Understanding and mitigating the charged particle background in X-ray observatories

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Credits

US WFI team:

- Eric Miller, Mark Bautz, Rick Foster (MIT)
- Gerrit Schellenberger, Ralph Kraft, Paul Nulsen (SAO)
- Dan Wilkins, Steven Allen (Stanford)
- David Burrows, Abe Falcone (PSU)

Athena WFI Background Working Group:

- Silvano Molendi, Fabio Gastaldello (INAF)
- Tanja Eraerds, Andreas von Kienlin, Arne Rau (MPE)
- Michael Hubbard, Jonathan Keelan, David Hall (Open University)
- And many more

Outline

- Why does the background matter?
- Brief introduction to
  - Components of background, orbits, and particle radiation sources
  - CCD event detection and background discrimination
- Current state of the art for background removal/modeling
- Can we do better?
  - Analysis of full frame data from Chandra and XMM
  - Self-Anti Coincidence (SAC)
  - Machine Learning and Neural Network

Why does the background matter?

- Future observatories, like Lynx and Athena, have ambitious science goals
  - Finding first groups and clusters
  - Mapping cosmic structure thru time
- Need deep observations of faint diffuse sources
- Background adds statistical and systematic uncertainty
- Observations of low surface brightness sources often currently limited by systematic uncertainty in background level
- Meeting goals requires both reducing the background and improving knowledge of the residual background

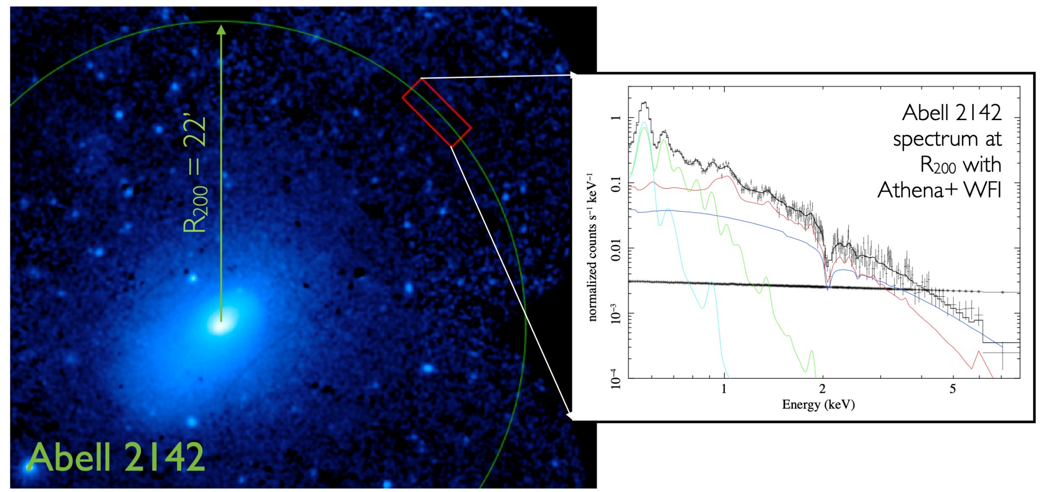
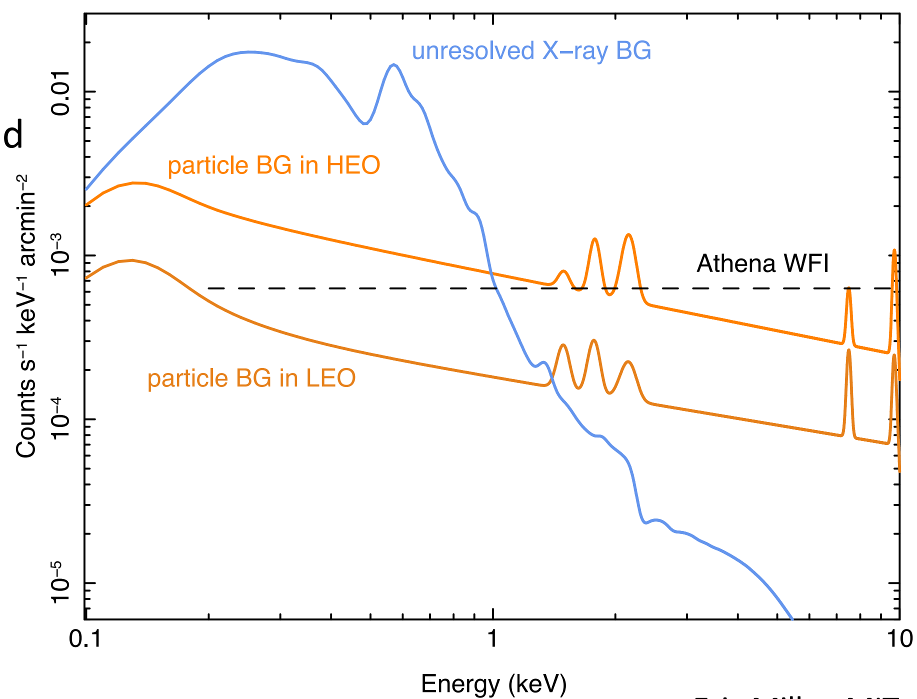


Figure 2: The combined X-IFU and WFI exposures will provide a temperature profile that will improve by an order of magnitude the present constraints on the thermodynamical properties of the ICM out to R_{500} and beyond. This plot presents a XMM mosaic of A2142 at z=0.09 (*right*) and a 100 k-sec WFI exposure of a region of 10 arcmin^2 across the virial radius (*left*): the gas emissivity, temperature and metallicity are constrained with relative uncertainties of 2, 3 and 18 per cent, respectively, at 90% confidence (see also Appendix).

Ettori+ 2013, arXiv:1306.2322, Athena WP
"The Hot and Energetic Universe:
The astrophysics of galaxy groups and clusters"

Components of Background

- Focused X-rays vs everything else
  - Diffuse XRB + unresolved point sources
  - Below 1-2 keV, XRB dominates the background
- Particle background
  - Galactic cosmic rays, solar energetic protons, Earth's trapped radiation
  - Temporally variable, depends on orbit
  - Mitigated thru shielding choices & event list filtering
- Unfocused cosmic hard X-ray background
  - Constant in time
  - Shielding & event filtering like particle bkg

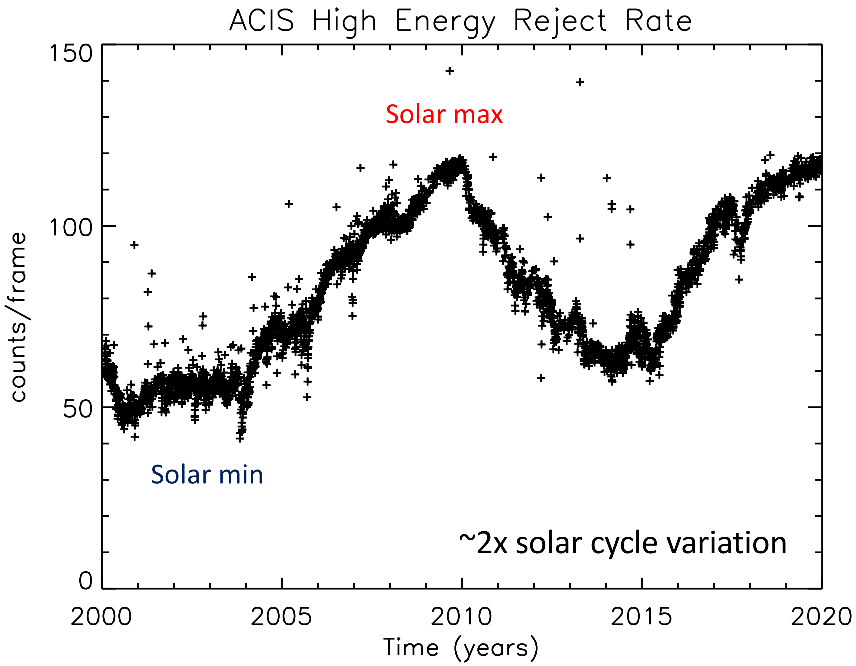


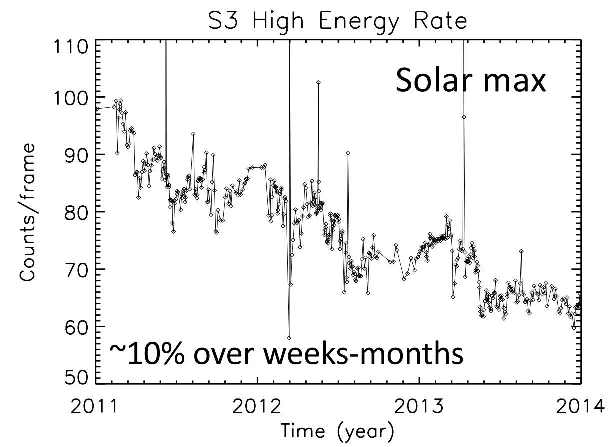
Eric Miller, MIT
Background simulation for AXIS

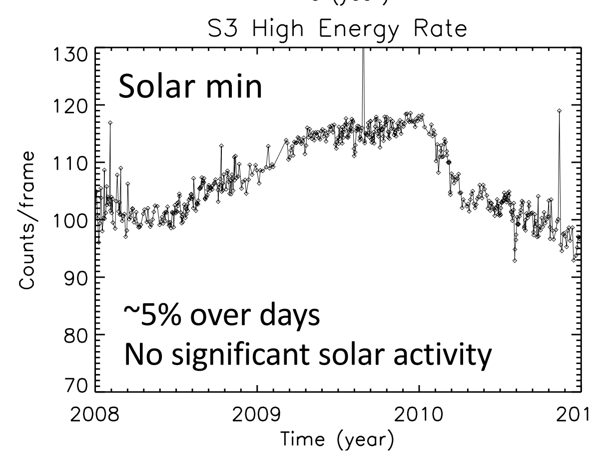
Types of Orbits

- Low-Earth Orbit (LEO) – Suzaku/Hitomi/XRISM, Swift, NuSTAR
  - Exposure to trapped radiation (South Atlantic Anomaly and high latitudes) depends on orbit inclination
  - Geomagnetic shielding of solar/Galactic particles, depends on orbit inclination
  - Background varies with orbit, geomagnetic shielding
- Earth-Sun L1/L2 (eROSITA, Athena), Lunar resonance (TESS, Arcus)
  - No exposure to Earth's trapped radiation except low-density magnetotail
  - No geomagnetic shielding, quiescent particle background is higher
- High-Earth Orbit (HEO) – Chandra, XMM
  - Transit thru trapped radiation belts at perigee while instruments are off
  - During science observations, environment should be similar to L1/L2
  - Possible exception – low energy proton flares?

Galactic Cosmic Rays (GCR)

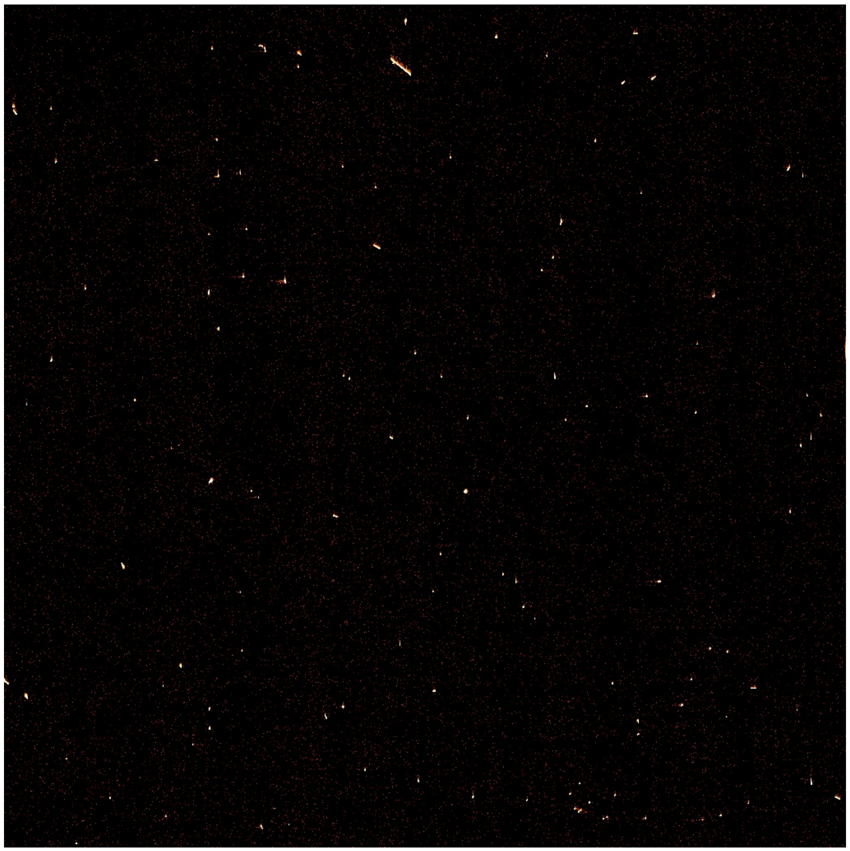






- Primary source of quiescent background in HEO and L1/L2
- Modulated by heliomagnetic field → solar activity
- Many timescales of variability
  - Solar cycle, ~2x over 11 years
  - Individual solar storms, ~10% over weeks-months
  - “Bubbling”, ~5% over days-weeks
- In LEO, further modulated by geomagnetic shielding

CCD Event Detection



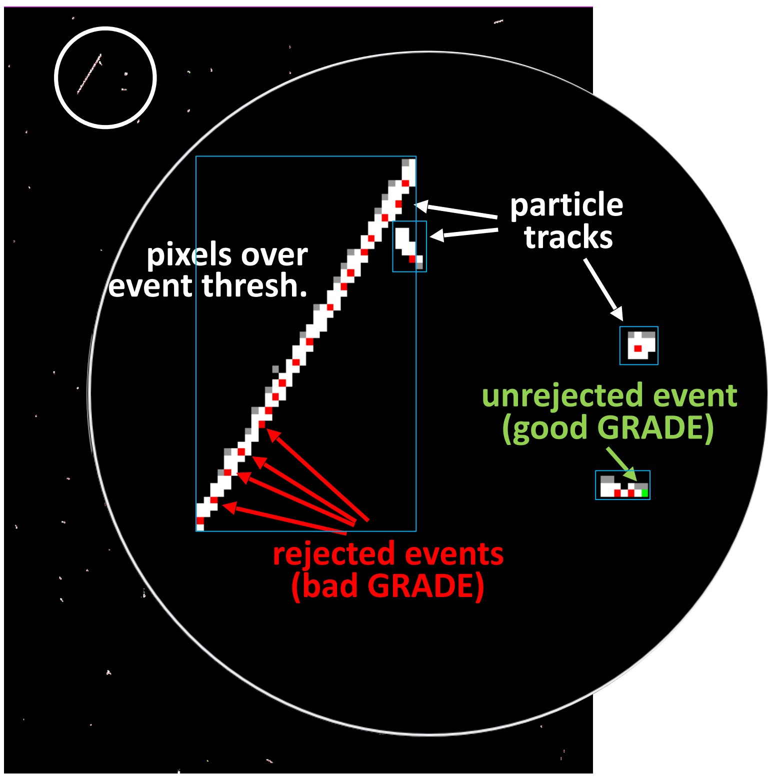
Sample ACIS-S3 raw data frames
Back-illuminated CCD
3.3 sec frame time

Nearly everything in this image is particle background

Telemetry limitations require discarding most pixels on-board

On-board processing identifies potential X-ray event candidates, telemeters subset most likely to be X-rays and not particles

Background Discrimination



- Event candidates are identified as local maxima above a threshold level
- Depending on instrument/mode, only a few pixels around candidate events are telemetered to the ground
- Some candidate events are flagged and removed on-board as likely particle events to further reduce telemetry
- On-ground filtering on grade/pattern (G02346) further reduces background
- Remaining unrejected background events cannot be easily distinguished from X-rays
- Additional contextual information in the discarded full frame data may be helpful in identifying background events that are masquerading as X-rays

Current State of the Art

- Standard event selection and grade filtering
- Specialized modes, i.e. ACIS Very Faint, allow for additional filtering and reduction of background by examining neighbor pixels
- Better statistical treatment of background, modeling not subtracting
  - For example, Eric Miller’s IACHEC talk, a case study for Suzaku and N132D
  - https://iachec.org/2020-iachec-online-meeting-date/
- More recently, particle simulation tools (Geant4) used pre-launch
  - Can inform instrument design choices to reduce background
  - May be outweighed by other needs – thermal, outgassing, radiation shielding

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Can we do better?

- Substantial effort by ESA in support of Athena on understanding and reducing all background components
  - ATHENA Radiation Environment Models and X-ray Background Effects Simulators (AREMBES)
    - Systematic analysis of in situ X-ray background data, primarily XMM
    - Characterization of particle environment in L1/L2 (particles, normalization, variability)
    - Optimization/validation of simulation tools (space physics list, mass models)
    - Many resulting publications
  - WFI and X-IFU Background Working Groups
    - Geant4 simulations informing instrument design decisions, flight and ground software
    - Studies of stray-light, CXB modeling, magnetic diverter to prevent soft proton flares
  - Self anti-coincidence was proposed as a method to reduce the background on the WFI and meet the challenging science requirement (Meidinger+ 2016)

Can we do better?

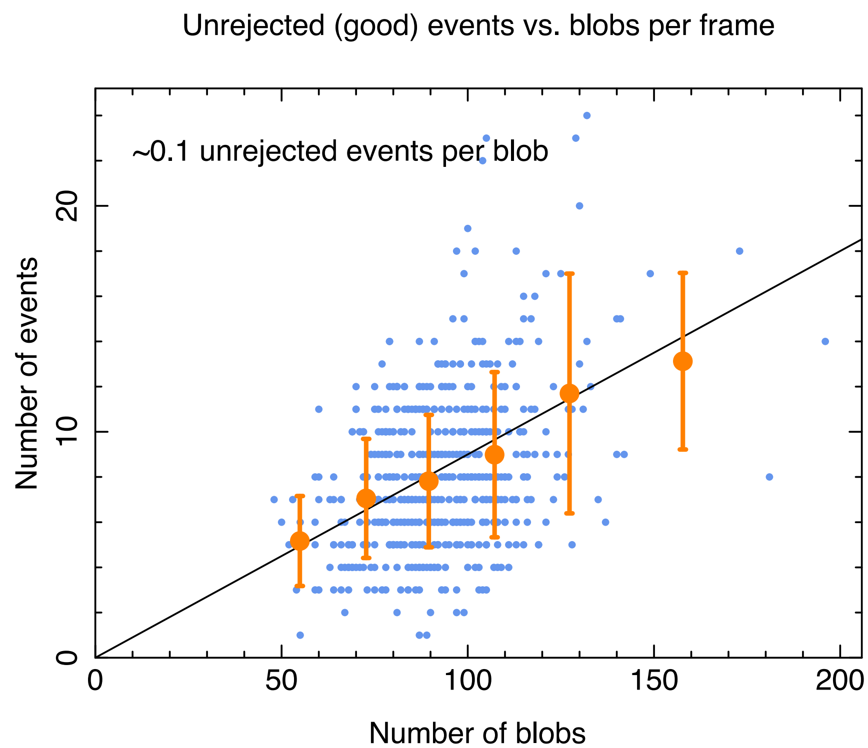
- The US participation in the WFI background WG:
  - Search for phenomenological correlations between unrejected background and particle tracks in full frame data from Chandra and XMM
  - Develop methods to identify unrejected background events using those correlations
  - Refine and validate those methods using Geant4 simulations of GCR protons and Athena WFI
  - Better understand origins of systematic background errors and strategies to reduce them
    - Determine magnitude and timescale of GCR spectral variability
    - Simulate and analyze the resulting unrejected background variability
- Work in progress!

Full Frame Data Analysis

- Examine specialized data modes that telemeter *all* pixel data
  - ACIS-S3 full frame while stowed (raw mode)
  - XMM EPIC-pn Small Window Mode (SWM) with Filter Wheel Closed (FWC) and MIP rejection off
  - No sky X-rays, only background
- Standard event finding
- Identify particle tracks/blobs with image segmentation
- Is the unrejected background correlated with the particle tracks? Yes!
- Primary GCR can interact with detector housing and produce secondary particles that also create events on the detector

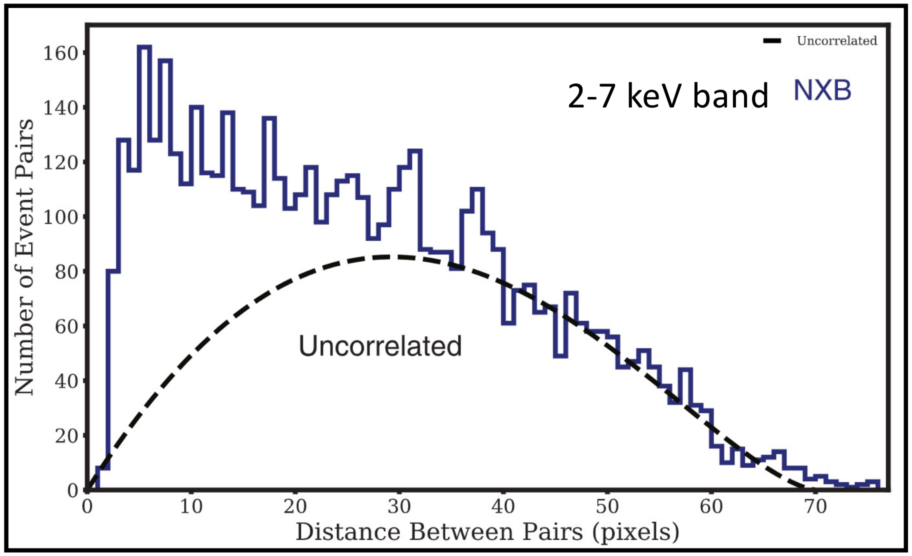
ACIS-S3 full frame

- Grant+ 2018 found a correlation between numbers of unrejected events and particle tracks
- Also found a strong spatial correlation to 20 or more pixels
- These results confirm that filtering event data by distance to a particle track (self-anti coincidence) could reduce the background



XMM EPIC-pn SWM

- Bulbul+ 2020 confirmed a significant spatial correlation between particle tracks and unrejected background events on scales up to 30 pixels
- Ongoing work will utilize the full potential of the PN Small Window Mode data (slew and pointed observations), by analyzing the full energy band and characterizing in detail the spectral and temporal variability (Schellenberger+ 2021 in prep)



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Exploiting the Correlation: Self Anti-Coincidence

- Detector can serve as its own anti-coincidence veto to further reduce the background
- Eliminate unrejected background events within a certain distance around each particle track pixel, partial veto scheme
  - Exclusion distance can be tuned depending on science goal, optimize signal-to-noise
- Removes both background events and real X-rays
  - Reduces systematic error at the expense of statistical precision
- Effectiveness of SAC requires a large enough detector to capture both the primary particle track and any secondaries and short enough frame time that primary and secondary events from different particles aren’t confused
- Requires more information than is normally telemetered for any current CCD instrument. Athena WFI should be sufficient.

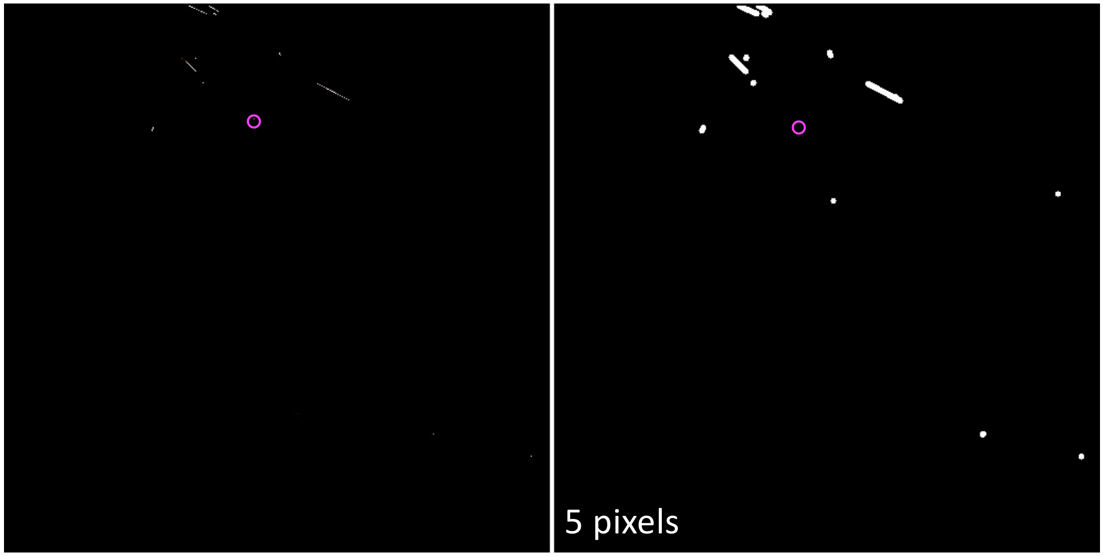
Miller+ 2021

Masking Around Particle Tracks

Simulated WFI frame, 5 msec frametime

Circle is unrejected background event

Left, original; Right, SAC rejection regions



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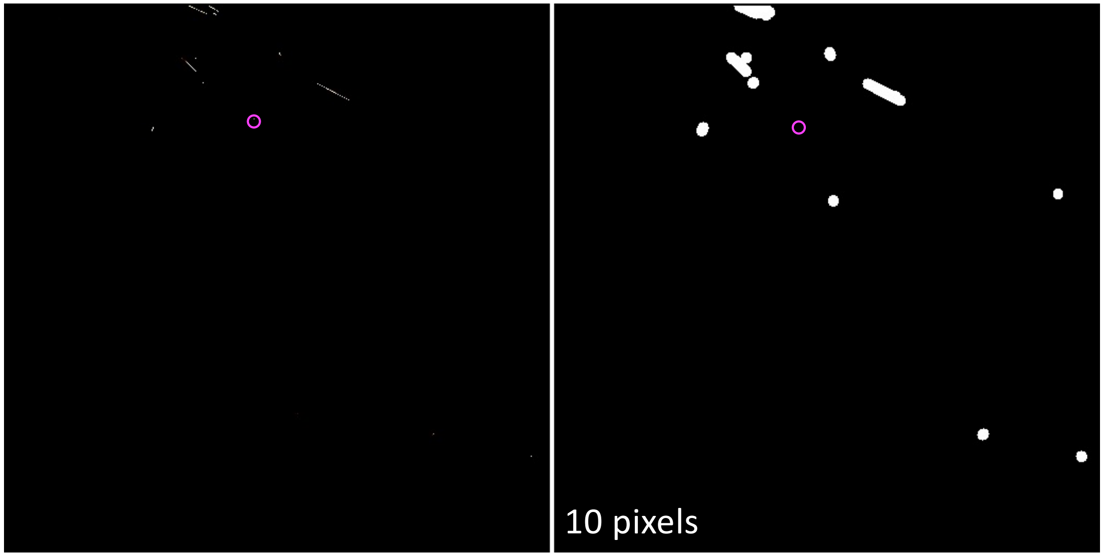

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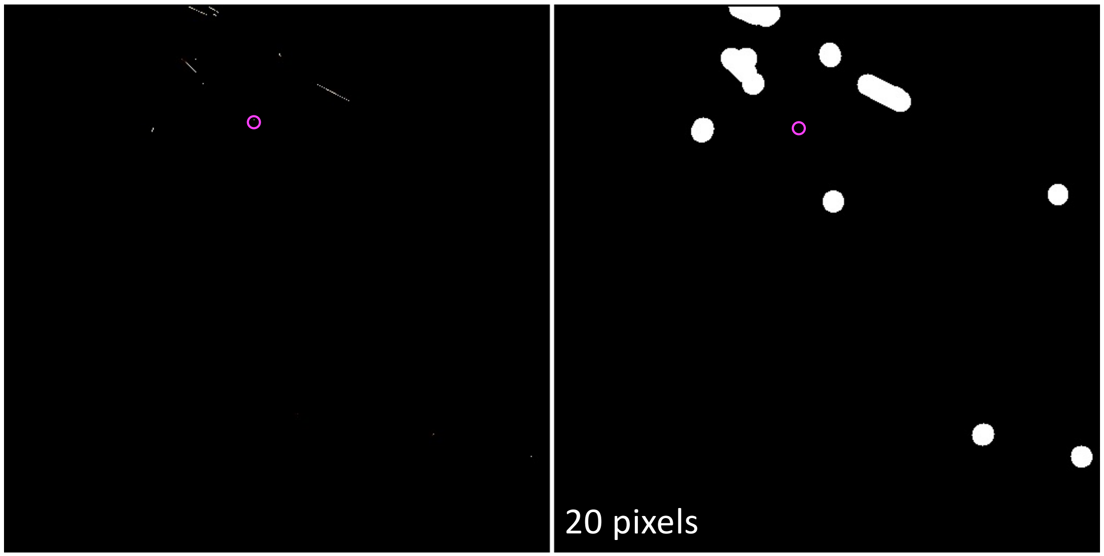

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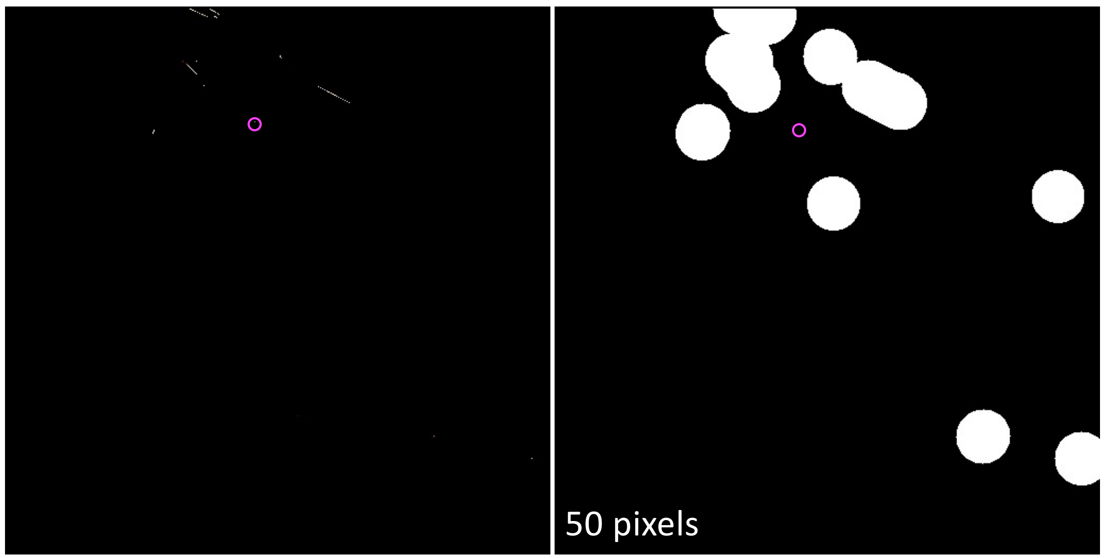

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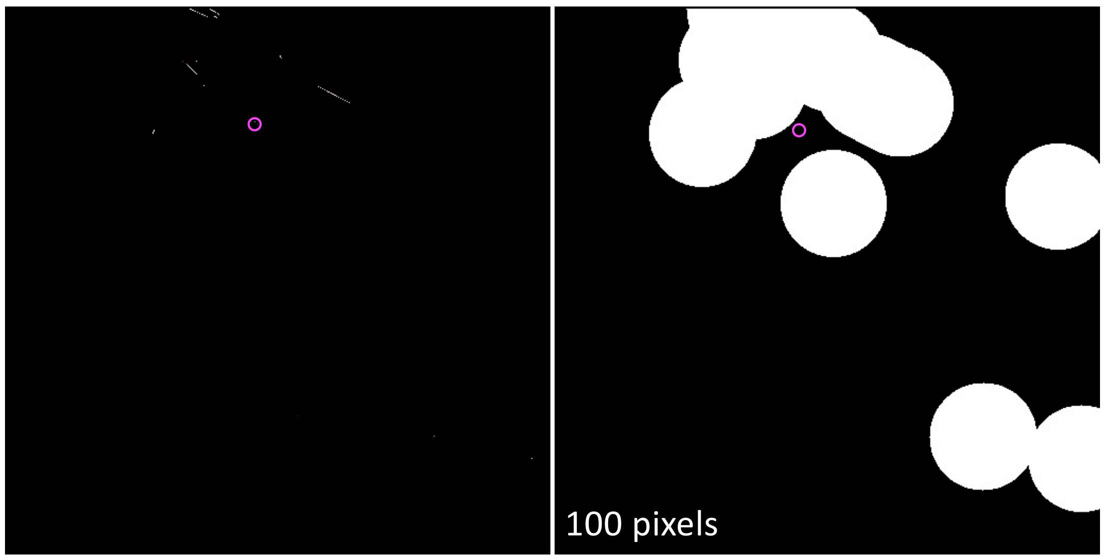

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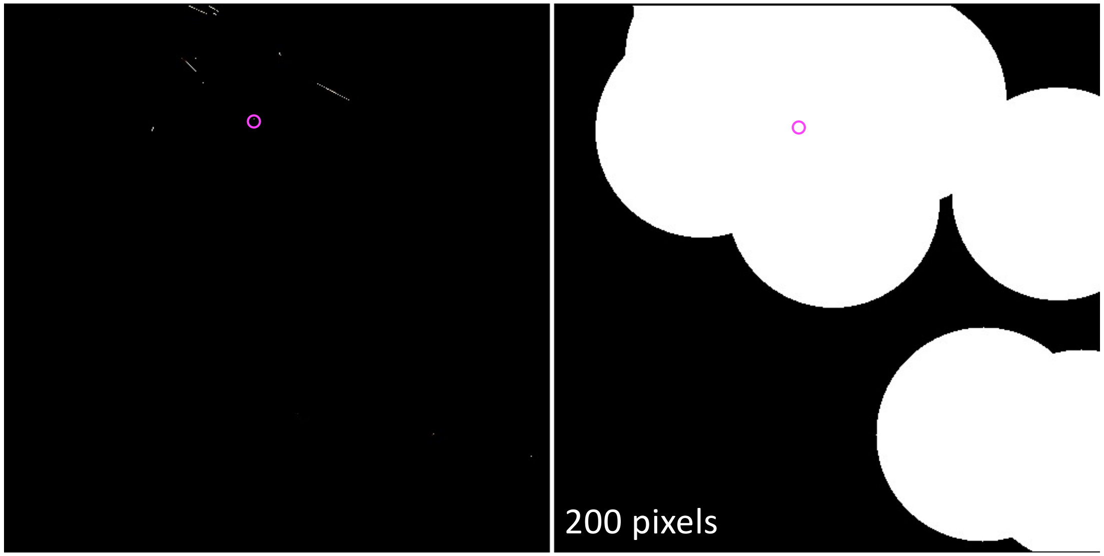

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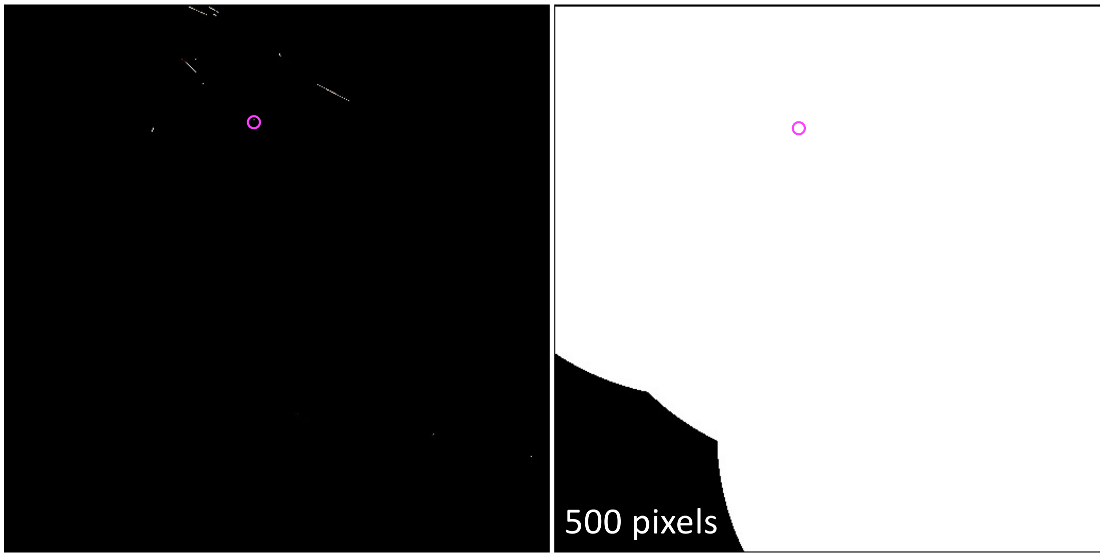

SNR Improvement with SAC

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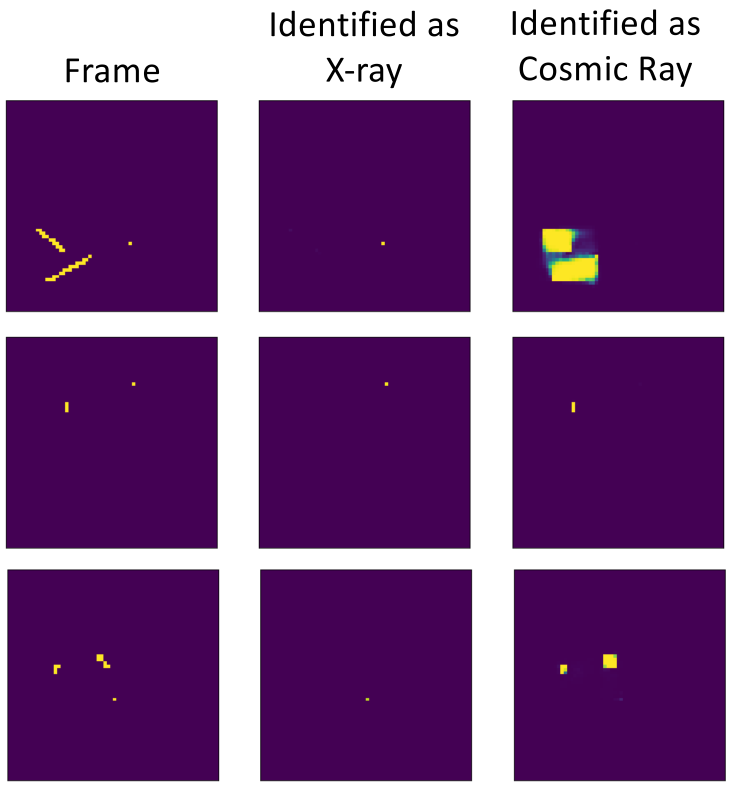
- By employing SAC can reduce the background as measured by:
  - Number of unrejected background events
  - Signal-to-background ratio
  - Signal-to-noise ratio
- Always accompanied by a loss of signal
- Turns irreducible systematic errors into statistical errors that are reducible by increase in exposure time
- For example, WFI deep survey (1.5 Msec) with a source size of 10 arcmin^2, improvements of ~35% in SNR are possible
- Utility of SAC highly depends on the science case; since filtering is done on the ground, no impact to science investigations that do not benefit
- Results are further described in Miller+ 2021

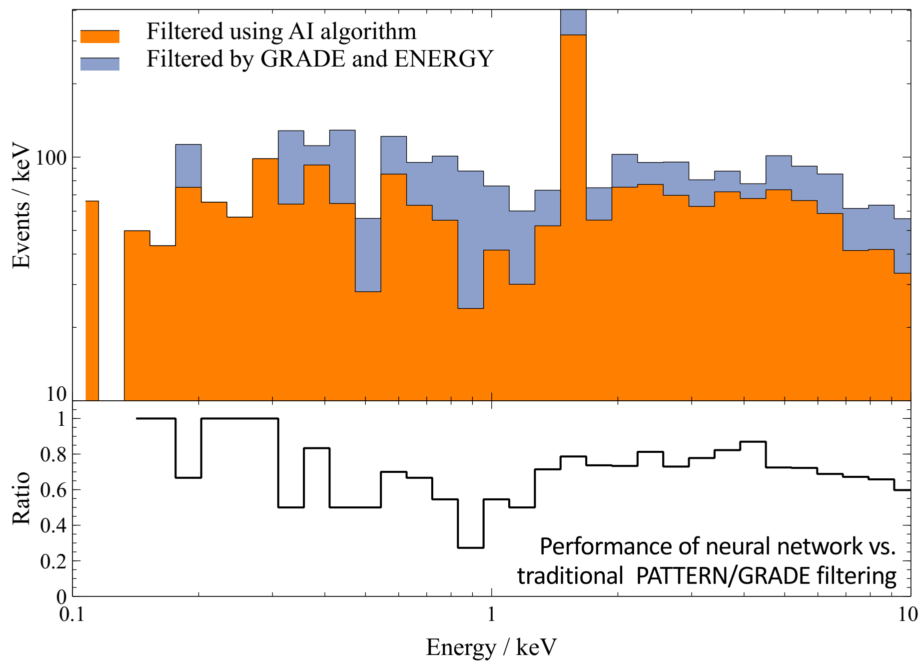
Background filtering with a neural network

- Train neural network to identify patterns of charge produced in detector by astrophysical X-ray photons and particle induced events
- Charge patterns due to particle background simulated using Geant4
- Each event assigned probability of being due to cosmic ray
- Filter background based on threshold probability



Wilkins+ 2020

Performance of neural network filtering



Wilkins+ 2020

Compare background after filtering with neural network to background filtered using traditional event selection

Filtering using prototype algorithm reduces background events in 0.3-10keV range by up to 27%.

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Summary

- Observations of low surface brightness sources often currently limited by uncertainty due to the background
- Background is variable on many timescales, better understanding of that variability can reduce systematic errors.
- Background events that otherwise resemble astrophysical X-rays can be distinguished by context
  - Proximity to particle tracks
- Self anti-coincidence with a variable exclusion radius offers improvements for some science cases
  - Requires additional data to be telemetered about particle tracks
- Prototype neural network filtering also shows promise in reducing background

For more information…

MIT analysis of simulated WFI data:
Miller+ 2021, JATIS submitted
Grant+ 2020, Proc. SPIE 11444

ACIS full frame data:
Grant+ 2018, Proc. SPIE 10699

XMM Small Window Mode data:
Bulbul+ 2020, ApJ 891
Schellenberger+ 2021, in prep

ML approach to background reduction:
Wilkins+ 2020, Proc. SPIE 11444

MPE WFI team background simulations:
Eraerds+ 2021, JATIS 7 (3)

And many other publications related to Athena and AREMBES

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Also thank you to the Spotify "Jazz for Study" playlist!