# The Resilience Problem in Extreme Scale Computing: Experiences and the Path Forward

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ORNL is managed by UT-Battelle, LLC for the US Department of Energy

# Motivation

- Resilience in extreme-scale supercomputers is an optimization problem between the key design and deployment cost factors:
  - Performance, resilience, and power consumption
- The challenge is to build a reliable system within a given cost budget that achieves the expected performance.
- This requires fully understanding the resilience problem and offering efficient resilience mitigation technologies.
  - What is the fault model of such systems?
  - What is the impact of faults on applications?
  - How can mitigation in hard-/software help and at what cost?


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# Characterizing Supercomputer Faults, Errors and Failures

**Novel Ideas:**

- Applies a unified taxonomy for supercomputer faults, errors and failures
- Understanding resilience is a data analytics problem, requiring fusion and analysis of different logs and system health data

**Impact:**

- Develops an understanding of observed and inferred supercomputer reliability conditions
- Extrapolates this knowledge to future systems
- Enables the systematic improvement of resilience in extreme-scale systems
- Keeps applications running to a correct solution in a timely and efficient manner in spite of frequent faults, errors, and failures

**Accomplishments:**

- Analyzed 1.2 billion node hours of logs from the Jaguar, Titan, and Eos systems at OLCF
- Developed tools for analyzing logs and creating a fault, error and failure catalog
- Created novel modeling techniques to characterize temporal and spatial failure behavior

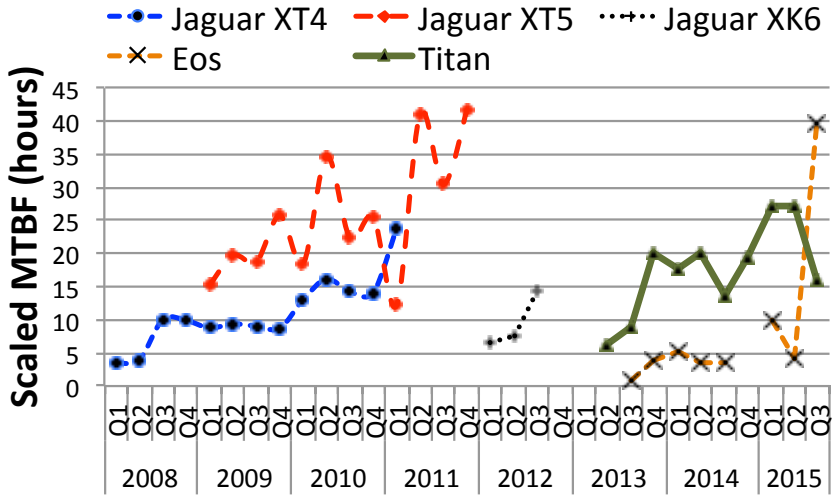
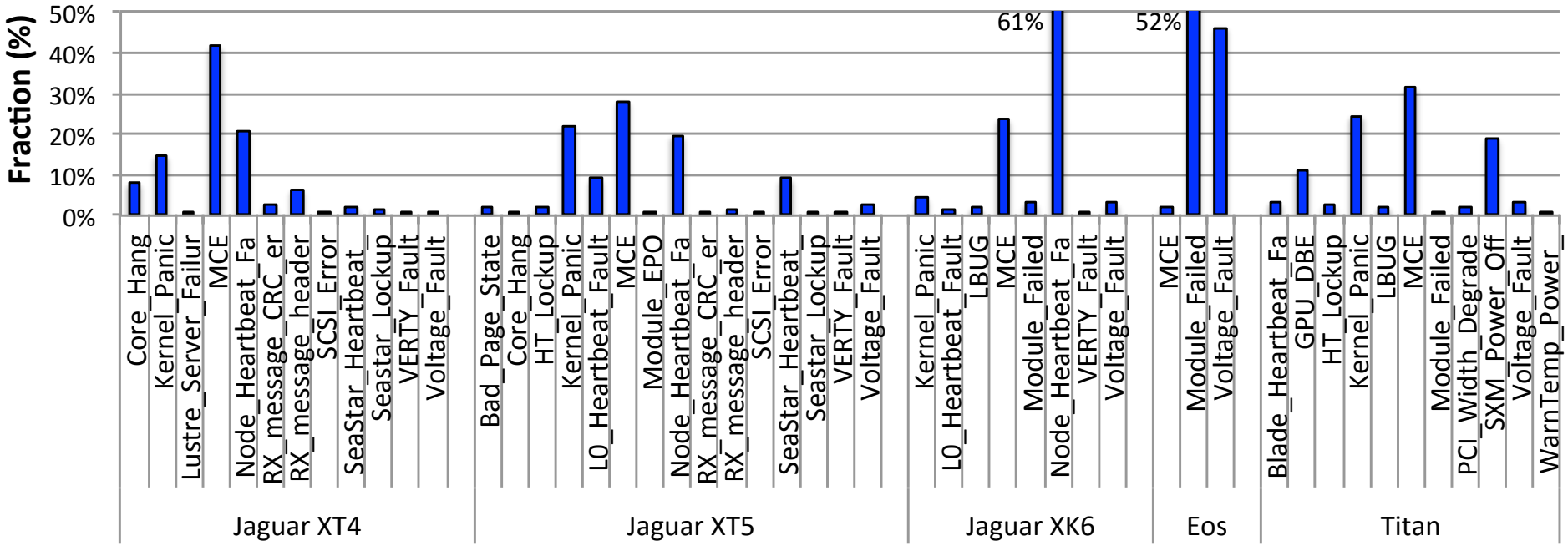



***Figure: Each system goes through phases of high and low stability due to continuous efforts of system administrators to improve overall system reliability***



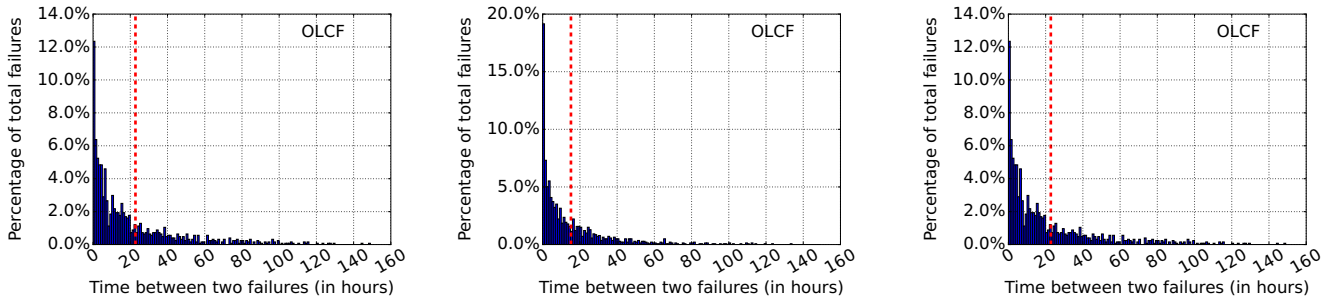
Saurabh Gupta, Devesh Tiwari, Tirthak Patel, and Christian Engelmann. **Reliability of HPC systems: Large-term Measurement, Analysis, and Implications.** SC'17. DOI 10.1145/3126908.3126937.

# Characterizing Supercomputer Faults, Errors and Failures



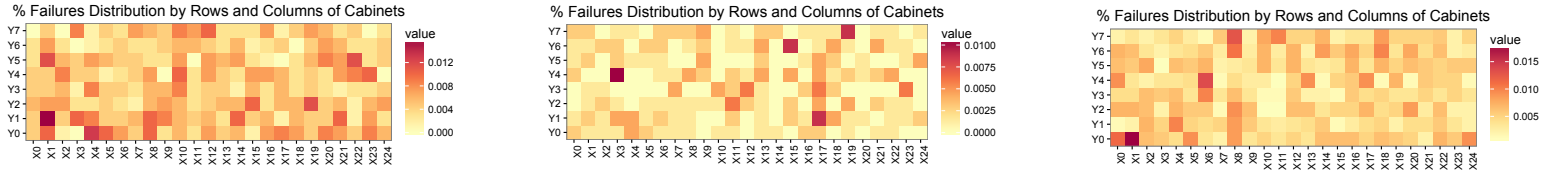

**Fraction of each failure type on the studied systems**

# Characterizing Supercomputer Faults, Errors and Failures



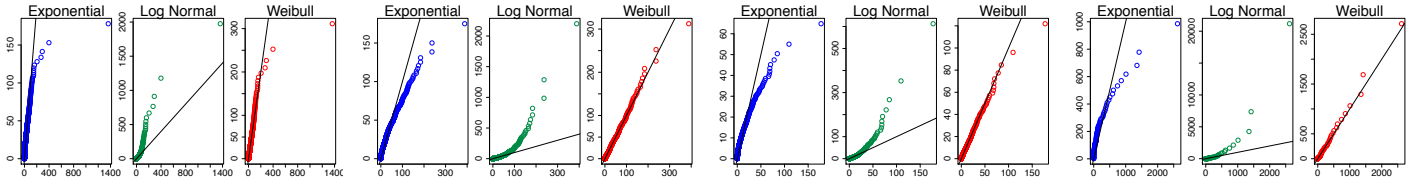

(a) Jaguar XT4 (b) Titan (c) Eos

**Failure inter-arrival time for 3 studied systems (MTBF as red vertical line)**




(a) Jaguar XT5 (b) Jaguar XK6 (c) Titan

**Spatial distribution of failures among cabinets for 3 studied systems**




(a) Jaguar XT4 (b) Jaguar XT5 (c) Jaguar XK6 (d) Eos

**QQ-plots showing goodness of fit for the failure inter-arrival times for 4 studied systems with different failure probability density functions (Weibull fits best)**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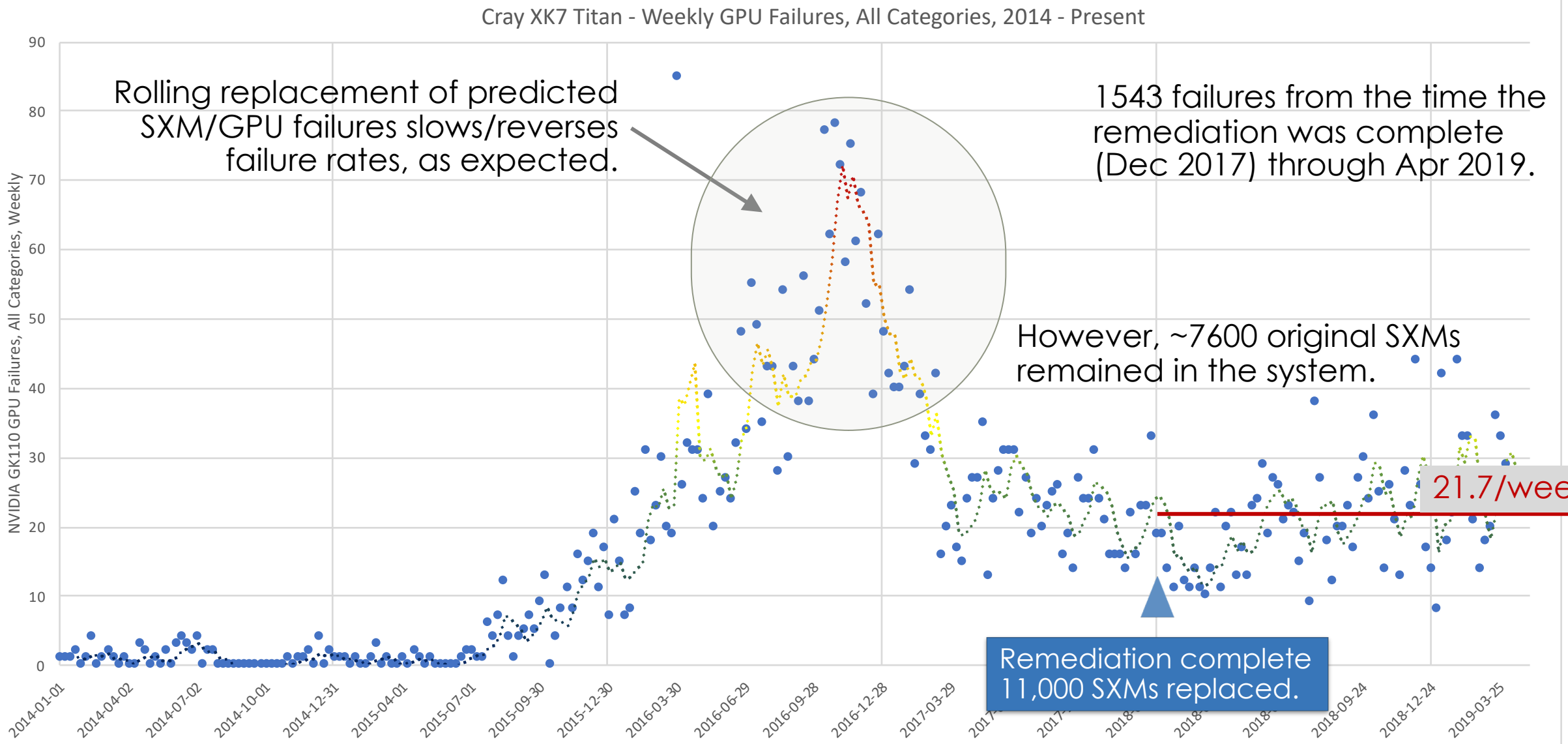
# Cray XK7 Titan – Weekly GPU Failures



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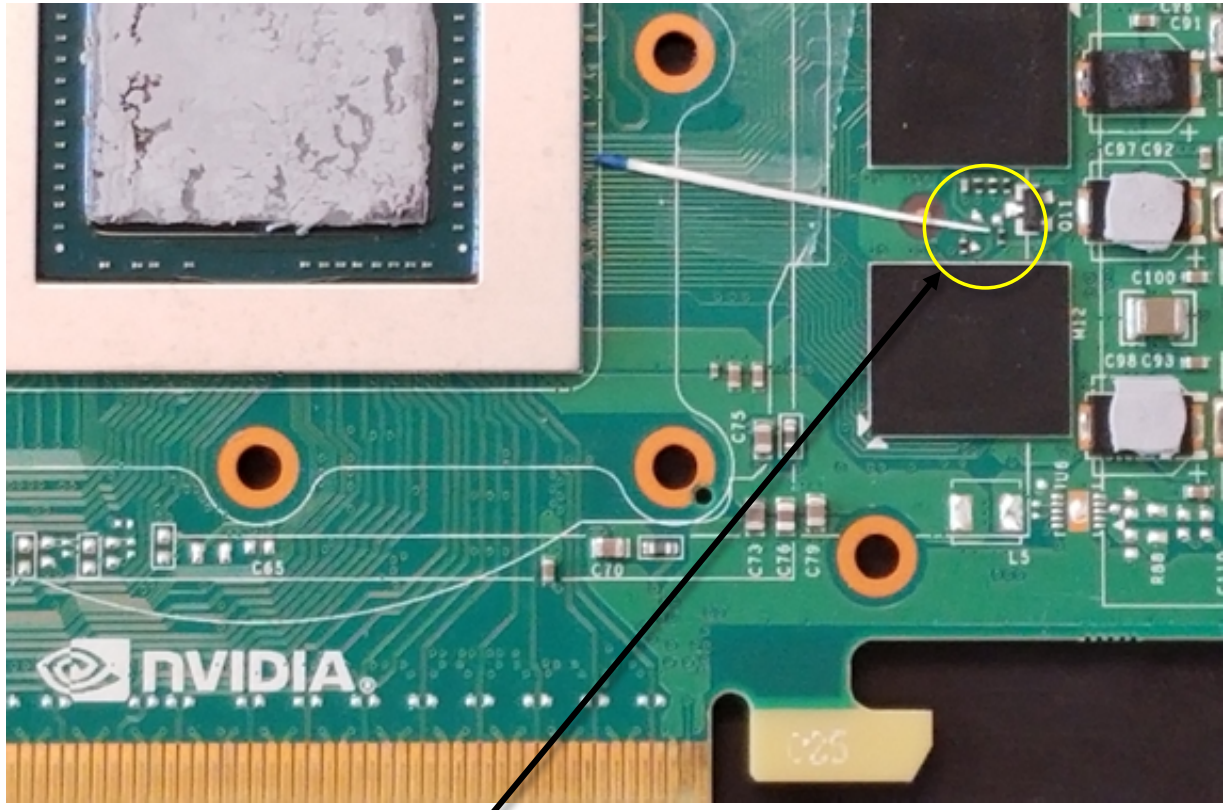
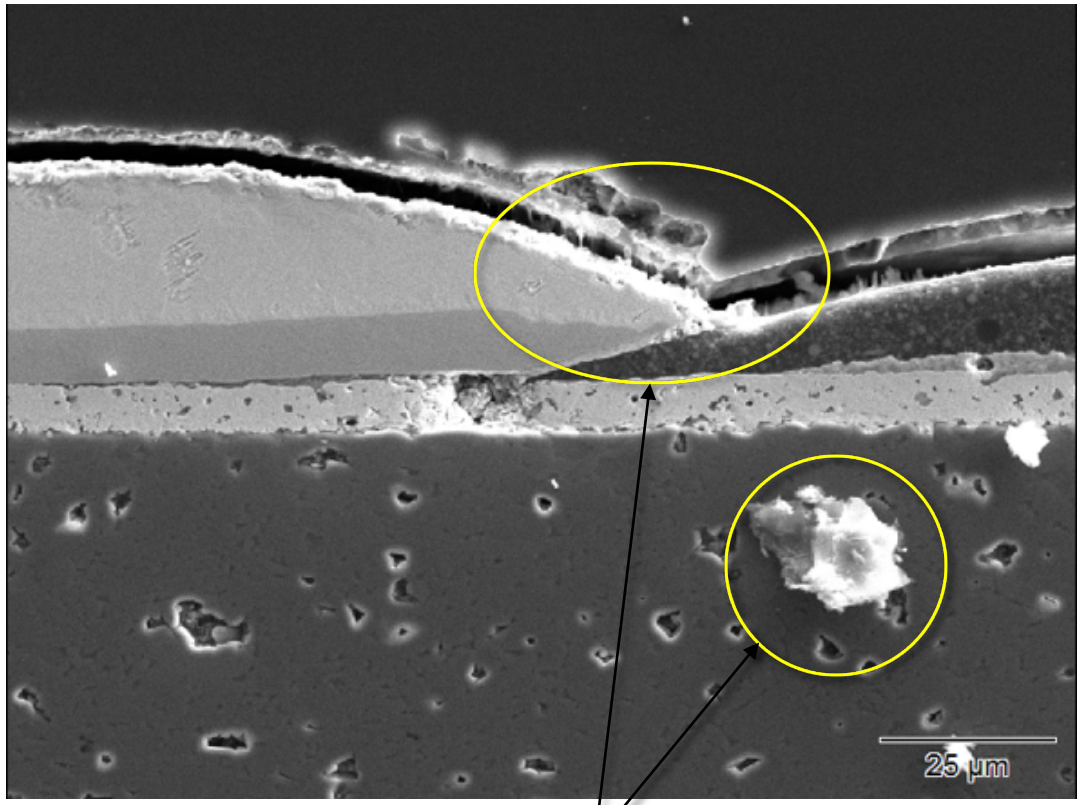
G. Ostrouchov, D. Maxwell, R. Ashraf, C. Engelmann, Mallikarjun Shankar, and James Rogers. **GPU Lifetimes on Titan Supercomputer: Survival Analysis and Reliability.** SC'20. DOI 10.1109/SC41405.2020.00045.

# Root Cause: Non-ASR Components on SXM GPU




*NVIDIA SXM – Location of a non-ASR*




*Silver-sulfide corrosion*
*"Flowers-of-Sulfur"*

ASR = Anti-Sulfur Resistor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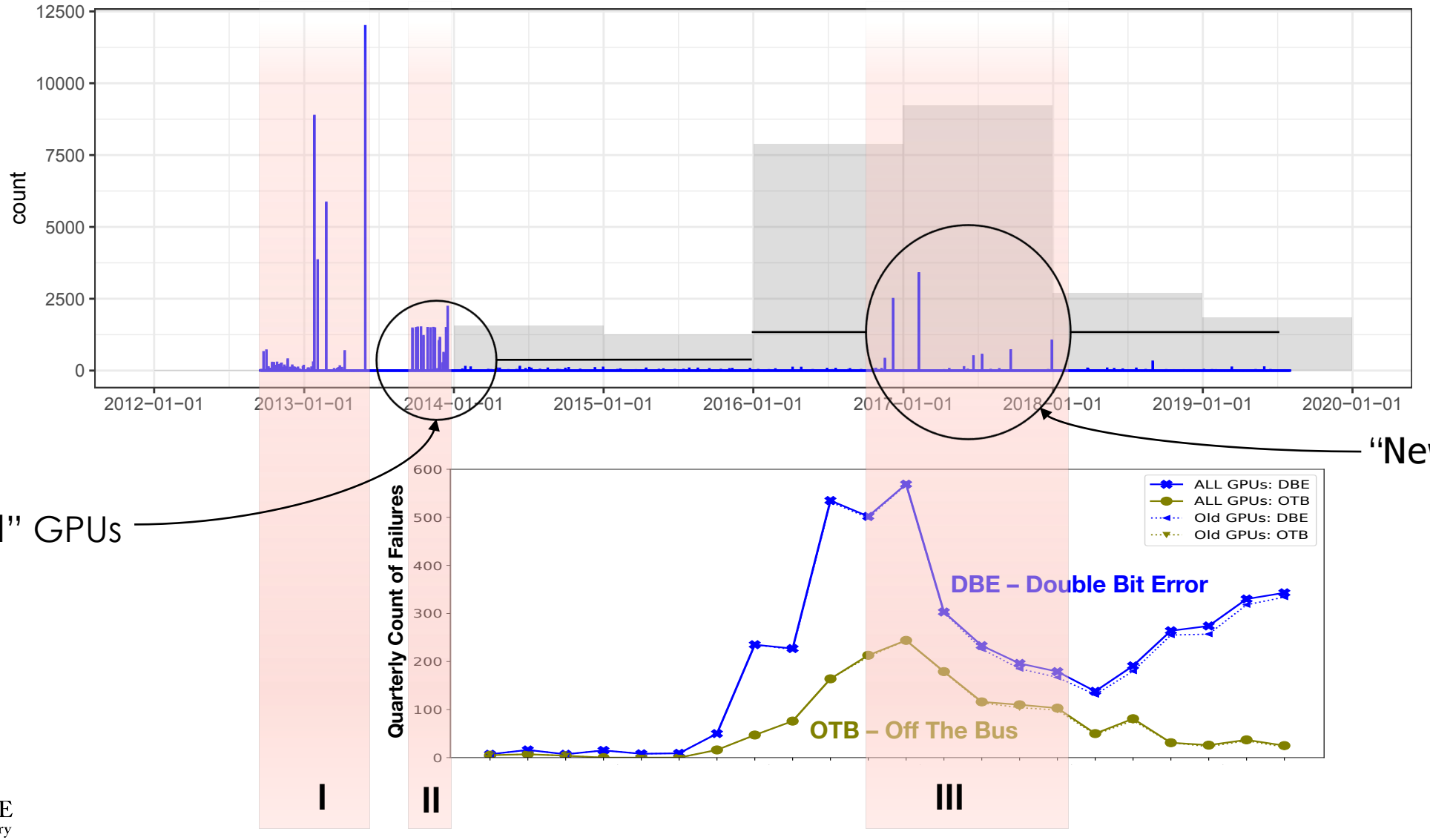
# GPU Failures and Replacements in ORNL's Titan

GPU swaps detected at inventories (narrow blue) and yearly sum totals for 2014 and later (wide gray)



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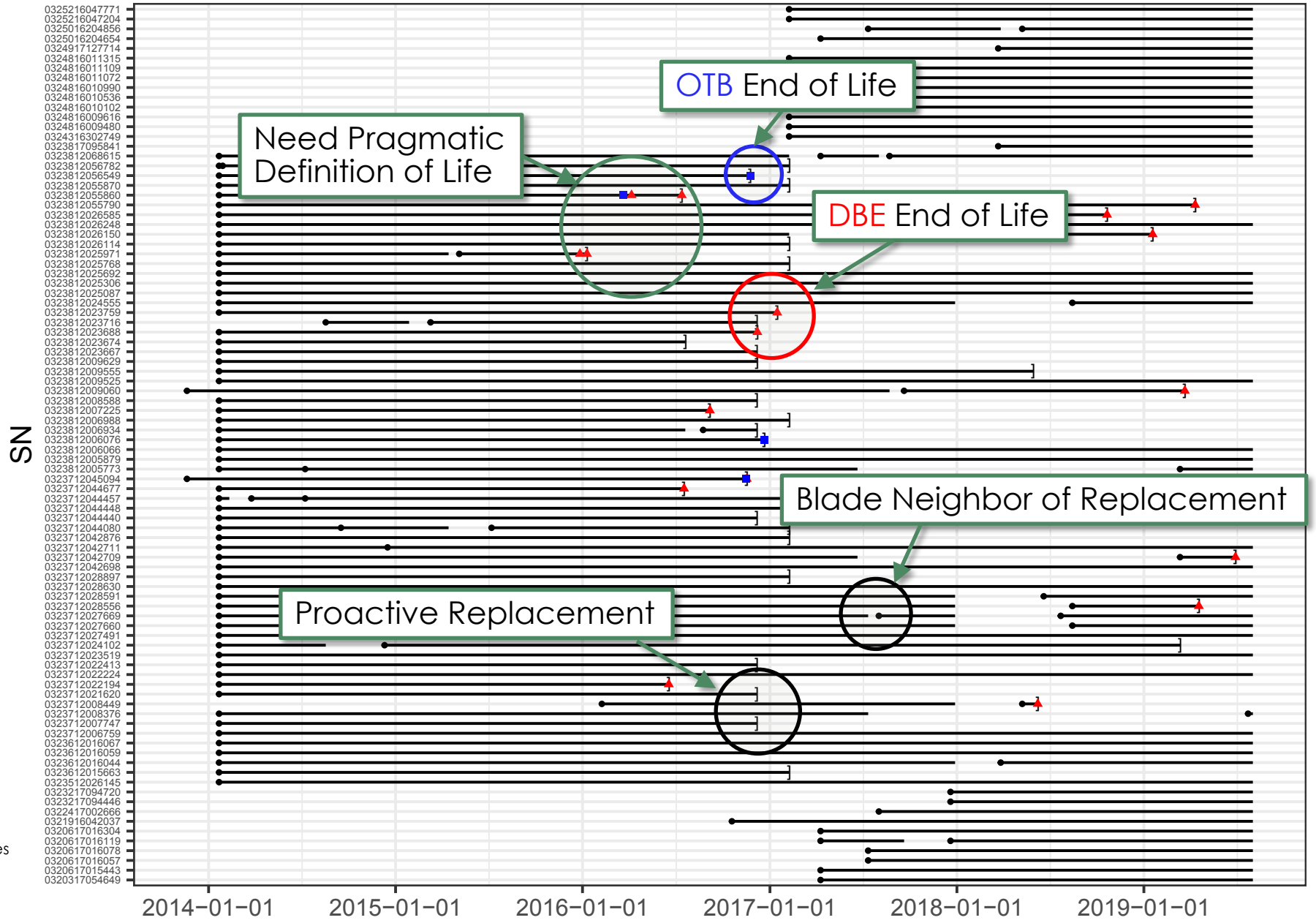
# GPU Life Visualization: Serial Number View

**Critical for:**

- Understanding data
- Defining GPU Life
- Data processing verification




Produced in R via `ggplot2` and `lubridate` packages



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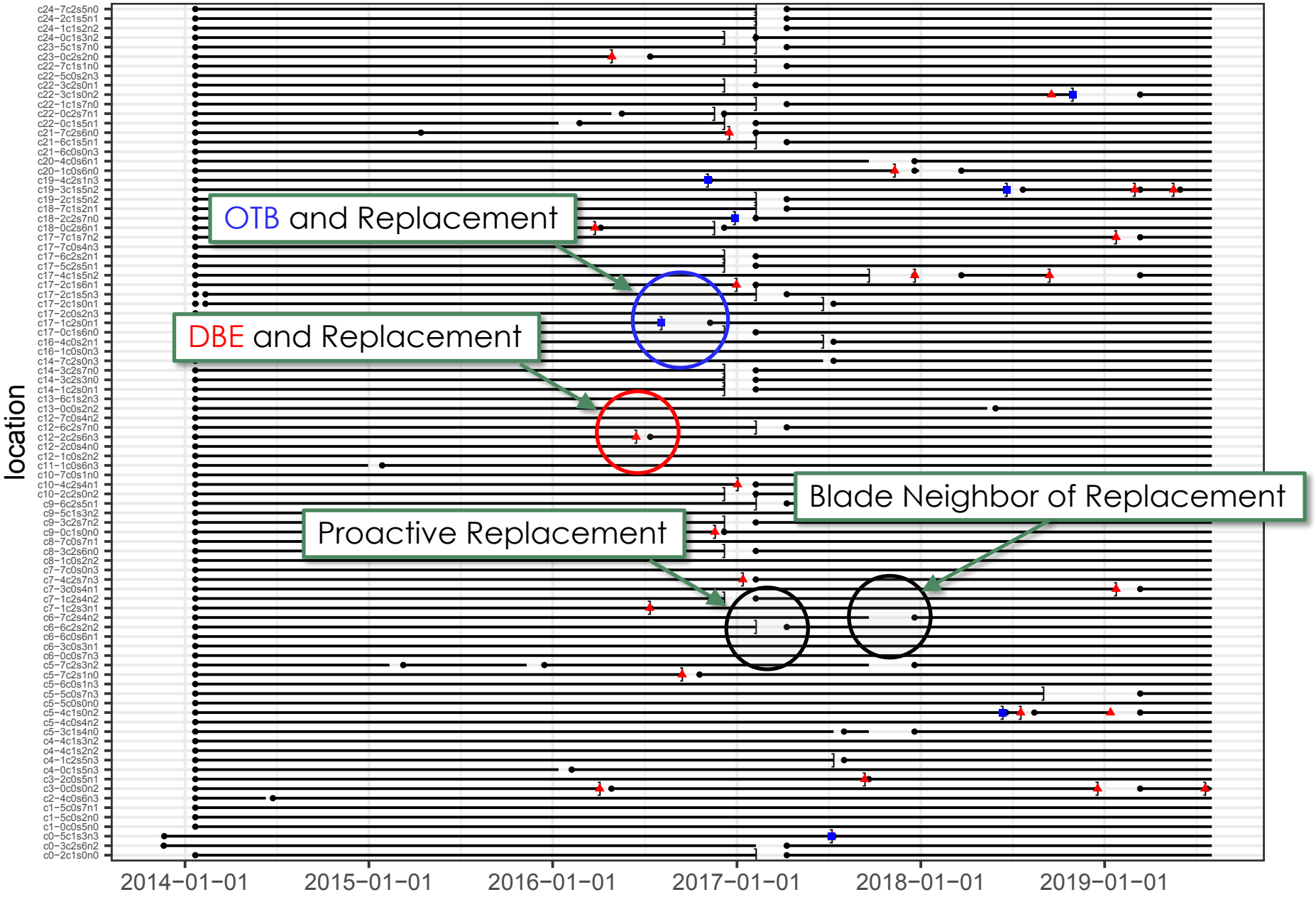
# GPU Life Visualization: Location View

**Critical for:**

- Understanding data
- Defining GPU Life
- Data processing verification




Produced in R via `ggplot2` and `lubridate` packages



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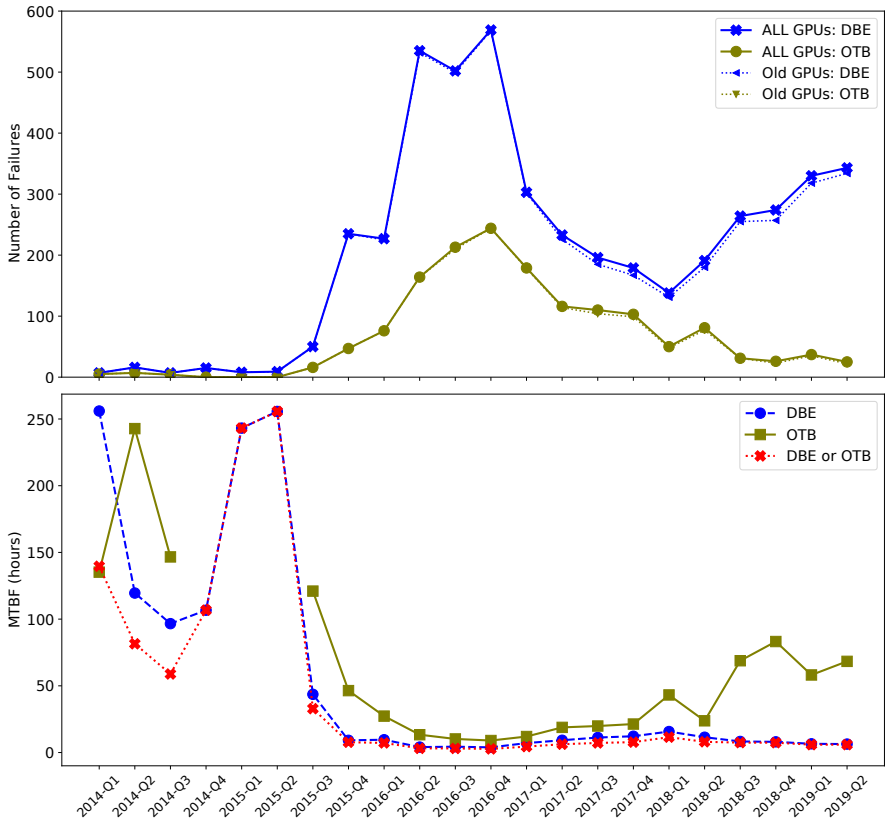
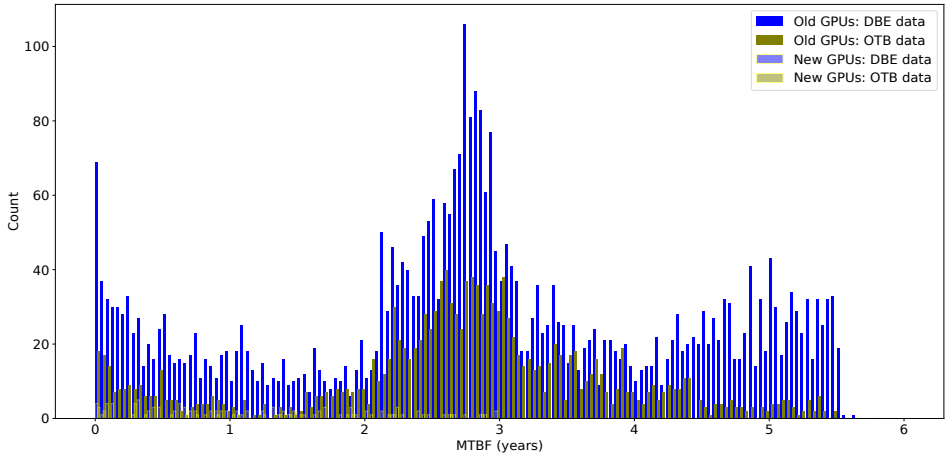
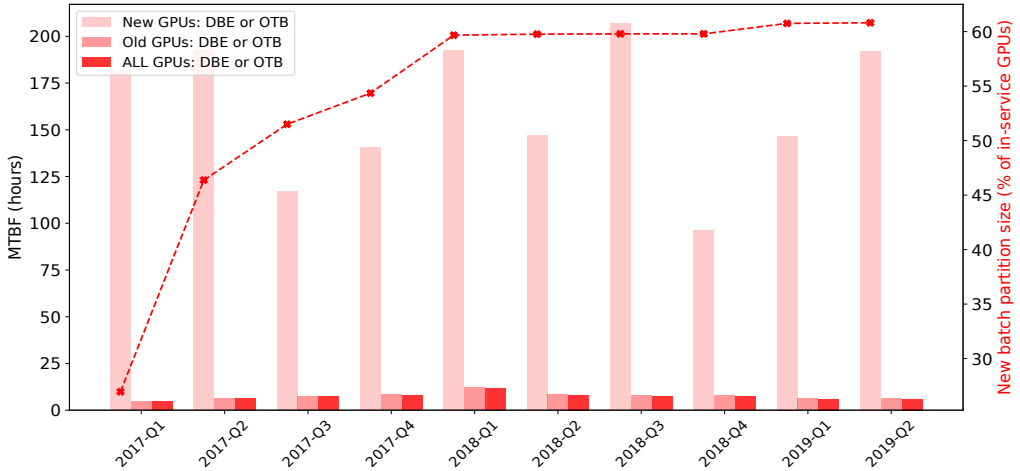
# Traditional Reliability in HPC is Focused on MTBF




**System-wide Reliability**: Quarterly number of failures (top) and MTBF (bottom).




**Individual GPU Reliability**: MTBF histogram for units that had at least one failure. Interpret carefully: lacks information from units with no failures!




**Old–New as Two Partitions**: MTBF differs by 12x factor!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# Kaplan-Meyer Survival Analysis

- Commonly used in Biostatistics and Biomedical research*
- Nonparametric
  - If $T$ is failure time and $F(t) = \Pr\{T < t\}$ is the cumulative failure distribution function
  - Then the survival probability, $S(t) = \Pr\{T \geq t\} = 1 - F(t)$, is its complement
  - Recursive computation $S(t_2) = \Pr\{\text{survive from } t_1 \text{to } t_2\}\, S(t_1)$
- Able to incorporate censoring
- Split population into groups
- Available uncertainty estimate

*E. L. Kaplan and P. Meier, "Nonparametric estimation from incomplete observations," *Journal of the American Statistical Association*, vol. 53, no. 282, pp. 457–481, 1958.


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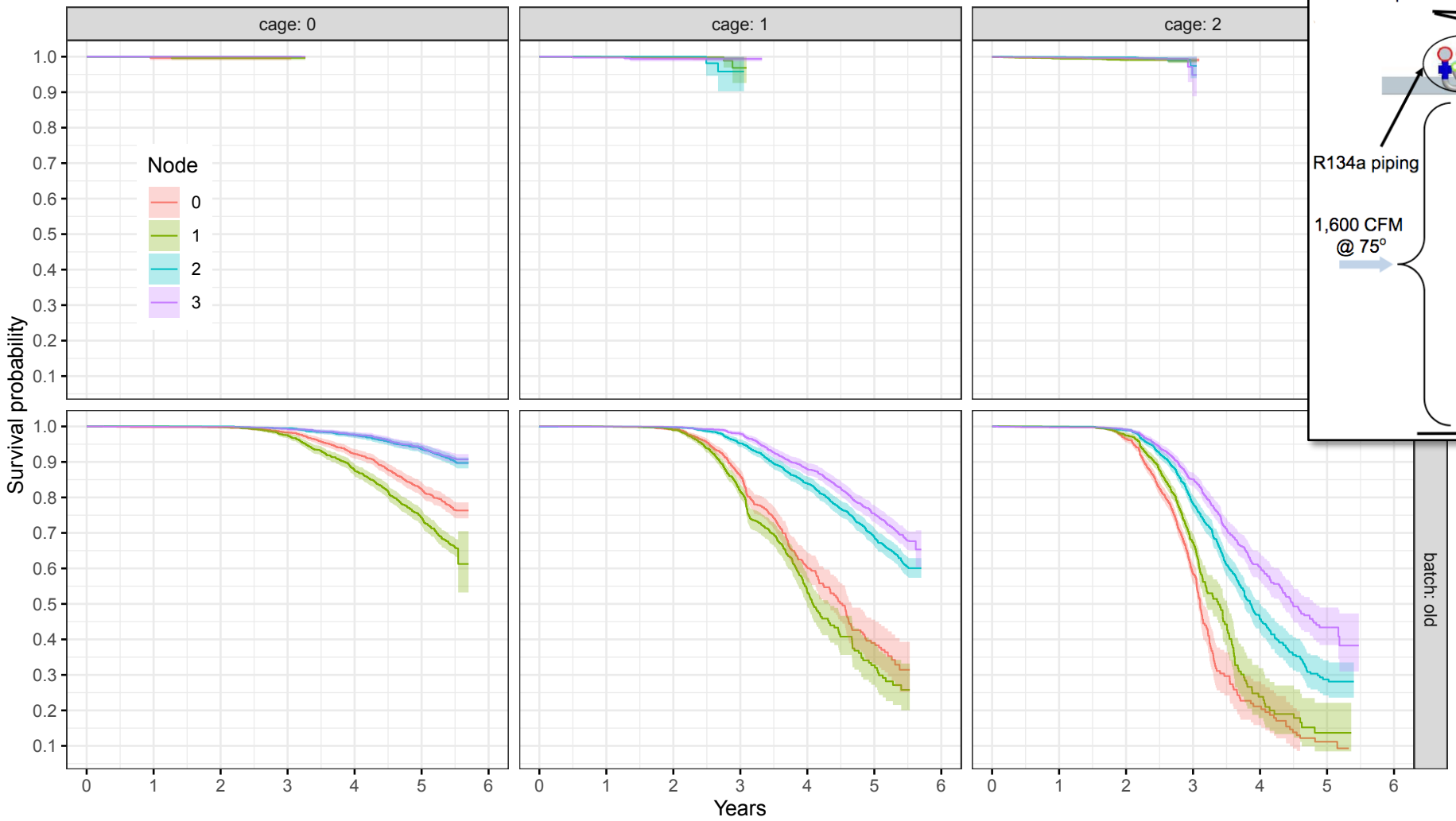
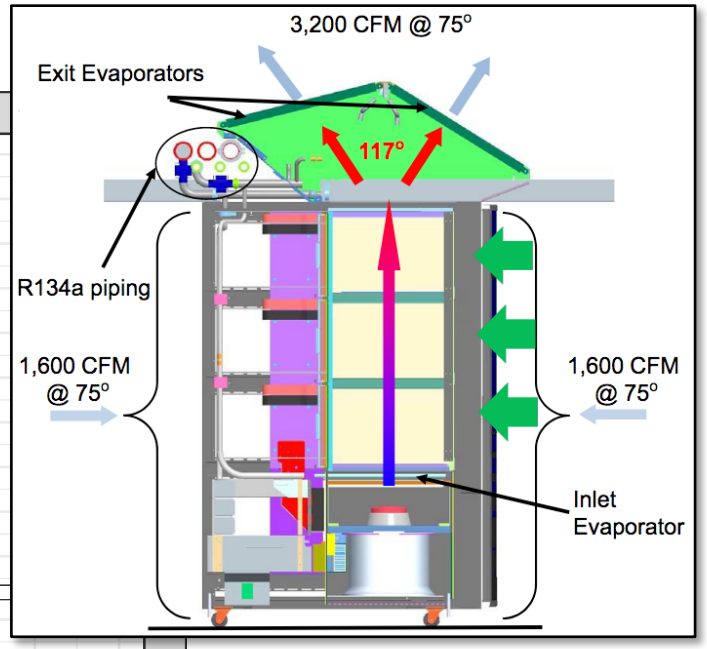
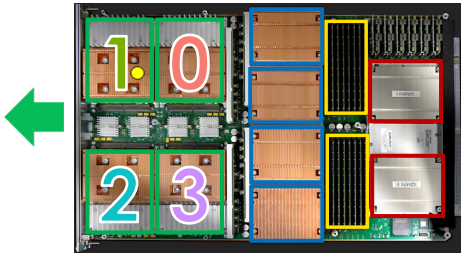
# Cage and Node Effect Explainable by Airflow in Cabinet



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# Cox Proportional Hazards Regression Model

- Commonly used in Biostatistics and Biomedical research*
- Able to adjust for covariate effects
- Each GPU is like a patient, affected by its location (treatment)
- The hazard for patient k is $H_k(t) = H_0(t)e^{\sum_1^n \beta_i x_i}$
  - Base hazard rate, $H_0(t)$, multiplied by a function of covariates (hazard coefficient)
- Semiparametric model
  - Baseline hazard is nonparametric (no functional shape assumption)
  - Hazard coefficient is a parametric function of covariates
- Assumes hazards are proportional

*D. R. Cox, "Regression models and life-tables," *Journal of the Royal Statistical Society. Series B (Methodological)*, vol. 34, no. 2, pp. 187– 220, 1972.
We use R packages `survival` and `survminer`.


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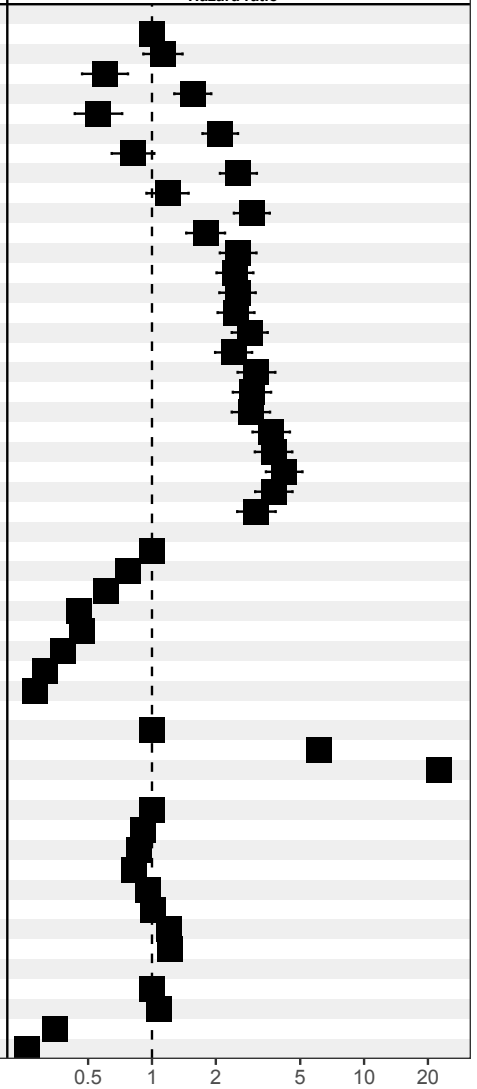
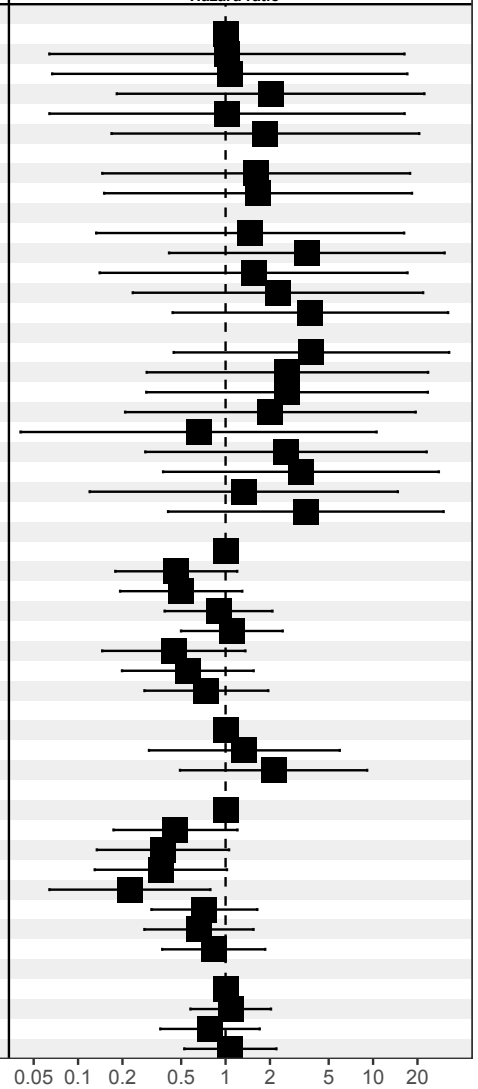
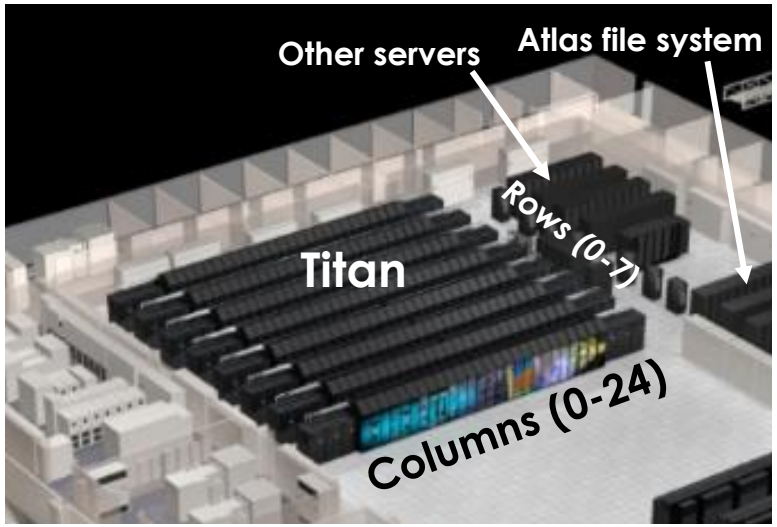
# Strong Signal in old Batch, Pattern Similar to K-M Analysis

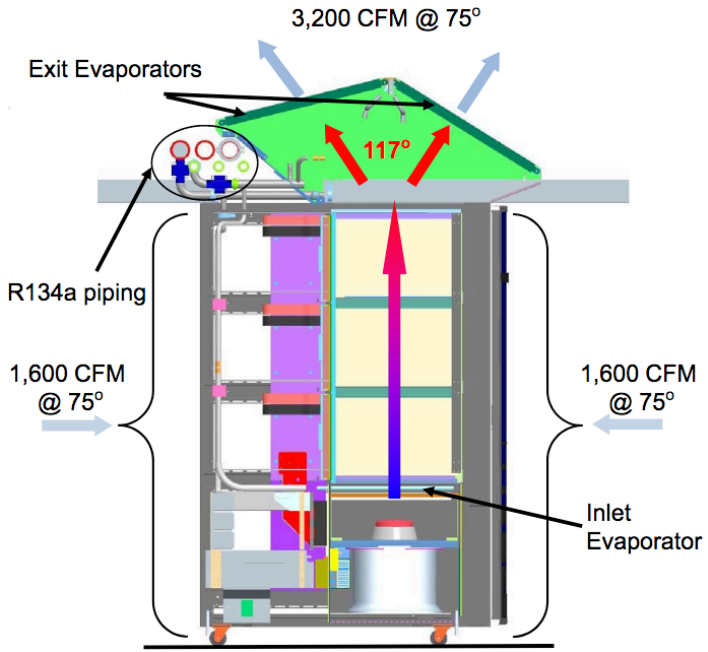
| Variable | | N | Events |
|---|---|---|---|
| col | | | |
| 0 | (X− 1) | 744 | 173 |
| 1 | (X− 2) | 759 | 169 |
| 2 | (X−25) | 772 | 97 |
| 3 | (X− 3) | 739 | 217 |
| 4 | (X−24) | 755 | 88 |
| 5 | (X− 4) | 759 | 266 |
| 6 | (X−23) | 752 | 125 |
| 7 | (X− 5) | 744 | 225 |
| 8 | (X−22) | 758 | 131 |
| 9 | (X− 6) | 758 | 259 |
| 10 | (X−21) | 739 | 180 |
| 11 | (X− 7) | 760 | 233 |
| 12 | (X−20) | 756 | 228 |
| 13 | (X− 8) | 759 | 242 |
| 14 | (X−19) | 743 | 228 |
| 15 | (X− 9) | 753 | 257 |
| 16 | (X−18) | 754 | 224 |
| 17 | (X−10) | 758 | 207 |
| 18 | (X−17) | 758 | 194 |
| 19 | (X−11) | 751 | 192 |
| 20 | (X−16) | 766 | 217 |
| 21 | (X−12) | 759 | 218 |
| 22 | (X−15) | 755 | 244 |
| 23 | (X−13) | 743 | 220 |
| 24 | (X−14) | 743 | 193 |
| row | | | |
| 0 | | 2363 | 795 |
| 1 | | 2352 | 639 |
| 2 | | 2351 | 565 |
| 3 | | 2363 | 596 |
| 4 | | 2371 | 687 |
| 5 | | 2334 | 577 |
| 6 | | 2339 | 472 |
| 7 | | 2364 | 696 |
| cage | | | |
| 0 | | 6240 | 1107 |
| 1 | | 6275 | 1746 |
| 2 | | 6322 | 2174 |
| slot | | | |
| 0 | | 2355 | 637 |
| 1 | | 2353 | 592 |
| 2 | | 2349 | 575 |
| 3 | | 2352 | 553 |
| 4 | | 2364 | 606 |
| 5 | | 2349 | 633 |
| 6 | | 2357 | 694 |
| 7 | | 2358 | 737 |
| node | | | |
| 0 | | 4712 | 1388 |
| 1 | | 4722 | 1494 |
| 2 | | 4697 | 1195 |
| 3 | | 4706 | 950 |




| Variable | | N | Events |
|---|---|---|---|
| col | | | |
| 0 | (X− 1) | 400 | 1 |
| 1 | (X− 2) | 389 | 1 |
| 2 | (X−25) | 384 | 1 |
| 3 | (X− 3) | 383 | 2 |
| 4 | (X−24) | 380 | 1 |
| 5 | (X− 4) | 399 | 2 |
| 6 | (X−23) | 378 | 0 |
| 7 | (X− 5) | 451 | 2 |
| 8 | (X−22) | 443 | 2 |
| 9 | (X− 6) | 473 | 0 |
| 10 | (X−21) | 457 | 2 |
| 11 | (X− 7) | 471 | 5 |
| 12 | (X−20) | 461 | 2 |
| 13 | (X− 8) | 462 | 3 |
| 14 | (X−19) | 469 | 5 |
| 15 | (X− 9) | 478 | 0 |
| 16 | (X−18) | 473 | 5 |
| 17 | (X−10) | 494 | 4 |
| 18 | (X−17) | 507 | 4 |
| 19 | (X−11) | 494 | 3 |
| 20 | (X−16) | 518 | 1 |
| 21 | (X−12) | 508 | 4 |
| 22 | (X−15) | 526 | 5 |
| 23 | (X−13) | 488 | 2 |
| 24 | (X−14) | 484 | 5 |
| row | | | |
| 0 | | 1875 | 15 |
| 1 | | 1662 | 6 |
| 2 | | 1638 | 6 |
| 3 | | 1277 | 9 |
| 4 | | 1285 | 11 |
| 5 | | 1256 | 4 |
| 6 | | 1241 | 5 |
| 7 | | 1136 | 6 |
| cage | | | |
| 0 | | 777 | 2 |
| 1 | | 4123 | 16 |
| 2 | | 6470 | 44 |
| slot | | | |
| 0 | | 1434 | 13 |
| 1 | | 1389 | 6 |
| 2 | | 1410 | 5 |
| 3 | | 1427 | 5 |
| 4 | | 1414 | 3 |
| 5 | | 1424 | 10 |
| 6 | | 1434 | 9 |
| 7 | | 1438 | 11 |
| node | | | |
| 0 | | 3495 | 19 |
| 1 | | 3513 | 20 |
| 2 | | 2209 | 10 |
| 3 | | 2153 | 13 |





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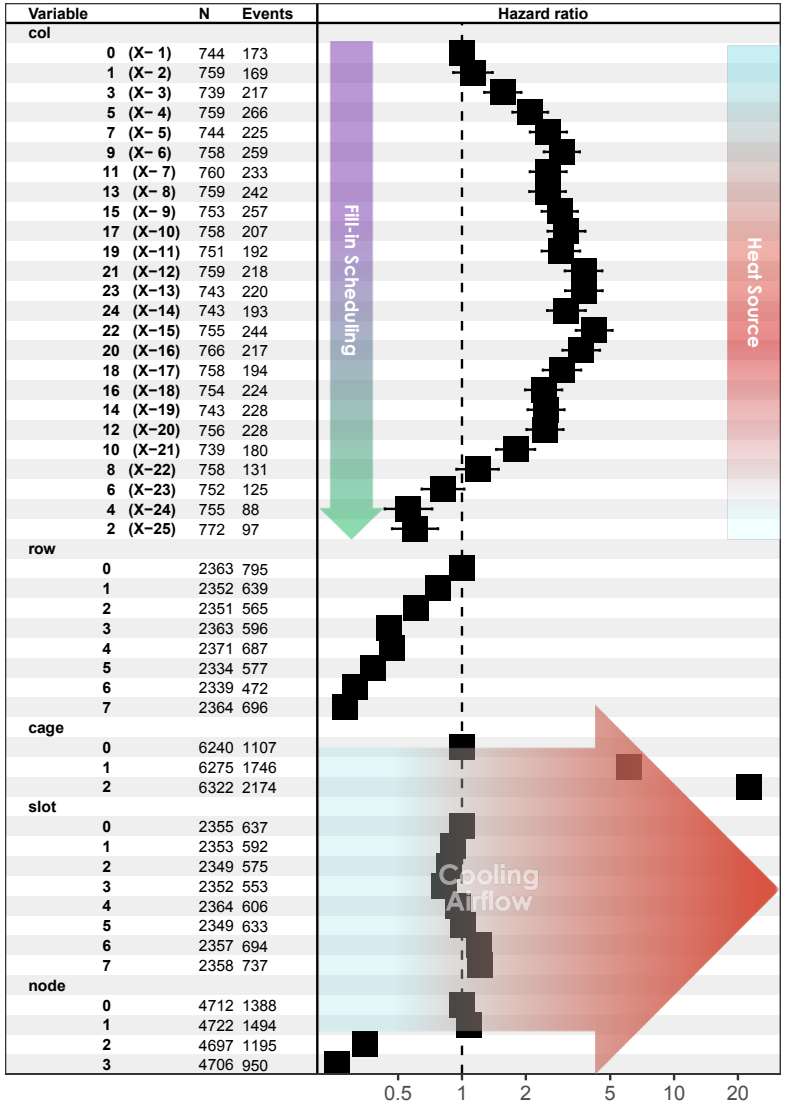
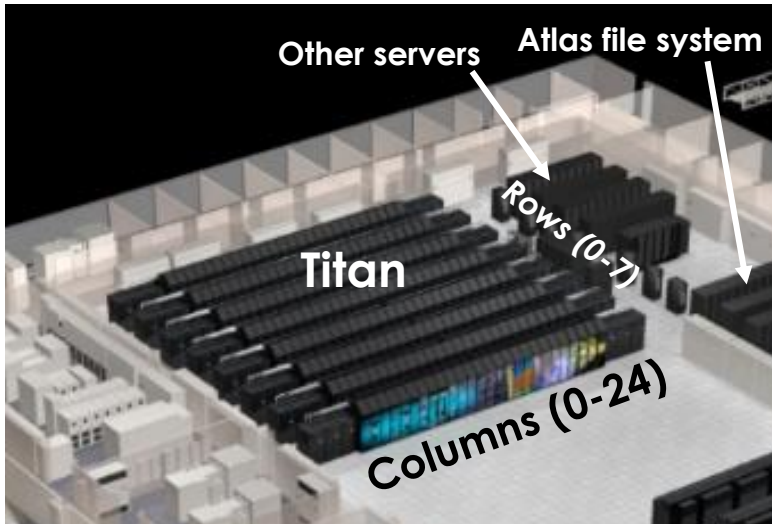
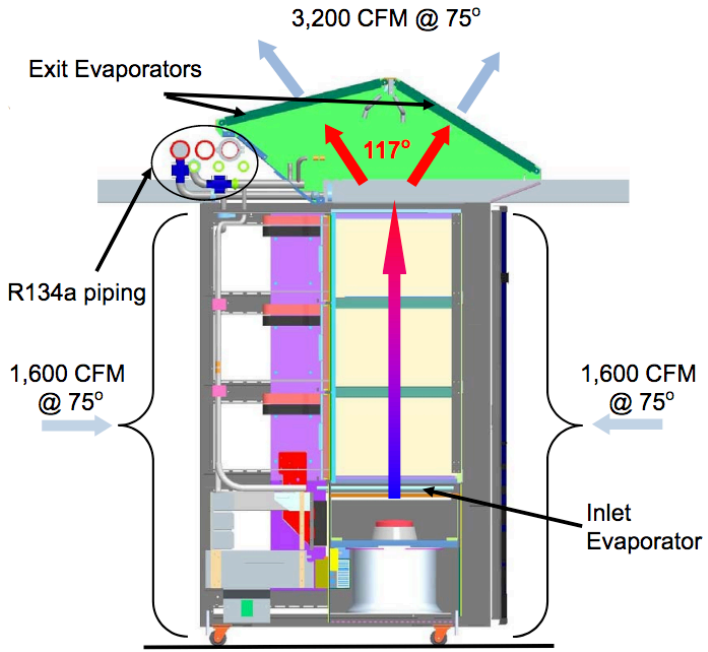
# Strong Signal in old Batch, Pattern Similar to K-M Analysis




Reordered columns based on Torus network





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# Future Research and Development Needs

- We need to design the HPC hardware/software ecosystem to be able to deal with high error and failure rates, expected and unexpected!
  - Resilience research and development is, in part, risk mitigation against the unexpected
  - There is always a cost/benefit trade-off that needs to be considered
  - Resilience mitigation mechanisms should be a toolbox with lots of options
- Resilience should be by design and not as an afterthought
  - Resilience is a crosscutting issue that should be considered everywhere (and not only in architecture)
    - After 25 years, MPI is still not fault tolerant, while PVM was fault tolerant 28 years ago in 1993


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# Questions?


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