Physics of the Cosmos

Future Innovations in Gamma rays Science Analysis Group

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and YOU!

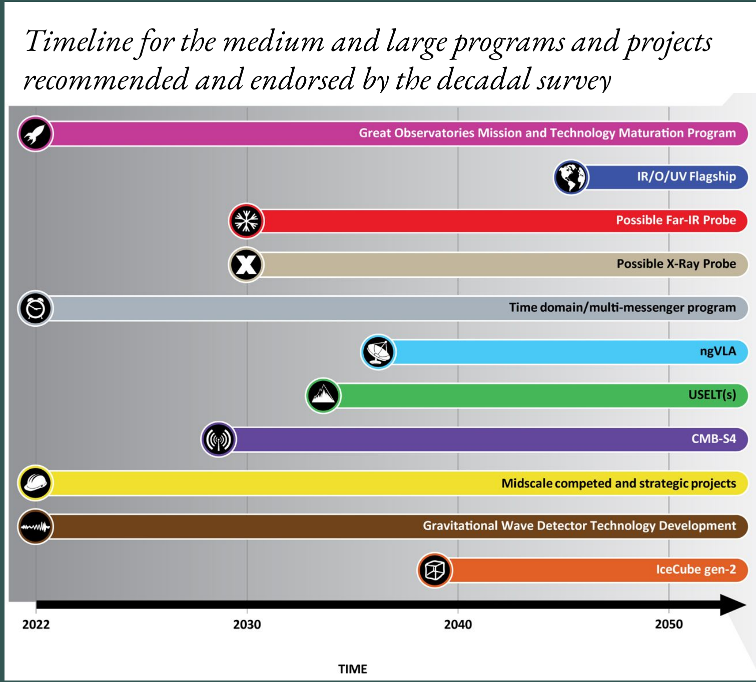
Michelle

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**.



Tiffany

Activities and Strategies of Successful Communities in NASA & Congressional Advocacy

- The whole community is behind reports that advocate for future missions, at least publicly.
- SAG Reports are specific and frequent.
- All of the smaller advocacy projects point to a single long term goal that is easy to explain to someone outside the field in less than 30 seconds.
- Everyone in the community and many people in adjacent communities know and respect this long term goal - they could repeat it if asked.

- Takeaway: We need that question for gamma-rays. Building all of the other infrastructure without it will point in too many directions, hurting clarity, staying power, and ultimately funding for missions and the science they enable.

Tiffany

Criteria for Driving Science Questions

- Long term - something that we can make meaningful progress toward in one mission with a supporting question of narrower scope, but that contributes back to the main question
  - If our main question can be answered with one mission, then we lose out on the impact of building out a generational following that all want us to find the answer
- Motivate mission and technology development
- Promote the science case that requires the most technologically - the most angular resolution, the most spectral resolution, the most effective area, the most sky coverage
  - The most sensitive instrument will also be able to detect data for science cases that require less sensitivity. Therefore advocating for the science case with the highest requirement advocates for all other science cases by default.
- Need identifiable observable or clear path to figuring out what that should be

NOT Important in this phase - “is the question easy to communicate” - We’ll figure out how to communicate it broadly in later steps.

Tiffany

Things we've done to try to identify Mission Driving Science Cases

- Reviewed previous reports - 1997 Gamma-ray Roadmap, Decadal, Snowmass Report
- Reviewed current state of the field - CGRO (1st Great Observatory), Fermi (Probe), Swift (Midex), COSI (SmEx), Glowbug, BurstCube, Starburst
- Hosted virtual talks and discussions on a variety of science and technology topics
- Hosted a conference at Michigan Tech to promote more dedicated discussion
- Compiled community inputs into a draft and requested feedback

We're not done, but we've noticed some patterns that address our criteria for questions.

Tiffany

Future Needs from Gamma-ray Telescopes

- There are probably limits on angular resolution with a survey instrument, but we need high angular resolution to study nuclear lines with more precision than COSI, and we need high sky coverage to monitor for GRBs.
- High spectral resolution instrumentation and high effective area can also be in conflict. Spectral resolution is again needed for lines, while effective area is important for jetted transients, especially blazars, where we want to resolve spectropolarimetry signals on the order of days because their physics changes rapidly.
- We've been trying to compile these kinds of requirements across categories of observables

Tiffany

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

Tiffany

Driving Science Cases

- Nuclear Lines - requires high angular resolution and high spectral resolution together
- GRBs - requires high sky-coverage, precision timing, fast alerts, (spectropolarimetry would also be useful)
- Blazars - requires high effective area for short timescale spectropolarimetry
- PTAs - requires consistent monitoring over long timescales; fundamentally multimessenger; far more scalable than radio PTAs
- Dark Matter - long timescale problem that unites elements of a lot of other objects under one purpose.

Zorawar

Science Case: Nuclear Lines

- Nuclear Lines: GRBs, novae, supernovae, magnetars …(and pulsar planets, see Zac Metzler's talk Thursday)
- Detection and characterization brings a whole new dimension and revolution to astronomy, similar to atomic spectroscopy
  - velocities, redshifts, line strengths and ratios, spatial distribution in galaxy or of remnants, time dependence in transients…
- Study isotopes and elements currently present and infer incipient elements from decay chain physics
- Study asymmetry of supernova explosions directly
- Study how much SN Ia really are standard candles
- Find r-process relics in our galaxy, and see how r-process elements mix

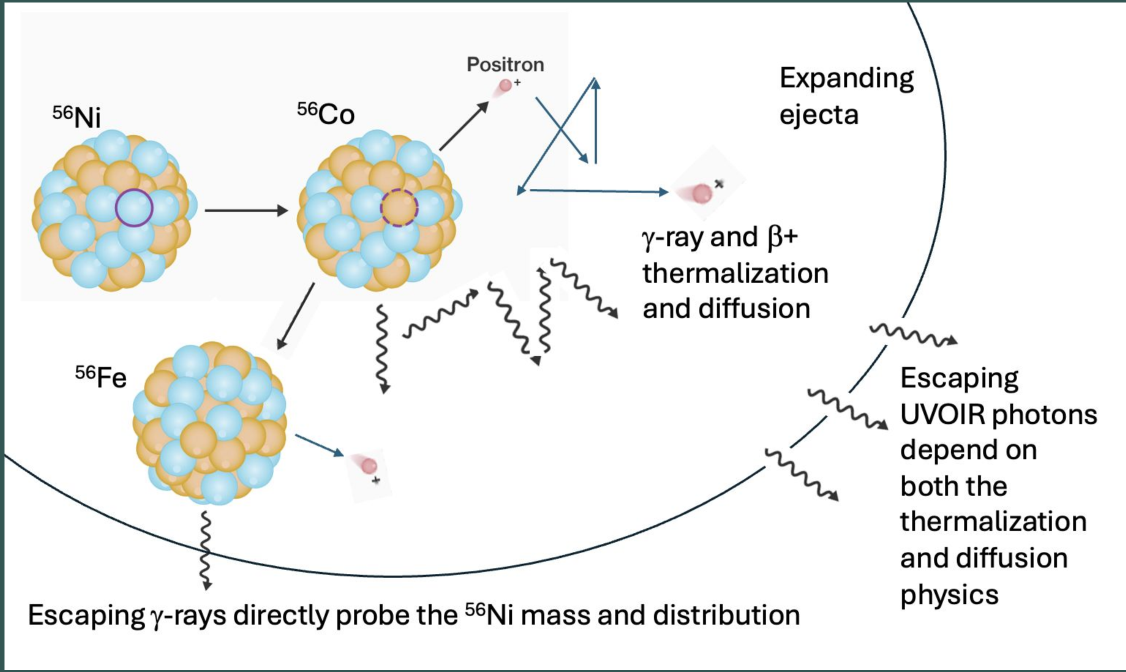
Zorawar

Nuclear Lines - Gamma Rays are a direct probe

Right: Decay of Nickel-56 produces positrons and gamma-rays.

If they are trapped, they thermalize and the fireball emits in the UV/O/IR

Those that escape provide a direct probe of mass and distribution, allowing one to confront simulations and answer big questions related to nucleosynthesis



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Nuclear Lines - sensitivity for Ia and CCSNe

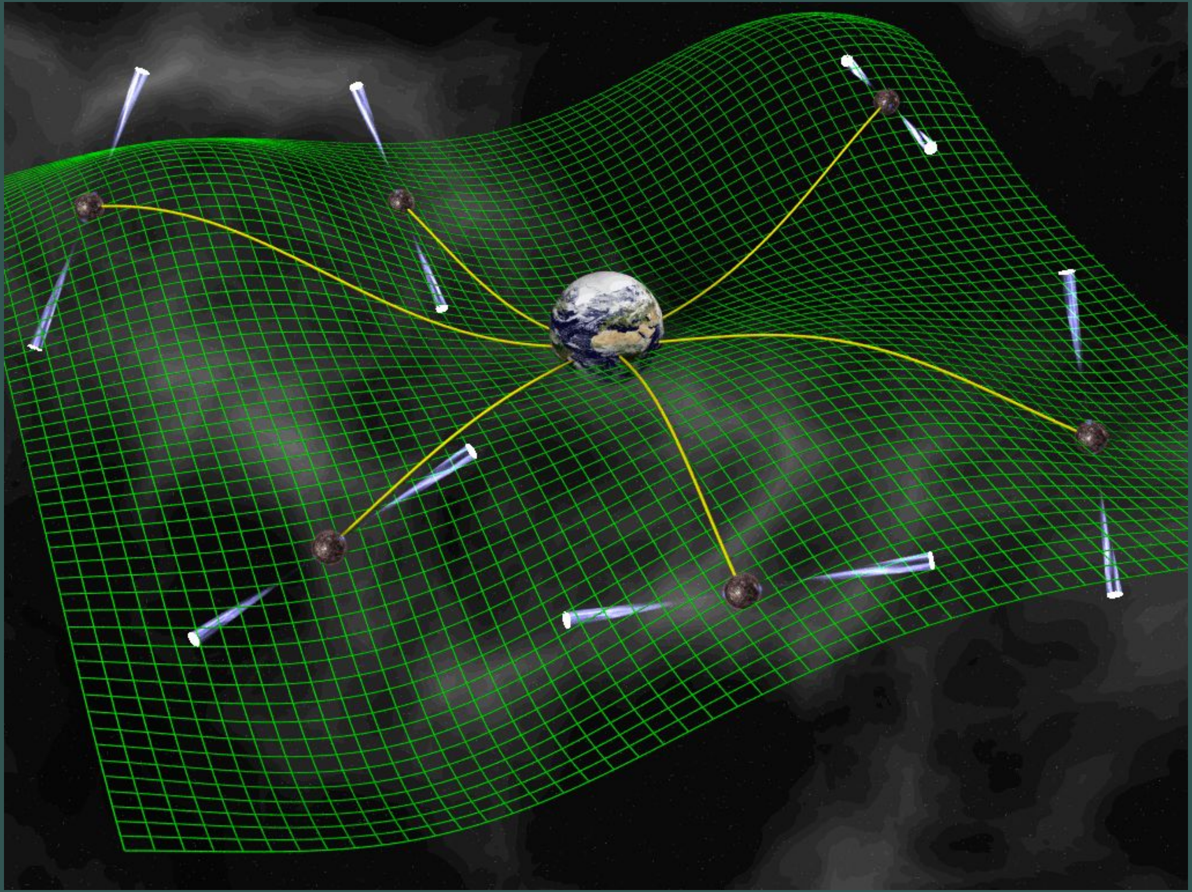
- Get from Eric

Zorawar

Science Case: PTAs

- Pulsar timing arrays are fundamentally multimessenger because the observation performed directly is of photons from pulsars, but the measurement of interest is of supermassive black hole mergers in gravitational waves.
- While PTAs can also be constructed from radio data, gamma-ray data is cleaner, has better sky coverage, and is scalable to a extreme number of pulsars.
- Addresses the larger question of how supermassive black holes (and their galaxies) form and evolve through mergers.
- Also requires ongoing study of pulsars
- Gamma-ray PTA also required to continue the science when radio PTAs hit physical limits associated with systematics, pulsar sky coverage and observing efficiency

PTAs - how does PTA work?



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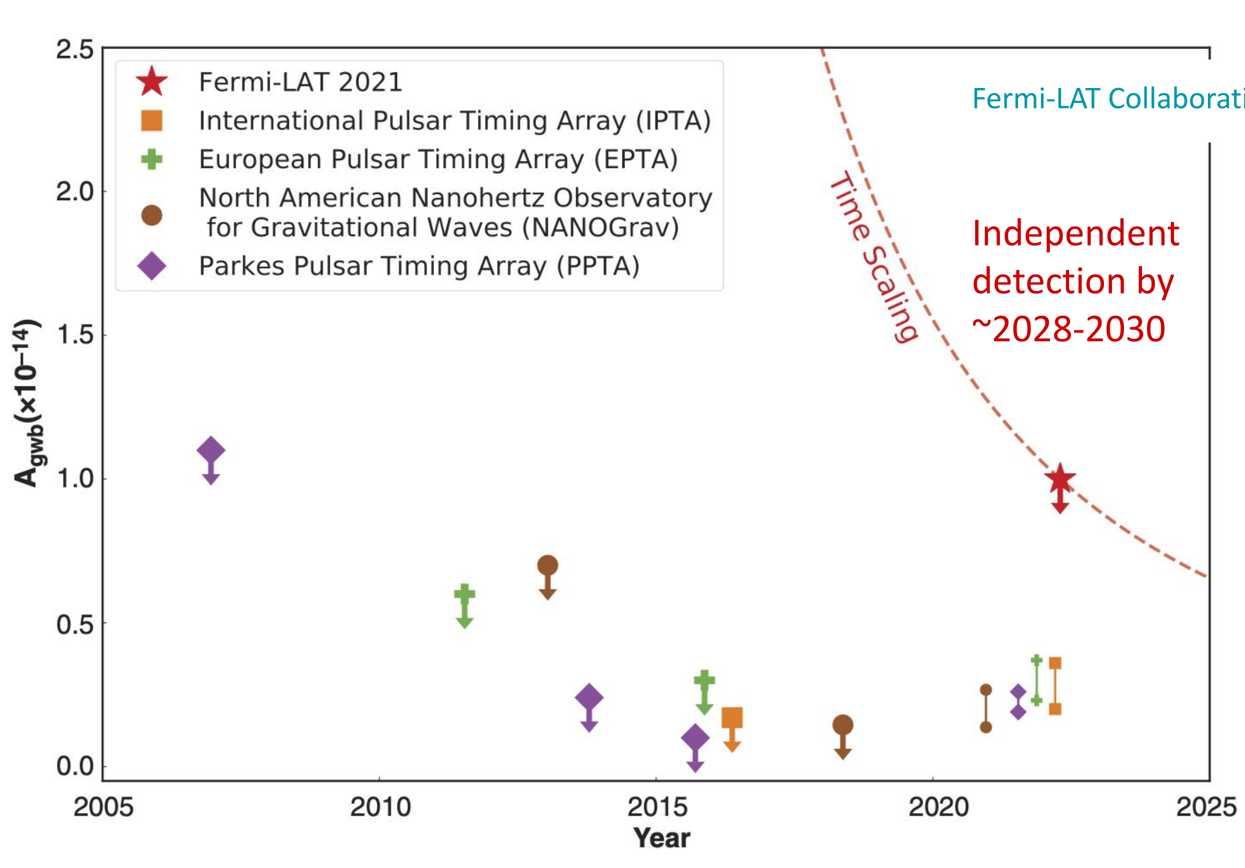
Fermi-LAT PTA

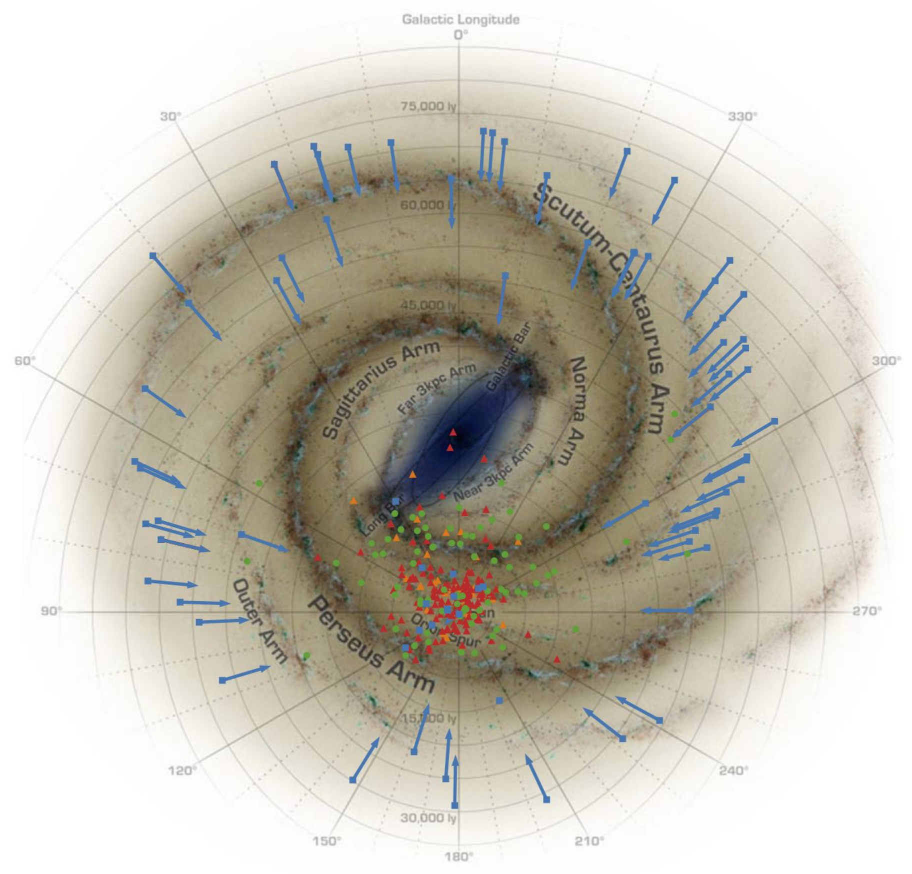


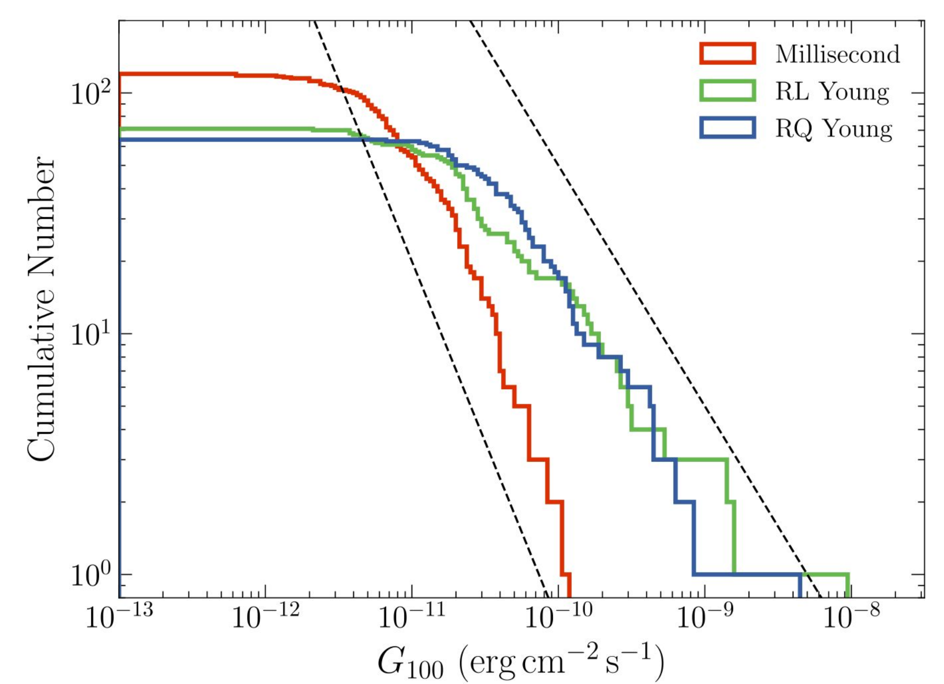
Fermi-LAT Collaboration+2021

Independent detection by ~2028-2030

Zorawar

PTAs - volume illustration for Fermi pulsars





D. Smith + Fermi-LAT Collaboration+2023

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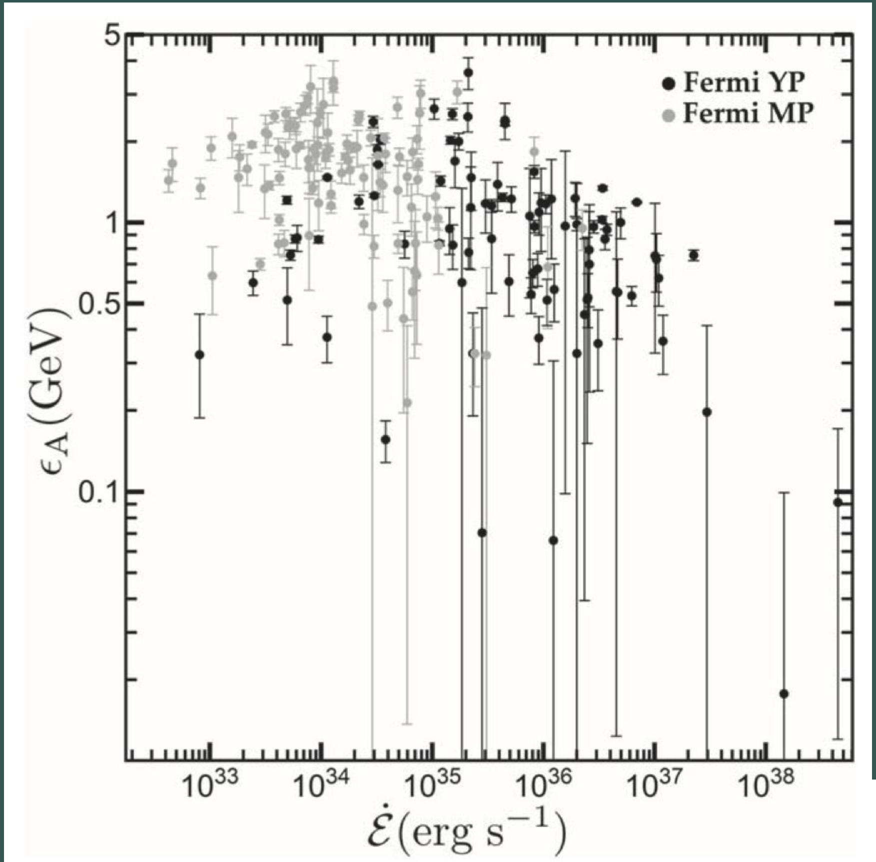
PTAs - millisecond pulsars peak emission in GeV



Kalapotharakos+2023

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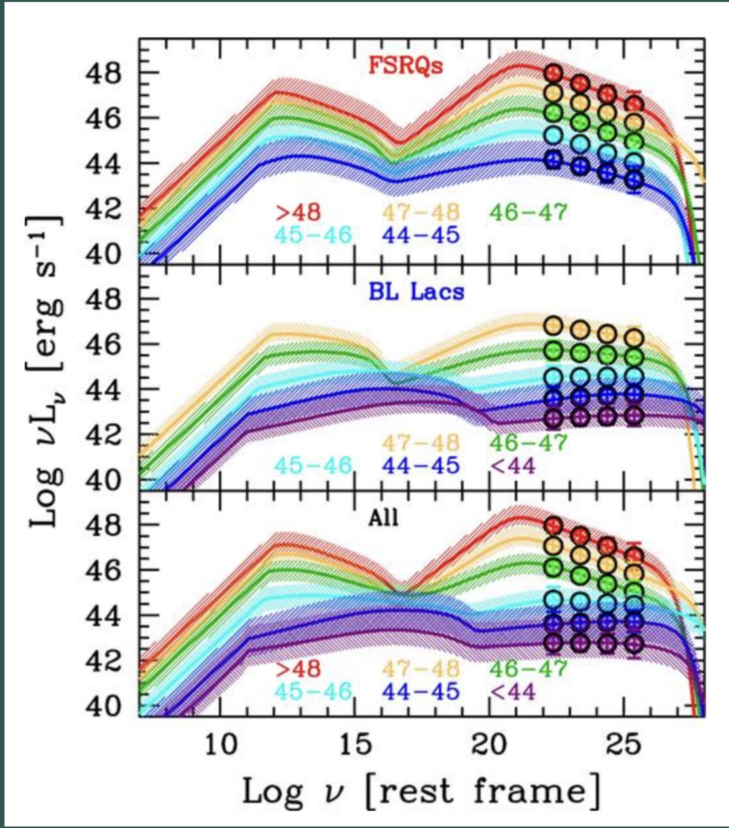
Science Case: Blazars

- Blazars represent a unique view of the largest astrophysical jets and they are sufficiently long lived to study over time
- Common questions in blazar physics relate to jet composition, which is fundamentally a question about how jets form, how they interact with the central engine (spin or accretion driven?), which are further related to galaxy and black hole evolution
  - Spectropolarimetry is most promising, although direct co-detection with neutrinos is also great
- Jetted active galaxies are also a prime location for cosmic ray acceleration, so understanding particle acceleration processes in blazars is an important piece of the cosmic ray spectrum, which still represents an animated debate.

Tiffany

Blazars - effective area by wavelength

- Ghisellini et al. (2017) used a sample of 749 blazars to remake the blazar spectrum plots from Fossati et al. (1998)
- Notice the range of luminosities, remembering that Fermi does not fully resolve all blazars.
- Notice also the spectral break between the traditional X-ray and gamma-ray bands for high synchrotron peaked BLLs.
- Limitations on dividing data along both temporal and spectral axes simultaneously can make interpretation difficult for some sources.



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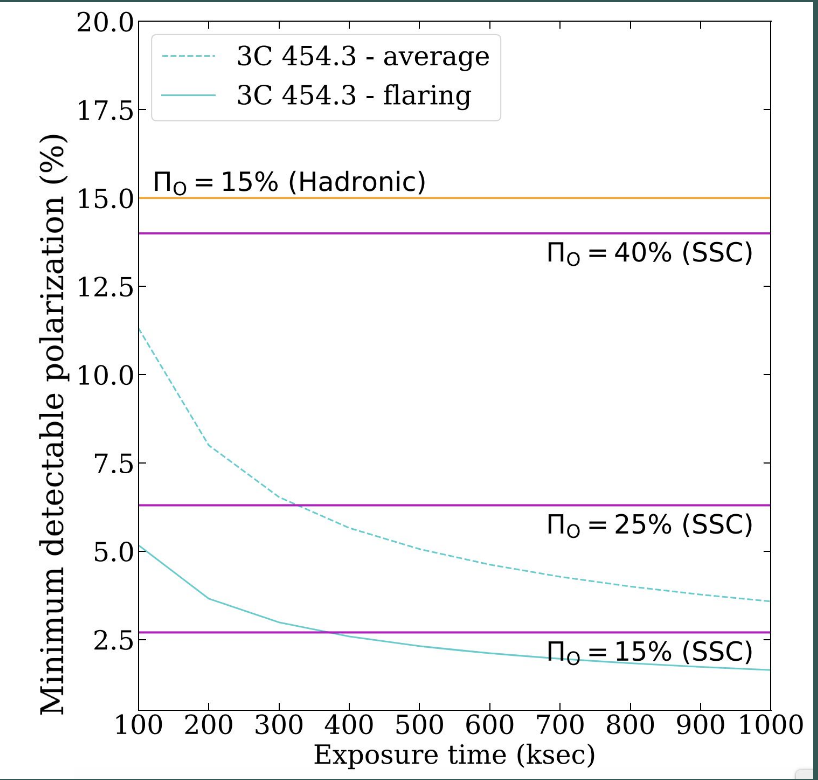
Blazars - Polarimetry & Exposure Time

- Polarization vs time
- magenta lines show the level of SSC polarization for PD (%) in optical polarization, and the orange lines show the hadronic polarization for 15% optical polarization during simultaneous multiwavelength flares (Zhang et al. 2024)
- 1 Ms ~11 days - Blazars change quickly & their polarizations are expected to evolve on similar timescales.



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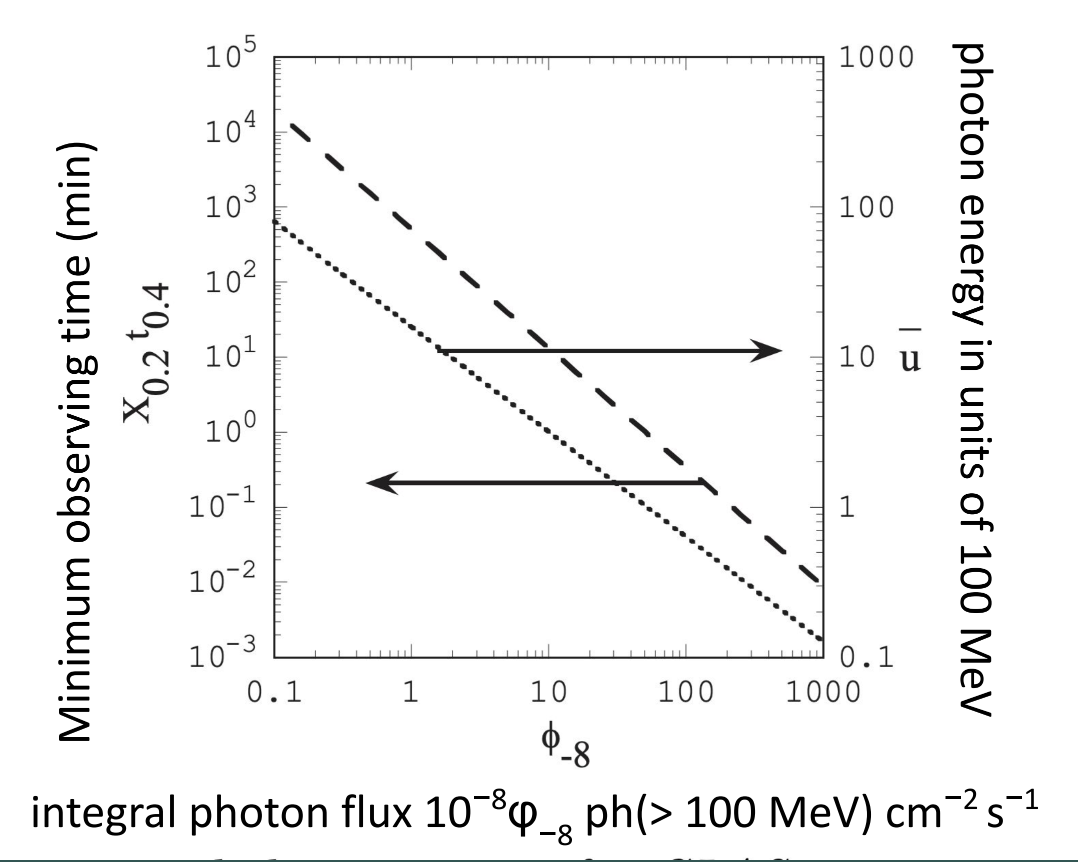
Blazars - need high effective area for spectropolarimetric measurements

- Effective area
- Dermer & Dingus, 2004
- Express the the minimum observing time for GLAST as a function of integral photon flux expected for blazars.
- Note that these fluxes were estimated according to the criterion of detecting 5 photons with a significance of 5 sigma, which would be insufficient for modern spectropolarimetry.



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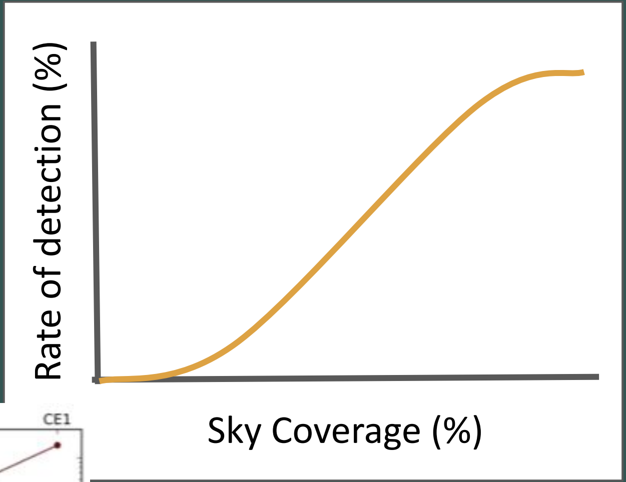
Science Case: GRBs

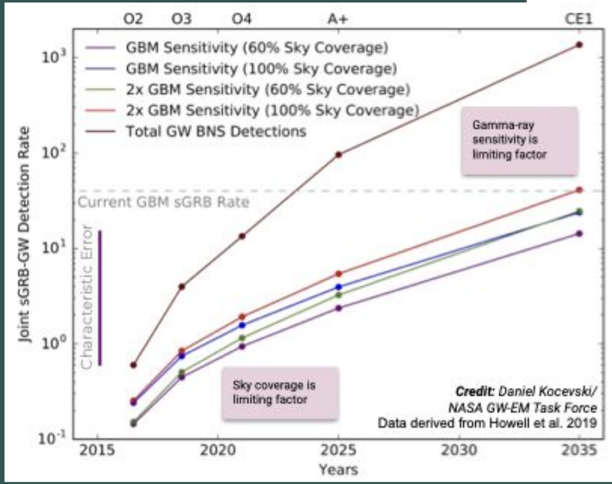
- Gamma-ray Bursts represents a diverse class of explosive transients.
- Gamma rays play a critical role in prompt detection, localization, and to probe the jet production, structure, and propagation.
  - Emission and particle acceleration
  - Quasi-Periodic Oscillations and nature of GRB engines
  - Progenitors and classes
  - Jet structure
  - Cosmology
  - Magnetar Giant Flares
- Capabilities needed for advancement
  - Wide-field, all-sky coverage
  - Localization
  - Energy resolution for possible lines
  - Effective area for QPOs and polarimetry

Michelle

GRBs: Sky coverage

- Sky coverage vs. detection probability
  - How much sky coverage is necessary to maintain good probability of detecting transient events
- Sensitivity and energy range vs distance probed
- Example:
  GW-EM task force report showing sky coverage vs sensitivity as limiting factors for joint detection





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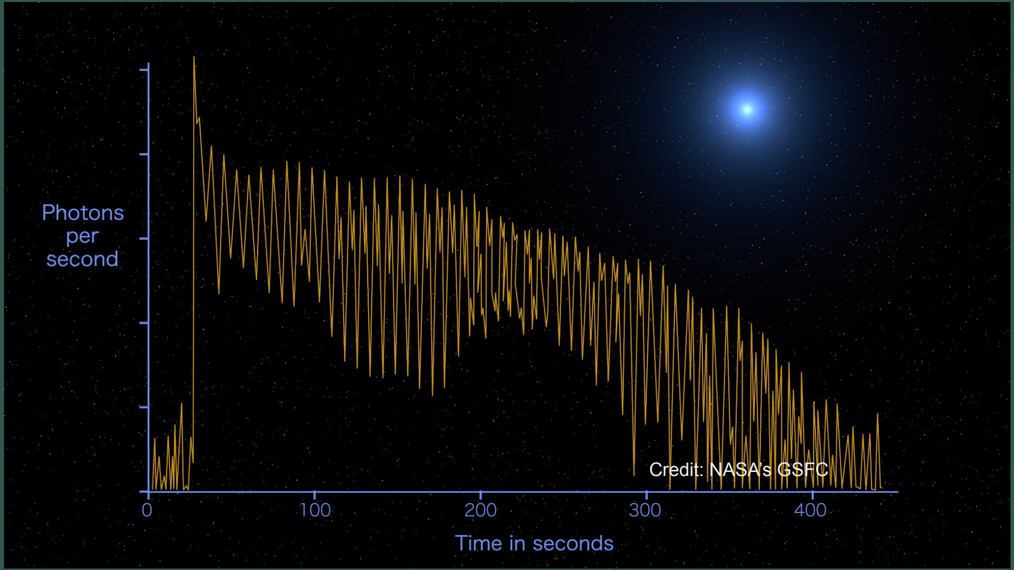
GRBs: Timing

- Quasi-Periodic Oscillation and temporal features -> microseconds resolution
  - PTA likely has stricter limits, and GRBs are photon limited.



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GRBs: Polarization

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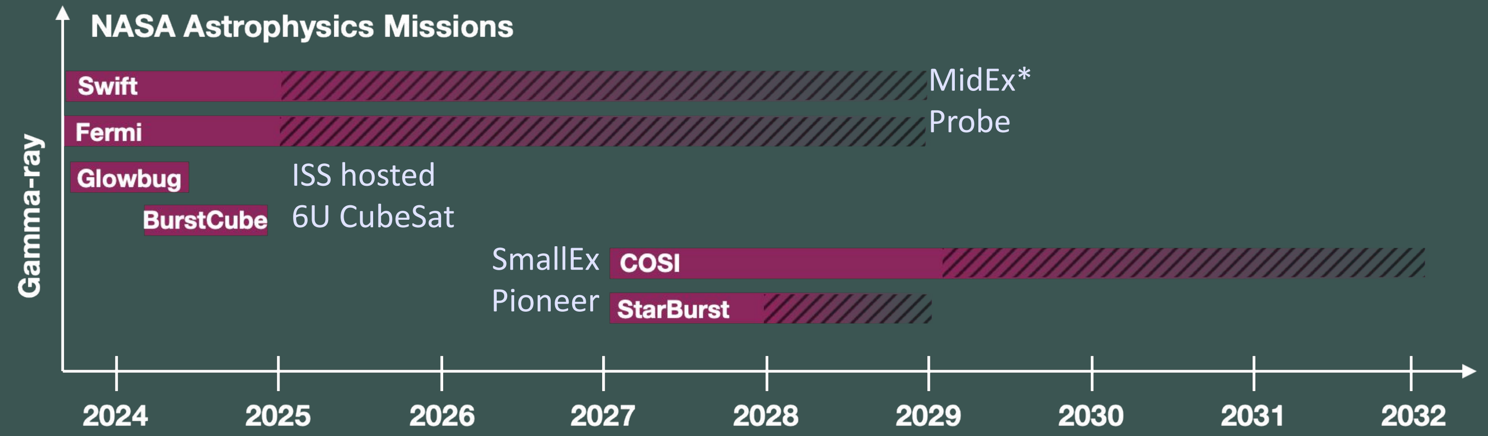
Discussion of Science

- What do you think about the approach to identifying science cases that serve the whole community?
- What do you think of how we prioritized the driving science cases?
- If someone were to build an instrument with requirements that satisfy the ones we've outlined here, would your science case be able to advance?
- Have we missed anything?

Gamma-ray Astronomy

Revolutionizing Astrophysics through continuous observations

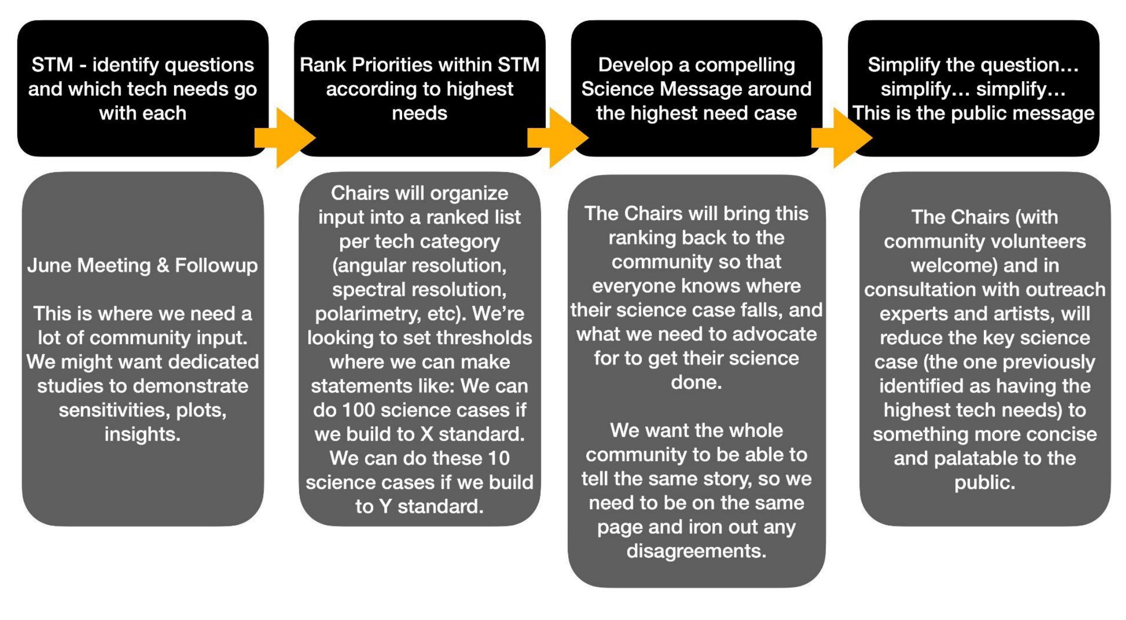
- Discoveries: new classes of transients and flares (GRBs, magnetars, novae, AGNs, multimessenger), large-scale/extended structures (Fermi Bubble), CR acceleration sites (SNR), particle interactions and accelerations (pulsars, jets etc.), constraints on DM.
- Issue: current major missions are all in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



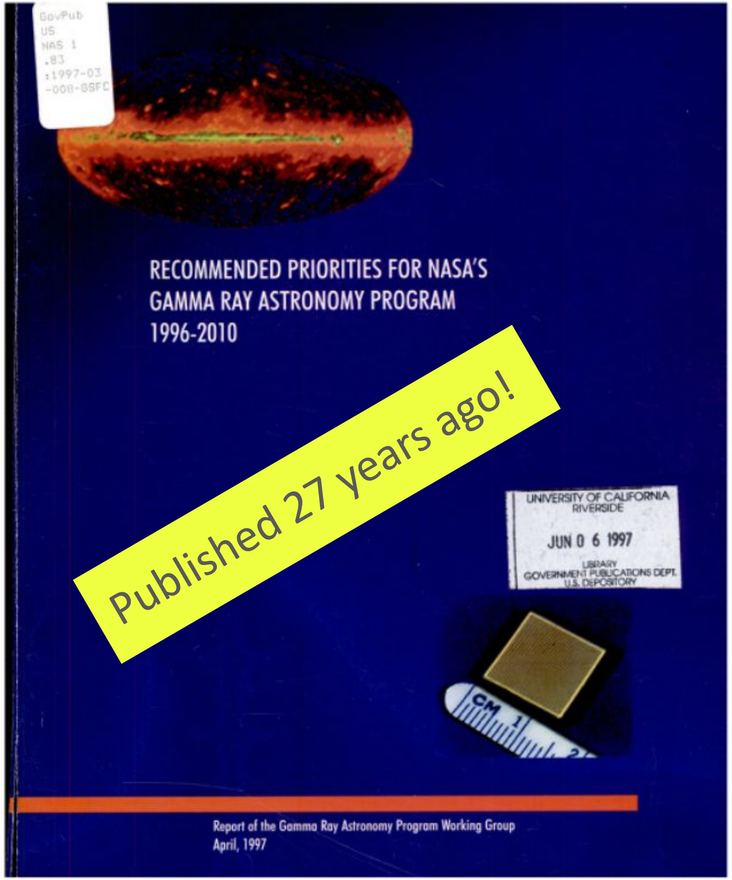
What are we doing

- 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

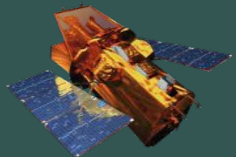


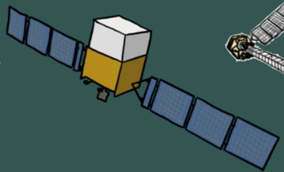
Next-generation, ~2 orders of magnitude improvement in sensitivity for:

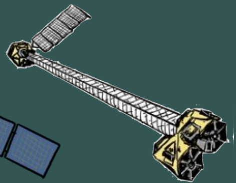
- High-energy coverage (10 MeV – 100 GeV) for particle acceleration and non-thermal processes in AGN and galactic sources -> **Fermi**
- Focusing hard X-ray up to ~100 keV to study accretion -> **NuSTAR**
- Nuclear line and MeV continuum to study nucleosynthesis sites -> **COSI**

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**: Ident
gamma-ray observations.

2. **Gamma-ray Mission Capabilities**: W
done by space-based gamma-ray mis
extended operation and funded miss

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

we need to make in theory and

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 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.

Theory and Computational Advancement

- This is a chapter in the report. We have some preliminary thoughts in the document that describe some of the problems, but we have not yet reached a consensus on the overall findings and path forward.
- There is insufficient support for theory, phenomenology and computational development and a general sense that splitting the funding for these into separate categories might help to support each of them individually.
- There was related Decadal recommendation.

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

Michelle

Technology Advancement

Imaging Techniques

- Focusing optics with multilayer coatings, extending to 100+ keV
  -> sub-arcminute resolution
  -> *Tier 2 tech gap*: High-throughput focusing optics for 0.1-1 MeV
- Coded aperture imaging -> arcminute resolution, wide field, and wide energy range
- Compton telescope -> MeV
- Pair production telescope -> GeV
- Phase Fresnel Lenses, keV
  -> micro-arcsecond resolution (diffraction limited)
  -> long focal length, ~km -> formation flying
- Laue Lens

2024 Astrophysics Strategic Technology Gaps, next solicitation 2026.

Michelle

Technology Advancement

Detector Technologies

- Scintillating materials:
  - newer and faster -> CeBr3, LaBr3:Ce
  - diamond – fast timing, low Z but high density, low TRL

  -> *Tier 3 tech gap*: charged-particle discriminating X-ray/gamma-ray detectors
- Silicon detectors
  - Monolithic CMOS sensors

  -> *Tier 3 tech gap*: low-power, low-cost semiconductor detectors
- Imaging calorimeters

  -> *Tier 3 tech gap*: high-energy-resolution gamma-ray detectors
- Time Projection Chamber: gas vs liquid

Tier 3 tech gap: large FOV and effective area gamma-ray detectors

Tier 3 tech gap: rad-tolerant, photon-counting light detectors

Michelle

Technology Advancement

Detector Technologies (cont)

- Readout electronics
  - Grid Activated Multi-Scale Pixel readout (GAMPix) for TPCs
  - SiPM readout

    -> *Tier 3 tech gap*: low-power readout for SiPM
  - Fast timing ASIC

  -> *Tier 3 tech gap*: dynamic switching for ultra-low-power, high-res charge readout

Michelle

Mission Capabilities and Infrastructure Needs

Mission Architecture and Communications

- Communications – referencing TDAMM Comm SAG report
    - Latencies – time-critical reporting
    - Bandwidth – increasing data volume from next-gen instrumentation
- Fast slewing
- Formation Flying

Onboard Processing

- Enable faster and autonomous decision making for time-domain phenomena
    - *Tier 2 tech gap*: High-performance computing for event reconstruction

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

Michelle

Discussion of Development and Infrastructure

- Theory, Phenomenology and Computation are part of the infrastructure that help us figure out what an experiment should test - what is the observable that indicates an answer to one of the Science Questions? Not every science case has a clear answer currently. More theory sometimes needs more data.
    - What should developing those roadmaps look like?
- What instrumentation can achieve the observation needed to answer the science questions outlined?
    - in near term / 5 years timeline
    - long term development investment
- Are there new technologies not included here?

Tiffany

Discussion of Development and Infrastructure

- We want to point to technologies and capabilities that would be appropriate to a range of mission sizes, from Explorer class to Flagship, but we cannot recommend specific missions because that is the role of the proposal process.
    - Do you agree with that goal?
    - Do you think we are on track to achieve it?

Tiffany

Discussion of Development and Infrastructure

- The Decadal defines how highly strategic technology gaps can be ranked. Since gamma-rays were not given a strategic mission recommendation in the Decadal, our technology gaps are minimally ranked, which hampers our technology development funding prospects.
  - It is important to have a strategic mission plan going into the next Decadal.
  - The FIGSAG report aims to connect community-wide science goals to instrumentation, theory, capabilities for near- and long-term development.
  - What are considerations for next steps, follow-on reports etc.?

What's Next?

🏆 GOAL	🧑🏽‍💻 REQUEST	⏱️ TIMELINE

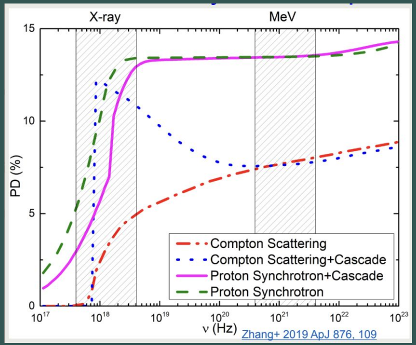
🏆 GOAL

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 **Fall 2025**.
3. Publish in a special edition in the ***Journal of High Energy Astrophysics***.

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