Board Manufacturing Correlation to IC Manufacturing Test

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Outline

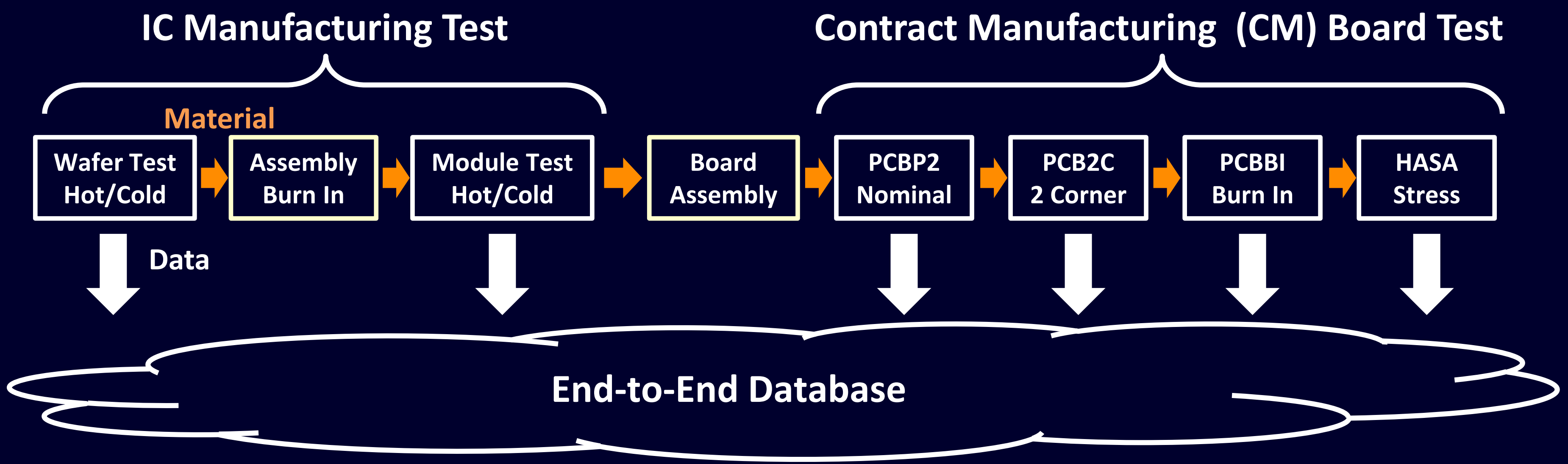
- ● Introduction
- Build the Database
- Identify Significant Correlations
- Quantify Cost/Benefit
- Conclusions

Introduction

- *Challenge*: Measure and exploit correlation between an IC factory and contract board manufacturer (CM).
  - Join naturally-occurring data from different factories.
  - Find IC factory to CM correlations hidden in the data.
  - Get IC yield vs CM failure rate for correlations.
- *Strategy*: Make an end-to-end database, and develop methods to analyze it.
  - Join IC factory and CM factory databases on IC ID-tag read at test steps in both factories.
  - Use rank statistics to find strongest correlations.
  - Construct special receiver operating characteristics based on strong correlations found.

Introduction

- A circuit board for an enterprise switch has 12 copies of an ASIC produced by the IC factory.
- Over 16 months..
  - About 240,000 ASICs went to the CM factory.
  - CM factory produced about 20,000 circuit boards.
- An end-to-end database was made by joining data from IC and CM factories.



IC Manufacturing Test

Contract Manufacturing (CM) Board Test

Material

Wafer Test Hot/Cold → Assembly Burn In → Module Test Hot/Cold → Board Assembly → PCBP2 Nominal → PCB2C 2 Corner → PCBBI Burn In → HASA Stress

Data

End-to-End Database

Final Application of ASICs

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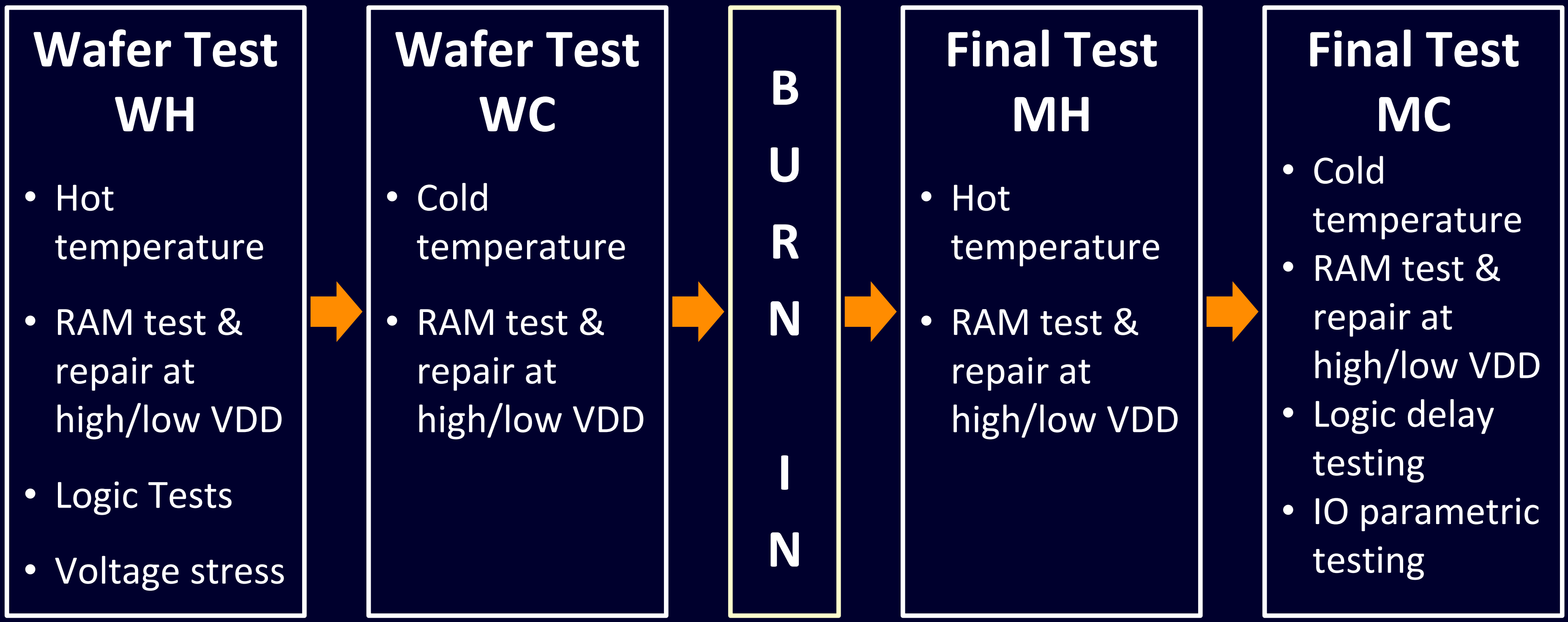
IC Manufacturing Test

- Pass/fail and parametric data are acquired.
- Each ASIC has a unique ID-tag.
- Data from each test step is tagged with the ID-tag.
- ID-tag encodes lot, wafer and xy location.



Wafer Test WH

- Hot temperature
- RAM test & repair at high/low VDD
- Logic Tests
- Voltage stress

Wafer Test WC

- Cold temperature
- RAM test & repair at high/low VDD

BURN IN

Final Test MH

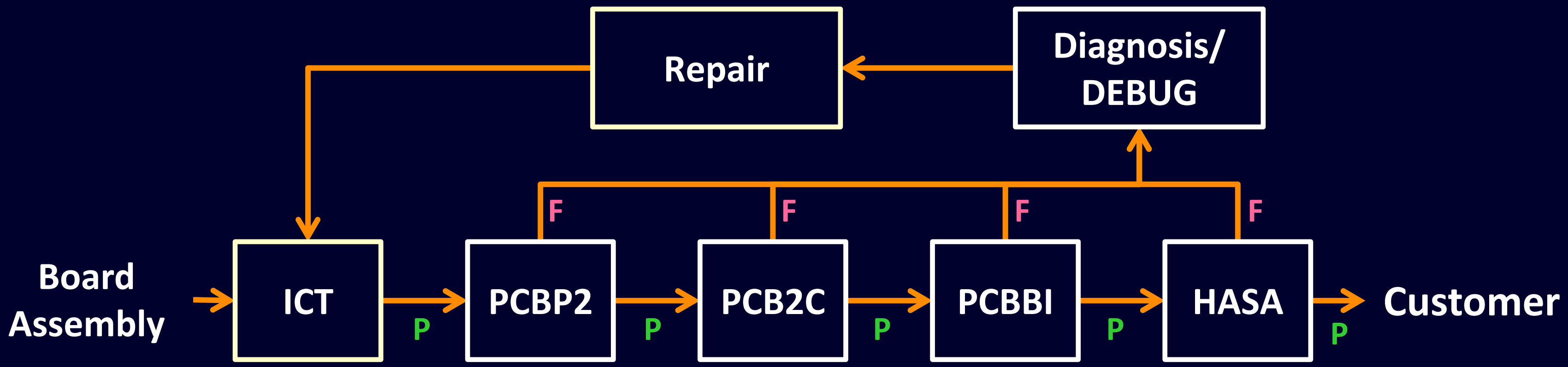
- Hot temperature
- RAM test & repair at high/low VDD

Final Test MC

- Cold temperature
- RAM test & repair at high/low VDD
- Logic delay testing
- IO parametric testing

CM Manufacturing Test

- Perfect board generates 4 x 12 = 48 records.
- Diagnosis/debug/repair generates *many* records!
  - – Identifies suspect ASICs.
  - – Tag suspect ASIC records by ID-tag, board SN, board socket, time stamp, test step, board fail signature.
  - – If replacement ASIC changes board fail signature, then replaced suspect ASIC is a valid failure.
    - Time stamps are used to unravel the history.



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Compute Correlations

- Reduce computation by grouping records from 100's of thousands of dies into a few 100 groups.
  - Group by useful attribute. eg. die location, xy.
  - Is there a *best* attribute to group by?
- Compute group attributes from die attributes.
  - Die pass/fail data becomes group fail fraction (fr).
  - Median parametric attribute value of dies in a group becomes the group value for the parametric attribute.
- Compute correlation among all pairs of attributes.
  - Within and between factories.

Group Attributes from Die Attributes

Attribute	Description	Attribute Category
x	x coordinate	Spatial
y	y coordinate	
R	Distance from wafer center	
WHfr	Fail fraction, wafer-level hot	Fail fractions in IC test.
WCfr	Fail fraction, wafer-level cold	
MHfr	Fail fraction, package-level hot	
MCfr	Fail fraction, package-level cold	
WafHIDD*	IDDQ at wafer test (hot, core area of chip)	Median parametric value in IC test.
WafCIDD*	IDDQ at wafer test (cold, core area of chip)	
ModIDD*	IDDQ at module test (core area of chip)	
Repairfuses*	Number of RAM repairs	
ProcMon*	Average of process monitors (smaller Þ faster)	
WMinVDD1-4	Min VDD at Wafer Test - various patterns	
MMinVDD1-4	Min VDD at Final Test - various patterns	
VM1 - 10	Min VDD for various LOS Delay patterns	
VM11 - 26	Min VDD for various LOC Delay patterns	
VMLB	Min VDD for LBIST	
VMAUTO	Min VDD for Autotest	
CMfr	Total fail fraction in CM	Fail fractions in board factory (CM).
PCBP2fr	Fail fraction at PCBP2 in CM	
PCB2Cfr	Fail fraction at PCB2C in CM	
HASAfr	Fail fraction at HASA in CM	
PCBBIfr	Fail fraction at PCBBI in CM	
DEBUGfr	Fail fraction at Diagnose/debug in CM	
TRAFFICfr	Fail fraction in "traffic" category in CM	
MEMORYfr	Fail fraction in "memory" category in CM	
LOGICfr	Fail fraction in "logic" category in CM	
BOOTfr	Fail fraction in "boot" category in CM	
OTHERfr	Fail fraction in other categories in CM	

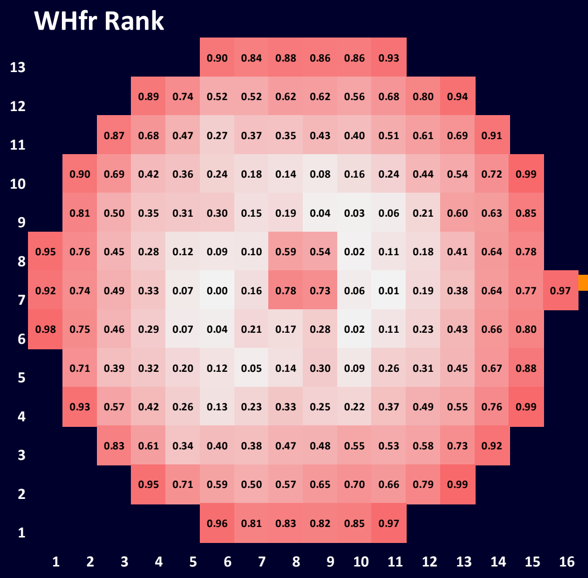
Measured on every die

Sampled

IC Factory

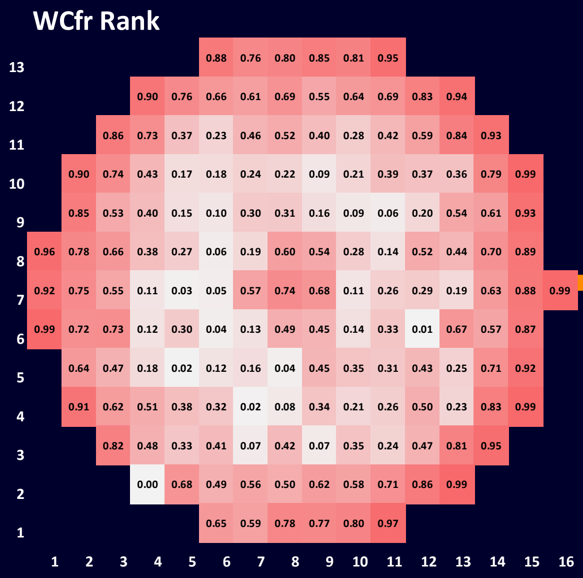
CM Factory

Evolution of xy Group Fail Rate Rank



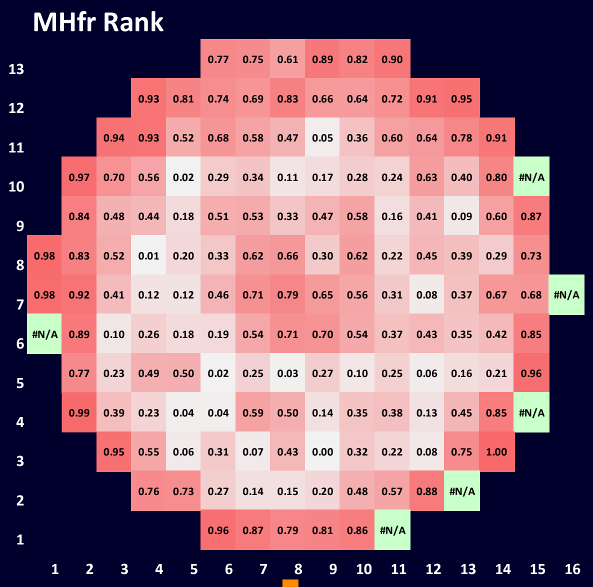
WHfr Rank

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
13						0.90	0.84	0.88	0.86	0.86	0.93					
12				0.89	0.74	0.52	0.52	0.62	0.62	0.56	0.68	0.80	0.94			
11			0.87	0.68	0.47	0.27	0.37	0.35	0.43	0.40	0.51	0.61	0.69	0.91		
10		0.90	0.69	0.42	0.36	0.24	0.18	0.14	0.08	0.16	0.24	0.44	0.54	0.72	0.99	
9		0.81	0.50	0.35	0.31	0.30	0.15	0.19	0.04	0.03	0.06	0.21	0.60	0.63	0.85	
8	0.95	0.76	0.45	0.28	0.12	0.09	0.10	0.59	0.54	0.02	0.11	0.18	0.41	0.64	0.78	
7	0.92	0.74	0.49	0.33	0.07	0.00	0.16	0.78	0.73	0.06	0.01	0.19	0.38	0.64	0.77	0.97
6	0.98	0.75	0.46	0.29	0.07	0.04	0.21	0.17	0.28	0.02	0.11	0.23	0.43	0.66	0.80	
5		0.71	0.39	0.32	0.20	0.12	0.05	0.14	0.30	0.09	0.26	0.31	0.45	0.67	0.88	
4		0.93	0.57	0.42	0.26	0.13	0.23	0.33	0.25	0.22	0.37	0.49	0.55	0.76	0.99	
3			0.83	0.61	0.34	0.40	0.38	0.47	0.48	0.55	0.53	0.58	0.73	0.92		
2				0.95	0.71	0.59	0.50	0.57	0.65	0.70	0.66	0.79	0.99			
1						0.96	0.81	0.83	0.82	0.85	0.97					



WCfr Rank

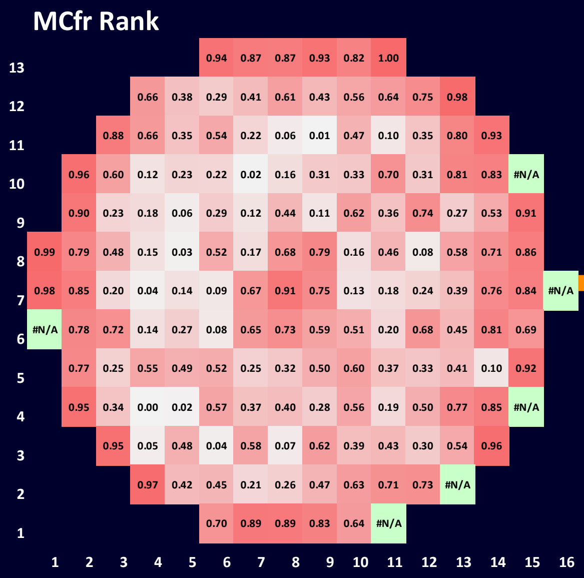
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
13						0.88	0.76	0.80	0.85	0.81	0.95					
12				0.90	0.76	0.66	0.61	0.69	0.55	0.64	0.69	0.83	0.94			
11			0.86	0.73	0.37	0.23	0.46	0.52	0.40	0.28	0.42	0.59	0.84	0.93		
10		0.90	0.74	0.43	0.17	0.18	0.24	0.22	0.09	0.21	0.39	0.37	0.36	0.79	0.99	
9		0.85	0.53	0.40	0.15	0.10	0.30	0.31	0.16	0.09	0.06	0.20	0.54	0.61	0.93	
8	0.96	0.78	0.66	0.38	0.27	0.06	0.19	0.60	0.54	0.28	0.14	0.52	0.44	0.70	0.89	
7	0.92	0.75	0.55	0.11	0.03	0.05	0.57	0.74	0.68	0.11	0.26	0.29	0.19	0.63	0.88	0.99
6	0.99	0.72	0.73	0.12	0.30	0.04	0.13	0.49	0.45	0.14	0.33	0.01	0.67	0.57	0.87	
5		0.64	0.47	0.18	0.02	0.12	0.16	0.04	0.45	0.35	0.31	0.43	0.25	0.71	0.92	
4		0.91	0.62	0.51	0.38	0.32	0.02	0.08	0.34	0.21	0.26	0.50	0.23	0.83	0.99	
3			0.82	0.48	0.33	0.41	0.07	0.42	0.07	0.35	0.24	0.47	0.81	0.95		
2				0.00	0.68	0.49	0.56	0.50	0.62	0.58	0.71	0.86	0.99			
1						0.65	0.59	0.78	0.77	0.80	0.97					



MHfr Rank

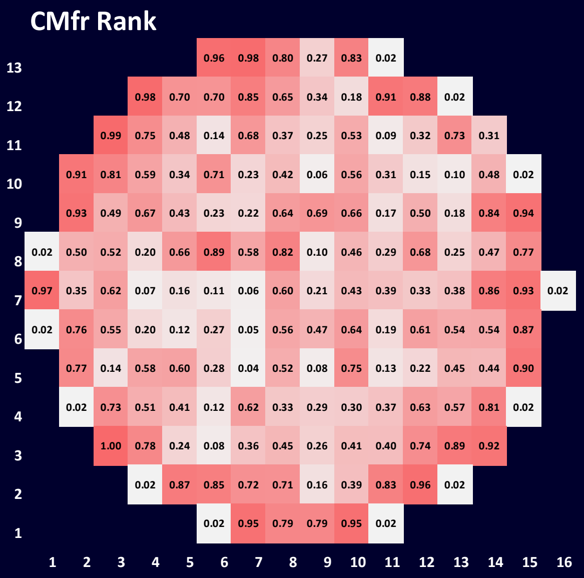
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
13						0.77	0.75	0.61	0.89	0.82	0.90					
12				0.93	0.81	0.74	0.69	0.83	0.66	0.64	0.72	0.91	0.95			
11			0.94	0.93	0.52	0.68	0.58	0.47	0.05	0.36	0.60	0.64	0.78	0.91		
10		0.97	0.70	0.56	0.02	0.29	0.34	0.11	0.17	0.28	0.24	0.63	0.40	0.80	#N/A	
9		0.84	0.48	0.44	0.18	0.51	0.53	0.33	0.47	0.58	0.16	0.41	0.09	0.60	0.87	
8	0.98	0.83	0.52	0.01	0.20	0.33	0.62	0.66	0.30	0.62	0.22	0.45	0.39	0.29	0.73	
7	0.98	0.92	0.41	0.12	0.12	0.46	0.71	0.79	0.65	0.56	0.31	0.08	0.37	0.67	0.68	#N/A
6	#N/A	0.89	0.10	0.26	0.18	0.19	0.54	0.71	0.70	0.54	0.37	0.43	0.35	0.42	0.85	
5		0.77	0.23	0.49	0.50	0.02	0.25	0.03	0.27	0.10	0.25	0.06	0.16	0.21	0.96	
4		0.99	0.39	0.23	0.04	0.04	0.59	0.50	0.14	0.35	0.38	0.13	0.45	0.85	#N/A	
3			0.95	0.55	0.06	0.31	0.07	0.43	0.00	0.32	0.22	0.08	0.75	1.00		
2				0.76	0.73	0.27	0.14	0.15	0.20	0.48	0.57	0.88	#N/A			
1						0.96	0.87	0.79	0.81	0.86	#N/A					

IC Factory | **CM Factory**



MCfr Rank

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
13						0.94	0.87	0.87	0.93	0.82	1.00					
12				0.66	0.38	0.29	0.41	0.61	0.43	0.56	0.64	0.75	0.98			
11			0.88	0.66	0.35	0.54	0.22	0.06	0.01	0.47	0.10	0.35	0.80	0.93		
10		0.96	0.60	0.12	0.23	0.22	0.02	0.16	0.31	0.33	0.70	0.31	0.81	0.83	#N/A	
9		0.90	0.23	0.18	0.06	0.29	0.12	0.44	0.11	0.62	0.36	0.74	0.27	0.53	0.91	
8	0.99	0.79	0.48	0.15	0.03	0.52	0.17	0.68	0.79	0.16	0.46	0.08	0.58	0.71	0.86	
7	0.98	0.85	0.20	0.04	0.14	0.09	0.67	0.91	0.75	0.13	0.18	0.24	0.39	0.76	0.84	#N/A
6	#N/A	0.78	0.72	0.14	0.27	0.08	0.65	0.73	0.59	0.51	0.20	0.68	0.45	0.81	0.69	
5		0.77	0.25	0.55	0.49	0.52	0.25	0.32	0.50	0.60	0.37	0.33	0.41	0.10	0.92	
4		0.95	0.34	0.00	0.02	0.57	0.37	0.40	0.28	0.56	0.19	0.50	0.77	0.85	#N/A	
3			0.95	0.05	0.48	0.04	0.58	0.07	0.62	0.39	0.43	0.30	0.54	0.96		
2				0.97	0.42	0.45	0.21	0.26	0.47	0.63	0.71	0.73	#N/A			
1						0.70	0.89	0.89	0.83	0.64	#N/A					

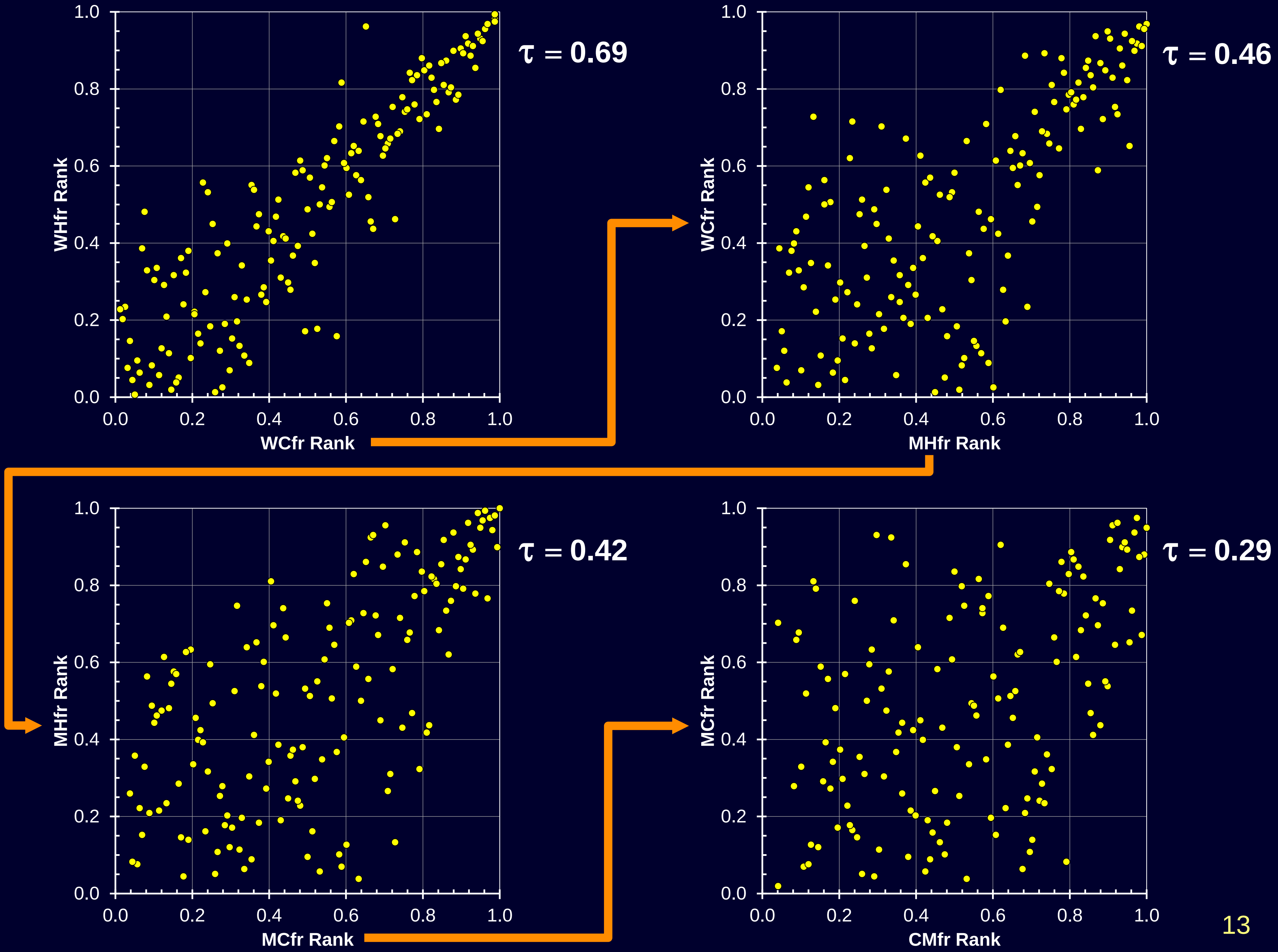


CMfr Rank

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
13						0.96	0.98	0.80	0.27	0.83	0.02					
12				0.98	0.70	0.70	0.85	0.65	0.34	0.18	0.91	0.88	0.02			
11			0.99	0.75	0.48	0.14	0.68	0.37	0.25	0.53	0.09	0.32	0.73	0.31		
10		0.91	0.81	0.59	0.34	0.71	0.23	0.42	0.06	0.56	0.31	0.15	0.10	0.48	0.02	
9		0.93	0.49	0.67	0.43	0.23	0.22	0.64	0.69	0.66	0.17	0.50	0.18	0.84	0.94	
8	0.02	0.50	0.52	0.20	0.66	0.89	0.58	0.82	0.10	0.46	0.29	0.68	0.25	0.47	0.77	
7	0.97	0.35	0.62	0.07	0.16	0.11	0.06	0.60	0.21	0.43	0.39	0.33	0.38	0.86	0.93	0.02
6	0.02	0.76	0.55	0.20	0.12	0.27	0.05	0.56	0.47	0.64	0.19	0.61	0.54	0.54	0.87	
5		0.77	0.14	0.58	0.60	0.28	0.04	0.52	0.08	0.75	0.13	0.22	0.45	0.44	0.90	
4		0.02	0.73	0.51	0.41	0.12	0.62	0.33	0.29	0.30	0.37	0.63	0.57	0.81	0.02	
3			1.00	0.78	0.24	0.08	0.36	0.45	0.26	0.41	0.40	0.74	0.89	0.92		
2				0.02	0.87	0.85	0.72	0.71	0.16	0.39	0.83	0.96	0.02			
1						0.02	0.95	0.79	0.79	0.95	0.02					

The CM factory has a residual radial dependency.

Tau Measures xy Group Fail Rate Correl’n



Measure Correlation by Kendall's Tau (τ)

- τ gives correlation between pairs of group attributes.
  - Count group pairs for which the attribute ranks are concordant (*k*) and discordant (*d*), and compute..

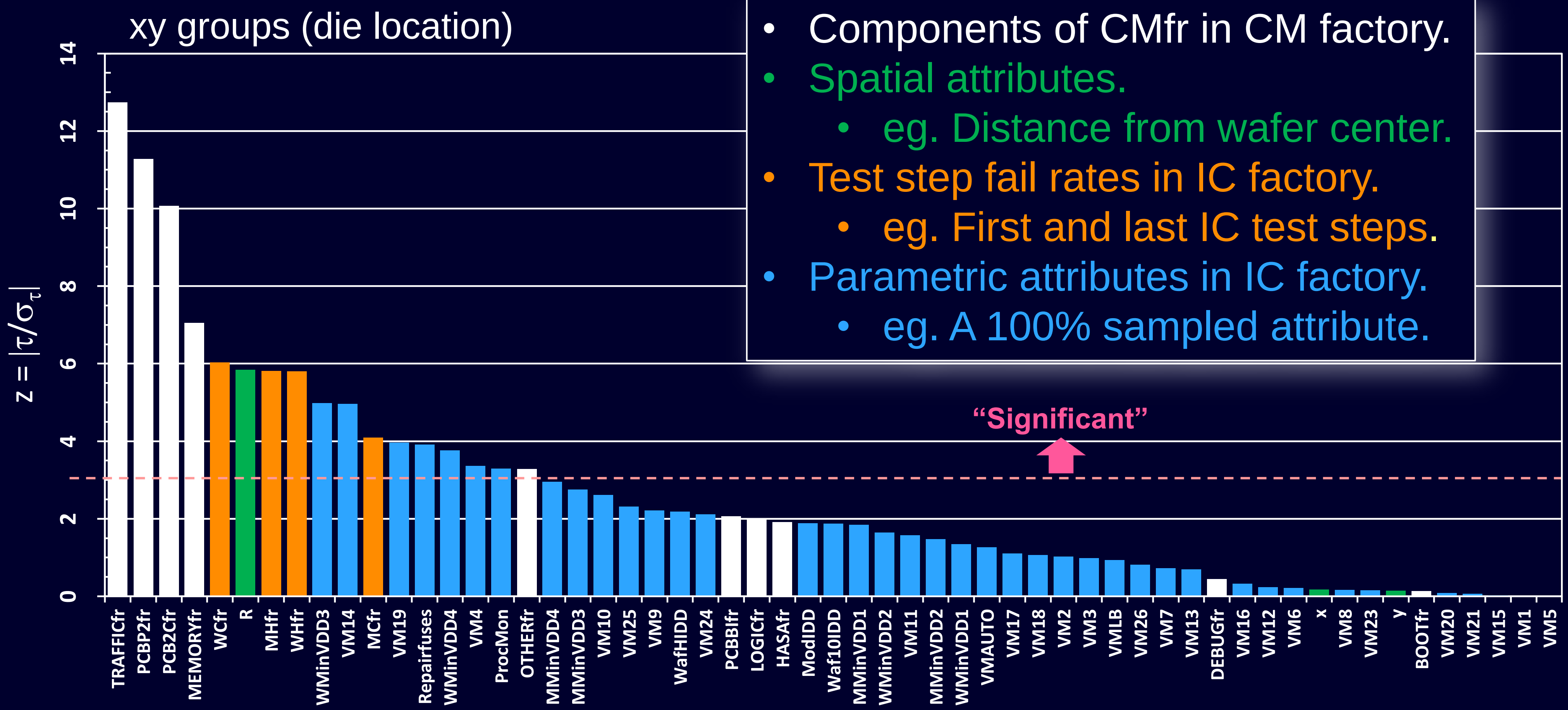
$$\tau = (k - d)/(k + d) \quad \text{(No ties)}$$

- There are complications, but there's a solution*
  - Ties from test binning.
  - Significance of τ requires uncorrelated variance, σ_τ^2.

* Gary Simon, "A nonparametric test of total independence based on Kendall's tau", *Biometrika* 1977, Vol. 64, No. 2, pp. 277-282.

CMfr Correlation to Other Group Attributes

- $z = |\tau/\sigma_\tau|$ measures significance of group CMfr correlation to other group attributes.



- Components of CMfr in CM factory.
- Spatial attributes.
  - eg. Distance from wafer center.
- Test step fail rates in IC factory.
  - eg. First and last IC test steps.
- Parametric attributes in IC factory.
  - eg. A 100% sampled attribute.

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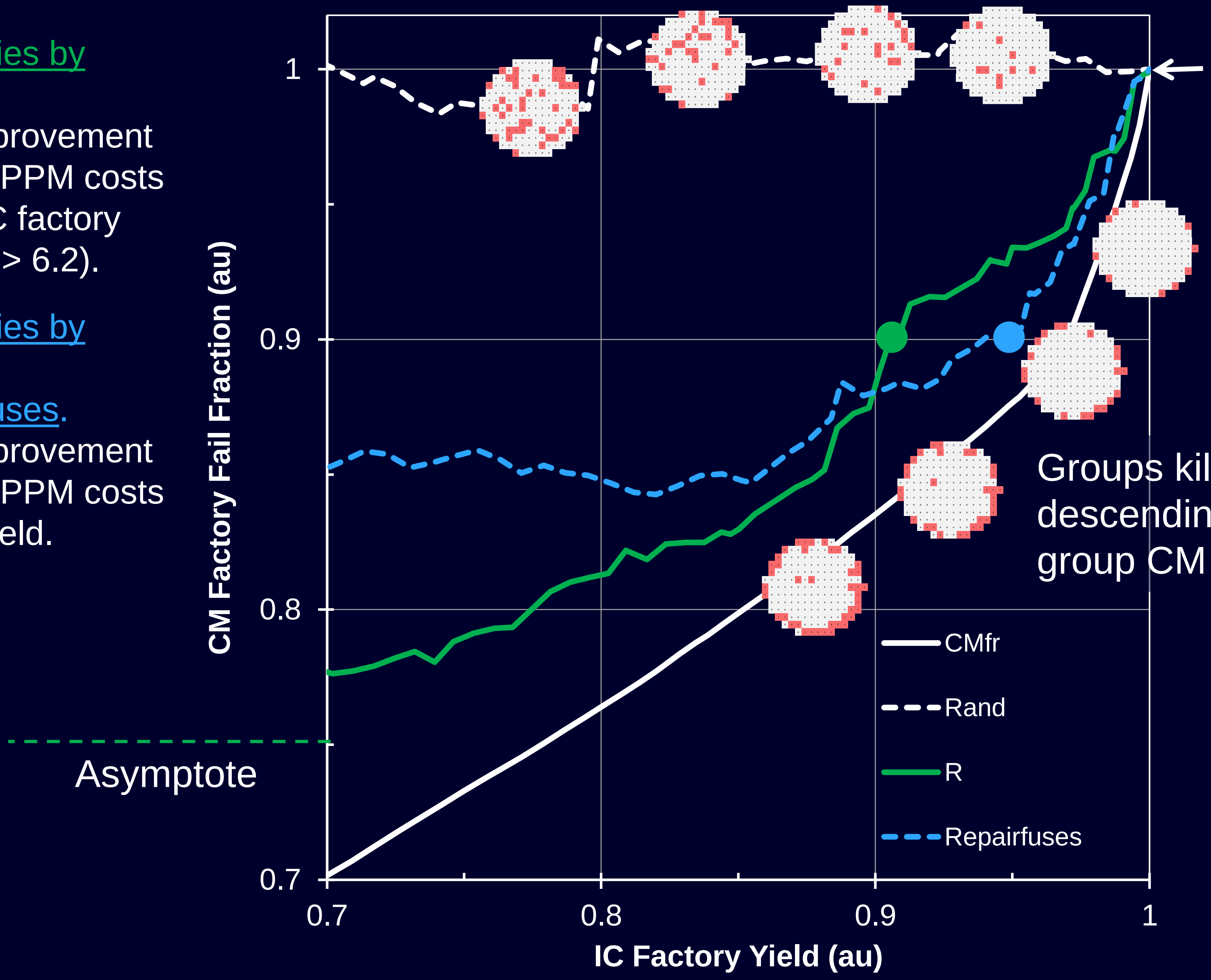
xy Receiver Operating Characteristic

- Rank xy groups by one of the group attributes:
  - Examples: **R**, **Repairfuses**
  - Best case: **CMfr**. Assumes knowledge of CM factory.
  - Worst case. **Rand**. Shuffled groups.
- Kill groups by kill limit applied to ranking attribute.
- Parametrically plot CM fail rate vs IC yield using kill limit as parameter.

xy Receiver Operating Characteristic

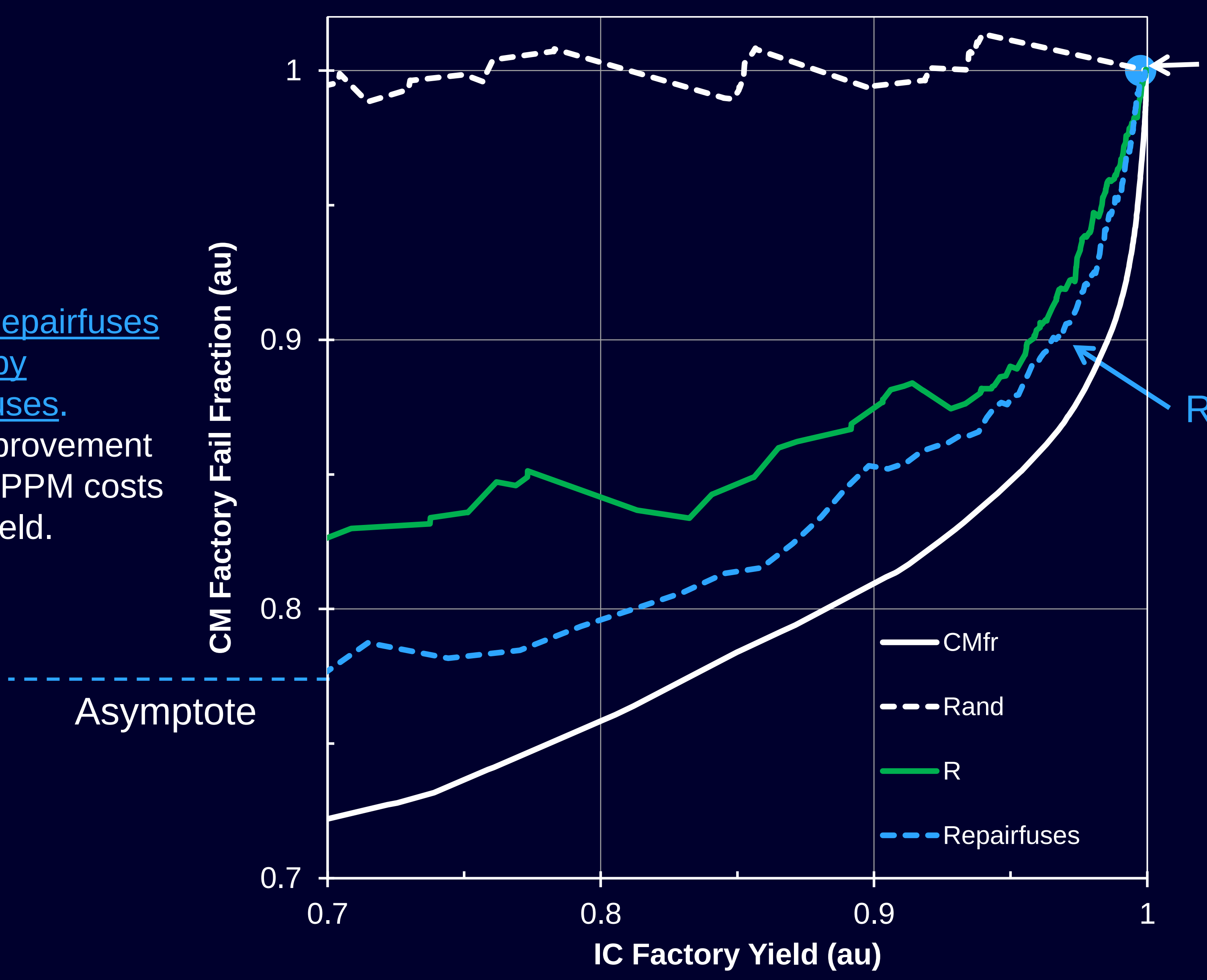


Yield and CM Fail Rate with no killed groups at WH.

Killing dies by radius.
10% improvement in CM DPPM costs 9% of IC factory yield (R > 6.2).

Killing dies by median Repairfuses.
10% improvement in CM DPPM costs 5% of yield.

Fuse Repair Receiver Operating Ch’stic



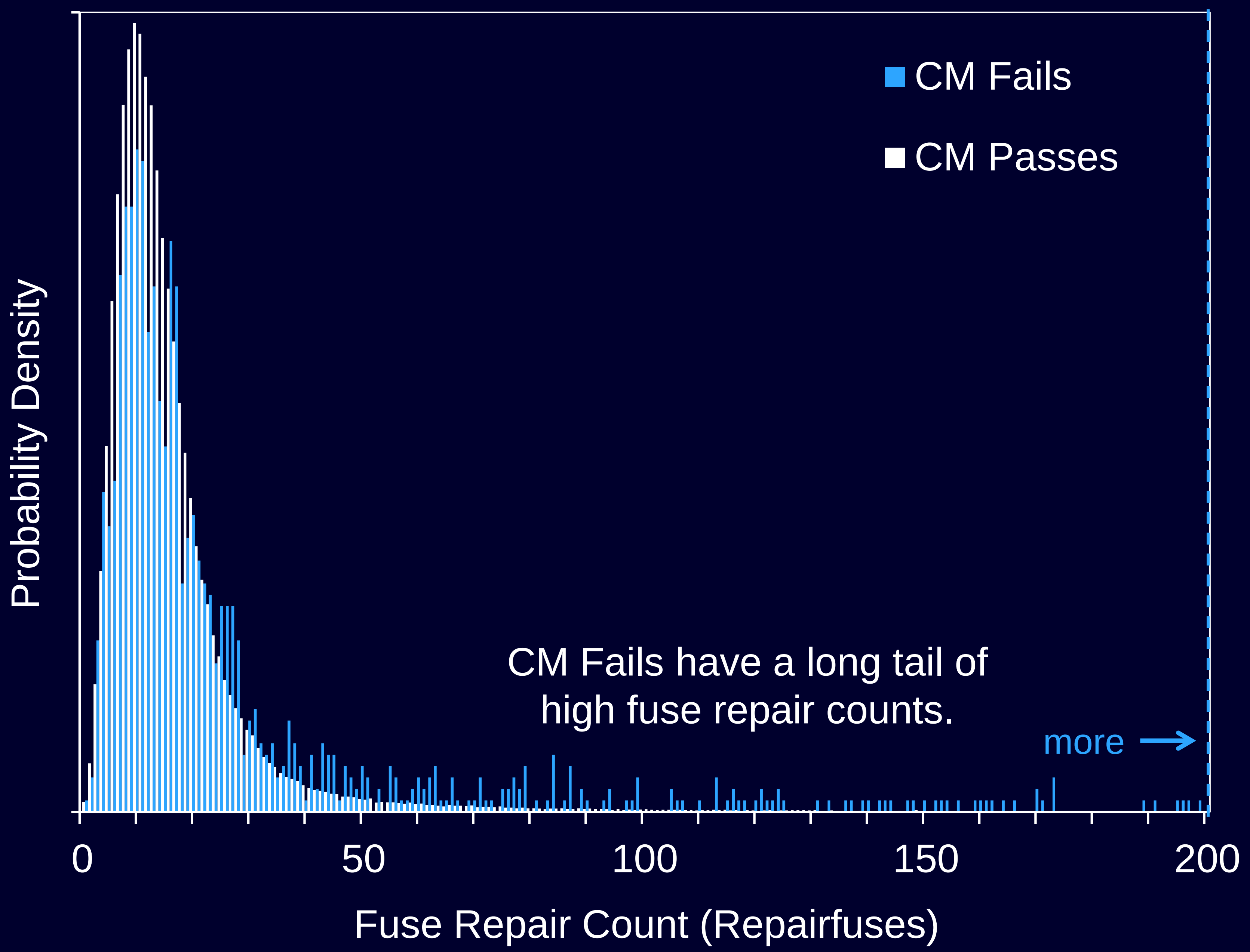
Yield and CM Fail Rate with no killed groups at WH.

Repairfuses = 50

Killing Repairfuses groups by Repairfuses. 10% improvement in CM DPPM costs 4% of yield.

Asymptote

Fuse Repair Count of ASICs Sent to CM



CM Fails have a long tail of high fuse repair counts.

more →

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Conclusions

- If the CM factory sees IC factory variation there is opportunity to add an IC factory screen to IC test.
  - Quality of IC test limits the benefit of added screen.
- Evaluate candidate attributes for added screen by
  - Rank statistics (Kendall τ) to find candidate attributes.
  - ROC analysis to quantify cost-benefit of candidate.
- The *best* attribute to screen by is not obvious.
  - eg. DRAM repair count was better than radius.
- Communication of risk/benefit does not require disclosure of CM fail rates and IC yield.
- Data automation between factories is a challenge to implementation.

Backup

Adaptive Test Using ROC

- *Training:* Determine kill limits for groups from ROC.
  - Acquire data for limited volume.
    - Use CM factory data, or System Test in IC factory.
  - Group dies by one chosen attribute.
  - Compute group attributes from die attributes.
  - Get ROC by ranking groups by group attribute values.
- *Production:* Kill groups of dies by comparing measured group attributes to kill limits.
  - On-tester. Group attribute is determined from each die separately. eg. R for xy groups.
  - Off-tester. Group attribute is determined from a volume of dies. eg. Repairfuses for xy groups.

Calculation of a ROC

ROC

(*FR* vs *Y* with r as parameter)

$$\begin{cases} Y(r) = Y_{\mathrm{WH}}(r) \cdot Y_{\mathrm{WC}}(r) \cdot Y_{\mathrm{MH}}(r) \cdot Y_{\mathrm{MC}}(r) \\ FR(r) = \sum_{\{g(i):i \le r\}} f_{\mathrm{CM}}(g) \Big/ \sum_{\{g(i):i \le r\}} c_{\mathrm{CM}}(g) \end{cases}$$

$$Y(r):\ \begin{cases} Y_{\mathrm{WH}}(r) = \sum_{\{g(i):i \le r\}} p_{\mathrm{WH}}(g) \Big/ \sum_{\{\forall g\}} c_{\mathrm{WH}}(g) \\ Y_{\mathrm{WC}}(r) = \sum_{\{g(i):i \le r\}} p_{\mathrm{WC}}(g) \Big/ \sum_{\{g(i):i \le r\}} c_{\mathrm{WC}}(g) \\ Y_{\mathrm{MH}}(r) = \sum_{\{g(i):i \le r\}} p_{\mathrm{MH}}(g) \Big/ \sum_{\{g(i):i \le r\}} c_{\mathrm{MH}}(g) \\ Y_{\mathrm{MC}}(r) = \sum_{\{g(i):i \le r\}} p_{\mathrm{MC}}(g) \Big/ \sum_{\{g(i):i \le r\}} c_{\mathrm{MC}}(g) \end{cases}$$

In examples, killing is done at WH.

$p_{\mathrm{X}}(g)$	Pass count at test step X for group g.
$f_{\mathrm{X}}(g)$	Fail count at test step X for group g.
$c_{\mathrm{X}}(g)$	Total count, $c = p + f$.
i	Rank of group by attribute of interest