One Trillion Time-Tagged Photons

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(Columbia University)

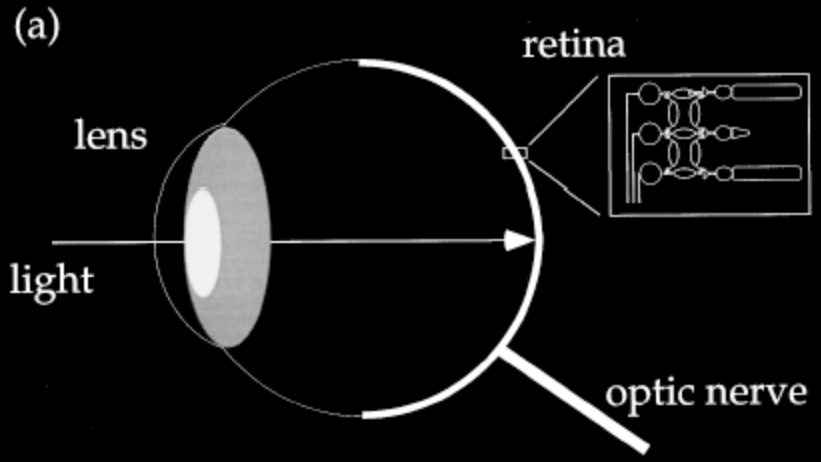
and the GALEX team

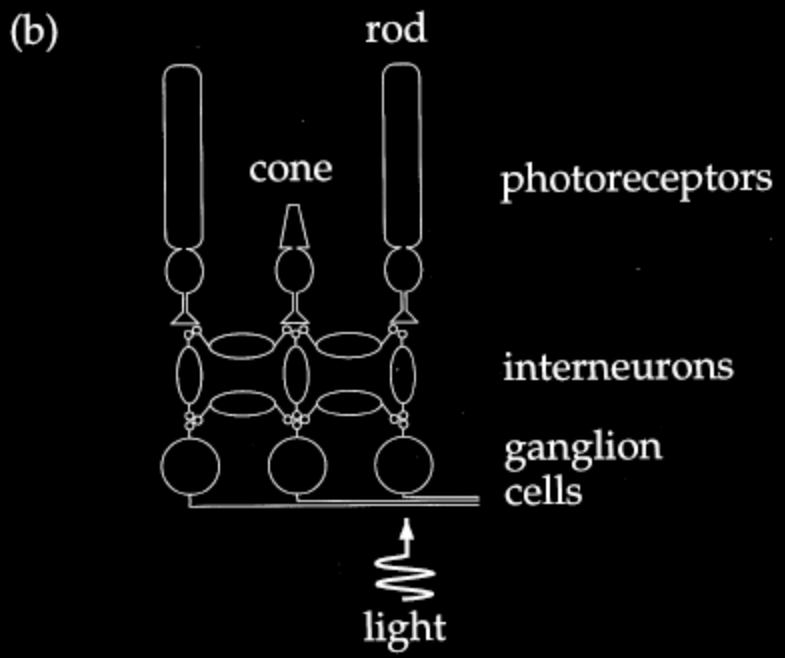
What Is a "Photon Counting" Detector?

(aka "Single Photon" Detector)

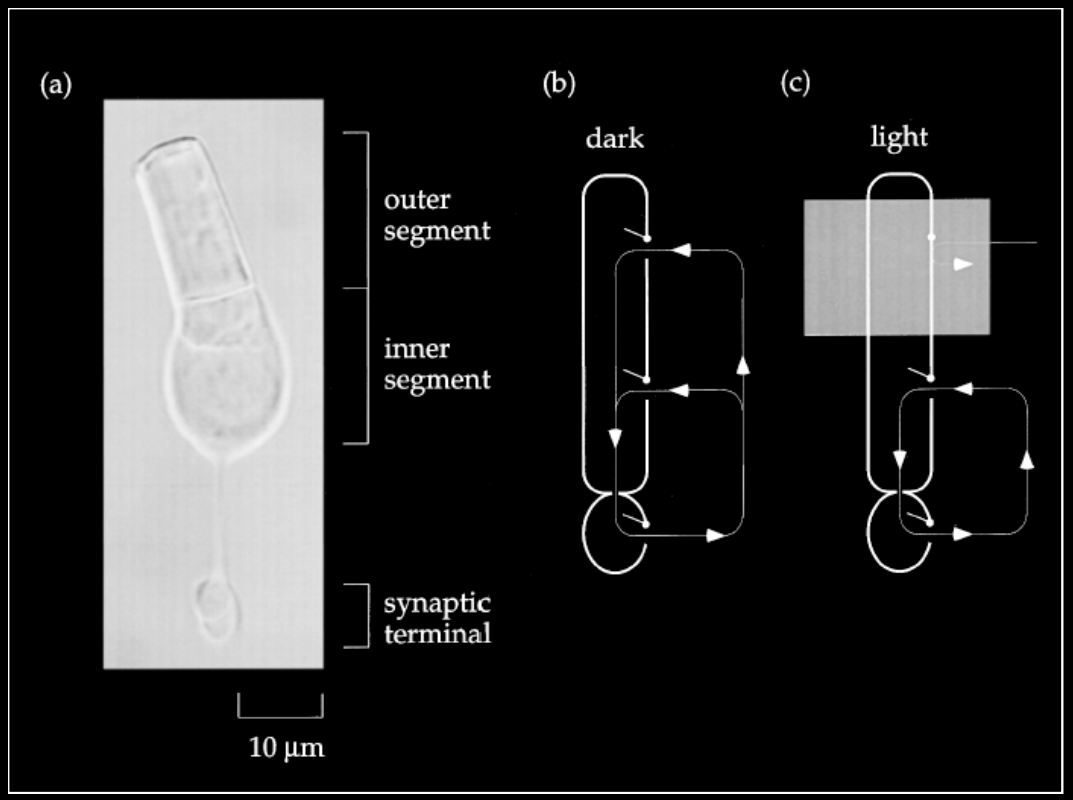
Photon Counting

The rods in your eye...





Rieke & Baylor (1998)

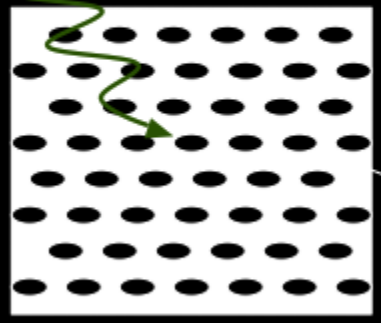


...and eye of toad

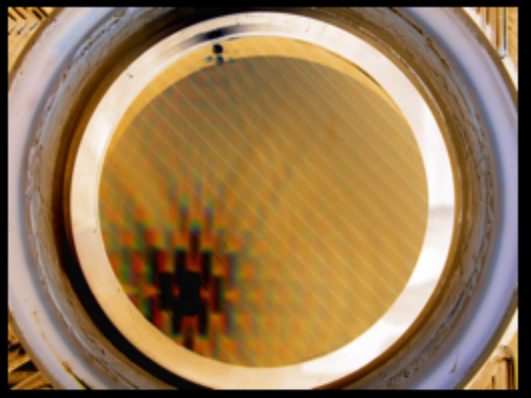
The GALEX Mission uses a Microchannel Plate Detector

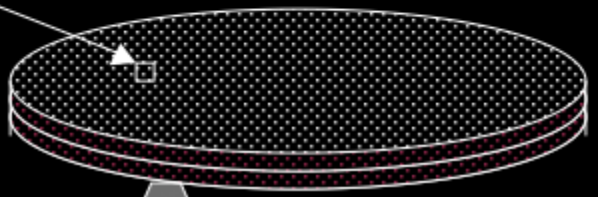
Photon Counting

Photon impinges on microchannel plate pores



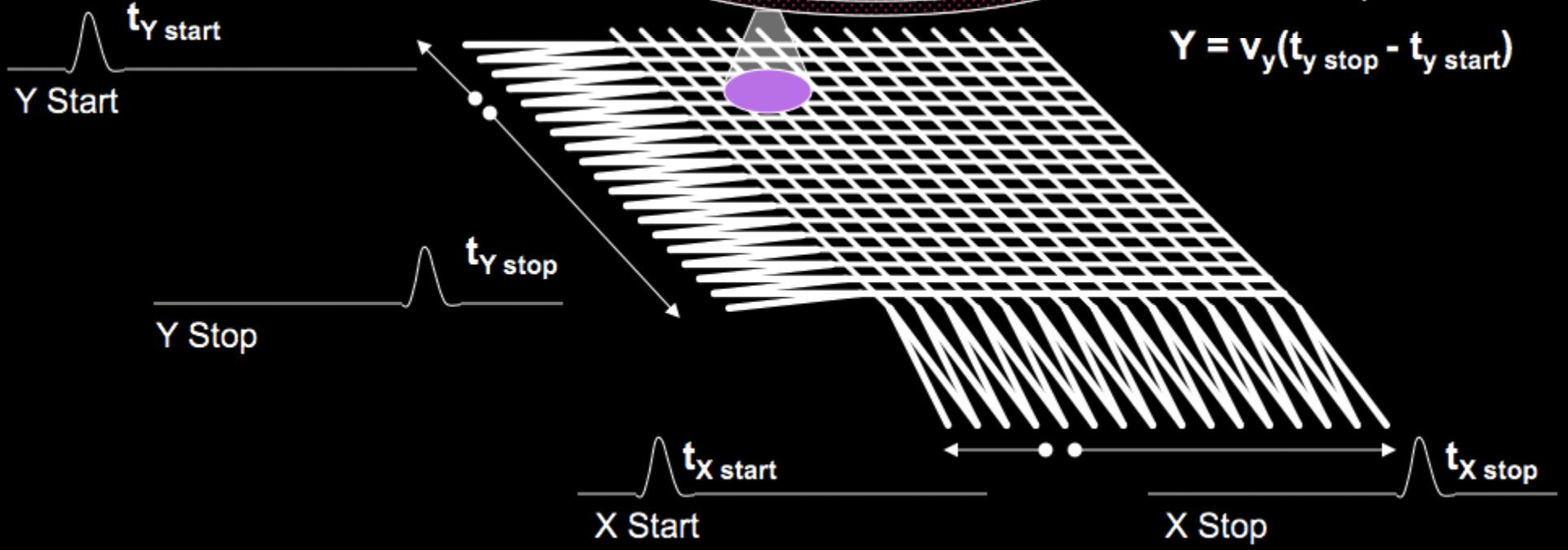
Microchannel plate preserves position information across the gain stage





$$X = v_x(t_{x\ stop} - t_{x\ start})$$

$$Y = v_y(t_{y\ stop} - t_{y\ start})$$



Photon Counting

Ideally single photons are detected unambiguously with no noise.

Photon Counting

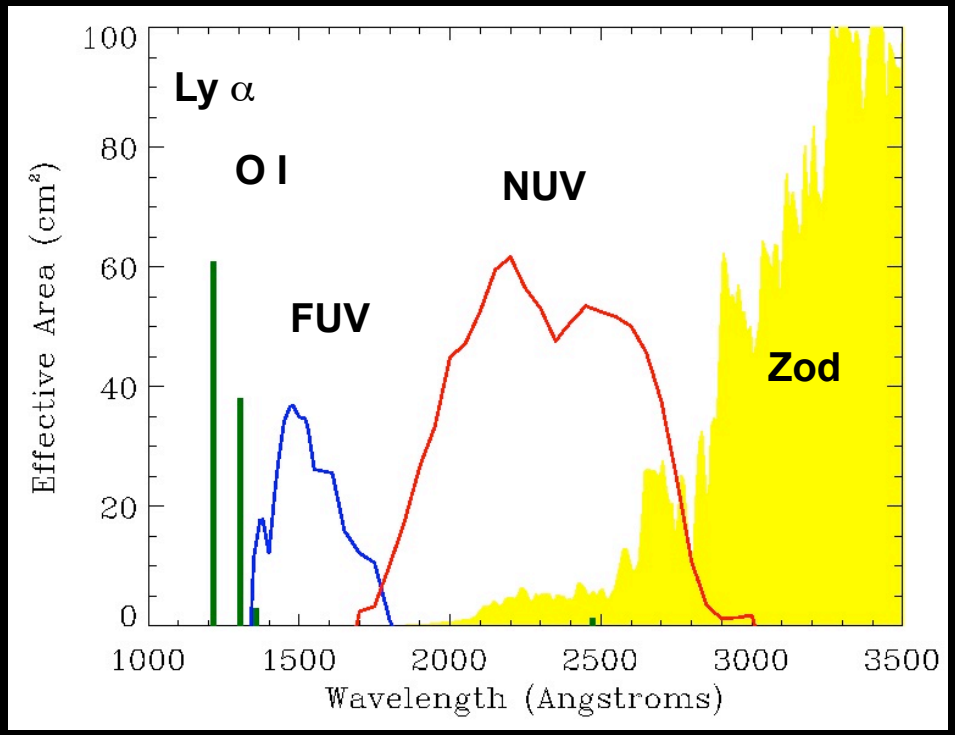
In practice noise is always present:

- Internal detector backgrounds (e.g. radioactivity, thermionic emission)
- "Local" backgrounds (e.g. space weather due to solar activity, thermal instrument)
- Astronomical background (e.g. night sky, zodiacal light)

Photon-counting devices are favored in applications where backgrounds are low (e.g. X-ray, gamma ray) or sources are bright but integration times are short

GALEX operates in regime between X-ray and optical:
Low/moderate sky background w/ many bright sources

GALEX has collected ~1,000,000,000,000 photons
in two ultraviolet bands



Photon Counting

Aspect Solution

Distortion/Offset/"Walk"

$$p_i(\alpha, \delta, t) = A(\alpha, \delta | x_{FP}, y_{FP}, t) \times T(x_{FP}, y_{FP} | x_{Det}, y_{Det}, q, xa, t) \times$$

$$\times R(x_{Det}, y_{Det}, q, xa, t | \text{photon word}_i)$$

Delay Line Timing

$$phot_i(\alpha, \delta, t) = A\ T\ R\ (\text{photon word}_i)$$

Photon sky position

Digitized photon word

Transformations can be determined ex post facto

Photon Counting

Time-tagged photon data

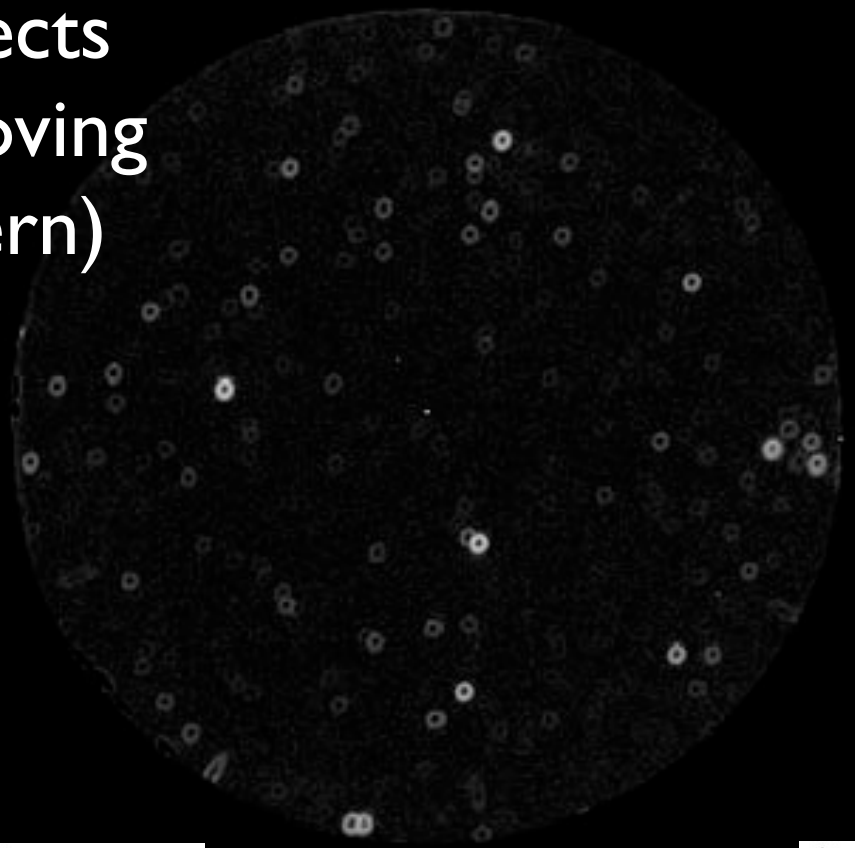
- Time-tagged photon data can be collected while moving (relax attitude control requirements)
- Many aspects of calibration including aspect solution can be refined ex post facto. (Optimal aspect reconstruction)

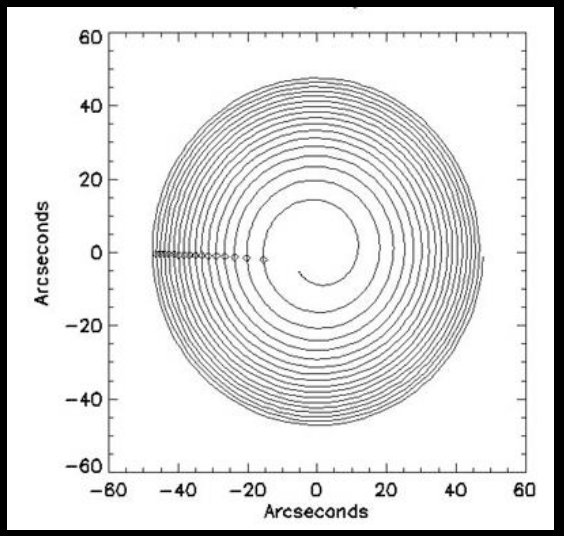
$$\bar{J}_{\mathrm{ML}} = \arg\max_{\bar{J}} \left\{ \sum_p \sum_i s_p(i + j_p) \ln[r_{\mathrm{ML}}(i, \bar{J})] - r_{\mathrm{ML}}(i, \bar{J}) - \ln[s_p(i + j_p)!] \right\}.$$

Aspect solution — Photon list — ML image

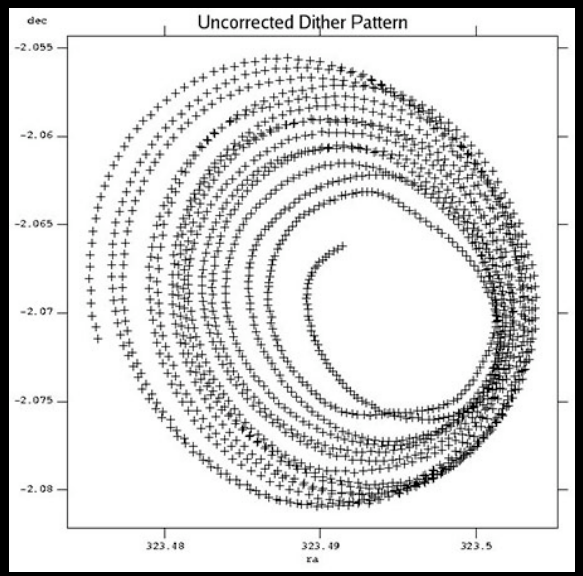
- Provides excellent compression for sparse images
- Allows time-series analysis on millisecond-second timescales (for astronomical sources and other transient/artifacts)

GALEX collects data while moving (dither pattern)



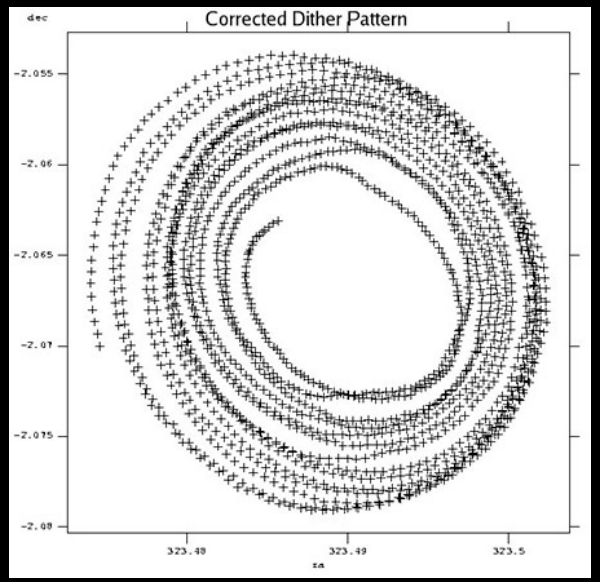


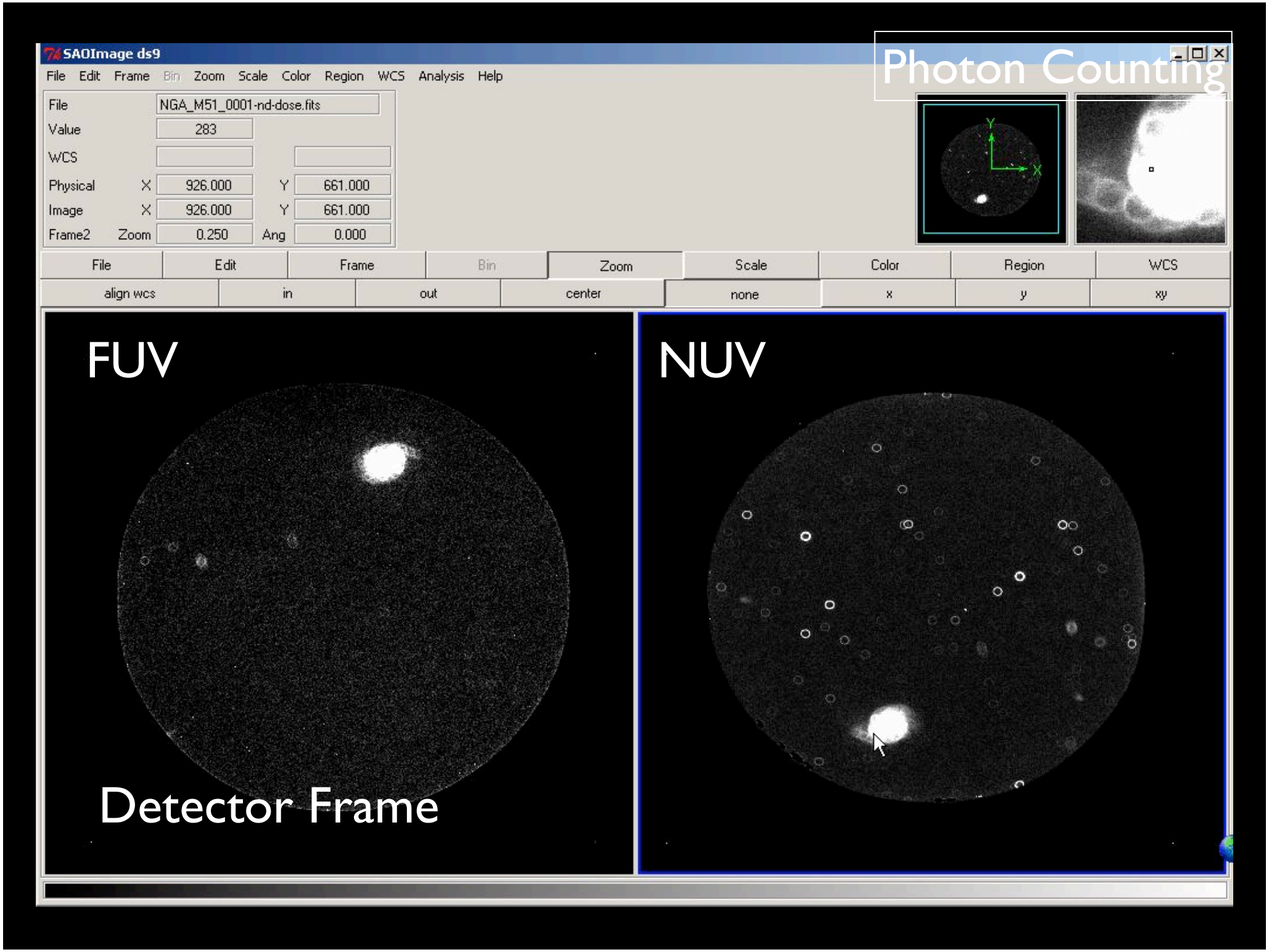
Ideal



Uncorrected

Corrected

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WCS
Physical X 926.000 Y 661.000
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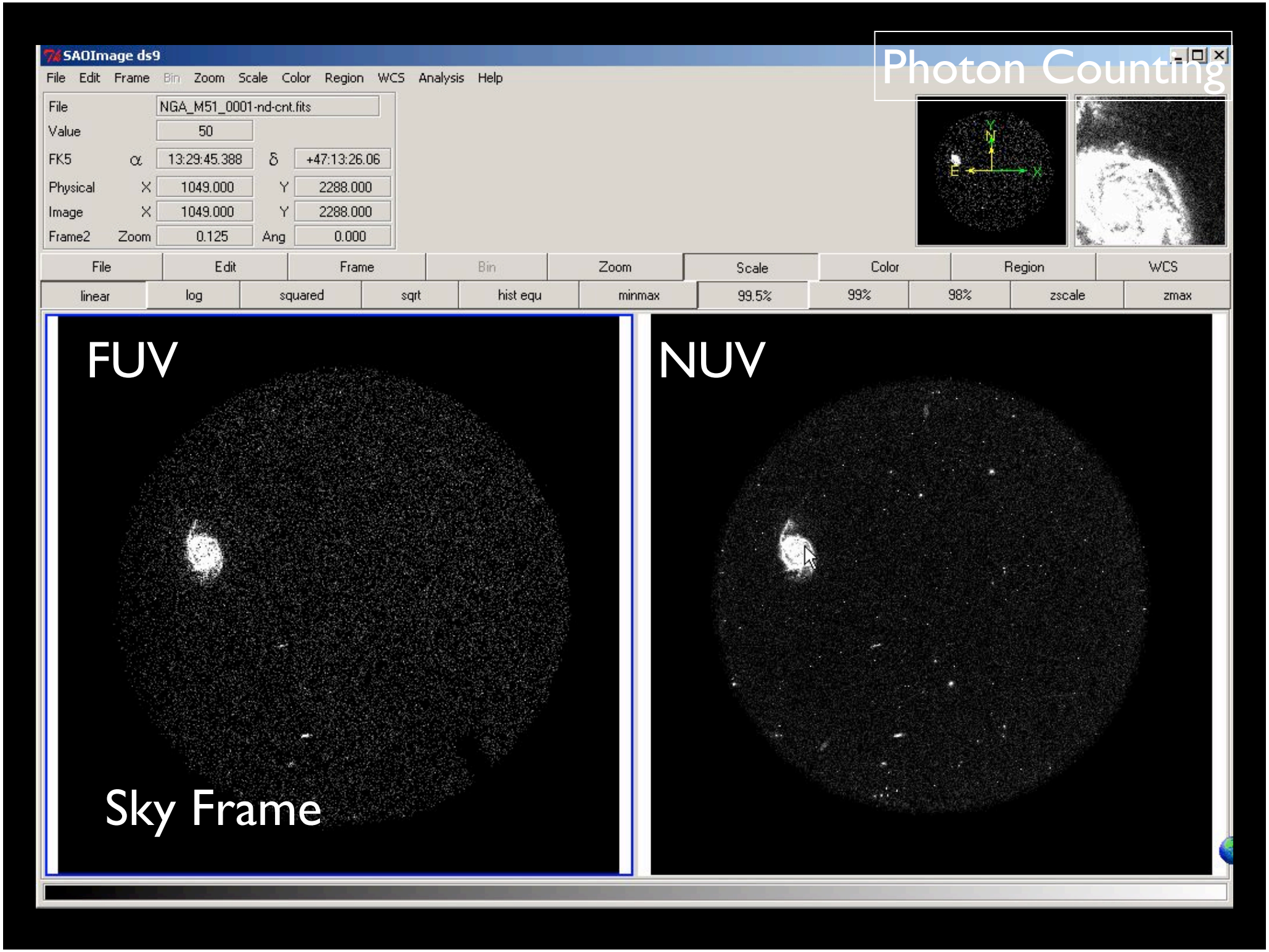
Photon Counting
FUV
NUV
Detector Frame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FK5 α 13:29:45.388 δ +47:13:26.06
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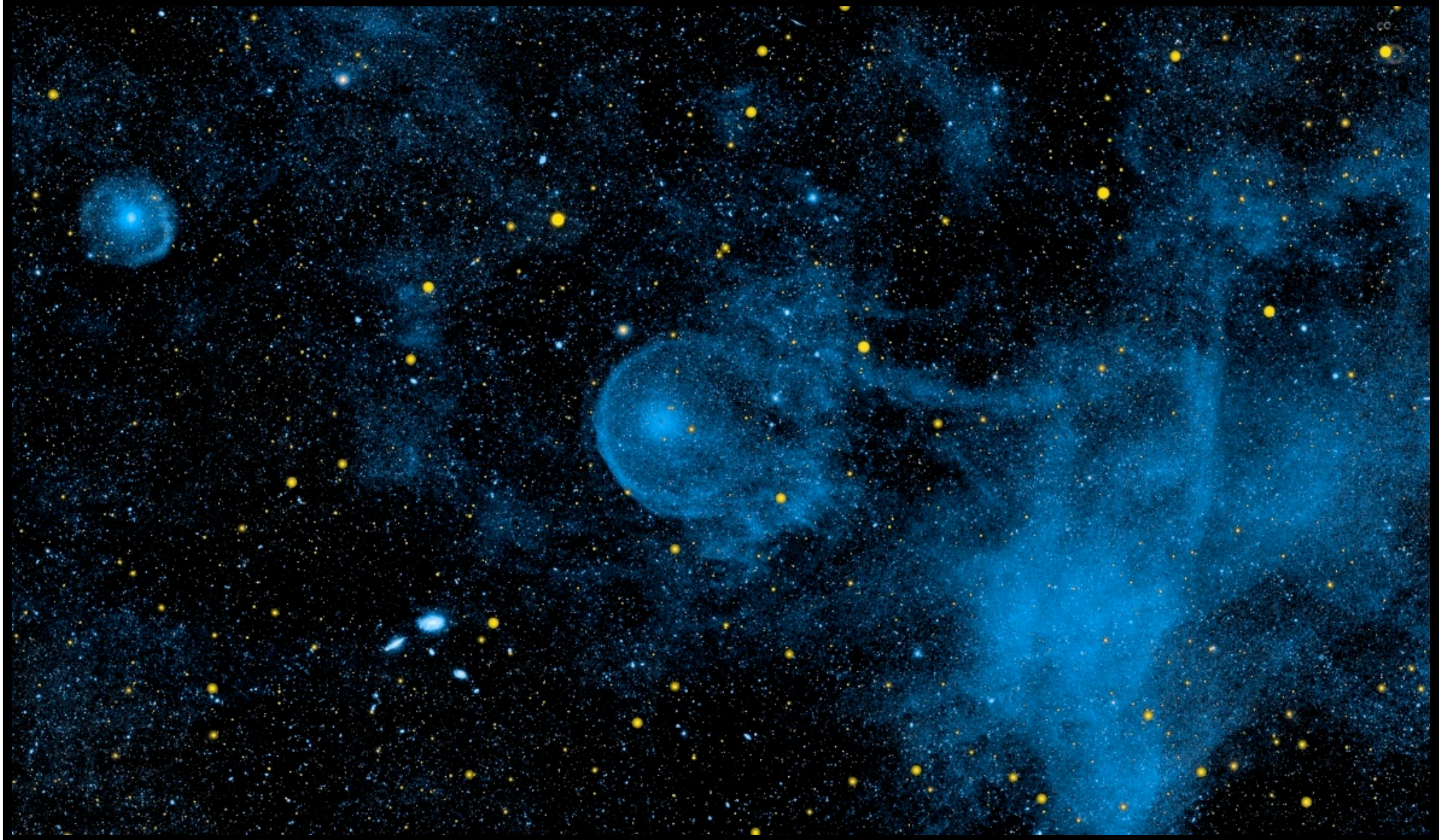
Image X 1049.000 Y 2288.000
Frame2 Zoom 0.125 Ang 0.000
File Edit Frame Bin Zoom Scale Color Region WCS
linear log squared sqrt hist equ minmax 99.5% 99% 98% zscale zmax
Photon Counting
FUV
Sky Frame
NUV

Photon Counting
M83

Photon Counting



CW Leo

Photon Counting

Satellite Transit ~ 10 min

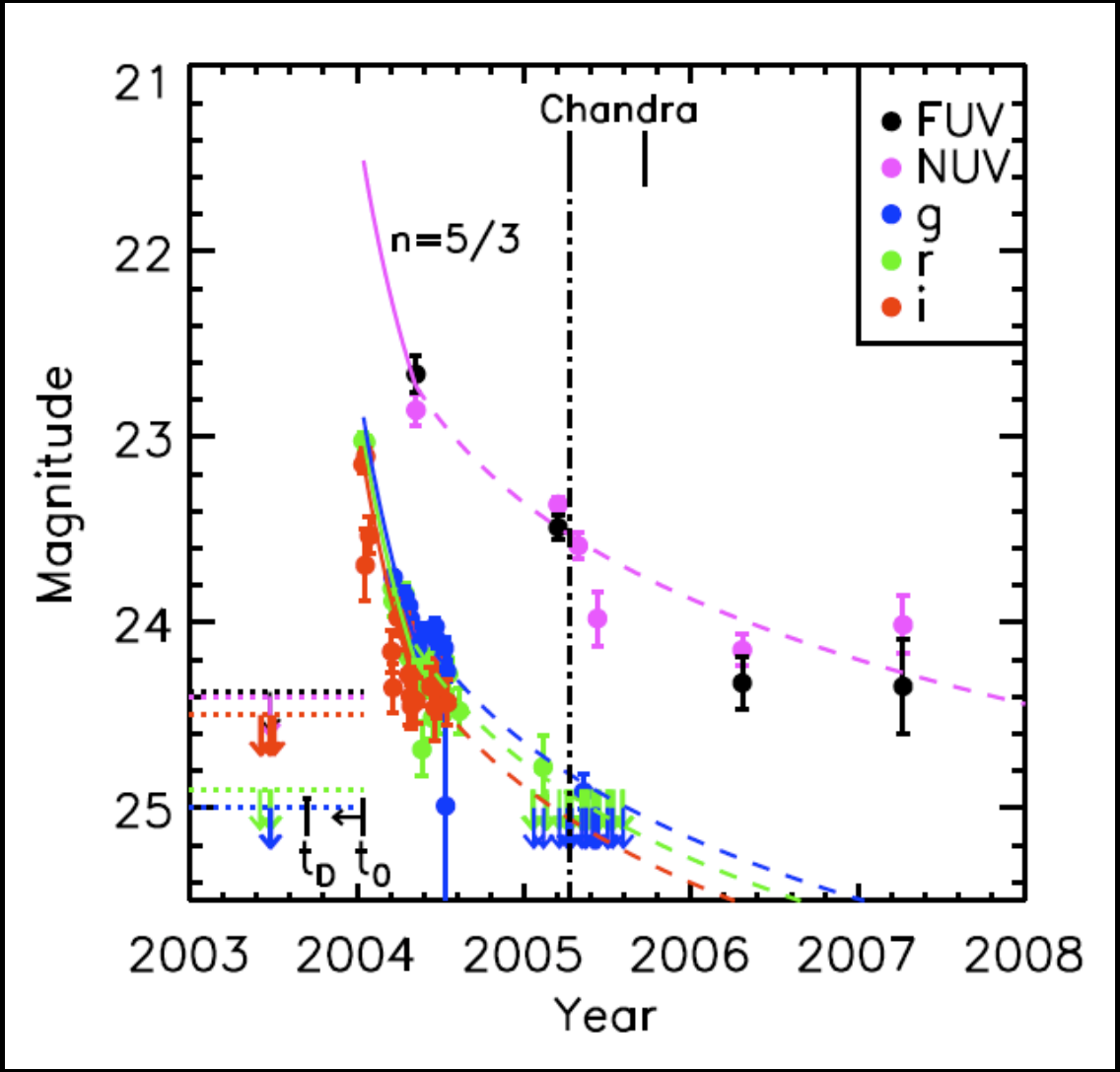
Photon Counting

Multiple Satellite Transit ~ 10 min

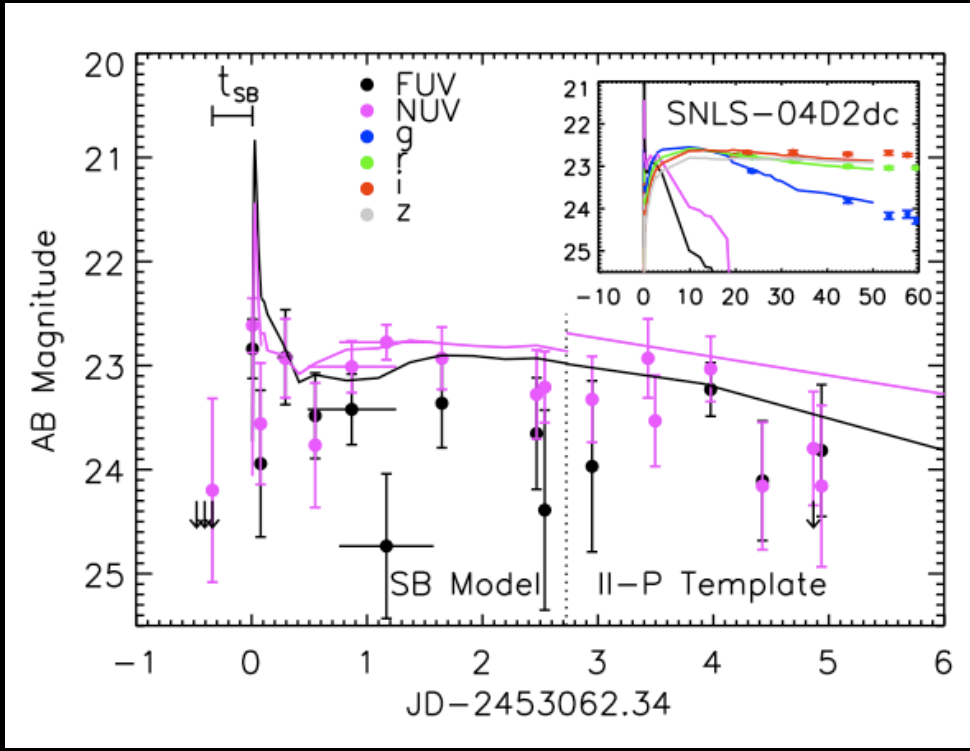
Photon Counting

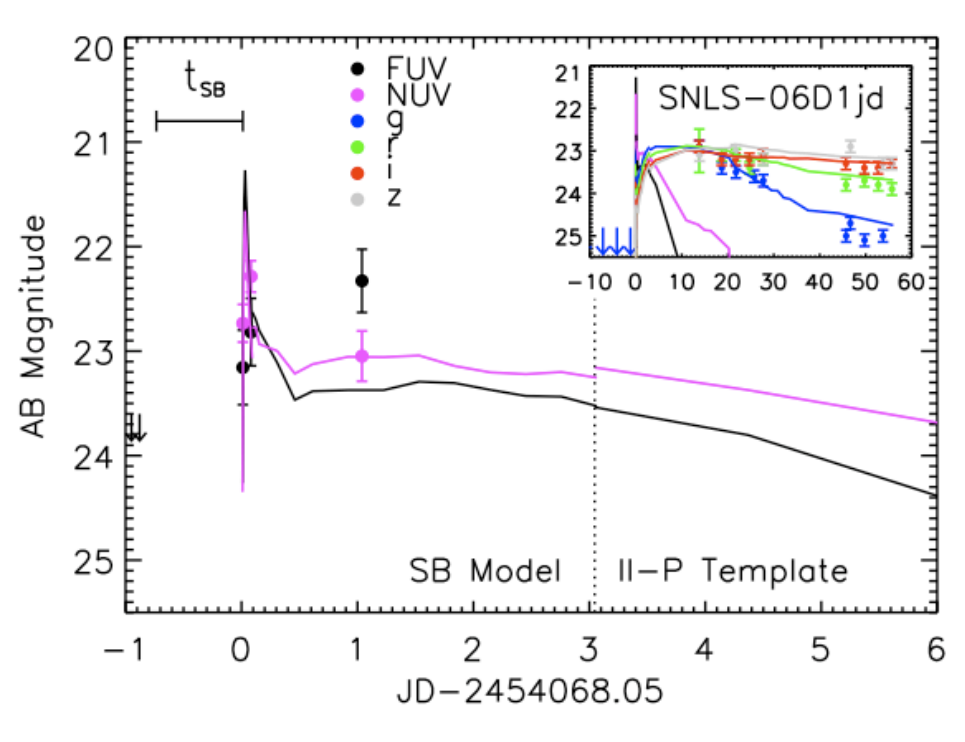
M-Dwarf Flare Star ~ 20 min (Welsh et al 2005)

Supermassive Black Hole - Tidal Capture Flares in the UV (Gezari et al 2008)

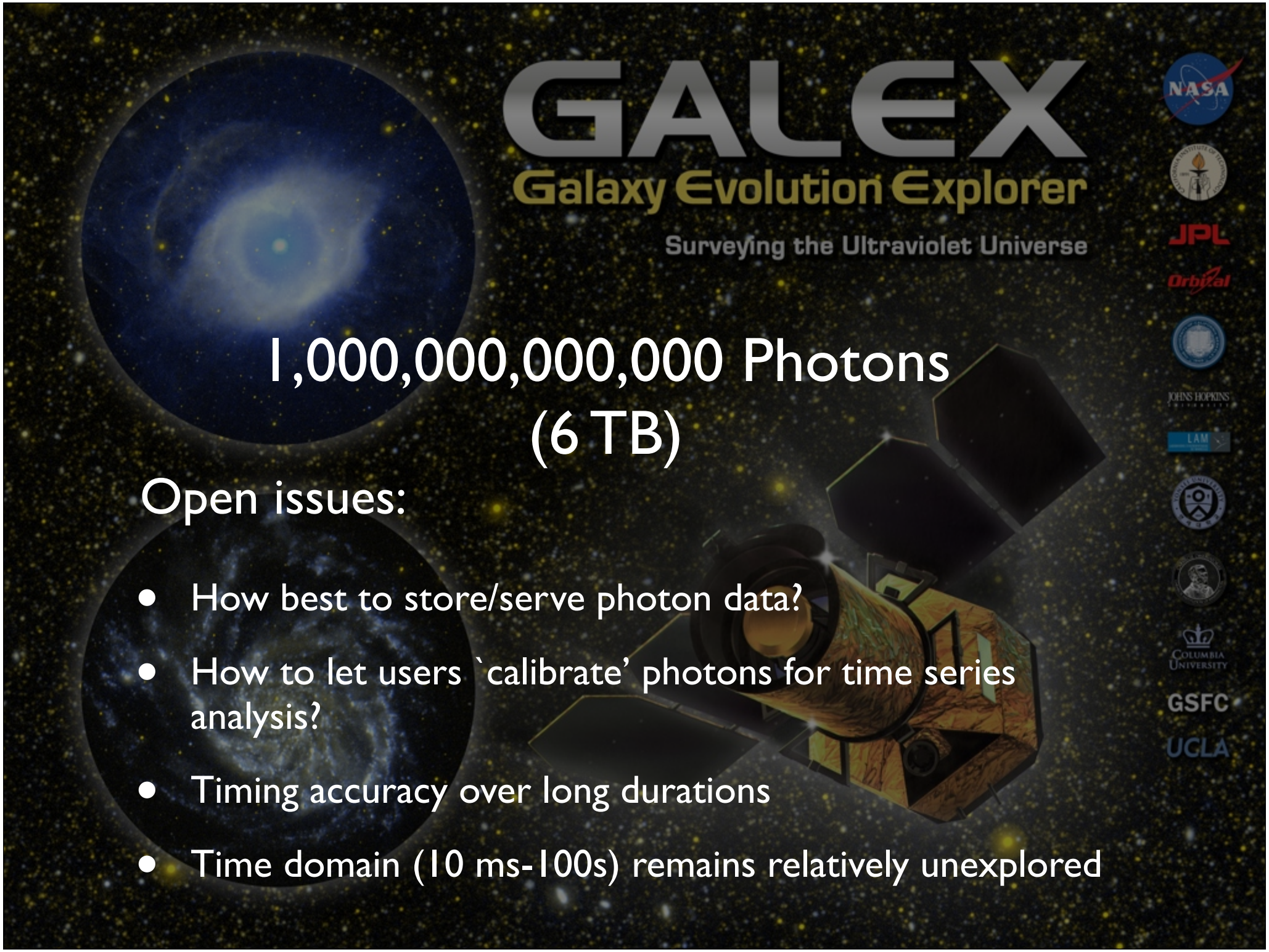


SN Type IIp - Shock Break Out Events
Rising edge of 2 SN detected ex-post facto in GALEX imaging (Gezari et al 2008, Schawinski et al 2008)





GALEX
Galaxy Evolution Explorer
Surveying the Ultraviolet Universe
1,000,000,000,000 Photons
(6 TB)
GALEX has provided to community in the form of images and catalogs
For good reason, raw photon data are considered a lower priority data set
NASA
JPL
Orbital
JOHNS HOPKINS
LAM
COLUMBIA UNIVERSITY
GSFC
UCLA



1,000,000,000,000 Photons (6 TB)

Open issues:

- How best to store/serve photon data?
- How to let users `calibrate' photons for time series analysis?
- Timing accuracy over long durations
- Time domain (10 ms-100s) remains relatively unexplored