John Adams Institute for Accelerator Science

Imperial College London

Plasma Accelerators as a source of fs X-rays for probing Matter Under Extreme Conditions

Stuart Mangles

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AGR Thomas (U. Lancaster),

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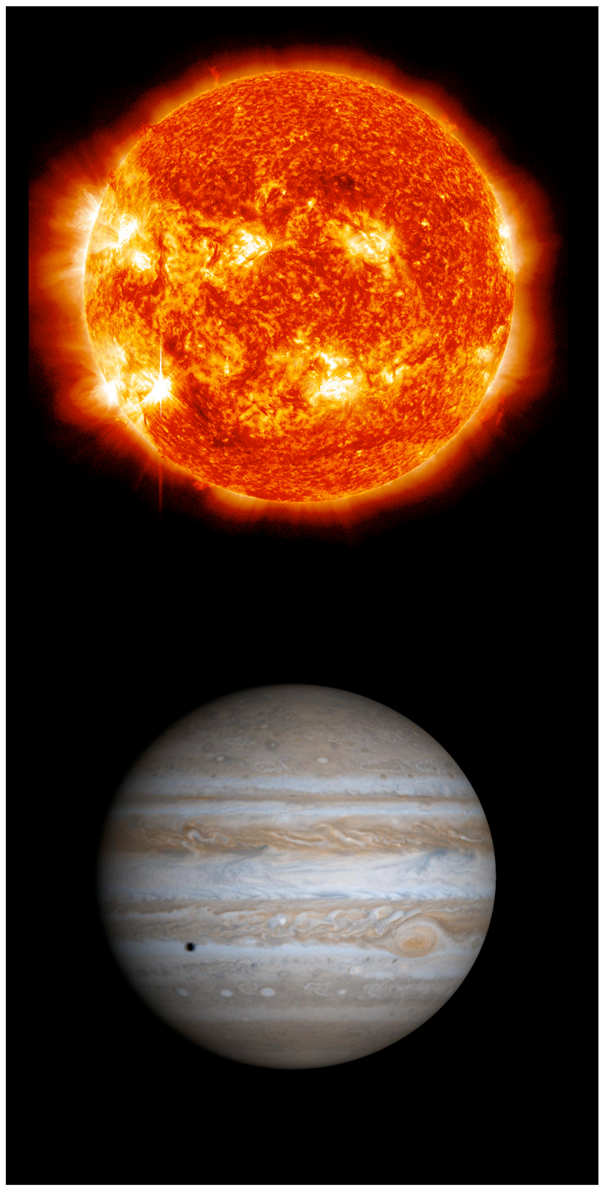
apologies if I forgot anyone!

Talk Outline

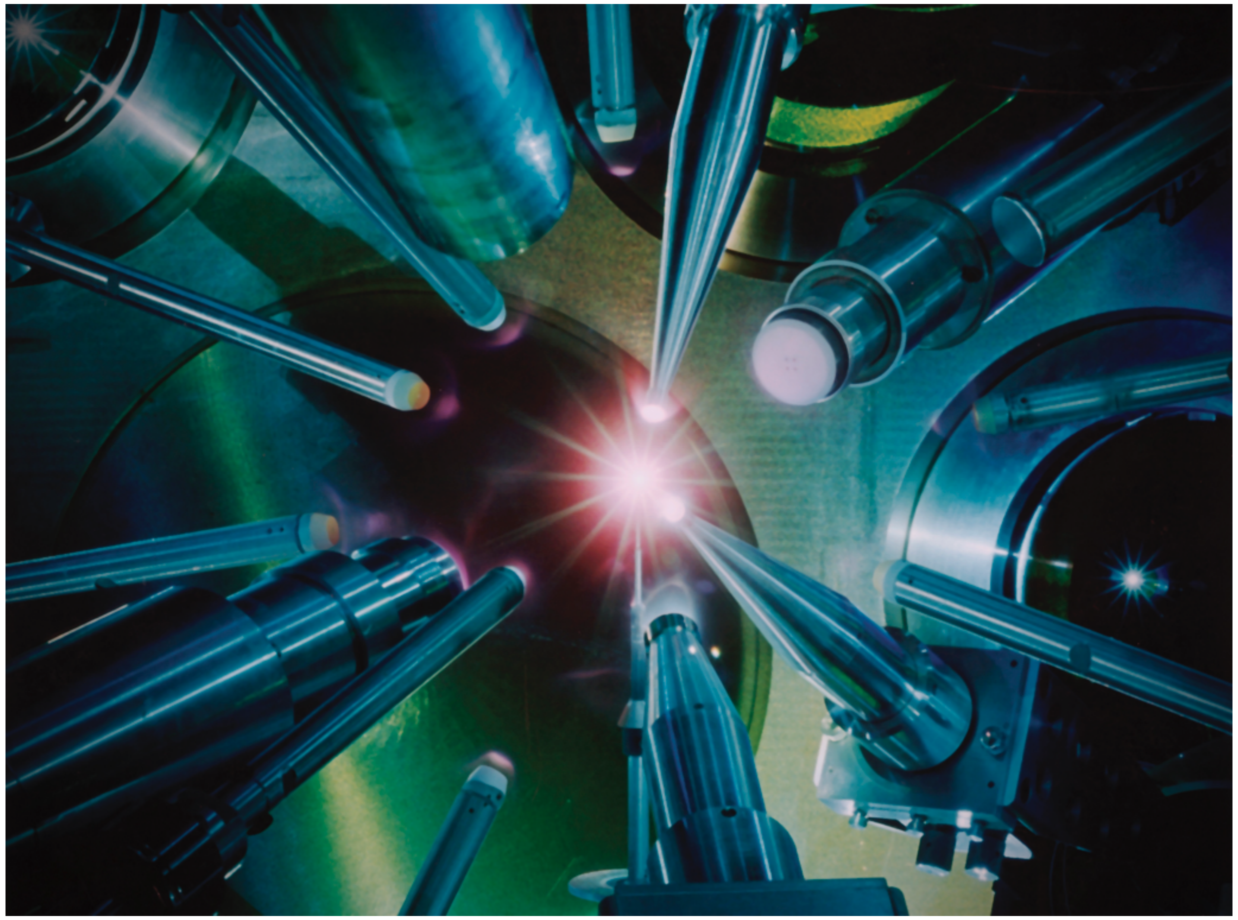
- Brief physics motivation: Why HEDP? Why betatron radiation?
- Current status of betatron radiation
- Some example experiments that could be performed
- Experimental Requirements for HEDP physics experiments

Much of the visible matter in the universe exists under extreme conditions



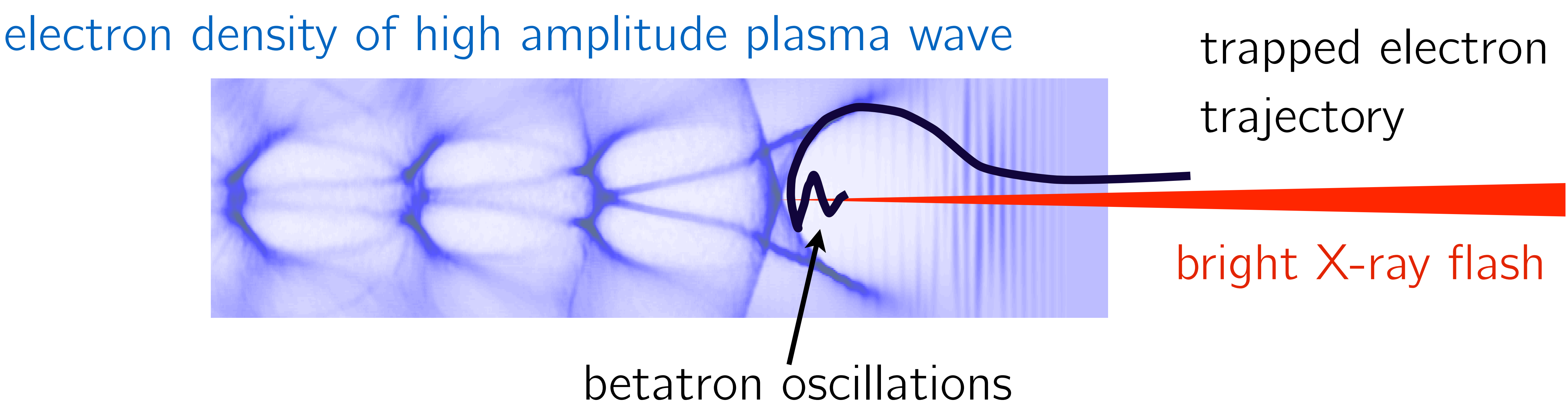
- Extremely high temperatures and/or pressures
  - **Hot Dense Matter**: inside stars
    - » (10^7 K, 10^{11} atmospheres)
  - **Warm Dense Matter**: inside planets
    - » (10^4 K, 10^7 atmospheres)

Extreme conditions can now be created in the laboratory



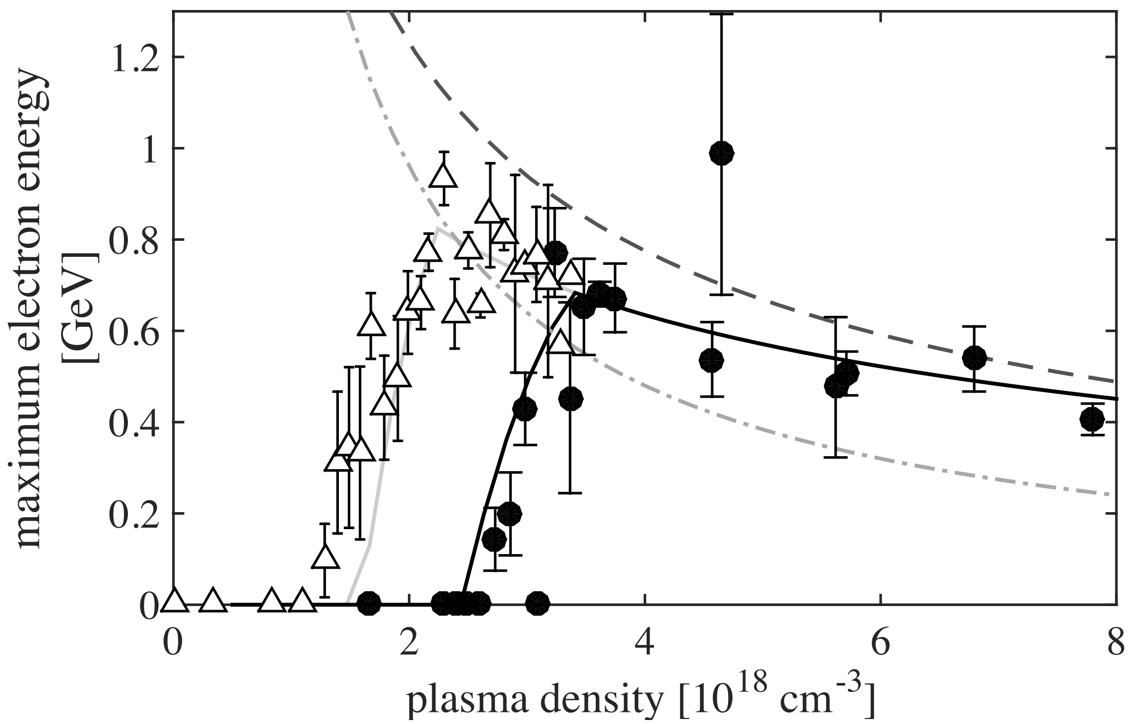
- Laboratory experiments only produce extreme states for very short periods of time (~10^{-12} s)
- How can we use measurements of very short lived experiments to help understand equilibrium situation inside stars & planets?

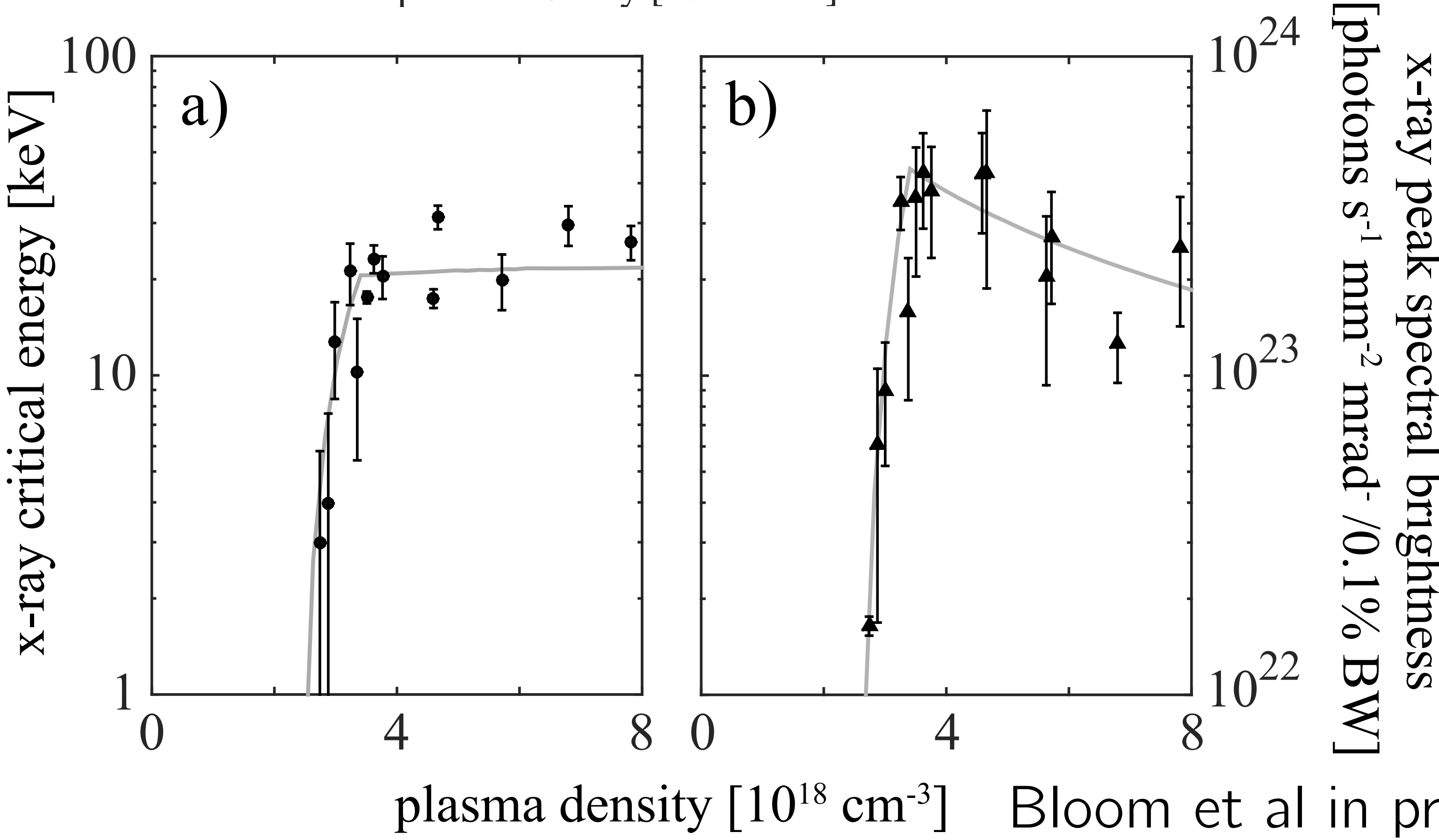
Laser wakefield accelerators produce an interesting X-ray source



- Laser wakefield accelerators can produce bright, ultra-short flashes of broadband X-rays
- Electrons trapped in wakefield structure both accelerate *and* oscillate
- Produces bright, short flashes of synchrotron radiation

Betatron Radiation could be an ideal tool for probing HEDP



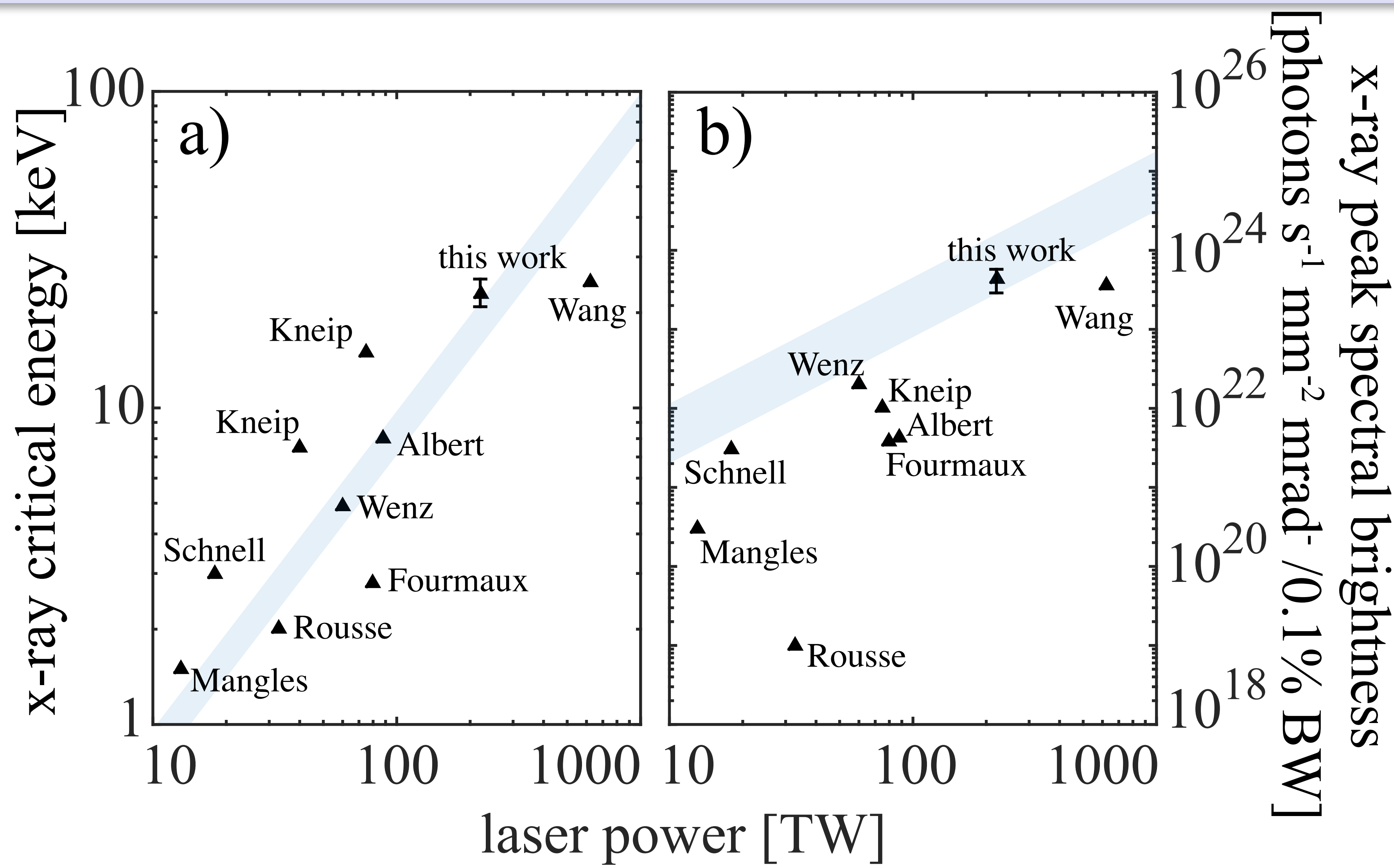


Bloom et al in prep.

- Betatron radiation produces bright, hard X-rays
- Analytic theory* is able to predict electron and X-ray properties
  - e-beam energy
  - X-ray spectrum
  - X-ray brightness

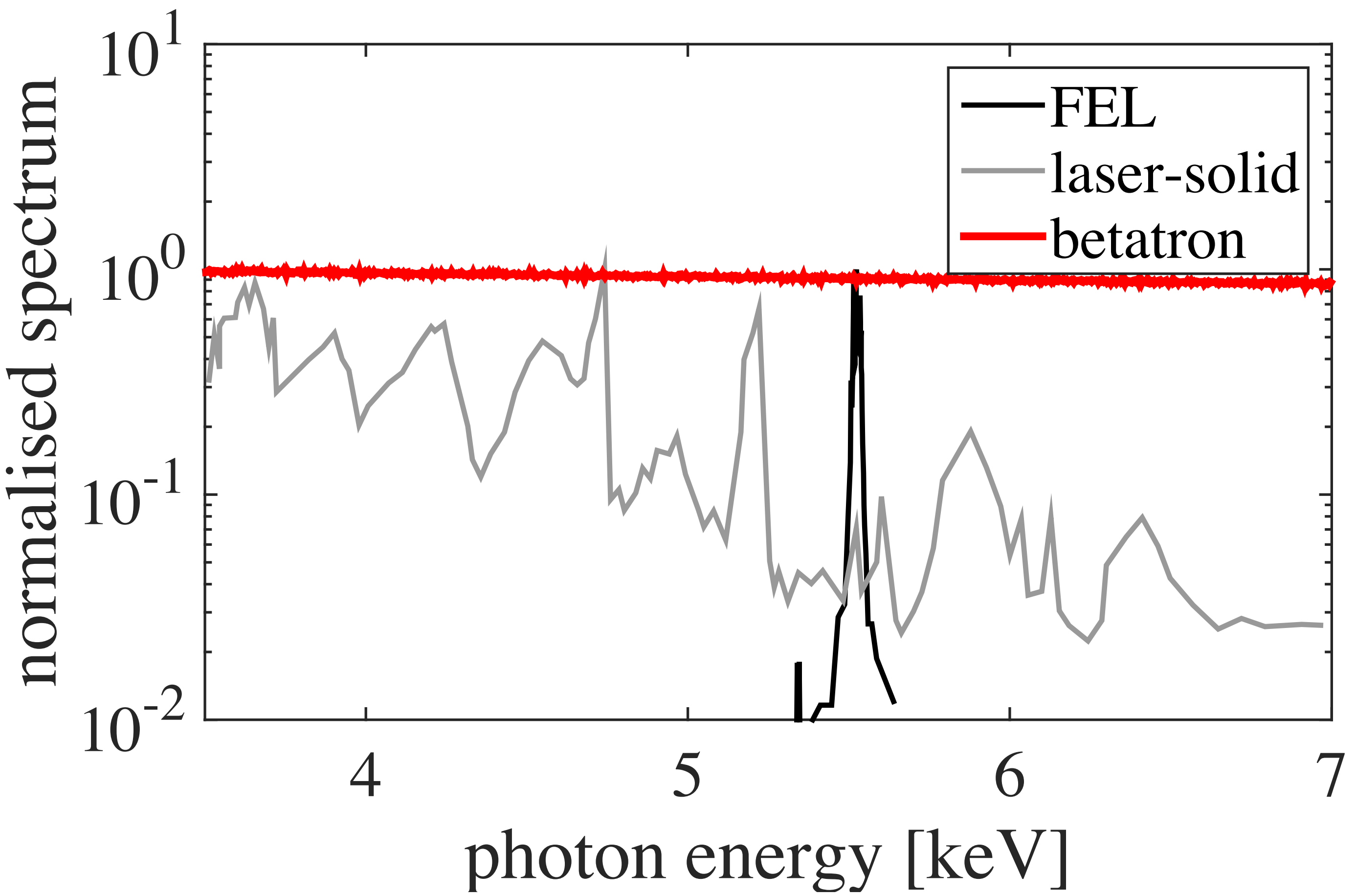
*Thomas PoP 2010

Betatron Radiation could be an ideal tool for probing HEDP



- Increasing laser power (and hence electron energy) has dramatic effect on X-ray properties
  - increase photon energy
  - increase of number of photons per shot (and brightness)

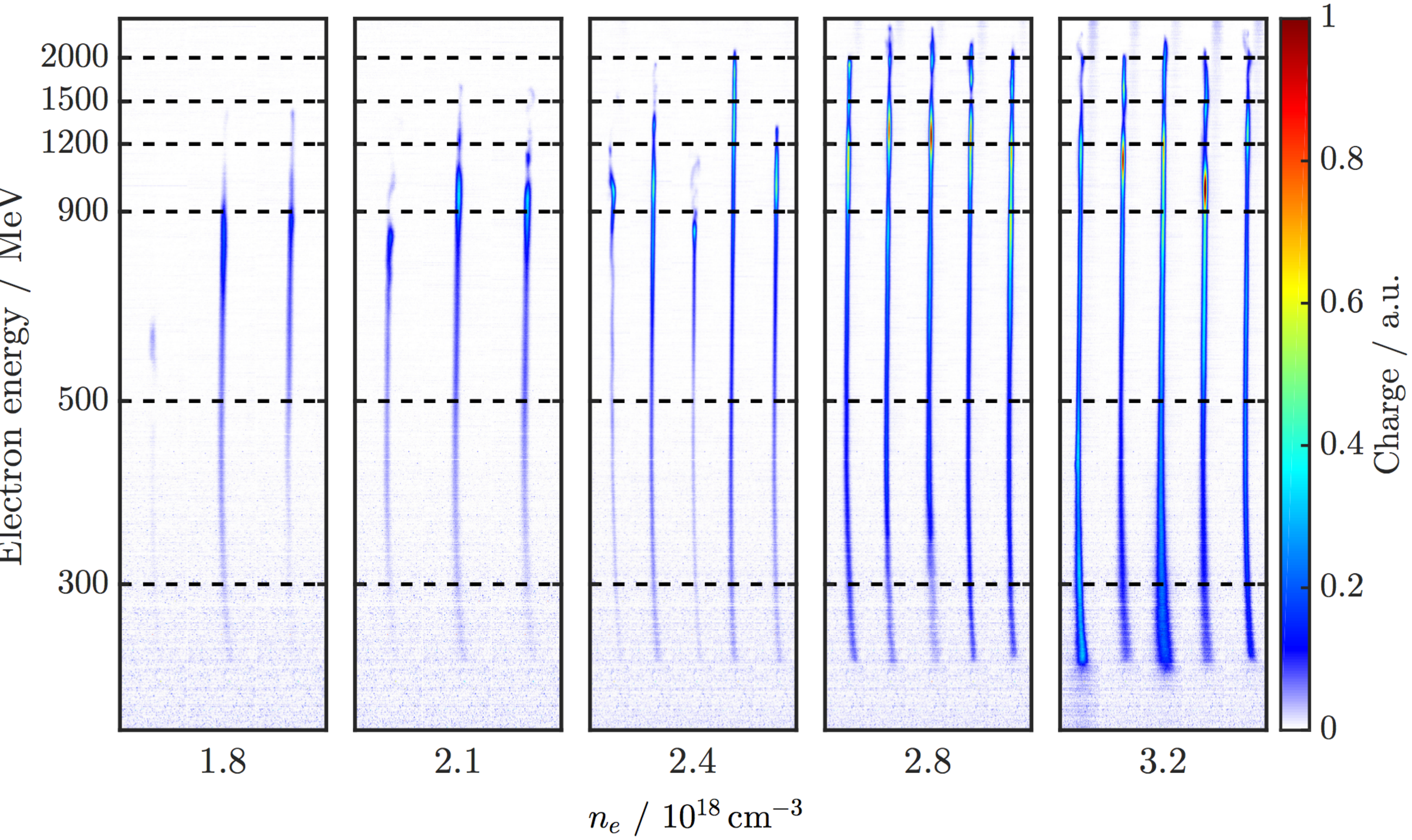
Betatron radiation is an X-ray source with unique properties

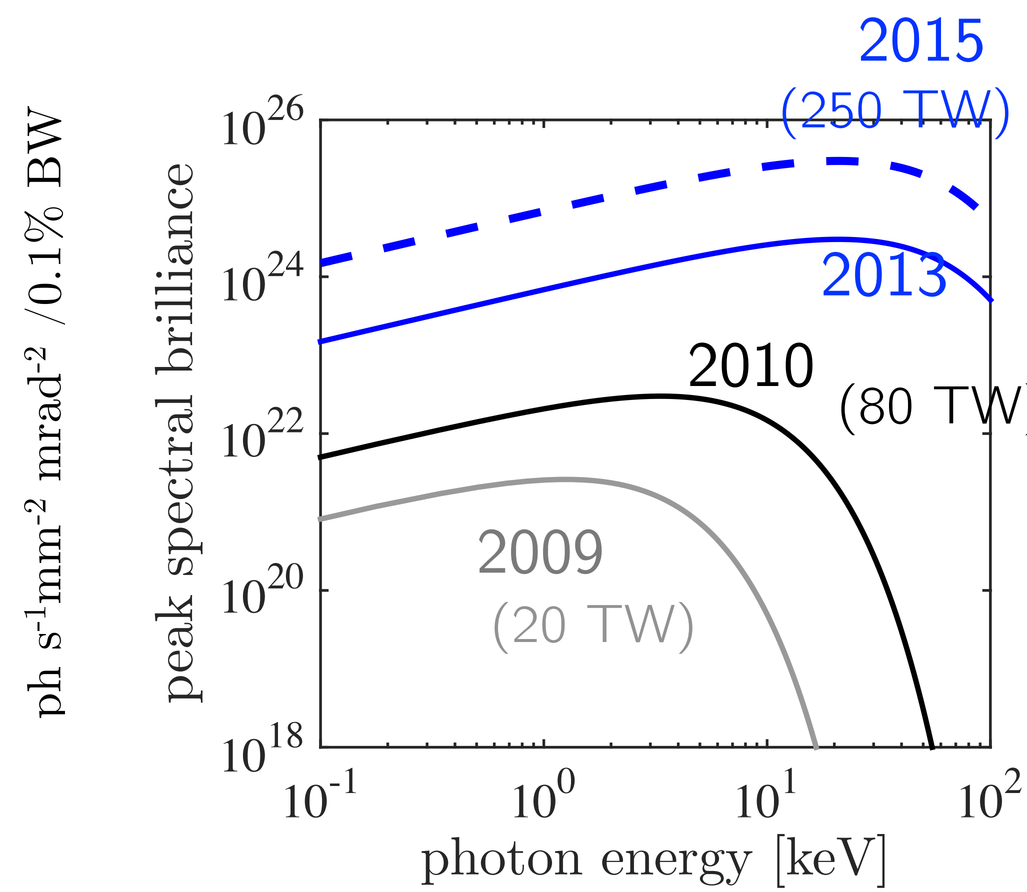


- Broadband and short pulse duration:
  - X-ray absorption spectroscopy
  - White light Laue diffraction
- Small source size:
  - X-ray phase contrast imaging

	Synchrotron	XFEL	Laser-solid	**Laser Wakefield**
duration	10 - 100 ps	<100 fs	1 - 10 ps	< 100 fs
bandwidth	broad and smooth	narrow	broad not smooth	broad and smooth

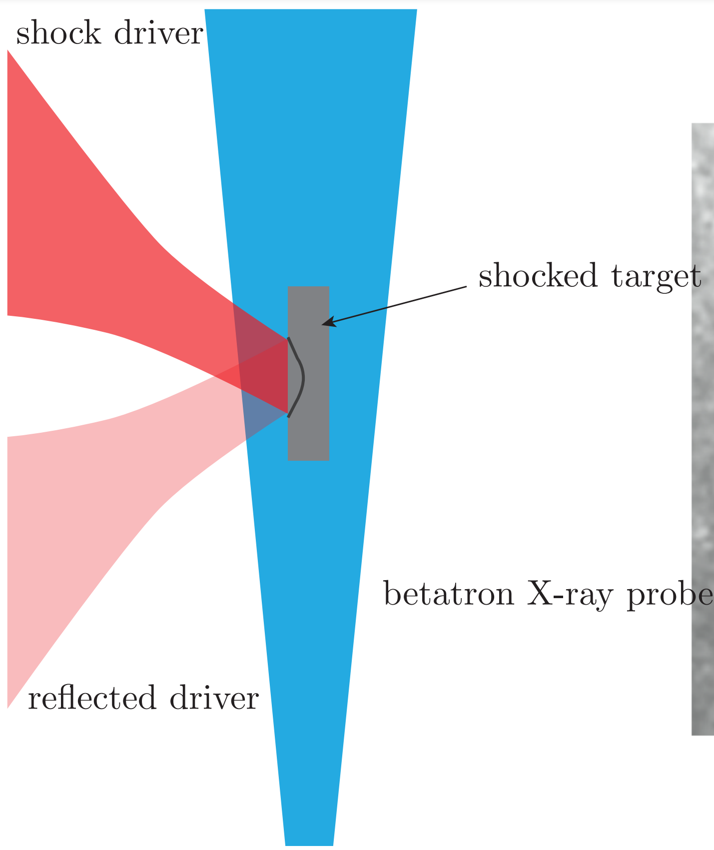
Betatron Radiation could be an ideal tool for probing HEDP

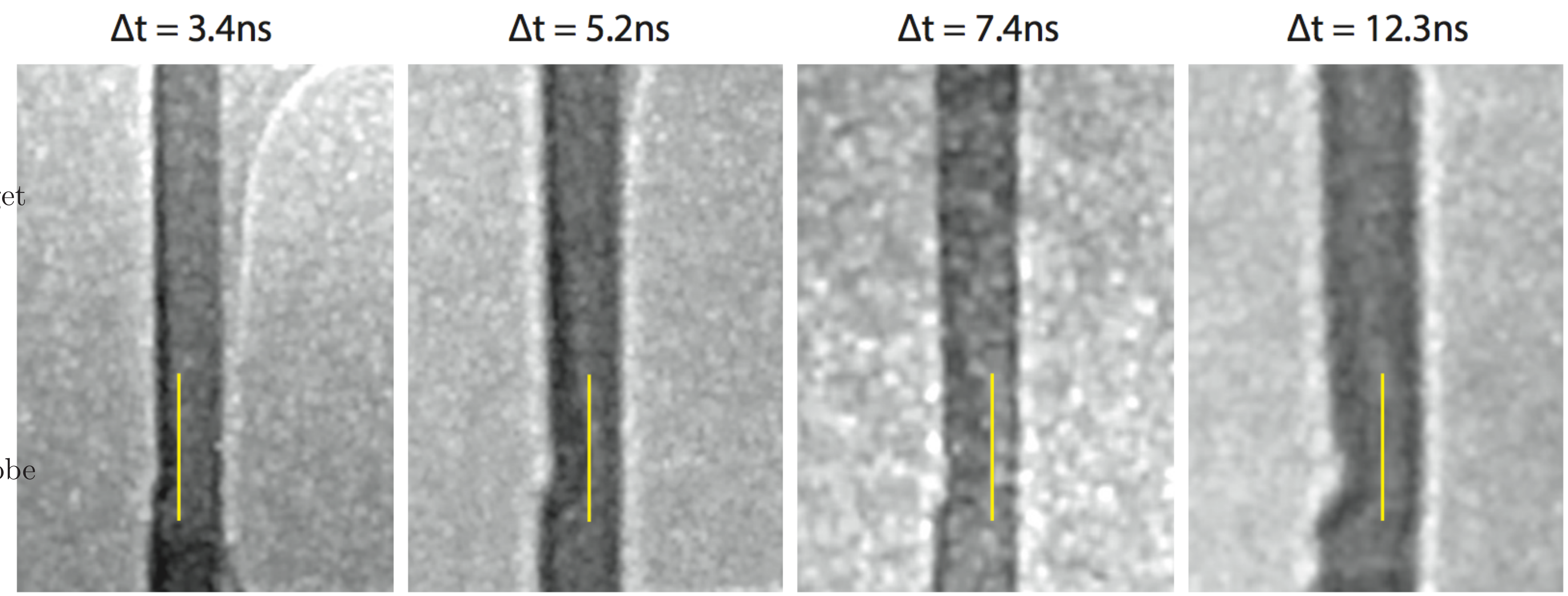




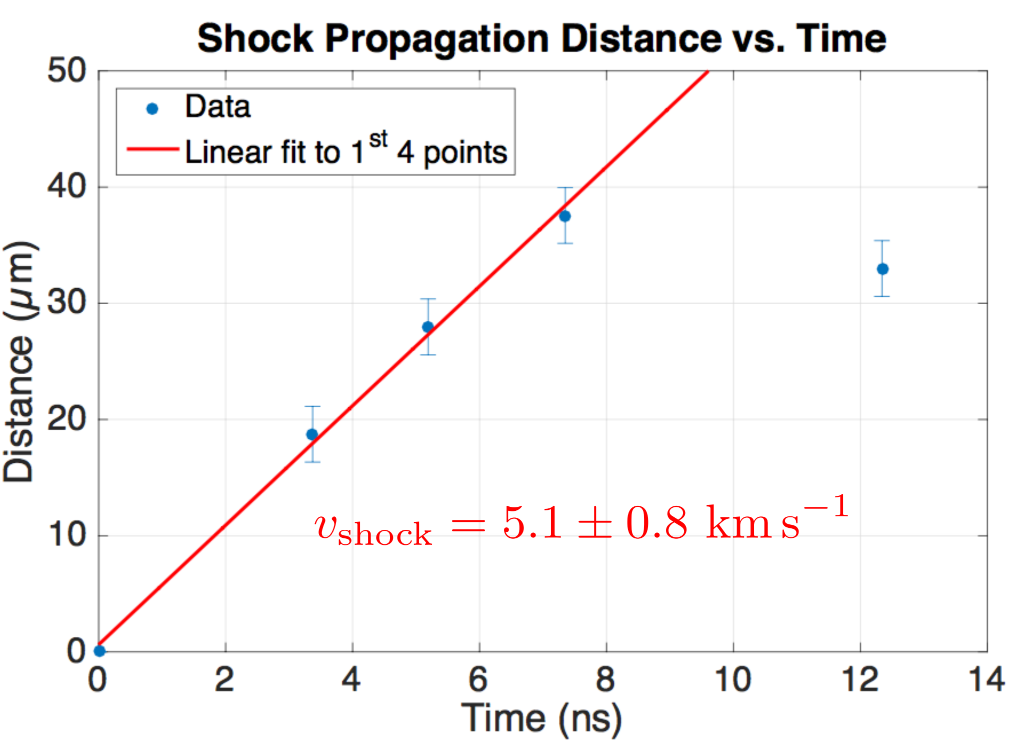
- Recent results on Astra Gemini using new f/40 geometry
  - Increase in e-ebeam energy to >2 GeV
  - Increase in X-ray photon numbers by x10 (to 3 x 10^{10} photons > 1 keV)

HEDP experiments: imaging shocks on the fly





J. Wood PhD thesis (submitted 2016)



- Initial "proof of principle" experiments indicate feasibility of directly measuring shock properties *inside* shocked target

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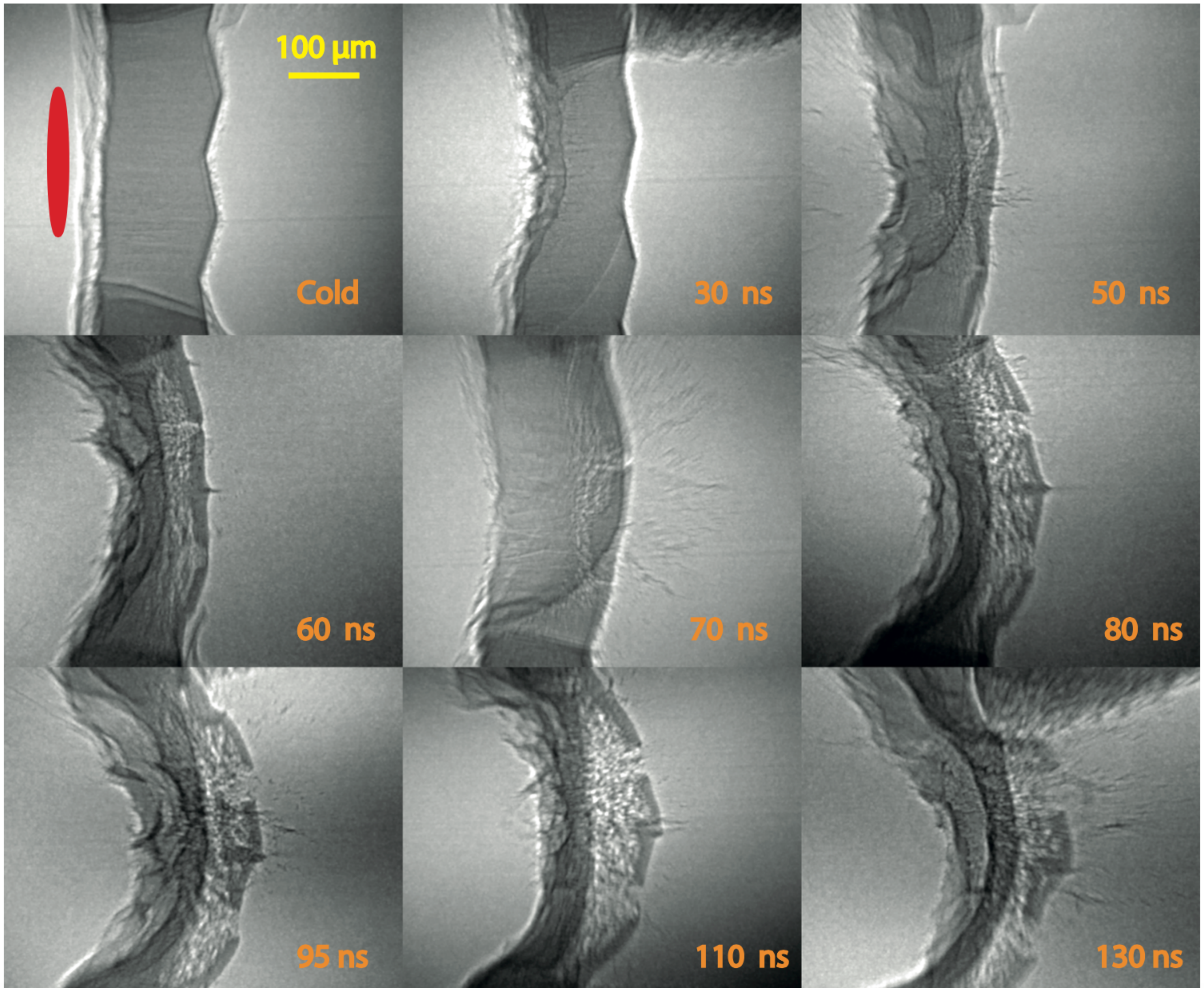
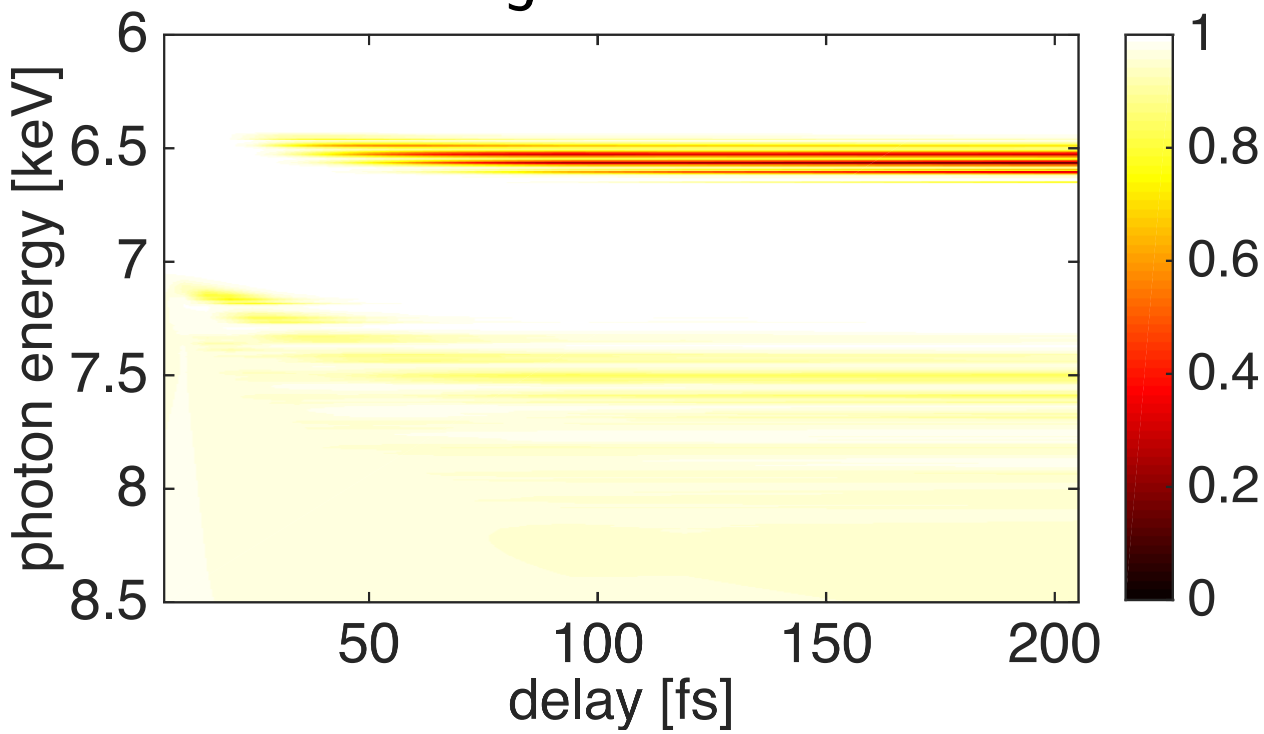


J. Wood PhD thesis (submitted 2016)

- Better shock driver (30 J, 30 ns)
- Enhanced betatron (10x more photons)
- Background mitigation (reducing Bremsstrahlung)
- Drastic improvement in image quality

HEDP experiments: ionisation dynamics of Hot Dense Matter

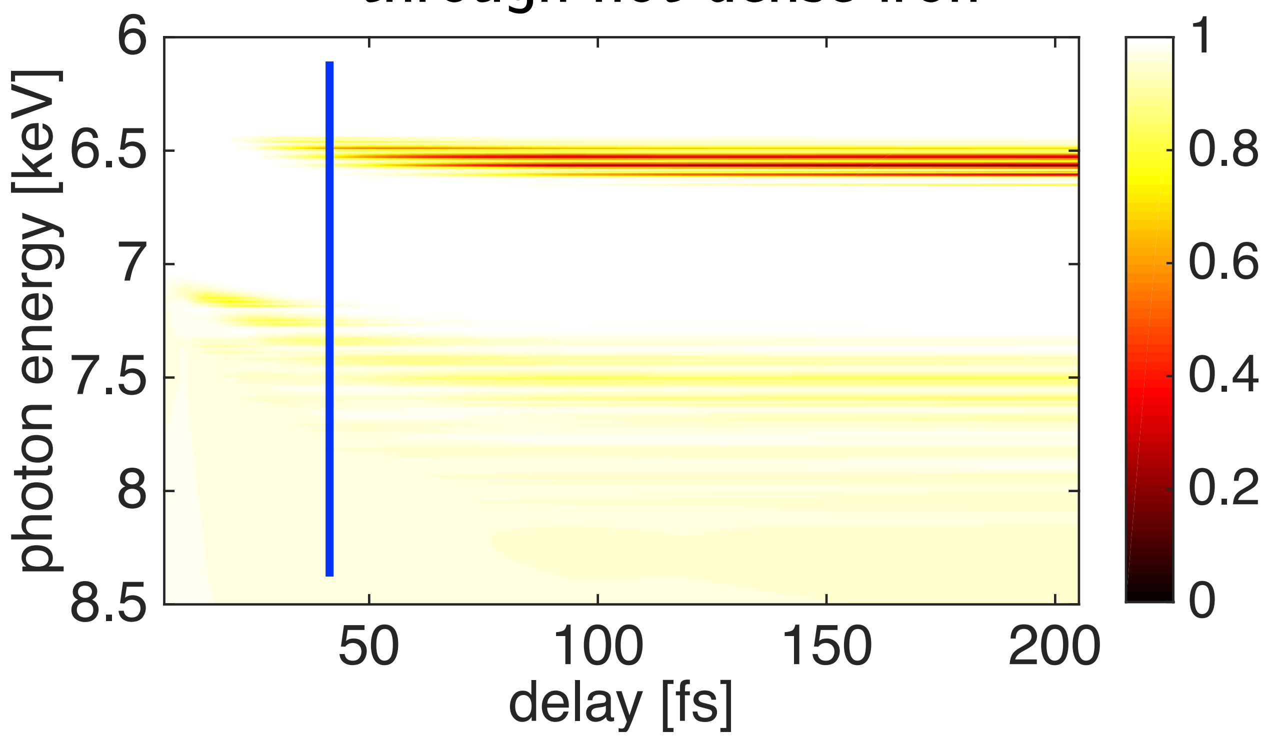


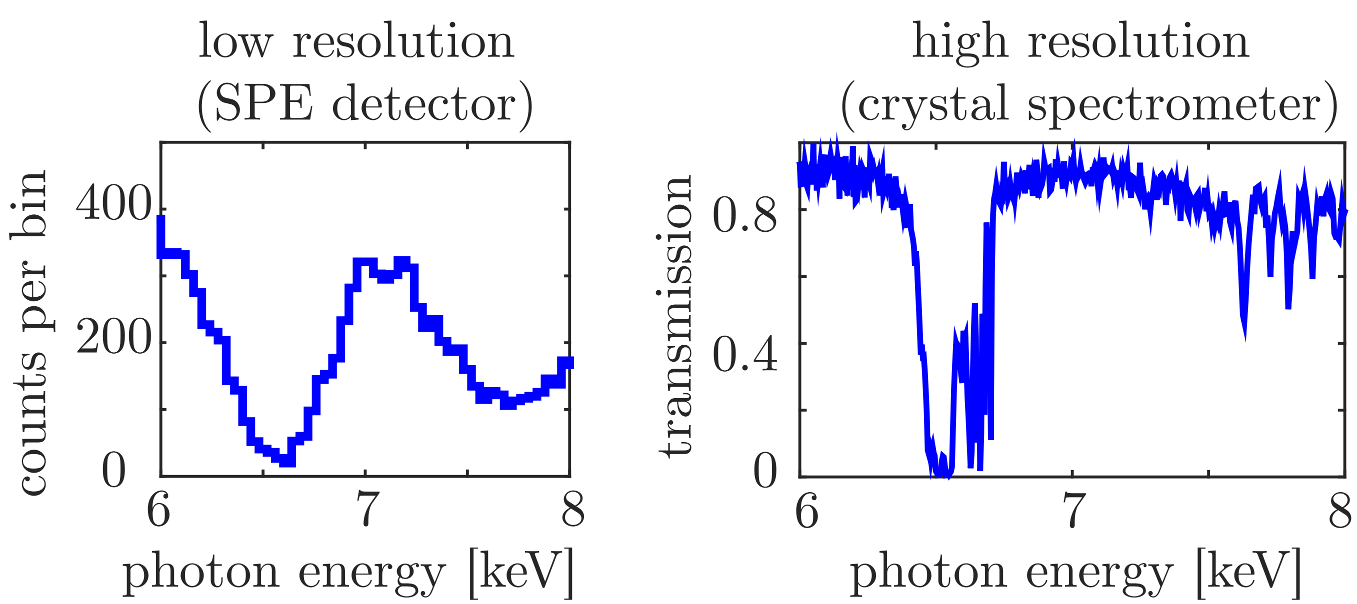
Example experiment 1:

- Rapid laser heating of iron to hot dense regime (1 g cm^{-3}, 500 eV)
- ***Femtosecond*** time-resolved ***X-ray absorption*** will reveal ionisation rates of inner shell electrons
  - Robust test of models used in astrophysics of solar interior

HEDP experiments: ionisation dynamics of Hot Dense Matter

predicted evolution of X-ray transmission through hot dense iron





predicted experimental measurements

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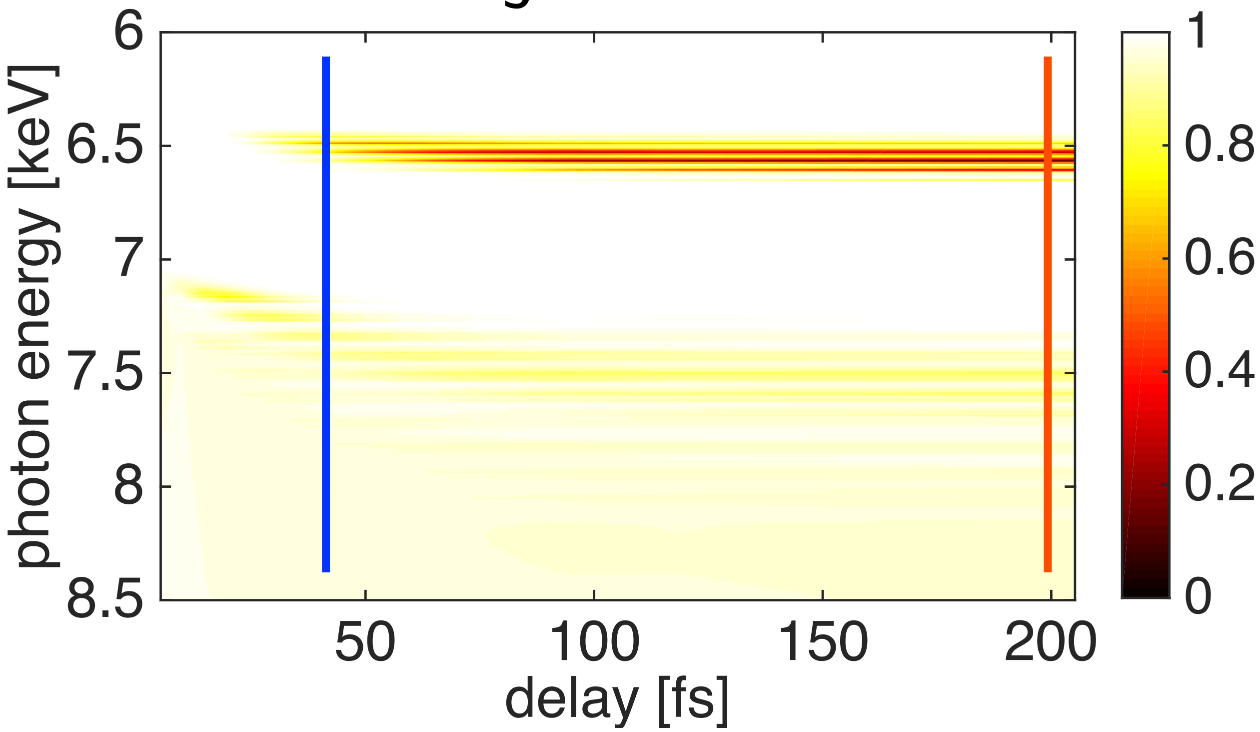

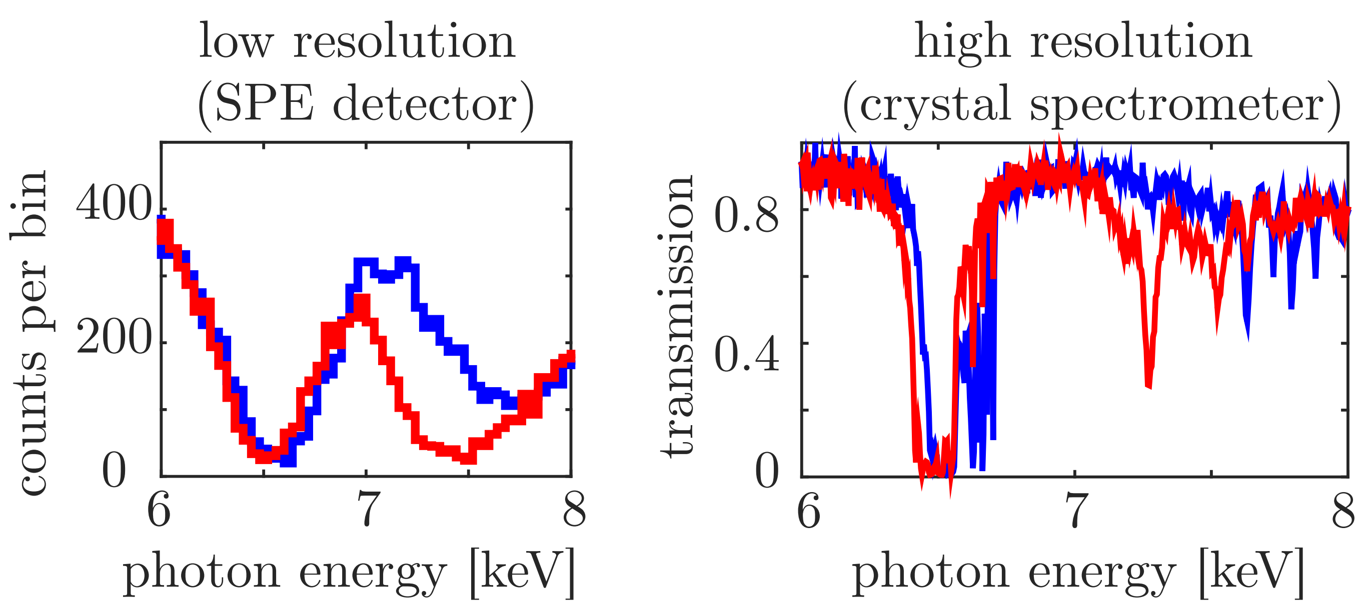

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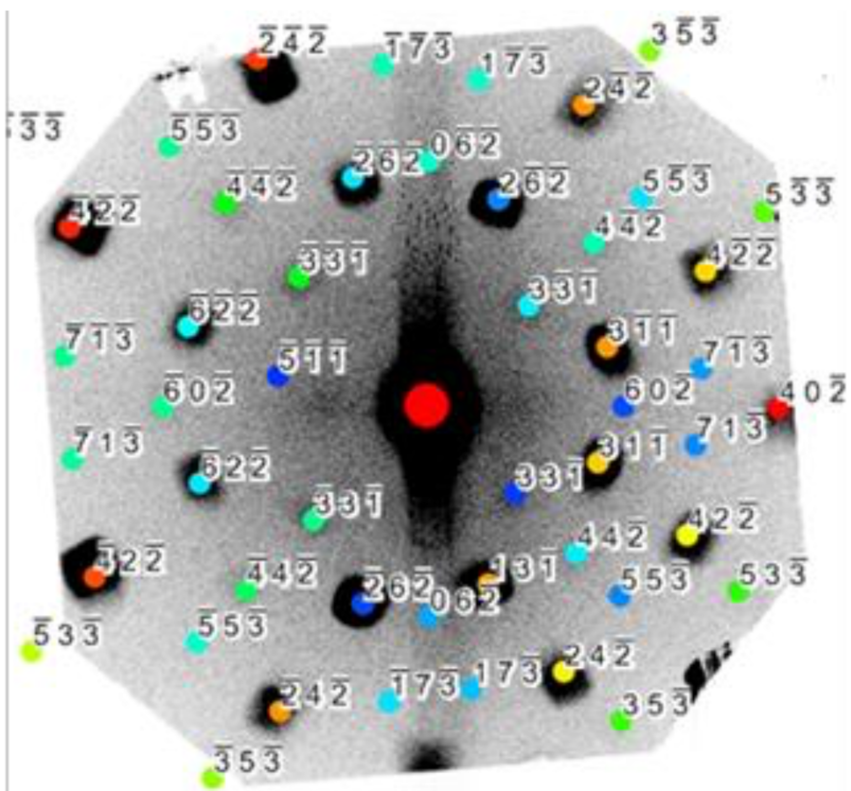
HEDP experiments: Probing lattice changes with time resolved X-ray diffraction



In-house Laue diffraction from LiF X-rays from Mo X-pinch*.

The spectral photon flux (photons per eV per mrad^2) delivered by the betatron source is an order of magnitude more than the X-pinch source

*courtesy Simon Bland

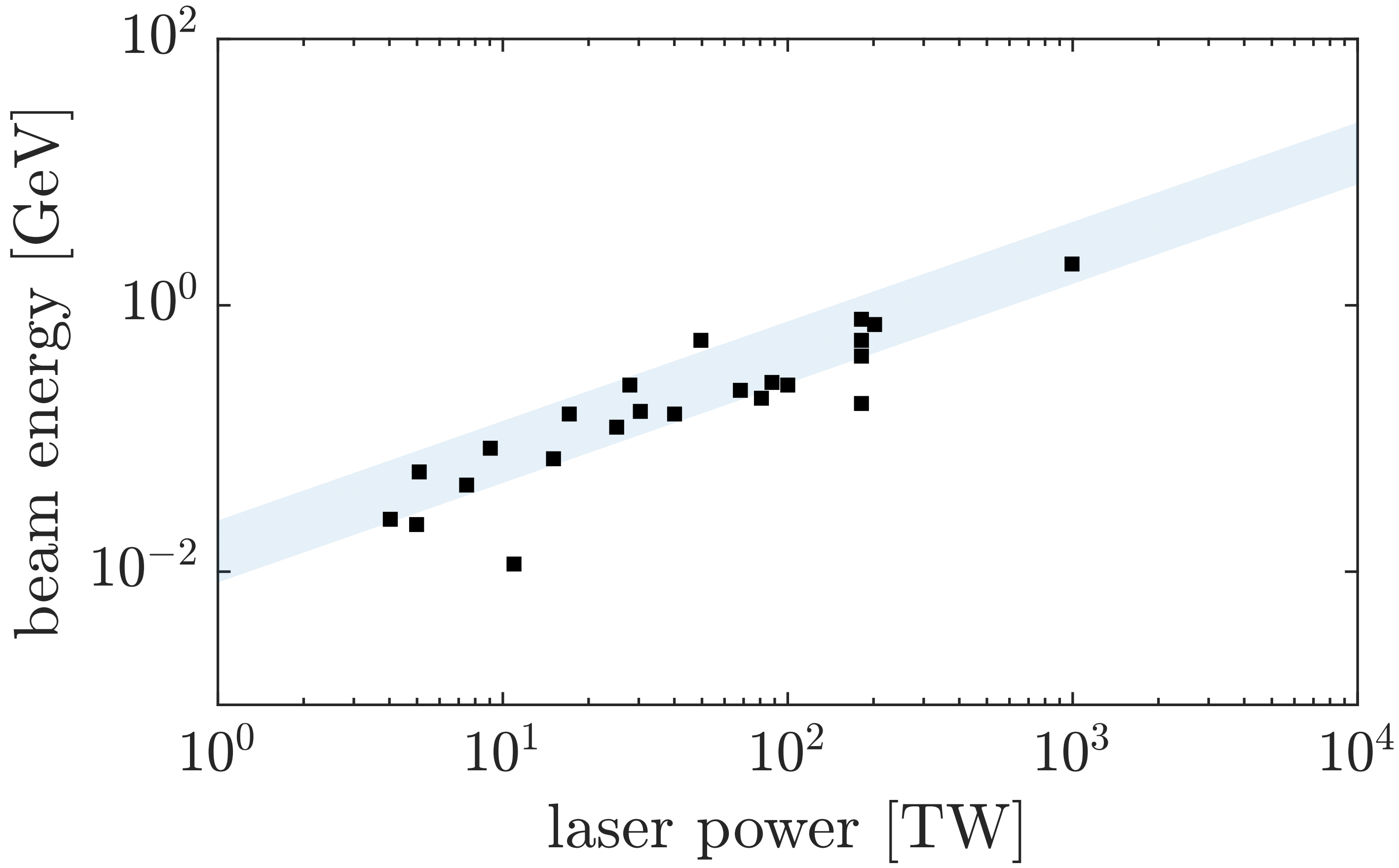
- White light Laue can be used to probe lattice level changes
  - e.g rapid change from BCC to HCP structure in Fe for pressures > 13 GPa
  - simulations suggest phase change occurs on picosecond timescale
  - experiments* have shown (detector resolution limited) timescale of 1 - 4 ns
- Can we do White Light Laue with betatron radiation?

*Kalantar, et al, Phys. Rev. Lett.(2005), Jensen et al., J. Appl. Phys. (2009)

Experimental requirements for performing HEDP experiments

- HEDP drivers
  - laser heater beam (short pulse): $E > 1$ J; $t = 30$ fs
  - laser shock driver (nano-second long pulse): $E > 10$ J $t > 10$ ns
  - synchronised with LWFA drive beam
- Photon source requirements
  - More photons (= high energy high charge e-beams)
- Background...
  - significant background from bremsstrahlung due to electron beam needs dealing with! better if electron beams are "clean" (no low energy tail)
  - self-emission from plasma
- Targets
  - match to repetition rate of Eupraxia...

Extending self-guiding accesses higher beam energy



- Self guiding, self-injection experiments follow scaling law

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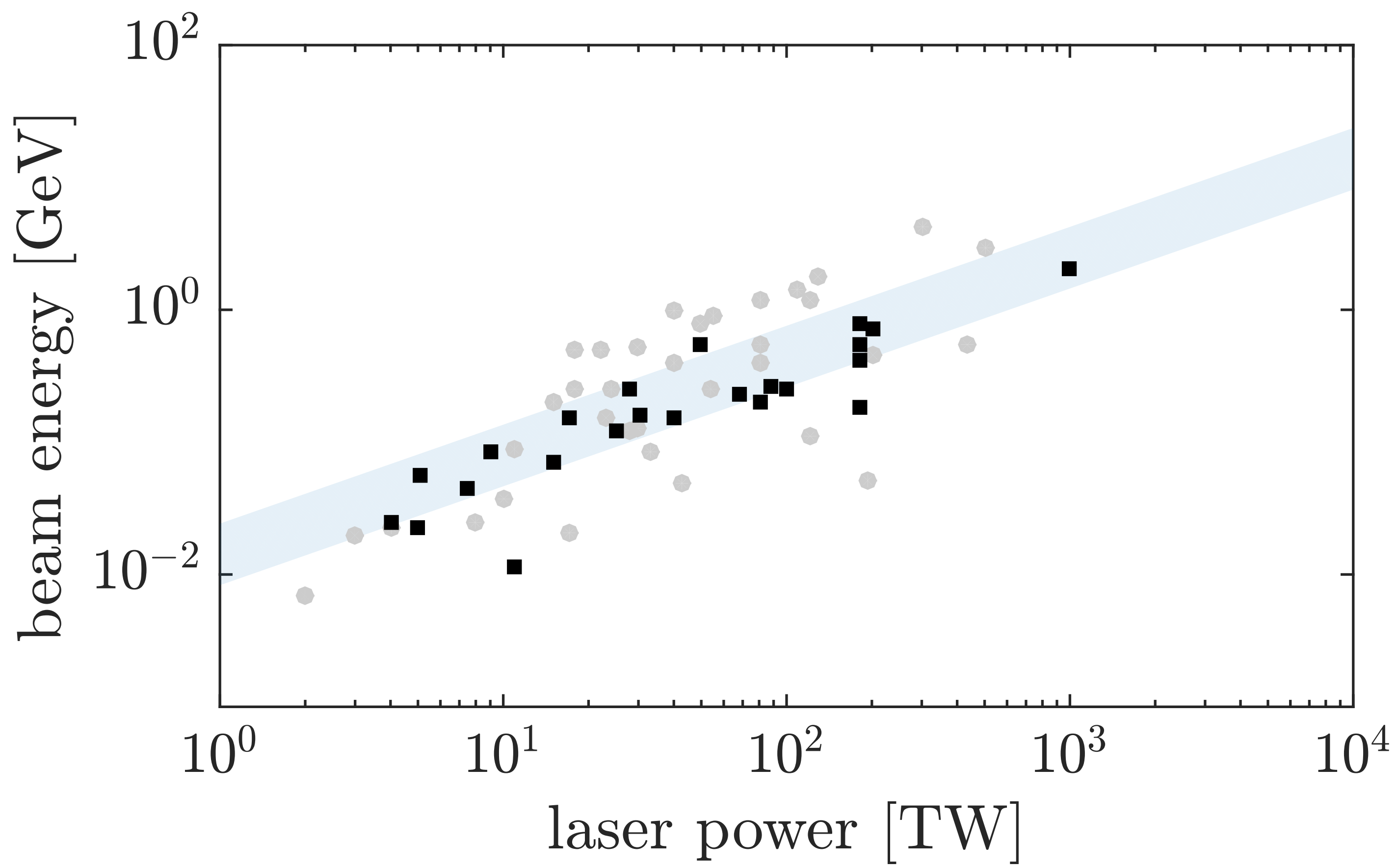

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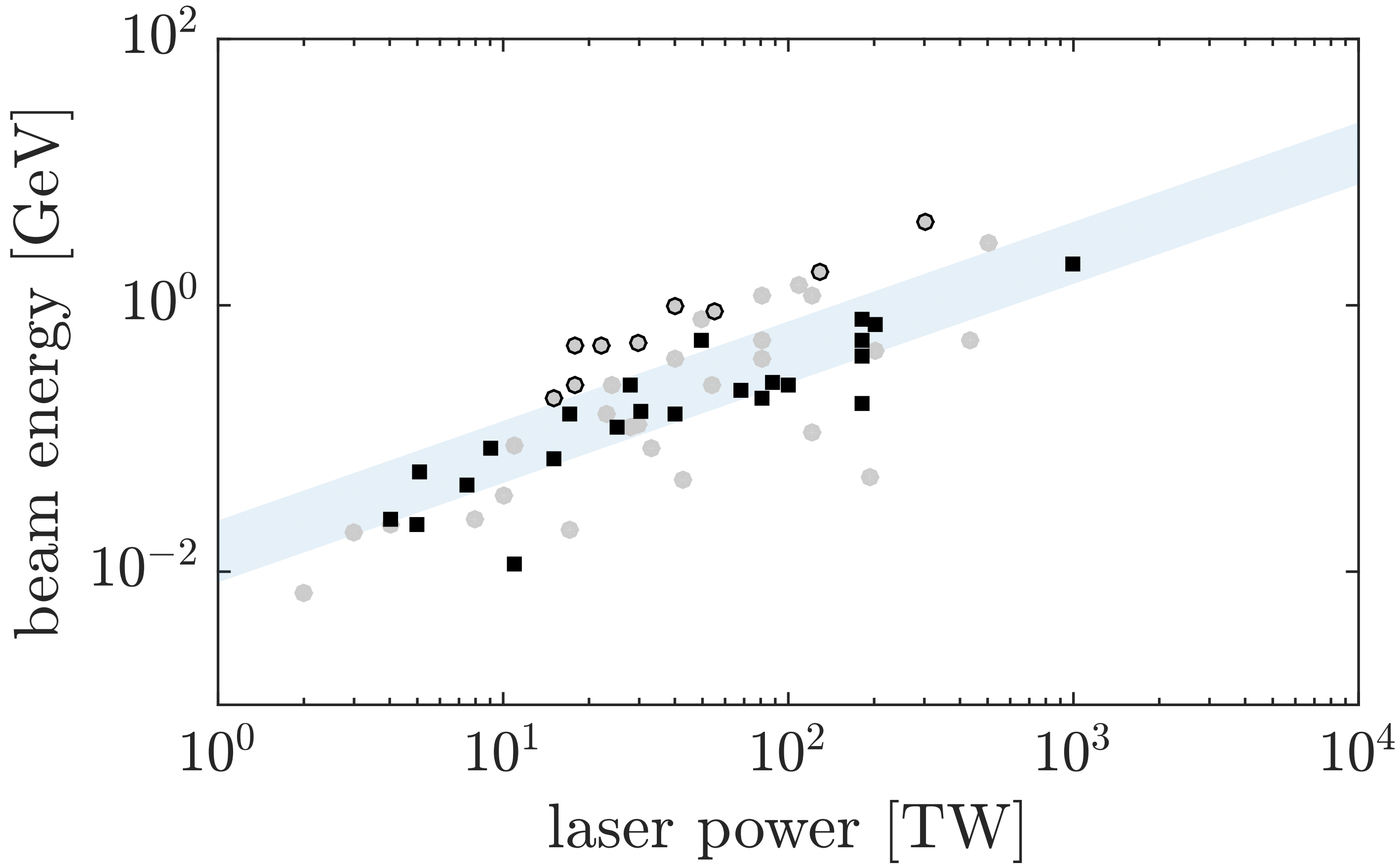

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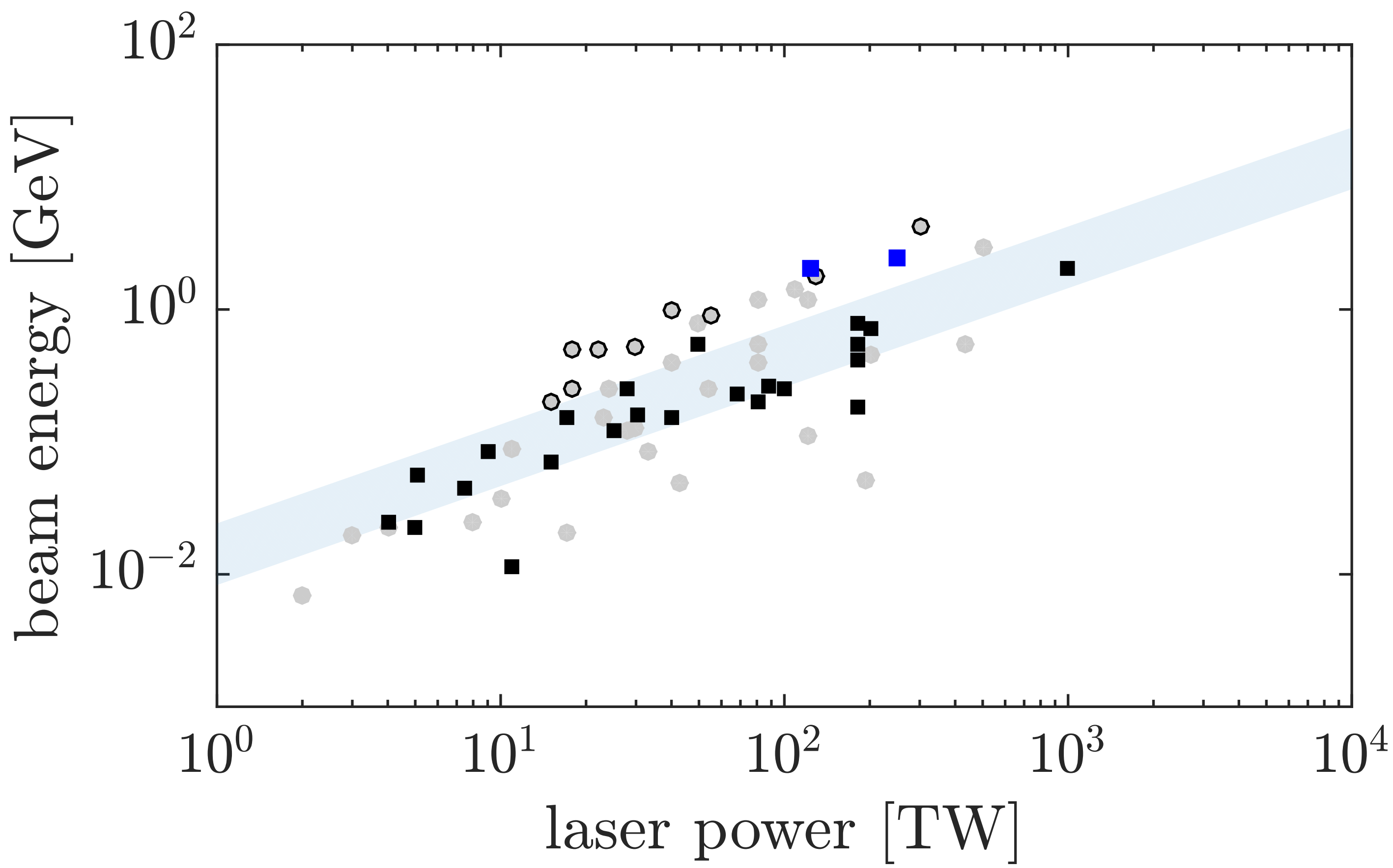

- self-guiding, self-injection experiments follow scaling law
- non-self injection/ non-self guiding can beat this scaling law
- capillary guided experiments beat scaling law
- 2015 Gemini results (f/40, self-guiding, self-injection) beat scaling law