



WASHINGTON STATE UNIVERSITY  
College of Pharmacy and  
Pharmaceutical Sciences

# Uncertainty in Plutonium Dose Modeling: Lessons from USTUR Autopsy Data

2026 USTUR Scientific Advisory Committee Meeting | Richland, Washington



Maia Avtandilashvili, Associated Research Professor

# USTUR Uncertainty Project: How it Started



## Post-Doctoral Research Project 2019 – 2023: Martin Šefl, PhD in Radiological Physics, Czech Technical University in Prague Objective Evaluating uncertainty in radiation dose assessment using post-mortem tissue measurement data

**Paper**

**Validation of Soluble Plutonium: 53-year Follow-up of Manhattan Project Worker**  
Martin Šefl, Miro Antošůvský, and Sergei Y. Tolmachev<sup>1</sup>

**Abstract**—This whole-body dose due to the United States... (text continues)

**INTRODUCTION**  
Nuclear workers involved in handling and processing... (text continues)

**CONCLUSION**  
On average, our results are in excellent agreement with published... (text continues)

**PLOS ONE**

**Plutonium in Manhattan Project workers: Using autopsy data to evaluate organ content and dose estimates based on urine bioassay with implications for radiation epidemiology**  
Martin Šefl<sup>1</sup>, Joey Y. Zhou<sup>2</sup>, Miro Antošůvský<sup>1</sup>, Steven L. McClellan<sup>3</sup>, Sergei Y. Tolmachev<sup>1</sup>

**Abstract**  
Radioactive dose estimates... (text continues)

**Introduction**  
The United States... (text continues)

**Conclusion**  
On average, our results are in excellent agreement with published... (text continues)

**Latent bone modelling for estimation of plutonium concentration in skeleton of former nuclear workers**  
Martin Šefl<sup>1</sup>, Joey Y. Zhou<sup>2</sup>, Miro Antošůvský<sup>1</sup> and Sergei Y. Tolmachev<sup>1</sup>

**Abstract**  
The United States... (text continues)

**Introduction**  
The United States... (text continues)

**Conclusion**  
On average, our results are in excellent agreement with published... (text continues)

**scientific reports**

**Validation of Bayesian modeling approach of uncertainty in organ doses using post-mortem measurements**  
Miro Antošůvský<sup>1</sup>, Martin Šefl<sup>1</sup>, Joey Y. Zhou<sup>2</sup> & Sergei Y. Tolmachev<sup>1</sup>

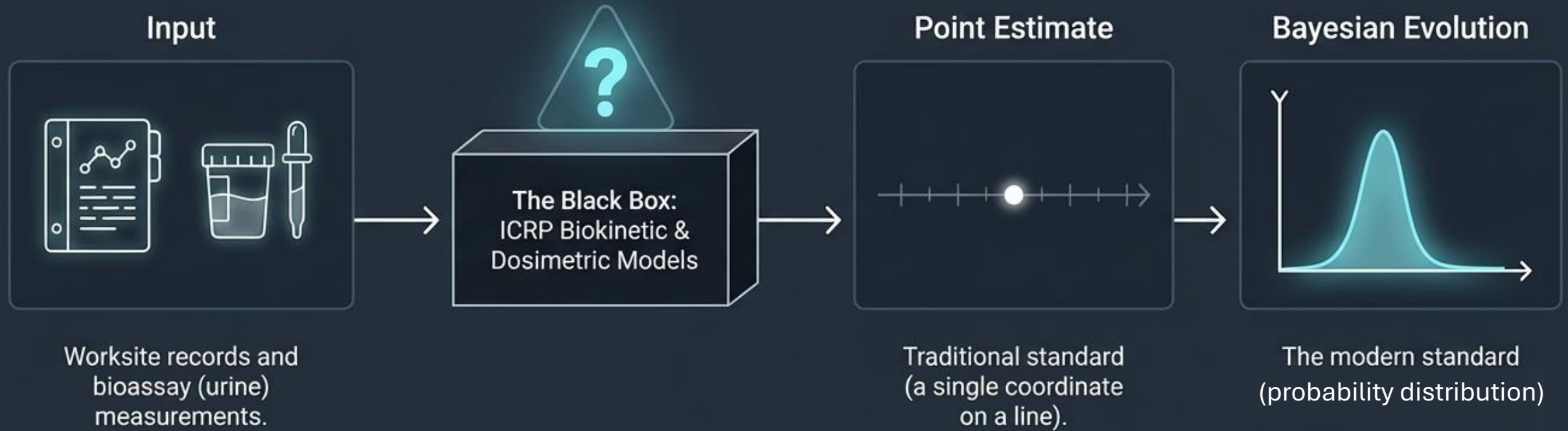
**Abstract**  
The Bayesian modeling... (text continues)

**Introduction**  
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# The Limits of the Standard Paradigm



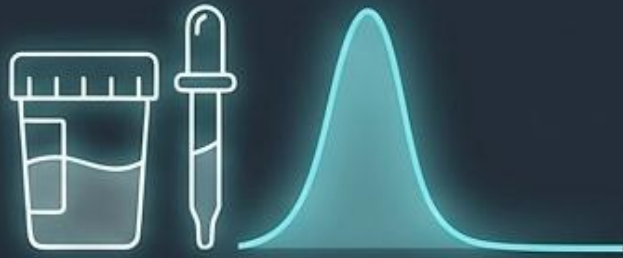
Bayesian methods modernized dose estimation by replacing single point estimates with probability distributions, ostensibly defining the true dose and mapping our uncertainty.

But this entire framework rests on a critical assumption: that the underlying structural architecture of the biokinetic model is essentially correct.



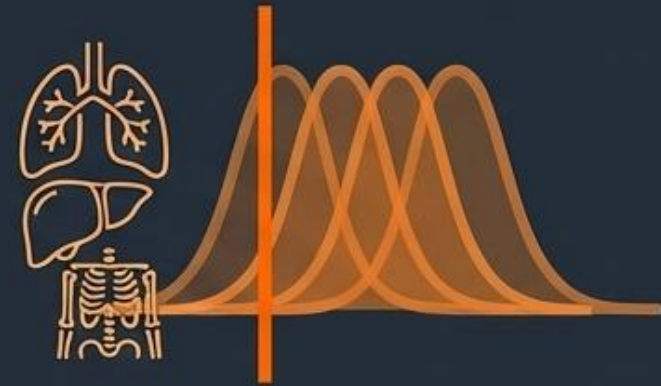
# Confronting Models with Ground Truth

## Predictive Engine



Maximum likelihood fit of urine bioassays generating a posteriori distributions of expected Plutonium organ activity at the time of death.

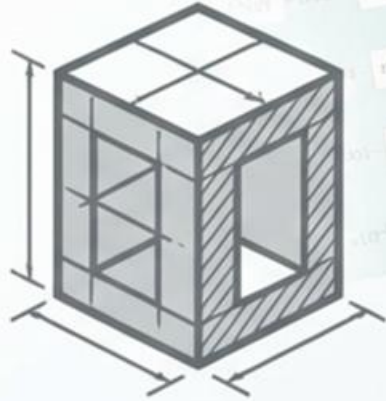
## Ground Truth Verification



Measured post-mortem  $^{239}\text{Pu}$  activities in the respiratory tract, liver, and skeleton.

**The Ultimate Test:** Do the Bayesian probability curves actually bracket the physical, post-mortem reality?

# In-house Analytical Engine: USTUR-iRAD



## Foundation

Built squarely on the latest ICRP OIR (Occupational Intakes of Radionuclides) biokinetic models.



## Architecture

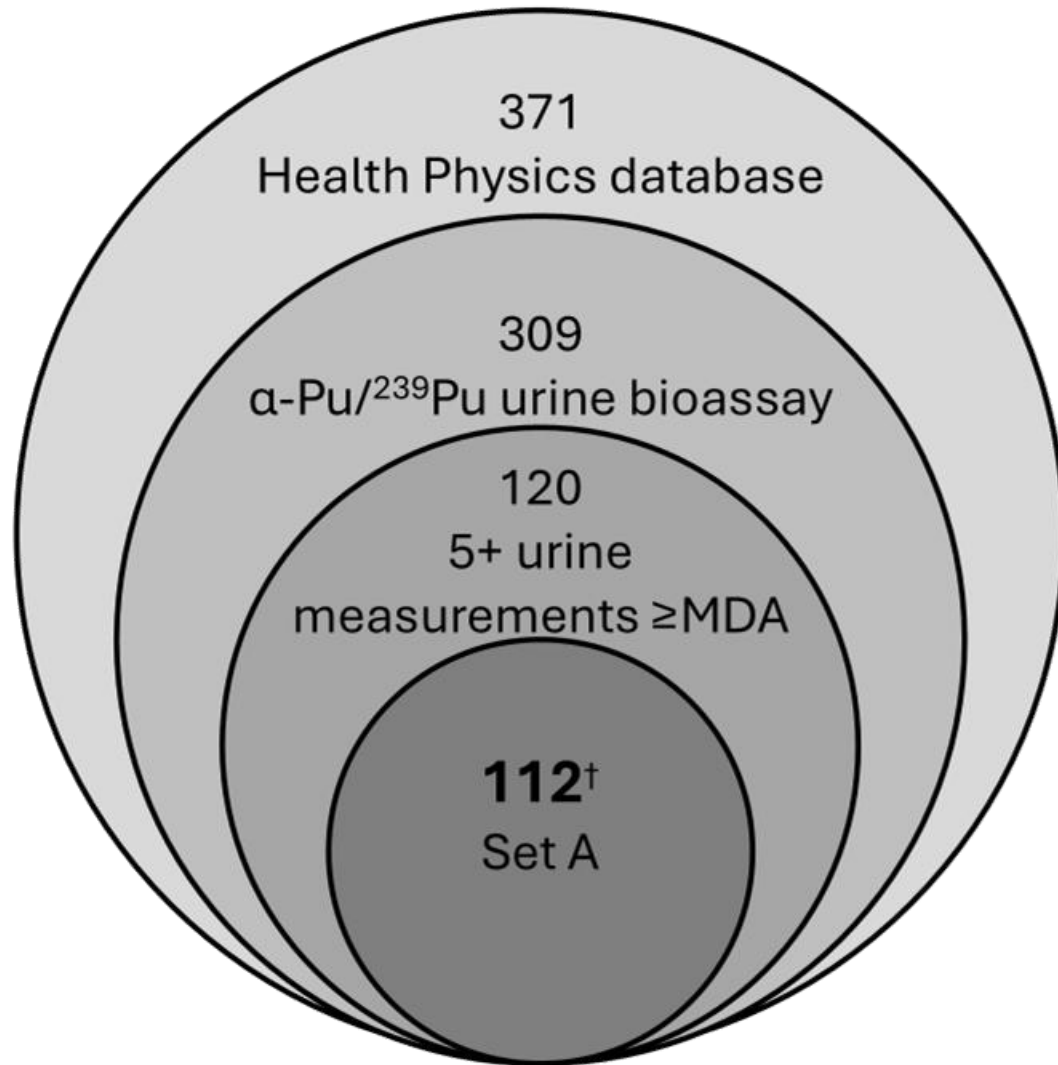
Object-oriented, adaptable code written natively in Python 3.9.



## Capability

A flexible computing environment engineered specifically to execute highly complex, multi-variable uncertainty simulations.

# Case Selection: Bioassay Organ Activity



## Radiochemical analysis



† - no extensive chelation

# Confronting The Model With Autopsy Reality

www.nature.com/scientificreports

**scientific reports**

OPEN **Validation of Bayesian modeling approach of uncertainty in organ doses using post-mortem measurements**

Maia Avtandilashvili<sup>1,2\*</sup>, Martin Šefl<sup>1,2</sup>, Joey Y. Zhou<sup>3</sup> & Sergey Y. Tolmachev<sup>1</sup>

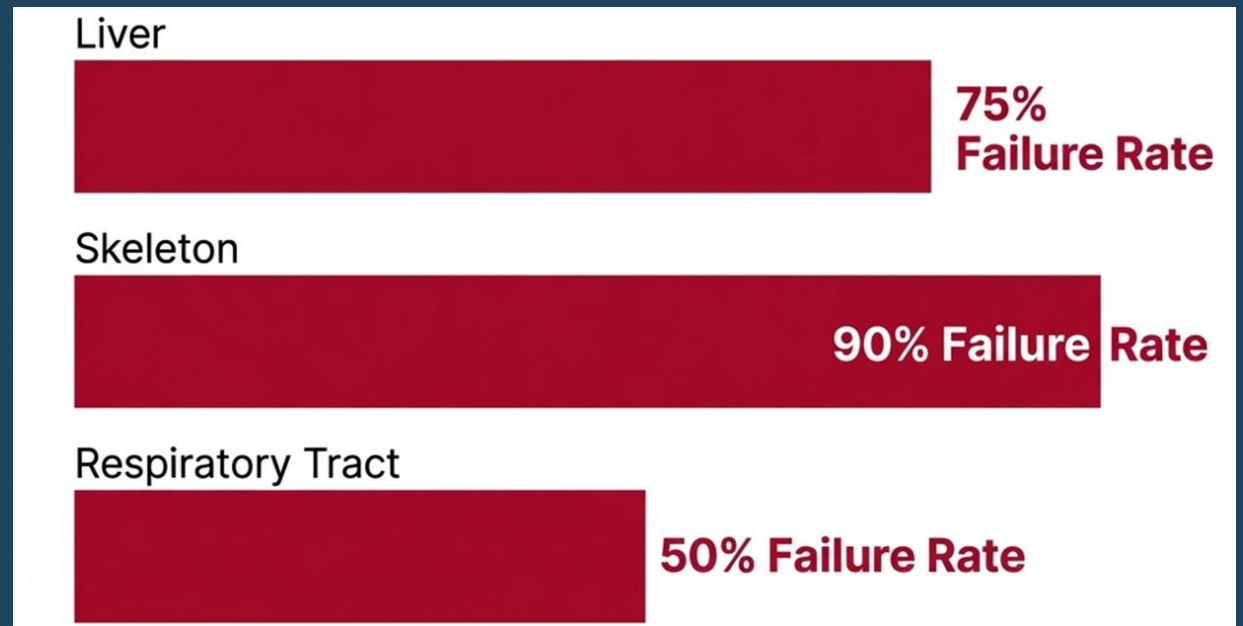
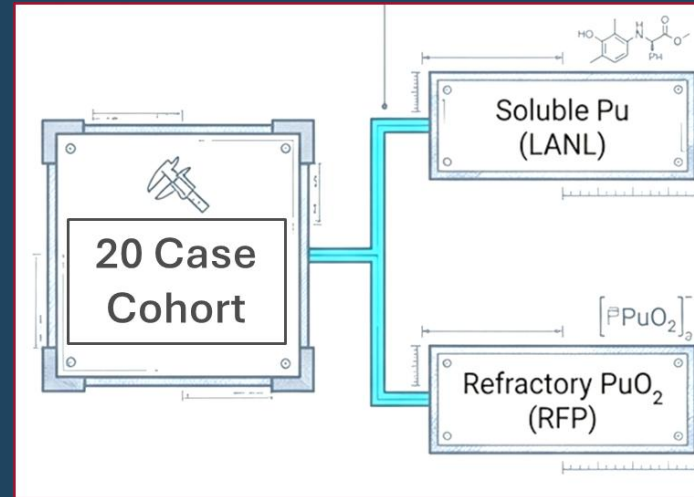
The biokinetic and dosimetry models recommended by the International Commission on Radiological Protection do not incorporate dosimetric uncertainty. Recently, Bayesian approach—offering distribution of dose estimates rather than a single point value—has been applied in epidemiological risk modeling. Although the true dose is unknown, Bayesian analysis is assumed to provide information on the true dose through a posterior distribution. This study presents a unique opportunity to validate that assumption. Radiation dose is directly related to the time-dependent radionuclide activity deposited or retained in organs and tissues. Therefore, uncertainties in organ activity predictions derived from biokinetic modeling can serve as proxies for the uncertainties in dose estimation. In this study, uncertainties in model predictions of <sup>239</sup>Pu organ activities were evaluated for 20 former nuclear workers with known plutonium inhalation. Ten individuals from Los Alamos were primarily exposed to soluble Pu-nitrate, while ten from Rocky Flats were exposed to insoluble PuO<sub>2</sub>. All individuals were volunteer tissue donors to the United States Transuranium and Uranium Registries. Urine bioassay data and post-mortem measurements of <sup>239</sup>Pu in the liver, skeleton and respiratory tract were used in the analysis. Latin hypercube sampling was employed to generate parameter sets for each

**Thank you, Martin!!!**

ONL Geometric standard deviation  
 HATM Human Alimentary Tract Model  
 HRTM Human Respiratory Tract Model  
 ICRP International Commission on Radiological Protection  
 IMBA Integrated Modules for Bioassay Analysis

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Scientific Reports | (2025) 15:30476 | https://doi.org/10.1038/s41598-025-04799-3 nature portfolio 1



# The Investigation Cohort: 35 Autopsy Cases

35 qualified cases out of the original 371 Health Physics database entries (filtered for  $^{239}\text{Pu}$  bioassays, 5+ urine measurements, and rigorous radiochemical post-mortem analysis).



## Hanford

15 cases

**Exposure:** Unspecified chemical compounds (diverse intake scenarios).



## Los Alamos

10 cases (UPPU Club members)

**Exposure:** Soluble  $^{239}\text{Pu}$ -nitrate.



## Rocky Flats

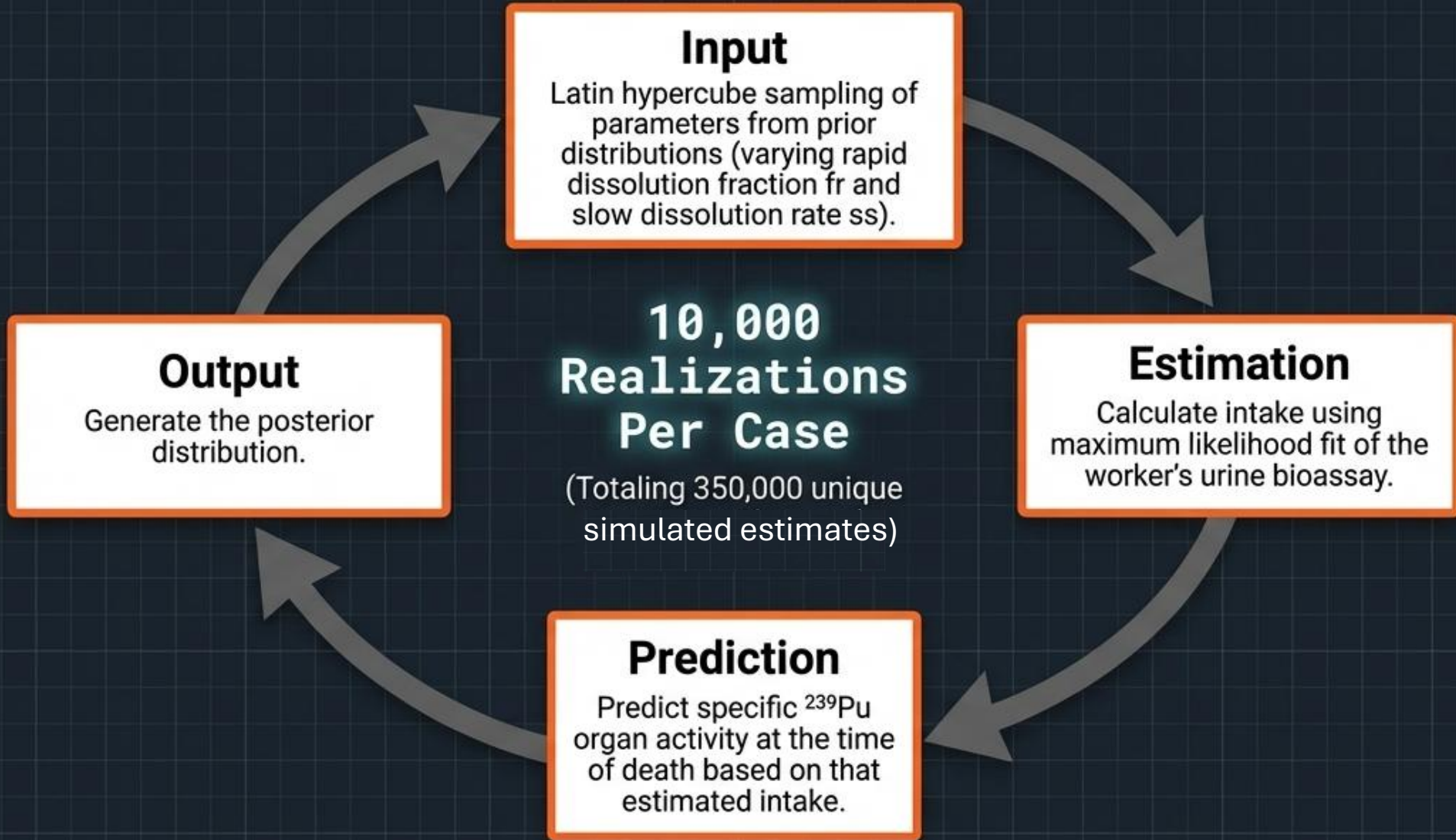
10 cases (9 involved in Pu fire accident)

**Exposure:** Insoluble  $^{239}\text{PuO}_2$ .

**Key Insight:** By testing models against both soluble and insoluble intakes across multiple facilities, the diagnostic test isolates the model's structural integrity from specific exposure noise.

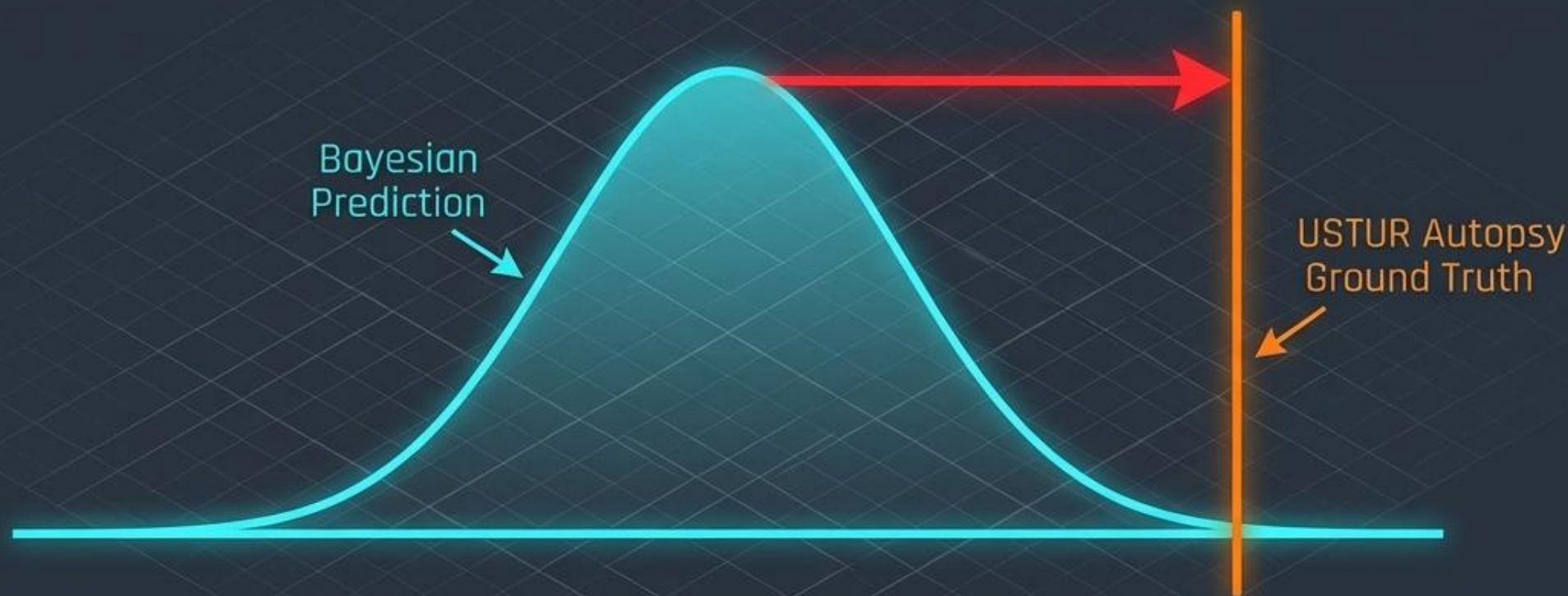


# The Computational Stress Test: USTUR-iRAD



# The Diagnostic Blueprint

Structural Flaws and Evidence-Based Fixes in Plutonium Dose Modeling

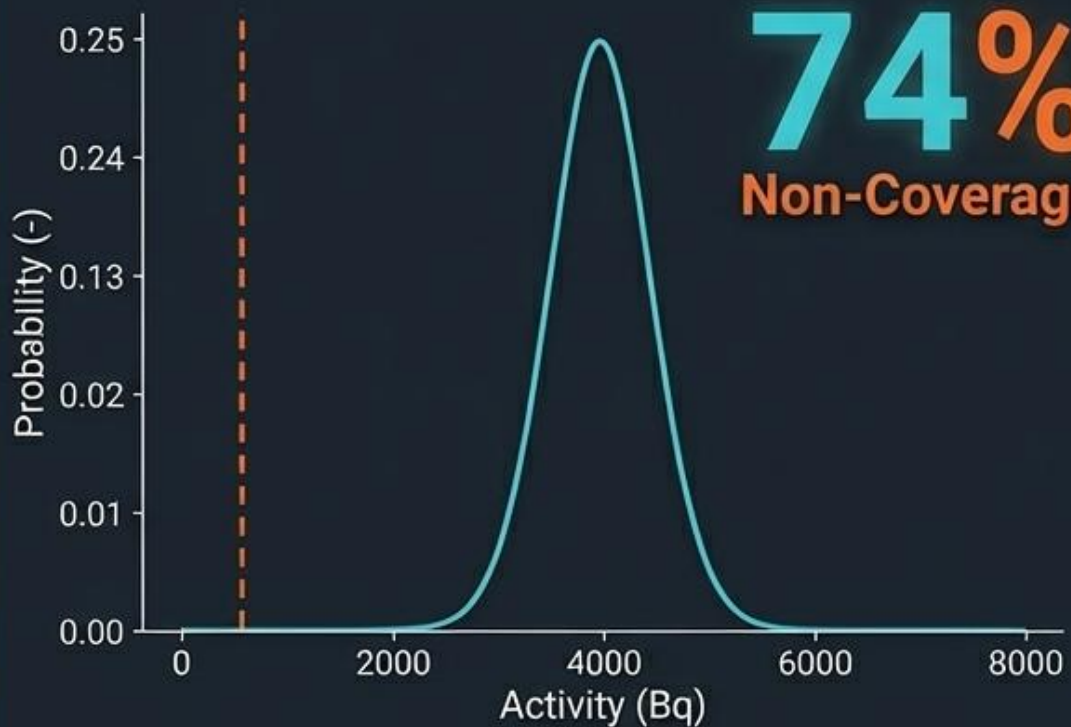


Based on post-mortem tissue analysis of 35 Manhattan Project and Cold War workers.



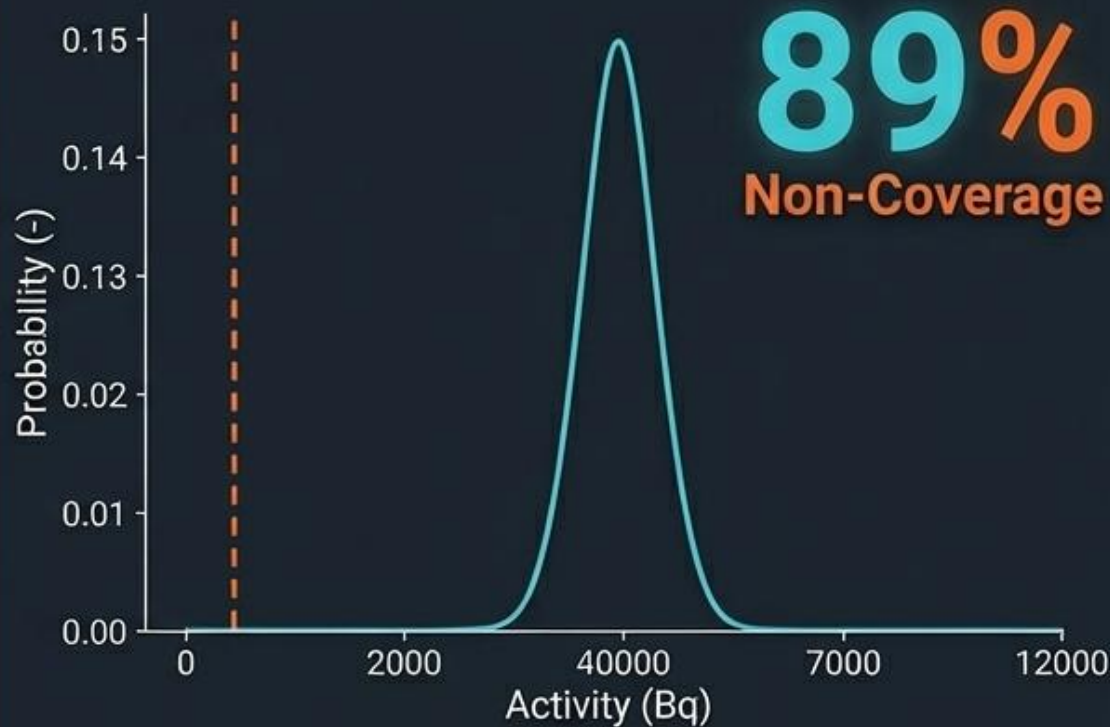
# Systemic Collapse: The Reality Check

## Liver



In 26 of 35 cases, the model fundamentally failed to bracket the true liver activity.

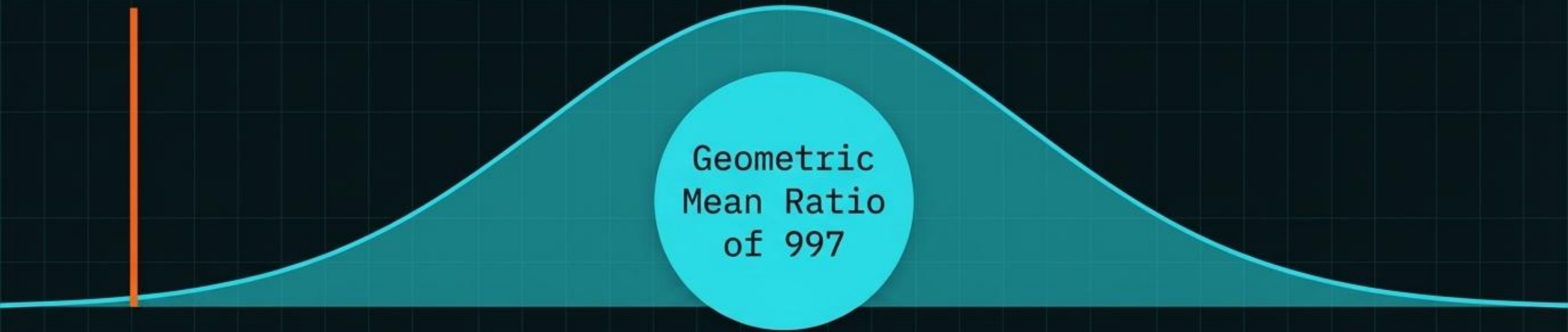
## Skeleton



In 31 of 35 cases, the model failed to bracket the true skeleton activity.



# The Illusion of Coverage: Respiratory Tract



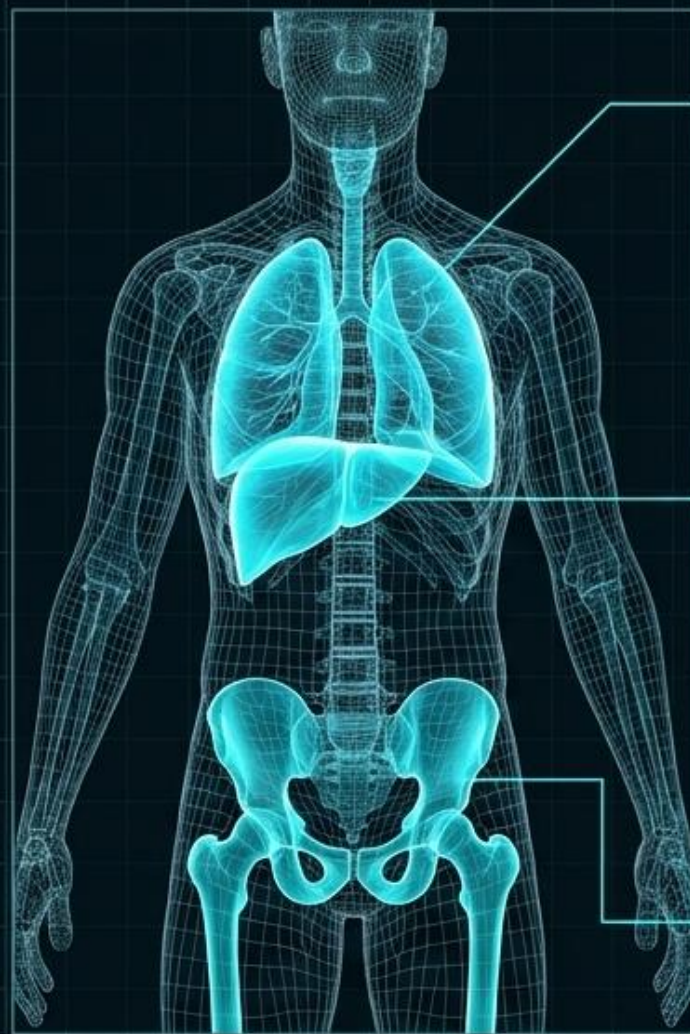
**The Symptom:** The model generates exceptionally broad distributions for the respiratory tract (the 97.5% quantile is nearly 1,000 times larger than the 2.5% quantile).

**The Failure:** Despite this massive, unhelpful spread, the predicted distributions still fail to cover the true value in 26% of cases (9 out of 35).

**When an uncertainty band spans three orders of magnitude and still misses the target, the model is not capturing biological reality; it is masking structural ignorance.**



# The Organ-Correlated Failure Map



Lungs: 26% Failure Rate  
(despite 997x spread)

Liver: 74% Failure Rate

Skeleton: 89% Failure Rate

These failures are not independent. The errors cascade systemically. Outliers are highly correlated across organs and reproducible across individuals, proving the error is built into the model's architecture.

# Root Cause: Stochastic Miss vs. Deterministic Bias

Stochastic Miss



Random errors caused by natural variation. Potentially fixable by simply widening parameter priors or increasing computational sampling.

Deterministic Bias



Systematic structural errors. The model predictions highly precise, but systematically biased. Requires core structural changes, not wider nets

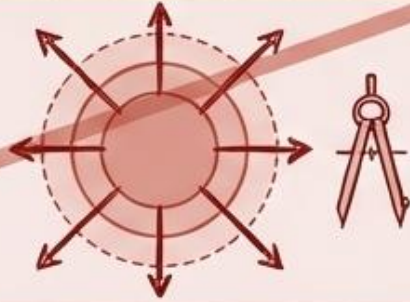
**The USTUR data proves the current biokinetic models suffer from deterministic bias.**



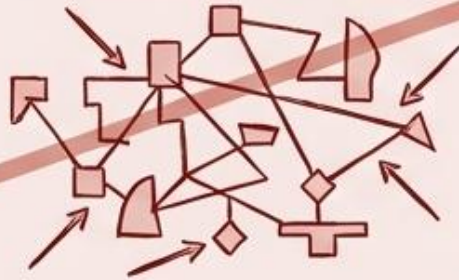
# The Paradigm Shift: From Tuning to Evolution

## Opportunistic Tuning (The Old Way)

1. Widening priors further in hopes of capturing outliers.



2. Adding free parameters at random.



3. Relying exclusively on urine-only likelihoods when autopsy data exists.



Urine-only



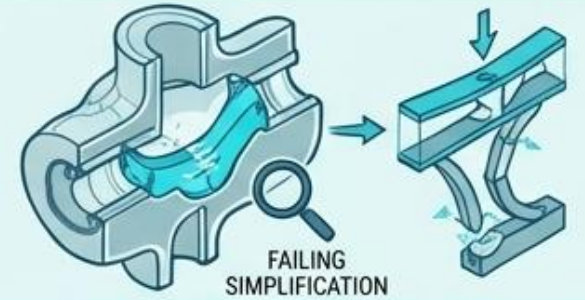
Autopsy Data

## Targeted Evolution (The New Way)

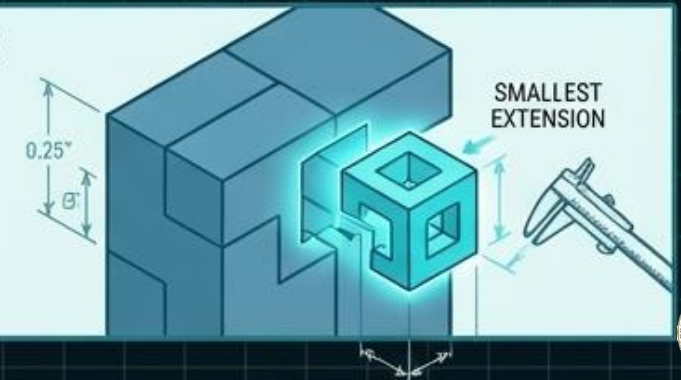
Separate structural bias from genuine intersubject variability.



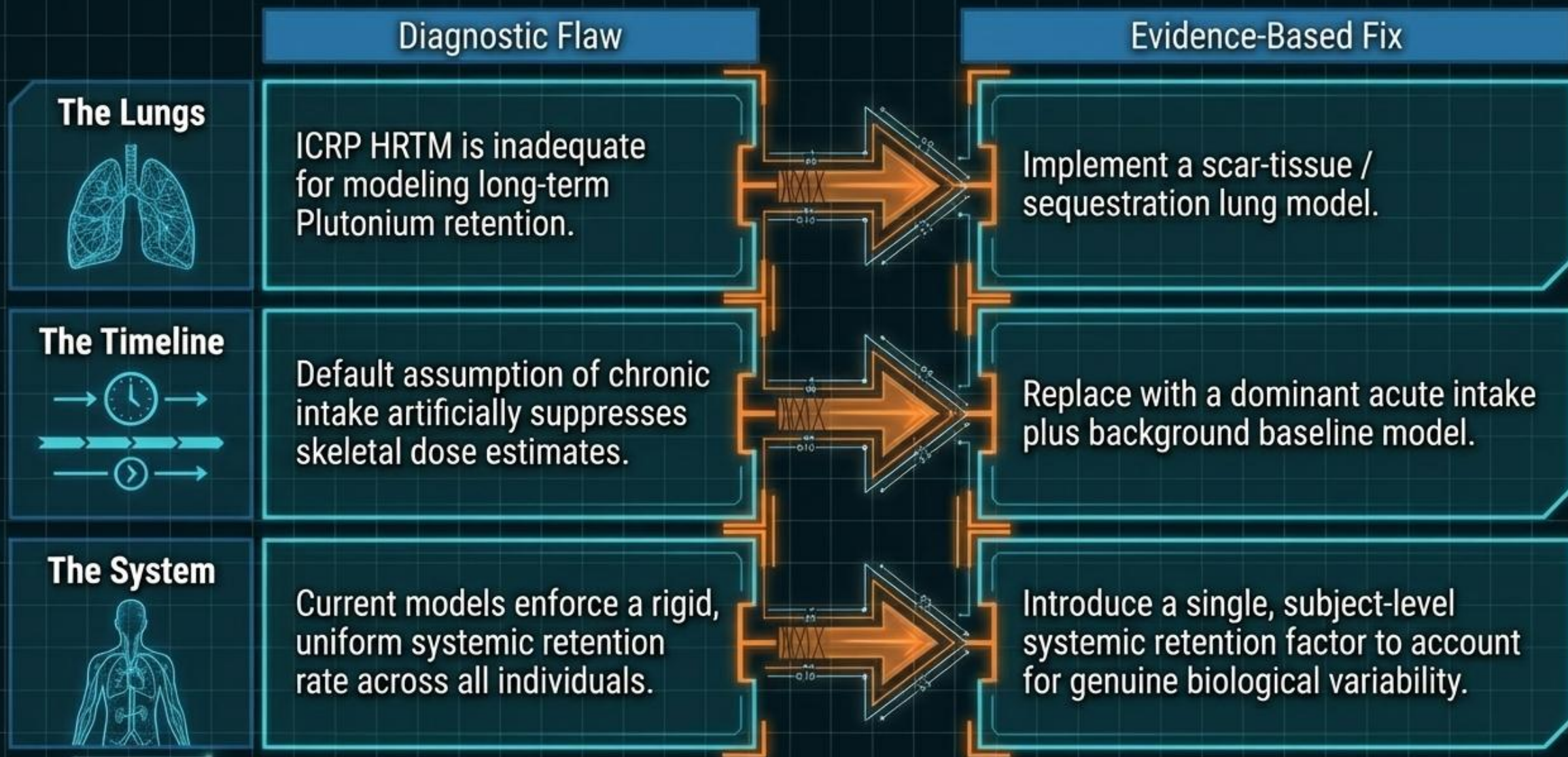
Identify failing structural simplifications.



Introduce the smallest necessary model extensions.

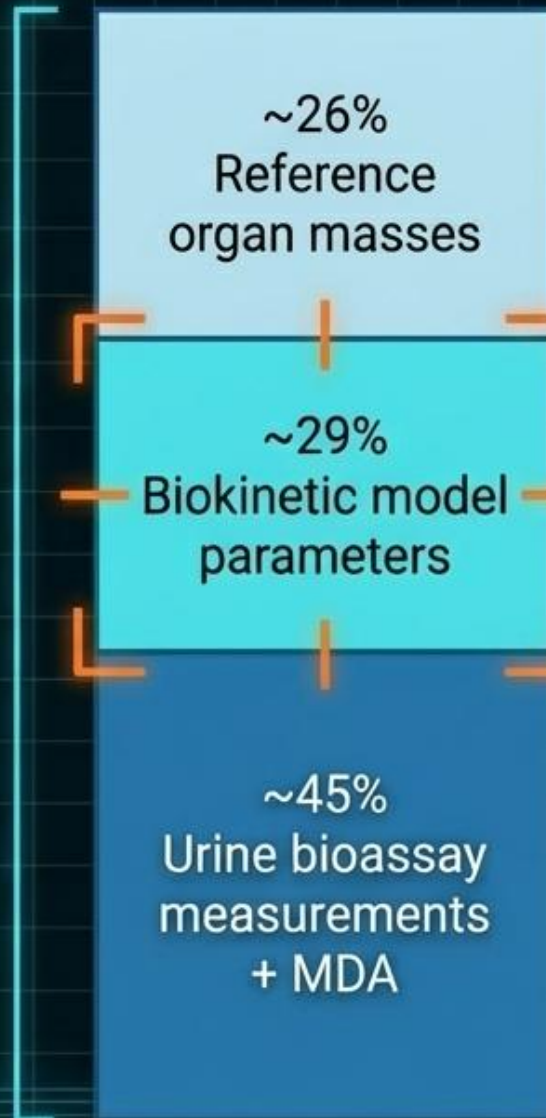


# The Evidence-Based Fixes



# Diagnosing the “Uncertainty Bucket”

~100% total uncertainty in yearly plutonium organ dose estimates



The USTUR autopsy data allows us to unpack this 29%. It is not just stochastic noise. It conceals three specific, structural Diagnostic Flaws:

## Diagnostic Flaw 1

1. Inadequate modeling of long-term respiratory retention.

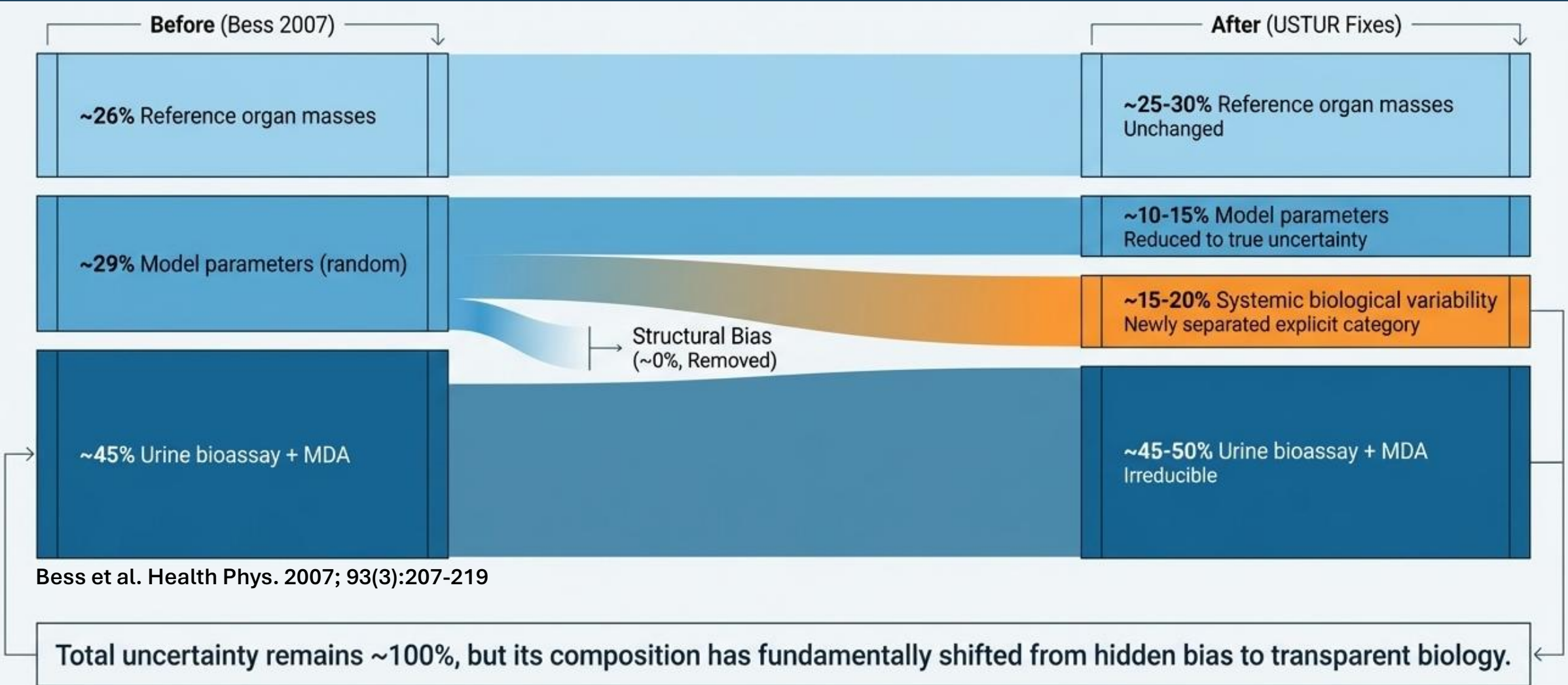
## Diagnostic Flaw 2

2. Unrealistic and unverified assumptions regarding intake timing.

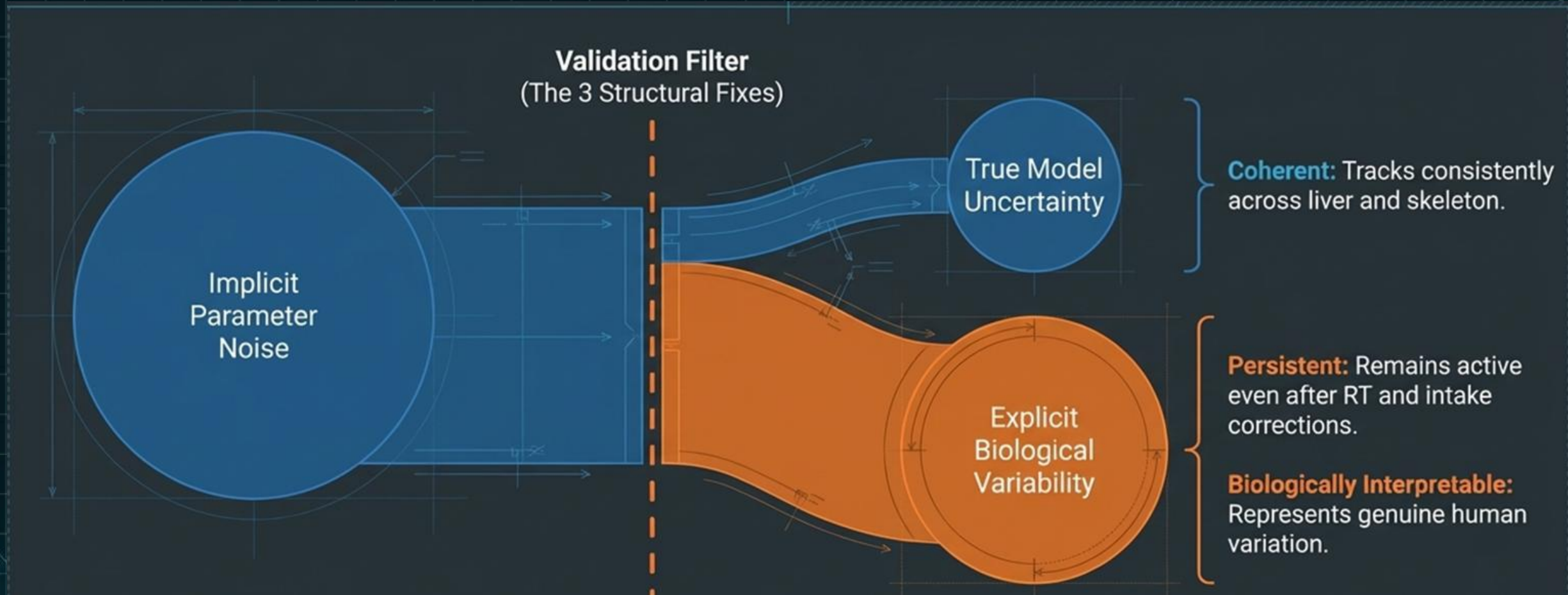
## Diagnostic Flaw 3

3. Missing inter-individual variability in long-term systemic retention.

# Reallocation Ledger: Conserving Total Uncertainty

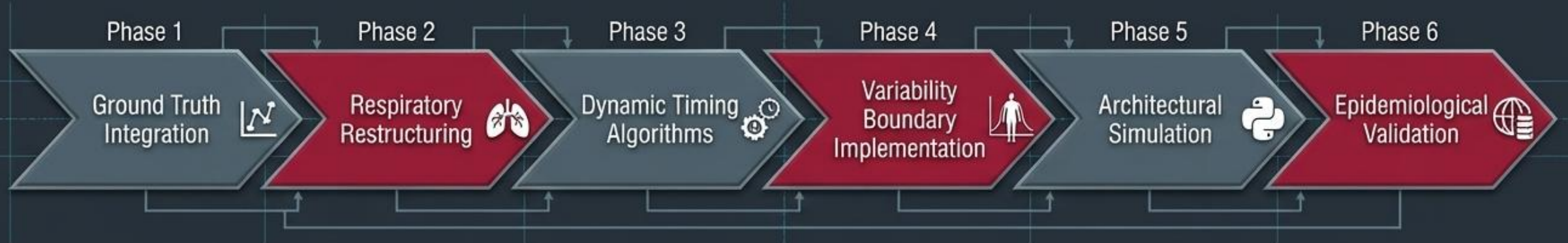


# From Quantification to Meaning



Implementing the structural fixes collapses the RMSE and removes systematic bias. Total uncertainty remains high (~100%, limited by bioassay fidelity), but it is reallocated from hidden structural bias to explicitly tracked biological variation.

# A Blueprint for Evolution: Guidance Over Criticism



## The Bottom Line:

Bayesian statistical methods are mathematically sound, but their application to Plutonium dosimetry has been undermined by incomplete biokinetic models.

## The Mandate:

By treating post-mortem data not as an anomaly, but as structural ground truth, we have mapped exactly what must change.

## The Result:

Implementing these minimal fixes restores predictive validity, supporting future epidemiology with honest, biologically grounded uncertainty.





**5<sup>th</sup> International Conference on Dosimetry and its Applications**  
**Prague, Czechia, June 7 – 11, 2026**