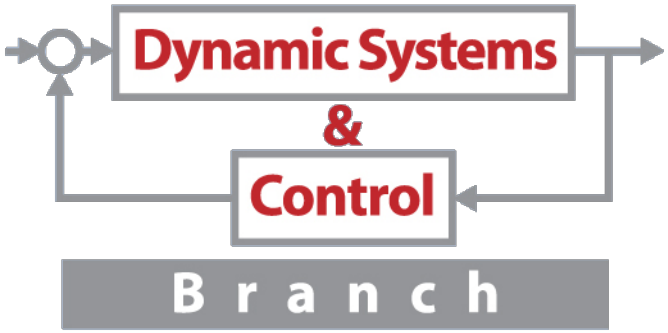
The NASA Langley UQ Challenge



ASME V&V Symposium, May 16-20, 2016

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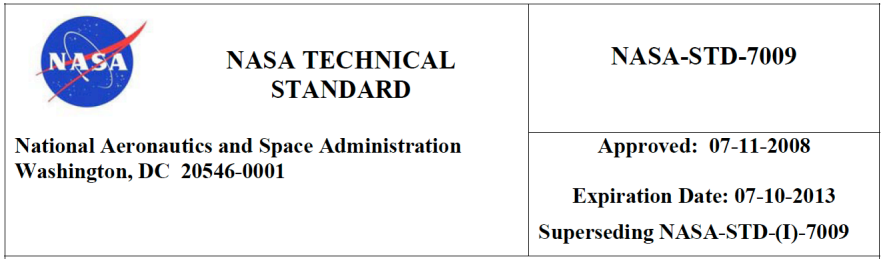
Hampton, VA, USA

Overview

- Introduction
- Problem statement
- Summary of responses

Motivation to NASA

- **UQ need**: NASA missions often involve the design of new vehicles and systems that operate in harsh domains under a wide array of operating conditions
- **UQ challenges**: Missions involve high-consequence, safety-critical systems for which data is either very sparse or prohibitively expensive to collect
- NASA modeling and simulation standards require UQ



NASA TECHNICAL STANDARD

NASA-STD-7009

National Aeronautics and Space Administration
Washington, DC 20546-0001

Approved: 07-11-2008

Expiration Date: 07-10-2013

Superseding NASA-STD-(I)-7009

UQ Challenge: Agenda

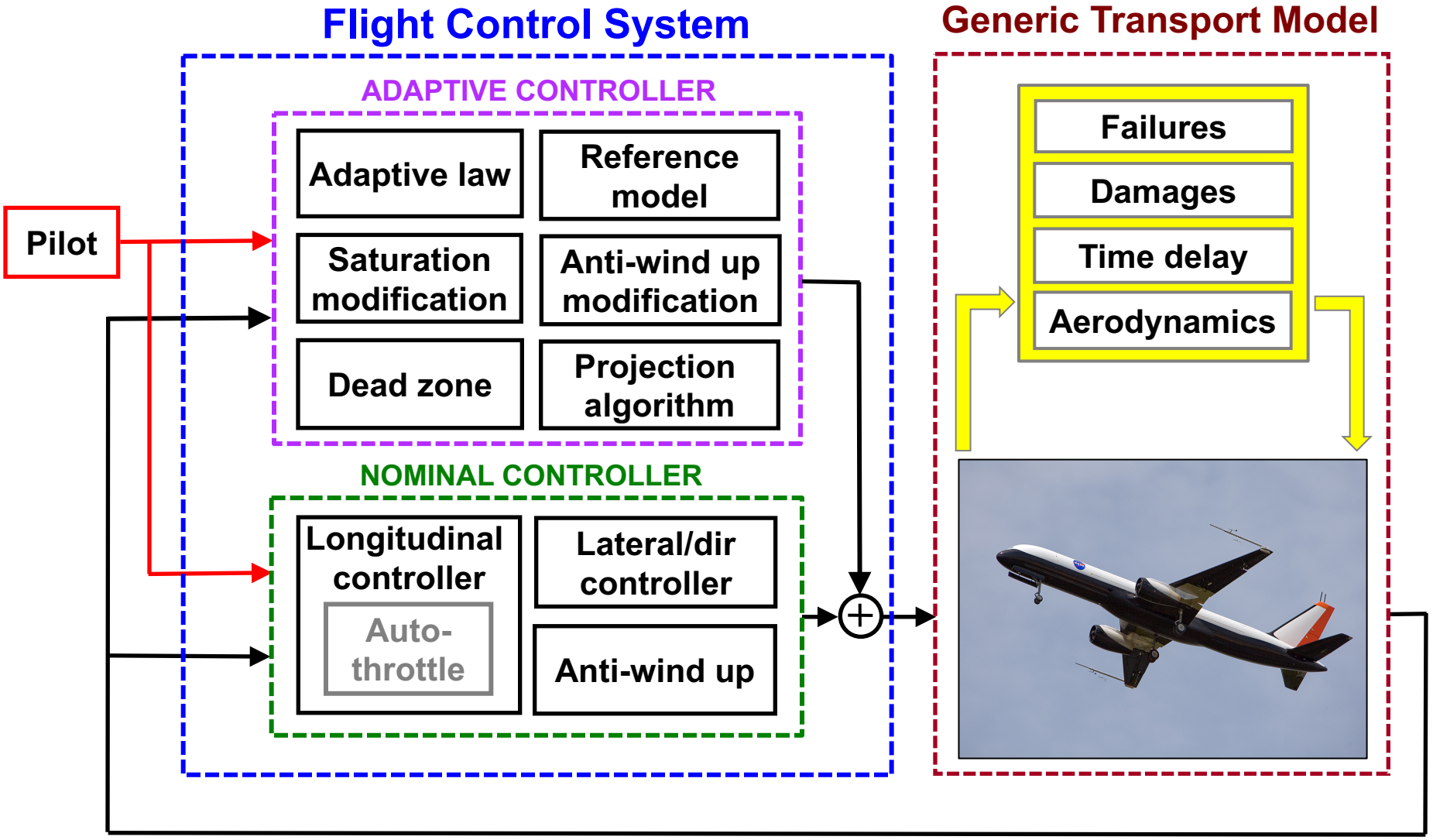
- 01/2013: 100+ UQ experts were invited to participate. Eleven groups from the US government, industry and academia accepted the invitation
- 10/2014: Papers compiled in a special UQ edition of the AIAA Journal of Aerospace Information Systems

	Organization	Title	Authors
1	Sandia National Labs	UQ methods for model calibration, validation and risk analysis	C. Safta, H. Najm, B. Debusschere, K. Sargsyan, K. Chowdhary, M. Eldred, L. Swiler
2	Los Alamos National Lab	Robust design applied to the NASA Langley UQ challenge	Kendra Van Buren, Francois Hemez
3	Ecole Centrale Paris/Supelec	Uncertainty and sensitivity analysis of the mathematical model of a…	Nicola Pedroni, Enrico Zio
4	Swiss Federal Institute of Technology	The Bayesian multilevel framework for the NASA multidisciplinary…	Joseph Nagel
5	Stinger and Ghaffarian Technologies	Subjective approach to UQ: solution to the NASA UQ challenge	Shankar Sankaraman
6	Institute for Risk and Uncertainty, U. Liverpool	An integrated and efficient numerical framework for UQ…	Edoardo Patelli, Mateo Broggi, Marco de Angelis
7	University of Florida	Prioritized information based UQ: the NASA UQ challenge…	A. Chaudhuri, G. Waycaster, N. Price, T. Matsumara, C. Park, R. Haftka
8	Vanderbilt University	Bayesian method framework for multidisciplinary UQ and optimization	Chen Liang, Snakaran Mahadevan
9	University of Southern California & Sandia National Labs	A probabilistic approach to the NASA Langley multidisciplinary UQ…	R. Ghanem, H. Meidani, E. Kalligiannaki, C. Thimmisetty, V. Keshavarzzadeh, I. Yadegaran, et. al
10	General Electric Global Research	A hybrid Bayesian solution to the NASA Langley multidisciplinary UQ	Ankur Srivastava, Arun Subramaniyan
11	Southwest Research Institute	A Bayesian probabilistic treatment of multiple uncertainty types	John McFarland, Barron Bichon, David Riha

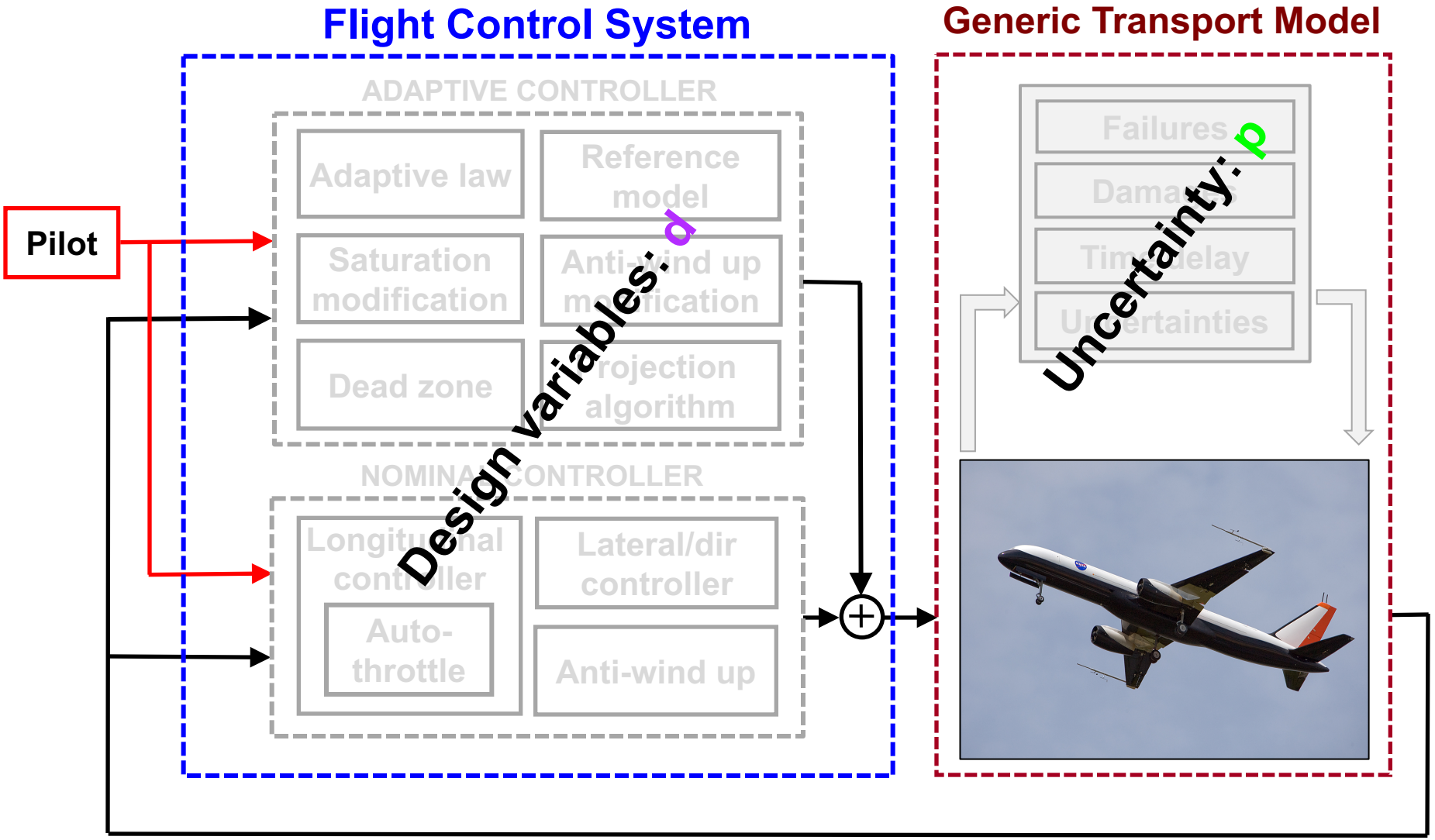
UQ Challenge: Physical System

- Dynamically scaled, highly instrumented flight test article

UQ Challenge: Model



UQ Challenge: Model



Sim @ {$p_{offnominal}$, d_2}

Sim @ $\{p_{offnominal}, d_3\}$

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Uncertainty Classification

- Aleatory uncertainty vs. Epistemic uncertainty

Caused by intrinsic variability, irreducible

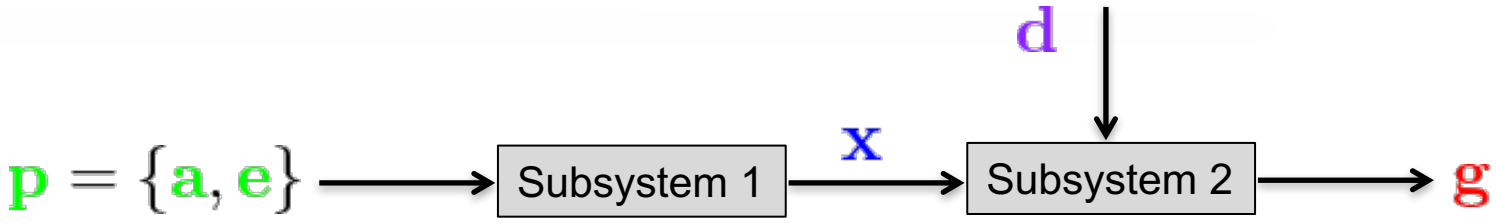
Caused by ignorance, reducible

- Philosophical distinction must impact the mathematics
- Substantive qualitative implications
- As more knowledge on the epistemic uncertainty is acquired what will this uncertainty would reduce to?

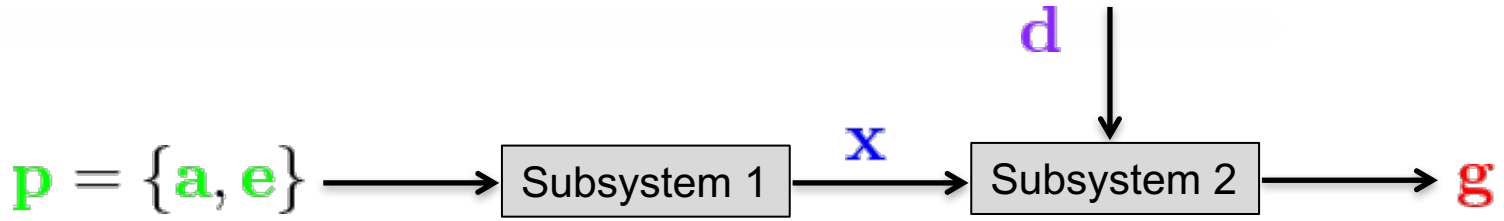
Uncertainty Classification

- Aleatory uncertainty
  - Modeled as a random variable
- Epistemic uncertainty
  - Modeled as an unknown constant in an interval
- Mixed uncertainty
  - Modeled as a distribution-fixed pbox

Framework

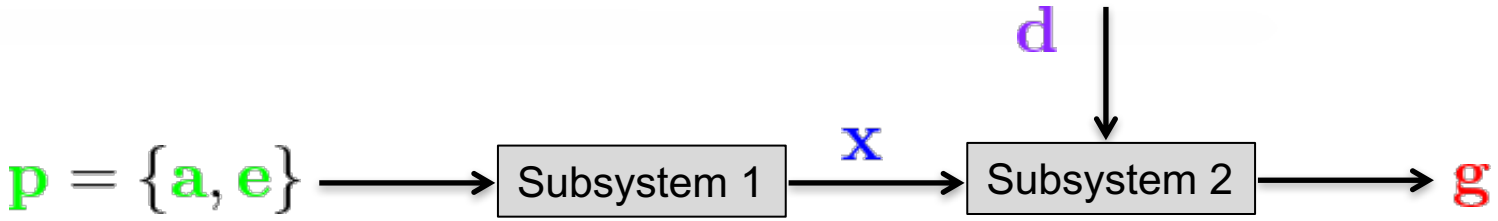


Framework



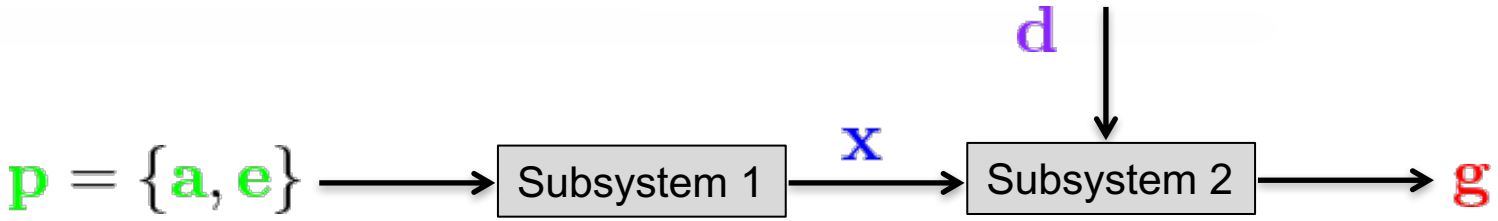
- Uncertain parameter, $\mathbf{p} \in \Re^{21}$: actuator failure, loss of control effectiveness, control surface dead-zone, and desired range of operating conditions
- Intermediate variable, $\mathbf{x} \in \Re^{5}$: angle of attack command, control effectiveness of control surfaces, time delay
- Design variable, $\mathbf{d} \in \Re^{14}$: controller gains
- Performance metrics, $\mathbf{g} \in \Re^{8}$: stability, angle of attack-, roll- and sideslip-tracking, response surface activity

Information Provided



- An uncertainty model (UM) for p
  - Type 1: aleatory, e.g. $p_1 = a_1 = N(1, 2)$
  - Type 2: epistemic, e.g., $p_2 = e_1 = [1, 5]$
  - Type 3: mixed, e.g., $p_3 = N(e_2, 1)$ where $e_2 = [1, 3]$

Information Provided



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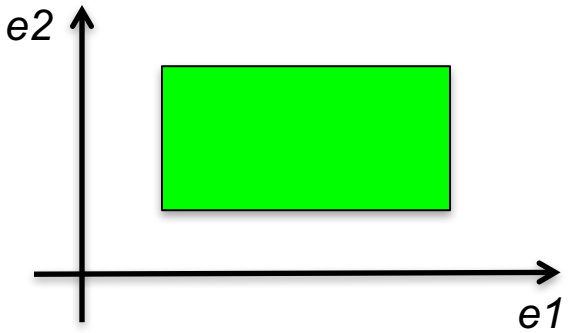
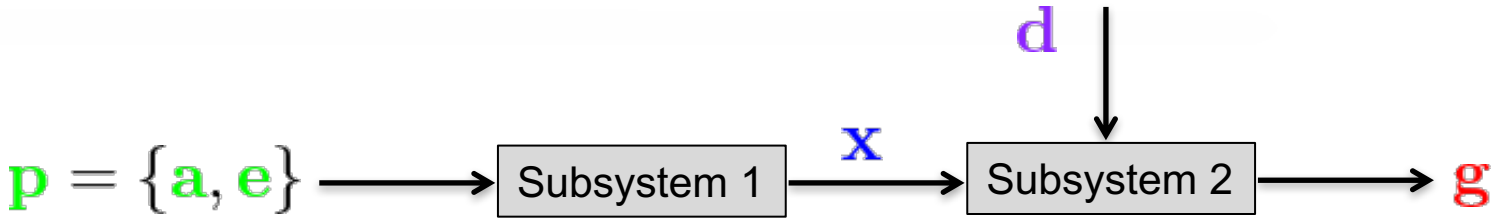


The more ignorance the larger the epistemic box

Information Provided



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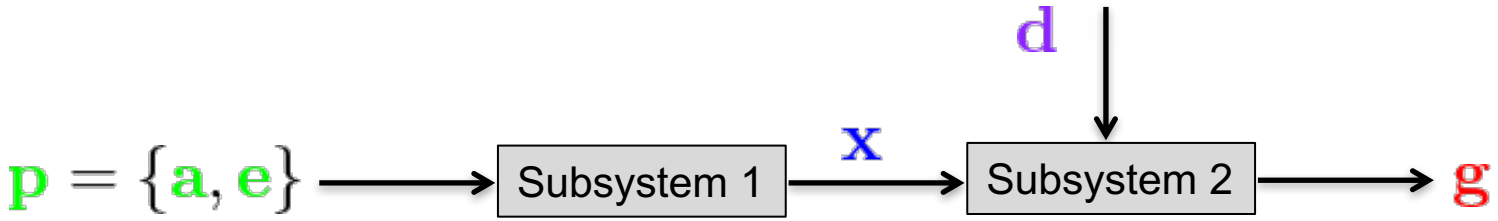
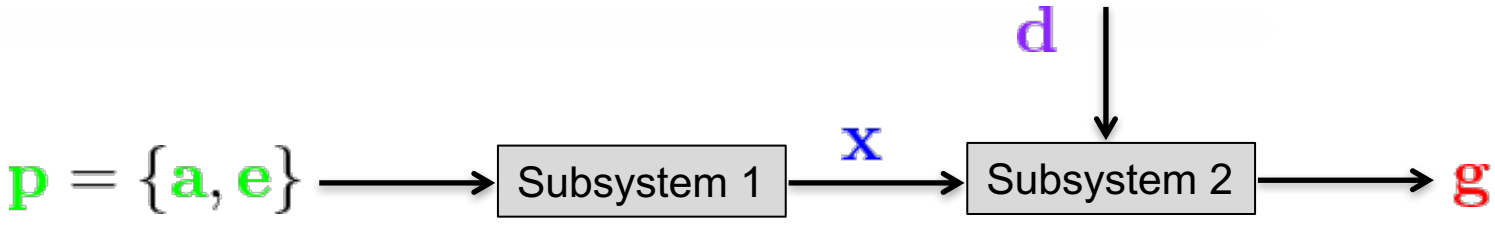
  - Type 1: aleatory, e.g. $p_1 = a_1 = N(1, 2)$
  - Type 2: epistemic, e.g., $p_2 = e_1 = [1, 5]$
  - Type 3: mixed, e.g., $p_3 = N(e_2, 1)$ where $e_2 = [1, 3]$
- Computational model for both subsystems
- Observations of the "true" x1
- A baseline design d

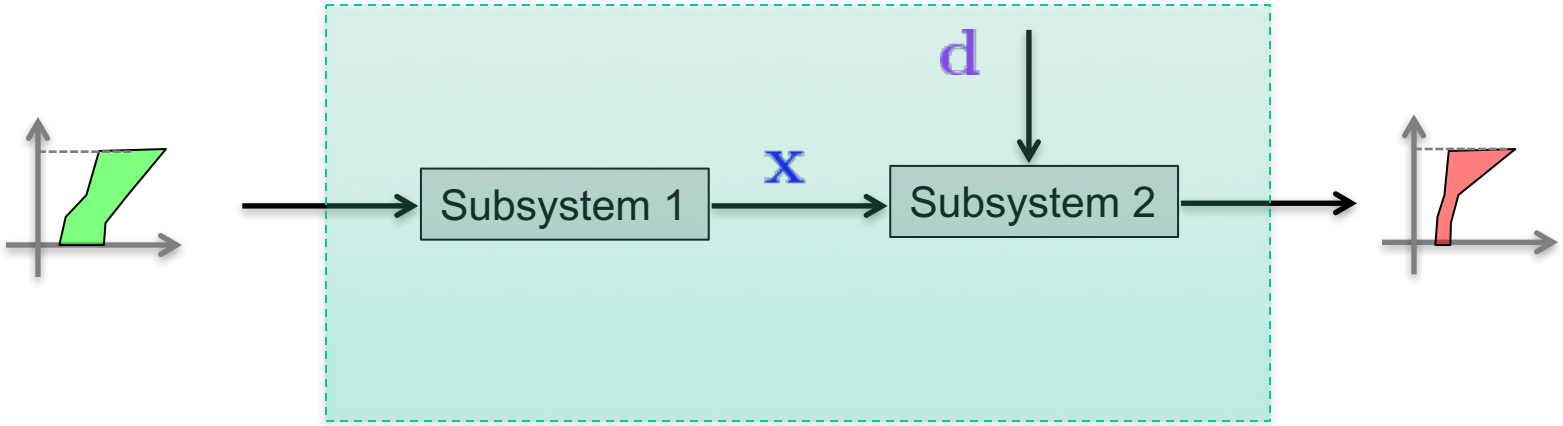
Metrics of Interest



- The mean: $J_1 = \mathbb{E}[\max(g)]$
- The probability of failure: $J_2 = \mathrm{Prob}[\max(\mathrm{g}) > 0]$

Metrics of Interest



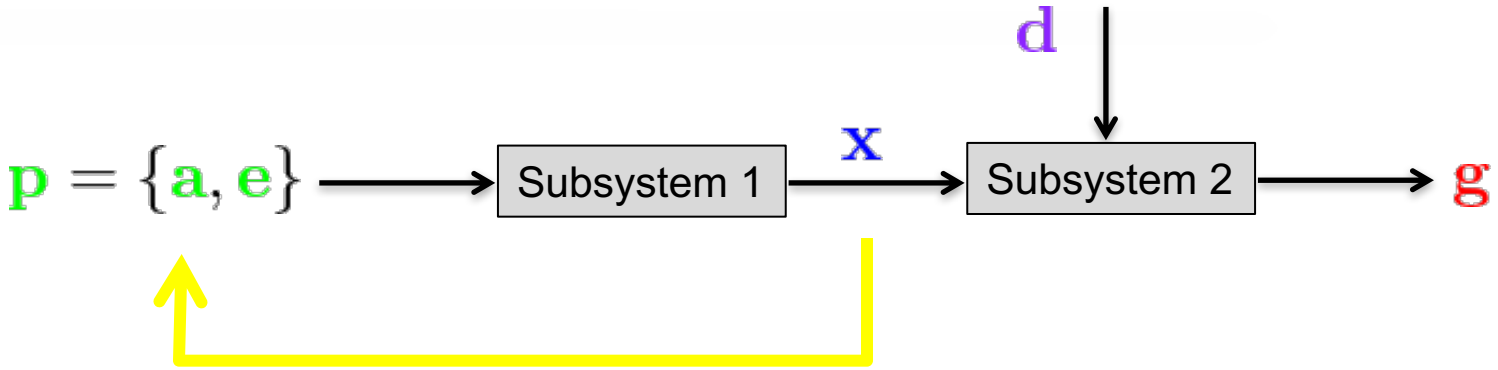


- *Metrics of interest vary in a range*

Tasks

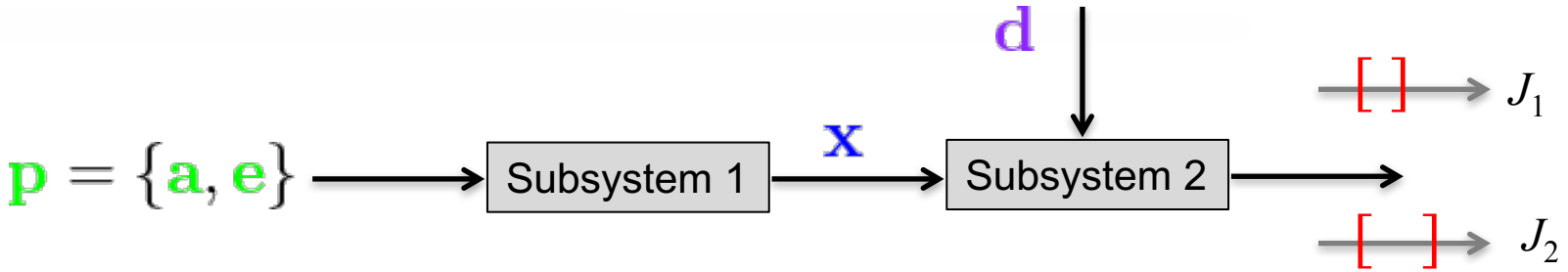
1. Model calibration
2. Global sensitivity analysis
3. Uncertainty propagation
4. Extreme case analysis
5. Robust design

Task 1: Model Calibration

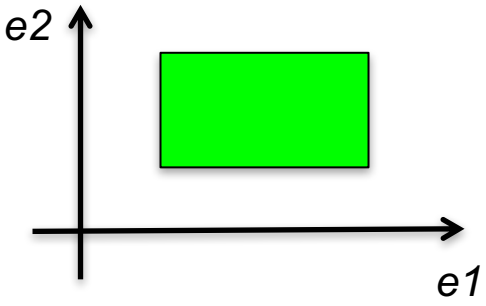


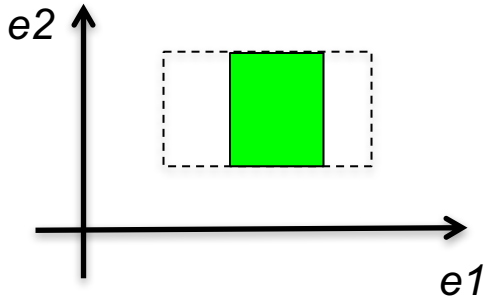
- Given an UM of p and observations of x_1 refine the UM

Task 2: Global Sensitivities

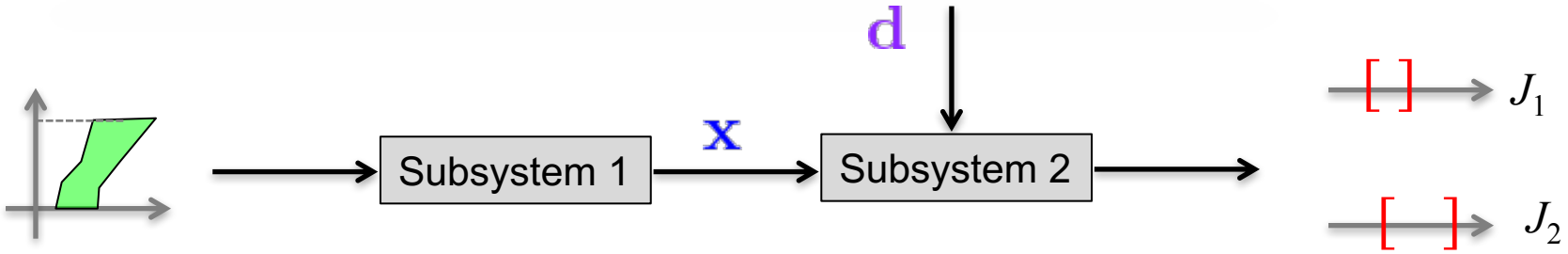


- Rank the parameters in p according to the sensitivity of a few metrics of interest



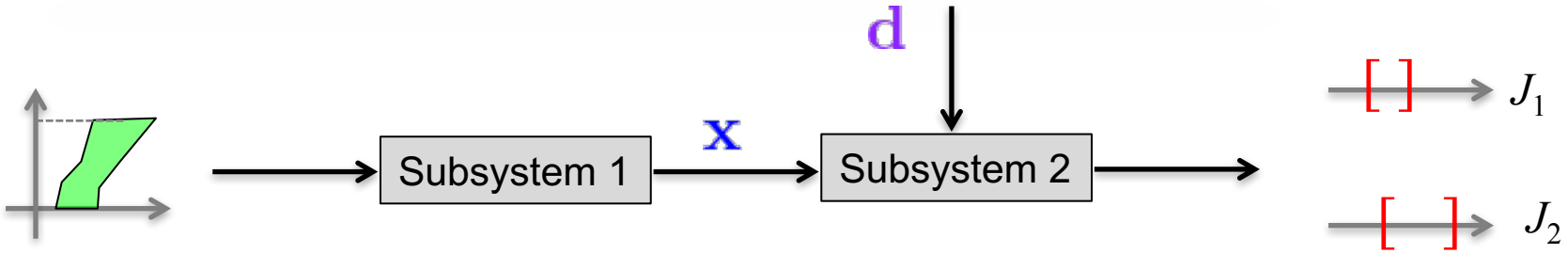


Task 3: Uncertainty Propagation



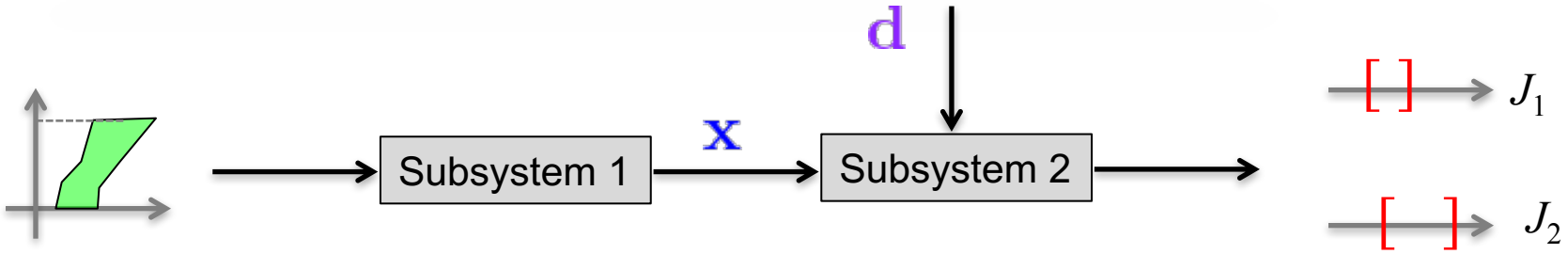
- Find range of J_1 and J_2 for original UM

Task 3: Uncertainty Propagation



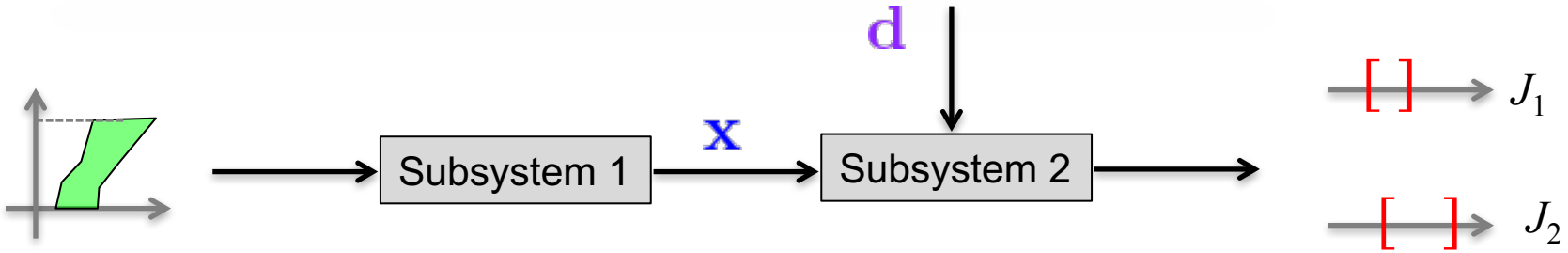
- Find range of J_1 and J_2 for original UM
- Why would the range could be inadmissibly wide?

Task 3: Uncertainty Propagation



- Find range of J_1 and J_2 for original UM
- Why would the range could be inadmissibly wide?
  - UQ methods are conservative
  - Epistemic uncertainty is too large
  - The design point d is not sufficiently robust

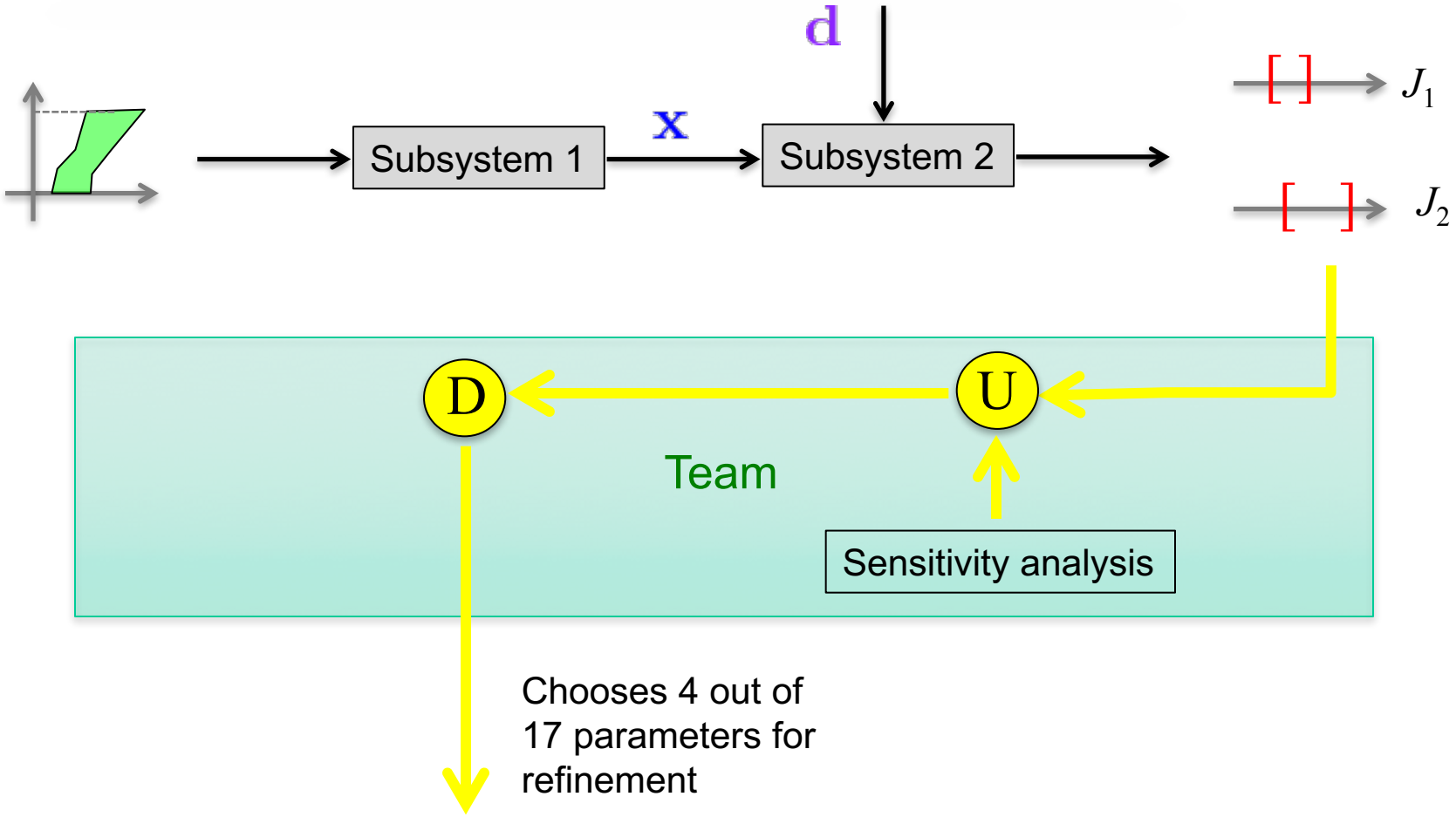
Task 3: Uncertainty Propagation



- Find range of J_1 and J_2 for original UM
- Why would the range could be inadmissibly wide?
  - UQ methods are conservative
  - Epistemic uncertainty is too large
  - The design point d is not sufficiently robust

➢ *Which epistemic uncertainties to refine given limited resources?*

Task 3: Uncertainty Propagation



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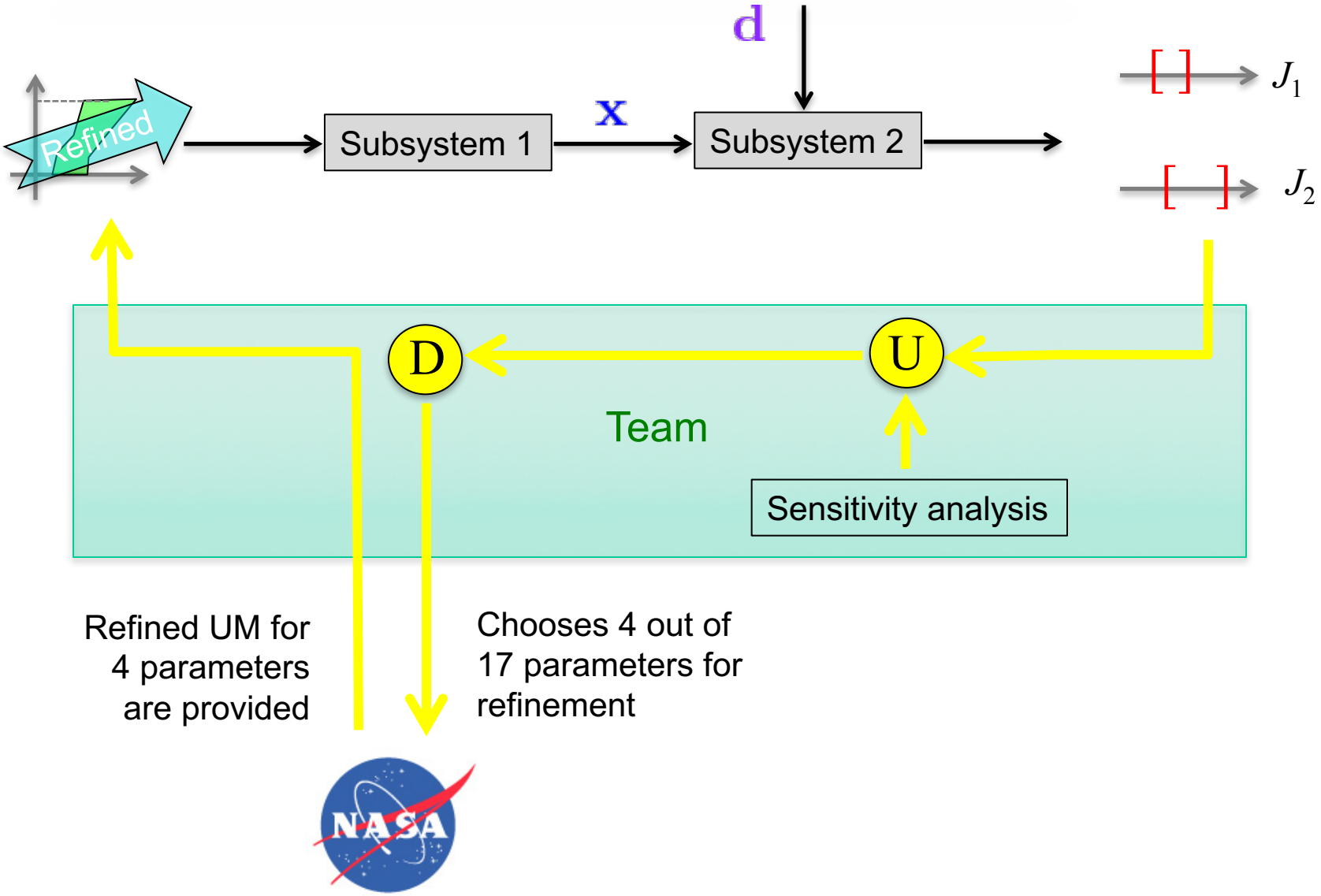
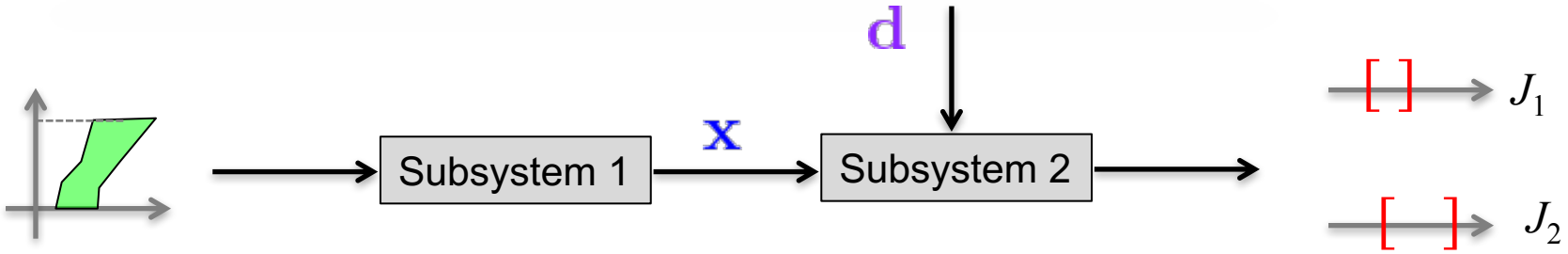


Task 3: Uncertainty Propagation



- Find range of J_1 and J_2 for original UM
- Decide which parameters to refine
- Find range of J_1 and J_2 for refined UM

➢ *Refinement of UM might not pay off*

Overview

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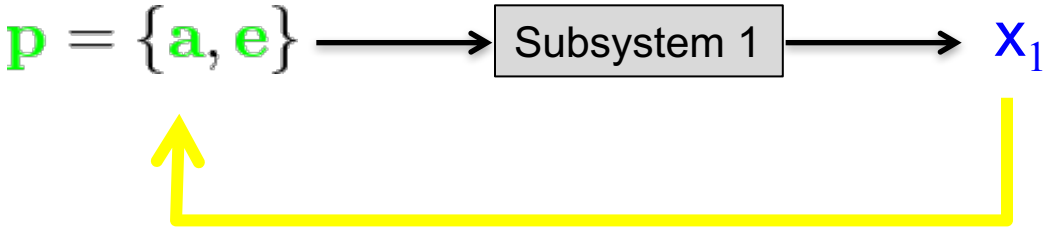
Task 0: Mathematical Framework

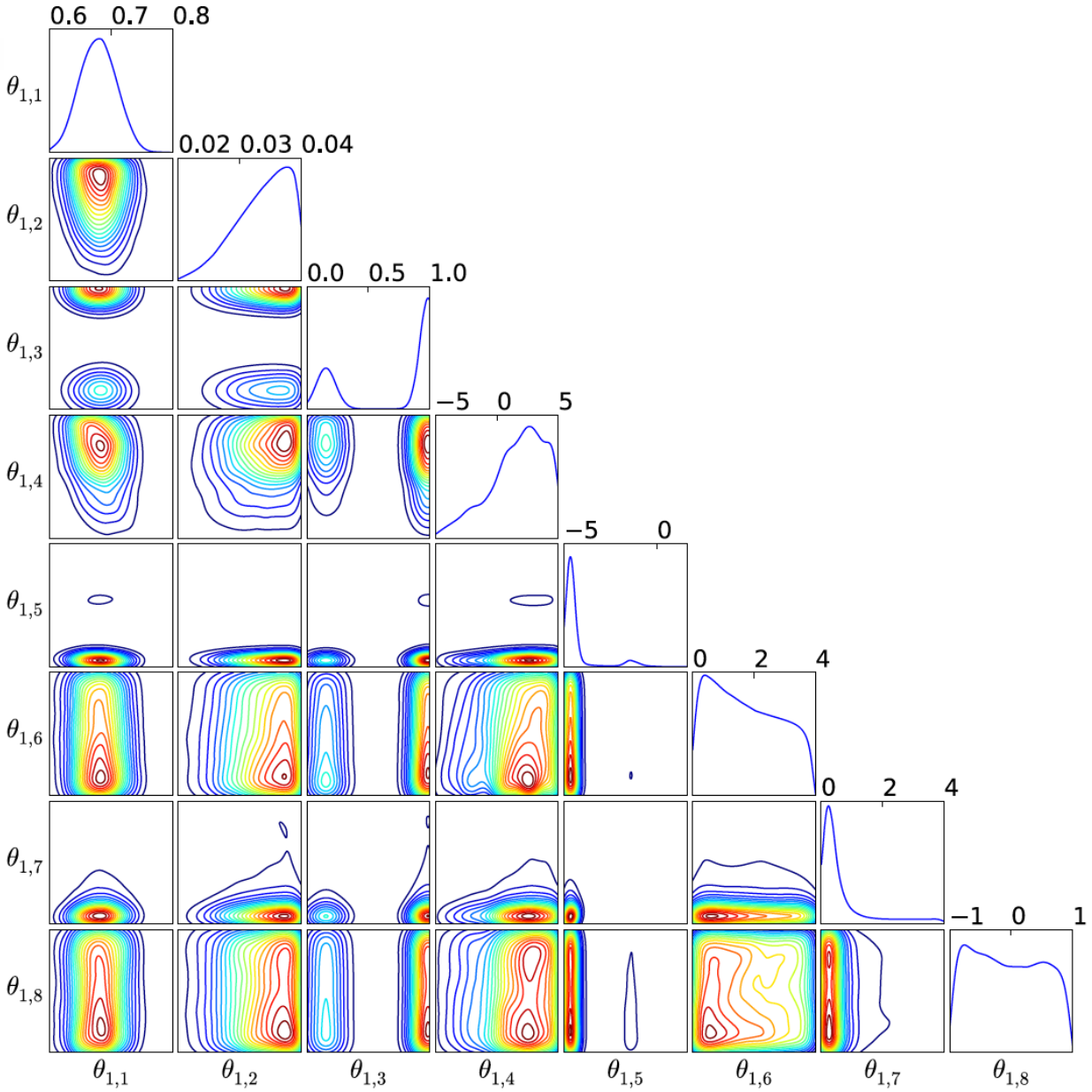
- Probabilistic
- Info-gap theory
- Random set theory
  - Random variables (RV)
  - Intervals
  - Distribution-free pboxes
  - Distribution-fixed pboxes
- Method-dependent

Task 1: Model Calibration



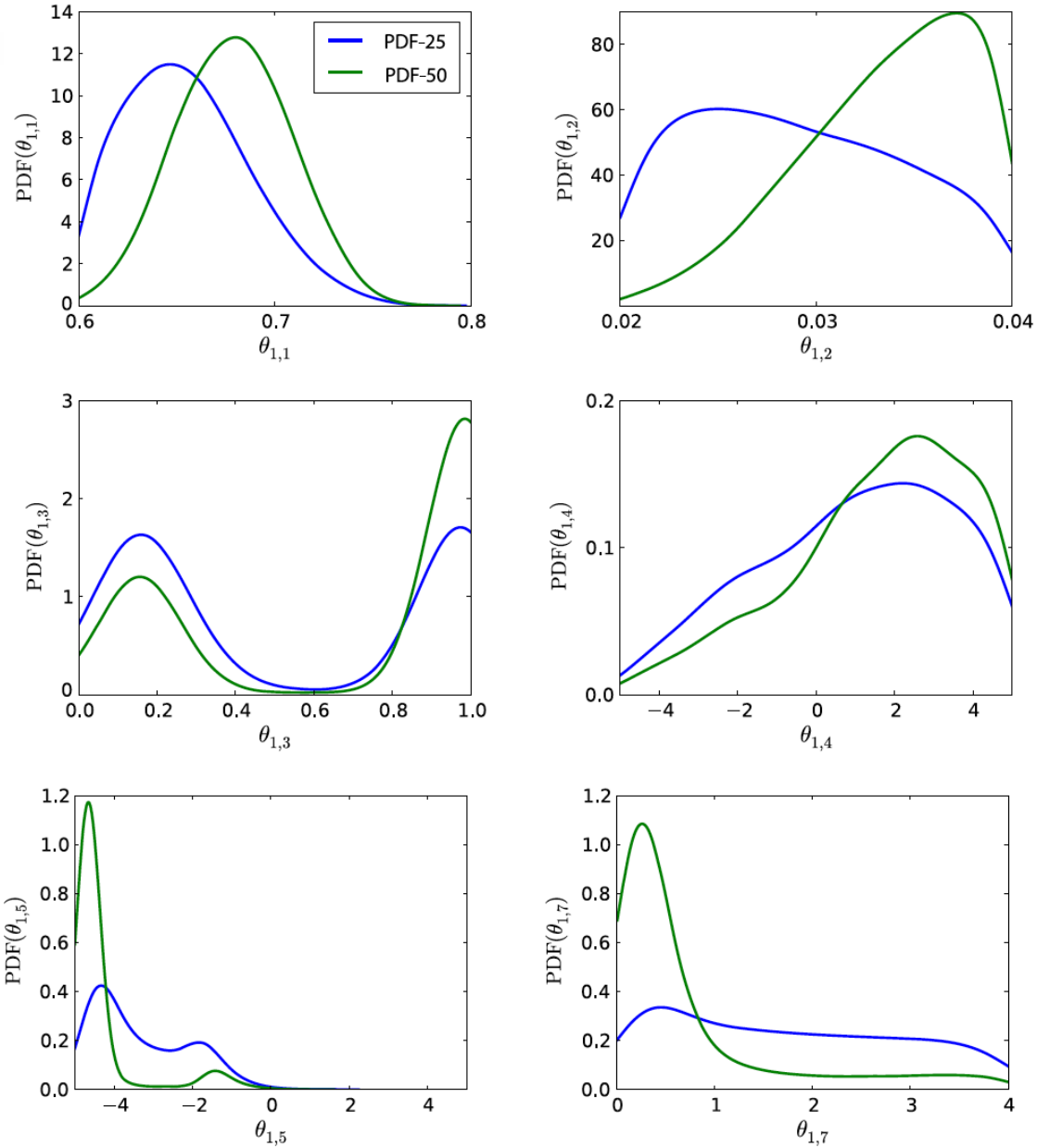
- Problem: dim(e)=8, dim(x_1)=1 output, CPU time=1s
- Solution strategies
  - **Bayesian calibration** with MCMC [1,6]
    - KDE or full likelihood and binning
    - Approximate Bayesian Computation (2 orders of mag better)
  - **KS-based approaches** for comparing empirical CDFs [3,7]

Task 1: Model Calibration



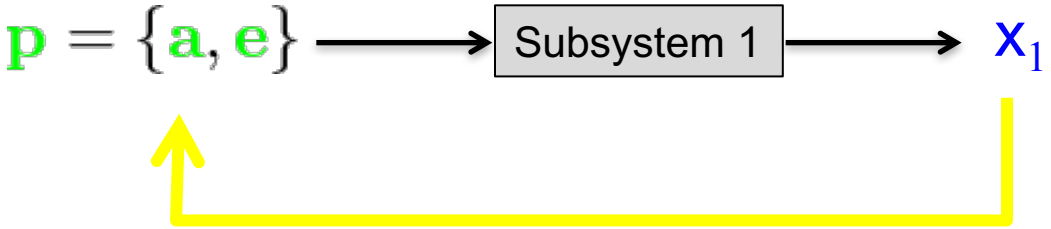
Refined UM [1]

Task 1: Model Calibration



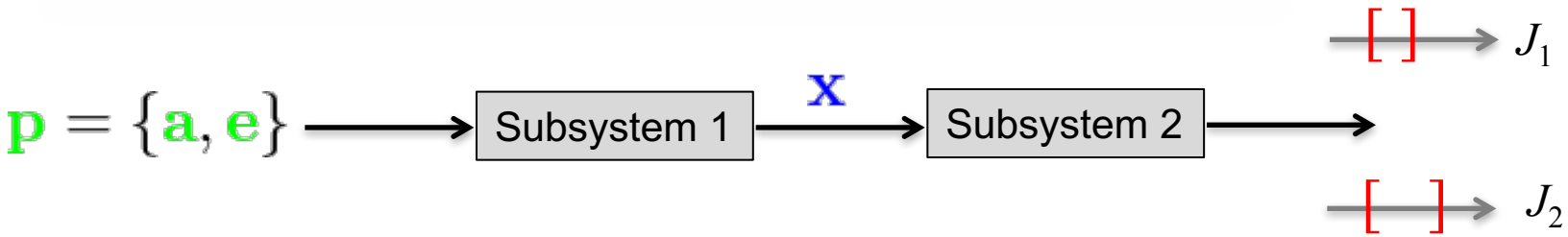
Posterior marginals [1]

Task 1: Model Calibration



- Comments on Bayesian Calibration
  - Higher fidelity of refined UM
  - Are the dependencies among parameters fictitious?
  - Reclassification of UM: intervals/independent RVs/dependent RVs
  - Refined UM for n=50 $\not\subset$ refined UM for n=25
  - Setup: n_{steps}:[5K, 500K], n_a:[5K, 100K], CPU time:[5h, 96h]

Task 2: Global Sensitivities

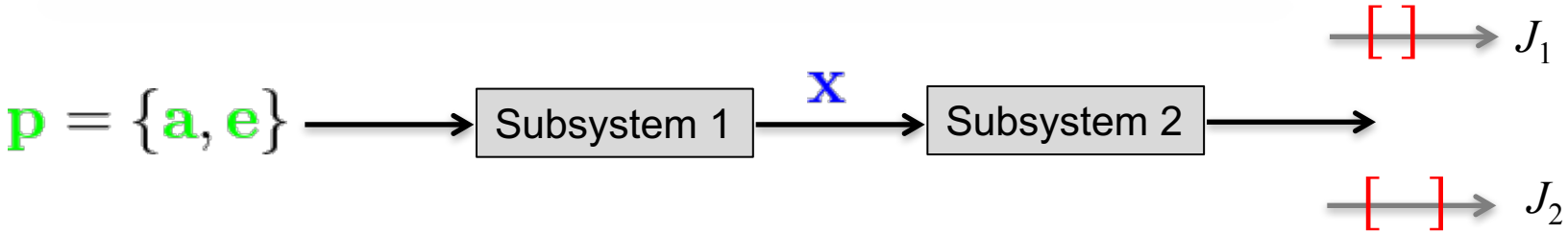


- Solution strategies
  - **Reduction in epistemic range** of a metric of interest caused by fixing the value of an epistemic parameter [3,6]
  - **ANOVA**: first-order sensitivity index and total-effect index

$$S_i = \frac{V_{x_i}\left[E_{\sim x_i}[y|x_i]\right]}{V[y]} \qquad St_i = \frac{E_{\sim x_i}\left[V_{x_i}[y|x_{\sim x_i}]\right]}{V[y]}$$

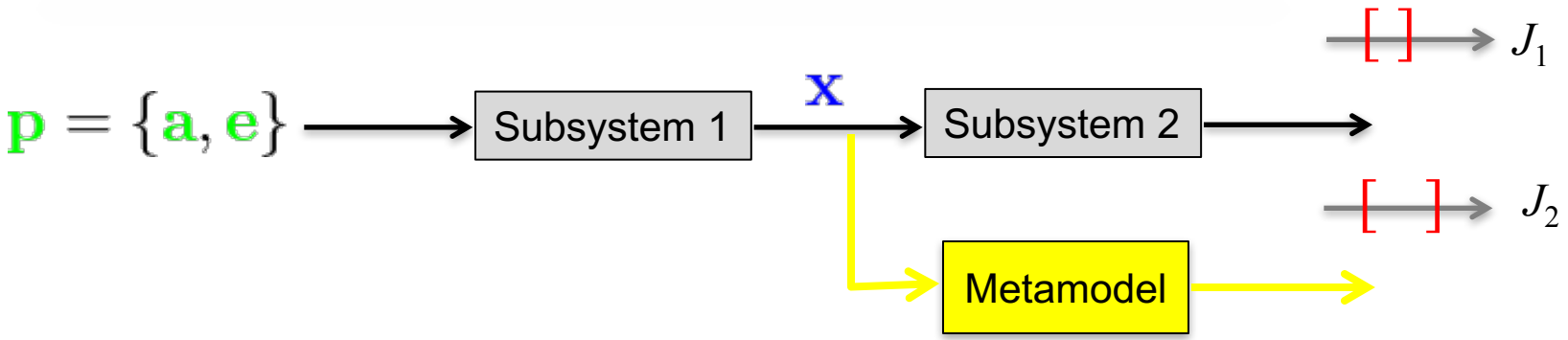
- What are the dependent and independent variables?

Task 2: Global Sensitivities



- Independent variable
  - Epistemic variable being a fixed unkown constant
  - Limit of the range of variation of epistemic variable
- Dependent variable
  - Area of the x1-pbox
  - Average over selected quantiles of the x1-pbox [11]

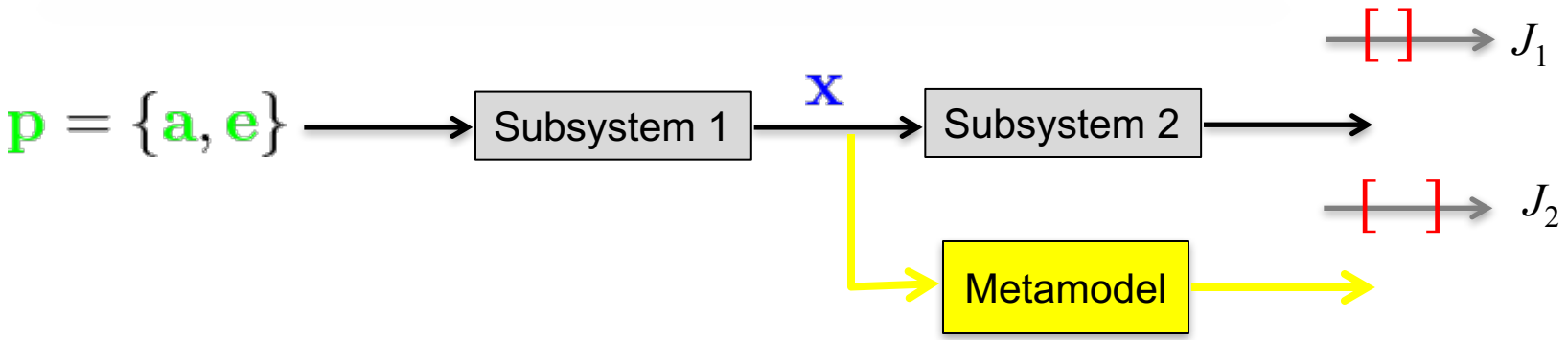
Task 2: Global Sensitivities



- Independent variable
  - Epistemic variable
  - Limit of the range of variation of epistemic variable
- Dependent variable
  - Area of the x1-pbox
  - Average over selected quantiles of the x1-pbox [11]
  - J_1 and J_2 after using a metamodel (PC, GP, NN) for Subsystem 2

Source of approximation error

Task 2: Global Sensitivities



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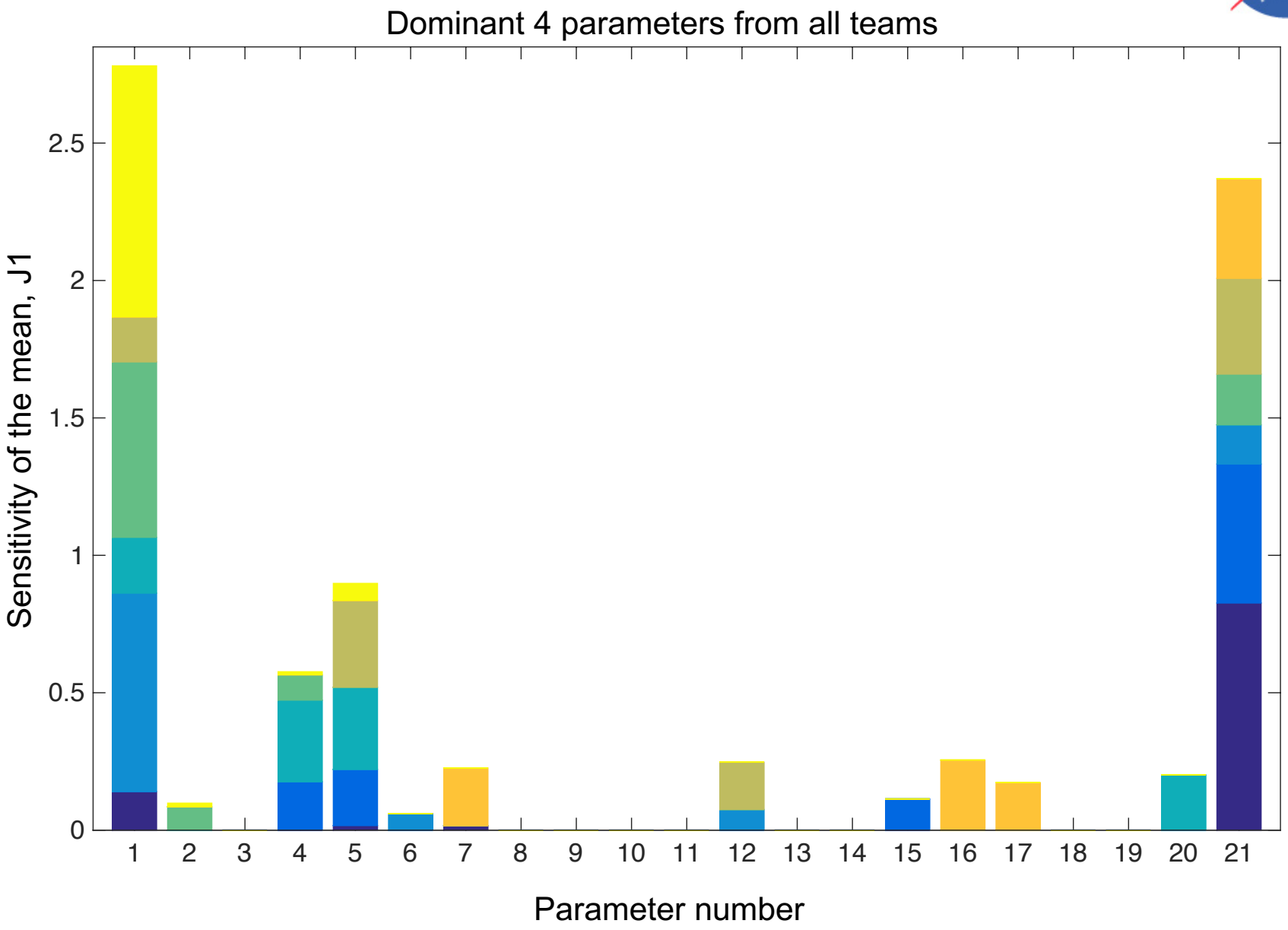
  - Epistemic variable
  - Limit of the range of variation of epistemic variable
- Dependent variable
  - Area of the x1-pbox
  - Average over selected quantiles of the x1-pbox [11]
  - J_1 and J_2 after using a metamodel (PC, GP, NN) for Subsystem 2
- ANOVA setup: n_e: [0.5K, 5K], n_a: [1K, 5000K]

Task 2: Global Sensitivities



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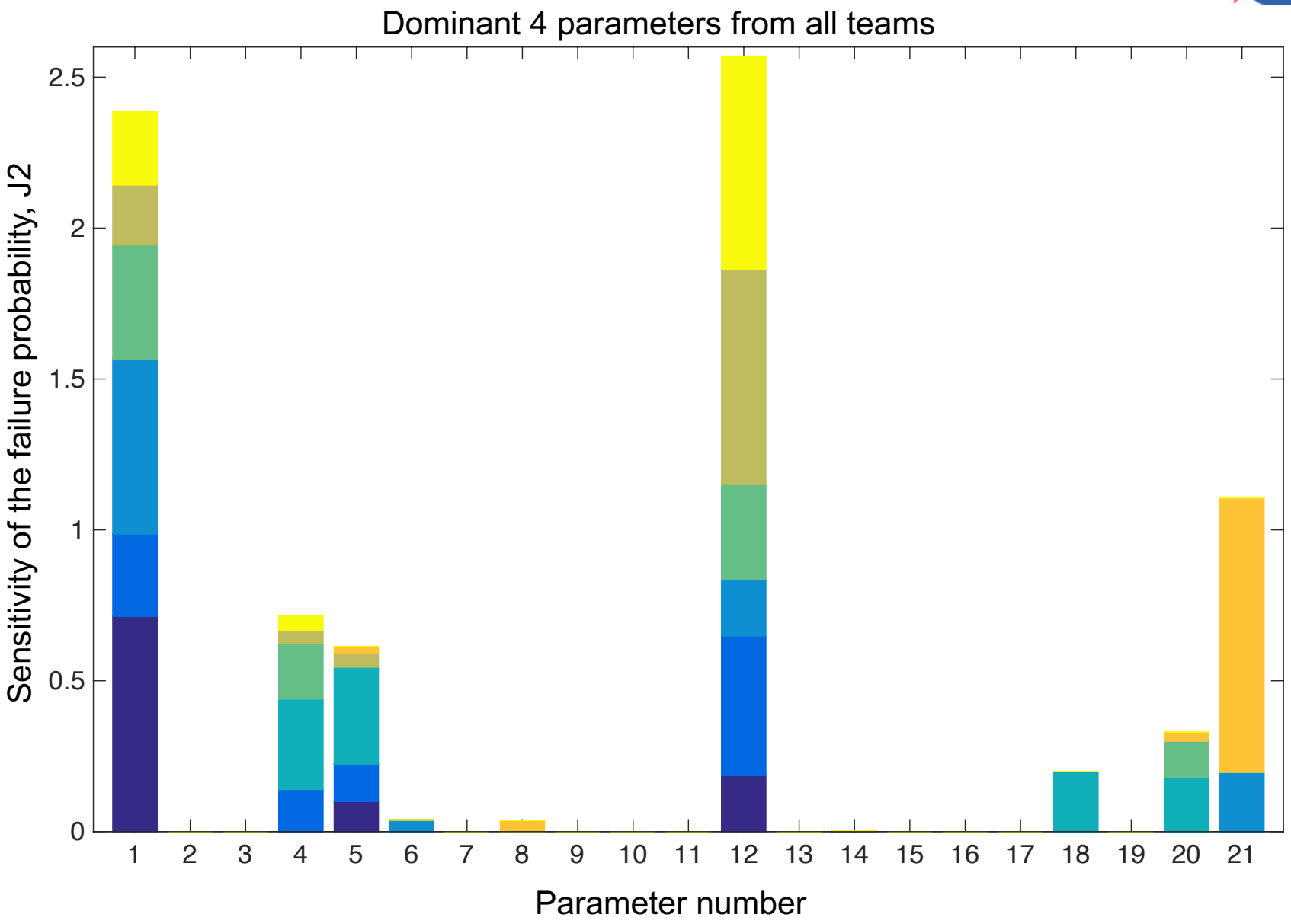
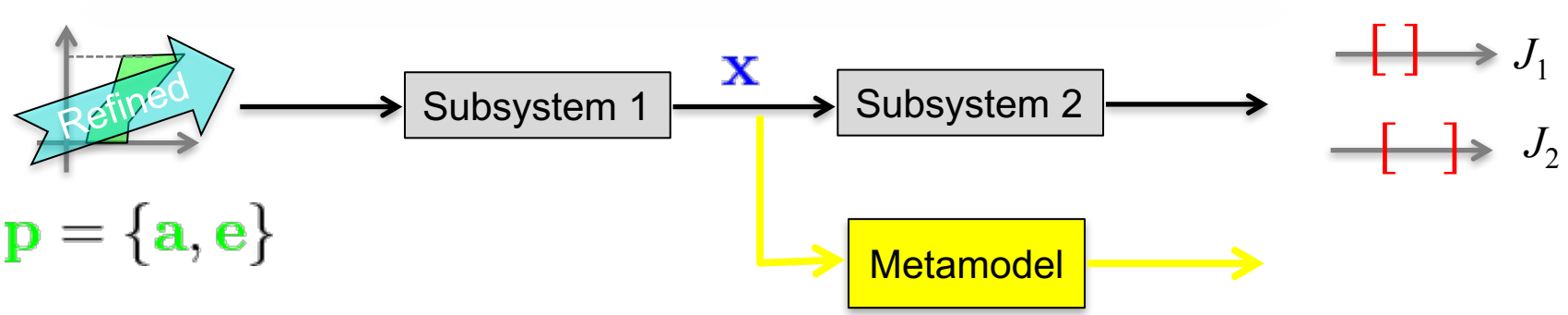


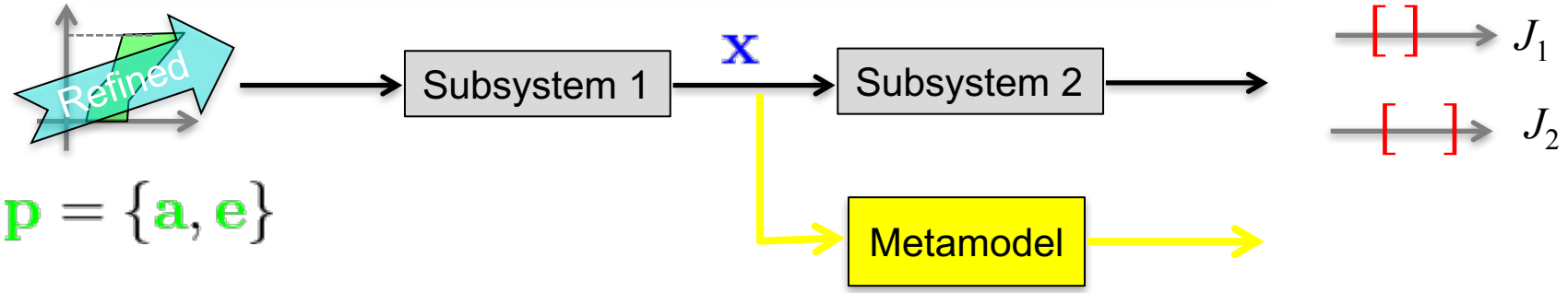
Task 3: Uncertainty Propagation

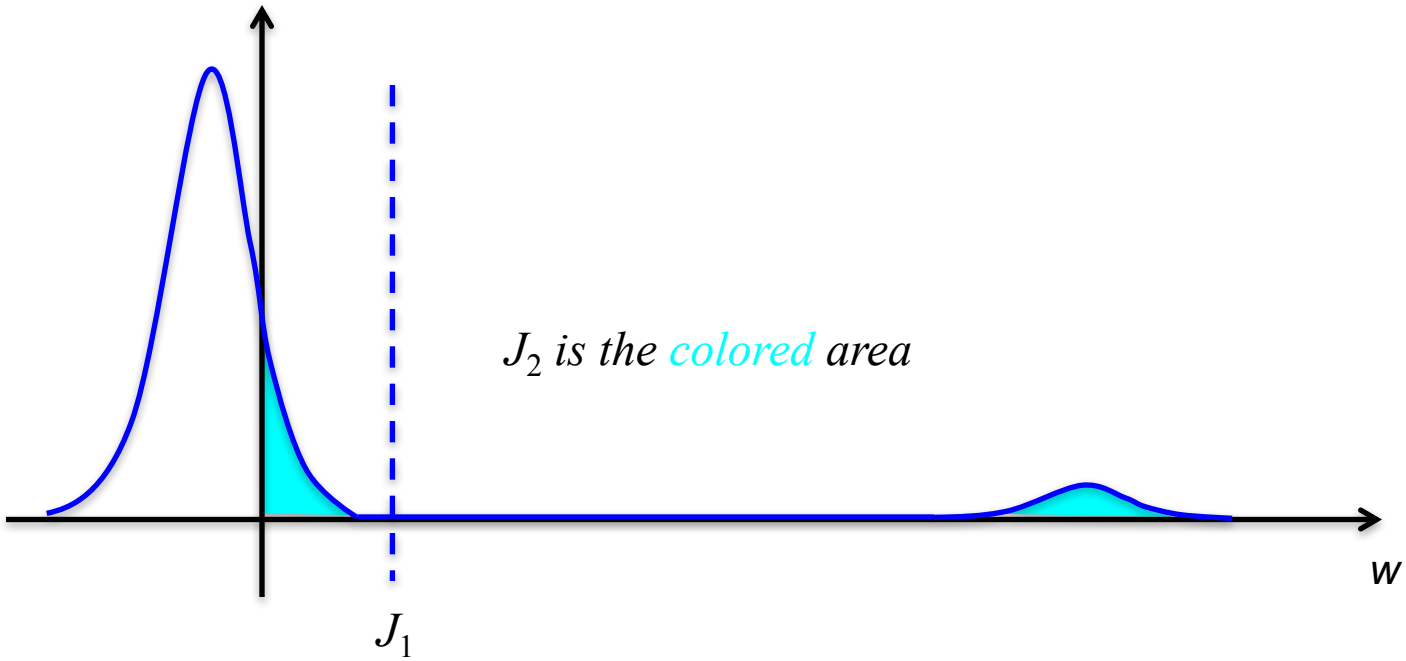


- Solution strategies
  - **2-level epistemic – aleatory**
    - Aleatory loop: n_a : [0.1K, 10K]
    - Epistemic loop by sampling (n_e : [0.5K, 5K]) or optimization (GA)
  - **2-level aleatory – epistemic**

- **Cascading effect**: results depend on the methods, numerical setup and decisions made upstream: calibration strategy, sensitivities, chosen parameters, and propagation method, etc.

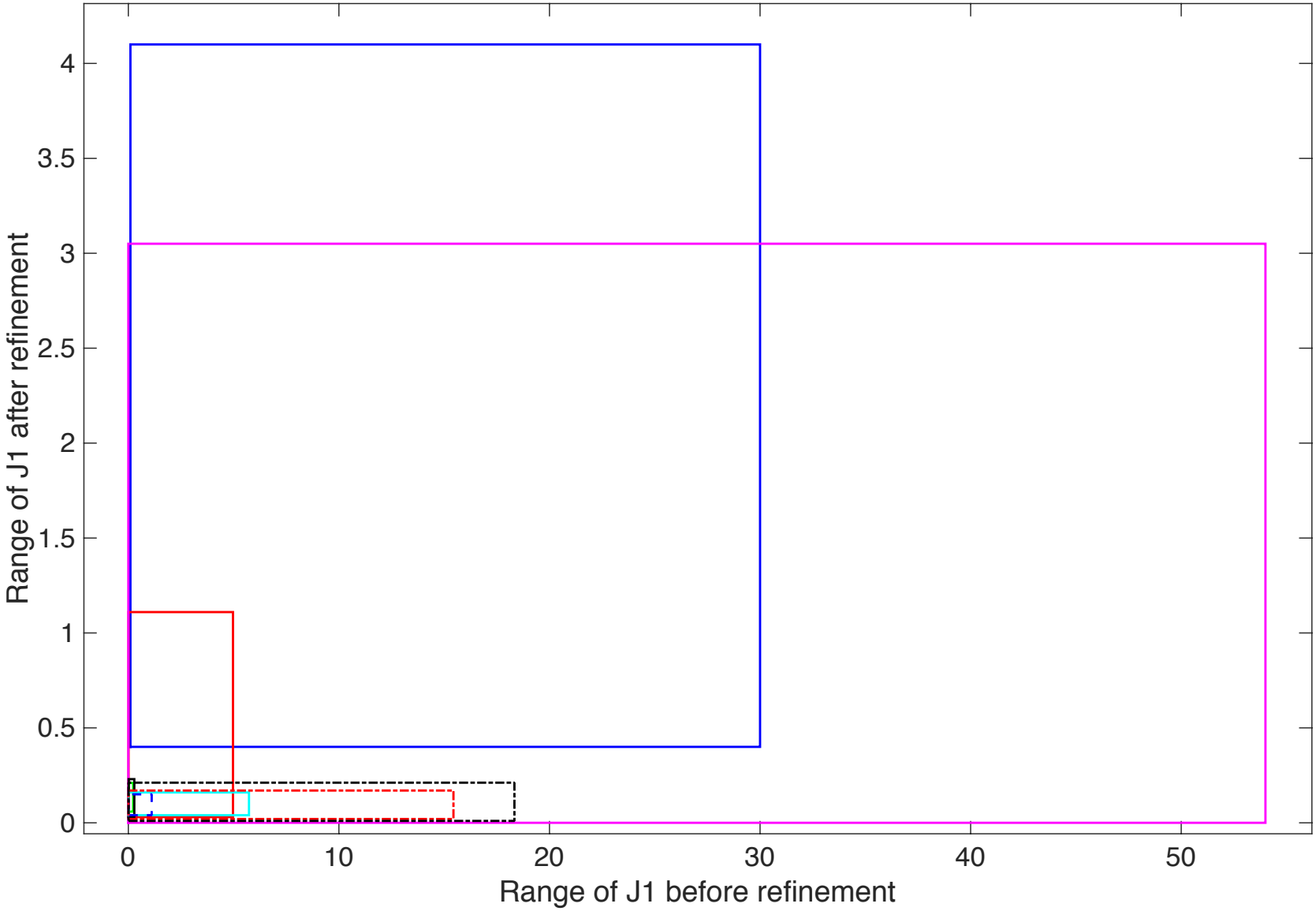
Task 3: Uncertainty Propagation



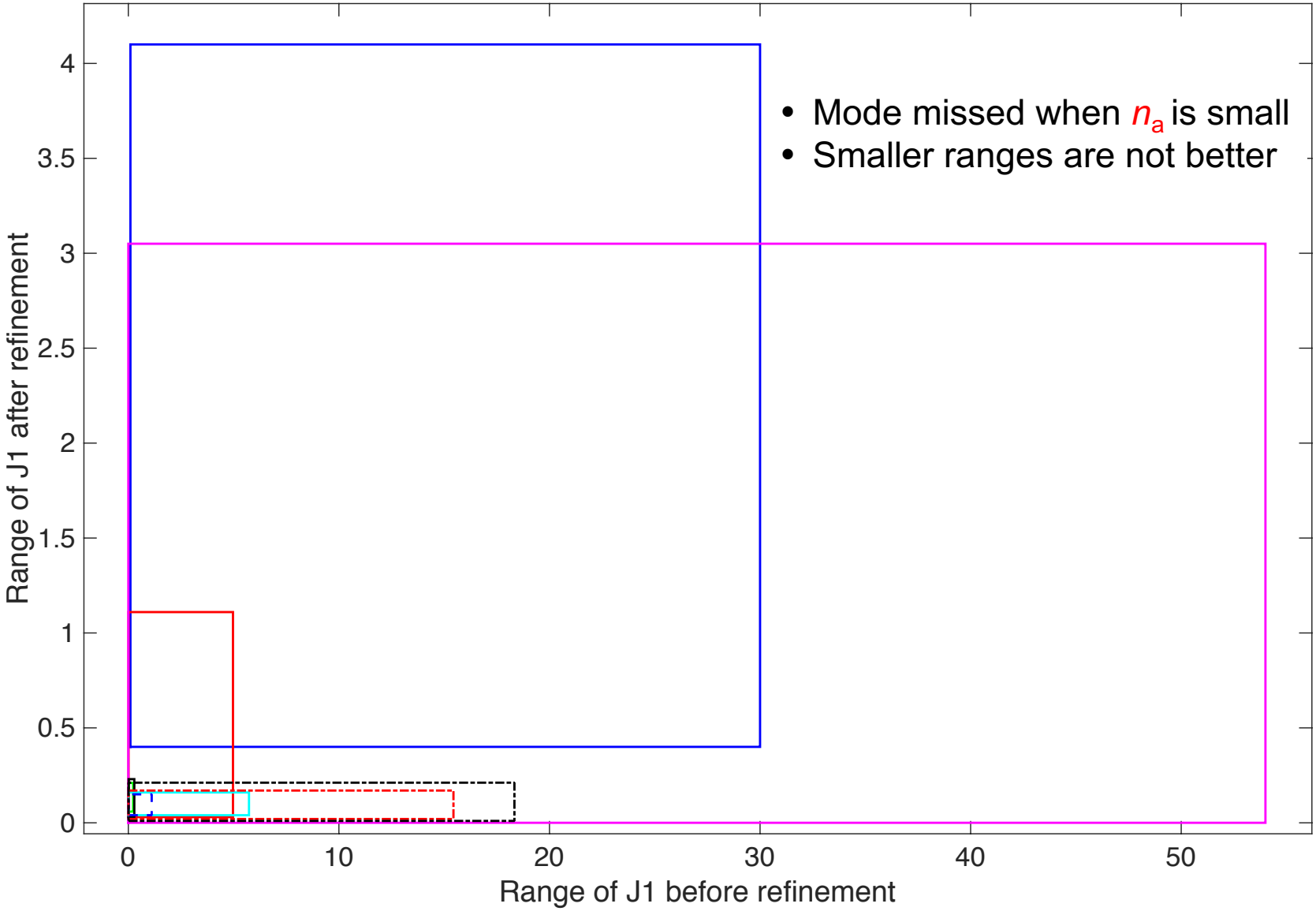


- *Small n_a leads to the underestimation of J1: critical info missing*

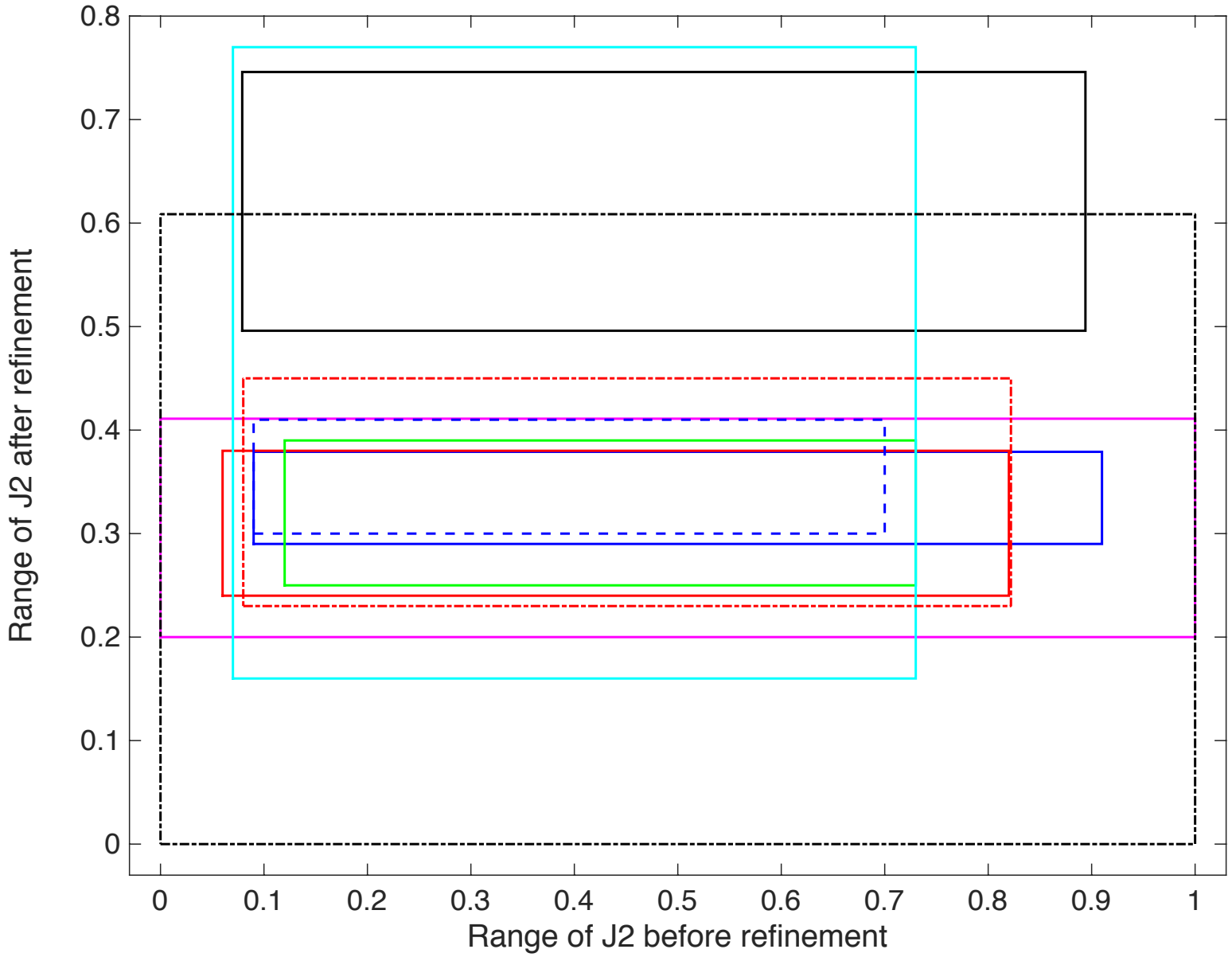
Task 3: Mean Value J_1



Task 3: Mean Value J_1



Task 3: Failure Probability J_2



Observations & Recommendations

- UQ Method verification: perform convergence studies
- Global sensitivities for different metrics are different
- Refine epistemic uncertainties in series: do full loop
- Beware of the cascading effect
- What is the approximation error of a surrogate model?

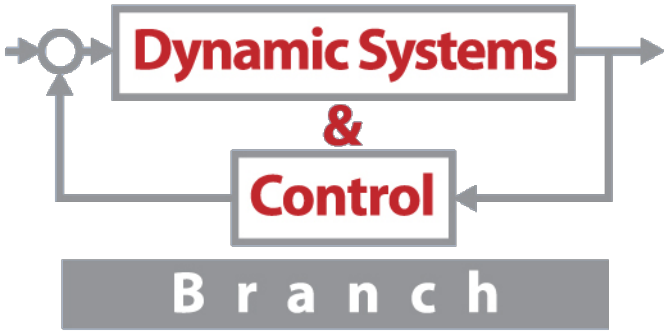
Observations & Recommendations

- Thanks to respondents
- Challenge was an end-to-end UQ problem replicating situations commonly found in practice
- Challenge aimed at breaching the gap between philosophy and mathematics of dealing with epistemic uncertainties
- Responses by UQ experts illustrate the state of the practice
- A considerable spread in the results observed
- Key UQ needs are not fully addressed by existing methods
- Further R&D needed

Conclusions

- Underestimation might lead to the wrong decision
- Overestimation might prevent making a decision
- State of knowledge might lead to wide predicted ranges
  - The UQ analyst does not need to apologize!!
- Decision maker should accept an inconclusive state
- Means to narrow the predicted uncertainty ranges
  - Refine epistemic UM: resources required
  - Use robust design
- UQ analyst vs. decision maker
  - UQ analyst: ask for resources, know what to ask for
  - Decision maker: challenge the UM, provide resources
- Good engineering must have precedence over the urgency of having to make a decision

The NASA Langley UQ Challenge



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