Simulation study of Muon Scattering Tomography for low-contrast medical imaging

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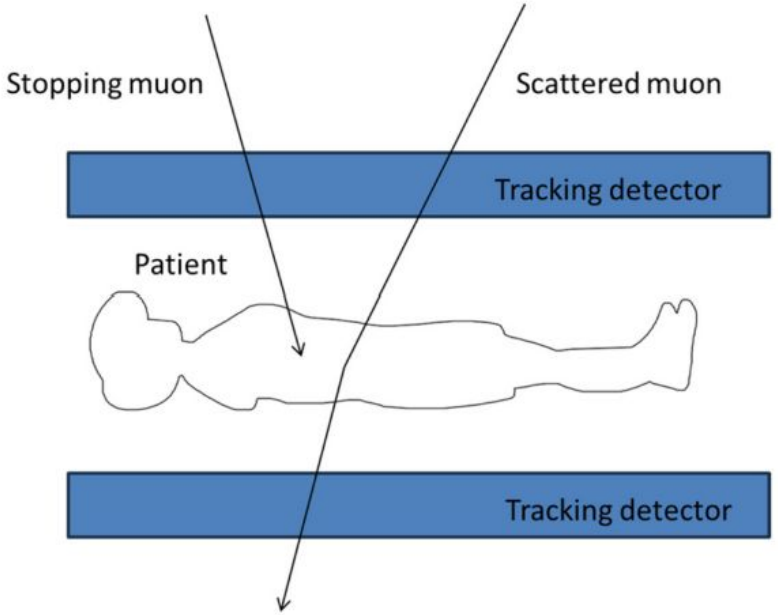
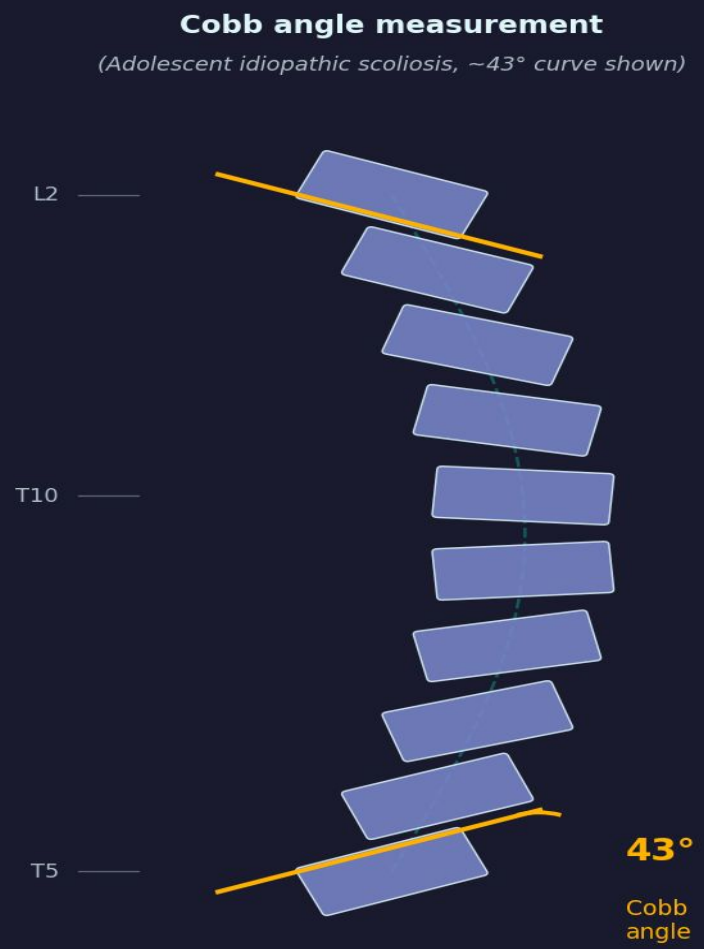


Scoliosis: a lifelong monitoring challenge

- Adolescent idiopathic scoliosis (AIS): ~3% prevalence
- Cobb angle — the primary clinical metric
  - Angle between tilted endplates on frontal X-ray
  - Progression >5° → clinical action
- Monitoring protocol: X-rays every 6–12 months
  - From diagnosis (~10 yrs) through skeletal maturity
  - Potentially 10–15 imaging episodes per patient
- Treatment milestones depend on accurate curvature tracking
- Mild curves (10–25°): observation only — imaging is the intervention

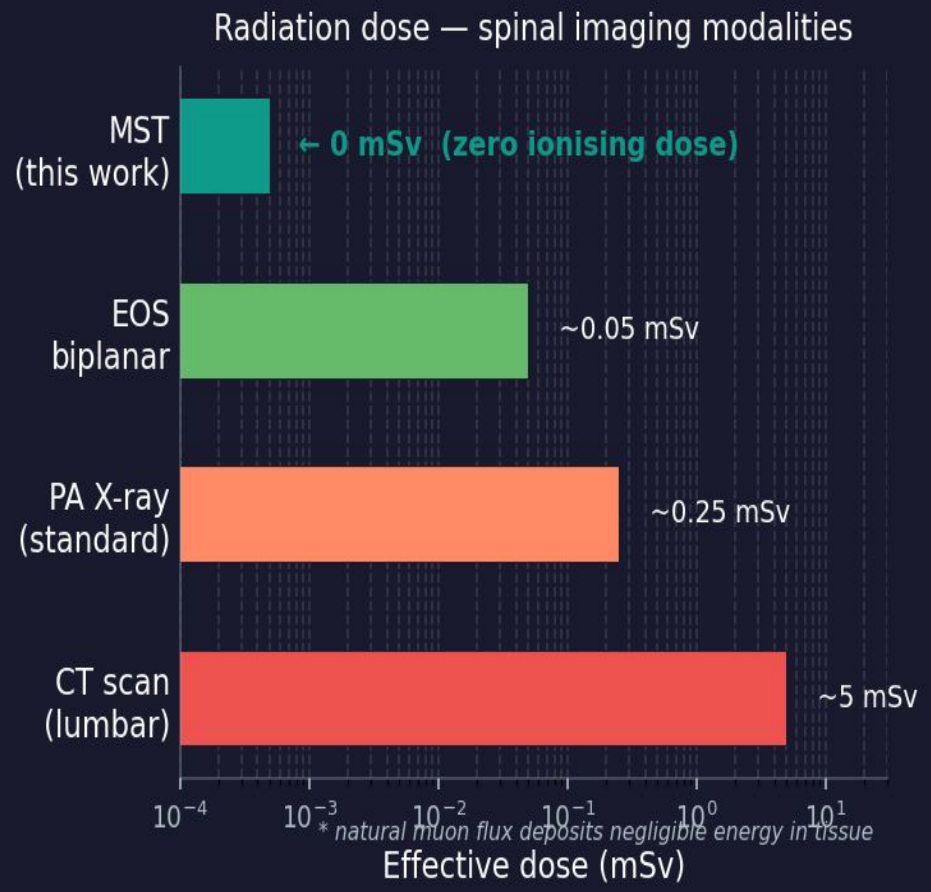


Scoliosis: a lifelong monitoring challenge

The radiation burden in pediatric follow-up

- Standard PA radiograph: ~0.1–0.3 mSv effective dose
- Bilateral (PA + lateral) series: ~0.5–1.5 mSv
- 10–15 exams over monitoring period → 5–15 mSv cumulative
- Pediatric radiosensitivity higher than adults
  - BEIR VII: lifetime attributable cancer risk ~0.05% per 100 mSv
  - Breast and thyroid especially sensitive in adolescent girls
- AIS is ~80% female — the most exposed demographic
- Low absolute risk, but preventable risk in a healthy population

The goal is not dose reduction — it is elimination.
Cosmic muons are omnipresent and deposit negligible energy in tissue.



Zero-dose follow-up via cosmic ray muons

Can naturally occurring cosmic-ray muons — which pass through the human body continuously, at zero clinical dose — image spinal curvature with sufficient precision to replace ionising X-rays for scoliosis follow-up?

Free & continuous

Muon flux ~170 $m^{-2}s^{-1}$ at sea level.
No source, no generator, no regulation.

Zero ionising dose

Muons lose ~2 MeV/cm in tissue.
Negligible biological effect at natural flux.

Scattering carries density information

Multiple Coulomb scattering scales with $\rho \cdot Z^2$.
Bone and soft tissue scatter differently.

This talk: we assess the physical feasibility through Geant4 simulations with ICRP 110 pediatric phantoms.

Muon Scattering Tomography: working principle

› Cosmic muons traverse tracking detectors above and below the object

› Incoming and outgoing track vectors measured precisely

› Scattering angle θ per muon contains density information:

– $\langle\theta^2\rangle \propto (L / X_0)$ where X_0 is radiation length

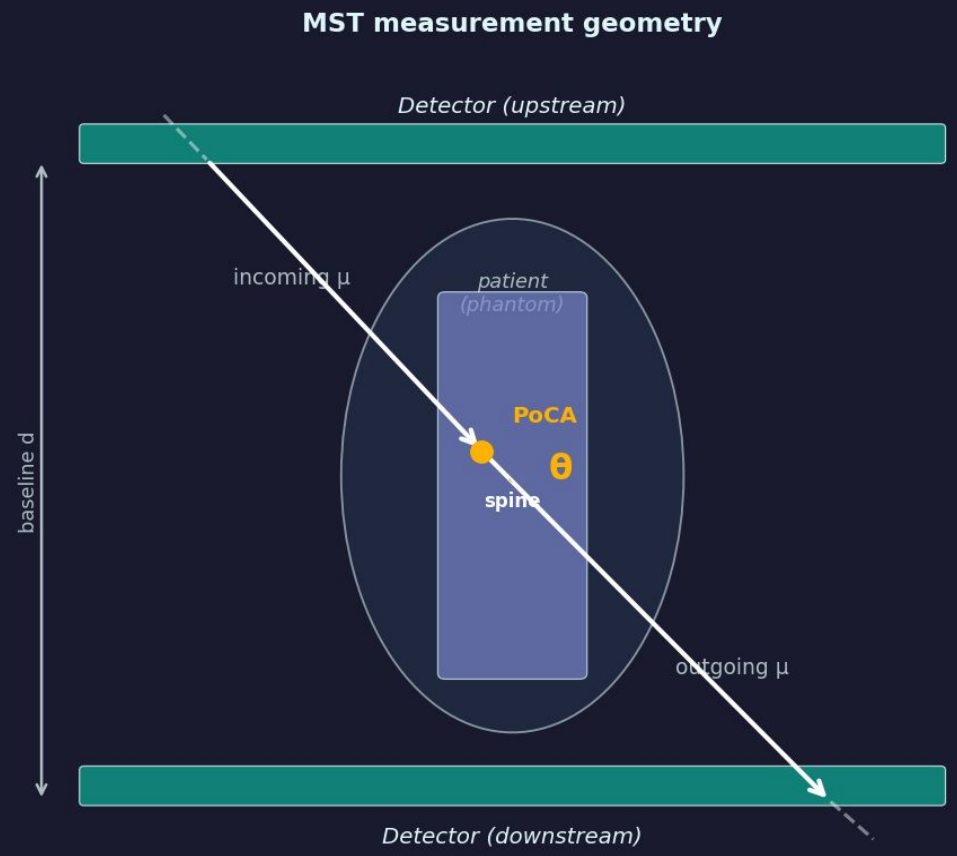
– X_0 depends on Z and ρ of the material

› Point of Closest Approach (PoCA) used for voxel assignment

› Statistical reconstruction over many muons ⟶ 3D density map

› Proven applications: nuclear security, volcano imaging, archaeology

› Medical application: unexplored territory



Why the spine is a favourable MST target

Density contrast

Bone: $\rho \approx 1.85$ g/cm³
Soft tissue: $\rho \approx 0.95–1.05$ g/cm³

Ratio ~2:1 — the best contrast available in the body.
Scattering angle difference is measurable.

Geometry

Vertebral column is elongated and quasi-linear.
Lateral projection: minimal overlapping structures.
Spinal canal and cortical bone well-separated.
Amendable to simplified reconstruction geometry.

Metric (Cobb angle)

We do not need to resolve fine anatomy.
Cobb angle is a global curvature estimate.
Extractable from reconstructed vertebral body centroids.
Lower spatial resolution requirement than anatomical imaging.

The spine uniquely combines high intrinsic density contrast with a global geometric metric — making it the most tractable MST target in the human body.

Clinical requirement: what precision do we need?

› Cobb angle: angle between maximally tilted endplates on PA X-ray

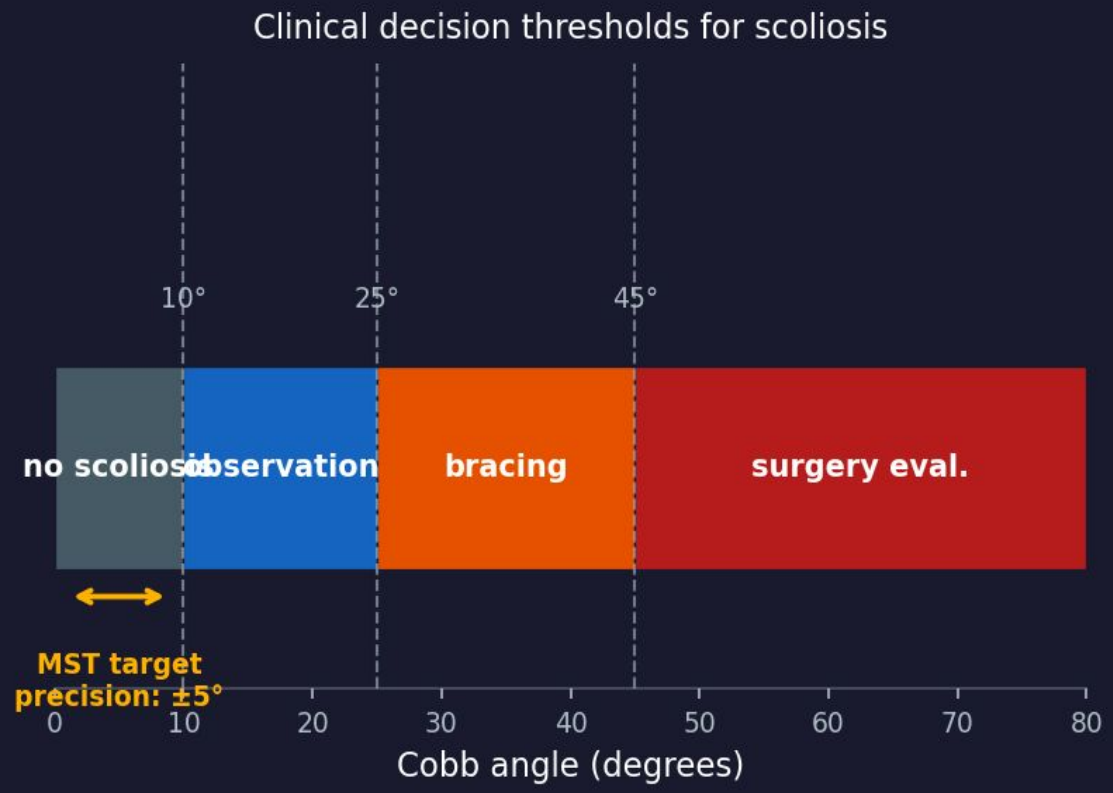
› Intraobserver variability in X-ray measurement: ±3–5°

› Clinical decision thresholds:

- <10°: not scoliosis
- 10–25°: observation — imaging is the only intervention
- 25–40°: bracing considered
- >45–50°: surgical evaluation

› Minimum detectable progression: ~5° (treatment trigger)

› ⟶ MST must achieve Cobb precision of ±5° or better



Simulation framework

Geant4 Setup

› Geant4 with standard EM physics list

› Muon flux: muon generator integrated with GEANT4 by Konstantin Borozdin. Based on PDG spectrum and Reyna approximation for theta-dependence.

Key Parameters

› Phantom: ICRP 110 pediatric voxel models

› Voxel size: 2–5 mm (configurable)

› Detector area: to encompass full torso

› Acquisition time: 1 min → 24 h (scan range)

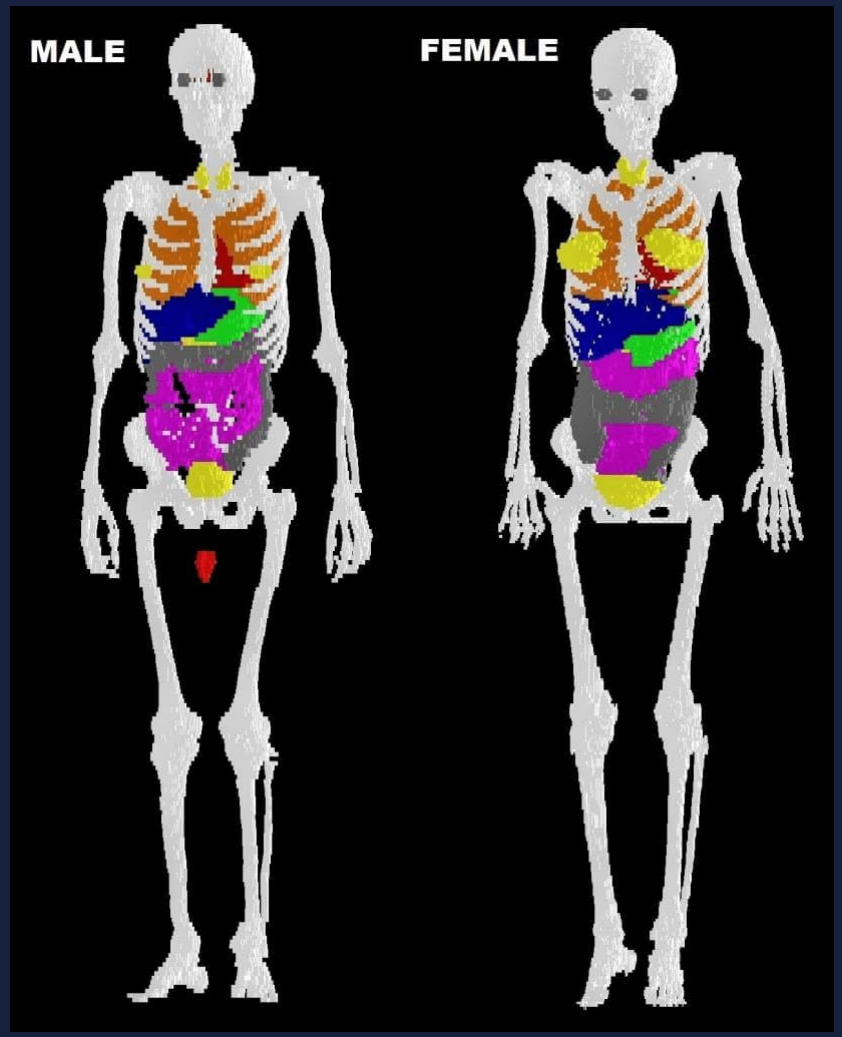
› Output: scattering angle density maps

All simulation code is custom Python/Geant4 — geometry, scoring, and reconstruction pipelines in development.

ICRP 110 pediatric phantom

- Reference computational phantoms (ICRP Publication 110)
- Voxelised whole-body male and female reference models
- Organ-by-organ tissue assignment with ICRP tissue compositions
- Tissue types relevant to MST:
  - Cortical bone: $\rho \approx 1.92$ g/cm³, $X_0 \approx 11.9$ cm
  - Trabecular bone: $\rho \approx 1.18$ g/cm³
  - Muscle: $\rho \approx 1.05$ g/cm³
  - Adipose tissue: $\rho \approx 0.95$ g/cm³
  - Cartilage: $\rho \approx 1.10$ g/cm³
- Pediatric phantom used: 10-year-old reference individual
- Spine ROI extracted from full phantom for focused simulation

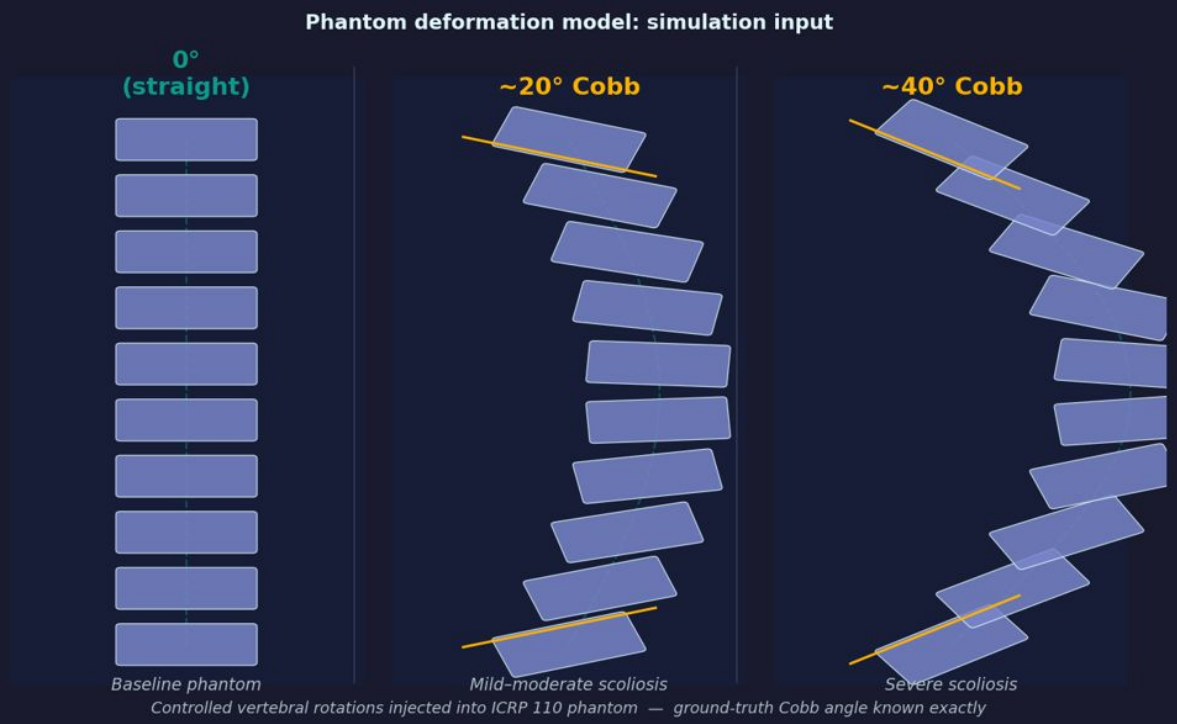
Using reference phantoms ensures reproducibility and comparability with radiological dose studies.



https://geant4.web.cern.ch/docs/advanced_examples_doc/example_ICRP110Phantom

Modelling scoliosis deformations

- Straight phantom = baseline (Cobb = 0°)
- Controlled lateral curvature introduced per-vertebra:
  - Rigid-body rotation of vertebral segments
  - Curvature parameterised by apex deviation and Cobb angle
  - Range: 0° → 50° Cobb in controlled steps
- Soft tissue deformation: simplified elastic displacement
- Key question: does MST correctly estimate the injected Cobb
- Secondary question: minimum detectable curvature change
- This defines reconstruction accuracy, not just image quality



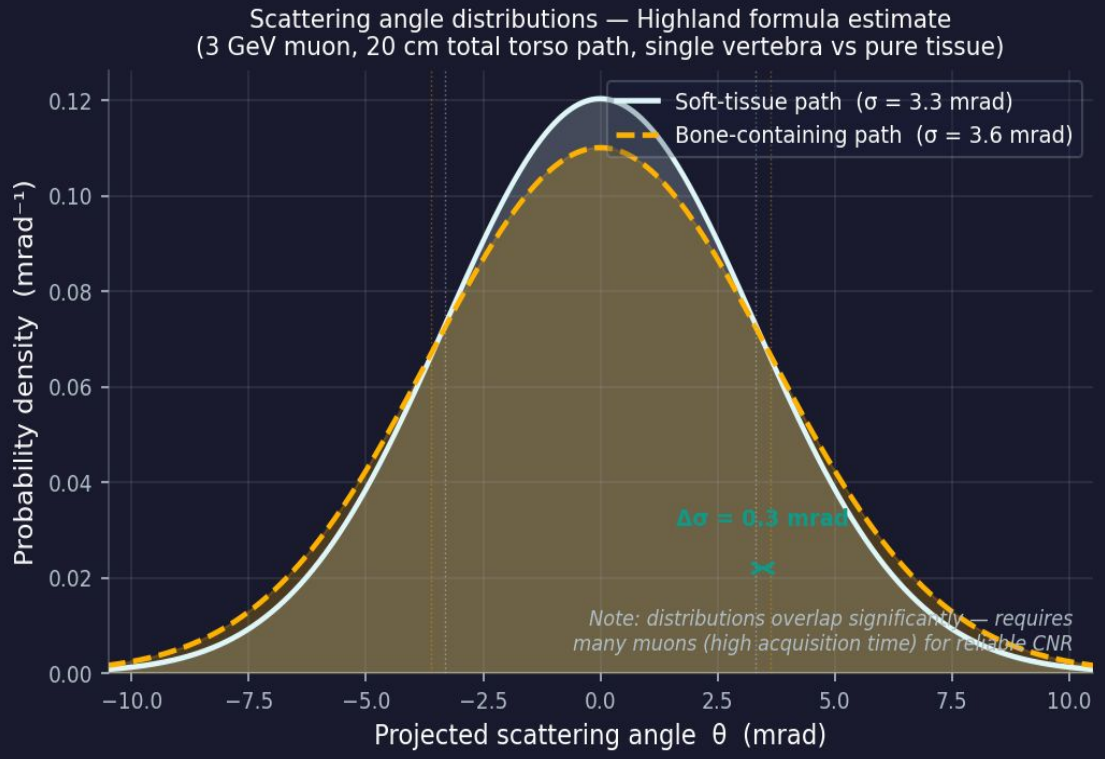
The simulation acts as a ground-truth oracle: we know the true Cobb angle, so we can directly evaluate reconstruction error.

Expected contrast: bone vs soft tissue

Before full reconstruction, we can estimate the scattering signal analytically:

$$\theta_0 = (13.6\ \text{MeV} / \beta cp) \cdot z \cdot \sqrt{(L/X_0)} \cdot [1 + 0.038 \ln(Lz^2/X_0)]$$

- For a 4 GeV muon traversing 10 cm of material:
  - Cortical bone ($X_0 \approx 11.9$ cm): $\theta_0 \approx 3.6$ mrad
  - Soft tissue ($X_0 \approx 35.8$ cm): $\theta_0 \approx 2.1$ mrad
  - Ratio ≈ 1.7 — detectable with sufficient statistics
- Contrast improves for lower-energy muons (more scattering)
- Low-energy muons also more likely to stop — tradeoff
- Detector angular resolution must be $\ll$ 1 mrad to resolve



Physical limits of MST in biological media

Three fundamental limits constrain MST in soft biological tissue:

1. Low density contrast — ρ ratio ~2:1 vs 10:1 in security applications
   X-ray and nuclear scanning benefit from larger Z differences; MST scattering contrast is inherently smaller.

2. Low flux — natural muons are sparse; statistical noise dominates at short acquisition times
   Unlike X-ray tubes, flux cannot be increased on demand. Longer acquisitions mean patient motion.

3. PoCA localisation uncertainty — scattering is distributed along the track, not at a point
   Spatial reconstruction inherently blurred; fine anatomy unresolvable. Cobb angle estimation may tolerate this.

Summary & outlook

The case

Pediatric scoliosis monitoring involves years of repeated ionizing imaging. The EOS precedent shows clinical appetite for dose-reduction innovation. We propose muon scattering tomography as a zero-dose follow-up modality.

The approach

Geant4 simulations with ICRP 110 pediatric phantoms. Controlled scoliosis deformations over 0–50° Cobb range. Quantifying CNR, spatial resolution, and Cobb angle RMSE as functions of acquisition time and detector resolution.

The finding so far

The physics argument is favourable: bone/soft-tissue density contrast is the highest in the body. The Cobb angle metric tolerates lower spatial resolution than anatomical imaging. Acquisition time is the key feasibility barrier — simulations are quantifying the exact trade-off.

Next steps:

Complete simulation sweep · Quantify Cobb RMSE vs time · Engage clinical collaborators for benchmarks · Explore enhanced detector geometry

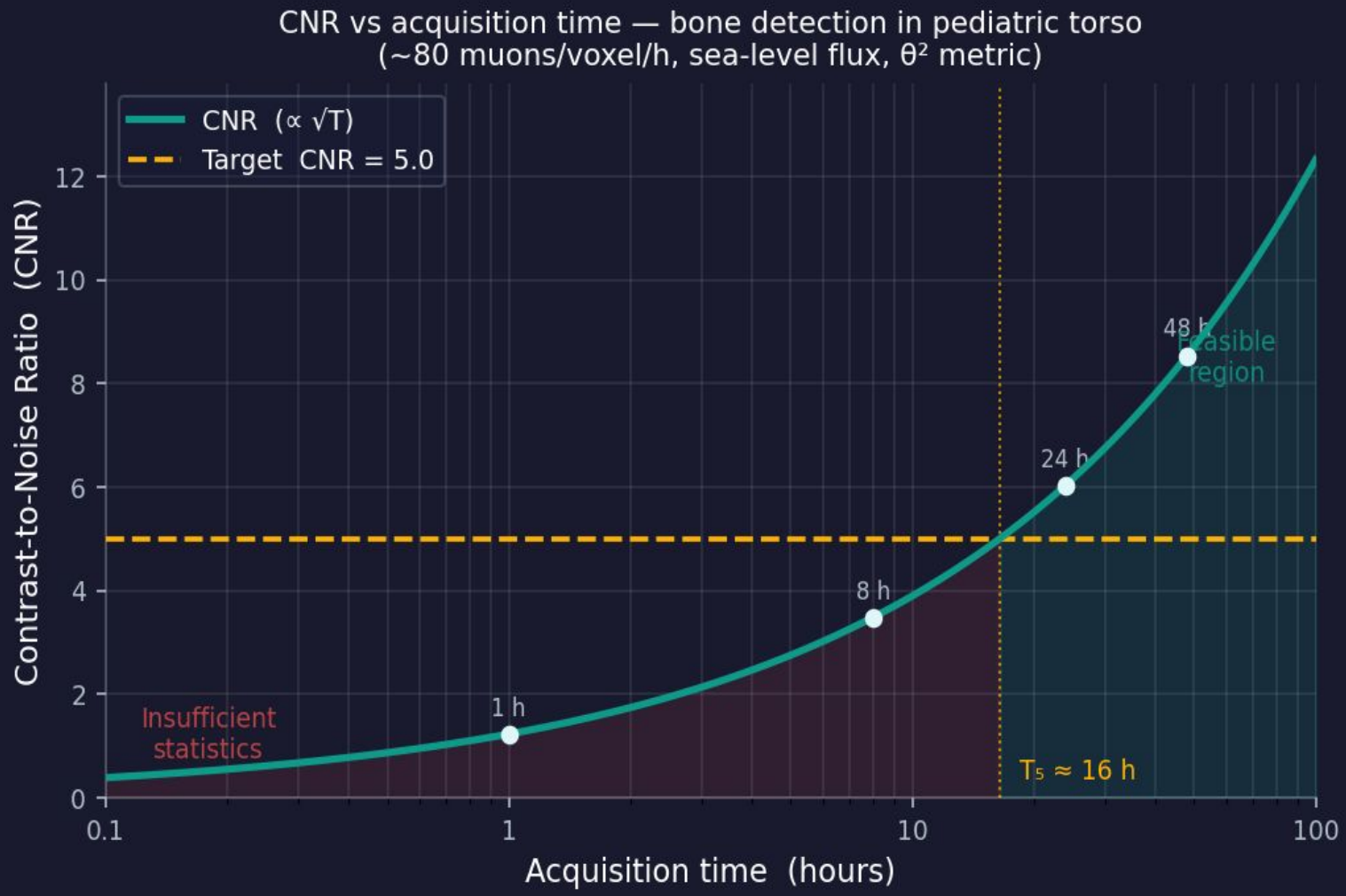
Thank you

Noemi Zabari · Konstantin Borozdin

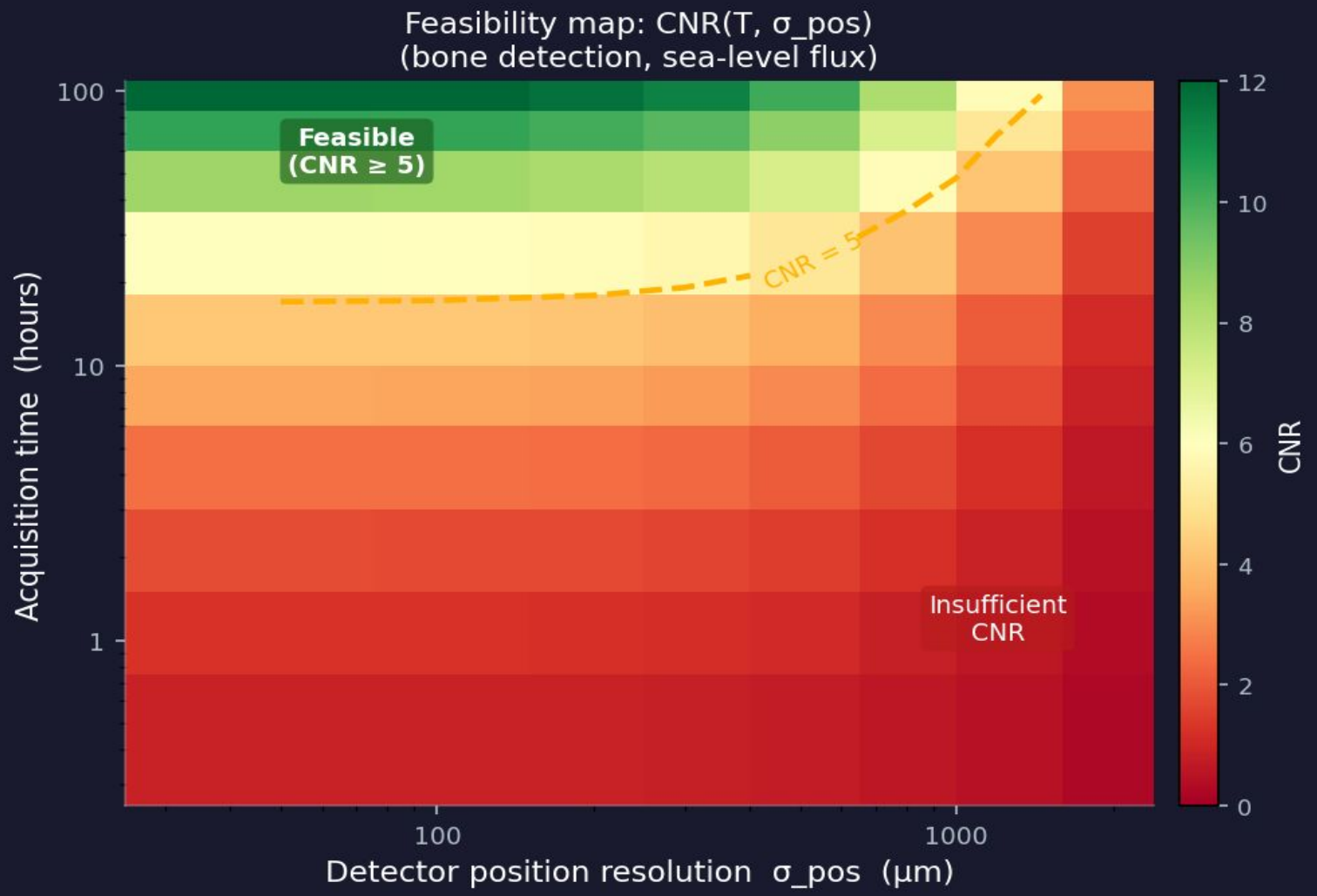
Questions?

Acquisition time: the central trade-off

- Natural muon flux: ~170 muons m^{-2} s^{-1} sr^{-1} (sea level, vertical)
- For 0.5 m^2 detector area, 2π sr acceptance: ~104 muons/min
- Useful muons (traversing spine): a fraction of total flux
- CNR scales as $\sqrt{N} \rightarrow$ CNR $\propto \sqrt{T}$ (acquisition time)
- Target CNR ≥ 5 for reliable bone detection
- → acquisition time becomes the key feasibility parameter



Parameter space for clinical feasibility



› Amber dashed line: CNR = 5 threshold

› Green region: feasible — achievable with realistic detectors + overnight acquisition

› Red region: insufficient statistics — either too short T or too poor resolution

› Key result: ~100 µm resolution detector + ~12 h acquisition reaches target CNR

› Simulation will validate with full Geant4 reconstruction

The EOS precedent: what drives innovation in spinal imaging

EOS System

› Biplanar slot-scan X-ray (2007 → clinical adoption)

› 10× dose reduction vs conventional radiograph

› Full-body weight-bearing 3D reconstruction

› Now standard of care in scoliosis centres globally

› Driven by clinical community demanding dose reduction

What comes next?

› EOS reached ~10–20× dose reduction — further gains are marginal

› Residual dose still exists; cumulative burden remains

› Motion artefacts in long acquisitions

› The next step is qualitatively different: zero ionising dose

› Requires a fundamentally different physics

The clinical community that drove EOS adoption is the natural partner to define benchmarks for the next generation of imaging — and to judge whether zero-dose MST can meet them.

Open questions and needed benchmarks

Physics questions

- What acquisition time achieves CNR ≥ 5 for cortical bone?
- What is Cobb angle RMSE as a function of T?
- How does patient size affect flux and contrast?
- Can optimised detector geometry improve sensitivity?
- Is a multi-view configuration advantageous?
- Role of muon energy selection / range cuts?

Clinical benchmarks needed

- Accepted Cobb angle measurement uncertainty in practice
- Minimum clinically meaningful progression (decision threshold)
- Acceptable examination duration (patient compliance)
- Positional reproducibility requirements
- Comparison modality: EOS follow-up protocols
- Population variability in juvenile spine geometry

Clinical input is essential to define whether the achievable MST performance is clinically useful — or whether the physics limits fall short of the requirement.

Future observables and evaluation metrics

Scattering angle distribution

Per-muon scattering angle θ
Compared bone vs soft-tissue voxels
Sensitivity to density contrast

Contrast-to-Noise Ratio (CNR)

CNR = (S_bone − S_tissue) / σ_tissue
Primary figure of merit
Function of acquisition time T

Spatial resolution

FWHM of reconstructed bone edge
Detector position resolution σ_pos
PoCA localisation uncertainty

Cobb angle estimation error

Vertebral centroid positions from reconstruction
Fitted spinal axis ⟶ Cobb angle
Residual vs ground truth