

# PROARTIS

## PROARTIS – WCET Analyses Techniques and Tools



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ARPA Workshop  
Berlin, January 22, 2013

*This project and the research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 249100.*



[www.proartis-project.eu](http://www.proartis-project.eu)

# Why do people need worst case timing?

## Timing margin

- Does the software fit the partition?

## Deadlines

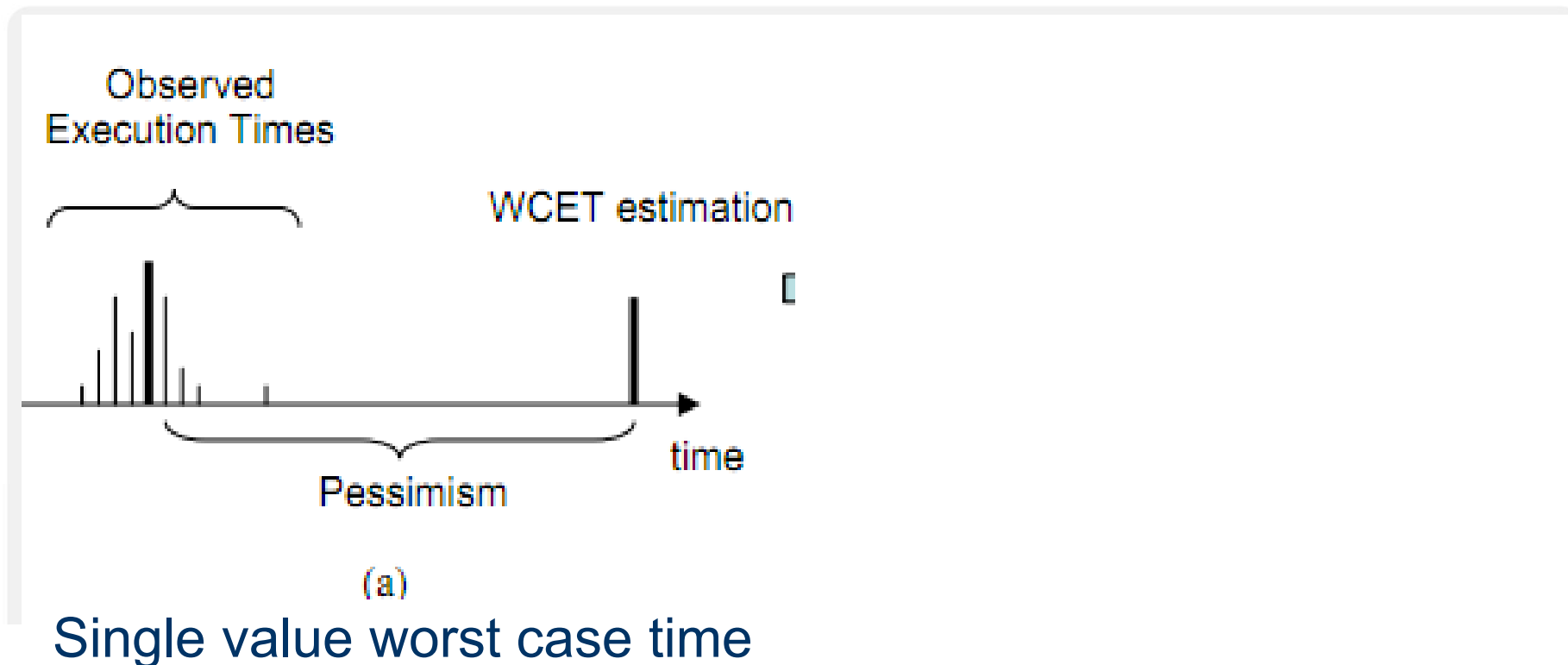
- Will it always run fast enough?

## Optimization/Design support?

- *Can I fit my software on a different processor?*

Worst  
Case  
Execution  
Time  
  
(WCET)

# Probabilistic Timing Analysis "PTA"



Can derive a probability of timing failure e.g. "per hour"

# Types of Probabilistic Timing Analysis

- 3 approaches to compute *probabilistic Worst Case Execution Time* (pWCET)

R5

- *Measurement Based* → "MBPTA" (*end to end tests*)
- *Static* → "SPTA" (*no testing*)
- *Hybrid* → "HyPTA" (*tests and code analysis*)

R5

of a program is a random variable describing the probability that the worst-case execution time of that program exceeds a given value  
ROSEGARDEN; 18.01.2013

# Probabilities



- *Random variable*

- Associates a number with each outcome of a random experiment
- Tossing a coin:  $\frac{1}{2}$  head,  $\frac{1}{2}$  tail

- *Independent random variables*

- They describe events that are not related
- Event A: “my laptop died” and event B: “The beamer does like my laptop”

R1

R6

- *Identically distributed random variables*

- Random variables that have the same distribution function
- Event A: “arrival of a client in a bank” and event B: “arrival of a car at a gas station”

R7

**R1** if random experiments are repeated sufficiently frequently under identical conditions, stochastic or statistical regularities can be found.

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**R6** Sample point = each outcome in a set  $S$  (sample space) of all possible outcomes;

RANDOM EVENT = a subset  $A$  of a sample space and contains those sample points for which the event is true;

PROBABILITY OF AN EVENT :

the probability of any event  $A$  is the sum of the weights of all sample points in  $A$ . If we denote the probability of event  $A$  by  $P(A)$  then  $0 \leq P(A) \leq 1$ ,  $P(\varnothing) = 0$ ,  $P(S) = 1$ ;

explained by one of three methods: the relative frequency method, the estimation method using the results of a series of observations, the subjective 'degree of belief' method;

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**R7** Independent random variables

Random variables that describe events which are not related

"Event A: my laptop died" and "Event B: the beamer does not like my laptop"

Identically distributed random variables

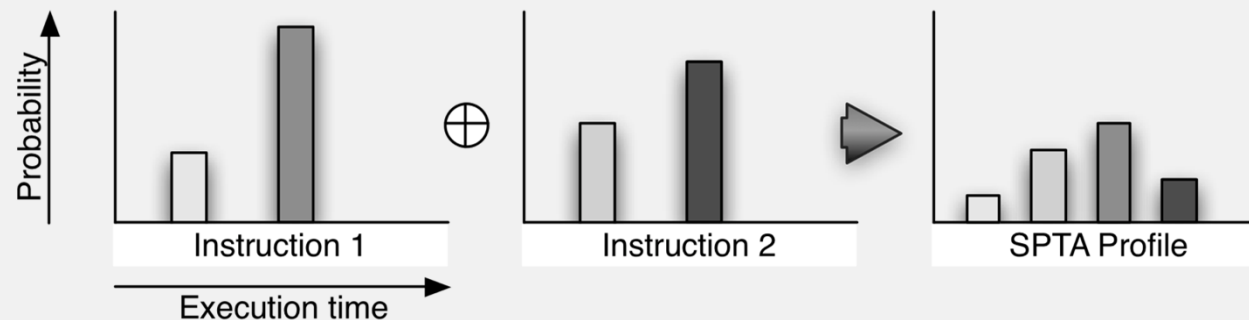
Random variables that have the same distribution function

"Event A: arrival of a client in a bank" and "Event B: arrival of a car at a gas station"

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# Static Probabilistic Timing Analysis

- The *pWCET* estimate is obtained by convolving the execution time profiles of each instruction



$$\begin{pmatrix} 1 & 2 \\ 0.7 & 0.3 \end{pmatrix} \otimes \begin{pmatrix} 7 \\ 1 \end{pmatrix} = \begin{pmatrix} 1+7 & 2+7 \\ 1 \cdot 0.7 & 1 \cdot 0.3 \end{pmatrix} = \begin{pmatrix} 8 & 9 \\ 0.7 & 0.3 \end{pmatrix}$$

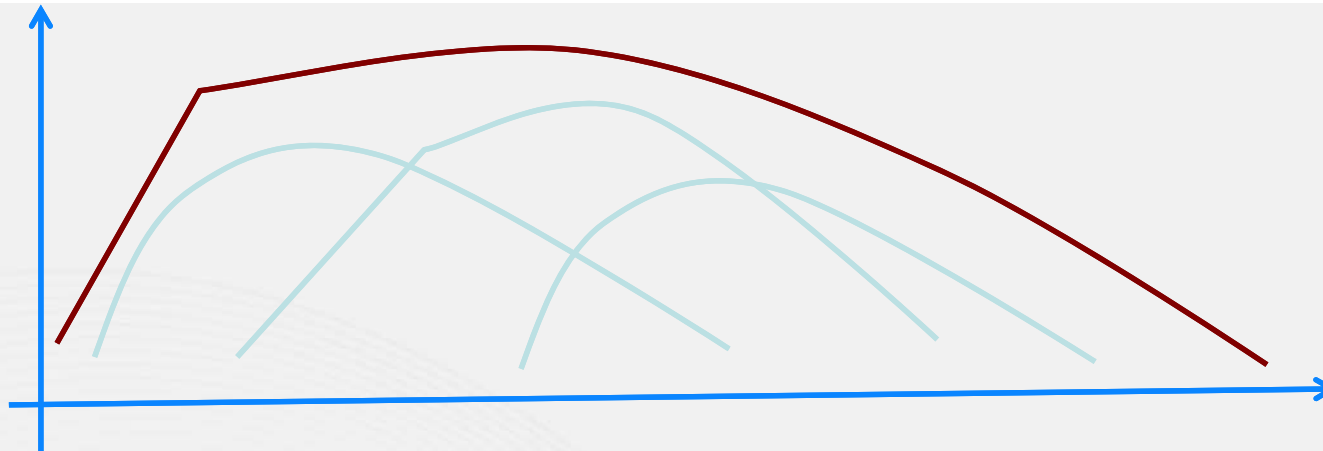
- The convolution requires independent random variables
- The execution times are defined by the same distribution



# Measurement Based Probabilistic Timing Analysis

- *The pWCET estimated is obtained by applying Extreme Value Theory (EVT)*

*Let  $\{\mathcal{X}_1, \mathcal{X}_2, \dots, \mathcal{X}_n\}$  be a sequence of i.i.d. random variables and let  $\mathcal{M}_n = \max\{\mathcal{X}_1, \mathcal{X}_2, \dots, \mathcal{X}_n\}$ . If  $F$  is a non degenerate distribution function and there exists a sequence of pairs of real numbers  $(a_n, b_n)$  such that  $a_n \geq 0$  and  $\lim_{n \rightarrow \infty} P(\frac{\mathcal{M}_n - b_n}{a_n} \leq x) = F(x)$ , then  $F$  belongs to either the Gumbel, the Frechet or the Weibull family.*



- EVT requires i.i.d. random variables

# MBPTA

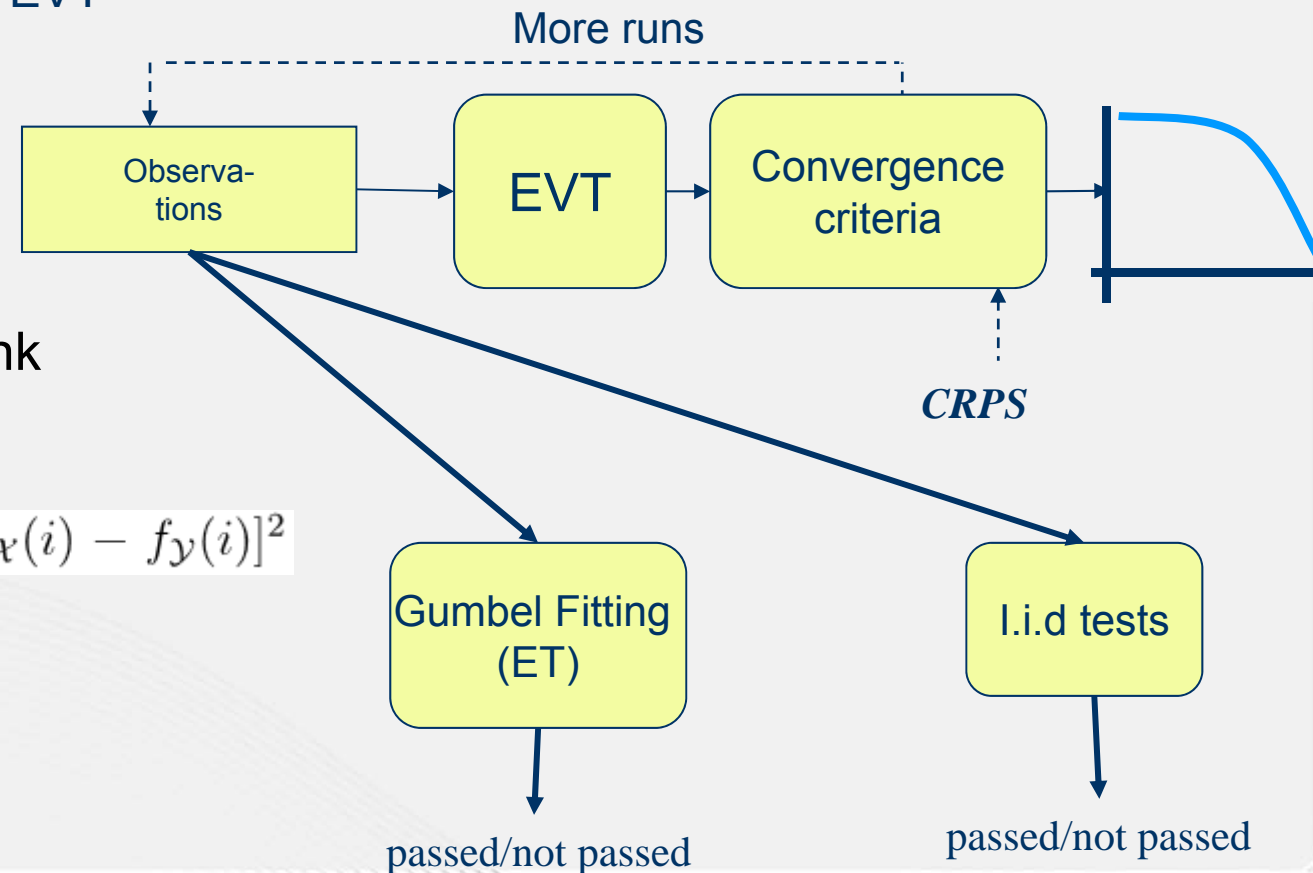
- *Steps of applying EVT*

- Observations
  - Grouping
  - Fitting
  - Comparison
  - Tail extension
- } EVT

- *Convergence*

- Continuous rank probability score

$$CRPS = \sum_{i=0}^{+\infty} [f_x(i) - f_y(i)]^2$$



# PROARTIS on Simple Programs

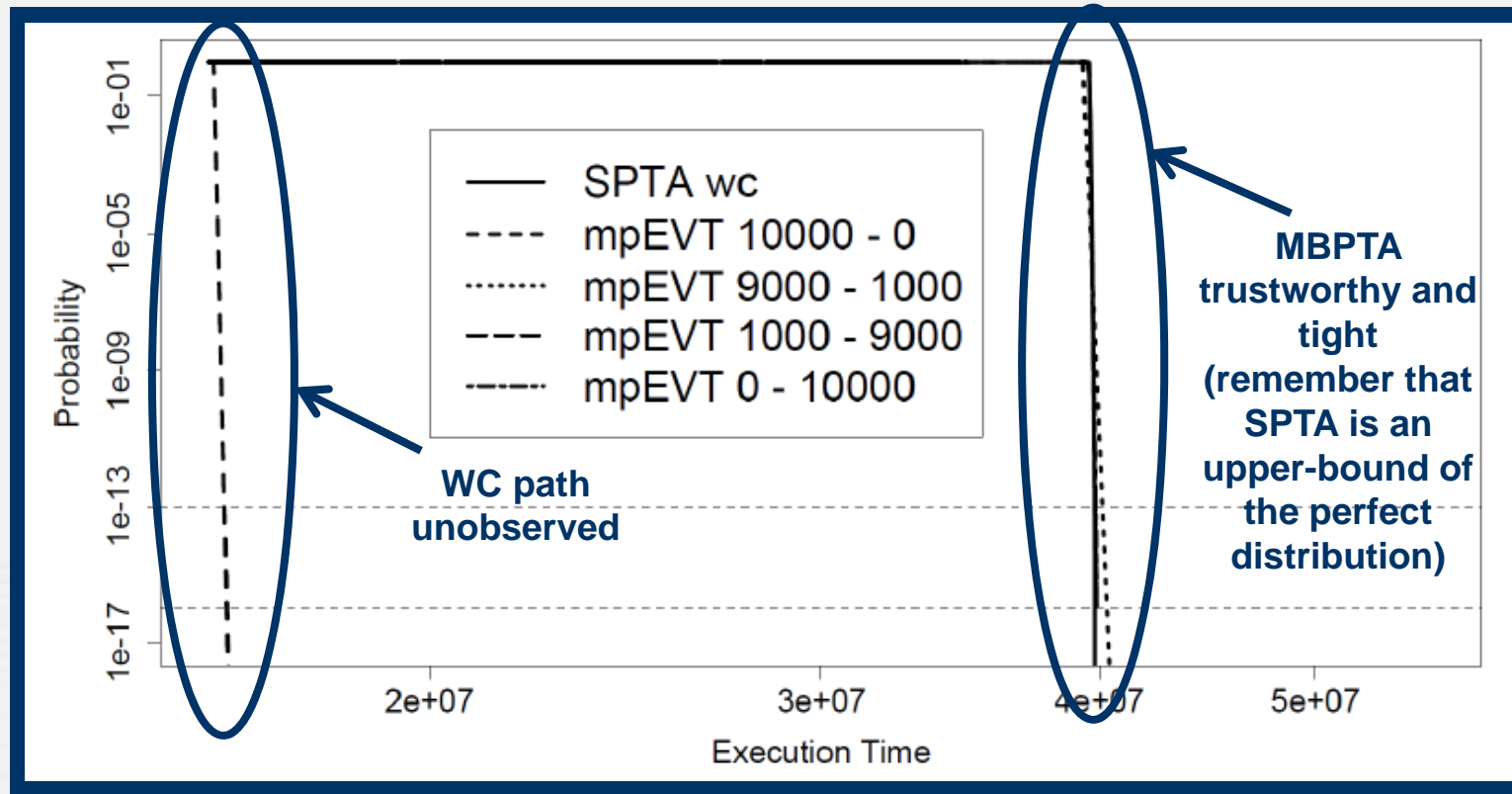
- Results for 11 EEMBC benchmarks

Benchmark	MBPTA $10^{-13}$ vs. SPTA	MBPTA $10^{-16}$ vs. SPTA
<i>a2time</i>	1.1%	2.0%
<i>aifftr</i>	1.2%	1.6%
<i>aifirf</i>	0.7%	0.9%
<i>aiifft</i>	0.5%	1.0%
<i>cacheb</i>	4.3%	6.3%
<i>canrdr</i>	2.4%	3.5%
<i>iirflt</i>	0.3%	0.5%
<i>puwmod</i>	2.0%	3.1%
<i>rspeed</i>	4.5%	7.0%
<i>tblook</i>	0.7%	1.0%
<i>ttspk</i>	3.6%	5.3%

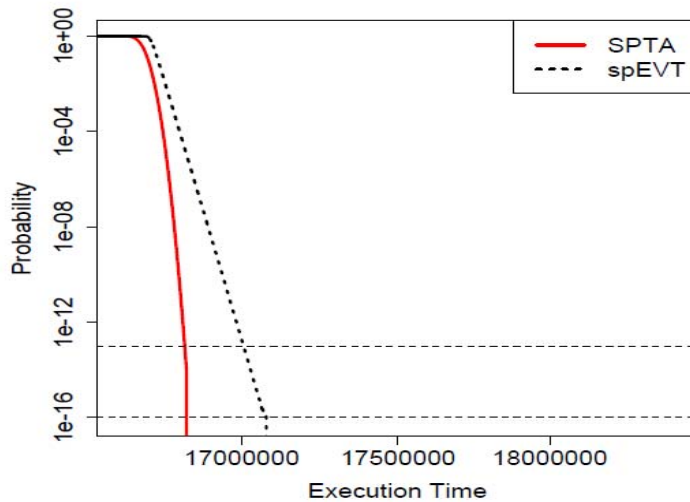
The lower the %,  
the closer the  
**PROARTIS**  
MBPTA analysis  
is to the  
theoretical value.

# Synthetic benchmark

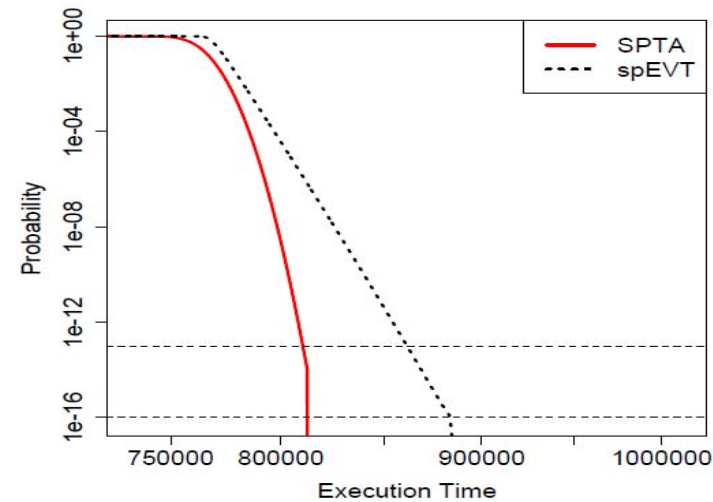
- Several paths, one of them much worse than the rest



# PROARTIS Results for Simple Programs



(a) aifirf

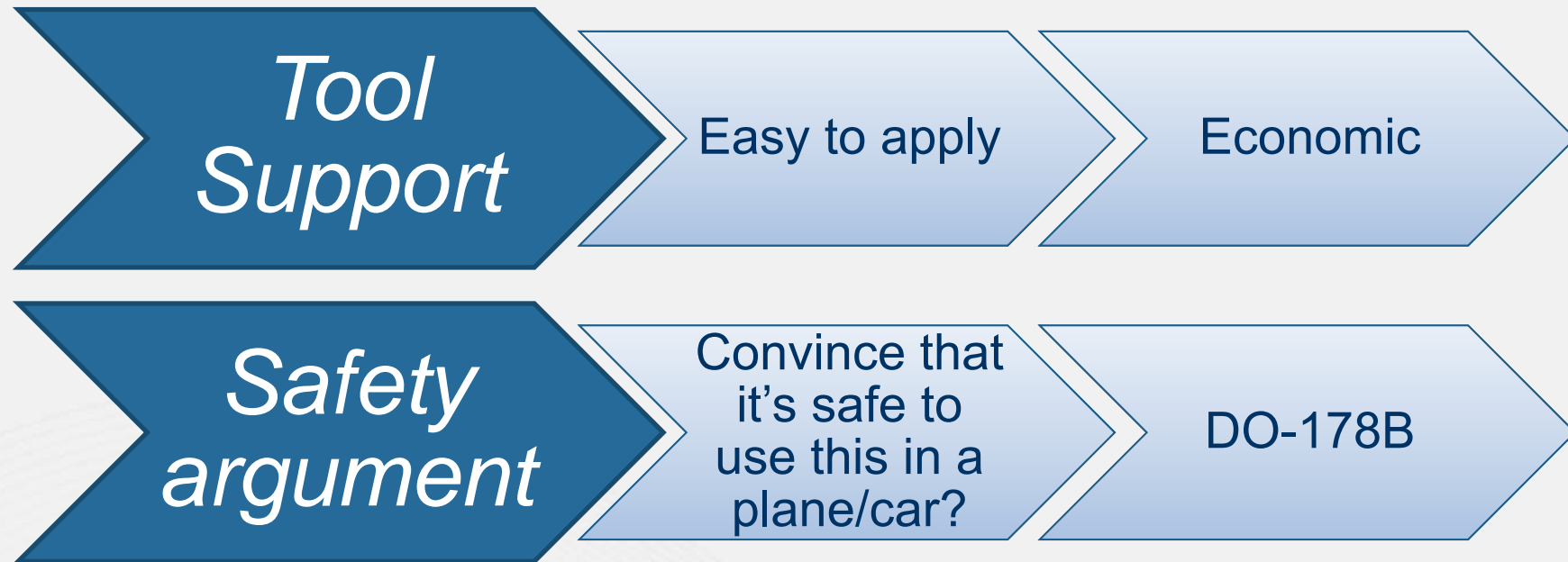


(b) rspeed

- *Conclusion:*
  - PROARTIS End-to-end (MBPTA) works for programs that have few paths.
- *How to do we deal with complex programs?*

# Industrial Application of Probabilities

What do we need to do before someone can use this research?



# Moving from simple to complex programs

Industrial Practice

$$WCET \leq HWM \cdot 1.2$$

PROARTIS  
End to End  
Measurements

$$WCET \leq \overset{\text{High water mark}}{HWM} \text{ (longest test)}$$

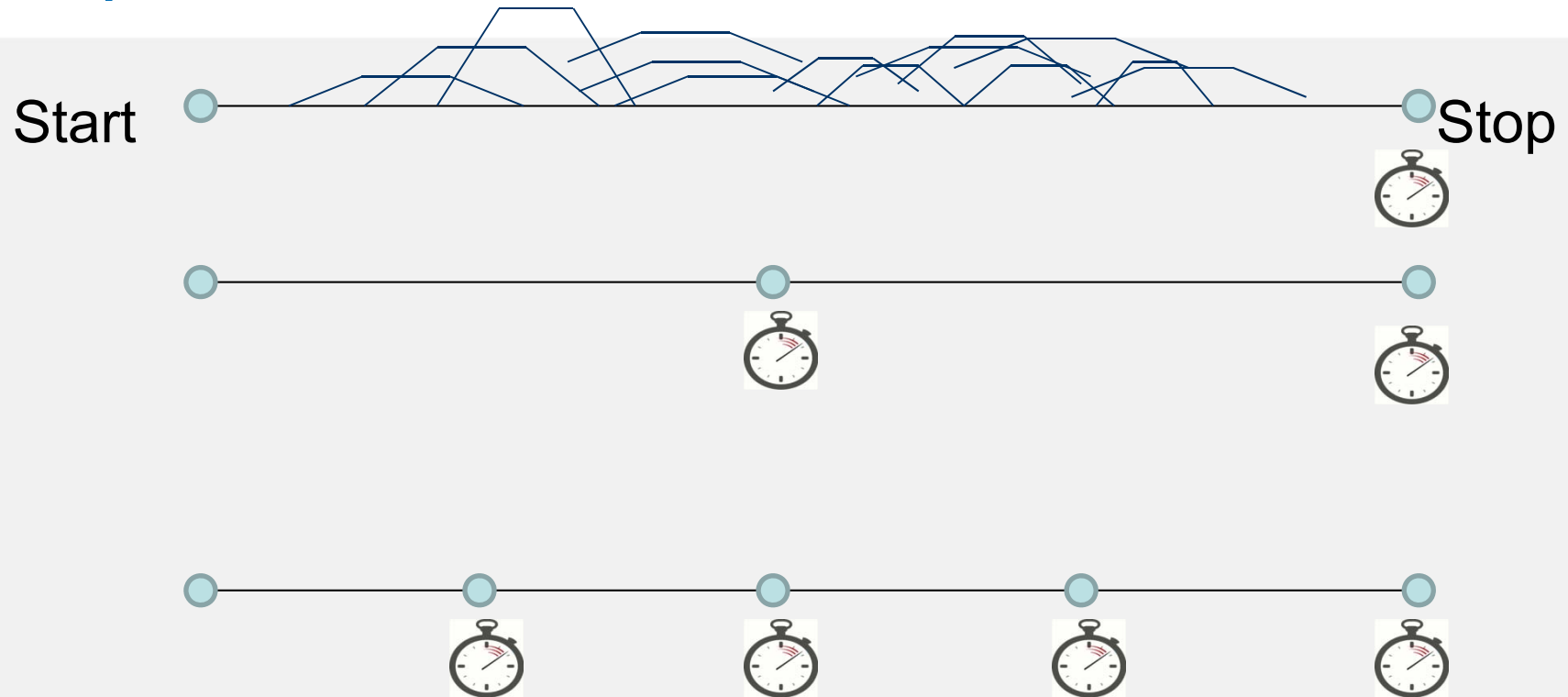
+  $f(20\%)$   
safety margin

PROARTIS  
Advanced  
Measurements

One Hard  
Testing  
Problem!

Mathematical  
Justification

# RapiTime WCET tool



RapiTime automates & simplifies  
measuring worst case execution times  
where there are many paths through a program



# Using RapiTime to reduce the complexity

Industrial Practice

$$WCET \leq HWM \cdot 1.2$$

PROARTIS  
End to End  
Measurements

$$WCET \leq HWM + f(...)$$

PROARTIS  
RapiTime

$$WCET \leq HWM_1 \oplus HWM_2 \oplus \dots$$

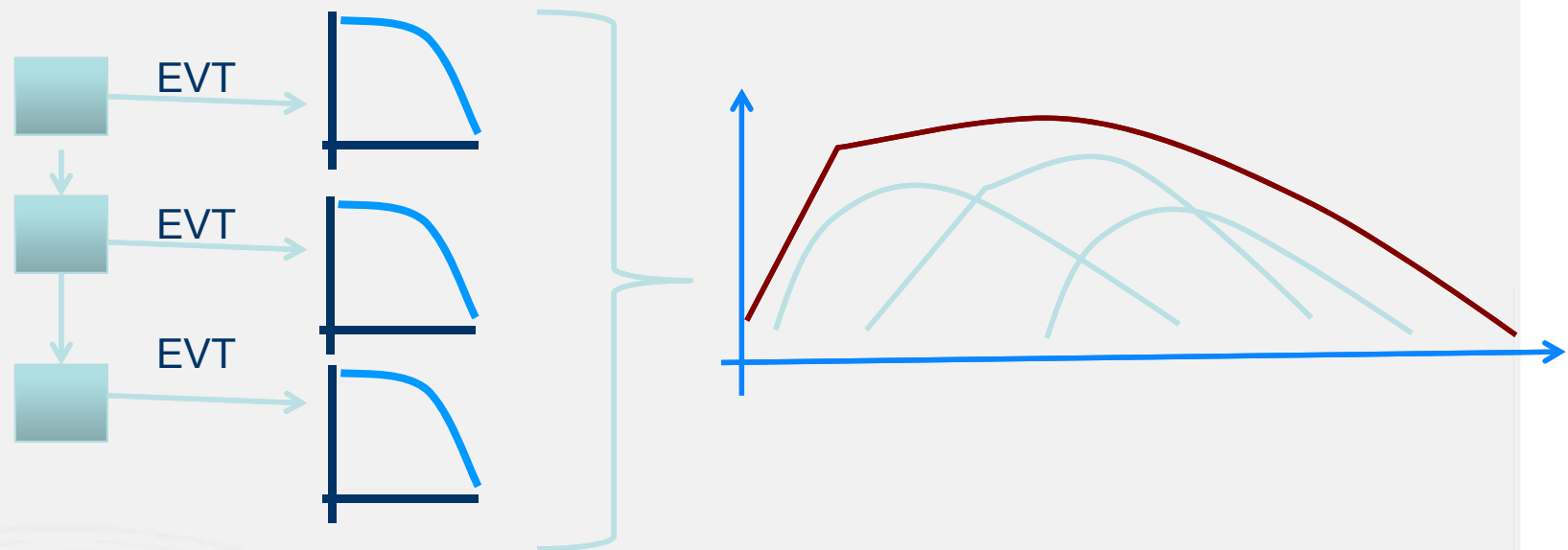
One Hard Testing Problem!

Mathematical Justification

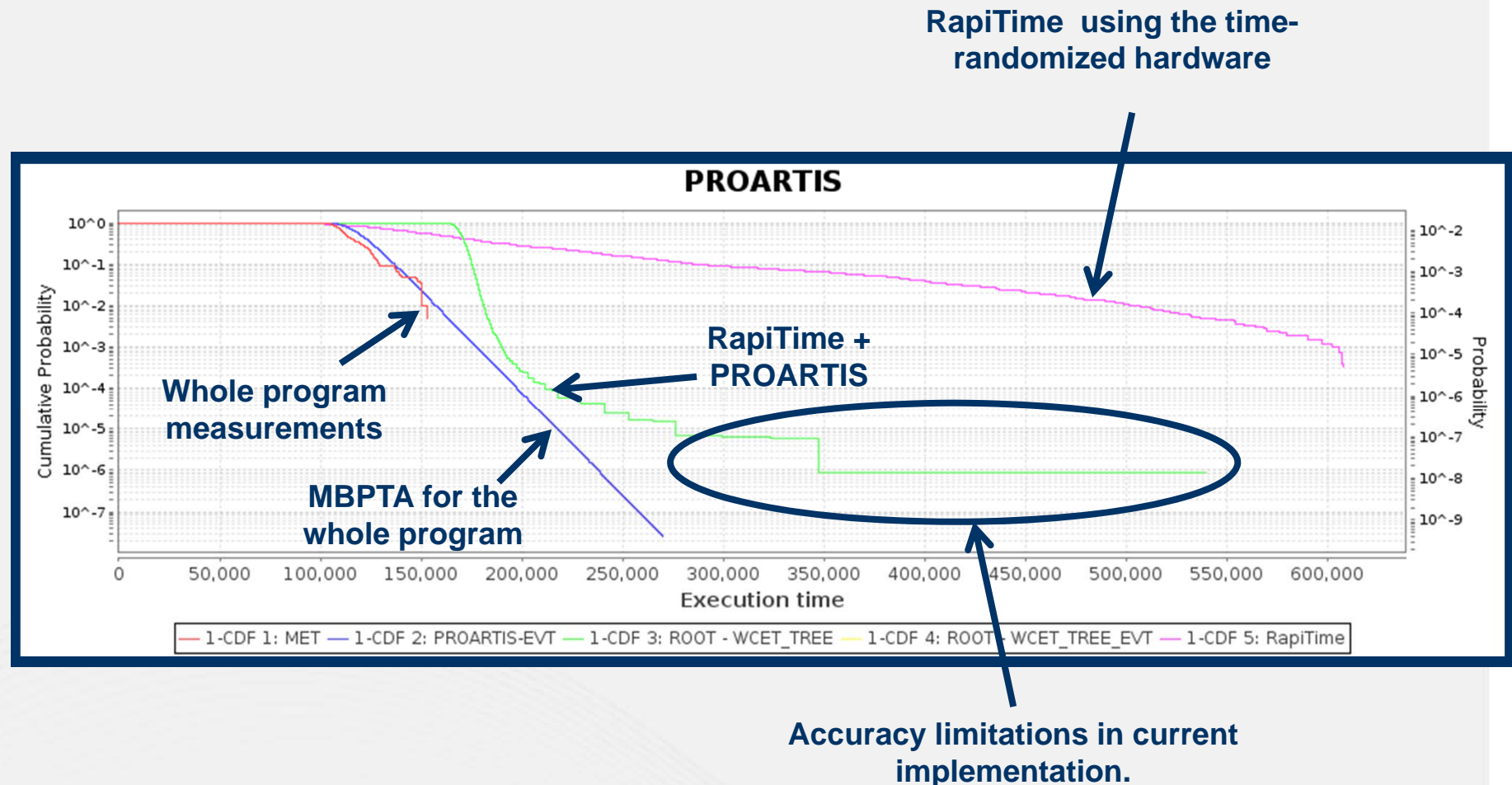
Advanced  
Measurements  
"HyPTA"

# HyPTA

- *Hybrid Probabilistic Timing Analysis*
- *The pWCET estimate is obtained by a combination of RapiTime and MBPTA*



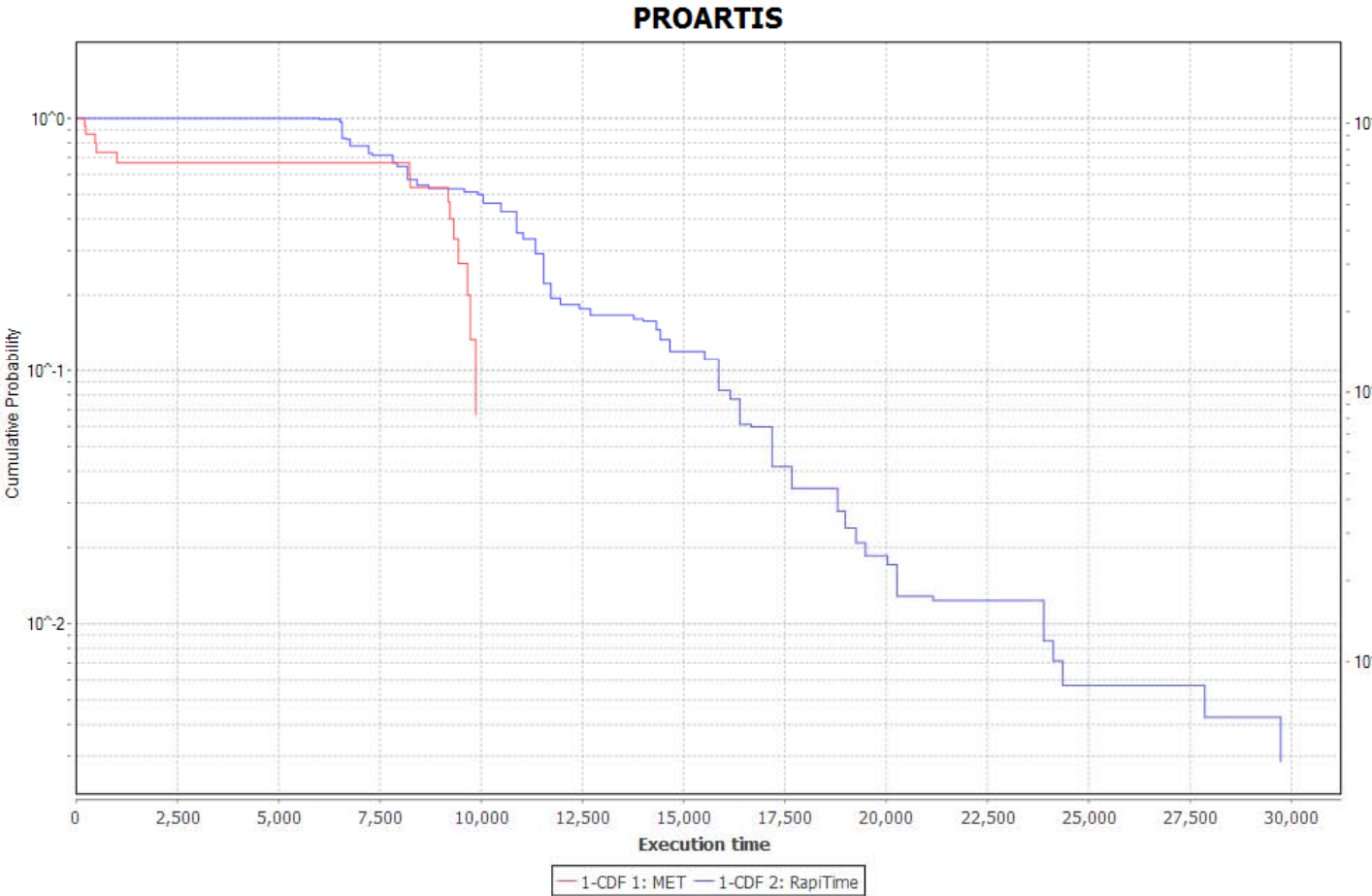
# HyPTA (RapiTime + PROARTIS)



PROARTIS WCET Estimates

Import profile EVT Tree WCET EVT WCET

- ☒ MET(15)
- ☒ RapiTime(50)



Weight = 5697.2, Max = 9864

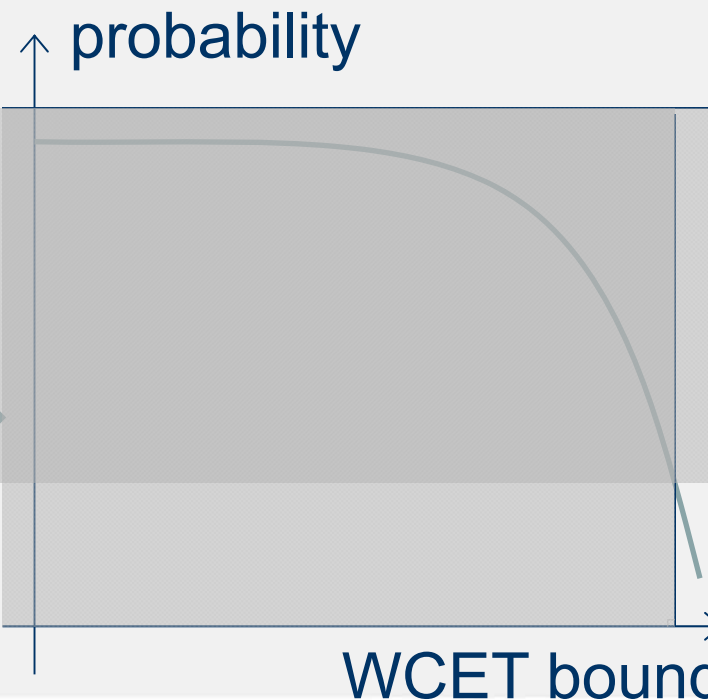
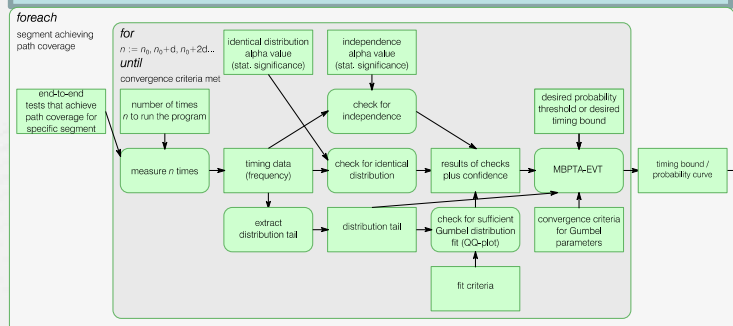
Type	P < 10 <sup>-3</sup>	P < 10 <sup>-6</sup>	P < 10 <sup>-9</sup>	P < 10 <sup>-12</sup>	Max
MET	9864	9864	9864	9864	9864
RapiTime	29739	29739	29739	29739	29739

# Certification – DO-178B

- *Airborne software certification*
- *“Software always does the same thing”*
  - *Software cannot have a probability of failure!*
- *Answer:*
  - *Systems can have a probability of failure*

DOES NOT  
COMPUTE

## PROARTIS



# Conclusion

## Timing Analysis

- Randomized timing behaviour IS analysable for WCET

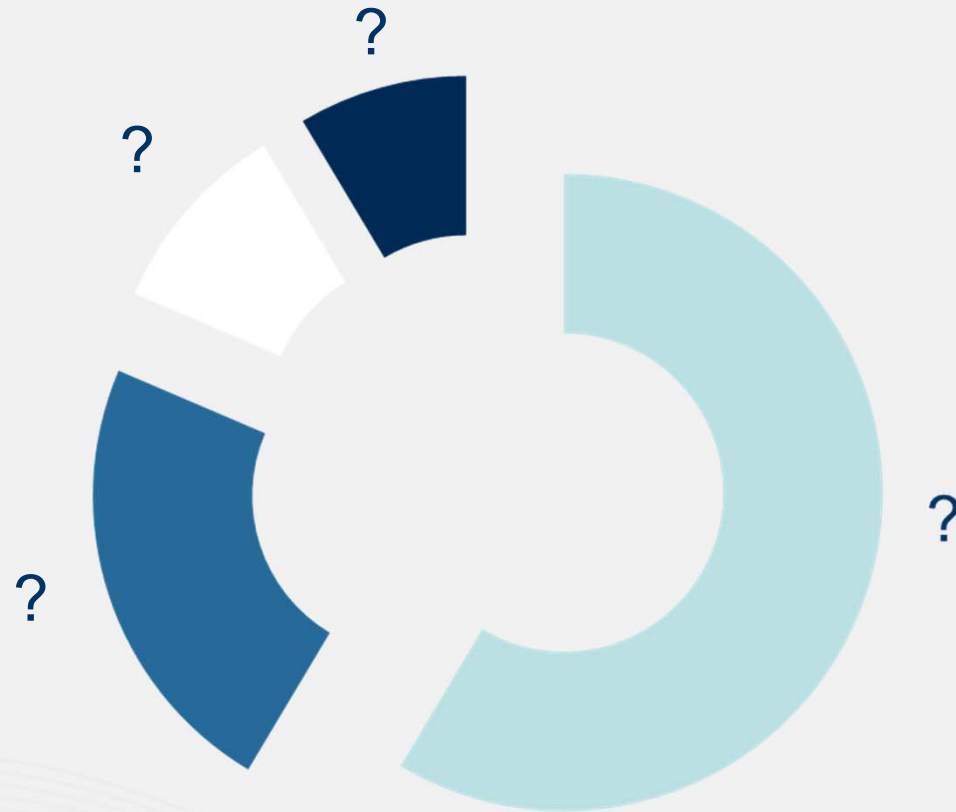
## Tool support

- Is available using extension of existing techniques

## Certification and Safety

- Strong argument is possible (in development)

# Questions ?



# EVT algorithm in real-time analyses

Let  $M$  be the vector of maxima by block

Test KS

If  $p\text{-value} > 0,05$  than maxima fit a GEV

Parameter Estimation

$\xi$ , the forme parameter of the GEV  $\approx 0$  than Gumbel type

Building return level parameter and studying graphs

Return level: keep the block giving the smallest return level