John Adams Institute for Accelerator Science

Applications of plasma accelerators

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Cern Accelerator School on High Gradient Wakefield Accelerators
Sesimbra, Portugal
15th March 2017

The CERN Accelerator School

http://cas.web.cern.ch/schools/sesimbra-2019 https://indico.cern.ch/event/759579/overview

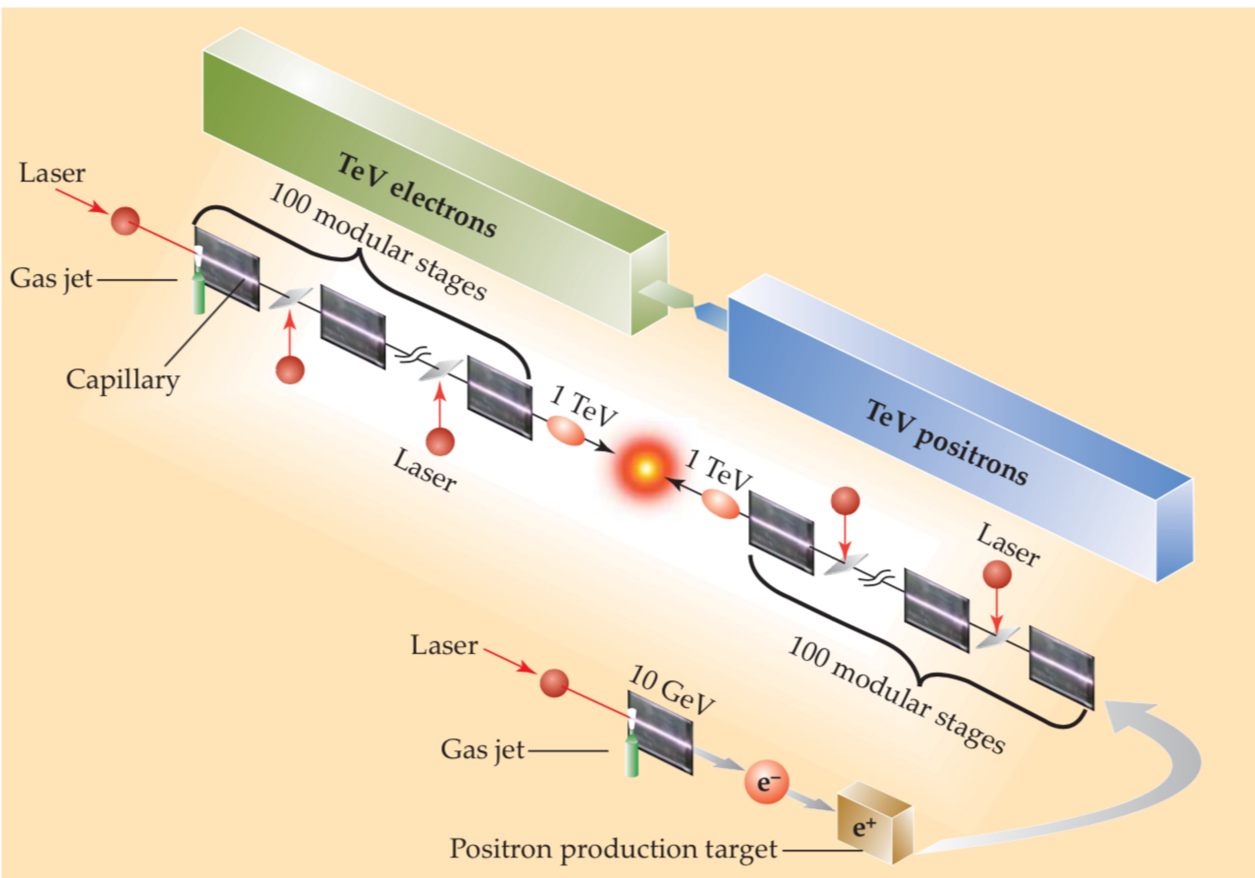
Applications: outline

- High Energy Physics
- Positron Sources
- Free Electron Lasers
- Synchrotron sources
- Compton sources
- High Field Physics

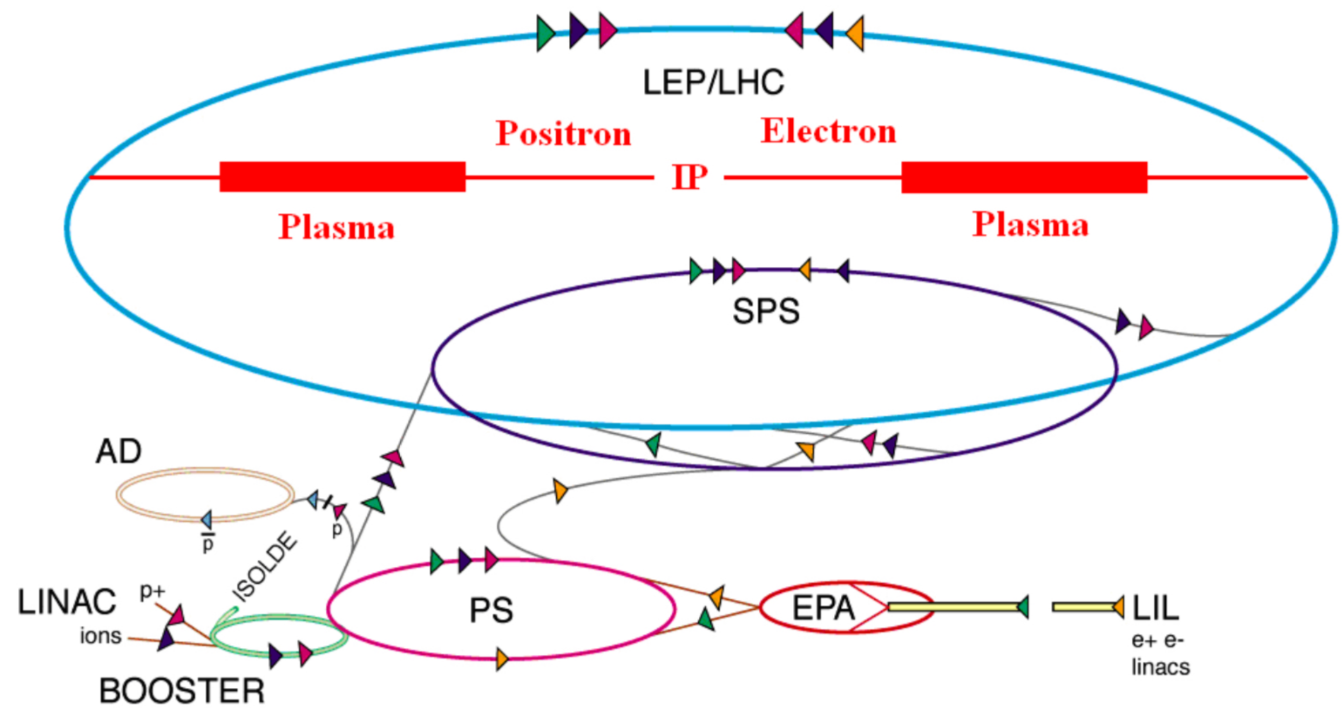
High Energy Physics

High Energy Physics

Goal: to get to 125 GeV to 1 TeV level



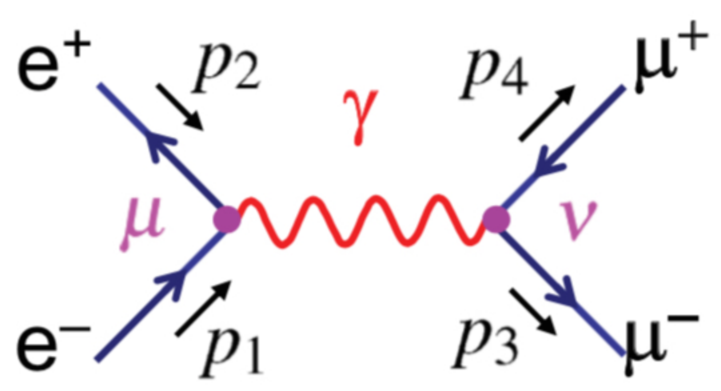
W. Leemans and E. Esarey, Laser-driven plasma-wave electron accelerators, Phys. Today 62, 44 (2009).

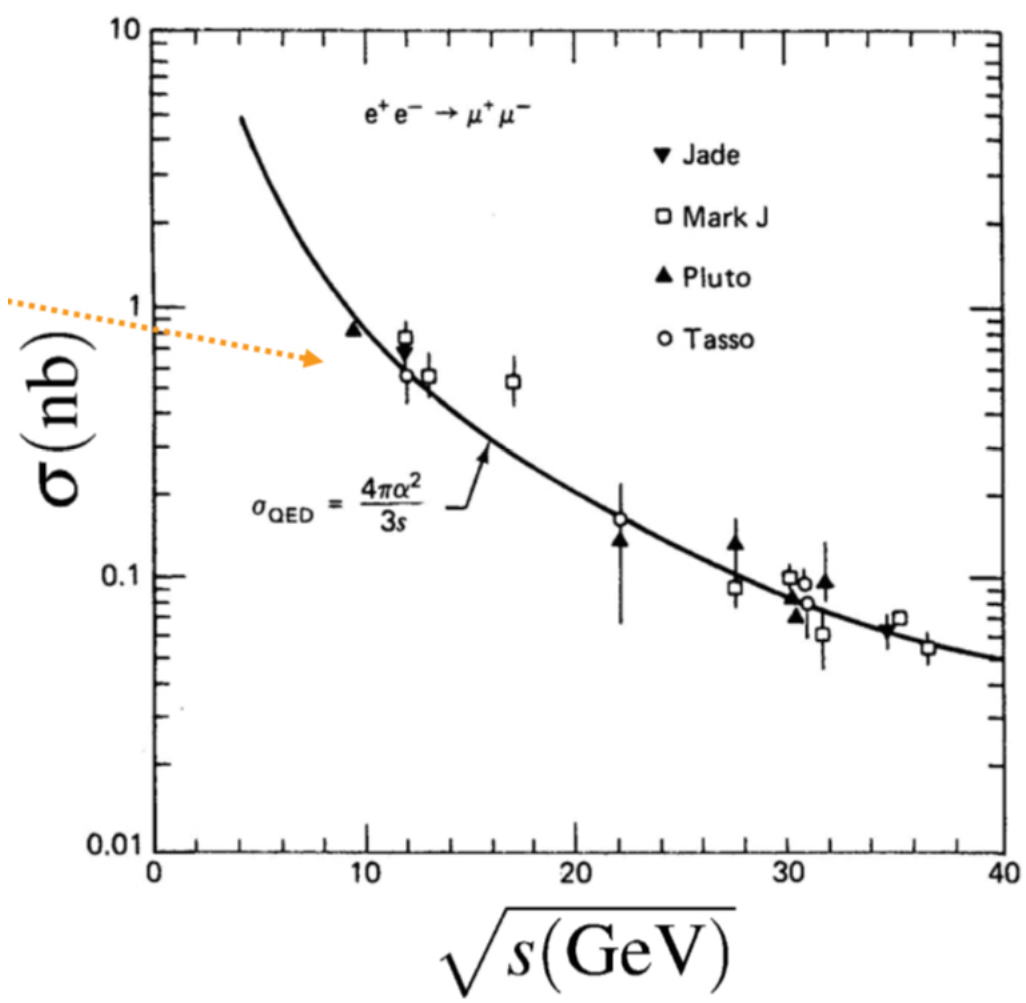


G. Xia, A. Caldwell, and P. Muggli, Future Colliders Based on a Modulated Proton Bunch Driven Plasma Wakefield Acceleration, Proc. IPAC2012 3039 (2012).

see also ALEGRO workshop: https://indico.cern.ch/event/732810/

Luminosity





Cross-section decreases rapidly with energy:

$$\sigma_T = \frac{4\pi\alpha^2}{3s} \propto \frac{1}{E^2}$$

To have enough events need high luminosity:

$$\mathcal{L} = \frac{fN^2}{4\pi\sigma_x\sigma_y}$$

Here f is collision frequency, and σ_x , σ_y are transverse beam sizes, and $N_p = N_e$

Luminosity

Total rate is produce of luminosity and cross-section:

$$\frac{dR}{dt} = \mathcal{L} \cdot \sigma_p$$

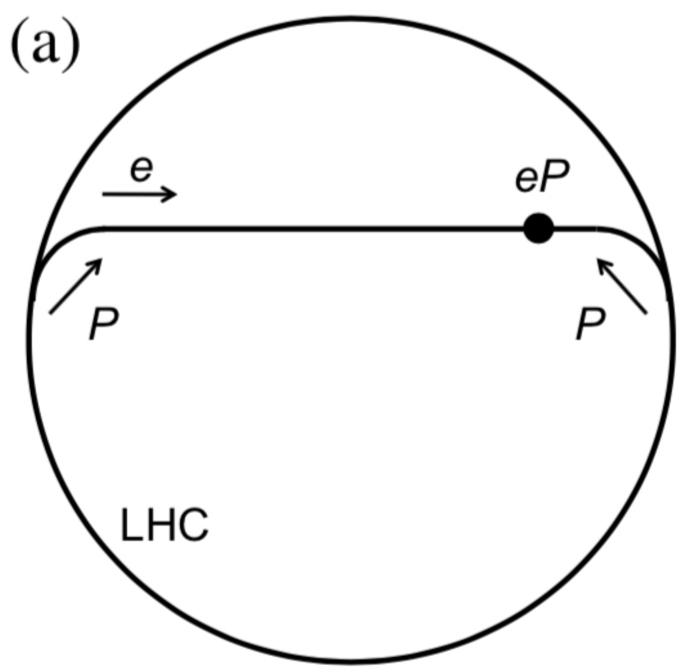
So to maintain enough events:

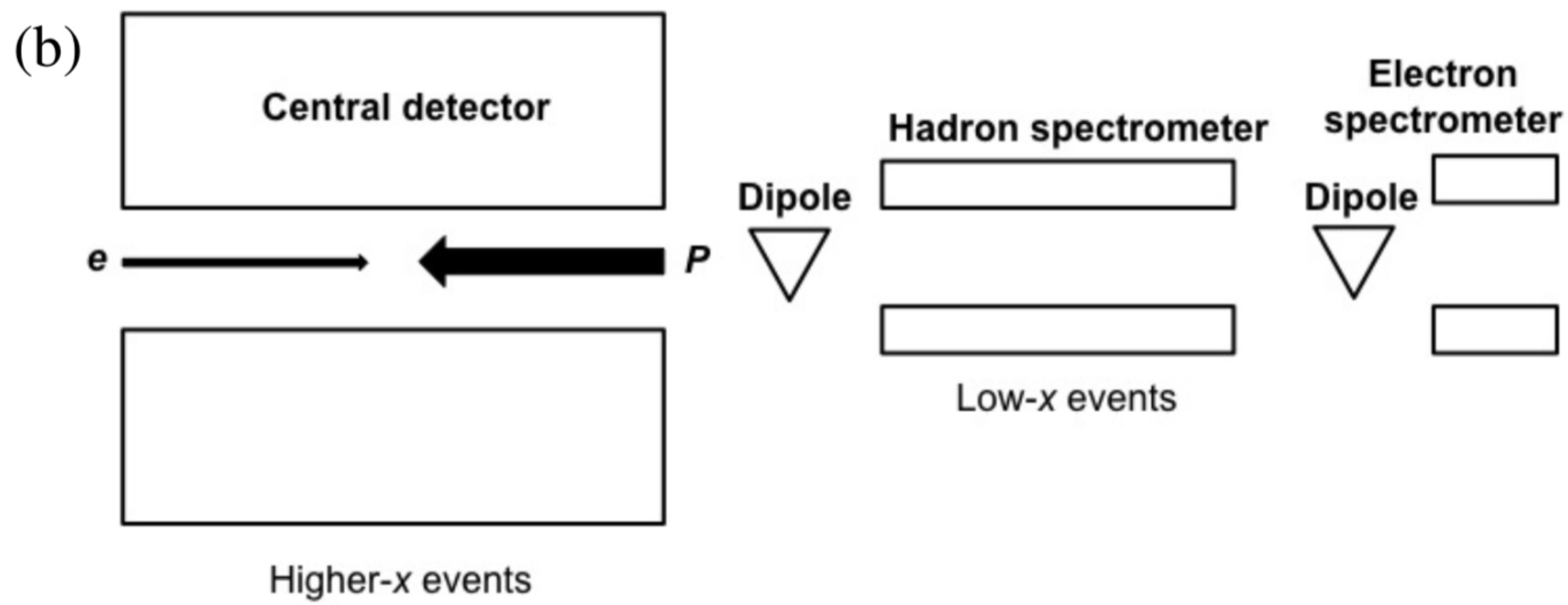
$$\mathcal{L}\left[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}\right] \approx E_{\mathrm{cm}}^2[\mathrm{TeV}]$$

Implies $fN/\sigma_x\sigma_y$ must increase in proportion to E^2

C. B. Schroeder, E. Esarey, C. G. R. Geddes, C. Benedetti, and W. P. Leemans, Physics considerations for laser-plasma linear colliders, Phys. Rev. Spec. Top. - Accel. Beams 13, 1 (2010).

ep collider





$$\mathcal{L} = \frac{f N_e N_P}{4\pi\sigma_x\sigma_y}$$

Take advantage of:

- large proton energy
- large proton number
- larger ep cross-section

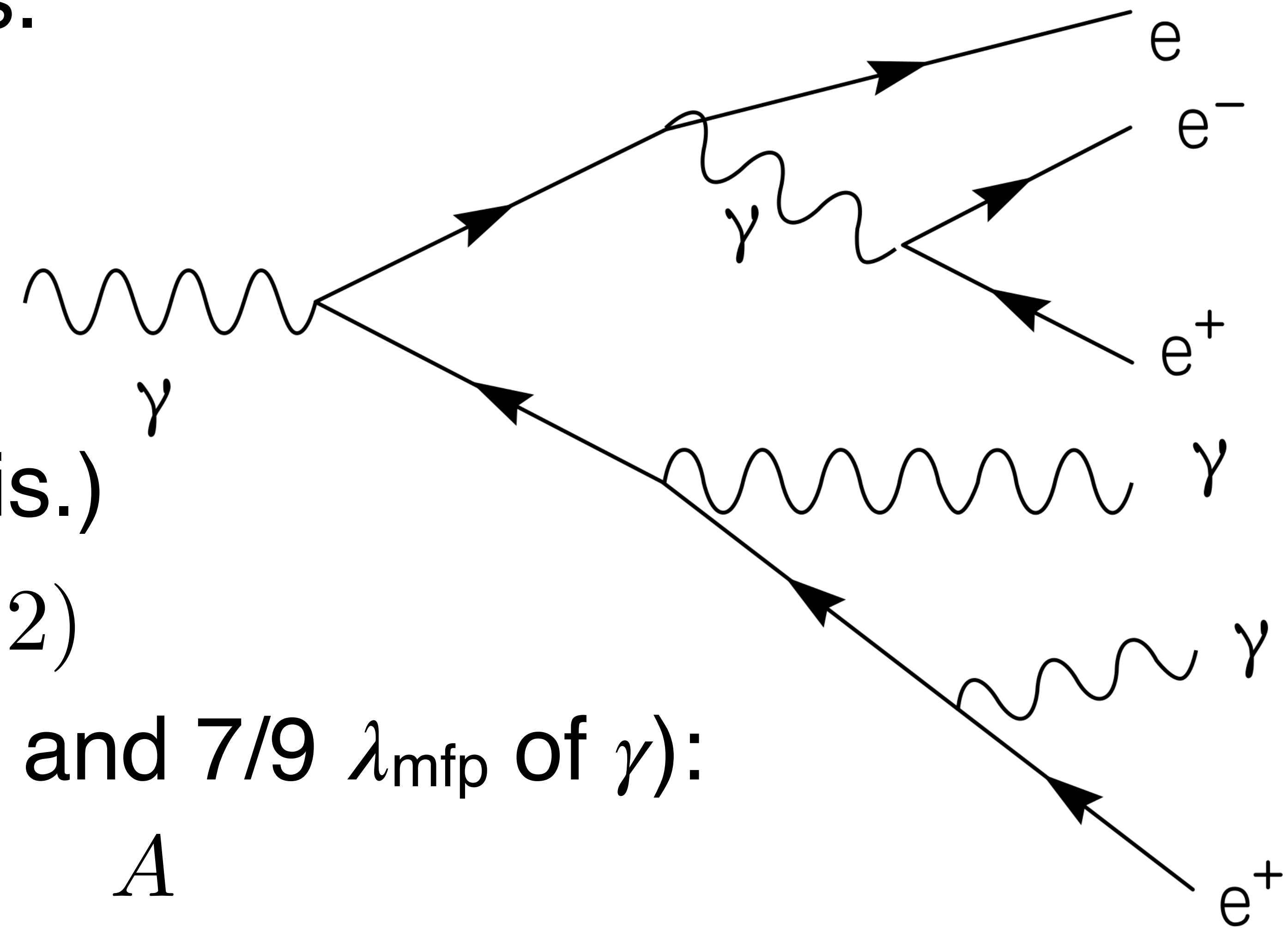
A. Caldwell and M. Wing, VHEeP: A very high energy electron-proton collider based on proton-driven plasma wakefield acceleration, Proc. Sci. 27-April-2015, (2015).

M. Wing, G. Xia, O. Mete, A. Aimidula, C. P. Welsch, S. Chattopadhyay, and S. Mandry, Collider design issues based on proton-driven plasma wakefield acceleration, Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 740, 173 (2014).

Positron Sources

Positron beams

Positrons generated in a cascade of ep pairs produced by brehmstrahlung photons.



Cascade length is:

$$X = X_0 \frac{\ln\left(E_0/E_\mathrm{c}\right)}{\ln 2}$$

Critical energy (brems=ionis.)

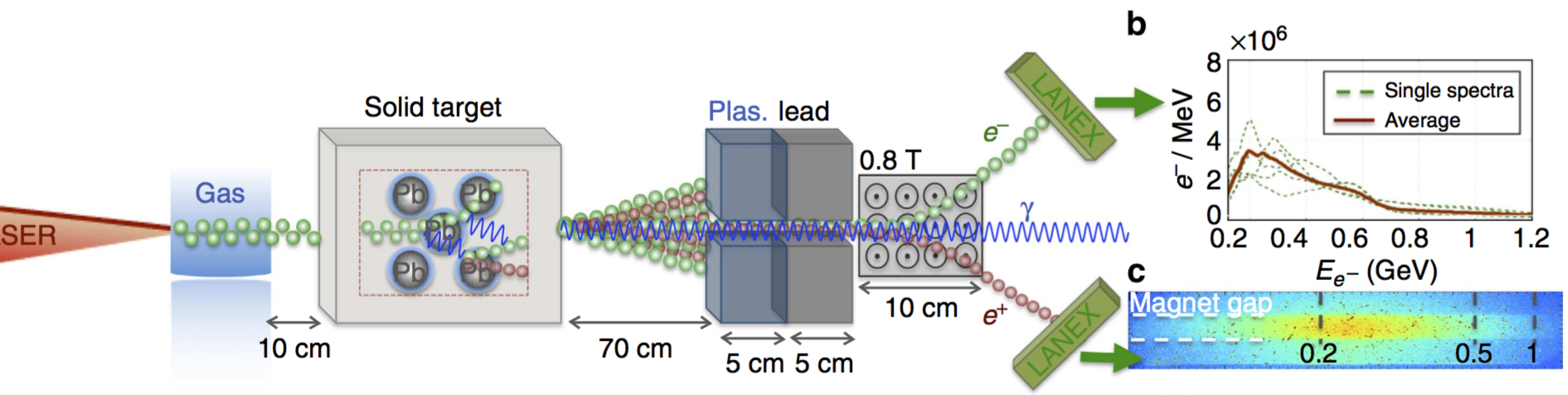
$$E_\mathrm{c} = 800\,\mathrm{MeV}/(Z+1.2)$$

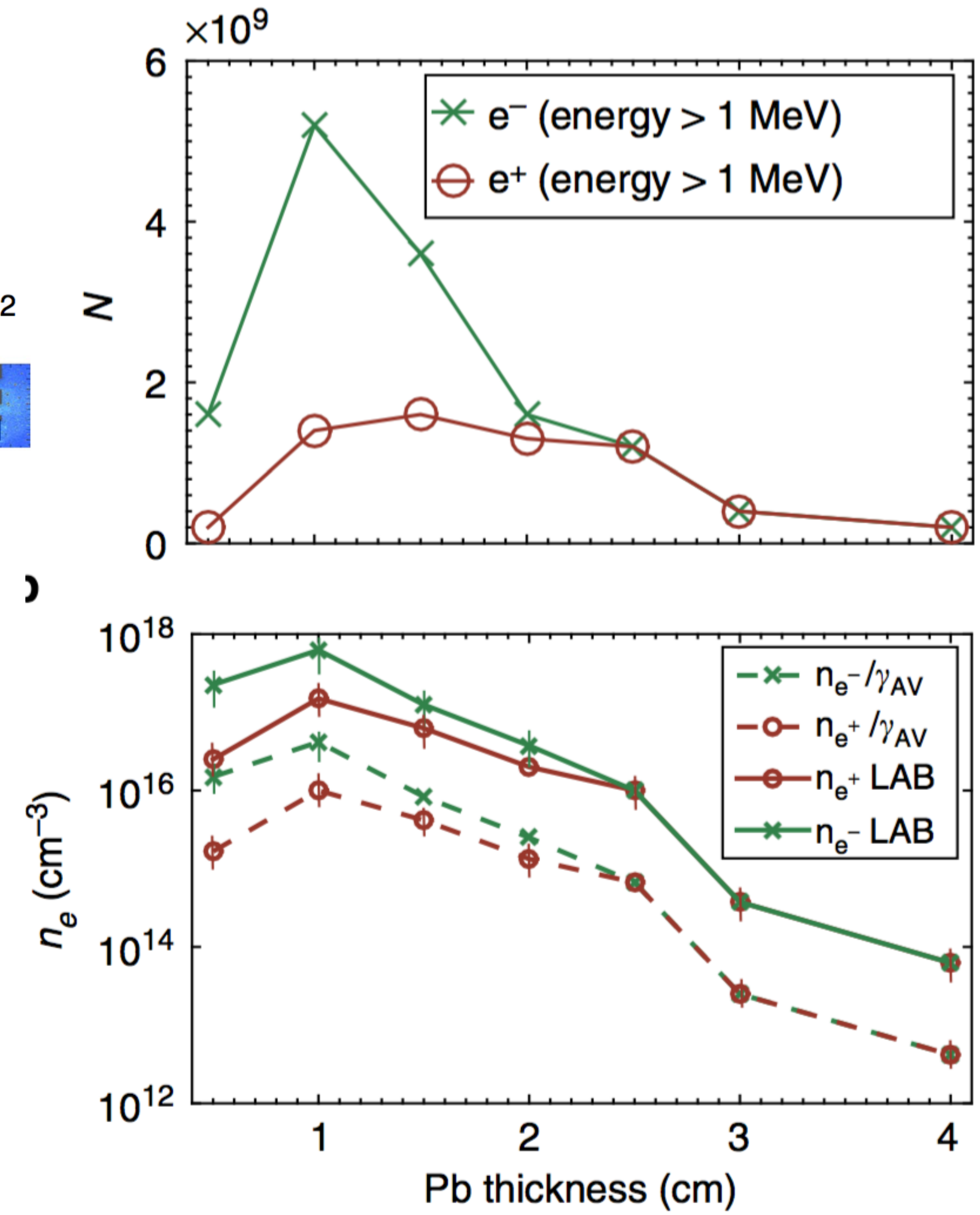
Radiation length (1/e for *e*- and 7/9 λ_{mfp} of γ):

$$X_0 = 716.4\ \mathrm{g\,cm^{-2}} \frac{A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}$$

For Pb, $E_c \sim$ 9.6 MeV, and $X_0 \sim$ 6.33 g cm-2, $\lambda_{\mathrm{mfp}} \approx$ 5.9 mm

Near-neutral Positron beams



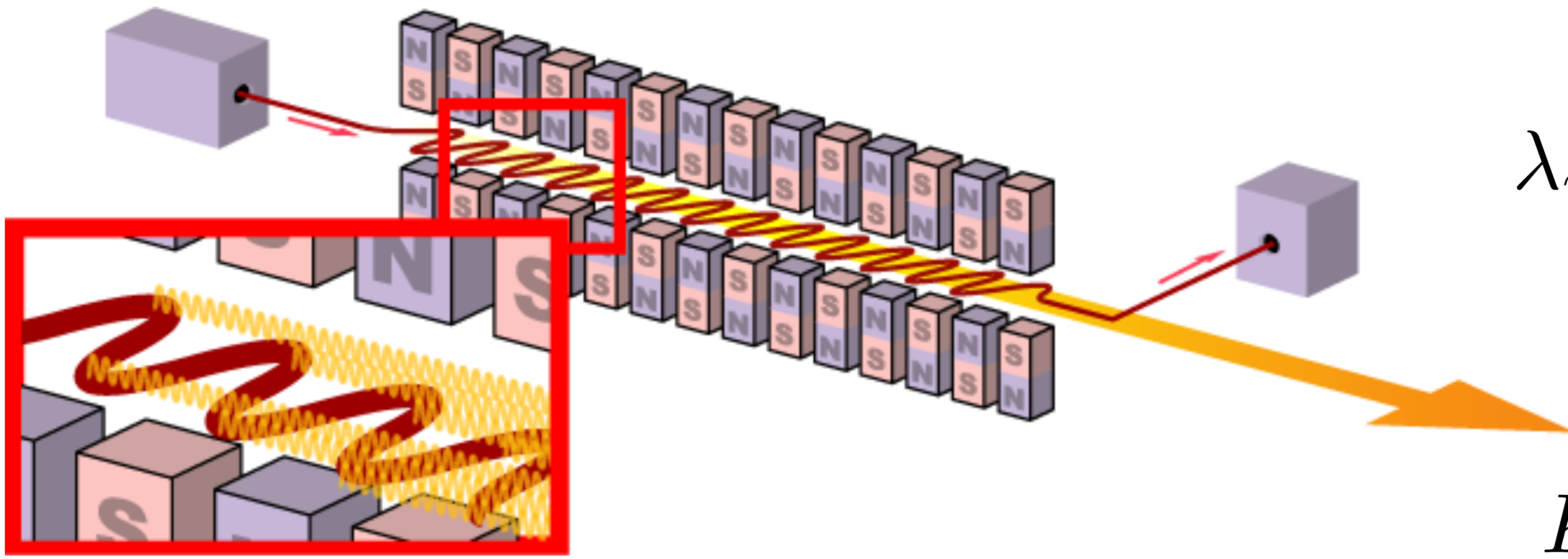


Generate neutral electron positron beams for simulating astrophysical scenarios.

Sarri, G. et al. Generation of neutral and high-density electron-positron pair plasmas in the laboratory. Nat. Commun. 6, 6747 (2015).

Free Electron Lasers

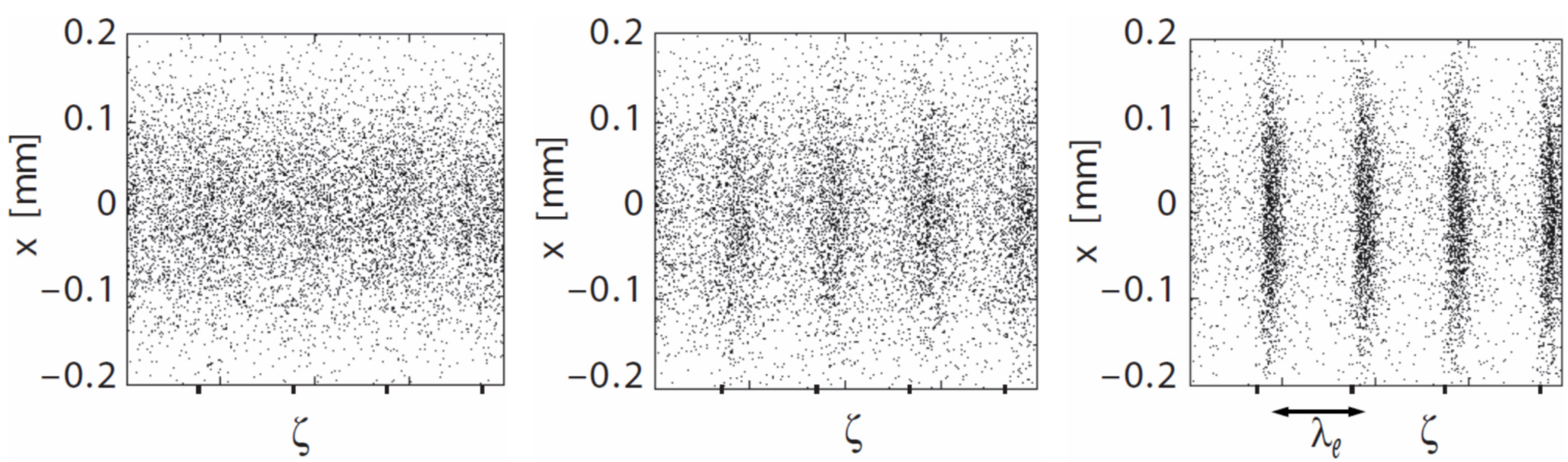
Undulators



$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$K = \frac{eB_0\lambda_\mathrm{U}}{2\sqrt{2}\pi m_0 c} \ll 1$$

Spontaneous (or seed) pulse causes microbunching



Bunches then emit radiation coherently $P_\Sigma \propto E_\Sigma^2 \approx N^2$

Undulators

Radiation is coherent causing further bunching leading to instability growth

$$P \propto \exp\left(z/L_{\mathrm{g}}\right) \qquad \text{with} \qquad L_g \propto \gamma \left(\frac{\lambda_u \sigma_r^2}{I}\right)^{1/3}$$

$L_g \approx$ 1..10 m and gain saturates for $L_s \approx$ 10..20 L_g

Undulator typically ≈ 100 m

Challenges

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$ → Typically $\lambda_u \approx 0.1$ m,
for x-rays ($\lambda_r \approx 0.1$ nm)
→ $\gamma^2 \approx 10^9$ → $E \approx 15$ GeV

$$L_g = \frac{1}{\sqrt{3}}\left(\frac{4mc}{\mu e}\frac{\gamma^3\lambda_u}{K^2}\frac{\sigma_r^2}{I}\right)^{1/3}$$ → High current needed for short gain length ≈ kA

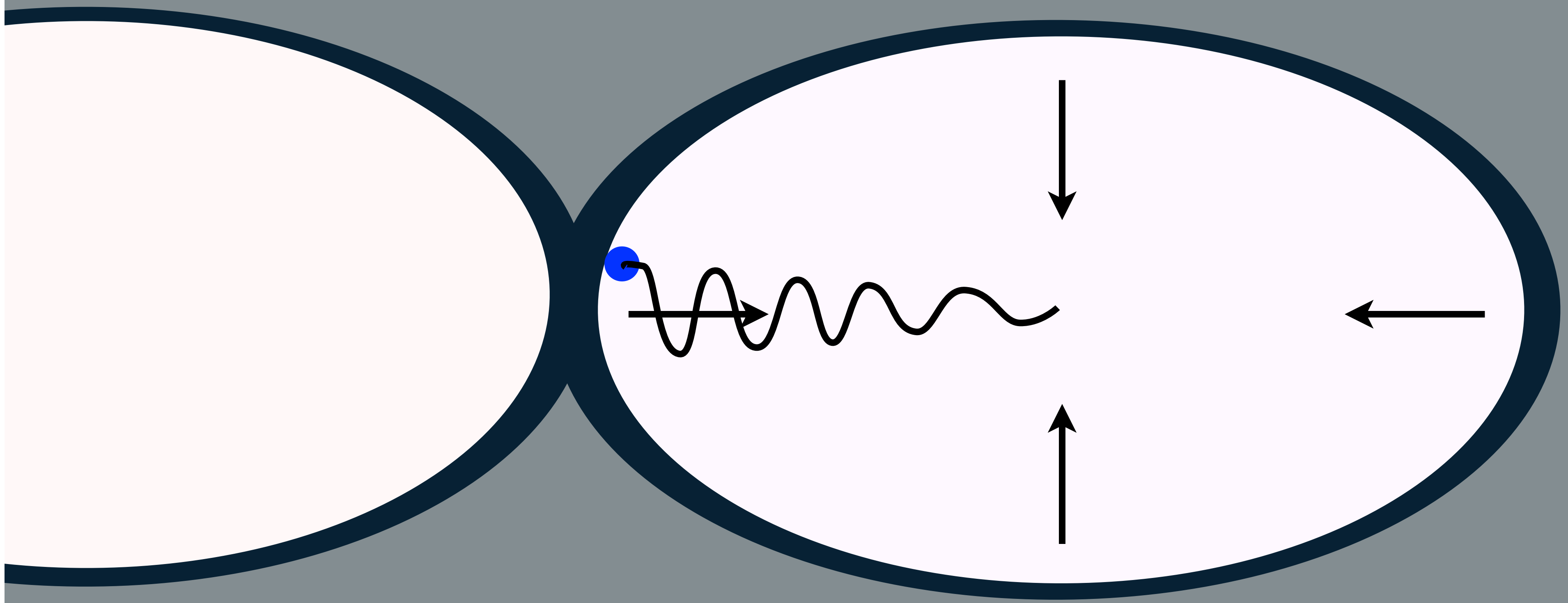
$$\sigma_r^2 \propto \lambda_l L_g$$ → Small spot sizes needed for overlap with radiation ≈ 10 μm

$$\varepsilon_n \leq \frac{\gamma\lambda}{4\pi}$$ → Good overlap in phase space

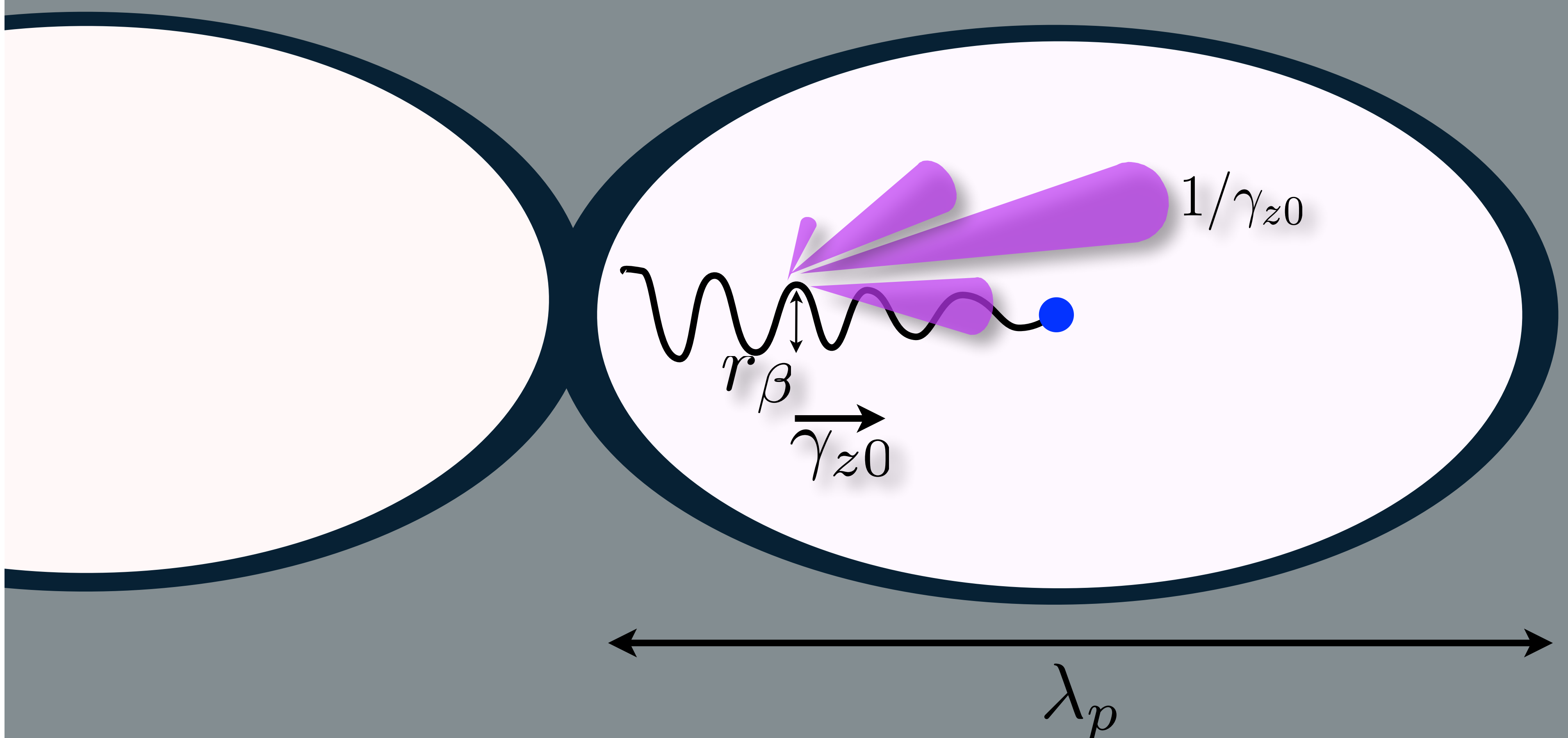
$$\frac{\Delta\gamma}{\gamma} \leq \frac{1}{2N_w}$$ → Energy spread must be less than velocity spread over undulator

Synchrotron Sources

Acceleration



Radiation



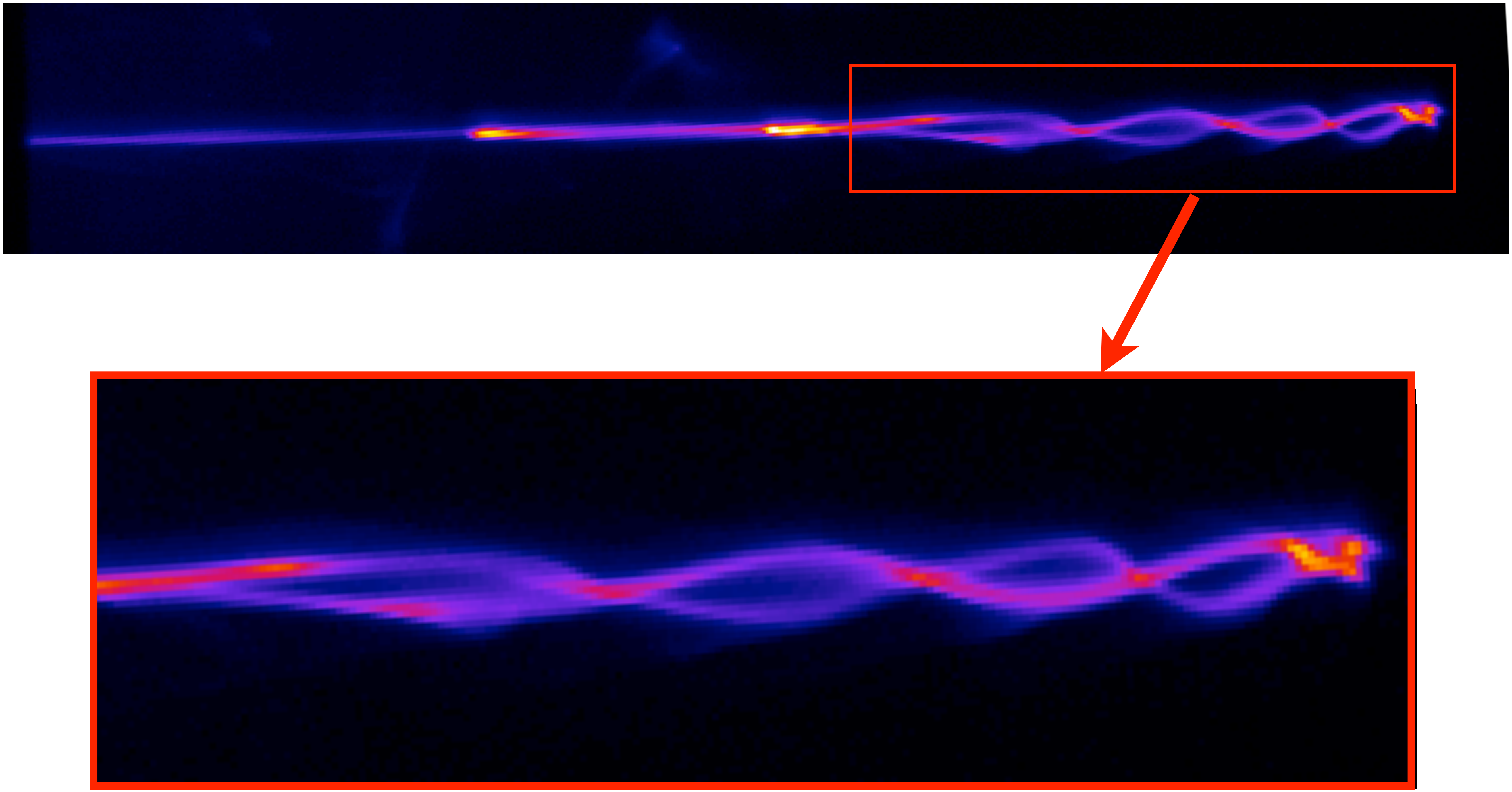
$$P_s = \frac{e^2 c}{3}\gamma_{z0}^2 k_\beta^2 a_\beta^2$$

$$a_\beta = \gamma_{z0} r_\beta k_\beta$$

$$\omega_c = 3\gamma^3 \omega_\beta^2 r_\beta / c$$

E Esarey PRE **65**, 056505 (2002)

Betatron Oscillations directly observed

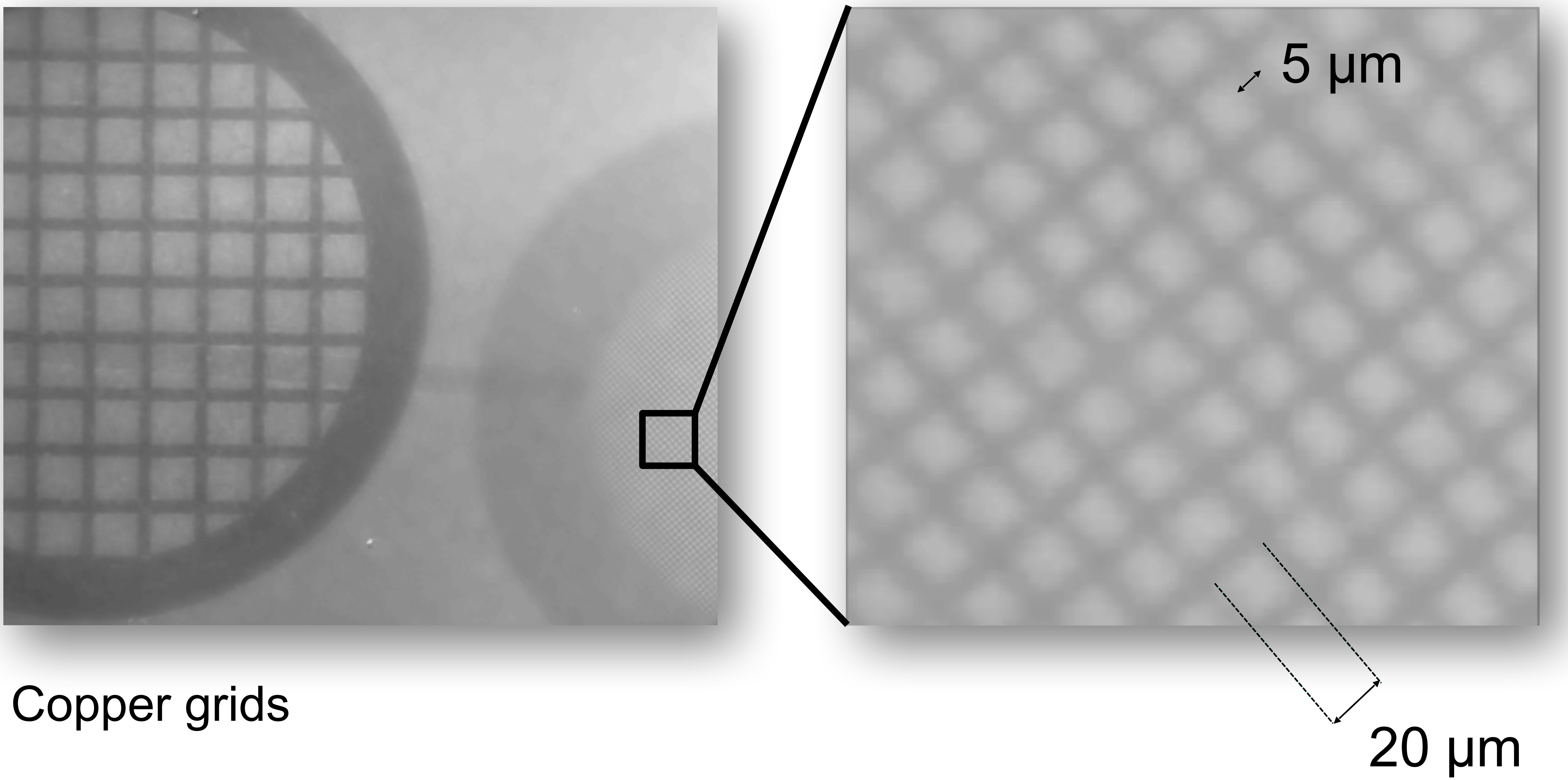


X-ray beams

Source size < 3 μm

Resolution target + processing

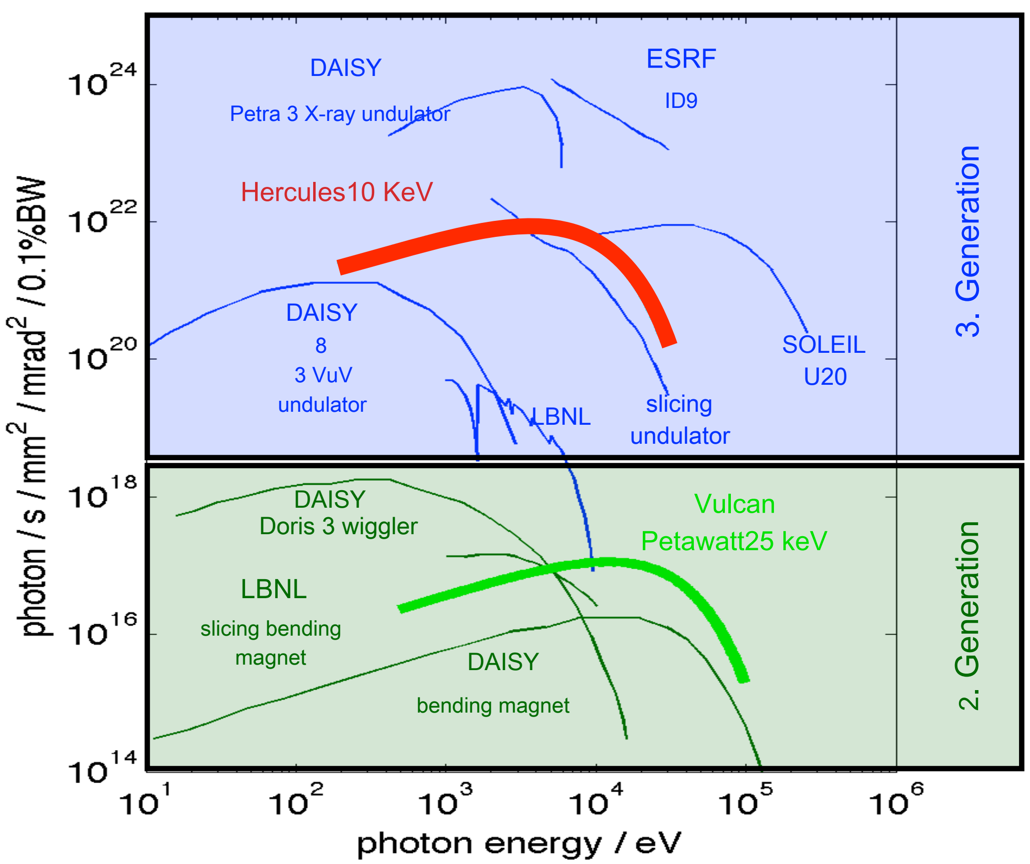
Zoom



Copper grids

Betatron Radiation

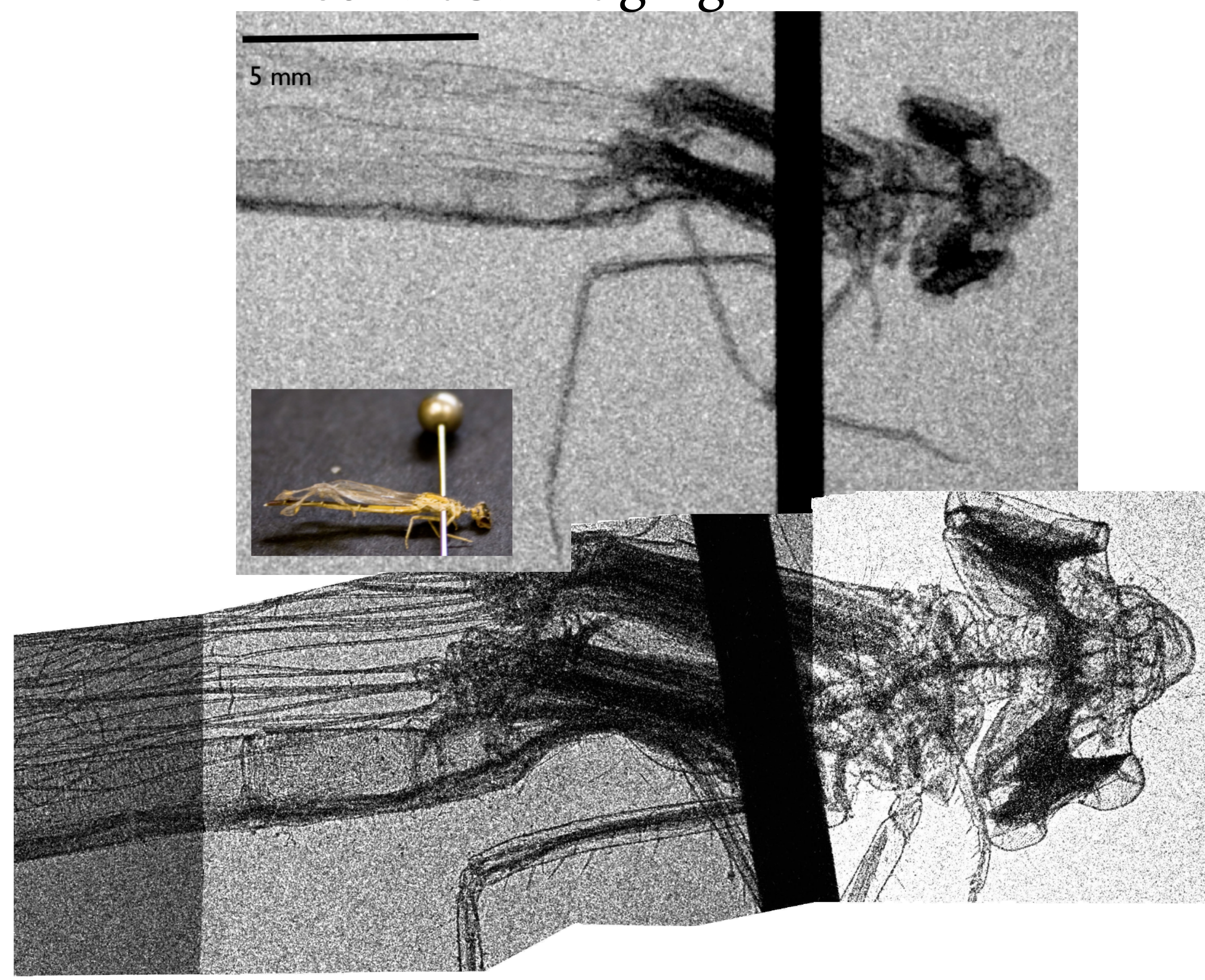
Betatron x-ray source shown to have comparable peak brightness to 3rd generation light source



other light sources from A. Rousse et al, EPJD, 2008

Kneip, S. et al. Bright spatially coherent synchrotron X-rays from a table-top source. Nat. Phys. 6, 980 (2010).

small source size ideal for phase contrast imaging



Kneip, S. et al. X-ray phase contrast imaging of biological specimens with femtosecond pulses of betatron radiation from a compact laser plasma wakefield accelerator. Appl. Phys. Lett. 99, (2011).

Properties of β-tron sources

'Hard' photon energy - E_{crit} > 25 keV

- investigating dense material, biological materials

Small source **size** (~ μm)

- intrinsically high resolution
- exhibits spatial resolution

Small **divergence** (~ 10 mRad)

- makes beam line

Short pulse (~10s fs)

- suitable for ultrafast dynamics

Bright (>10^9 photons per shot)

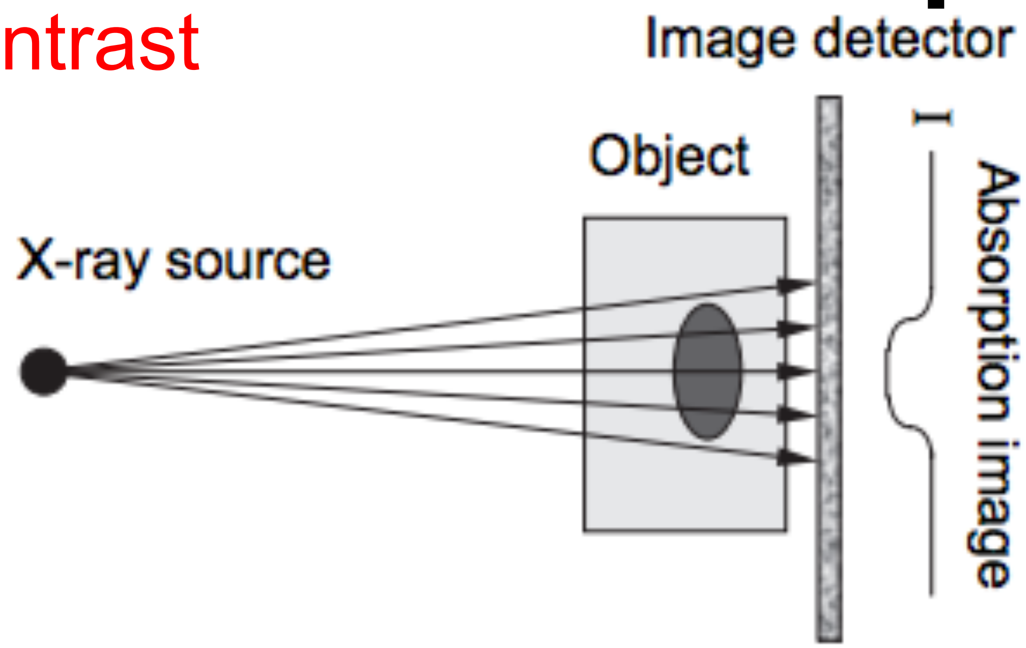
- suitable for single shot imaging

All of these things makes for a unique imaging capability

Phase vs. absorption contrast

Absorption contrast

Contrast through photon absorption



Phase shift   Absorption

$$n = 1 - \delta - i\beta$$

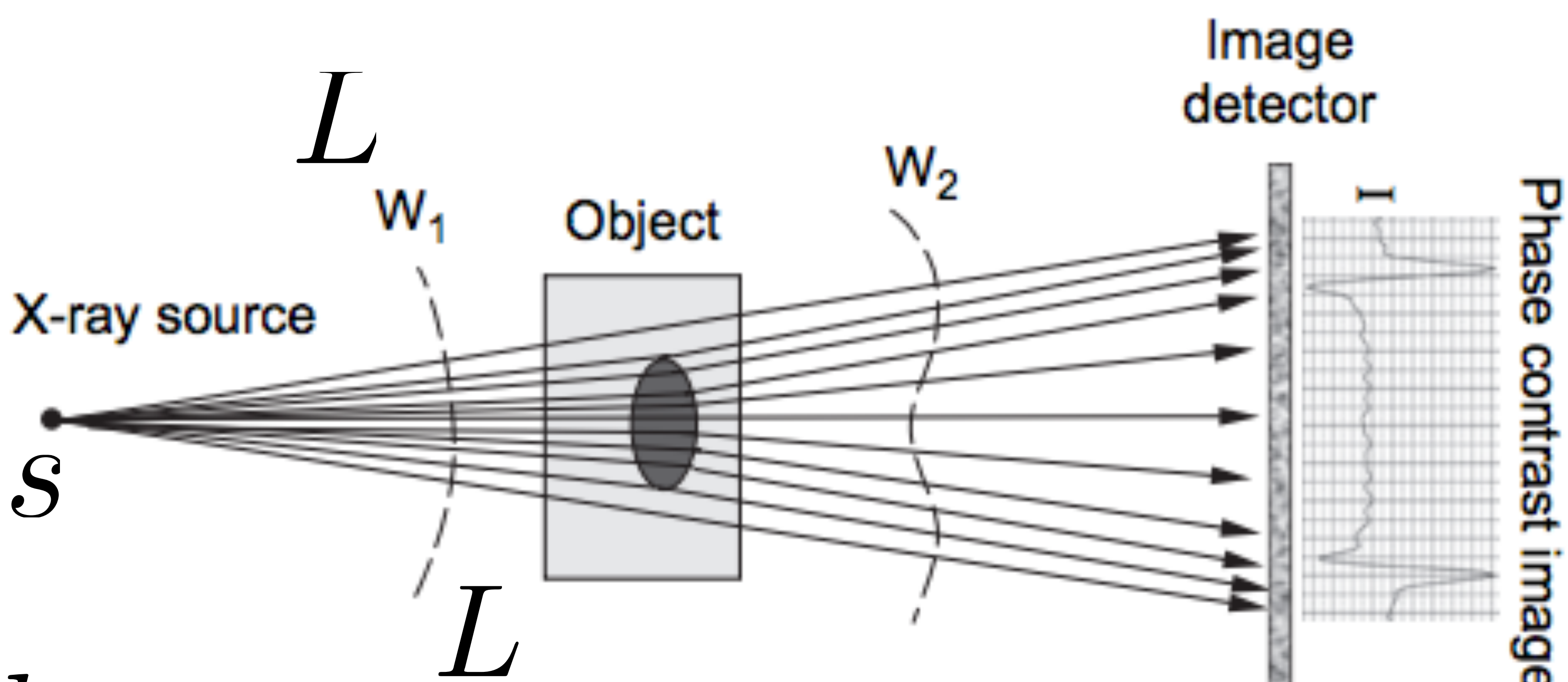
$$\frac{\delta}{\beta} \propto E^2$$

Phase contrast

Object deflects photons, highlighting edges

Propagation-based, works for polychromatic sources

L



s

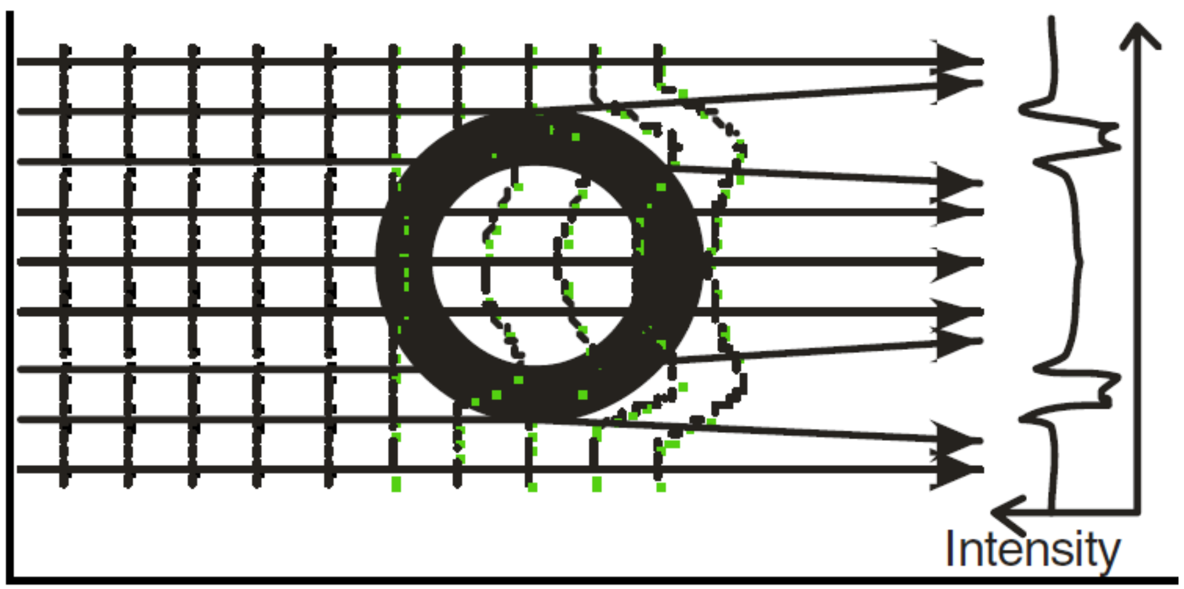
$$l_{coh} = \frac{L}{sE}$$

Zhou S-A and Brahme A, Physica Medica (2008) **24**

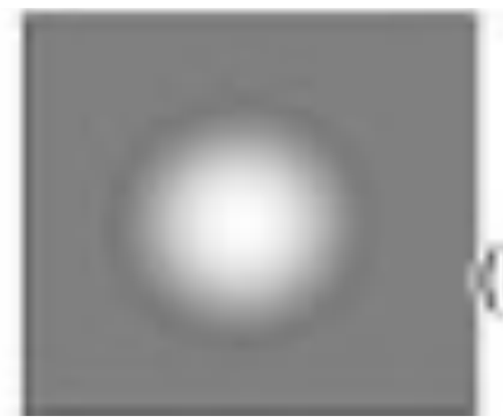
Propagation based phase contrast

Imperial College London

Background - Phase contrast: diffraction rather than absorption

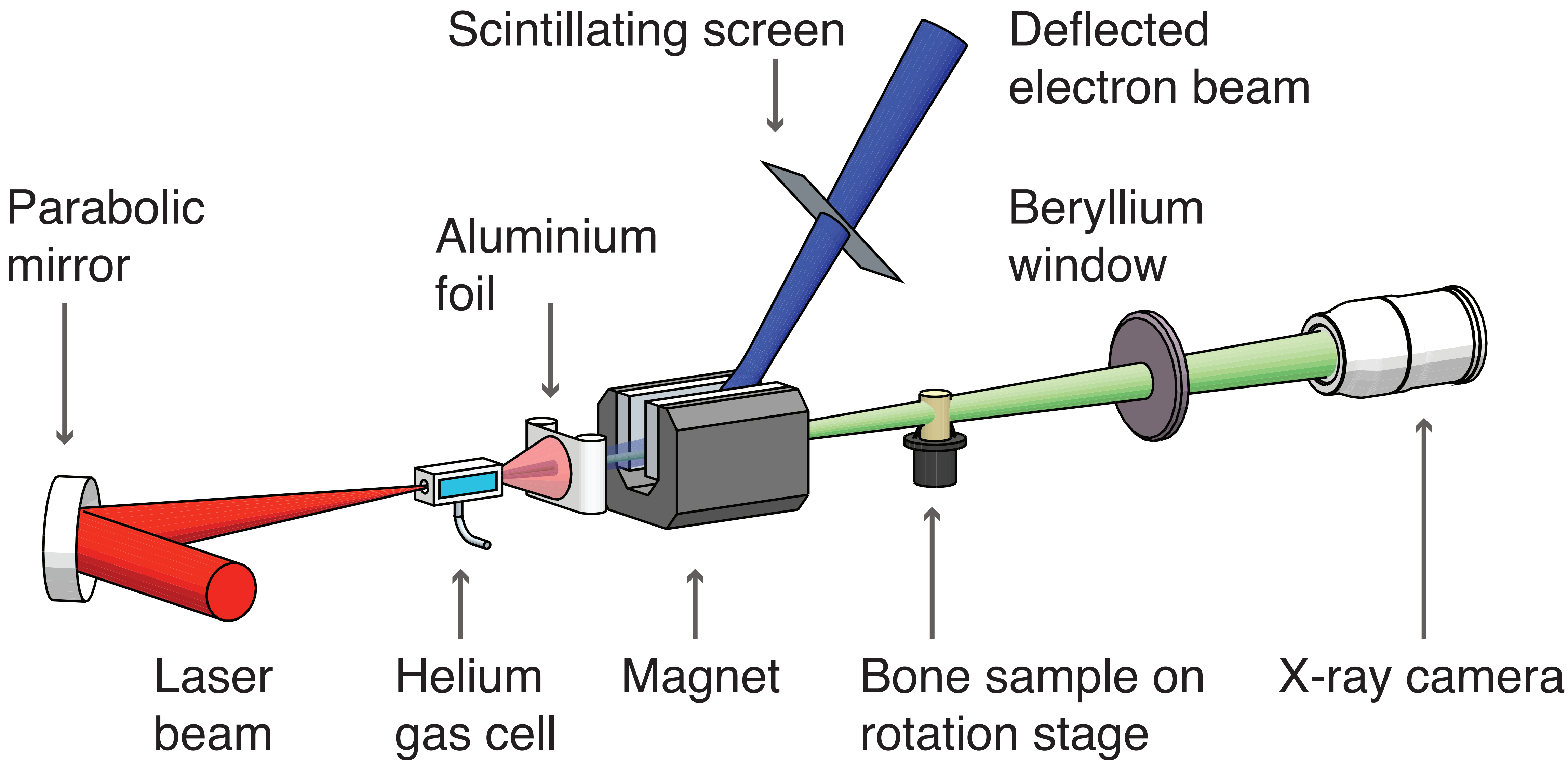


Absorption contrast

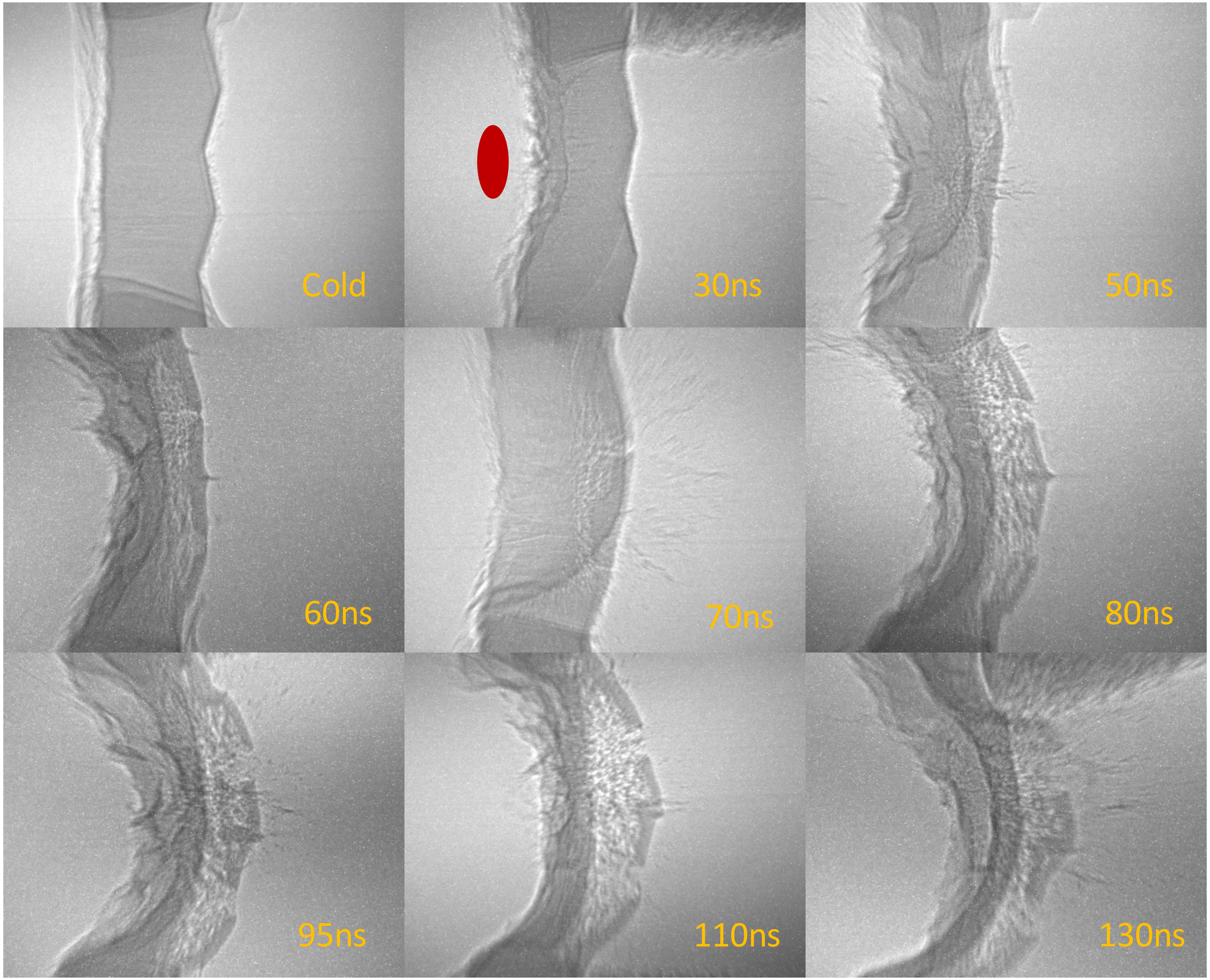


- Conventional radiography shows difference of absorption in material
- Phase contrast generated by defections of x-rays through material...
- ... much more sensitive when differences in refractive index are small

Experimental Set-up



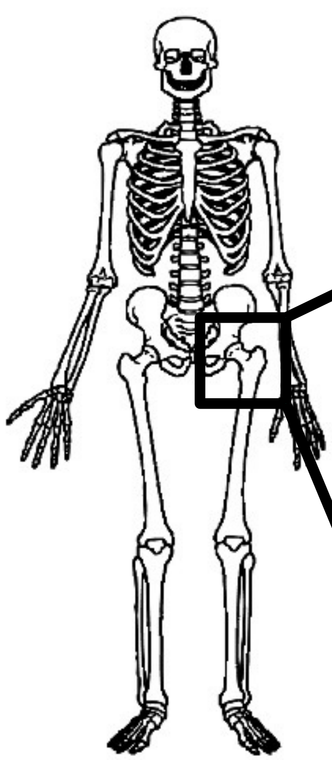
Time Series: corrugated target

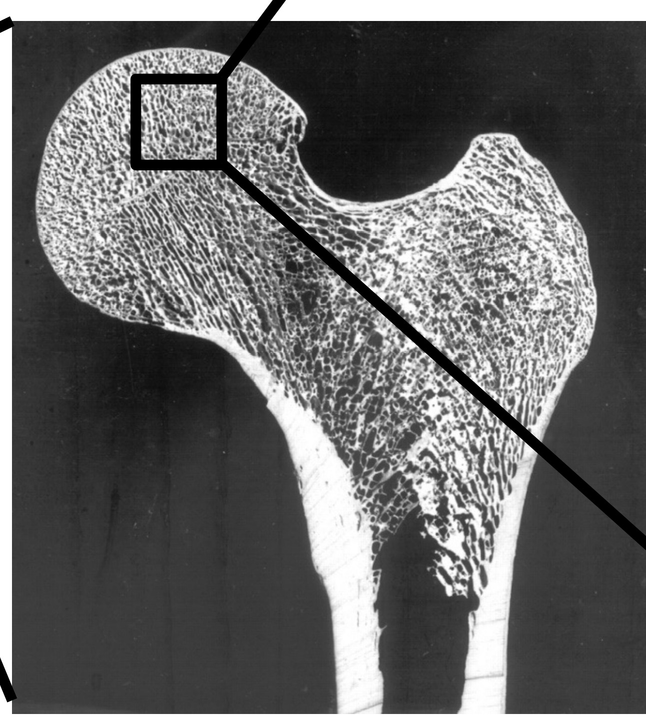


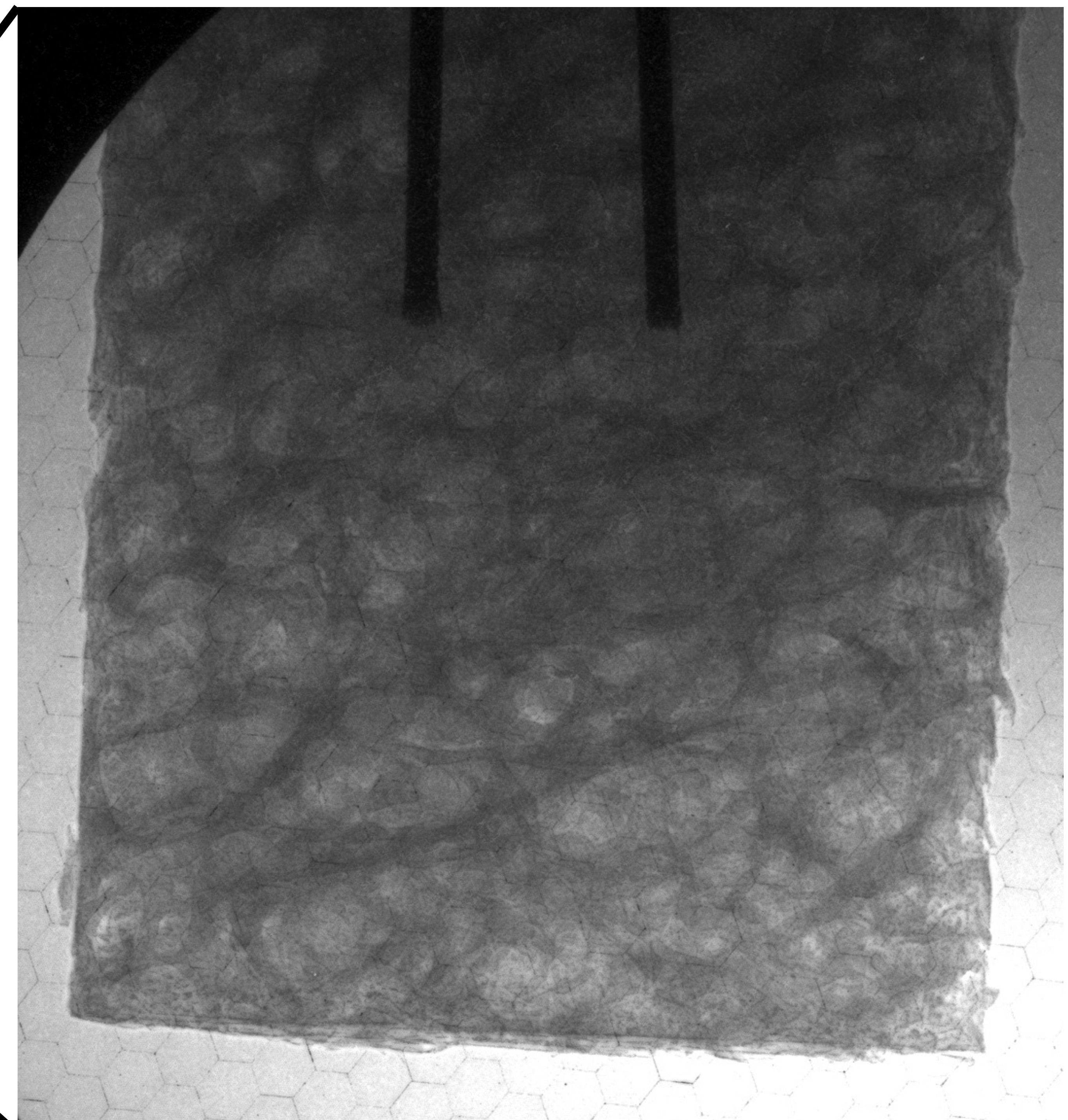
Bone tomography

Cylindrical trabecular bone section from human femur

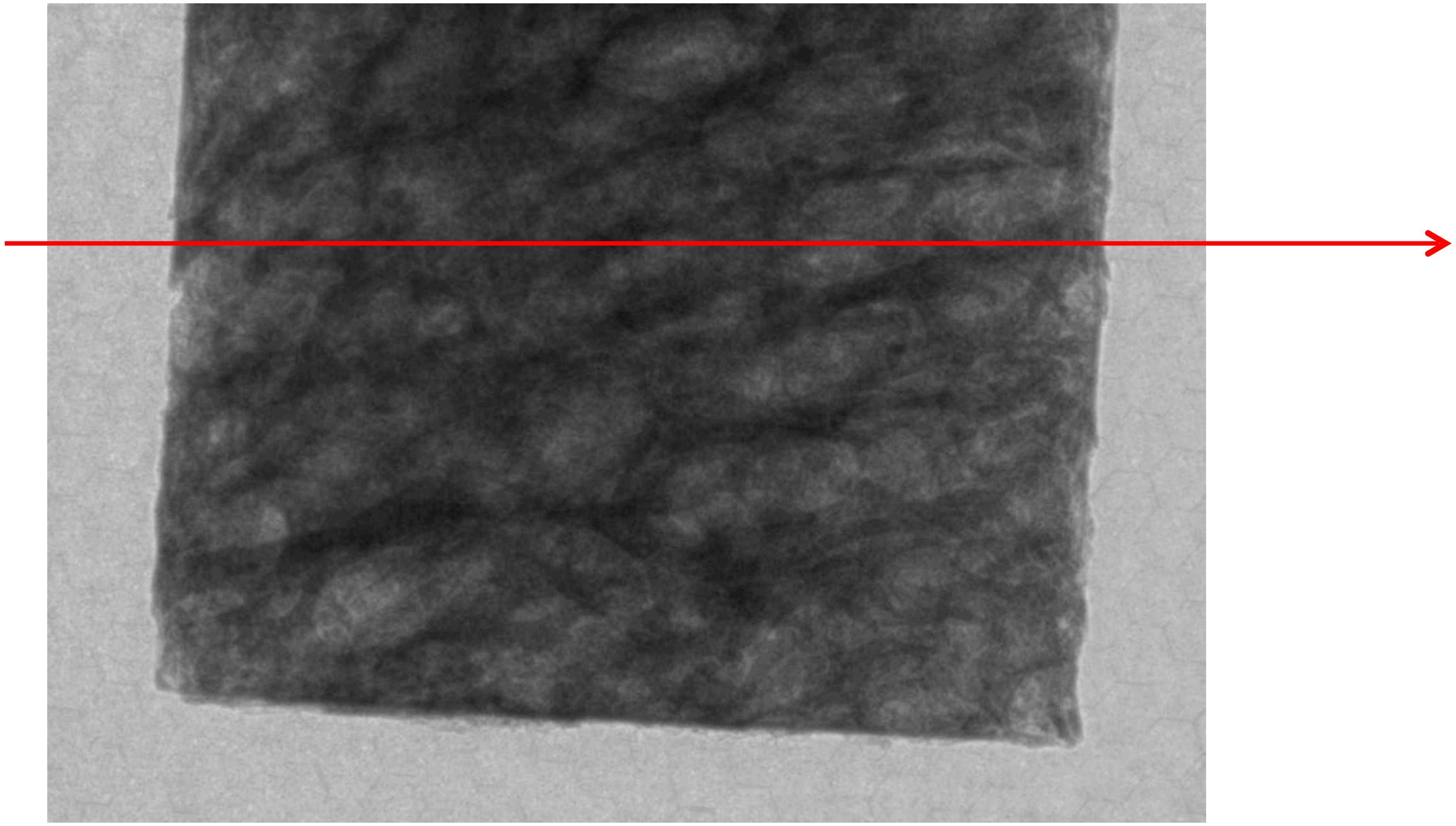
- ✓ Single shot
- ✓ Good contrast
- ✓ High resolution
- beam profile

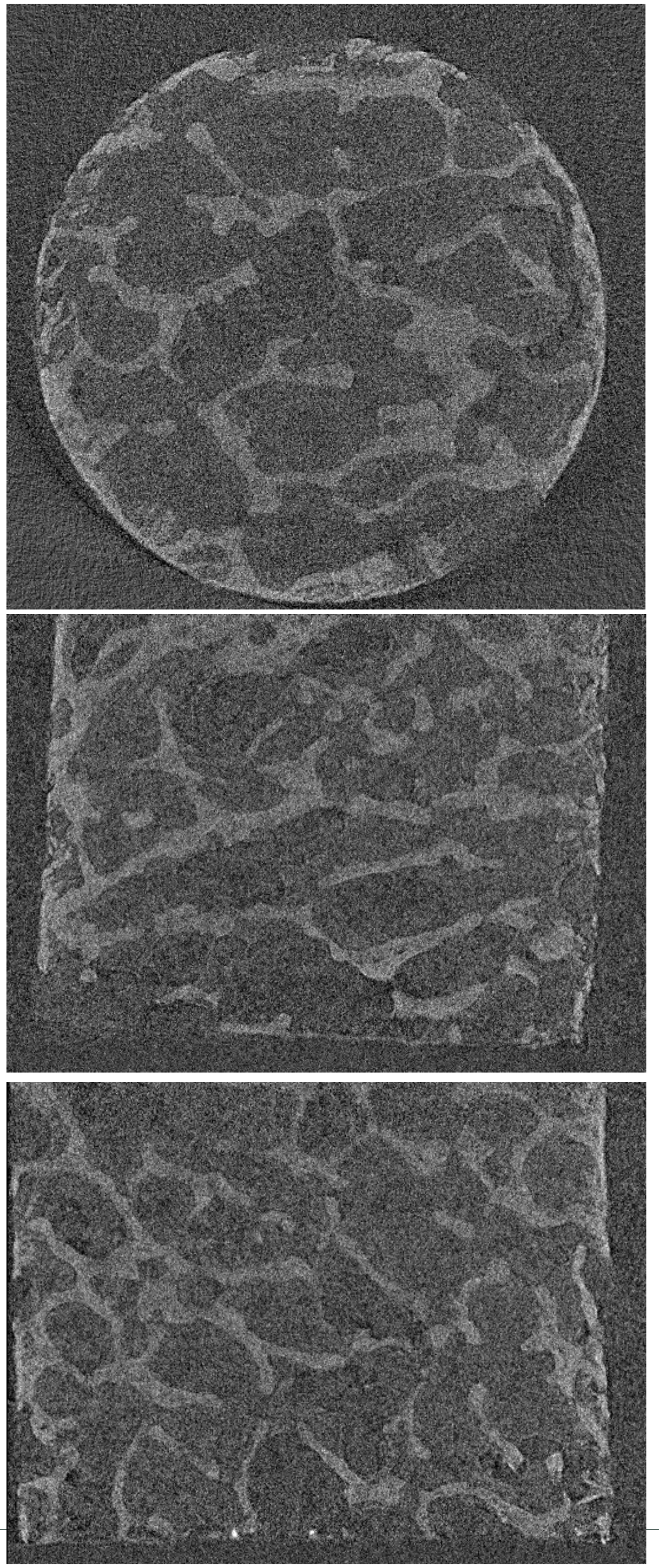






Record 180 consecutive projections

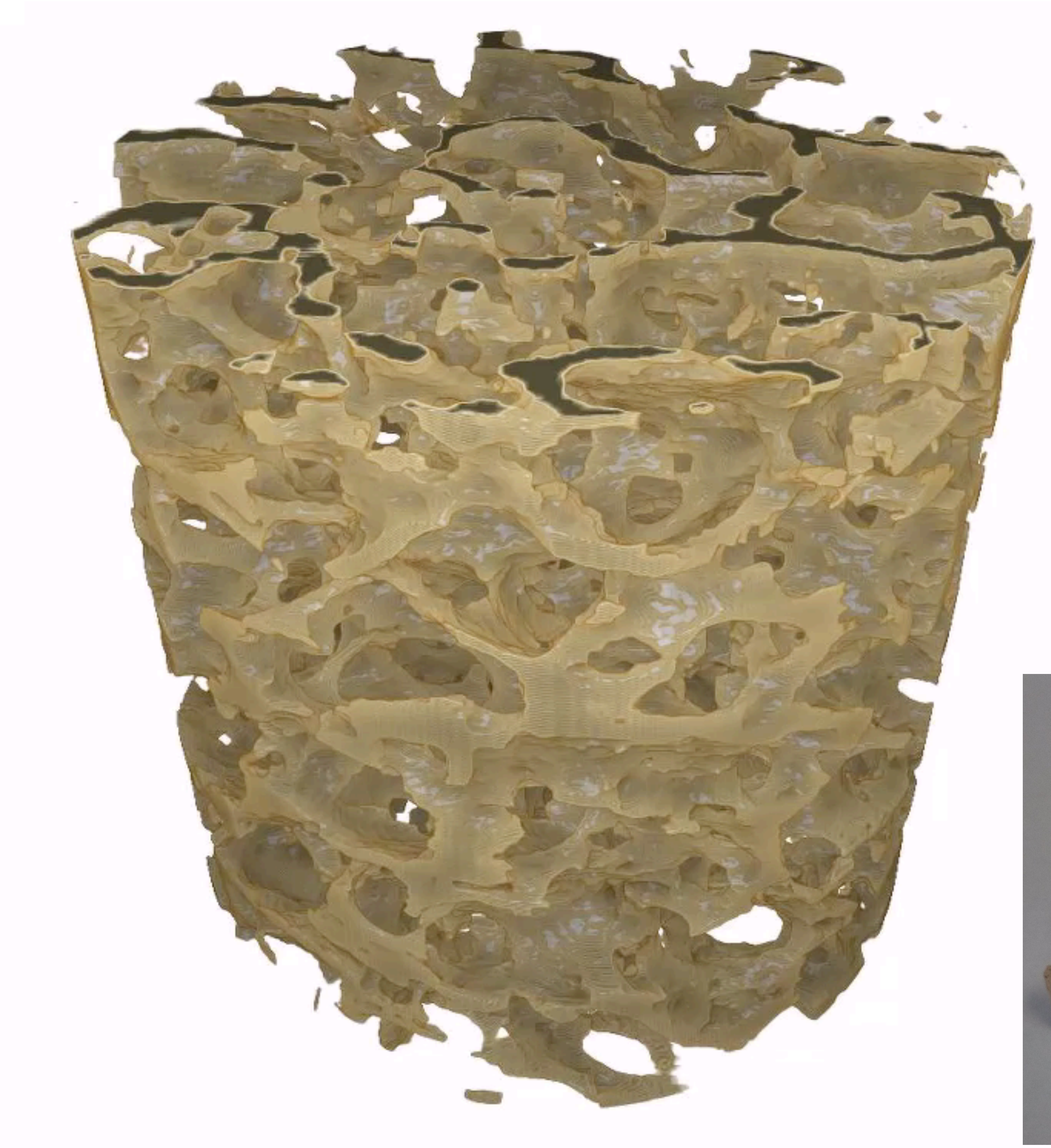




Reconstruct single-pixel slices at a time (after correcting for beam fluctuations)

Repeat to recover full 3D reconstruction

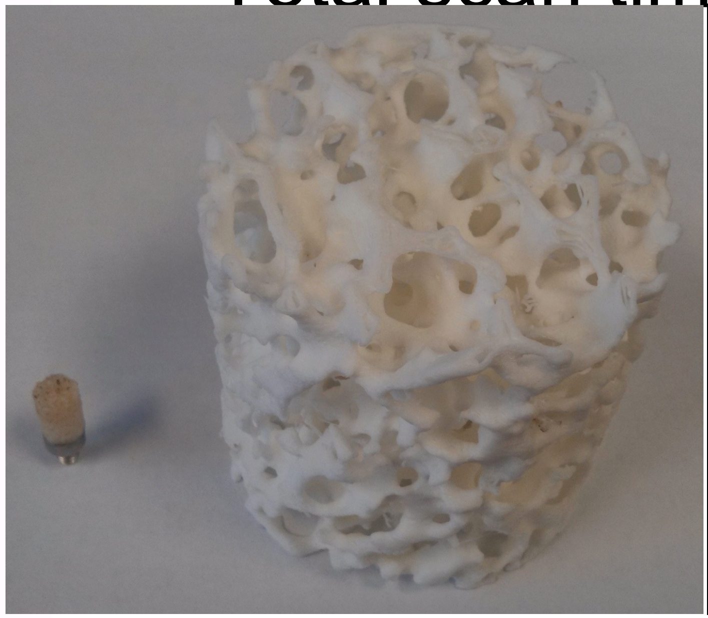
3D reconstruction

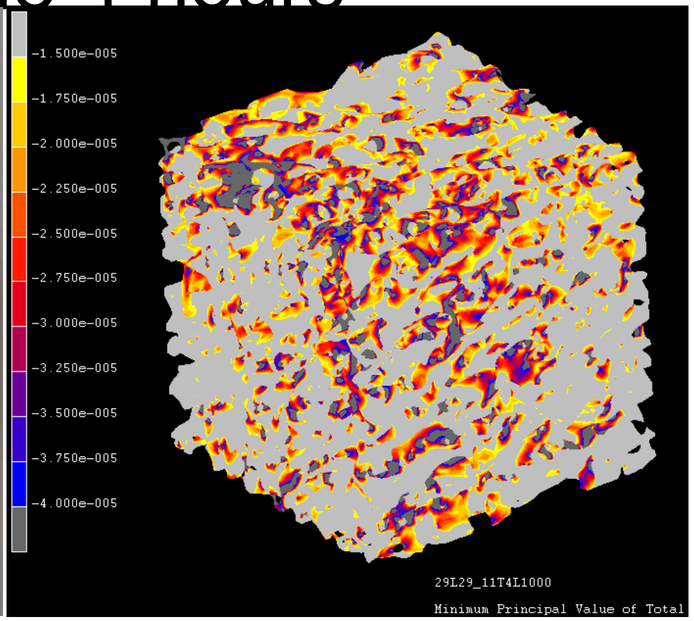


Voxel size
4.8 x 4.8 x 4.8 µm

Best resolution ~50 µm, limited by number of projections, photon noise and detector PSF

Total scan time 4 hours





Cole, J. et al. Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone. Sci. Reports 5:13244 (2015).

Phase contrast for soft tissue imaging

- Absorption contrast is poor for soft tissues since they are uniform
- Phase contrast provides an image of the tissue structures
- Phase contrast imaging of soft tissues showing near histologic quality obtained in synchrotrons

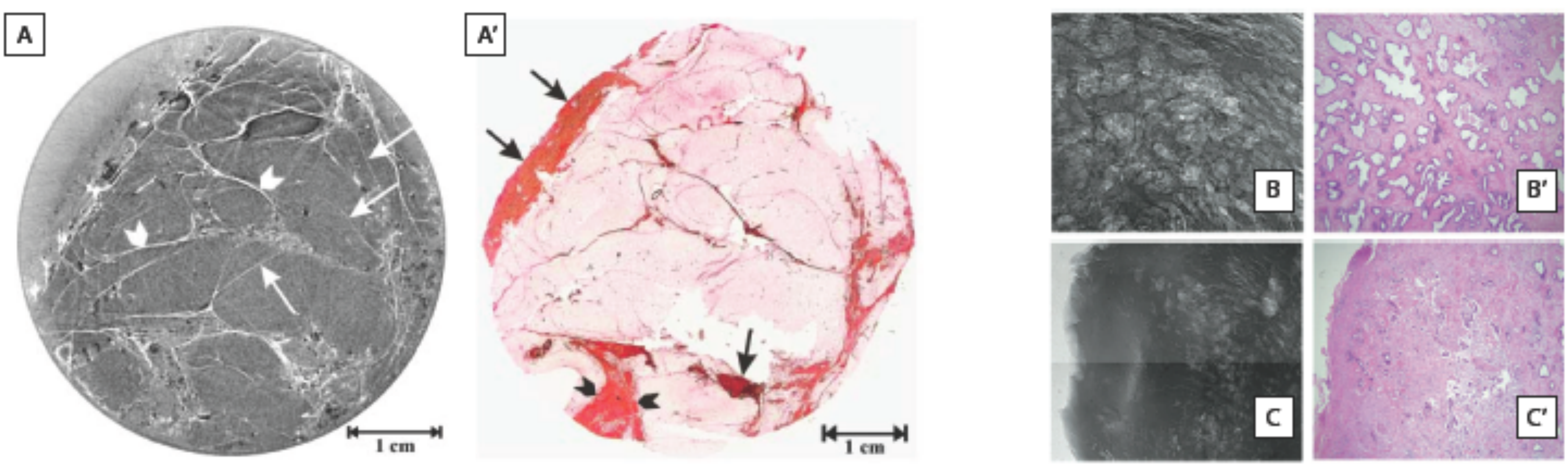
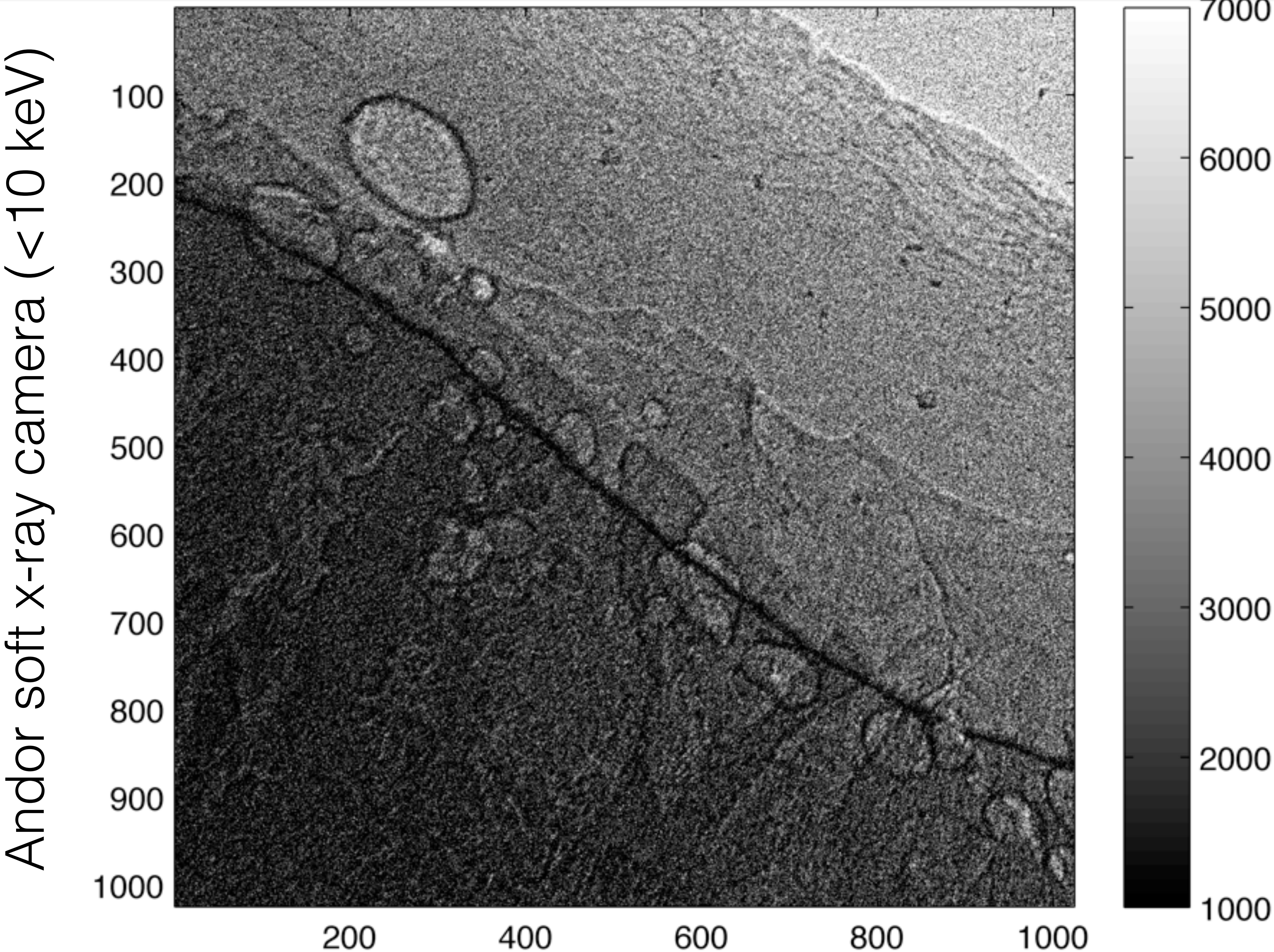


Figure 1: Phase contrast (A, B, C) and histology (A', B', C') of human breast and prostate tissue (taken with conventional synchrotron), showing near histologic image definition in phase contrast imaging [9,10].

[9] C. Y. Yoon, et. al., Int. J. Urol. **14**, 96 (2007).
[10] J. Keyrilainen, et. al., Acta Radiol. **51**, 866 (2010).

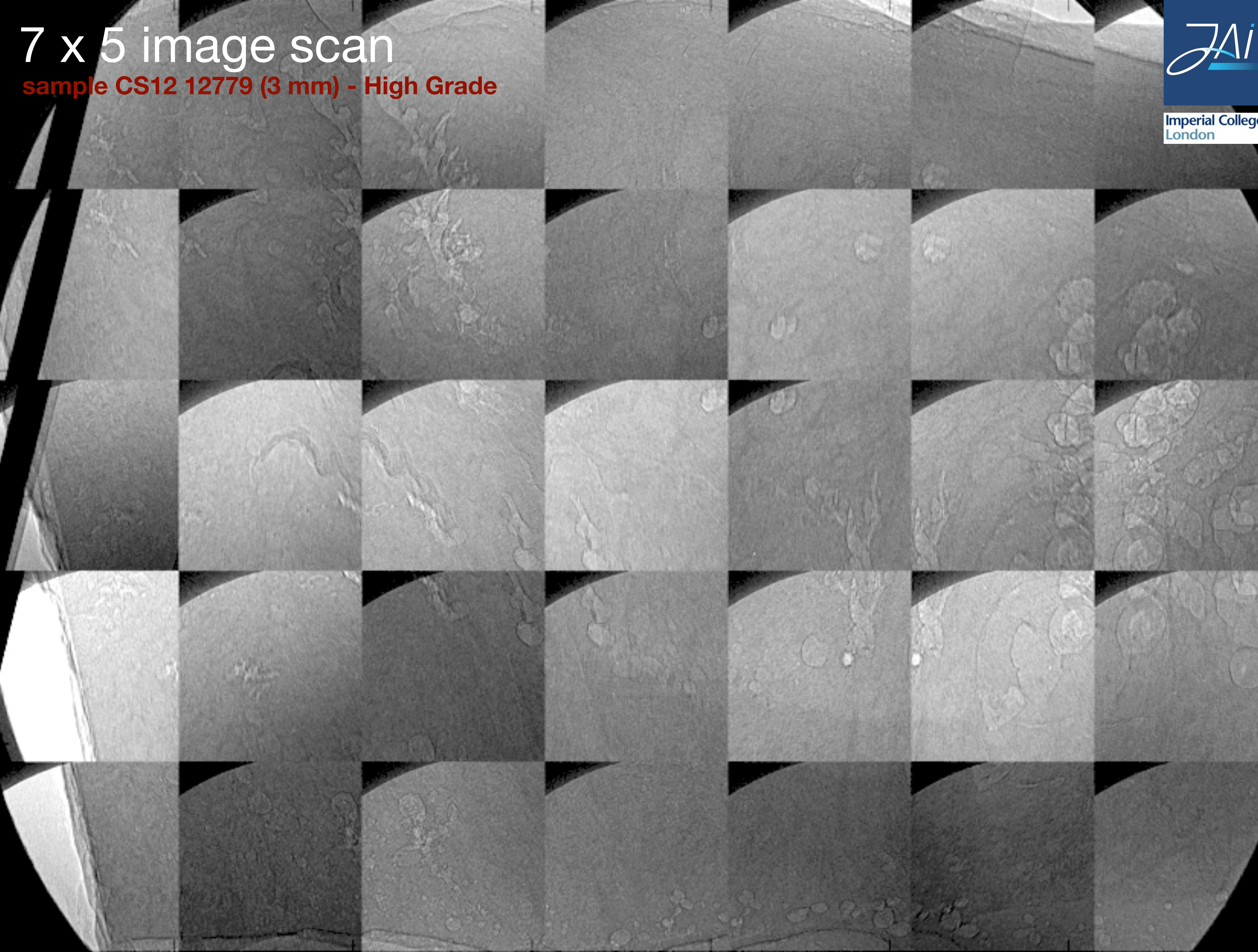
Typical raw x-ray image



Imperial College London

7 x 5 image scan

sample CS12 12779 (3 mm) - High Grade



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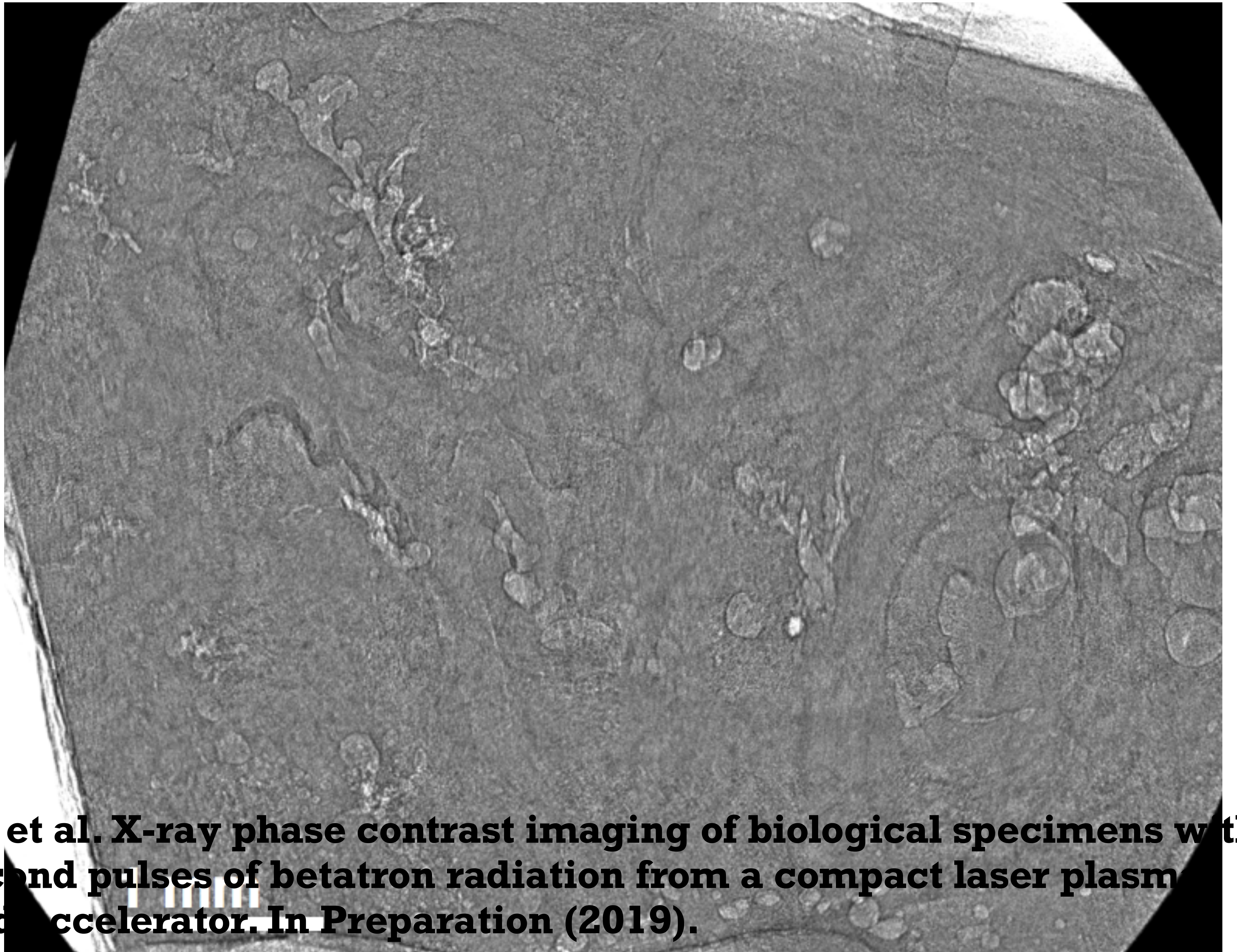
UNIVERSITY OF OXFORD

Royal Holloway University of London

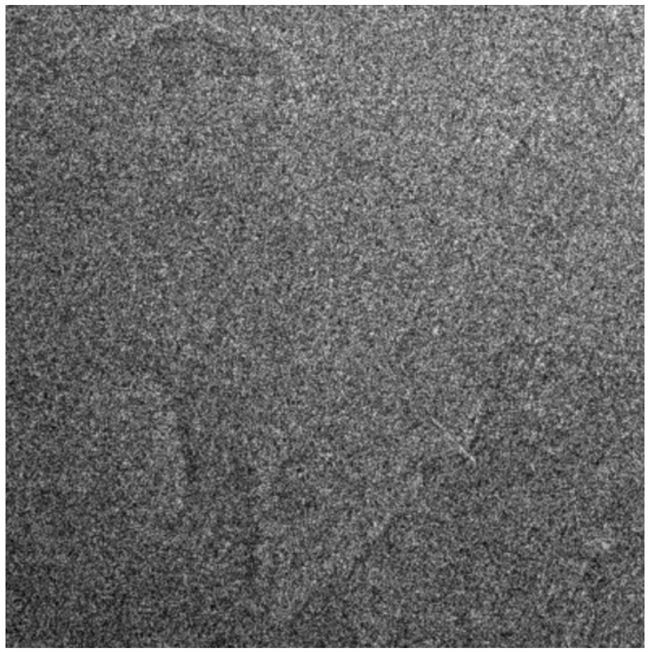
Prostate Imaging with Gemini



Lopes N. et al. X-ray phase contrast imaging of biological specimens with femtosecond pulses of betatron radiation from a compact laser plasma wakefield accelerator. In Preparation (2019).

Breast raster scan

Raw data

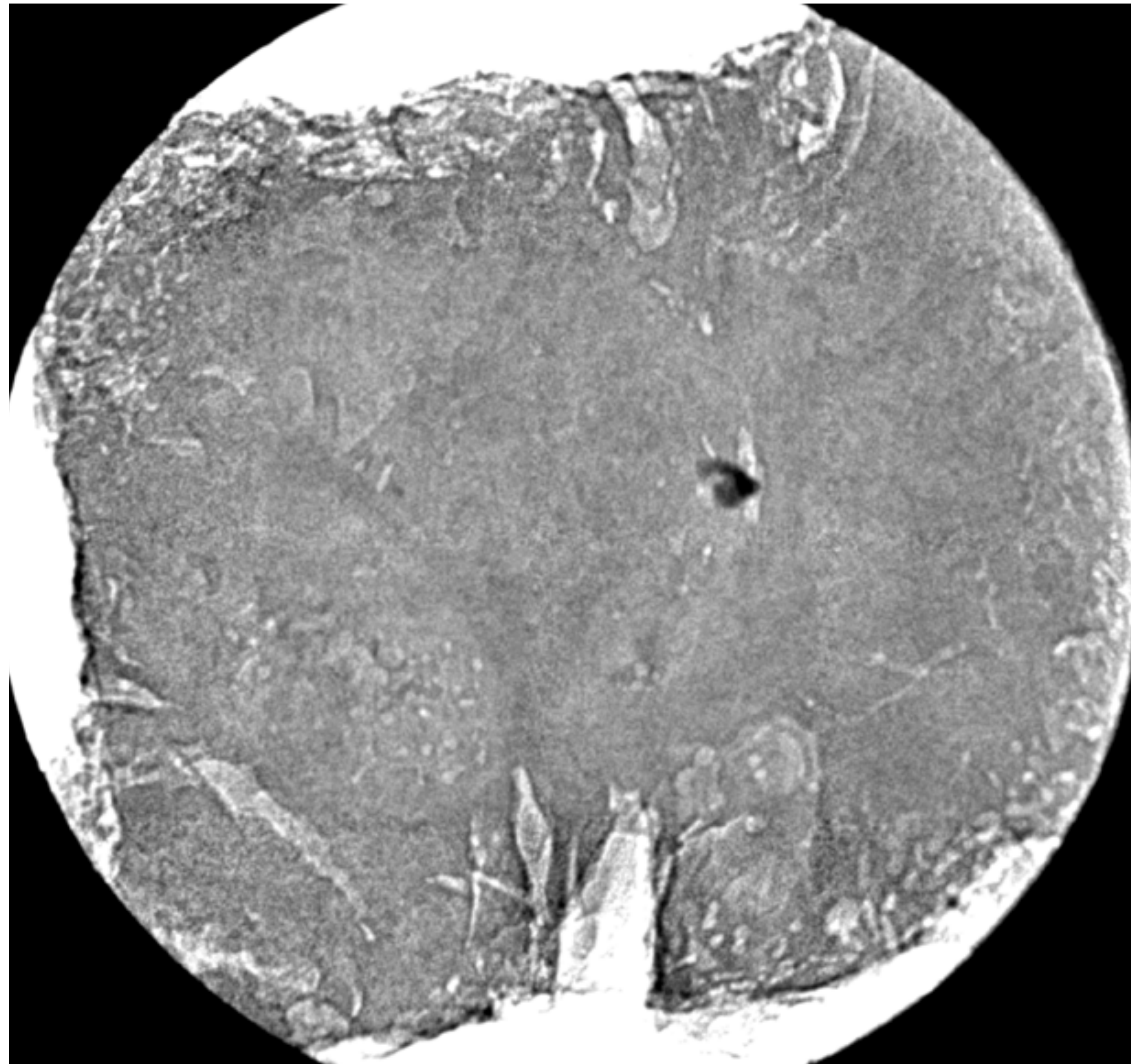


Raw data relatively noisy

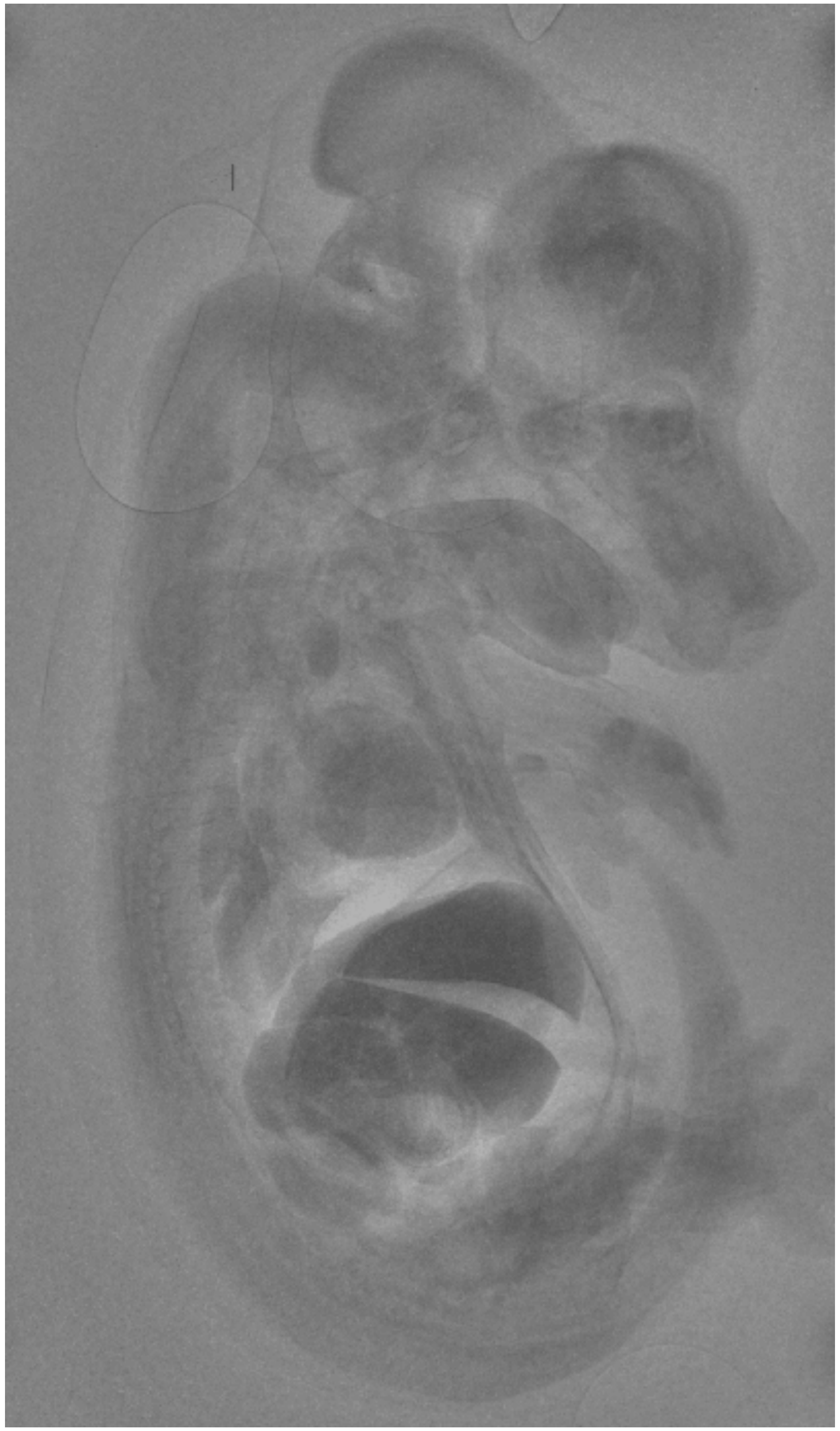
Advanced stitching and denoising techniques developed at IC

(Nelson Lopes)

Raster scan + noise reduction



14.5 day Mouse Embryo Tomography



14.5 day Mouse Embryo Tomography

J. M. Cole, et al, High-resolution μCT of a mouse embryo using a compact laser-driven X-ray betatron source, Proc. Natl. Acad. Sci. U. S. A. 115, 1802314115 (2018).

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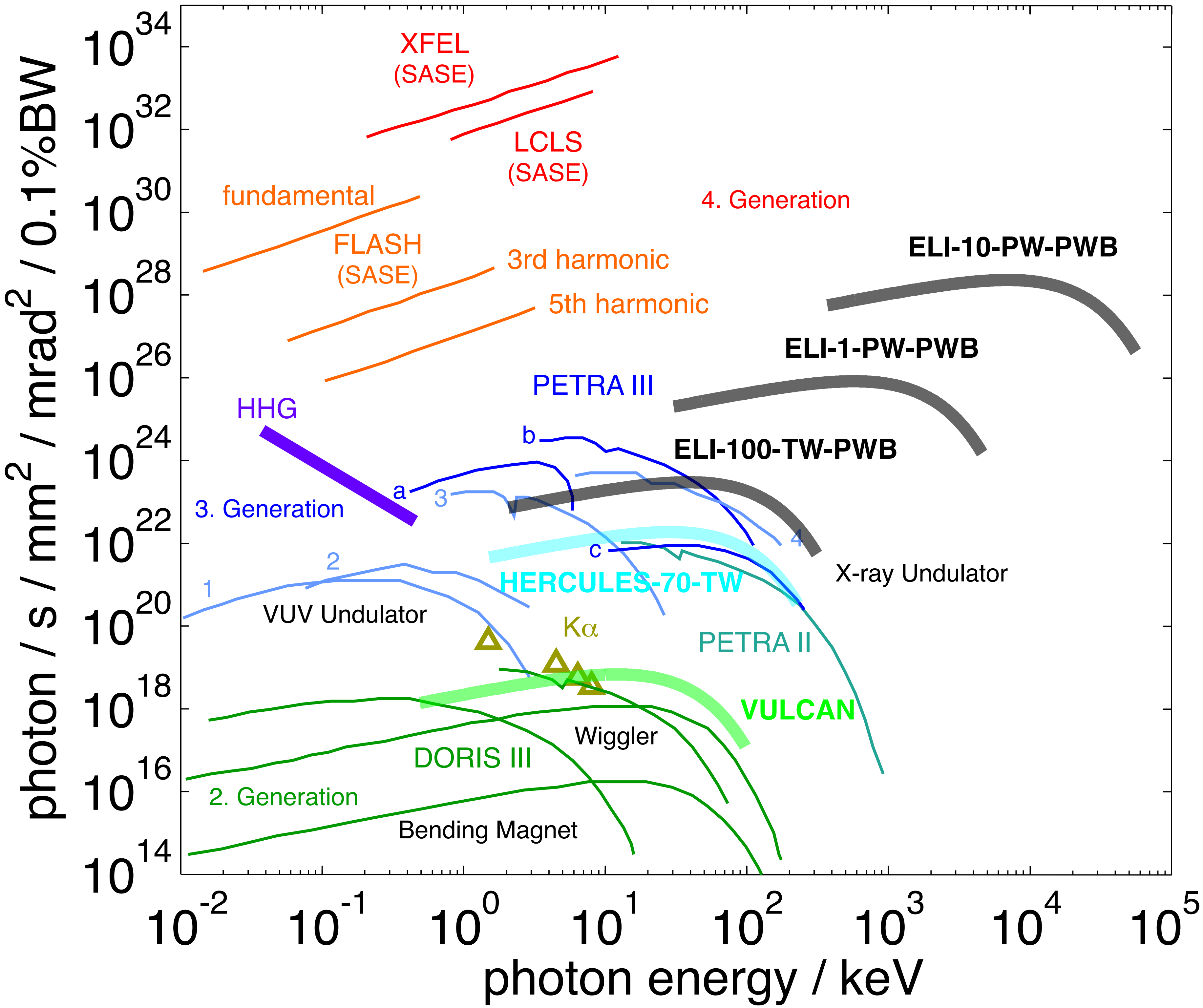
Next generation



Compton Sources

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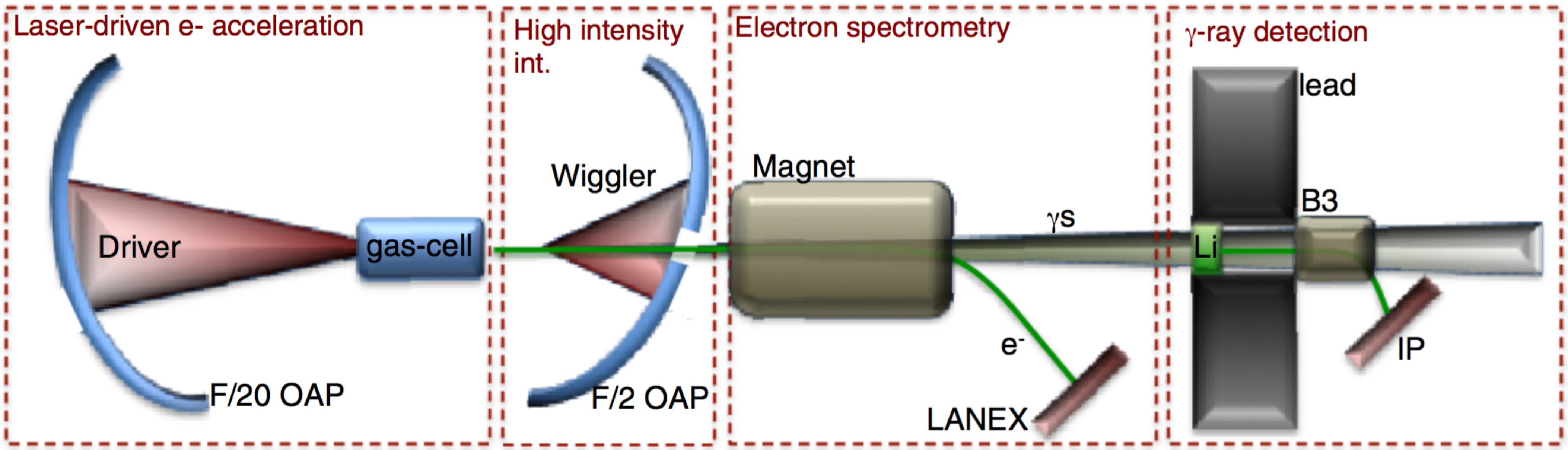
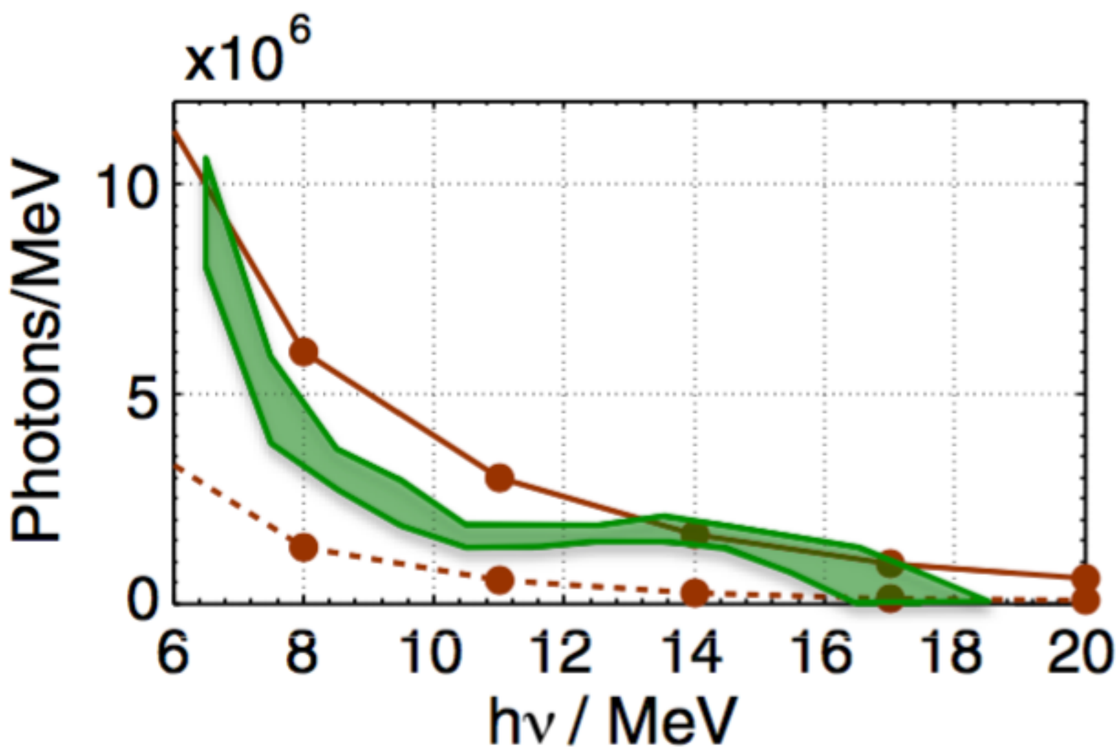
Imperial College London
University of Oxford
Royal Holloway University of London

Compton Scattering



$$E_s = 4\gamma^2 \hbar\omega$$

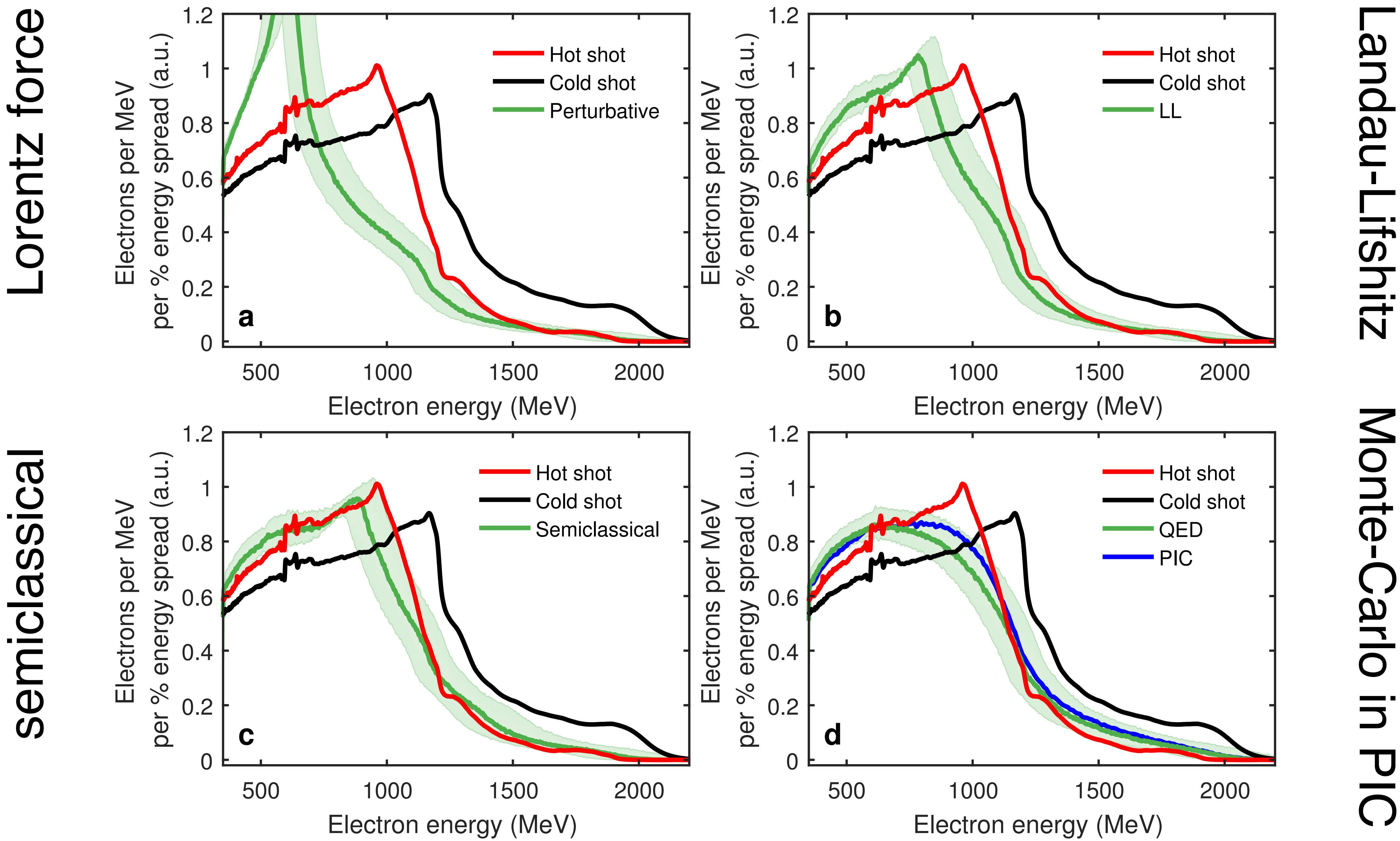


B >10^{20} photons / sec mrad^2 mm^2 0.1%BW

Sarri, G. et al. Ultrahigh Brilliance Multi-MeV γ-Ray Beams from Nonlinear Relativistic Thomson Scattering. Phys. Rev. Lett. 113, 224801 (2014).

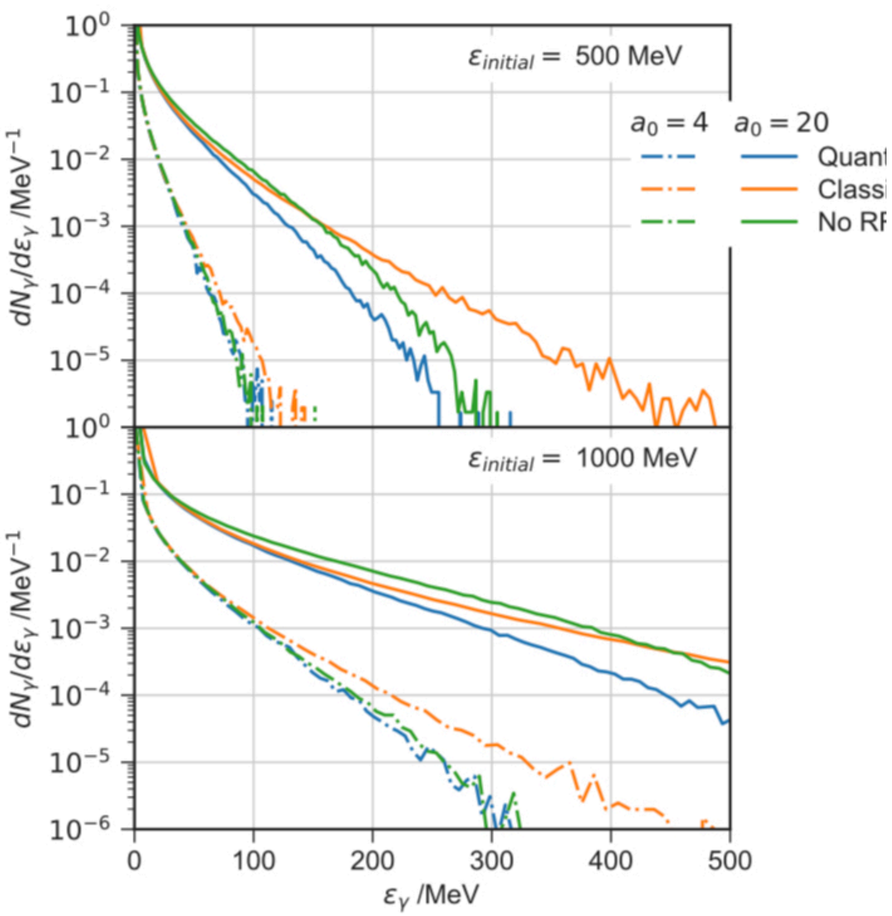
High Field Physics

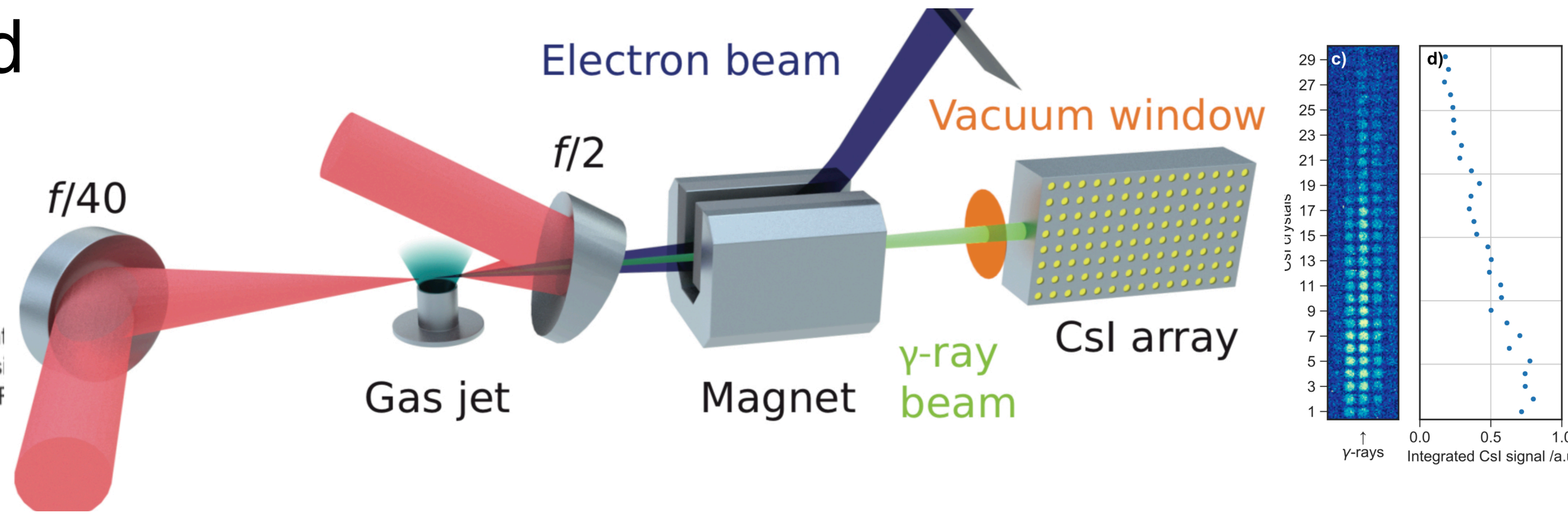
Radiation reaction I

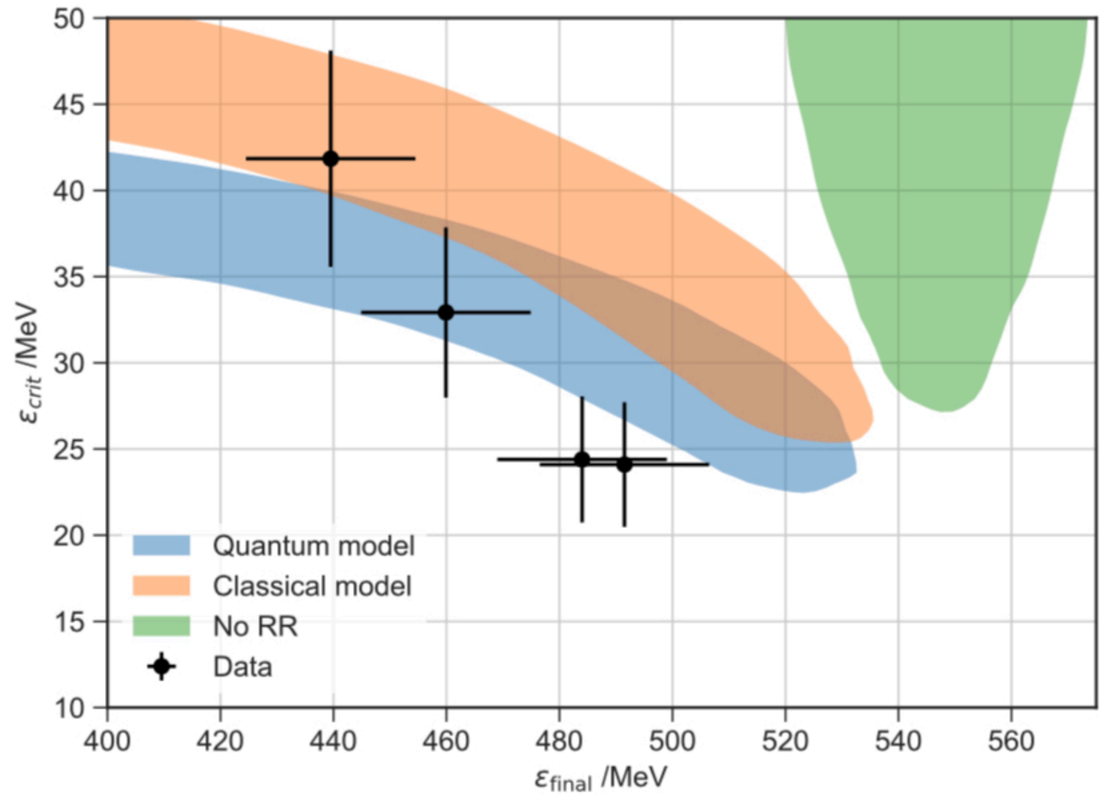


Radiation reaction II

Following experiment used CsI as a γ-spectrometer





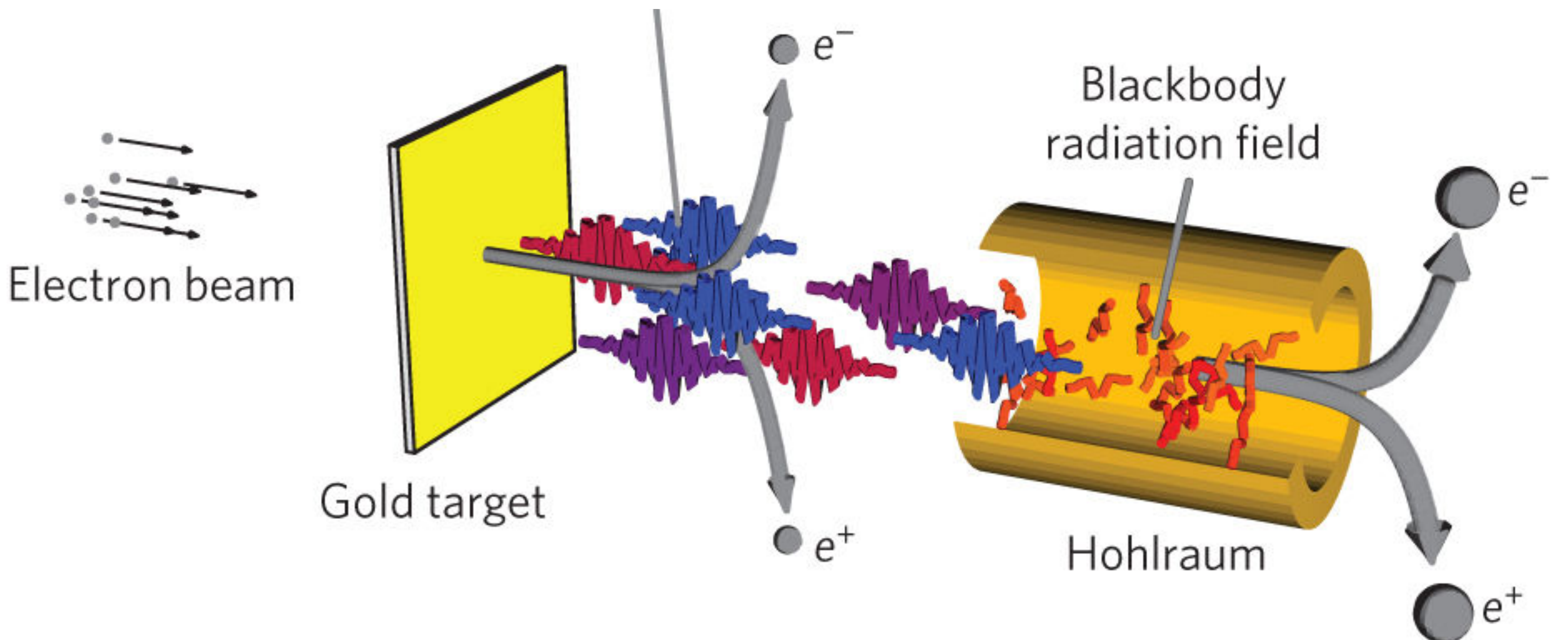


Results suggestive of importance of quantum corrections

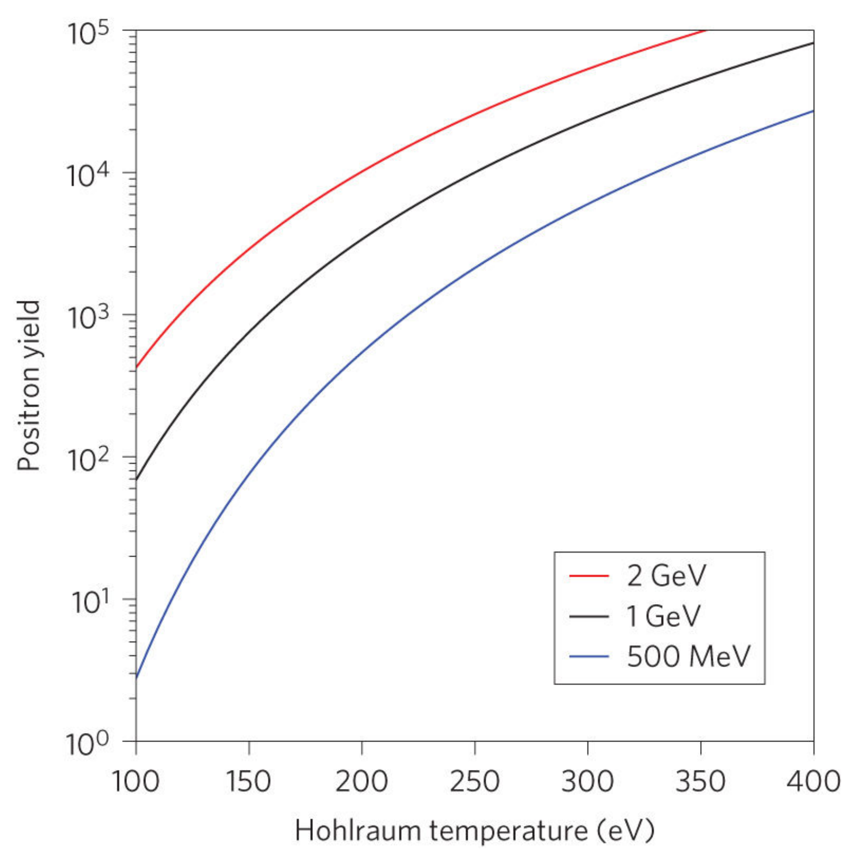
Classical RR significantly overestimates γ - energies

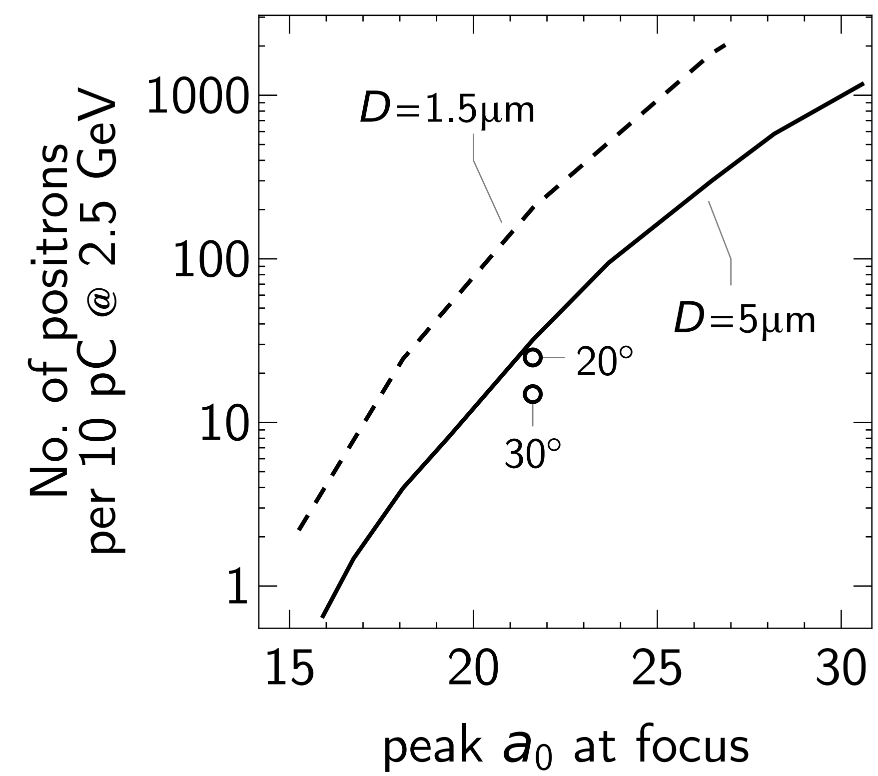
Cole, J. M. et al. Experimental Evidence of Radiation Reaction in the Collision of a High-Intensity Laser Pulse with a Laser-Wakefield Accelerated Electron Beam. Phys. Rev. X 8, 11020 (2018).

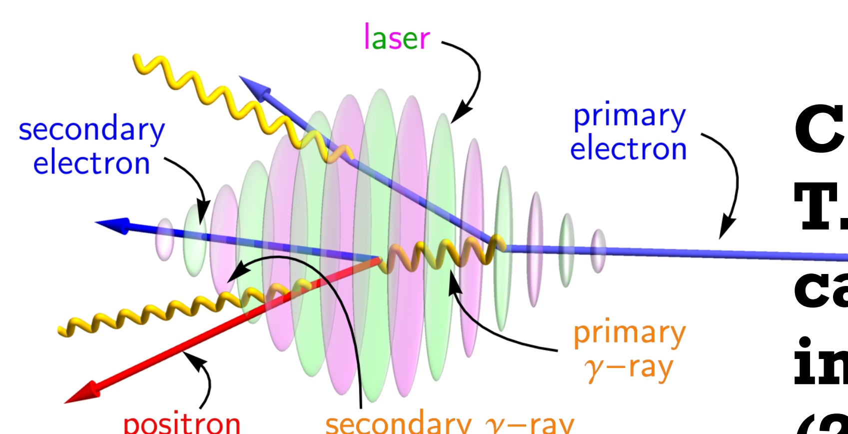
Photon-photon collisions



Pike, O. J., Mackenroth, F., Hill, E. G. & Rose, S. J. A photon–photon collider in a vacuum hohlraum. Nat. Photonics 8, 434–436 (2014).







Cole, J.S.M., Blackburn T. G. Electromagnetic cascades in high-intensity laser fields (2018).

Applications

- High Energy Physics → experiments being designed
- Positron sources → lab based sources of e^+ possible
- Free Electron Lasers → wakefield based FELs trialled
- Synchrotron (betatron) → radiation ideal for imaging
- Compton (gamma) → leads to radiation reaction
- High Field Physics → used to study QED effects