JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Ex Luna, Scientia

The Lunar Occultation eXplorer (LOX)

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12th Integral Conference &
1st AHEAD Gamma-Ray Workshop

A New Observational Paradigm for Nuclear Astrophysics

Breaking through roadblocks toward the Next-Generation

Moon as Occulting Disk

- Repeated Occultation → Temporal Modulation
- Detection/Characterization/Monitoring
- Eliminates Kinematic Reconstruction Requirements

Ephemeris/Geometry

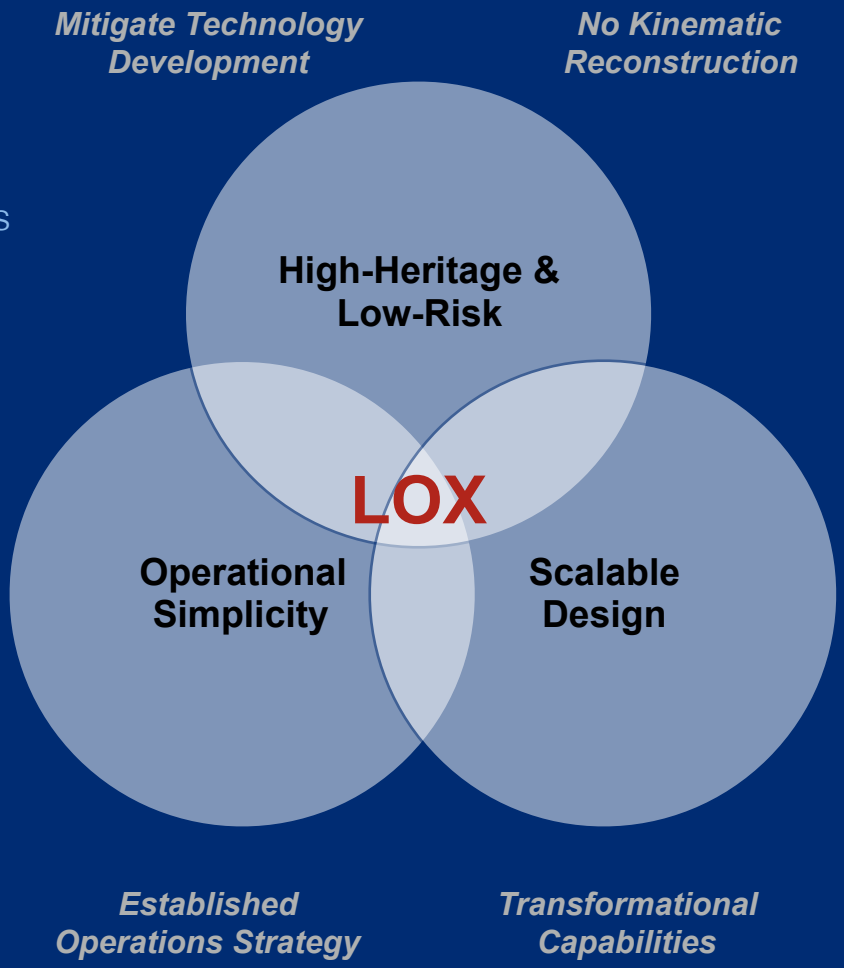
- Field-of-View → Orbit Altitude
- Sky Coverage & Sensitivity
- Implementation Trades (not technology)

Gamma-Ray Light Bucket (Spectrometer)

- Non-Imaging → Large-Area, Non-Monolithic
- Scalability
- Mitigates Technology Development Lifecycle

Operations

- Time-Resolved Spectra
- Planetary Orbital Geochemistry
- Established Protocols



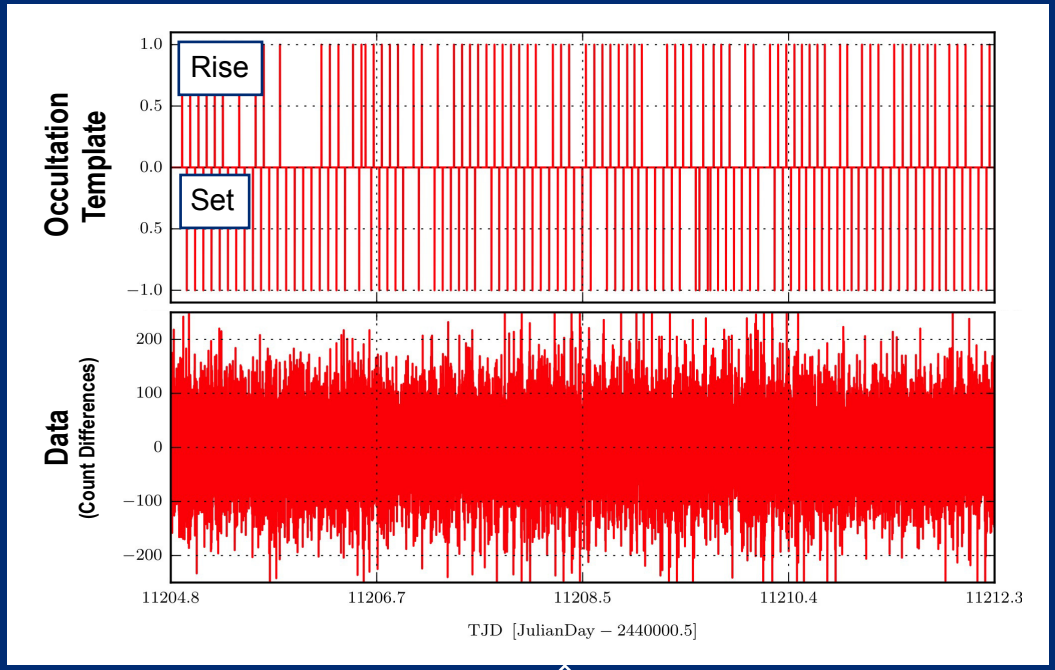
Lunar Occultation Technique (LOT)

Temporal Modulation

Occultation is a Measure of Difference

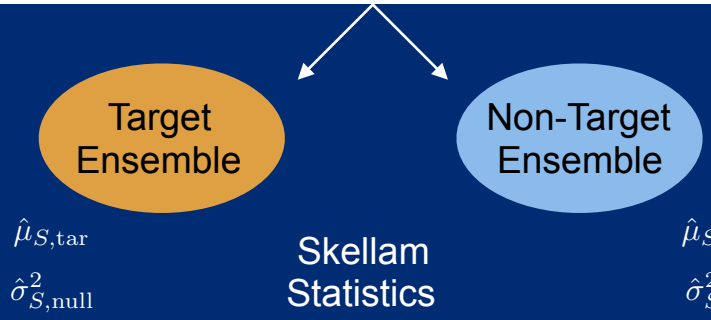
Source Location
Lunar Ephemeris
S/C Ephemeris

Time-Resolved Spectra
(Line or Band)



Unique Template:
Relative Orientation

Time Series of
Acquired Count
Differences



RSM & Lawrence (2016)
RSM (2019)

Lunar Occultation Technique (LOT)

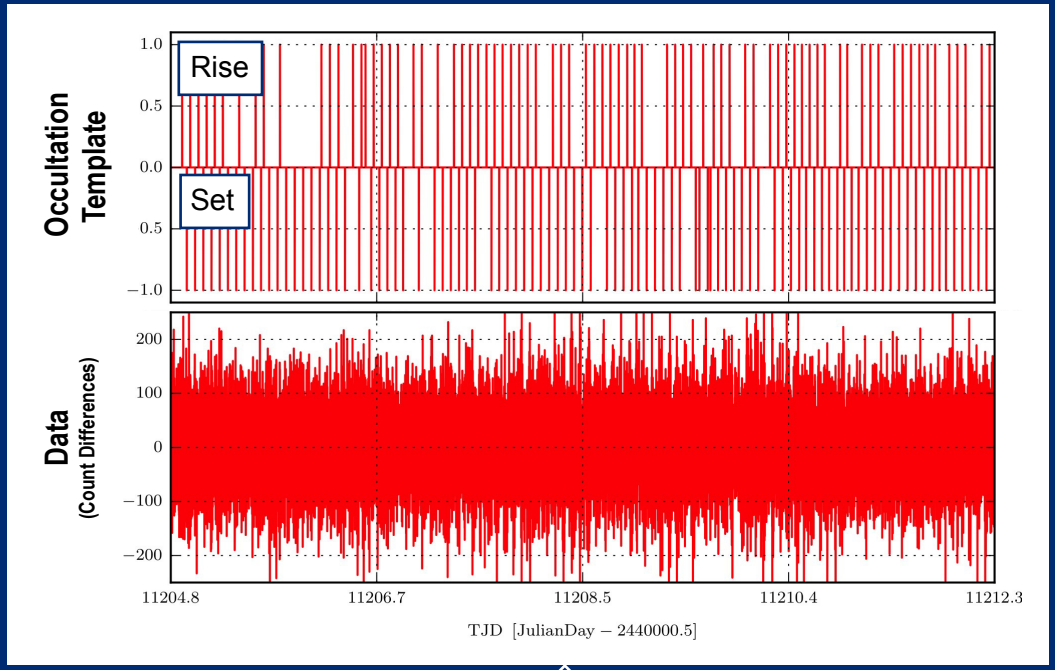
Temporal Modulation

Occultation is a Measure of Difference: On-Off

Template is Unique

Source Location
Lunar Ephemeris
S/C Ephemeris

Time-Resolved Spectra
(Line or Band)



Unique Template:
Relative Orientation

Time Series of
Acquired Count
Differences

Target Ensemble

$\hat{\mu}_{S,\mathrm{tar}}$

$\hat{\sigma}^2_{S,\mathrm{null}}$

Non-Target Ensemble

$\hat{\mu}_{S,\mathrm{null}}$

$\hat{\sigma}^2_{S,\mathrm{tar}}$

Skellam Statistics

$\mu_S = 0$

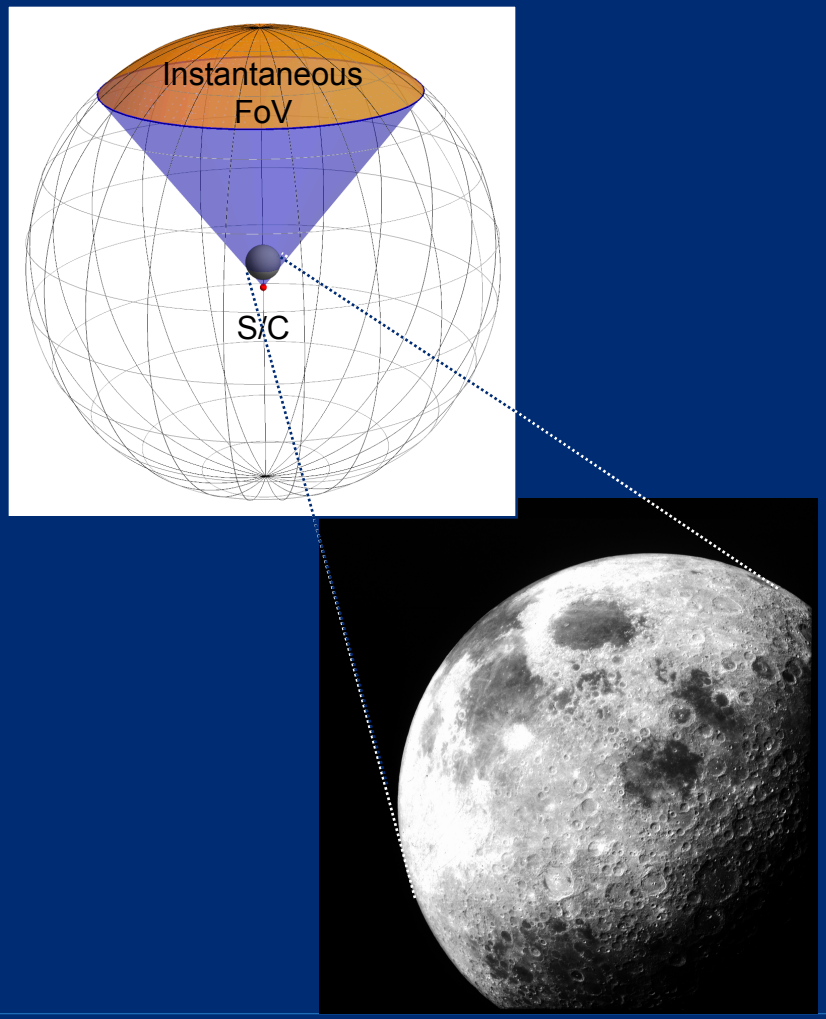
$\sigma^2_S = 2\mu_{\mathrm{bck}}$

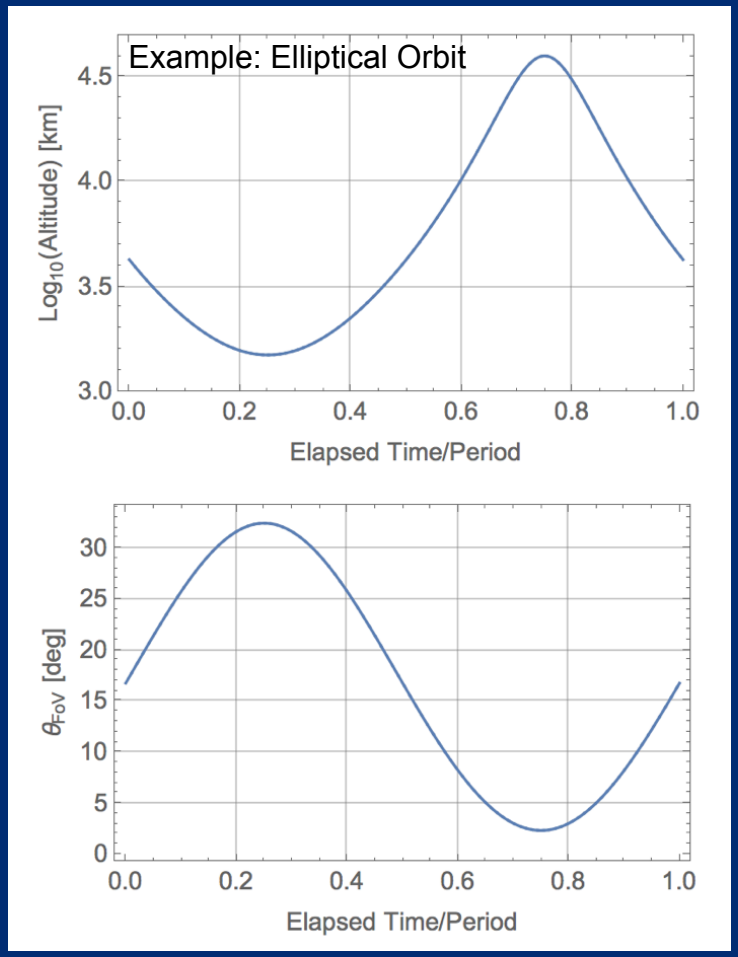
RSM & Lawrence (2016)
RSM (2019)

Lunar Occultation Technique (LOT)

Geometry & Ephemerides

$$\theta_{\mathrm{FoV}} = \sin^{-1}\left(\frac{R_M}{R_M + h}\right)$$

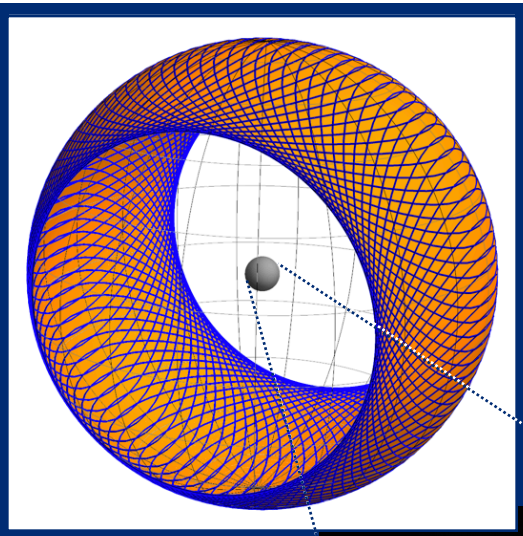


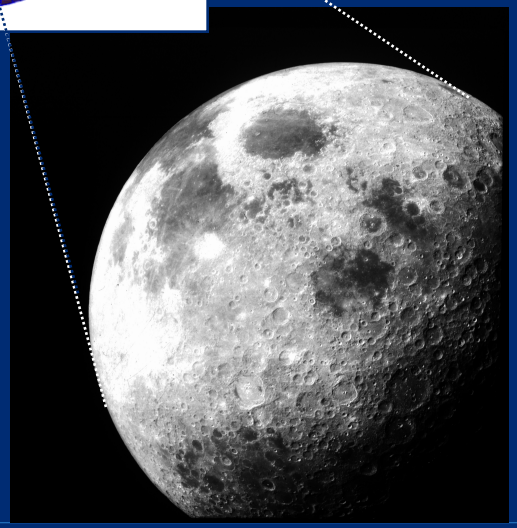


Lunar Occultation Technique (LOT)

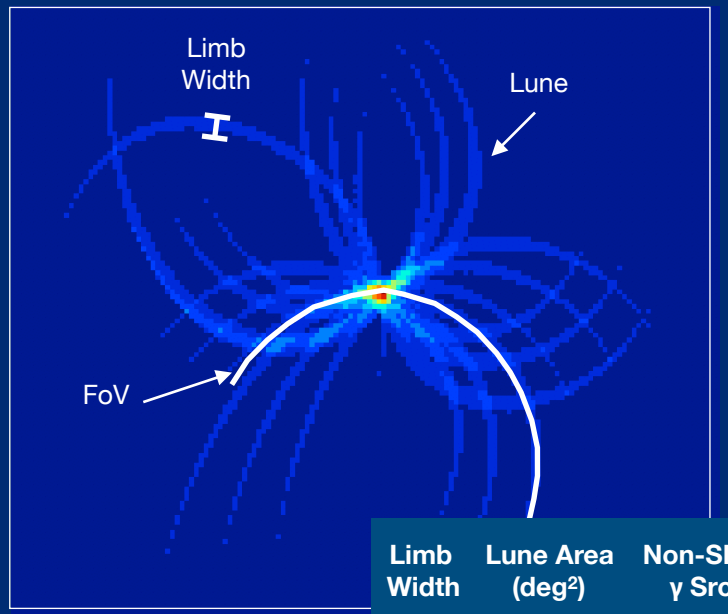
Geometry & Ephemerides

$$\xi(t) = [\beta(t) \leq \theta_{\mathrm{FoV}} \; ? \; 0 : 1] = \begin{cases} 0, & \text{if not occulted} \\ 1, & \text{if occulted} \end{cases}$$





- LOT performance variation w/ S/C-Moon geometry
- FoV (Moon solid angle)
- Source localization (projected limb width)

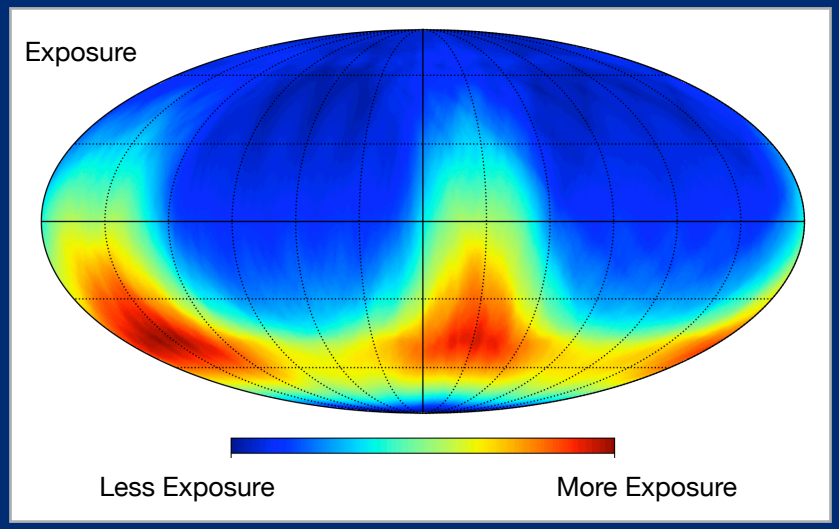


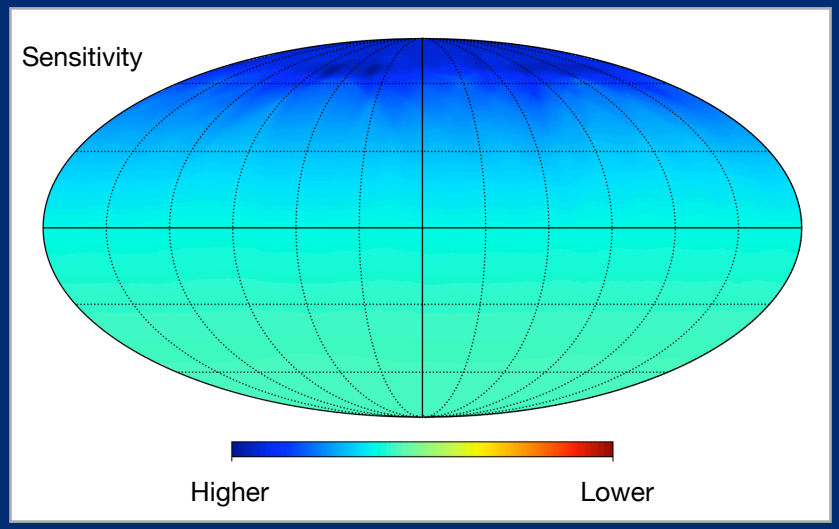
	Limb Width	Lune Area (deg^2)	Non-SNela γ Srcs*
10^4 km orbit, 10 s	1”	3.2×10^{-2}	0.00023
	1’	1.9	0.014
	0.5˚	68	0.5
10^2 km orbit, 32 s	1˚	115	0.83

*7.2×10^{-3} src/deg^2
Δt=10 sec

Sky Coverage & Sensitivity

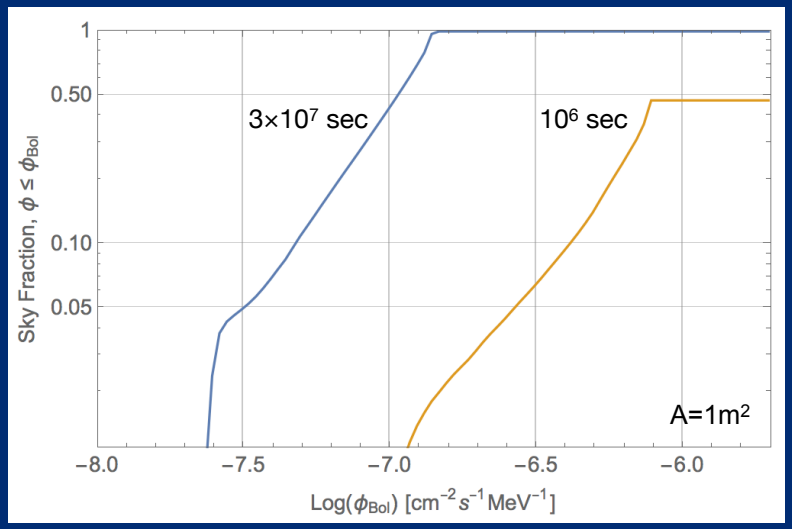
Ephemeris Dependent





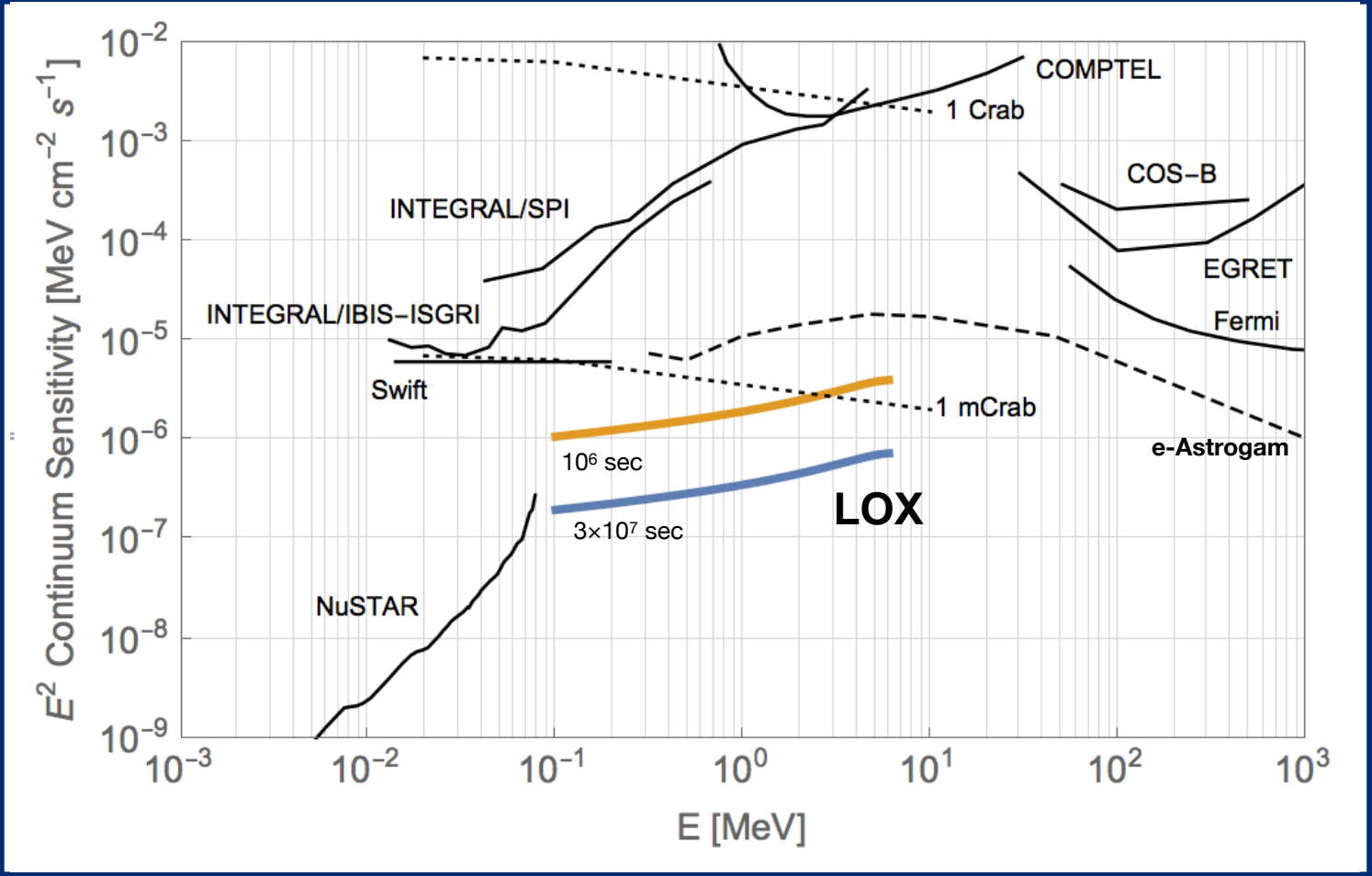
$$\phi_{\mathrm{LOT}}(\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{MeV}^{-1}) = \frac{t_c}{2\epsilon A_\circ\,\Delta E}\sqrt{\frac{2R_\mathrm{B}}{T}}\left(\left|1-\frac{\hat{\sigma}^2_{\mathrm{S,tar}}}{\hat{\sigma}^2_{\mathrm{S,null}}}\right|\right)^{1/2}$$

Δt	Acquisition Cadence (sec)
$\varepsilon A_\circ$	Effective Area (cm²)
R_B	Background Rate (Hz)
T	Observation Period (sec)
$\hat{\sigma}^2_{S,\mathrm{tar}}$	Variance, Target Ensemble
$\hat{\sigma}^2_{S,\mathrm{null}}$	Variance, Null Ensemble



Lunar Occultation eXplorer (LOX)

Sensitivity



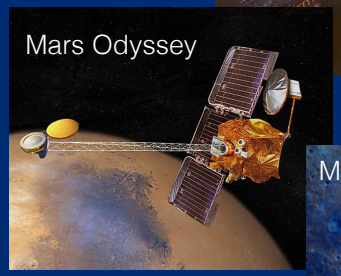
Crab: Jourdain & Roques (2009)

Observation Interval:10^6 second (LOX = elapsed time)
ΔE/E=1
Threshold Significance: 3σ

Multi-Source Simultaneous All-Sky Monitoring at Full Sensitivity

Lunar Occultation Technique (LOT)

Leverage 20+ Years of Experience in Planetary Orbital Geochemistry



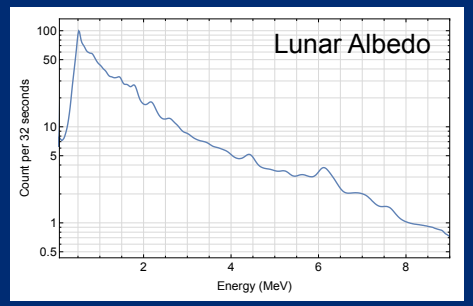
GRS & Airless Planetary Bodies

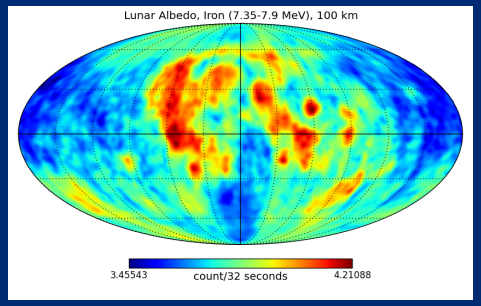
- Extensive Operational Record
- Time Resolved Spectra
- Data Processing/In-situ Calibration
- Established Operations Profile

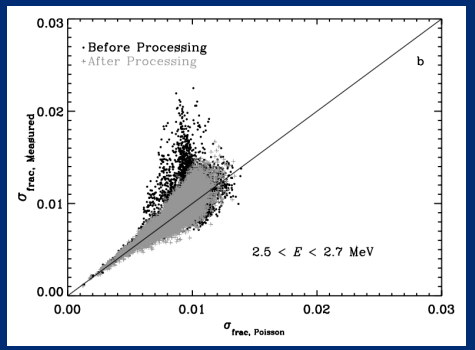
The Case for the Moon

- Lack of Atmosphere
- Lack of Magnetosphere
- Benign Background Environment
- Varies w/ CR Flux
- Well-Established Lunar Albedo
- Easily Monitored

Lawrence et al. (1998)
Feldman et al. (1999)
Lawrence et al. (2002)
Feldman et al. (2004)
RSM et al. (2012)
Peplowski et al. (2012)
RSM et al. (2014)
RSM & Lawrence (2016)







Poisson Limit
~0.5-1% Fractional Uncertainty

Lunar Occultation eXplorer (LOX)

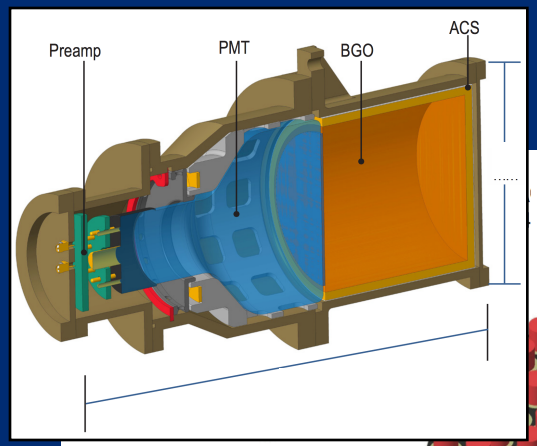
Implementation - High-Heritage, Low-Risk

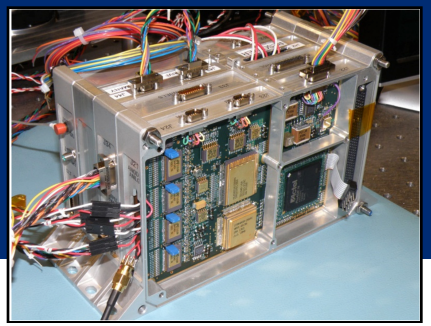
Highly Scalable
Limited only by SWAP

Every LOX Needs a BAGEL…

Big Array for Gamma-Ray Energy Logging

- 0.1-10 MeV
- BGO, 7.13 g/cm^3, non-Hygroscopic
- σ_E/E~10% (FWHM @ 0.662 MeV)
- Phoswich Configuration
- Fault-Tolerant Implementation





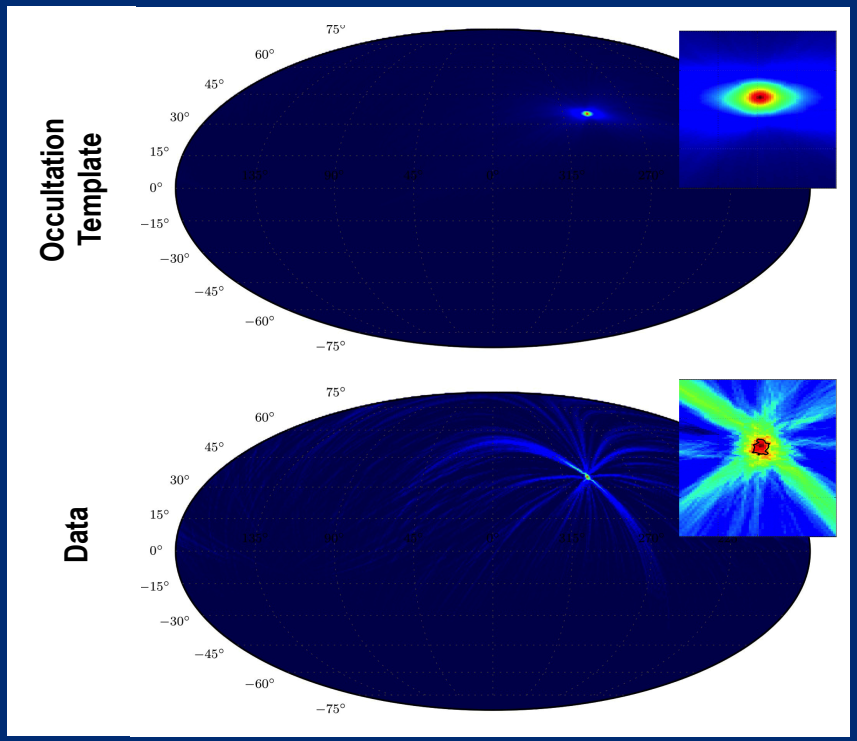
Lunar Occultation Technique (LOT)

Validation

RSM & Lawrence (2016)
RSM & Peplowski (2019)

In-Situ Validation & Test

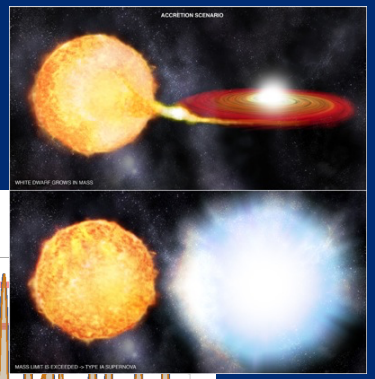
- Lunar Prospector GRS
- Broadband Spectrum Acquisition (0.05-9 MeV)
- 32 sec Acquisition Cadence (567 days)
- 1.29×10^8 Spectra

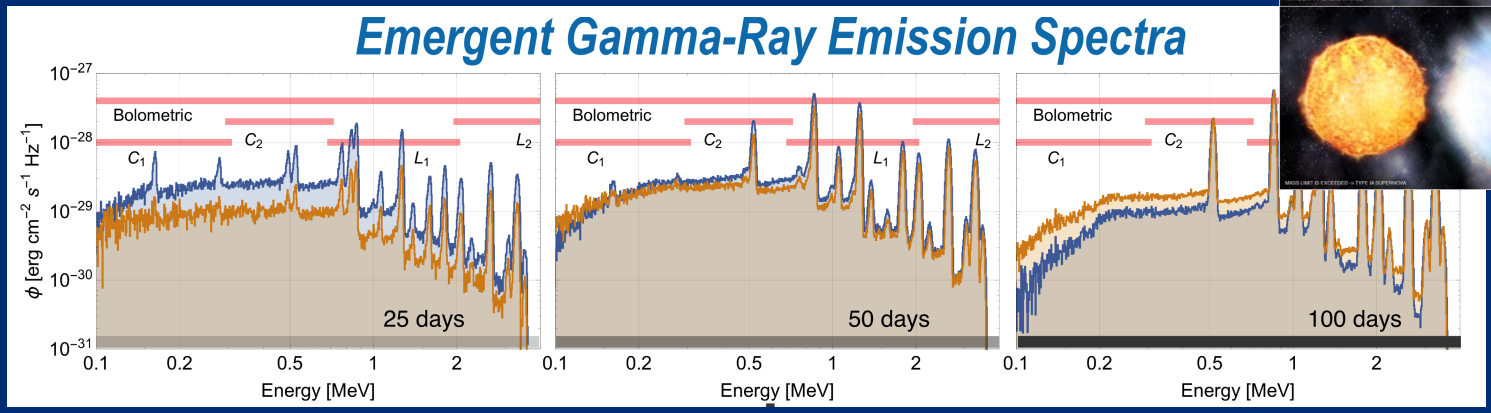


Catalog in Preparation
+
Mars Odyssey GRS

Thermonuclear (Type-Ia) Supernovae

Beacons of the Cosmos





- **Science Goal**: Probe Thermonuclear Physics of SNeIa
  - Fundamental Parameters (M_{tot}, M_{Ni}, KE_{tot}) and Their Proxies
  - Progenitor Classification
  - Volumetric Distribution of ^{56}Ni
  - Nuclear Flame/Structure
- **Science Goal**: Diversity → Sensitivity Horizon: 100 Mpc+
  - Population Statistics
  - Census of SNeIa Sub-Classes
  - Census of SNeIa Environments
- **Science Goal**: The Standard Candle & Precision Cosmology
  - Deconvolution of core (nuclear), atmospheric (atomic), and external (reddening)

LSST Large Synoptic Survey Telescope

WFIRST Wide-Field Infrared Survey Telescope — Astrophysics • Dark Energy • Exoplanets

Precision Cosmology

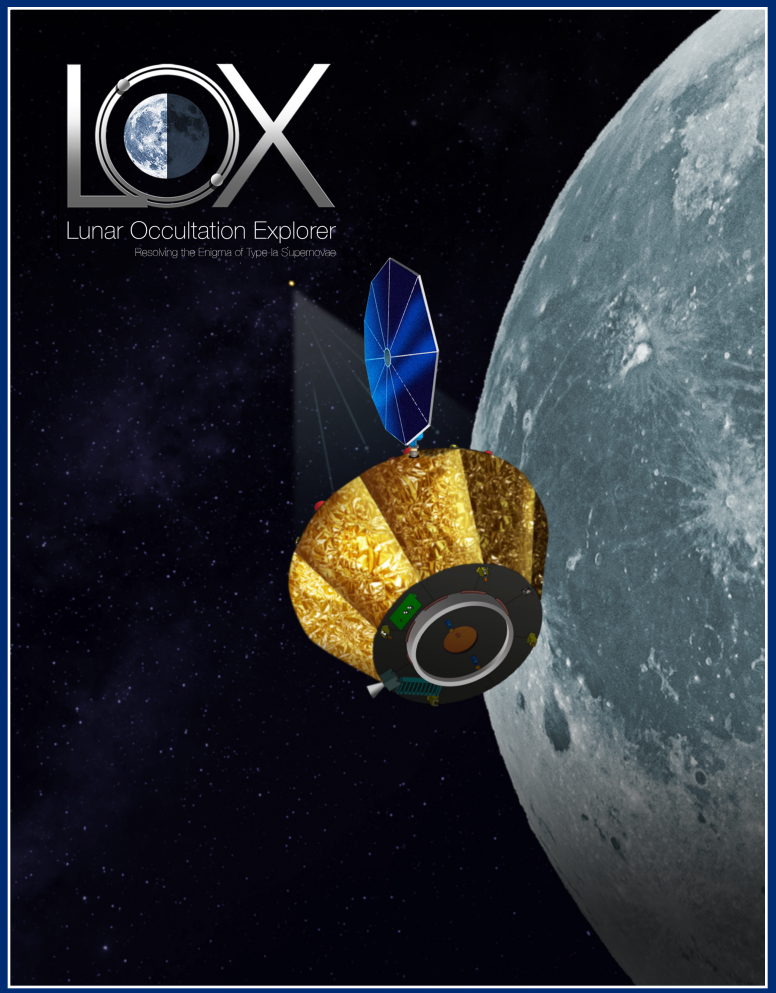
A New Observational Paradigm for Nuclear Astrophysics

High-Heritage, Low-Risk
- Mitigate Technology Development
- Leverage Established Operational Approach

Operational Simplicity
- Time-Series Based Analyses
- No Kinematic Reconstruction/All Data to Ground

Establish Moon as Platform for Astro
- Well-Characterized Albedo
- Benign/Easily Monitored Background Environment

Transformational Observational Capabilities
- Discovery Enabling Sensitivity
- ~Uniform Sky Coverage/All-Sky Monitoring
- Multiple Programmatic Opportunities
  - SMEX
  - MIDEX
  - AstroProbes
  - Other
- High-Priority Astrophysics



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