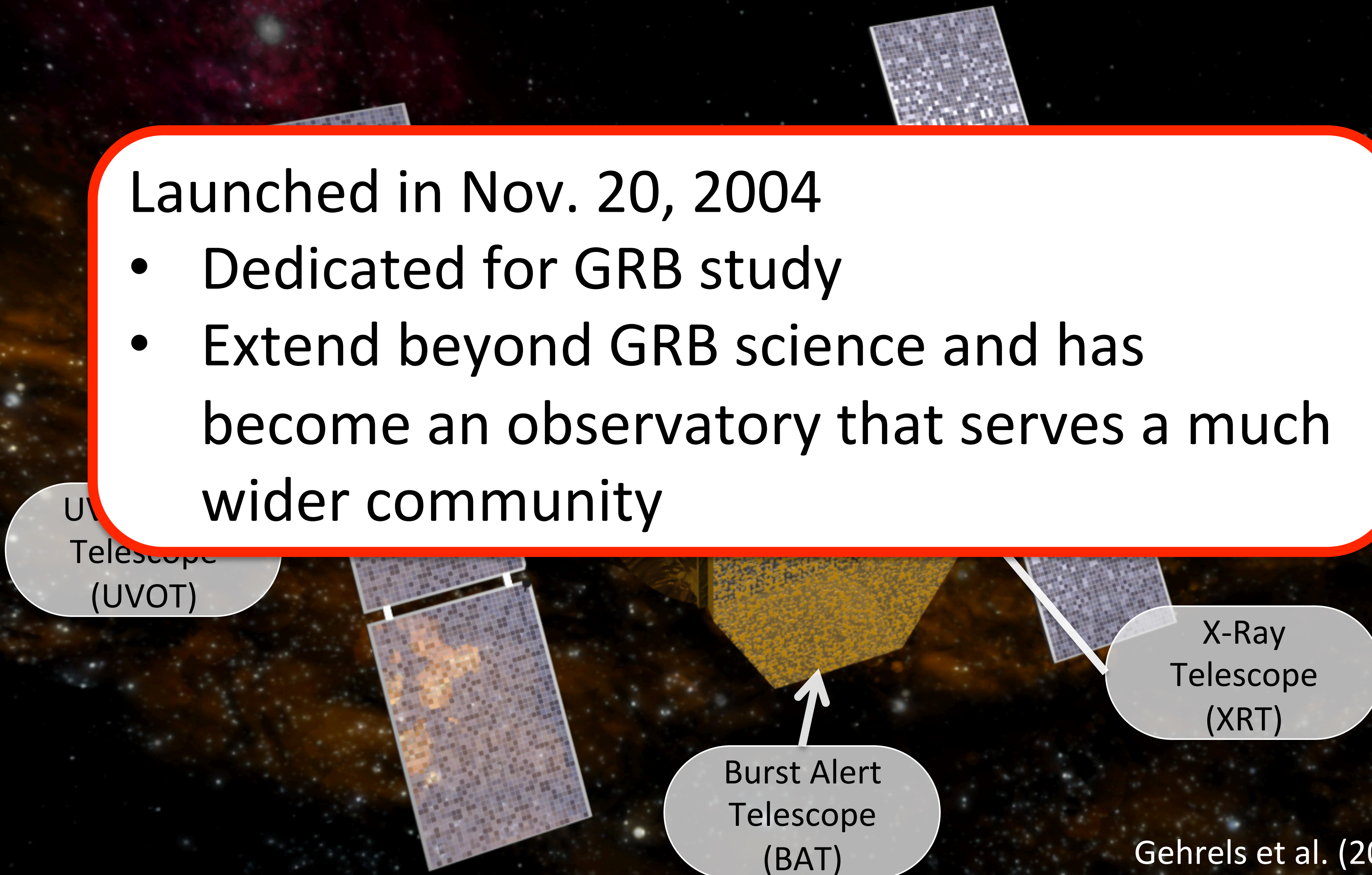
Neil Gehrels *Swift* Observatory

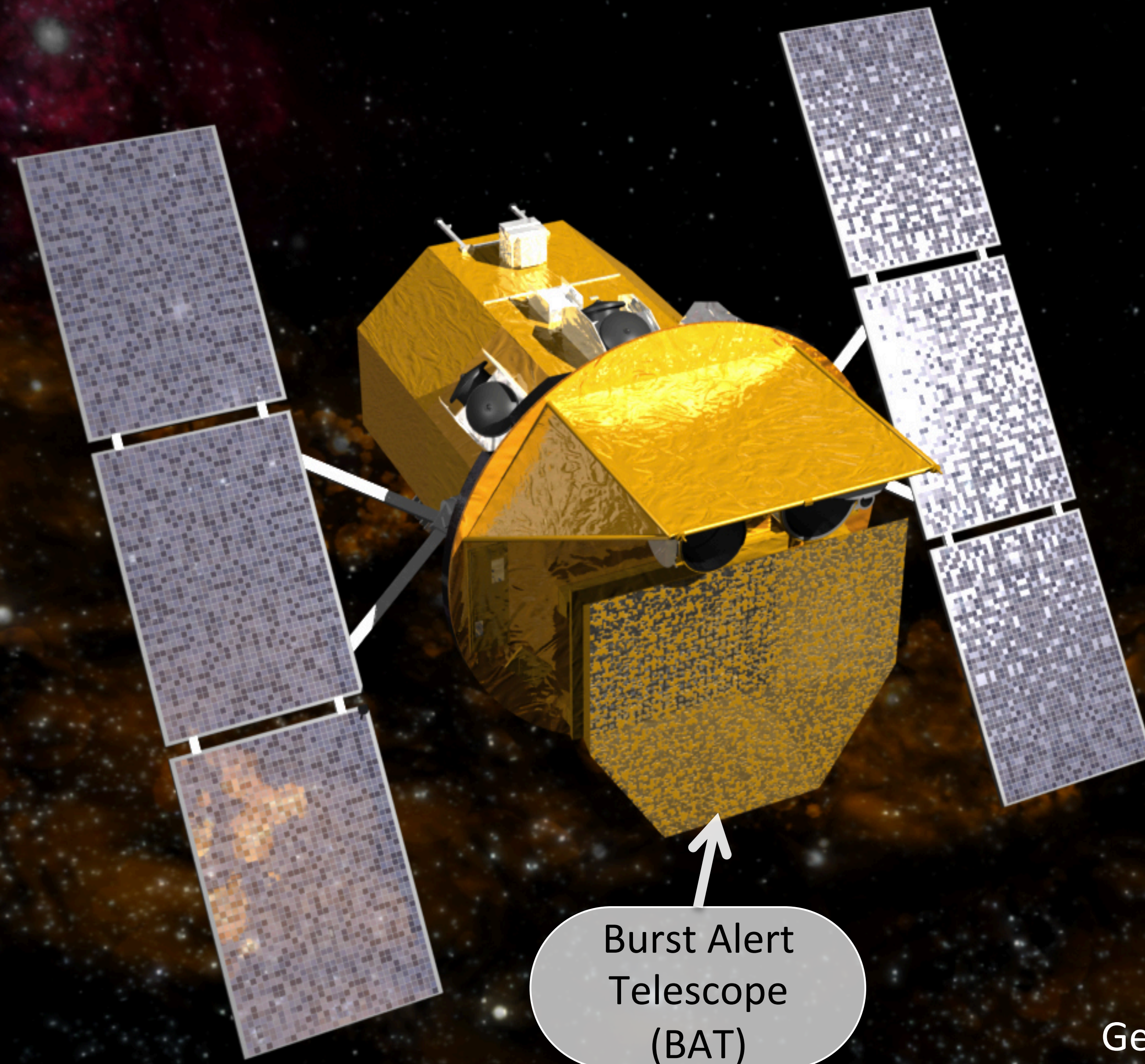
Launched in Nov. 20, 2004

- Dedicated for GRB study
- Extend beyond GRB science and has become an observatory that serves a much wider community



Gehrels et al. (2004)

Neil Gehrels *Swift* Observatory



Gehrels et al. (2004)

Burst Alert Telescope (BAT)

- Responsible for finding GRBs
- 15-350 keV
- Large field of view (~ 1/6 of the sky) → Increase the number of GRB detections
  - ~1.4 sr (half coded)
  - ~ 2 sr (fully coded)
- Decent localization in hard X rays (~ 3 arcmin) → Enable prompt follow-up of narrow field instruments

Swift GRBs to date: 15.9 Years after Launch

1326 GRBs (～ two per week)

459 GRBs with distance measurements

Swift/BAT GRB catalog:
https://swift.gsfc.nasa.gov/results/batgrbcat/

15.9 Years of *Swift*

Fractional Observing Time

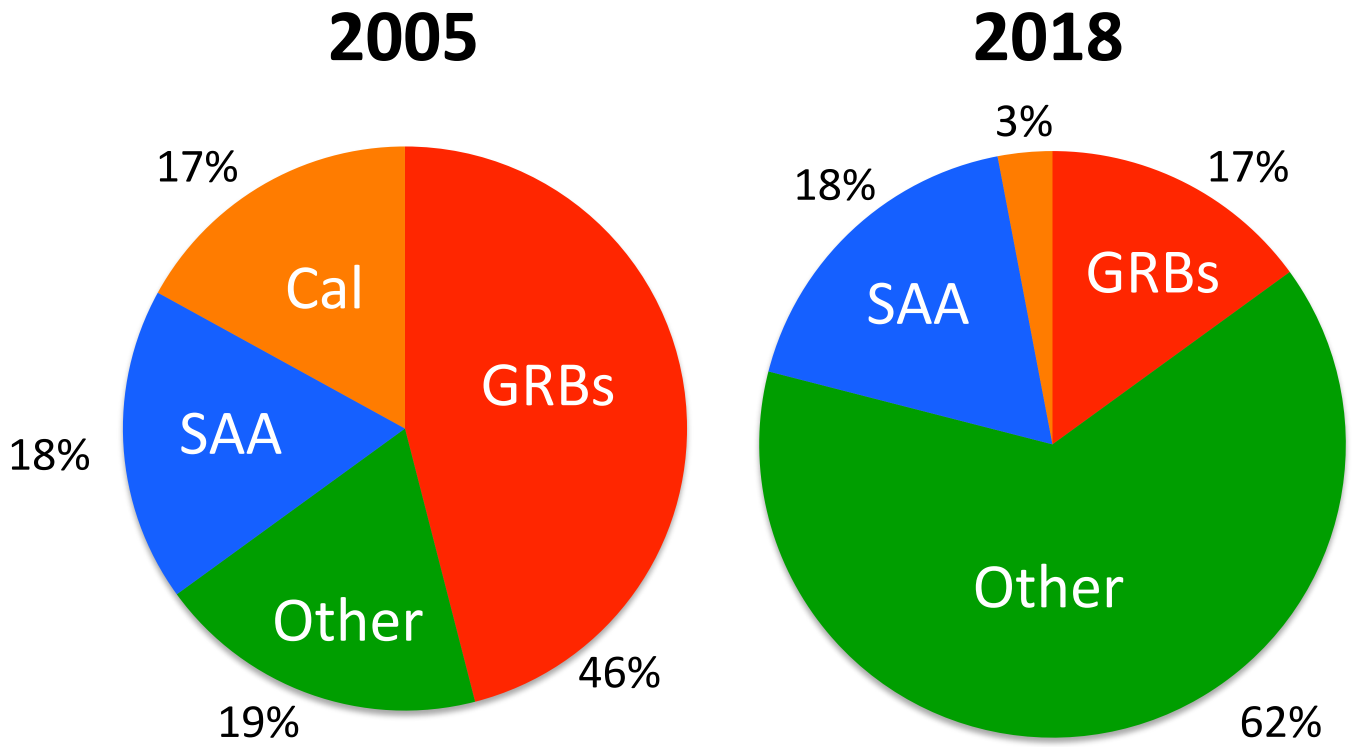


Figure credit: PSU webpage

Ref: Swift 2019 Senior Review Proposal

15.9 Years of *Swift*

Fractional Observing Time

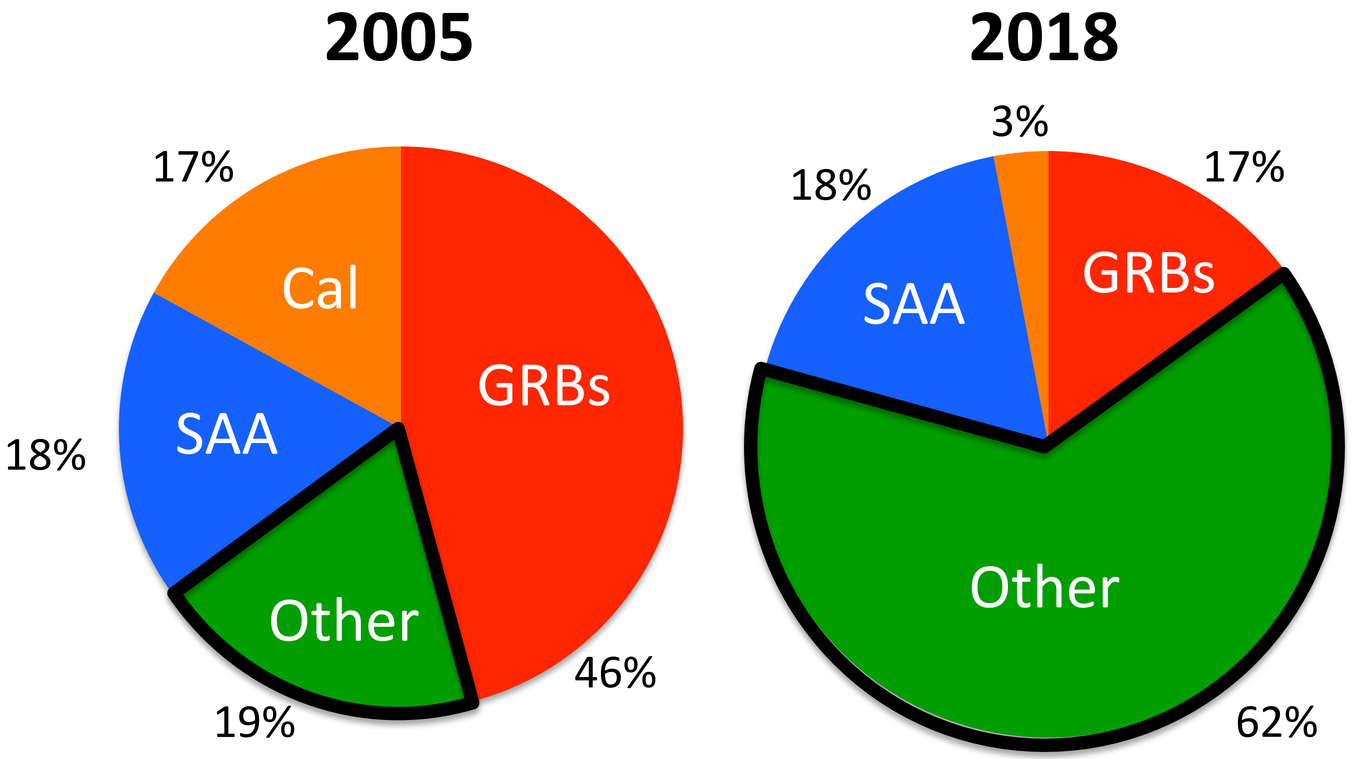
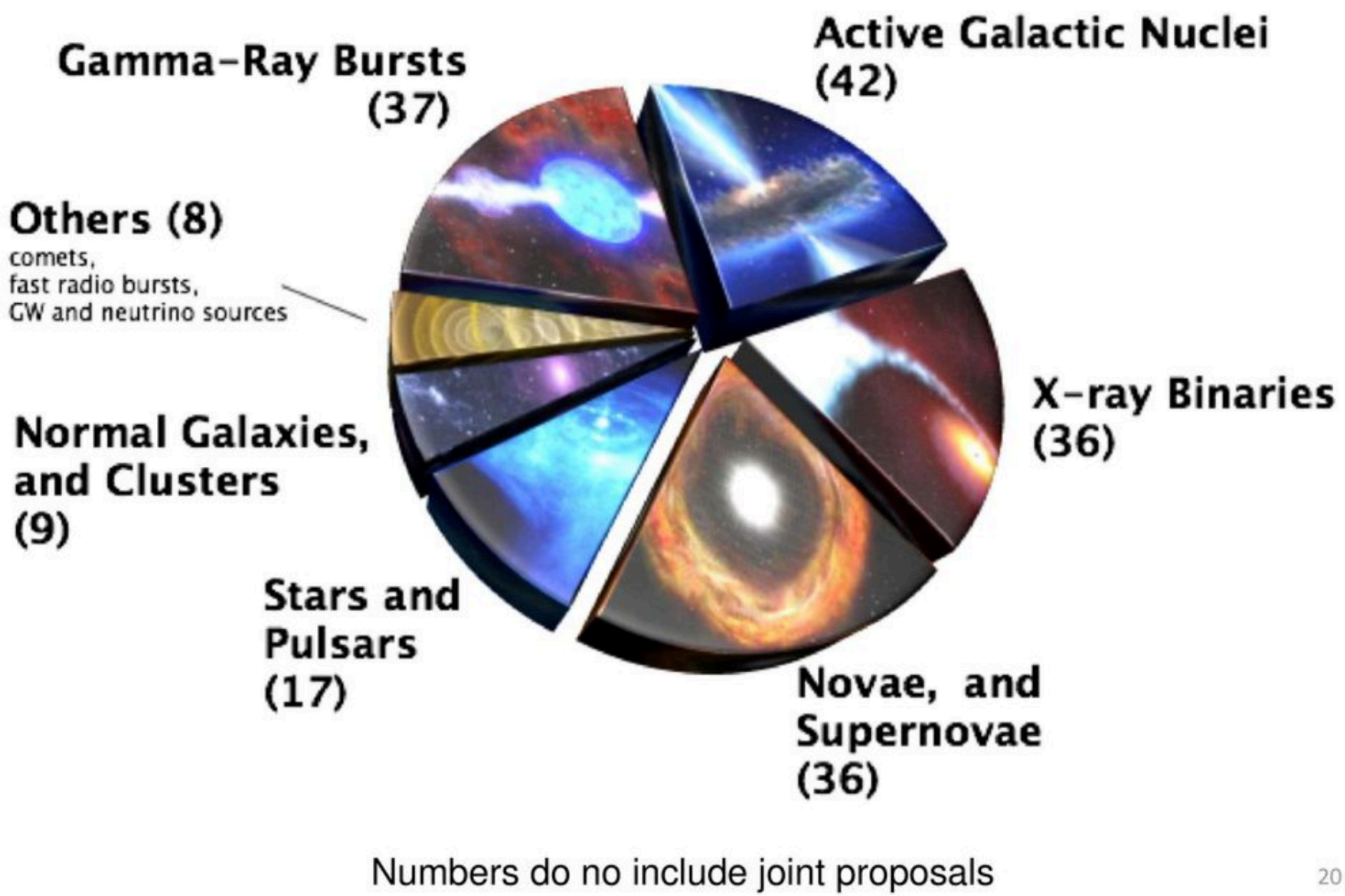


Figure credit: PSU webpage

Ref: Swift 2019 Senior Review Proposal

Beyond GRBs
Exploring the Universe with BAT

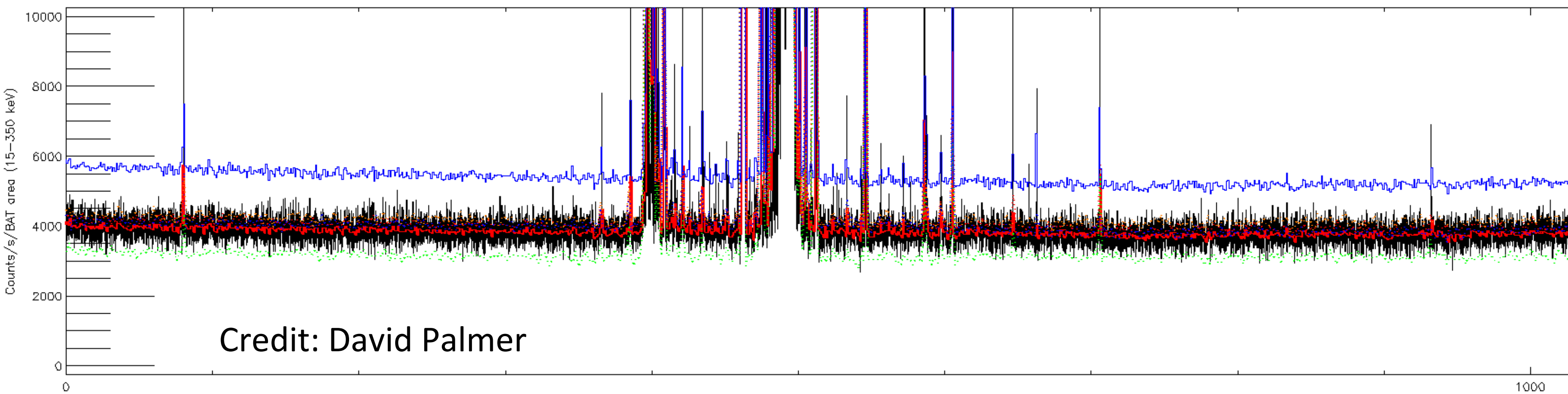


Credit: Topics of Swift GI proposals someone's talk at Penn State

Beyond GRBs
Exploring the Universe with BAT

- BAT triggers on sources beyond GRBs. E.g.,
  - Soft Gamma-ray Repeaters (SGRs)

BAT light curve on the forests of bursts
from recent activities of SGR 1935+2154 related to fast radio bursts



Beyond GRBs
Exploring the Universe with BAT

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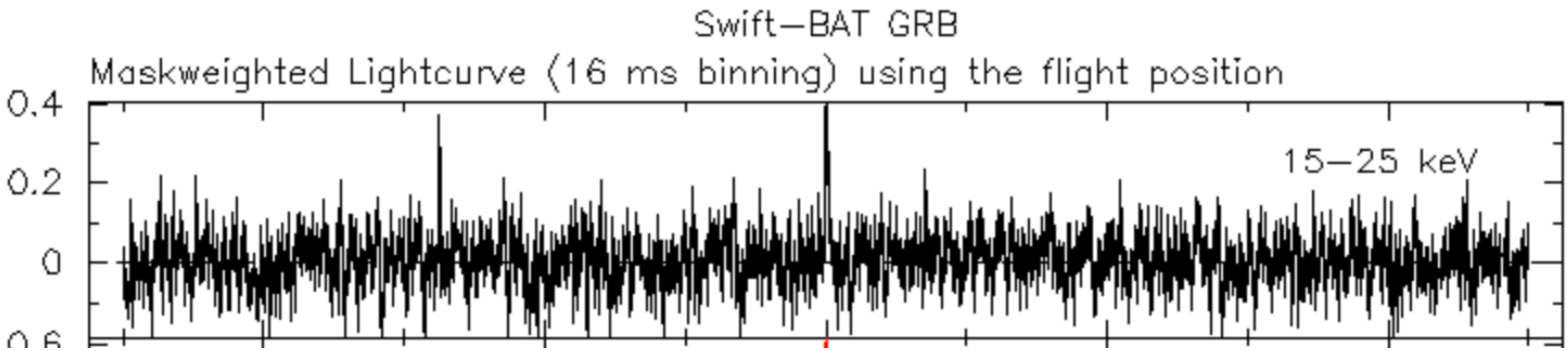
  - Soft Gamma-ray Repeaters (SGRs)

A new SGR just triggered by BAT last Saturday!



Beyond GRBs
Exploring the Universe with BAT

- BAT triggers on sources beyond GRBs. E.g.,
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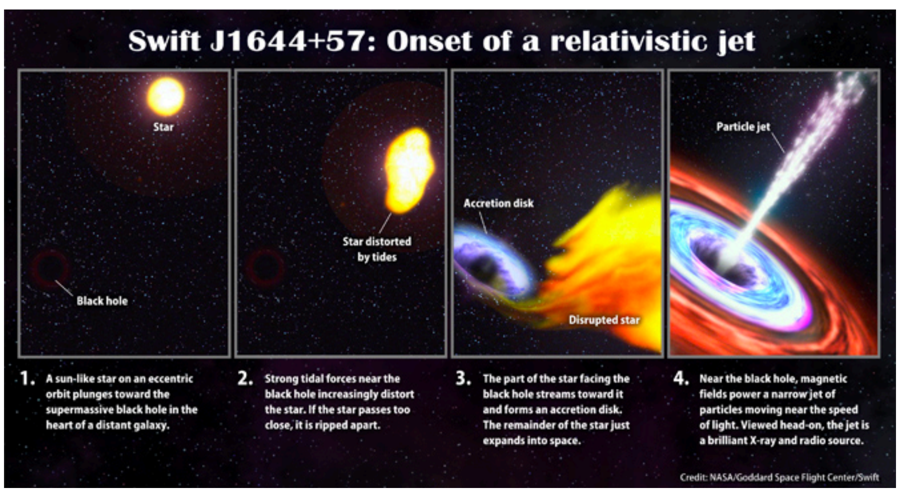
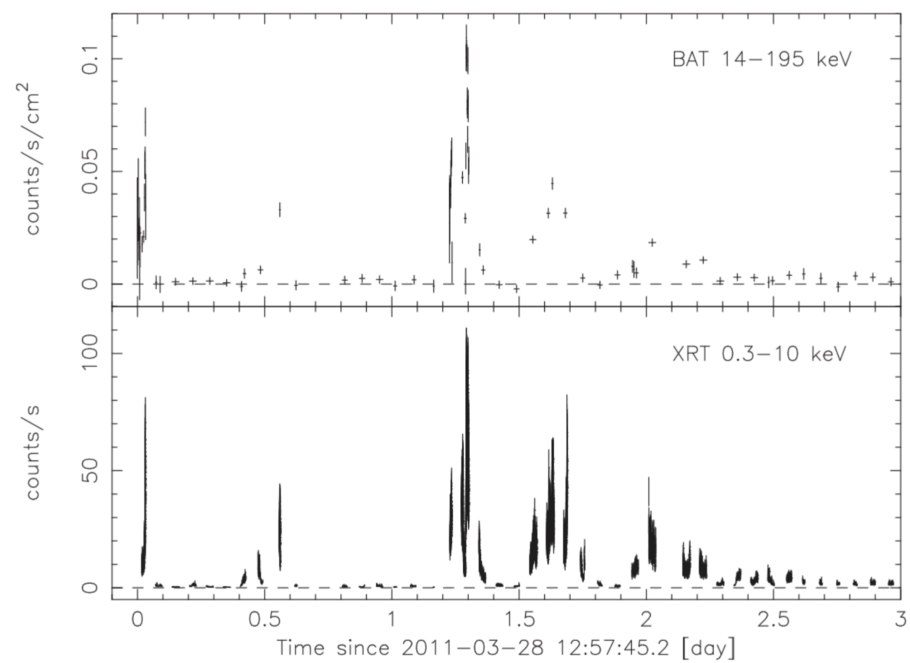
  - Tidal disruption event



Credit: nasa.gov

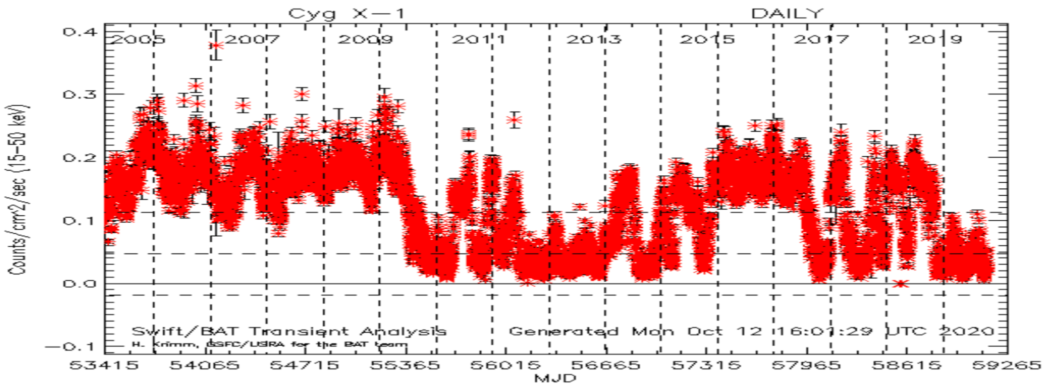
Burrows et al. (2011)



Beyond GRBs
Exploring the Universe with BAT

- BAT triggers on sources beyond GRBs. E.g.,
  - Soft Gamma-ray Repeaters (SGRs)
  - Tidal disruption event
- Long-term monitoring of hard X-ray sources
  - Monitoring > 2000 known sources
  - ~ 16 years and counting…

BAT transient monitor daily light curve
Krimm et al. (2013)



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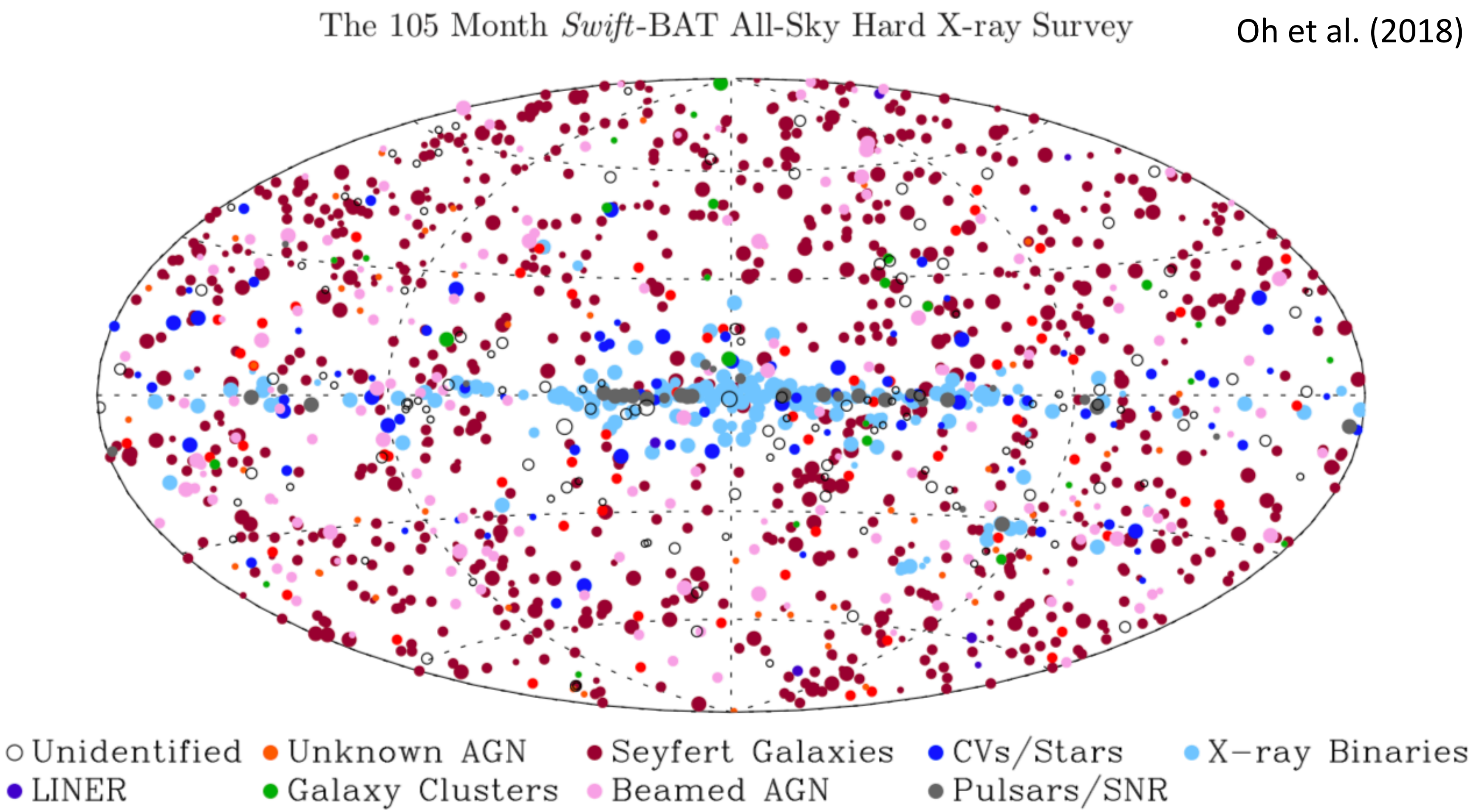
Beyond GRBs
Exploring the Universe with BAT

Oh et al. (2018)



Beyond GRBs
Exploring the Universe with BAT

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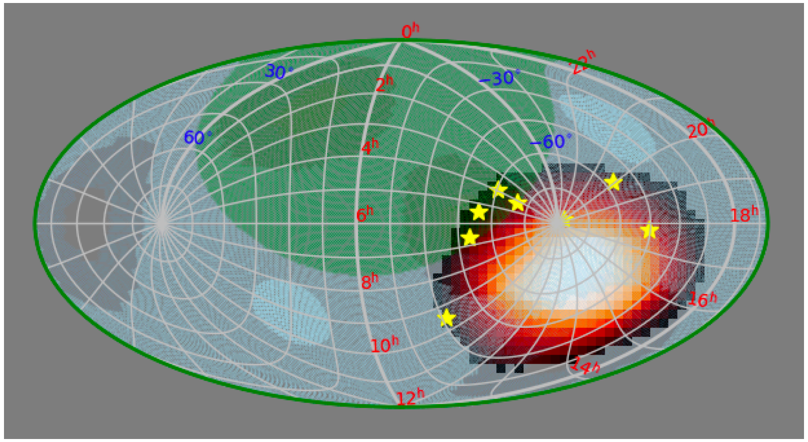
- Numerous counterpart searches

Beyond GRBs
Exploring the Universe with BAT

- GW counterpart searches

Table 1: Summary of the BAT prompt counterpart search for the O3 run (from April 1st to October 25th, 2019).

Number of LVC triggers	33
Number of triggers with at least one neutron star	11
Number of triggers in BAT FoV (>10% overlap)	14
Number of credible BAT counterparts	0



Lien et al. 2019

- FRB counterpart searches

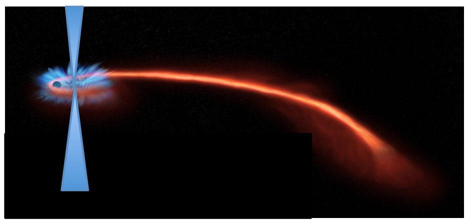
TABLE 3
SUMMARY OF OBSERVATIONS AVAILABLE PER FRB.

FRB Name	*Fermi* GBM	*Fermi* LAT	*Swift* BAT
010125	N	N	N
010621	N	N	N
010724	N	N	N
090625	Y	Y	N
110220	N	N	N
110523	Y	N	N
110626	Y	N	N
110703	Y	N	N
120127	N	N	N
121002	N	N	N
121102	Y	Y	N
130626	N	N	N
130628	Y	Y	N
130729	Y	N	N
131104	Y	N	N
140514	N	N	N
150215	Y	Y	Y
150418	Y	Y	N
150807	Y	N	N
160317	Y	Y	N
160410	N	N	Y
160608	Y	Y	N
170107	N	N	N

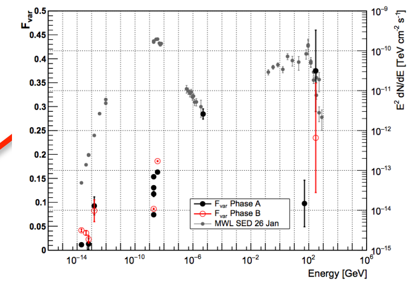
Cunningham et al. 2019

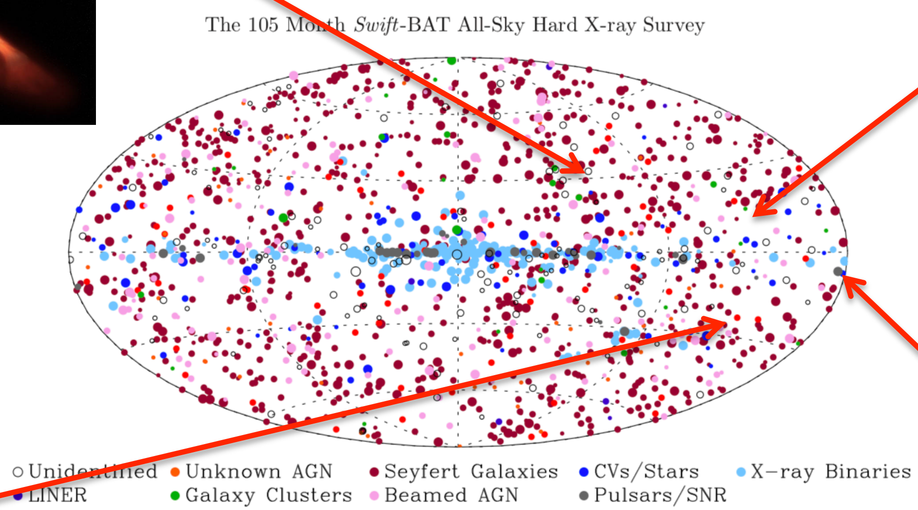
Beyond GRBs
Exploring the Universe with BAT

AT2018cow: A white dwarf tidal disruption event?
(Kuin et al. 2018)

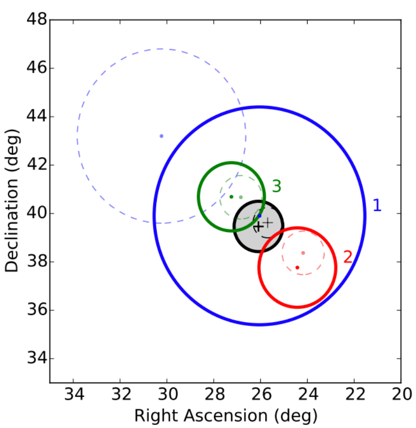


Multi-wavelength characterization of the blazar S5 0716+714 during an unprecedented outburst phase
(MAGIC Collaboration, A&A, 2018)

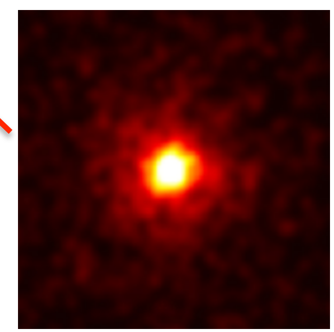




Oh et al. (2018)



Multiwavelength follow-up of a rare IceCube neutrino multiplet
(IceCube Collaboration, A&A, 2017)



The largest glitch observed in the Crab pulsar
(Shaw et al. MNRAS, 2018)

Beyond GRBs
Exploring the Universe with BAT

- BAT triggers on sources beyond GRBs. E.g.,
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Beyond GRBs
Exploring the Universe with BAT

- BAT triggers on sources beyond GRBs:

Achievable thanks to
- Large field of view
- Decent localization

in hard X ray.

- Deep hard X-ray survey on mosaic images throughout the entire mission time.
- Numerous counterpart searches

Beyond GRBs
Exploring the Universe with BAT

- BAT triggers on sources beyond GRBs:

Achievable thanks to
- Large field of view
- Decent localization

→ Coded mask technique

in hard X ray.

20 years and counting…

- Deep hard X-ray survey on mosaic images throughout the entire mission time.
- Numerous counterpart searches

Coded-mask technique

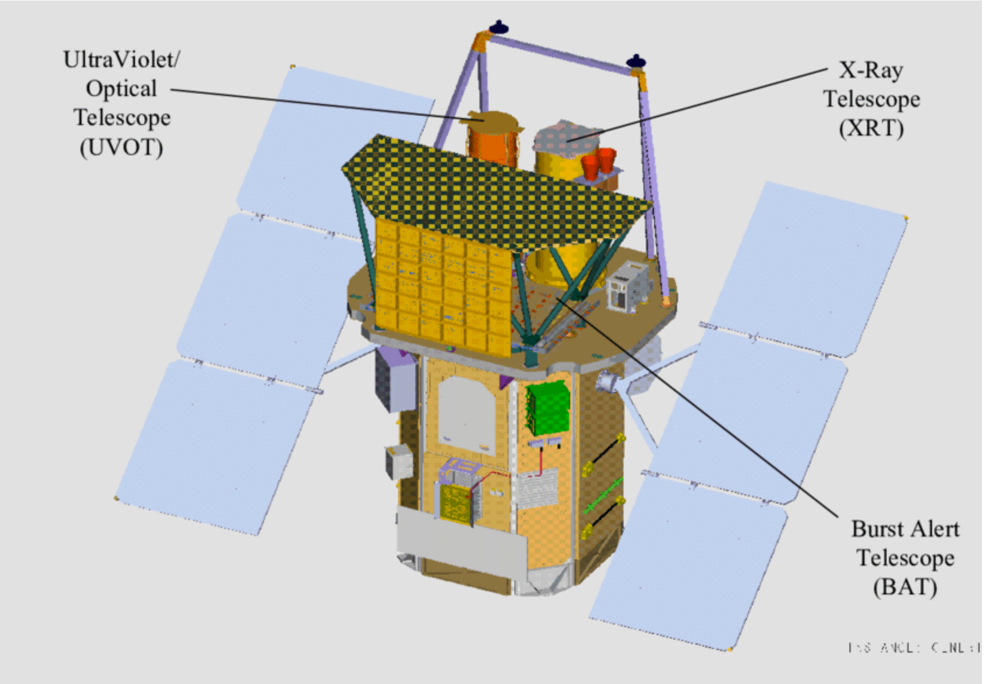


Fig credit: Hullinger et al. 2006

Coded-mask technique

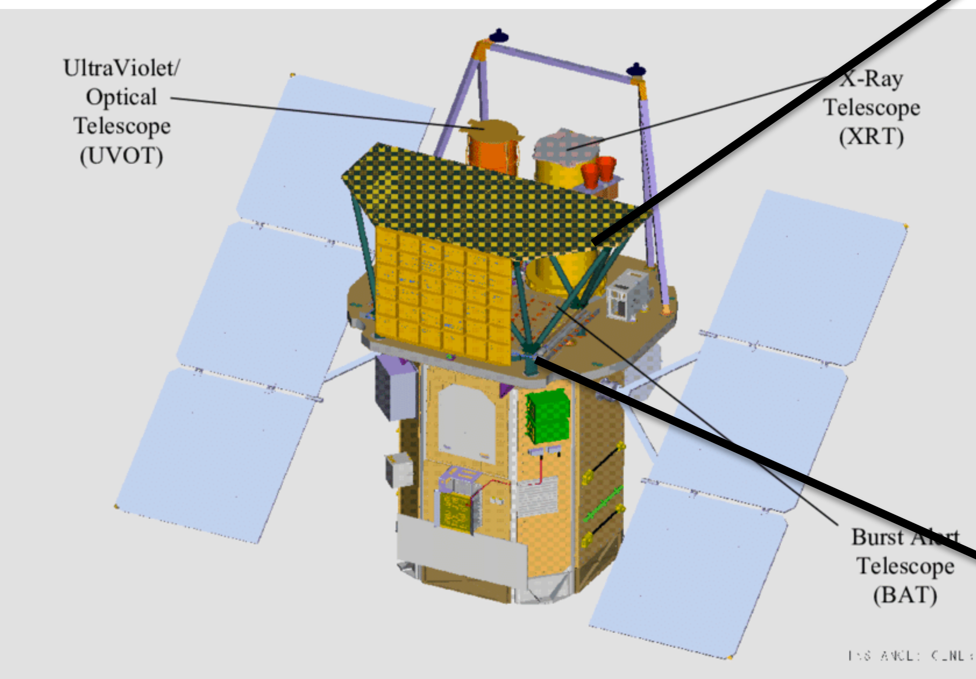
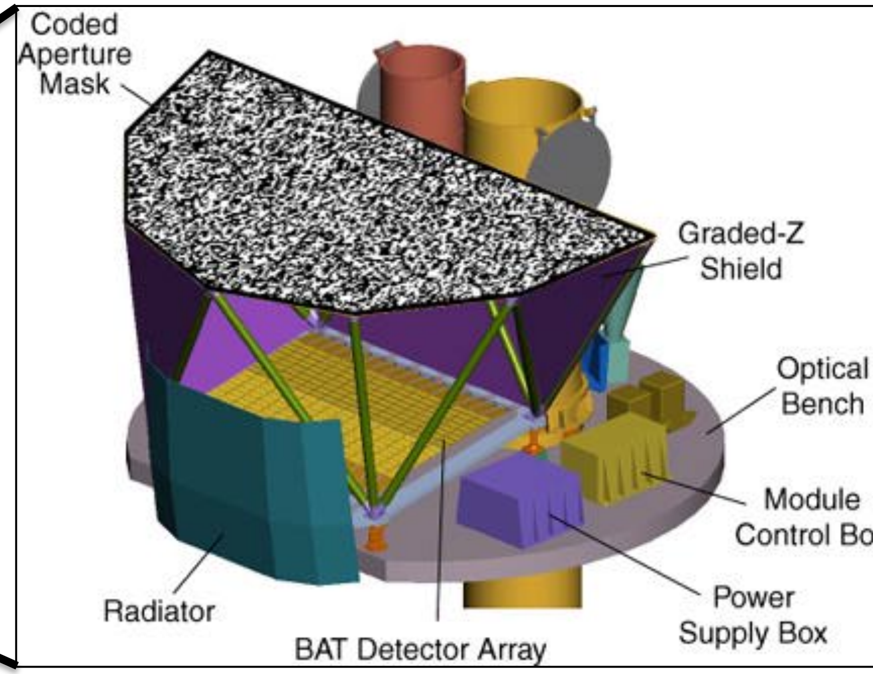


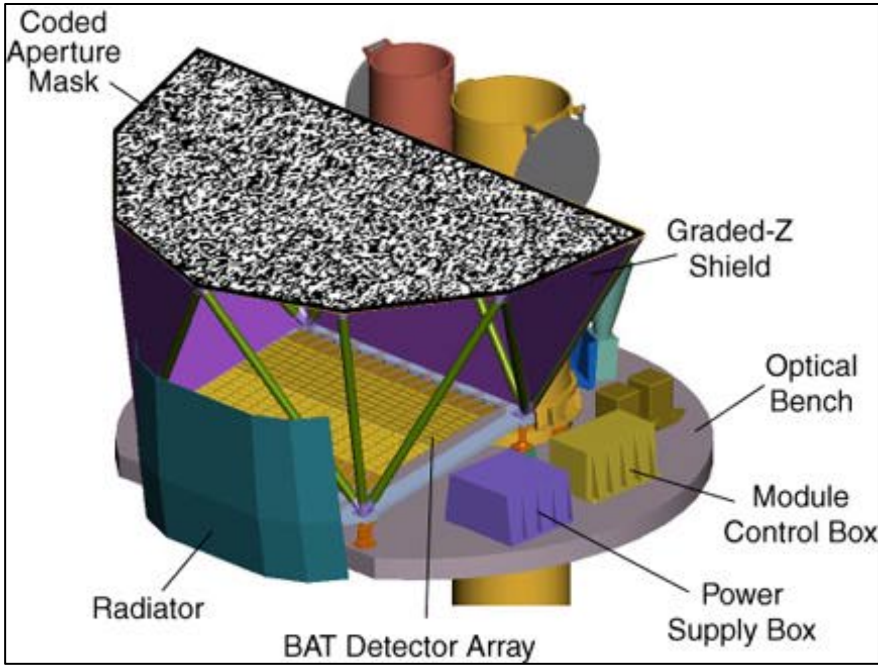
Fig credit: Hullinger et al. (2006)



Credit: NASA/Swift webpage

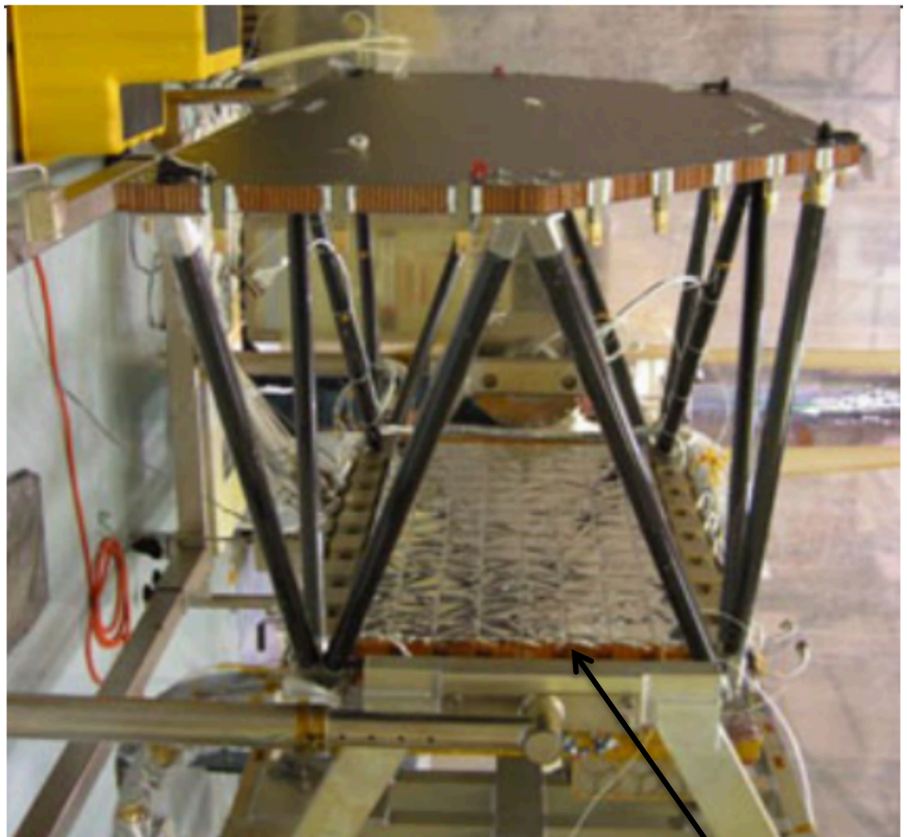
Coded-mask technique

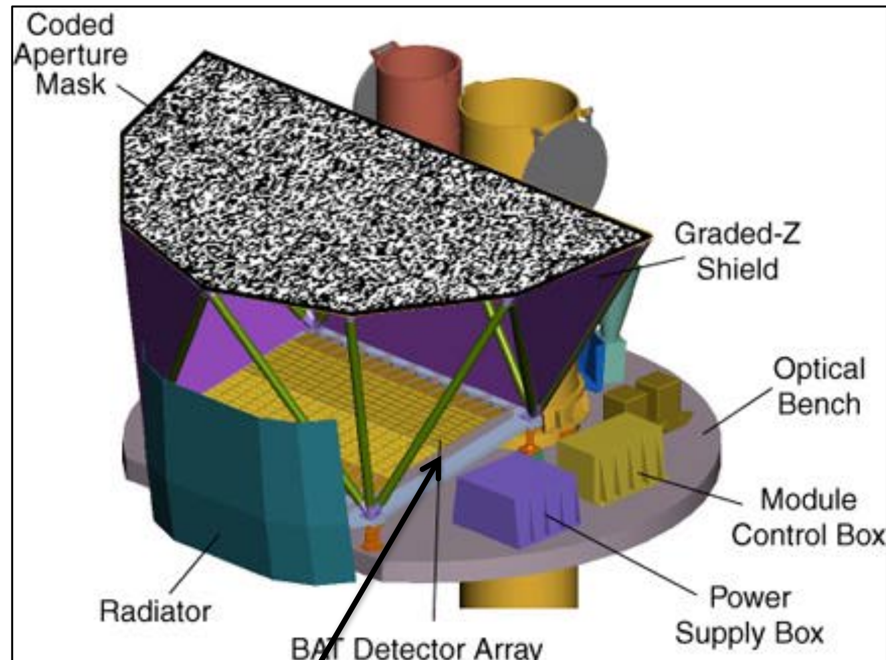
Coded Aperture Mask



Credit: NASA/Swift webpage

Coded-mask technique



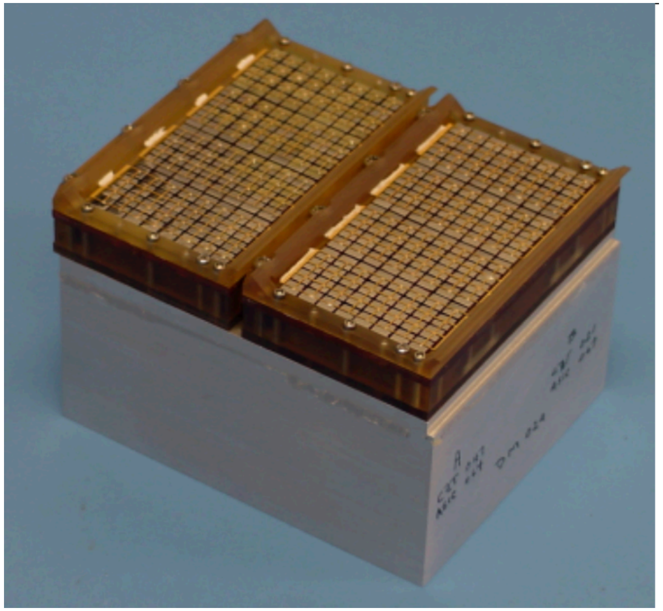


Credit: NASA/Swift webpage

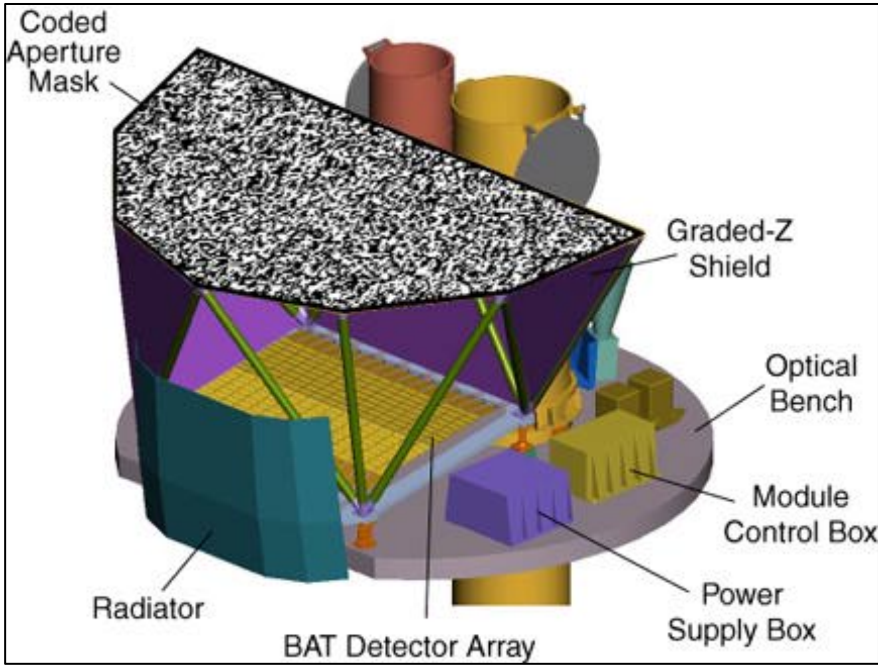
BAT detector array

Coded-mask technique

A Detector Module (128*2 detectors)

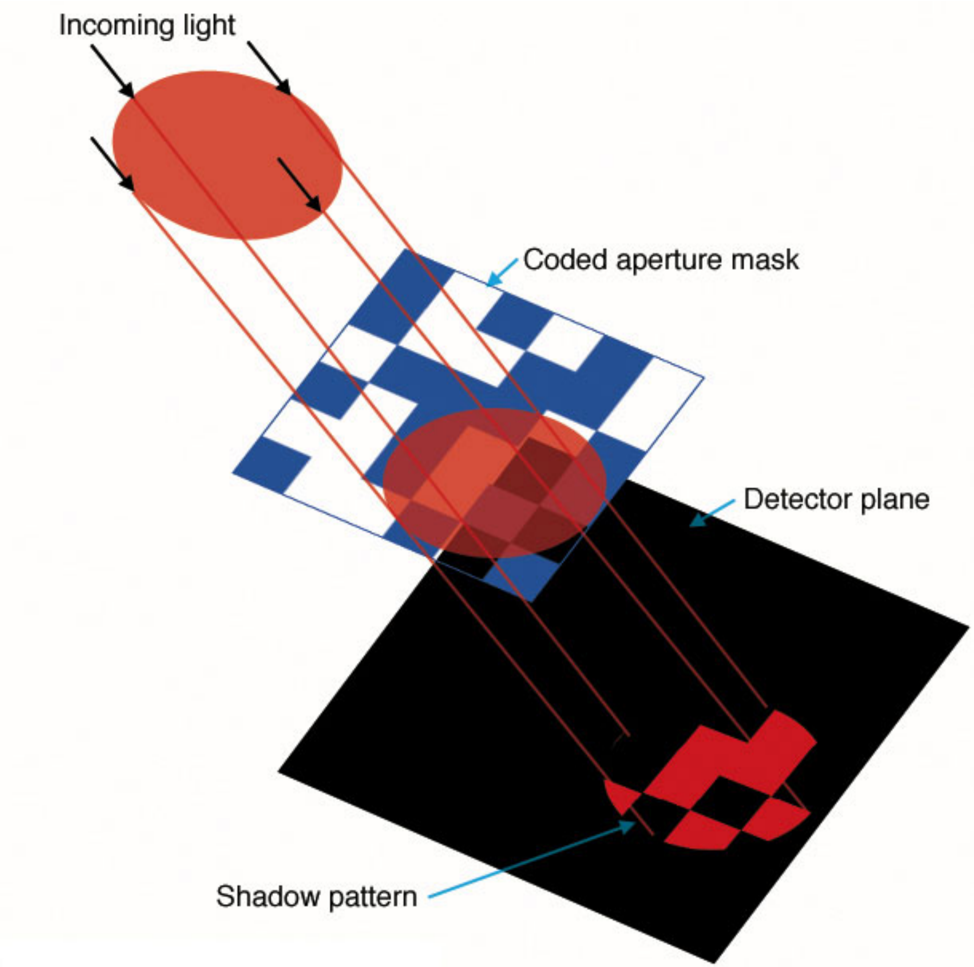


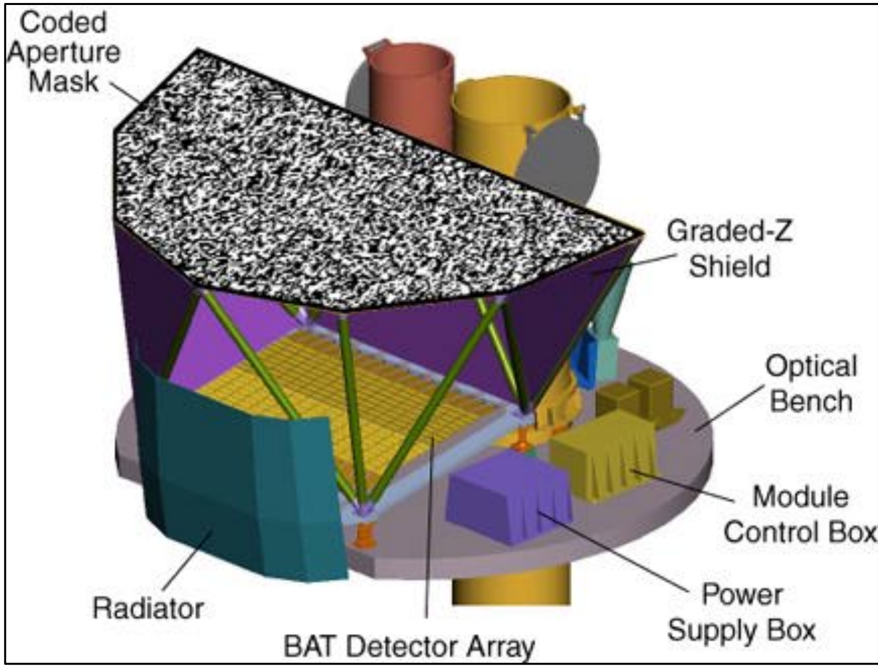
BAT detectors:
32,768 CZT (CdZnTe) detectors
Energy range:
15-350 keV for detection
(15-200 keV for imaging)



Credit: NASA/Swift webpage

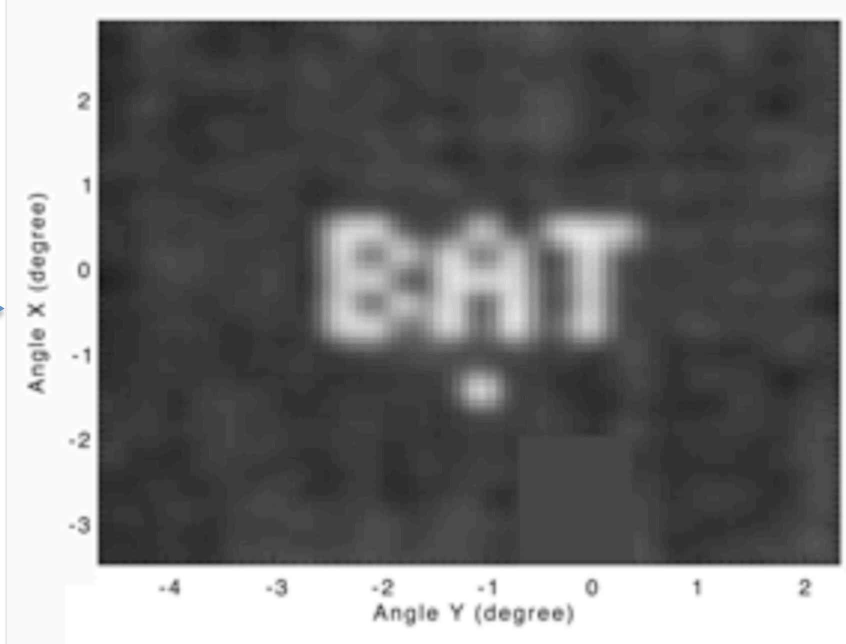
Coded-mask technique





Credit: NASA/Swift webpage

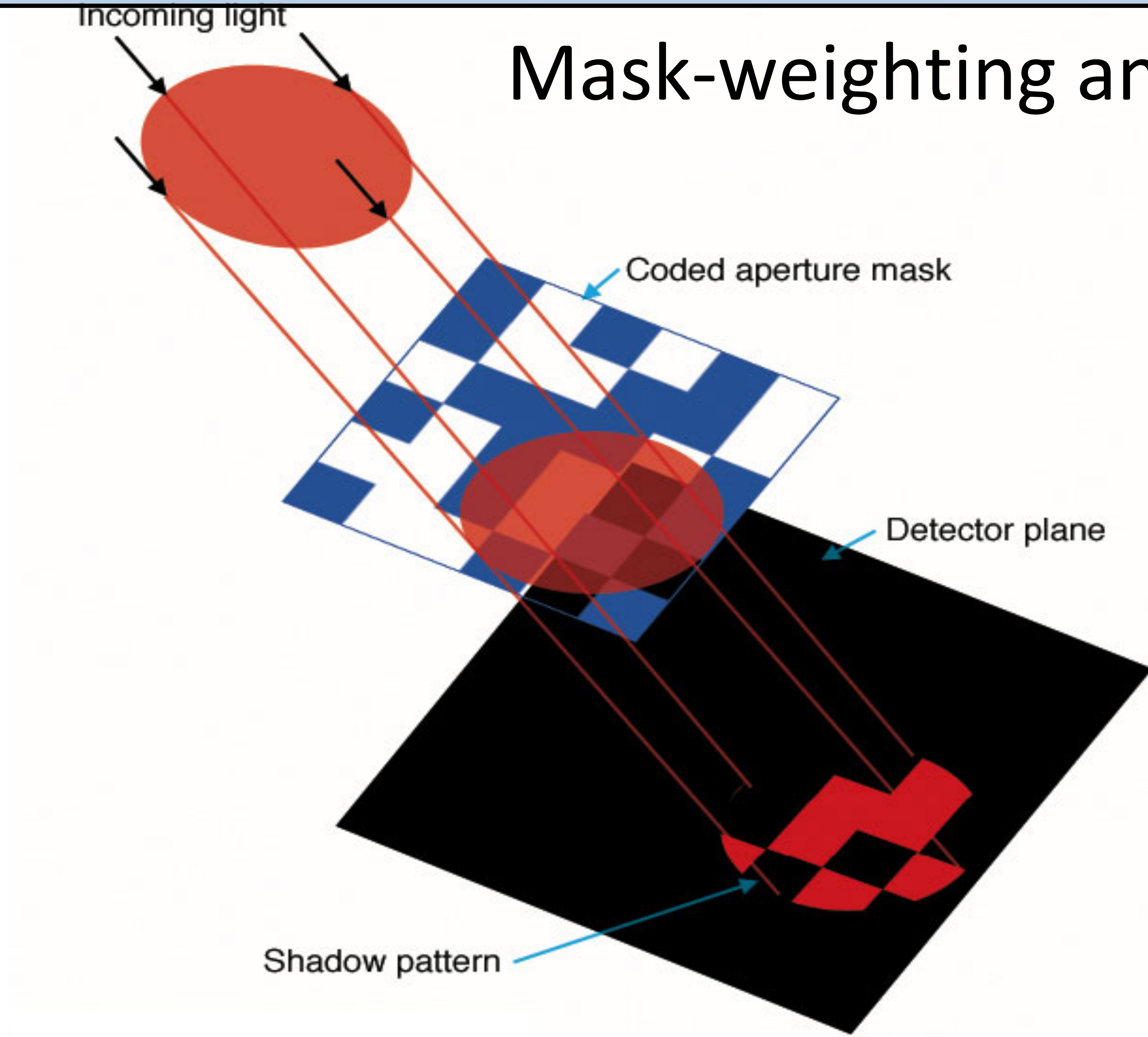
Coded-mask technique



Markwardt et al. (2007)

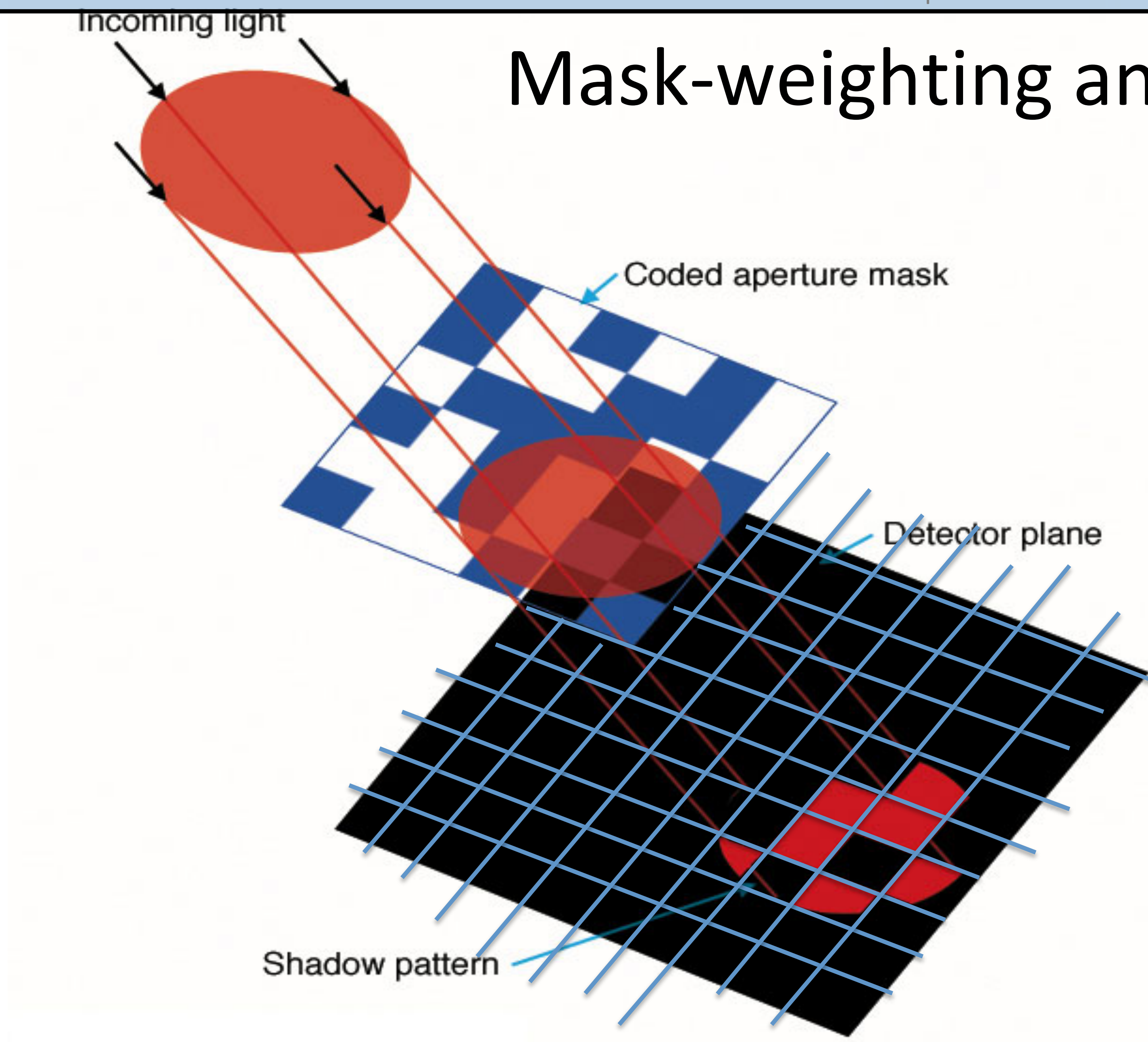
Barthelmy et al. (2005)

Mask-weighting analysis



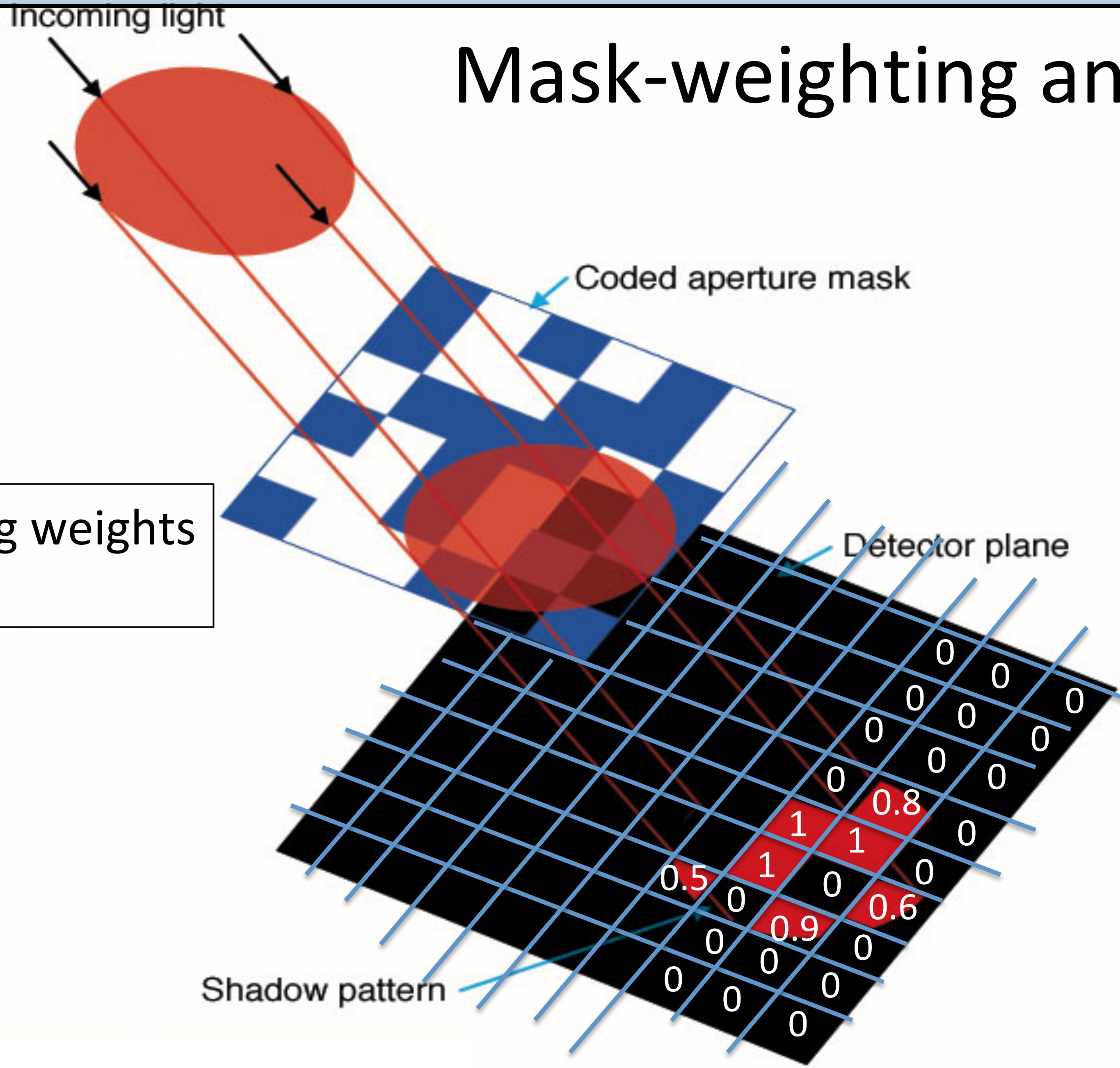
Credit: NASA's Imagine the Universe and NASA/Swift

Mask-weighting analysis



Credit: NASA's Imagine the Universe and NASA/Swift

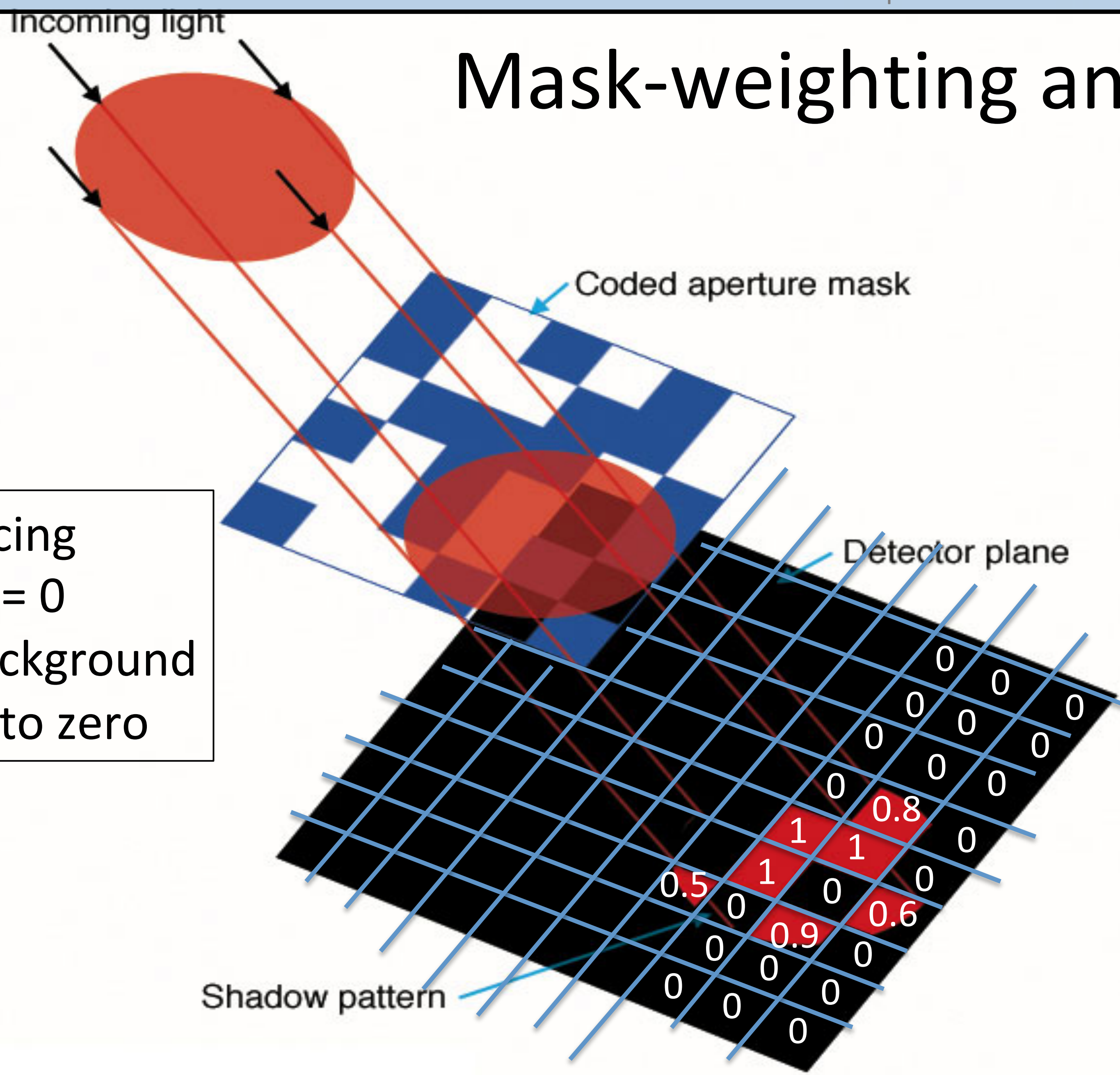
Mask-weighting analysis



Assigning weights (w_i)

Credit: NASA's Imagine the Universe and NASA/Swift

Mask-weighting analysis



Rebalancing
Sum(w_i) = 0
→ So background average to zero

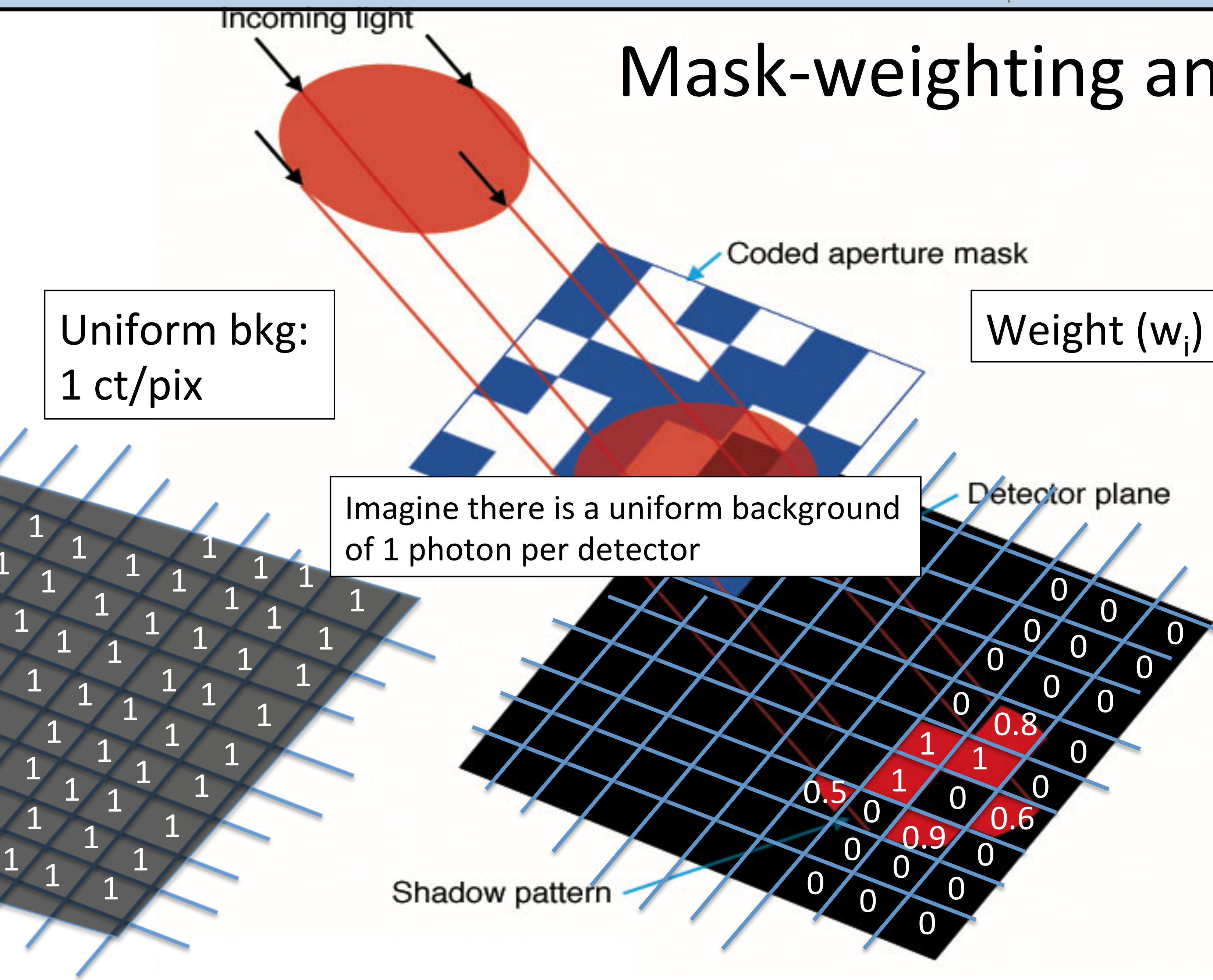
Credit: NASA's Imagine the Universe and NASA/Swift

Mask-weighting analysis

Uniform bkg:
1 ct/pix

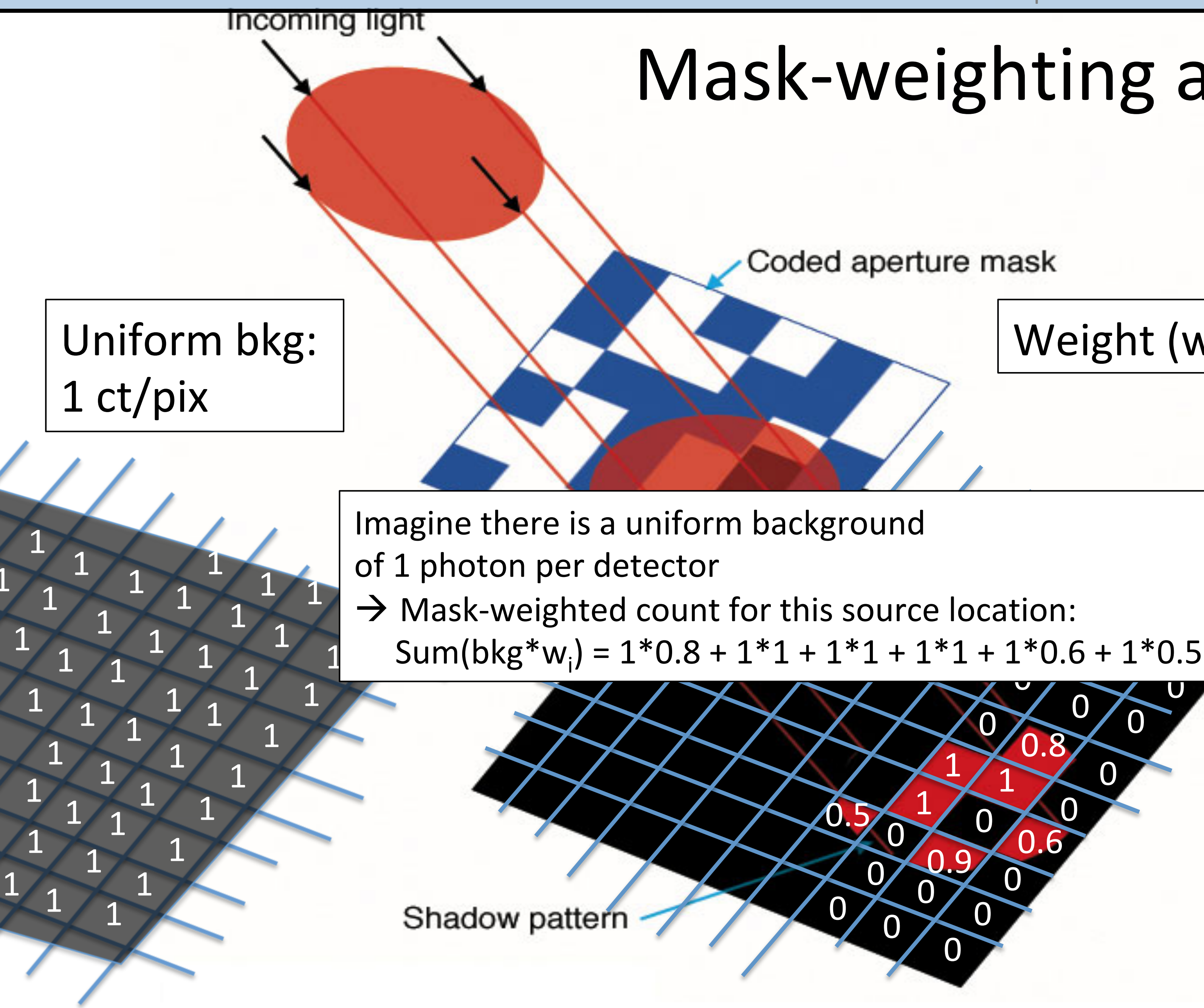
Weight (w_i)

Imagine there is a uniform background of 1 photon per detector



Credit: NASA's Imagine the Universe and NASA/Swift

Mask-weighting analysis



Uniform bkg:
1 ct/pix

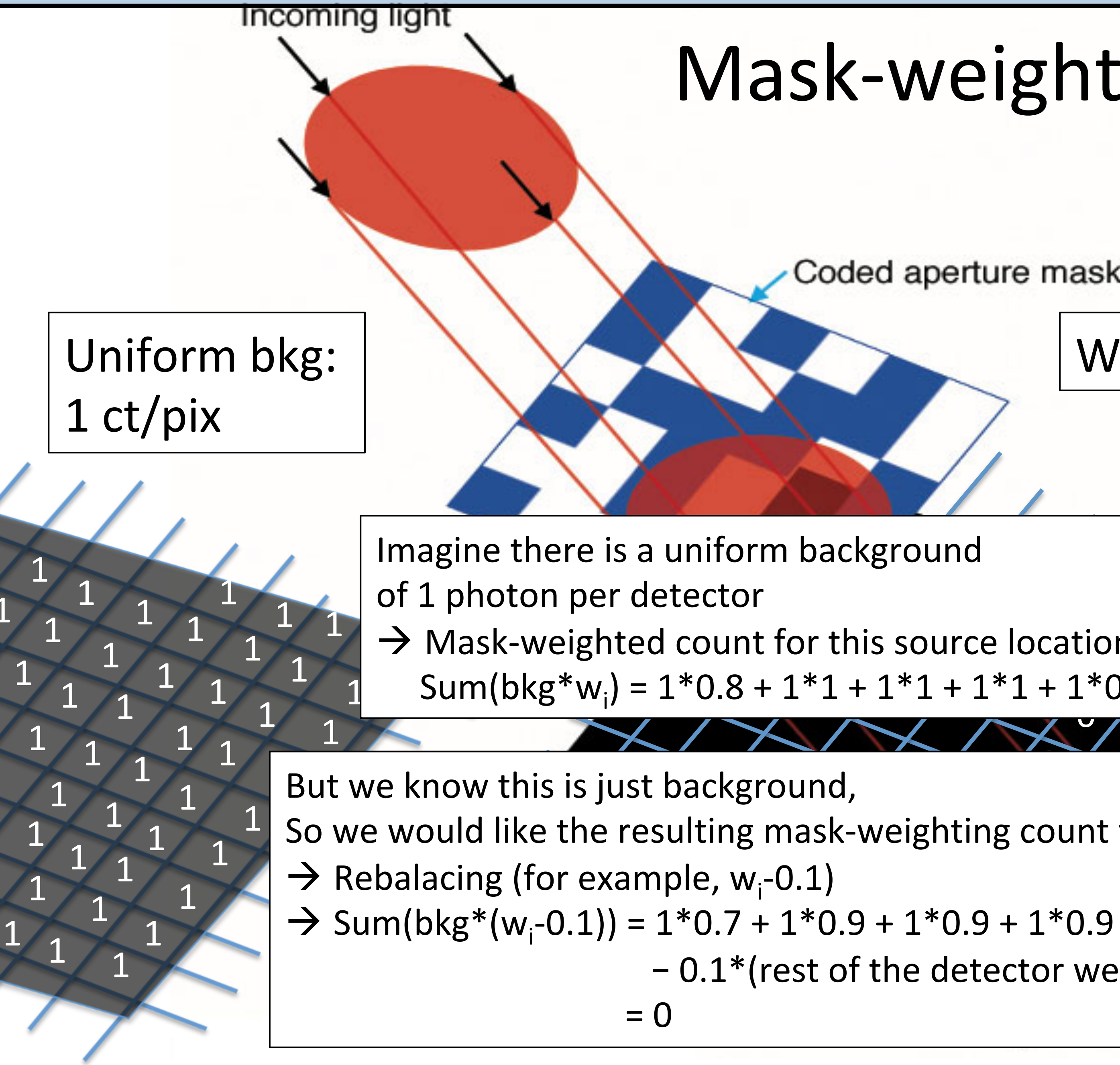
Weight (w_i)

Imagine there is a uniform background of 1 photon per detector

→ Mask-weighted count for this source location:
$\text{Sum}(\text{bkg}*w_i) = 1*0.8 + 1*1 + 1*1 + 1*1 + 1*0.6 + 1*0.5 + 1*0.9 = 5.8$

Credit: NASA's Imagine the Universe and NASA/Swift

Mask-weighting analysis



Uniform bkg:
1 ct/pix

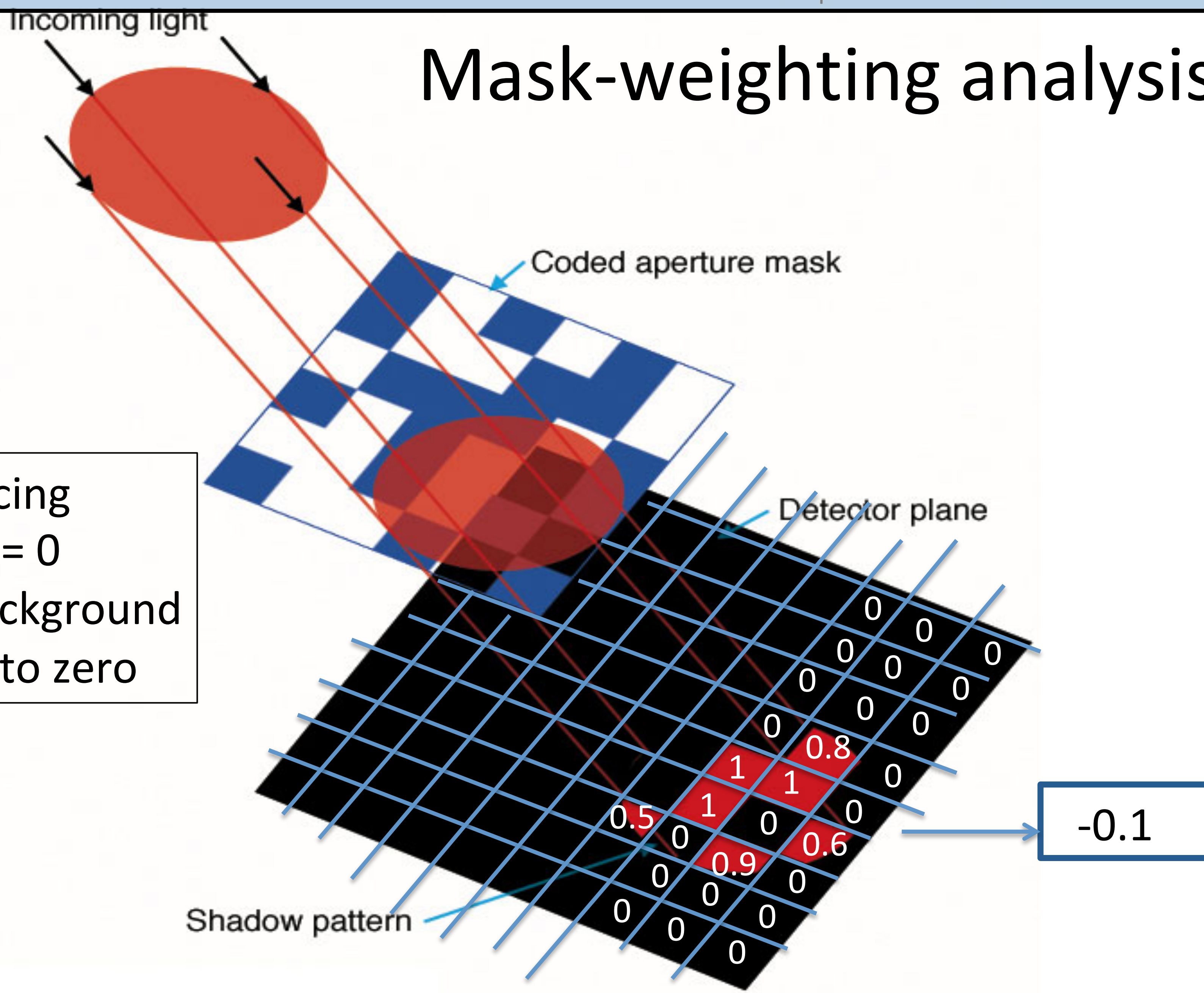
Weight (w_i)

Imagine there is a uniform background
of 1 photon per detector
→ Mask-weighted count for this source location:
Sum(bkg*w_i) = 1*0.8 + 1*1 + 1*1 + 1*1 + 1*0.6 + 1*0.5 + 1*0.9 = 5.8

But we know this is just background,
So we would like the resulting mask-weighting count to be zero
→ Rebalacing (for example, w_i-0.1)
→ Sum(bkg*(w_i-0.1)) = 1*0.7 + 1*0.9 + 1*0.9 + 1*0.9 + 1*0.5 + 1*0.4 + 1*0.8
− 0.1*(rest of the detector weights)
= 0

Credit: NASA's Imagine the Universe and NASA/Swift

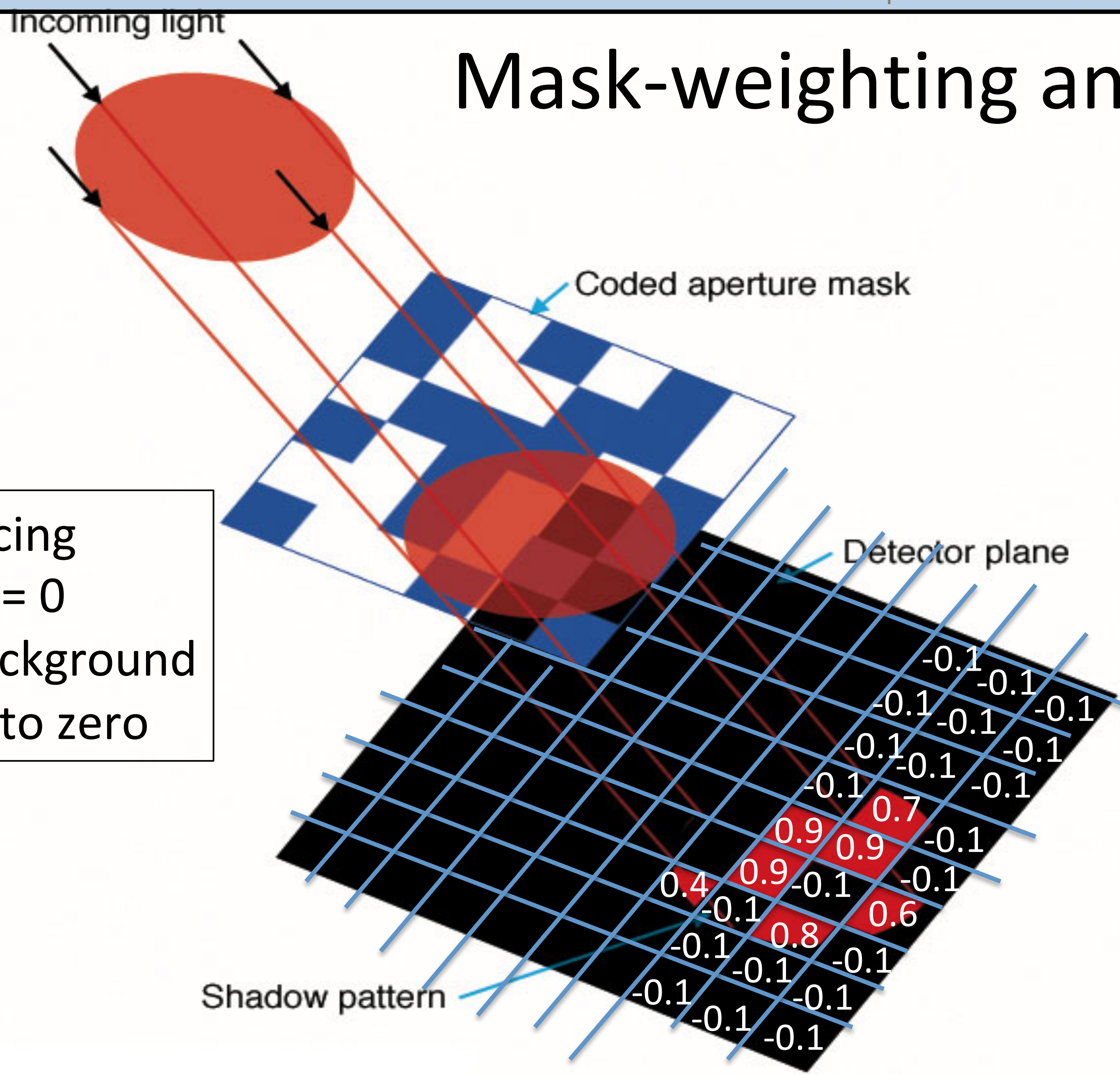
Mask-weighting analysis



Rebalancing
Sum(w_i) = 0
→ So background average to zero

Credit: NASA's Imagine the Universe and NASA/Swift

Mask-weighting analysis



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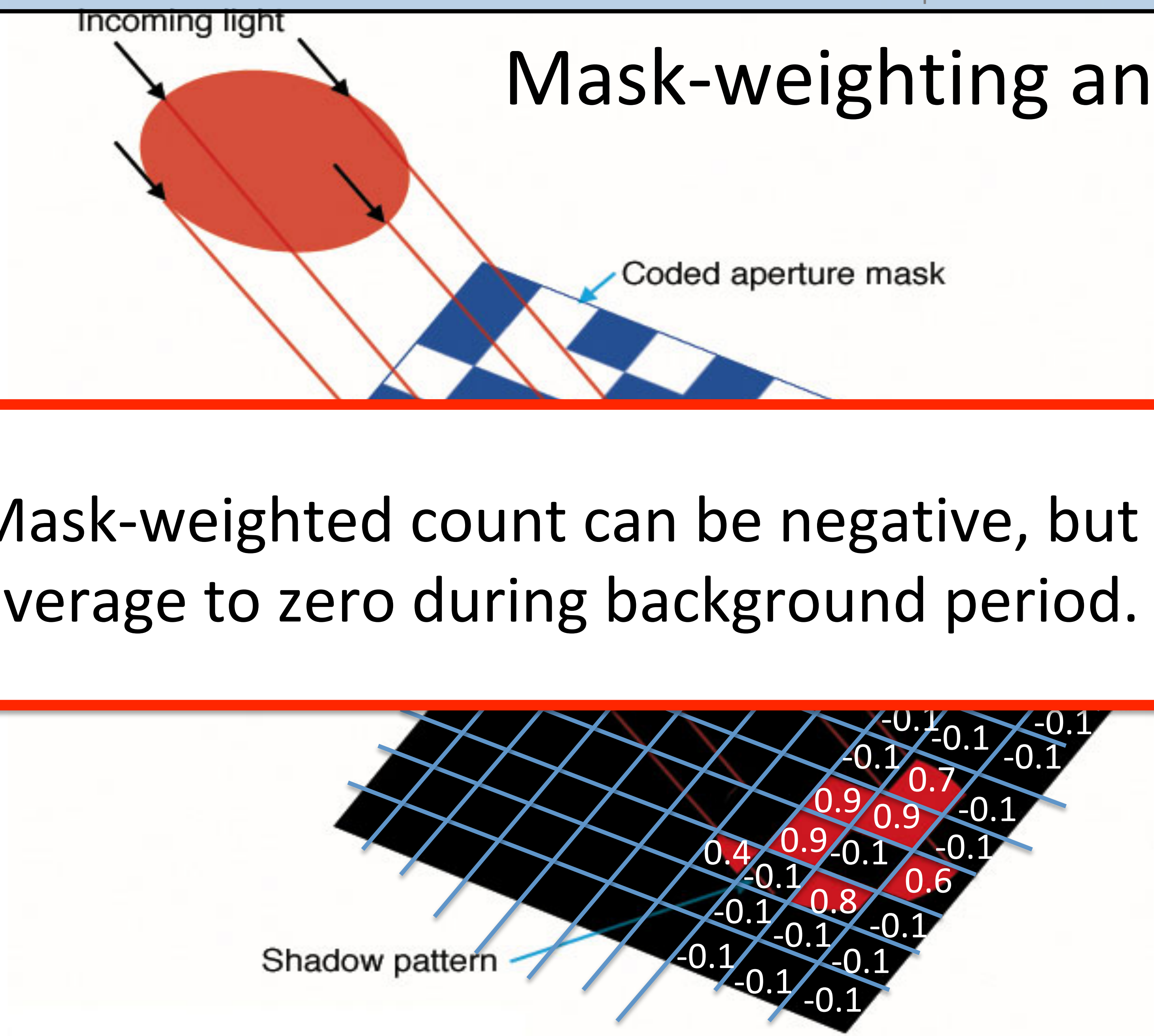
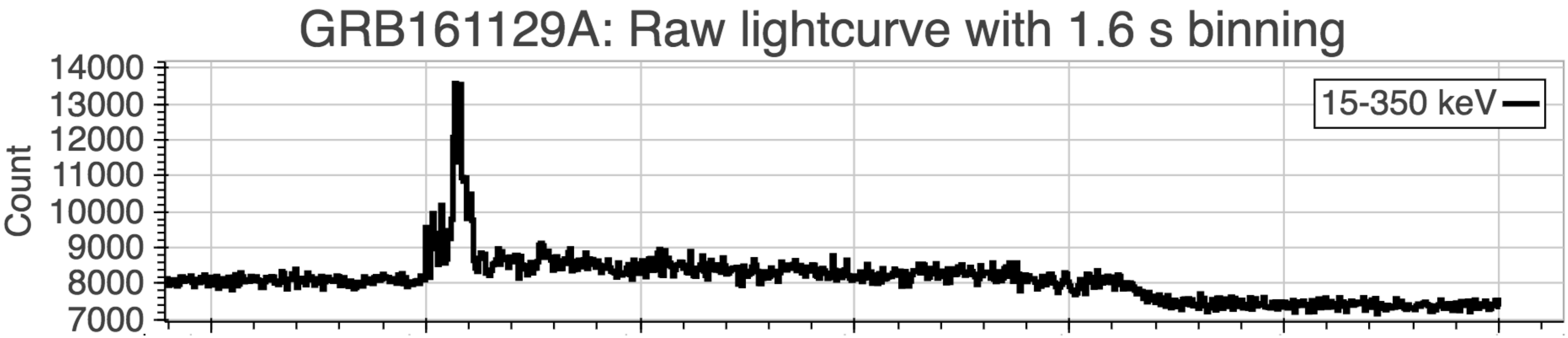
Mask-weighting analysis

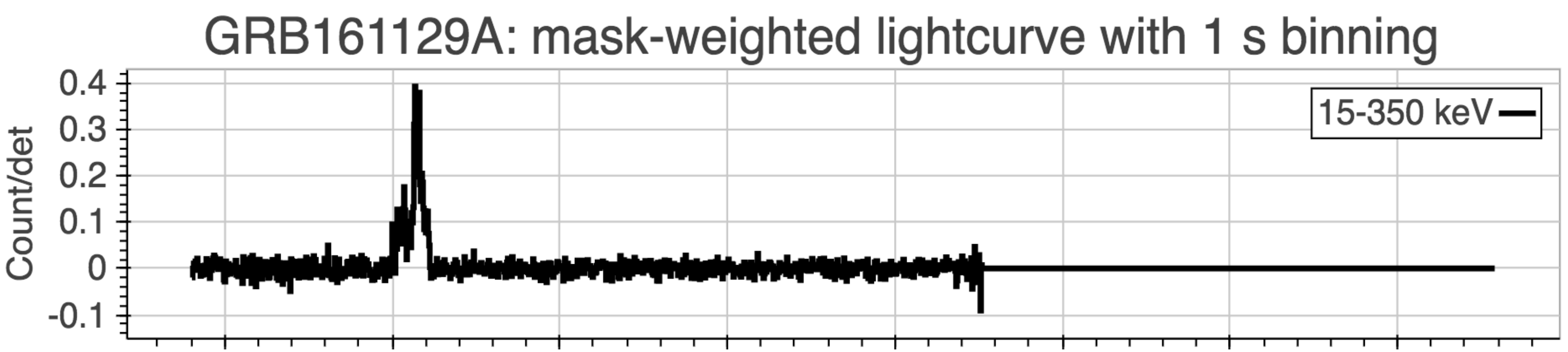


Mask-weighted count can be negative, but will average to zero during background period.

Credit: NASA's Imagine the Universe and NASA/Swift

Mask-weighted light curve





Mask-weighted light curve

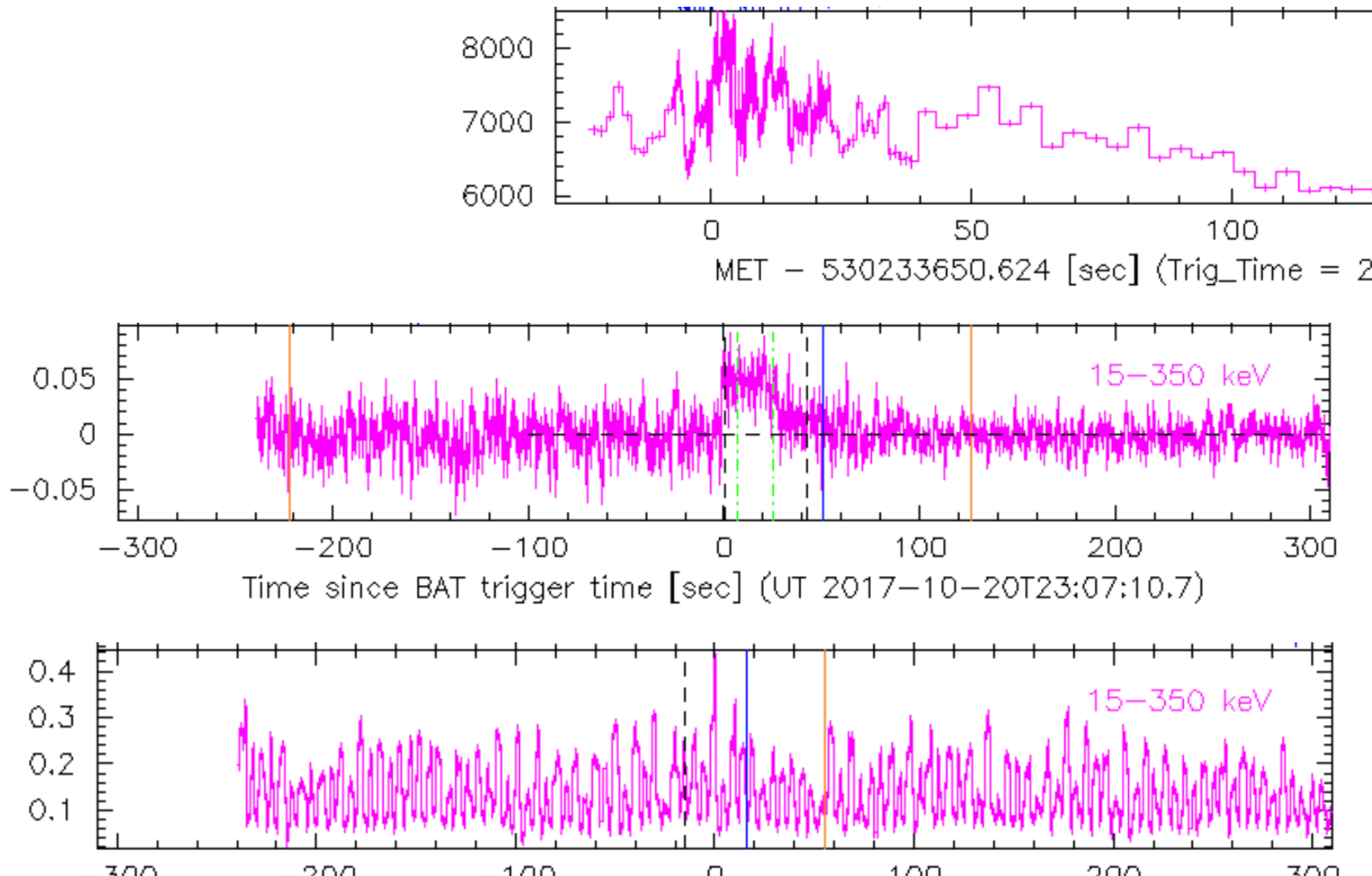
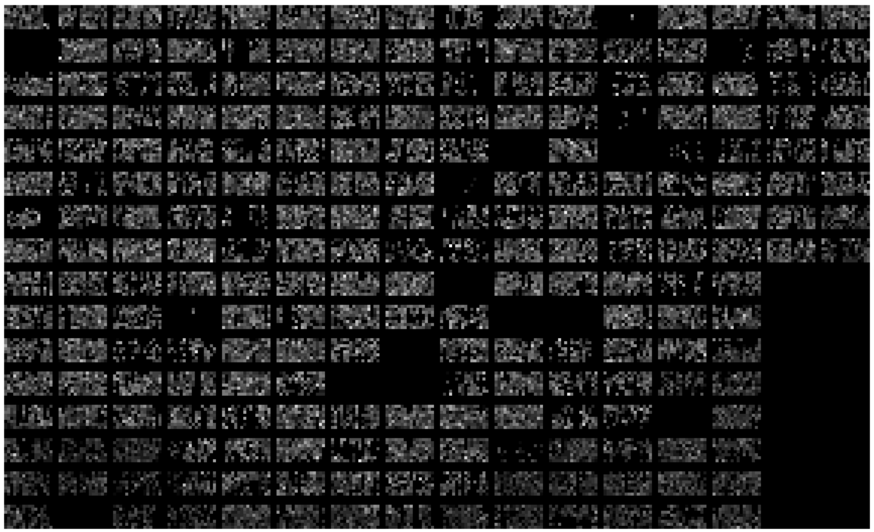
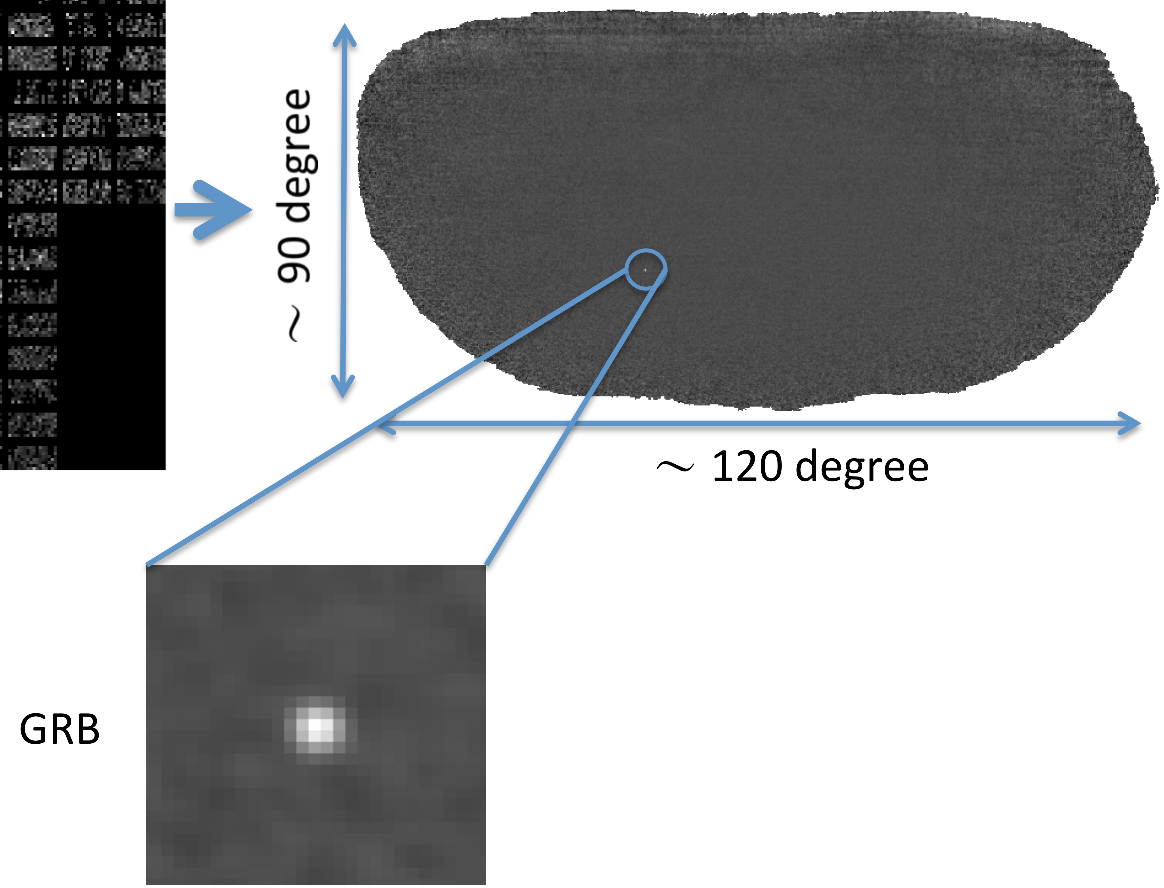


Image reconstruction

Detector Plane Image

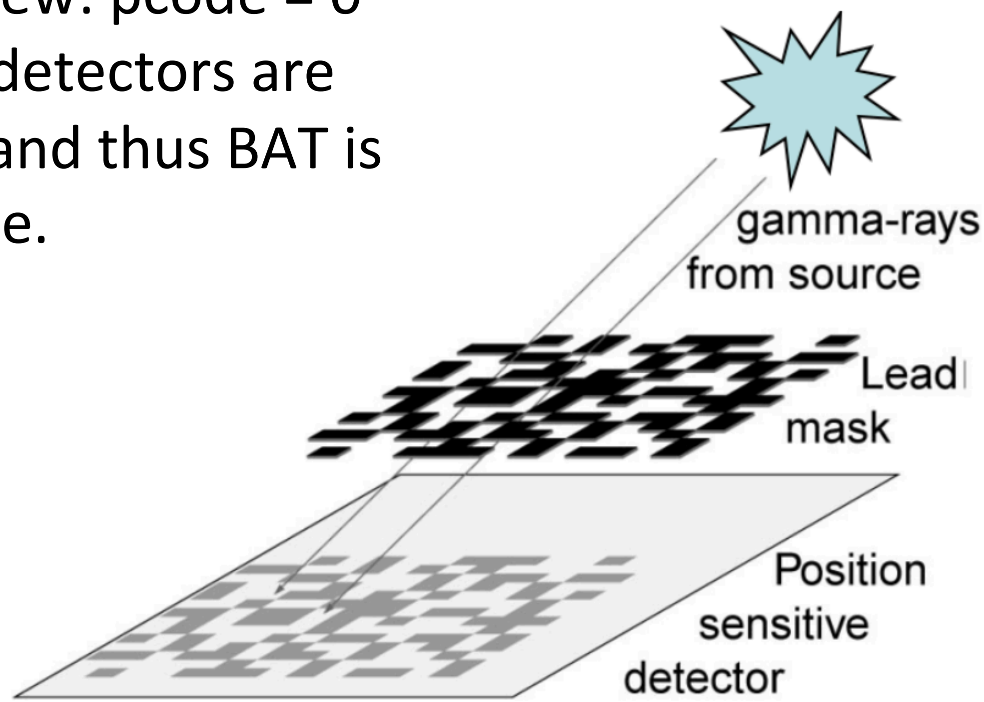


Reconstructed Sky Image

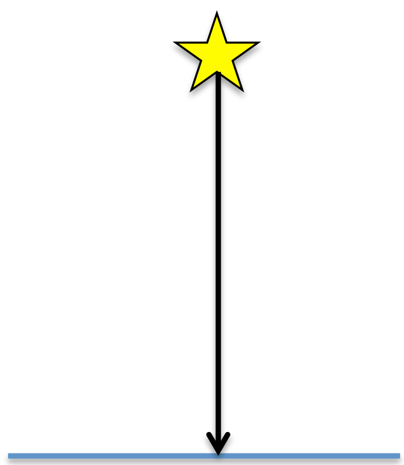


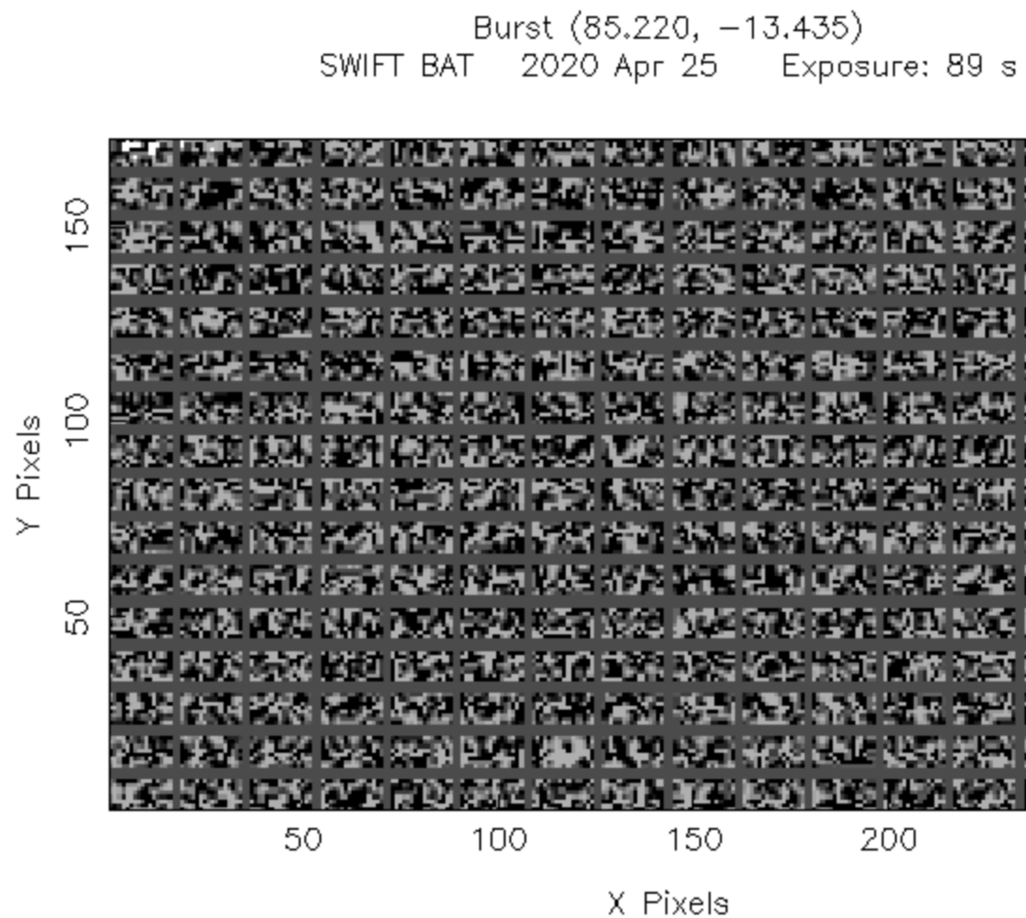
Partial coding fraction

- Fraction of illuminated area
- Source comes in from the zenith (0 deg boresight angle): pcode = 1
- Source out of the field of view: pcode = 0
- Larger pcode means more detectors are illuminated by the source, and thus BAT is more sensitive to the source.



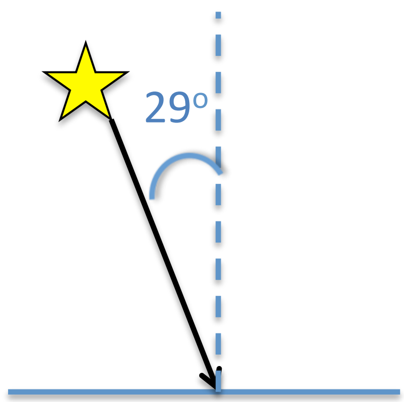
Partial coding fraction



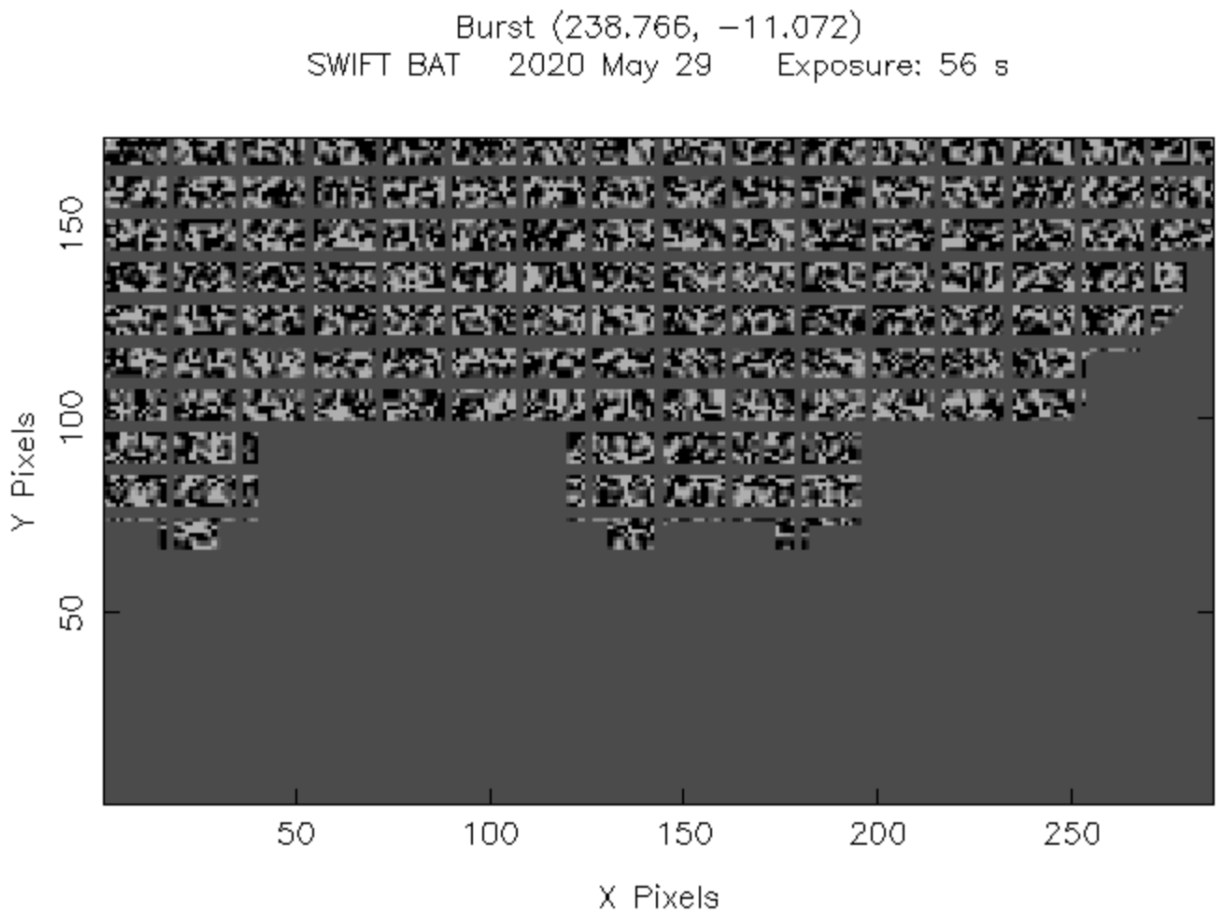


pcode = 1
theta = 0 deg

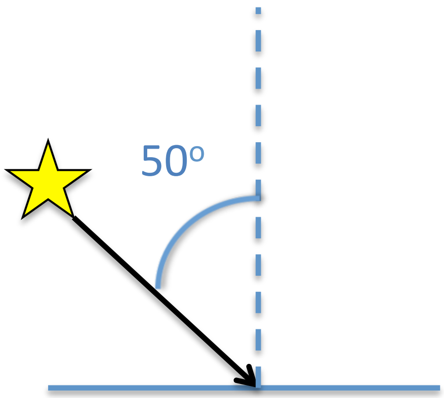
Partial coding fraction



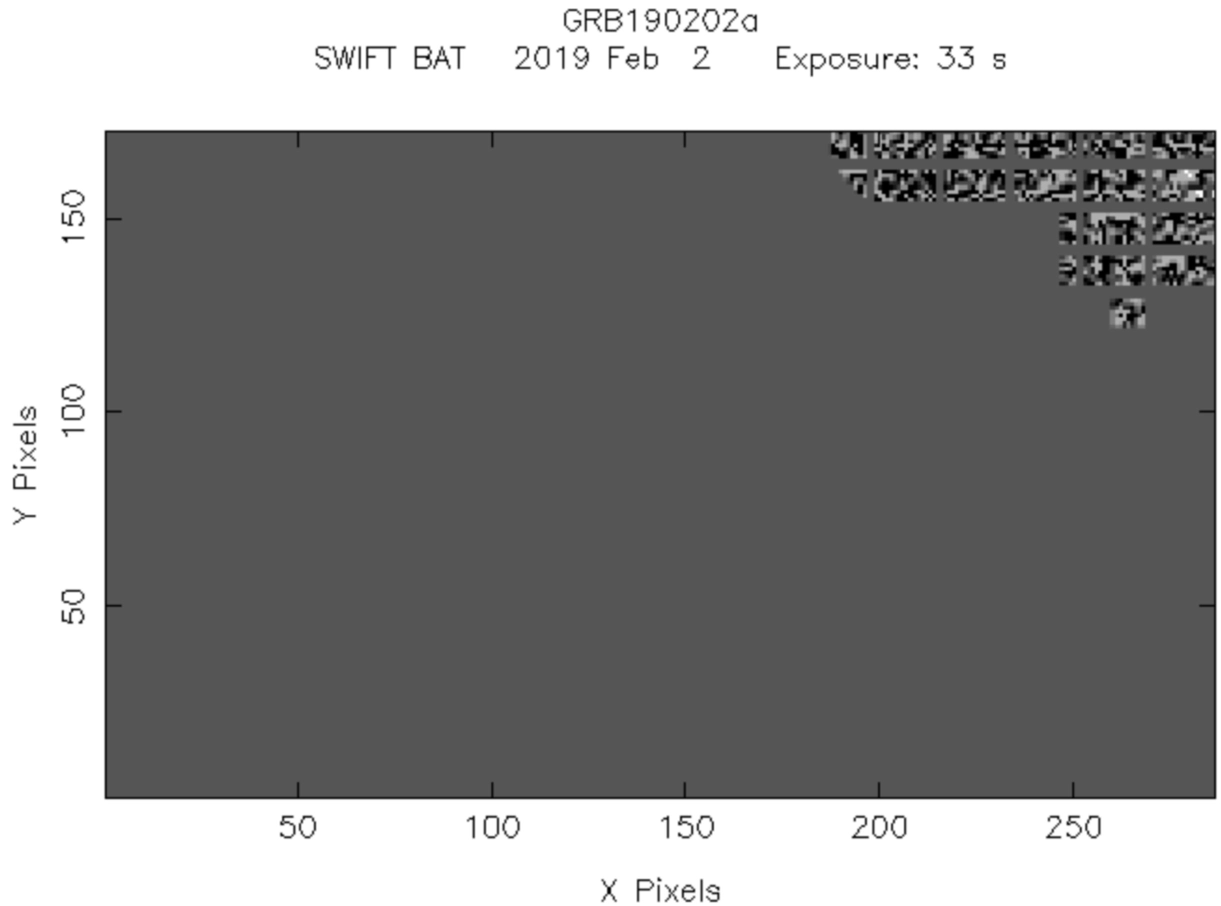
pcode = 0.5
theta = 29 deg



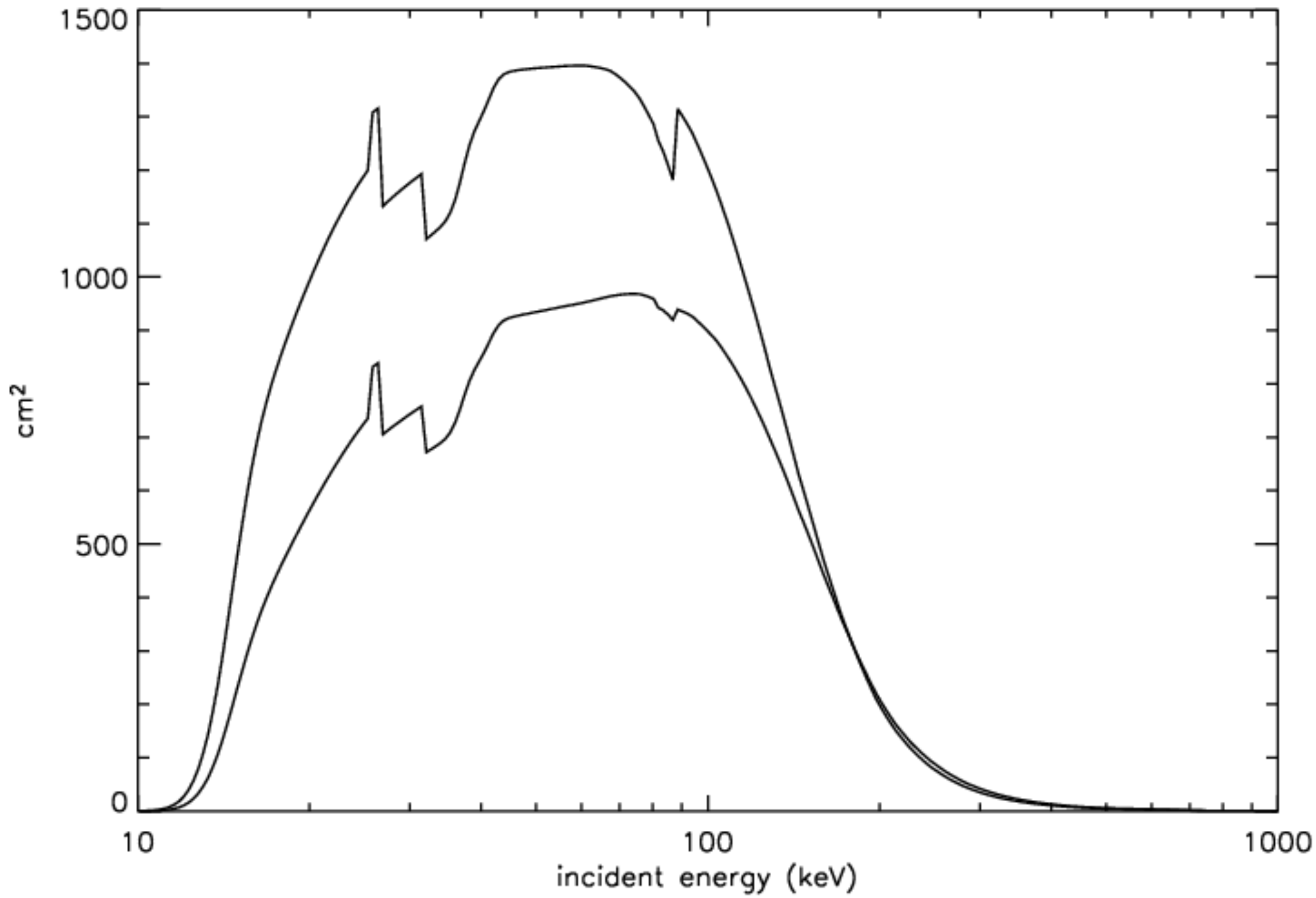
Partial coding fraction



pcode = 0.04
theta = 50 deg

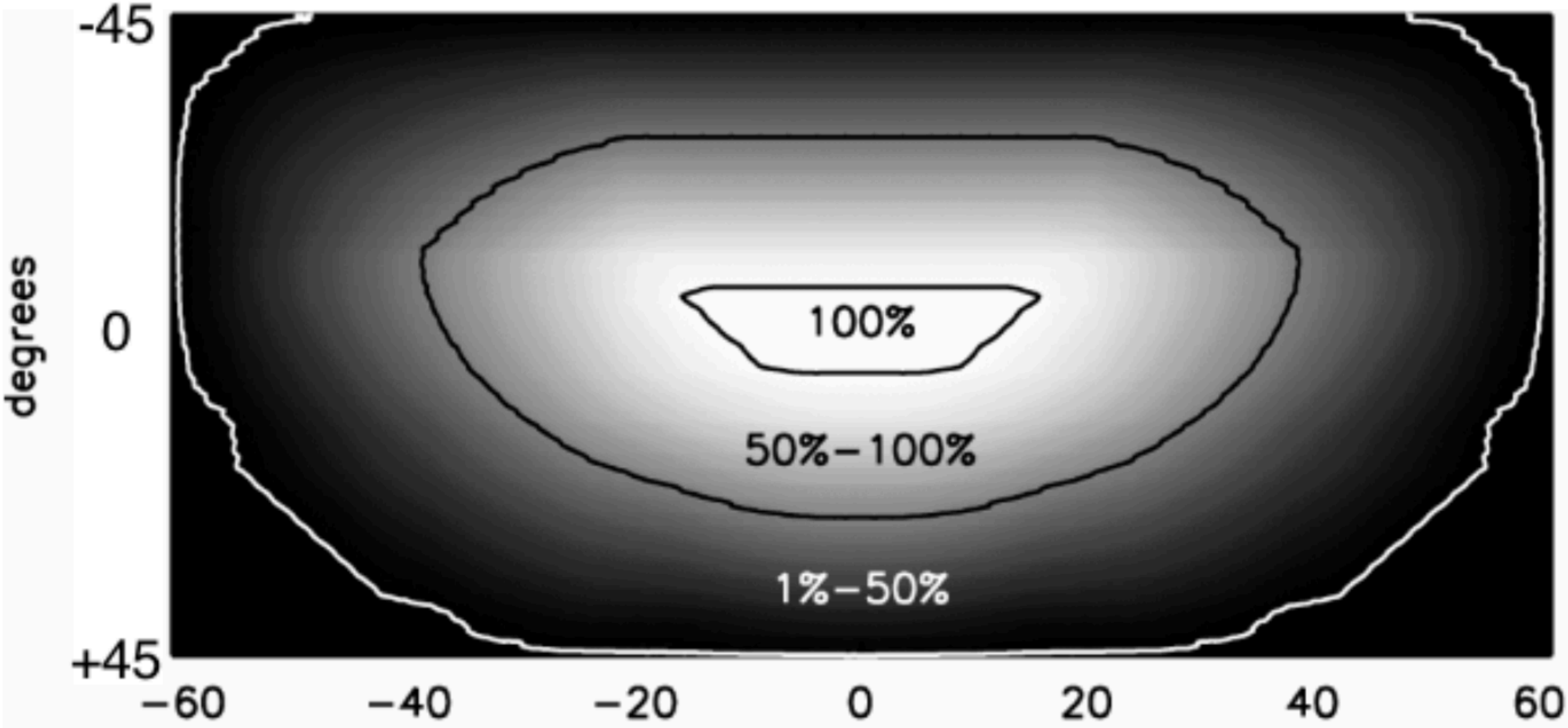


Partial coding fraction
vs
BAT effective area

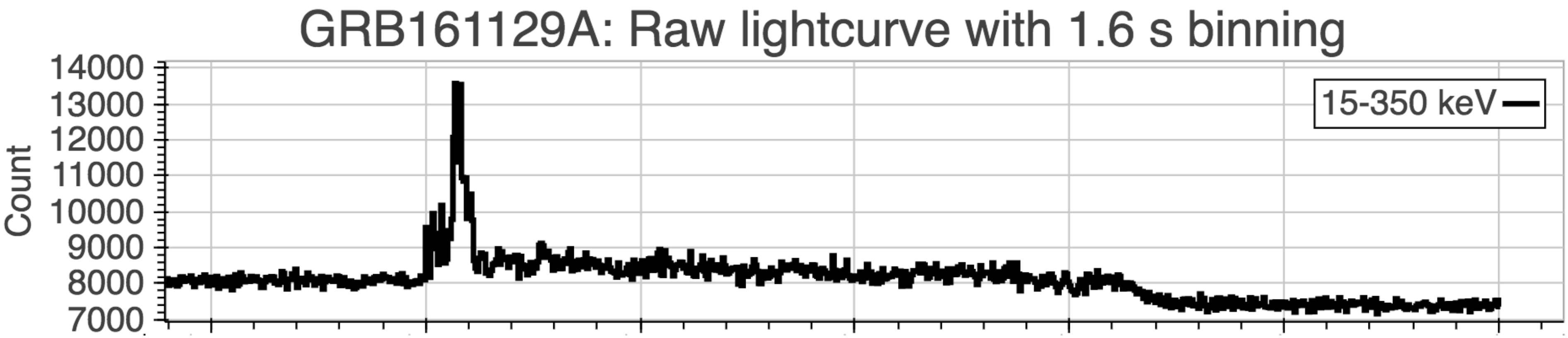


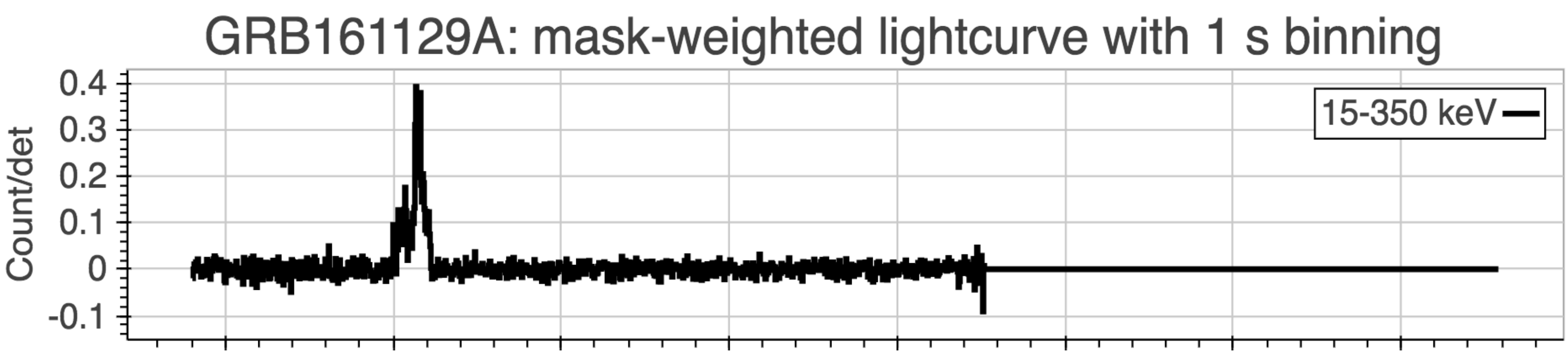
Ref: https://swift.gsfc.nasa.gov/analysis/bat_digest.html

Partial coding fraction vs BAT field of view



Mask-weighted count





Mask-weighted count

- Definition:

  Background subtracted counts

  per fully illuminated detector

  for an equivalent on-axis source

Ref: https://swift.gsfc.nasa.gov/analysis/threads/batfluxunitsthread.html

Mask-weighted count

- Definition:

Background subtracted counts

per fully illuminated detector

for an equivalent on-axis source

Illuminated detector ~ # of enabled detector x pcode

Ref: https://swift.gsfc.nasa.gov/analysis/threads/batfluxunitsthread.html

Mask-weighted count

- Definition:

  Background subtracted counts

  per fully illuminated detector

  for an equivalent on-axis source

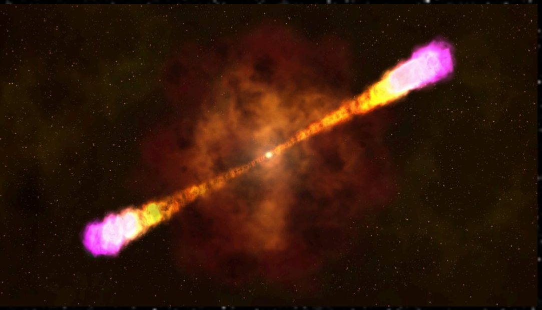
  → cos(θ) effect

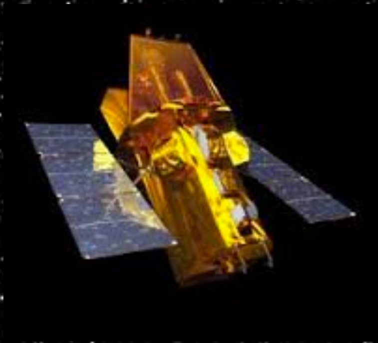
Ref: https://swift.gsfc.nasa.gov/analysis/threads/batfluxunitsthread.html

Summery of coded mask instrument

- Pros:
  - Large field of view
  - Decent localization for hard X ray
  - Decent background estimation
- Cons:
  - Reduced sensitivity for the same number of detectors (mask covers > half of the detectors)
  - Challenging to deal with diffuse sources
  - All sources in the field of view will contribute to the noise
- Sensitivity depends on the partial coding fraction

Exploring the Universe with BAT





BAT data type

DATA type	Description	Energy range	Can generate Image?	Time bin	Continuous?
Event data	Complete info of each photon	All	✔	Customizable (> 100 us)	✗
Survey data	Pre-binned detector plane image	80 channels (14-195 keV)	✔	~ 300 s	✔ (except during SAA and slew)
Scaled map data	Detector plane scaled map for image triggers	15-50 keV	✔	~ 8 s	✔ (except during SAA and slew)
Rate data	Raw (not background subtracted) light curves	4 channels (15-25, 25-50, 50-100,100-350 keV)	✗	64 ms, 1 s, 1.6 s	✔

For more info, see Markwardt et al. (2007)

BAT public products

- BAT GRB catalog (event data)
  - https://swift.gsfc.nasa.gov/results/batgrbcat/
- BAT transient monitor (scaled map data)
  - https://swift.gsfc.nasa.gov/results/transients/
- BAT survey catalog (survey data)
  - https://swift.gsfc.nasa.gov/results/bs105mon/

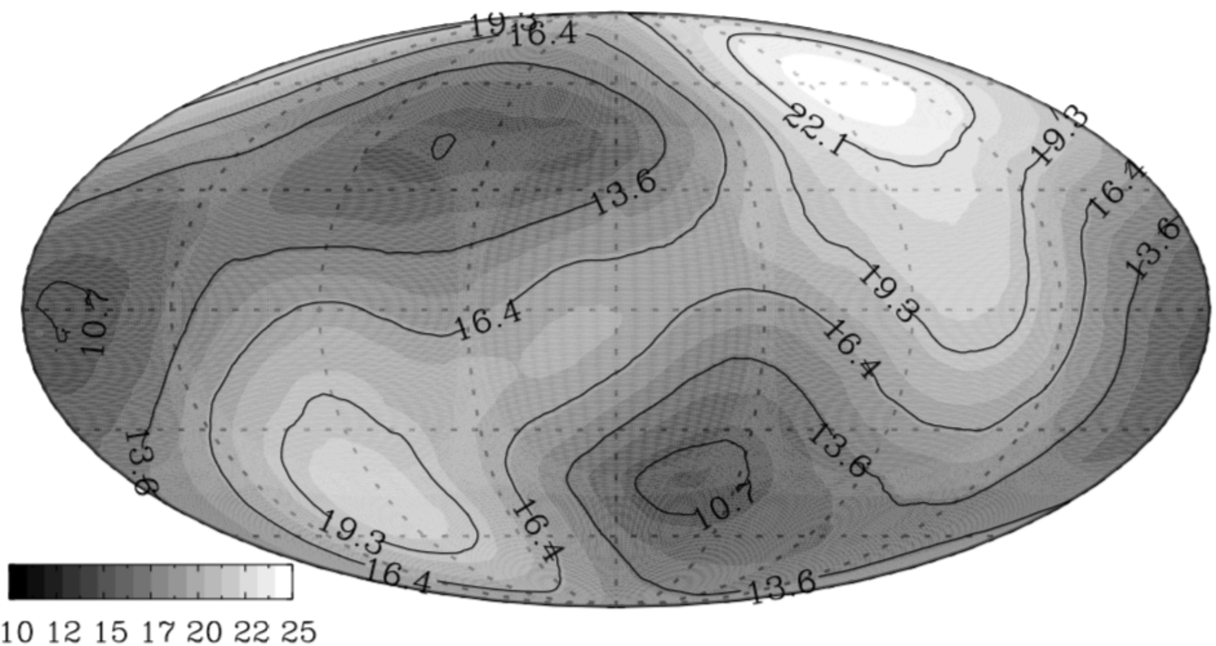
BAT transient monitor

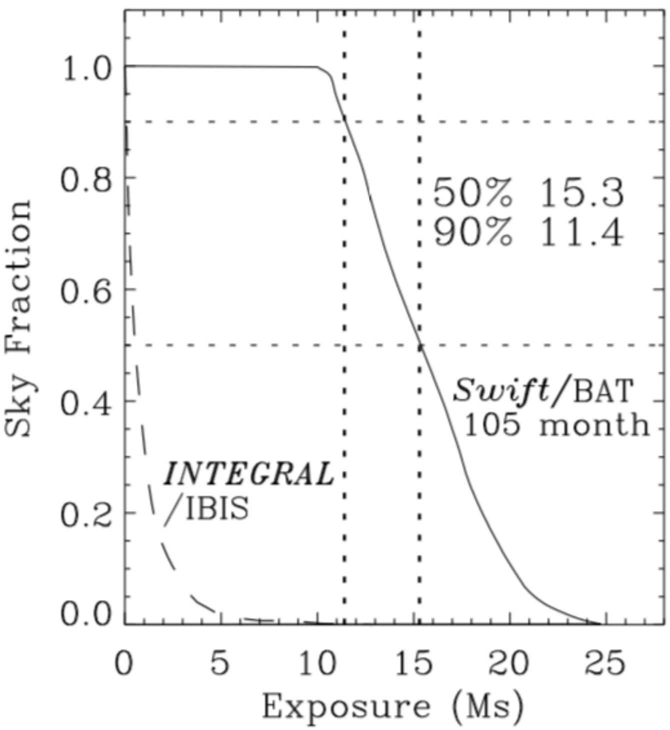
- Krimm et al. (2013)
- Product made from scaled map data
- https://swift.gsfc.nasa.gov/results/transients/
- Energy range: 15-50 keV
- Monitoring > 1000 sources
  - daily light curves
  - orbital light curves (time bins of ~ 64 second up to a couple thousand second).
- Updated every few hours
- If you'd like to add your favorite source to the monitoring list, send me an email!

BAT survey catalogs

- Product made from BAT survey data
  - Source detections on mosaic images
- Existing BAT survey catalog
  - 3-month (Markwardt et al. 2005)
  - 22-month (Tueller et al. 2008)
  - 70-month (Baumgartner et al. 2013)
  - 105-month (Oh et al. 2018)
  - Upcoming: 157-month (Lien et al. 2021 in prep)
  - Other BAT survey catalogs:
    (using different analysis process)
    - The Palermo Swift-BAT Hard X-ray Catalogs
      - 39-month, 54-month, (Cusumano et al. 2010)
    - 60-month (Ajello et al., 2012)
    - 3-year (Burlon & Ajello et al. 2011)

BAT survey exposure time

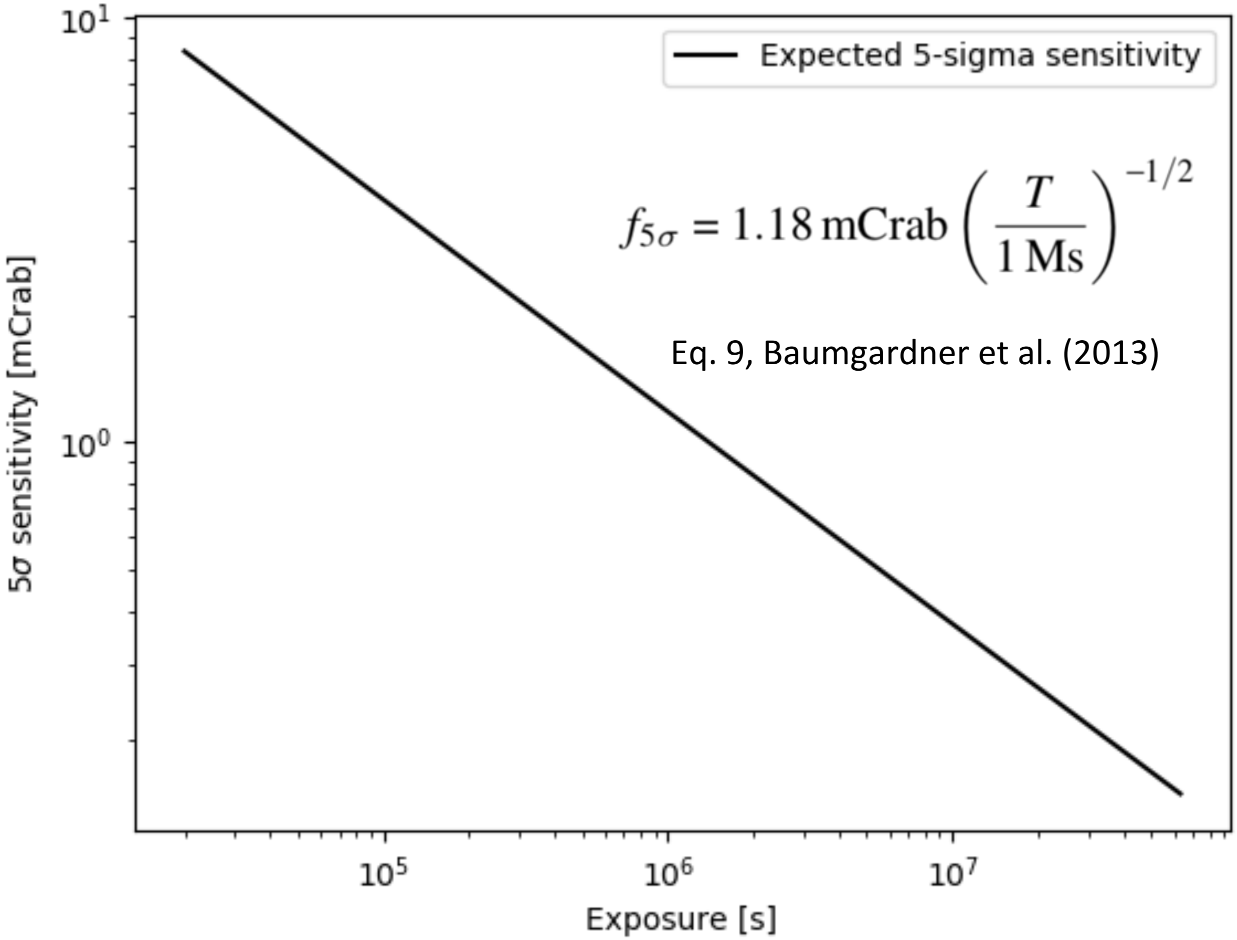




Oh et al. (2018)

BAT sensitivity

1 mCrab = 2.42 x 10^{-11} erg/s/cm^2



2.42 x 10^{-10}

9.86 x 10^{-11}

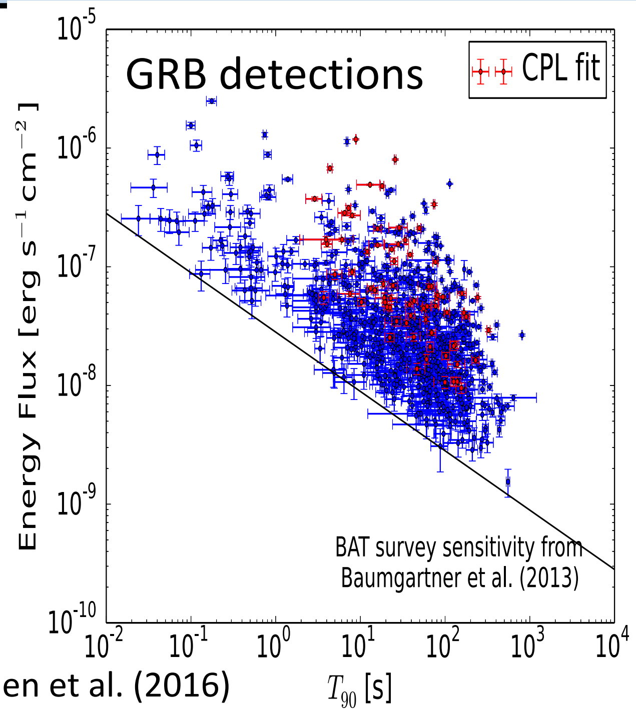
2.42 x 10^{-11}

9.86 x 10^{-12}

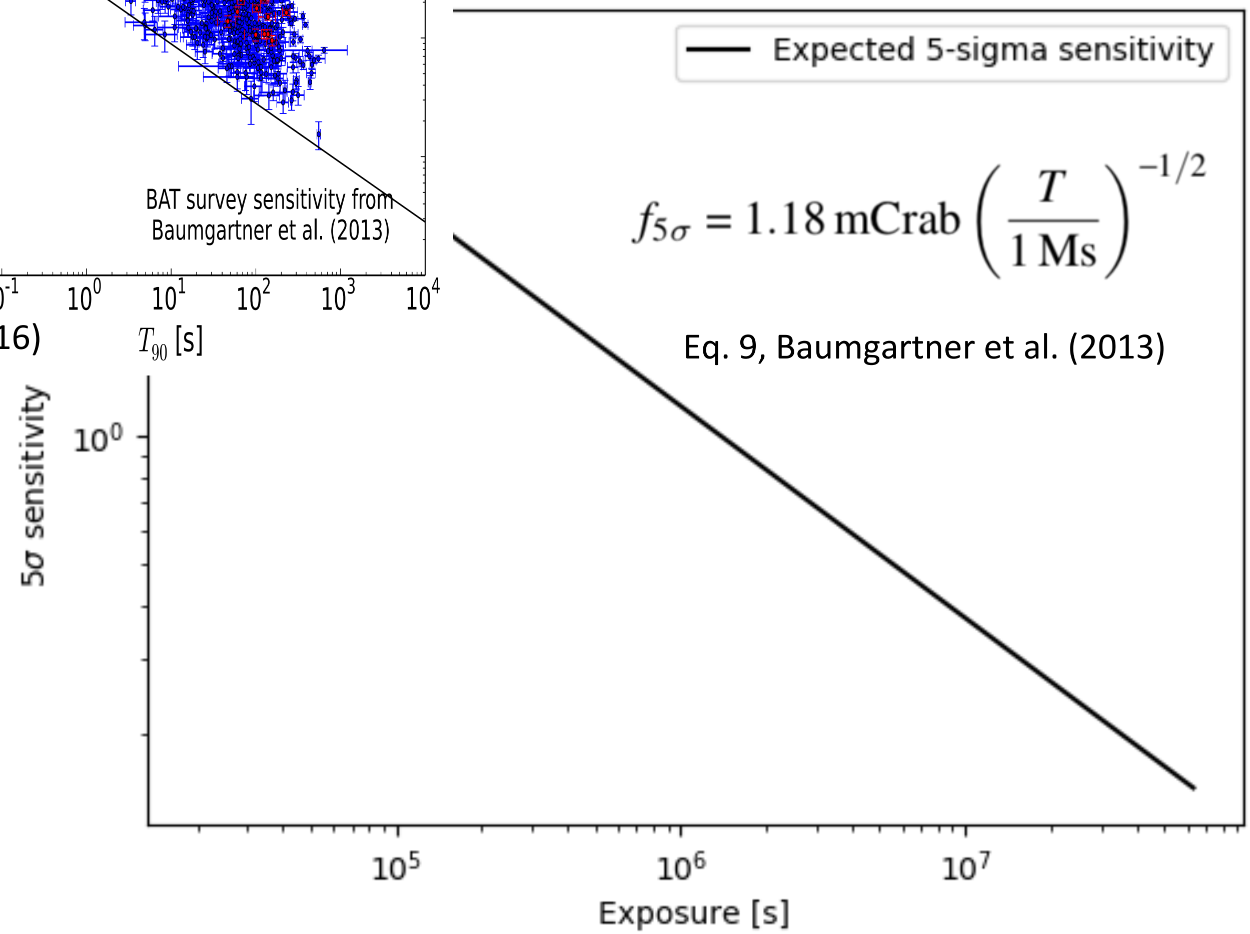
2.42 x 10^{-12}

T sensitivity

rab = 2.42 x 10^{-11} erg/s/cm^2



Lien et al. (2016)



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9.86 x 10^{-11}

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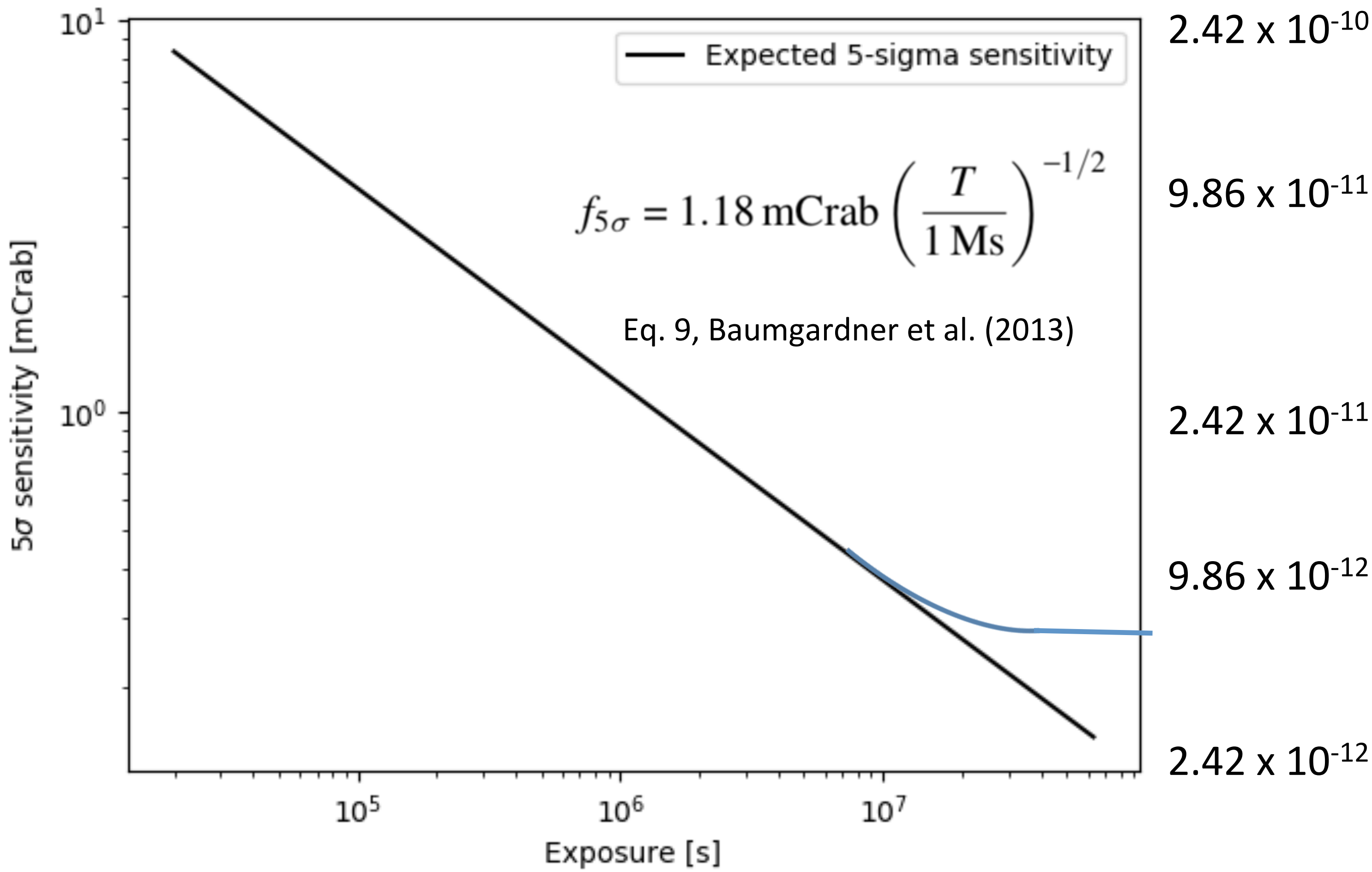
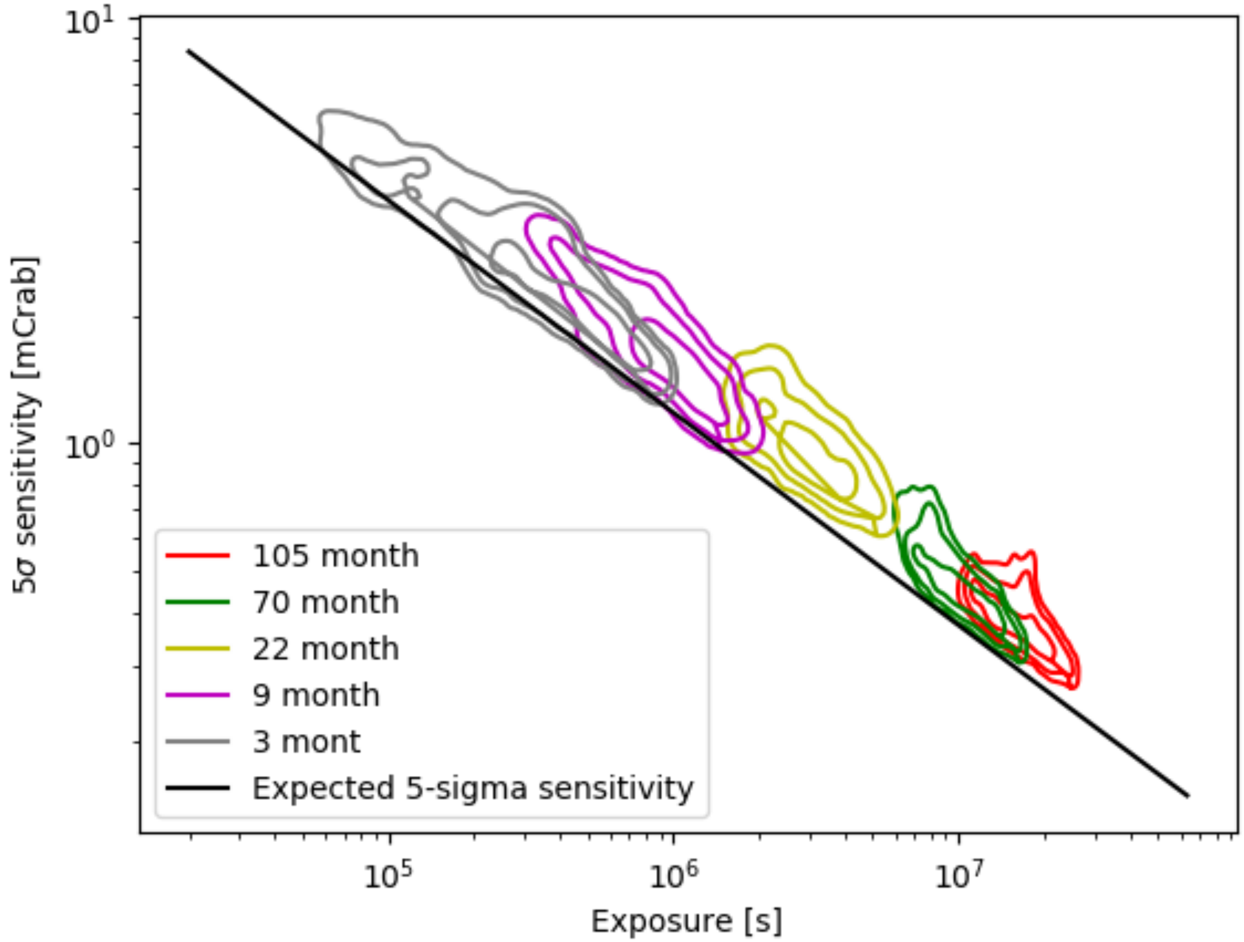


BAT survey catalogs

1 mCrab = 2.42 x 10^{-11} erg/s/cm^2



2.42 x 10^{-10}

9.86 x 10^{-11}

2.42 x 10^{-11}

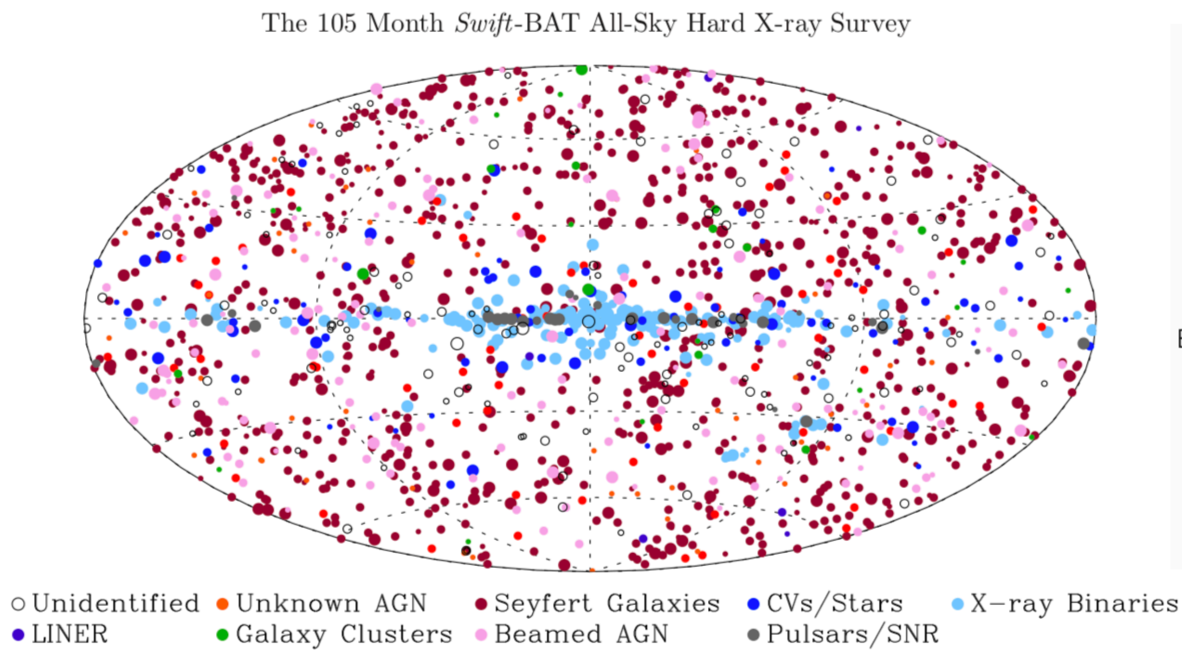
9.86 x 10^{-12}

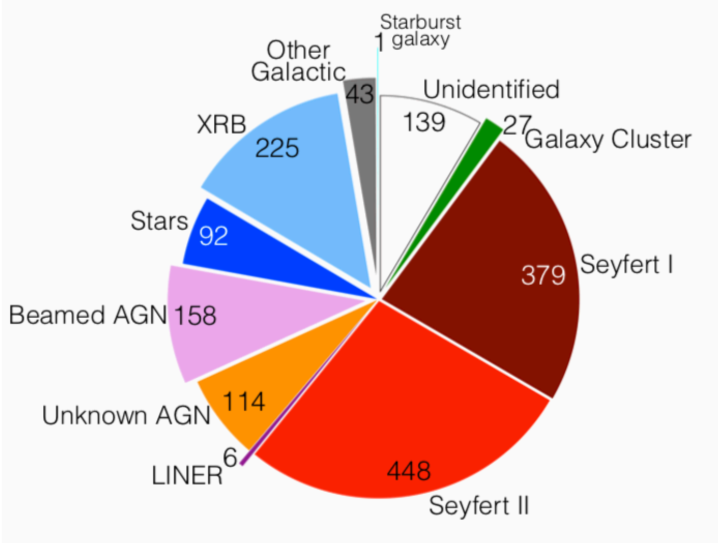
2.42 x 10^{-12}

Markwardt et al. (2005); Tueller et al. (2008); Tueller et al. (2010); Baumgartner et al. (2013); Oh et al. (2018)

BAT survey catalogs

105 month



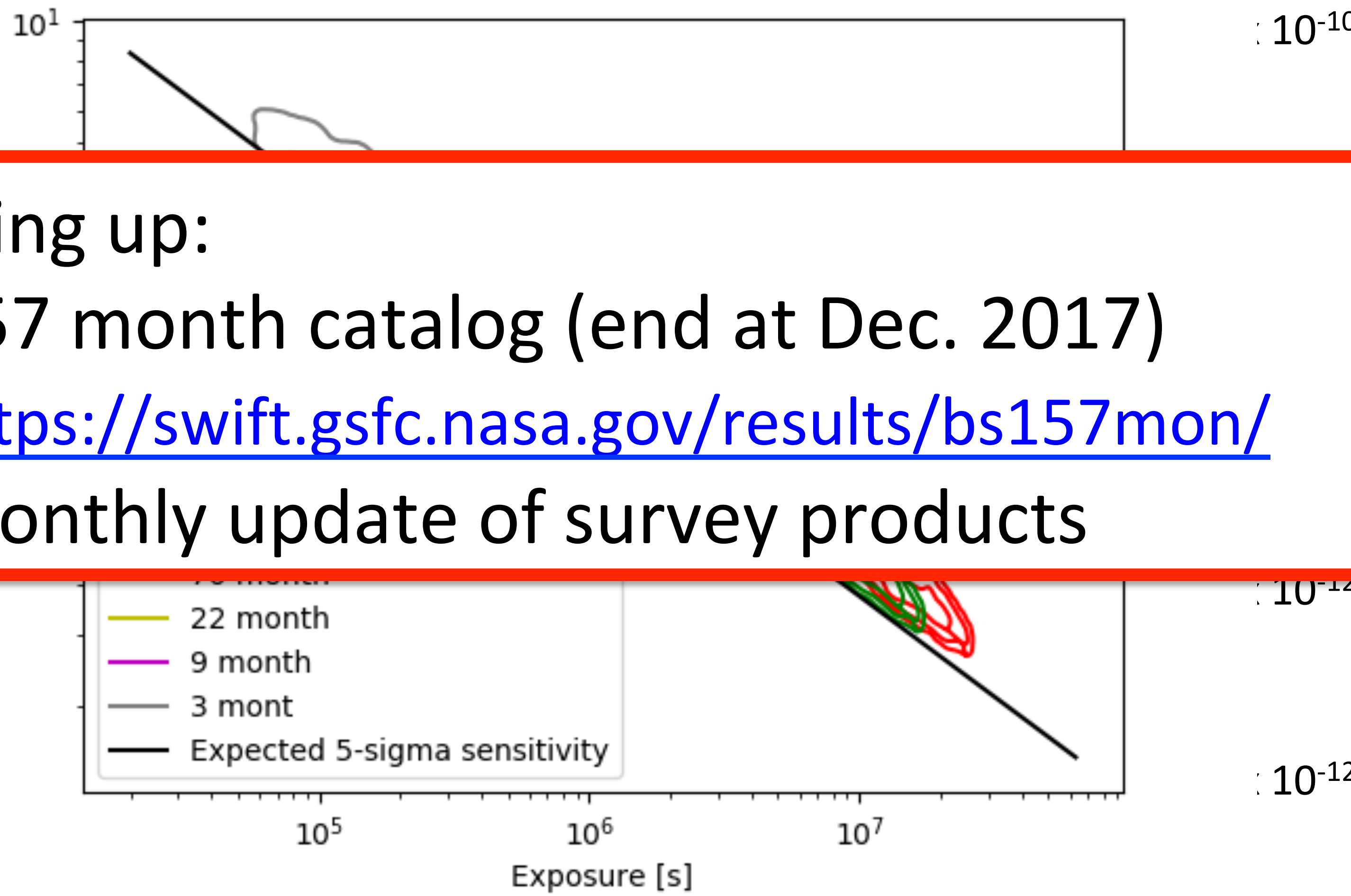


Oh et al. (2018)

Product at: https://swift.gsfc.nasa.gov/results/bs105mon/

- From Dec. 2004 to Aug. 2013.
- Monthly light curves, spectra…etc.

BAT survey catalogs



Coming up:

- 157 month catalog (end at Dec. 2017)
  https://swift.gsfc.nasa.gov/results/bs157mon/
- Monthly update of survey products

Markwardt et al. (2005); Tueller et al. (2008); Tueller et al. (2010); Baumgartner et al. (2013); Oh et al. (2018)

BAT survey catalogs

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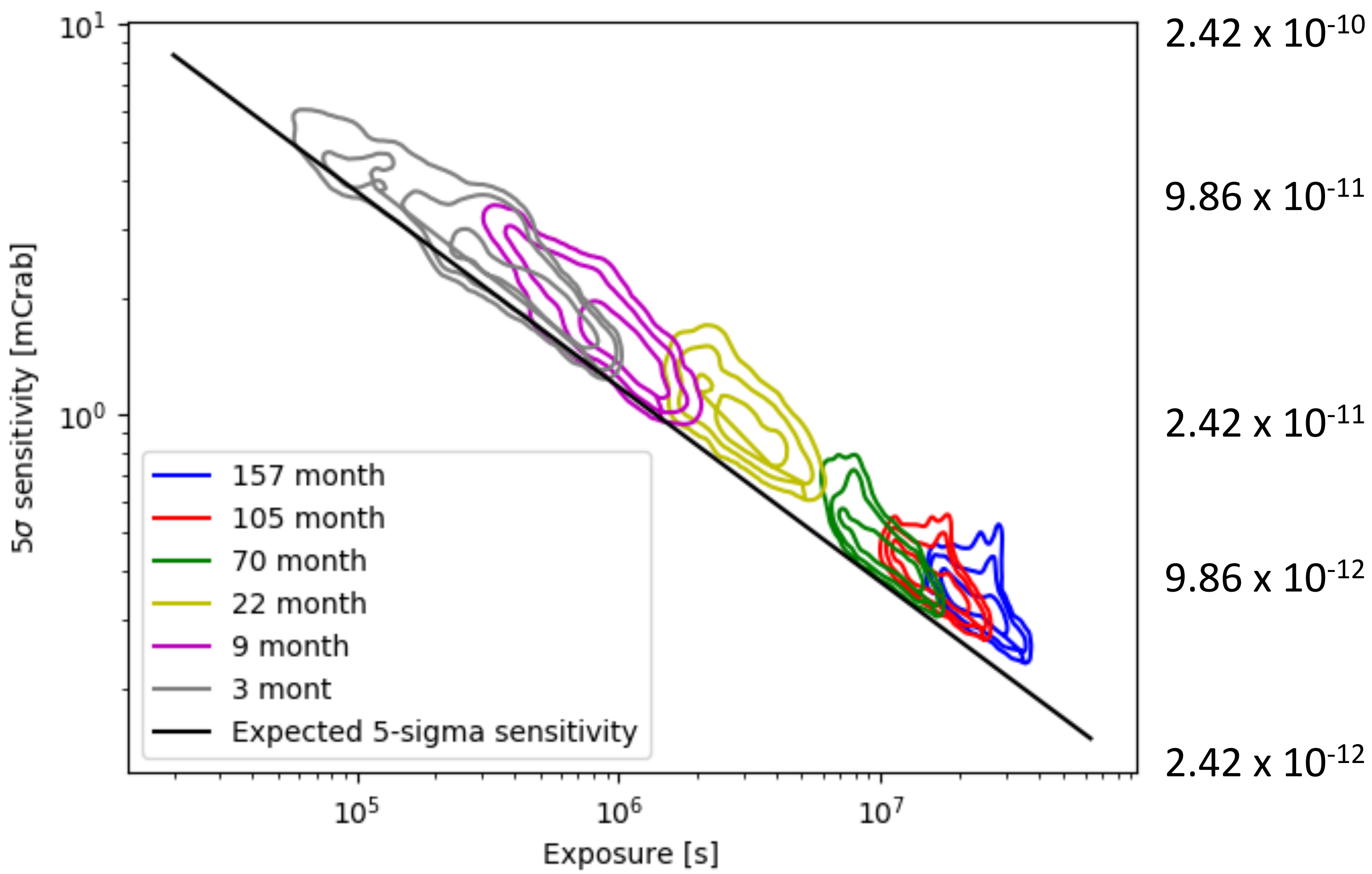


Markwardt et al. (2005); Tueller et al. (2008); Tueller et al. (2010); Baumgartner et al. (2013); Oh et al. (2018)

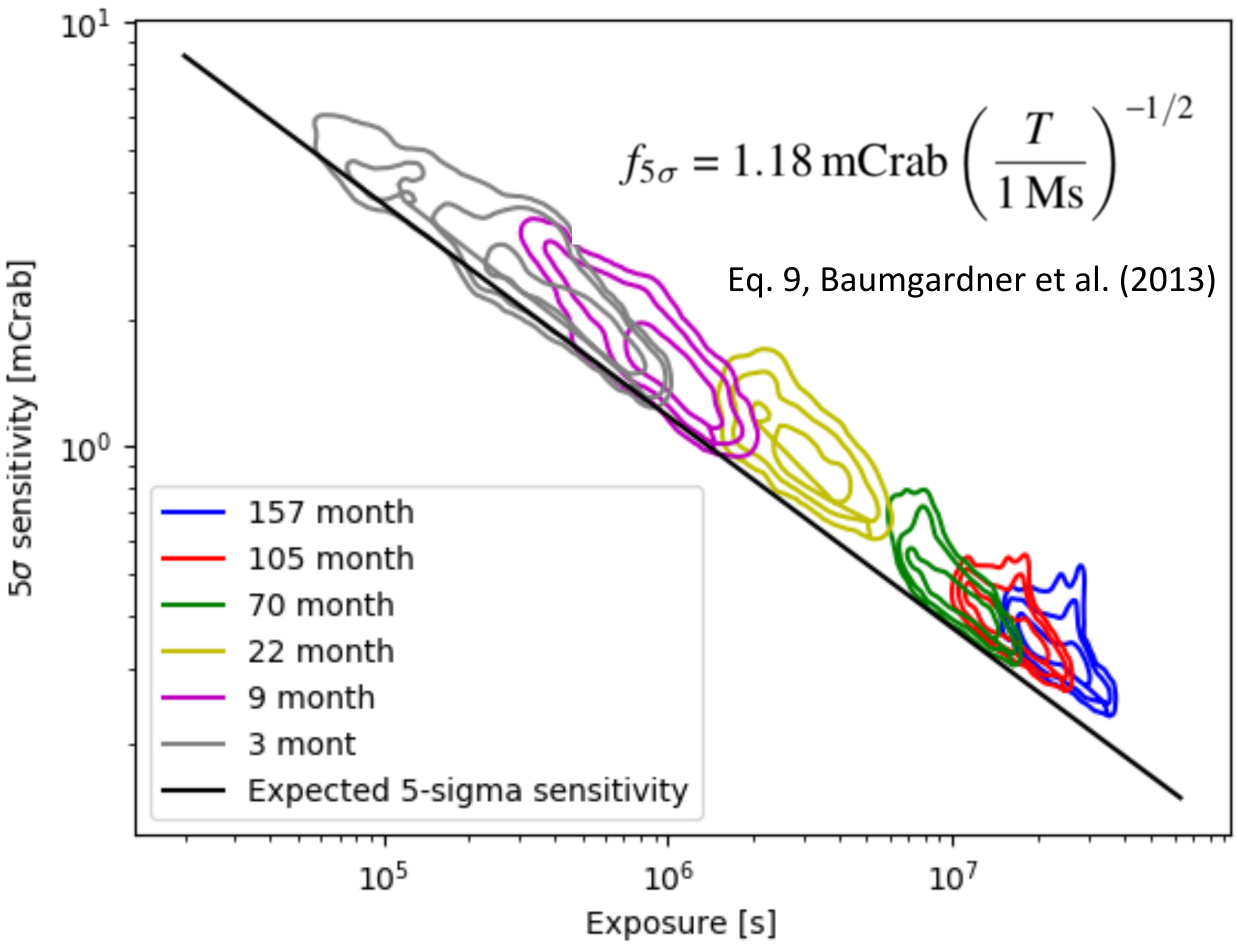
What if your favorite source is not in the public catalogs?

- (Send me an email)
- Do your own search
  - All Swift data are available on HEASARC:

    https://heasarc.gsfc.nasa.gov/cgi-bin/W3Browse/swift.pl

Will your sources be detected in BAT?

1 mCrab = 2.42 x 10^{-11} erg/s/cm^2



2.42 x 10^{-10}

9.86 x 10^{-11}

2.42 x 10^{-11}

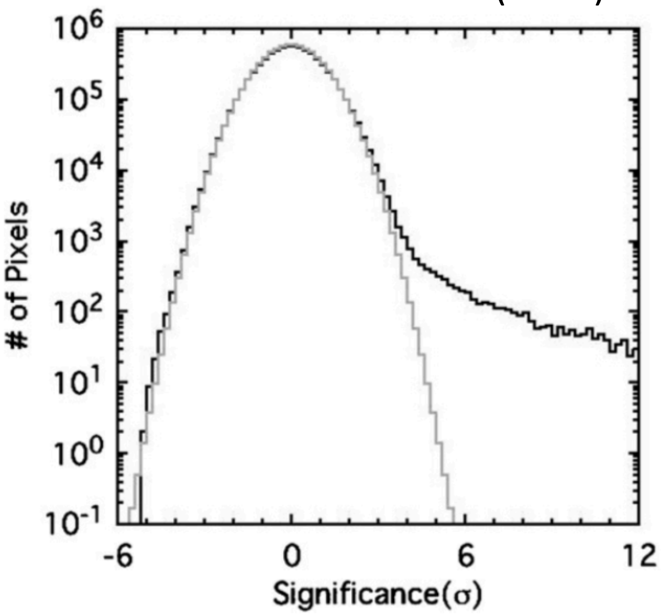
9.86 x 10^{-12}

2.42 x 10^{-12}

What is a real detection?

- What counts as a detection in BAT?
  - BAT onboard trigger algorithm: over 600 trigger criteria with different count rate threshold, ~ 7 sigma for image threshold.
  - BAT survey catalog: 4.8 sigma.
    - 1.54 false detections in the mosaic sky map of 1.99×10^6 pixels (Tueller et al. 2010).

Tueller et al. (2010)



What is a real detection?

BAT significance	false-detection rate		Number of false detection per image	
σ	Gaussian statistics	Actual data	Gaussian statistics	Actual data
$1.0 - 2.0$	1.36×10^{-1}	1.51×10^{-1}	18133	20133
$2.0 - 3.0$	2.14×10^{-2}	3.74×10^{-2}	2853	4987
$3.0 - 4.0$	1.32×10^{-3}	4.47×10^{-3}	176	596
$4.0 - 5.0$	3.14×10^{-5}	2.81×10^{-4}	4.19	37.47
$5.0 - 6.0$	2.86×10^{-7}	2.16×10^{-5}	0.038	2.88
$6.0 - 7.0$	9.85×10^{-10}	$\lesssim 2.40 \times 10^{-6}$	1.31×10^{-4}	0.32
$7.0 - 8.0$	1.28×10^{-12}	~ 0	1.71×10^{-7}	~ 0

What is a real detection?

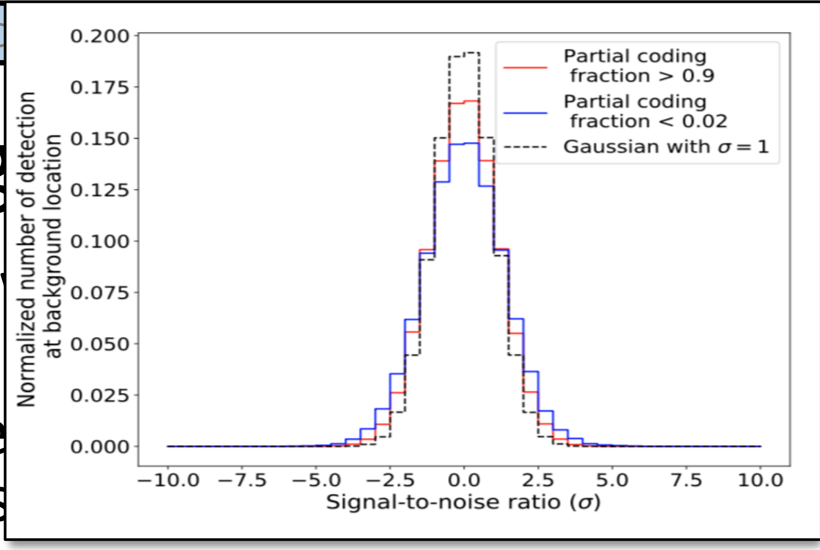
Sub-threshold events

Source	Original messenger	BAT search results [ref.]
GW170817	GW & gamma rays	Occulted by the Earth [9]
LIGO/VIRGO events	GW	Sub-threshold ($\lesssim 5\sigma$) [10]
AT2018cow	Optical	Sub-threshold ($\lesssim 4\sigma$) [11]
Fast Radio Bursts	Radio	Sub-threshold ($< 5\sigma$) [12, 13, 14]
Blazar flare S5 0716+714	X-rays & optical & radio	Sub-threshold ($< 3\sigma$) [15]
Mrk 501 flare	TeV gamma ray	Sub-threshold ($\lesssim 4\sigma$) in daily images Detection (19σ) in 62 ks image [16]
IceCube neutrino multiplet	neutrino	Sub-threshold ($\sim 4.0\sigma$) [17]

Looking for dim signals in BAT: Things to be aware of

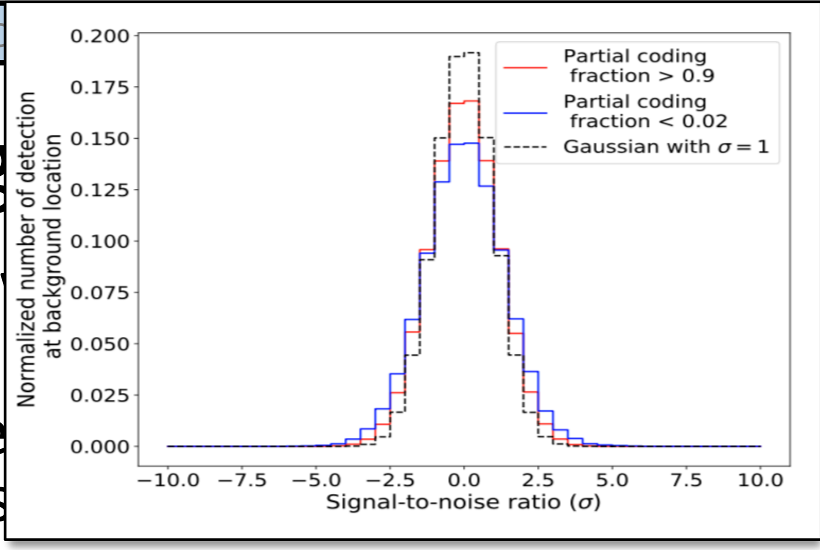
- Any sources in the FOV will affect the noise/flux estimation for your interested source.

Looking for dim sig
Things to be a



- Any sources in the FOV will affe estimation for your interested s
- BAT noise generally follows Gaussian statistics, however, we do see slight divergence from Gaussian, which might be especially important for sub-threshold signals.

Looking for dim sig
Things to be a



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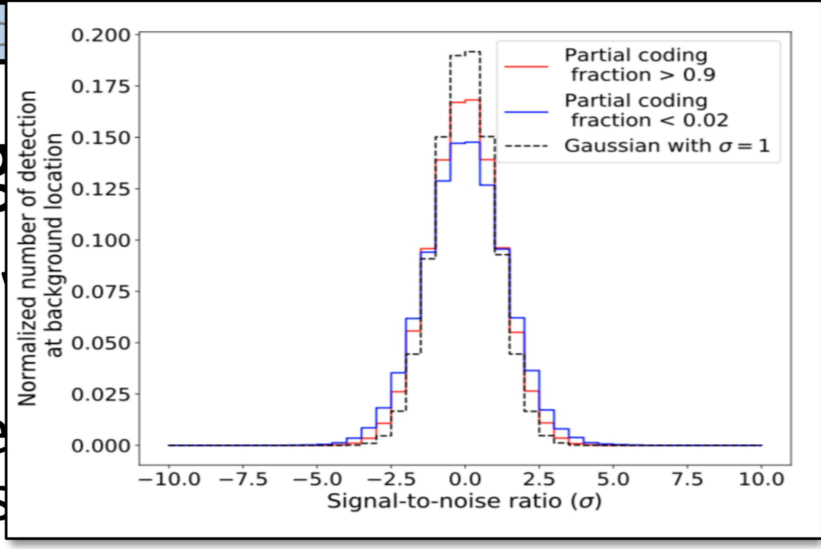
- More systematic noise at the edge of the field of view.

Looking for dim sig
Things to be a



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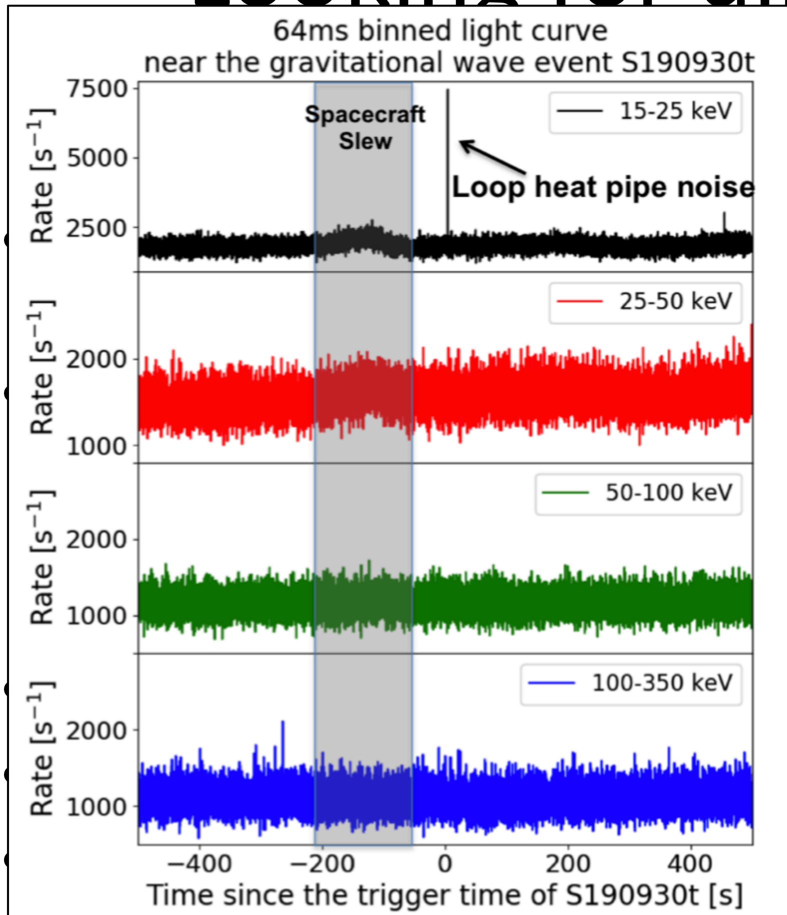
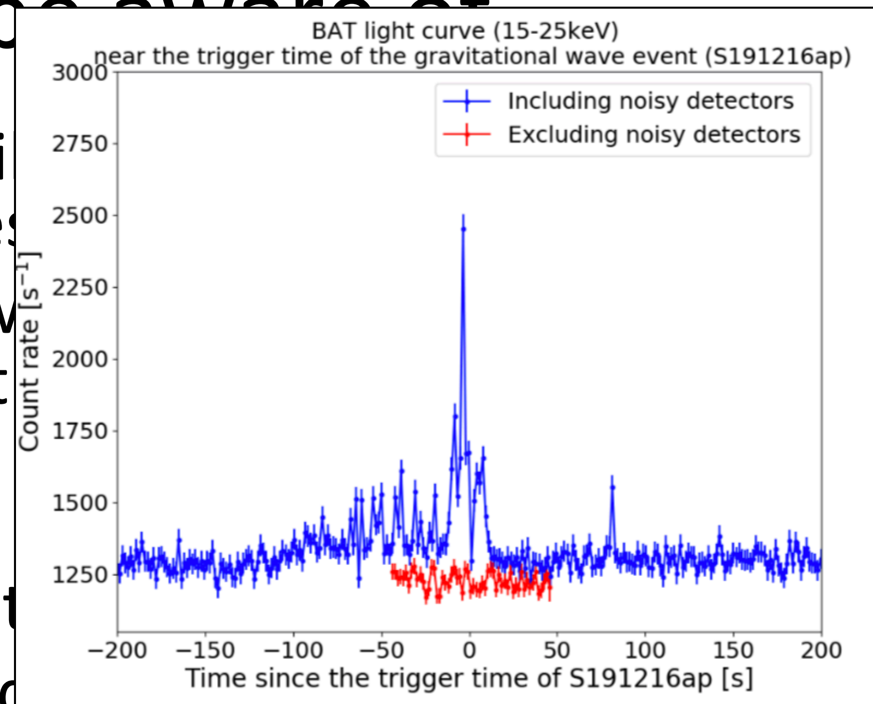
- Be cautious of sources under ~ 7 sigma in an image.

Looking for dim signals in BAT: Things to be aware of

- Any sources in the FOV will affect the noise/flux estimation for your interested source.
- BAT noise generally follows Gaussian statistics, however, we do see slight divergence from Gaussian, which might be especially important for sub-threshold signals.
- More systematic noise at the edge of the field of view.
- Be cautious of sources under ~ 7 sigma in an image.
- There is additional systematic noise when integrating over ~ a few days (patter noise).

Looking for dim signals in BAT: be aware of





- ... matic noise when integrating over ~ a few days (patter noise).
- Detector noise that mimics a burst.

Summary

- BAT is useful for many astrophysical studies
  - Large field of view (~ 1/6 of the sky)
  - Decent source localization (~ 3 arcmin, depends on source brightness)
  - 16 years of data
- Coded mask technique acts differently than focusing instruments
- Be cautious about sub-threshold signals and detections with low partial coding fractions.
- If you have any questions, please email me: amy.y.lien@nasa.gov