Quantum Entanglement of Positron Annihilation Gamma

Fundamental research and applications to Positron Emission Tomography (PET) imaging.

Laura Stephenson

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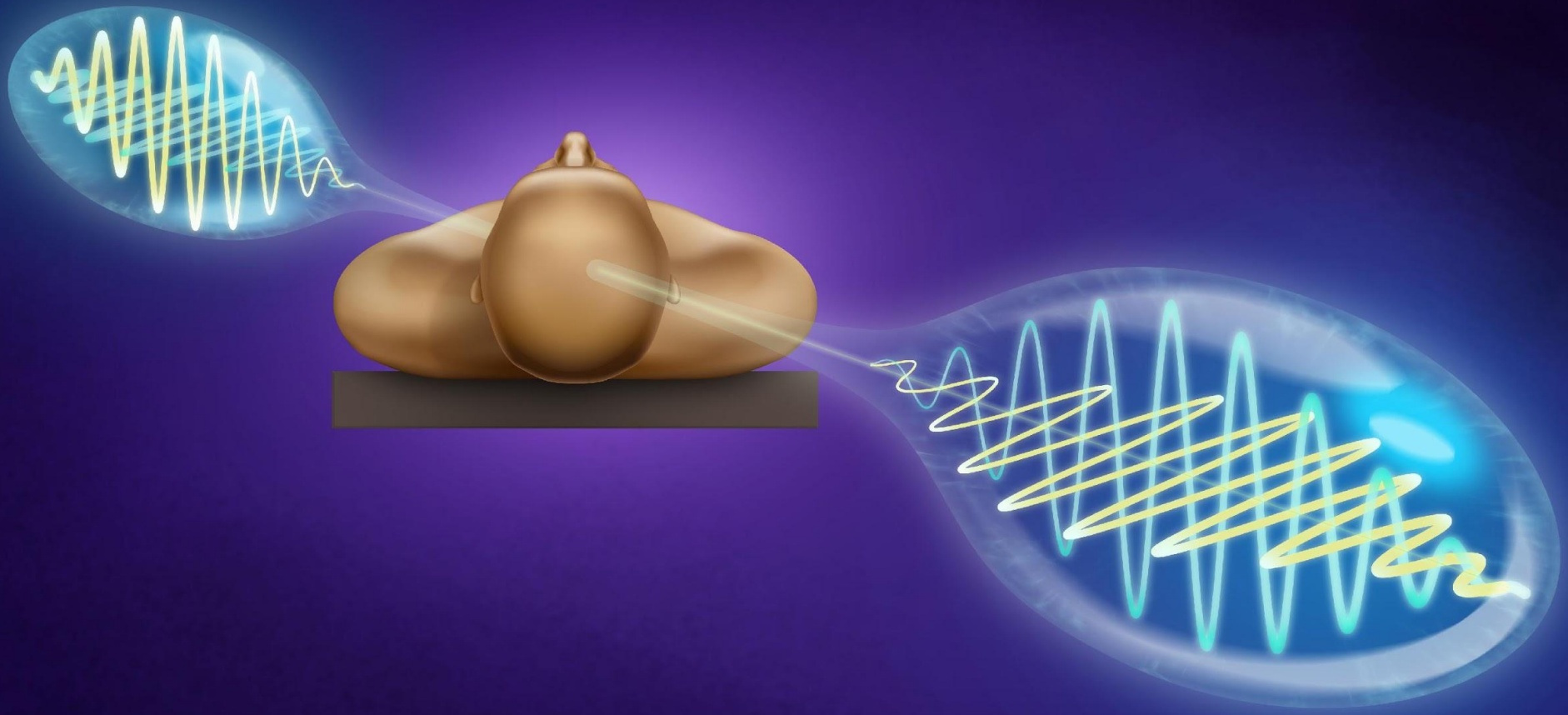
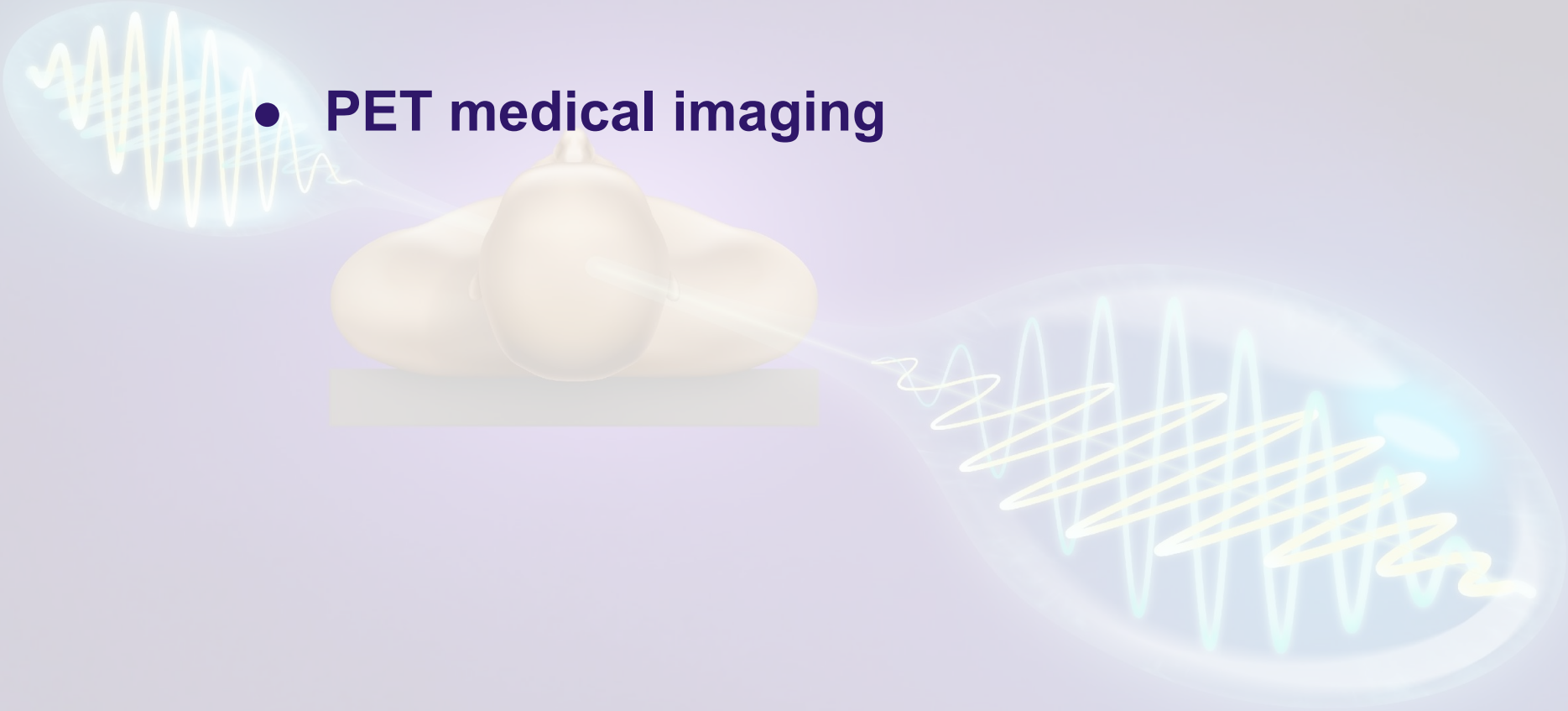
Prof Kenji Shimazoe, Dr Mizuki Uenomachi, Macoto Fujimoto, Dr Peter Caradonna, Moh Hamdan, Riku Sato (University of Tokyo)
Prof Steve Archibald, John Wright, Dr Isaline Renard (King's College London)
Prof Harry Tsoumpas (Groningen PET research centre)



- **PET medical imaging**



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- Observing high-energy photonic entanglement

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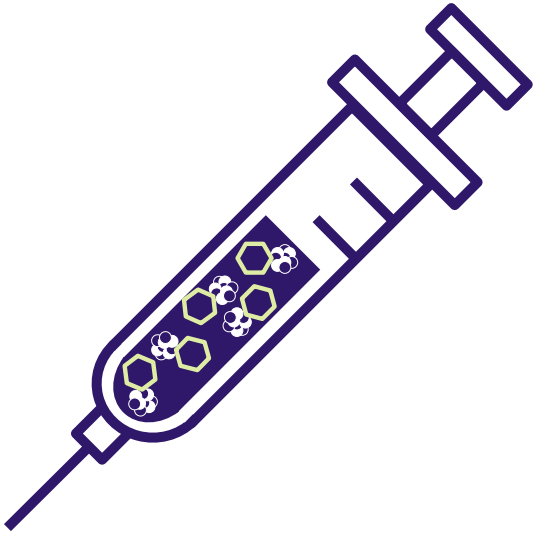
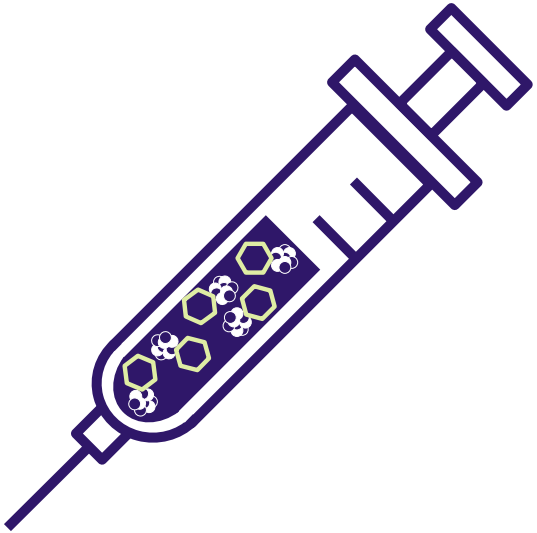
- Mysteries of Decoherence of Entanglement
- Novel method of PET Imaging

Positron Emission Tomography



Patient is injected with a **radiopharmaceutical**: Positron emitter labeled to biological molecule.

Positron Emission Tomography



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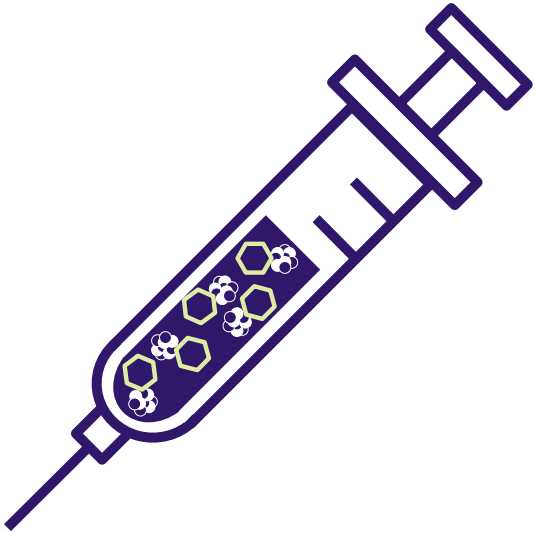

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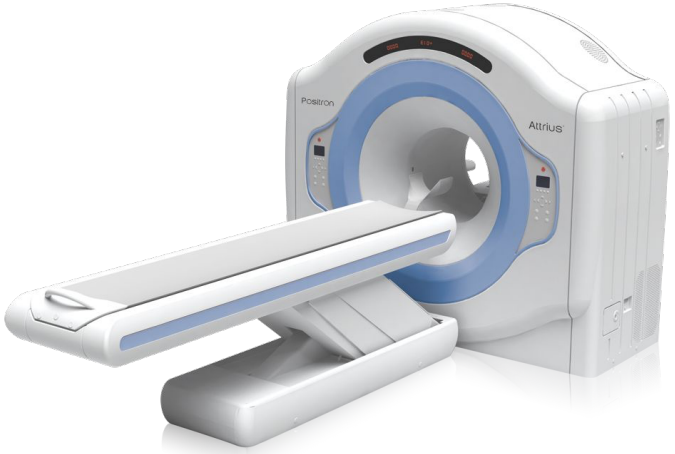


Patient enters scanner, positrons **annihilate** with electrons in the patient generating photons.

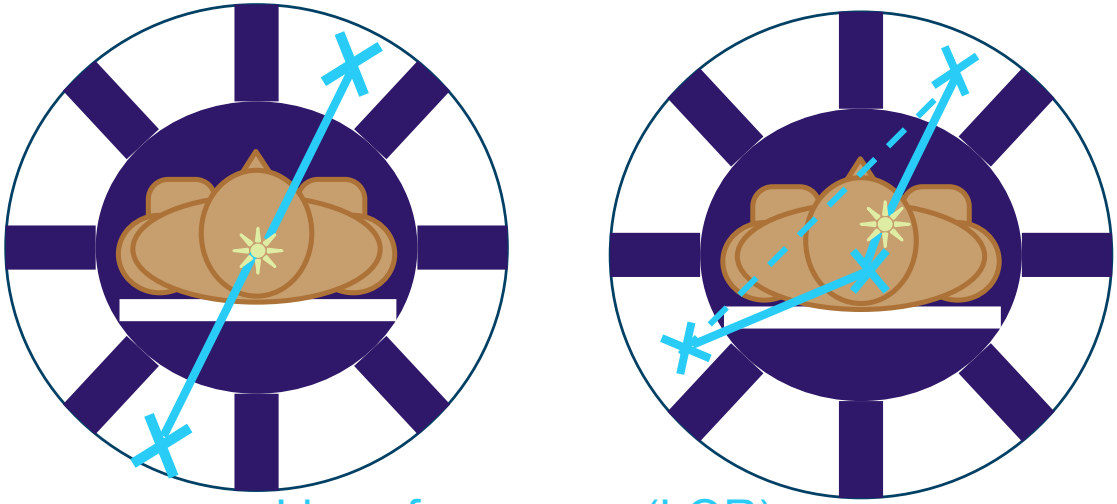
Challenges in PET Images

Line of response (LOR)

Good Event

Two back-to-back photons detected in the scanner and true LOR reconstructed

Challenges in PET Images



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Scatter Event

Photon(s) scatter(s) in the patient leading to incorrect LOR reconstruction

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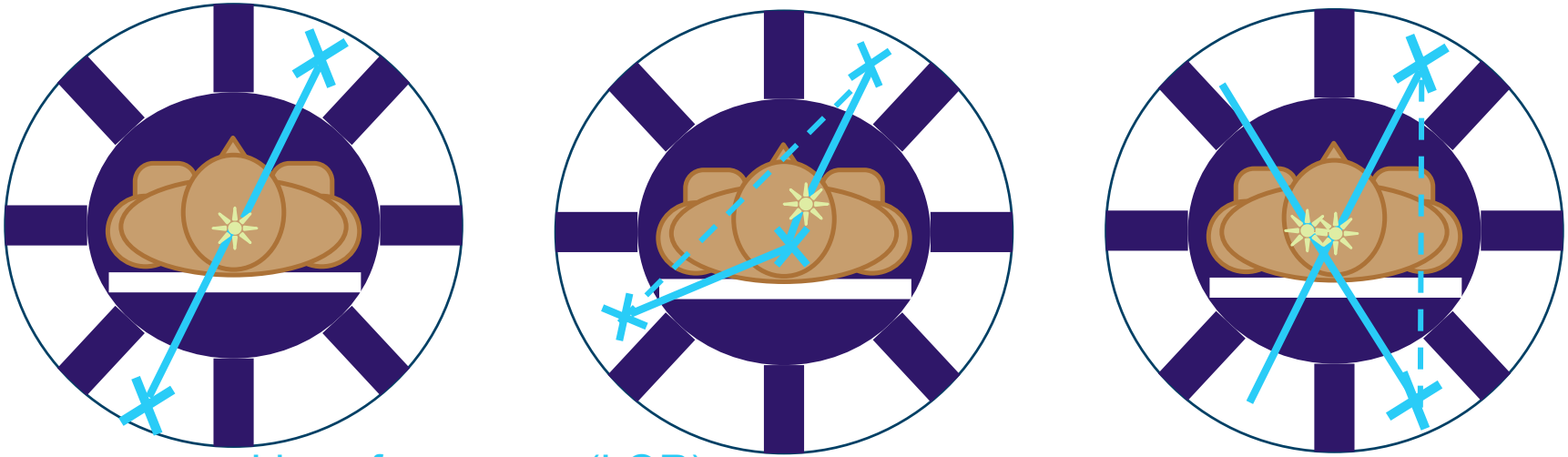

Line of response (LOR)

Good Event

Two back-to-back photons detected in the scanner and true LOR reconstructed

Scatter Event

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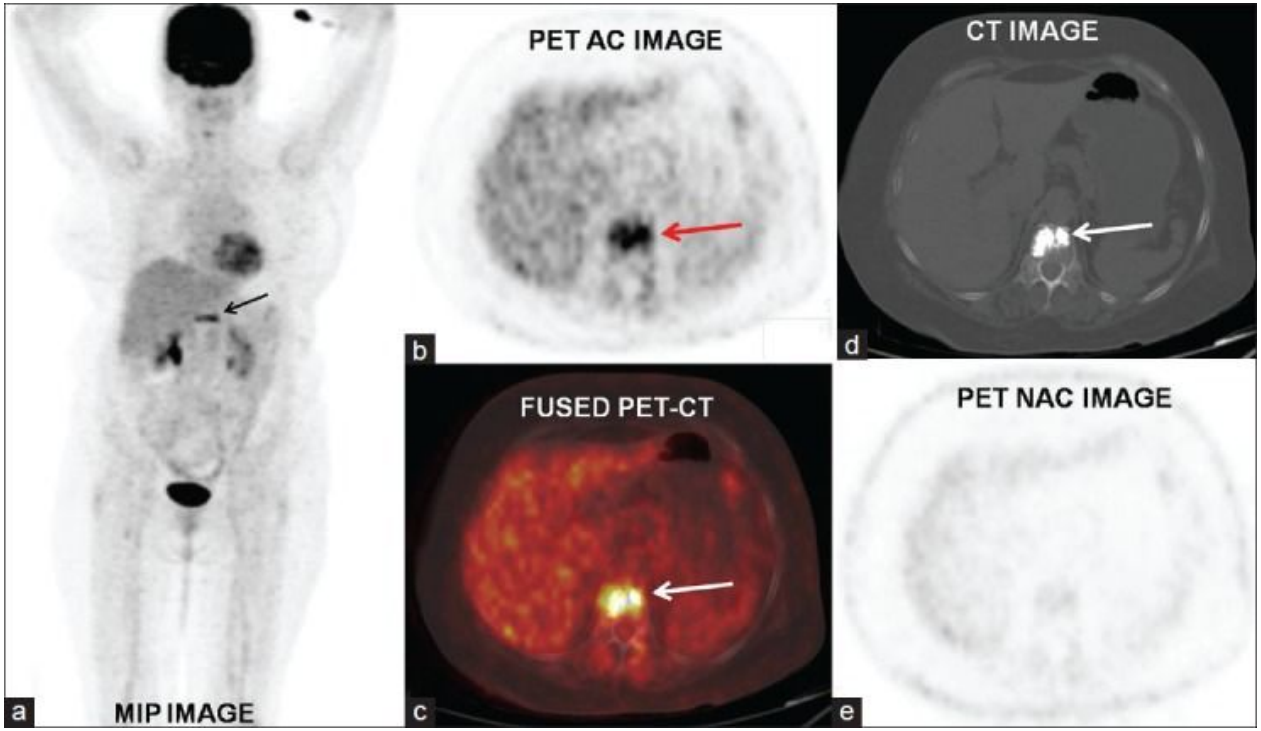
Coincident Event

Two e^+ annihilations occur generating four photons and incorrect LOR reconstructed

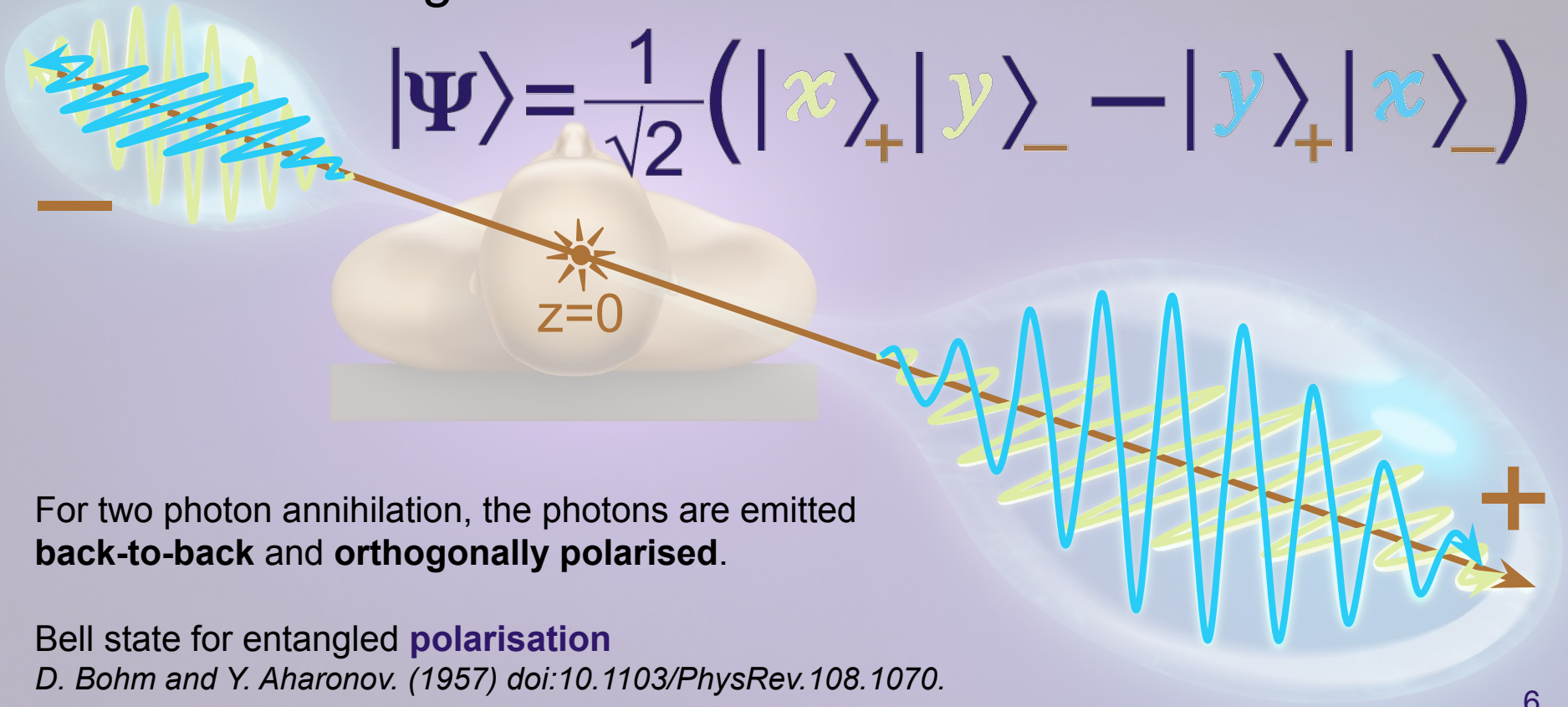


A) **MIP** Maximum Intensity Projection
B) **AC-PET** Attenuation corrected PET
C) **CT** image
D) **fused PET-CT**
E) **PET NAC** Non attenuation corrected PET
Diagnosis: Abnormal update of FDG tracer in D10 vertebrae, CT shows increased bone cement.

Joshi et al. (2014) doi:10.4103/0972-3919.125783

Photonic Entanglement

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|x\rangle_+|y\rangle_- - |y\rangle_+|x\rangle_-\right)$$



For two photon annihilation, the photons are emitted **back-to-back** and **orthogonally polarised**.

Bell state for entangled **polarisation**

D. Bohm and Y. Aharonov. (1957) doi:10.1103/PhysRev.108.1070.

Compton polarimeters

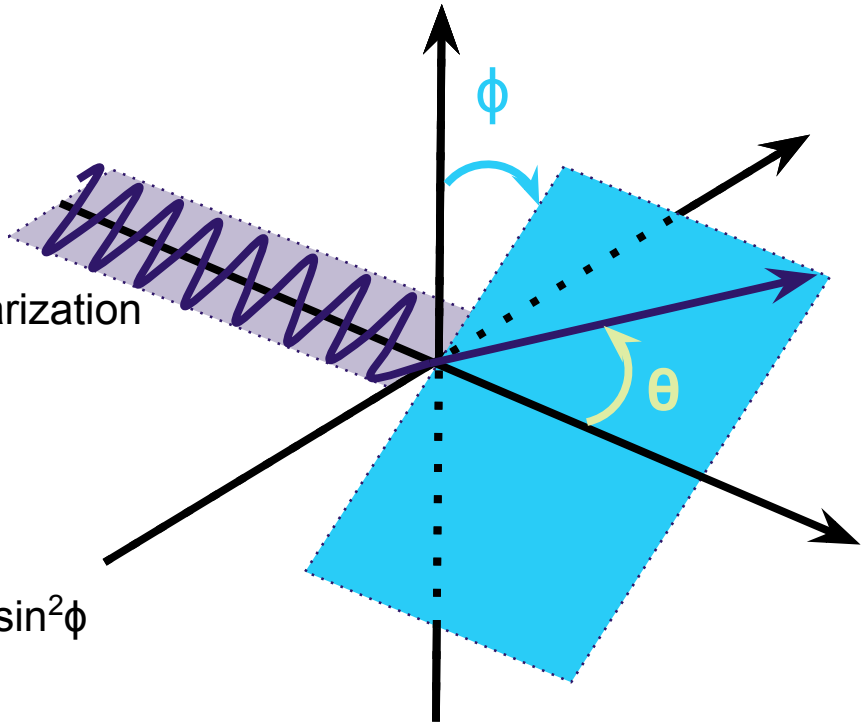
Compton scattering (CS)

$$\gamma + e^- \rightarrow \gamma' + e^{-'}$$

The scattering plane, ϕ, is dependant on the polarization

$$I = \frac{e^4}{r^2 m^2 c^4} I_0 \frac{\sin^2\phi}{[1+\alpha(1-\cos\theta)]^3}$$

CS described by Klein Nishina is proportional to $\sin^2\phi$
Therefore CS depends on γ polarization.

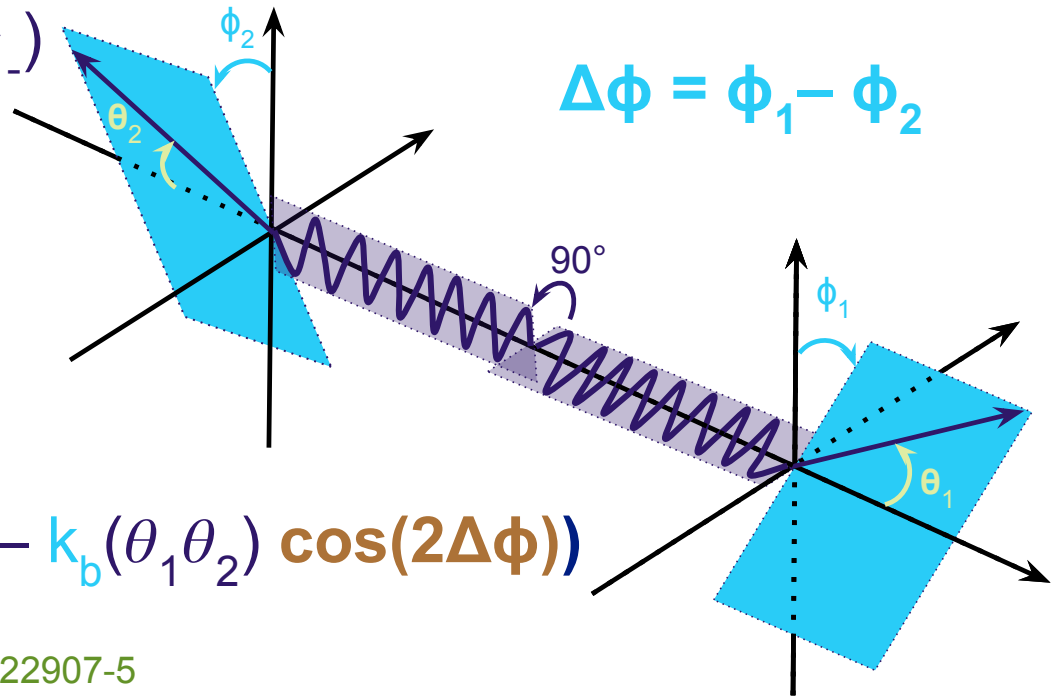


Yazaki, 2017,doi:10.2183/pjab.93.025

Double Compton Scattering

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|x\rangle_+ |y\rangle_- - |y\rangle_+ |x\rangle_- \right)$$

Taking the wavefunction of entangled photons, $|\Psi\rangle$, and incorporating it into Klein Nishina for CS gives double differential cross section:



$$\Delta\phi = \phi_1 - \phi_2$$

$$\frac{d^2\sigma}{d\Omega_1 d\Omega_2} = \frac{r_0^4}{16}\left(k_a(\theta_1\theta_2) - k_b(\theta_1\theta_2)\cos(2\Delta\phi) \right)$$

Watts et al. (2021) doi:10.1038/s41467-021-22907-5

Witnessing Entanglement

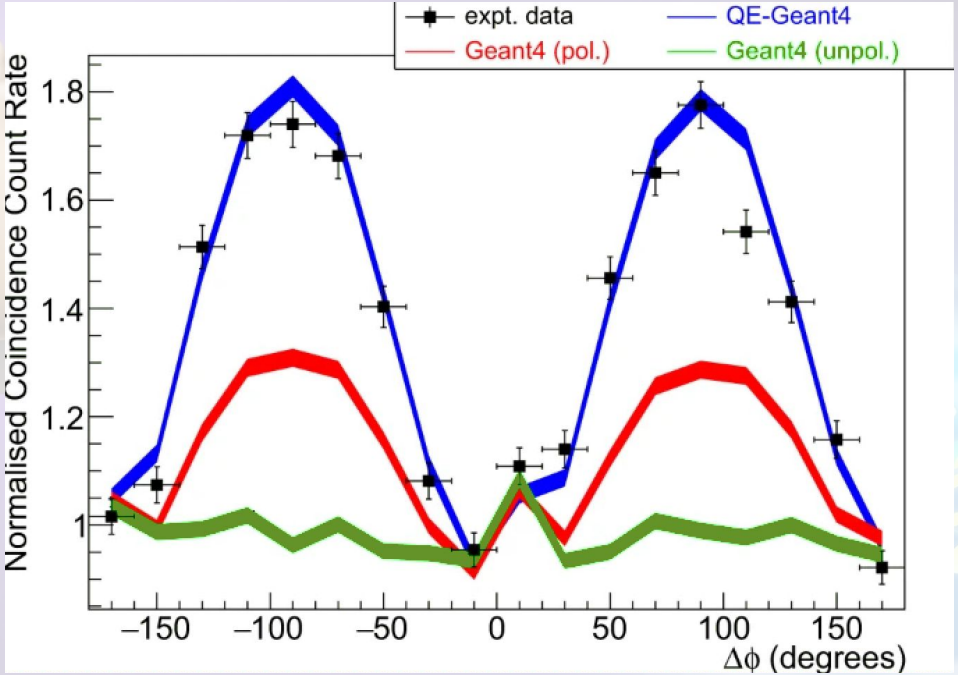
$$R = \frac{P_{\perp}(\theta)}{P_{//}(\theta)} \leq 2.85$$

R = 1.85 ± 0.004

University of York's QE Geant4 Simulation

R ≤ 1.63 (classical limit orthogonally polarised)

R ≈ 1 (unpolarised)



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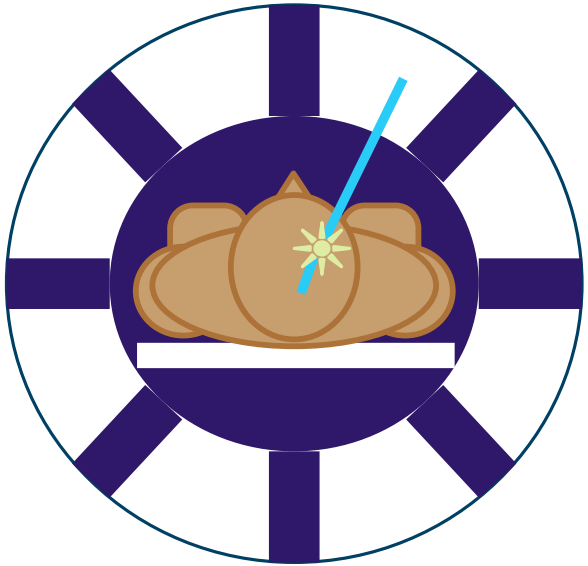
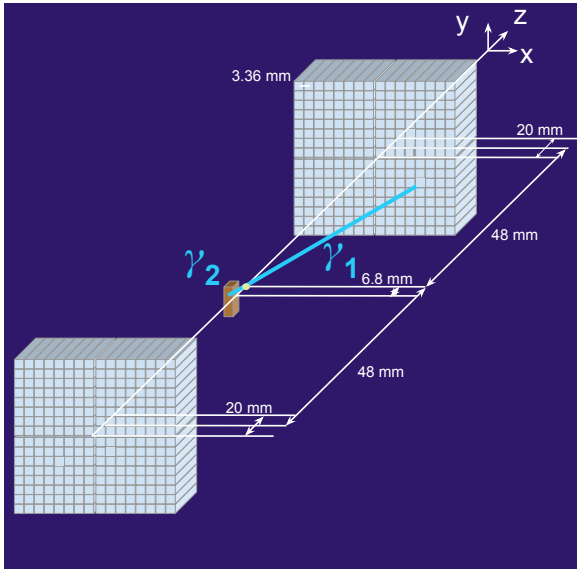
GithubRepository:https://github.com/Geant4/geant4/blob/master/source/processes/electromagnetic/lowenergy/src/G4LivermorePolarizedComptonModel.cc

Triple Compton Scatter (TCS)





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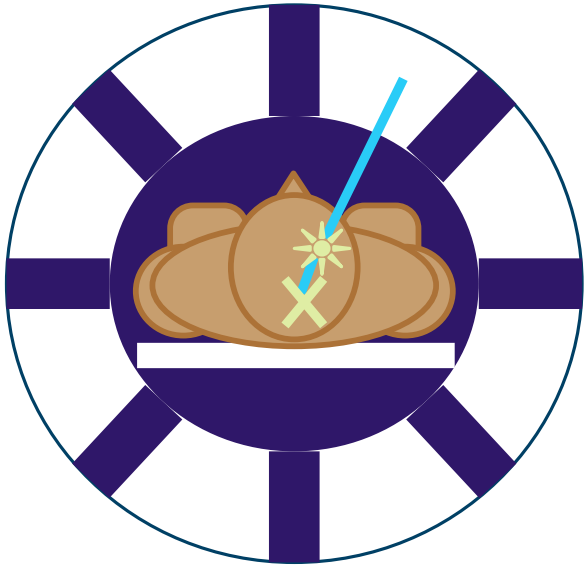

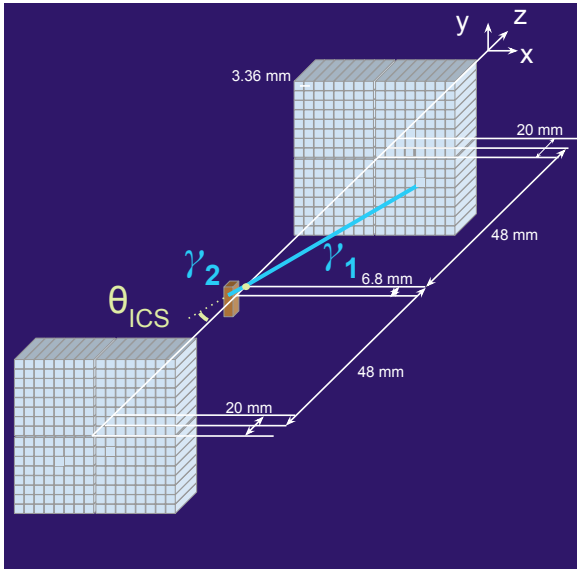

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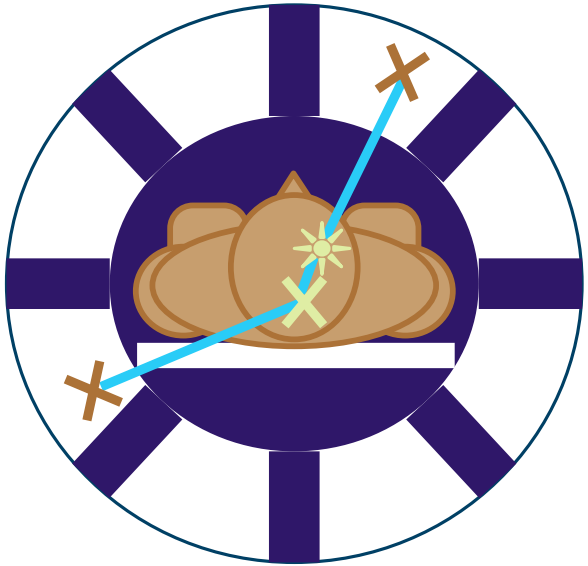

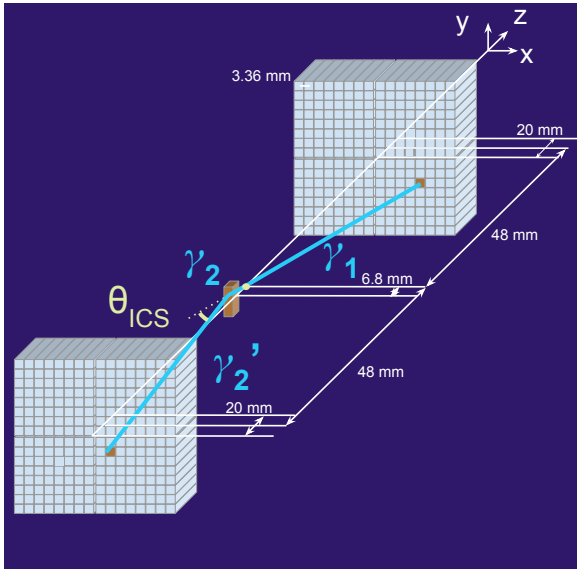

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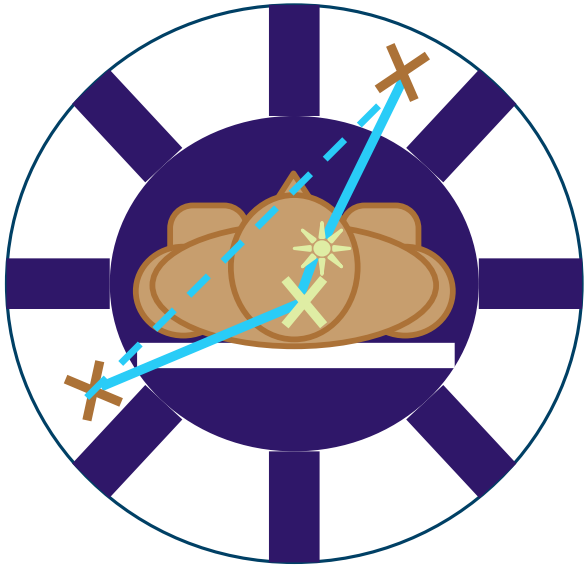

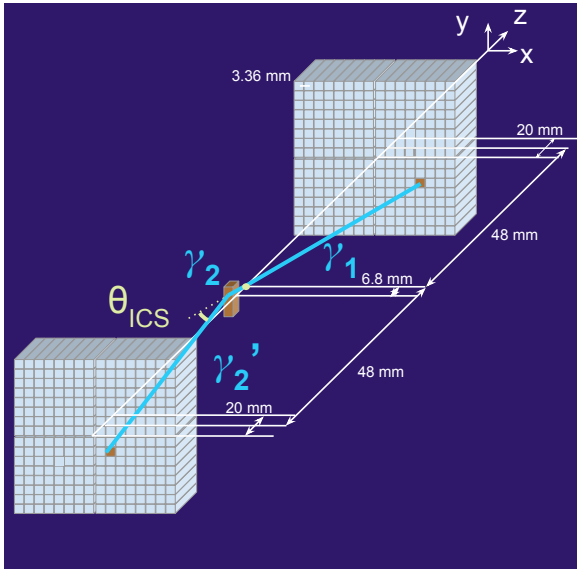

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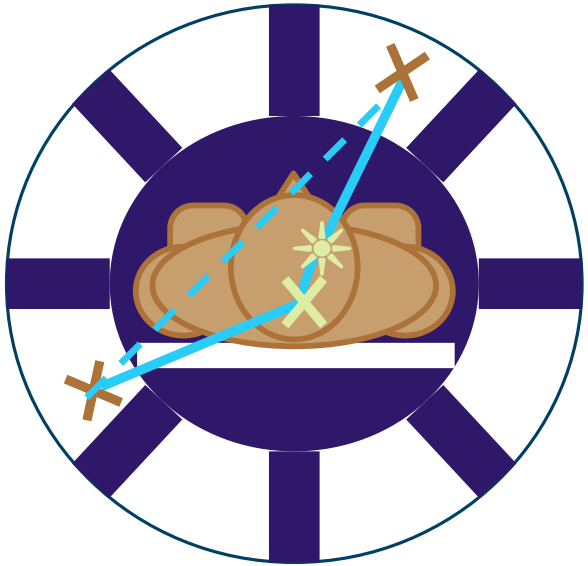

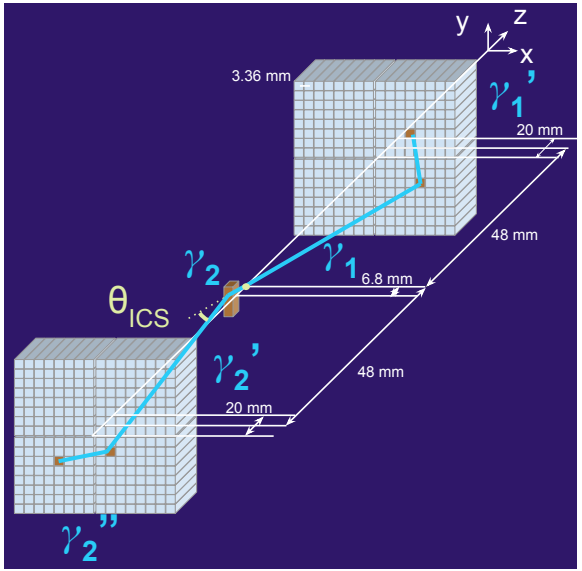

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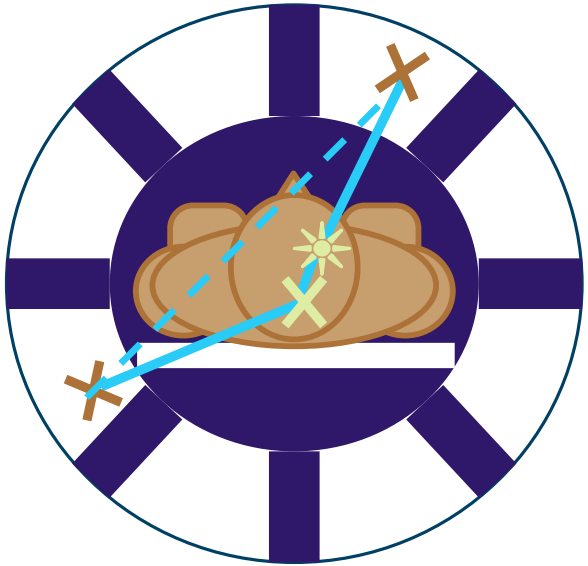

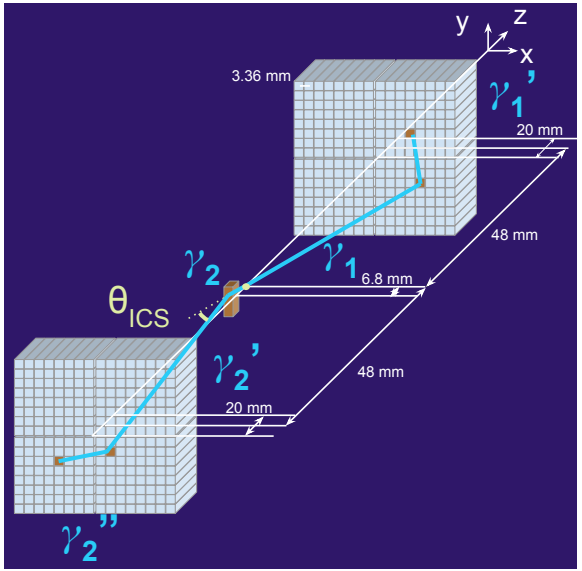

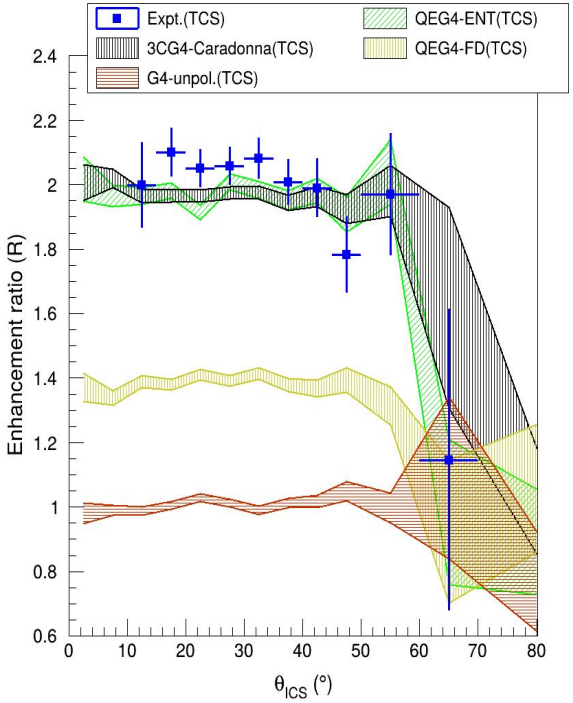

Bordes et al. (2024) doi:10.1103/PhysRevLett.133.132502

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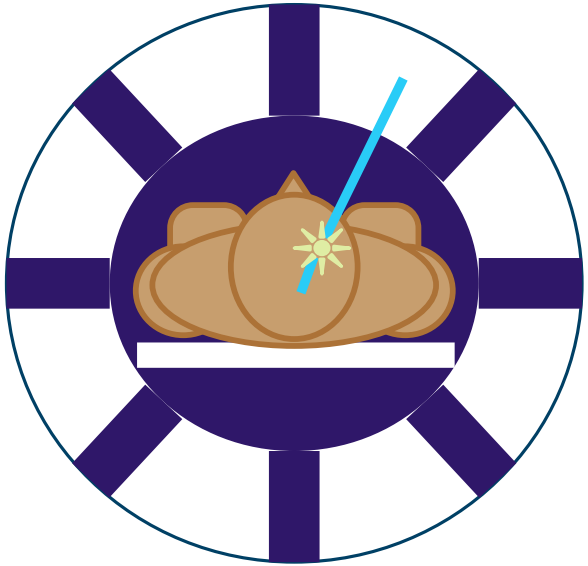

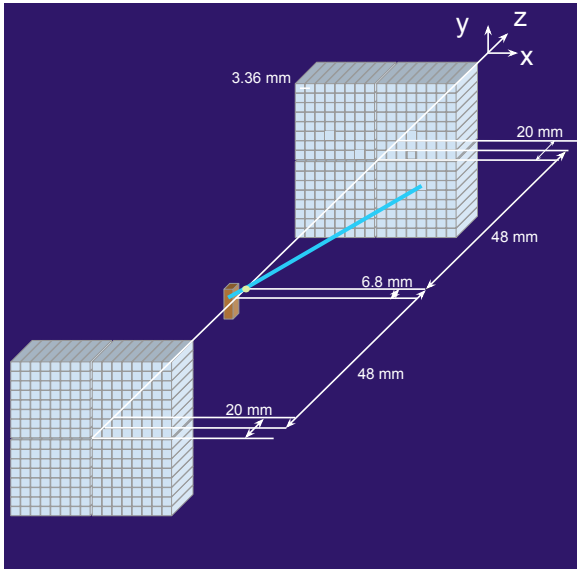

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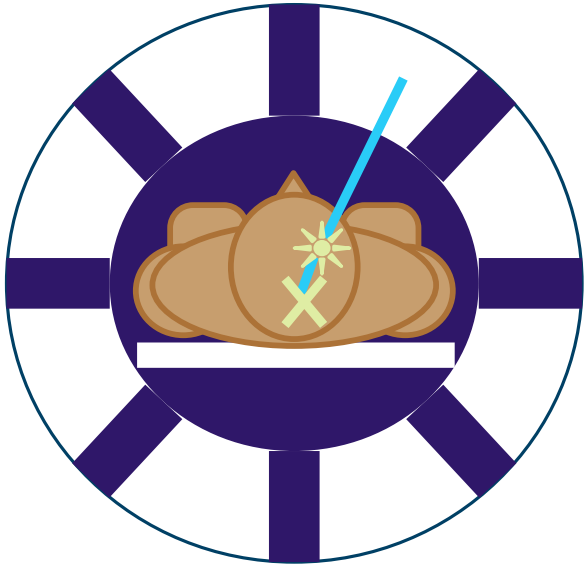

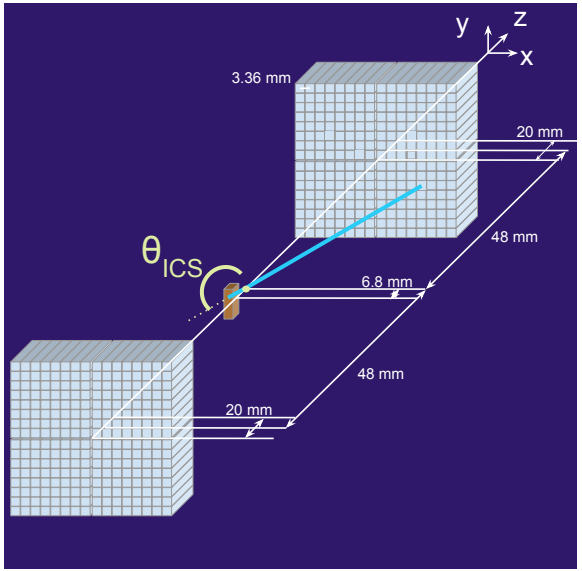

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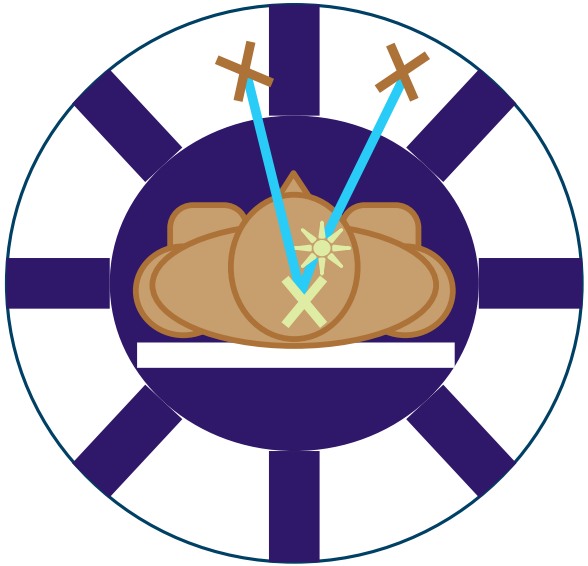

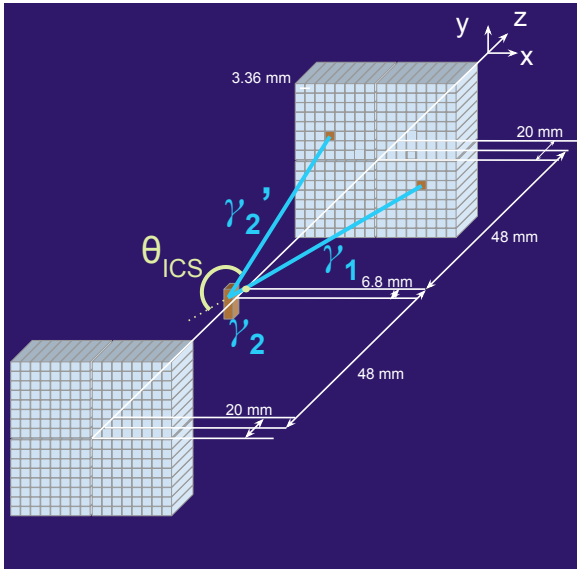

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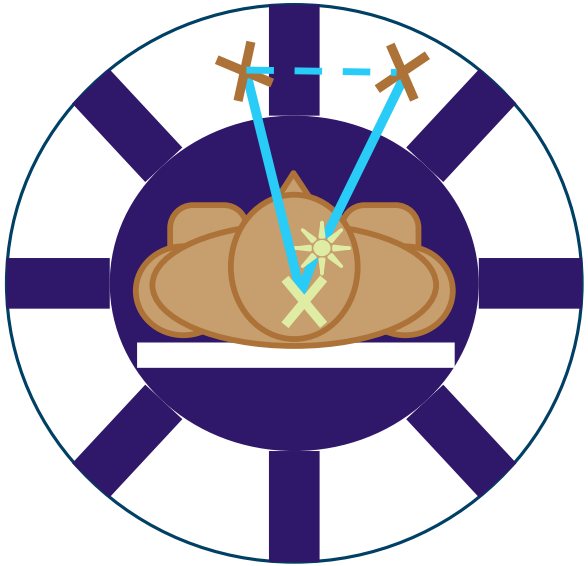

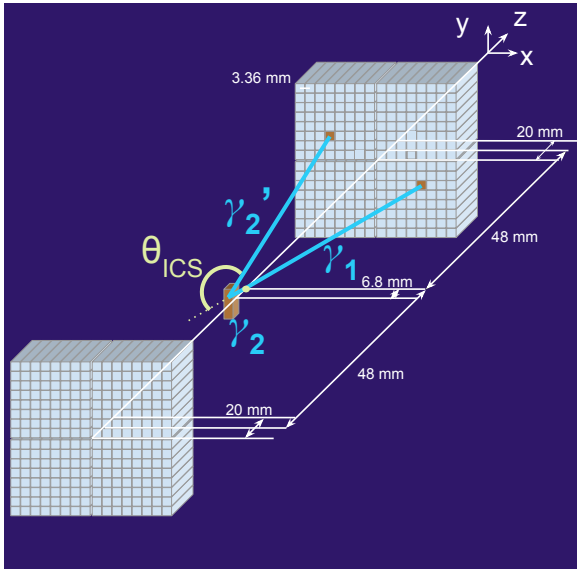

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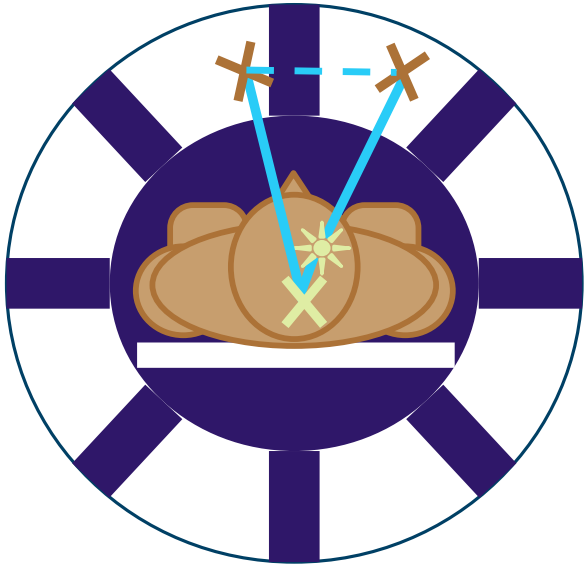

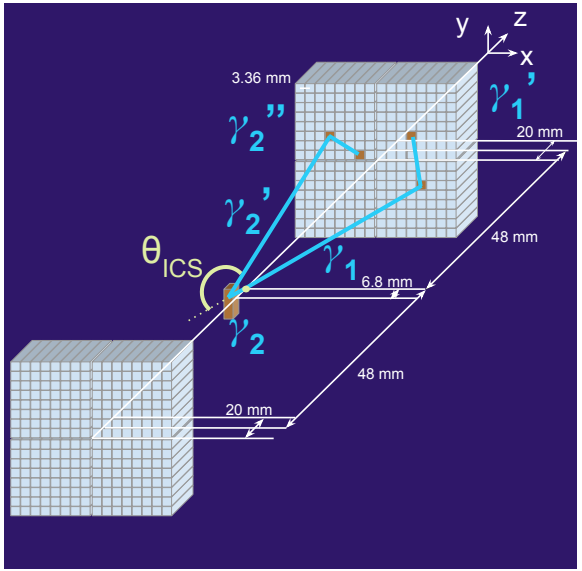

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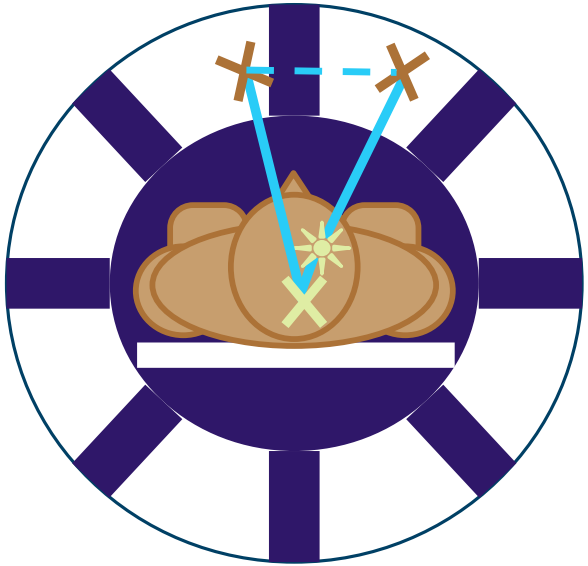

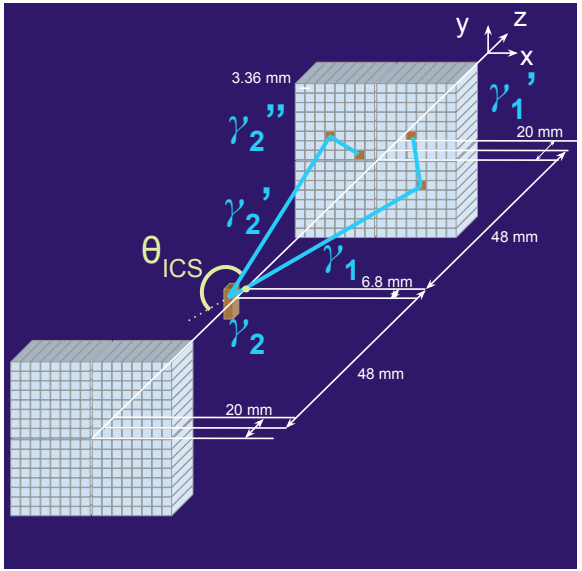

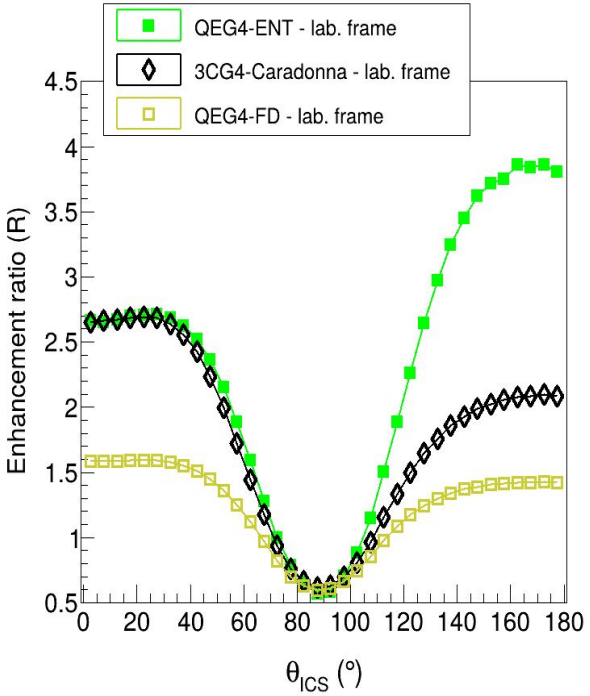

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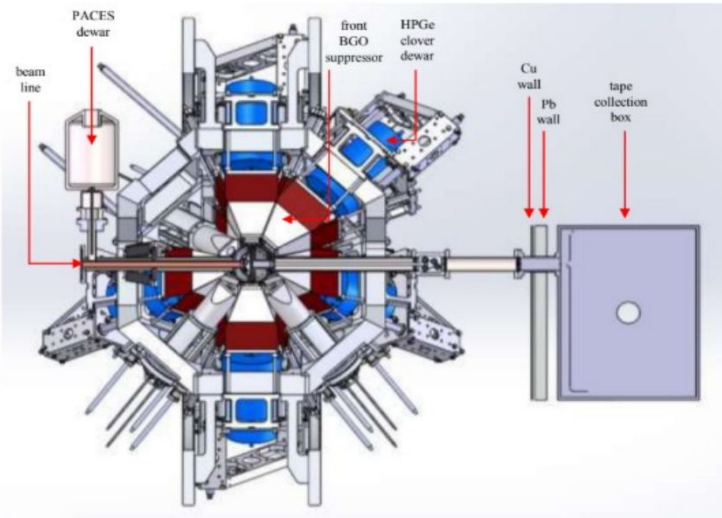
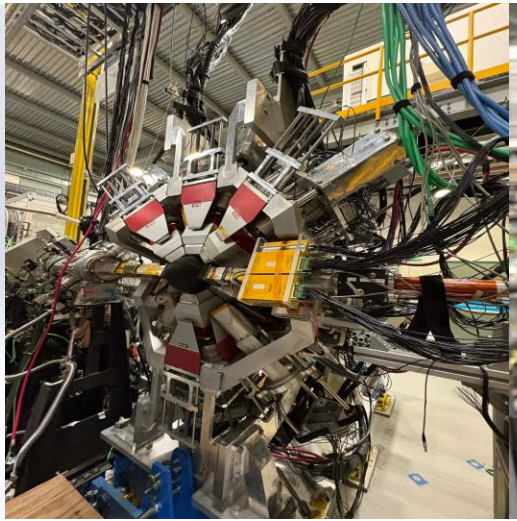
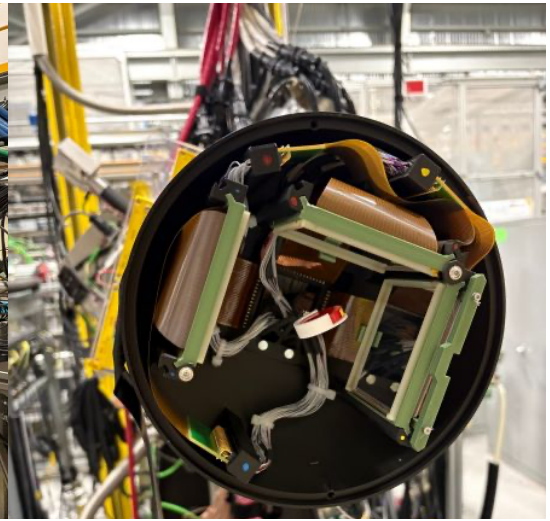
Future Experiment

GRIFFIN coupled with dedicated DSSD (double-sided silicon strip detector) polarimeter hopes to give access to **higher order compton scatter** measurements.

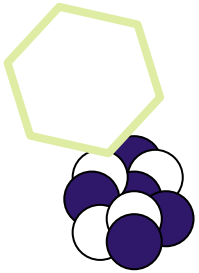






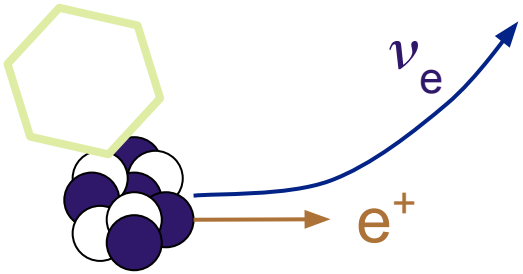
Towards Environmental Sensitivity and PET Biomarkers

Positron Annihilation



Unstable nucleus labeled to Biological molecule

Positron Annihilation



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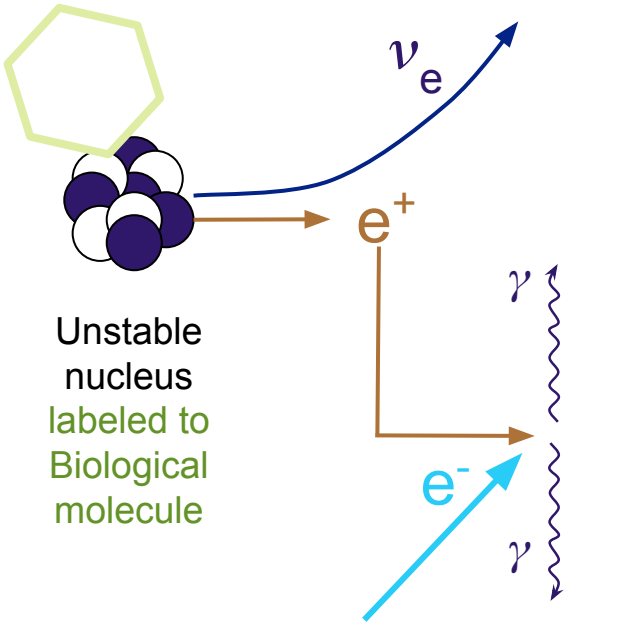
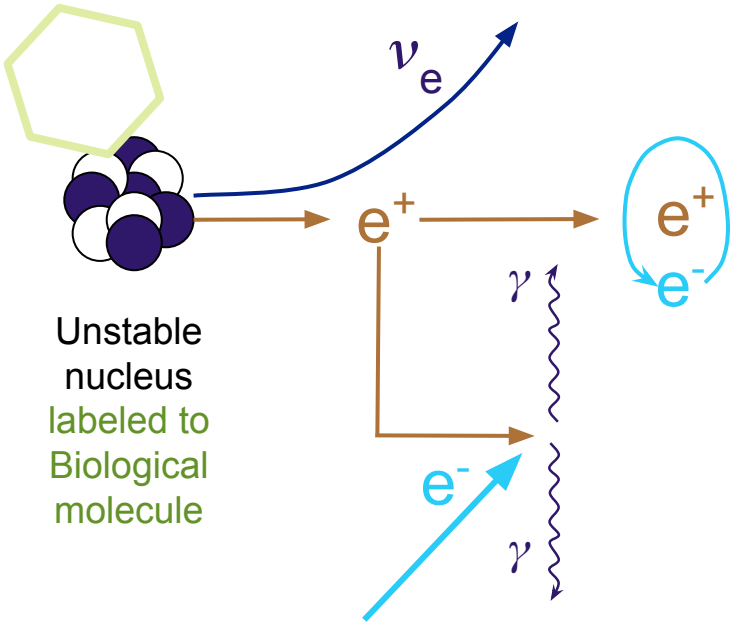


Unstable nucleus labeled to Biological molecule

Free positron Annihilation

Positron Annihilation



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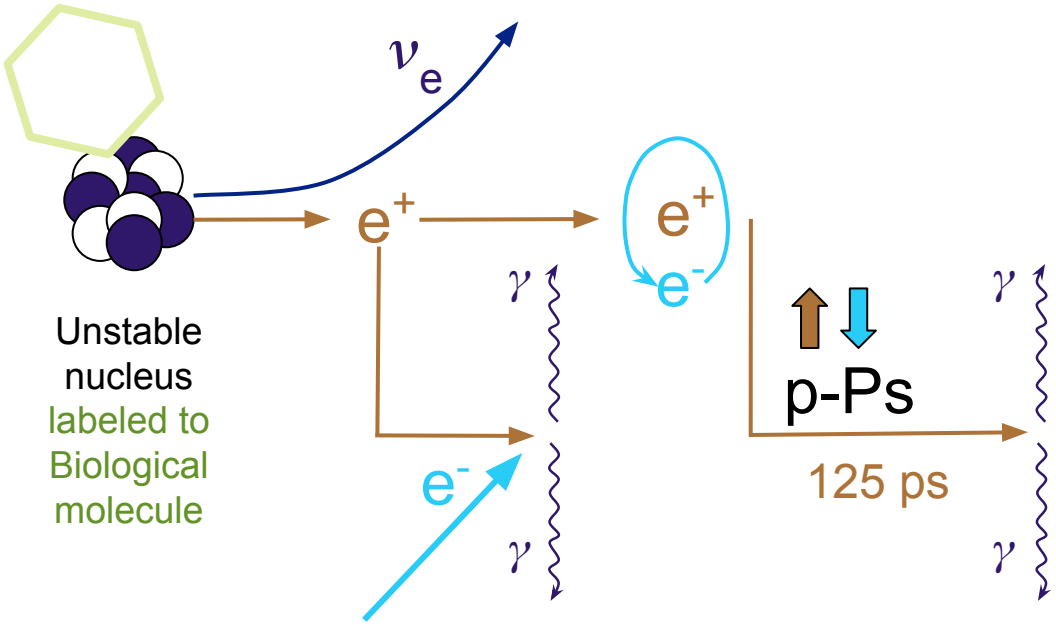
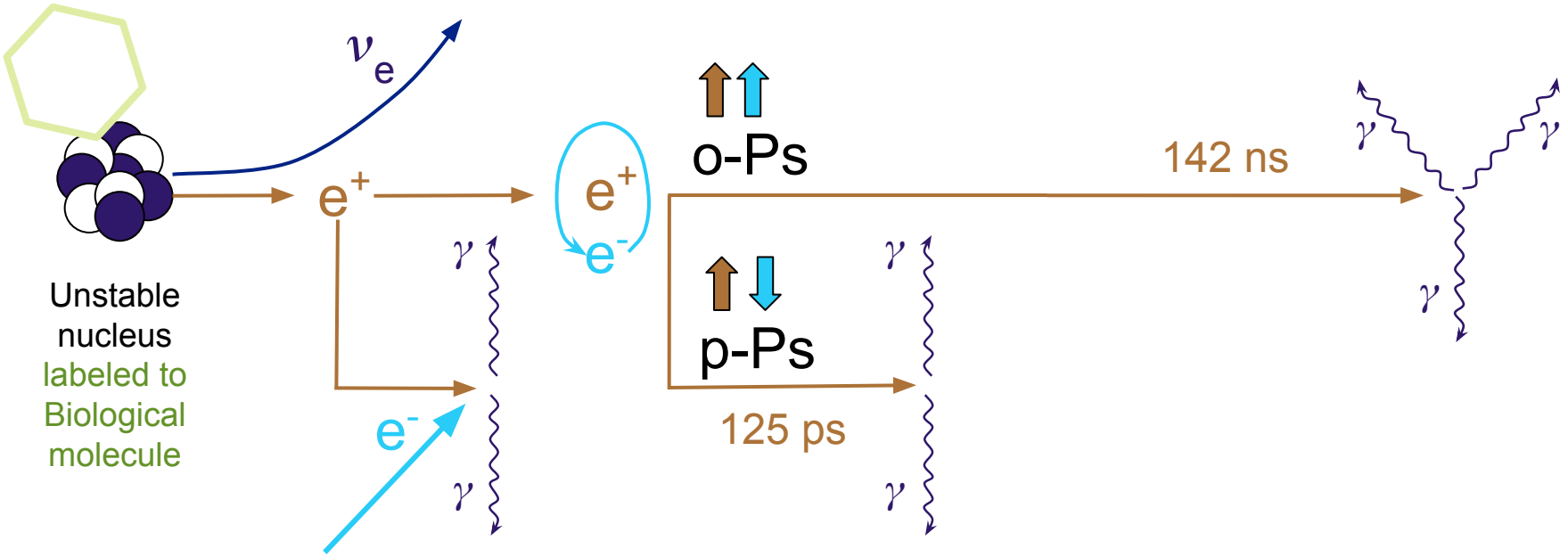


Positron Annihilation



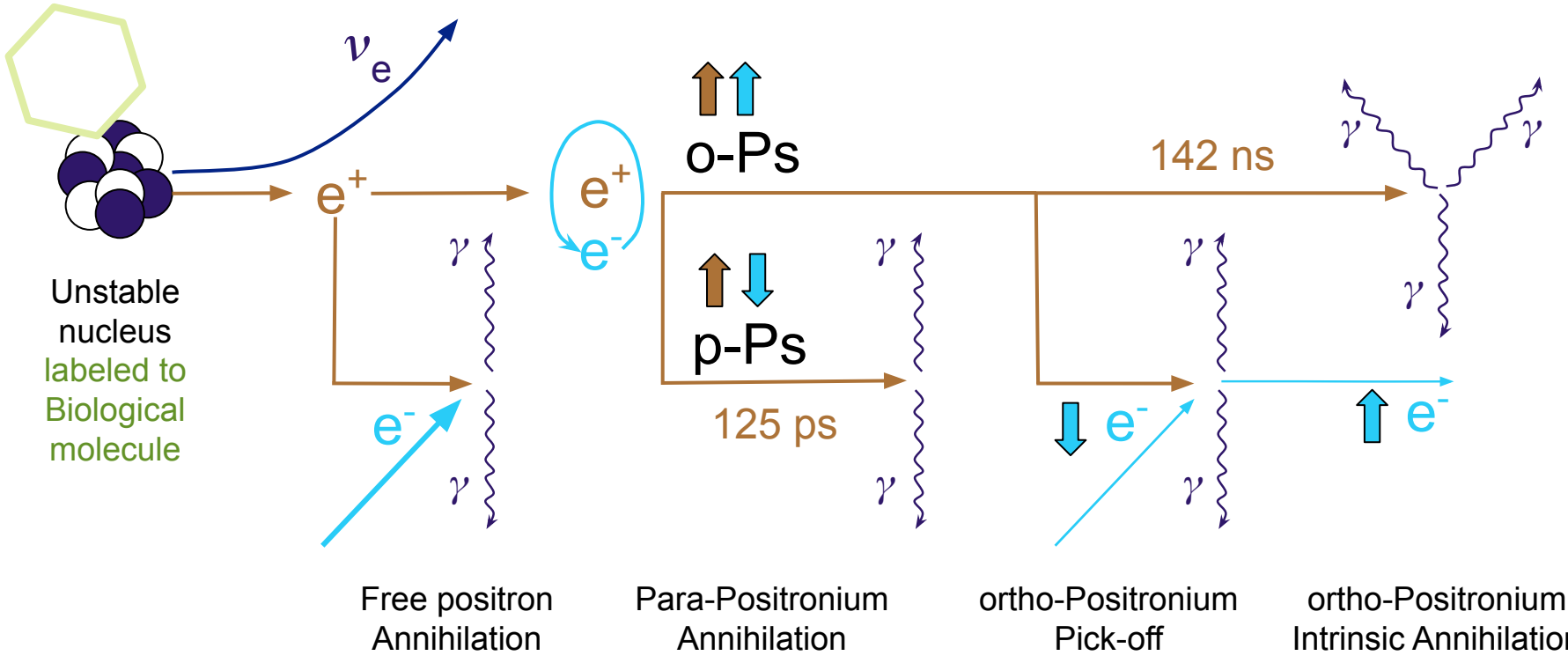
Unstable nucleus labeled to Biological molecule

Free positron Annihilation

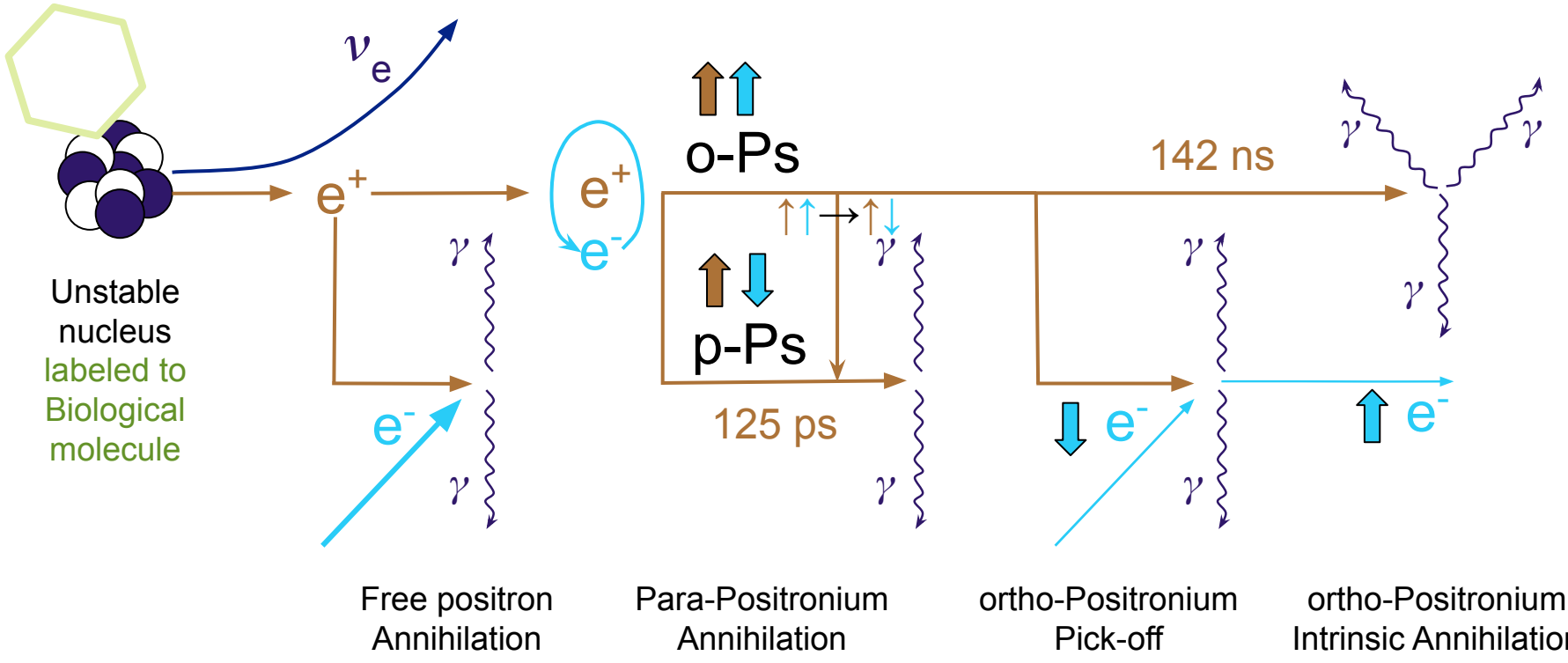
Para-Positronium Annihilation

ortho-Positronium Intrinsic Annihilation

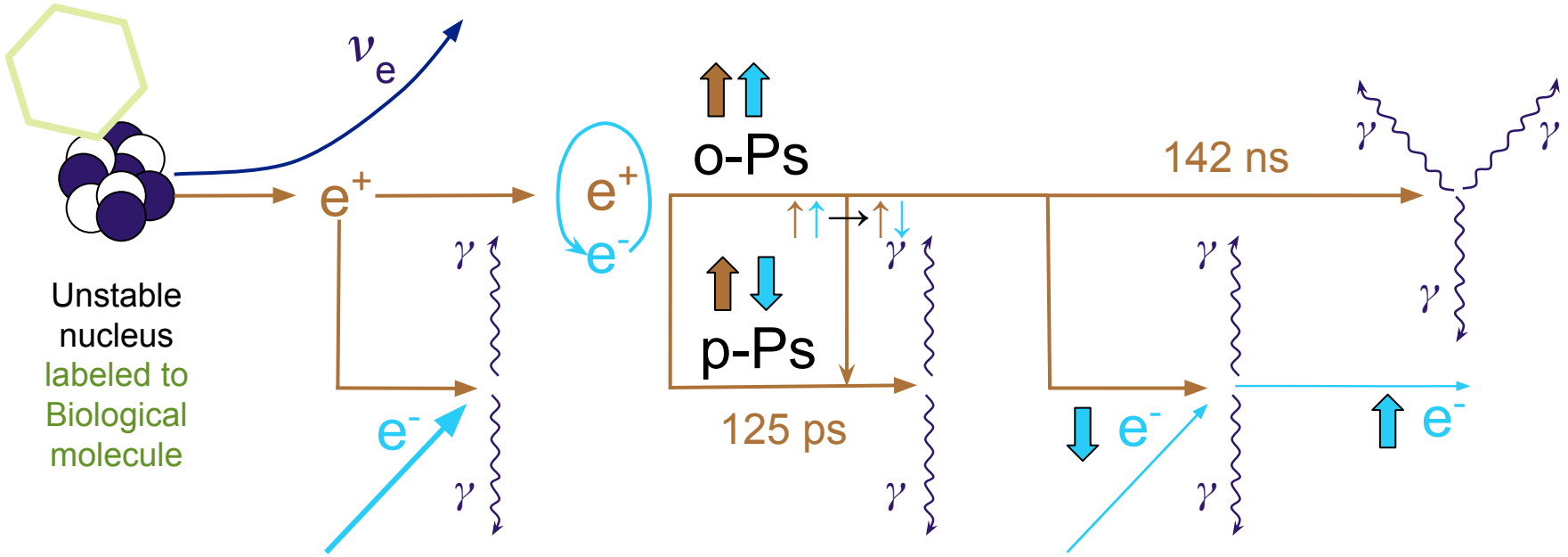
Positron Annihilation



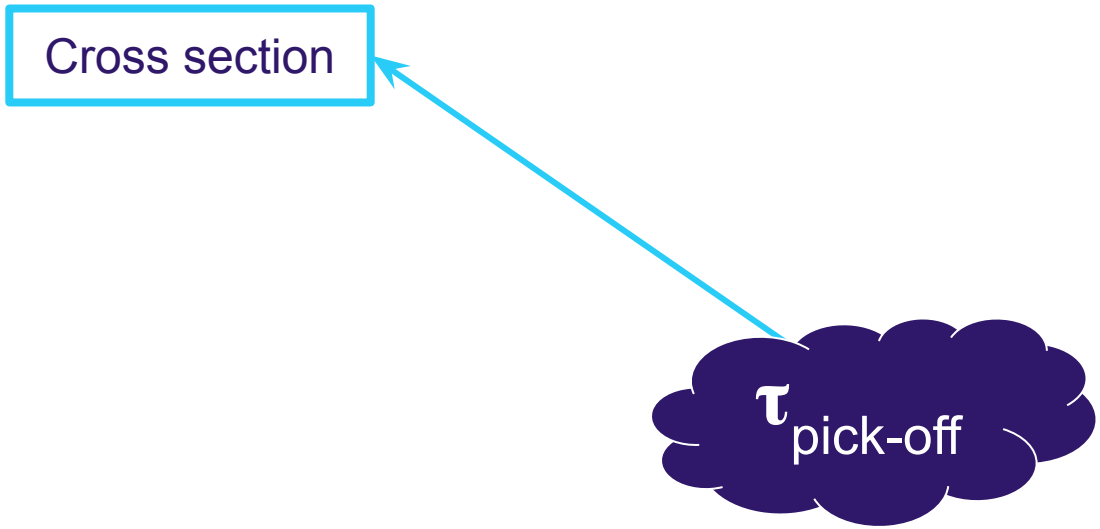
Positron Annihilation

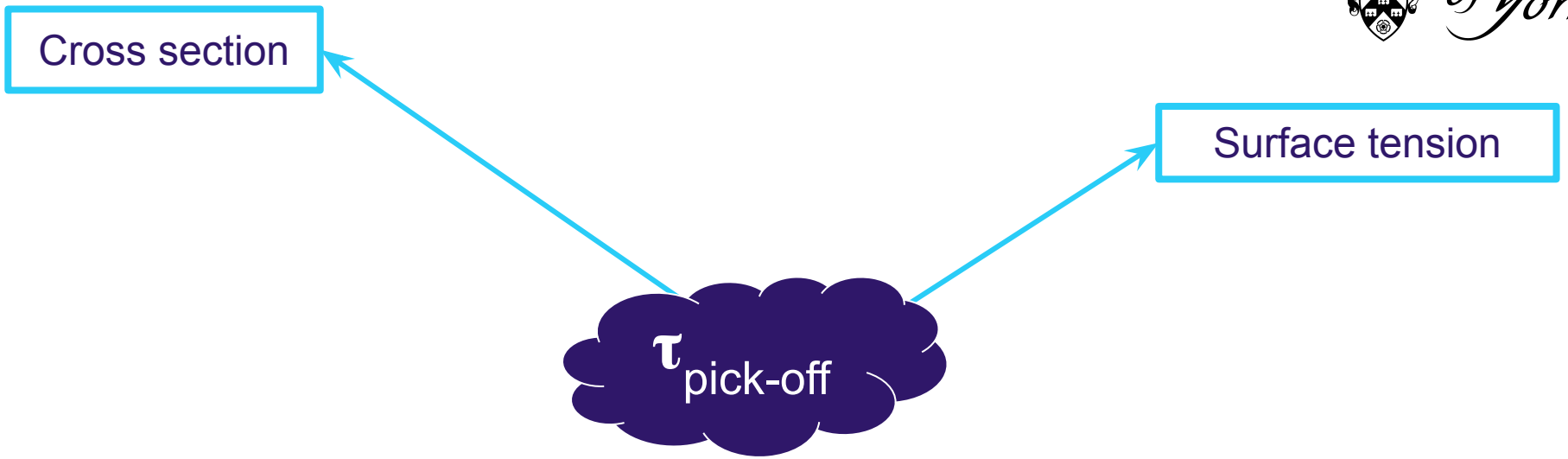


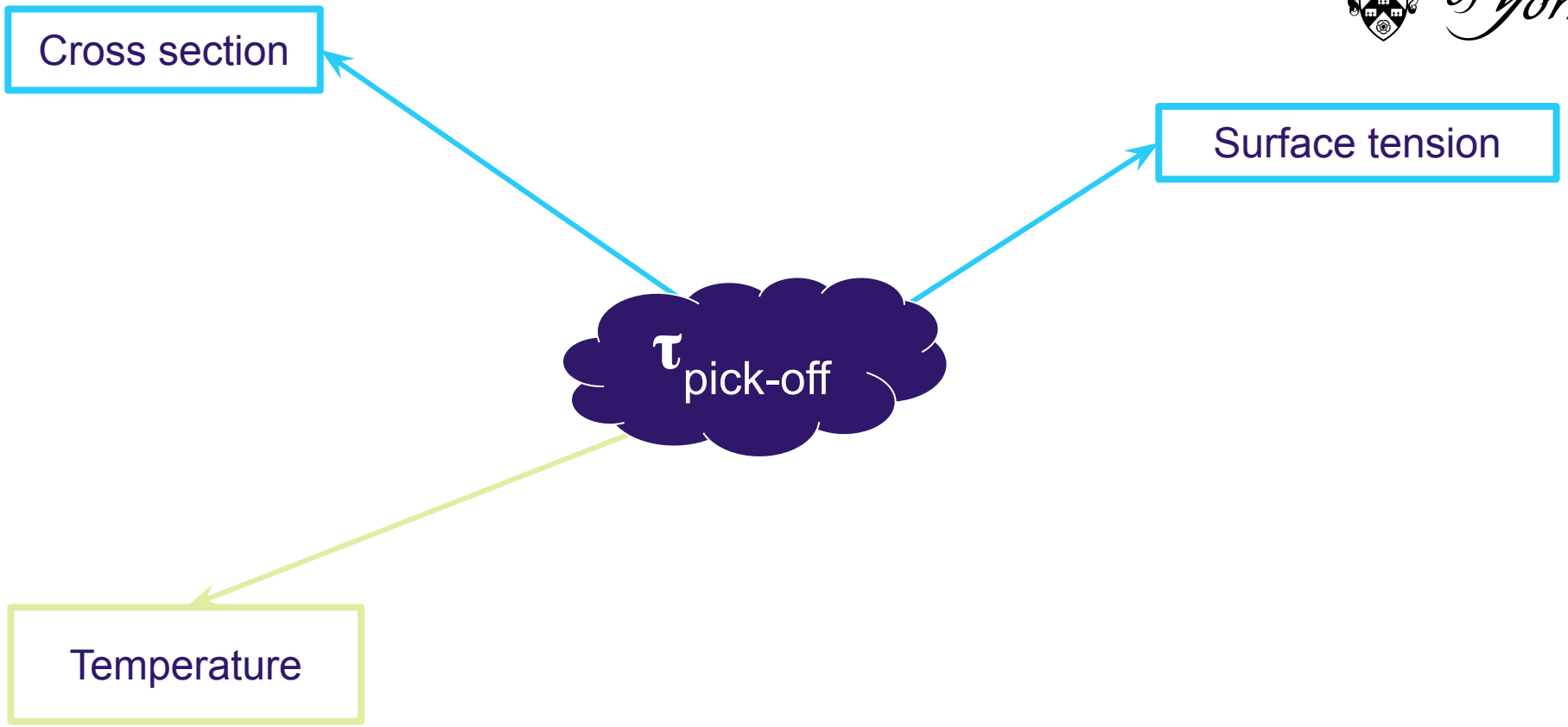
Positron Annihilation

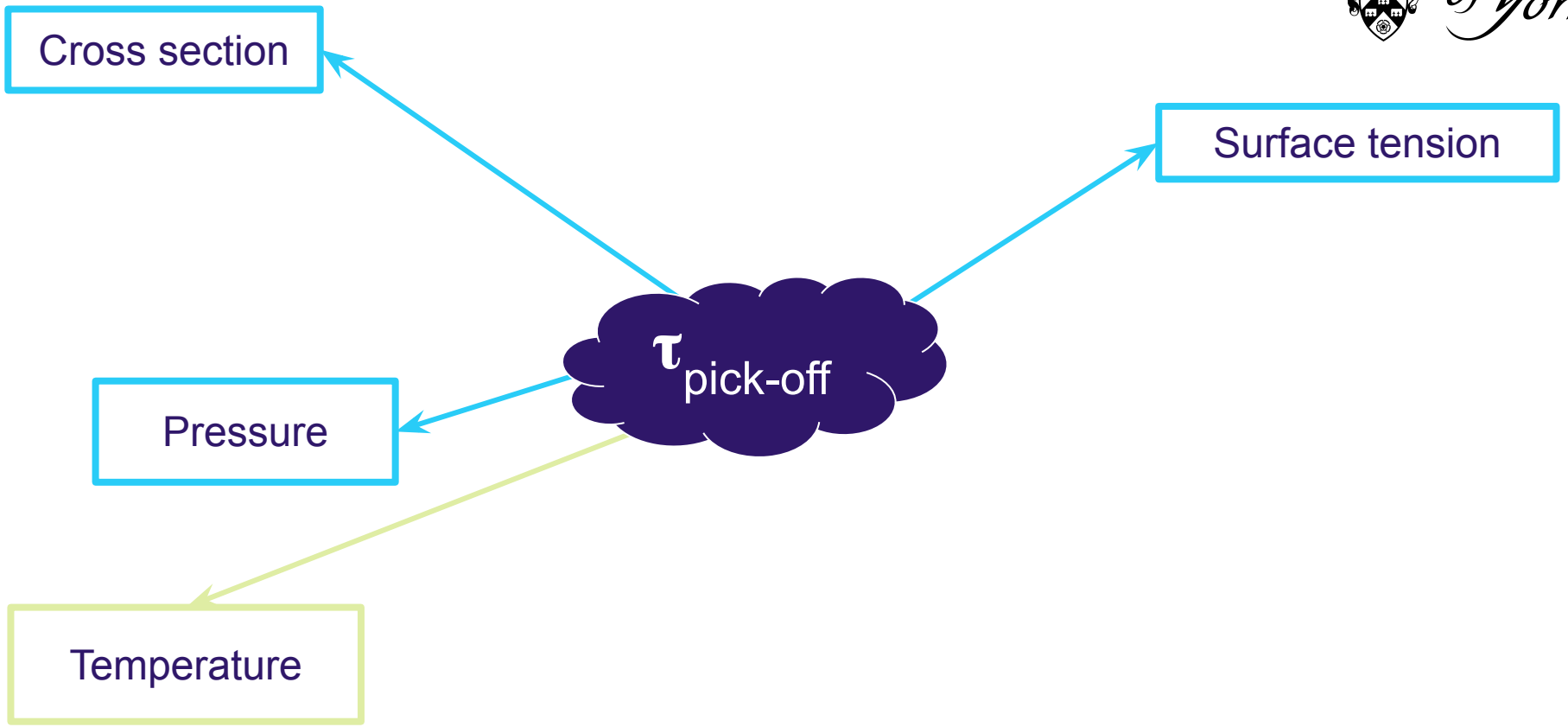


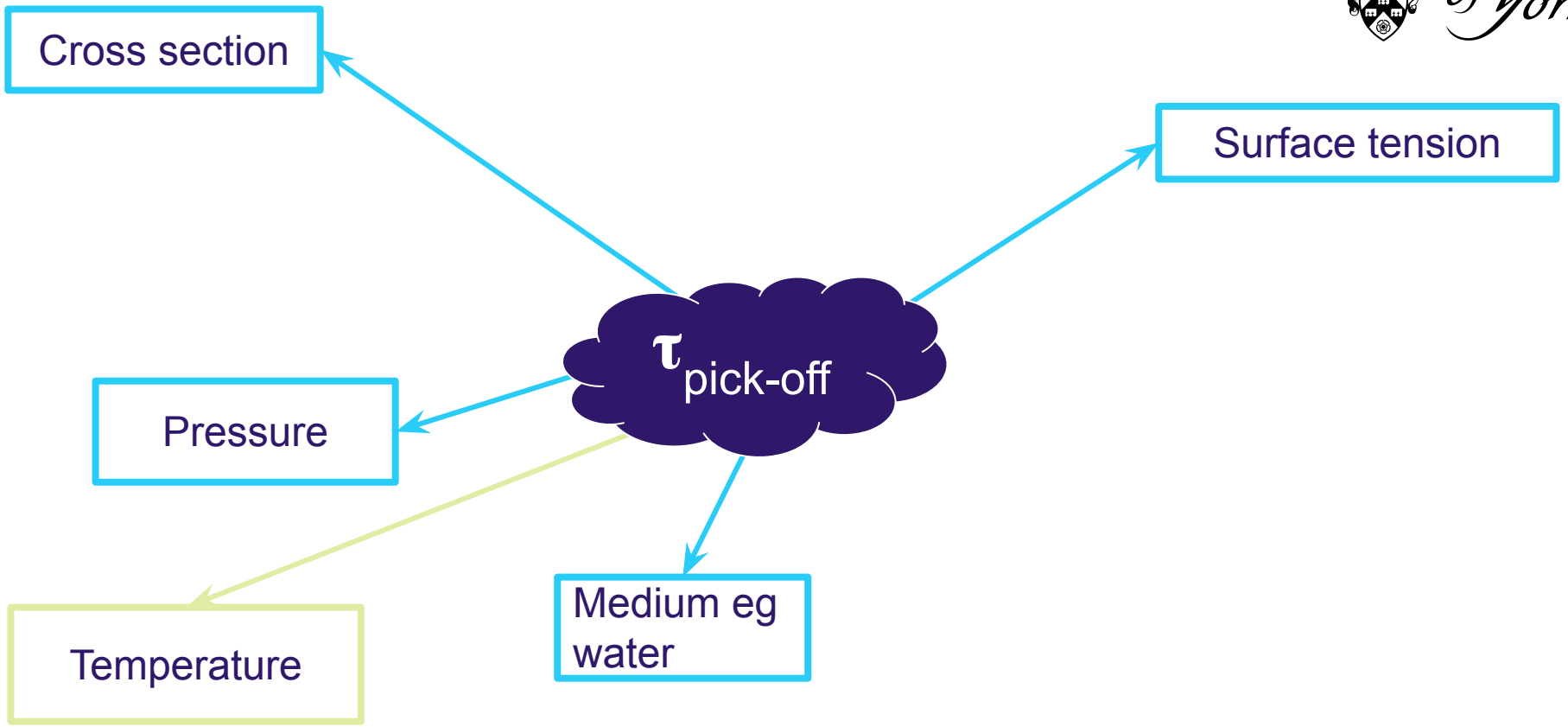

τpick-off

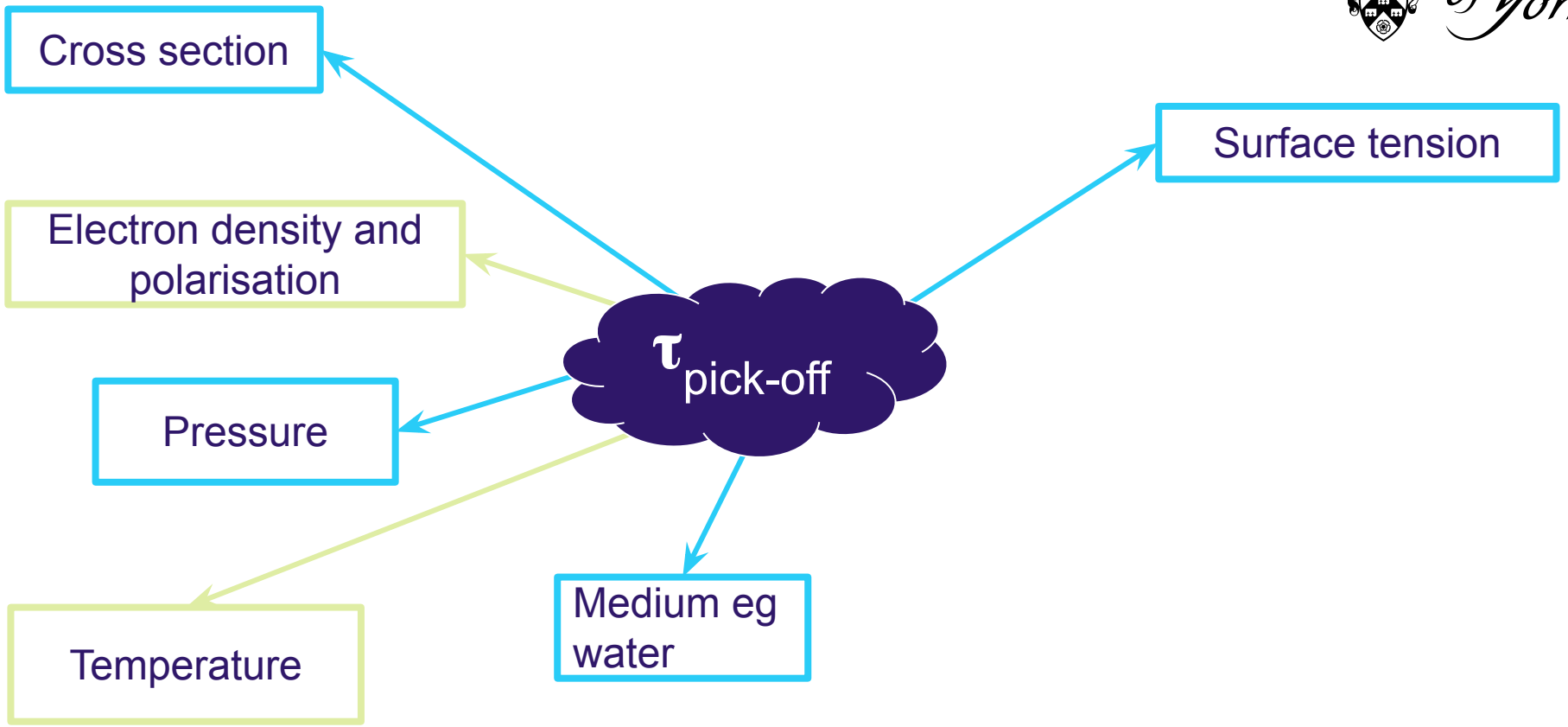

Cross section
τpick-off

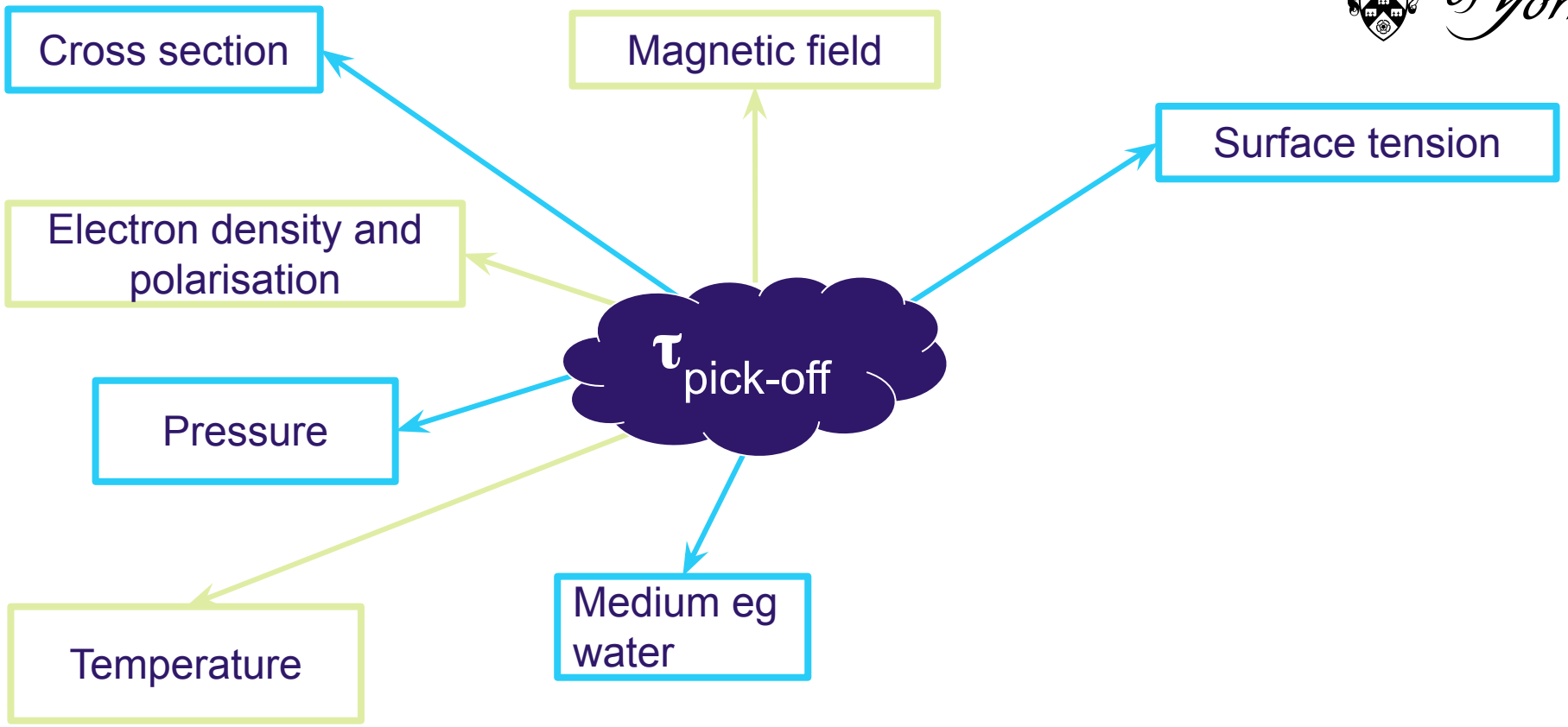

Cross section
Surface tension
τ pick-off

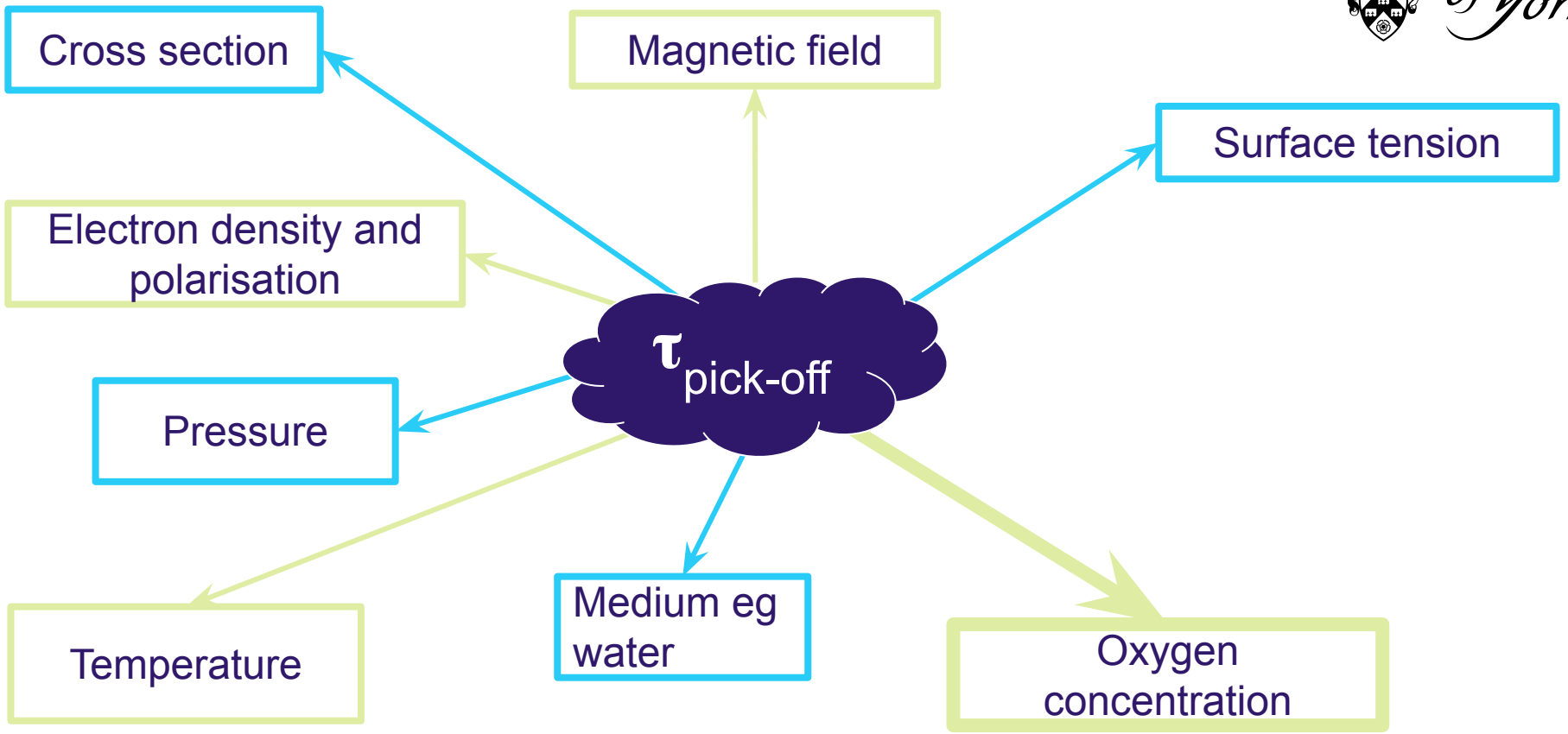

Cross section
Surface tension
$\tau_{pick\text{-}off}$
Temperature

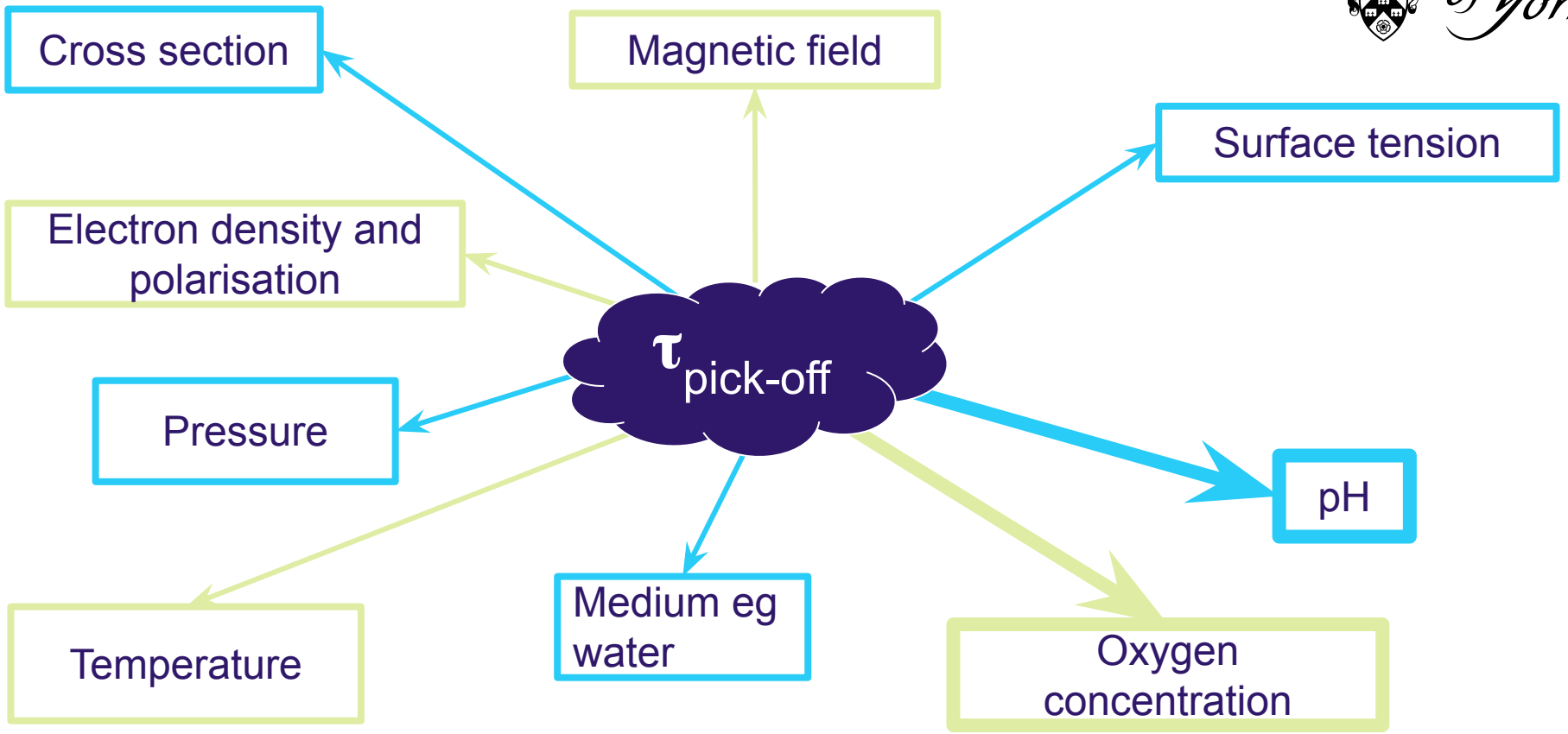

Cross section
Surface tension
τpick-off
Pressure
Temperature

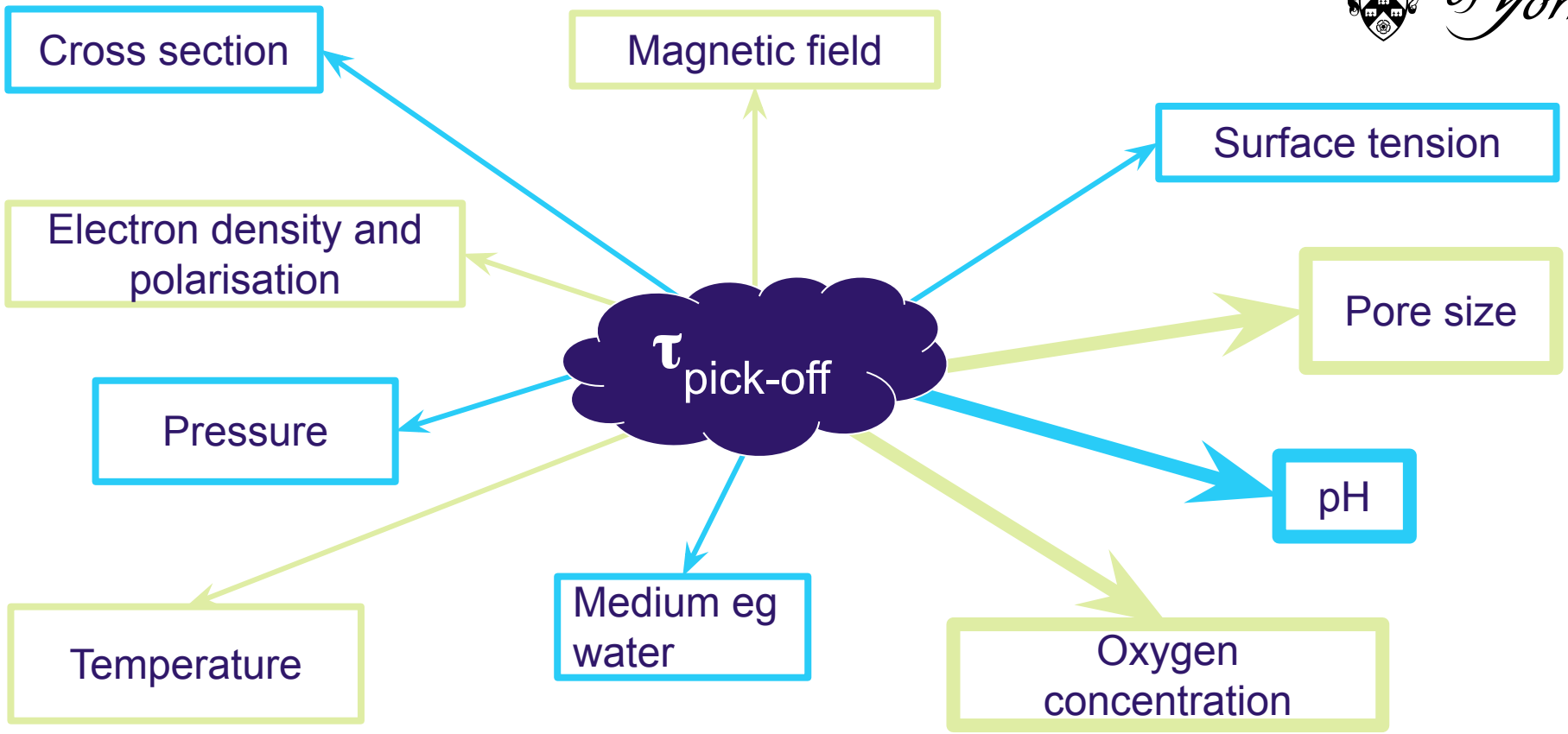

Cross section
Surface tension
τ pick-off
Pressure
Temperature
Medium eg water


Cross section
Surface tension
Electron density and polarisation
τ pick-off
Pressure
Medium eg water
Temperature

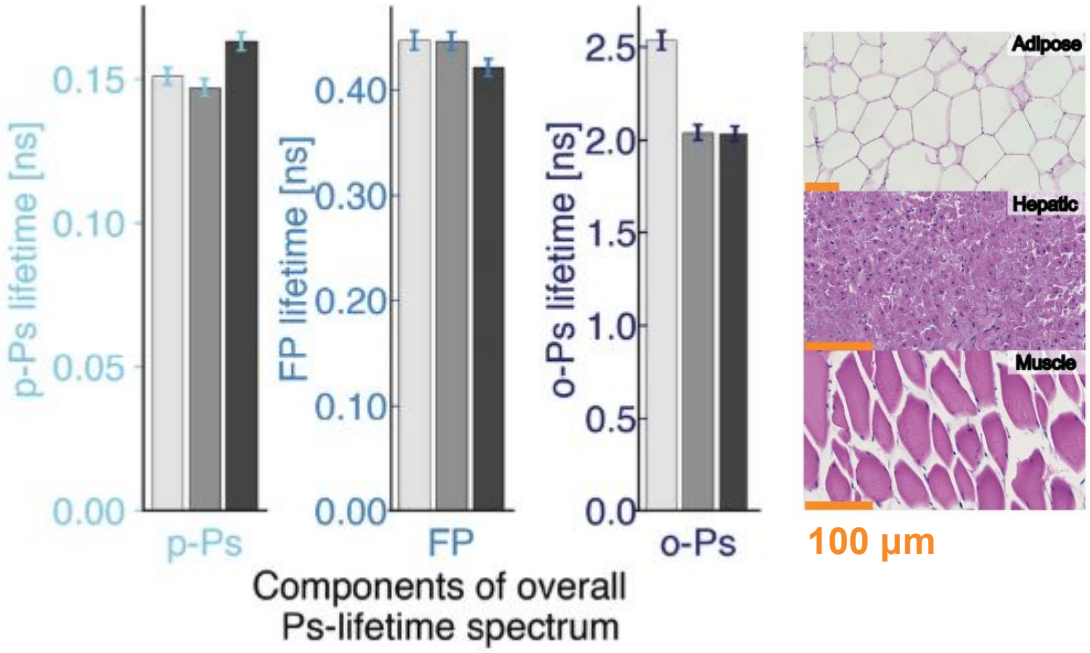

Cross section
Magnetic field
Surface tension
Electron density and polarisation
τ pick-off
Pressure
Medium eg water
Temperature


Cross section
Magnetic field
Surface tension
Electron density and polarisation
τpick-off
Pressure
Temperature
Medium eg water
Oxygen concentration


Cross section
Magnetic field
Surface tension
Electron density and polarisation
τ pick-off
Pressure
pH
Temperature
Medium eg water
Oxygen concentration

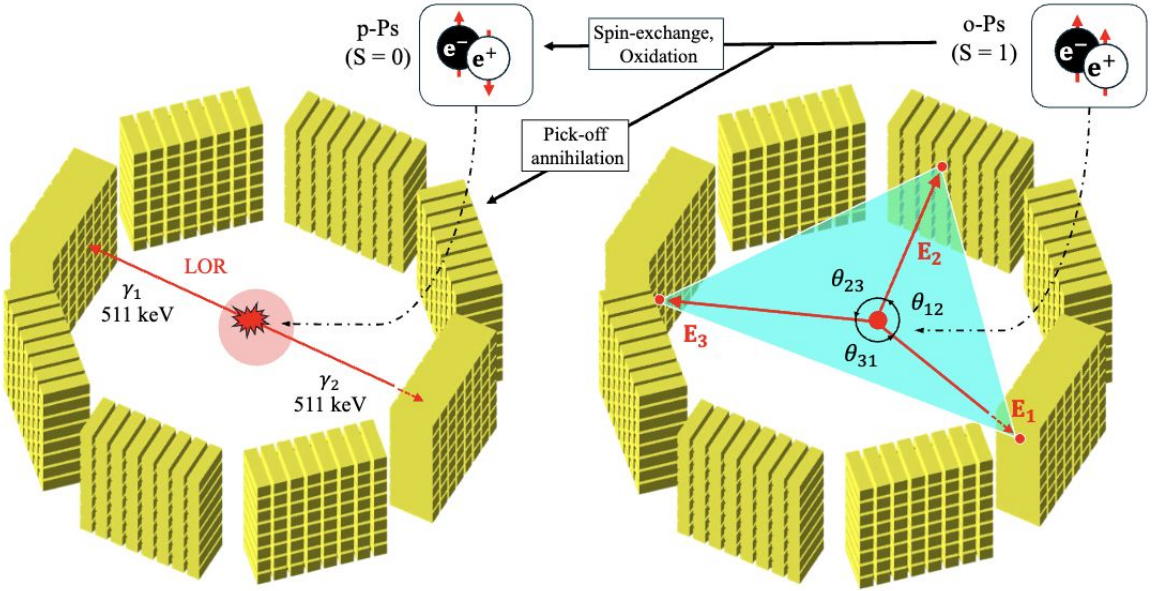

Cross section
Magnetic field
Surface tension
Electron density and polarisation
Pore size
τ pick-off
Pressure
pH
Temperature
Medium eg water
Oxygen concentration

Positronium in Tissue



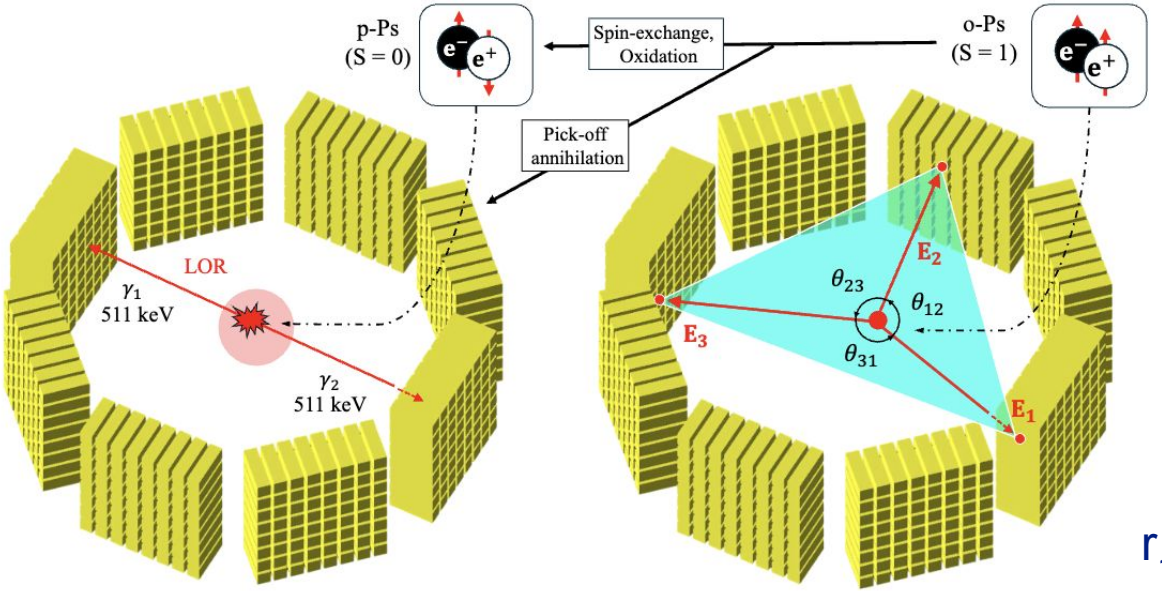
Ashish V. Avachat et al.(2024) doi:10.1038/s41598-024-71695-7

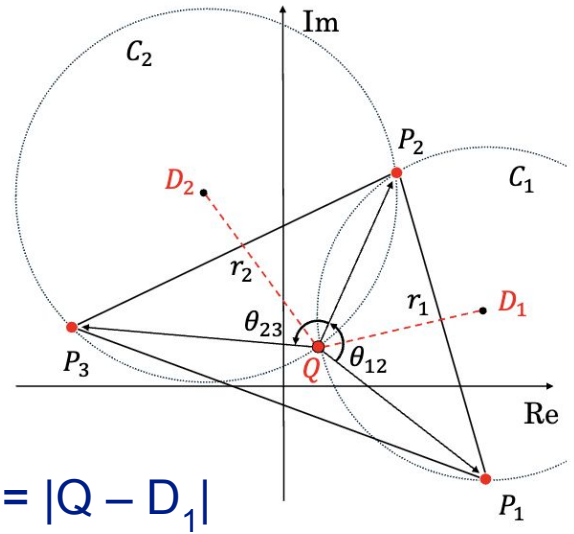
Direct 3γ Imaging of o-Ps decay



Fujimoto et al. (2025) pre-print doi:10.21203/rs.3.rs-7272322/v1

Direct 3γ Imaging of o-Ps decay



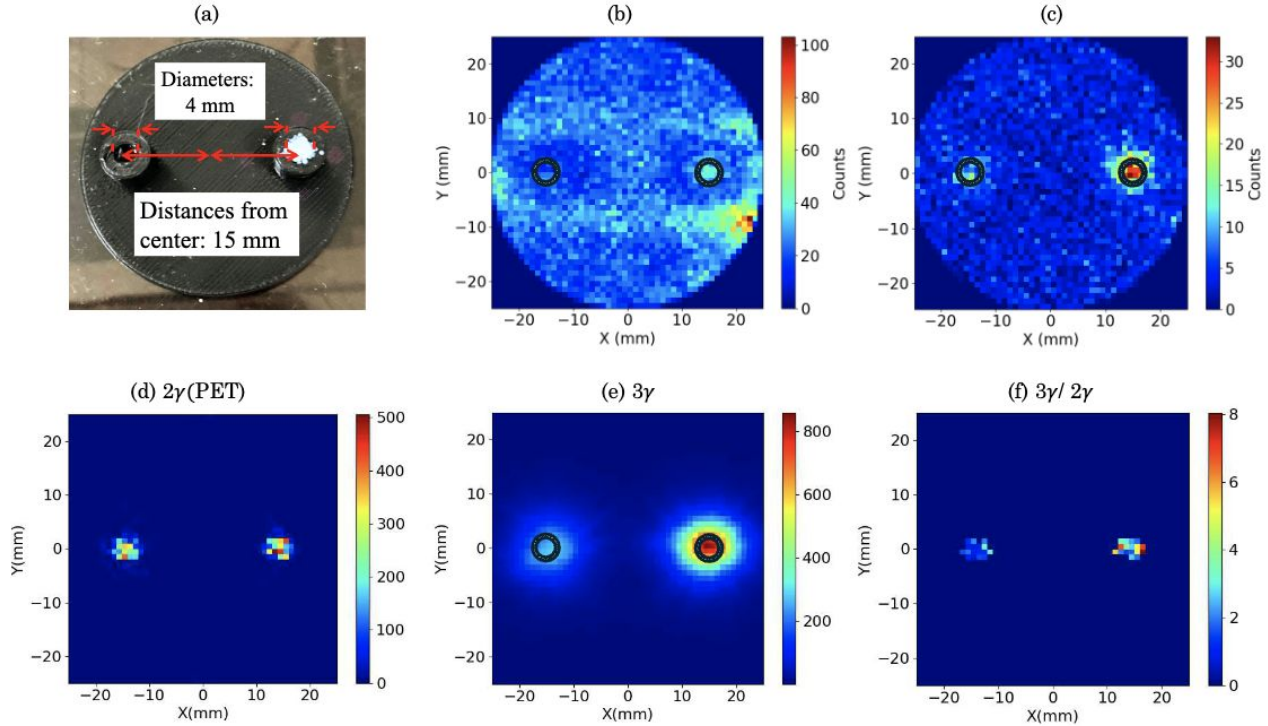


$r_1 = |Q - D_1|$

$r_2 = |Q - D_2|$

Fujimoto et al. (2025) pre-print doi:10.21203/rs.3.rs-7272322/v1

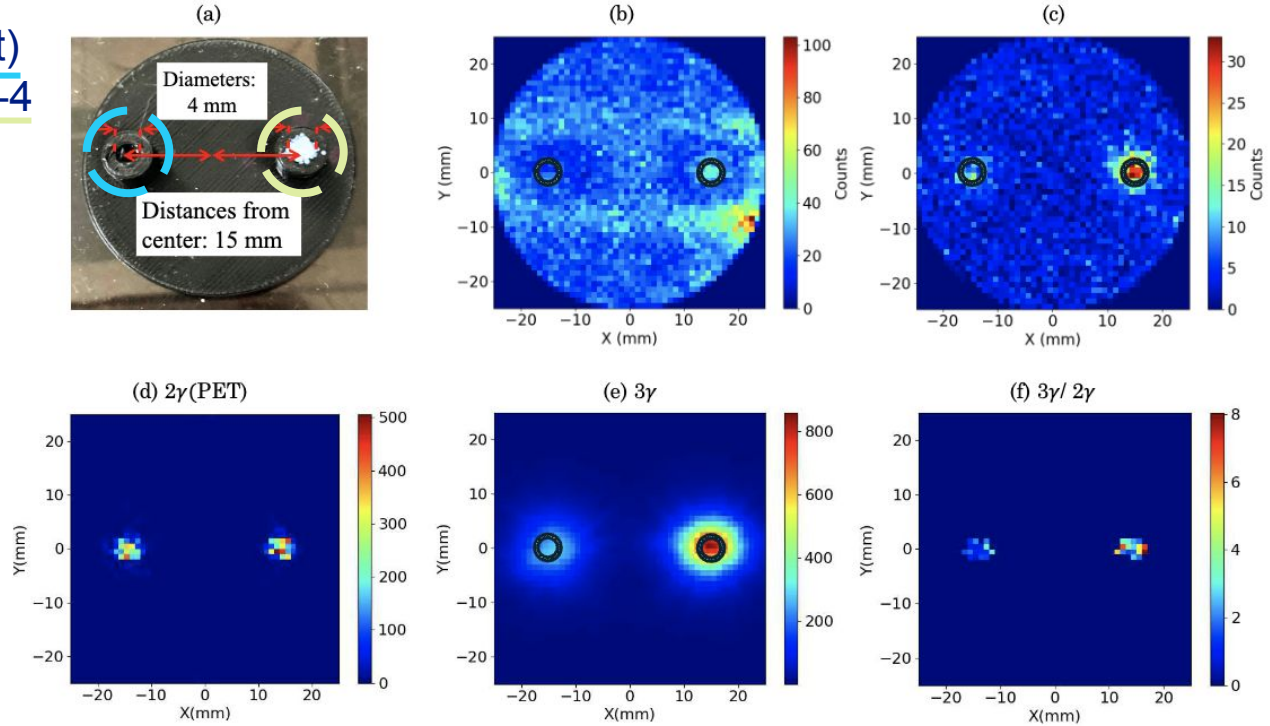
First $3\gamma/2\gamma$ Ratio Image!



Fujimoto et al. (2025) pre-print doi:10.21203/rs.3.rs-7272322/v1

First $3\gamma/2\gamma$ Ratio Image!

a) Water (left) Porous XAD-4 (right)



Fujimoto et al. (2025) pre-print doi:10.21203/rs.3.rs-7272322/v1

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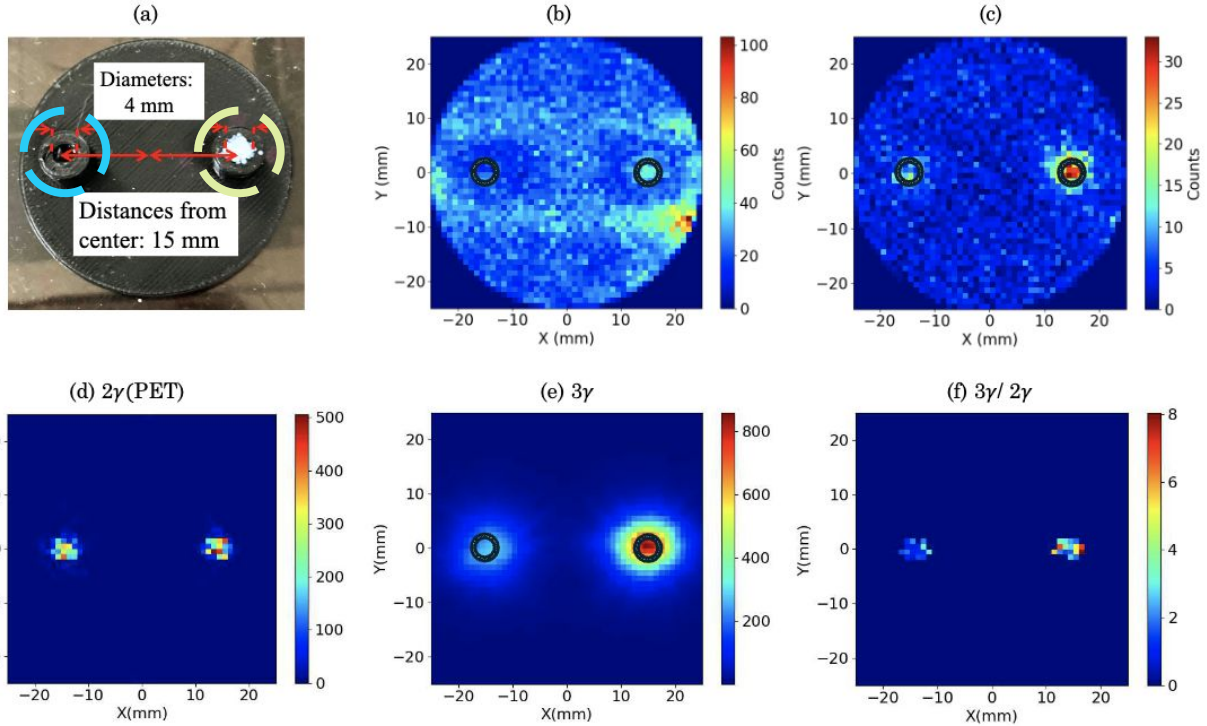

b) Triple coincidence

Fujimoto et al. (2025) pre-print doi:10.21203/rs.3.rs-7272322/v1

First $3\gamma/2\gamma$ Ratio Image!

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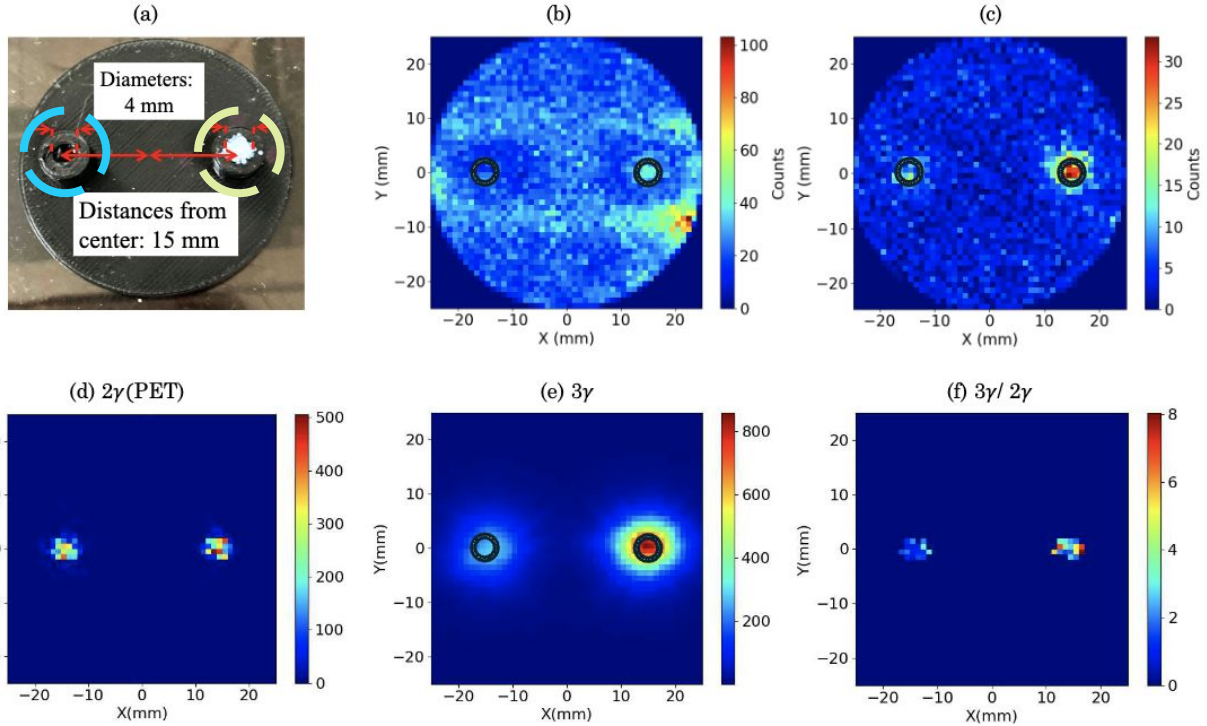


b) Triple coincidence

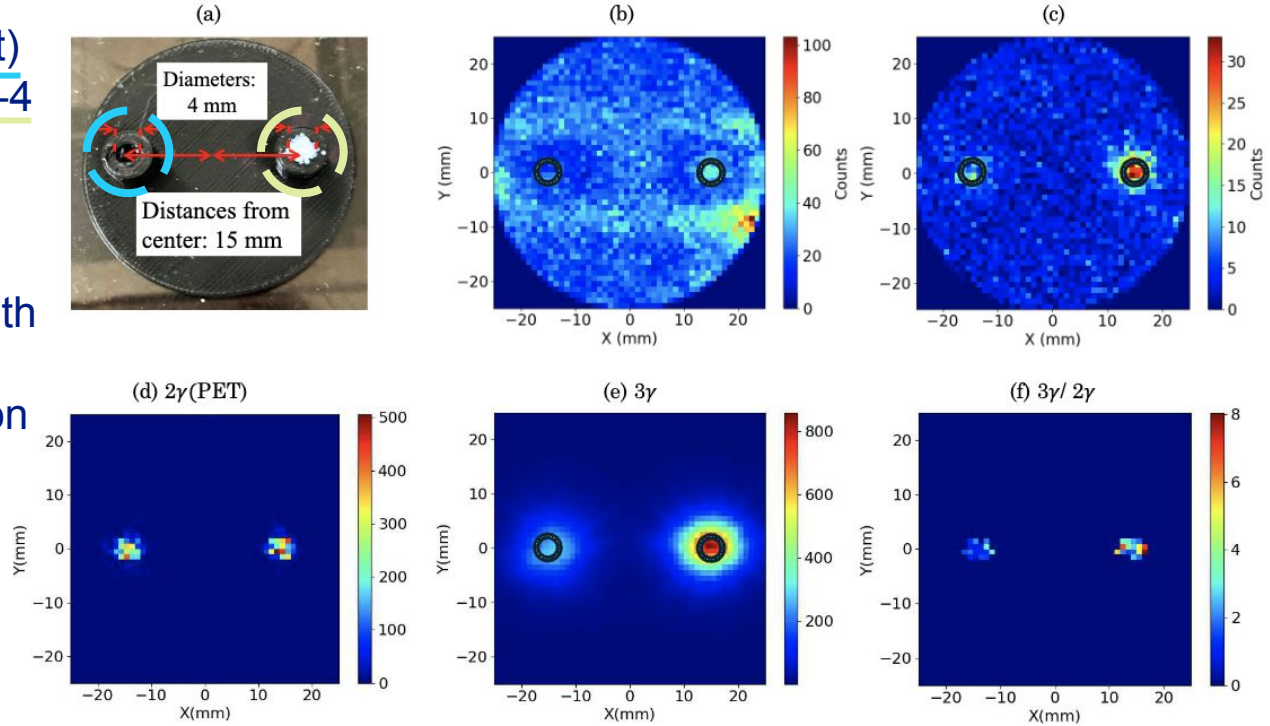
c) Triple coincidence $E_{total} \geq 985$ keV

Fujimoto et al. (2025) pre-print doi:10.21203/rs.3.rs-7272322/v1

First $3\gamma/2\gamma$ Ratio Image!

a) Water (left) Porous XAD-4 (right)

d) 2γ PET with ML-EM reconstruction



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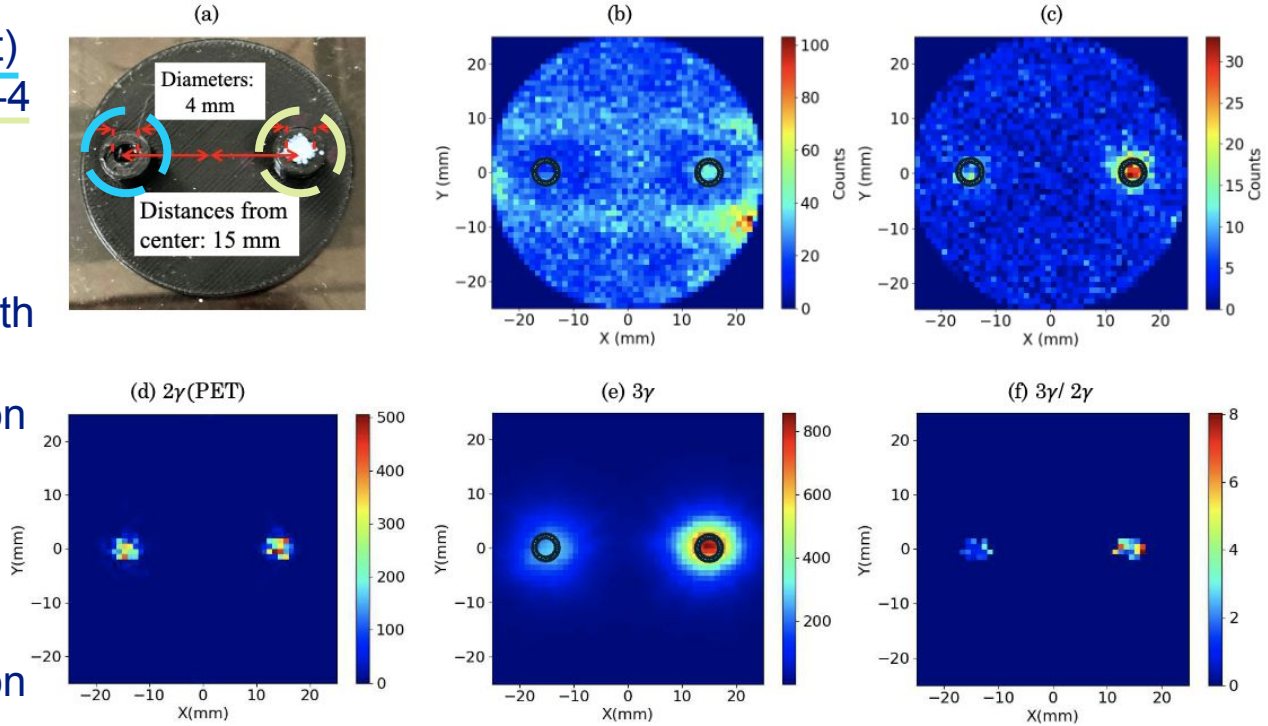
Fujimoto et al. (2025) pre-print doi:10.21203/rs.3.rs-7272322/v1

First $3\gamma/2\gamma$ Ratio Image!

a) Water (left) Porous XAD-4 (right)

d) 2γ PET with ML-EM reconstruction

e) 3γ direct annihilation reconstruction



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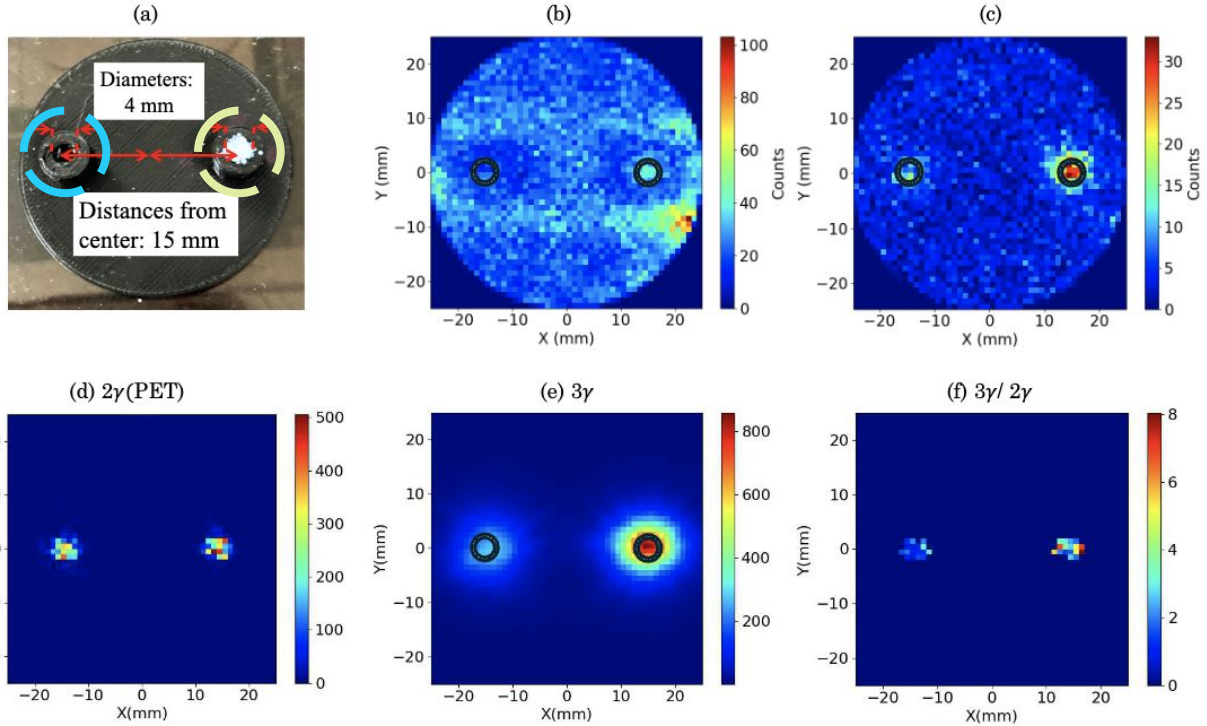


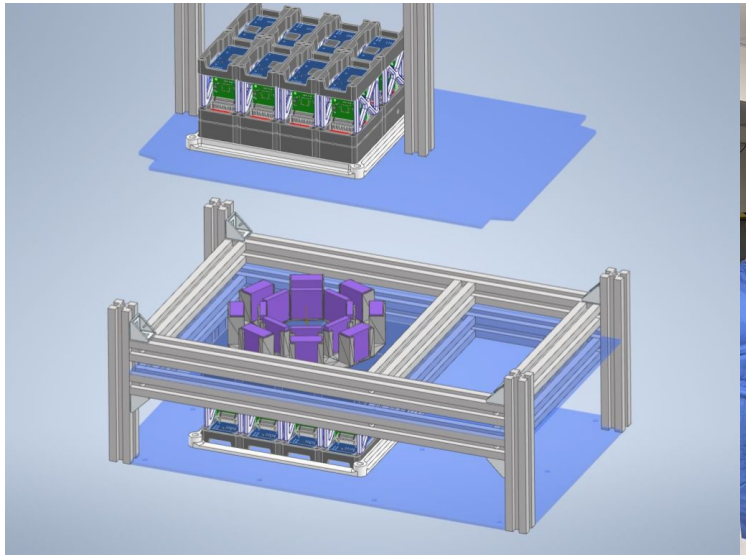
b) Triple coincidence

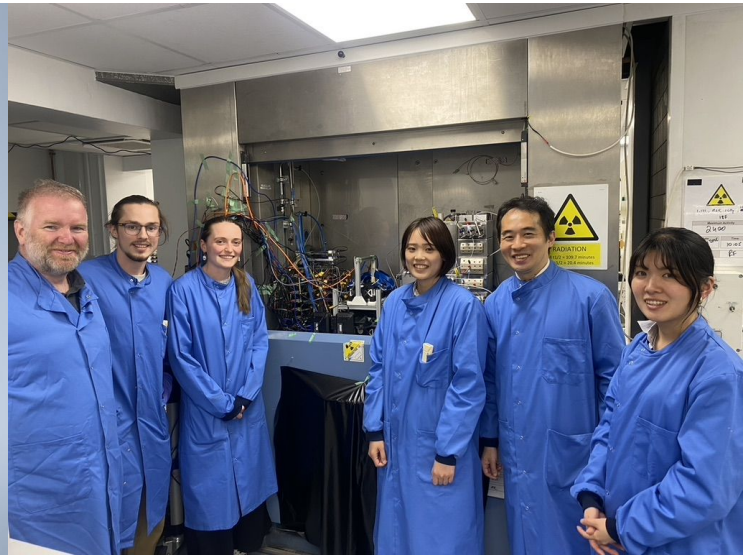
c) Triple coincidence $E_{total} \geq 985$ keV

f) FIRST $3\gamma/2\gamma$ decay ratio image!

Fujimoto et al. (2025) pre-print doi:10.21203/rs.3.rs-7272322/v1

LYSO/GAGG Detector (York/Tokyo Collab.)



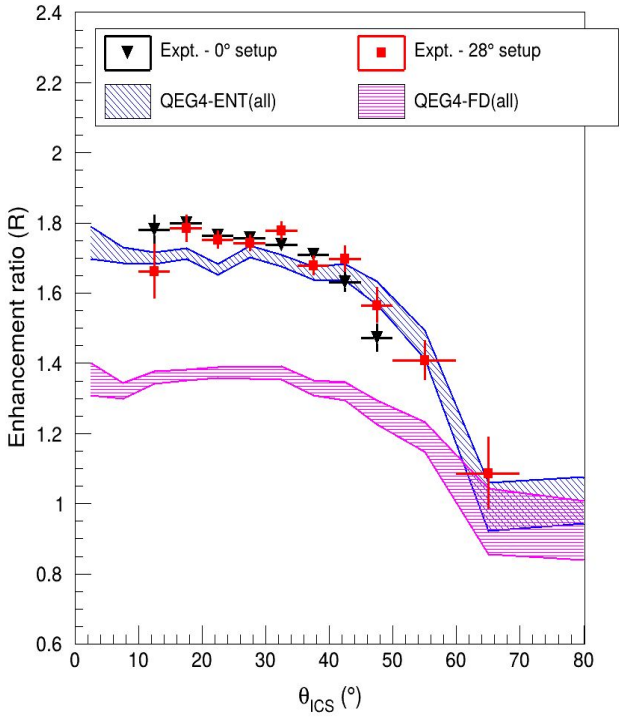


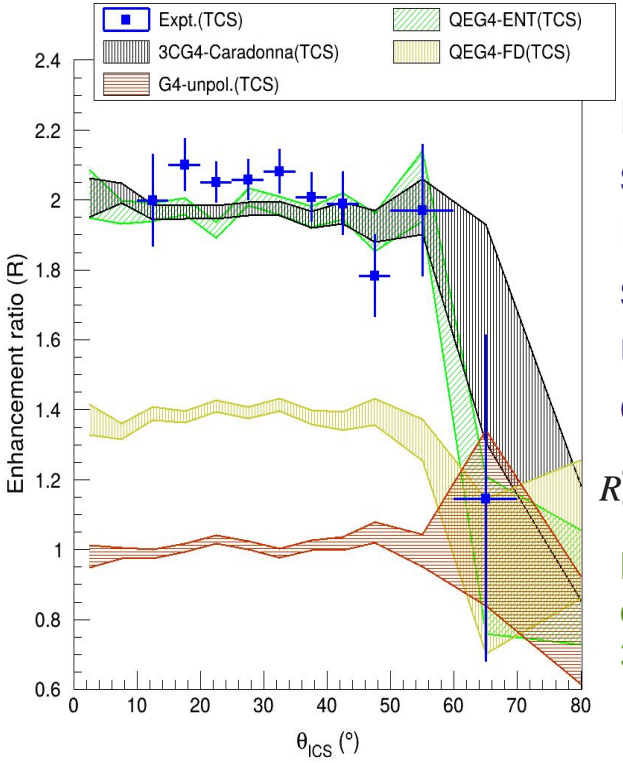
- First QE measurement of tripartite system from O-Ps decay
- First nuclear Cascade QE studies (In-111 & Lu-177)
- AI medical image reconstruction - QE adds powerful new information

Thank you

Any Questions?

Multiple Scattering Deconvolution





Left) **with** multiple scattering
Right) **without** multiple scattering deconvolved using simulated data and equation:

$$R^{\mathrm{TCS}}_{\mathrm{expt}} = \{\{R^{\mathrm{all}}_{\mathrm{expt}} - R^{\mathrm{all}}_{\mathrm{sim}}\}/f^{\mathrm{TCS}}_{\mathrm{sim}}\} + R^{\mathrm{TCS}}_{\mathrm{sim}}$$

Bordes et al. (2024) doi:10.1103/PhysRevLett.133.132502

BackScattering Increased Enhancement Ratio

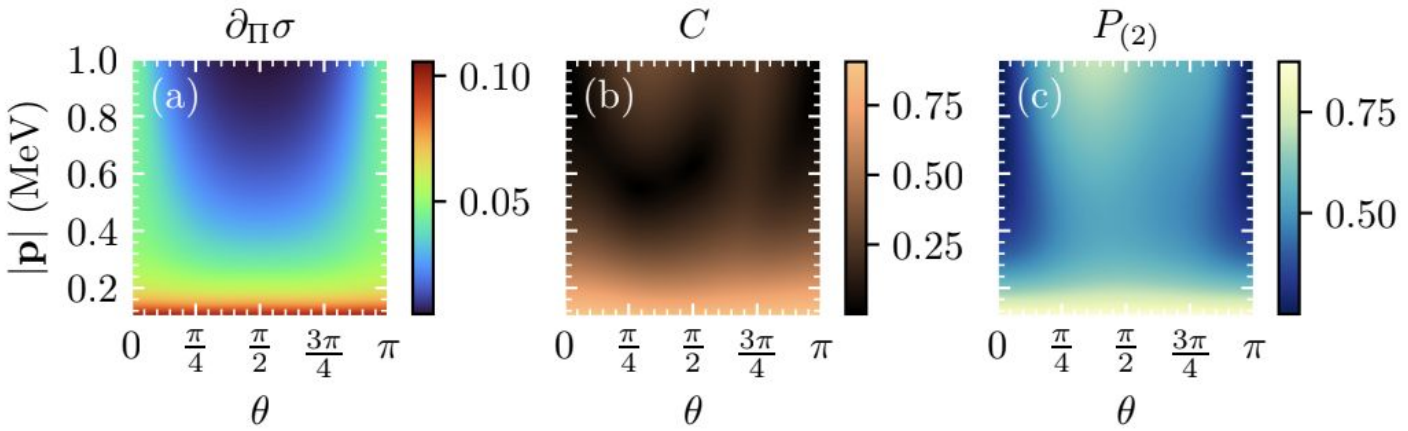
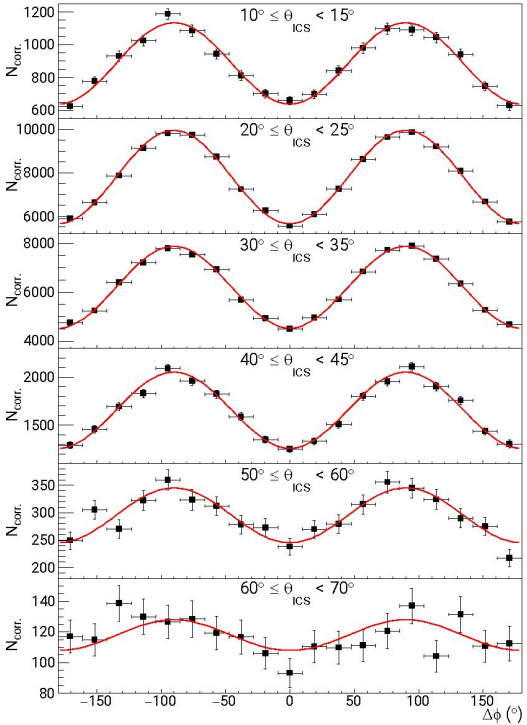


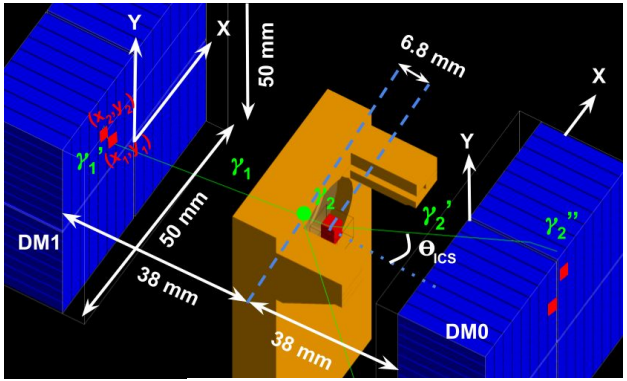
Figure 2: The differential cross section (a), concurrence (b) and two-photon degree of polarization (c) of the photon pair created in the annihilation process $e^+e^- \to 2\gamma$. These results are for $\phi = 0$ and an interval of polar angles $\theta \in [0, 2\pi]$ and initial electron-positron CM momenta $|\mathbf{p}| \in [0.1, 1]$ MeV.

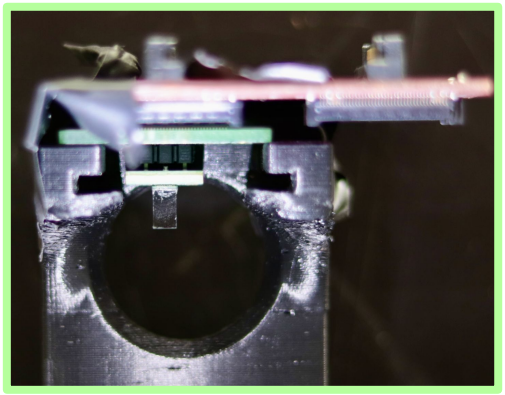
Analysing power increases when the energy of the gamma decreases!

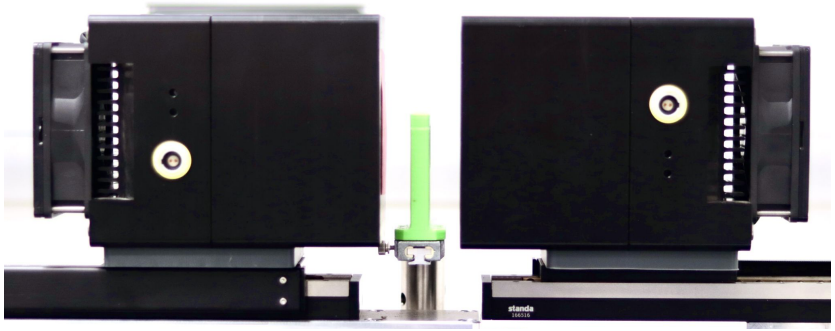
Figure and caption reproduced from Smeets et al. (2025) doi: 10.48550/arXiv.2509.12127

BackScattering Enhancement Ratios and Setup

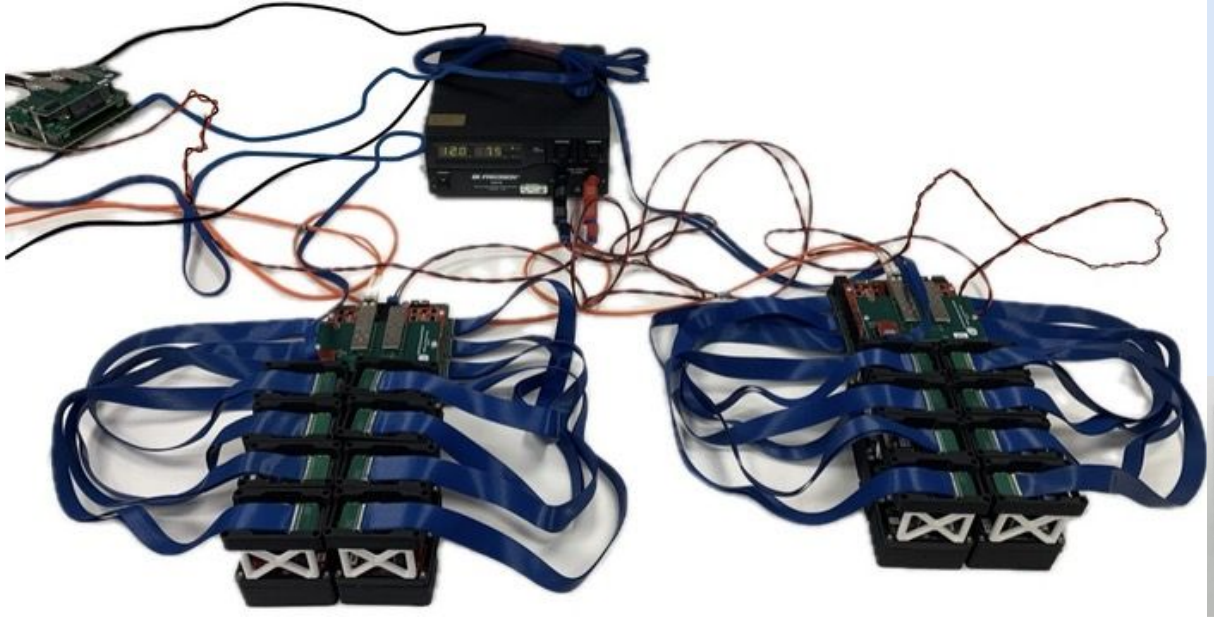


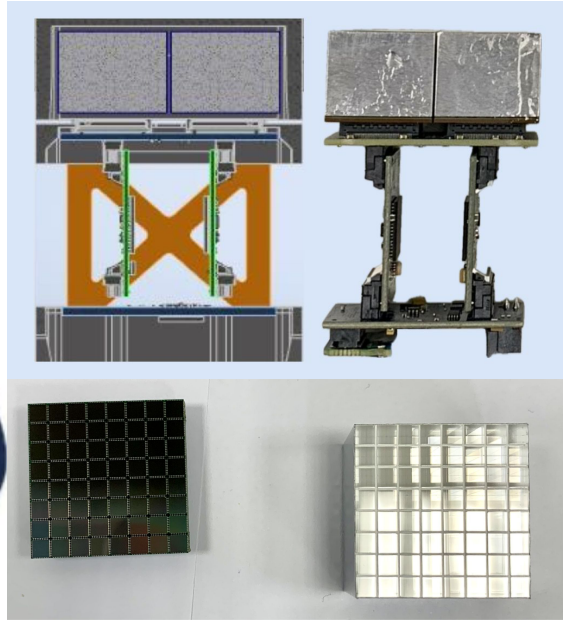




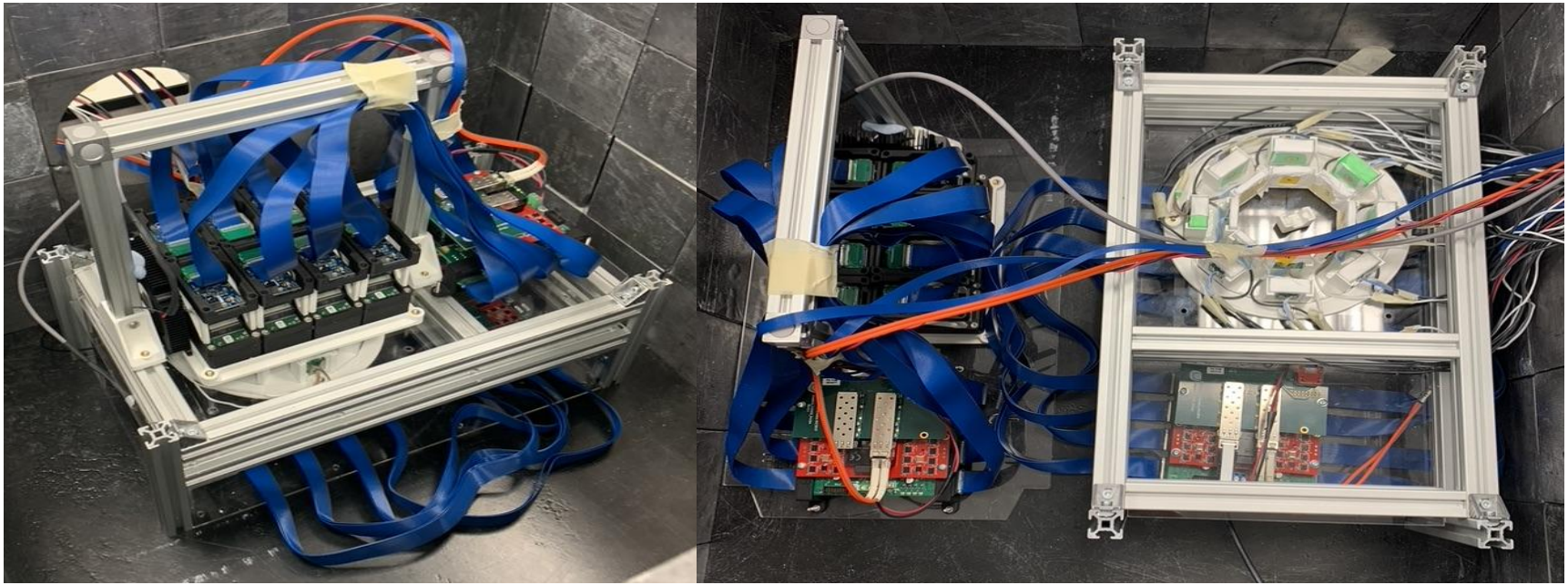


Detector Photographs LYSO array





Detector Photographs LYSO + GAGG



Cross section[1]

$$\langle \sigma \nu \rangle = \left(\frac{V_m}{N_0} \right) \lambda$$

Magnetic Field[5]

$$\lambda_{o-Ps}(H) = \frac{\lambda_{o-Ps} + \xi^2 \lambda_{p-Ps})}{1 + \xi^2}$$

$$\xi = \frac{\sqrt{1+x^2}-1}{x} \quad x = \frac{4\mu_B H}{\Delta E}$$

Surface Tension[1]

$$\lambda_p = 0.061\gamma^{0.50}$$

$$\lambda_p = 0.046\gamma^{0.55}$$

Electron Polarisation[1]

$$\frac{\lambda_p}{V_m} \propto P_z$$

pick-o

Pressure[1]

$$\lambda_p = \lambda_0 \left(1 + \frac{P_0}{P} \right)^n$$

Temperature[1]

$$\lambda_p(T) \approx \lambda_t + \theta(T_0 - T)$$

Water

$\tau_{\text{pick-off}}$ = 1848± 3 ps [3]

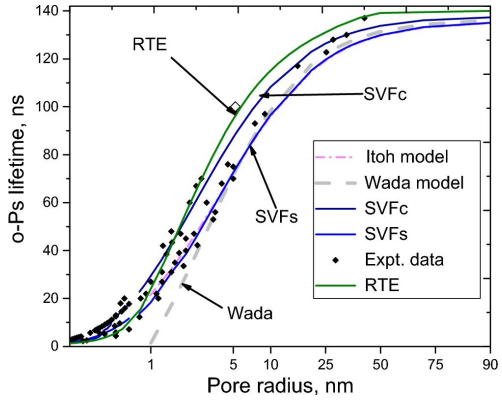
$\tau_{\text{pick-off}}$(27°C)= **2.07 ± 0.05 ns** [4]

$\langle \sigma v \rangle$=1.45 ± 0.04 × 10^{-14} cm^3s^{-1}

$\tau_{\text{pick-off}}$(82°C)= 2.17 ± 0.09 ns [4]

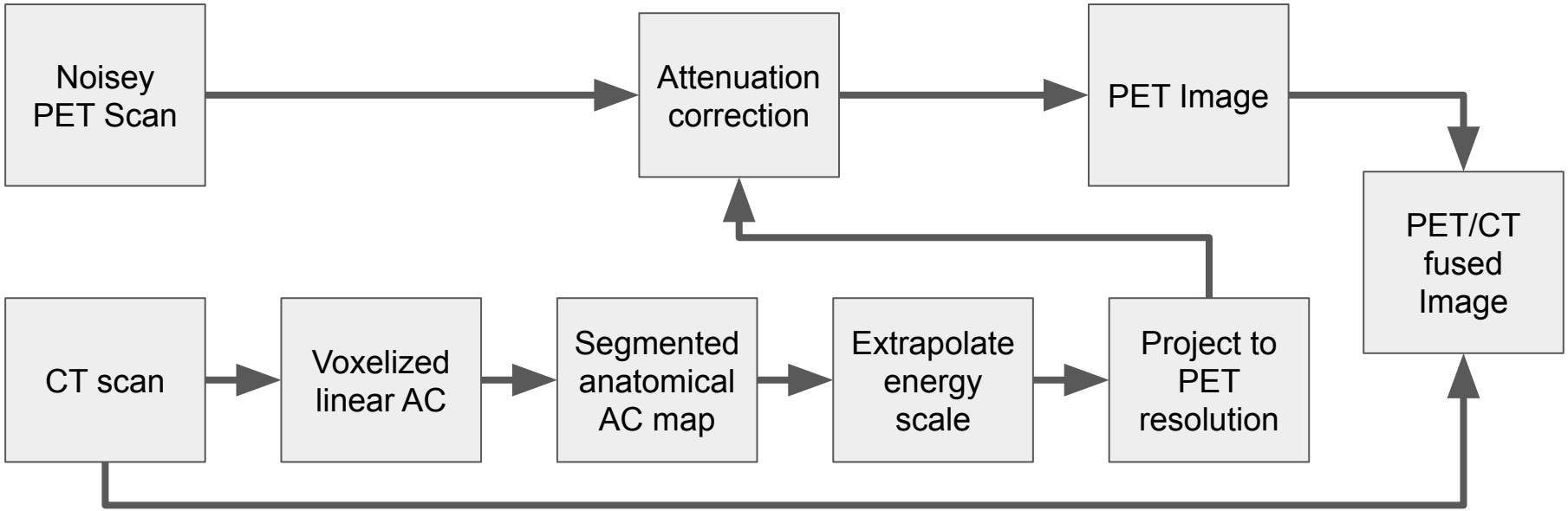
$\langle \sigma v \rangle$=1.43 ± 0.06 × 10^{-14} cm^3s^{-1}

Pore Size[2]

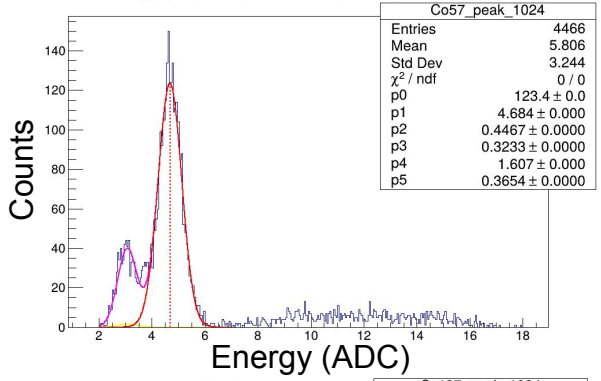


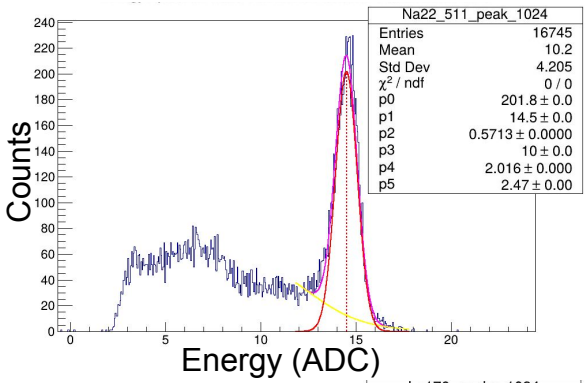
[1] S. J. Tao. 1972 DOI:10.1063/1.1677067. [2] PM Gordo et al. 2013, DOI: 10.1088/1742-6596/443/1/012055. [3] Petra Castellaz, Andreas Siegle, and Hermann Stoll. 2002, doi: 10.14494/jnrs2000.3.2_R1. [4] Peter R. Gray, Charles F. Cook, and Gene P. Sturm Jr. 1968 doi: 10.1063/1.1668776. [5] Sergey V. Stepanov et al. (2011) doi: 10.4028/www.scientific.net/MSF.666.109.

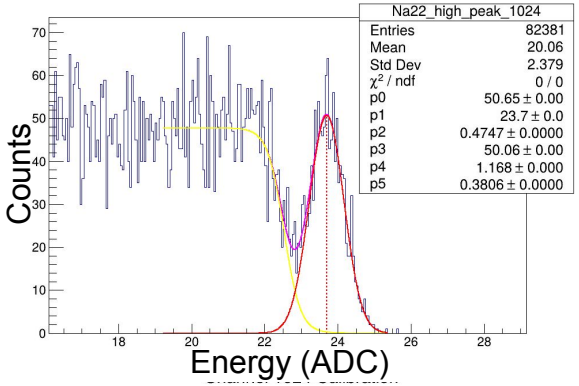
Attenuation Coefficients (AC)

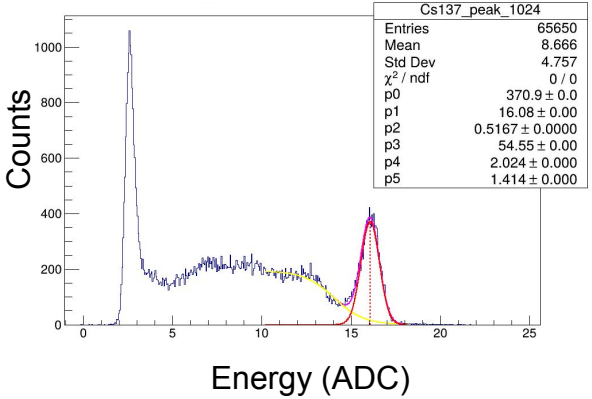


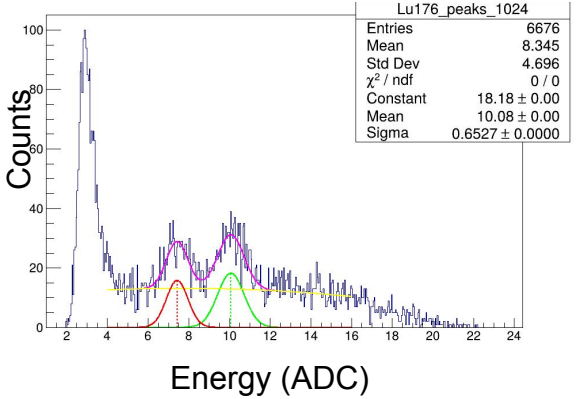
Current Analysis Improvement

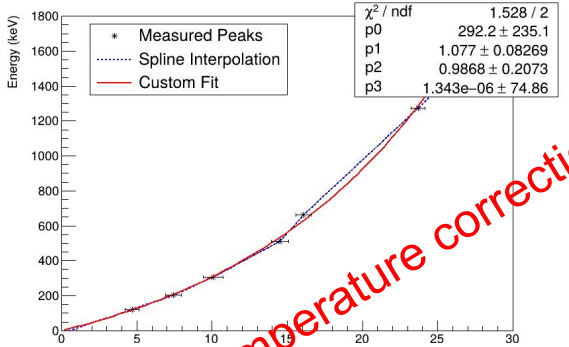






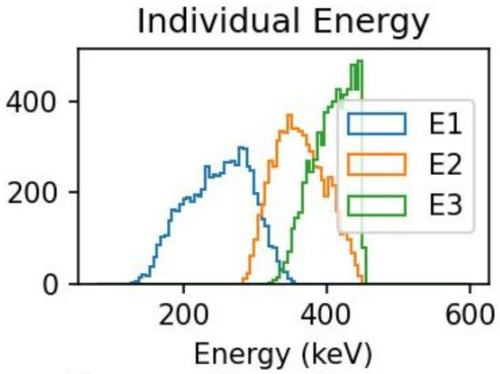


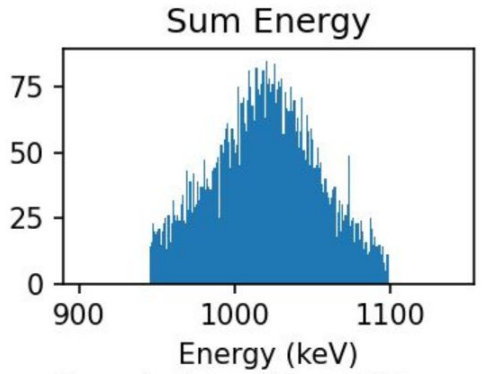


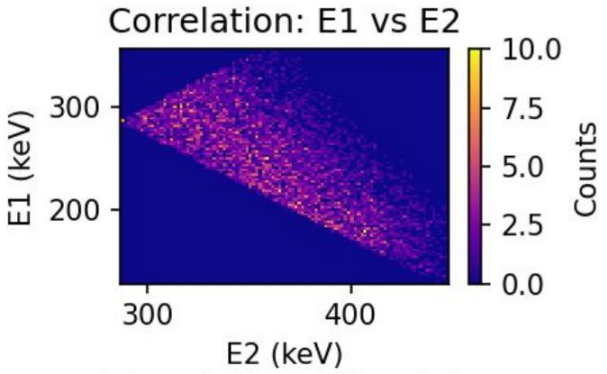


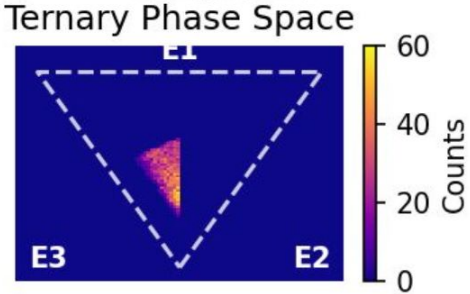
Temperature correction

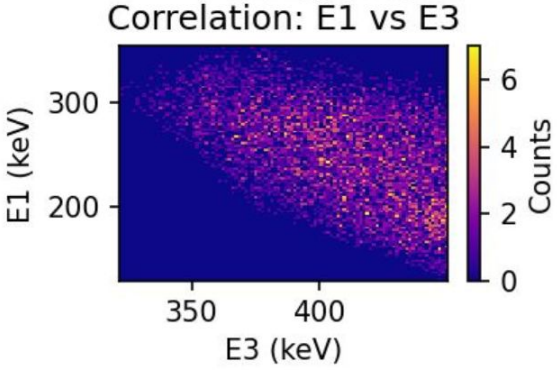
Photon Energies in 3γ Analysis

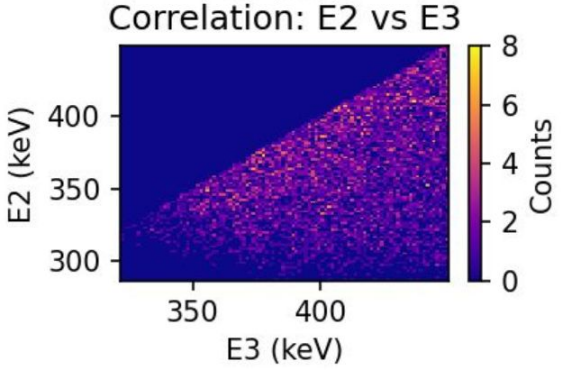












Ore Powell Plot

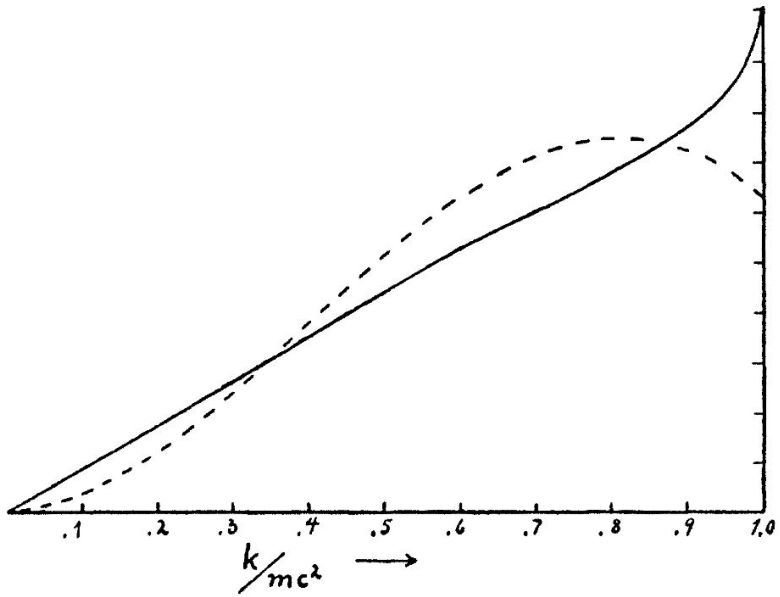


FIG. 2. Energy spectrum of photons resulting from three-photon annihilation of an electron and a positron. The abscissa is the photon energy in units mc^2 and the ordinate is proportional to the number of photons per unit energy interval. (Dashed curve: statistical estimate.)

Ore, Powell, (1949) doi: 10.1103/PhysRev.75.1696

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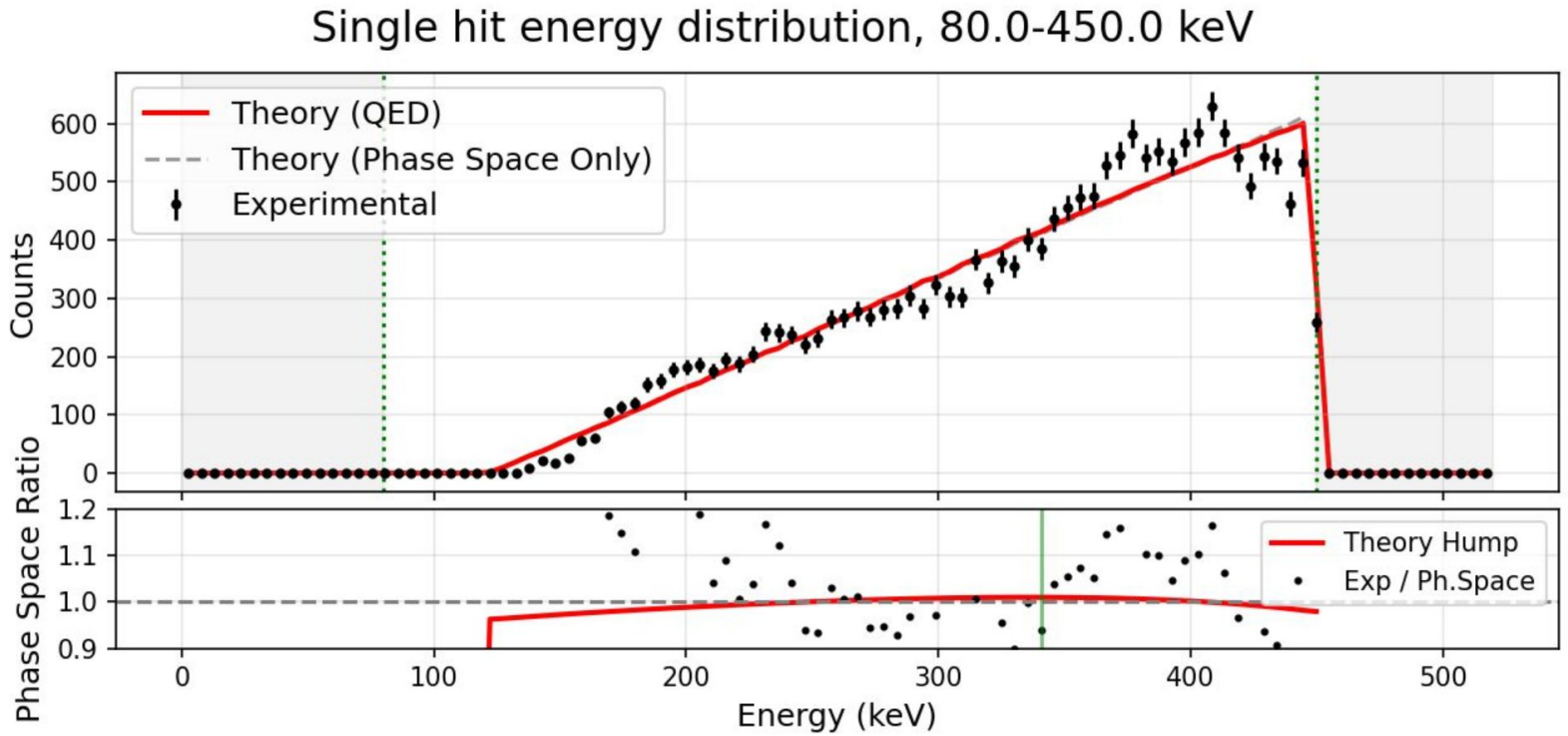
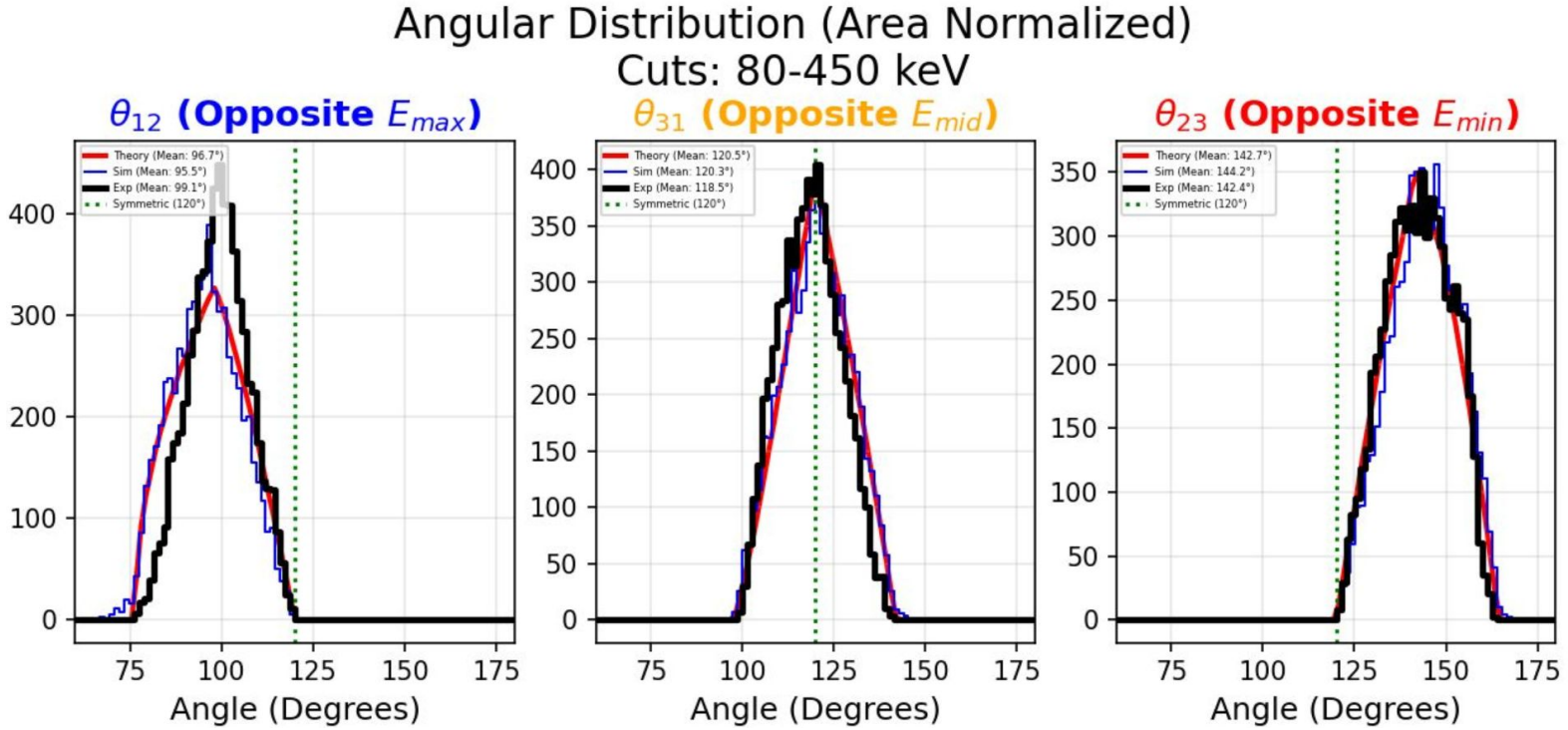
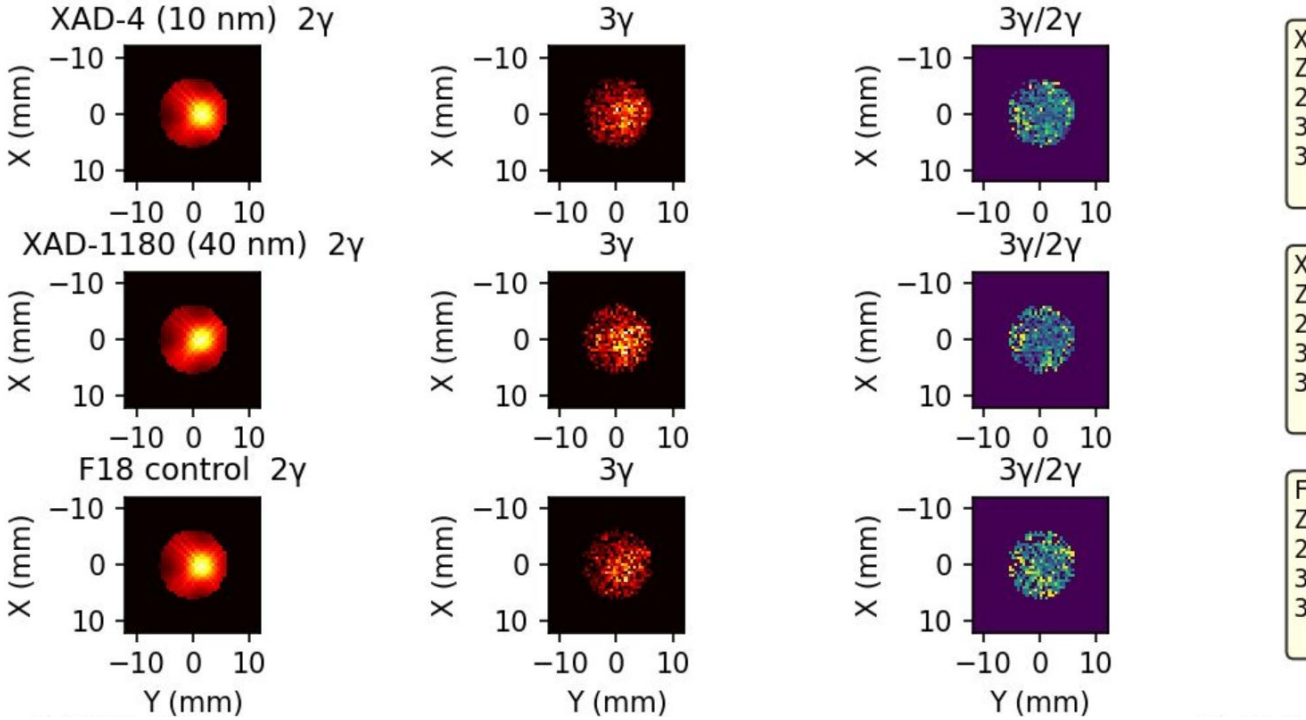


Interphotonic angels in 3γ Analysis



Preliminary Results



Stats

```
XAD-4 (10 nm)
Z: [-31.4, 22.6] mm
2γ: 15065353
3γ: 980
3γ/2γ: 0.000065
```

```
XAD-1180 (40 nm)
Z: [-31.4, 22.6] mm
2γ: 16458069
3γ: 780
3γ/2γ: 0.000047
```

```
F18 control
Z: [-31.4, 22.6] mm
2γ: 14190273
3γ: 682
3γ/2γ: 0.000048
```