# When Single Events Really Are Single: Statistics of Destructive/Disruptive Events

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To be presented by Raymond Ladbury at the 2011 Single Event Effects (SEE) Symposium, April 12-14, 2011, La Jolla, CA.

## Risk Mitigation vs. Risk Avoidance

Risk = Probability(failure)× Consequences(failure)

**Risk Avoidance**

- Examples:
  - Avoid SEL susceptible parts
  - Operate MOSFETs in "Safe Operating Area" (SOA)
- Two possible cases
  - Probability(failure) ≈ 0 → Use it
  - Probability(failure) > 0 → Don't
- Problem: Eliminates critical parts
  - SEL—Memories, ADCs…
  - SEB—Bipolar Microcircuits
  - SEGR—MOSFET SOAs not safe
- Some parts can't be eliminated

**Risk Mitigation**

- Risk Mitigation means bounding risk
  - Consequences always severe
    - Reducing consequences expensive
  - Rate estimation is problematic
    - Mechanisms not fully understood
    - Device models imperfect
- DSEE cross sections hard to measure
  - Event counts usually small
    - One per run if truly destructive
  - Cross section points may require multiple runs AND multiple parts
    - Fluence errors
    - Dose effects
    - Part-to-part variation

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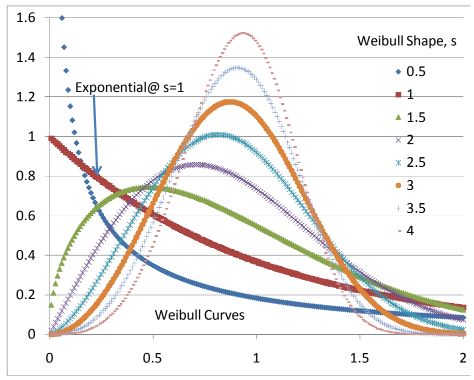
# Poisson Errors—one at a time

- Queuing theory: Poisson nature of SEE→ fluences between events exponentially distributed
  - Does exponentially distributed fluence give a better σ estimate?
  - If not, does it indicate fluences have some systematic error?
- How do we test fluences for exponential distribution?
  - Weibull distribution with shape parameter s=1→exponential.
  - s<1 implies "infant mortality"
  - s>1 implies "wear-out"
  - Other: Ratio of standard deviation to mean→1 for exponential

Weibull curves for width=1 as a function of shape parameter, s.

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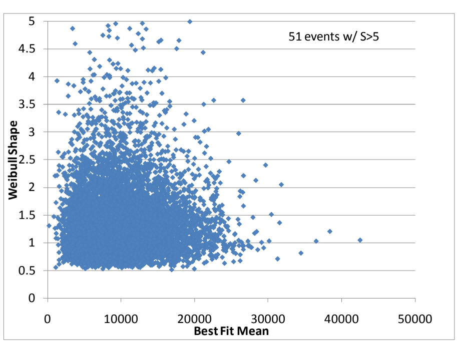
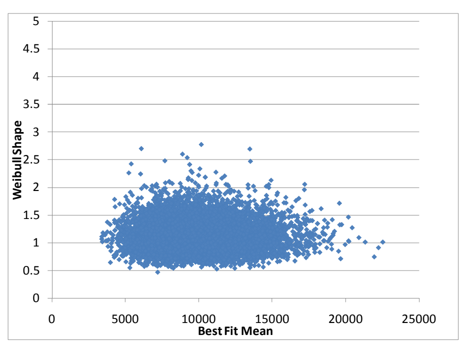
# Distribution Convergence w/ Event Count

Mean=10000 w/ No Systematic Errors

Cross section based on 5 events




Cross section based on 15 events

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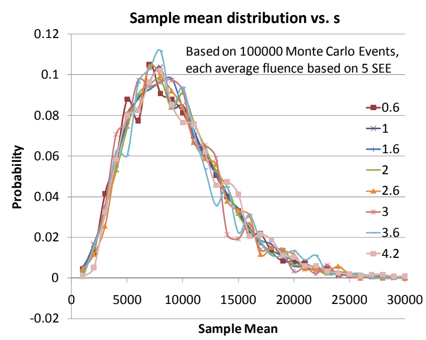
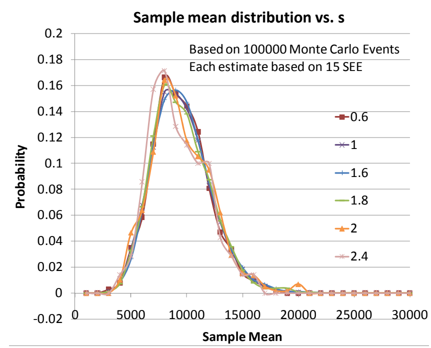
# Lesson I: You Can't Beat Statistics

- Errors on sample mean converge to 0 as $1/n^2$, regardless of s.
- Mean converges more rapidly and reliably than any other statistic.

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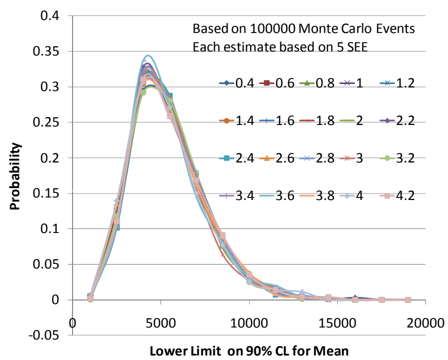
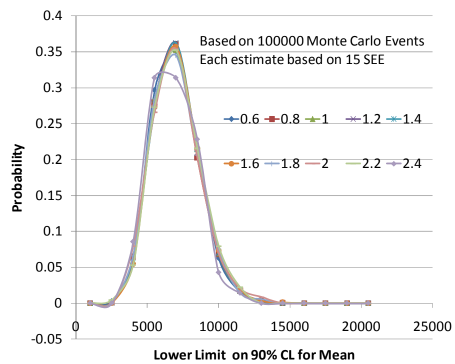
# Lesson I: You Can't Beat Statistics (Cont'd)

- Similarly, lower Confidence limits on estimated mean also converge independent of s. For n SEE, $\alpha$ confidence interval for mean $\mu$

$$\frac{2n*\mu_{ML}}{\chi^2(1-\alpha,2n)} < \mu < \frac{2n*\mu_{ML}}{\chi^2(\alpha,2n)}$$

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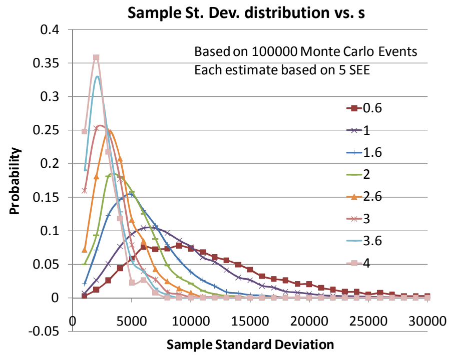
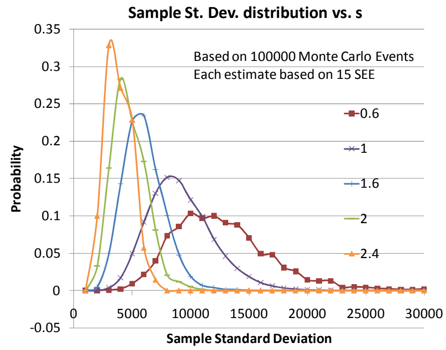
# Where Statistics Beat You

- Measures of part-to-part variation, e.g. standard deviation, converge much more slowly than the mean and not surprisingly do depend on s:

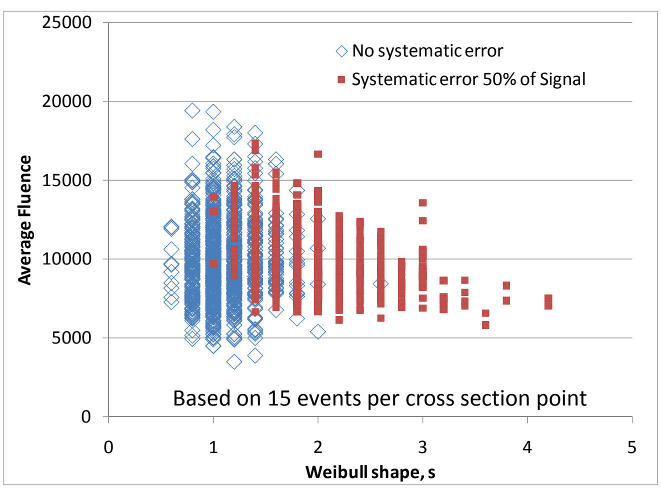
$$\frac{\sigma}{\mu} = SQRT\left(\frac{\Gamma(1+2/s)}{\Gamma(1+1/s)^2} - 1\right)$$






# Where this matters



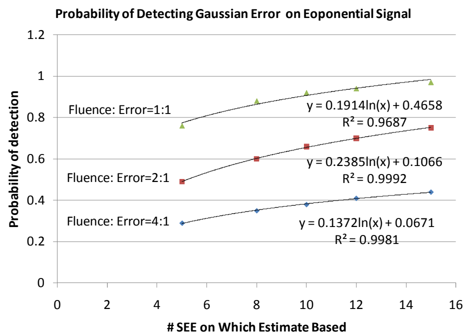

Morris et al. (2010) showed dosimetry systematic errors were significant sources of rate uncertainty.

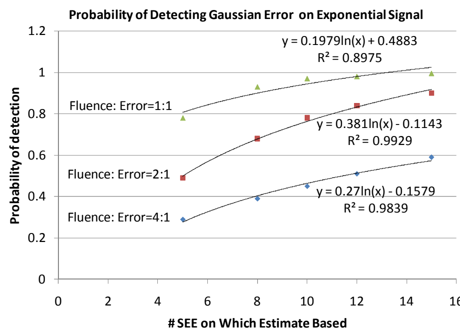
Adding Gaussian Noise to the signal results in larger values for s.

The larger the error, the more likely it is to be detected.

## Detecting Systematic Fluence Errors

- Set trigger level for ratio of Weibull shape,s where we get only 10% false triggers if there is no systematic error
  - Can also use ratio of standard deviation to mean , σ/μ
- Log-likelihoods for Weibull and exponential best fits :
  - Log(LIK(Weibull))-Log(LIK(Exp))
- Allow 10% false triggers for events with no systematic error

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## Part-to-Part Variation

- Destructive SEE involve processes and device characteristics that may not be tightly controlled in non-rad-hard processes— more variable than SEU
- If all events destructive, testing can't determine part-to-part variation
  - Random errors on fluences will swamp any likely part-to-part differences
  - Even if # errors>1 per part, but still small, part-to-part variation still highly uncertain.
- How do we do hardness assurance without knowing worst-case part?
  - Use other methods to bound part-to-part variation
    - Examples: Breakdown VGS distribution for MOSFETs may give an idea
  - Modeling based on measurements and/or device data
  - Engineering Judgment???
  - Derating application conditions? (Back to risk avoidance)
- Example: SEL
  - Good news: Usually can stop current rise short of destructive failure; statistics can be good
  - Bad news: Multiple modes, some destructive, some not;
    - Usually cannot be distinguished, so analysis may overstate possible failure rate
- Example: SEGR
  - It's all bad news—all events destructive, so part-to-part variation cannot be determined

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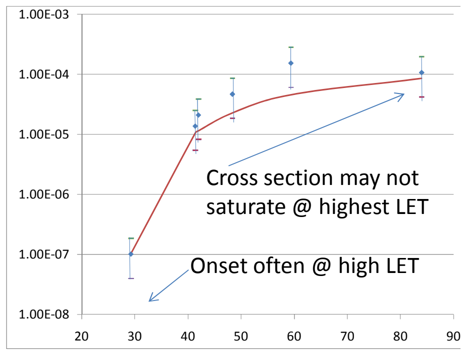
# SEL: The Good Destructive Failure

- Cross section is susceptibility metric
  - Affected by random + systematic errors
  - Statistical errors can even affect qualitative conclusions on temperature, energy, angular dependence, etc.
- Usually can avoid failure by current limiting/shutdown in test
  - Can accumulate statistics
  - Can measure part-to-part variance
    - Depends on parasitics—not usually controlled
  - Won't know if SEL would be destructive
- Usually high LET onset
  - Limited ions available
  - Effective LET increases number of points
- Charge-collection volume uncertain
- Failure modes like SEB or snapback will pose similar issues

- Model will likely look similar—but more complicated—than RPP
  - Comparison with cryogenic SEL may elucidate both mechanisms

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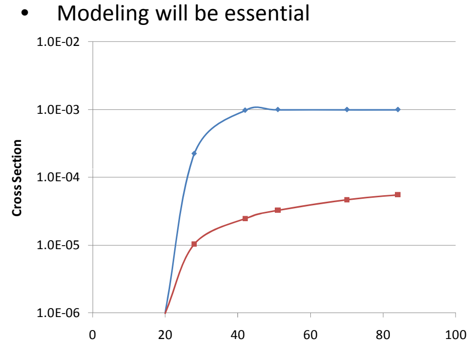
# SEGR—The Really Bad Boy

- SEGR mechanism(s) uncertain
  - depends on LET, Z, angle, range…
  - Random and systematic errors make dependencies hard to measure
- Susceptibility measure of is onset VDS or VGS, not cross section
  - Usual methods not sensitive to threshold behavior
- Effective LET does not apply
  - Tuning to different ions costly and SEGR depends on Z
  - Using degraders could result in systematic errors due to straggle
- SEGR always destructive
  - Usual methods cannot measure part-to-part variation

- What does cross section vs. LET look like for SEGR in MOSFETs?
  - Curves below yield identical results ~95% of time by most test methods
  - Method yields $\sigma$ at (LET, Z), not (LET,Z ± 1) or (LET ± $\varepsilon$, Z)
- Modeling will be essential

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## Estimating DSEE Rates: SEL vs. SEGR

- SEL charge collection volume likely a complicated 3D structure
  - Well suited to Monte Carlo estimation
- Data to constrain model include
  - Cross section vs LET, range, tilt, roll
    - Temperature??
- Remaining issues:
  - What is charge collection volume?
  - How do we treat multiple SEL sensitive volumes with broadbeam testing?
    - Can laser testing complement broadbeam ion testing?
  - What role will modeling play?
  - How do we distinguish between truly destructive events, latent damage and nondstructive SEL?
- Model for SEGR very complicated
  - Involves oxide response as well as Si
  - Susceptibility depends not just on LET, but ion species,range and angle
  - Sometimes also TID or past ion strikes
- Truly destructive nature of SEGR limits data to constrain models
  - Cannot estimate part-to-part variation
  - Typical test matrix might include 5-6 ions, 2-3 energies, 3 angles each
  - 30-54 test conditions
    - $\sigma$estimate requires >3 parts/condition= 100-200 parts for full characterization!
- Modeling could decrease cost, but requires detailed knowledge of parts
  - Needed for both $\sigma$ vs. LET curve and to estimate part-to-part variation

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## Conclusions

- Low event counts and systematic errors contribute significantly to rate uncertainty for destructive SEE
  - SEL risk can be estimated and managed
    - Current limiting allows accumulation of statistics for each part
      - Allows part-to-part variation, systematic errors etc. to be estimated.
      - Can't distinguish destructive and "nondestructive" modes, but OK as a worst case
    - Mechanisms and charge collection make rates uncertain, but OK as a worst case
    - Result: Expect more SEL related headaches coming up on a project near you!
  - Inherently destructive nature of SEGR incentivizes risk avoidance
    - Can only measure average part susceptibility (either $\sigma$ or onset VDS, VGS)
    - Complex dependence on LET, Z, ion range, angle precludes rate estimation
      - Low statistics, part-to-part variation make it difficult and expensive to resolve dependencies
    - Result: Progress will be slow—and expect SEGR to cause more headaches for designers than radiation experts.
- For all destructive SEE, understanding random and systematic errors is key to better understanding mechanisms.

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