A Probabilistic Method of NXB Removal for X-ray Astronomy

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Take Home Message

This is not a talk about how to estimate non x-ray background events - it is a talk about how to better remove them from your event list. The calculations and images were designed for ART-XC data, but can be applied to any high energy event list data. It is especially well suited to diffuse, low signal-to-noise regions of the sky or moving telescopes.

The Key Challenge

X-ray astronomy is almost always photon starved, and in many instances we only observe a few sky + NXB counts in a region of interest. We want to separate the sky from the background.

The simple calculation

- Observe k counts in a detector/sky region
- Expect μ_N NXB events in this region
- Interested in the expected number of sky events, μ_S
- Naively, $\mu_S = k - \mu_N$

Limitations

Simple subtraction has limitations for X-ray data at low counts

- Subtraction can go negative - not physical
- Fluctuations can make spurious signals appear "real" and vice-versa
- Difference of two Poisson RV's is not a Poisson
- Cannot ID any specific event as sky/NXB.

Assumptions

- We will assume that μ_N and μ_S are Poisson processes.
- We observe k_N NXB counts and k_S sky photons, but only know that $k_N + k_S = k$.

We consider each possible count state individually and take the weighted average over all states. What are the values of μ_S that are consistent with k observed counts given μ_N?

The Math I

The Poisson distribution is at the center of all of these calculations

$$P(k|\mu) = \frac{e^{-\mu} \times \mu^{k}}{k!}$$

The Math II

Per-state net counts estimated as the maximum of a simple Poisson

$$\frac{\partial \mathsf{P}(\mathbf{k}_\mathsf{S}|\mu_\mathsf{S})}{\partial \mu_S} = 0 \rightarrow \bar{\mu}_\mathsf{S}(\mathbf{k}_\mathsf{N}) = \mathbf{k}_\mathsf{S} = \mathbf{k} - \mathbf{k}_\mathsf{N}$$

Weights for each state are the background probabilities

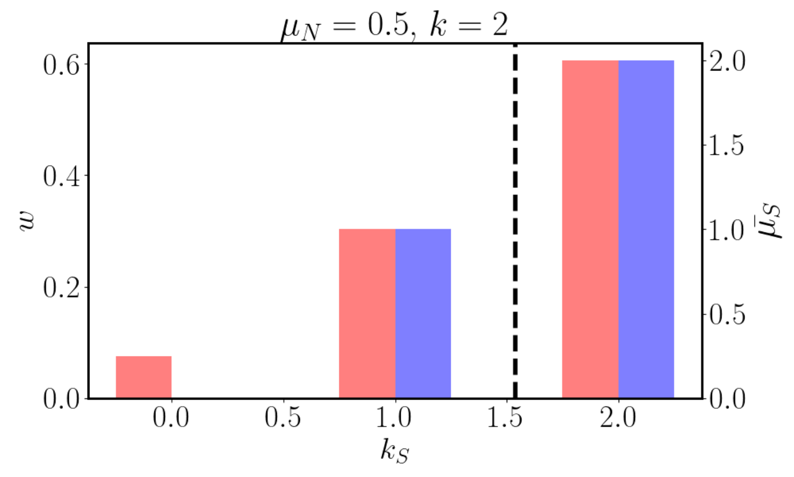
$$\mathbf{w}(\mathbf{k}_\mathsf{N}|\mu_\mathsf{N}, \bar{\mu}_\mathsf{S}, \mathbf{k}) = \mathsf{P}(\mathbf{k}_\mathsf{N}|\mu_\mathsf{N})$$

The Math III

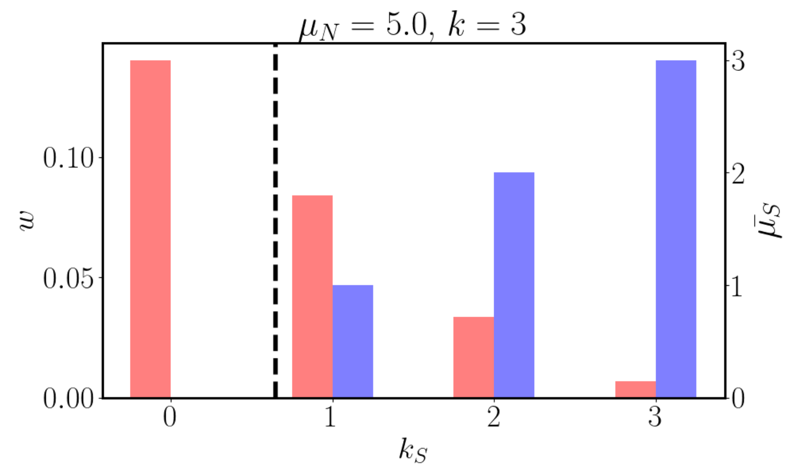
Final result is weighted average over all states

$$\mu_{\mathsf{S}}^{\star} = \frac{1}{\mathsf{V}_1} \sum_{\mathbf{k}_{\mathsf{N}}=0}^{\mathbf{k}} \bar{\mu}_{\mathsf{S}}(\mathbf{k}_{\mathsf{N}}) \times \mathbf{w}(\mathbf{k}_{\mathsf{N}} | \mu_{\mathsf{N}}, \bar{\mu}_{\mathsf{S}}, \mathbf{k})$$

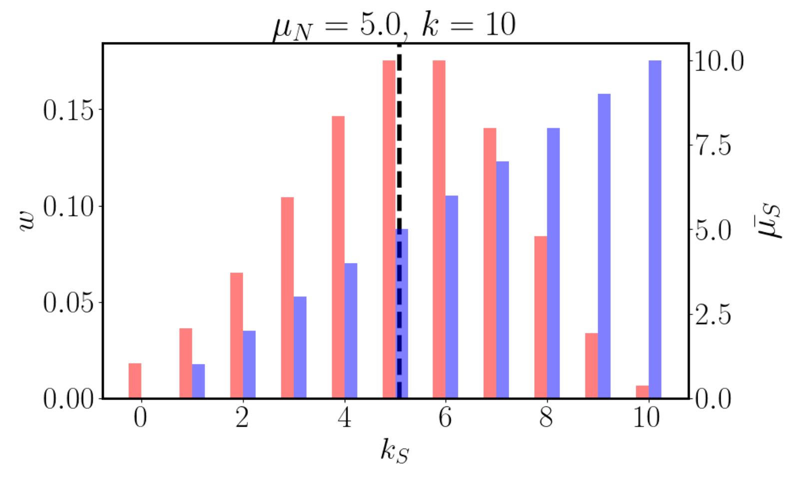
Examples



Examples



Examples



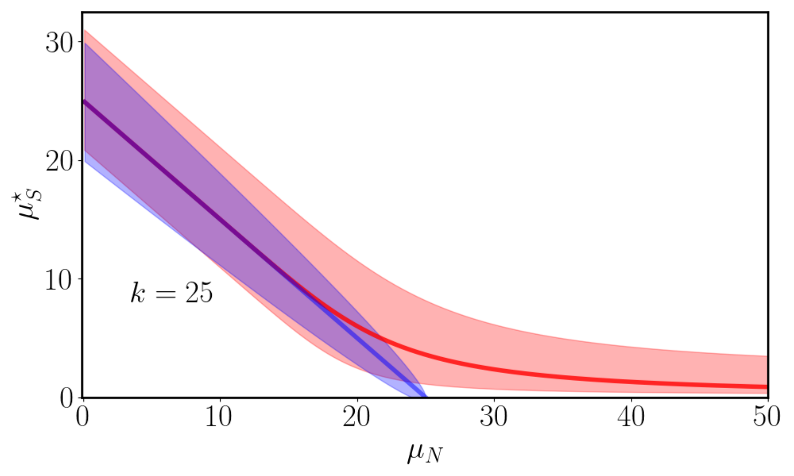
Uncertainties

We can calculate a central $c \times 100\%$ confidence interval (x_L, x_U) analytically

$$\frac{\gamma_L(k+1, x_L + \mu_N) - \gamma_L(k+1, \mu_N)}{\Gamma_U(k+1, \mu_N)} = \frac{1-c}{2}$$

$$\frac{\gamma_L(k+1, x_U + \mu_N) - \gamma_L(k+1, \mu_N)}{\Gamma_U(k+1, \mu_N)} = \frac{1+c}{2}$$

Old Versus New Calculation



Advantages of this New Method

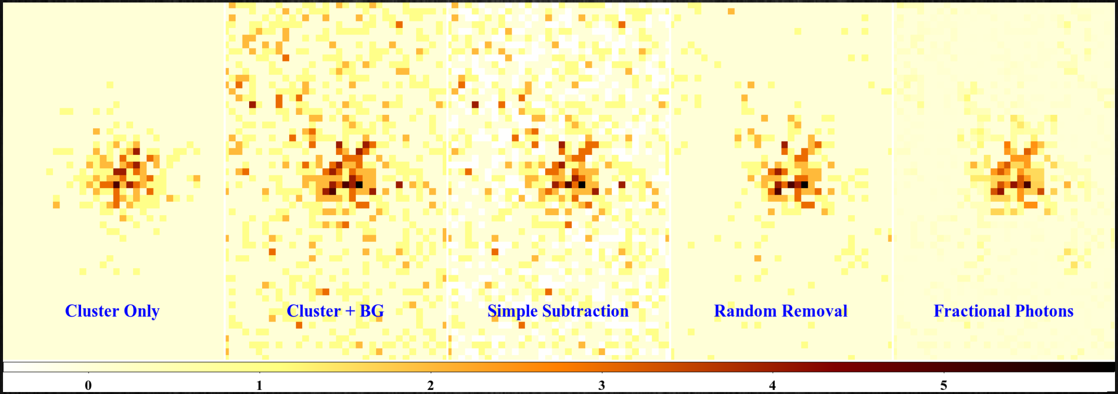
- Always non-negative. Only get zero net counts when zero counts observed
- Net counts converge to zero as $\mu_{\mathsf{N}} >> \mathsf{k}$
- Monte Carlo simulations show small bias (~ 0.5 counts high using ground truth inputs) that otherwise does not vary with input parameters.
- Can construct event specific probabilities $\mathsf{p_S} = \frac{\mu^\star_{\mathsf{S}}}{\mu^\star_{\mathsf{S}} + \mu_{\mathsf{N}}}$.

Event Specific Probabilities

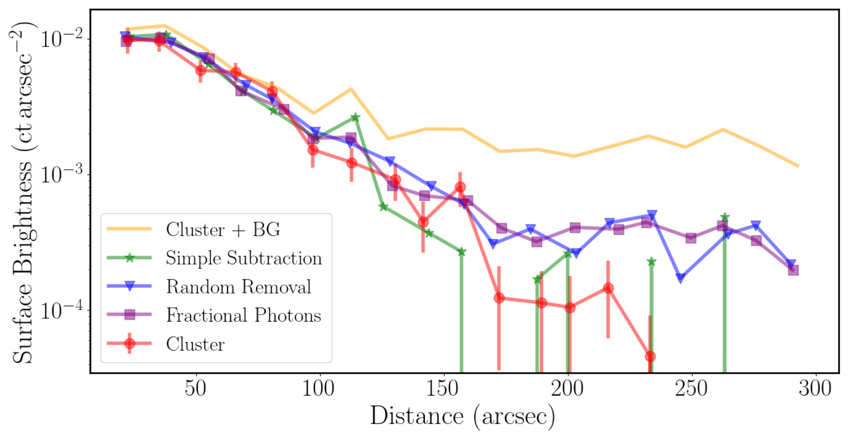
Here are three ways to use event specific probabilities (p_S) to clean images of NXB for X-ray telescopes, depending on your interests and needs:

- Random Removal: select a random number between 0 and 1 for each event. If that random number is less than p_S keep it.
- Fractional Photons: Instead of projecting 1 whole event onto the sky, only project p_S events.
- False Probability: Project $p_N = 1 - p_S$ onto the sky. As you add telescopes take the product in order to reduce noise.

Simulated Cluster Images



Simulated Cluster Profiles



Next Steps

- Paper coming to MNRAS soon - just got first referee report
- A version of this calculation for Chandra data will be integrated into CIAO, with development and science testing underway
- Develop use with other observatories
- Investigate use with other modes beyond imaging