Particle background and transient study in preparation for Athena WFI

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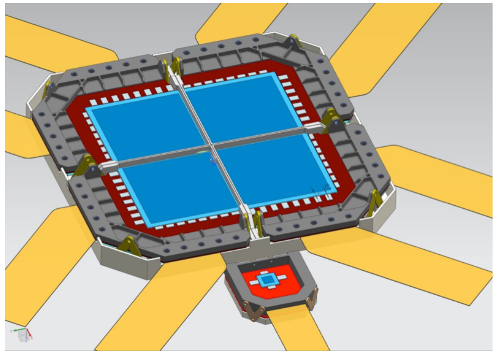
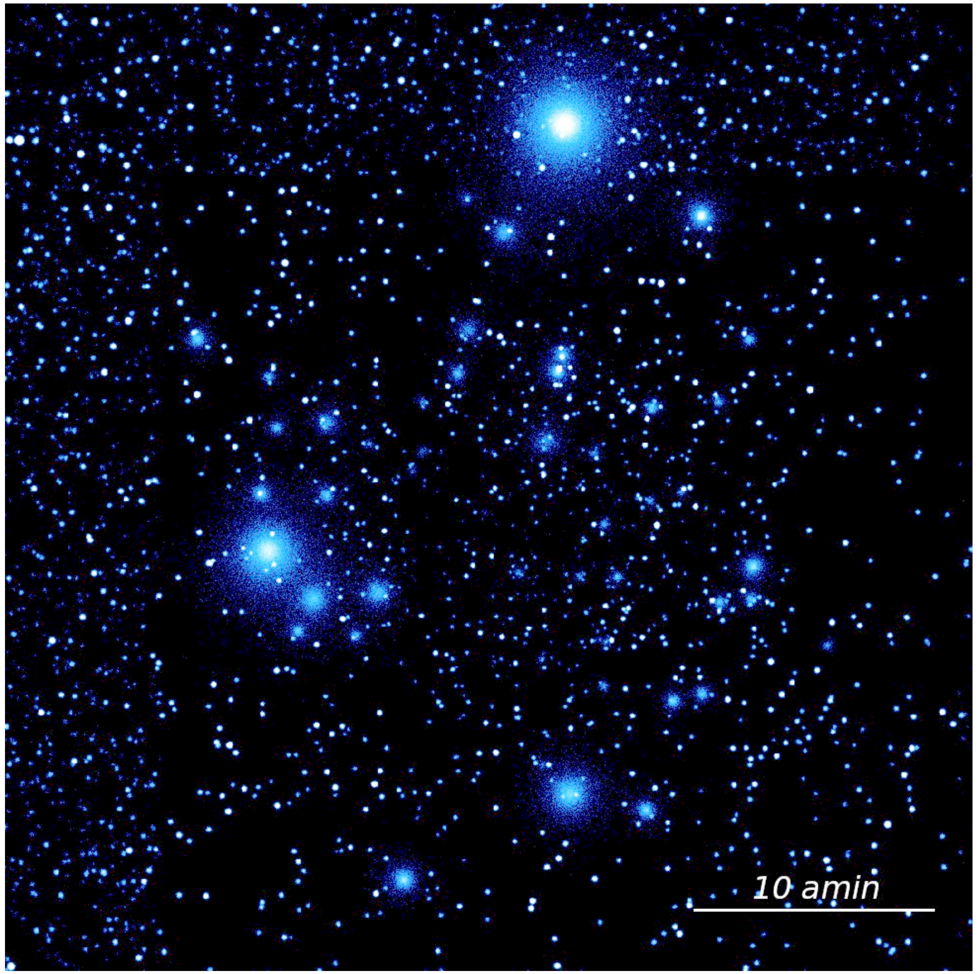
Dan Wilkins (Stanford)
Amanpreet Kaur (Penn State)
for the US Athena WFI Team

Athena will survey deep and wide



Wide-Field Imager (WFI)
Large Area Detector (LAD)
Arrays of DEPFET active pixels
40' x 40' FOV
5" PSF
5 msec frame time



- Mapping cosmic structure through time
  - Distant groups and clusters
  - Nearby cluster outskirts
  - Requires low, known background
- Transients

US Athena WFI Team

MIT
Eric Miller — **Background simulations and mitigation**
Catherine Grant, Mark Bautz, Rick Foster

SAO
Gerrit Schellenberger — **Validation of mitigation strategies with real data**
Ralph Kraft, Paul Nulsen

Stanford
Dan Wilkins — **Background mitigation using machine learning**
Steven Allen, Sven Hermann

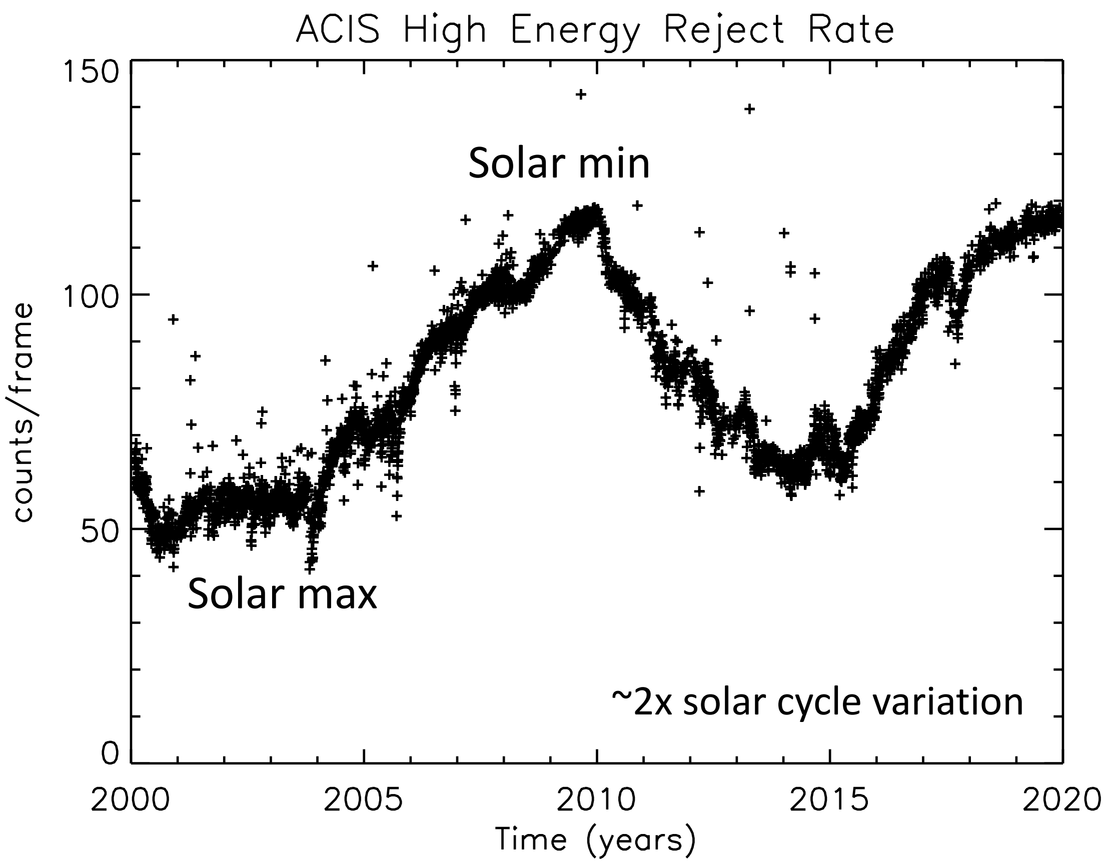
Penn State
Amanpreet Kaur — **Transient event detection**
David Burrows, Abe Falcone

With many thanks to the Athena WFI Consortium and 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…

Why does the WFI background matter?

- Background adds statistical uncertainty
  Minimize the background
- Background adds systematic uncertainty
  Maximize knowledge of residual background
- Galactic CRs are primary source of quiescent background >1 keV at Athena L1 orbit
- 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

- Current WFI requirement is
  2% background knowledge



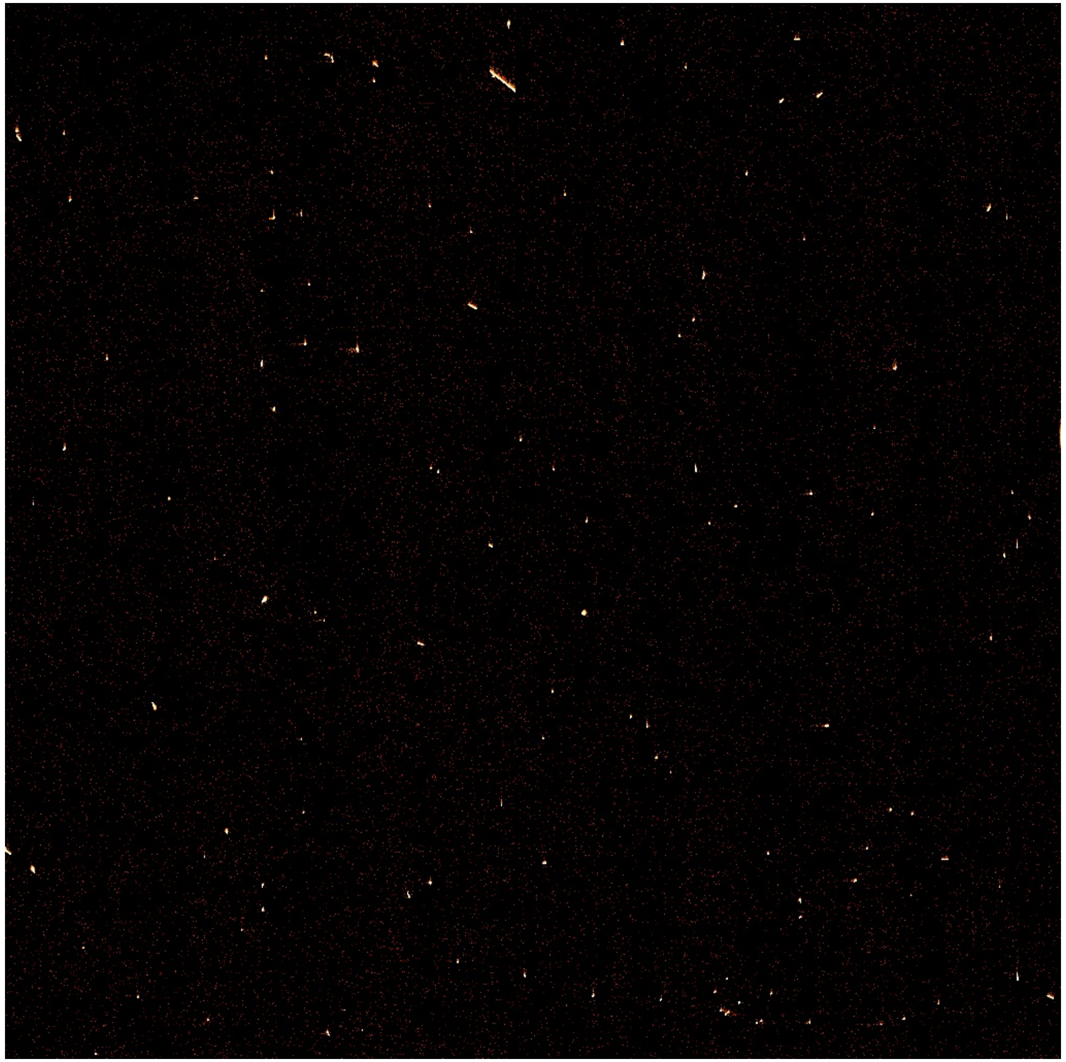
Substantial Athena background effort

ATHENA

- ATHENA Radiation Environment Models and X-ray Background Effects Simulators (AREMBES)
  - Analysis of XMM background data
  - Characterization of particle environment (particles, normalization, variability)
  - Optimization and validation of simulation tools (Geant4 input)
  - Many publications cf. Eraerds+2021
- 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
- US team efforts
  - Search for correlations between cosmic ray tracks and unrejected events in Chandra and XMM data Grant+2018, Bulbul+2020, Schellenberger+ in prep
  - Develop methods to identify unrejected events using those correlations Grant+2020, Wilkins+2020
  - Refine and validate those methods using Geant4 simulations Miller+2021
  - Understand systematic background errors and strategies to reduce them ongoing

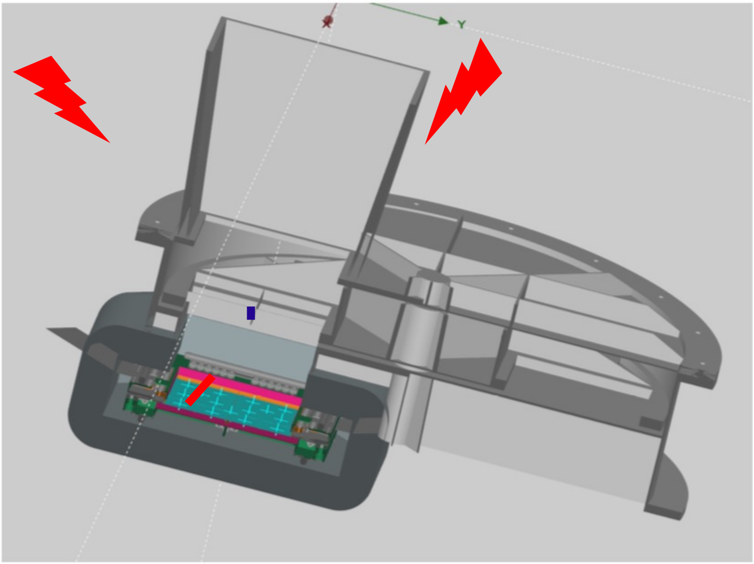
Chandra ACIS particle background

- Sample ACIS-S3 raw data frames
- Back-illuminated CCD
  3.3 sec frame time
- Nearly everything in this movie is particle background
- Telemetry limitations require discarding most pixels on-board; only candidate X-ray events are recorded

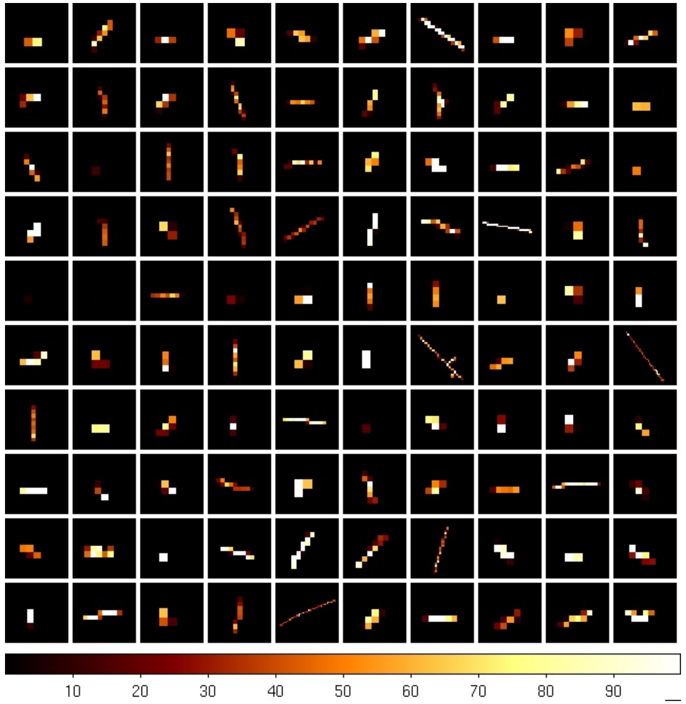


Simulating the WFI background with Geant4

- Generate 100 million GCR protons, shoot them through the WFI housing
- Some interact directly with the detector and produce a particle track (1 million)
- Some produce a secondary particle that interacts with the detector (10 thousand)
  - X-ray or electron secondaries produce “valid” events, indistinguishable from celestial X-rays
  - Accompanying primary particle track is sometimes present



Geant4 simulations by Open University



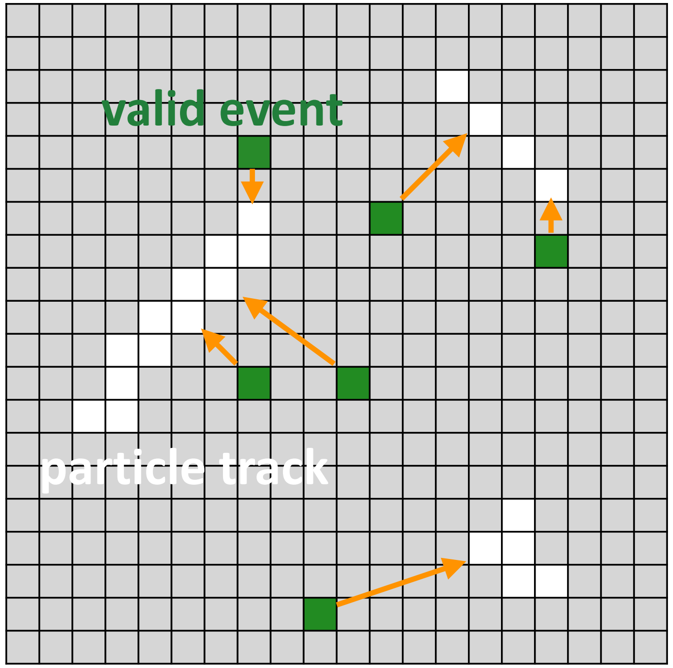
Correlation: particle tracks and valid events

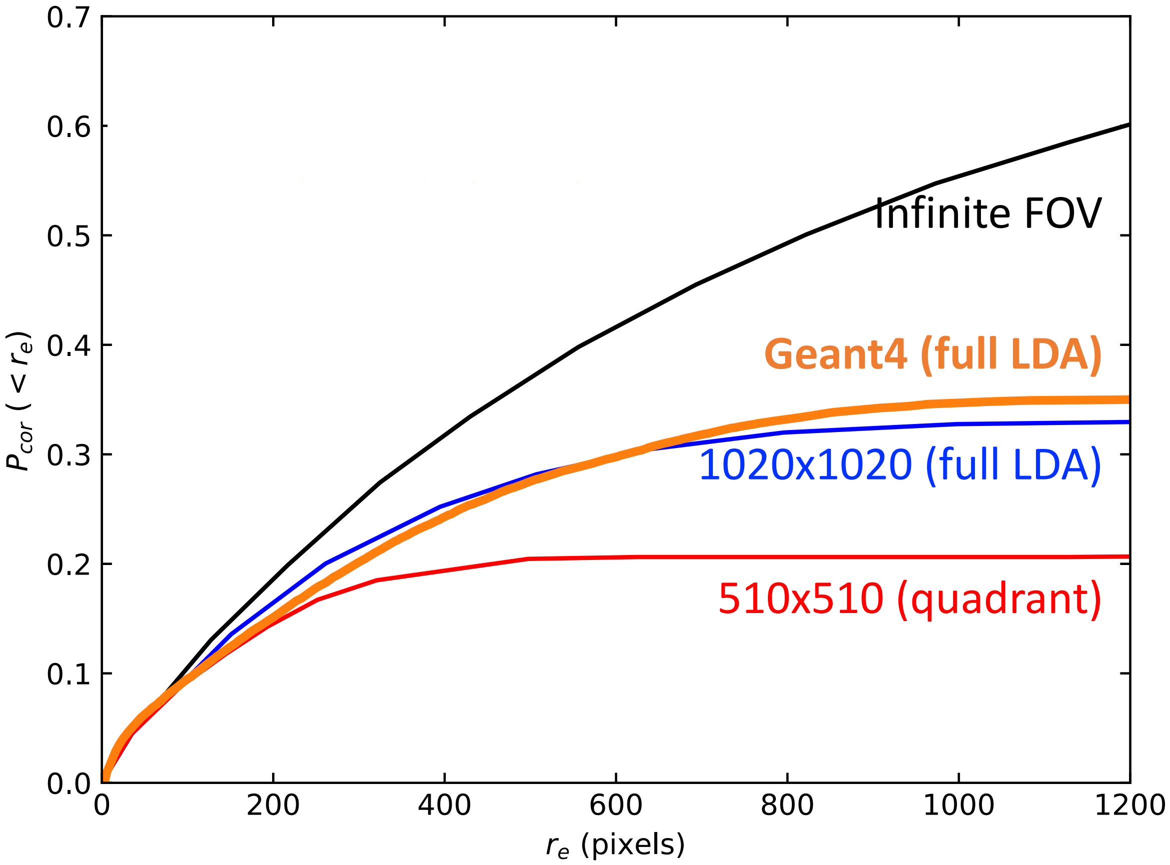
Case			
Case A	# of primaries producing **particle track** but **no valid event**	909,823	**(97.3%)**
	Fraction of 2–7 keV background	0%	
	# of particle tracks per primary	**1.12**	
Case B	# of primaries producing **valid event** but **no particle track**	16,842	**(1.8%)**
	Fraction of 2–7 keV background	65%	
	# of particle tracks per primary	0.00	
Case C	# of primaries producing **valid event** and **particle track**	8,839	**(0.9%)**
	Fraction of 2–7 keV background	35%	
	# of particle tracks per primary	**1.89**	

We get about 3 particle tracks per 5-ms frame, compared to dozens for ACIS 3-s.
WFI frame time is not quite fast enough to use anti-coincidence and drop a whole frame when we see a cosmic ray track, but we can do something similar.

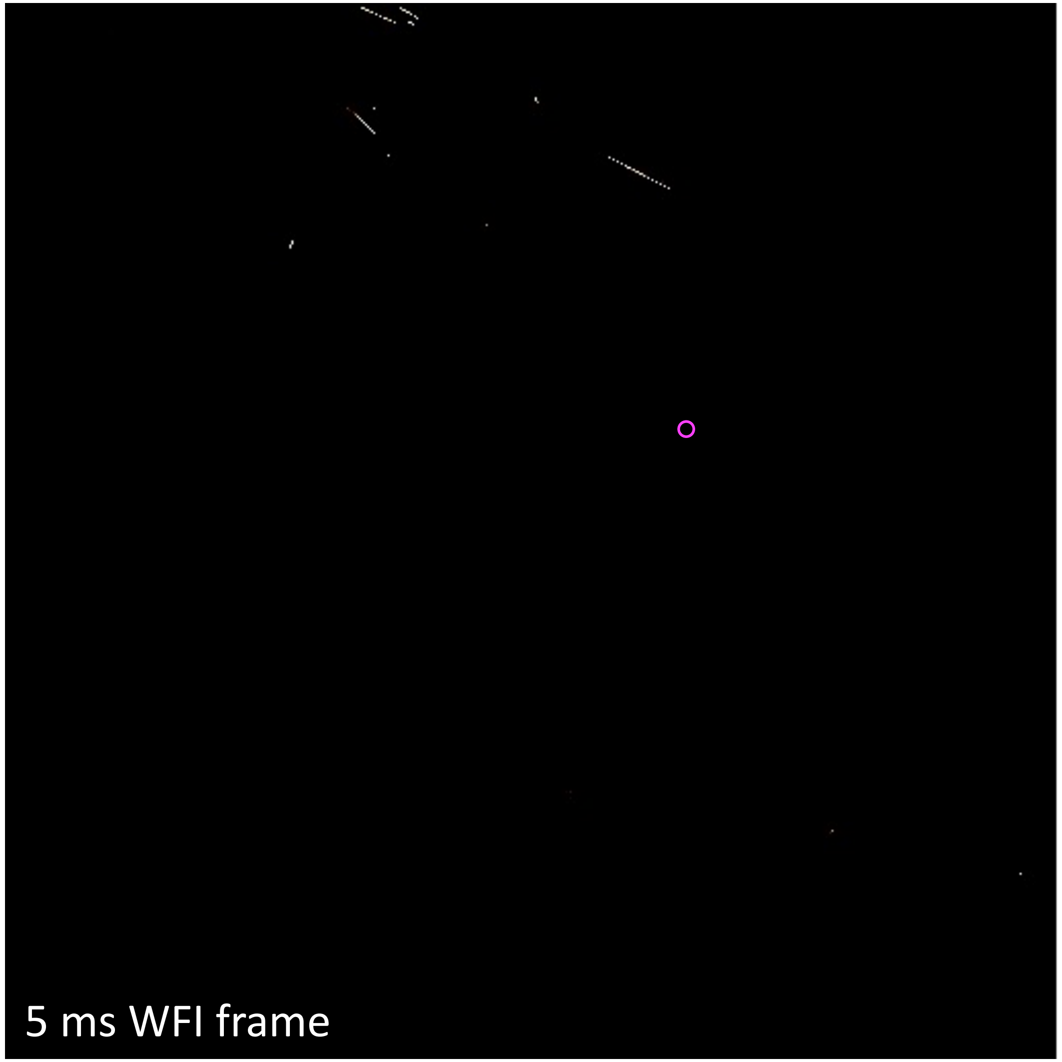
Spatial correlation: particle track and valid events

P_{cor} = cumulative probability of getting a valid event within r_e of a particle track





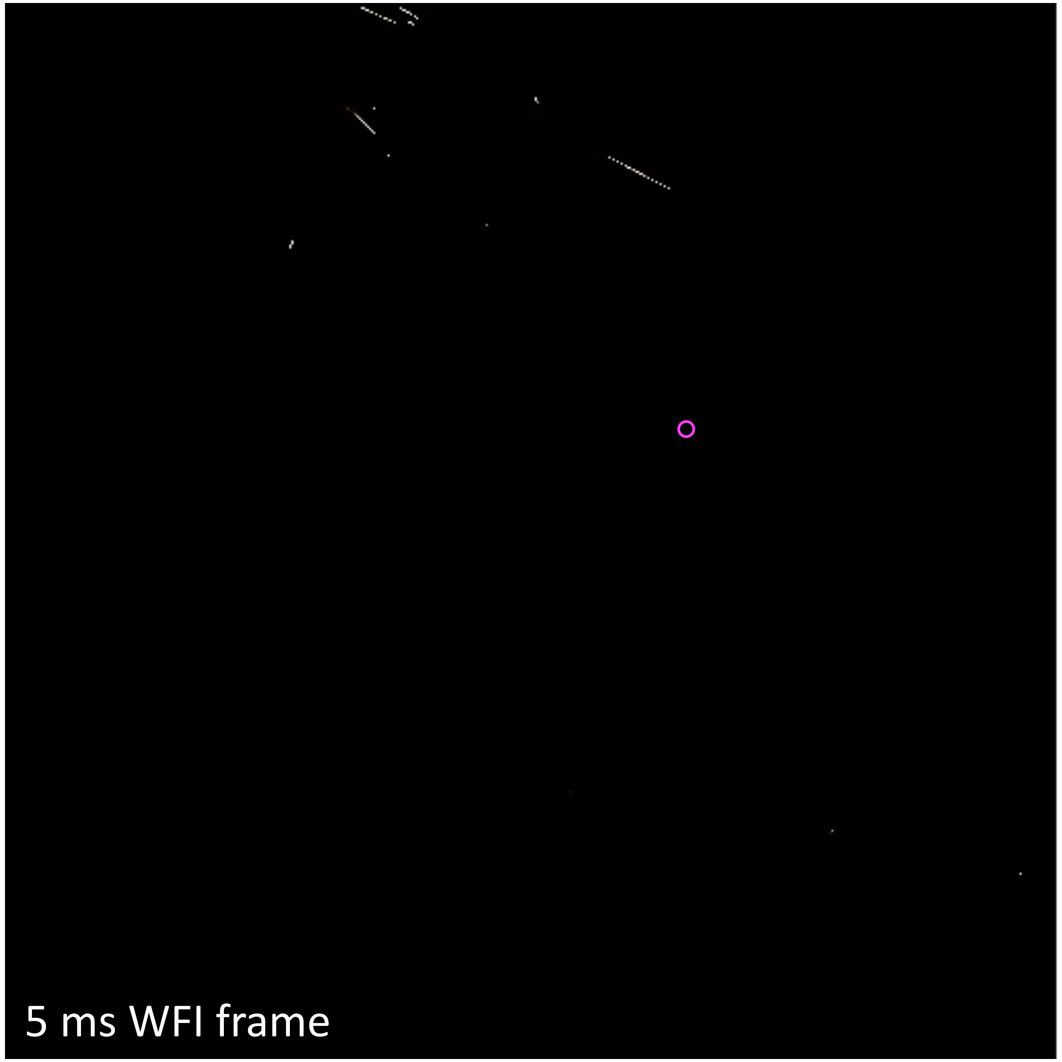
Self Anti-Coincidence (SAC)

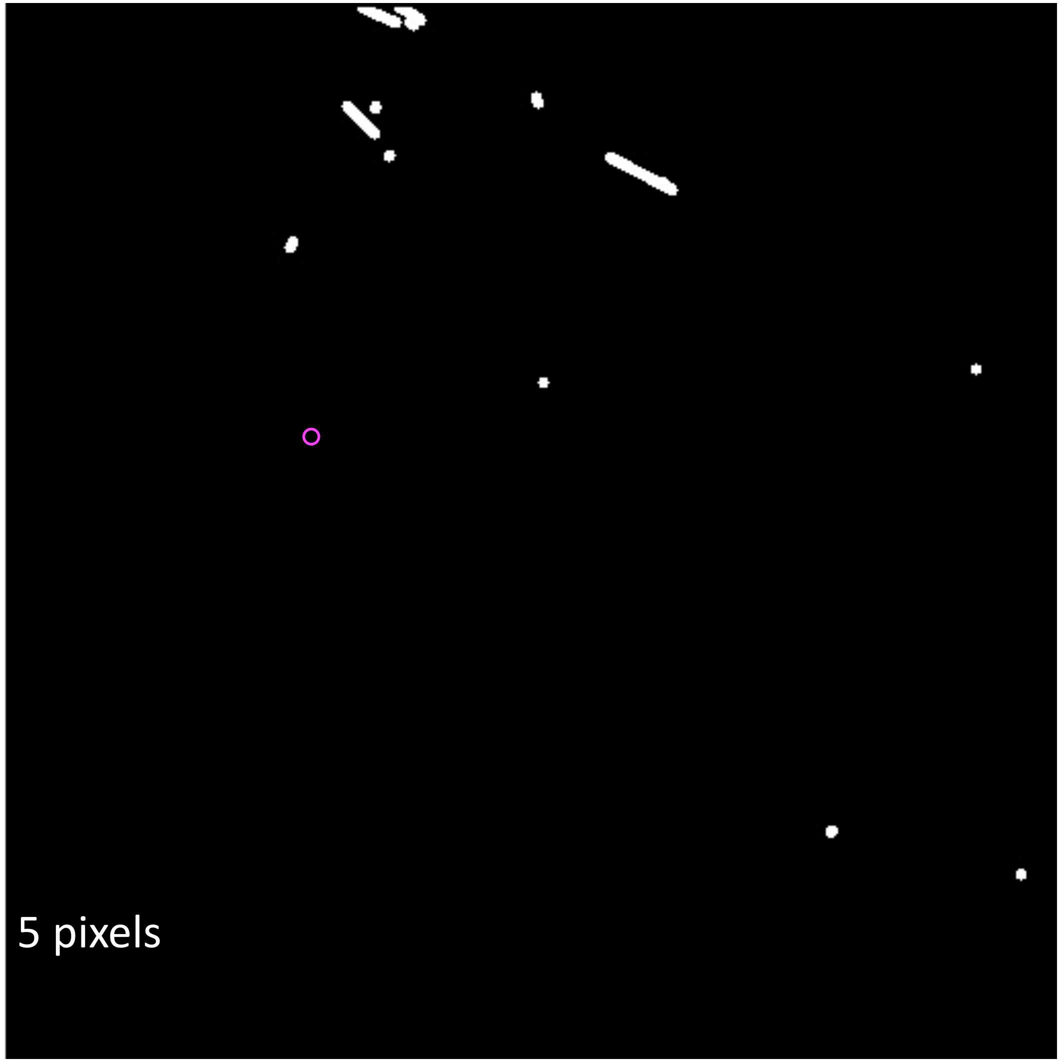


- Spatial correlation between particle tracks and secondary valid events
- Mask around particle tracks to reduce unrejected background
- WFI becomes its own partial-veto, anti-coincidence detector
- Size of mask can be tuned depending on science

- Requires all pixels with signal to be telemetered!

Self Anti-Coincidence (SAC)





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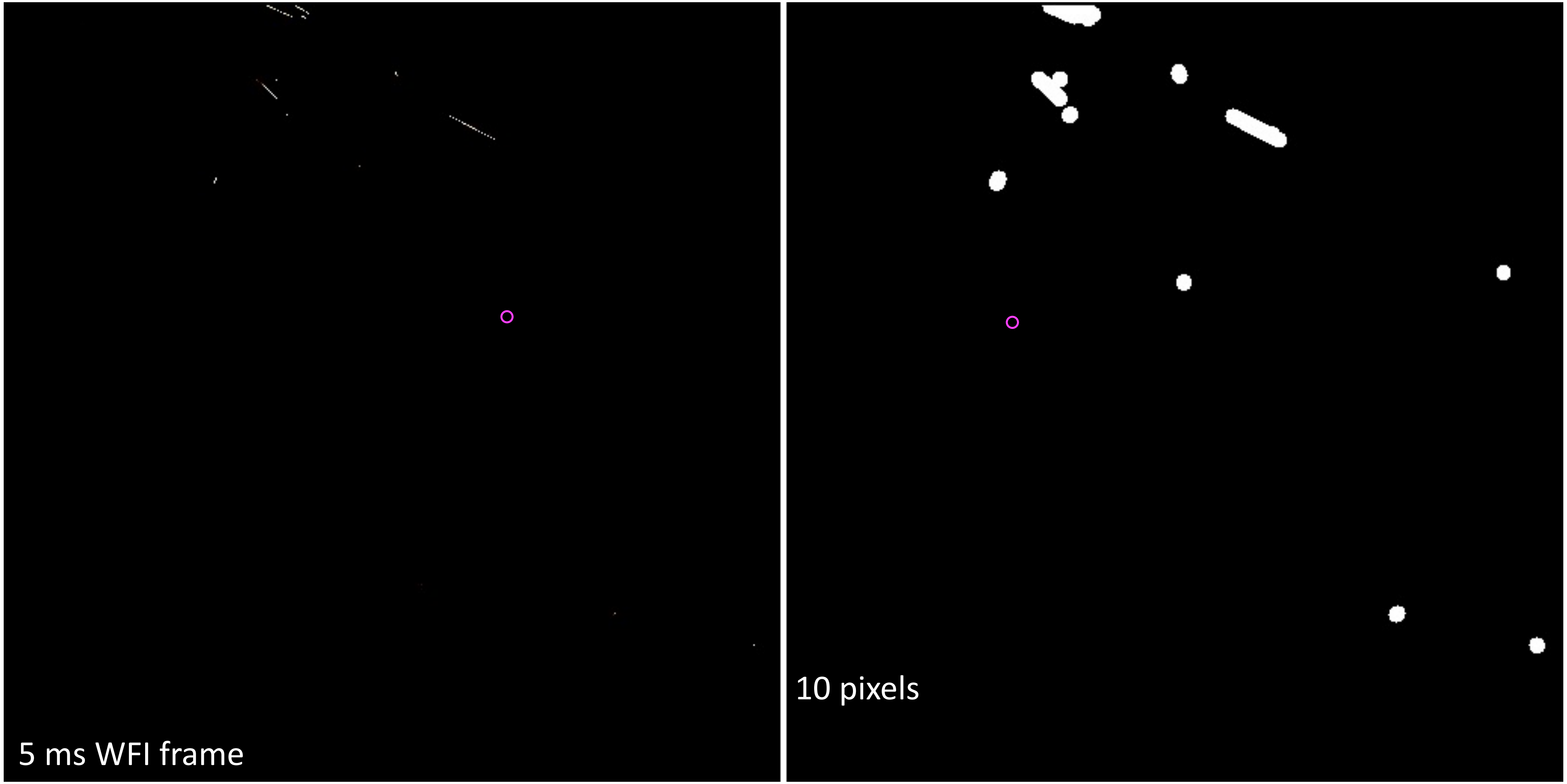

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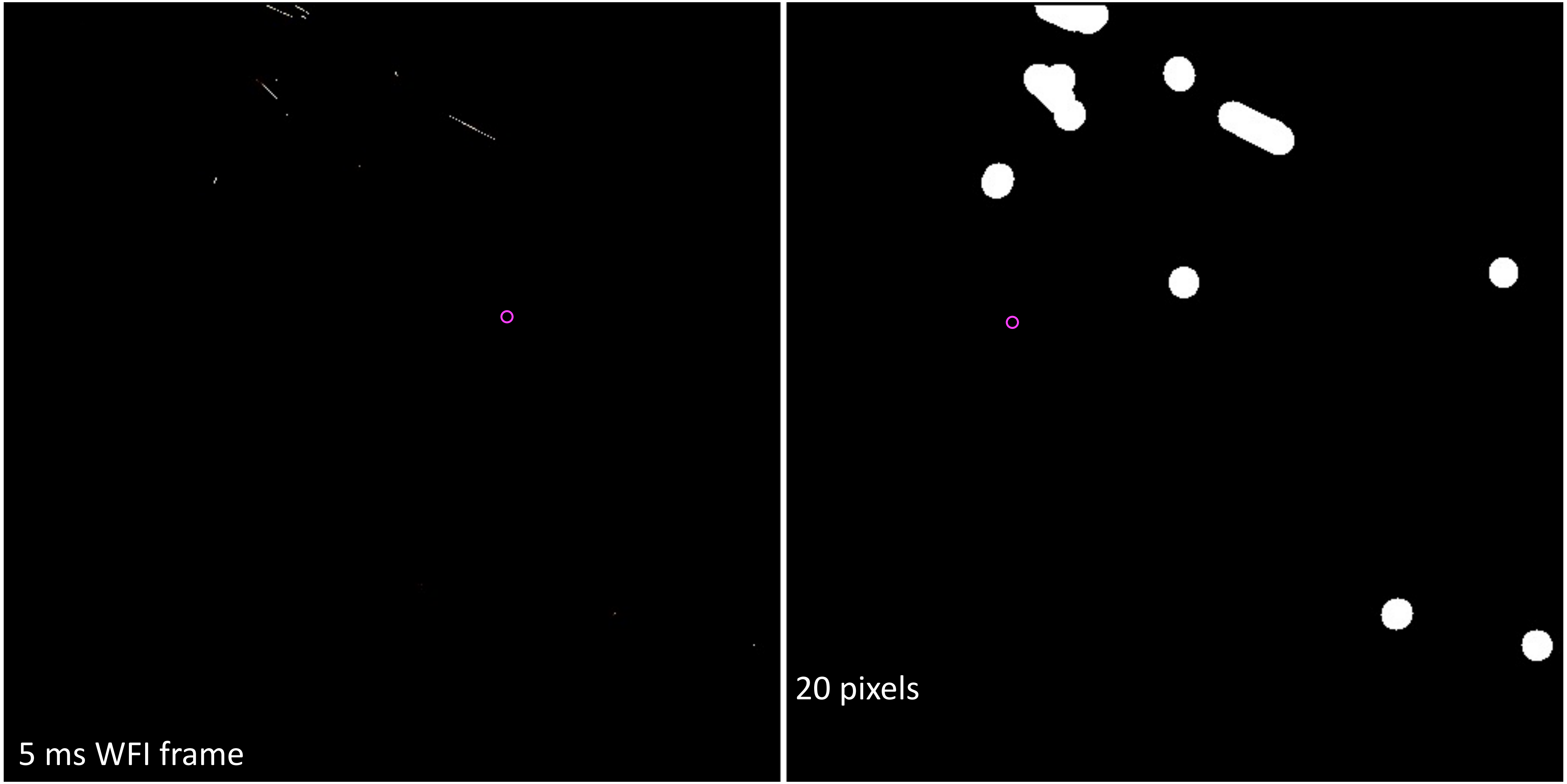

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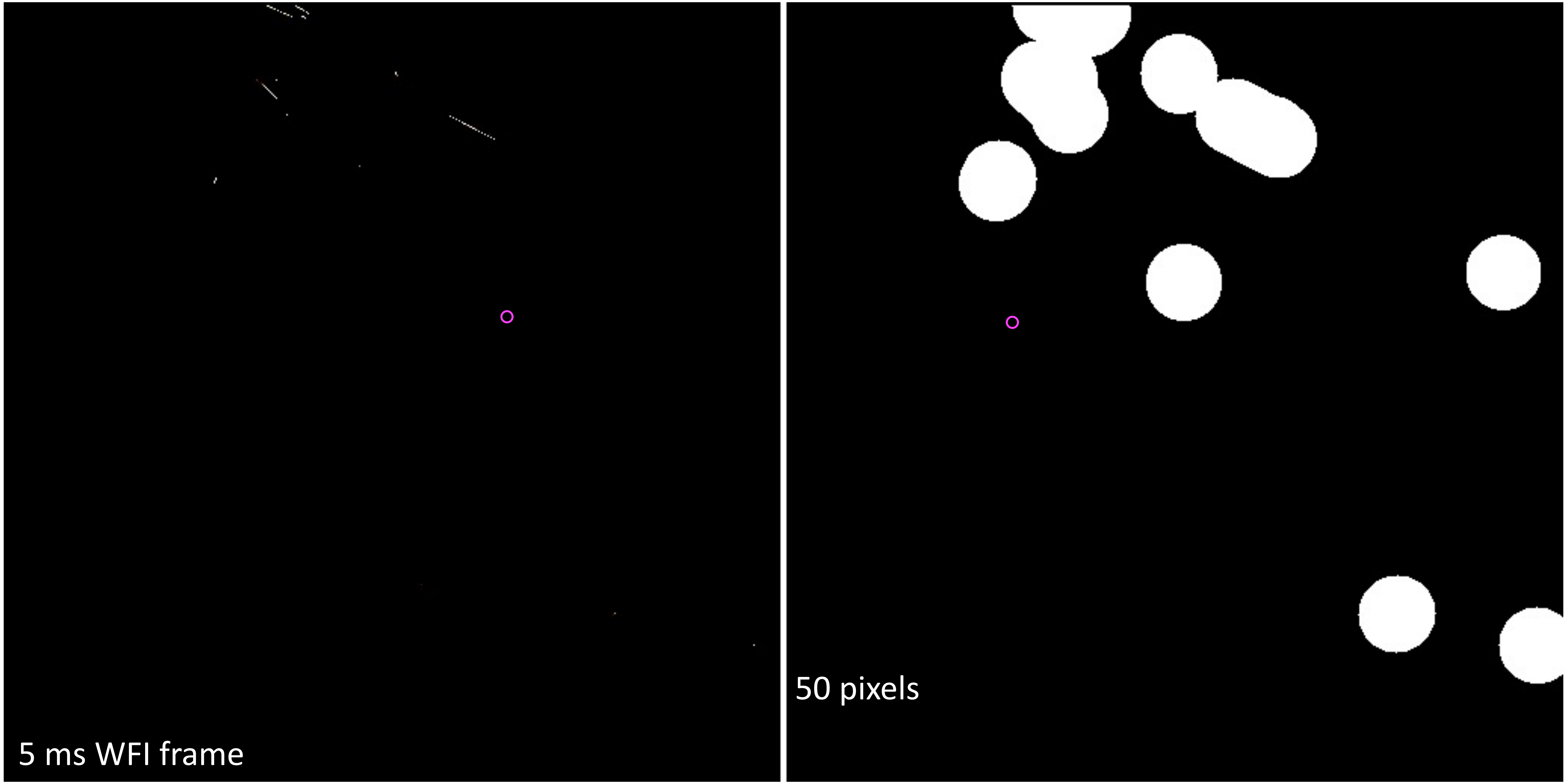

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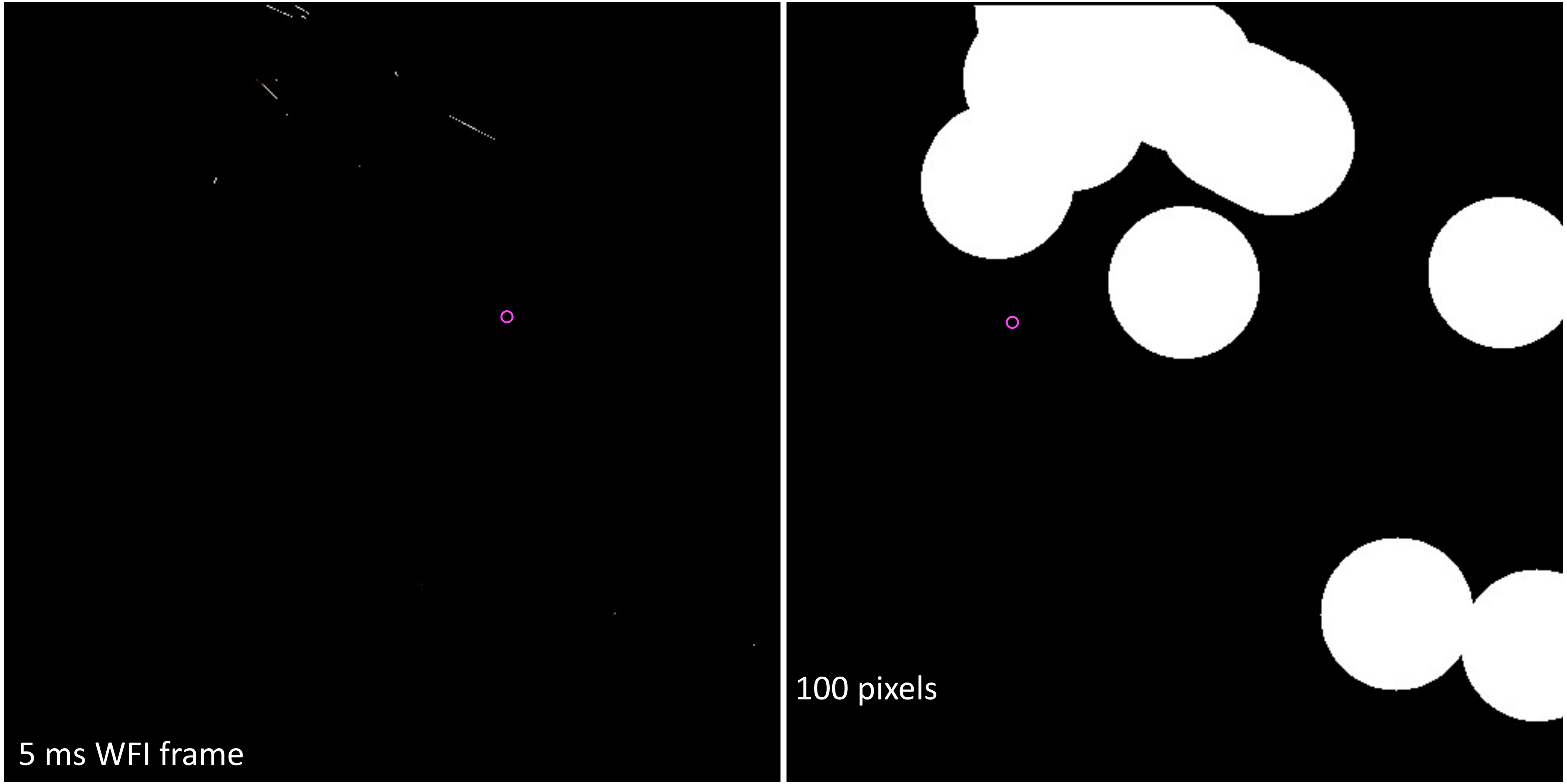

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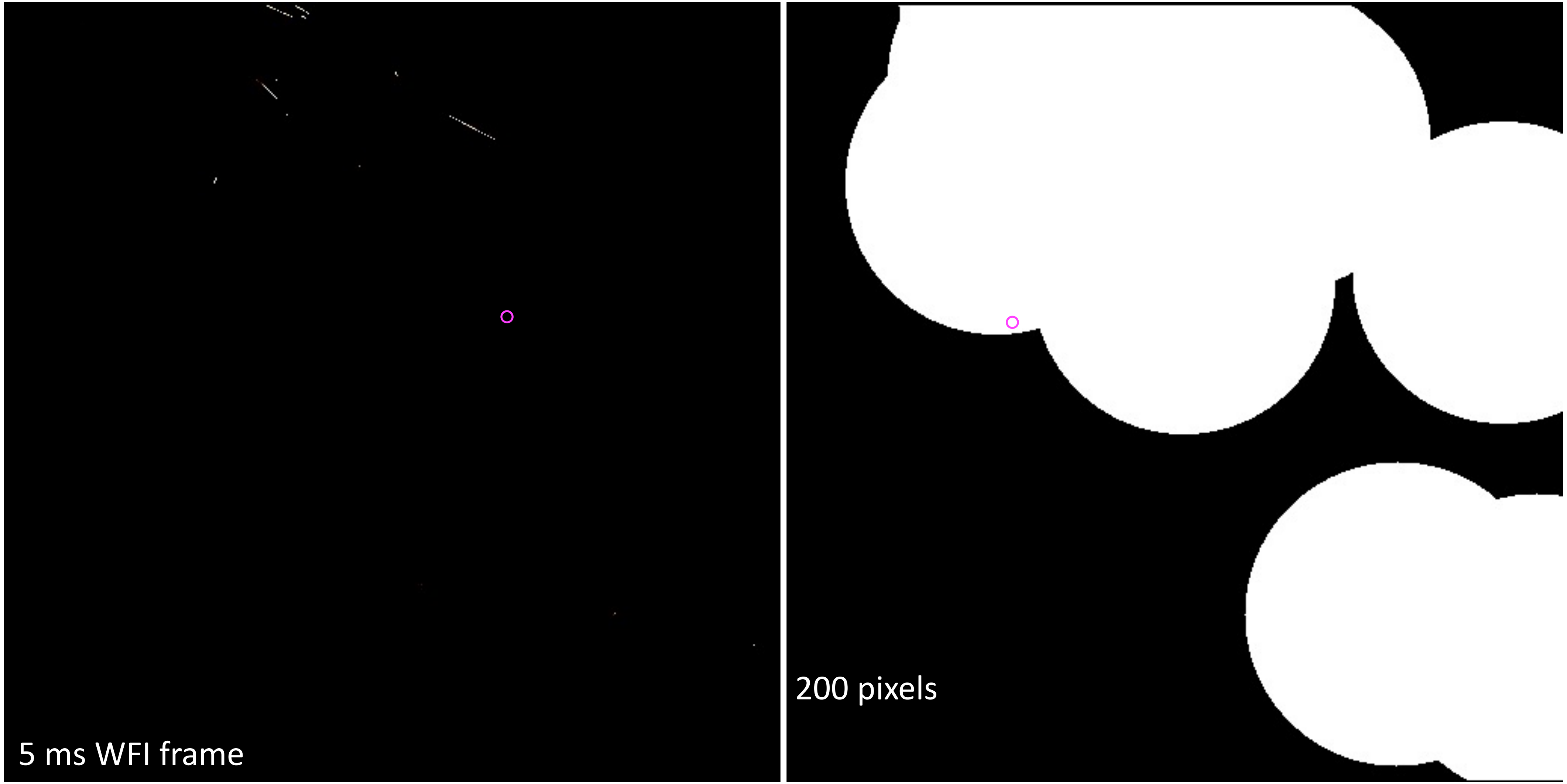

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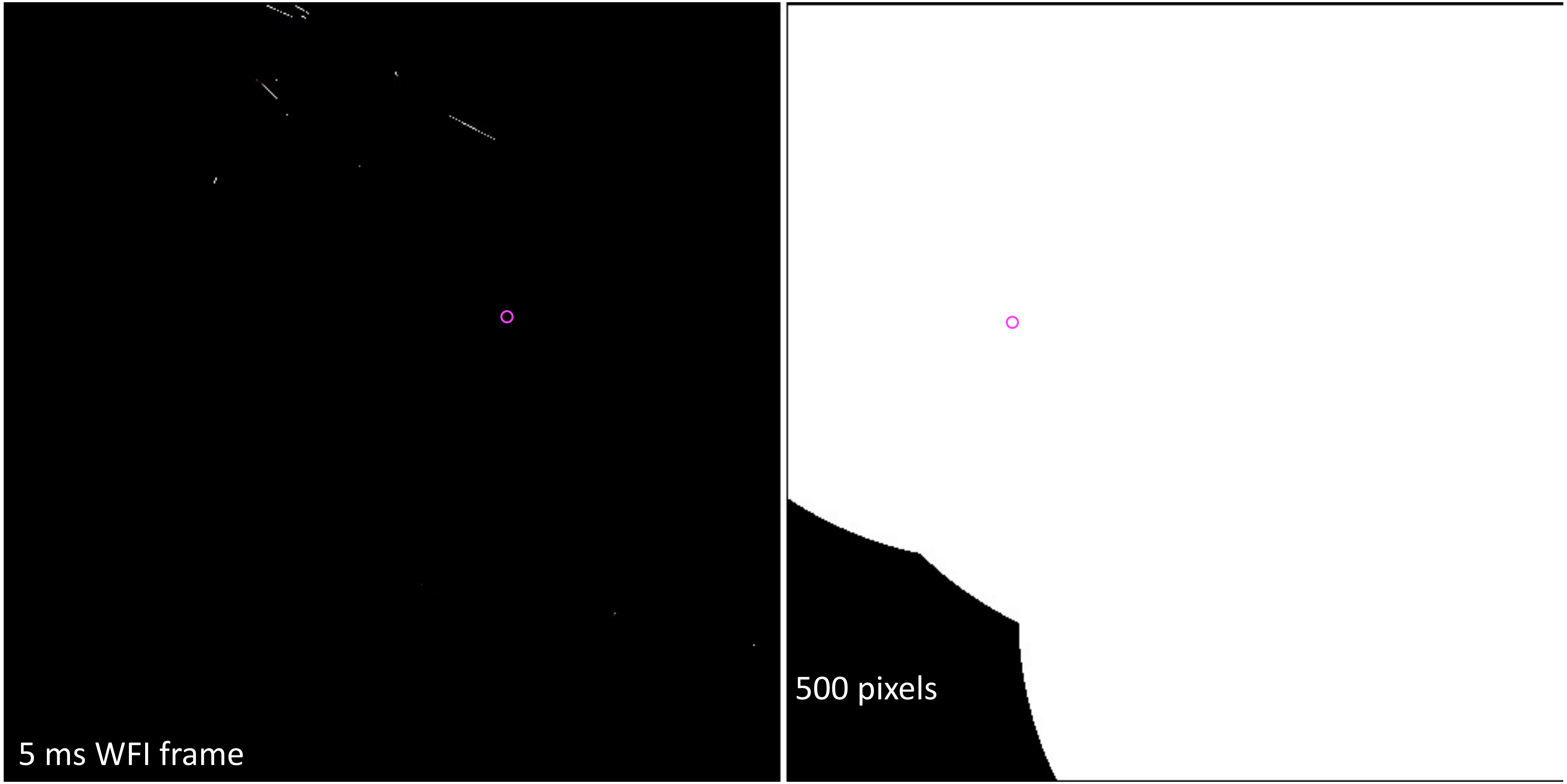
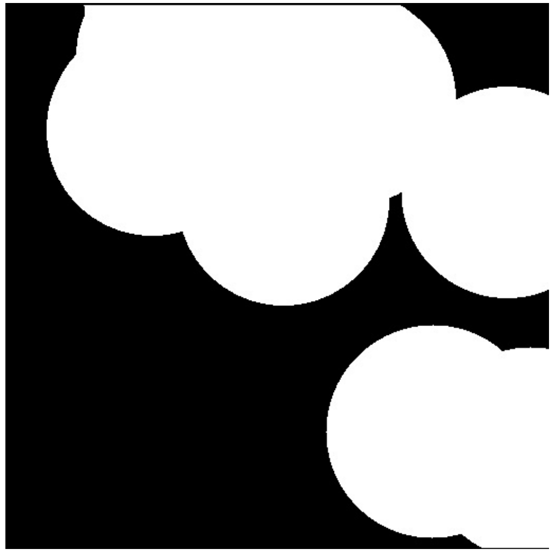
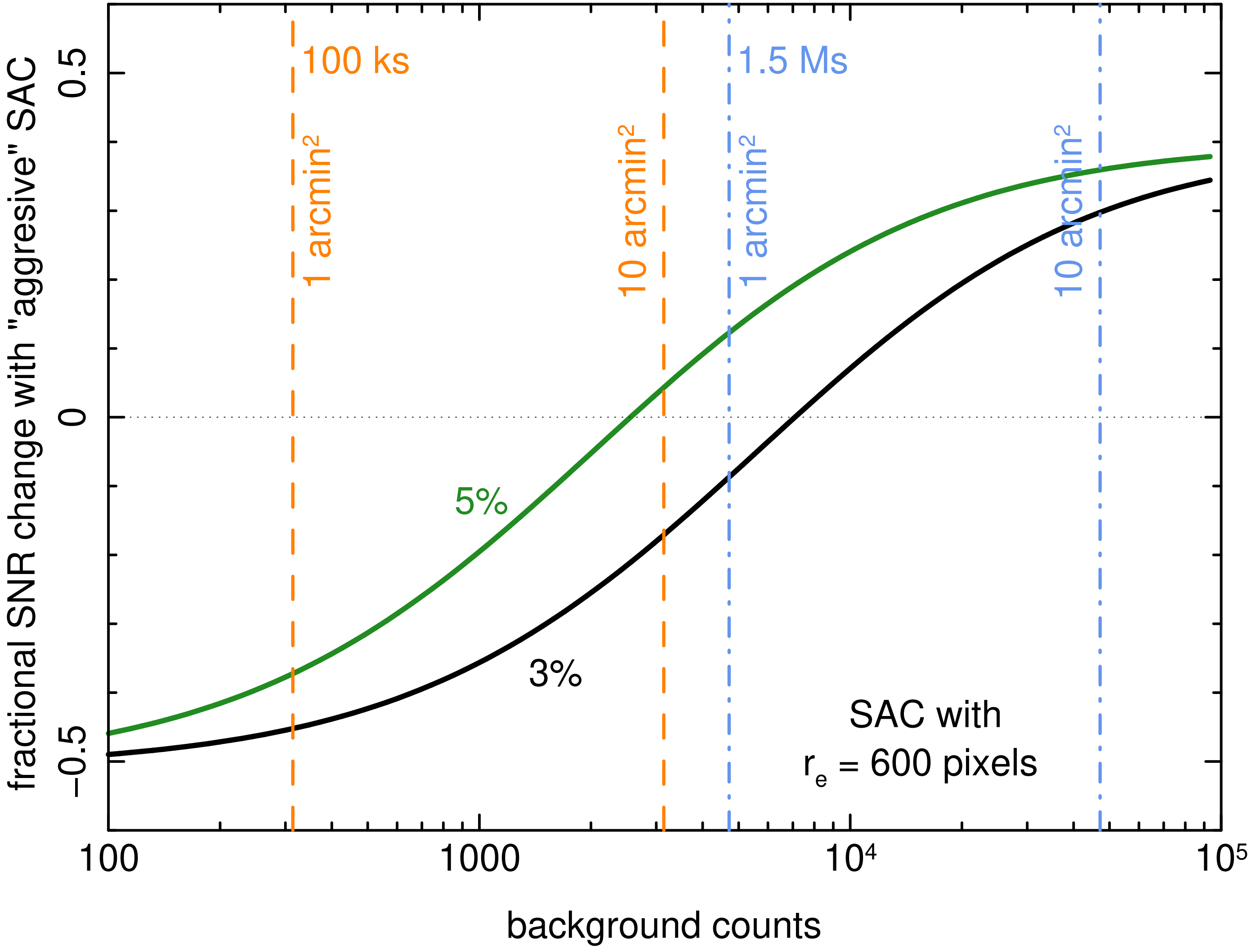


Example — WFI Deep Survey

- "Aggressive" masking can convert systematic errors to statistical ones
- Eliminates signal, but loss can be made up with longer exposure



$$SNR = \frac{S_0}{(S_0 + B_0 + \sigma^2 B_0^2)^{1/2}}$$



Summary

- Simulations of cosmic ray protons interacting with WFI
- Strong spatial correlation between particle tracks and secondary unrejected events
- Spatial masking can reduce systematic error
  - Self Anti-Coincidence: WFI as its own particle monitor
  - Selective: can be tuned or not used depending on science goal
  - All pixels with signal must be telemetered
- Future work
  - Incorporate GCR variability: can produce ~2% variations in unrejected BG
- References
  - Miller+2021, JATIS, submitted
  - Eraerds+2021, JATIS, 7, 3, 1
  - Bulbul+2020, ApJ, 891, 1, 13
  - Grant+2020, SPIE, 1144442
  - Wilkins+2020, SPIE, 114442O
  - Grant+2018, SPIE, 106994H

Mitigating the effects of particle background on the Athena Wide-Field Imager

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