Physics
of the Cosmos

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An Overview of Future Innovations in Gamma-ray Science

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NASA Astrophysics Big Questions

- How does the Universe work?
  - How do supermassive black holes form?
    - Gravitational Collapse - Dark Matter
    - Coevolution/Star Formation - GRBs, Blazars
    - Mergers - Pulsar Timing Array
- How did we get here?
  - What are we made of?
    - Origin of Elements - Nucleosynthesis
    - Extreme Accelerators - Magnetars, GRBs
- Are we alone?
  - Gamma-ray host star activity impacts habitable zones

How Did We Get Here?

- Origin of Elements
  - The building blocks of life require nucleosynthesis in supernovae
    - Studying nucleosynthesis requires gamma-ray lines
    - Nickel-56 traces the explosive engine of core-collapse supernovae
    - Nuclear transients require temporal resolution of 1-10 days coinciding with energy resolution of <1%, and remnants require an angular resolution down to 10”
- Extreme Accelerators
  - Jetted compact objects, especially pulsars and magnetar GRBs
  - Active galaxies, dark matter, large scale structure

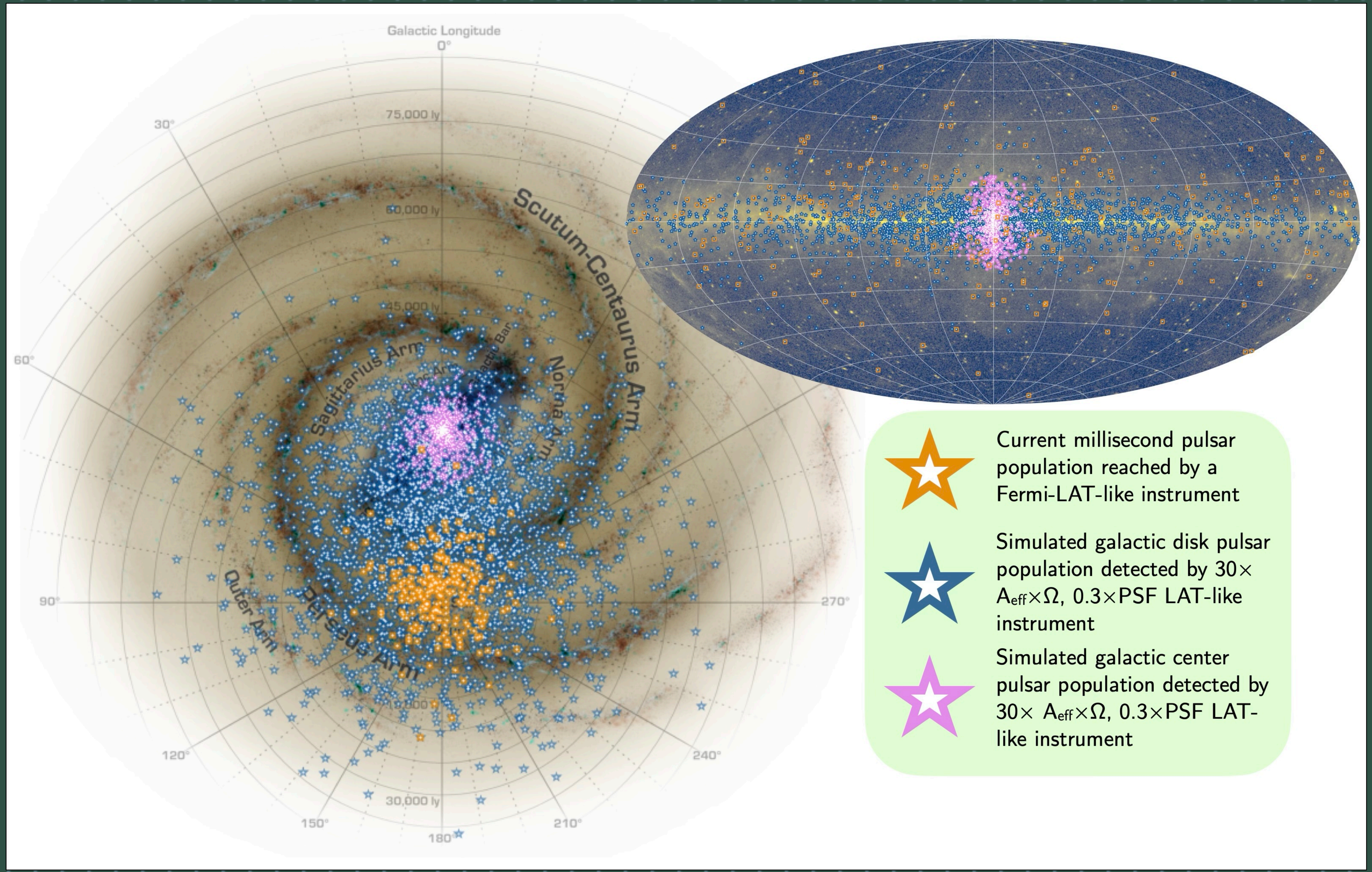
How Does The Universe Work?

- How do supermassive black holes grow?
  - SMBHs co-evolve with galaxies, in dark matter halos
  - Gamma-ray bursts mark early star formation
  - High-redshift blazars probe the active phase of early SMBHs
  - The greatest uncertainties in understanding blazars as an engine require MeV spectropolarimetry
- How do supermassive black holes merge?
  - Major mergers are one pathway to grow SMBHs
  - The most scalable detector for SMBH mergers is a gamma-ray pulsar timing array to detect very low-frequency gravitational waves
  - Pulsar spectra peak in the GeV regime

Why Gamma Rays Are Needed

- MeV and GeV gamma rays probe physical concepts and astrophysical objects that are inaccessible at other wavelengths or with other messengers.
  - To study supermassive black hole formation and growth, we need to access information about dark matter, blazars and major mergers.
  - We need to make specific measurements in MeV lines and MeV polarization, as well as achieving spectral and temporal sensitivity in both MeV and GeV regimes.
- Current gamma-ray missions serve the interests of the broader community as well as industry
  - There is no comparable survey telescope currently in the pipeline, a process that is expected to take 2 decades once started.

GeV Pulsar Timing Array



☆ Current millisecond pulsar population reached by a Fermi-LAT-like instrument

☆ Simulated galactic disk pulsar population detected by 30× $A_{\text{eff}}\times\Omega$, 0.3×PSF LAT-like instrument

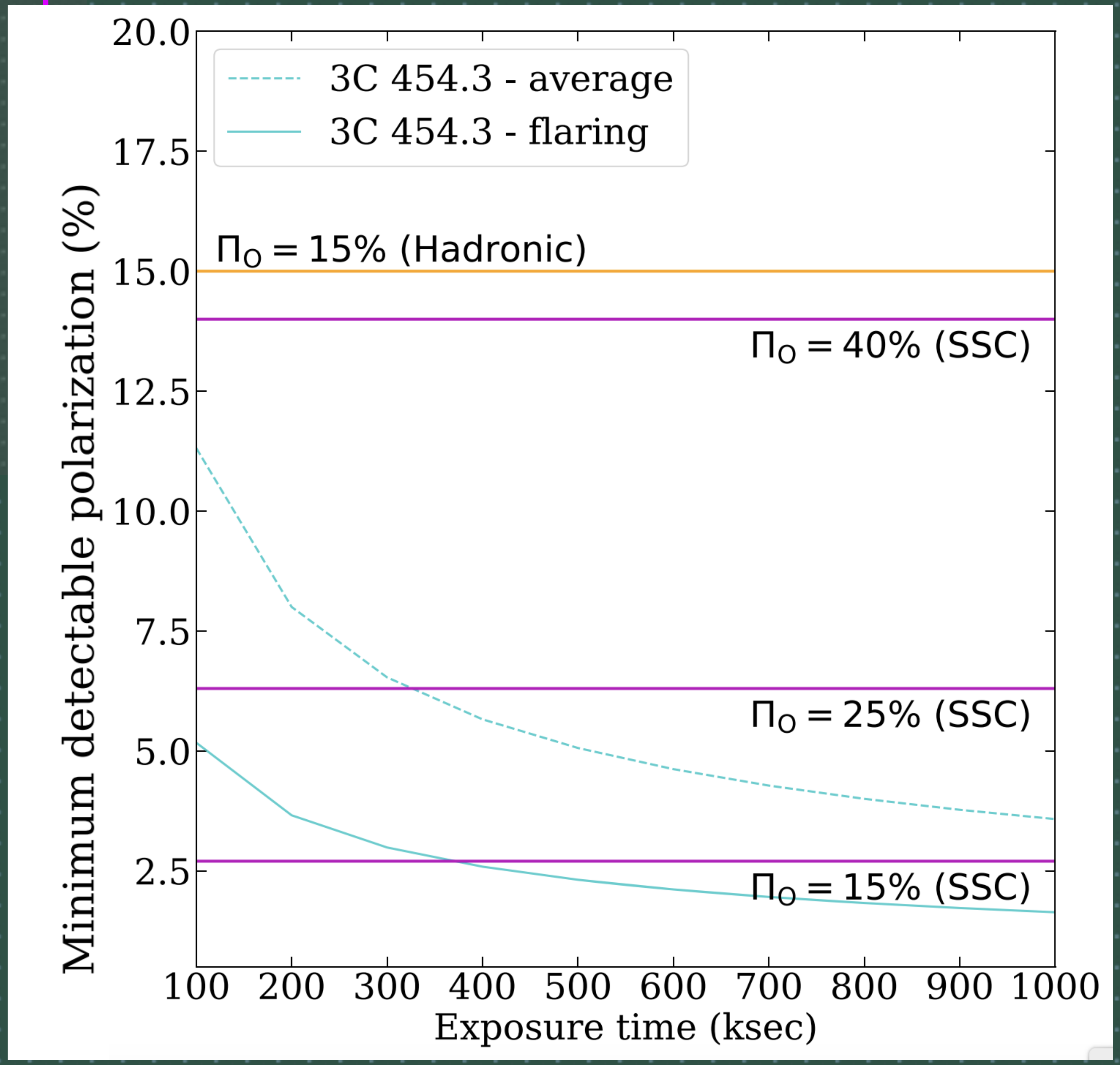
☆ Simulated galactic center pulsar population detected by 30× $A_{\text{eff}}\times\Omega$, 0.3×PSF LAT-like instrument

Key Science Questions:
Gamma-Ray Pulsar Timing Array

1. Question/Goal: How do supermassive black holes form and merge? Are angular structures in the low frequency GW sky or individual sources?
2. Why Gamma rays? 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.
3. What we know so far: Radio PTAs are detecting a signal, we don't know what it is or whether it is even uniform on the sky. Radio telescopes are limited to one hemisphere.
4. What we need next: A high acceptance 0.1-5 GeV instrument with decent or good angular resolution and timing accuracy.

Key Science Questions: Blazars

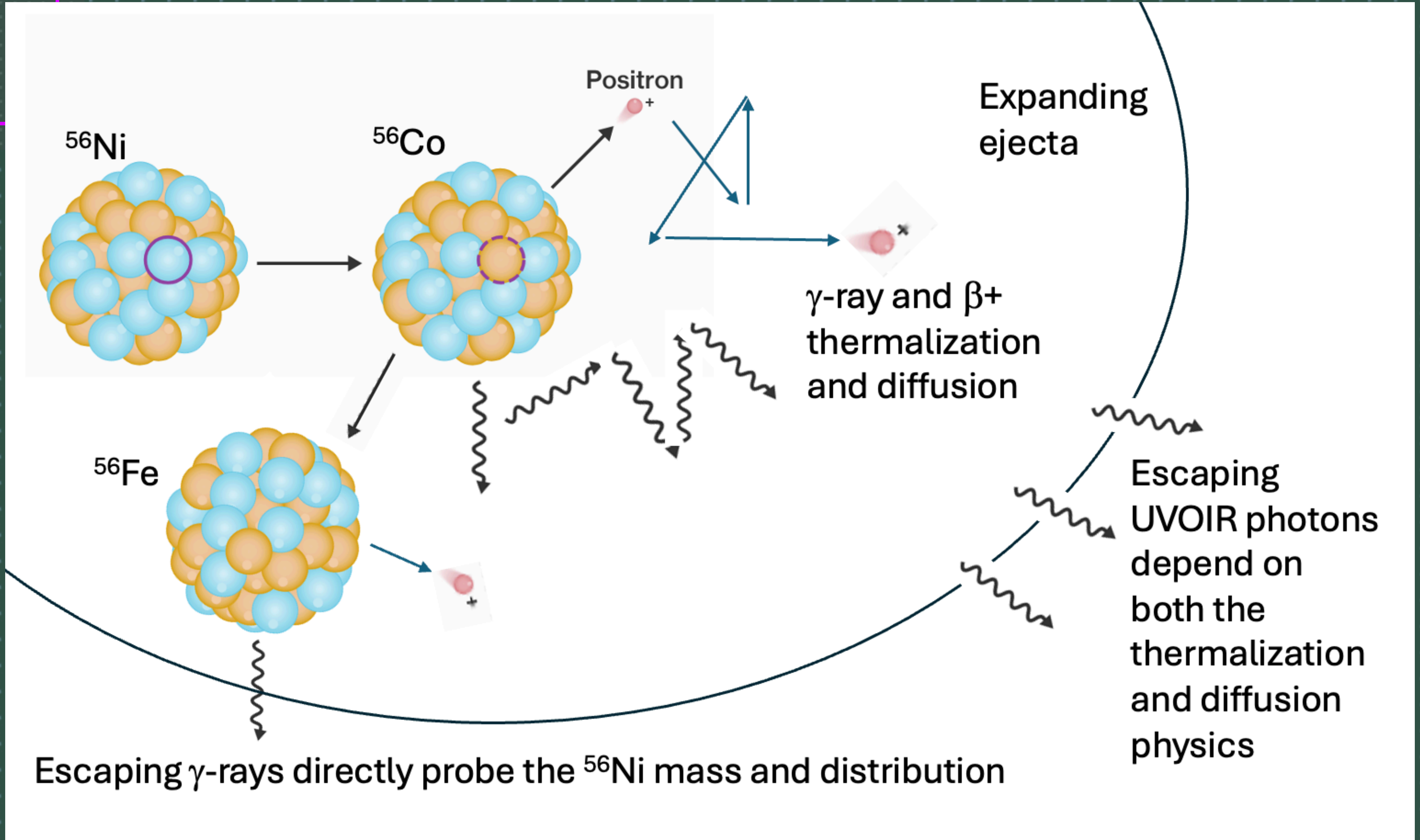
1. Question/Goal: Supermassive Black Hole Evolution (during the jetted AGN phase); Particle acceleration in jets for energy & CRs
2. Why Gamma rays? The nature of jet launching provides the jet composition. Jet composition is more uniquely probed (and less reliant on rare events) by MeV polarization. Blazar studies are usually multiwavelength endeavors that rely on survey data from Fermi, regardless of the community originating the study.
3. What we know so far: Blazar jets are at least partially leptonic (from lower energy data), but some have evidence of hadronic acceleration (from neutrinos).
4. What we need next: High effective area instrumentation in the MeV regime, ideally a wide FoV survey to reduce pointing bias associated with flares.



Zhang et al (2024)

Key Science Questions: Supernova Engine

1. Question: How do supernova (SN) engines work? Critical in determining compact remnant formation (black holes and neutron stars), formation and dissemination of the elements.
2. Why Gamma rays? Gamma rays provide a nearly direct probe of the asymmetries in the inner SN ejecta set by the SN engine. X-ray, UVOIR observations limited by uncertainties in the plasma, atomic, shock and transport physics and contaminated by broad set of sources. Gamma-ray observations of ^{56}Ni, ^{57}Ni, ^{44}Ti, … focus on the engine itself (both thermonuclear and core-collapse supernovae).
3. Successes thus far: Gamma rays from ^{56}Ni decay in SN 1987A proved mixing, ^{44}Ti distribution in the Cas A SN remnant proved the role of convection.
4. What we need:
   a. Observations: Large observation sample – narrow-field instruments that can detect SNe to Virgo cluster; time-resolved to probe element distribution, high spectral resolution (~1%) to measure ejecta velocity distribution and distinguish decay lines.
   b. Theory: Improved explosion models, nuclear physics (bridges with nuclear physics community - Nuclear physics community is primed to address this)



γ-ray and β+ thermalization and diffusion

Escaping UVOIR photons depend on both the thermalization and diffusion physics

Escaping γ-rays directly probe the ^{56}Ni mass and distribution

Key Science Questions: Heavy Element Formation

1. Question: What are the production site(s) of r-process
2. Why Gamma rays? Uncertainties in explosive engines, power sources as well as plasma, atomic and transport physics make it difficult to probe r-process element production in kilonova. Gamma ray (and high energy X-rays, >30keV) of kilonova observations provide definitive identification of r-process isotopes.
3. Progress thus far: model predictions complete, no detections yet.
4. What we need:
    1. Observations: For remnant detection – wide-field with >100 sensitivity over COSI needed; To map remnant morphology, arcmin spatial resolution for ejecta distribution, ~1% energy resolution to measure Doppler shifted lines for 3D mapping.
    2. Theory: Although not needed for first detections, nuclear physics studies will improve exact analysis (goal of FRIB). Improved mass ejection models and nuclear physics allow astronomers to also probe explosion mechanisms.

Executive Summary

- *Gamma rays probes the most extreme phenomena in our Universe: stellar death and birth of black holes, how they grow, where they reside, and how they are powered.*
- *The United States pioneered space-based gamma-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.*
- List of extraordinary discoveries in the past decades, made possible by continual US investment in high energy missions and tech development.
- Leading open topics uniquely address by gamma-ray observations:
    - Cosmic explosions -- What is their origin? 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?

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Future Innovations in Gamma Rays

We will explore gamma-ray science priorities, necessary capabilities, new technologies, and theory needs to inspire work toward 2040.
Get involved and stay informed:
https://forms.gle/VBijBgapMRwJm9dU6

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Questions?