Efficient probabilistic methods for leak-before-break analysis

Klaus Heckmann, Jürgen Sievers, GRS

2nd International Seminar on
Probabilistic Methodologies for Nuclear Applications

Ottawa, Ontario, Canada, October 25–26, 2017

Outline

Leak-before-break

Background

- LBB in the new German safety standard KTA 3206
- Probabilistic structure analysis code PROST

PROST PRObabilistic STructure analysis

Theory

- Probabilistic structure analysis and LBB: The transition concept
- Efficient probabilistic methods for LBB

Application

- Break preclusion and break probability
- Comparison of LBB assessment methods
- Uncertainties in probabilistic LBB

Outline: Background

Background

- LBB in the new German safety standard KTA 3206
- Probabilistic structure analysis code PROST

PROST PRObabilistic STructure analysis

Theory

- Probabilistic structure analysis and LBB: The transition concept
- Efficient probabilistic methods for LBB

Application

- Break preclusion and break probability
- Comparison of LBB assessment methods
- Uncertainties in probabilistic LBB

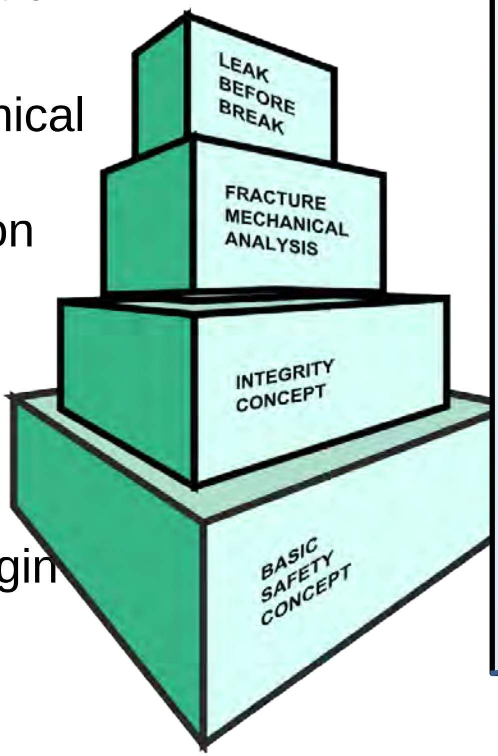
LBB in new German standard KTA 3206 (& comparison with US)

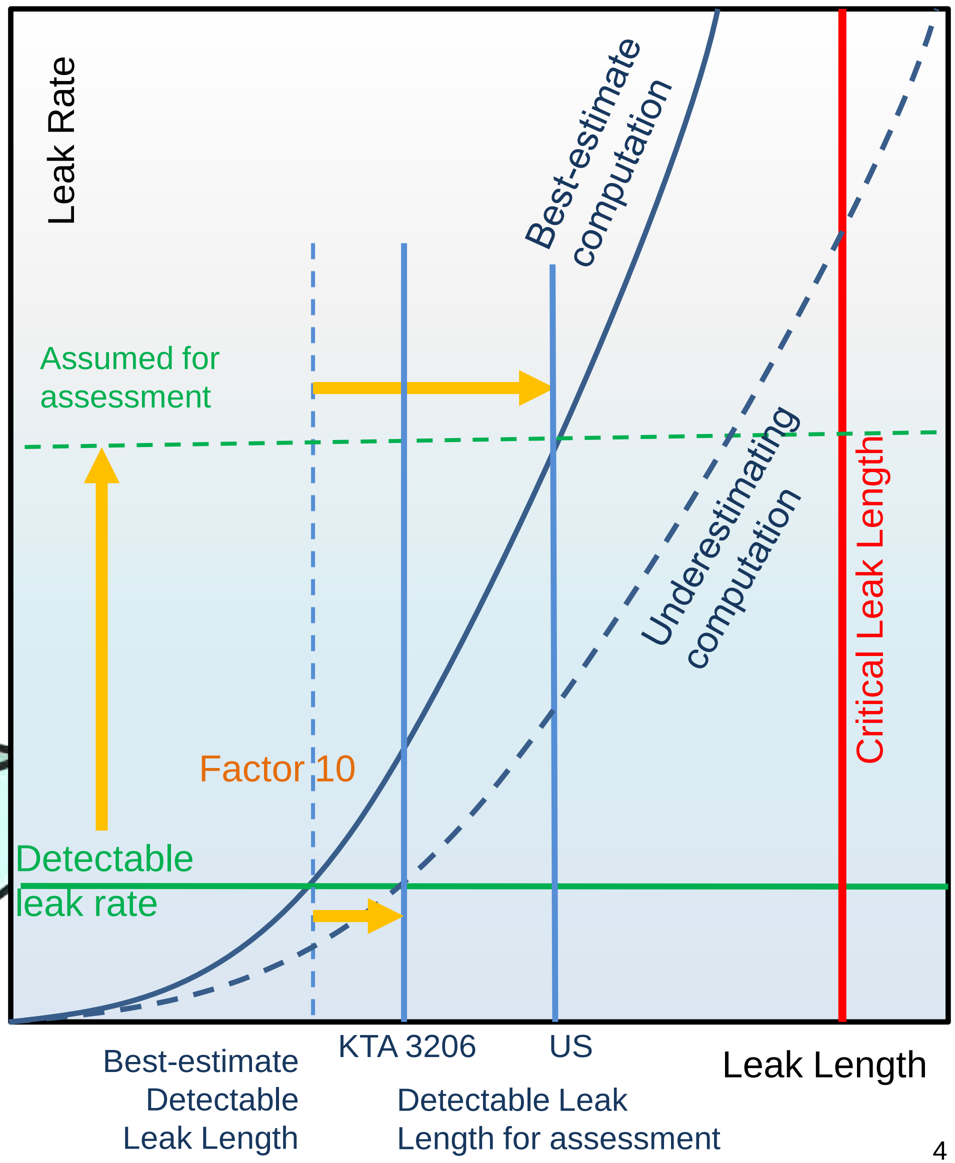
Traditional procedure (US):

- Best-estimate
- safety margin (~x10)

New safety standard KTA 3206 in 2014

- Fracture mechanical analysis for rupture preclusion
- Including LBB procedure
  - Conservative leak rate
  - no safety margin



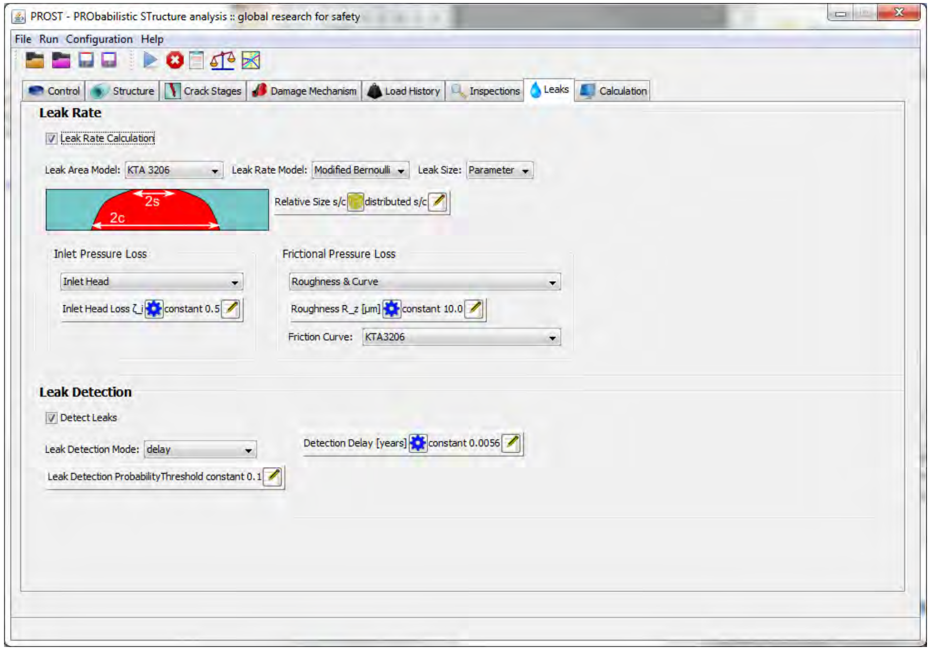


The PROST code

- Structure analysis of (flawed) pipes and vessels
- Loading and load-time-function
  - Complex operation cycles
  - Accident load events
- Damage
  - Fatigue, corrosion, ductile tearing
- Fracture mechanics
  - Flaw assessment
  - Crack growth analysis
- Leakage
  - Leak rate models
  - Leak-before-break
- Deterministic/probabilistic use
- Application of technical standards

PROST

- Graphical user interface
- Documentation
- Validation
- Developed by GRS
- Used by
  - GRS
  - External Institutions



Outline: Theory

PRObabilistic
STructure
analysis

Background

- LBB in the new German safety standard KTA 3206
- Probabilistic structure analysis code PROST

Theory

- Probabilistic structure analysis and LBB: The transition concept
- Efficient probabilistic methods for LBB

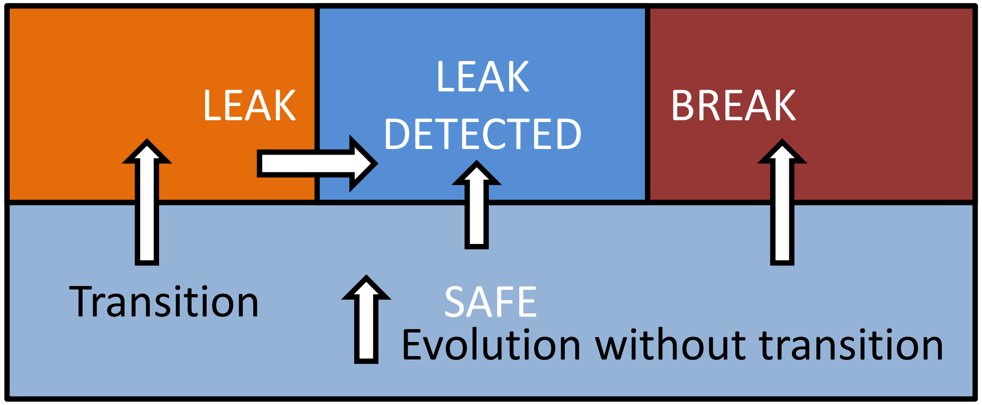
Application

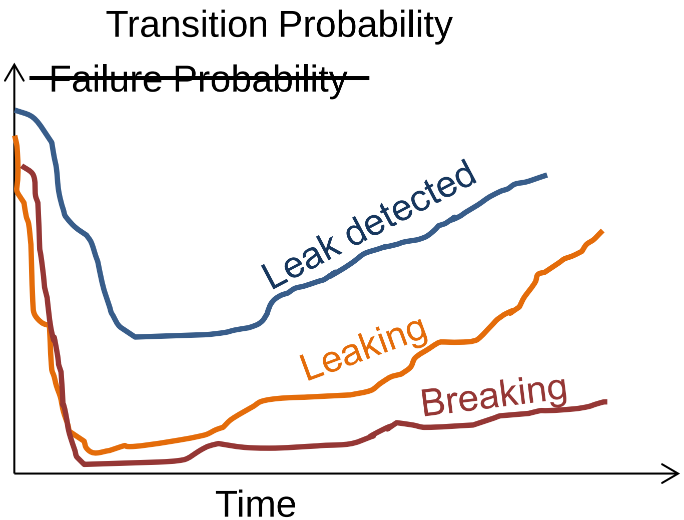
- Break preclusion and break probability
- Comparison of LBB assessment methods
- Uncertainties in probabilistic LBB

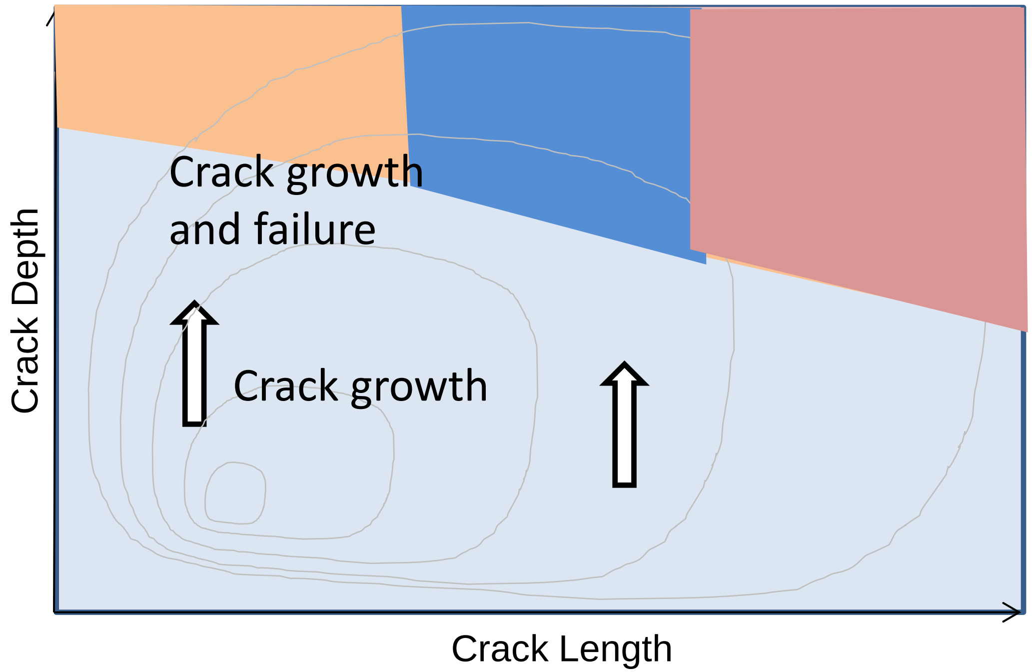
The transition concept

Qualitative structure integrity diagram

- Static situation
- Time-dependent problems
- Multiple failure modes
- Leak-before-break analysis







Efficient probabilistic techniques

The efficiency and reliability of a sampling technique depends on the investigated problem.

Which method is suitable for determination of leak/break probability in nuclear piping?

Challenges

- Very low probabilities
  - $p_{break} \approx 10^{-8}$
- High parameter dimension
  - dim = ca. 10
- Time-dependent probability
  - Annual failure during e.g. 40 years operation
- Multiple failure modes / transitions / limit state functions
  - Crack formation, crack initiation/growth, leak, detection, break

Sampling techniques

- Monte Carlo Simulation
- Quasi Monte Carlo Simulation
- Equidistant Stratification
- First-Order Reliability (FORM)
- Spherical Sampling
- FORM-based Importance Sampling
- **Vegas**

Graphical comparison of sampling techniques

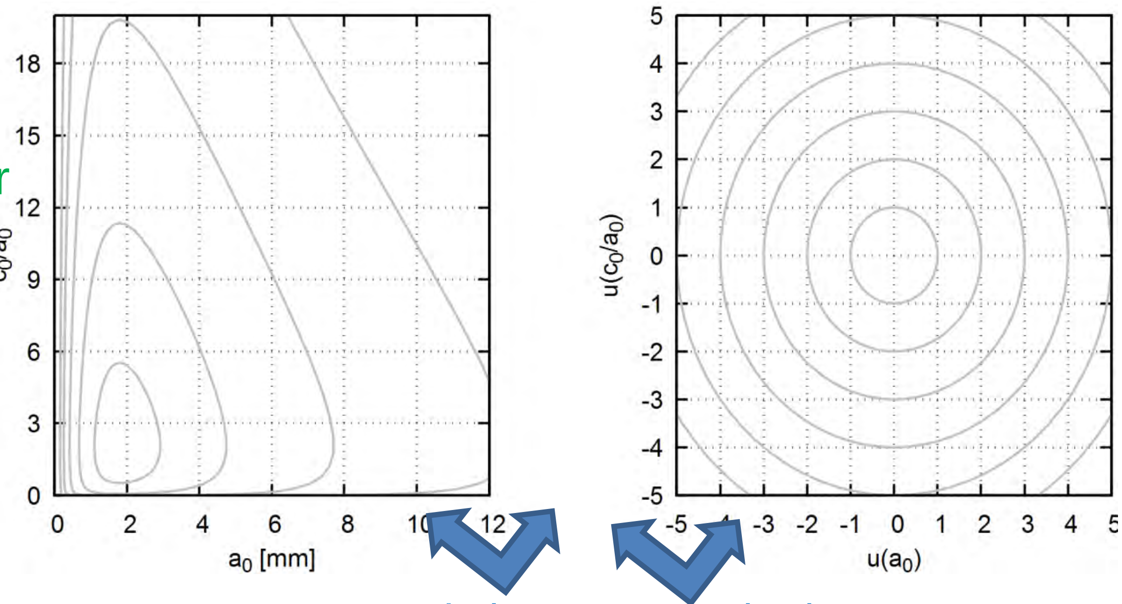
Illustrative 2-d Example (from NURBIM Fatigue benchmark*, simplified)

- Small pipe (t=11.1 mm), manufacturing cracks
- Fatigue crack growth ($2 \cdot 10^4$ cycles in 40 years)
- Distributed initial crack size: depth a, aspect ratio c/a

Comparison of found failures after 10^4 evaluations

*NURBIM: Nuclear Risk Based Inspection Methodology for Passive Components, EC Project, 2004

Parameter Space (x-space)



Standard Normal Space (u-space)

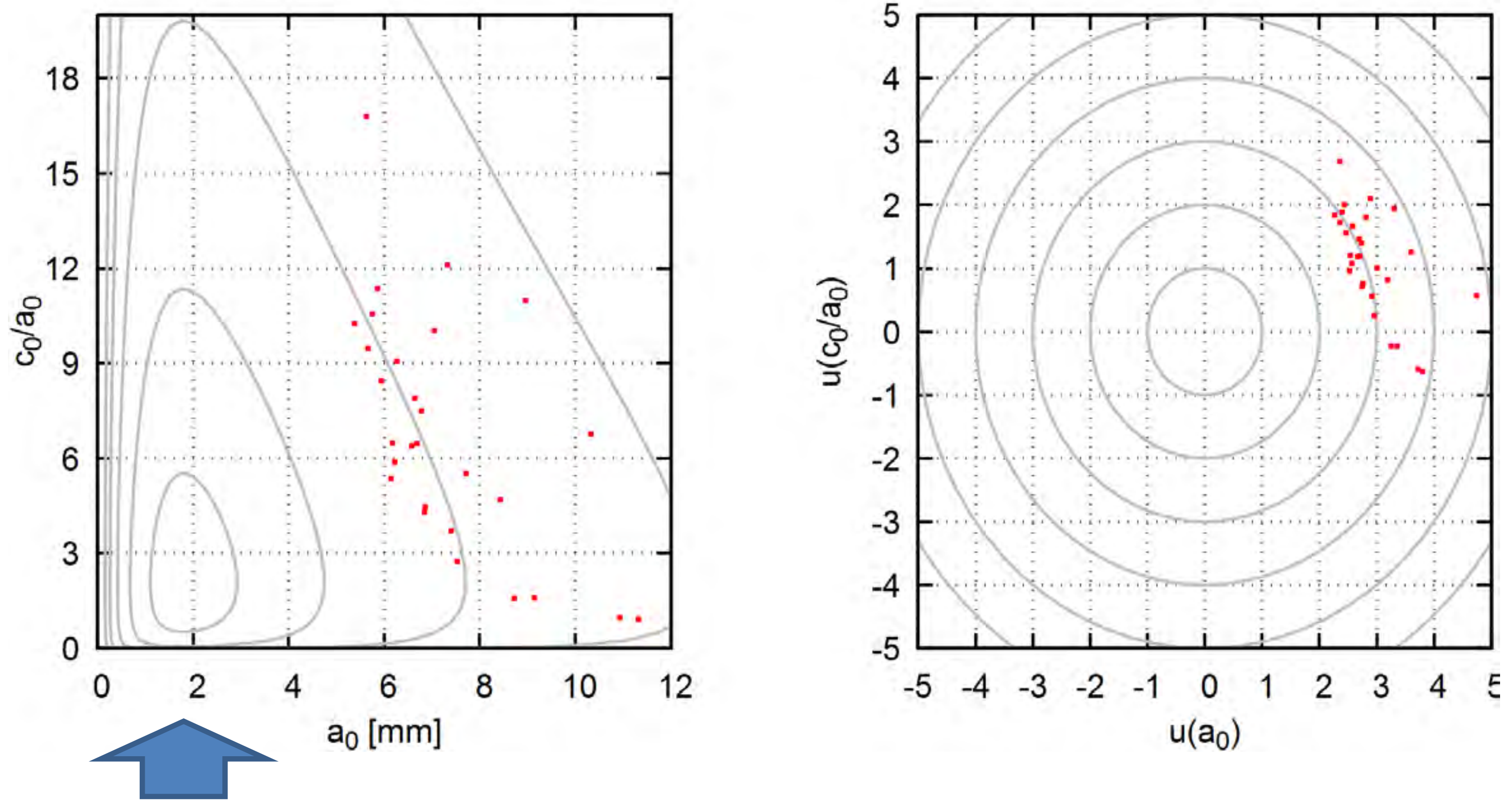
F Cumulative Distribution Function

Standard Normal Distribution Φ

2 representations, connected by variable transformations

Simple Monte Carlo Simulation

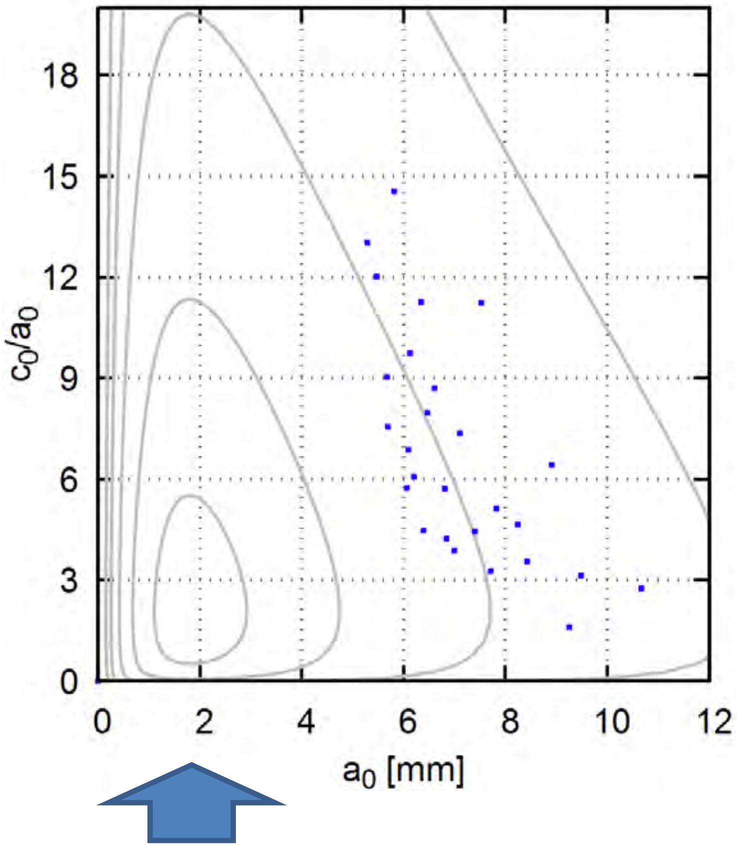
(Pseudo-)Random generation of parameter sets

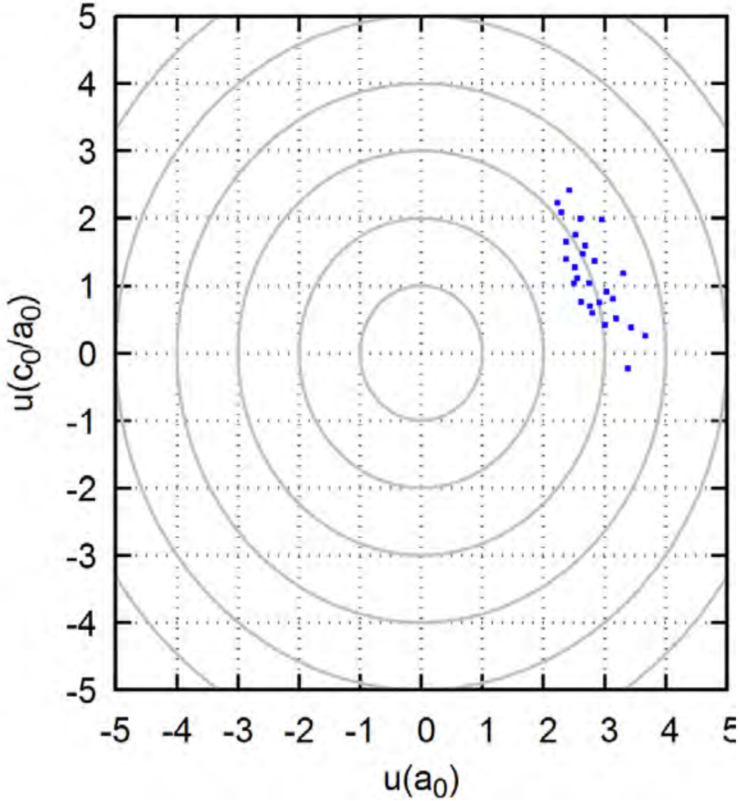


Evaluation of 10^4 parameter sets: 29 leaks found → Leak probability = $\frac{29}{10^4}$ = 0.29 %

Quasi Monte Carlo Simulation

Low-discrepancy series (quasi random numbers) instead of pseudo-random numbers

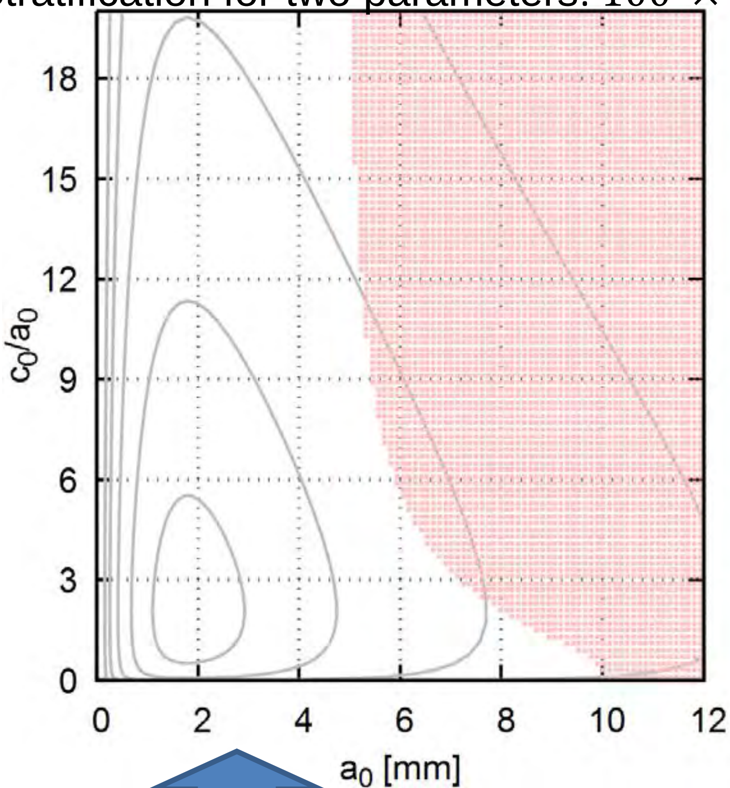


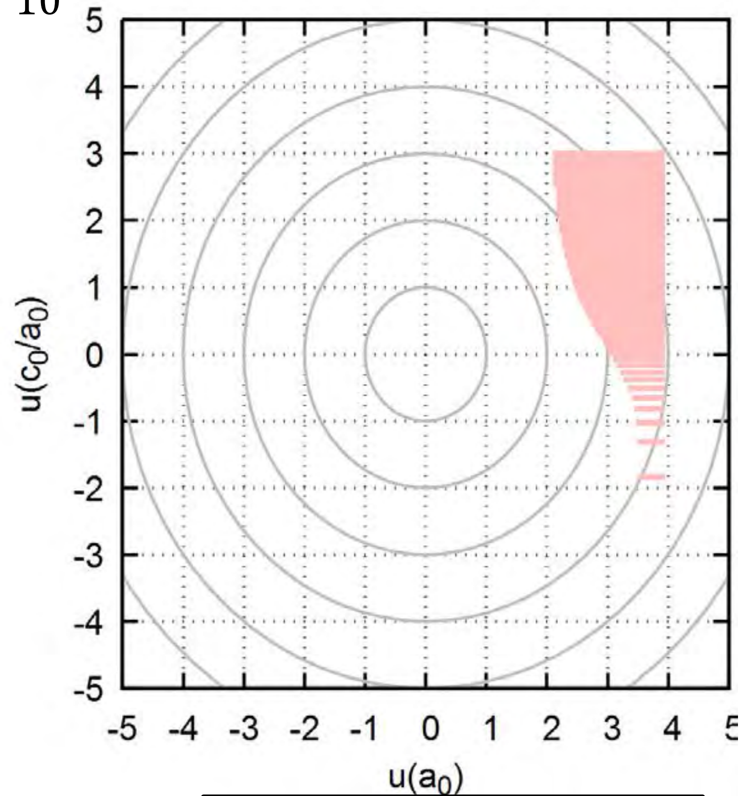


Evaluation of 10^4 parameter sets: 28 leaks found → Leak probability = $\frac{28}{10^4}$ = 0.28 %

Equidistant stratification

Equidistant strata in x-space, evaluation of the central value for each stratum
Stratification for two parameters: $100 \times 100 = 10^4$



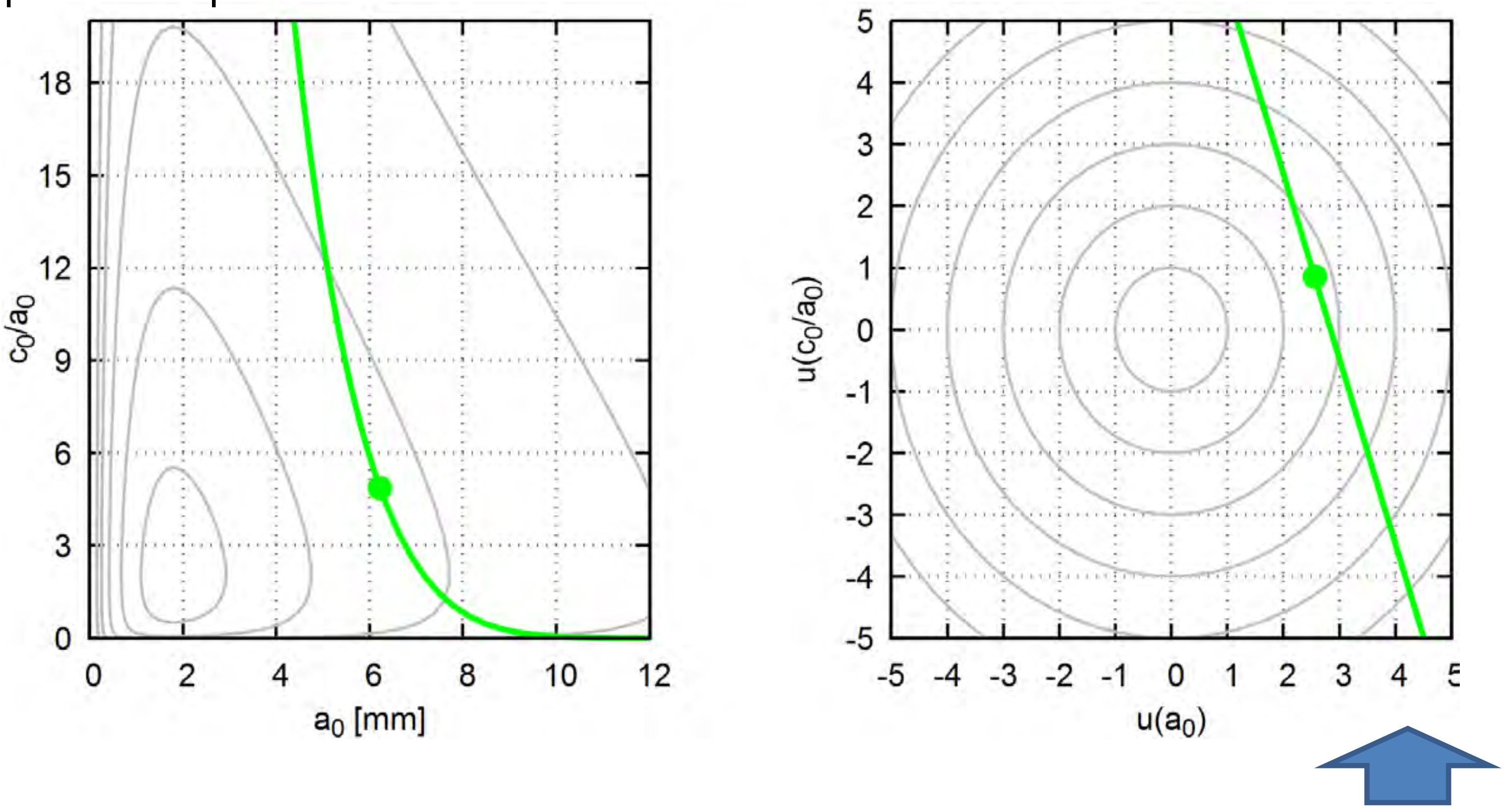


Evaluations with leak

Evaluation of 10^4 parameter sets: Leak probability = $\sum_{i=1}^{5045} w_i$ = 0.278 %

First-Order Reliability Method (FORM)

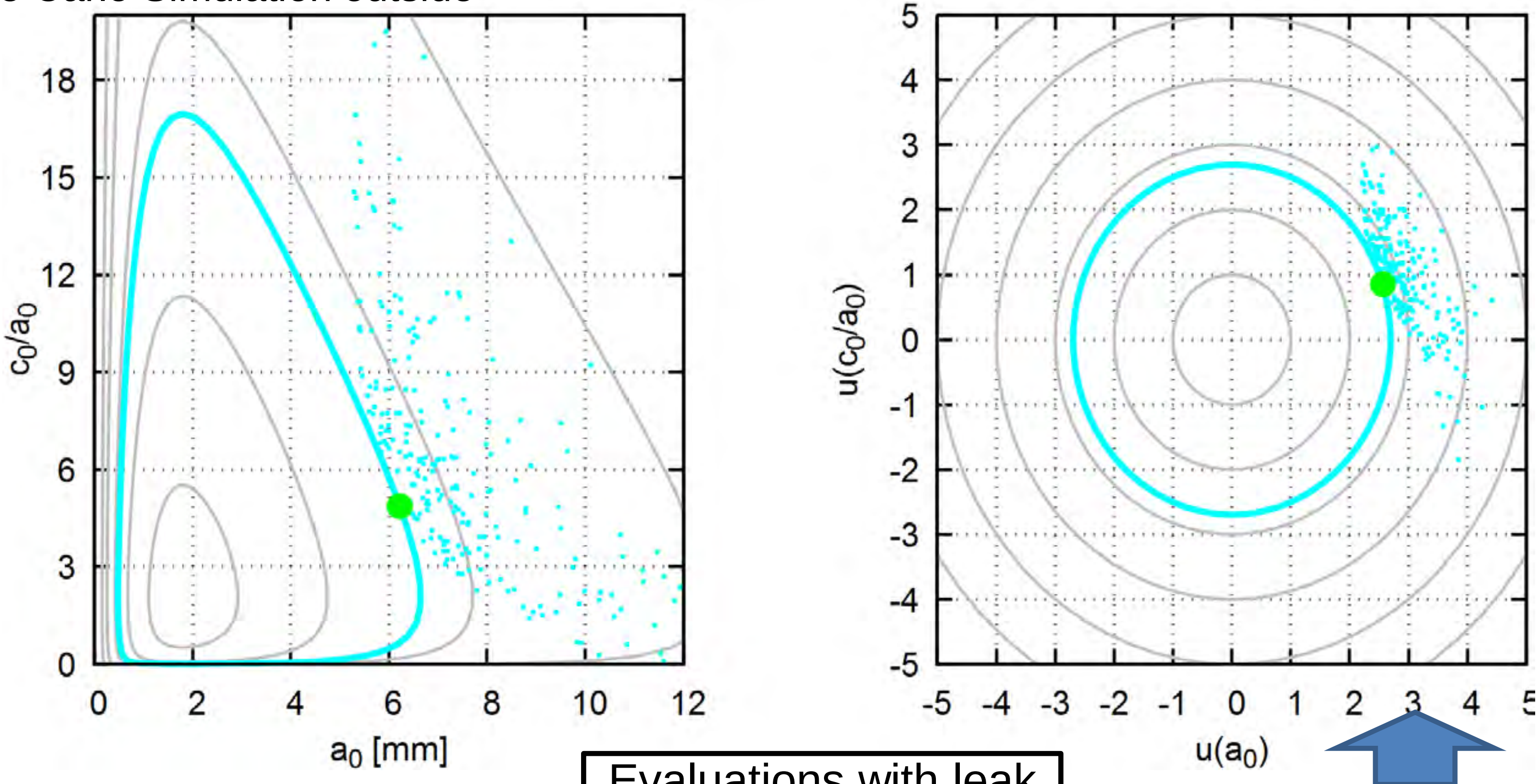
Identification of the Design Point / Most Probable Point
Assumption of a specific limit state function



Evaluation of 10^4 parameter sets: Leak probability = $\int_{\text{beyond line}} \Phi(u)\ d^2u$ = 0.35 %

Spherical Sampling

Exclusion of u-values smaller than the design point absolute value
Monte Carlo Simulation outside

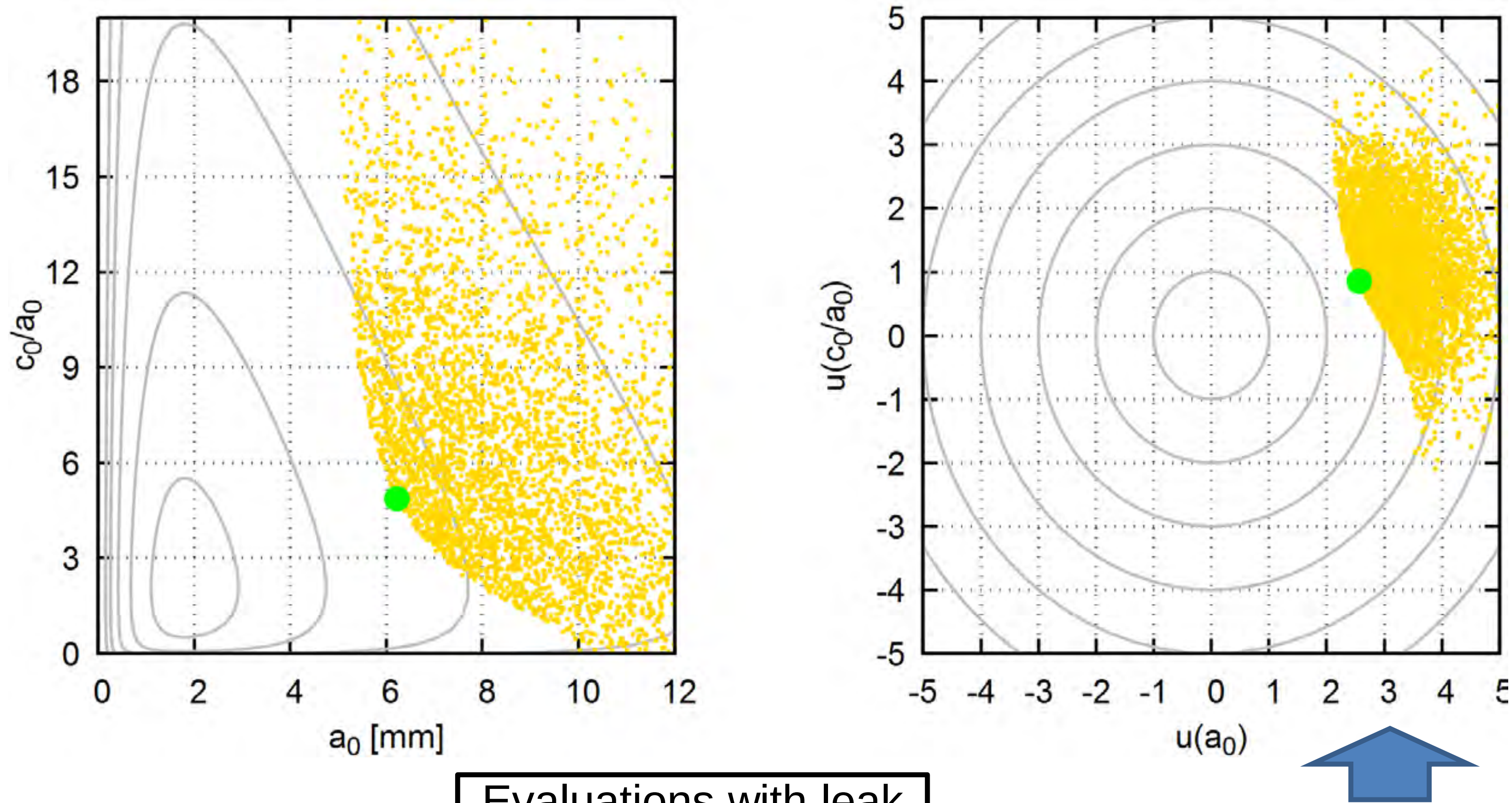


Evaluation of 10^4 parameter sets: Leak probability = $0.123 \times \frac{235}{10^4}$ = 0.288 %

Outside-probability

Importance Sampling (based on design point)

Importance sampling around the design point

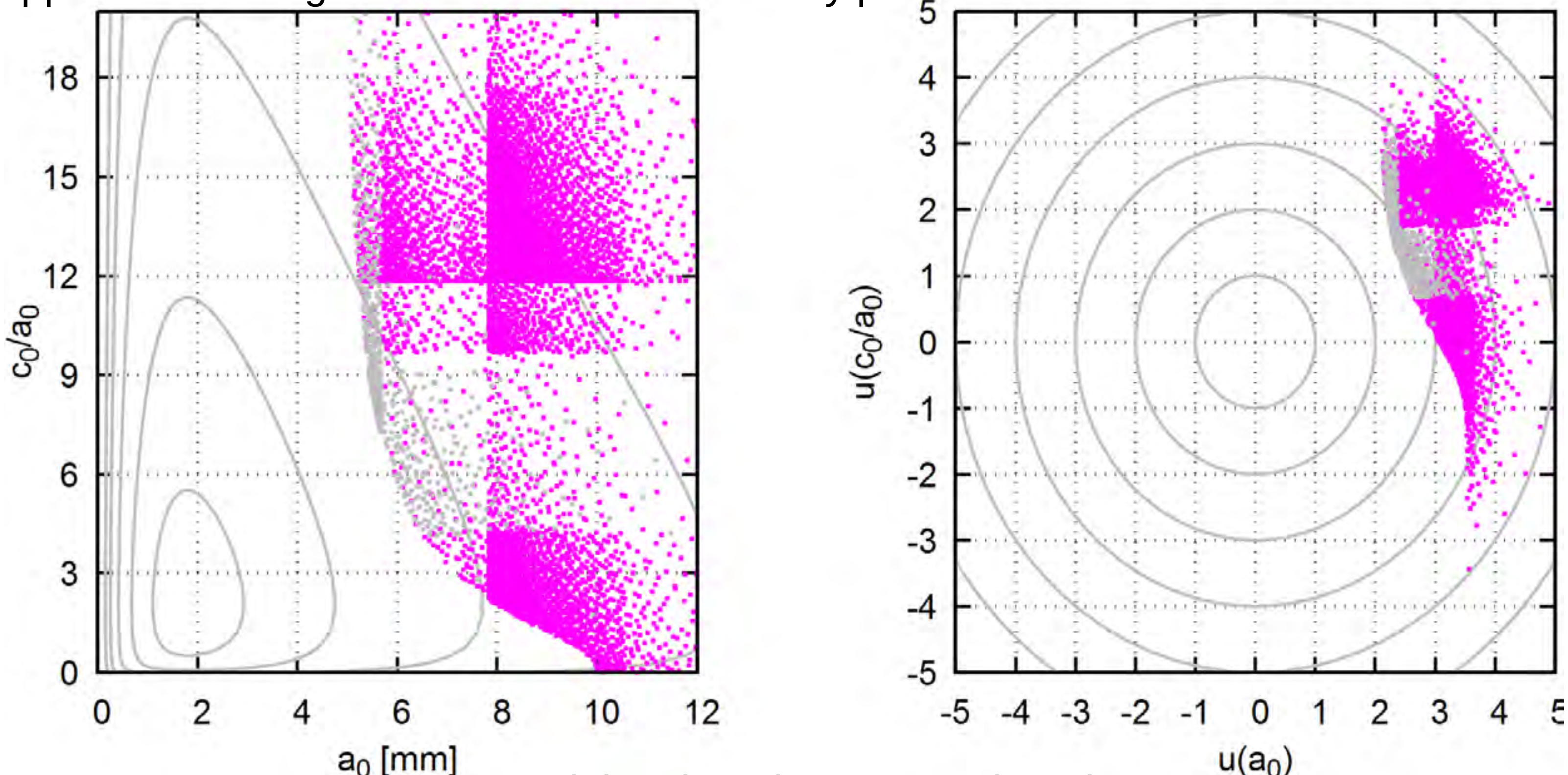


Evaluation of 10^4 parameter sets : Leak probability = $\sum_{i=1}^{4637} \frac{f_i}{\psi_{i_i}}$ = 0.282 %

weight

Vegas

Iterative adaption of sampling regions, Used in particle physics (scattering amplitudes, …), Proposed 1978 by P. LePage, improved in 2005 by T. Hahn
First application of Vegas to the structural reliability problem



Pink: 1 iteration; gray: 2 iterations

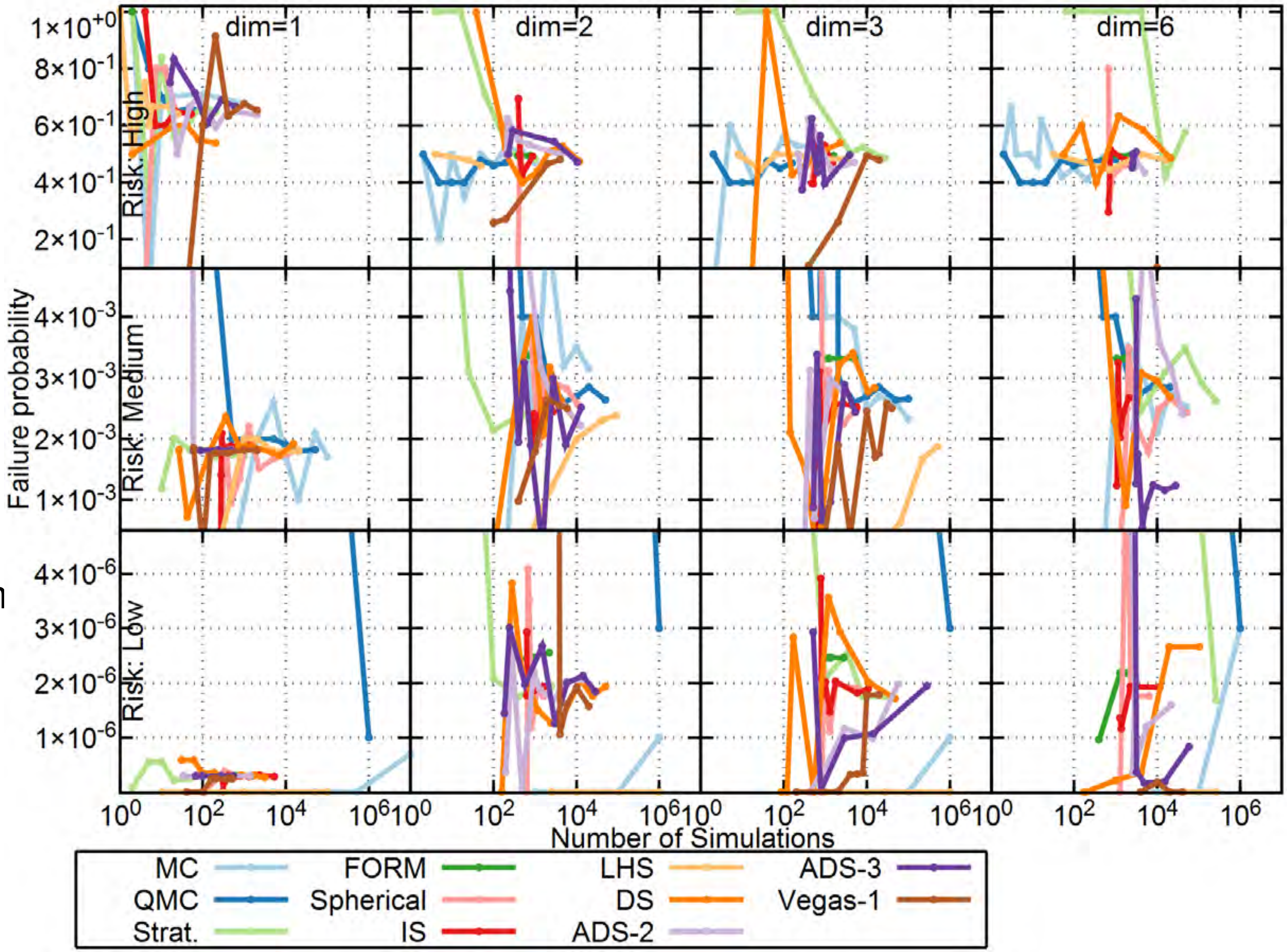
Efficiency

Efficiency mainly depends on

- Failure probability
- Number of distributed parameters

Case study:

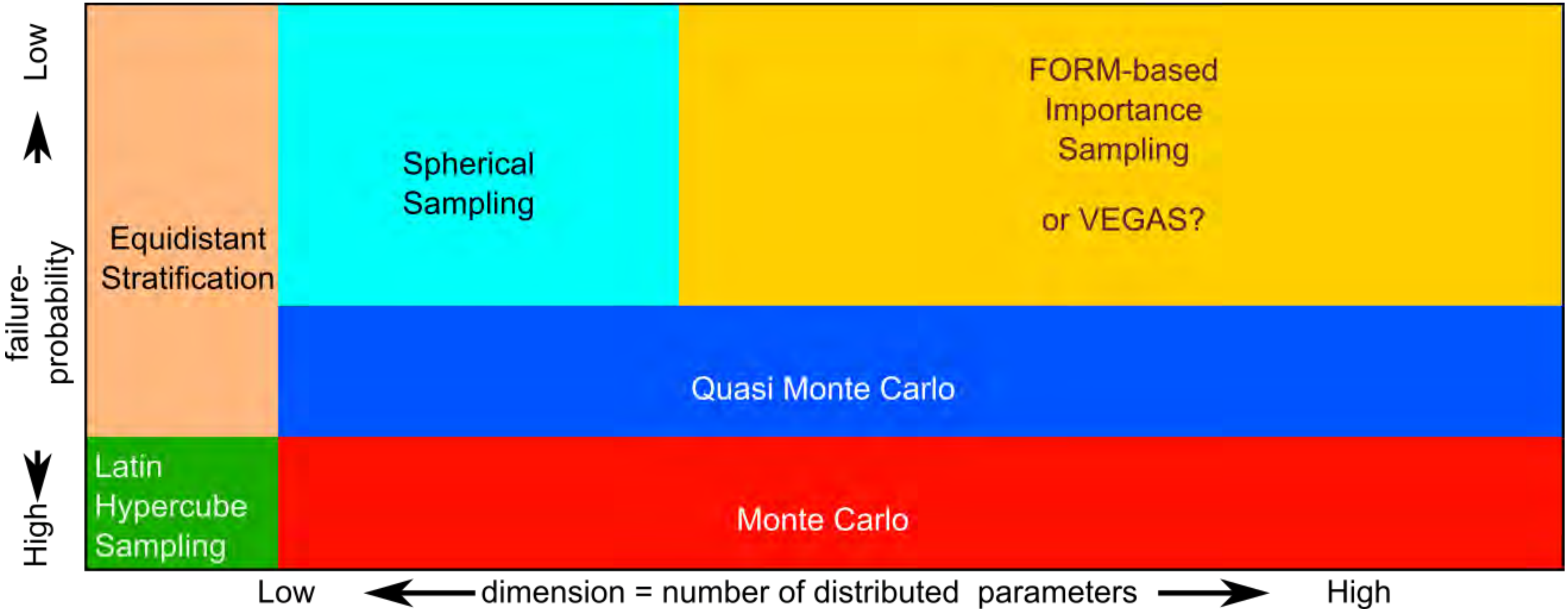
- Variate both
- Apply sampling techniques
- Failure vs. Number



Efficiency

Recommended sampling technique mainly depends on two quantities

- Failure probability
- Number of distributed parameters



Outline: Application

Background

- LBB in the new German safety standard KTA 3206
- Probabilistic structure analysis code PROST

PROST PRObabilistic STructure analysis

Theory

- Probabilistic structure analysis and LBB: The transition concept
- Efficient probabilistic methods for LBB

Application

- Break preclusion and break probability
- Comparison of LBB assessment methods
- Uncertainties in probabilistic LBB

Break preclusion and break probability

Open questions:

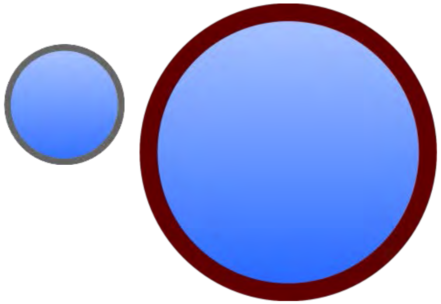
- How can a successful deterministic verification be translated into a probability?
- Is it in agreement with operational experience?

Method of answer:

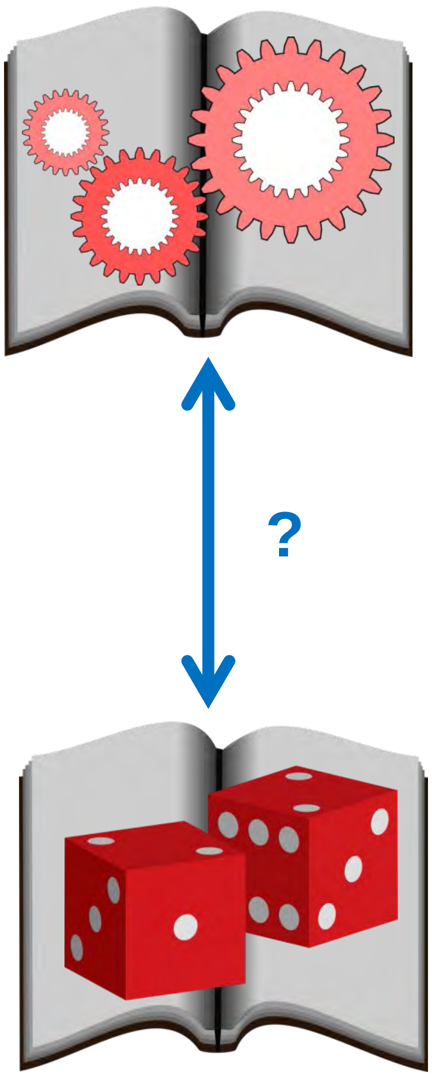
- Probabilistic fracture mechanics!

Two examples (from standard)

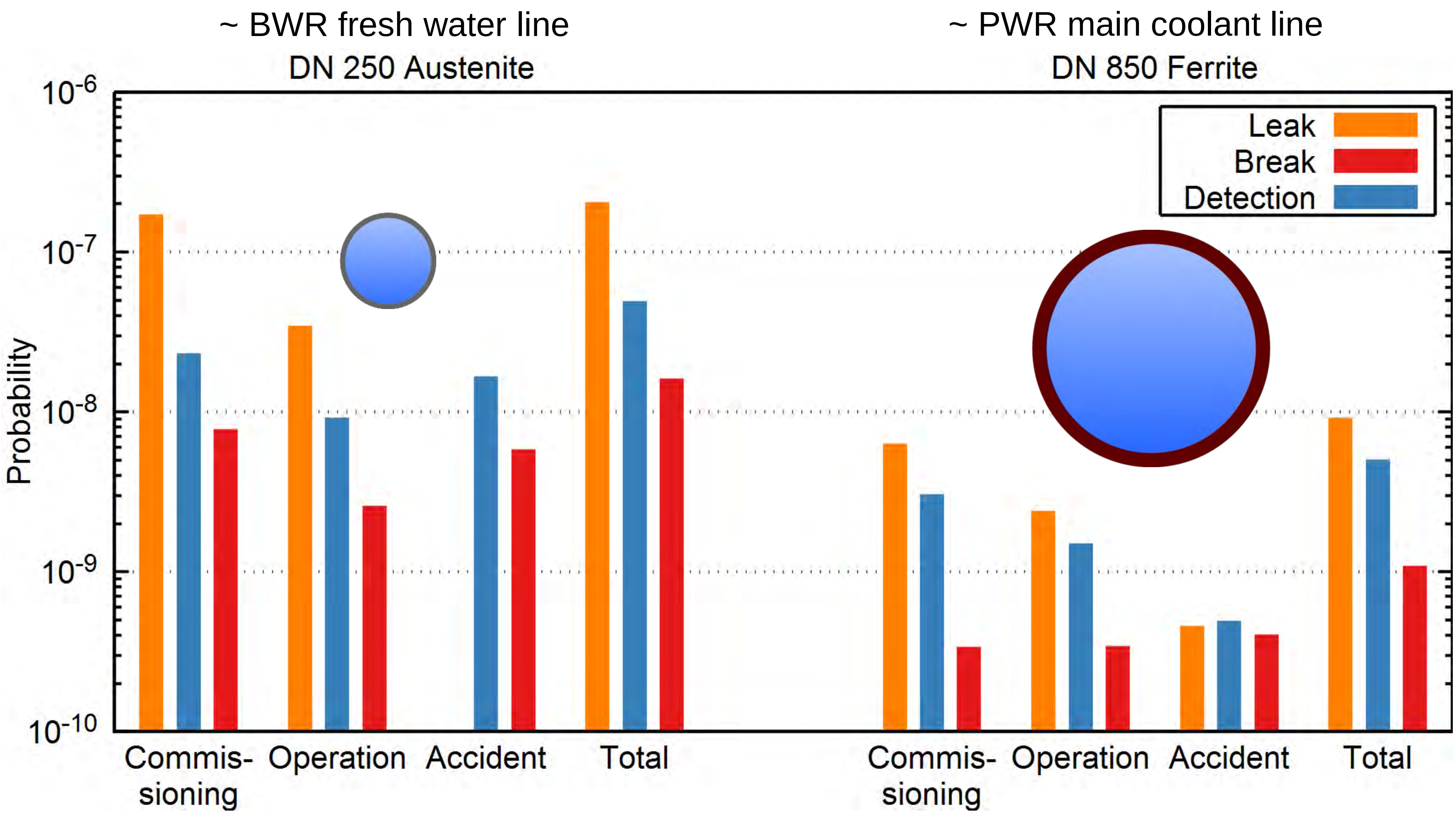
- DN 250, Stainless Steel,
  ~ BWR fresh water line
- DN850, Ferritic Steel,
  ~PWR main coolant line



- 11 distributed parameters
- FORM-based Importance Sampling



LBB probabilities computed with PROST



Reference for further reading: KH+JS et al., 41st MPA-Seminar, Stuttgart, 2015

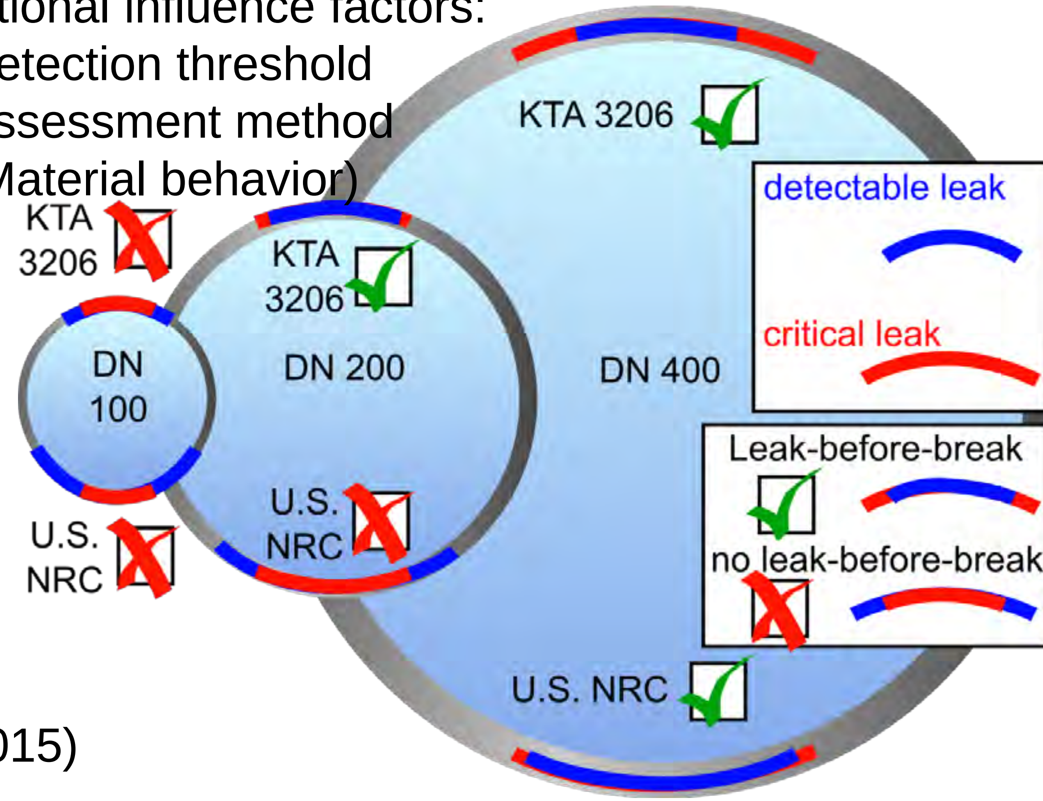
Comparison of LBB methods

Typical LBB Trend

- Large diameter piping:
  - Generic LBB behavior
- Medium diameter piping
  - LBB challenging
- Small diameter piping:
  - No LBB behavior

Additional influence factors:

- Detection threshold
- Assessment method
- (Material behavior)



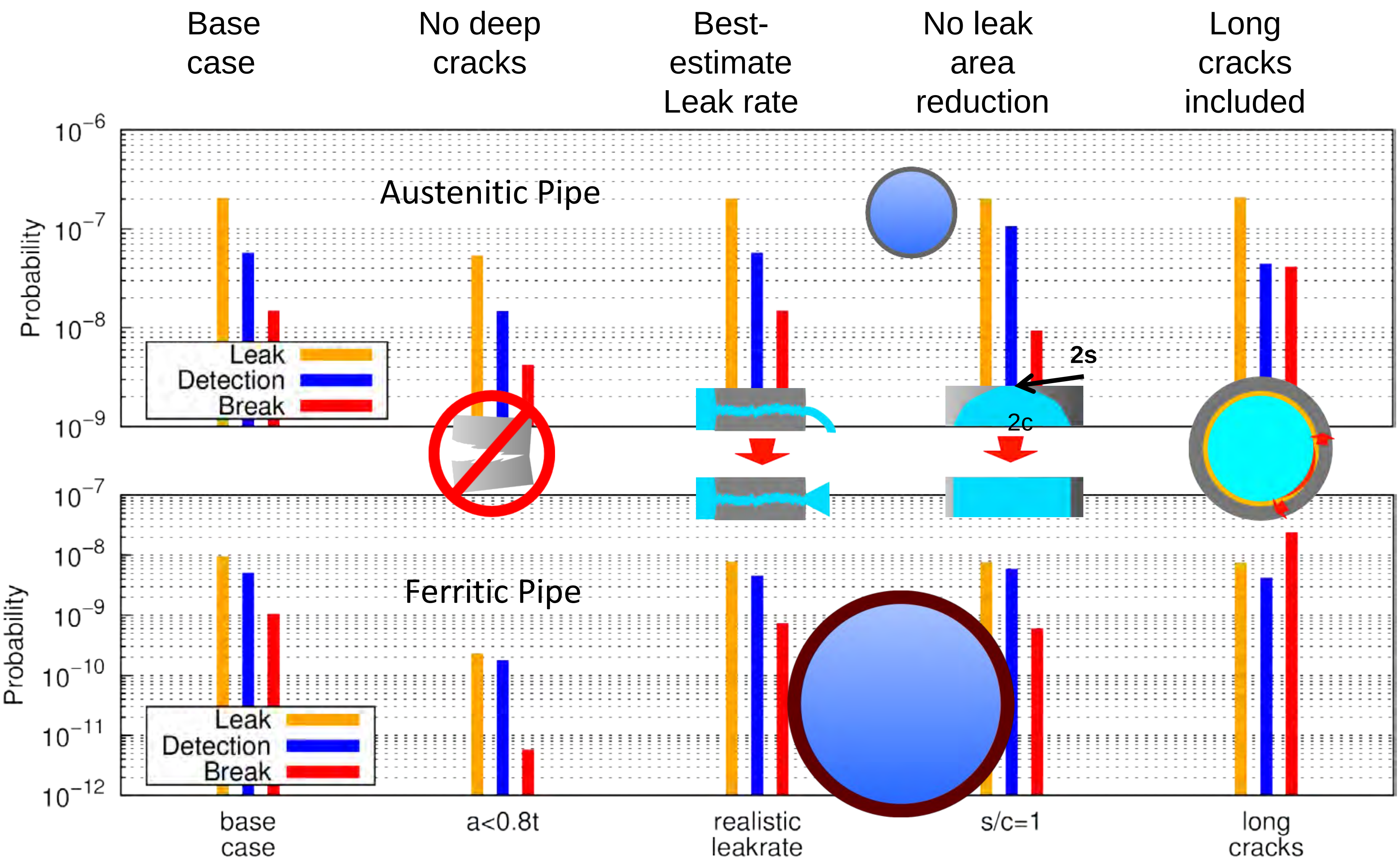
Comparison of leak modeling in probabilistic LBB assessment

- Bhindiraman, Blom, SMiRT-23 (2015)

Simulation	Rupture Probability	Rel.-Index β
Original	1E-8	5.6
PROST	3E-43	13.7

Reference for further reading: KH+JS, “Leak-Before-Break Analyses of PWR and BWR Piping Concerning Size Effects”, submitted to Nucl. Eng. Des.

Sensitivity analysis (total probability after 40 years)



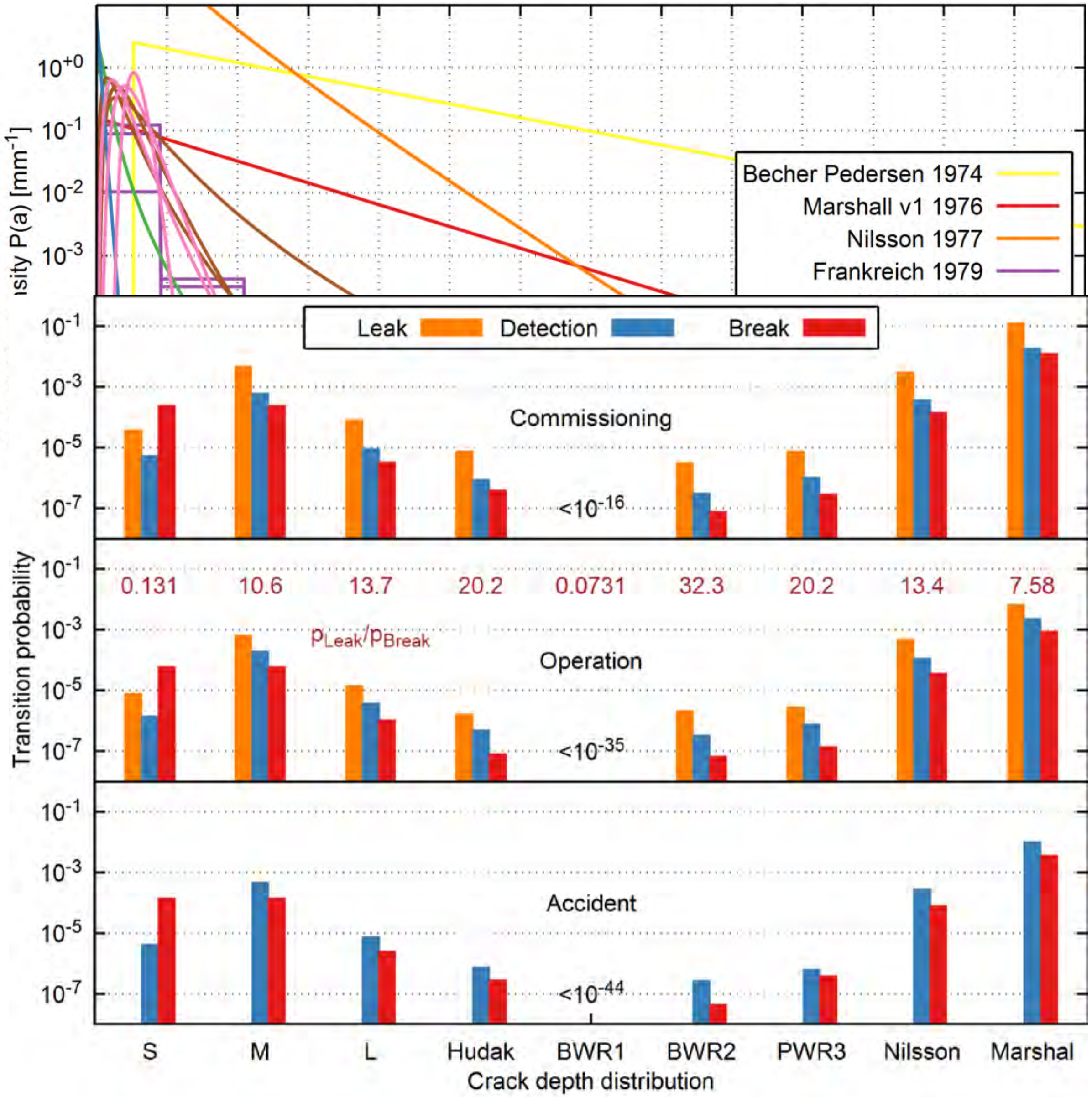
Uncertainties in probabilistic LBB

Components with high reliability

- Verly low failure probabilities
- Contributions from the tails of the distribution functions
- Epistemic uncertainties

Variating initial flaw size distributions

- Total probabilities
  - ?
- Promising
  - Conditional probabilities
  - Operational experience



Summary and outlook

- New LBB method in German safety standard KTA 3206
- Probabilistic LBB: transition concept
- High reliability + many distributed parameters: efficient algorithms (like VEGAS)
- Break preclusion = high reliabilities
- Traditional LBB methods too conservative in some situations
- Epistemic uncertainties: Look at conditional probabilities?