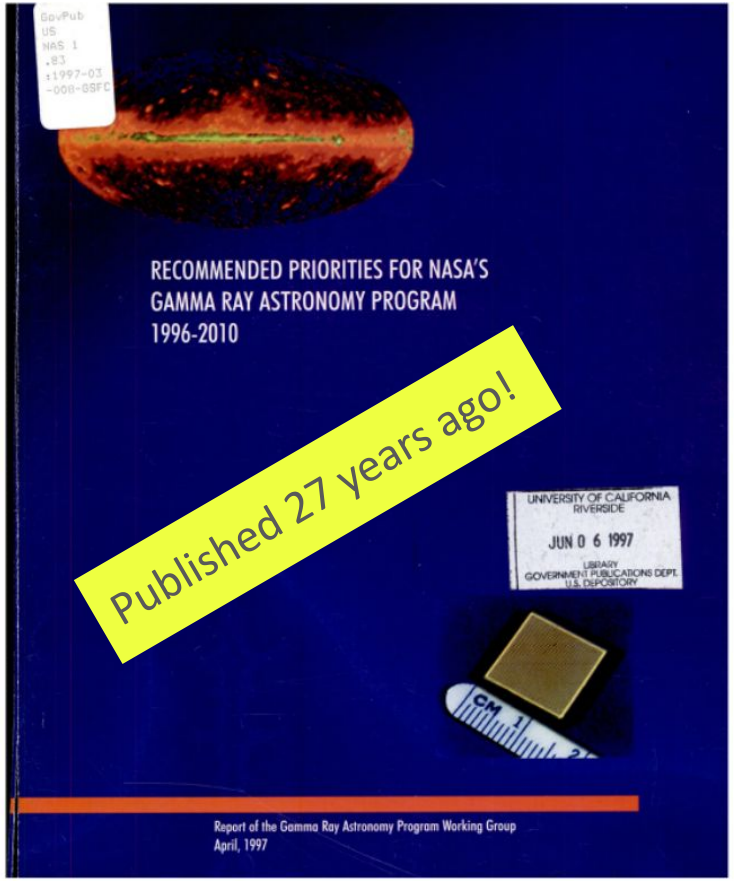
What are we doing

- Build consensus to **strategically advance gamma-ray missions over the next 2-3 decades**.
- Define gamma-ray science in terms of intrinsic value.
- Simplify and streamline our ask for policymakers and the public.
- Report for the Astrophysics Advisory Committee (APAC) to communicate with NASA HQ.

We need your help!



1997 Gamma-Ray RoadMap

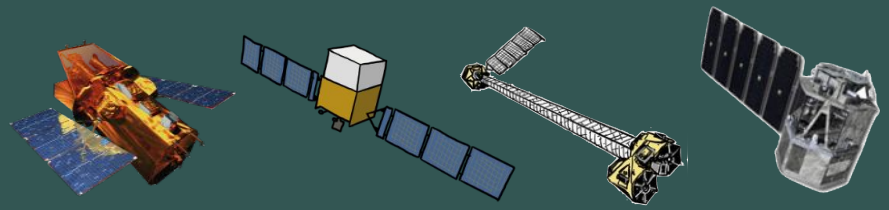


Next-generation, ~2 orders of magnitude improvement in sensitivity for:

- High-energy coverage (10 MeV – 100 GeV) for particle acceleration and non-thermal processes in AGN and galactic sources -> **Fermi**
- Focusing hard X-ray up to ~100 keV to study accretion -> **NuSTAR**
- Nuclear line and MeV continuum to study nucleosynthesis sites -> **COSI**

Near-term -> **Swift, Fermi**

- GRB localization mission to study origin of GRBs
- Hard X-ray all-sky survey and monitor for transients



FIGSAG Overview

1. **Gamma-ray Science Priorities**: Identify opportunities uniquely afforded by gamma-ray observations.
2. **Gamma-ray Mission Capabilities**: Which science objectives are only done or best done by space-based gamma-ray missions, considering the current missions in extended operation and funded missions in development.
3. **Technology Investment**: What new technologies/methodologies exist and what is needed to achieve the science priorities.
4. **Theory and Analysis Needs**: What advances do we need to make in theory and analysis to achieve the science priorities.
5. **Synergies with Other Programs**: How do these goals tie to the broader astrophysics and physics community. What are the timelines to align with current priorities in multi-messenger astronomy.

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N. Kurahashi Neilson, Neutrino Astronomy and Fermi, Monday

- IceCube's success based on decade+ overlapping operational period with Fermi. **Will future Neutrino Telescopes have a gamma-ray partner?**

What neutrino astronomy needs

- Survey Telescope with wide FOV to match all-sky nature of neutrino telescopes
- Ability to follow up neutrino alerts with large angular error
- Coverage of MeV to TeV energy
- Galactic understanding?

S. Ronchini, Current and future role of Fermi for MMA

Future challenges:

☆ Presence of (and coordination among) γ/X-ray detectors indispensable in 3G GW era to maximize the scientific return

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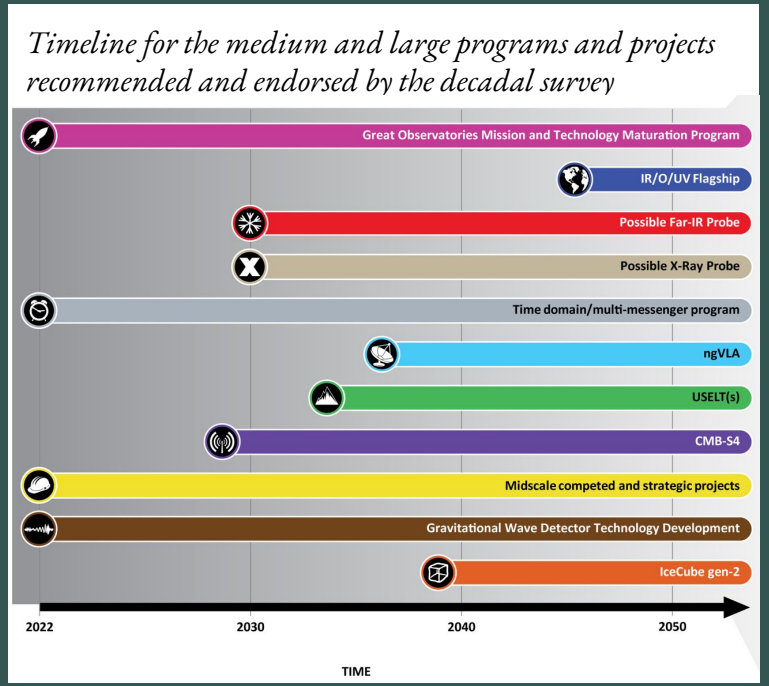
5. **Synergies with Other Programs**: How do these goals tie to the broader astrophysics and physics community. What are the timelines to align with current priorities in multi-messenger astronomy.

FIGSAG Primary Question

What science has not or cannot be done with existing or funded space-based gamma-ray instrumentation? i.e beyond Fermi and COSI, looking ahead to the fleet environment of the 2030s and 2040s.

Astro2020 decadal: era of multimessenger and multiwavelength astronomy…
Gamma rays are not just supporting!
What is best study with gamma-ray observations?

Defining the gamma-ray community and our science **intrinsically**.



FIGSAG Activities So Far

Jan 9 – Kickoff at AAS meeting

Feb 29 – Gamma-ray Science Priorities

Mar 21 – Theory and Analysis Needs

Apr 10 – Special discussion session at HEAD meeting

May 23 – Technology Investment

Jun 24-28 – Workshop at MTU

Aug 1 – Workshop summary and Report

Aug 22 – Technology and Mission Capabilities

https://pcos.gsfc.nasa.gov/sags/figsag/figsag-events.php

Virtual meeting recordings and notes are available on FIGSAG events page.

Discussion Overview: Science

Started with a wide range of topics in gamma-ray astronomy:

- **Nature of Dark Matter/Dark Energy**: e.g. 511 keV line, reaching the thermal relic.
- **Formation and Merging of Supermassive Black Holes**
- **Origins of Heavy Elements in our Galaxy**: e.g. gamma-ray spectroscopy to map nuclear lines and sites of heavy element production.
- **Sources of Cosmic Ray Accelerations**: e.g. unexplored MeV gap, probe structures within our Galaxy.
- **Existence of Life in Our Galaxy**: e.g. techno signatures (reactors), host star / gamma-ray activity and impact on habitable zones.
- **Questions not Included Above**: e.g. crossover between gamma-ray spectroscopy and lab plasma physics.

Discussion Overview: Theory and Analysis Needs

- **Plasma Physics Theory & Modeling (Standard Model Physics)**: data needed to better inform models, e.g. timing and polarization.
- **Nuclear Modeling & Simulations (Cross sections & Lines)**: large number of numerical studies needed to calculate observables, improvements to quantify uncertainty – couple with high-performance computing and AI to tease out trends.
- **Data Analysis & Simulation Methods**: data mining challenges and software limitations, challenges in multi-mission analyses.
- **Particle Physics Modeling & Simulations (Beyond Standard Model)**: need better modeling of astrophysical sources that contribute as background and foreground, as the expected signal levels are weak.

Scientific Challenge and Open Questions

Understanding explosive engines

- **Zoo of explosive transients** – the diversity observed within cosmic explosions is not modeled by current theories.
- **Jets** – fundamentals of jet physics, similarity and dissimilarity of jets produced by blazars and GRBs, jetted TDEs as the link?
- **Central engines** – long lived? How are prompt and extended emissions powered?
- **Accretion processes** – gap between supernova and kilonova, neutron star-black hole/white dwarf binaries?

Theory needs: development for jet formation and propagation, particle acceleration and cooling, radiation transfer. Models to quantify polarization variability.

Observational needs: time-dependent polarization, fine timescale prompt emission spectra

Near term: joint discovery space with current suite of observatories

Scientific Challenge and Open Questions

How and where are particles accelerated

- **Magnetic fields, structures and evolution** – pulsar halos in MeV and GeV; polarization of jets on different scales, PWNe, and pulsar binaries.
- **Composition, tracers of leptonic and hadronic emission** – MeV features in SNRs; winds, outflows, and starbursts in our Galaxy and others; neutrino associations.
- **Jet launching, jet structures at different scales** – jetted TDEs and Galactic binaries; variability and polarization in blazars and GRBs.
- **Acceleration and Transport** – outflow dissipation of various magnetizations; synchrotron vs curvature radiation; morphologies of pulsar halo, PWNe, and diffuse.

Open questions: How does the pulsar machine work? How do binaries influence locally measured cosmic ray spectrum? What are the origins of cosmic rays, PeVatrons, neutrinos? How do cosmic rays influence structure of other galaxies?

Scientific Challenge and Open Questions

Gamma rays from nuclear decay

- **Nuclear decay from transients** – constraints on explosions and probe the properties of the engine (e.g. asymmetries); how standardizable are the standard candles Ias?
- **Radioactive elements in remnants and beyond** – direct probe of actual SN yields from long-lived radioactive isotopes.
- **Nuclear Physics**

In the next 50 years, gamma-rays from the decay of radioactive isotopes provide the only nearly- direct probe at sufficiently high distances to build the samples of events to study these engines.

Scientific Challenge and Open Questions

Nature of dark matter

- **Role of gamma rays in DM searches** – crucial in searches for DM lines, high polarization degrees can indicate DM interactions.
- **DM substructures** – GeV excess at Galactic Center, in tension with dwarf spheroidal galaxies?
- **Particle/wave nature** – expand search parameter space to include axions, PBHs etc.
- **Broader implications** – role of DM in formation and evolution of large scale structures.

Theoretical advancements: CR transport, 3D modeling of the Galaxy, DM interaction modelling

Instrumentation needs: higher angular resolution (target arcminute), spectral resolution (~1% for Mx<400GeV), MeV coverage

Example Matrix

Observable Type	Sensitivity Requirement	Key Achievable Science
Polarization	1% MDP in 1 day	Definitive blazar jet composition & particle acceleration
	10% MDP in 1 week	jet composition in hadronic scenarios, magnetar outbursts physics
Angular Resolution	0.05 degrees	Resolve sources in the galactic center to constrain diffuse emission models
	0.1 degrees	Probes DM (needs to be more specific)
Energy Resolution	1%	Measure Doppler shift velocities for supernovae
	3%	Measure Nuclear lines in our galaxy (vs COSI?)
Effective Area	>30x LAT at 0.1-1GeV	Pulsar Timing Array (how is this different from current PTAs?)
	>10x COSI	Galactic line science and archeology

Technology Overview

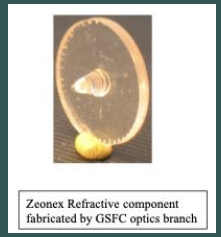
- Silicon detectors
  - AstroPix – Monolithic CMOS sensors
- Imaging calorimeters
- Time Projection Chamber: gas vs liquid
- Scintillating materials:
  - newer and faster: CeBr3, LaBr3:Ce
  - diamond – fast timing, low Z but high density, low TRL
- Coded mask
- Focusing optics up to 100s keV
- Laue Lens
- Phase Fresnel Lenses
  - micro-arcsecond resolution (diffraction limited), long focal length (formation flying)
- Readout electronics
  - Grid Activated Multi-Scale Pixel readout (GAMPix) for TPCs

R. Caputo's talk

T. Aramaki's talk

J. Wood's talk

P. Bloser's talk



J. Krizmanic's talk

Mission Capabilities and Infrastructure Needs

Machine Learning – Event reconstruction, data mining in archives, sky monitoring, extended data fitting in high-level data products.

Data Processing – Foundational data processing is as important to the mission as the hardware.

- onboard processing for more complicated analyses
- high bandwidth downloads to support additional ground processing
- direct spacecraft-to-spacecraft communications to lower repointing latency
- common core tools for producing better understanding of spacecraft responses, e.g. MEGAlib, GEANT4.
- cross-mission analyses, sustaining software and community efforts.

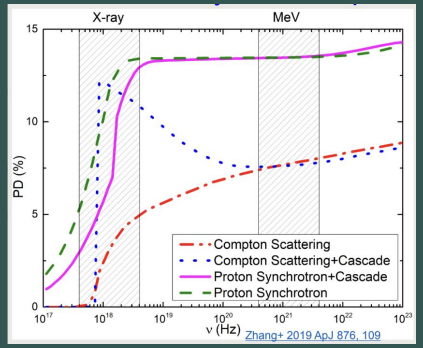
What's Next?

🏆 GOAL

Define the ***science drivers*** for the **next several decades** of gamma-ray astrophysics, connecting to ***sensitivity thresholds***, ***technology requirements***, and ***infrastructure needs*****.**

👩‍💻 REQUEST

Quantify sensitivity and performance needs.
Plots of angular resolution, sky coverage, and effective area requirements for the driving science cases.
What are we missing?



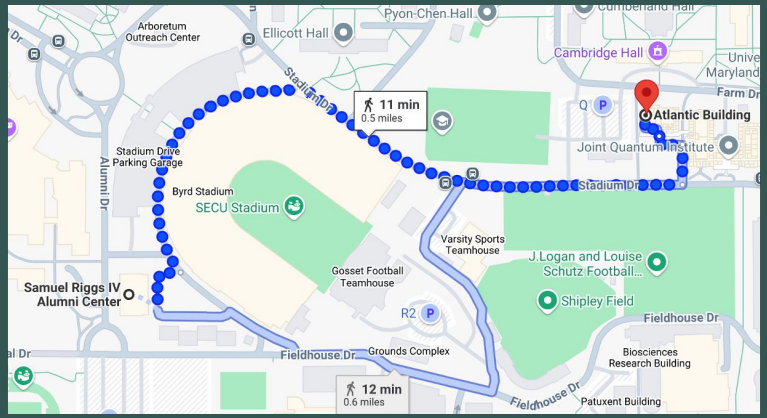
⏱️ TIMELINE

1. Draft report for community feedback by **Spring 2025**.
2. Target submission to the ***NASA Astrophysics Advisory Committee*** by **Summer 2025**.
3. Publish in a special edition in the ***Journal of High Energy Astrophysics***.

Upcoming Events

Session **this Friday, Sep 13 2pm**
Location: **Atlantic Building Room 2400**
Attend virtually

- Historic Overview: 1997 report on priorities for NASA's gamma-ray astronomy program - D. Thompson
- Going Beyond Fermi – L. Hays
- Strategic motivation for specific science priorities that will drive gamma-ray discoveries in the next several decades:
  2:30 pm MeV Lines
  2:50 pm 10-min break
  3:00 pm Burst-like Transients
  3:20 pm Pulsars and Magnetars
  3:40 pm Blazars and Jets



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