Novel PET with Opaque Liquid Scintillator Detection Technology

Adrien Hourlier,
on behalf of
the LPET consortium
2022/06/14

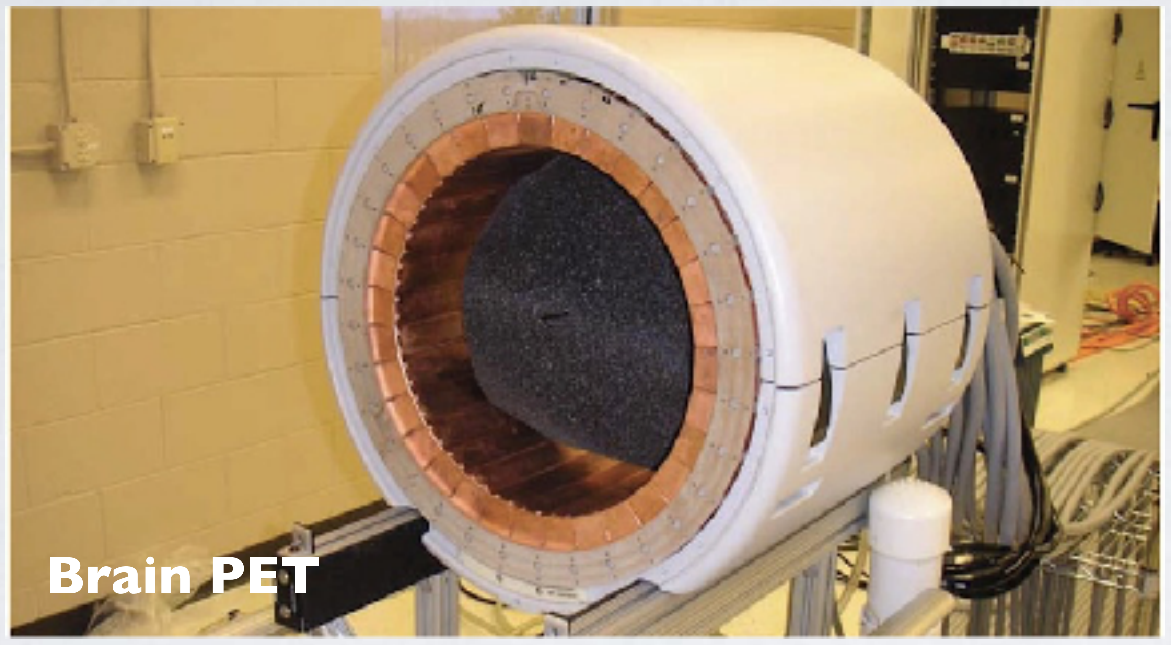
Institut Pluridisciplinaire Hubert CURIEN STRASBOURG
Université de Strasbourg

adrien.hourlier@iphc.cnrs.fr

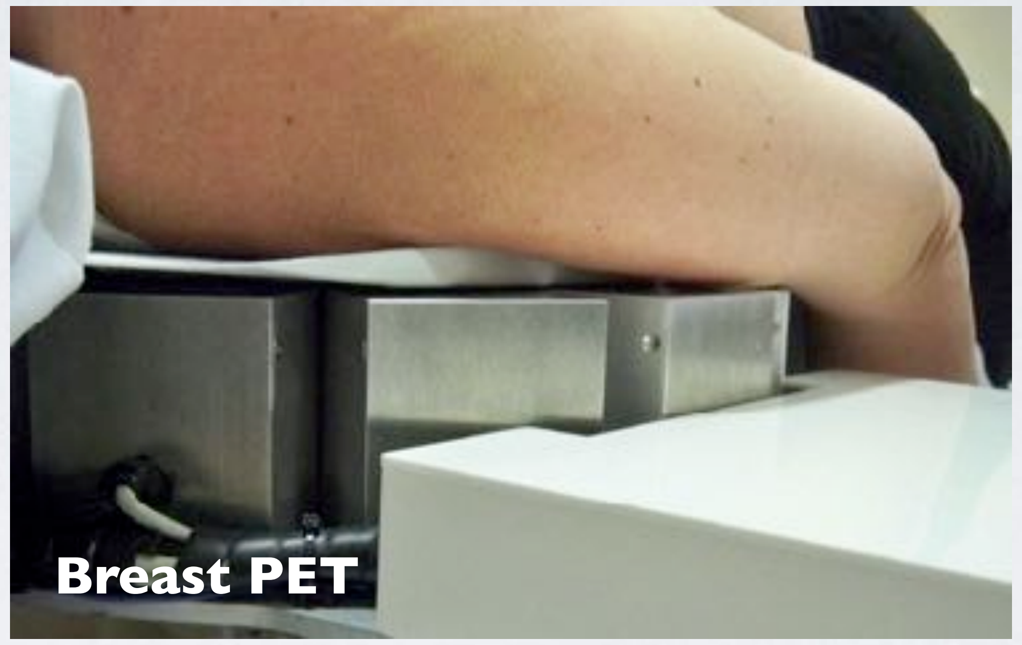
Full body / Organ dedicated PETs

CareMiBrain (Oncovision)

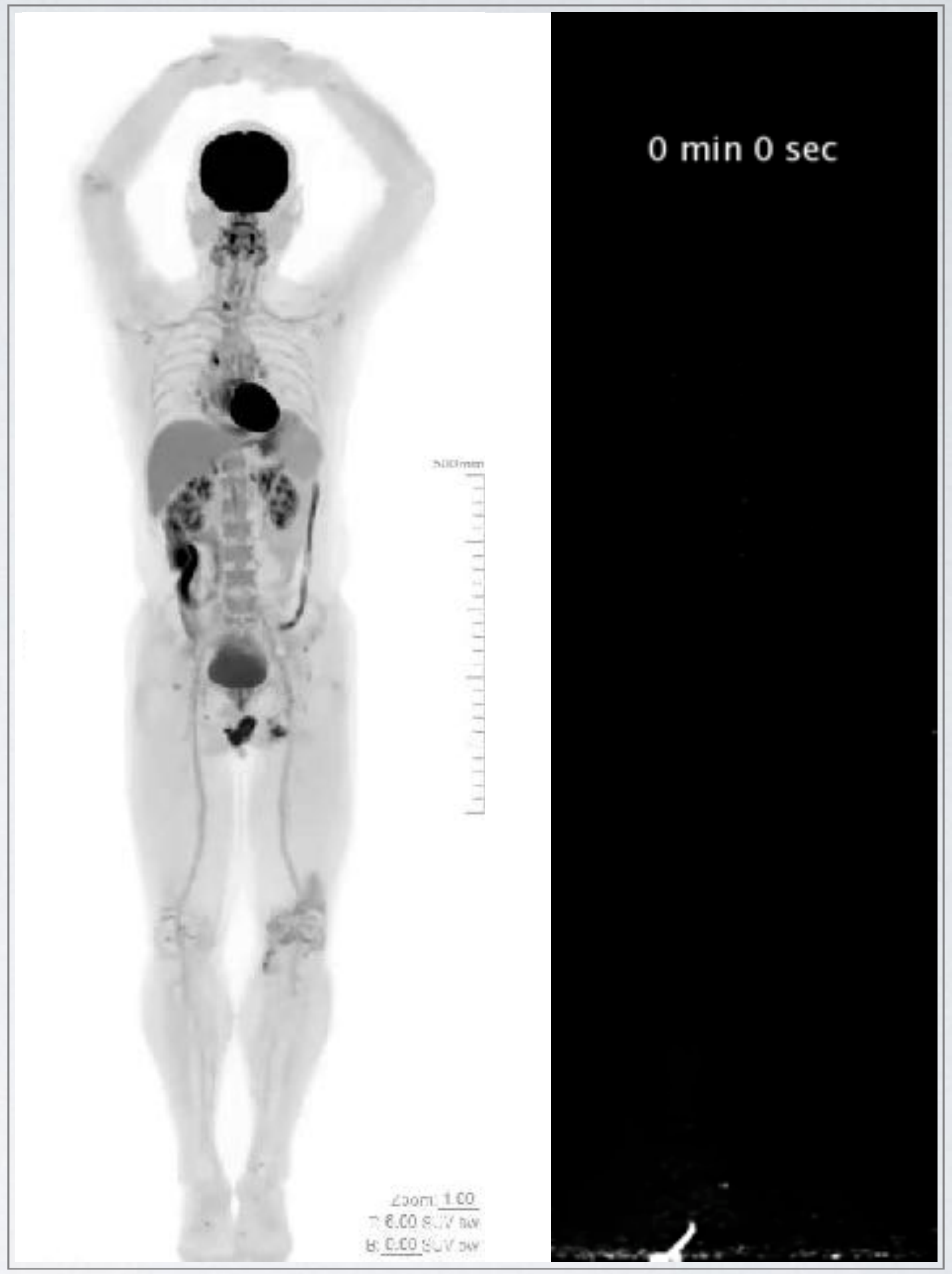
L. Caldeira, et al., "Reconstruction of PET Data Acquired with the BrainPET using STIR," IEEE NSS/MIC, 2012.



F.C. David, et al., IEEE Trans. Med. Imag., DOI 10.1109/TMI.2018.2799619, 2018.



R.D. Badawi et al., Jour. of Nucl. Med. 2019, 60 (3) 299-303



Explorer
1 bed, 20 min

Explorer
1 sec/frame

Organ Dedicated PET :

- Brain, prostate, breast, heart…
- Closer to region of interest : increased detection efficiency
- Dedicated segmentation / improved spatial resolution
- Improved contrast by reduction of noise from other organs

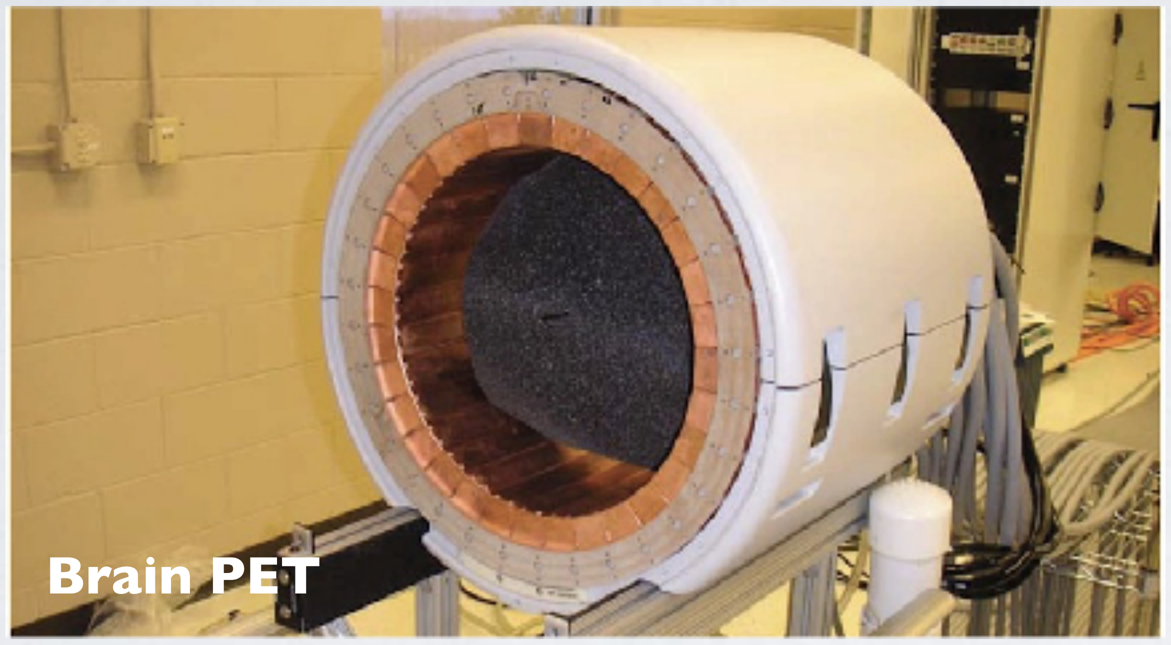
Full body PET : Explorer (uExplorer, PennPET Explorer)

- Increased detection efficiency by increased collection solid angle
- Same total acquisition time : better image quality
- Diagnostic-worthy images in 1 min!
- Dynamical studies of full-body biodistribution at the second level

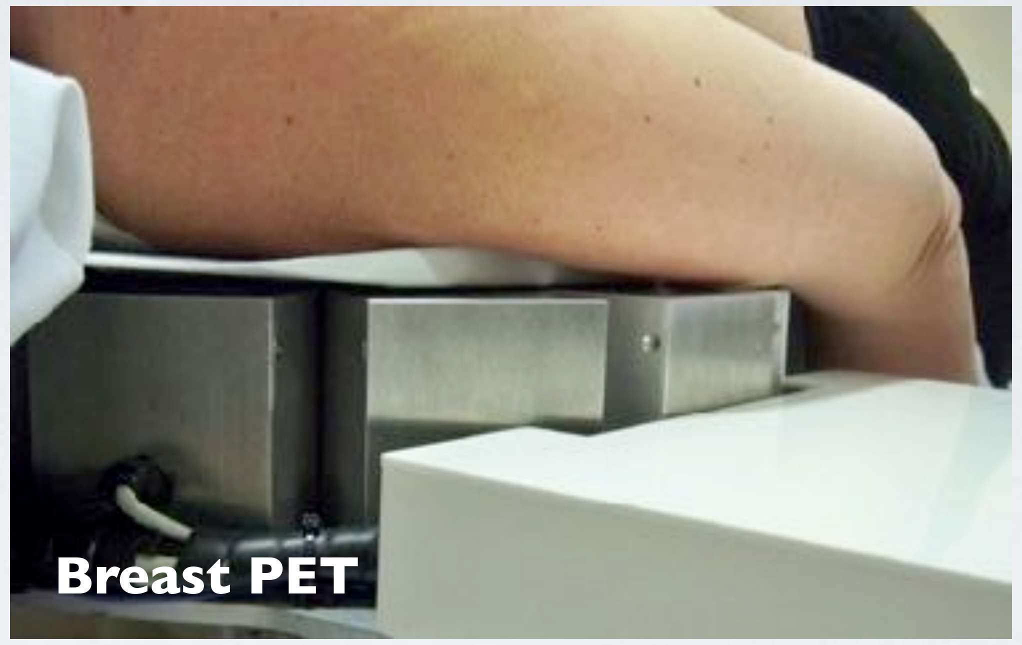
Full body / Organ dedicated PETs

CareMiBrain (Oncovision)

L. Caldeira, et al., "Reconstruction of PET Data Acquired with the BrainPET using STIR," IEEE NSS/MIC, 2012.



F.C. David, et al., IEEE Trans. Med. Imag., DOI 10.1109/TMI.2018.2799619, 2018.



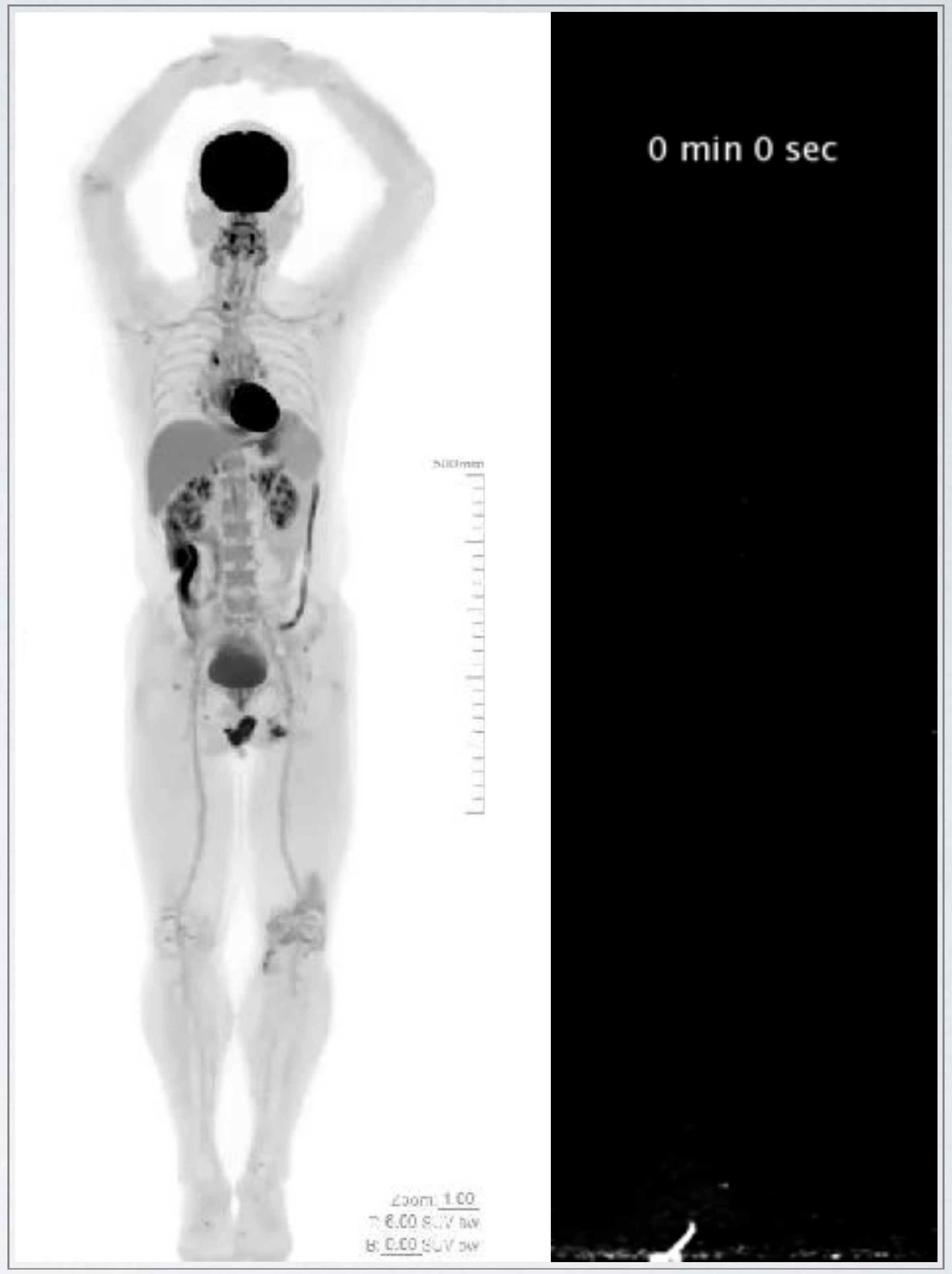
Organ Dedicated PET :

- Brain, prostate, breast, heart…
- Closer to region of interest : increased detection efficiency
- Dedicated segmentation / improved spatial resolution
- Improved contrast by reduction of noise from other organs

Full body PET : Explorer (uExplorer, PennPET Explorer)

- Increased detection efficiency by increased collection solid angle
- Same total acquisition time : better image quality
- Diagnostic-worthy images in 1 min!
- Dynamical studies of full-body biodistribution at the second level

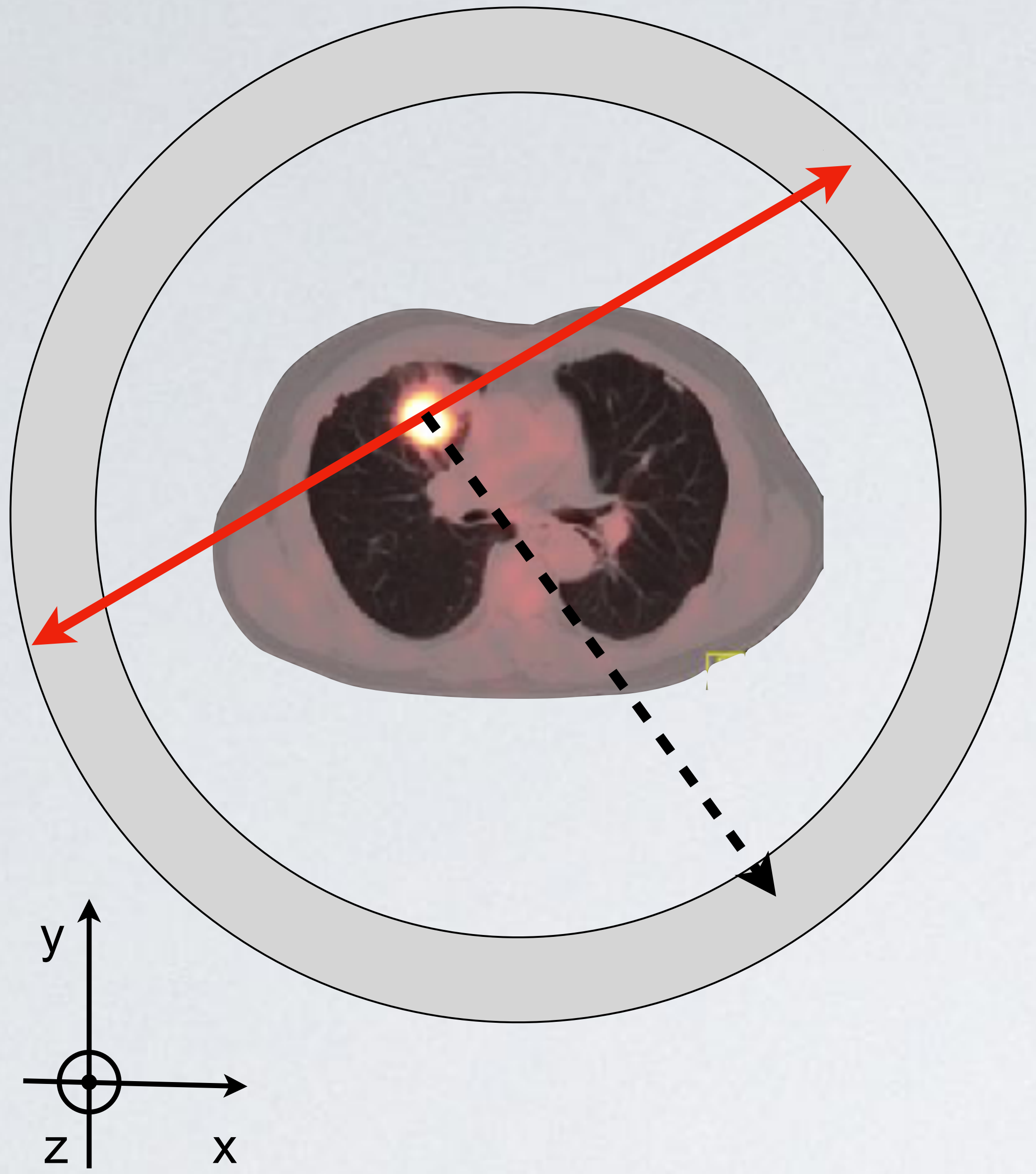
R.D. Badawi et al., Jour. of Nucl. Med. 2019, 60 (3) 299-303



Explorer
1 bed, 20 min

Explorer
1 sec/frame

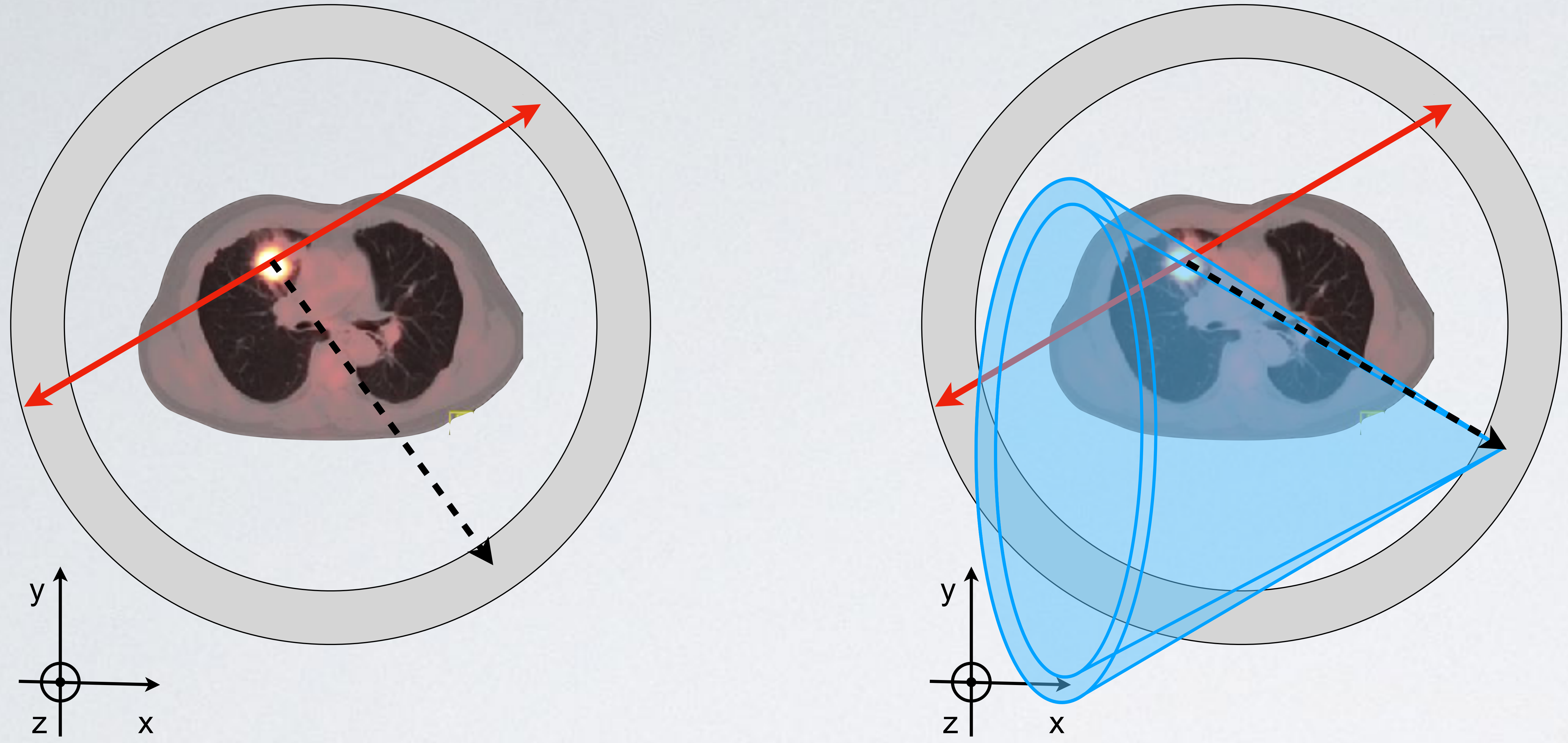
3γ imaging



- Change isotopes $\beta^+ \Rightarrow (\beta^+, \gamma)$
- $^{44}\mathrm{Sc} \rightarrow {}^{44}\,\mathrm{Ca}^*\ e^+\ \nu_e$

  $\hookrightarrow {}^{44}\mathrm{Ca}\ +\ \gamma(1.157 MeV)$

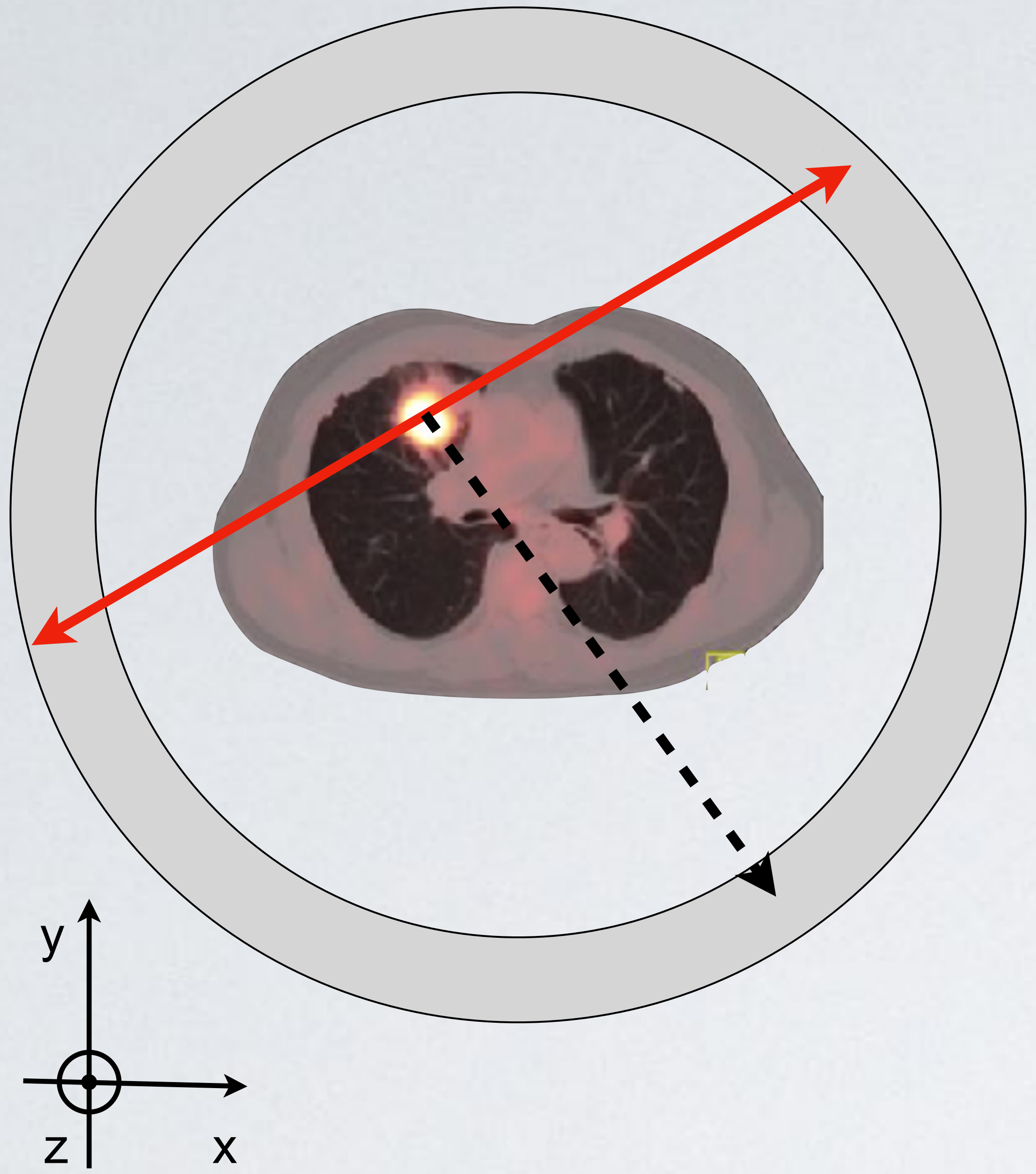
3γ imaging

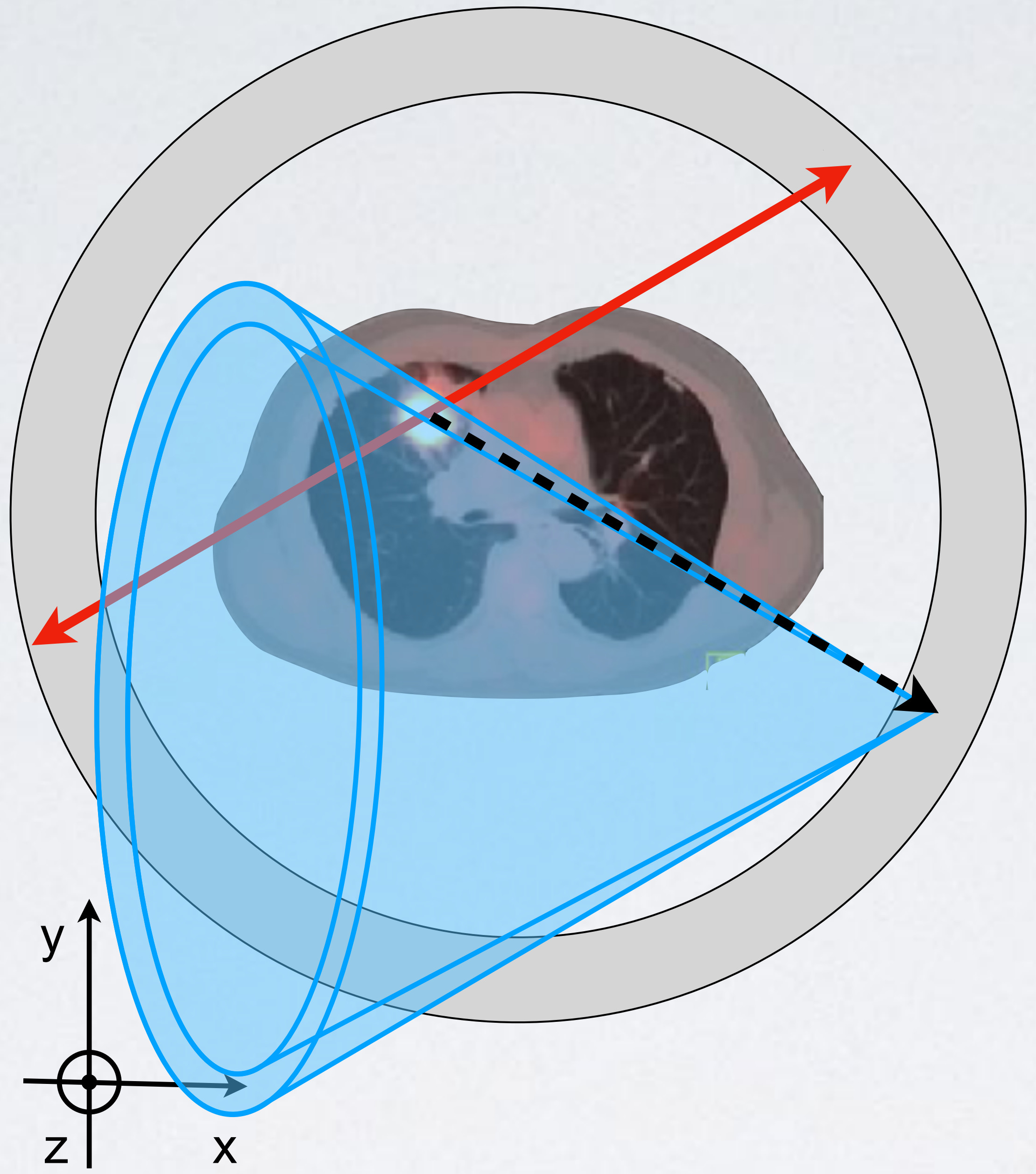


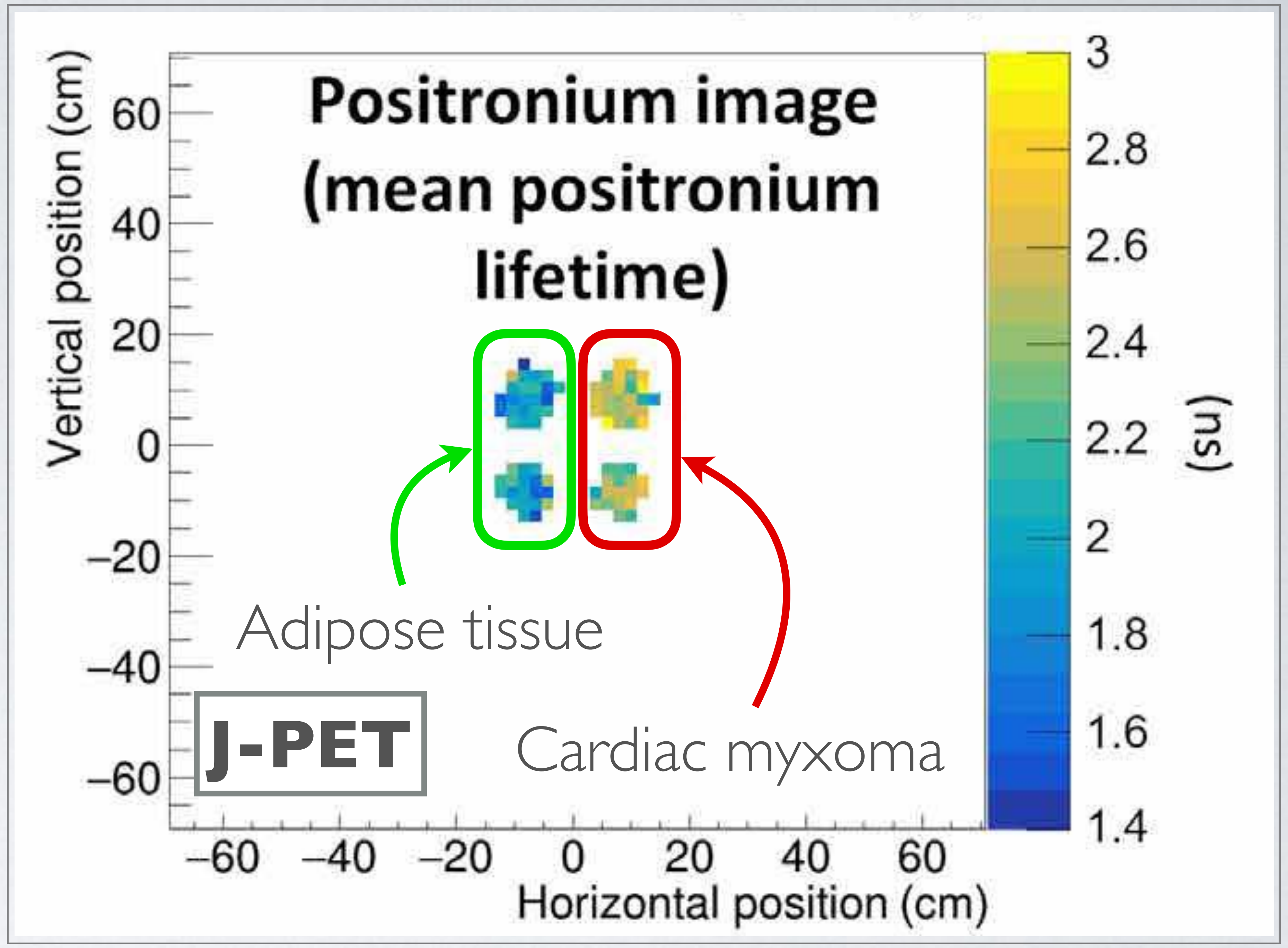
- Change isotopes β+ ⇒ (β+,γ)
- $^{44}\text{Sc} \rightarrow ^{44}\text{Ca}^{*}\ e^{+}\ \nu_e$
  $\hookrightarrow ^{44}\text{Ca} + \gamma(1.157 MeV)$
- **Pseudo-TOF :**
  - Compton detector ⇒ cone of incidence direction of the γ
  - intersection cone-LOR ⇒ localization of decay

D. Giovagnoli et al., 2021, doi: 10.1109/TRPMS.2020.3046409.

3γ imaging







Moskal *et al.*, *Sci. Adv.* 2021; **7** : eabh4394

- Change isotopes $\beta^+ \Rightarrow (\beta^+,\gamma)$
- $^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}^*\ e^+\ \nu_e$

  $\hookrightarrow {}^{44}\mathrm{Ca} + \gamma(1.157 MeV)$
- **Pseudo-TOF :**
  - Compton detector ⇒ cone of incidence direction of the γ
  - intersection cone-LOR ⇒ localization of decay

  D. Giovagnoli et al., 2021, doi: 10.1109/TRPMS.2020.3046409.

- **Ortho-Positronium lifetime :**
  - $(e^+ - e^-)$ metastable state
  - delay between the prompt 1.16 MeV γ and the two 511 keV photons
  - impact of the biological tissue the decay occurs in

LiquidO Technology

- Objective : move away from the segmented LYSO:Ce crystals

- **Identify each γ interaction point**
  - Fine segmentation of light detector
  - Slow down light propagation so that 2 interactions stay resolved longer

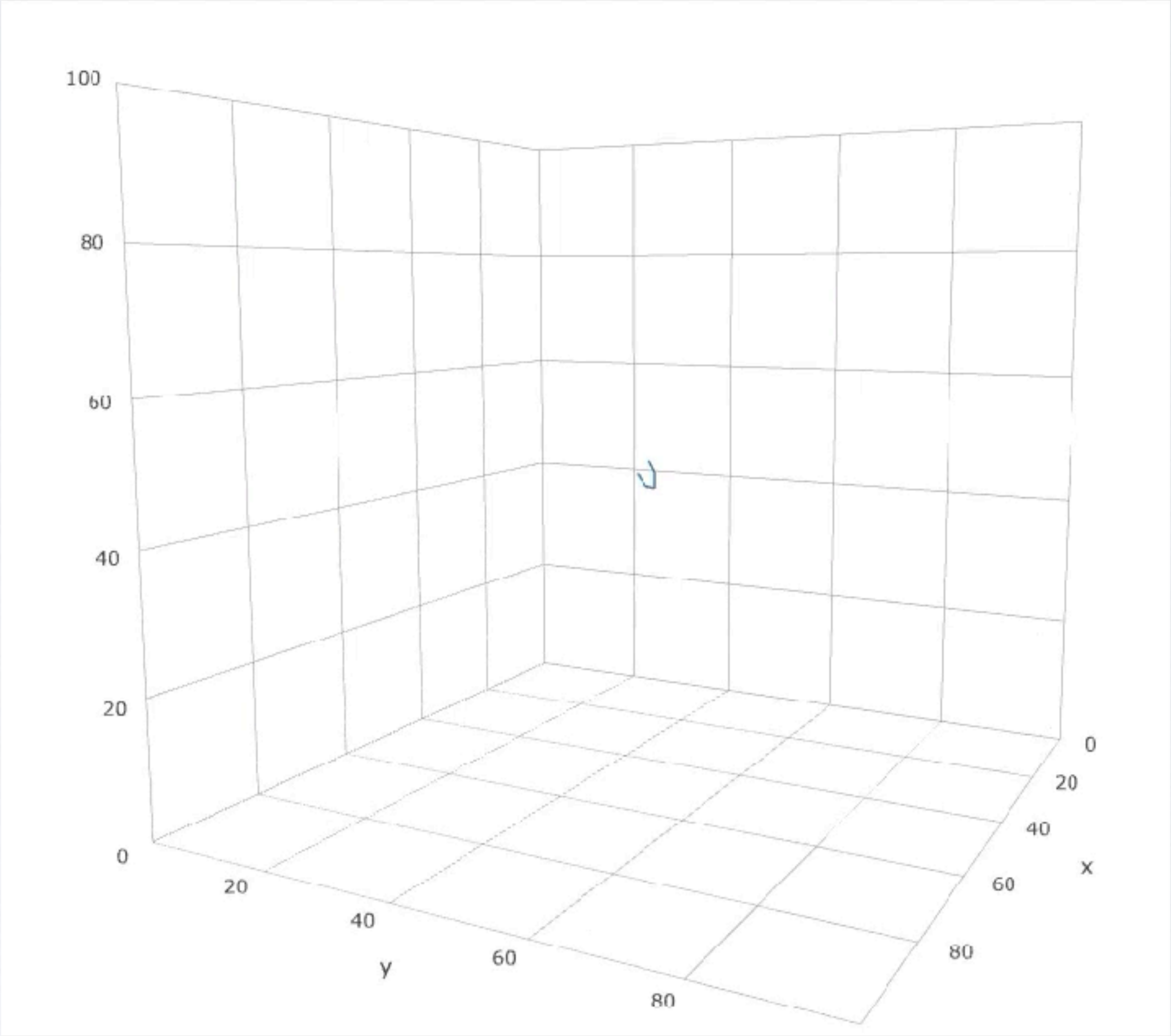
- **LiquidO :**
  - **New** : first proposed in 2019 (A. Cabrera, CERN seminar)
  - Opaque organic scintillator
  - Stochastic light trapping through Mie scattering
  - Self-segmentation without losses due to mechanical segmentation

LiquidO Technology

- Objective : move away from the segmented LYSO:Ce crystals

- **Identify each γ interaction point**
    - Fine segmentation of light detector
    - Slow down light propagation so that 2 interactions stay resolved longer

- **LiquidO :**
    - **New** : first proposed in 2019 (A. Cabrera, CERN seminar)
    - Opaque organic scintillator
    - Stochastic light trapping through Mie scattering
    - Self-segmentation without losses due to mechanical segmentation

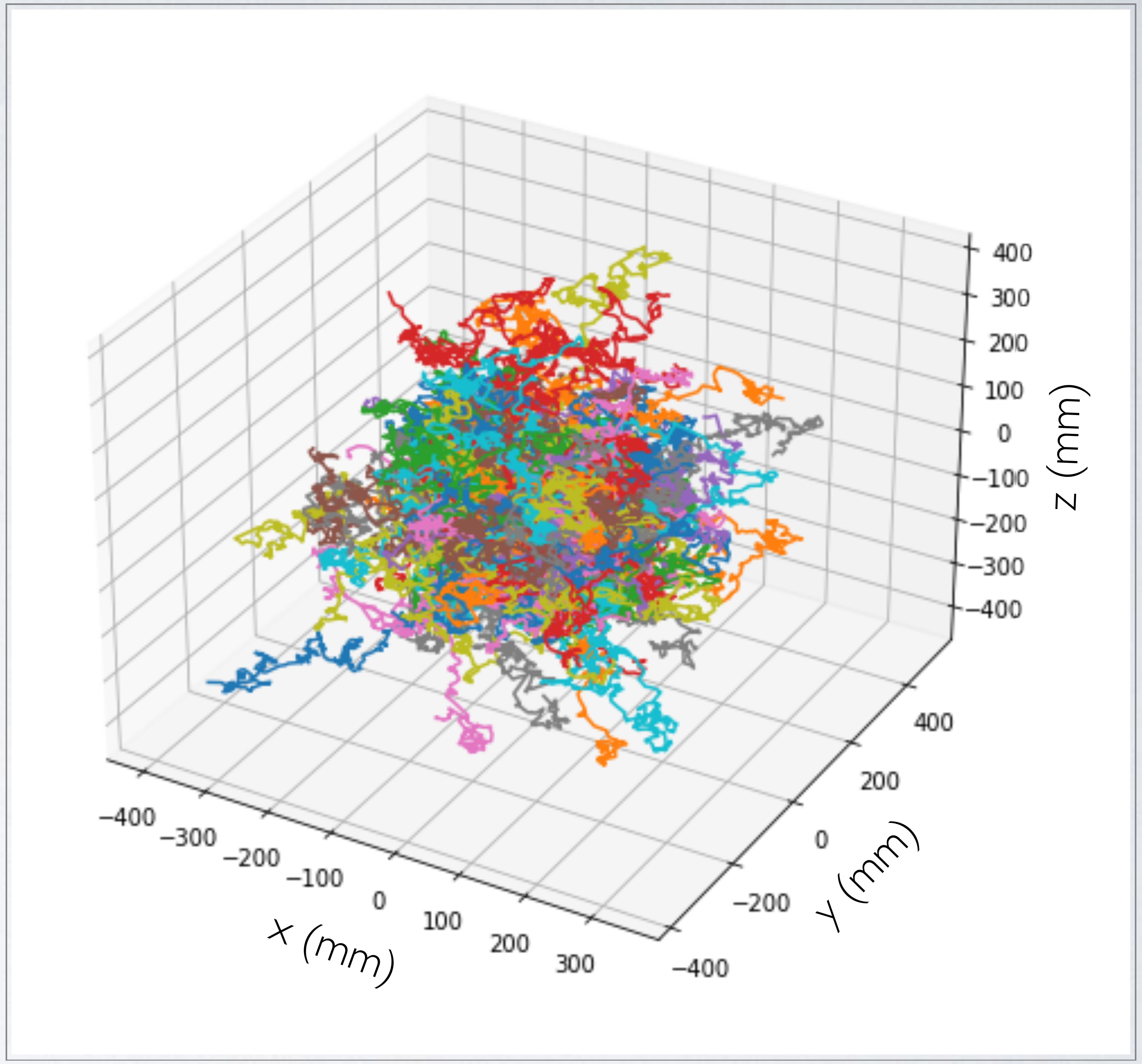


LiquidO Technology

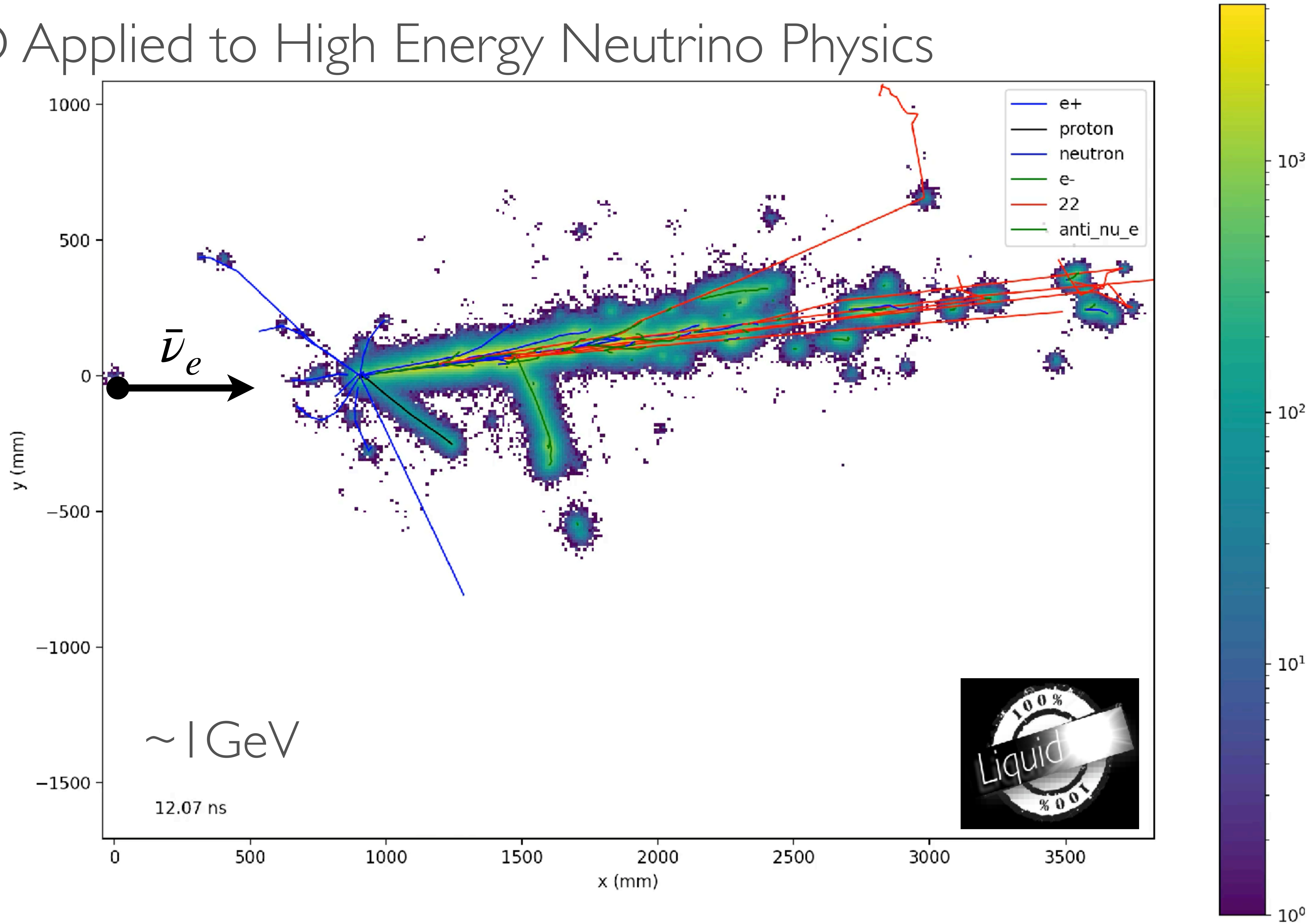
- Objective : move away from the segmented LYSO:Ce crystals

- **Identify each γ interaction point**
  - Fine segmentation of light detector
  - Slow down light propagation so that 2 interactions stay resolved longer

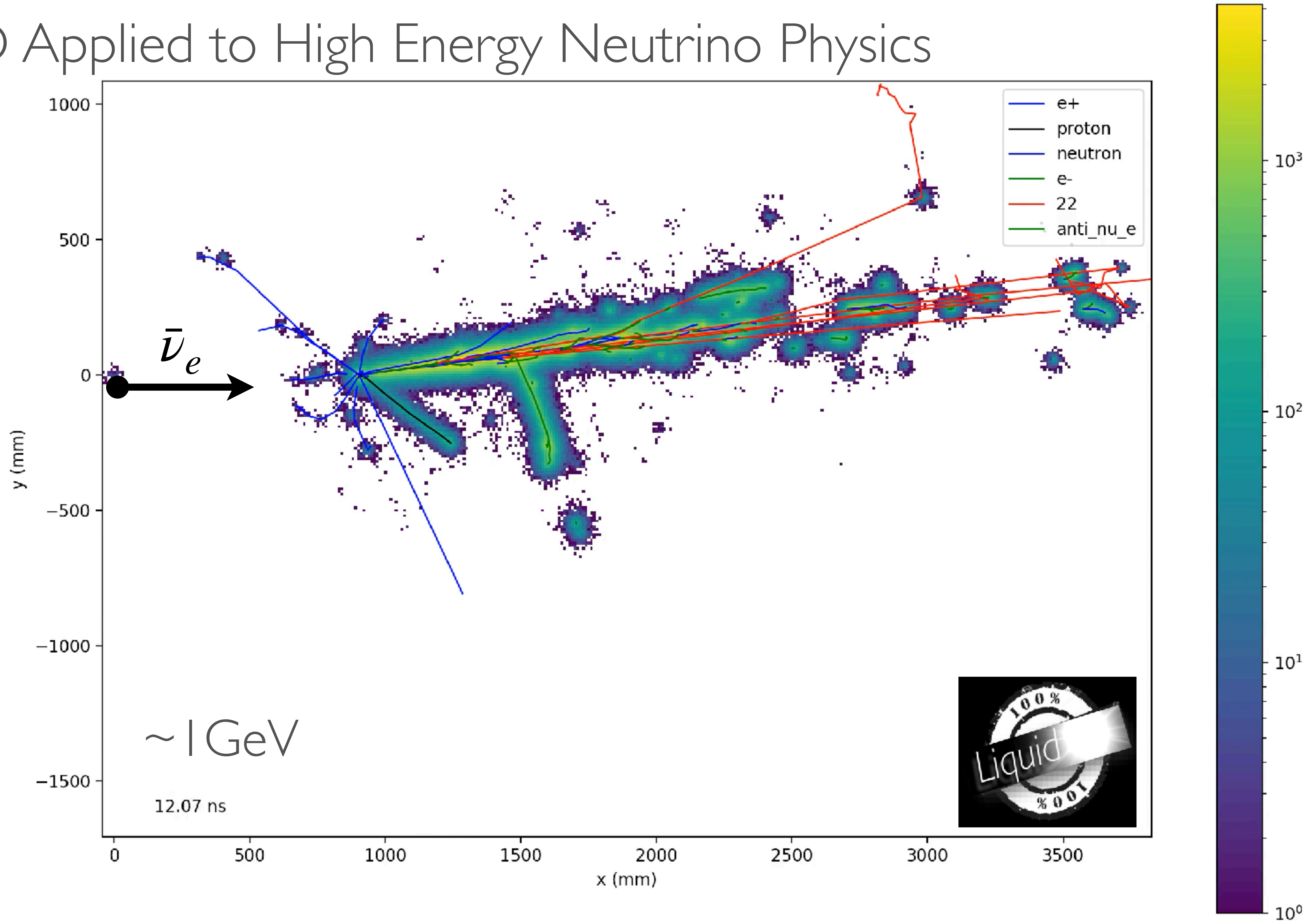
- **LiquidO :**
  - **New** : first proposed in 2019 (A. Cabrera, CERN seminar)
  - Opaque organic scintillator
  - Stochastic light trapping through Mie scattering
  - Self-segmentation without losses due to mechanical segmentation



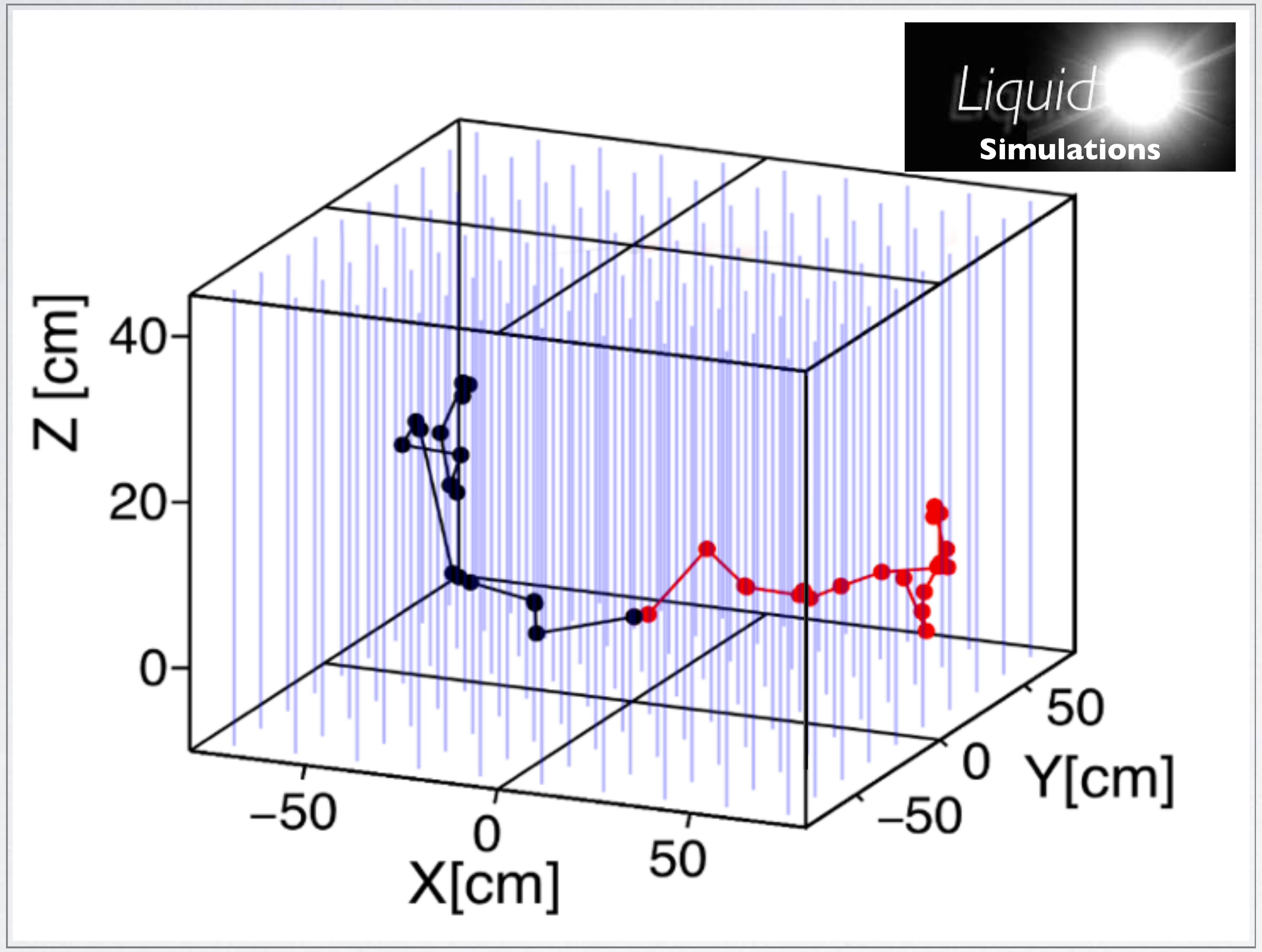
LiquidO Applied to High Energy Neutrino Physics



LiquidO Applied to High Energy Neutrino Physics

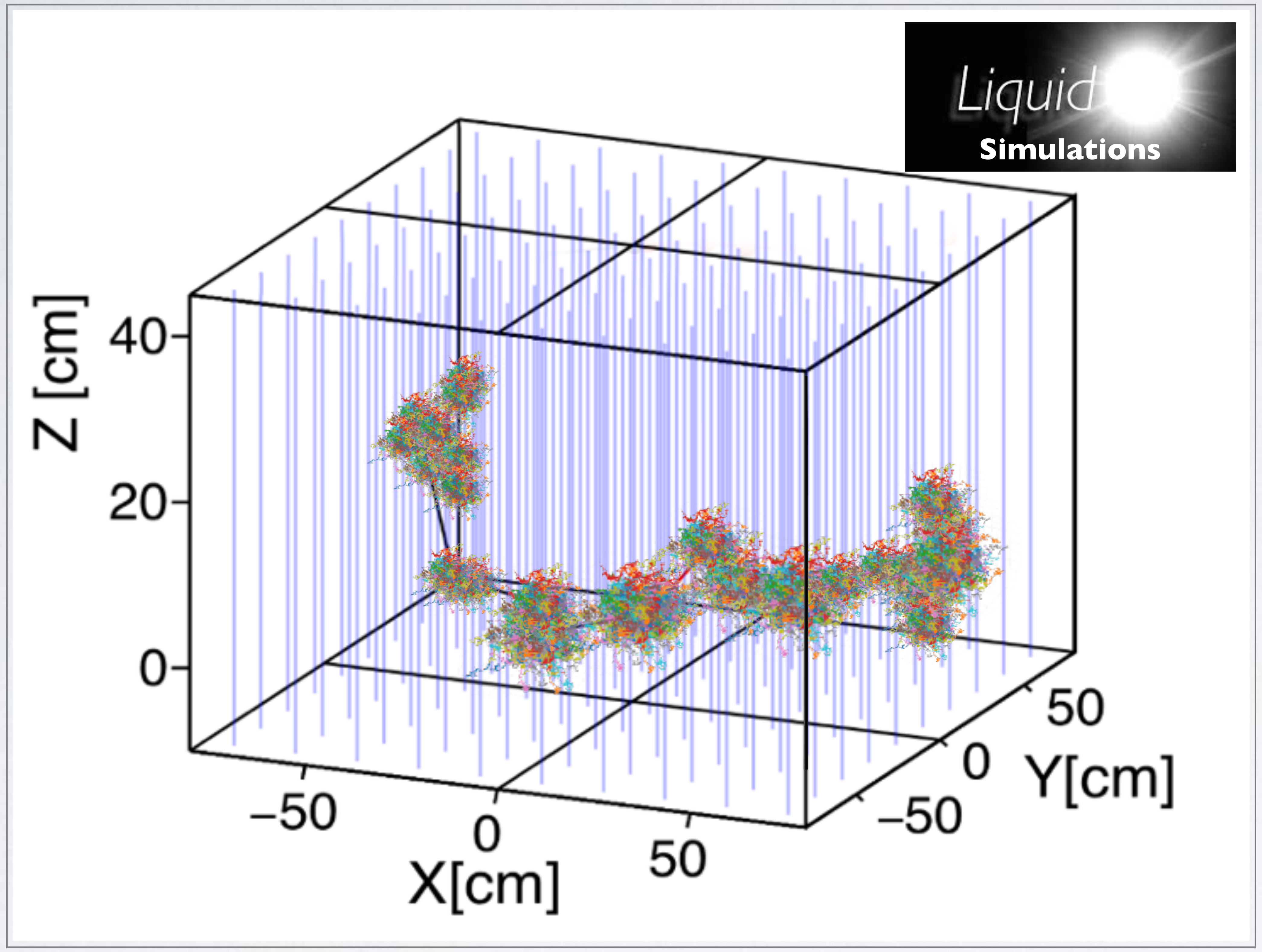


LiquidO Detection Principle



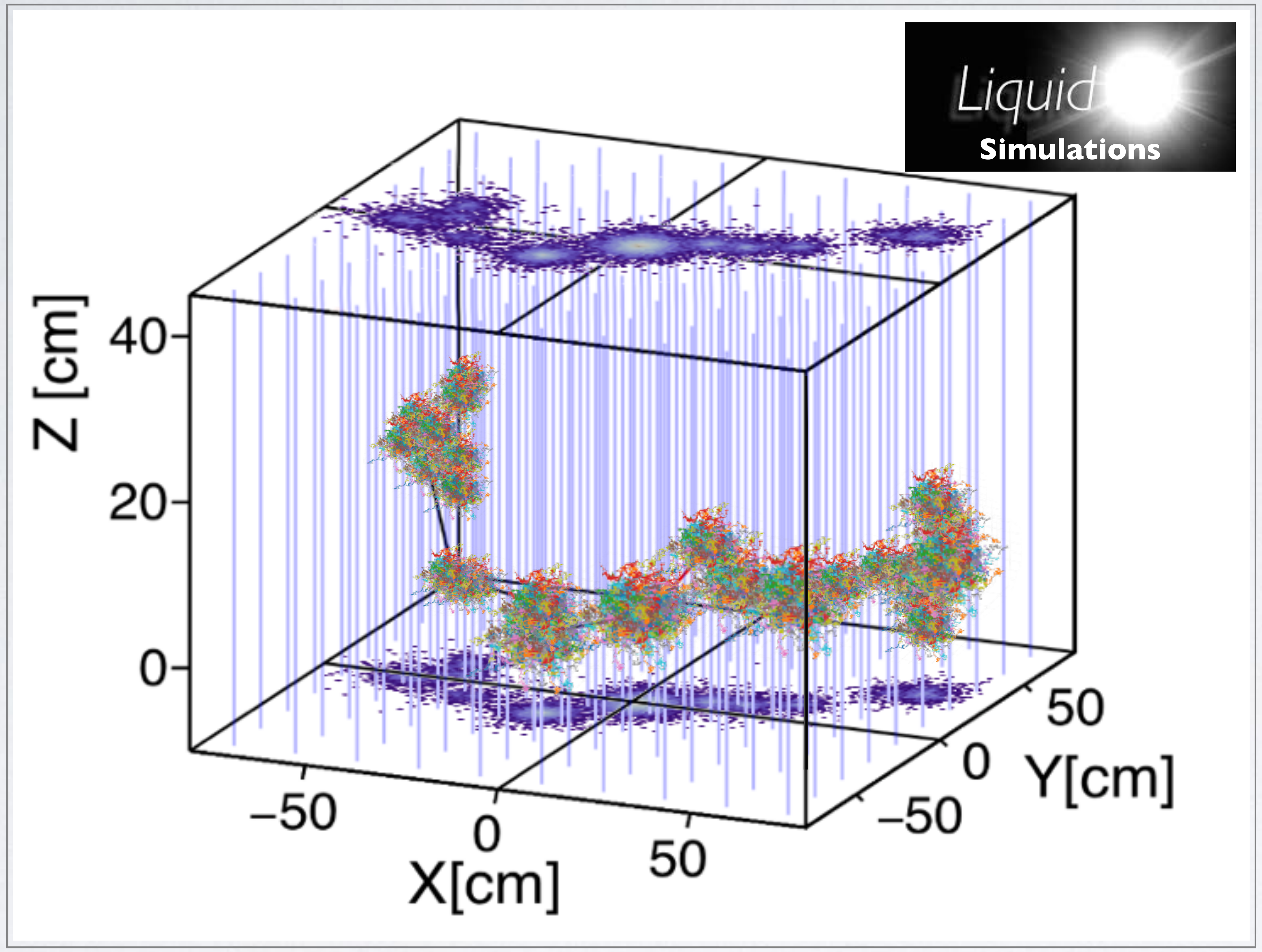
A. Cabrera et al. Communications Physics 4, 273 (2021)

LiquidO Detection Principle



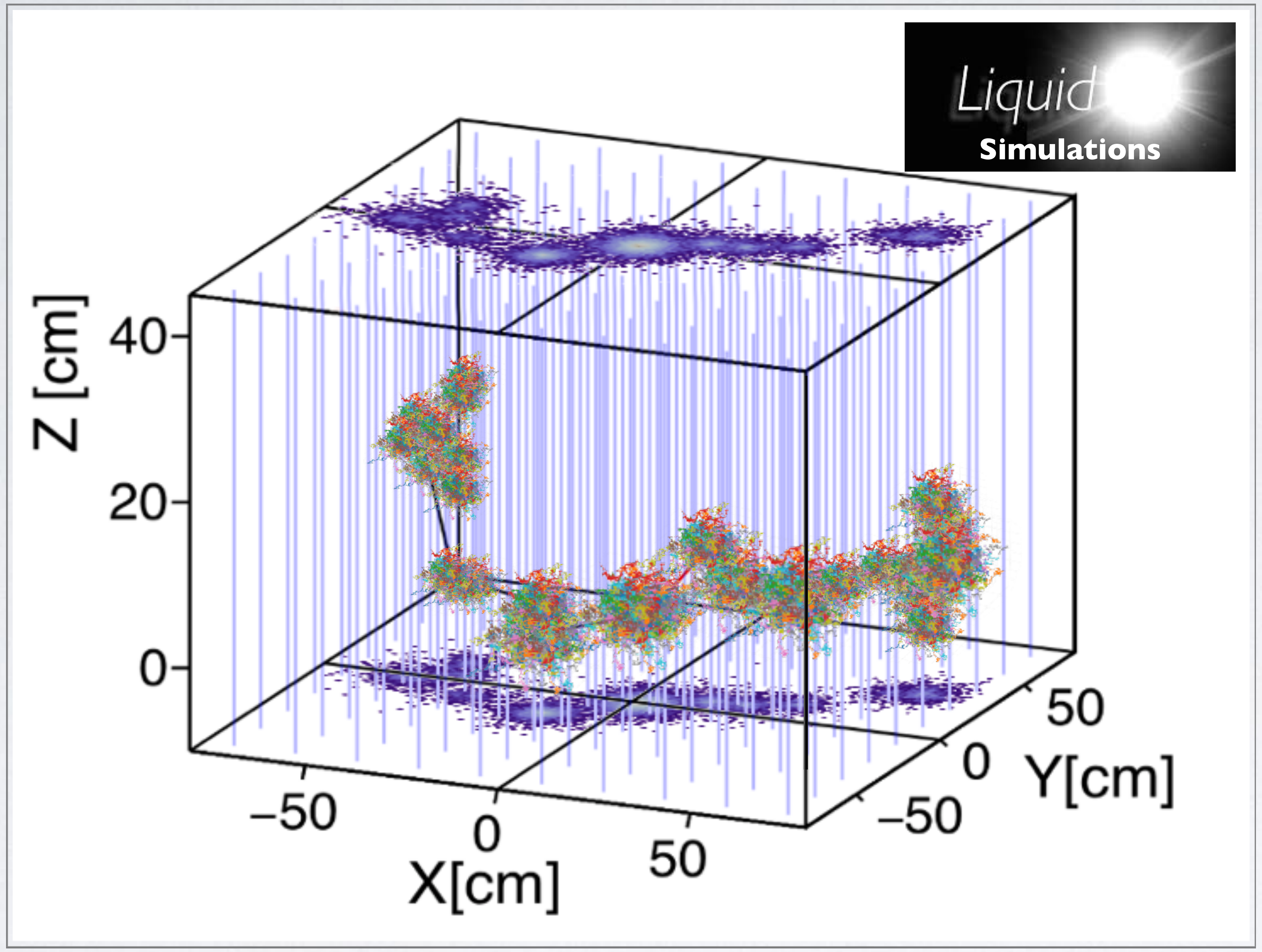
A. Cabrera et al. Communications Physics 4, 273 (2021)

LiquidO Detection Principle

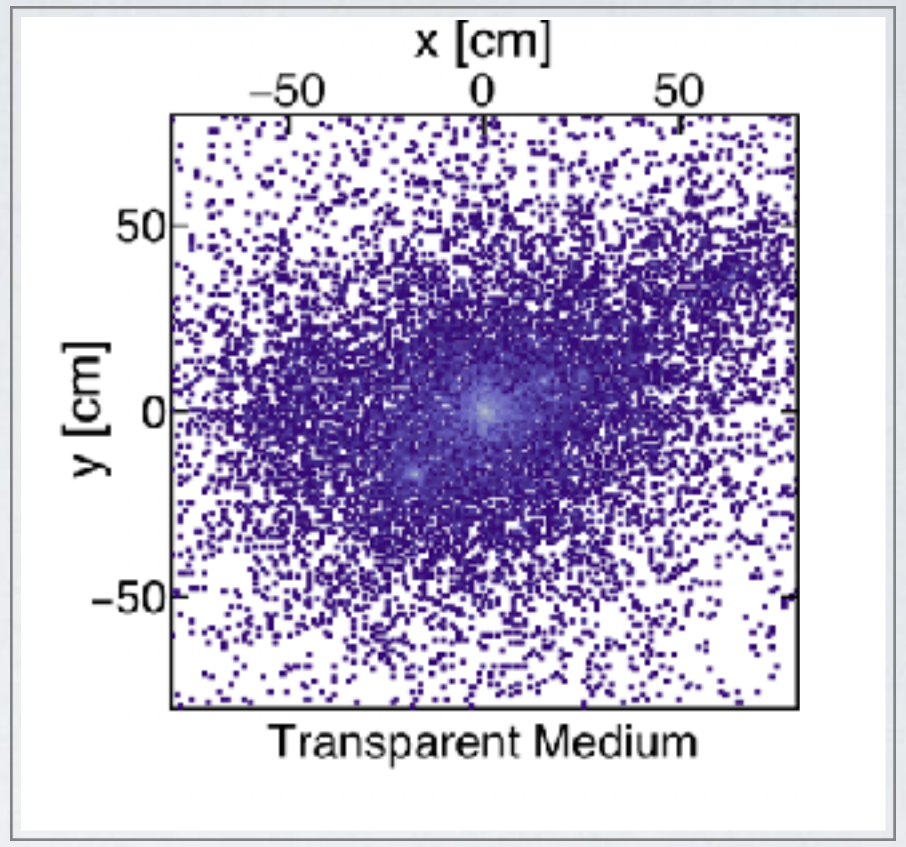


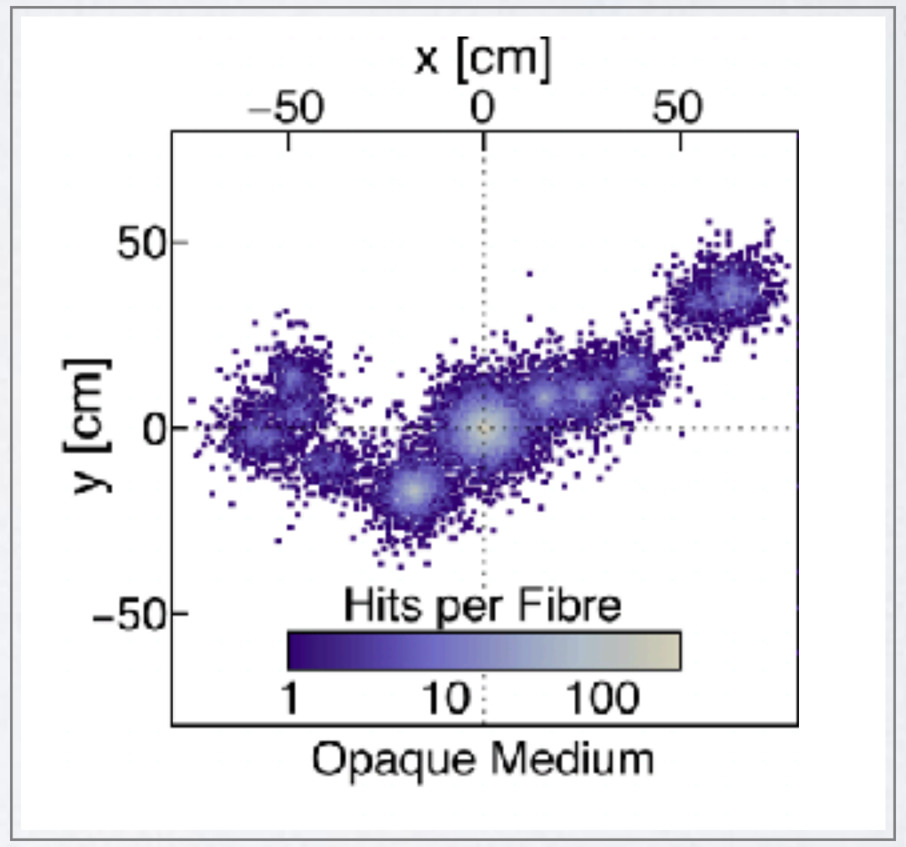
A. Cabrera et al. Communications Physics 4, 273 (2021)

LiquidO Detection Principle



A. Cabrera et al. Communications Physics 4, 273 (2021)

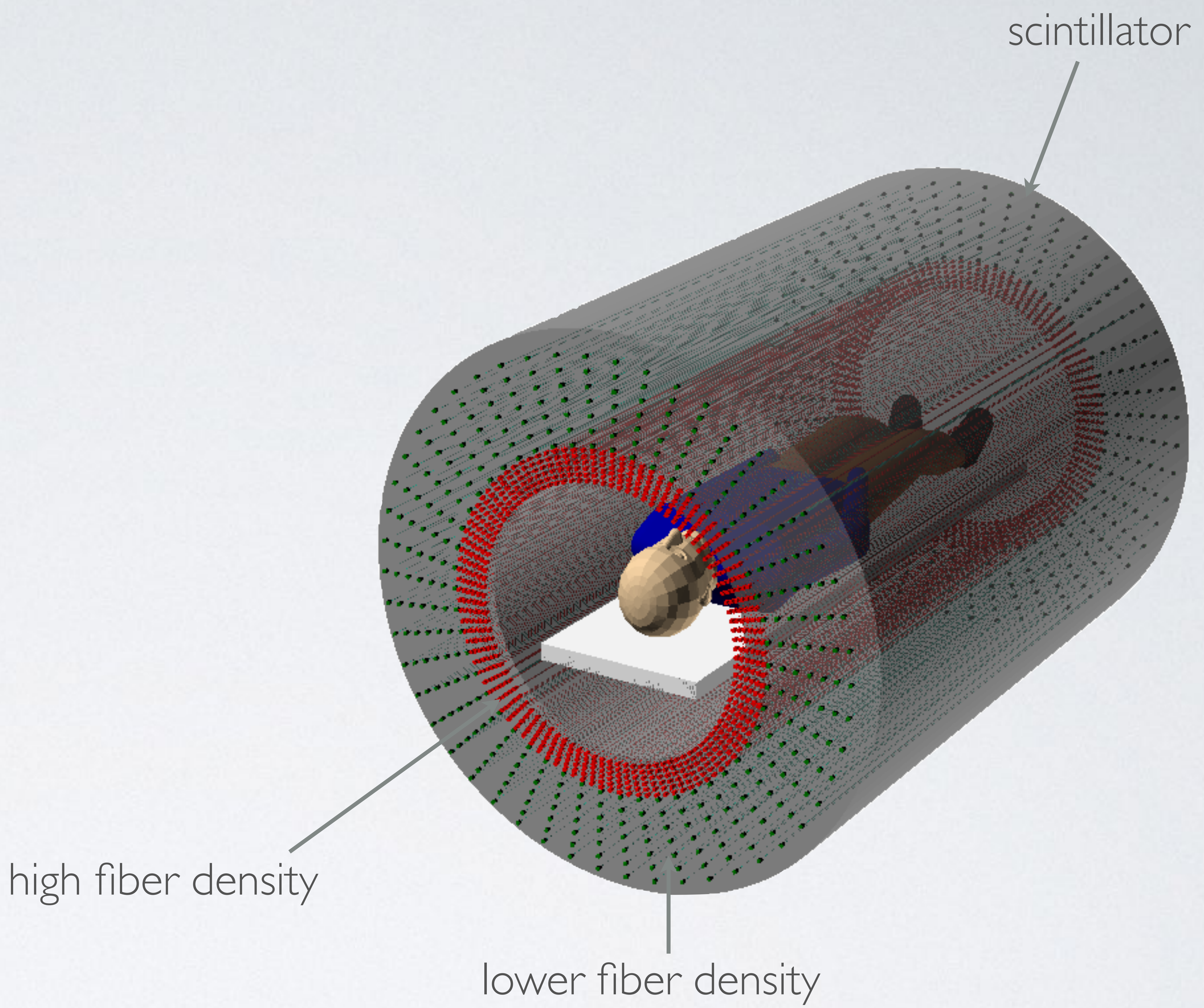




L-PET working principle

Inner tracker

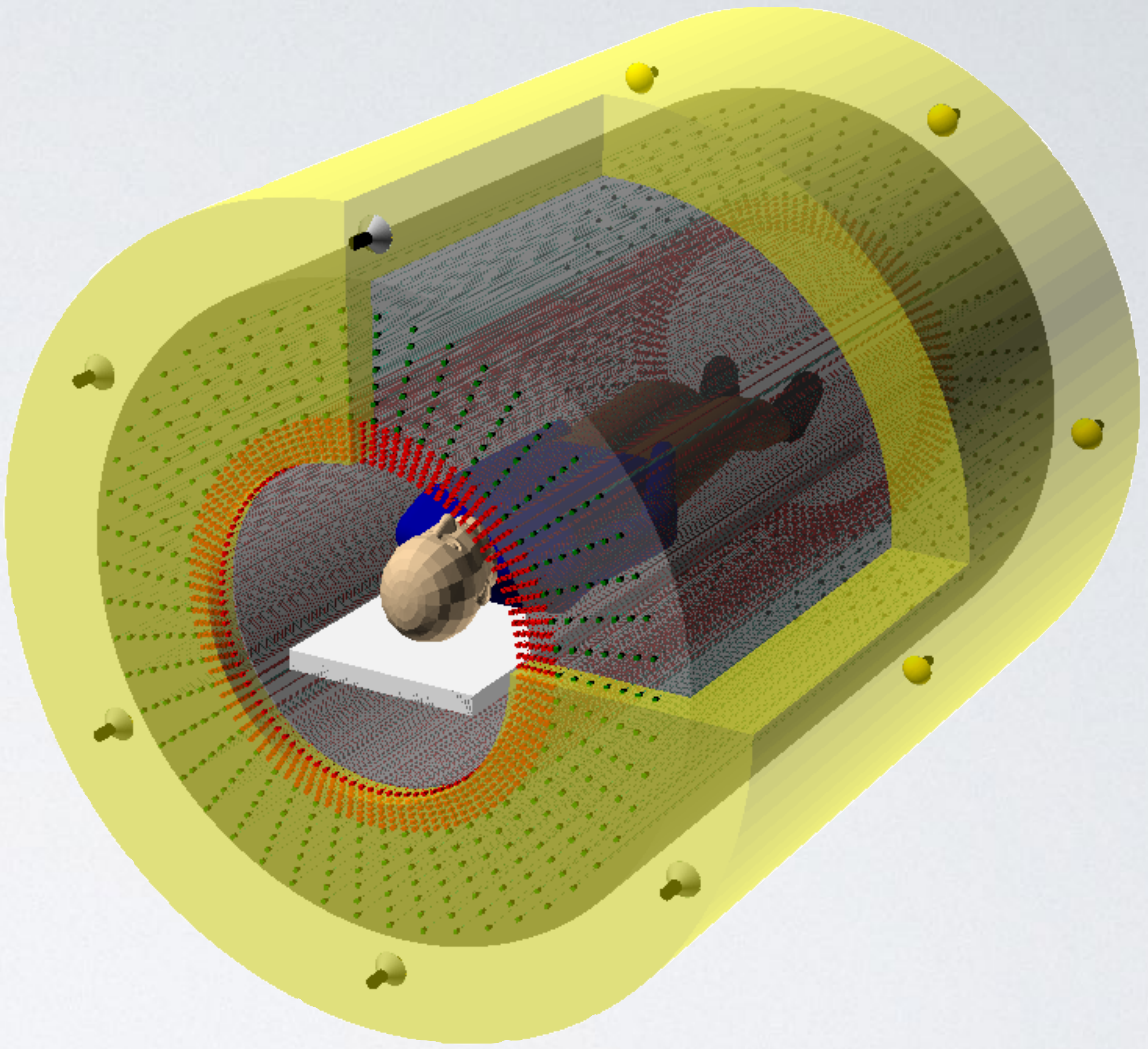
- LiquidO
- axial optical fibers ⇒ possible whole body PET
- Si-PM + fast digitizer readout (10 GS/s)



L-PET working principle

Inner tracker
- LiquidO
- axial optical fibers ⇒ possible whole body PET
- Si-PM + fast digitizer readout (10 GS/s)

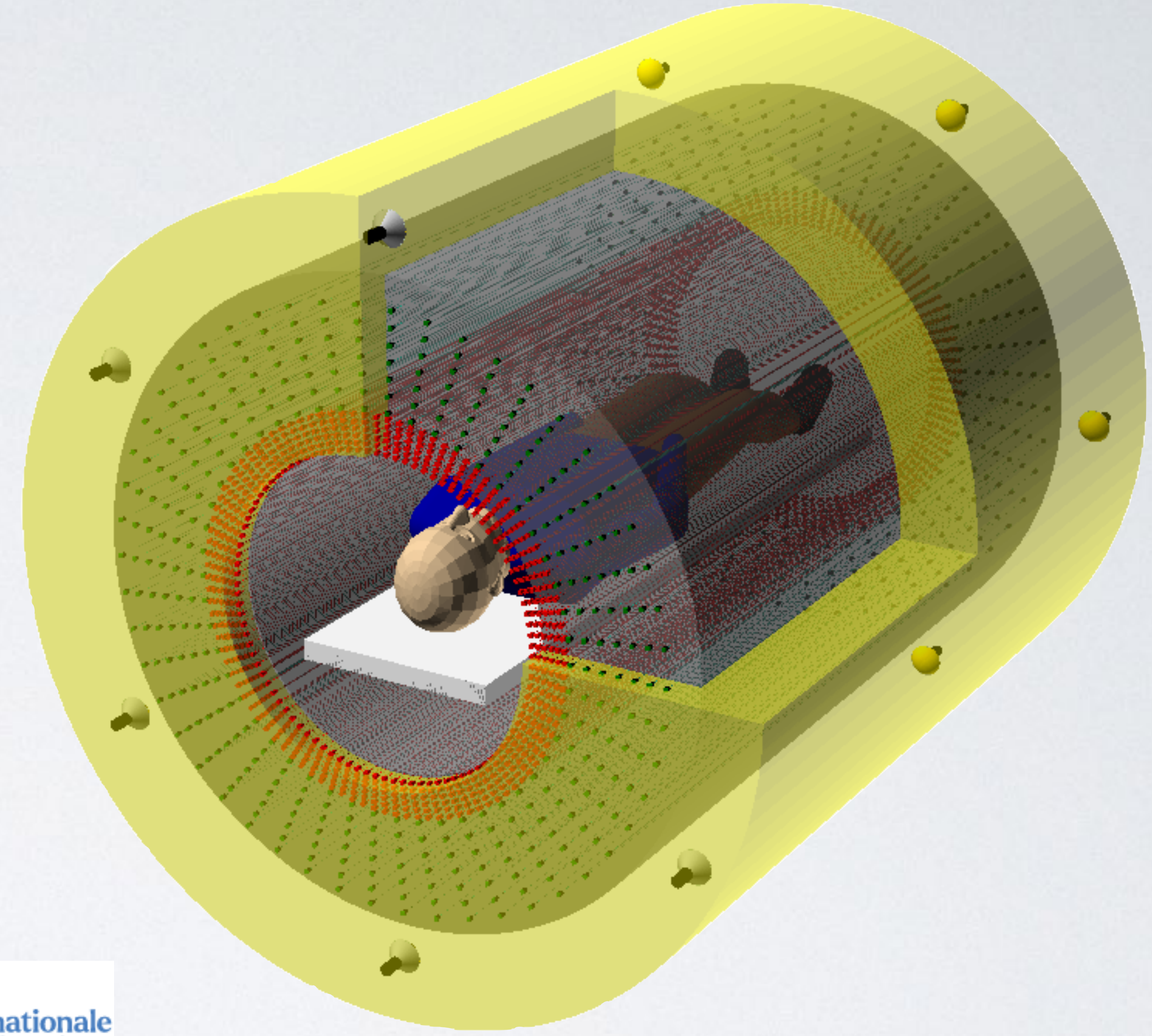
Outer calorimeter
- 'vintage' liquid scintillator + PMT
- ensure full γ calorimetry at the MeV scale



L-PET working principle

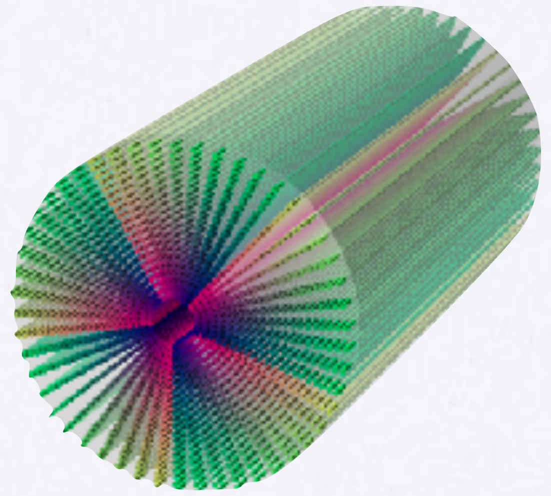
Inner tracker
- LiquidO
- axial optical fibers ⇒ possible whole body PET
- Si-PM + fast digitizer readout (10 GS/s)

Outer calorimeter
- 'vintage' liquid scintillator + PMT
- ensure full γ calorimetry at the MeV scale



ANR funding
- test feasibility of the new technology
- test gamma tracking capabilities
- test image reconstruction
- validate simulations & physics
- Establish requirements for future prototypes

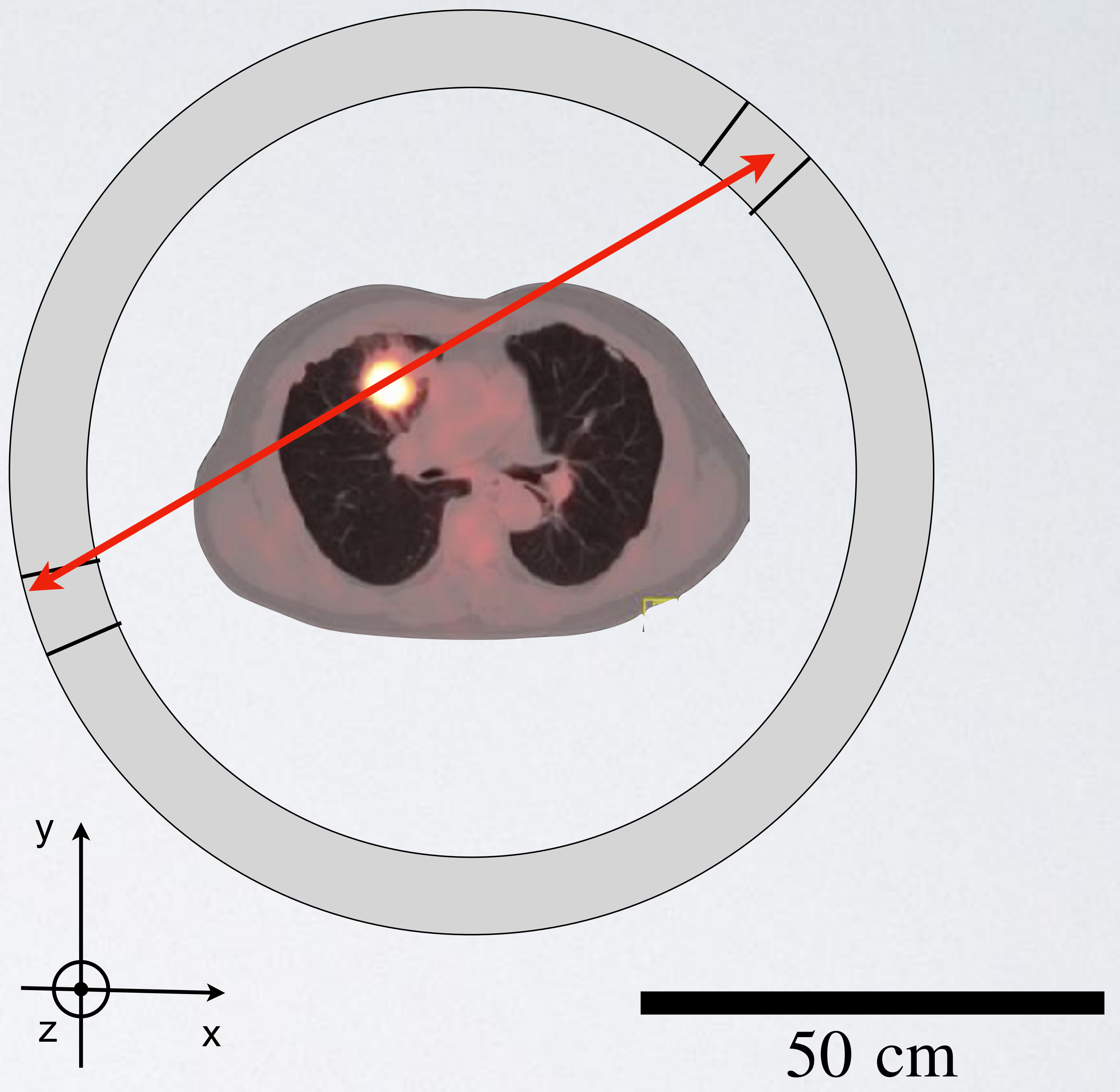
anr agence nationale de la recherche AU SERVICE DE LA SCIENCE



Paradigm shift

“Traditional” PET

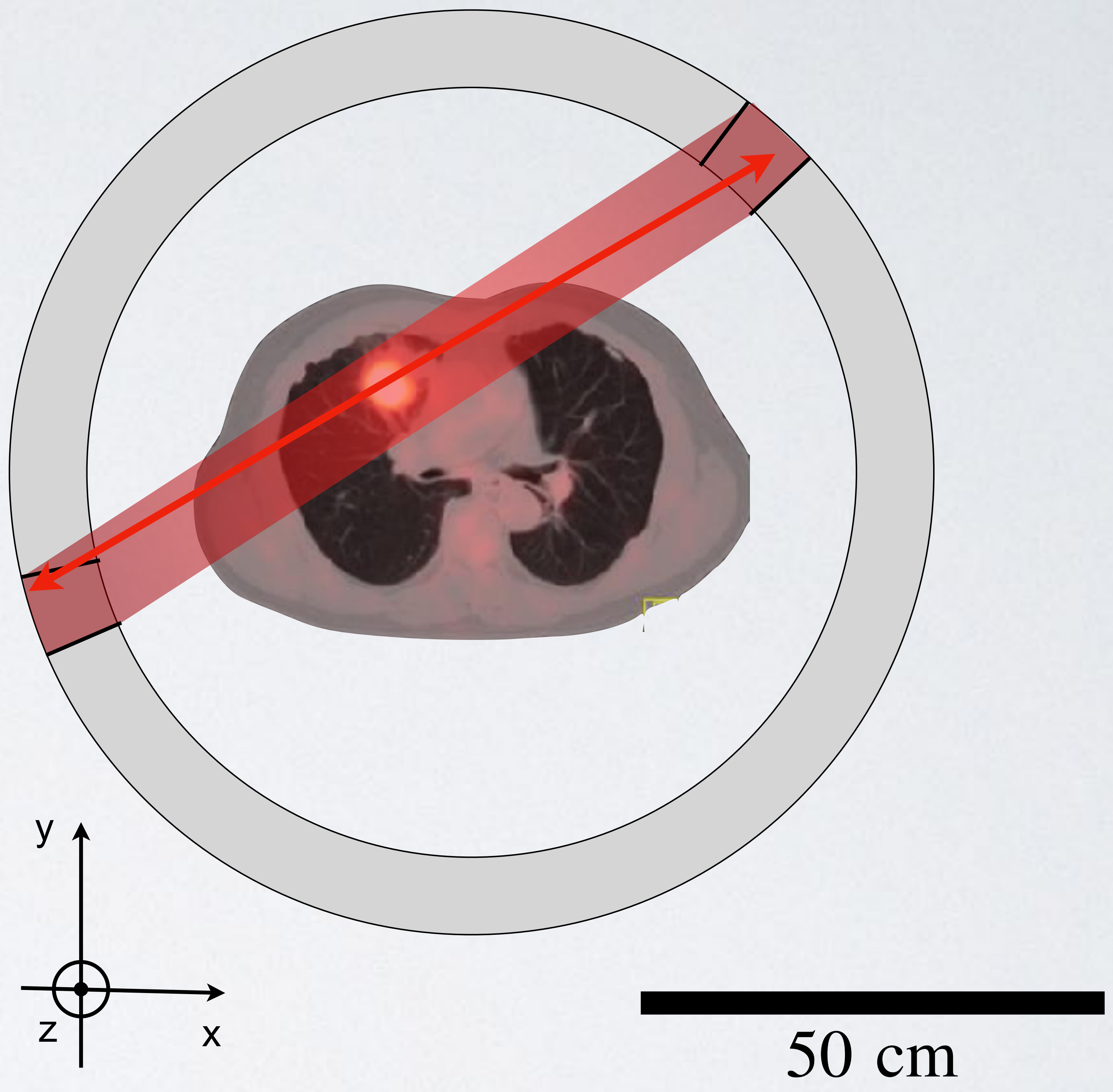
- Most commonly : light barycenter in a scintillator crystal module (Anger logic)
- Lack of Depth Of Interaction information : interaction point degeneracy within the crystal ~cm
- Coincidence time resolution ~250 ps



Paradigm shift

"Traditional" PET

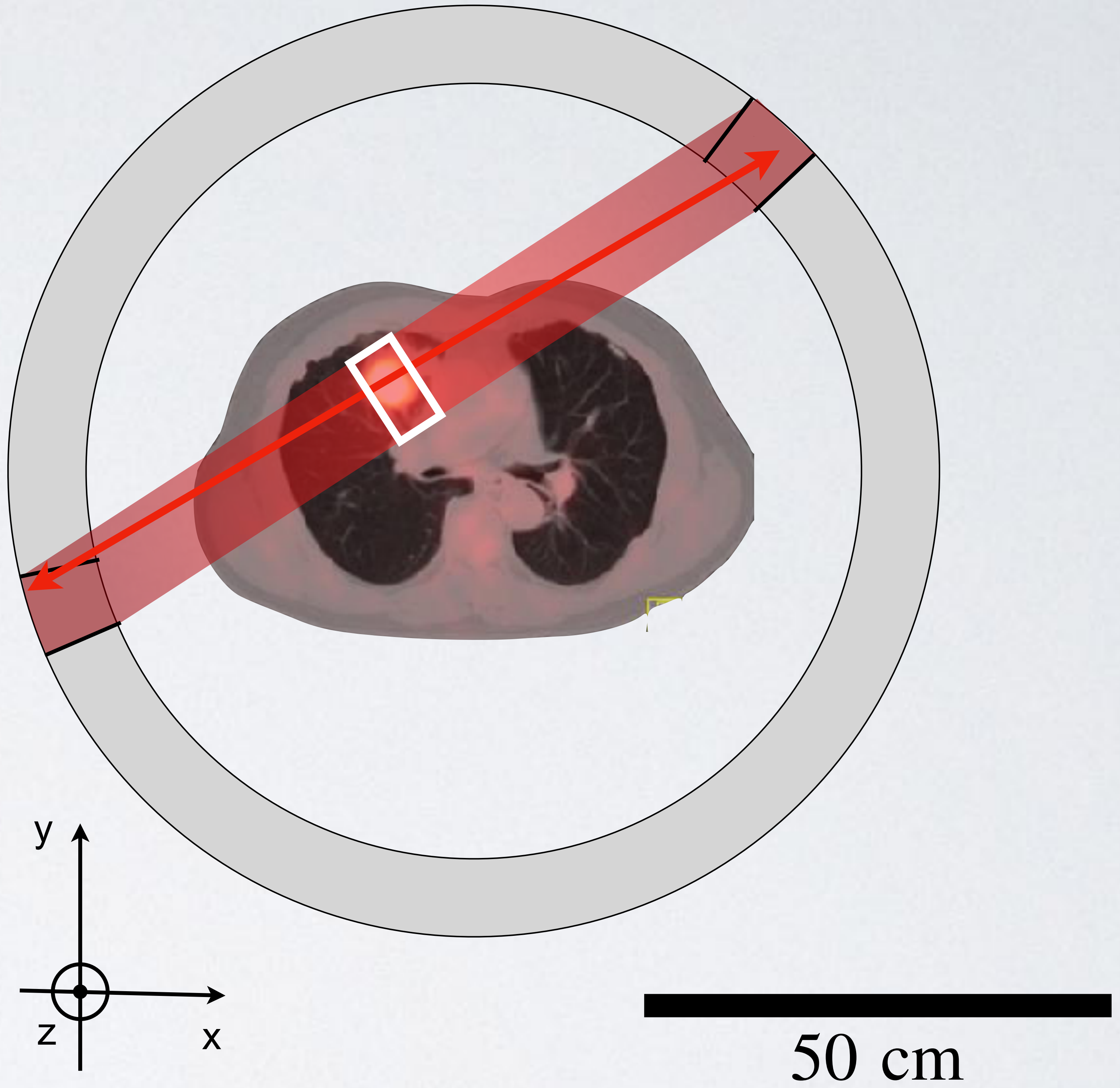
- Most commonly : light barycenter in a scintillator crystal module (Anger logic)
- Lack of Depth Of Interaction information : interaction point degeneracy within the crystal ~cm
- Coincidence time resolution ~250 ps



Paradigm shift

“Traditional” PET

- Most commonly : light barycenter in a scintillator crystal module (Anger logic)
- Lack of Depth Of Interaction information : interaction point degeneracy within the crystal ~cm
- Coincidence time resolution ~250 ps

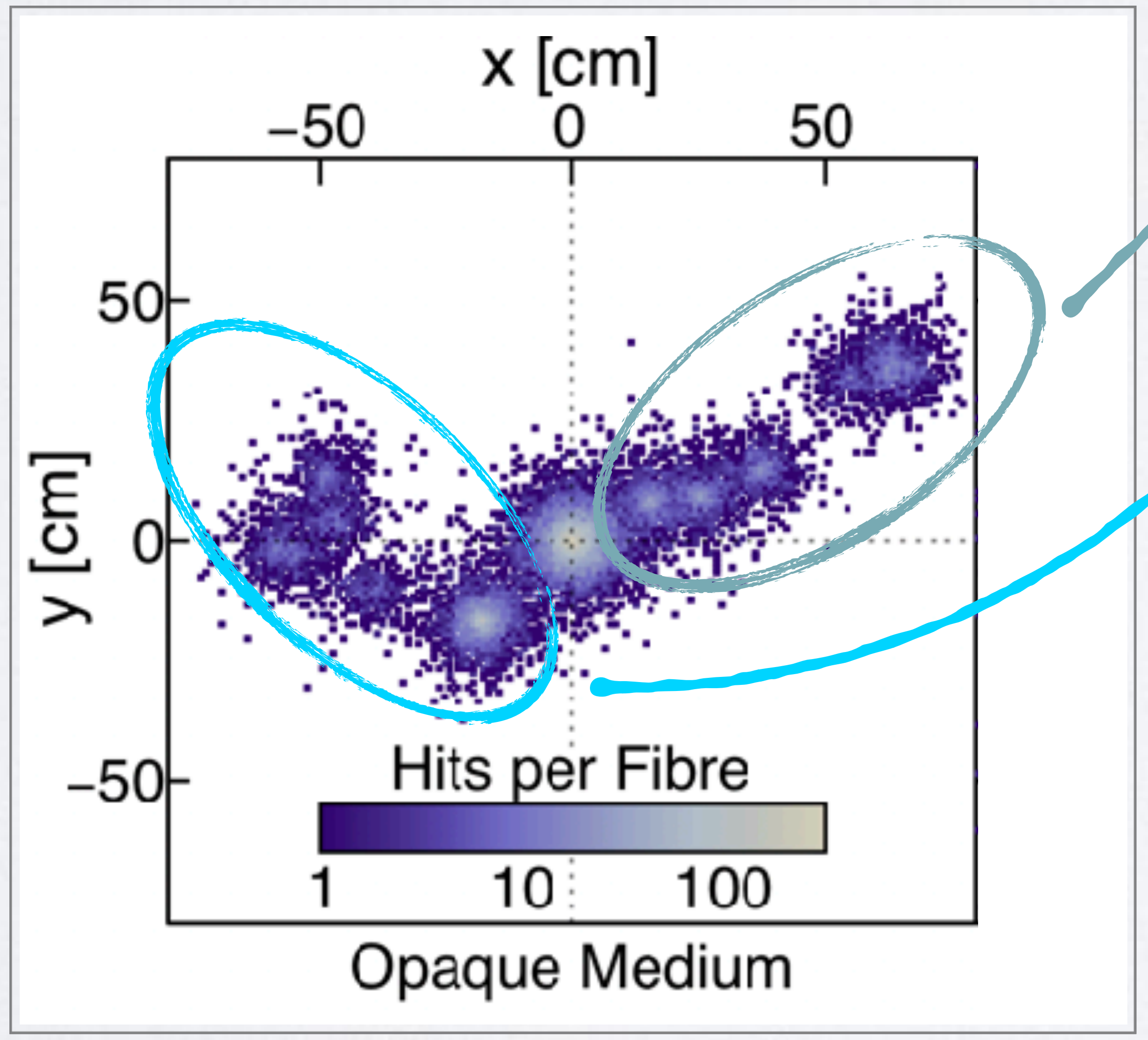


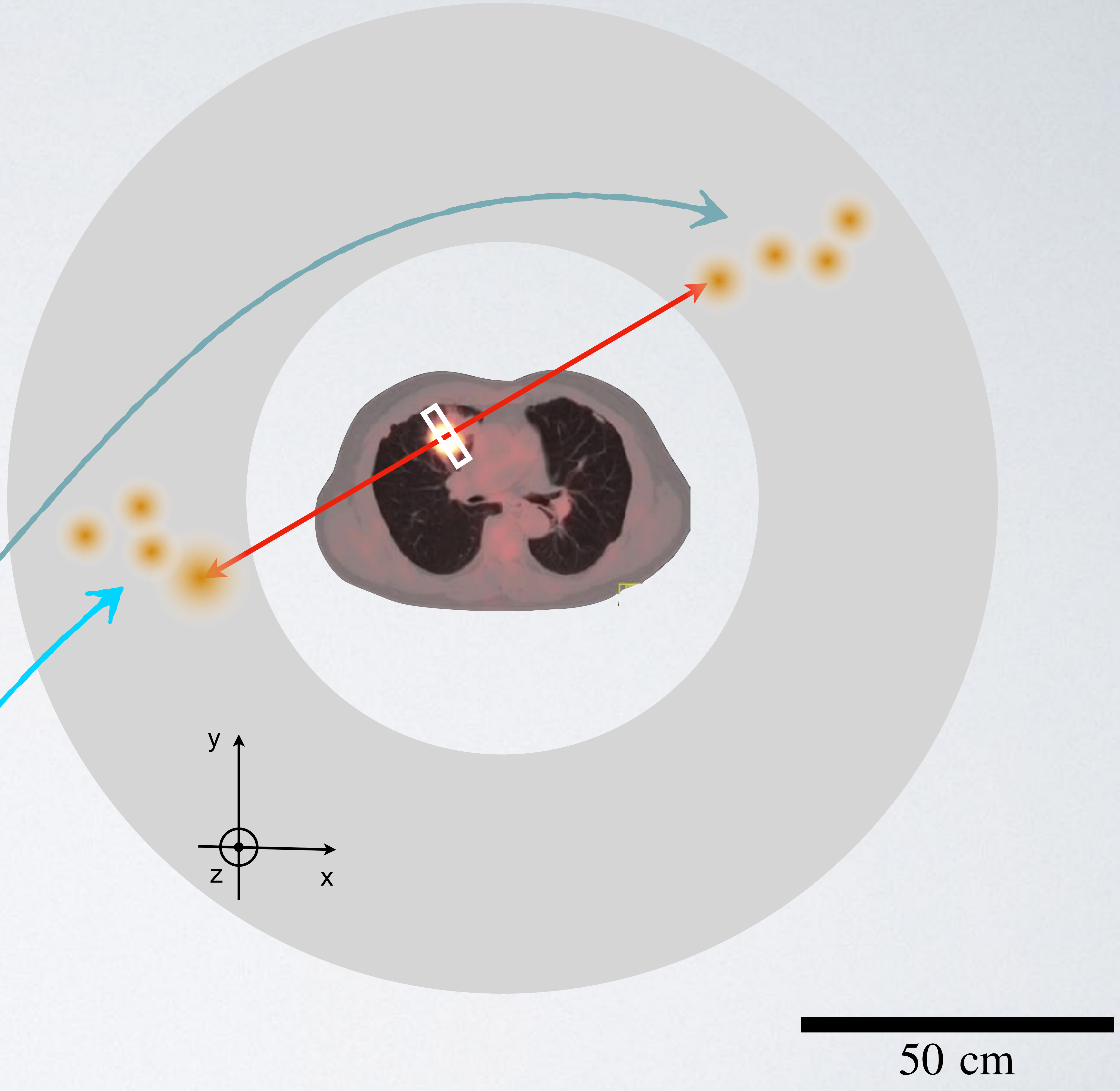
Paradigm shift

Full event topology reconstruction

- Low Z material : Compton dominated, large events
- 40 cm thick ~ 90% detection efficiency
- Resolutions : ~ mm (x,y) et ~100 ps

- Depth of Interaction
- Gamma Tracking : track successive Compton interactions
- Continuous medium





Paradigm shift

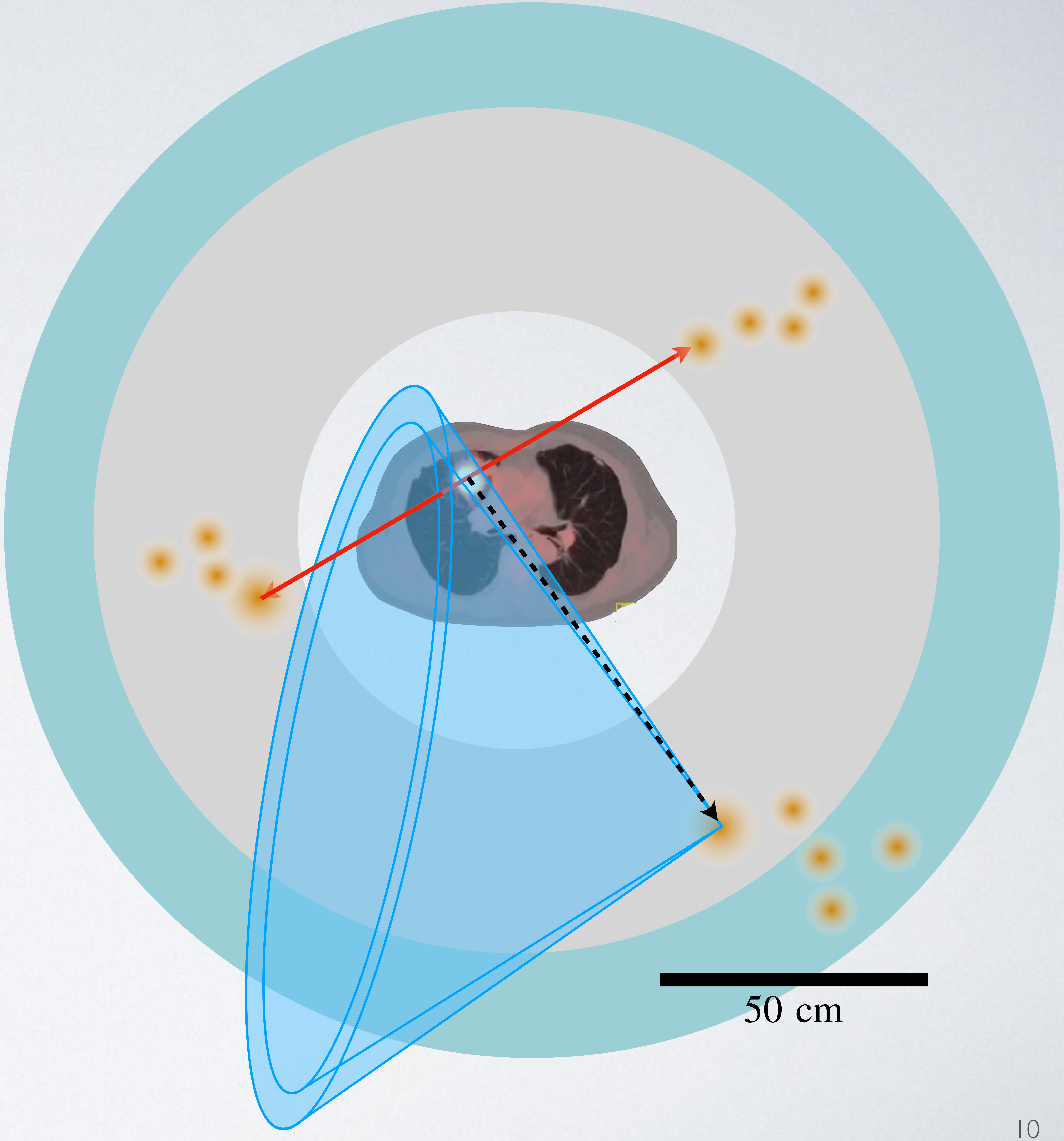
Full event topology reconstruction

- Low Z material : Compton dominated, large events
- 40 cm thick ~ 90% detection efficiency
- Resolutions : ~ mm (x,y) et ~100 ps

- Depth of Interaction
- Gamma Tracking : track successive Compton interactions
- Continuous medium : manageable system response matrix?

3 γ imaging

- Reconstruct incoming direction of the γ, point back to line of response
- Locate decay along the line of response objective 3mm



Paradigm shift

Full event topology reconstruction

- Low Z material : Compton dominated, large events
- 40 cm thick ~ 90% detection efficiency
- Resolutions : ~ mm (x,y) et ~100 ps

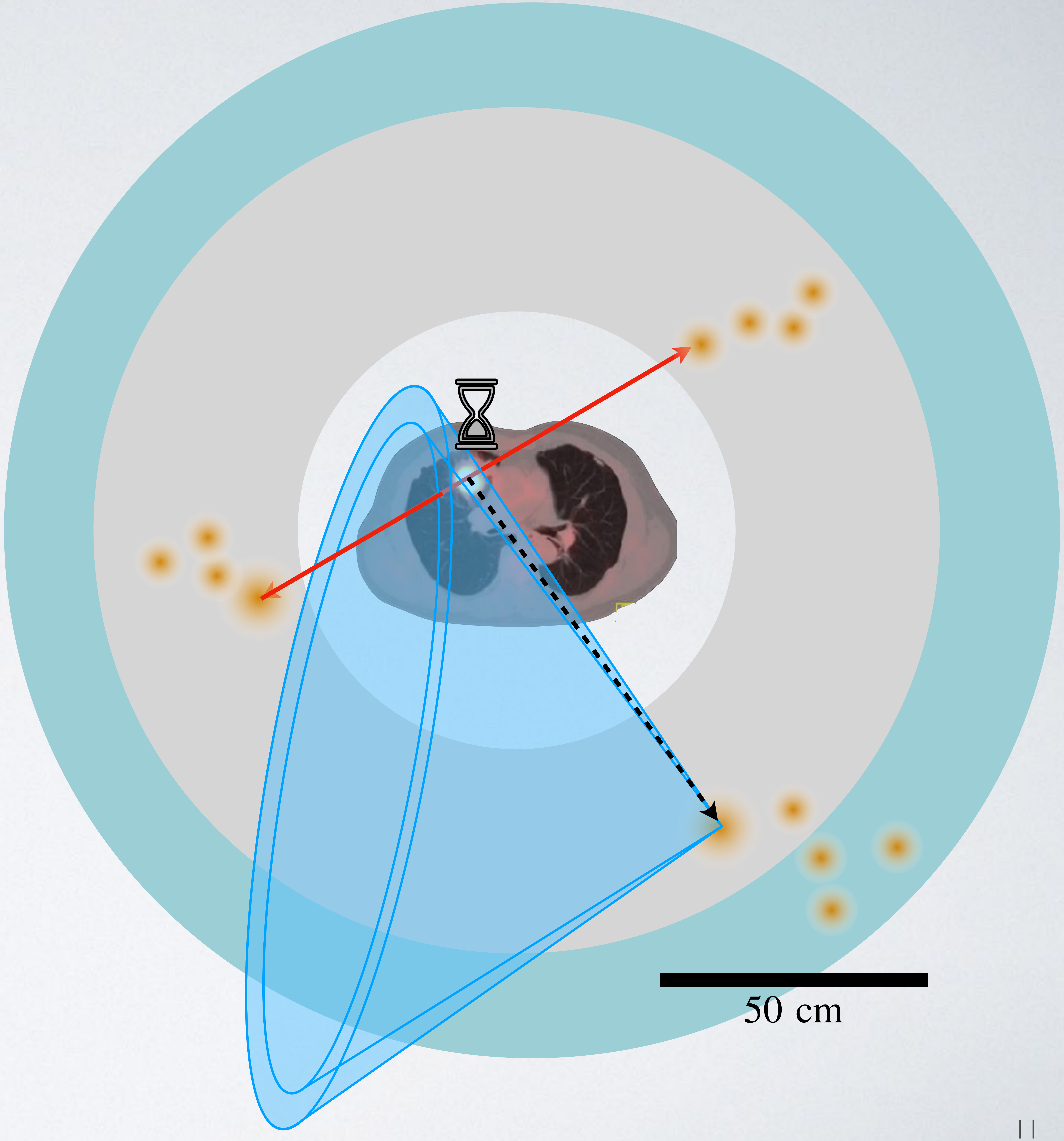
- Depth of Interaction
- Gamma Tracking : track successive Compton interactions
- Continuous medium : manageable system response matrix?

3 γ imaging

- Reconstruct incoming direction of the γ, point back to line of response
- Locate decay along the line of response objective 3mm

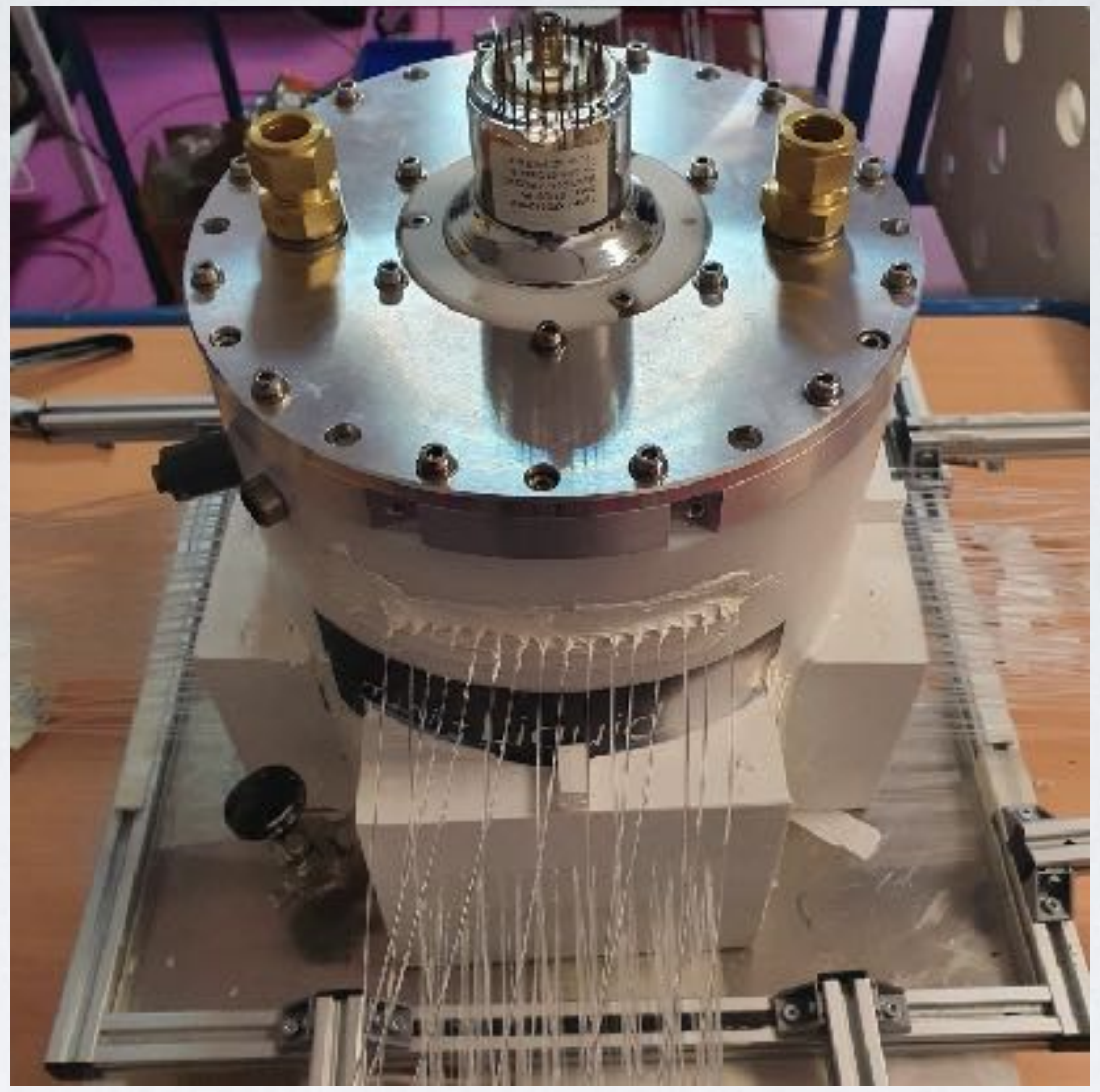
Ortho-positronium lifetime measurement

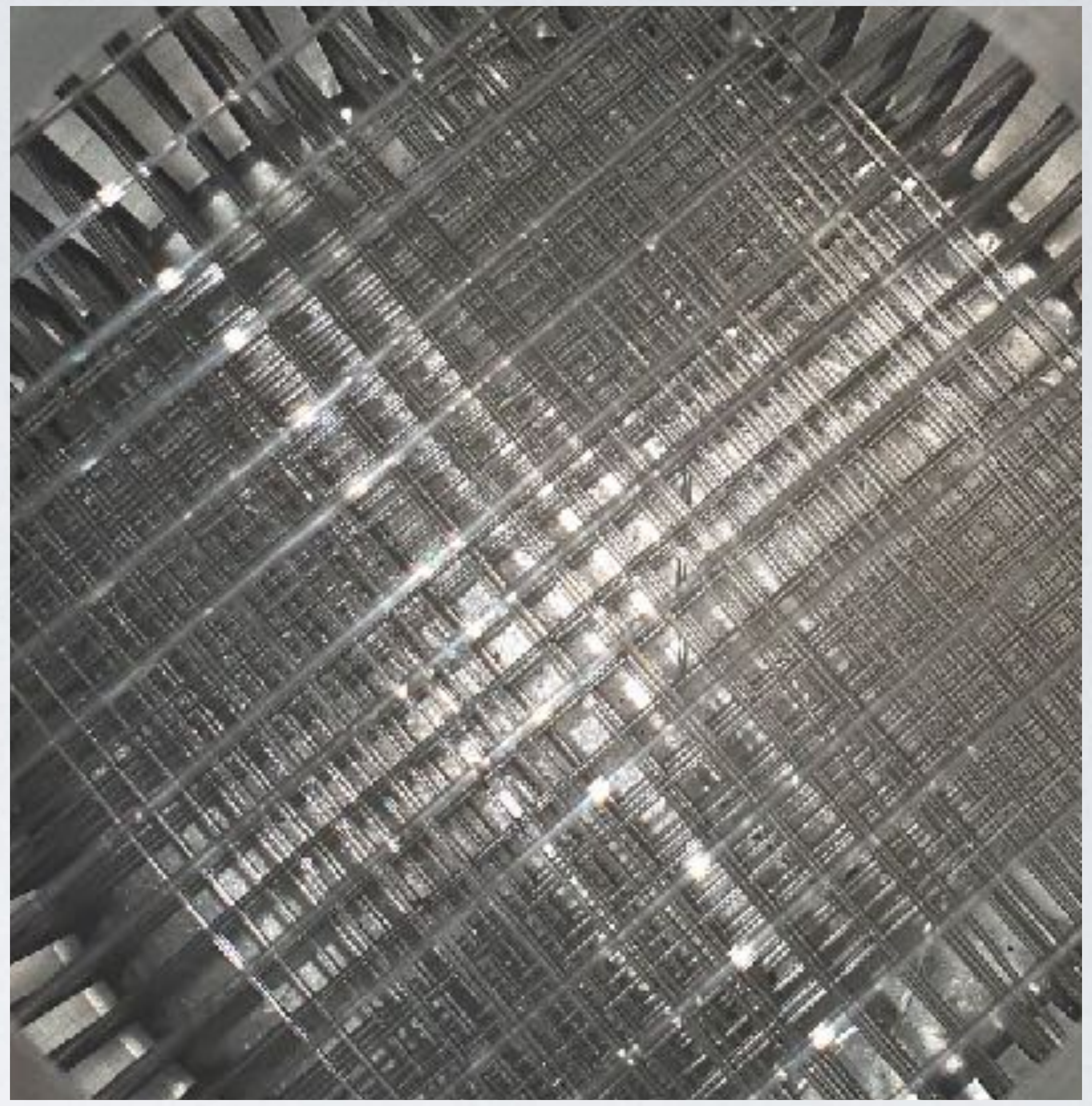
- Mesure Δt between MeV - γ from $^{44}\mathrm{Sc}$ decay and annihilation photons
- Map O-Ps lifetime in vivo?
  $\Rightarrow$ new parametric imaging?



Technological developments

C. Buck, B. Gramlich and S. Schoppmann 2019 JINST 14 P11007

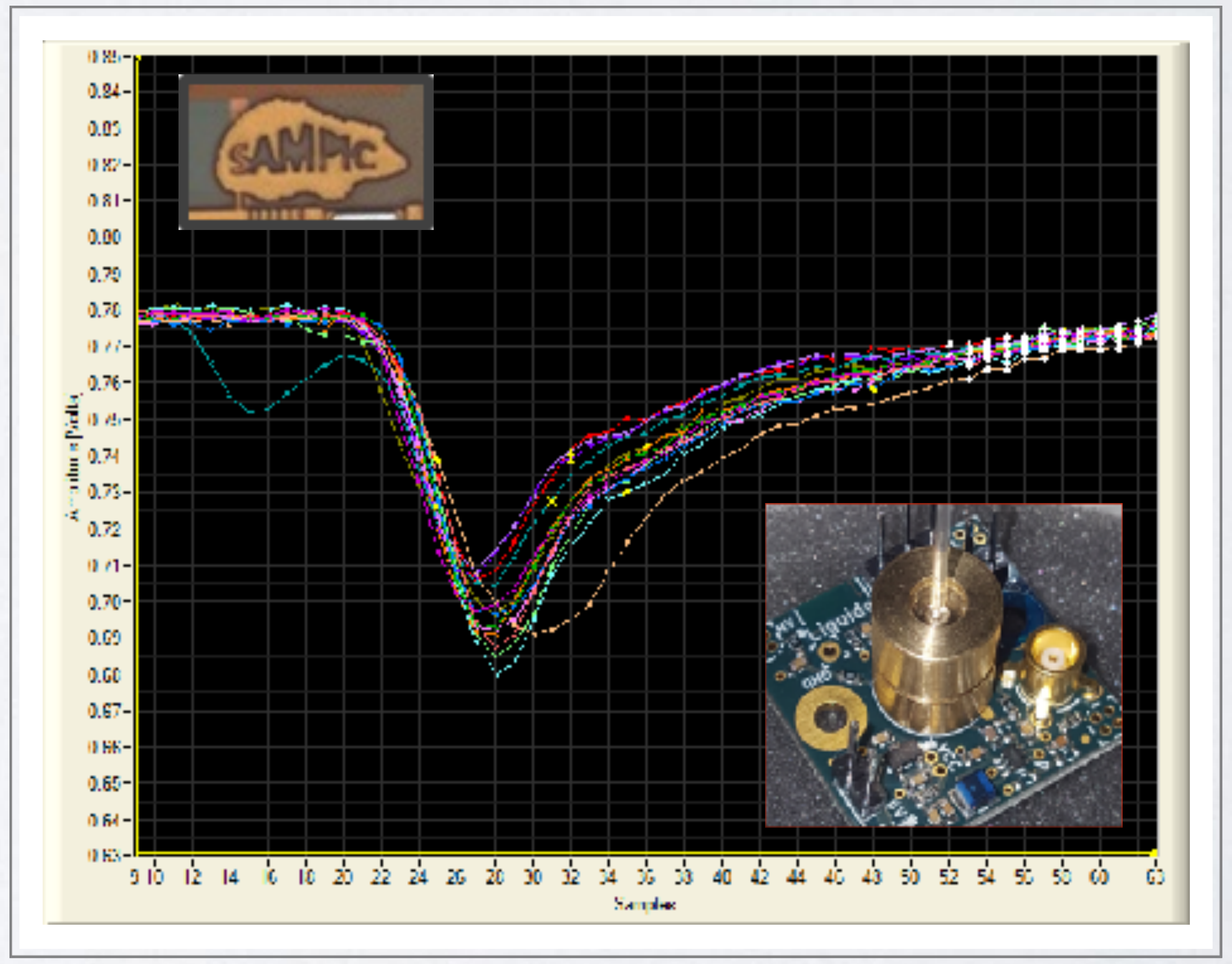




Optimization of scintillator:
- no longer the need for extreme transparency
- what best scattering length? how to achieve it?

Digitization:
- Fast SiPM
- Fast digitizer (Sampic)
- huge dataflow

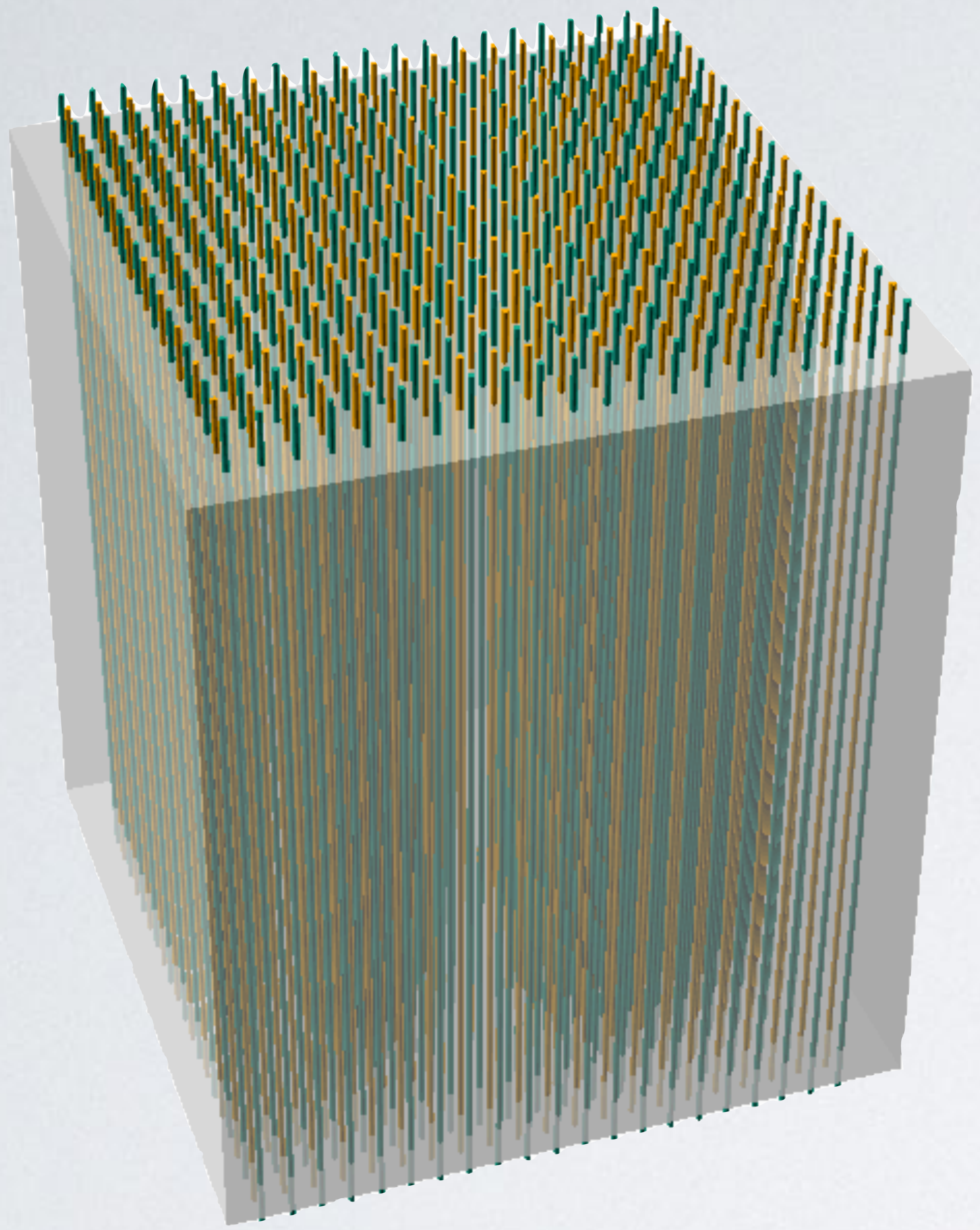
Prototypes :
- proof of concept validation of light trapping
- studies of various scintillators



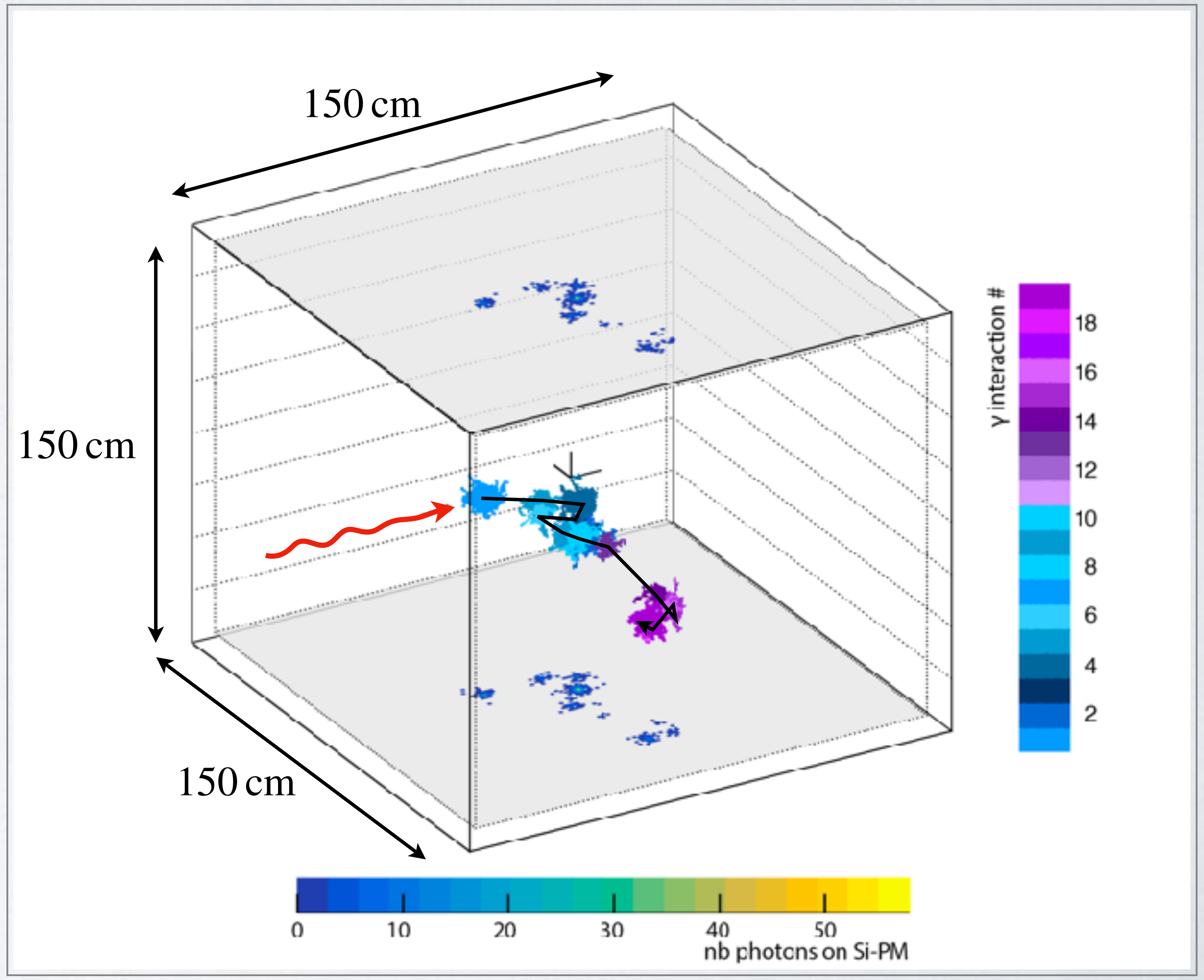
NIM paper (2016): Measurements of timing resolution of ultra-fast silicon detectors with the SAMPIC Waveform Digitizer

(2019) Fast electronics for particle Time-Of-Flight measurement, with focus on the SAMPIC ASIC

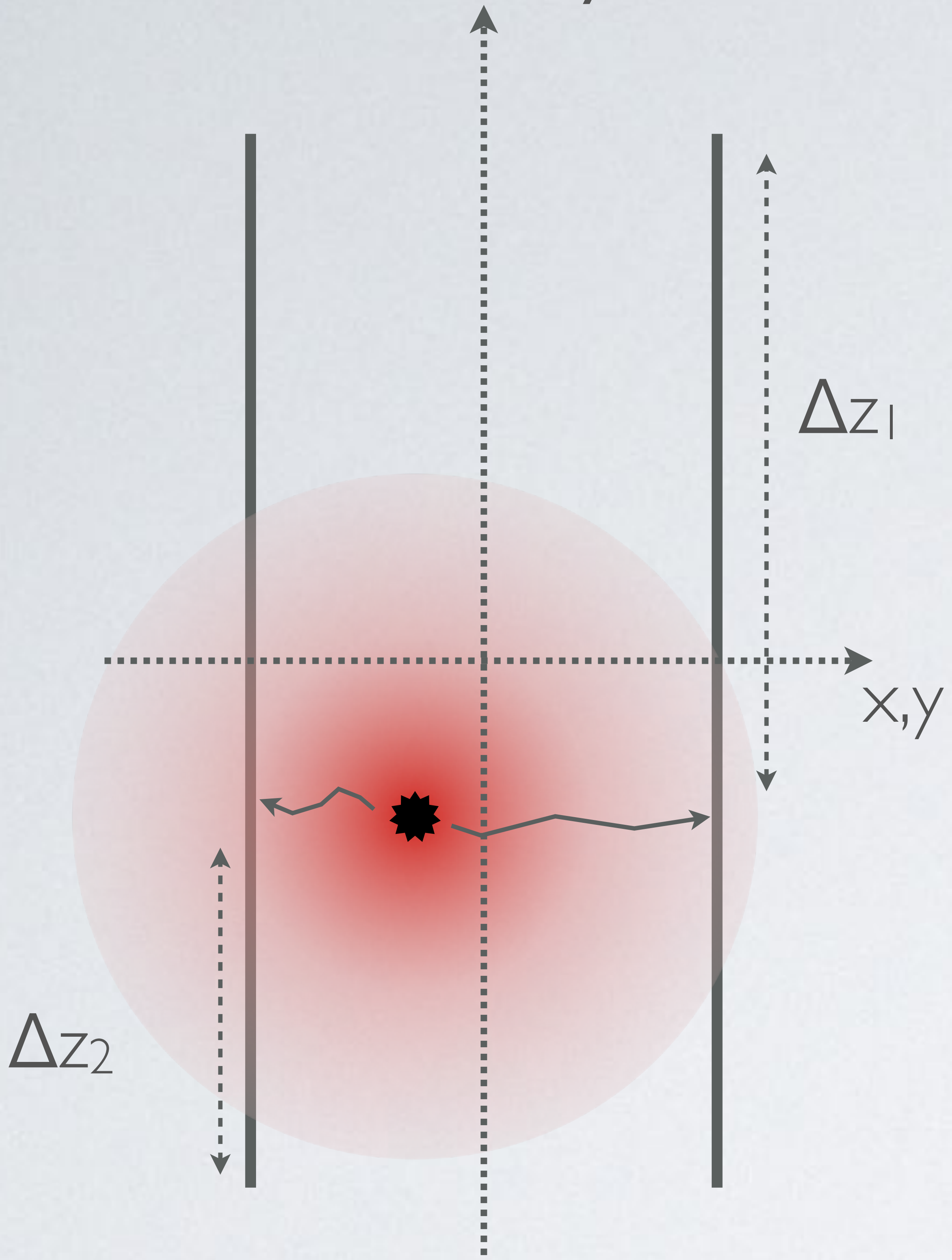
Preliminary simulations

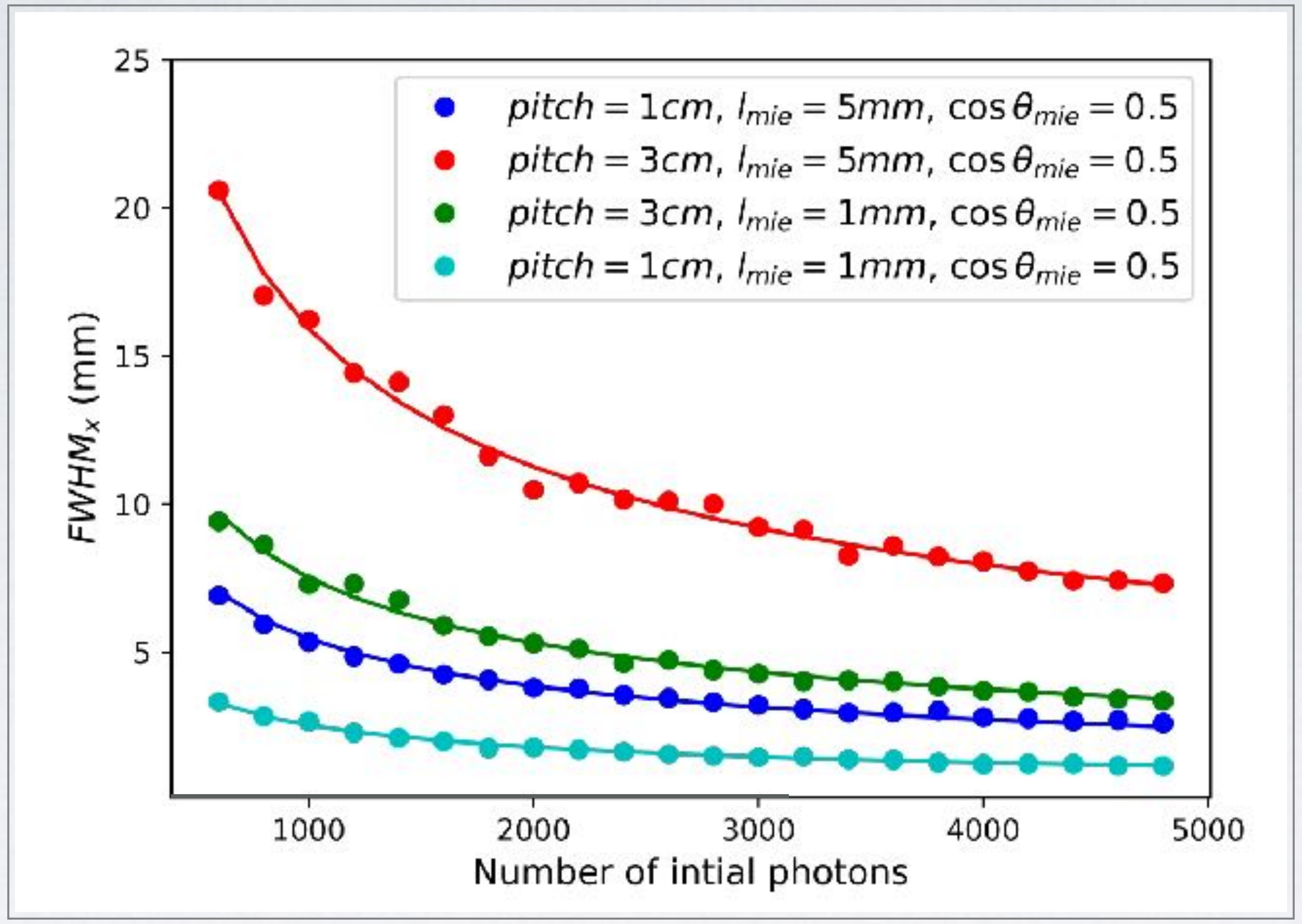


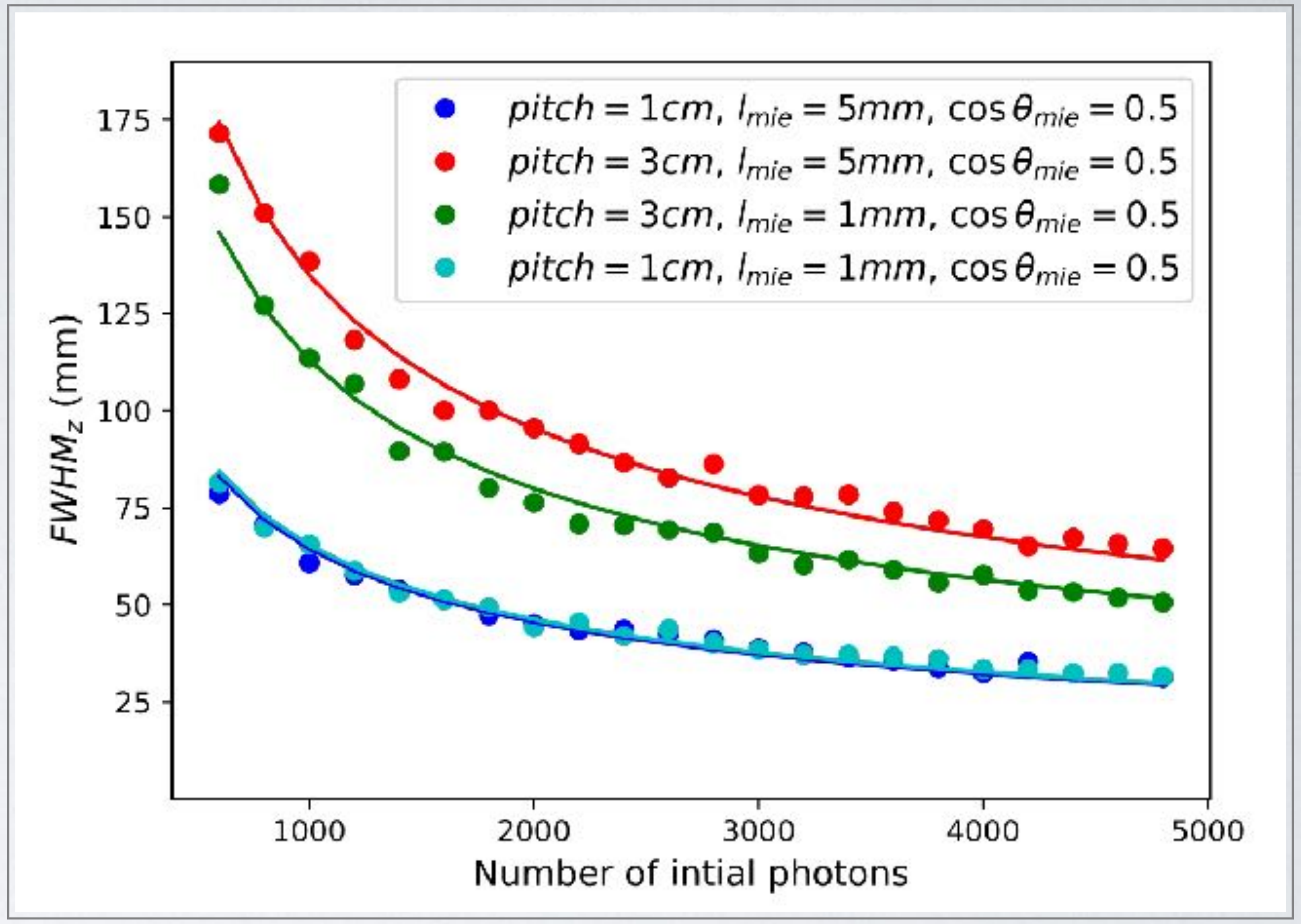
- LiquidO is designed for neutrino physics at the MeV-GeV scale → applicable to our needs in TEP?
- Getting started with a cubic volume to understand the technology :
  - cube of organic scintillator (150x150x150) cm3
  - vertical optical fibers
  - Mie & Rayleigh scatterings
  - absorption in scintillator & fibers



Preliminary results

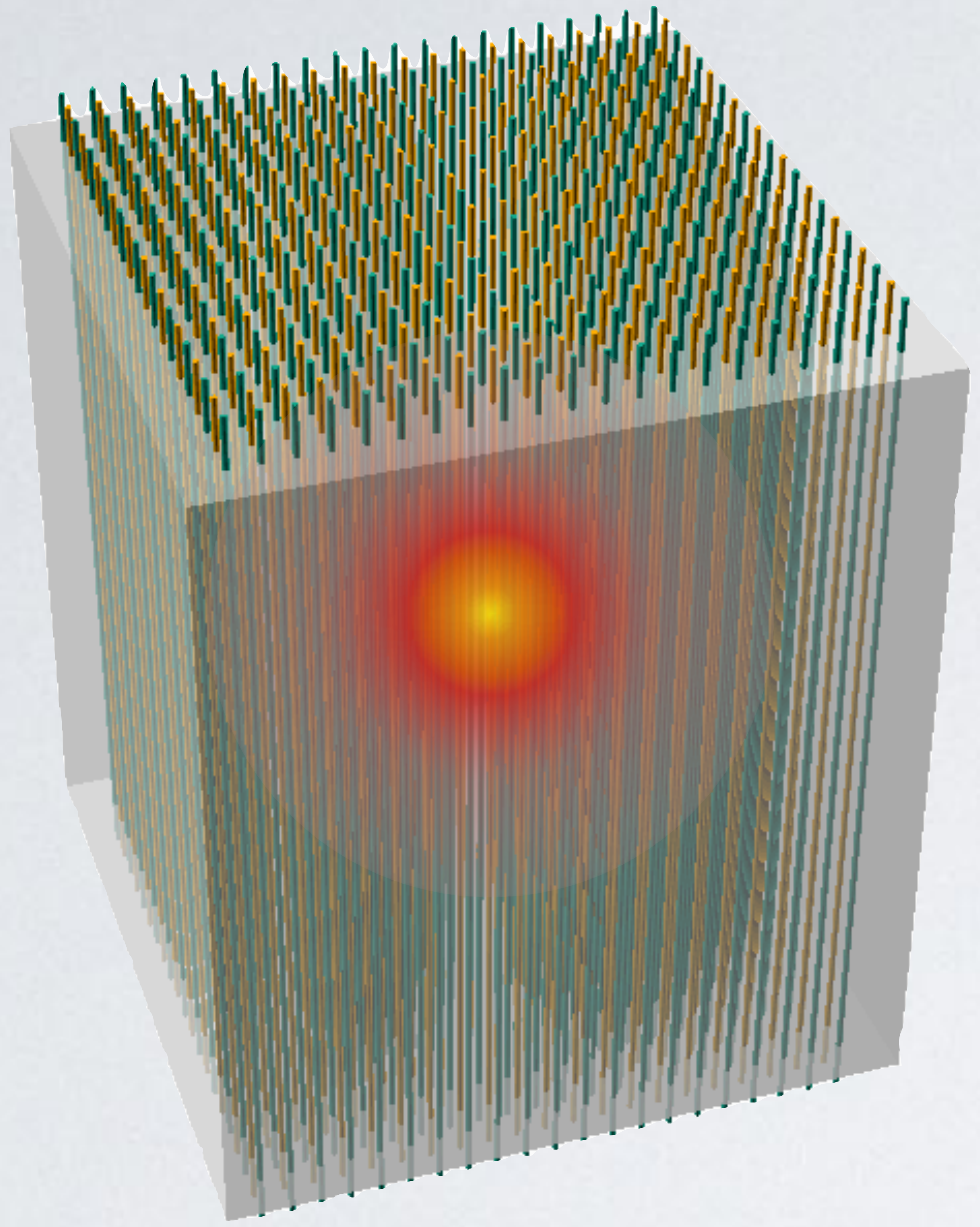


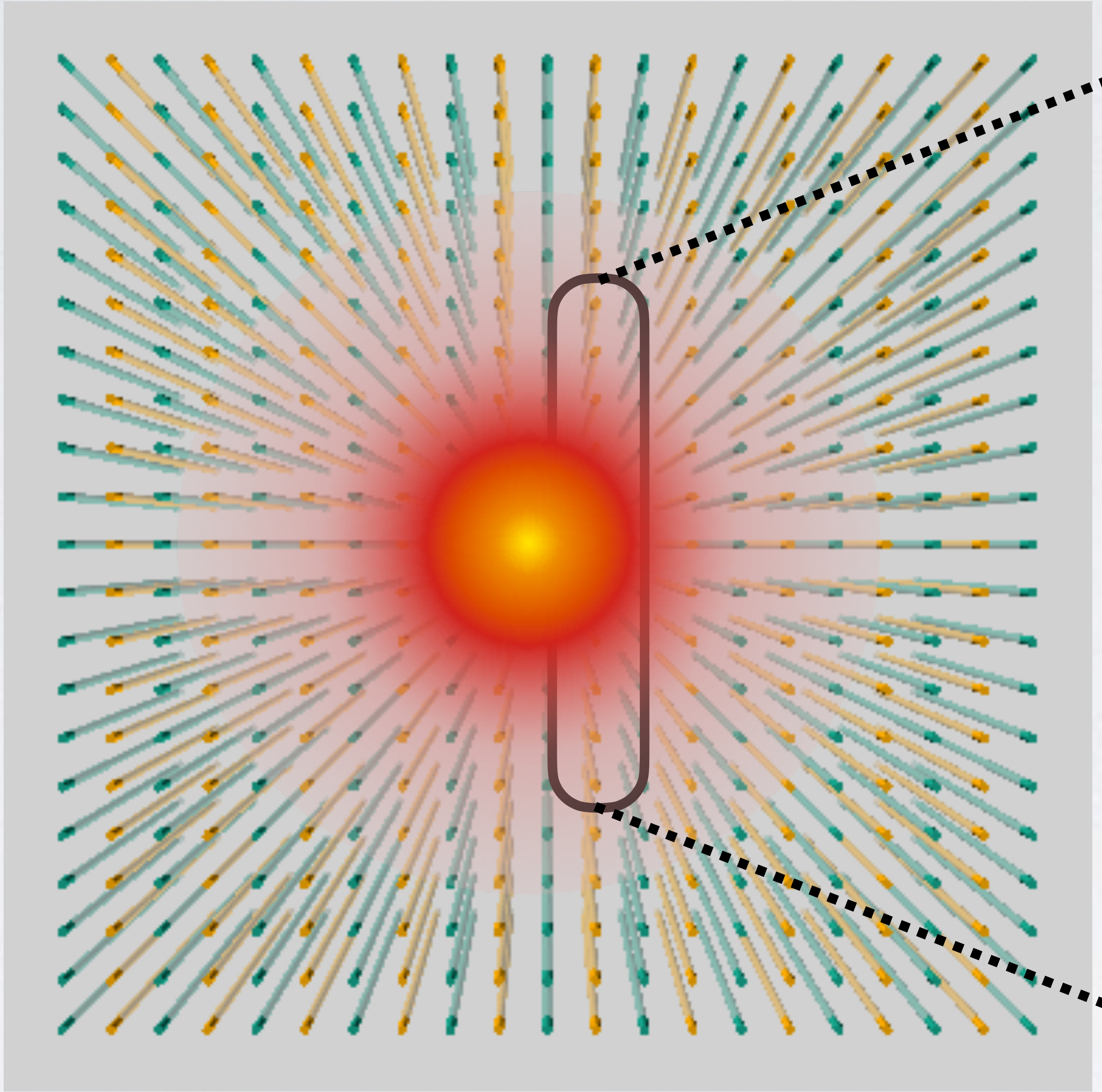


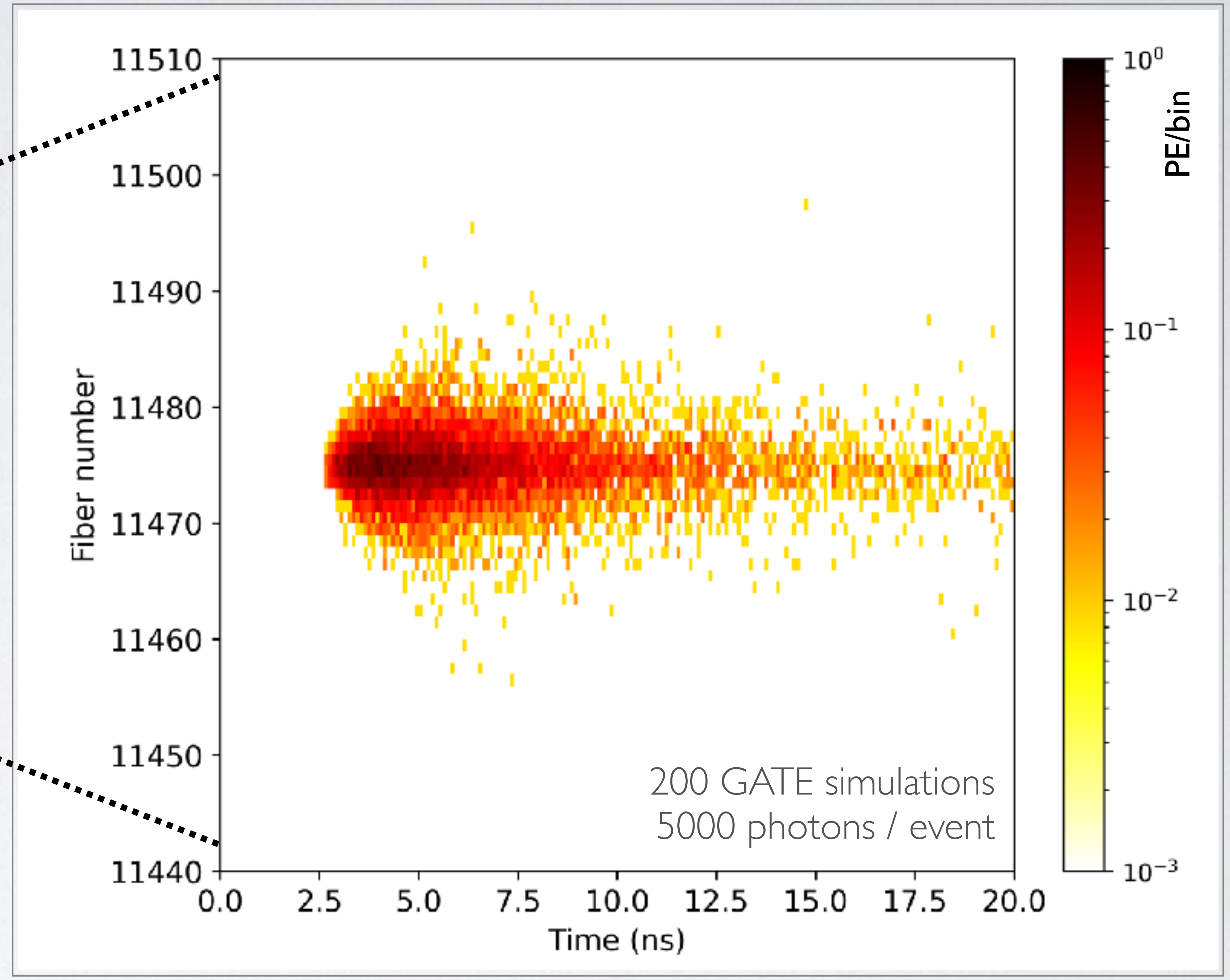


- Single emission point in the scintillator
- X,Y reconstruction : barycenter of light
- Z reconstruction : by ΔT of the first photons collected on top and bottom

Perspectives, improvements in Z measurement

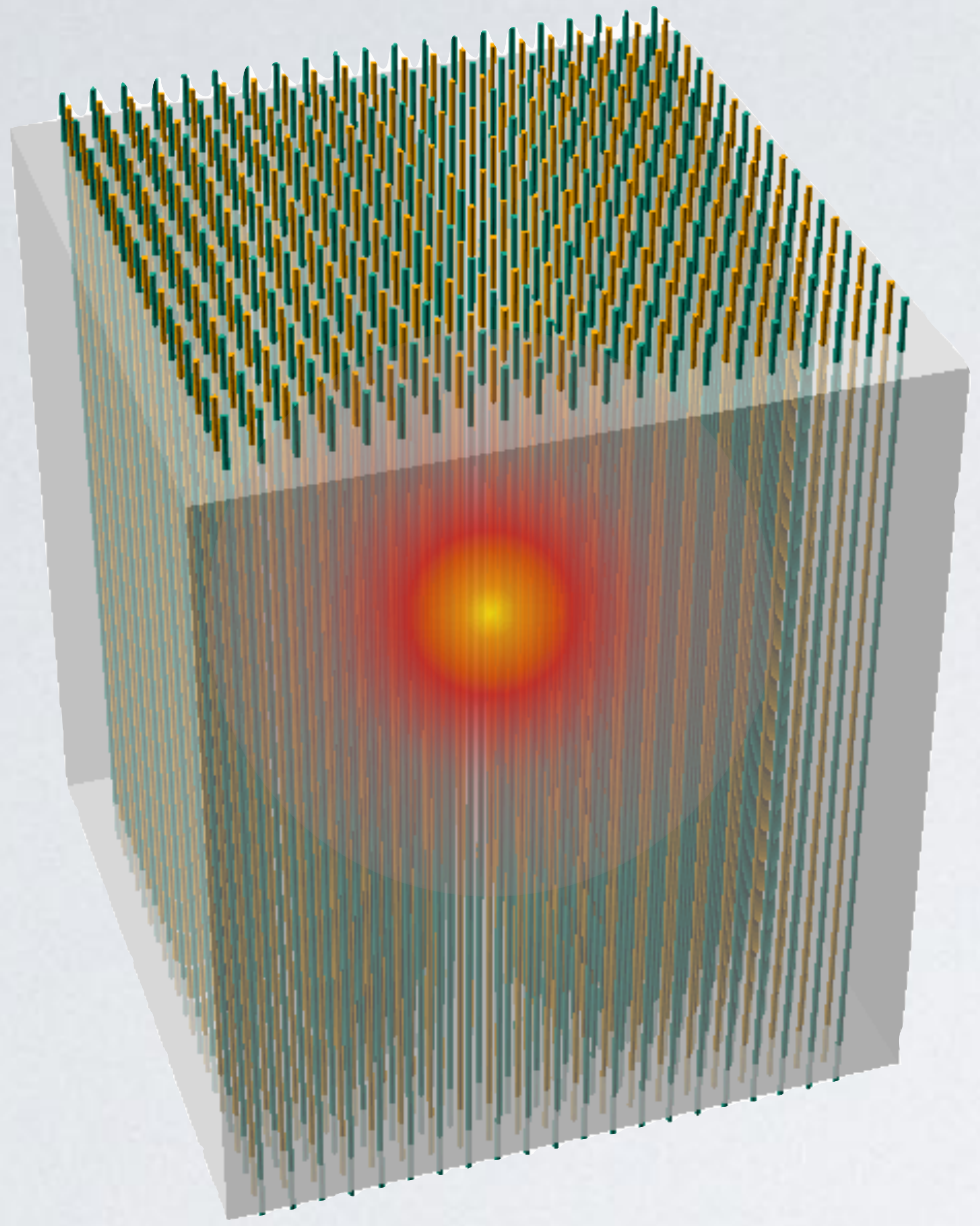


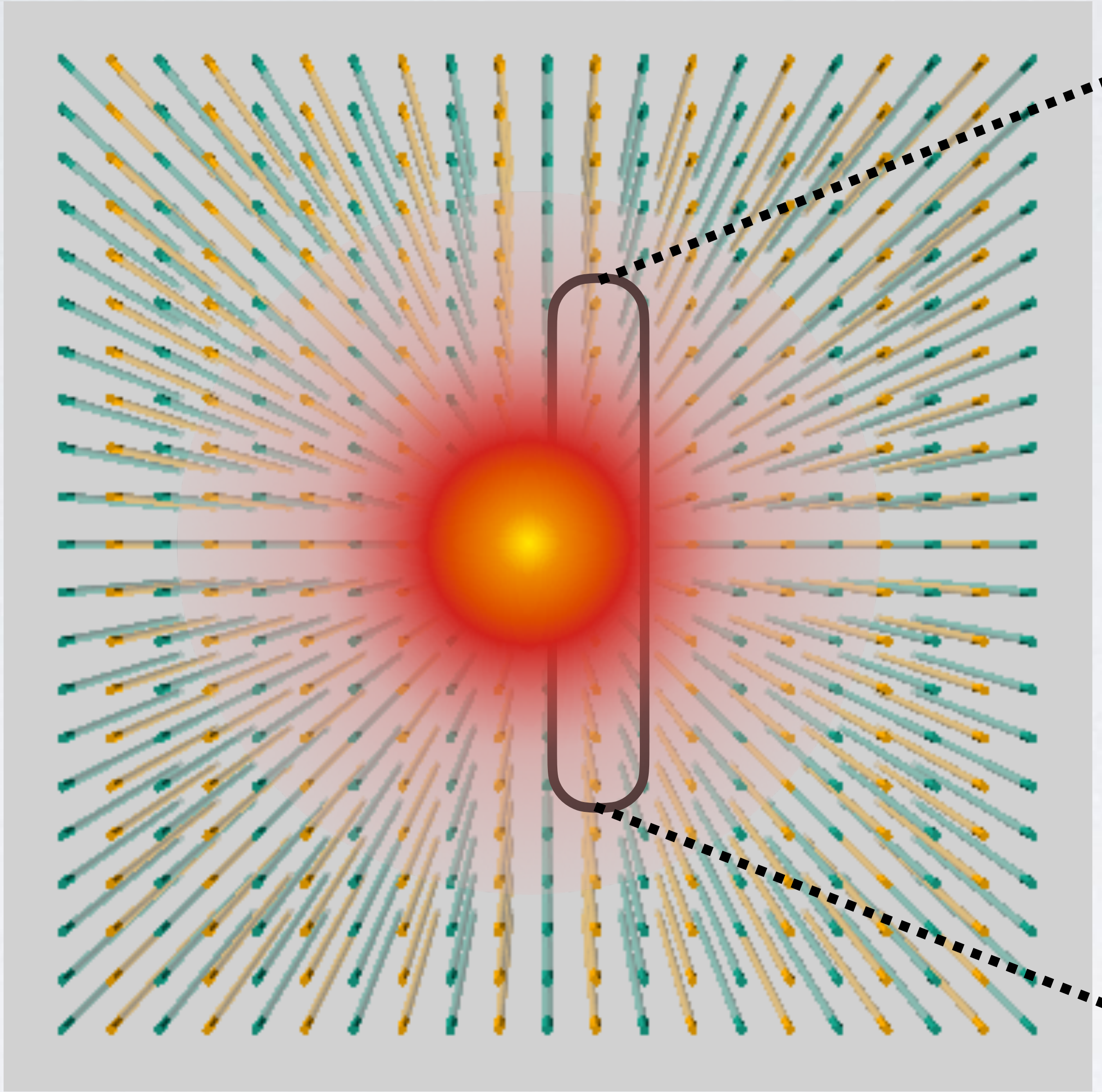


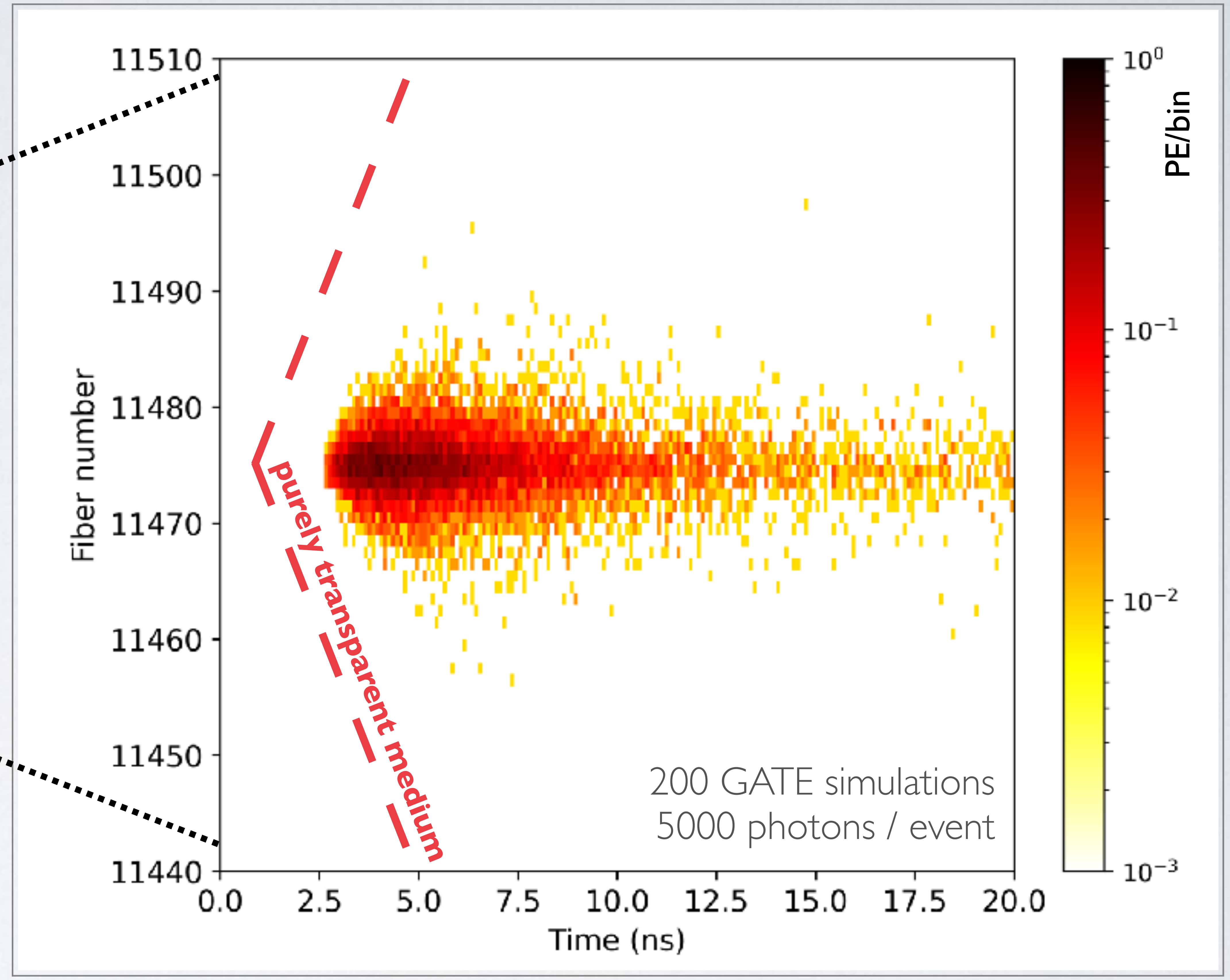


- Correlation between neighbouring fibers waveforms
- Diffusive medium $\Rightarrow t \propto r^2$ slower than transparent medium
- Pulse shape in each waveforms is Z-dependent
- **Input these correlations and pulse shape in spatial reconstruction**
- **Use Machine Learning networks ? change fiber distribution?**

Perspectives, improvements in Z measurement

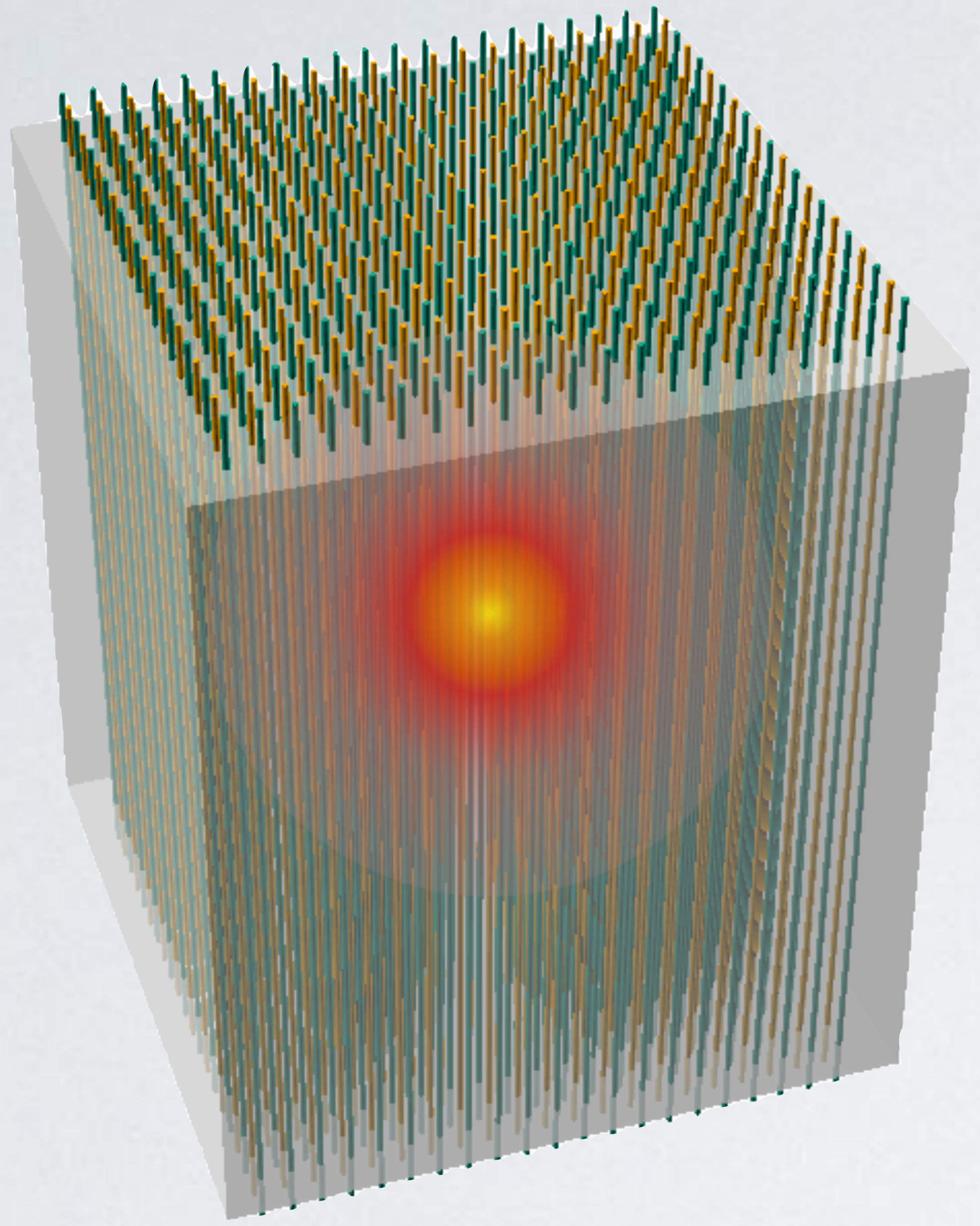


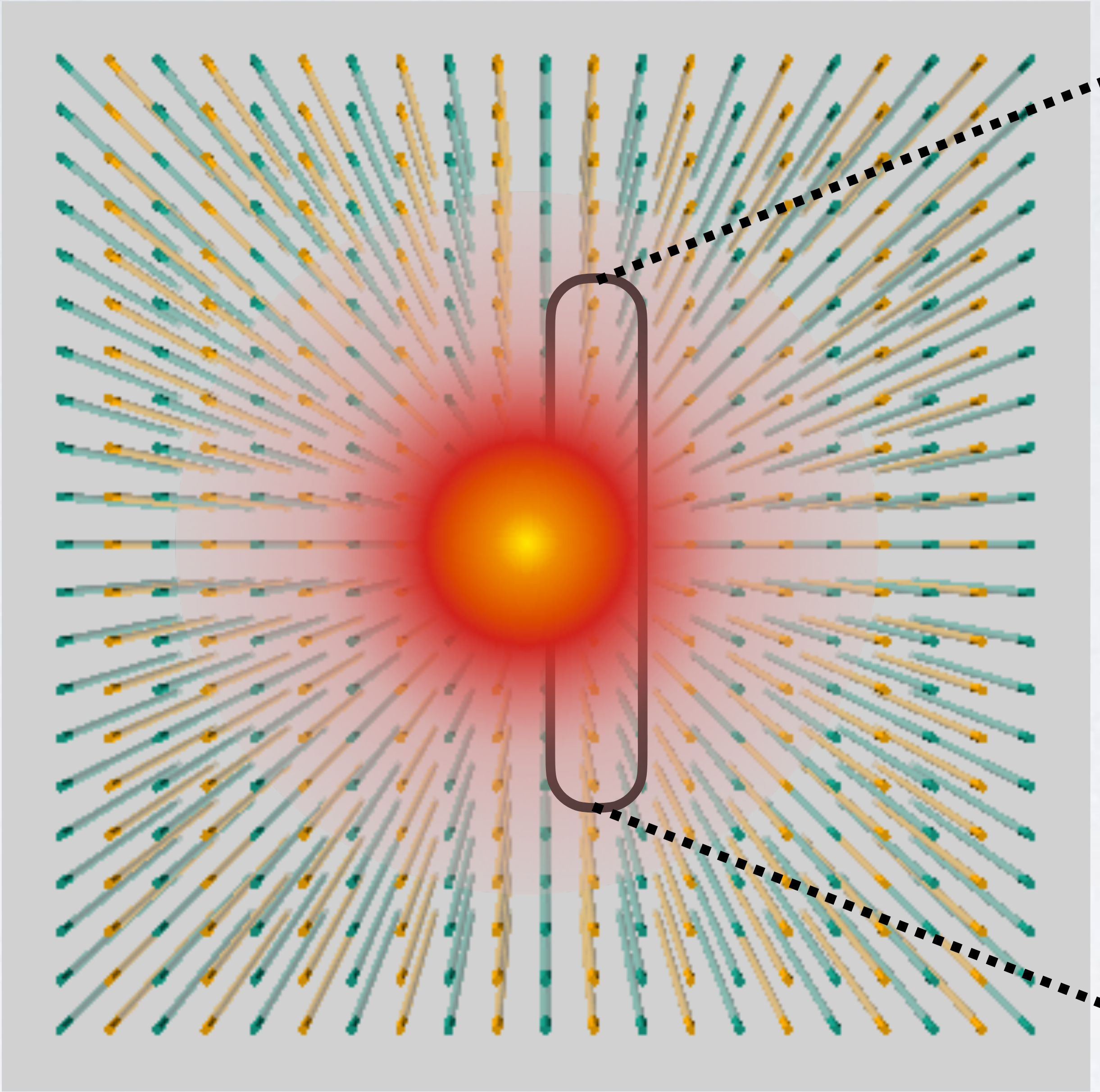


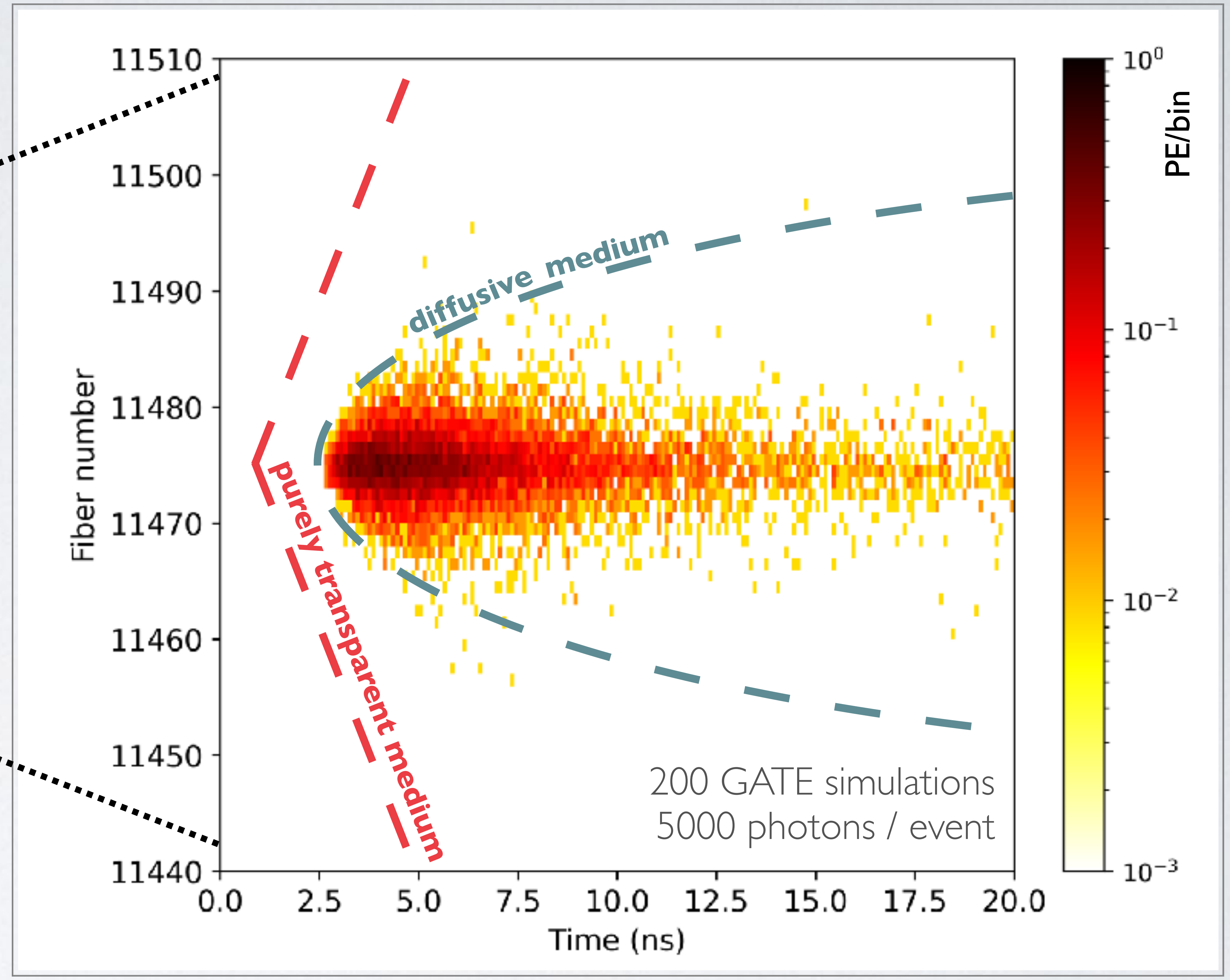


- Correlation between neighbouring fibers waveforms
- Diffusive medium $\Rightarrow t \propto r^2$ slower than transparent medium
- Pulse shape in each waveforms is Z-dependent
- **Input these correlations and pulse shape in spatial reconstruction**
- **Use Machine Learning networks ? change fiber distribution?**

Perspectives, improvements in Z measurement





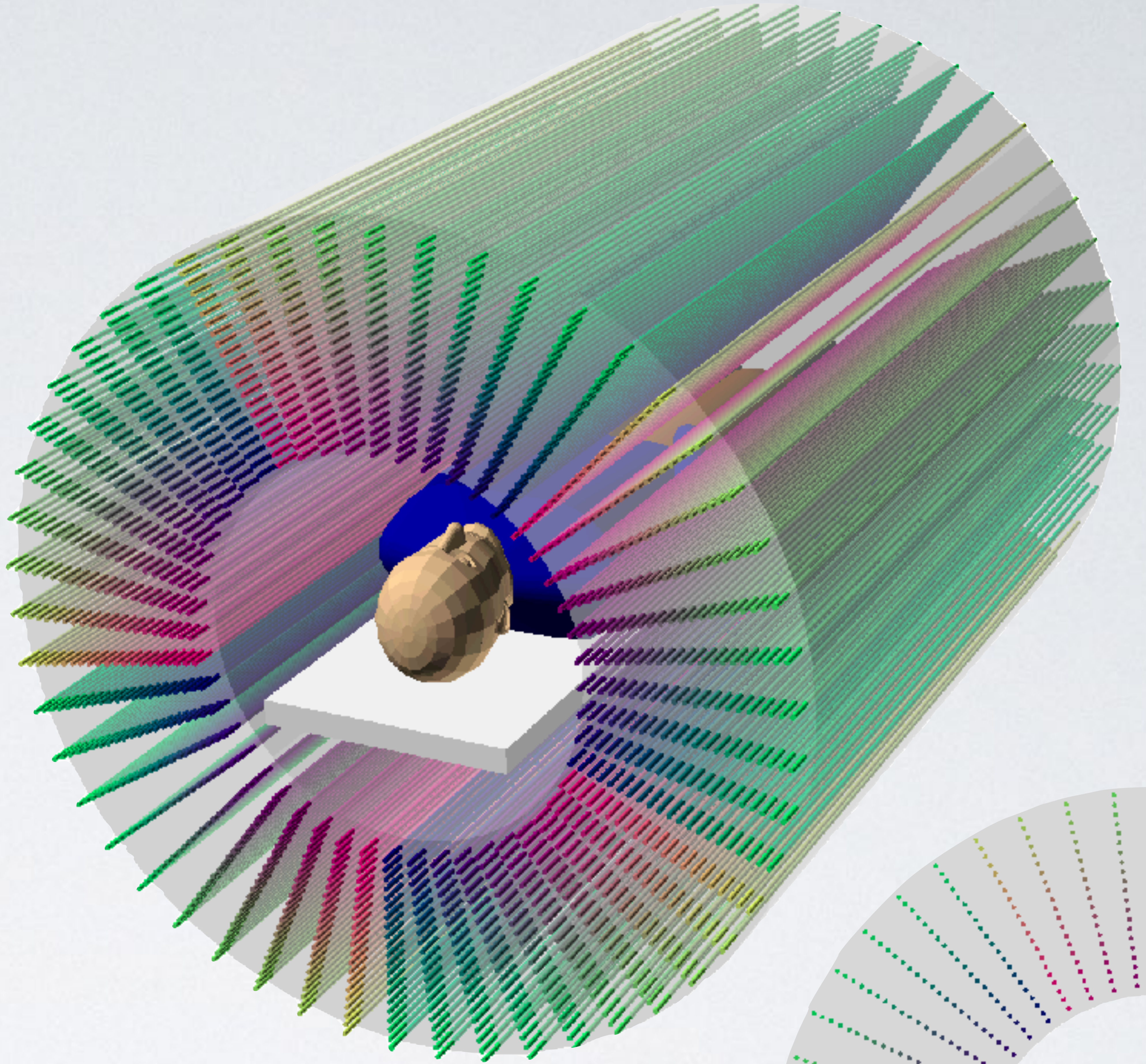


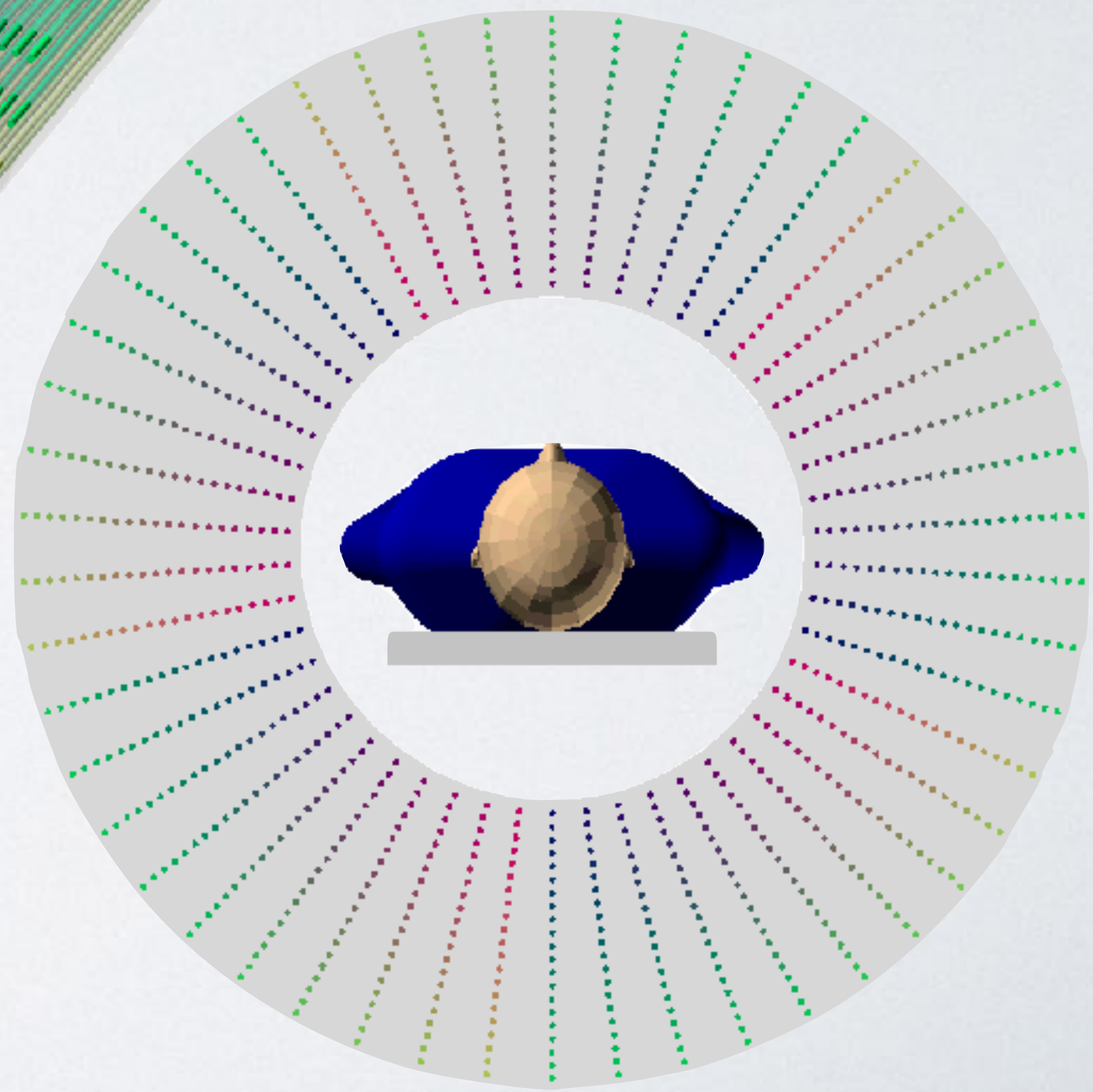
- Correlation between neighbouring fibers waveforms
- Diffusive medium $\Rightarrow t \propto r^2$ slower than transparent medium
- Pulse shape in each waveforms is Z-dependent
- **Input these correlations and pulse shape in spatial reconstruction**
- **Use Machine Learning networks ? change fiber distribution?**

Insurance Policy : Radial Fibers

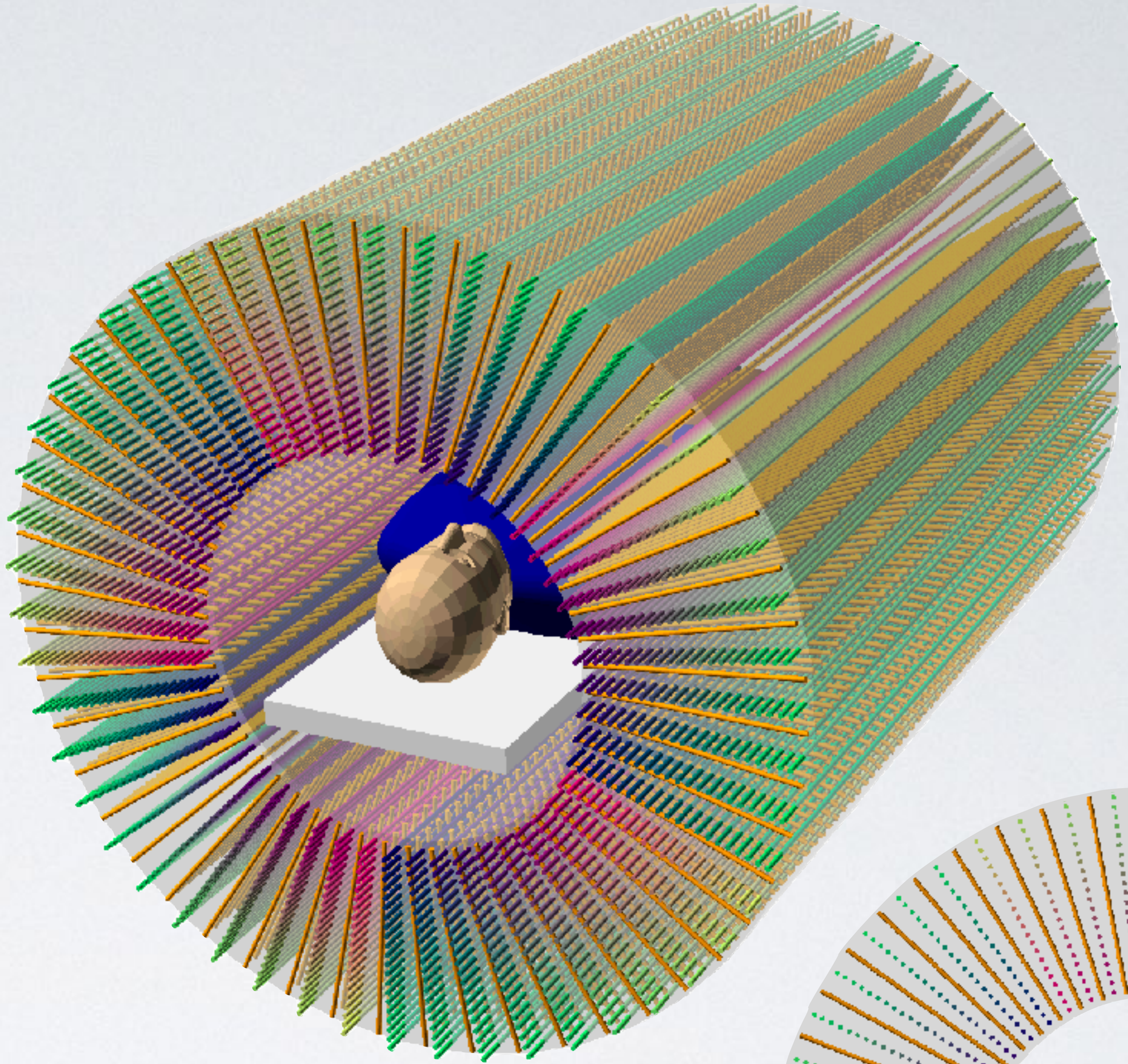
Target :
mm-level resolution on 1st Compton interaction in all dimensions

- native from the axial fibers in (X,Y) ✅
- not so easy in Z…





Insurance Policy : Radial Fibers

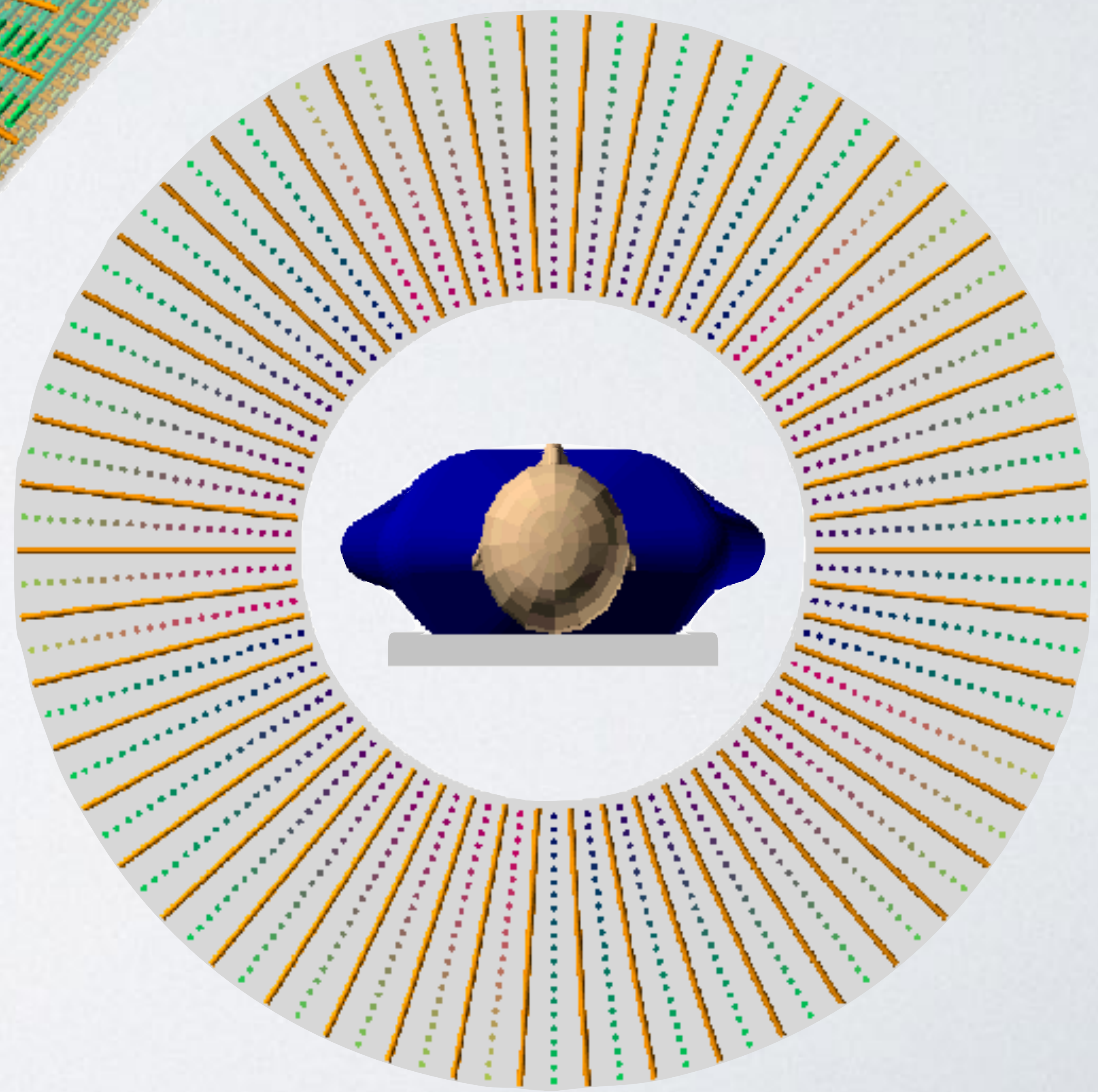


Target :
mm-level resolution on 1st Compton interaction in all dimensions

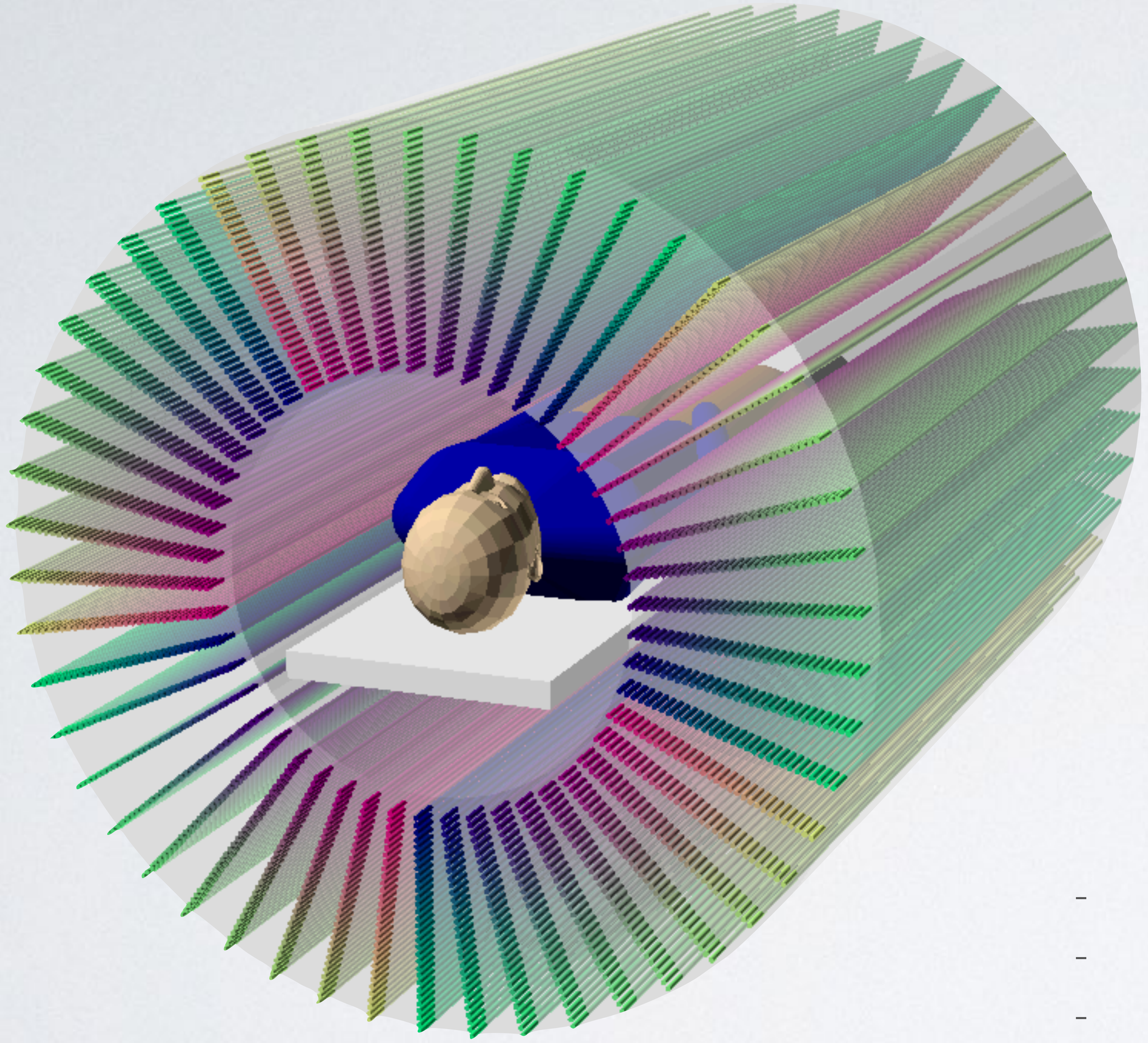
- native from the axial fibers in (X,Y) ✅
- not so easy in Z…

Possible solution :
add radial fibers (orange) between the axial fibers

- mm resolution in Z ✅
- high number of channels to instrument
  - data volume ⚠️
  - complex mechanical engineering ⚠️
  - cost of whole body PET ⚠️ → maybe an organ-dedicated PET ?

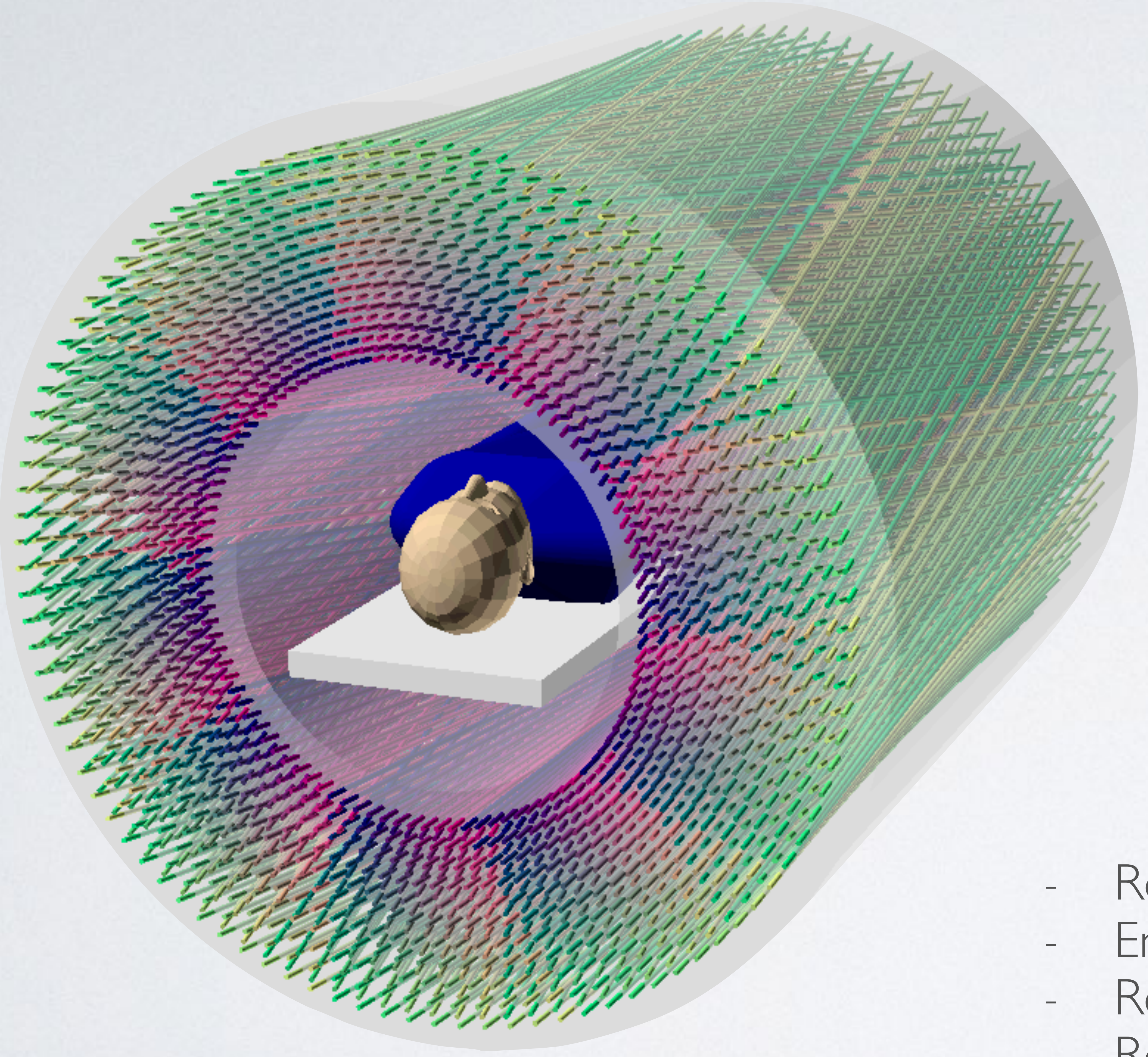


Smarter ways to constrain Z



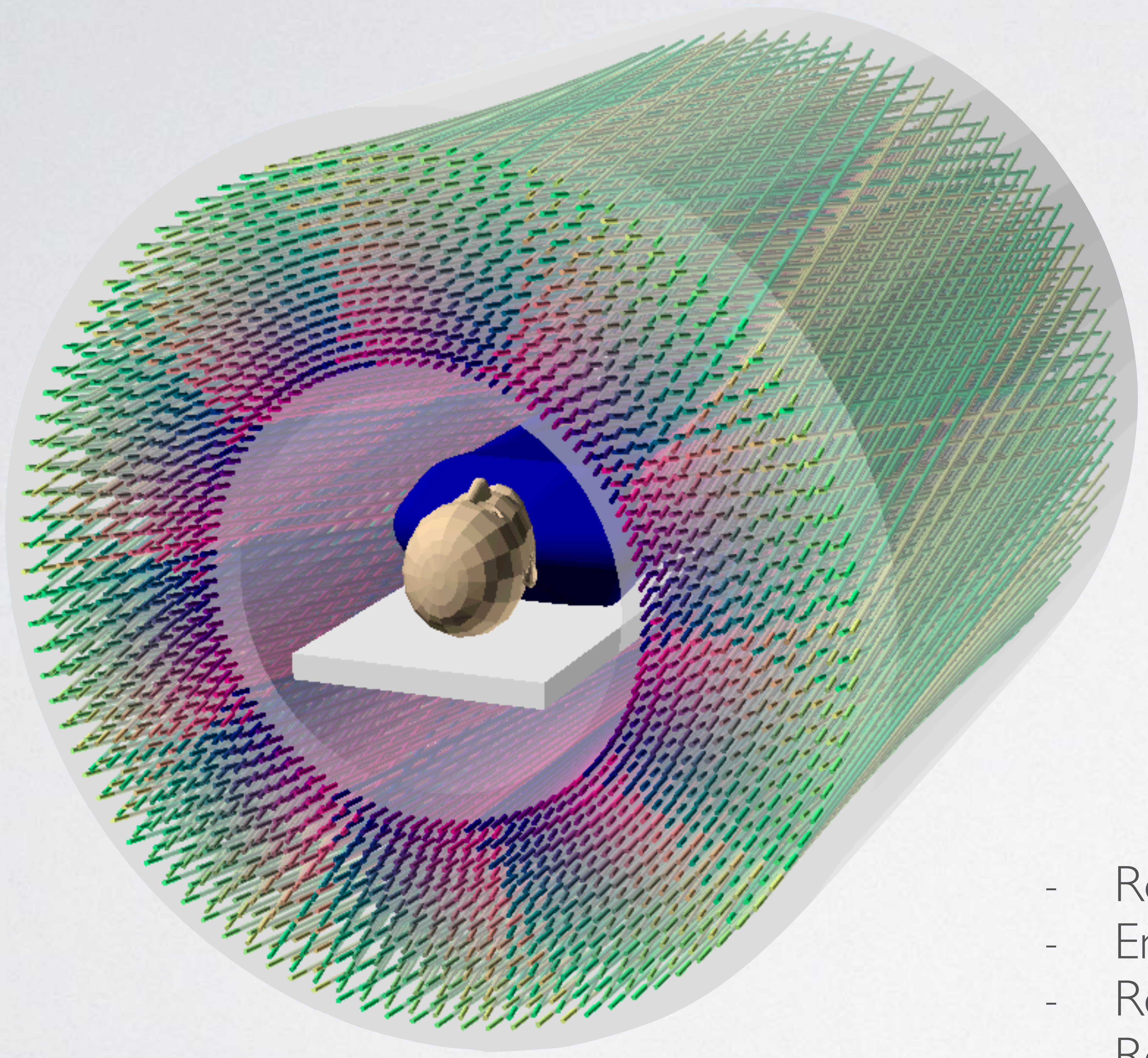
- Rotate fibers ±10° : geometrical constraints in Z
- Emission point is the intersection of two lines
- Resolution in (X,Y) < mm-level
- Resolution in Z ~ cm-level
- Purely topology for now

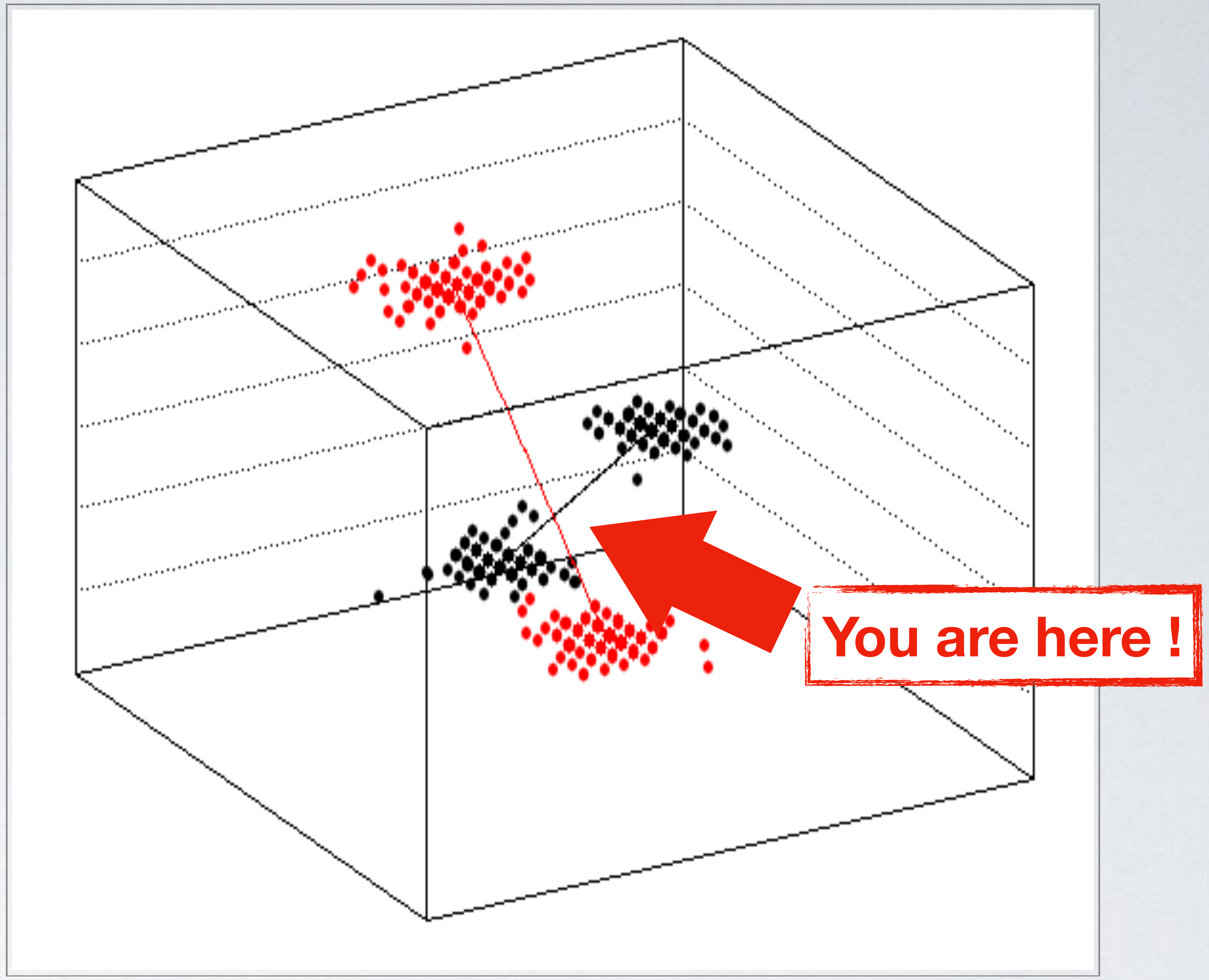
Smarter ways to constrain Z



- Rotate fibers ±10° : geometrical constraints in Z
- Emission point is the intersection of two lines
- Resolution in (X,Y) < mm-level
- Resolution in Z ~ cm-level
- Purely topology for now

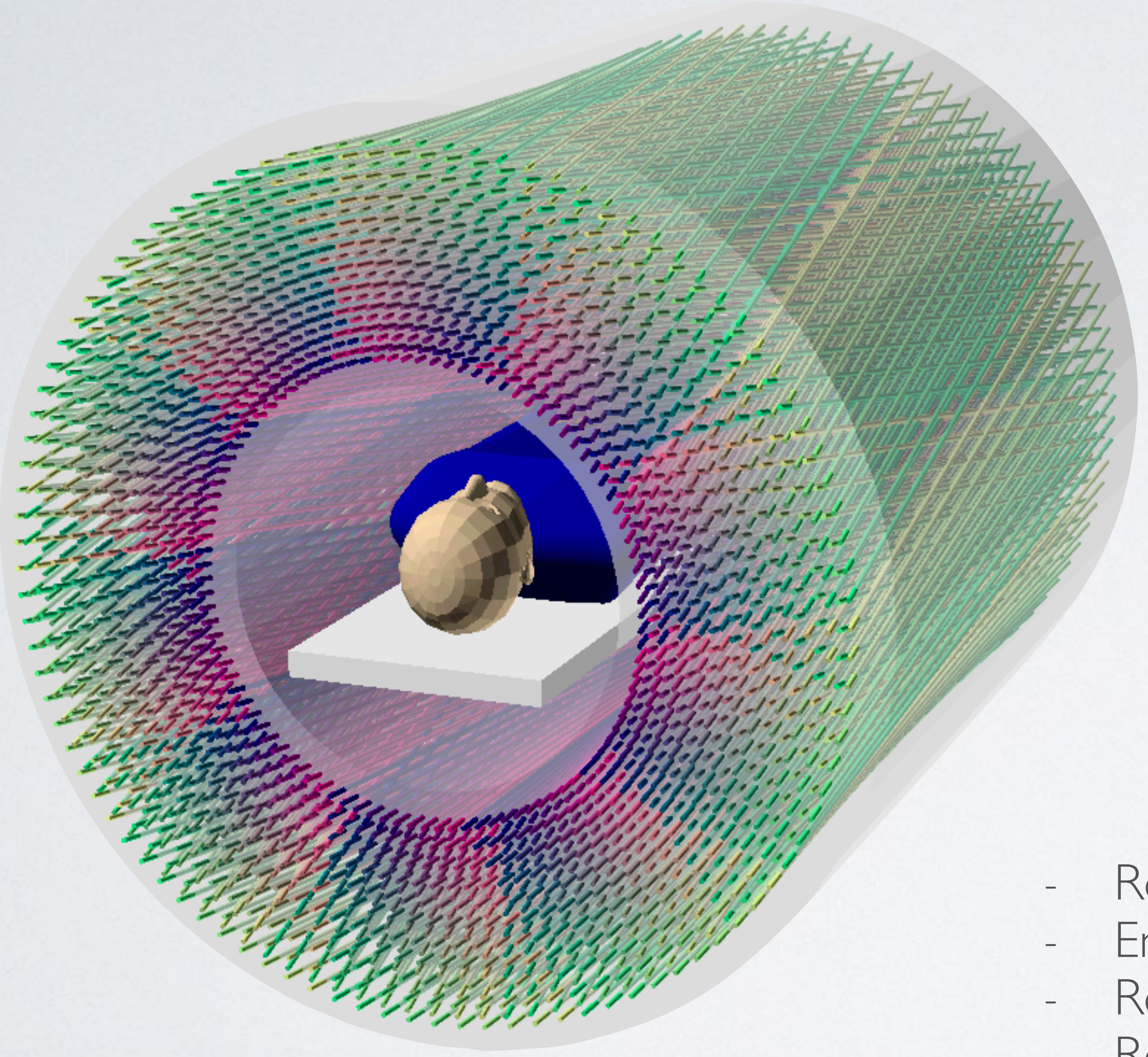
Smarter ways to constrain Z

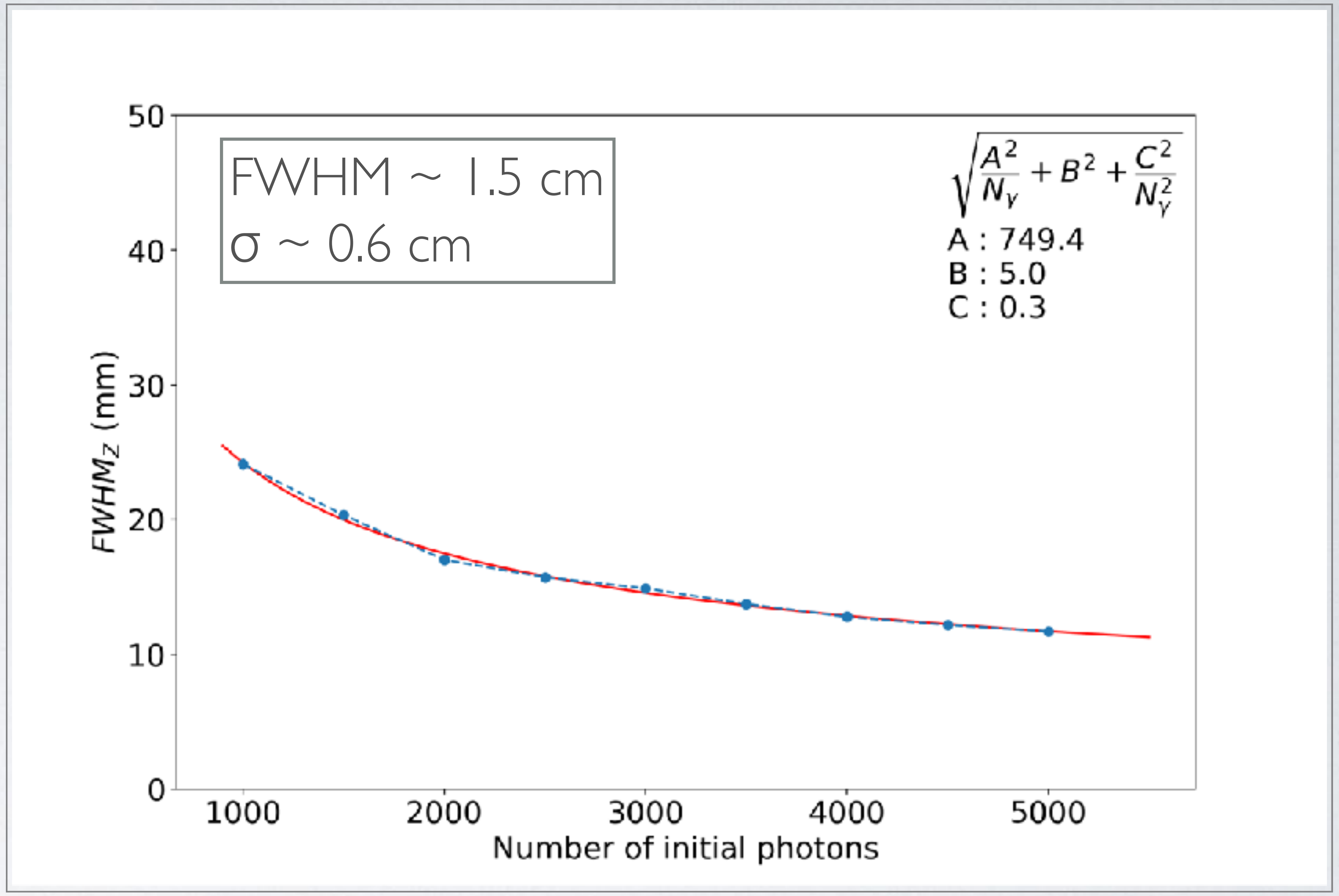




- Rotate fibers ±10° : geometrical constraints in Z
- Emission point is the intersection of two lines
- Resolution in (X,Y) < mm-level
- Resolution in Z ~ cm-level
- Purely topology for now

Smarter ways to constrain Z





- Rotate fibers ±10° : geometrical constraints in Z
- Emission point is the intersection of two lines
- Resolution in (X,Y) < mm-level
- Resolution in Z ~ cm-level
- Purely topology for now

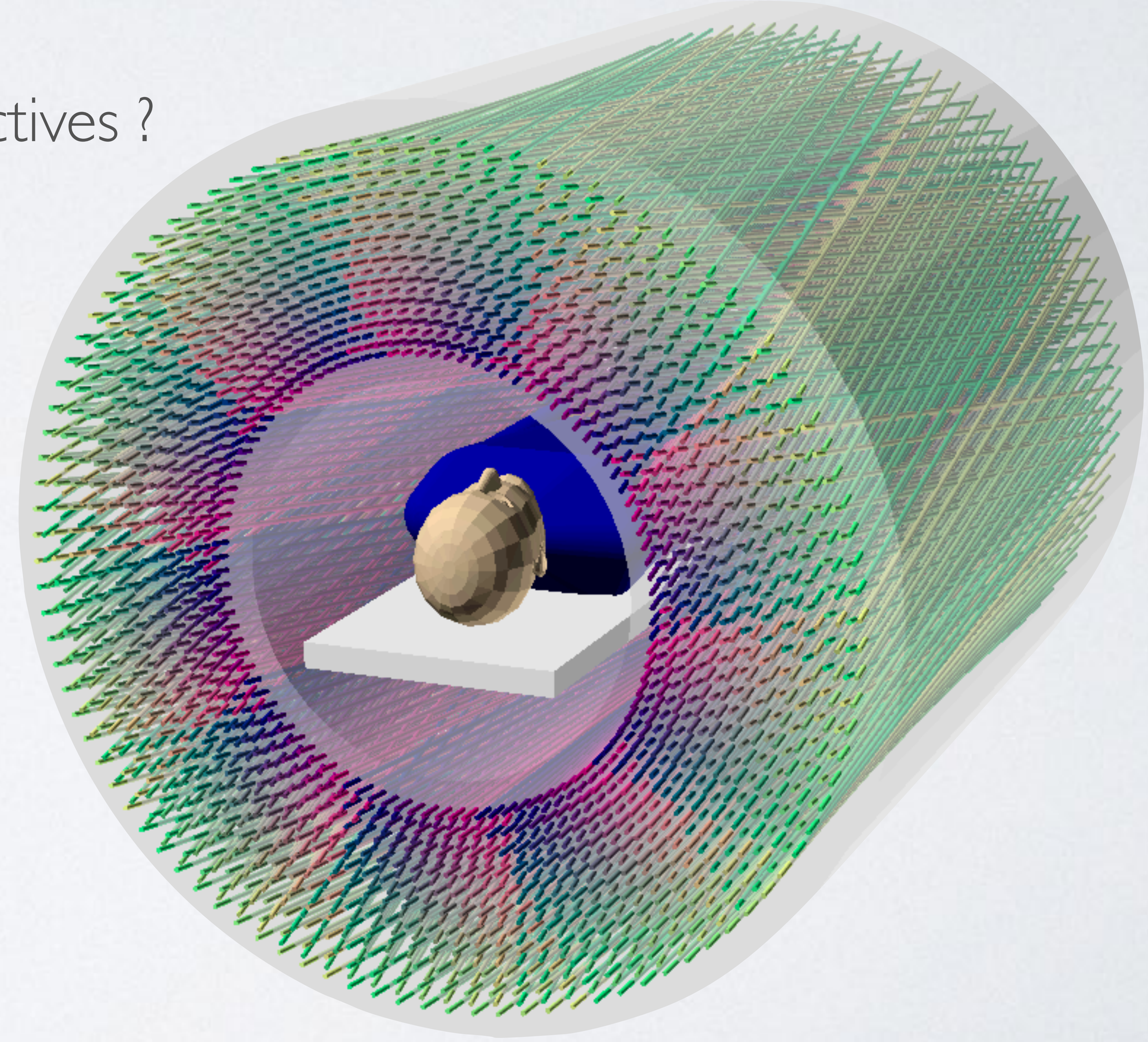
Summary

L-PET proposes to use an innovative detection technology

- Continuous detector
- Axial fiber distribution ⇒ full body coverage
- ~90% detection efficiency
- Millimeter-level spatial resolution
- ~100 ps coincidence time resolution
- 3γ imaging
- O-Ps lifetime parametric imaging ⇒ new diagnostic perspectives ?

ANR Funding for a first demonstrator

- test feasibility of the new technology
- test gamma tracking capabilities
- test image reconstruction
- validate simulations & physics
- Establish requirements for future prototypes

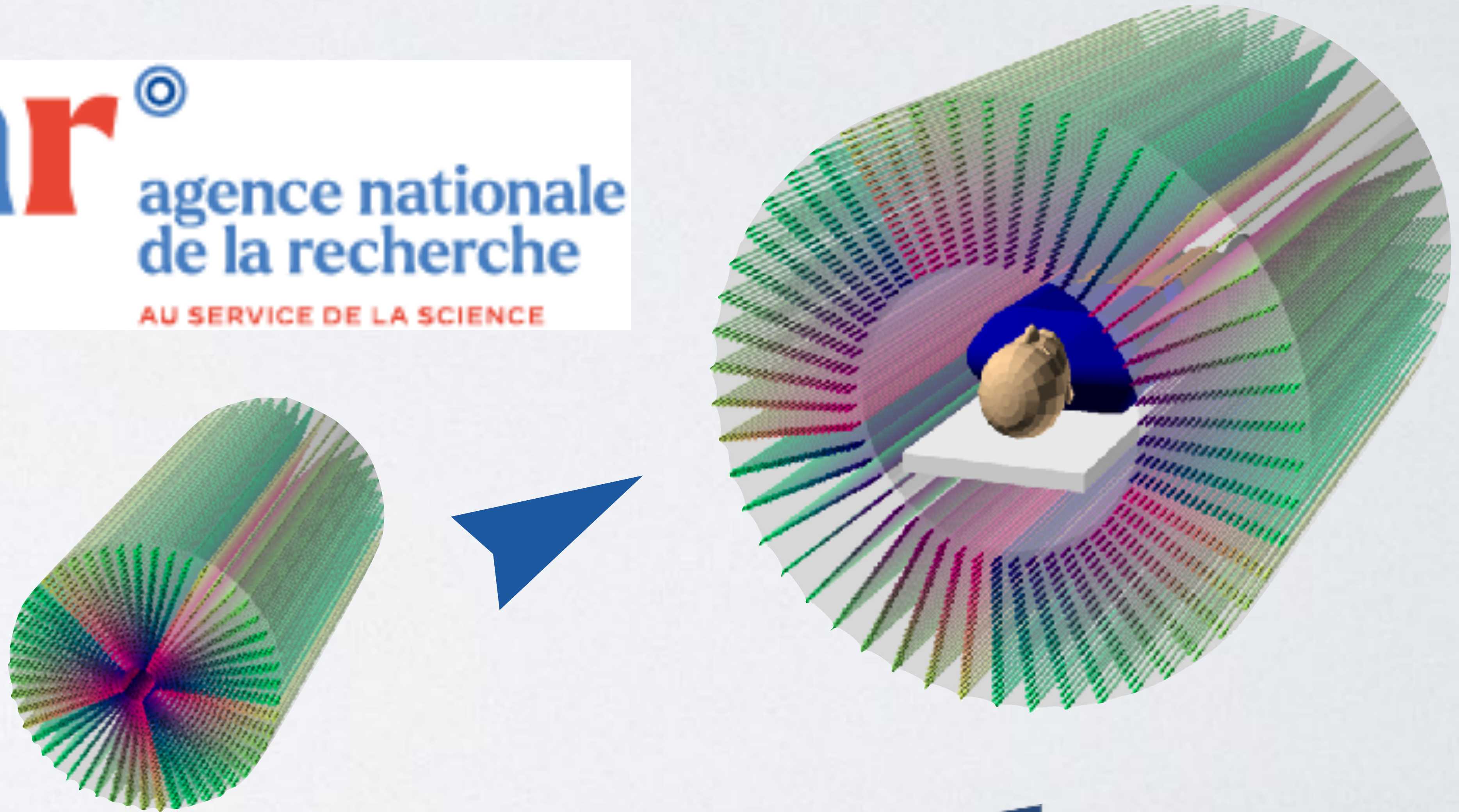


LPET-OTech Consortium

M. Bongrand[d], C. Bourgeois[aα], D. Brasse[*b], D. Breton[aα], M. Briere[aα], A. Cabrera[†aα], V. Chaumat[aα], A. Dahmane[b], R. Gazzini[aα], D. Giovagnoli[b], F. Haddad[d], A. Hourlier[b], G. Hull[aα], P. Lanièce[aβ], F. Lefevre[d], P. Loaiza[aα], J. Maalmi[aα], Y. Mellak[c], T. Merlin[c], R. Mastrippolito[aβ], C. Marquet[‡aα], L. Ménard[aβ], D. Navas-Nicolás[aα], P. Pillot[d], L. Simard[aα], D. Stocco[d], M.-A. Verdier[aβ], D. Visvikis[c], and F. Yermia[d]

[aα]Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
[aβ]Université de Paris Cité, CNRS/IN2P3, IJCLab, 91405 Orsay, France
[b]Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
[c]LaTIM, INSERM U1101, Université de Brest, 29609 Brest, France
[d]Subatech, CNRS/IN2P3, Nantes Université, IMT-Atlantique, 44307 Nantes, France

anr agence nationale de la recherche AU SERVICE DE LA SCIENCE



CNRS Inserm IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis Subatech LATIM

LiquidO Consortium*

J. dos Anjos[a], L. Asquith[r], J.L. Beney[q], T.J.C. Bezerra[r], M. Bongrand[q], C. Bourgeois[fα], D. Brasse[g], D. Breton[fα], M. Briere[fα], J. Busto[b], A. Cabrera[†fα], A. Cadiou[q], E. Calvo[c], H. Carduner[q], V. Chaumat[fα], E. Chauveau[h], M. Chen[n], P. Chimenti[e], F. Dal Corso[kα], A. Dahmane[g], J.-F. Le Du[fα], S. Dusini[kα], A. Earle[r], C. Frigerio-Martins[e], J. Galán[s], J.A. García[s], R. Gazzini[fα], A. Gibson-Foster[r], D. Giovagnoli[g], P. Govoni[jα,jβ], M. Grassi[kβ], W.C. Griffith[r], F. Haddad[q], J. Hartnell[r], A. Hourlier[g], G. Hull[fα], I.G. Irastorza[s], L. Koch[iα], P. Laniéce[fα,fβ], P. Lasorak[r], C. Lefebvre[n], F. Lefevre[q], P. Loaiza[fα,fβ], G. Luzón[s], J. Maalmi[fα], F. Mantovani[dα,dβ], C. Marquet[h], M. Martínez[s], L. Ménard[fα,fβ], D. Navas-Nicolás[fα], H. Nunokawa[m], M. Obolensky[fα,fβ], J.P. Ochoa-Ricoux[o], C. Palomares[c], P. Pillot[q], J.C.C. Porter[r], M. S. Pravikoff[h], M. Roche[h], B. Roskovec[l], M.L. Sarsa[s], S. Schoppmann[iβ], A. Serafini[kα,kβ], L. Simard[fα], M. Sisti[jα], D. Stocco[q], V. Strati[dα,dβ], J.-S. Stutzmann[q], F. Suekane[‡p], M.-A. Verdier[fα,fβ], A. Verdugo[c], B. Viaud[q], A. Weber[iα], and F. Yermia[q]

[a]Centro Brasileiro de Pesquisas Físicas (CBPF), Rua Xavier Sigaud 150, Rio de Janeiro, 22290-180, Brazil
[b]Université d'Aix Marseille, CNRS/IN2P3, CPPM, Marseille, France
[c]CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Av. Complutense 40, E-28040 Madrid, Spain
[dα]INFN, Ferrara Section, Via Saragat 1, 44122 Ferrara, Italy
[dβ]Department of Physics and Earth Sciences, University of Ferrara, Via Saragat 1, 44122 Ferrara, Italy
[e]Departamento de Física, Universidade Estadual de Londrina, Rodovia Celso Garcia Cid, PR 445 Km 380, Campus Universitário Cx. Postal 10.011, CEP 86.057-970, Londrina – PR, Brazil
[fα]Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
[fβ]Université de Paris Cité, CNRS/IN2P3, IJCLab, 91405 Orsay, France
[g]Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
[h]Université de Bordeaux, CNRS, LP2I Bordeaux, UMR 5797, F-33170 Gradignan, France
[iα]Johannes Gutenberg-Universität Mainz, Institut für Physik, Staudingerweg 7, 55128 Mainz, Germany
[iβ]Johannes Gutenberg-Universität Mainz, Detektorlabor, Exzellenzcluster PRISMA+, Staudingerweg 9, 55128 Mainz, Germany
[jα]INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy
[jβ]Dipartimento di Fisica, Università di Milano-Bicocca, I-20126 Milano, Italy
[kα]INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy
[kβ]Dipartimento di Fisica e Astronomia, Università di Padova, via Marzolo 8, I-35131 Padova, Italy
[l]Institute of Particle and Nuclear Physics Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2 180 00 Prague 8, Czech Republic
[m]Department of Physics, Pontifícia Universidade Católica do Rio de Janeiro, C.P. 38097, 22451-900, Rio de Janeiro, Brazil
[n]Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, Ontario K7L3N6, Canada
[o]Department of Physics and Astronomy, University of California at Irvine, 4129 Frederick Reines Hall, Irvine, California 92697, USA
[p]RCNS, Tohoku University, 6-3 AzaAoba, Aramaki, Aoba-ku, 980-8578, Sendai, Japan
[q]Subatech, CNRS/IN2P3, Nantes Université, IMT-Atlantique, 44307 Nantes, France
[r]Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom
[s]Centro de Astropartículas y Física de Altas Energías (CAPA), Universidad de Zaragoza, Calle Pedro Cerbuna 12, 50009 Zaragoza, Spain

*Email: `LiquidO-Contact-L@in2p3.fr`.
†Email: `anatael@in2p3.fr`.
‡Email: `suekane@awa.tohoku.ac.jp`