



Laser-Plasma Applications III: Nuclear activation beyond the Giant Dipole Resonance

Aarón Alejo

Photoreactions

Reaction	$10^{10} \times \text{Yield, C}^{-1}$		
	Experiment	CMPNR	TALYS
(γ , p)			
(γ , 2n)			
(γ , 3n)			
(γ , 4n)			
(γ , 4n1p) _m			
(γ , 5n)			
(γ , 5n1p)			
(γ , 6n)			

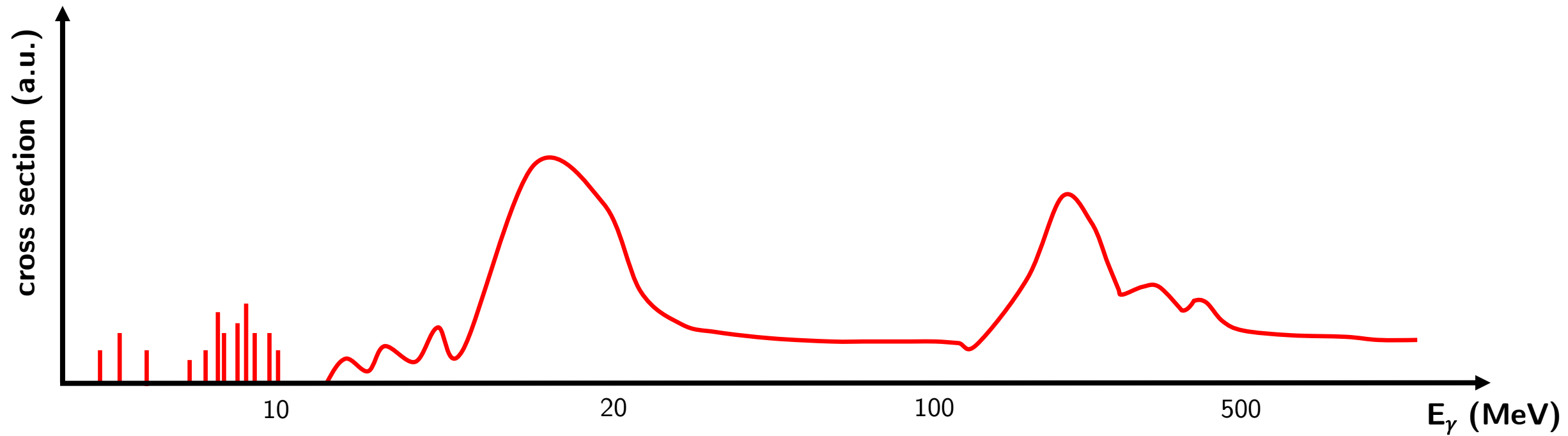
Photoreactions: Mechanisms



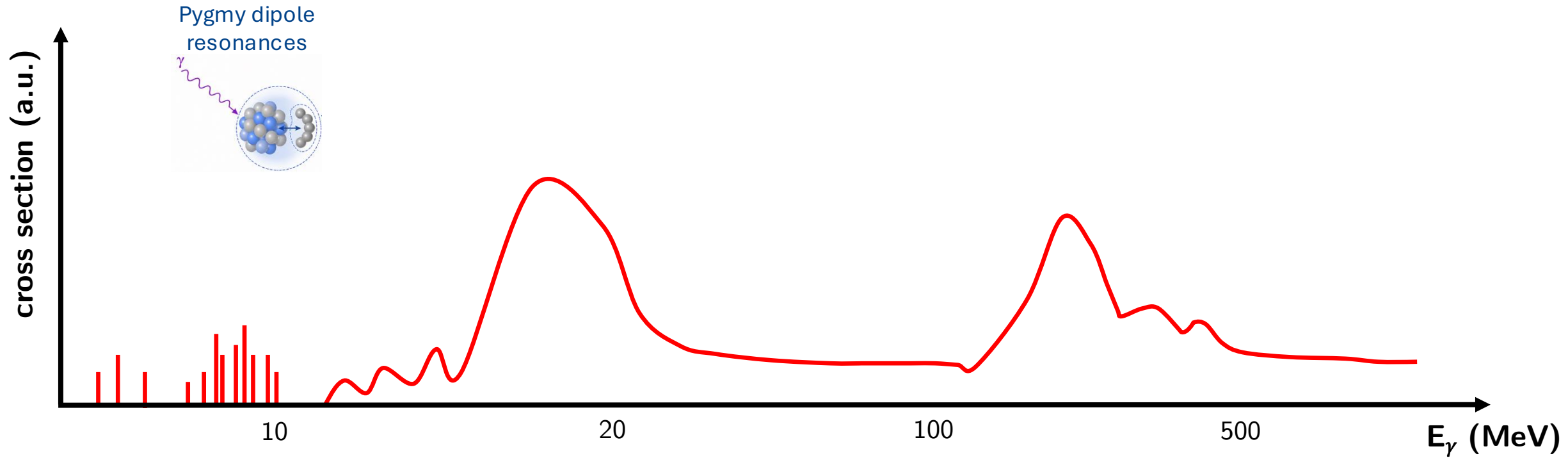
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Photoreactions: Mechanisms



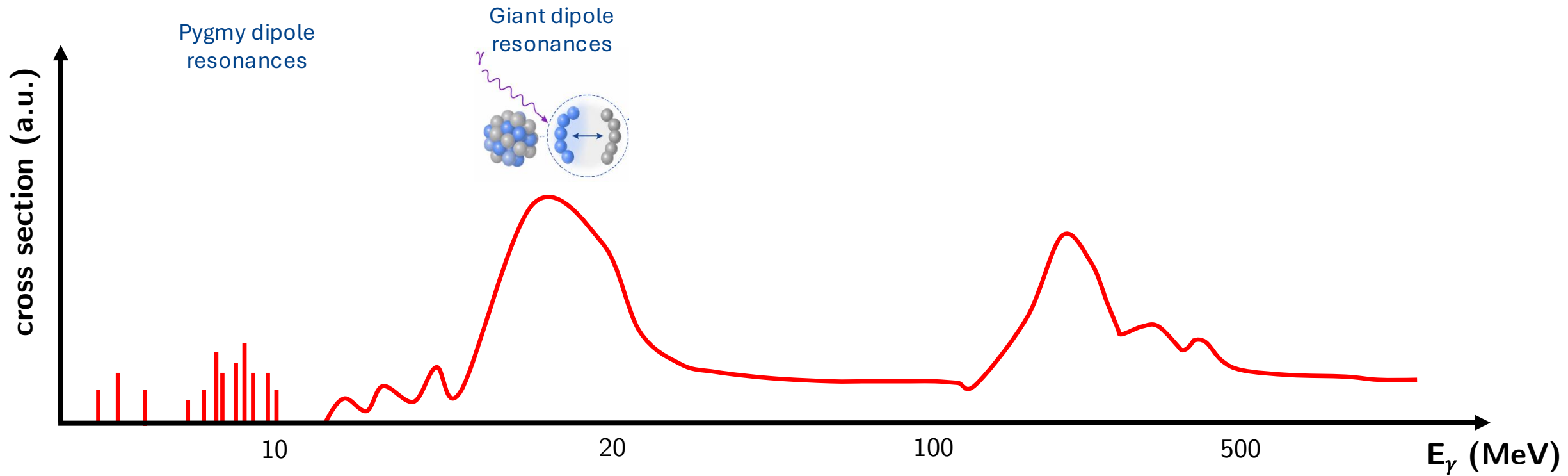
Pygmy dipole resonances

An '*out-of-phase*' oscillation of the excess neutron skin against the saturated $N=Z$ nuclear core.

- Sensitive to the neutron equation of state (EOS).
- Prominent in exotic neutron-rich nuclei.

Crucial for stellar nucleosynthesis and r-process neutron capture rates.

Photoreactions: Mechanisms



Giant dipole resonance

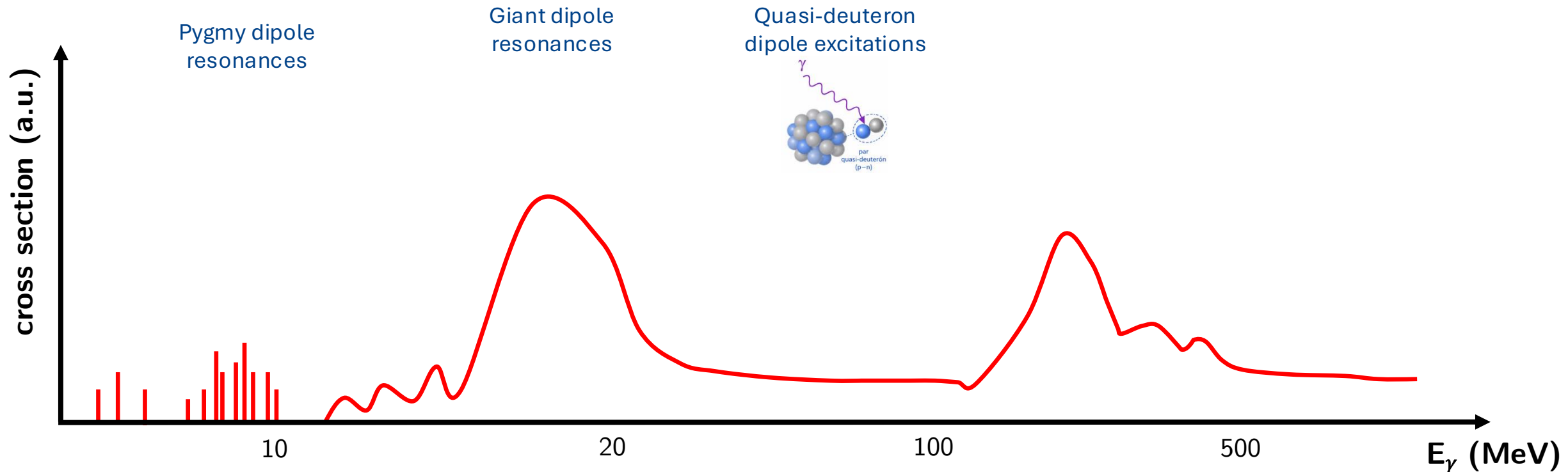
Envisages all protons oscillating collectively in opposition of phase against all neutrons.

→ Restoring force provided by the nuclear symmetry energy.

→ Energy scales roughly as $E_{\text{GDR}} \approx 77 A^{-1/3} \text{ MeV}$ ($\lambda \sim 10\text{s of fm}$)

Provides a sensitive probe of nuclear deformation and collective structure.

Photoreactions: Mechanisms



Quasi-deuteron dipole (Levinger Model)

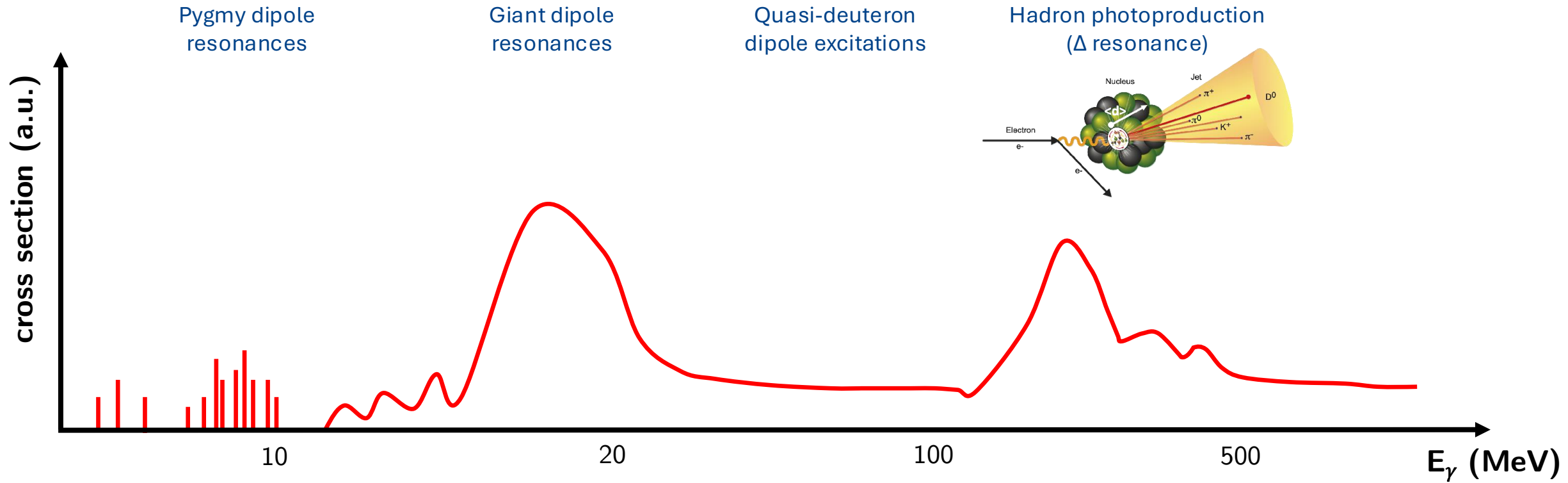
At 30 MeV - 140 MeV, the photon wavelength becomes smaller than the nuclear radius ($\lambda < R$)

→ The photon can no longer see the nucleus as a whole.

→ Interacts locally with strongly correlated nucleon pairs (neutron-proton pairs).

Cross section is proportional to the number of n-p pairs inside the nucleus: $\sigma_{QD} = L \cdot (N \cdot Z / A) \sigma_{fd}$

Photoreactions: Mechanisms



Hadron photoproduction Transition from collective nuclear physics to individual nucleon/quark degrees of freedom: Photon interacts directly with a single bound nucleon.

→ The photon excites a nucleon into its lowest baryonic resonance state: $\Delta(1232)$ isobar



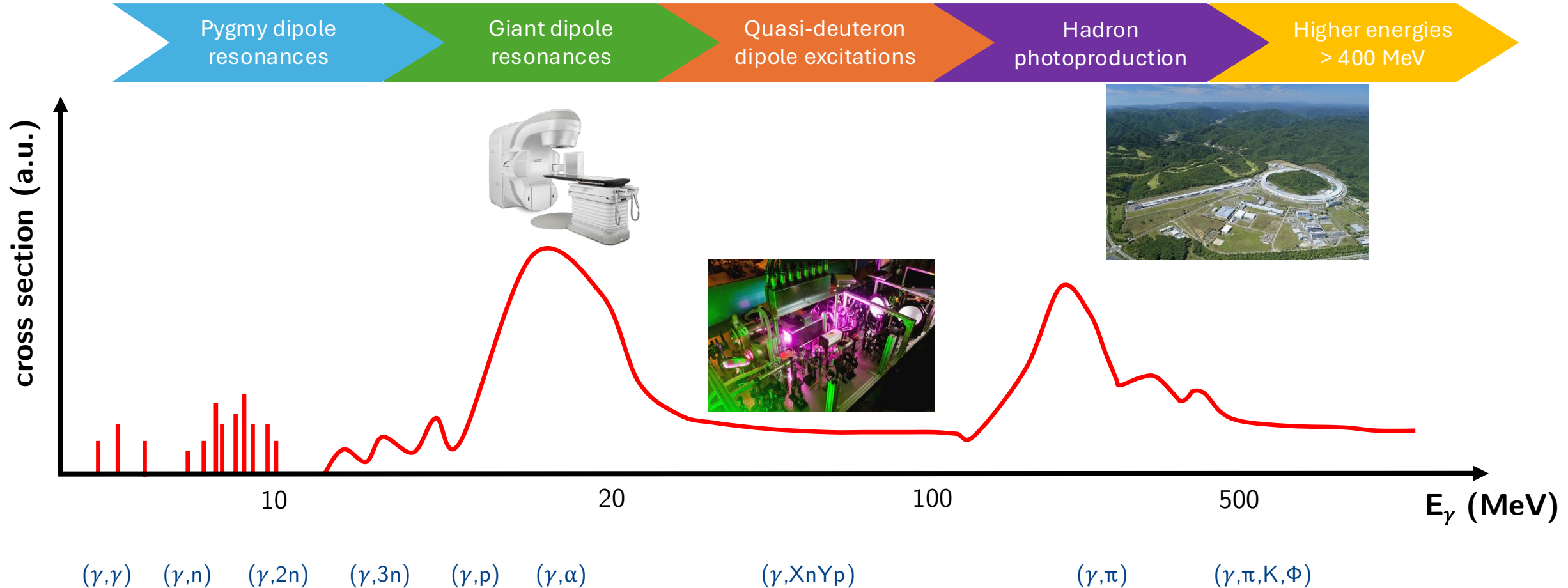
Photoreactions



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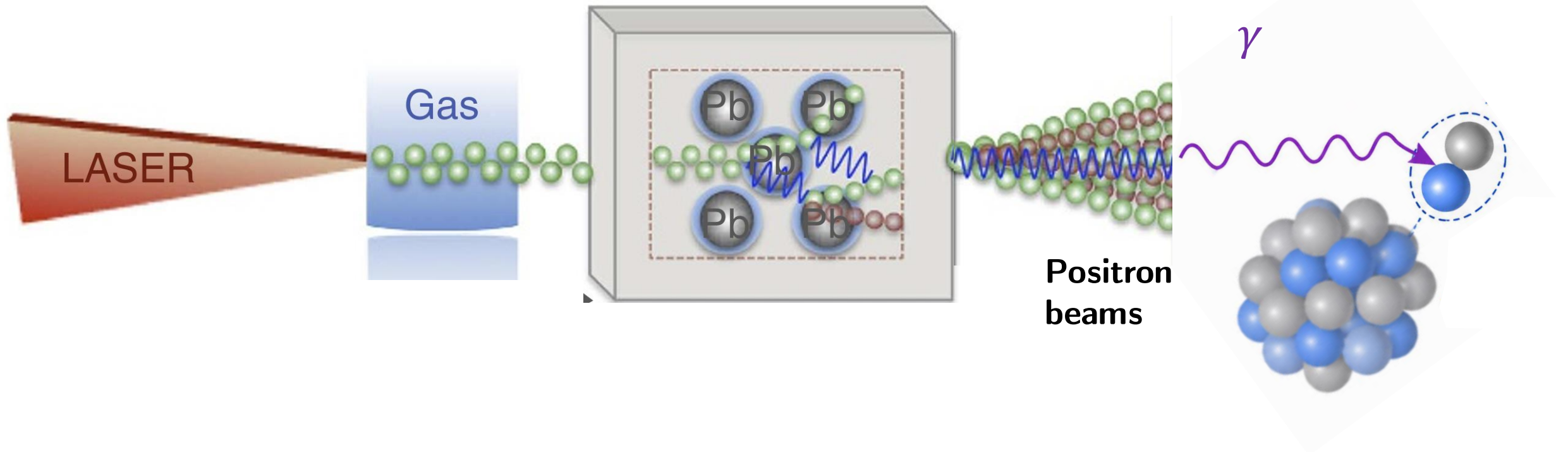


What would this experiment look like?

Electron
acceleration

High-energy photons:
Bremsstrahlung

Studying photoreactions
in the lab



- Electron acceleration
- Producing high-energy photons: Bremsstrahlung & QED cascades
 - Laser-driven positron sources
- Studying photoreactions in the lab



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Laser-driven electron acceleration

Laser wakefield acceleration



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Laser wakefield acceleration



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Linear wake wave →

Laser wakefield acceleration



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Non-linear wake wave

Laser wakefield acceleration



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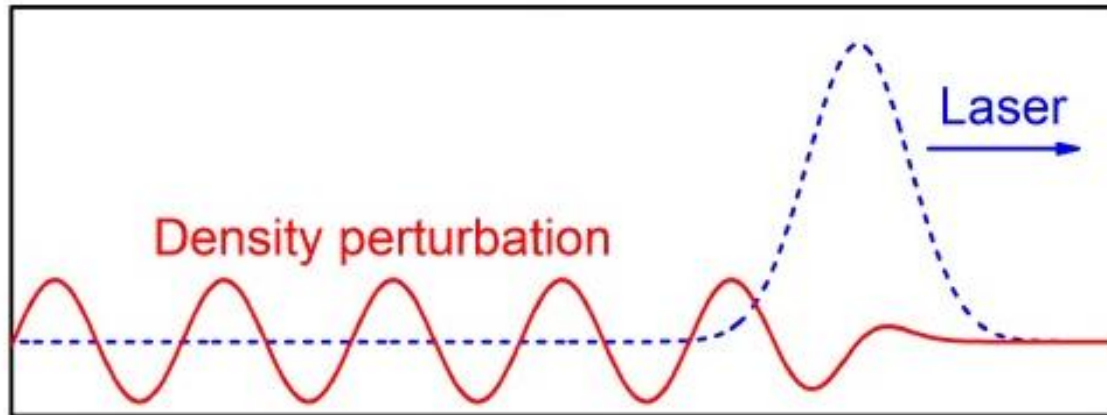
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Wake-surfing

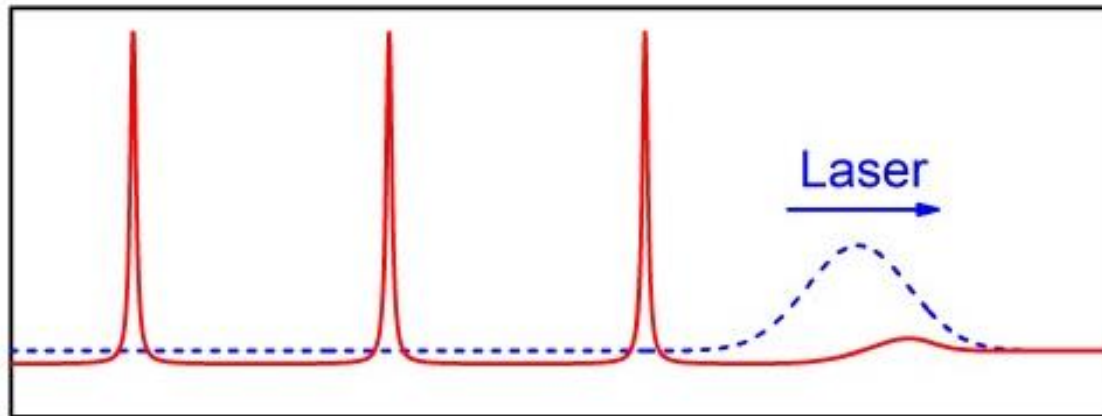


Laser wakefield acceleration



Linear Regime

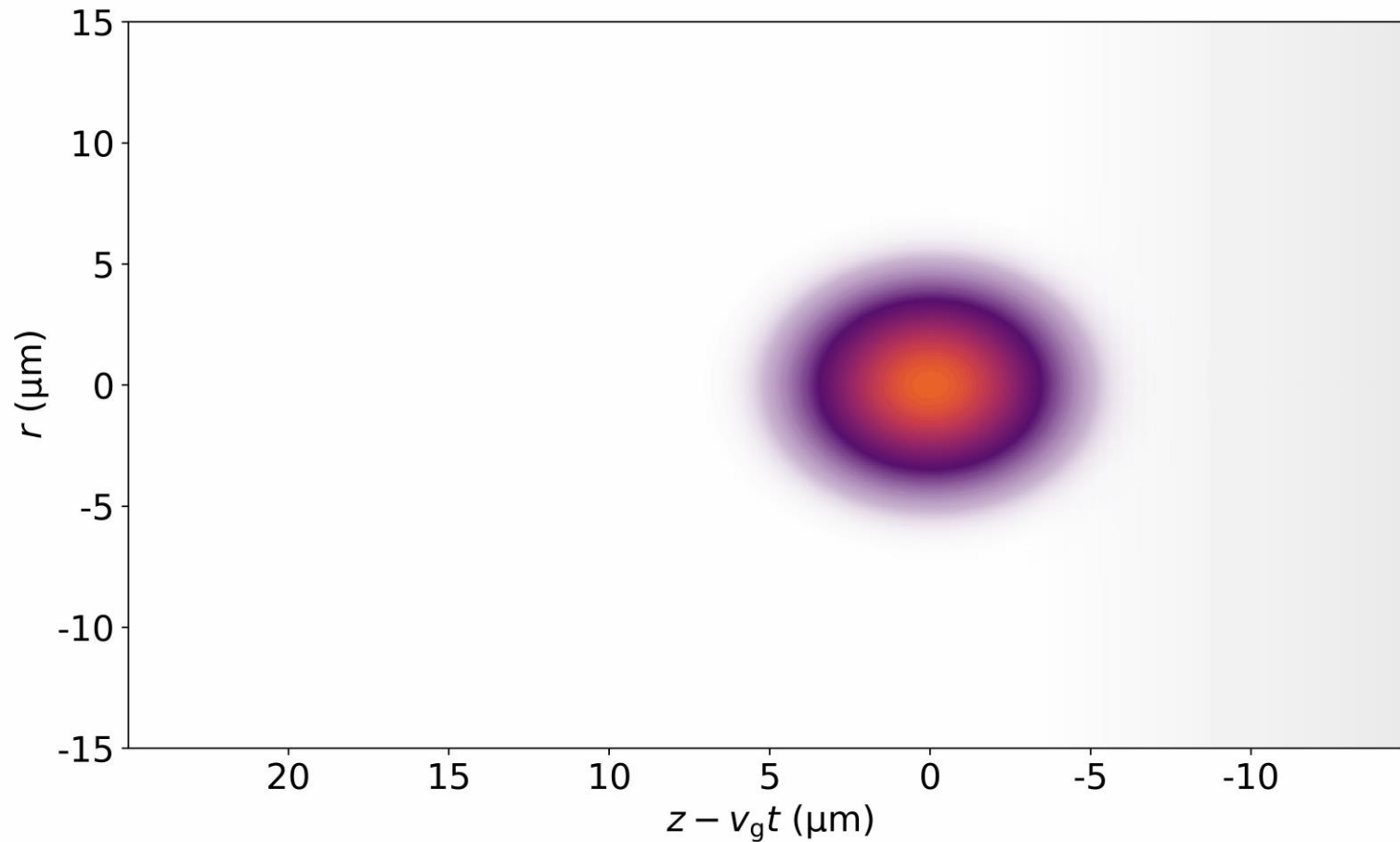
- Laser intensity $10^{16} \leq I \text{ (W cm}^{-2}\text{)} \leq 10^{18}$
- Linear plasma wave
- Small accelerating fields, stable process



Non-Linear Regime

- Relativistic intensities: $I \text{ (W cm}^{-2}\text{)} > 10^{18}$
- Non-linear regime: wave-breaking instability
- Strong accelerating fields: $E_z \sim 1 \text{ GV cm}^{-1}$

Bubble regime



Bubble regime

- Ponderomotive force *kicks* electrons out
- Ions remain immobile $\Rightarrow$ An ion cavity appears behind the pulse
- Electrons attracted by the ions $\Rightarrow$ bubble-like structure of electrons surrounding the cavity
- Charge-separation field appears capable of **accelerating electrons inside the bubble.**

The dream: a 10 GeV stage

→ Great interest in a stable, 10-GeV electron stage, with applications such as bright γ -ray sources, free electron lasers, or future colliders

→ Scaling laws indicate that the energy gain per stage can be optimized by

1. Decreasing plasma density

$$\Delta W \propto n_e^{-1}$$

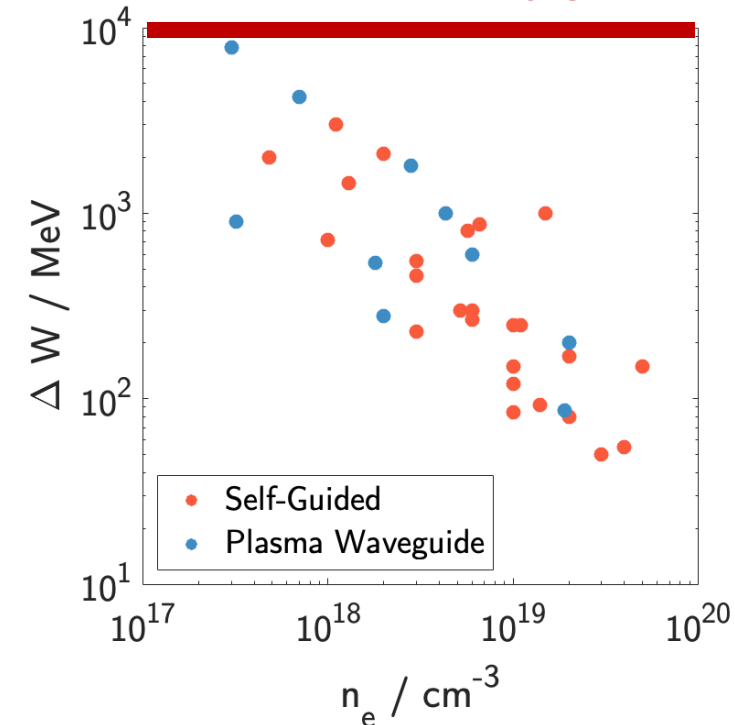
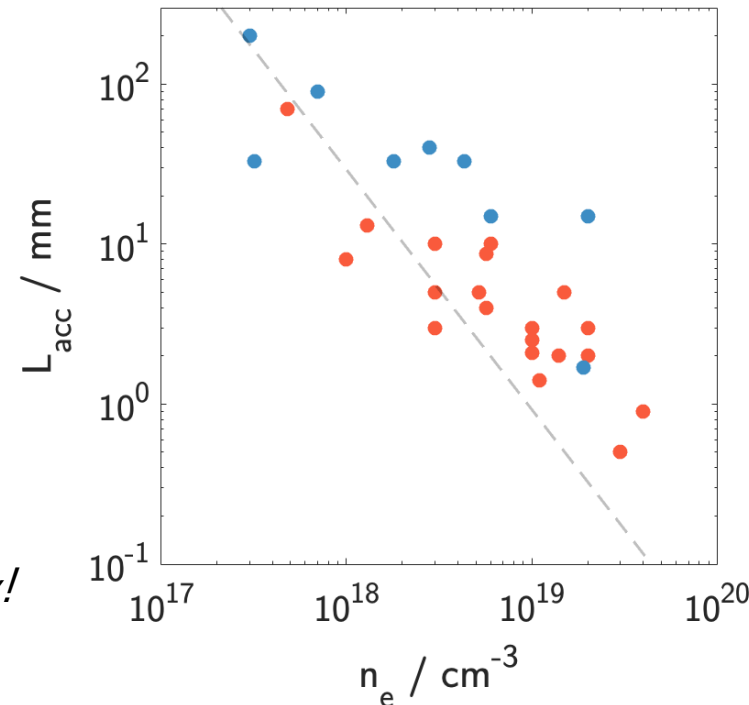
2. Increasing stage length

$$L_{\text{acc}} \propto n_e^{-3/2}$$

also, larger spot size $\Rightarrow$ higher laser energy!

Experimental Scalings since the
“Dream Beam” papers in 2004

10GeV



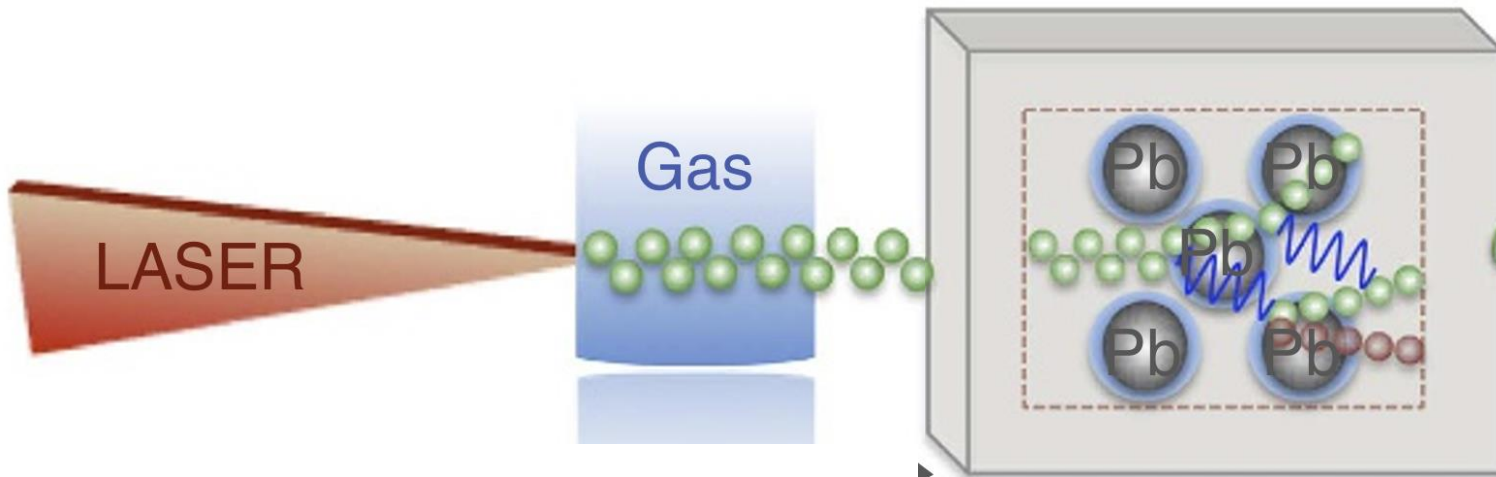


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Bremsstrahlung sources & QED cascades



Bremsstrahlung radiation

Radiation produced when a relativistic charged particle is deflected in the Coulomb field of an atomic nucleus.

→ Radiation cross-section scales quadratically with atomic number (Z^2)

→ Broad, continuous photon energy spectrum extending up to the maximum kinetic energy of the incident electron beam.

LD bremsstrahlung sources



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Ultrashort duration

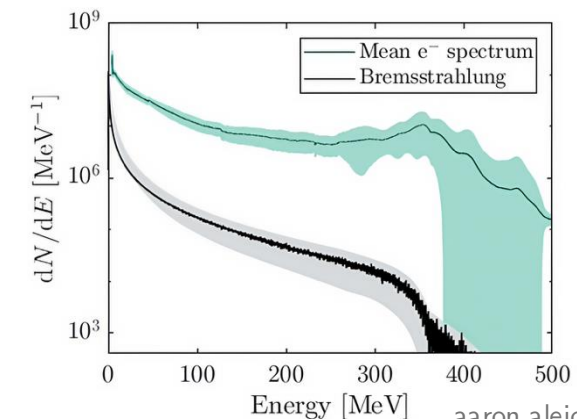
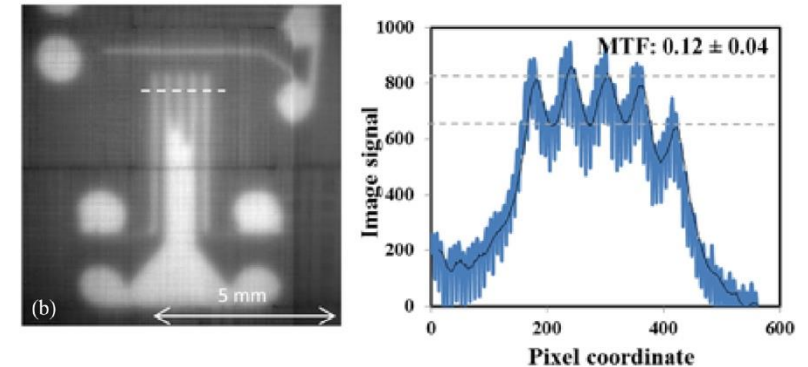
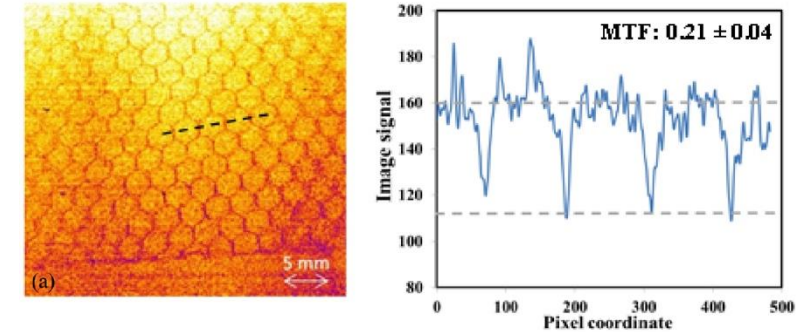
The X-ray pulse duration is related to the electron bunch duration, on the order of that of the laser pulse: **typically sub-ps**

Small source size

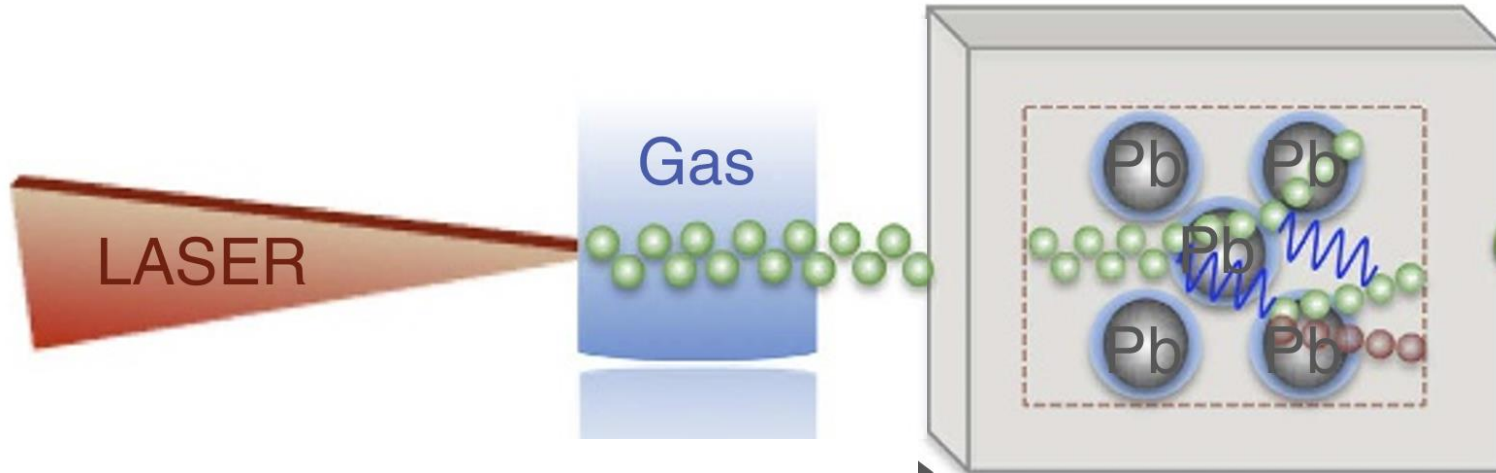
The quality and resolution of a radiography depends directly on the source size of the X-ray beam: **micrometer-scale source**

High energy

Photon energy spectrum extending up to the maximum kinetic energy of the incident electron beam, up to **GeV-scale** for LWFA electrons.

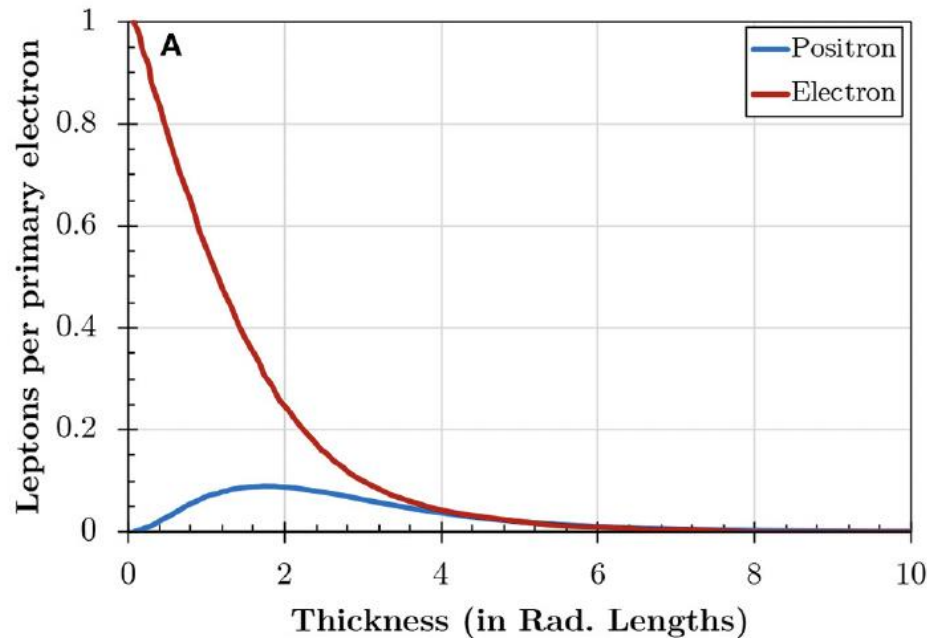


QED Cascades



QED Cascade

Feedback loops of
electron radiation $\rightarrow \gamma$ emission $\rightarrow$ pair creation.



$$\frac{\partial f_{\pm}}{\partial \ell} = - \int_0^1 dv \psi_{\text{rad}}(v) \left[f_{\pm}(E, \ell) - \frac{1}{1-v} f_{\pm}\left(\frac{E}{1-v}, \ell\right) \right] + \int_0^1 \frac{dv}{v} \psi_{\text{pair}}(v) f_{\gamma}\left(\frac{E}{v}, \ell\right),$$

$$\frac{\partial f_{\gamma}}{\partial \ell} = \int_0^1 \frac{dv}{v} \psi_{\text{rad}}(v) \left[f_{-}\left(\frac{E}{v}, \ell\right) + f_{+}\left(\frac{E}{v}, \ell\right) \right] - \mu_0 f_{\gamma}(E, \ell),$$



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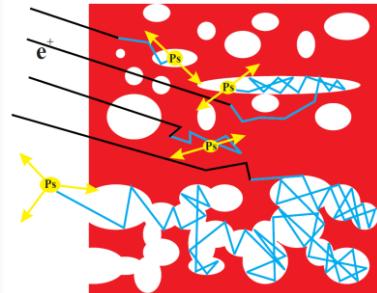
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Laser-driven positron sources

Laser-driven positron beams

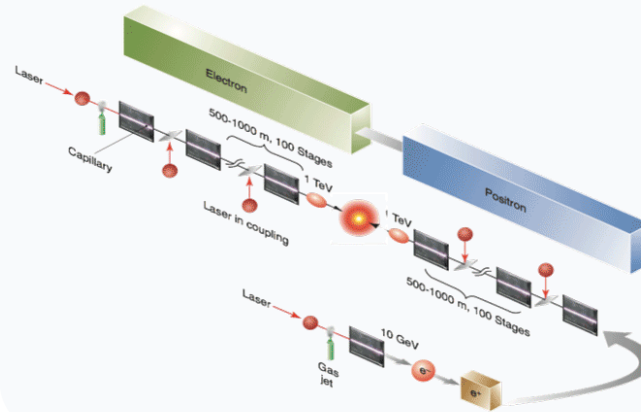
PALS

Positron annihilation lifetime spectroscopy is a technique for material characterisation based on the different lifetime of ortho- and para-positronium (0.12 ns vs 142 ns)



Colliders

Studies towards a plasma-based e-p collider, including the positron source. (ALLEGRO)



Astro in Lab

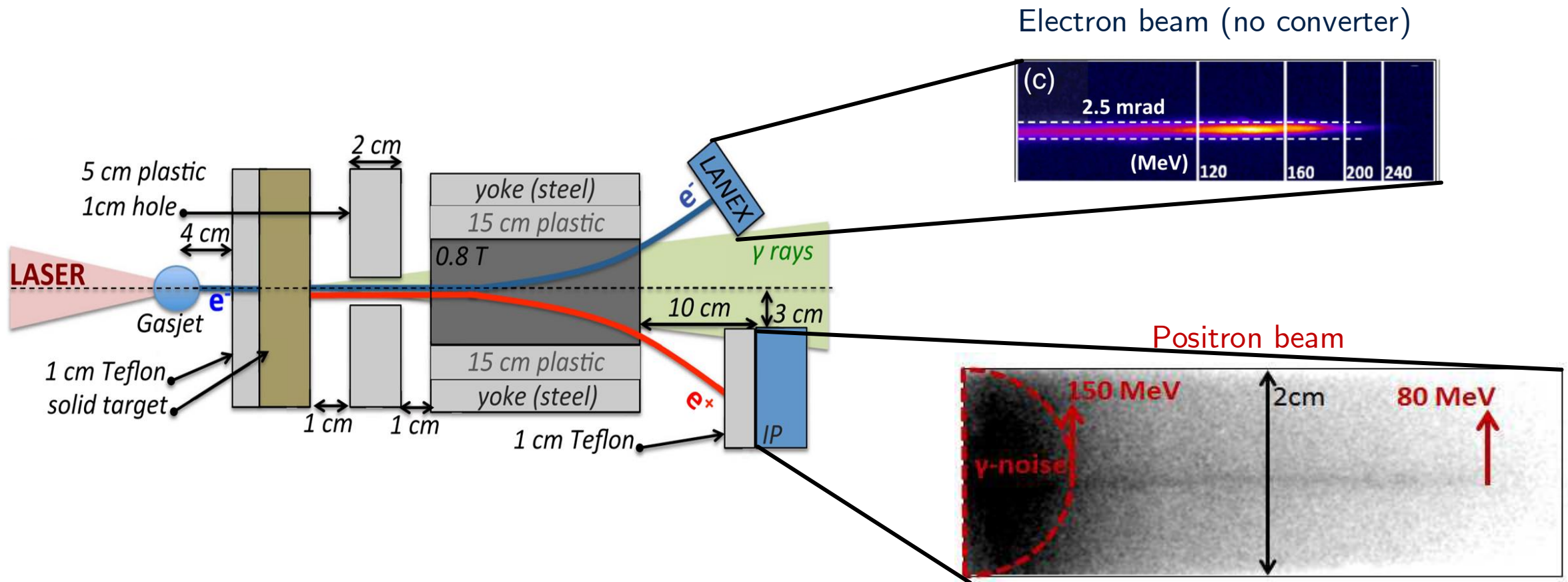
Electron-positron plasmas are suspected to play a critical role in astrophysical phenomena, including electron-positron jets.



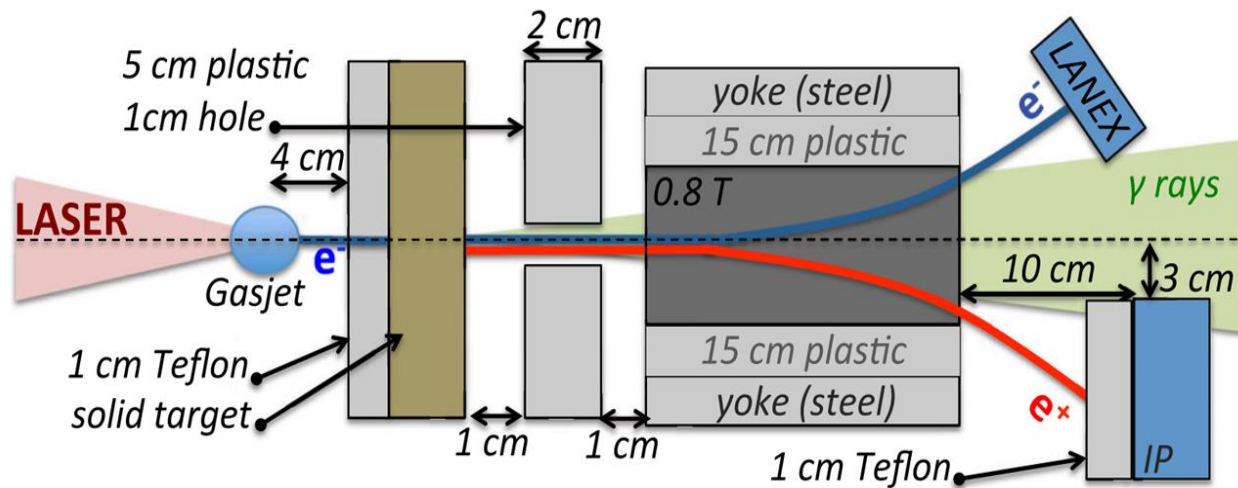
	References	Laser facility	Laser params	Positron yield (e^+ /shot)	Average flux (e^+ /s)	Positron ratio
Solid	Chen et al. [85, 86]	Titan (LLNL)	$\lambda = 1054 \text{ nm}$, $\tau = 0.7 - 10 \text{ ps}$, $E_L = 120-250 \text{ J}$	$10^9 - 10^{10}$	5×10^6	1 – 5%*
	Chen et al. [99]	Orion	$\lambda = 1054 \text{ nm}$, $\tau = 0.7 - 10 \text{ ps}$, $E_L = 120-250 \text{ J}$	$10^{10} - 10^{11}$	1×10^7	1 – 5%*
	Chen et al. [87, 99]	Omega-EP (LLNL)	$\lambda = 1054 \text{ nm}$, $\tau = 10 \text{ ps}$, $E_L = 100-850 \text{ J}$	$10^{10} - 10^{12}$	2×10^7	1 – 5%*
	Liang et al. [100]	Texas PW	$\lambda = 1057 \text{ nm}$, $\tau = 130 - 245 \text{ fs}$, $E_L = 80-130 \text{ J}$	$10^8 - 10^{10}$	3×10^6	1 – 30%
Gas	Gahn et al. [91, 92]	Atlas (MPQ)	$\lambda = 790 \text{ nm}$, $\tau = 130 \text{ fs}$, $E_L = 0.22 \text{ J}$	10^6	1×10^7	< 1%
	Sarri et al. [90, 94]	Hercules (UMich)	$\lambda = 800 \text{ nm}$, $\tau = 30 \text{ fs}$, $E_L = 0.8 \text{ J}$	$10^5 - 10^7$	1×10^6	1 – 10%*
	Sarri et al. [95, 101]	Gemini (CLF)	$\lambda = 800 \text{ nm}$, $\tau = 38 - 46 \text{ fs}$, $E_L = 14 \text{ J}$	$10^7 - 10^8$	5×10^6	1 – 50%
	Xu et al. [96]	Shangai IOFM	$\lambda = 800 \text{ nm}$, $\tau = 45 \text{ fs}$, $E_L = 3.75 \text{ J}$	$10^5 - 10^6$	6×10^2	1 – 50%
Next-Gen	Alejo et al. [102]	EuPRAXIA-like (100 pC, 5 GeV)	-	3×10^9	3×10^{10}	1 – 50%
	Alejo et al. [102]	ELI NP-like (100 pC, 20 GeV)	-	5×10^9	5×10^9	1 – 50%

[A. Alejo et al., Frontiers in Physics 7, 49(2019)]

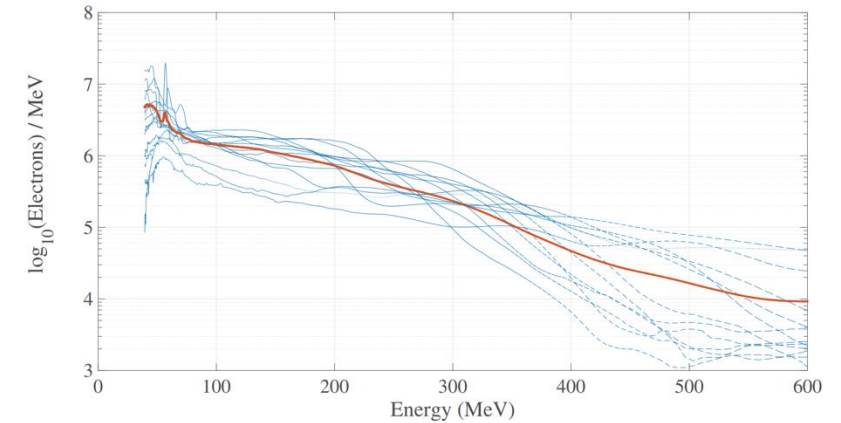
A typical experiment



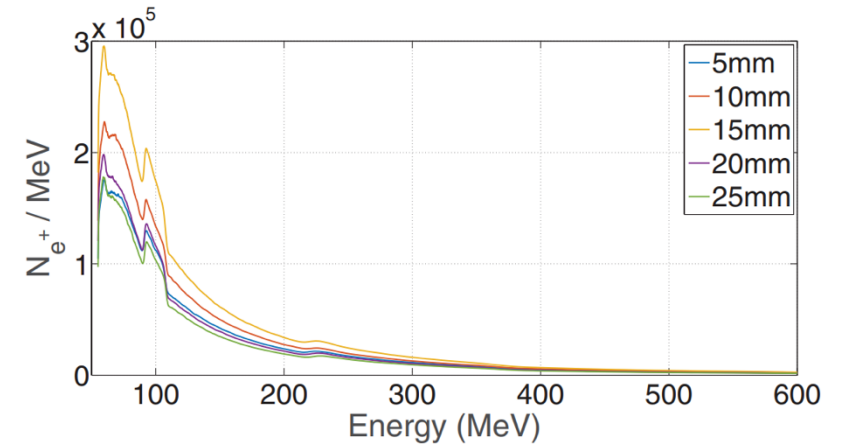
A typical experiment



Electron beam (no converter)



Positron beam

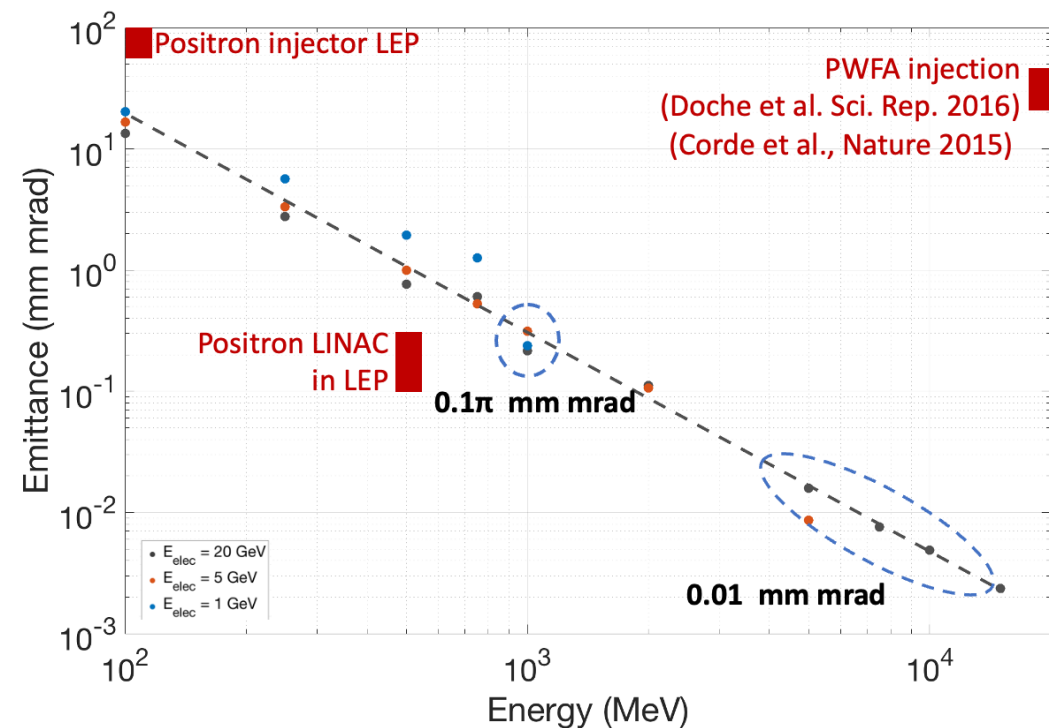
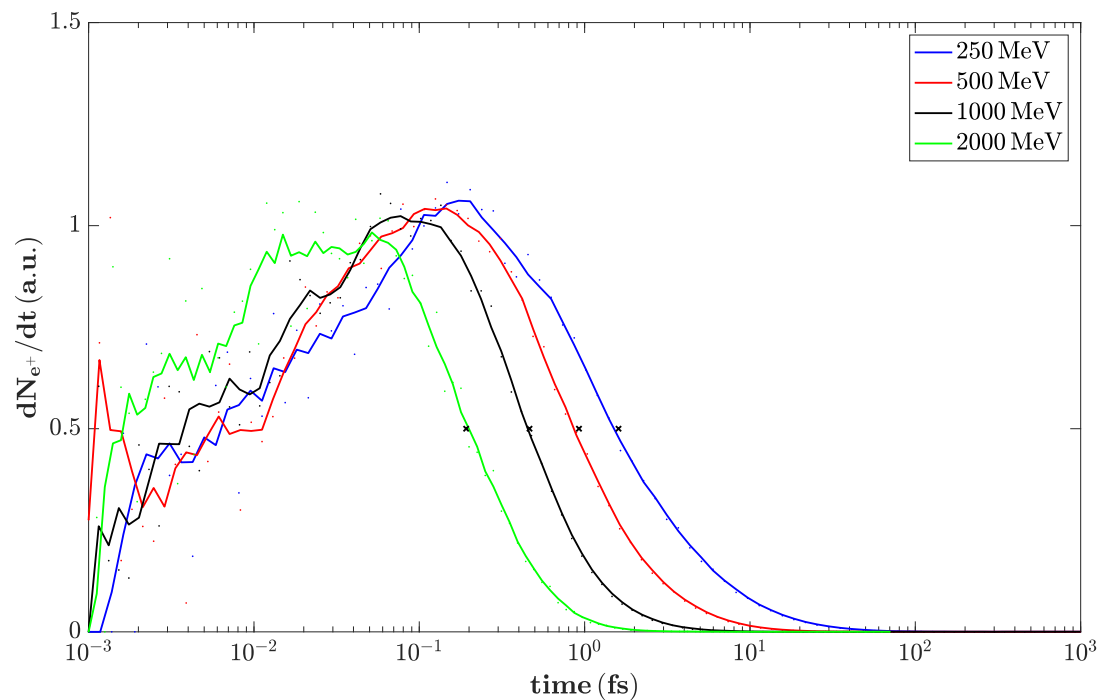


Positron beams



Towards a laser-based collider

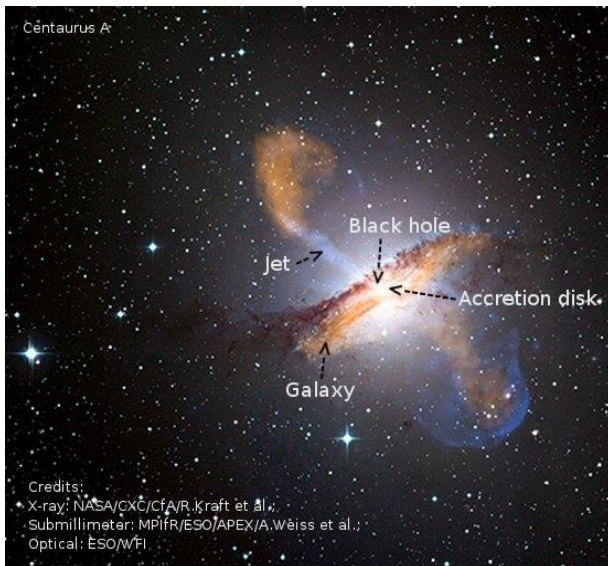
Laser-driven positron beams exhibit characteristics that make them suitable for injection in secondary stages and further acceleration



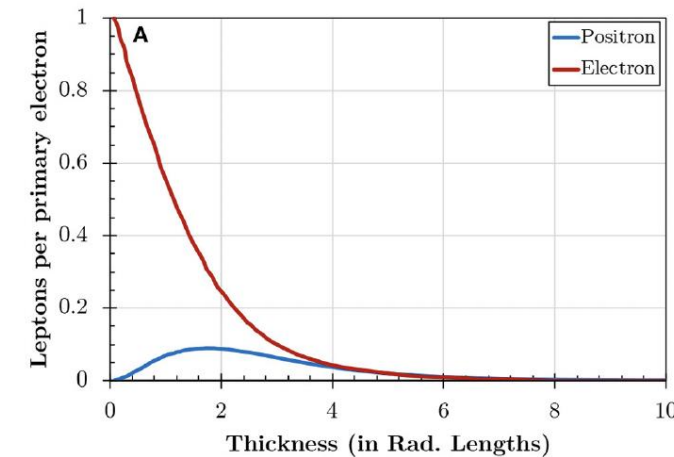
Neutral EP beams



Highly-collimated electron-positron jets are observed being emitted by massive and powerful objects, such as quasars, pulsars, and active galactic nuclei



- Power-law spectrum: $n(\gamma) \propto \gamma^{-(2\alpha+1)}$, $\alpha \leq 0.5$
- Some predominantly leptonic
- Relativistic
- Strong interaction with the intergalactic medium
- Related to Gamma Ray Bursts:
 - Largest single events observed in the Universe
 - Requires Equipartition $\sim 10^{-1} - 10^{-5}$

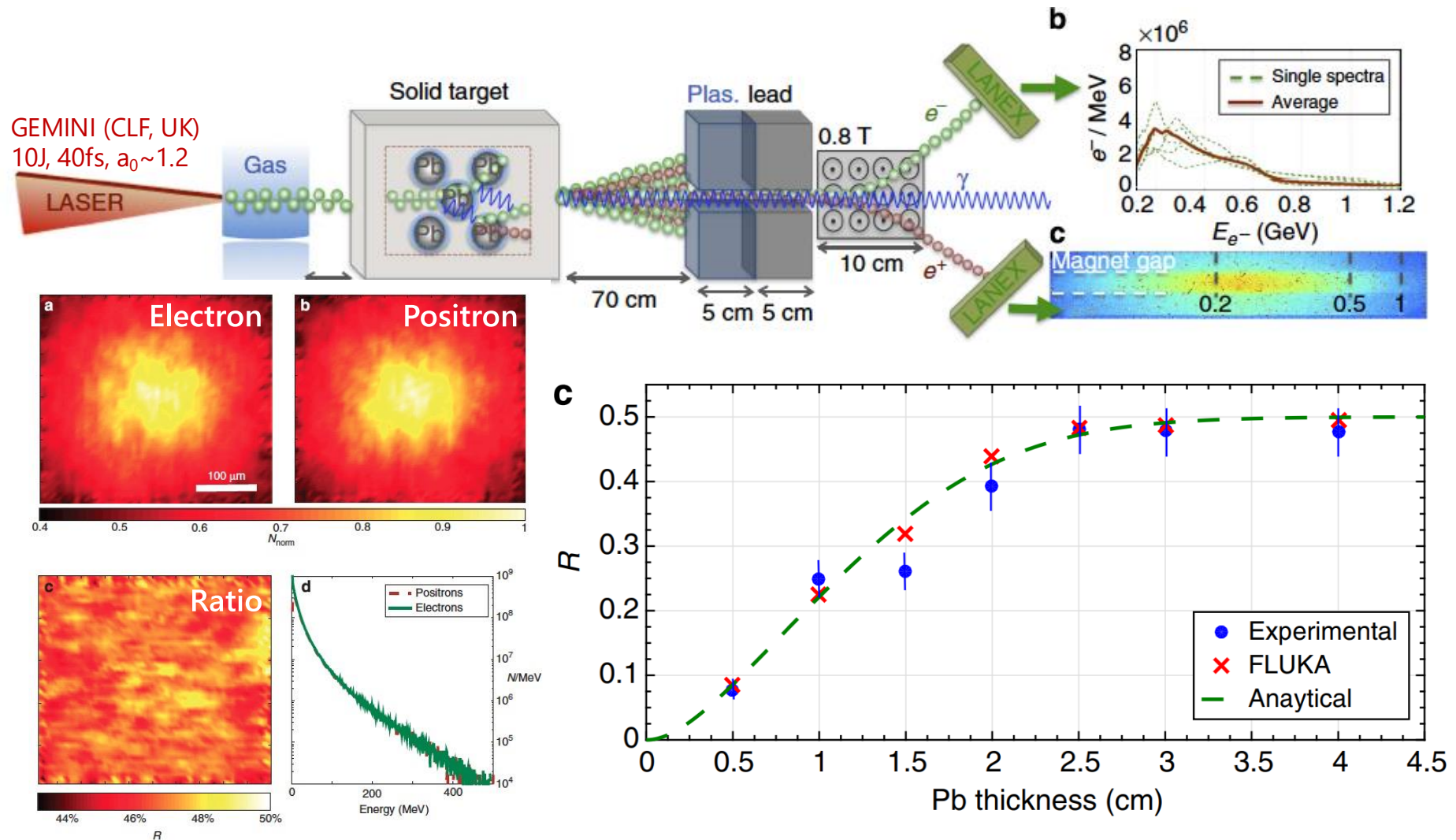


The generation of gamma rays requires strong and long-lived magnetic fields

- Intergalactic magnetic field ($\sim$ nT) too small
- MHD shock-compression, equipartition of 10^{-11}
- Fields from the central engine, equipartition of 10^{-7}
- Weibel-generated fields, too short-lived

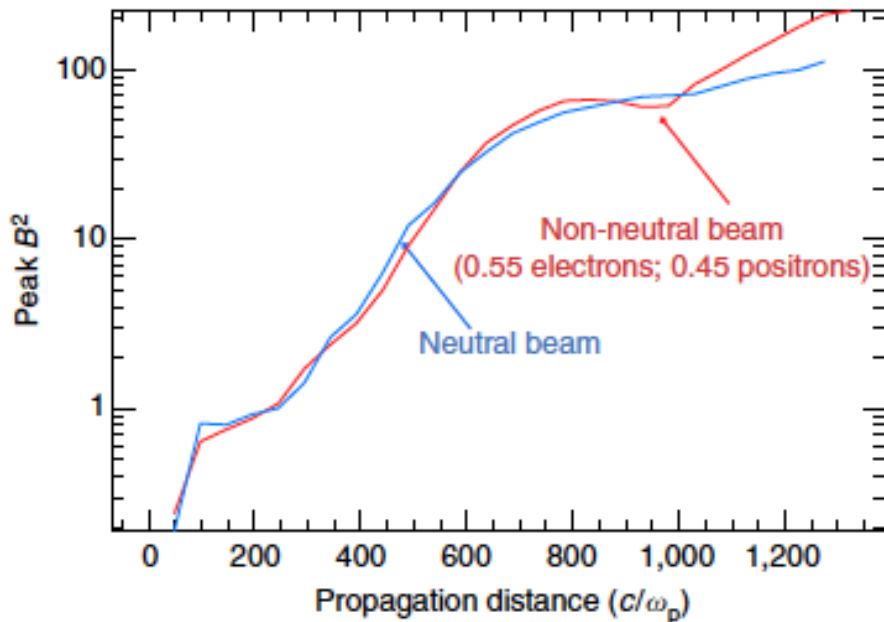
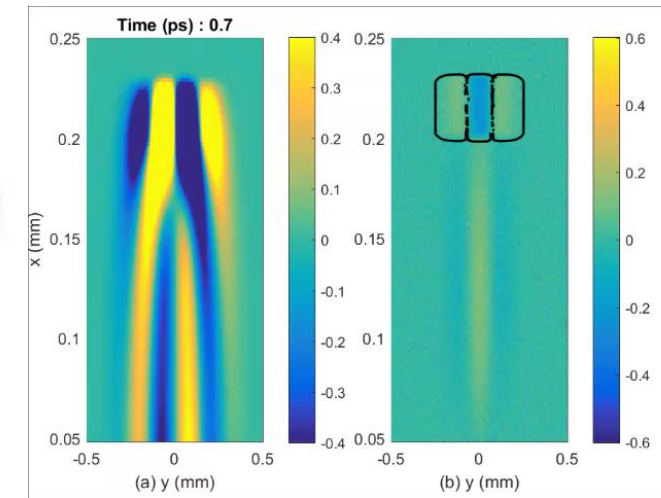
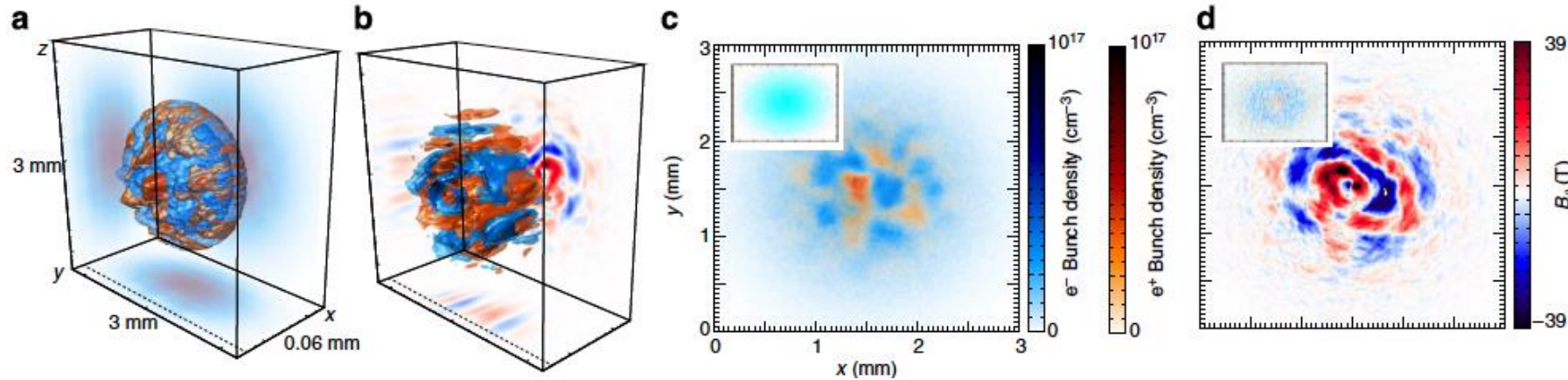
Electron-positron
beam filamentation?

Neutral EP beams

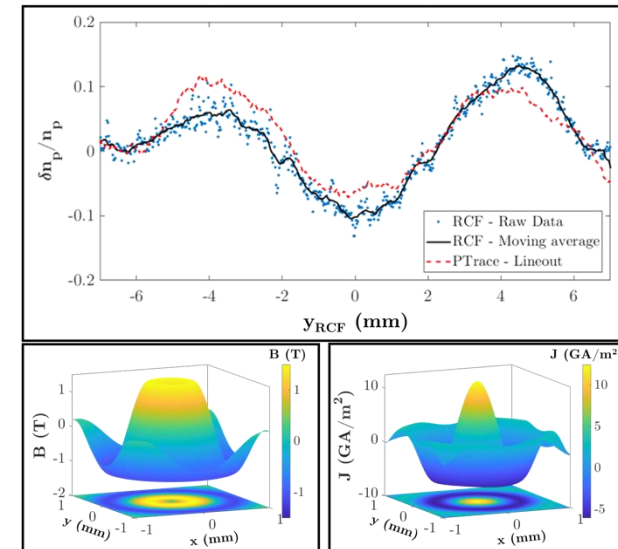


G. Sarri *et al.*, Nature Communications 6, 6747 (2015)

Neutral EP beams



- ☐ Strong filamentation only for neutral beams ($>40\%$)
- ☐ Saturation reached at $\sim 800 \ c/\omega_p$
- ☐ Generation of strong B fields
- ☐ Equipartition of the order of $10^{-2} - 10^{-4}$
- ☐ Long-lived fields
- ☐ These for an ideal beam (collimated and monoenergetic), also appear for realistic cases!





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Photoreactions in the lab

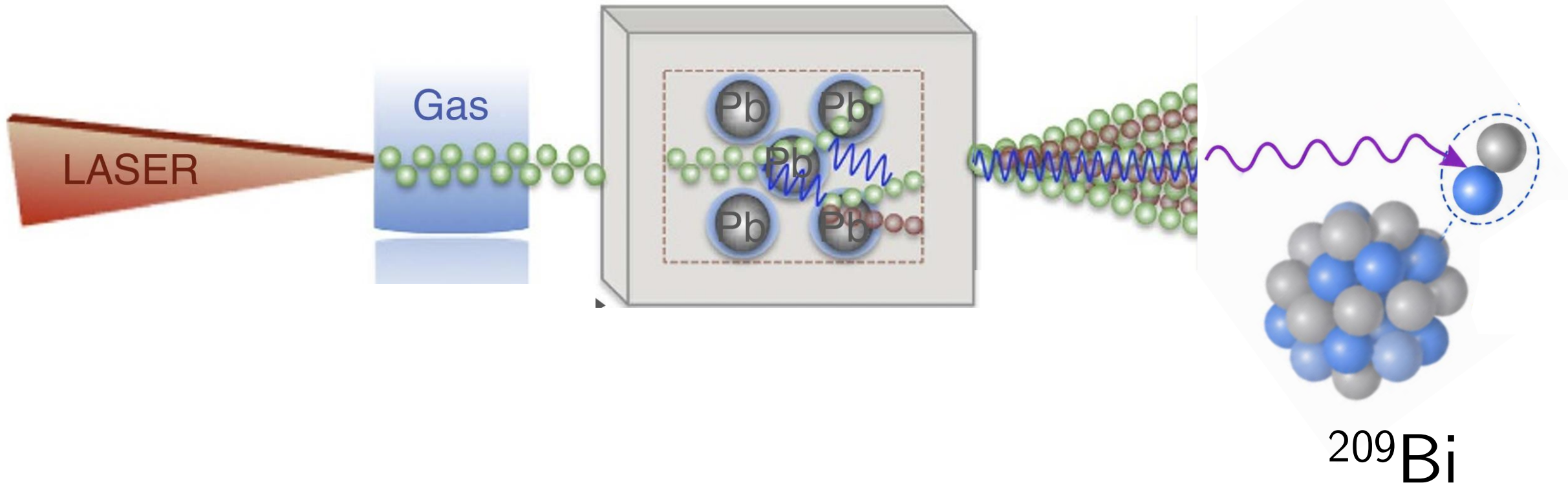
Photoactivation using lasers



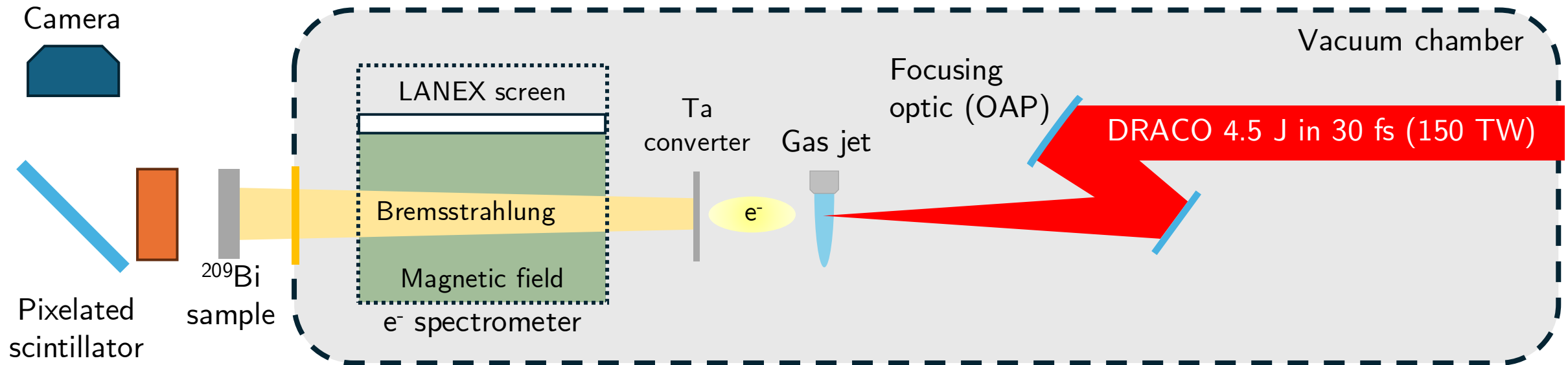
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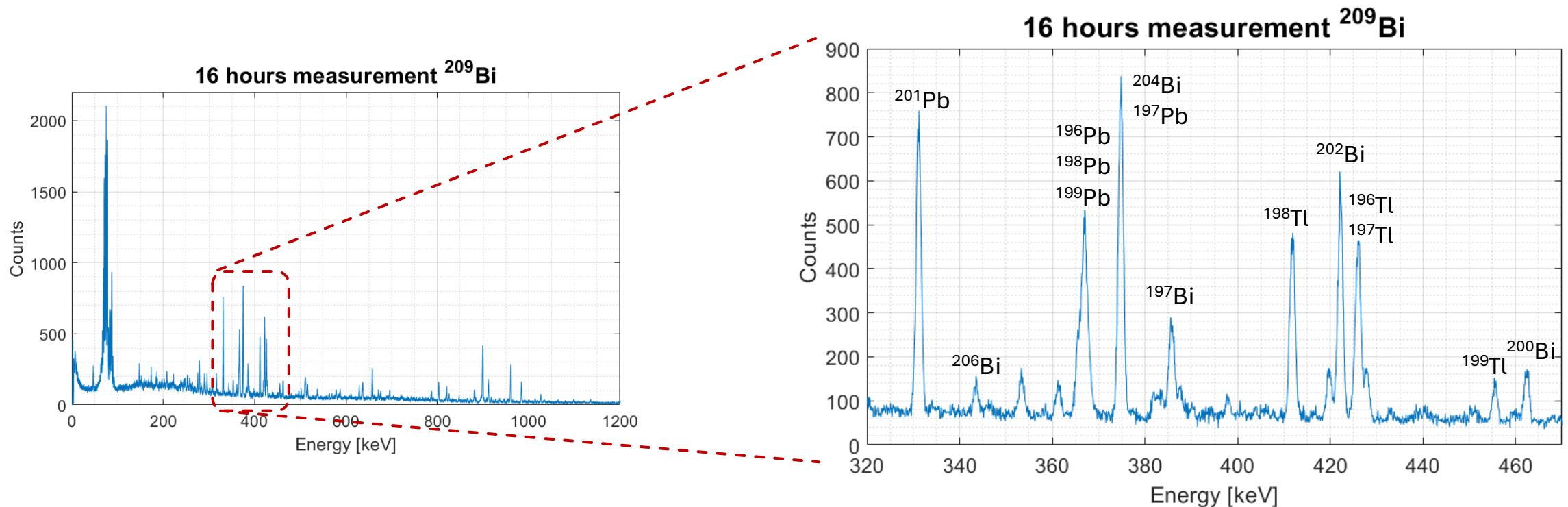
Photoactivation of ^{209}Bi



Photoactivation of ^{209}Bi



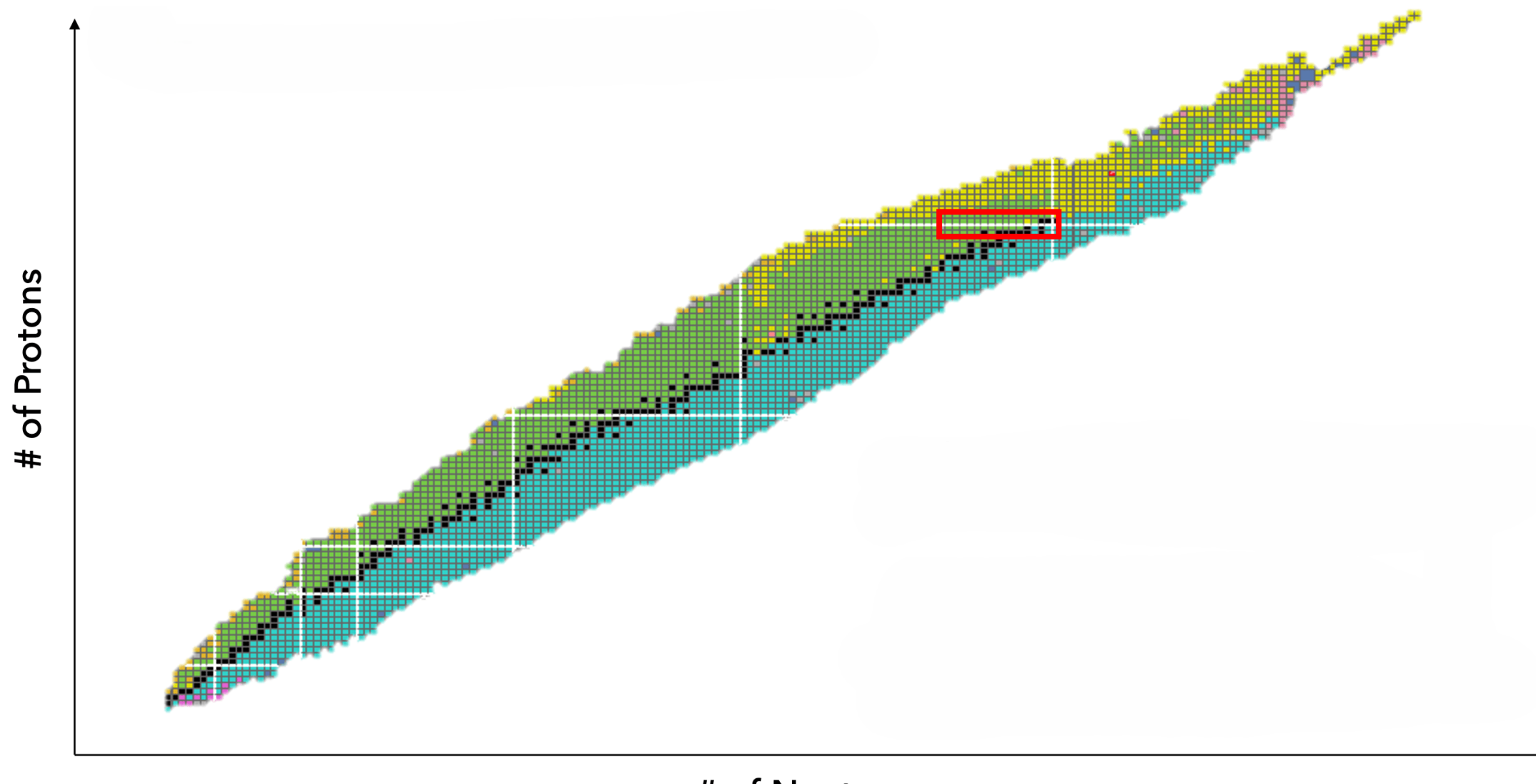
- The ^{209}Bi sample was irradiated for about 1 hour at 0.1 Hz (370 shots).
- The sample was successfully activated and measured with a HPGe detector.
- Laser-plasma interaction creates an extremely harsh environment → HPGe detector must be in a different room (7 min transfer time).
- A short-lived activity of 10-100 Bq was measured.



Photoactivation of ^{209}Bi



- 25 different isotopes were identified.





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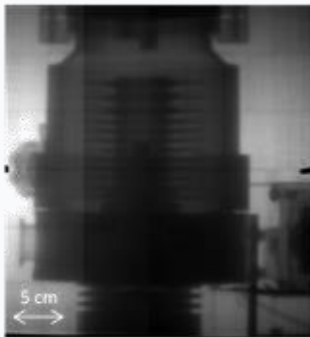
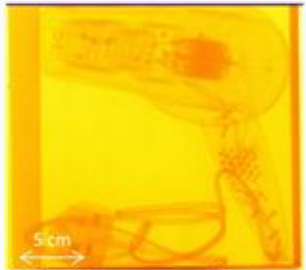
Summary

Take-home



γ sources

Highly energetic photon beams can be generated through bremsstrahlung, characterised by high energy, ultrashort duration and small source size.



e^+ sources

Ultrashort positron beams generated through QED cascades, with uses in applications and relevant to astrophysical scenarios.



Nuclear

Laser-driven sources can enable some experiments relevant for certain nuclear studies, including studies of photonuclear reactions.

83	¹⁸³ Bi 63.6 s	¹⁸⁴ Bi 95 s	¹⁸⁶ Bi 183 s	¹⁹⁰ Bi 308 s	¹⁹⁷ Bi 9.3 min	¹⁹⁸ Bi 10 min	¹⁹⁹ Bi 27 min	²⁰⁰ Bi 36 min	²⁰¹ Bi 103 min	²⁰² Bi 1.7 h	²⁰³ Bi 11.8 h	²⁰⁴ Bi 11.2 h	²⁰⁵ Bi 15.3 d	²⁰⁶ Bi 6.2 d	²⁰⁷ Bi 31.6 y	²⁰⁸ Bi 3.7e5 y	²⁰⁹ Bi stable
82	¹⁹² Pb 3.5 min	¹⁹³ Pb 5.8 min	¹⁹⁴ Pb 11 min	¹⁹⁵ Pb 15 min	¹⁹⁶ Pb 37 min	¹⁹⁷ Pb 8.1 min	¹⁹⁸ Pb 2.4 h	¹⁹⁹ Pb 90 min	²⁰⁰ Pb 21.5 h	²⁰¹ Pb 9.3 h	²⁰² Pb 5.6e4 y	²⁰³ Pb 51.9 h	²⁰⁴ Pb stable	²⁰⁵ Pb 1.7e7 y	²⁰⁶ Pb stable	²⁰⁷ Pb stable	²⁰⁸ Pb stable
81	¹⁹¹ Tl 5.2 min	¹⁹² Tl 9.6 min	¹⁹³ Tl 22 min	¹⁹⁴ Tl 33 min	¹⁹⁵ Tl 1.2 h	¹⁹⁶ Tl 1.8 h	¹⁹⁷ Tl 2.84 h	¹⁹⁸ Tl 5.3 h	¹⁹⁹ Tl 7.4 h	²⁰⁰ Tl 26.1 h	²⁰¹ Tl 3.4 d	²⁰² Tl 12.3 d	²⁰³ Tl stable	²⁰⁴ Tl 3.8 y	²⁰⁵ Tl stable	²⁰⁶ Tl 4.2 min	²⁰⁷ Tl 4.8 min
80	¹⁹⁰ Hg 20 min	¹⁹¹ Hg 49 min	¹⁹² Hg 4.9 h	¹⁹³ Hg 3.8 h	¹⁹⁴ Hg 444 y	¹⁹⁵ Hg 10.5 h	¹⁹⁶ Hg stable	¹⁹⁷ Hg 64.1 h	¹⁹⁸ Hg stable	¹⁹⁹ Hg stable	²⁰⁰ Hg stable	²⁰¹ Hg stable	²⁰² Hg stable	²⁰³ Hg 46.6 d	²⁰⁴ Hg stable	²⁰⁵ Hg 5.1 min	²⁰⁶ Hg 8.3 min
	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126
	# Neutrons (N)																