

COMPACT ALL-OPTICAL PRECISION-TUNABLE NARROWBAND HARD COMPTON X-RAY SOURCE

Dr Kristjan Pöder

Team leader “Laser-plasma acceleration and applications”

kristjan.poder@desy.de

Deutsches Elektronen-Synchrotron DESY, Machine Division, Hamburg, Germany

Accelerator Research and Development, Matter and Technologies
Helmholtz Association of German Research Centres, Berlin, Germany



Acknowledgements

MPL - Plasma Accelerator and Laser Group at DESY



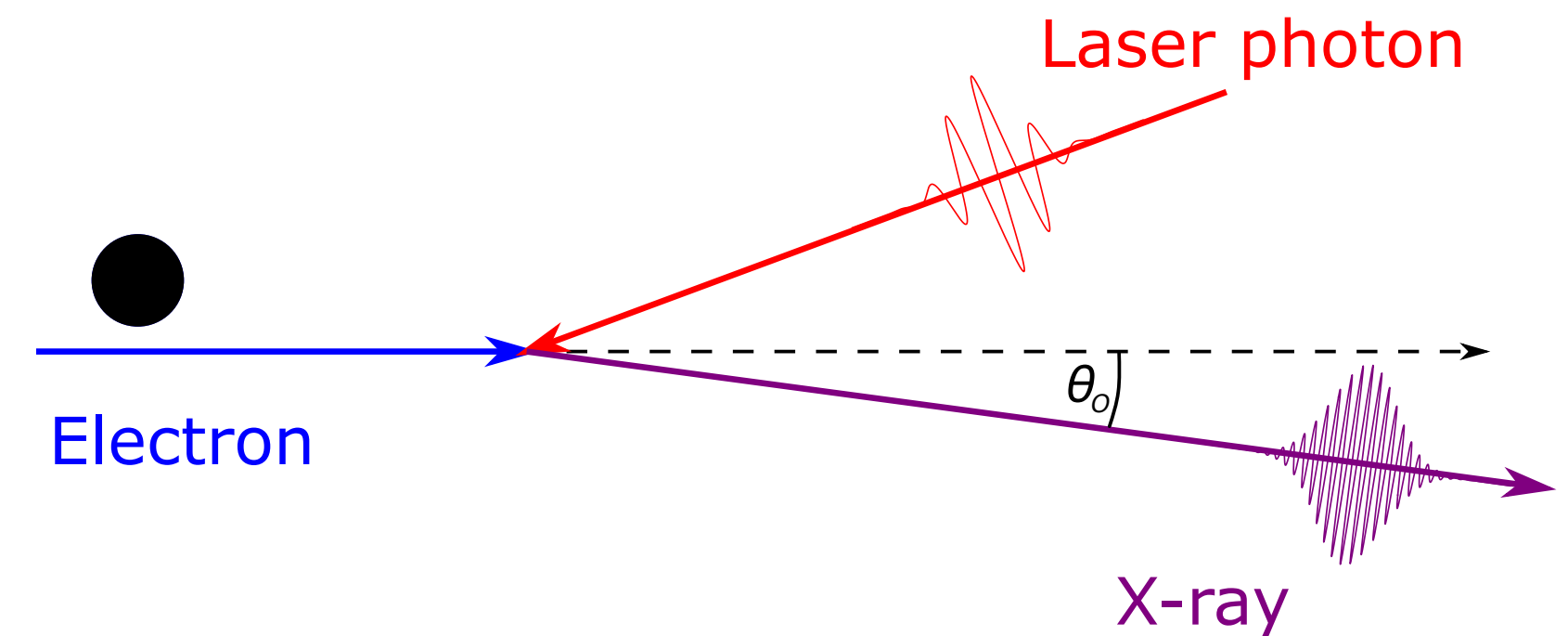
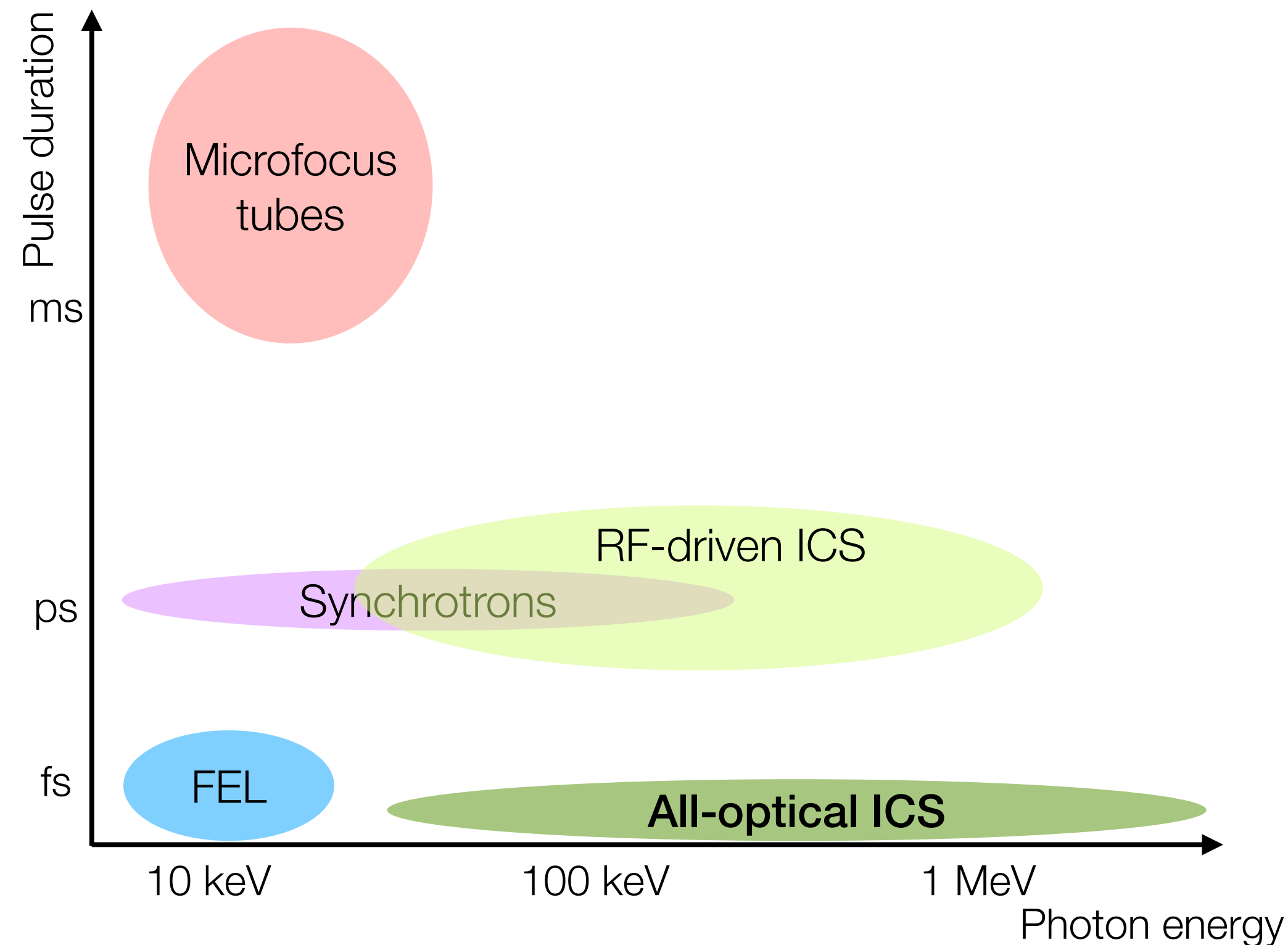
Fig: Marta Mayer (DESY)



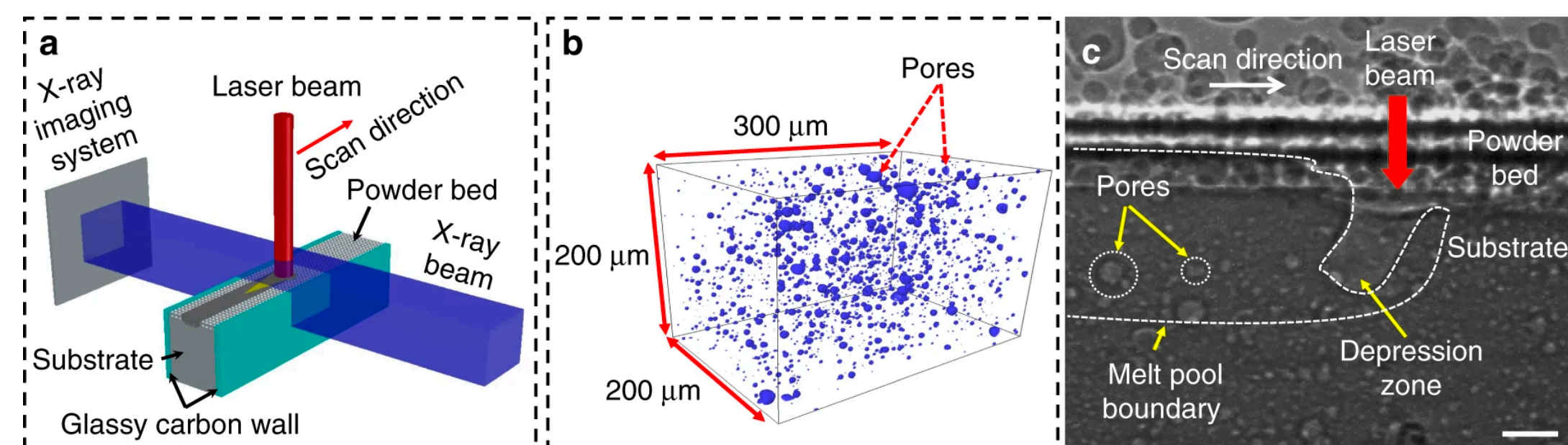
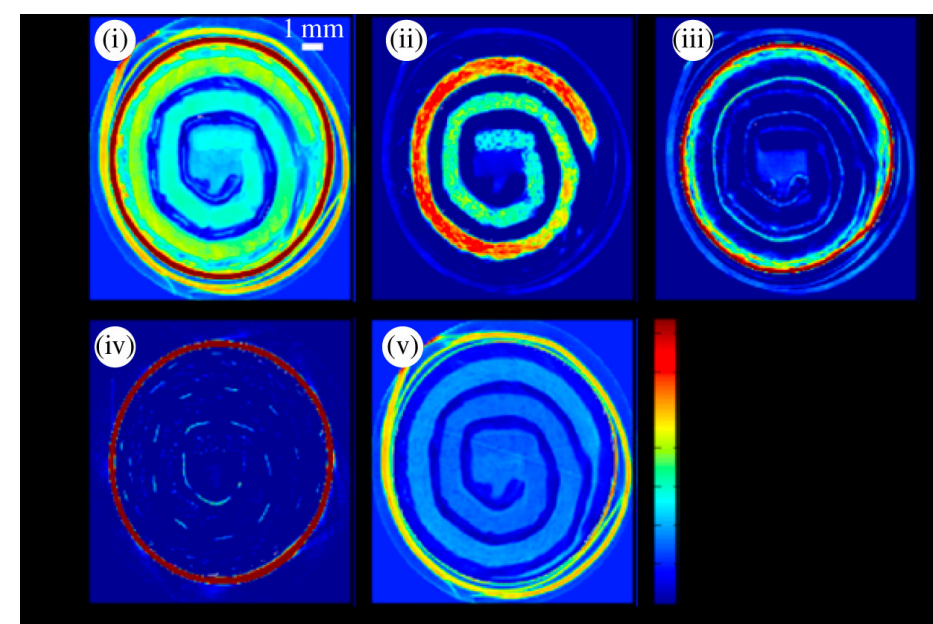
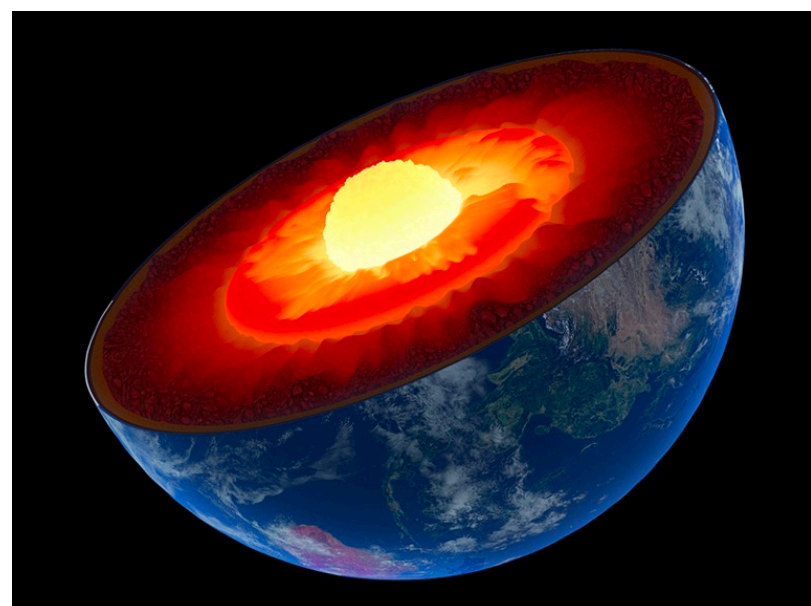
See out webpage at plasma.desy.de
For a full list of teams and activities

Light source landscape

All-optical high energy, short pulse light sources are sought after for applications

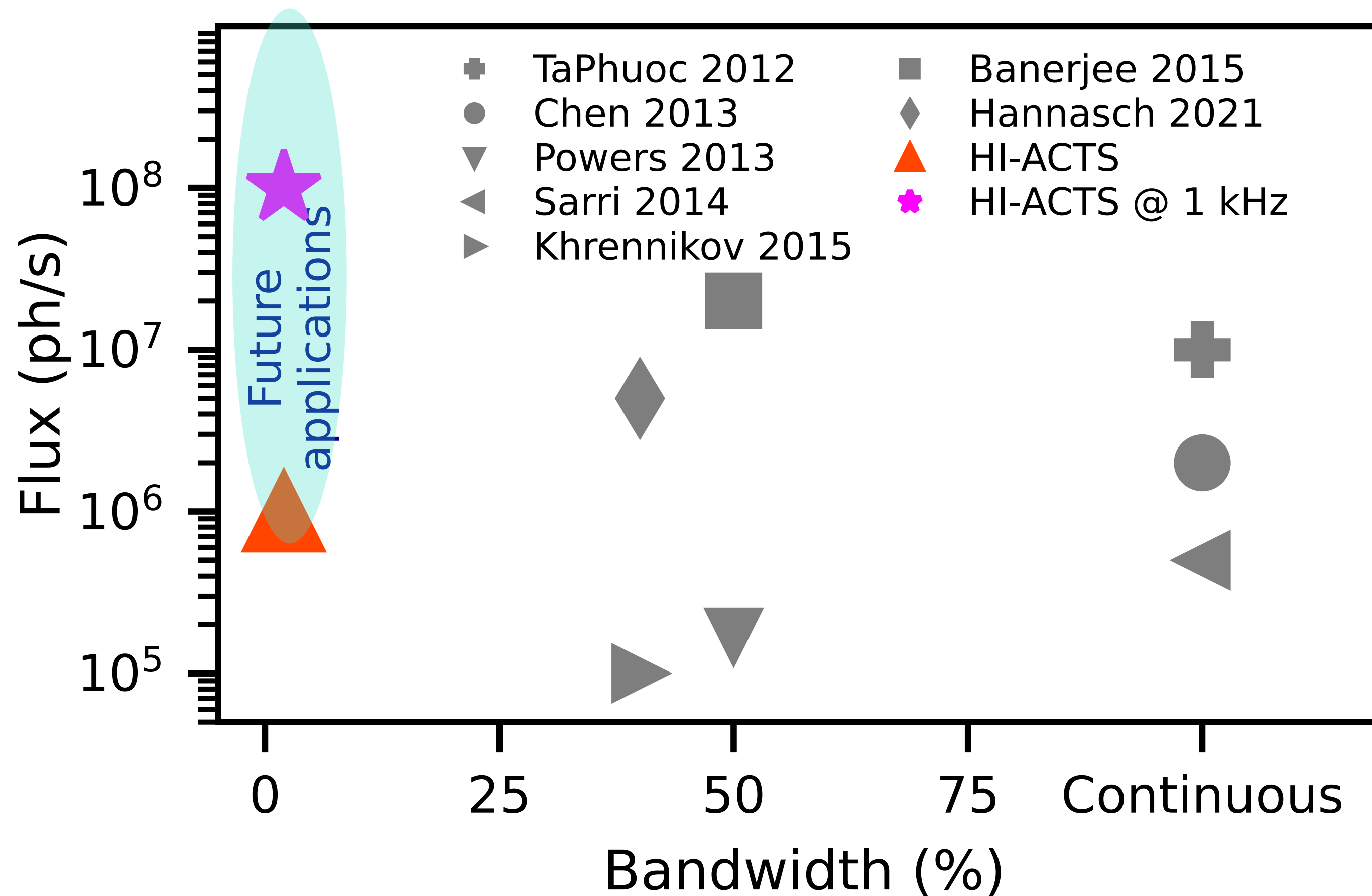


$$\omega_x = \frac{2\gamma_e^2(1 - \beta \cos \theta_I)}{1 + \gamma_e^2\theta_O^2 + a^2/2} \omega_L$$



Bandwidth of all-optical ICS sources is too large

Many applications require bandwidth in the percent range



Applications out of sight without reduced bandwidth!

X-ray bandwidth is mainly determined by electron beam

The electron bandwidth and divergence are hardest to control - often the leading contributors

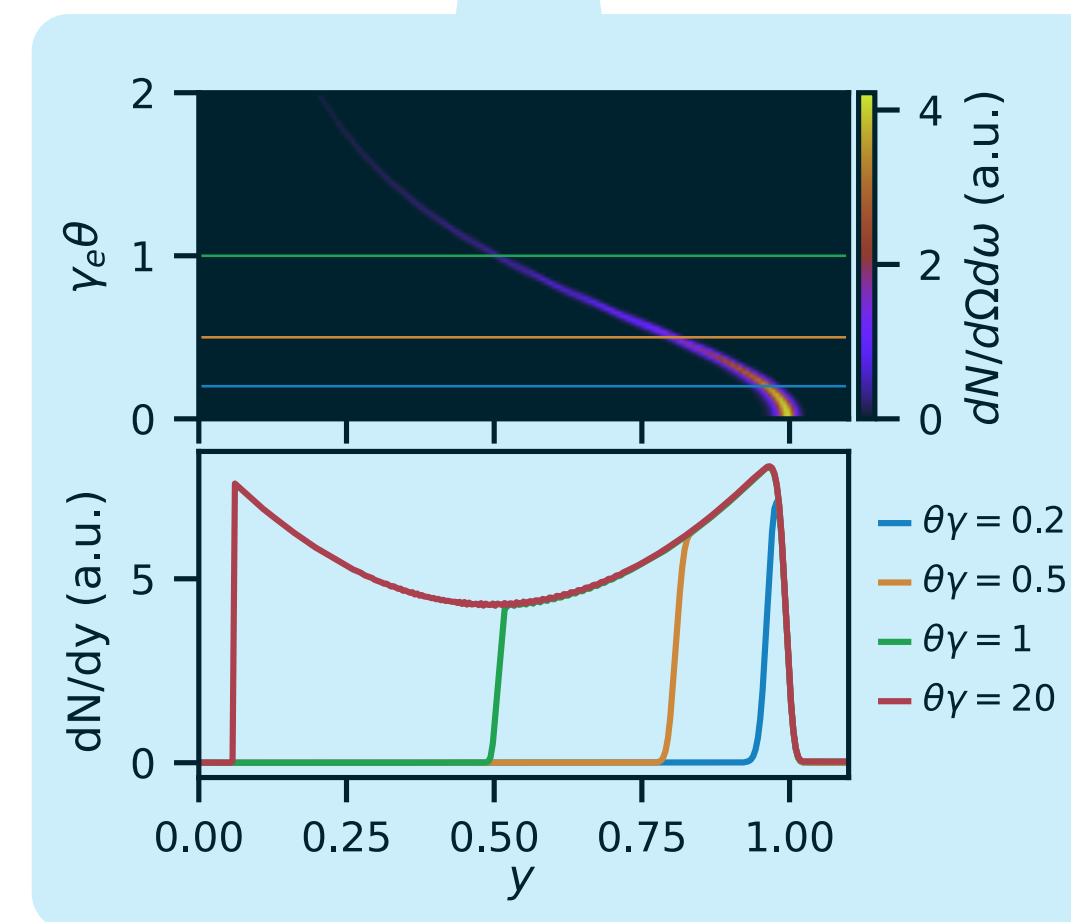
$$\frac{\Delta\omega_x}{\omega_x} = \sqrt{\left(\frac{2\delta\gamma_e}{\gamma_e}\right)^2 + \left(\frac{\gamma_e^2\sigma_\theta^2}{4}\right)^2 + \left(\frac{\delta\omega_L}{\omega_L}\right)^2 + \left(\frac{a_0}{2}\right)^2 + \kappa^2}$$

Best 0.5-1% ^(2,3)
-> few % BW

Best 0.2
mrad@500MeV ⁽²⁾
-> few % BW

TiSa:
40nm@800nm
-> 5%BW

fs-pulses:
 $a_0 \sim 1$
-> tens% BW



Need a method to control and reduce the divergence and bandwidth of electron beams!

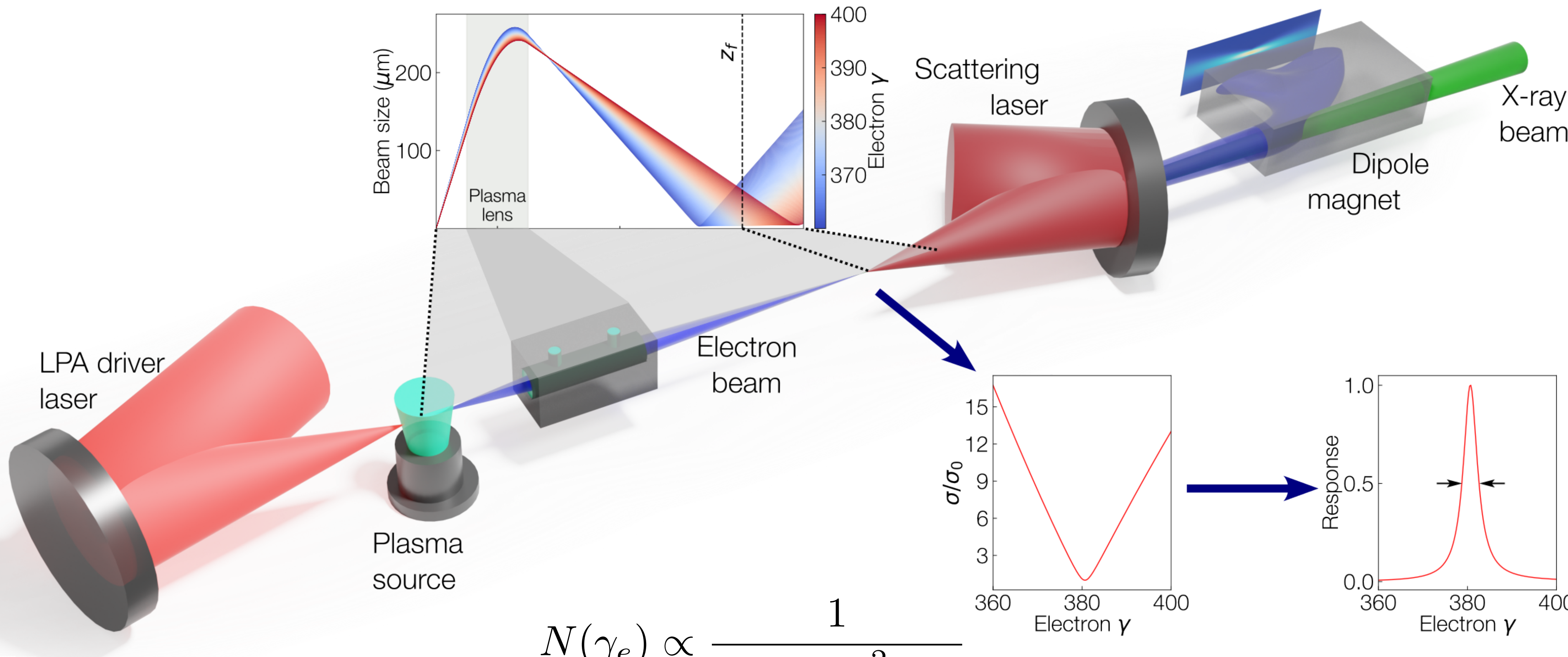
(1) Rykovanov et al, J. Phys. B 47, 234013 (2014)

(2) Wang et al, PRL **117**, 124801 (2016)

(3) Kirchen et al, PRL **126**, 174801 (2021)

Active plasma lens enables control of ICS bandwidth

The compact electron optic also allows tuning the central energy of the X-rays



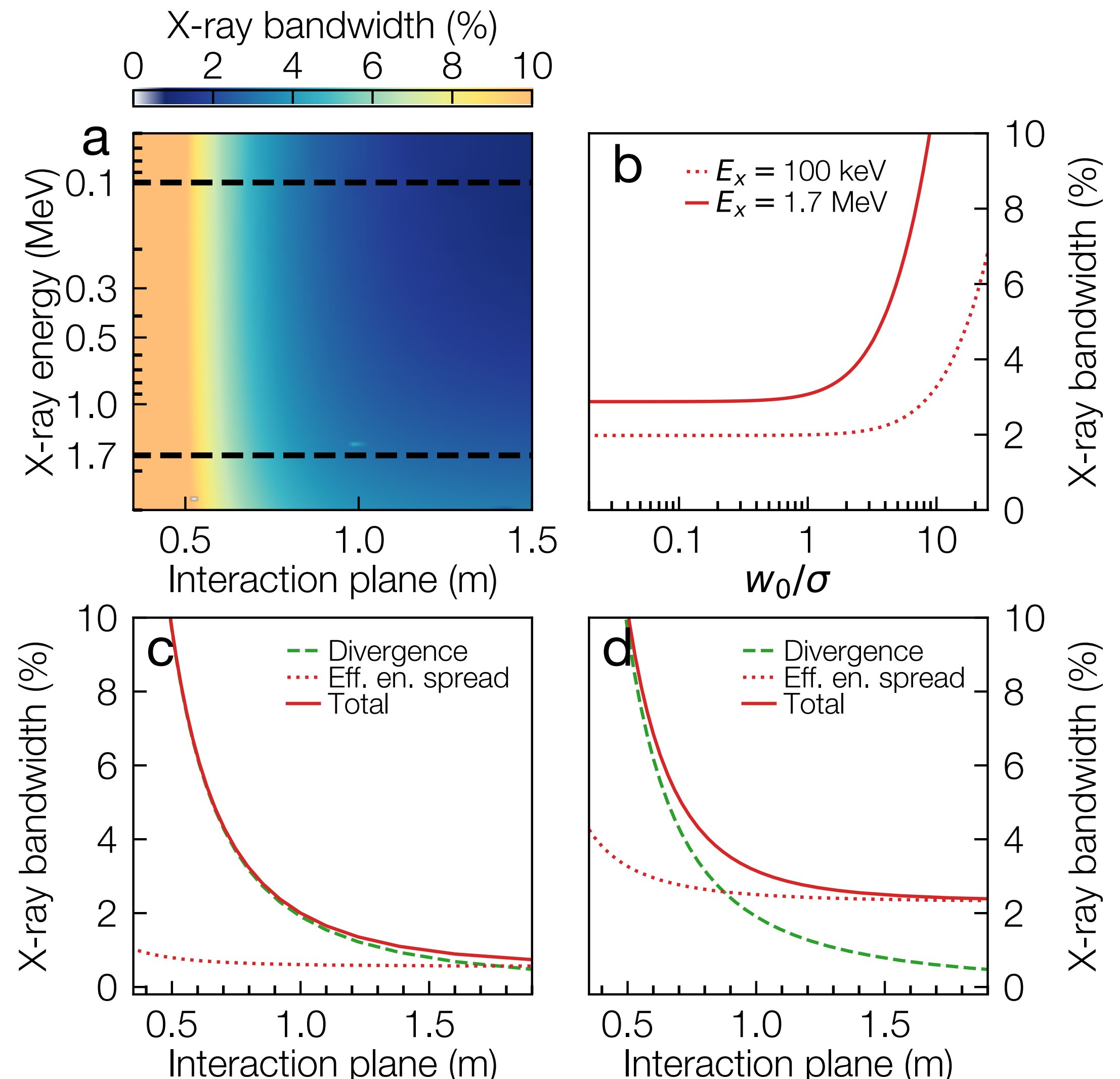
$$N(\gamma_e) \propto \frac{1}{\left(\frac{2\sigma(\gamma_e)}{w_0}\right)^2 + 1}$$

APL-tailoring enables percent-level X-ray bandwidths

Electron spectrum and divergence interacting with scattering laser controlled

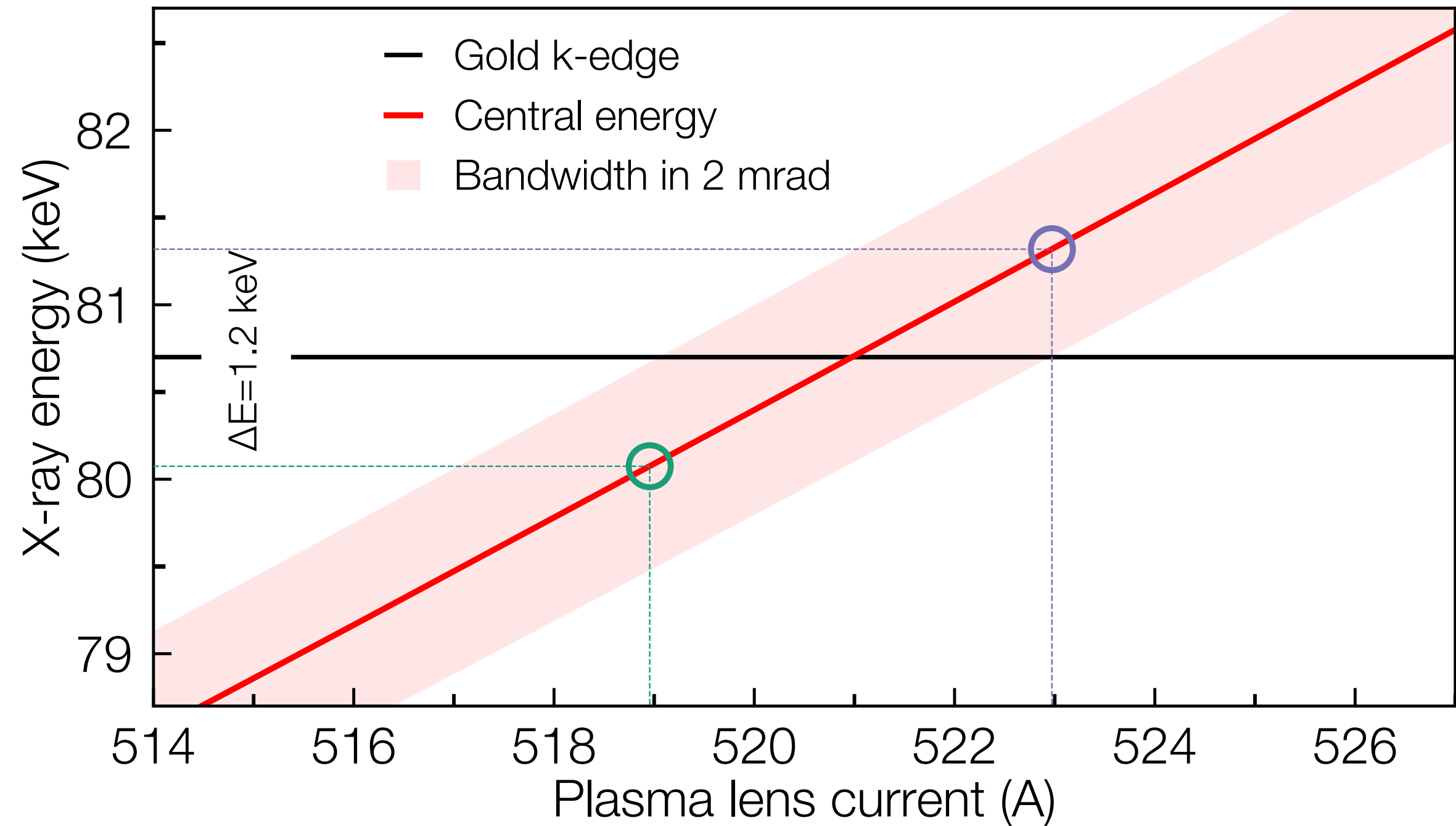
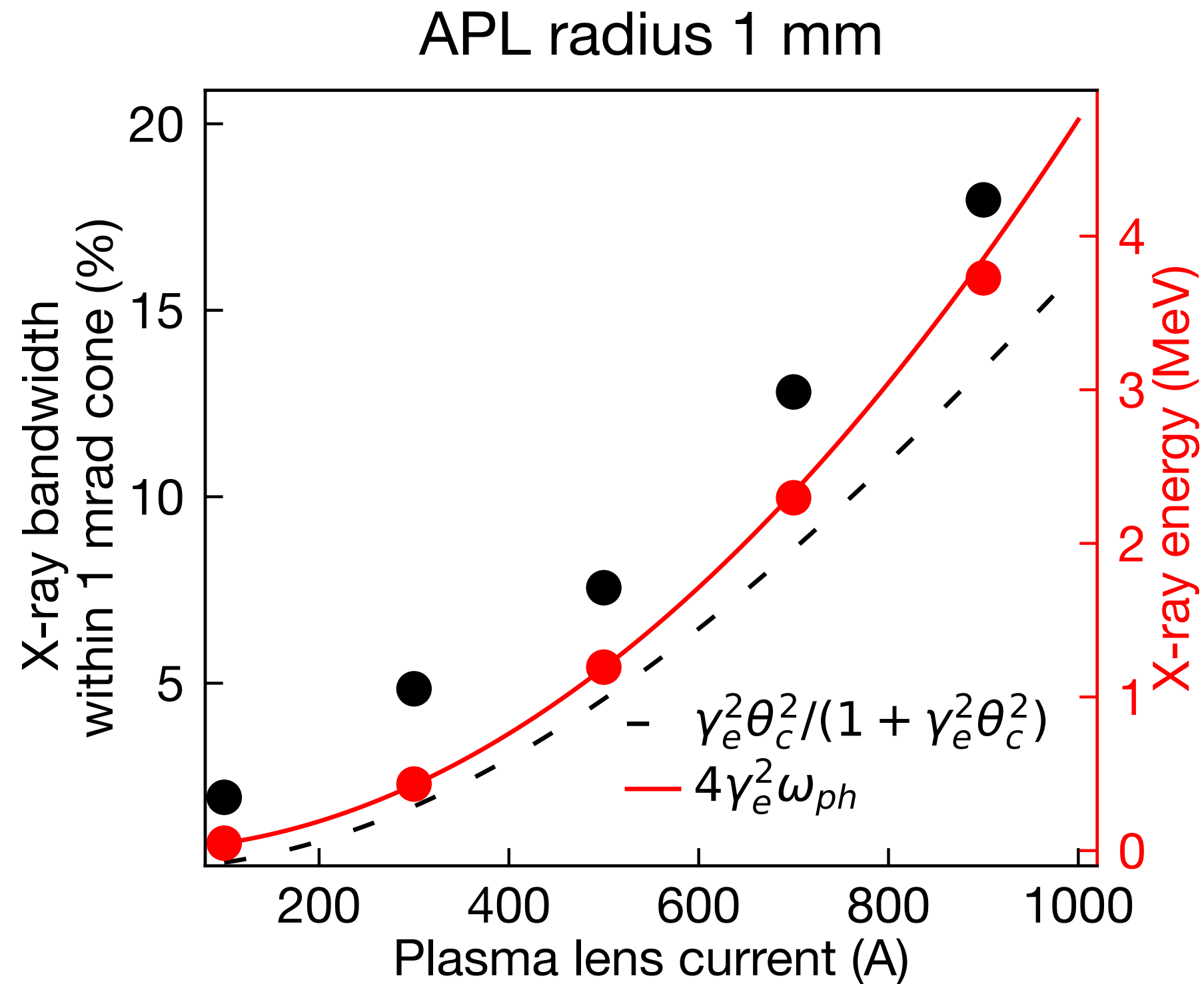
$$N(\gamma_e) \propto \frac{1}{\left(\frac{2\sigma(\gamma_e)}{w_0}\right)^2 + 1}$$

- > Effective energy spread determined by laser-electron overlap
 - > Electron energy determined by APL only -> increased stability
- > Beam imaging reduces divergence
 - > Electron pointing jitters reduced -> increased stability



Central energy tunable over a wide range

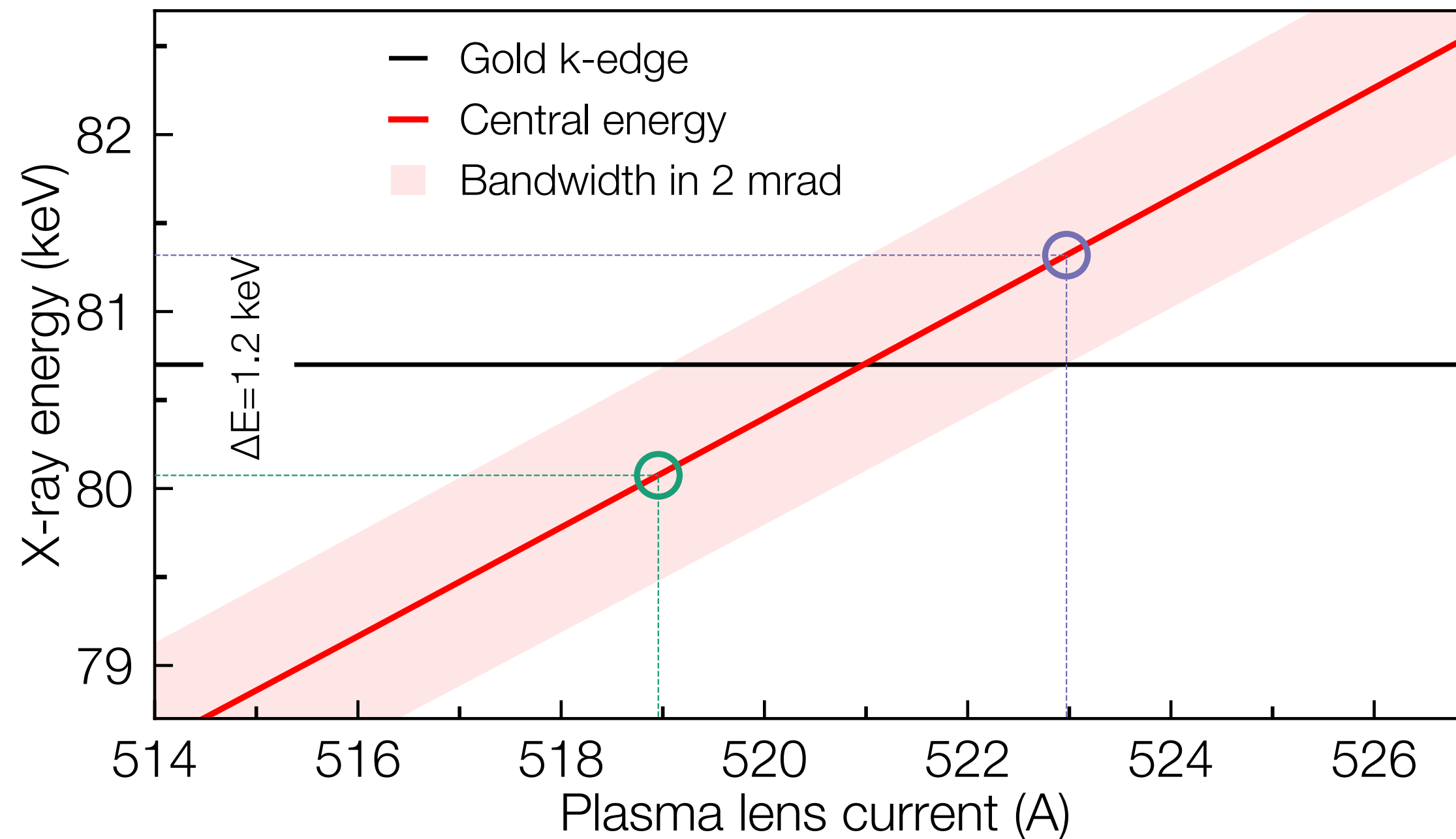
APL current can be flexibly and accurately tuned, varying resulting X-ray energy



No moving parts!
Overlap and alignment maintained!

Central energy tunable over a wide range

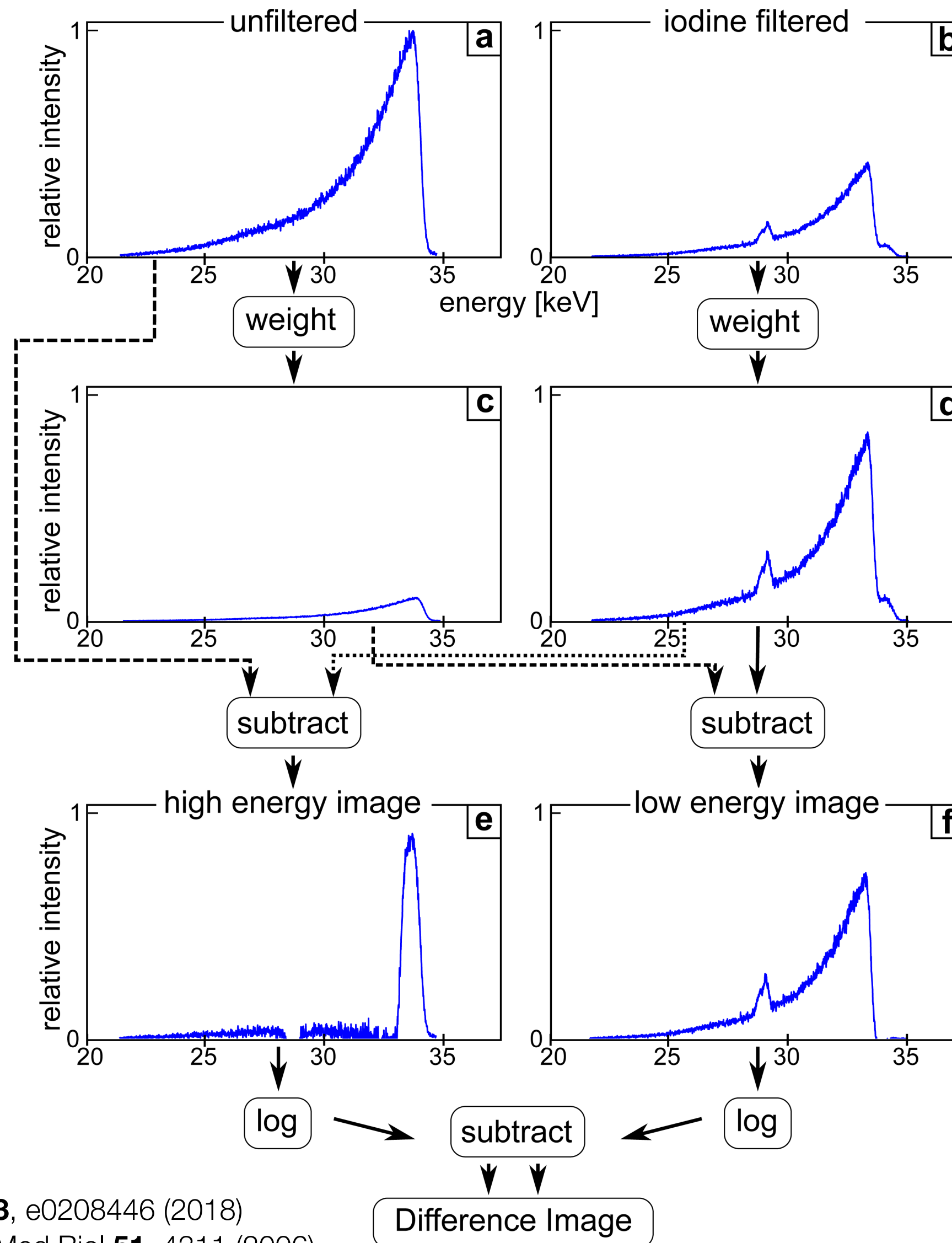
APL current can be flexibly and accurately tuned, varying resulting X-ray energy



Yields 10^5 photons per shot into 1 mrad half-cone
Assuming 10 pC/MeV, 1J, 1 ps laser!

K-edge subtraction imaging benefits from precision tuning

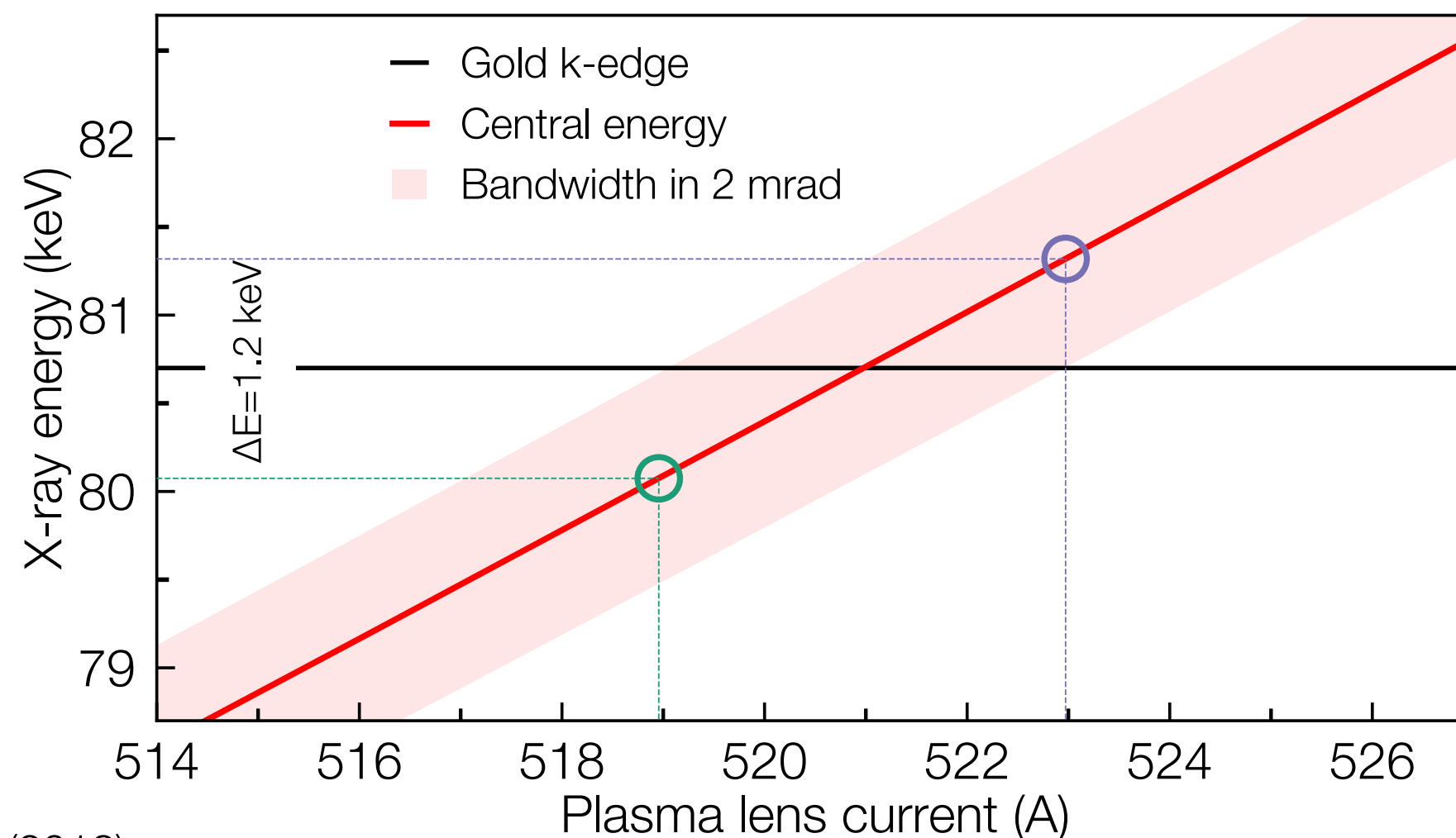
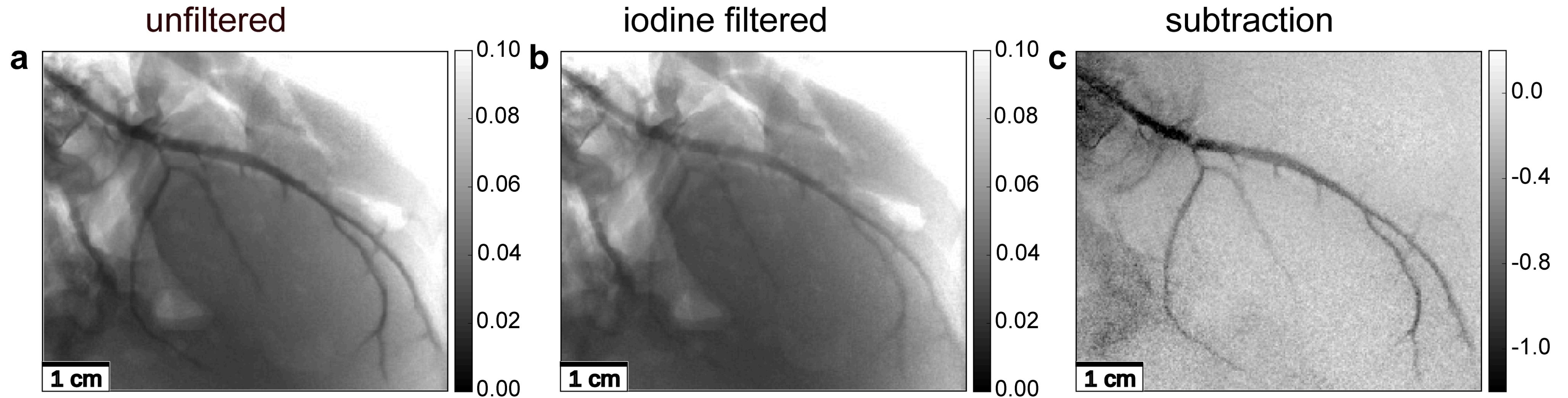
Delivered dose reduced with decreased energy separation



$$Im_{KES} = \log(Im_{high}) - \log(Im_{low})$$

K-edge subtraction imaging benefits from precision tuning

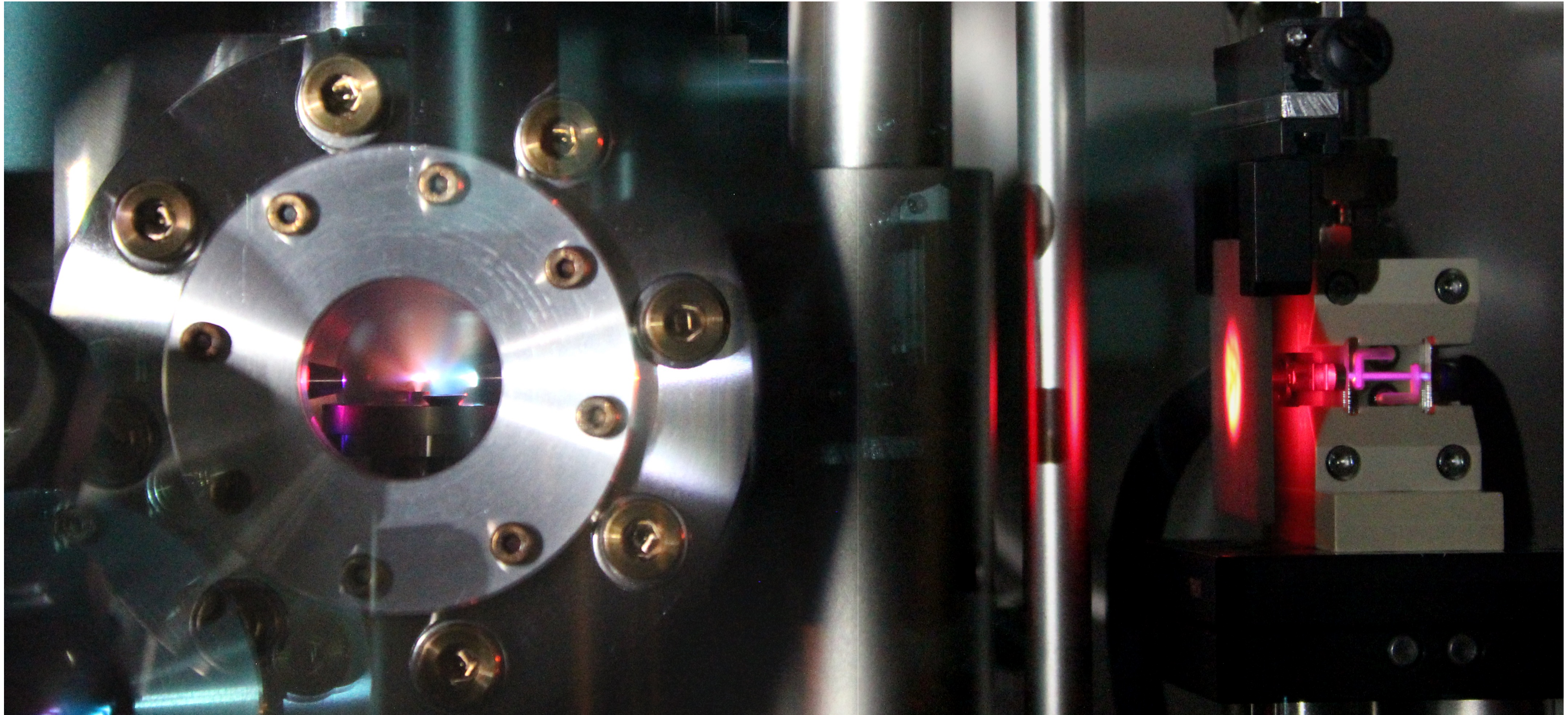
Delivered dose reduced with decreased energy separation



$$Im_{KES} = \log(Im_{high}) - \log(Im_{low})$$

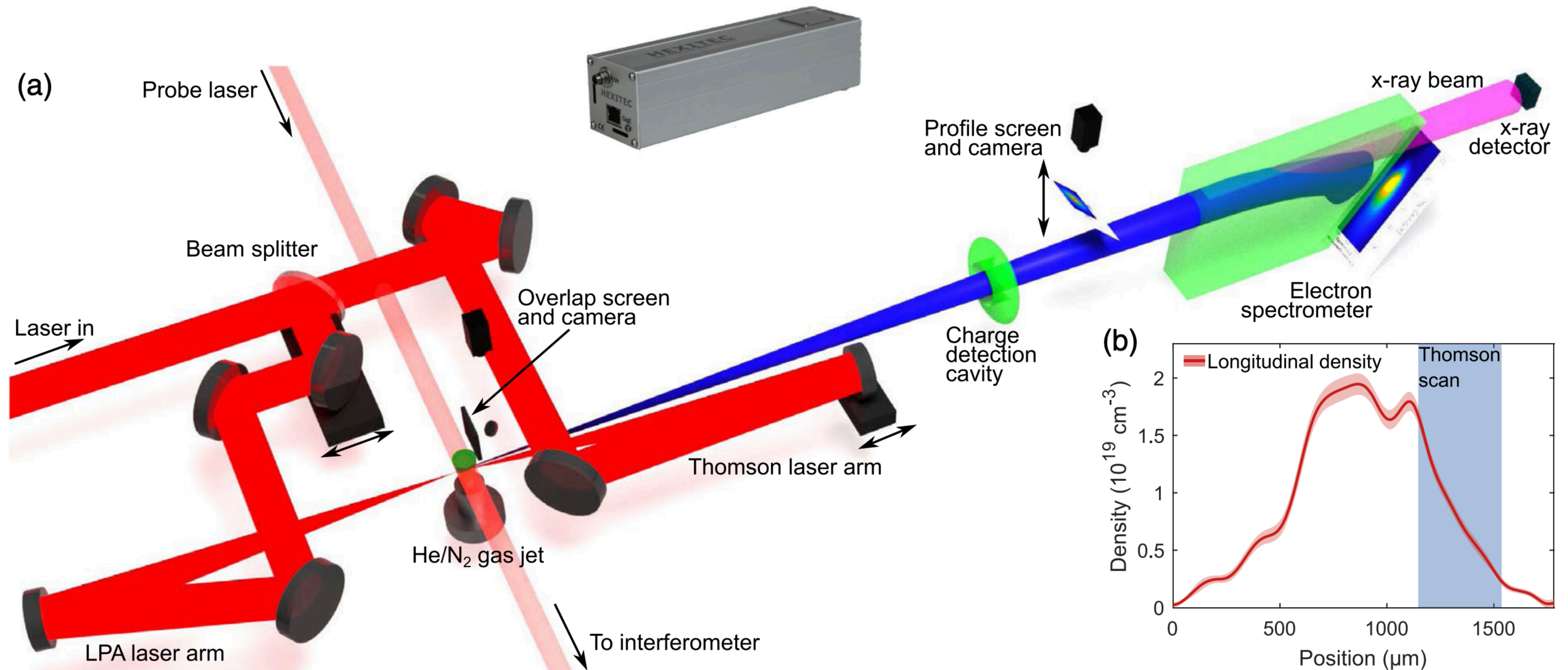
Experimental demonstration of tunable ICS source

All-optical, all-plasma architecture also good for pretty pictures!



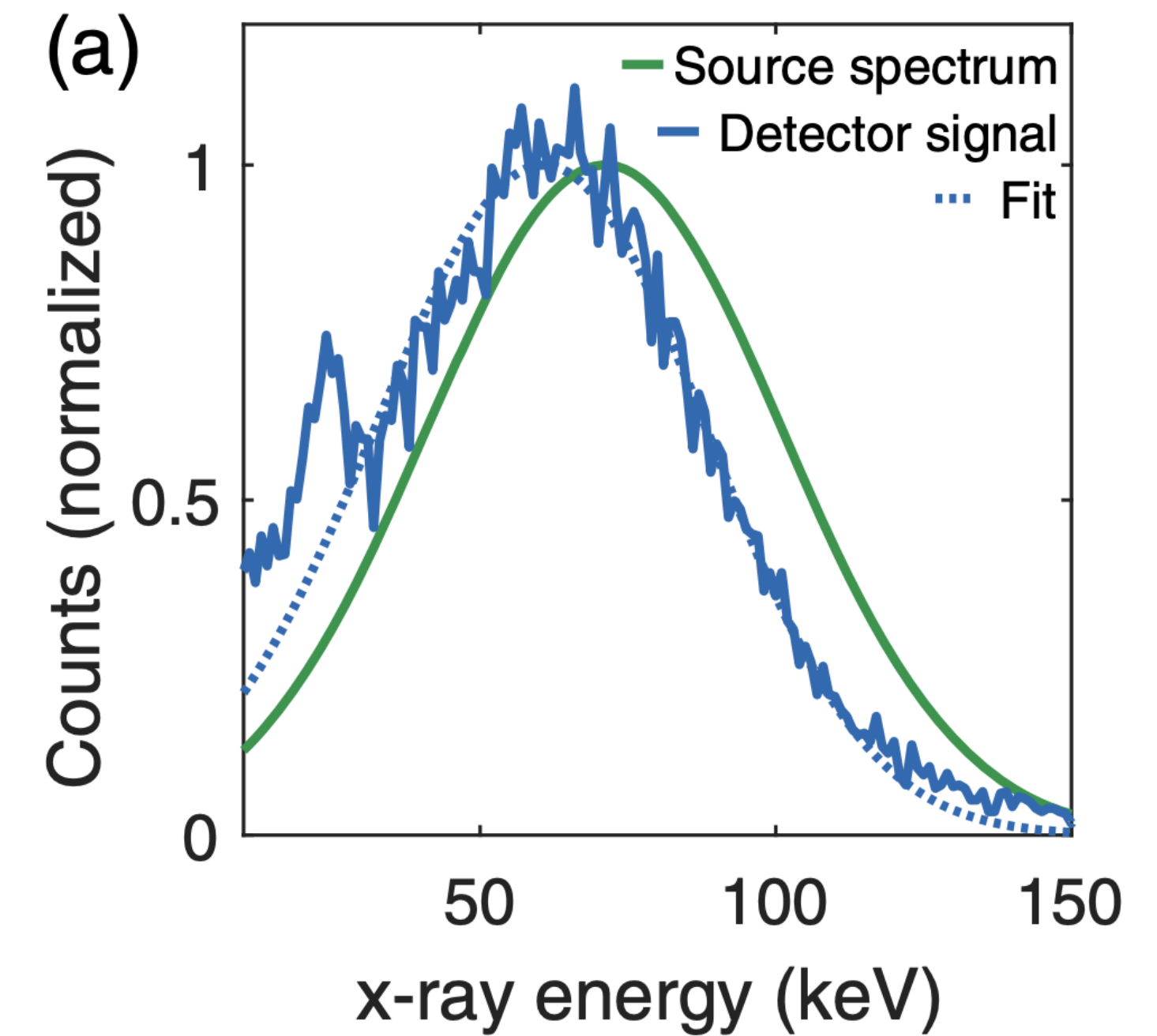
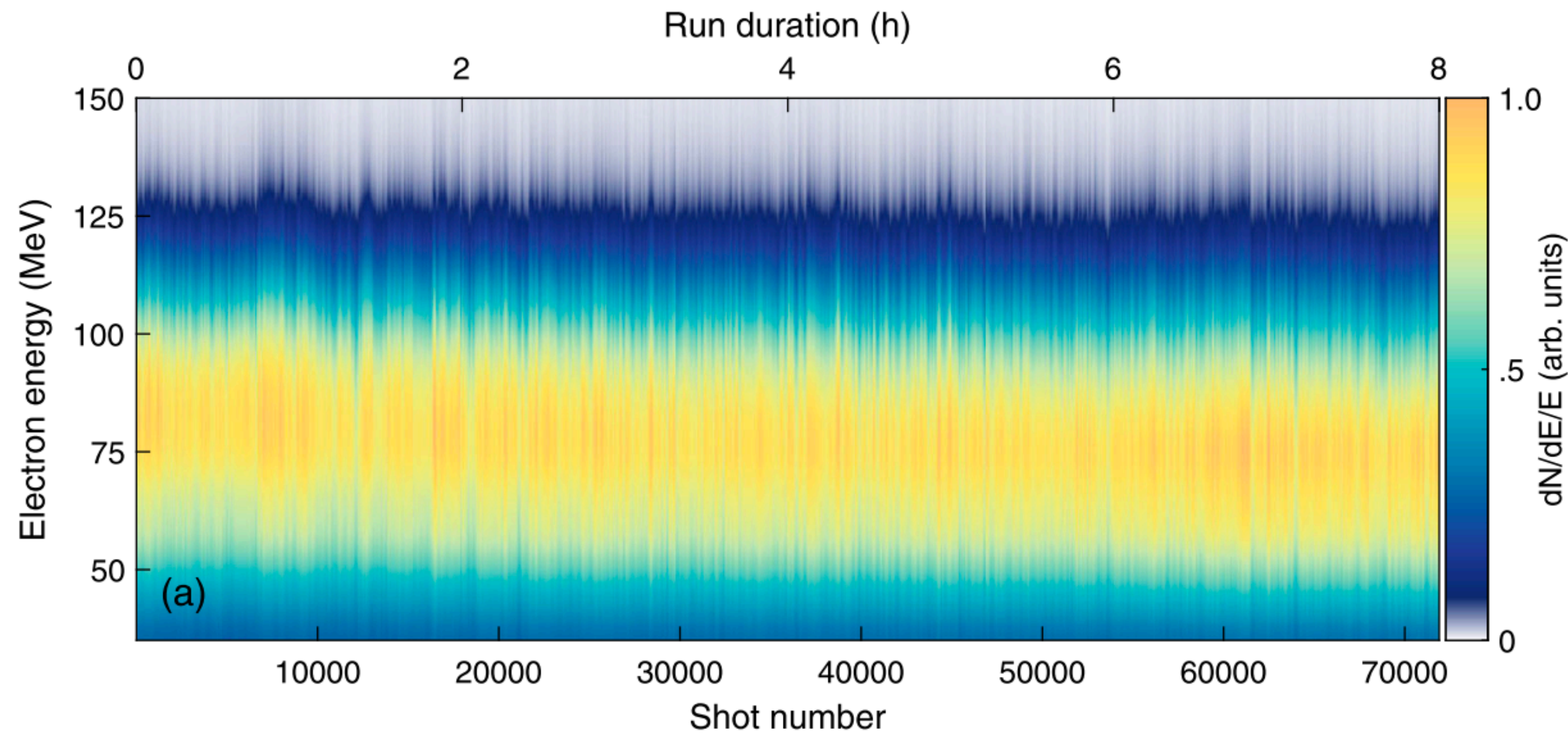
Experimental demonstration

‘Classical’ scattering setup with IP being at the output of the plasma



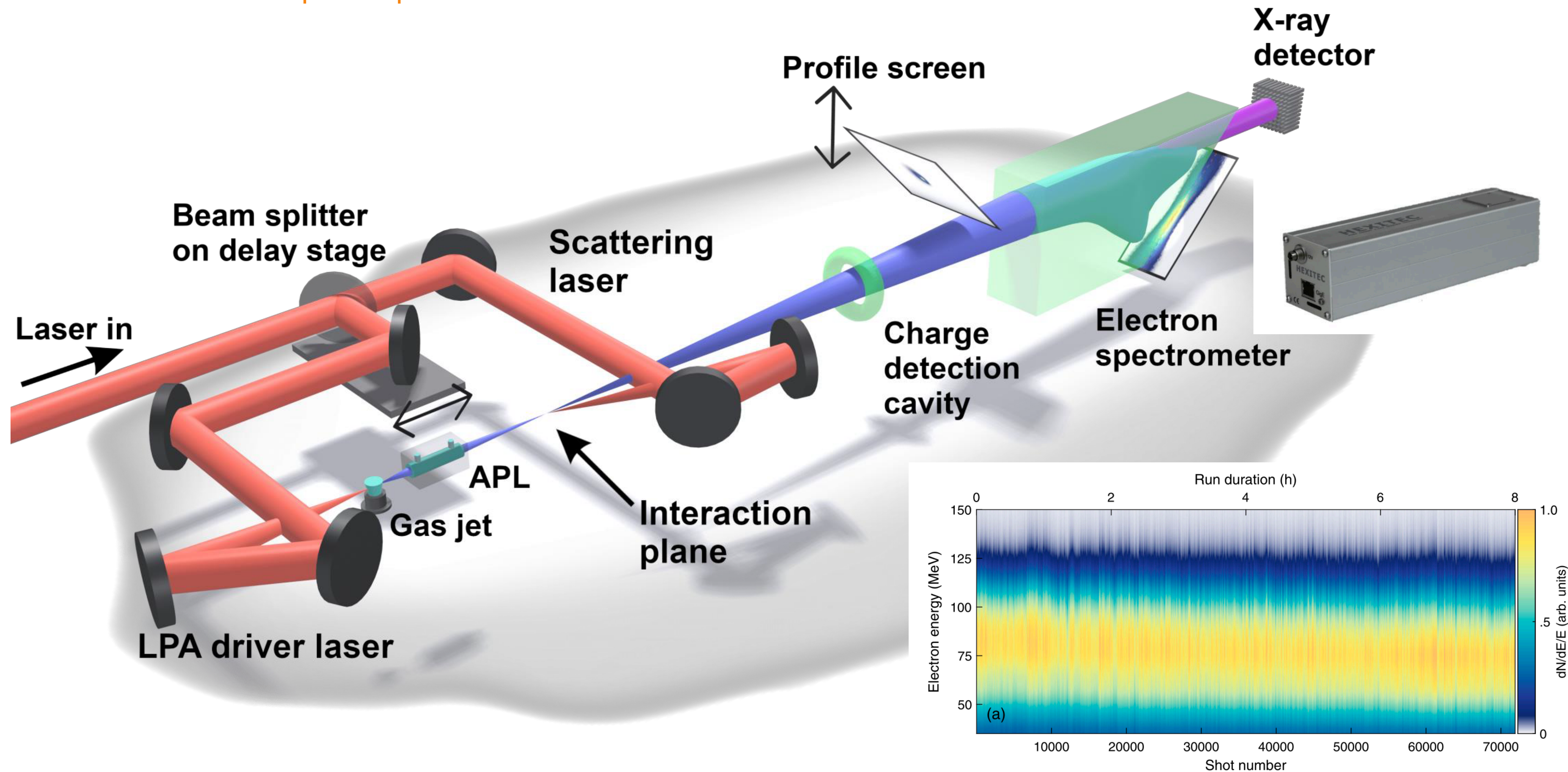
‘Standard’ ICS results show broad spectrum

‘Classical’ scattering setup heavily reliant on electron beam quality



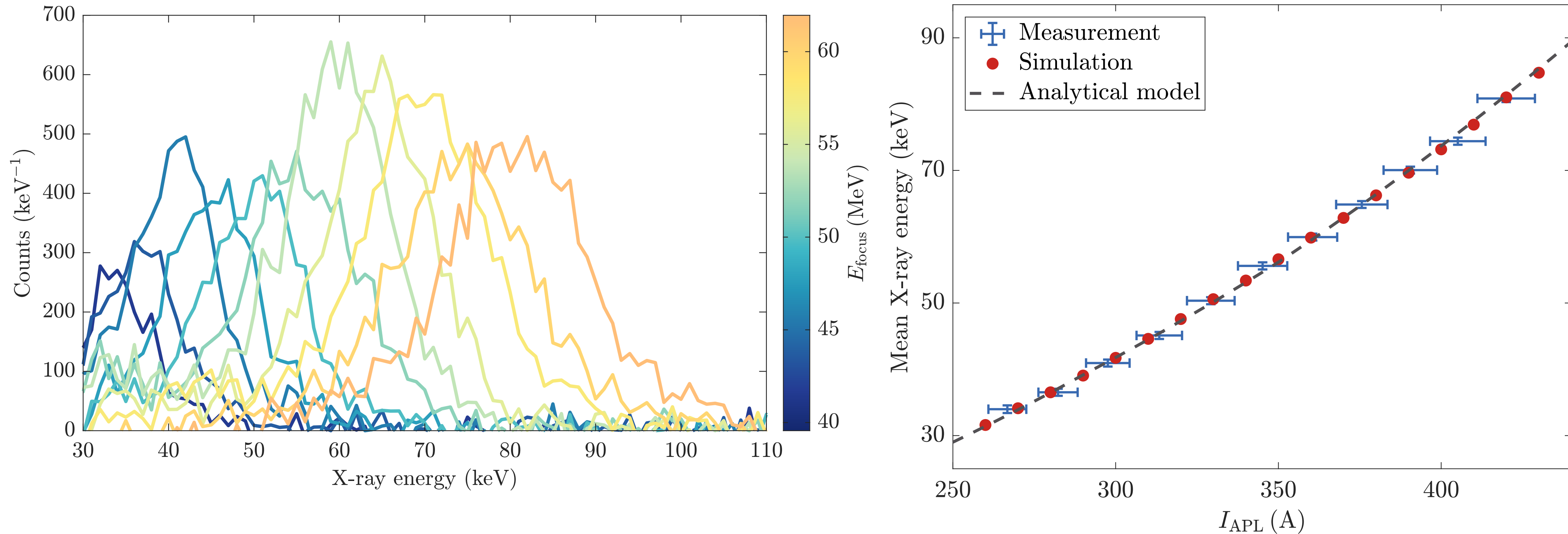
Experimental demonstration

Metre-scale setup set up at DESY for demonstration of bandwidth control



Experimental demonstration

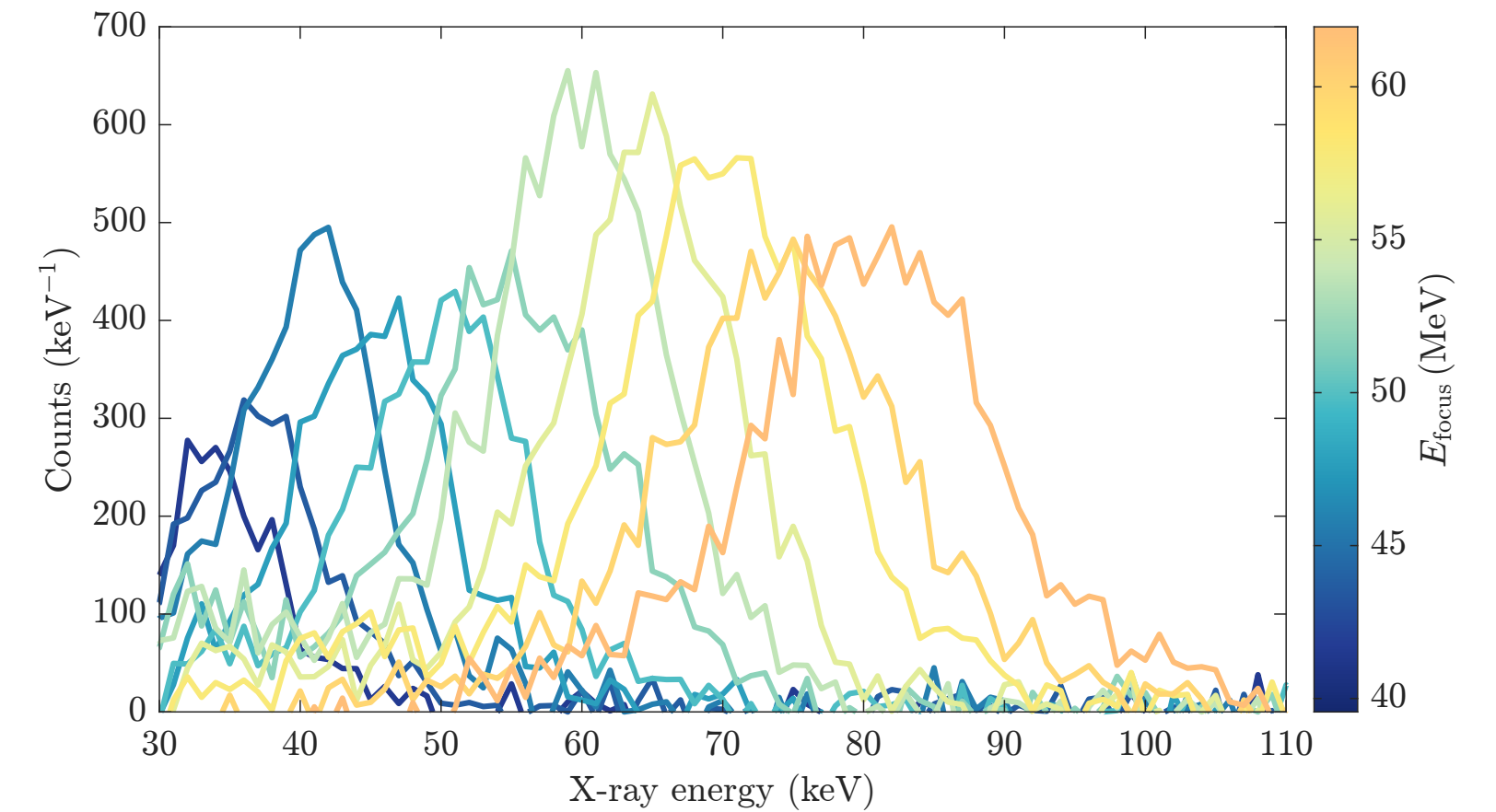
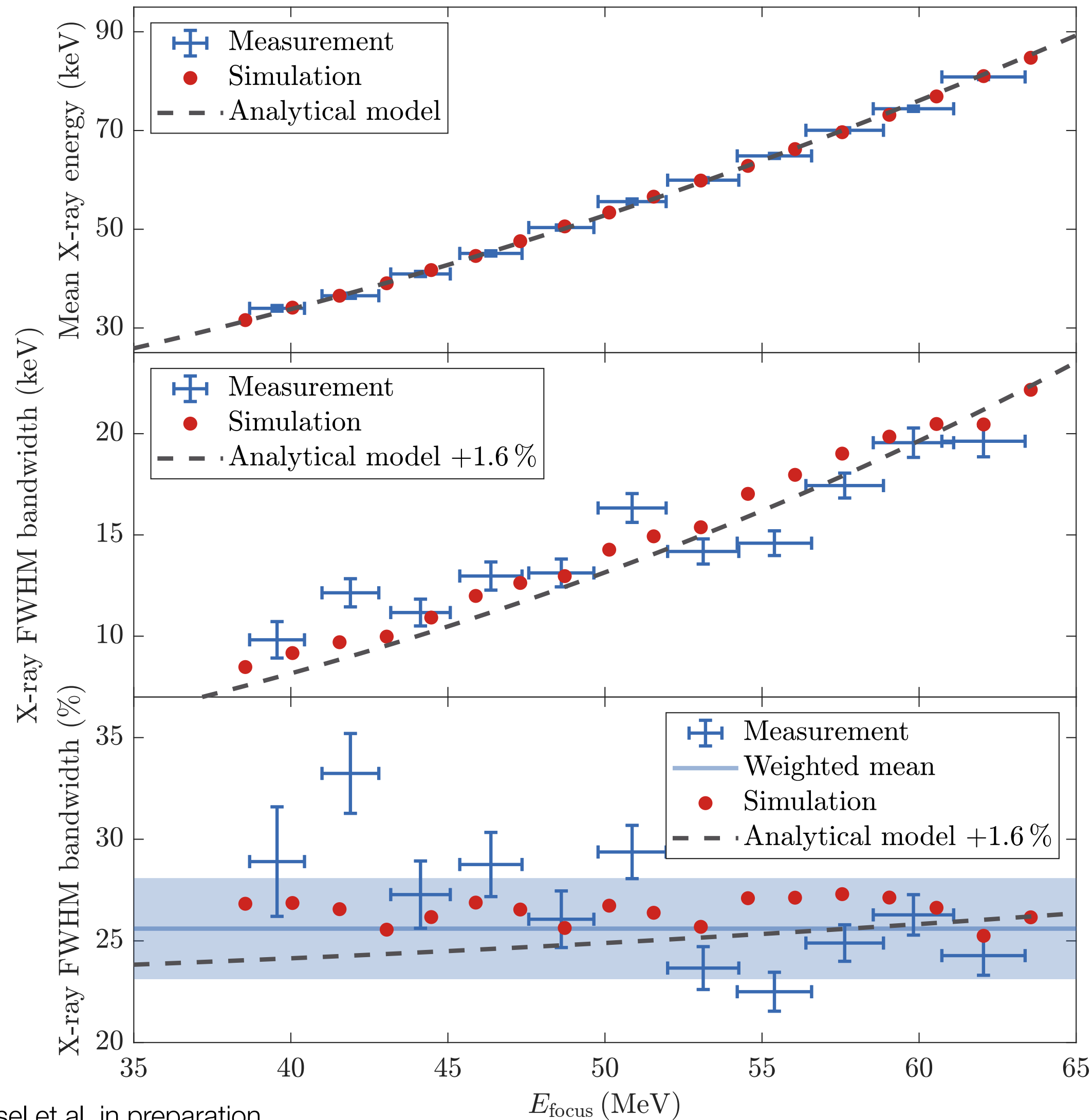
Varying the plasma lens current changes the central energy of the measured X-rays



No moving parts!
Overlap and alignment maintained!

Experimental demonstration

Results closely follow theory, highlighting importance of control of laser pulse



Experimental demonstration

Results closely follow theory, highlighting importance of control of laser pulse

Average bandwidth across the shots: 25.6 % (raw >75%)

$$\frac{\Delta\omega_x}{\omega_x} = \sqrt{\left(\frac{2\delta\gamma_e}{\gamma_e}\right)^2 + \left(\frac{\gamma_e^2\sigma_\theta^2}{4}\right)^2 + \left(\frac{\delta\omega_L}{\omega_L}\right)^2 + \left(\frac{a_0}{2}\right)^2 + \kappa^2}$$

7-11 % contr.
(raw >60%)

1 % contr.
(raw >20%)

9% contr.

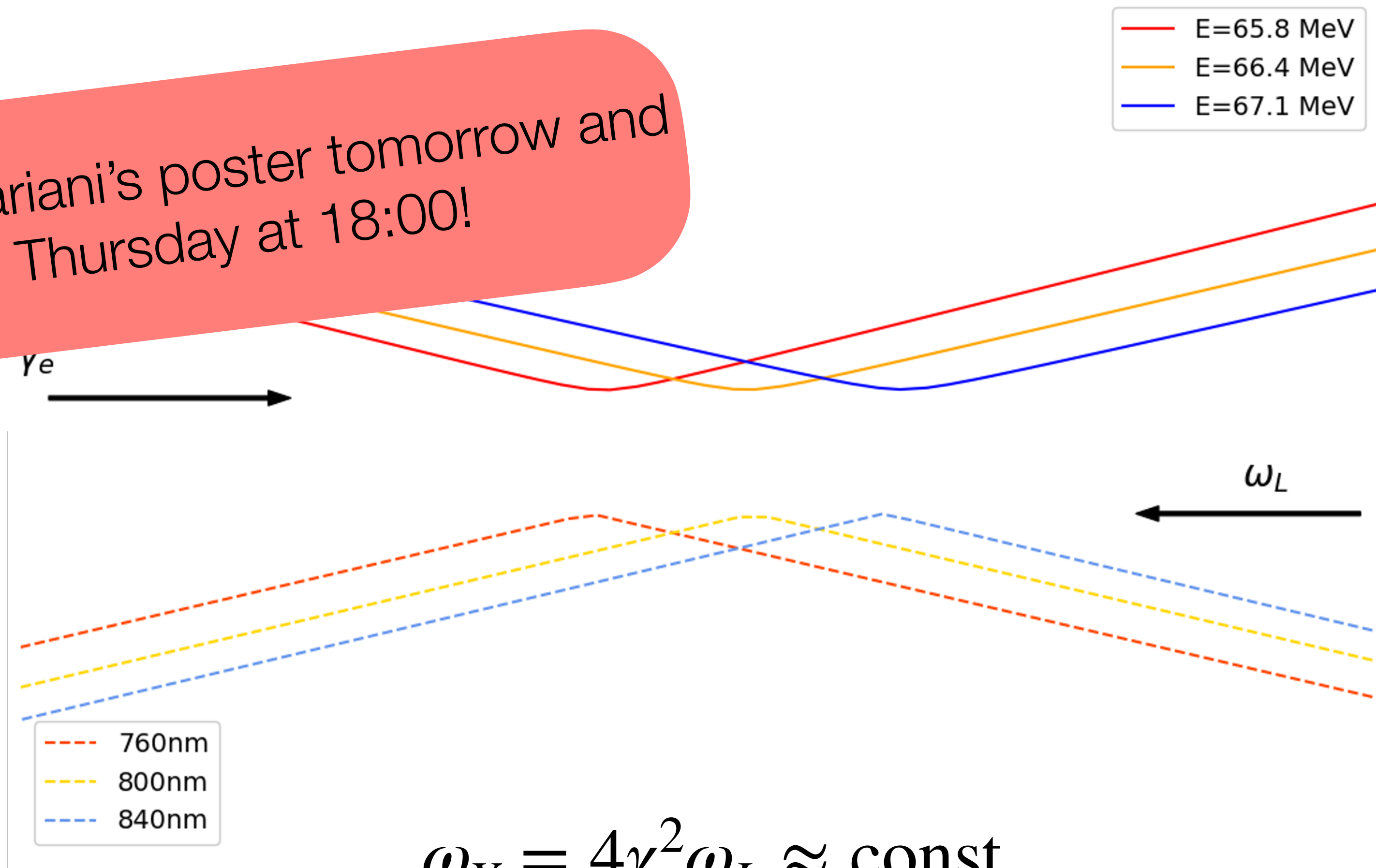
20% contr.

Dominated by laser -> electron beam contribution greatly reduced!

Tailoring the scattering pulse to reach ultimate bandwidths

Implementing flying focus to match the chromaticity of the electron beam

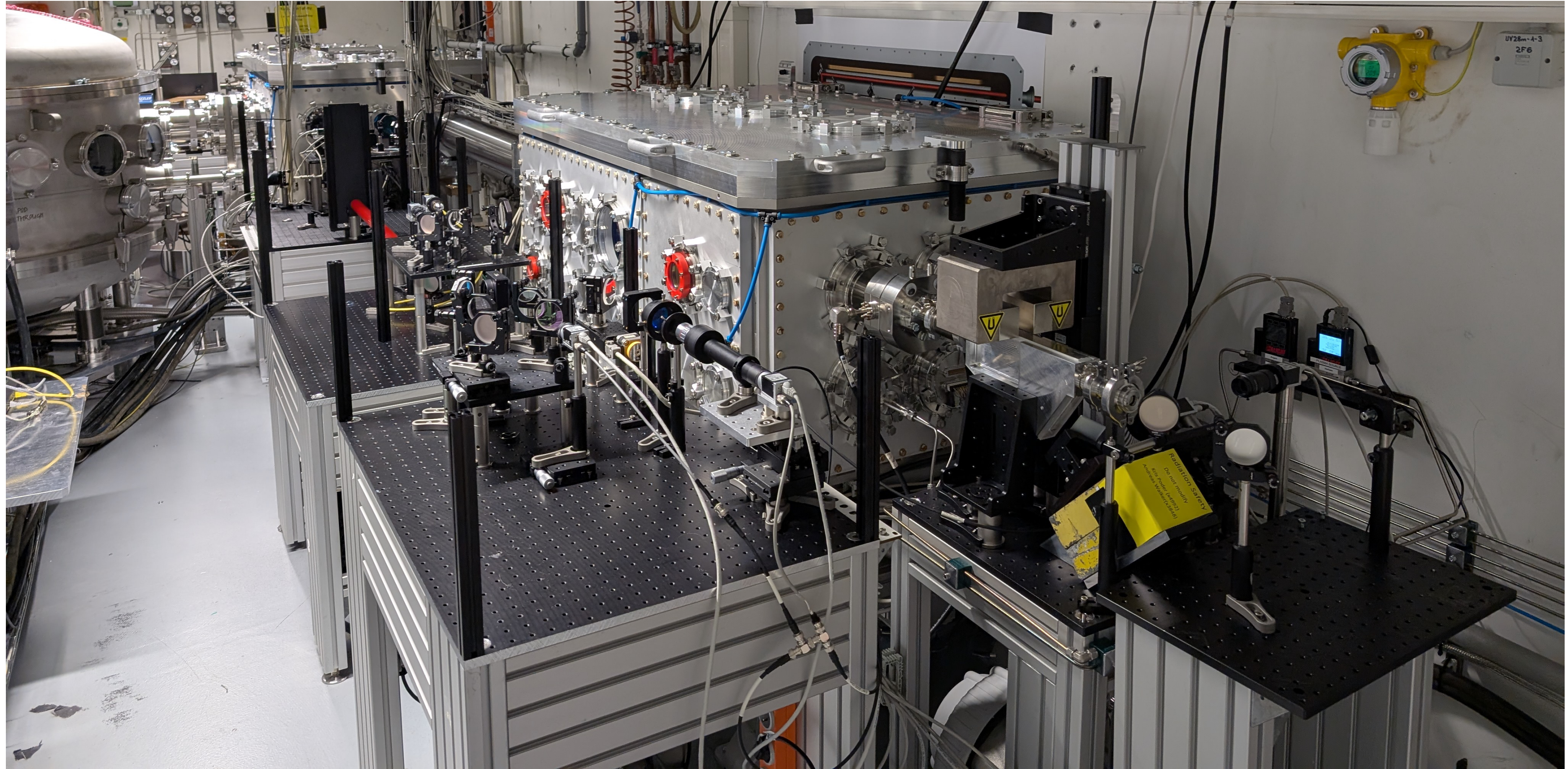
See Cristina Mariani's poster tomorrow and talk on Thursday at 18:00!



$$\omega_X = 4\gamma_e^2 \omega_L \approx \text{const}$$

APHEX source is expected to make first light in 2026

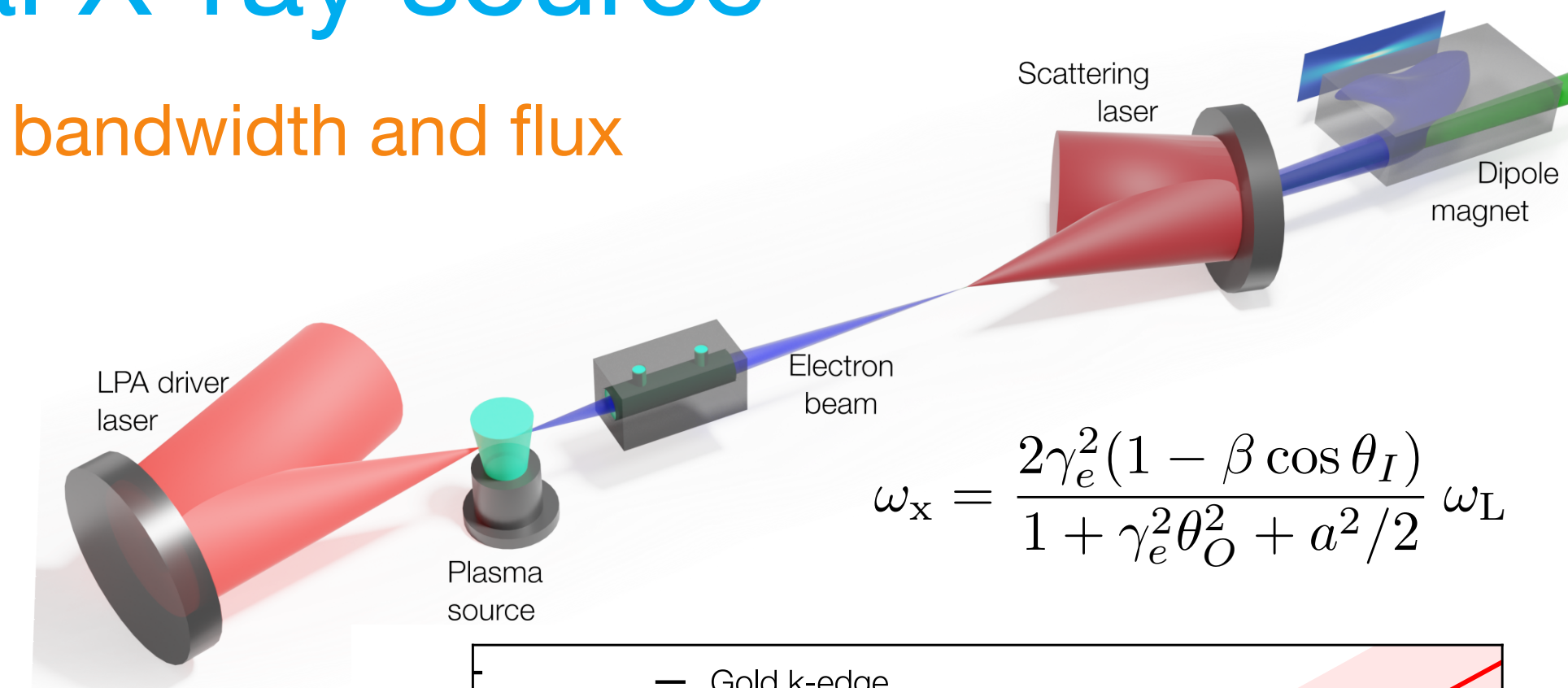
APHEX targets medical and industrial applications in the 100s of keV energy range



Demonstration of tunable all-optical X-ray source

Compact all-plasma achitecture allows application-relevant bandwidth and flux

- > Tailoring electron beam with an APL enables %-level X-ray bandwidth and tuning
 - > Effective e-beam bandwidth $\ll$ e-beam energy spread
 - > Beam divergence substantially reduced
 - > OoM tuning range, limited by electron spectrum
- > Increased spectral stability
 - > Imaging reduces pointing-driven bandwidth jitter
 - > Electron energy variations suppressed
- > Scattering-laser dominated regime reached
 - > Flying focus will reduce effects of laser bandwidth
- > Push towards developing this compact technology to applications
 - > $>10^8$ ph/s flux at kHz



$$\omega_x = \frac{2\gamma_e^2(1 - \beta \cos \theta_I)}{1 + \gamma_e^2\theta_O^2 + a^2/2} \omega_L$$

