Galactic Annihilation Line Explorer (GALE)

Balloon-borne mission to study the fine structure of positron annihilation in the Galactic bulge

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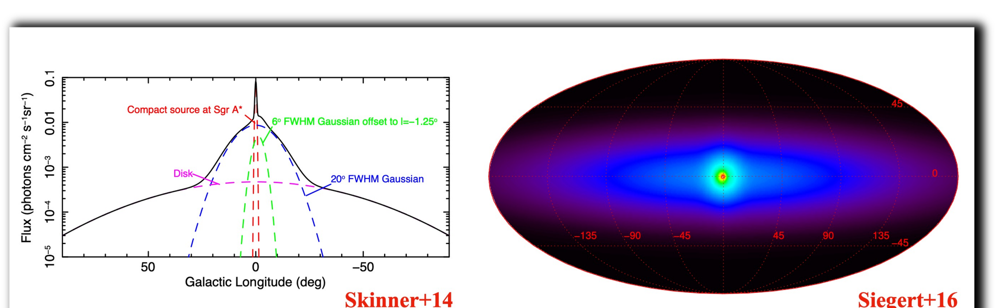
Abstract

The nature of the 511-keV line emission from positron annihilation in the inner Galaxy has remained a long-standing mystery in astrophysics. A key aspect of the problem is determining if the positrons are produced by unresolved faint point sources, or diffusely, possibly of an exotic nature. This problem cannot be fully resolved by any currently operating (INTEGRAL) or planned (COSI) gamma-ray missions, since neither of them combines the requisite angular resolution and point source sensitivity needed. Therefore, to address this problem, we are proposing the GALE mission to the NASA Pioneer program. GALE will be a high-sensitivity, coded-aperture mask (CAM) telescope, flown on an ultra-long duration balloon flight, and it will observe the 511-keV emission from the Galactic bulge at an angular resolution of ~10 arcminutes. These observations will likely lead to profound insights regarding the sources of positrons in the Galactic bulge, and the nature of the positron injection, propagation, and annihilation.

Current Observations

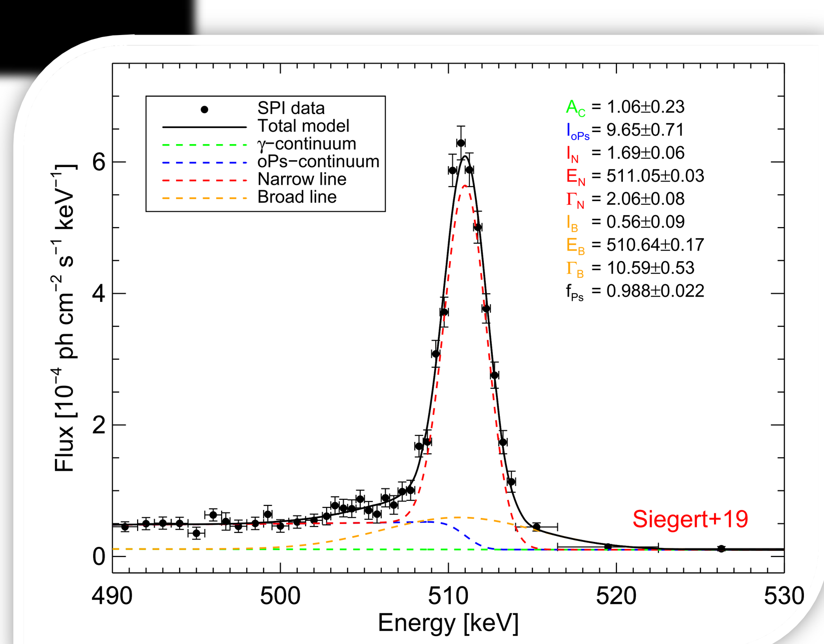
Most of our knowledge about positron annihilation in the Galaxy comes from INTEGRAL/SPI observations, which has an angular resolution of ~2.6 degrees. The morphology can be described with four components, shown below. There is a central point source coincident with Sgr A*, two bulge components, and a component coincident with the Galactic disk. However, the true morphology of the emission from the inner Galaxy remains unknown, due to the limited angular resolution of the current observations.



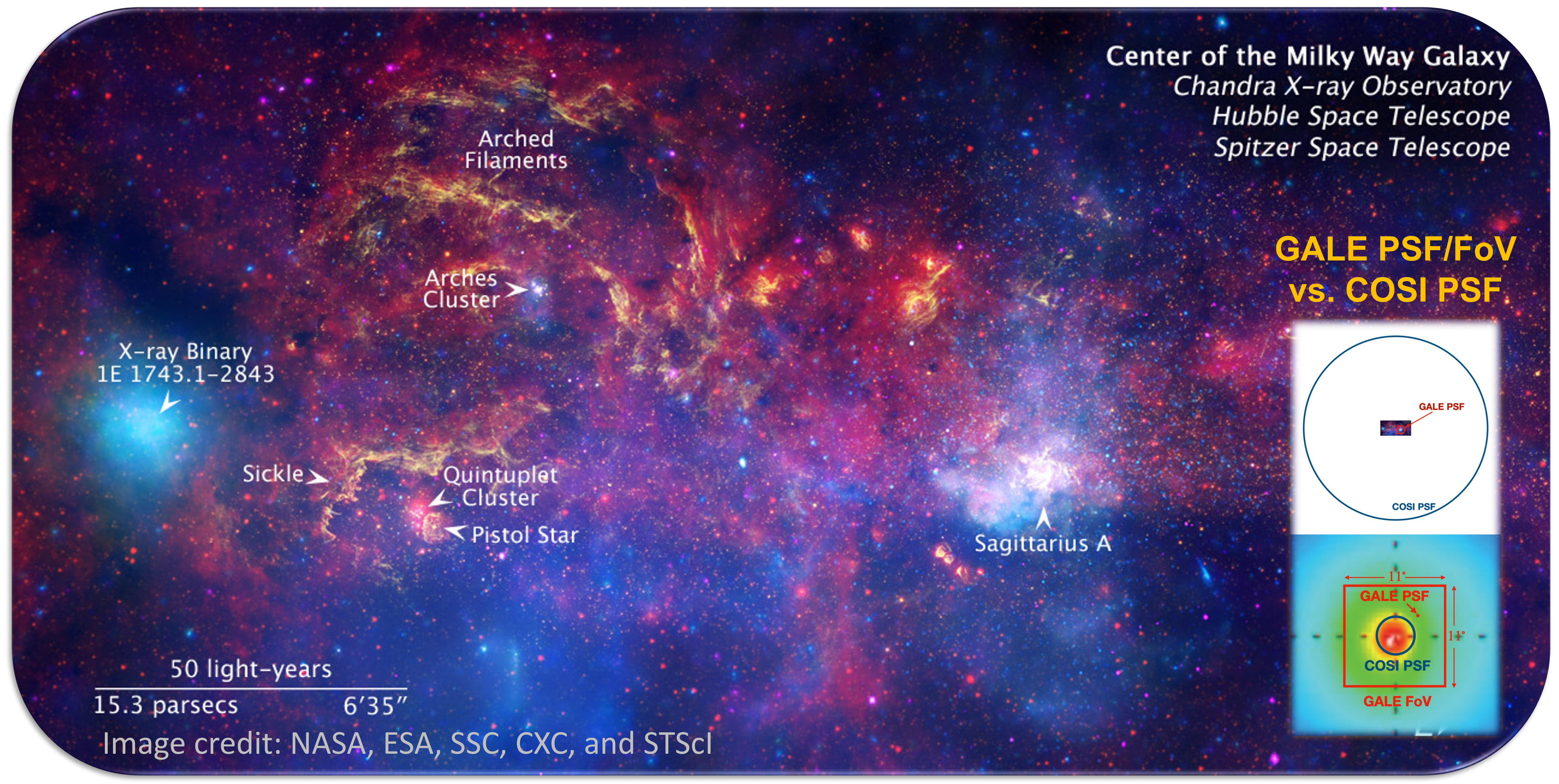
Comp.	G. Lon. position [deg]	G. Lat. position [deg]	Lon. extent (*FWHM*) [deg]	Lat. extent (*FWHM*) [deg]
NB	–1.25	–0.25	5.75	5.75
BB	0.00	0.00	20.55	20.55
Disk	0.00	0.00	141.29	24.73
GCS[a,b]	–0.06	–0.05	0.00	0.00

The emission spectrum contains information about how the positrons annihilate, as well as the medium in which the annihilation occurs. There is prominent 511-keV line emission, consisting of both a narrow line and a broad line, as well as the ortho-positronium continuum at lower energies, resulting from the three-photon decay of positronium – an intermediate bound state between an electron and positron.

The observed positron annihilation rate in the Galactic bulge is (1-2) $\times 10^{43}\ e^{+}\ s^{-1}$, with a positronium fraction of ~1, and a bulge to disk luminosity ratio of ~1. Overall, the current observations imply that there is likely a concentrated source of positrons towards the central regions of the Galaxy which can't be accounted for with known mechanisms.

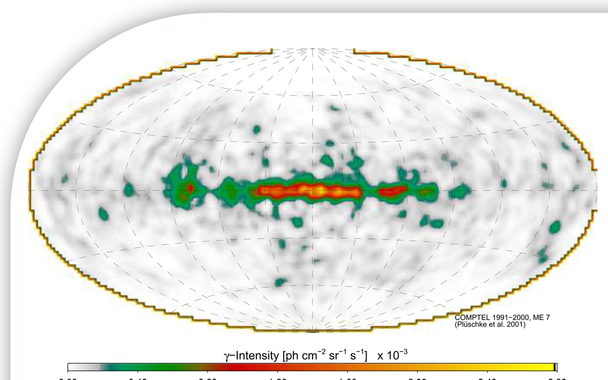


What are the Primary Sources of Positrons in the Inner Galaxy?

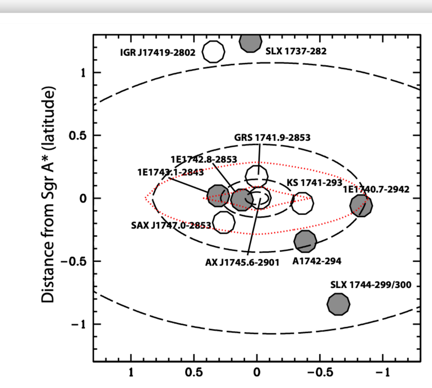


Peering into the heart of the central molecular zone (CMZ), we can start to get a sense of the rich astrophysical environment that GALE will begin to probe in gamma rays (50 keV – 1 MeV), as we will observe the inner 11 degrees of the Galaxy at an angular resolution of ~10 arcminutes (~ 30X improvement over current best measurements). The inset to the right shows a comparison of GALE's PSF/FoV to COSI's PSF, highlighting the fact that GALE will be highly complementary to the COSI mission.

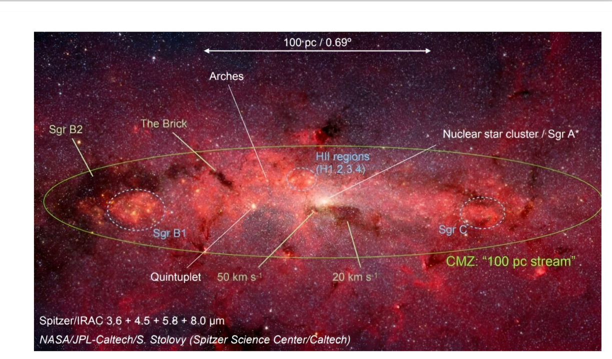
Some of the Many Possible Positron Sources!



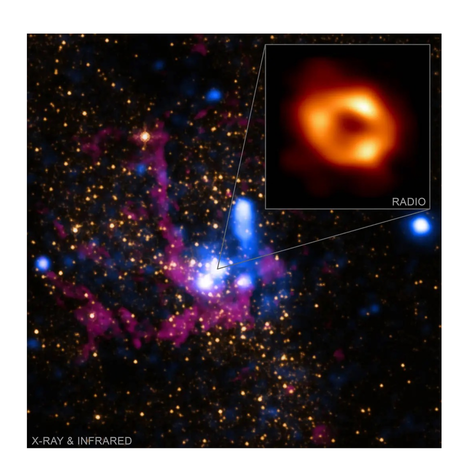
Massive Stars & ccSN
e.g. as traced by ^{26}Al produced from stellar winds and ccSN.



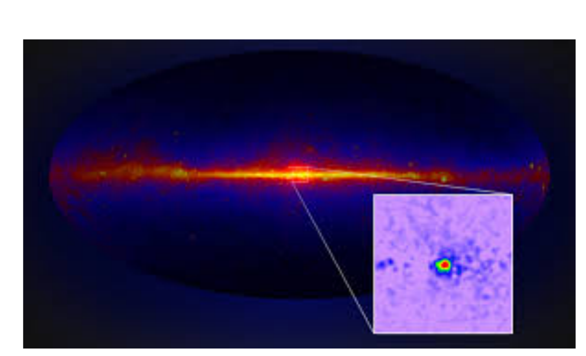
X-ray binaries
e.g. the population from IBIS/ISGRI



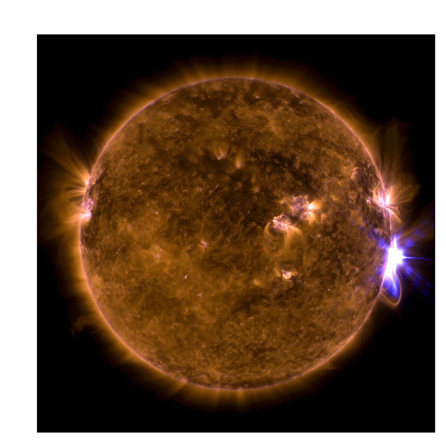
CMZ
Full diameter of ~2.8° (400 pc), comparable to SPI resolution.



Sgr A*
e.g. pair production in accretion disk, corona, or jets, previous activity with enhanced accretion rates, etc.



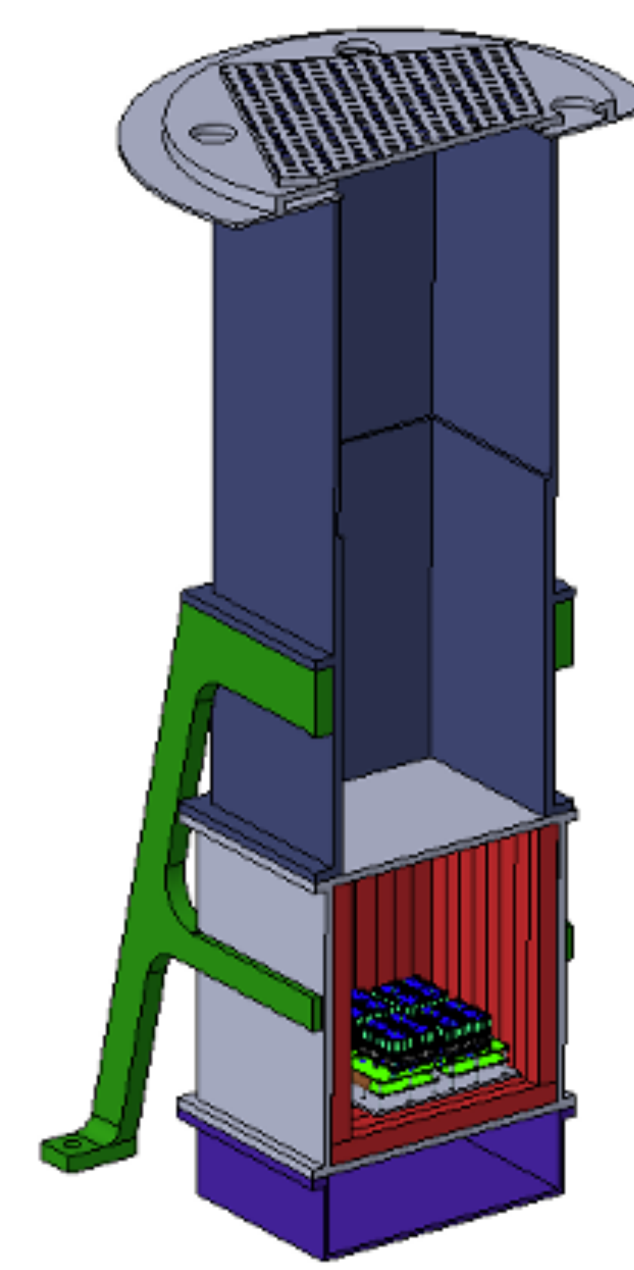
Dark Matter
i.e., MeV-scale, primordial BHs, secondary from GeV-scale, etc.



Solar flares and Others
Solar flares, Pulsars, CR secondaries, Type 1a SN, classic novae.

Summary of the main astrophysical sources that are expected to produce positrons.

The GALE Instrument

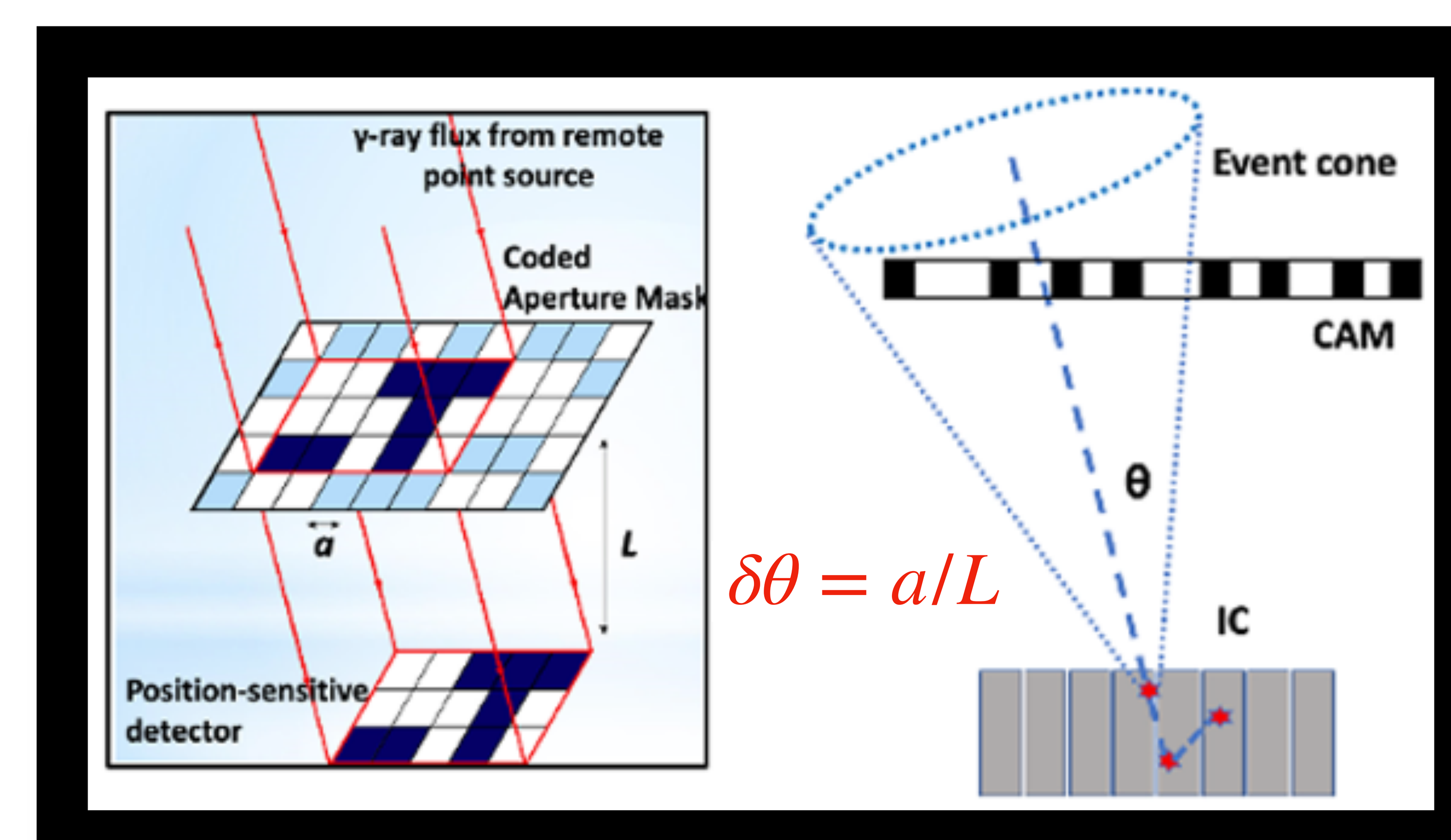


GALE is a combined CAM/Compton telescope that uses a cadmium zinc telluride (CZT) gamma-ray imaging calorimeter (ImCal) as its position-sensitive detector (PSD). It is sensitive to gamma rays between 50 keV – 1 MeV. To achieve the required pointing accuracy, GALE will be mounted to the Wallops Arc-Second Pointer (WASP).

Instrument parameters (baseline):

- Shield opening: 40 cm x 40 cm
- CZT area: 20 cm x 20 cm
- Mask size: 40 cm x 40 cm
- Mask element pitch: 3 mm
- Mask thickness: 10 mm
- Mask-CZT distance: 100 cm
- Fully-coded FoV: 11°
- Instrument FoV (defined by Shield): 11°×11° , or 0.04 sr
- Energy resolution: 1-2% FWHM at 1 MeV
- Angular resolution: 10 arcmin
- Point source sensitivity (5σ): $< 10^{-4}$ ph cm^{-2} s^{-1} at 511 keV.
- Uses active and passive shields.
- Mass: 500 kg
- Electrical power: 150 W
- Overall dimensions: $150 \times 50 \times 50\ \mathrm{cm}^3$

Imagining Technique Basics



- With a CAM, the incident flux forms a shadow pattern on the PSD.
- Using the measured shadow pattern and the known mask pattern, deconvolution techniques can be used to reconstruct the source region with an angular resolution given by $\delta\theta = a/L$.
- The CZT ImCal serves as the PSD for the CAM. It also serves as a standalone Compton telescope.

References: Skinner, G., et al., PoS, INTEGRAL WS (2014): 1-10; Siegert, T. et al., A&A 586 (2016): A84; Siegert, T., et al., A&A 627 (2019): A126.

NASA Postdoctoral Program

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