EUROPEAN UNION

GOVERNMENT OF ROMANIA

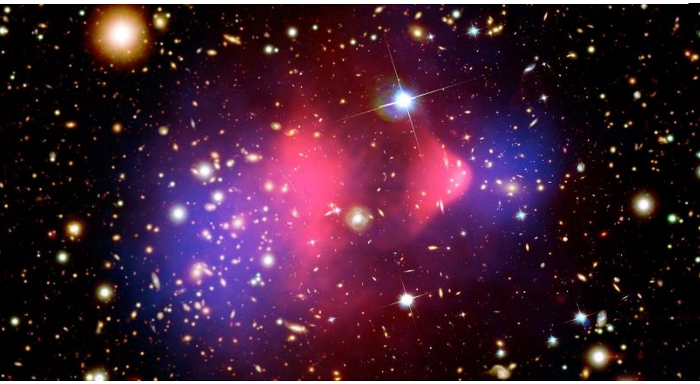
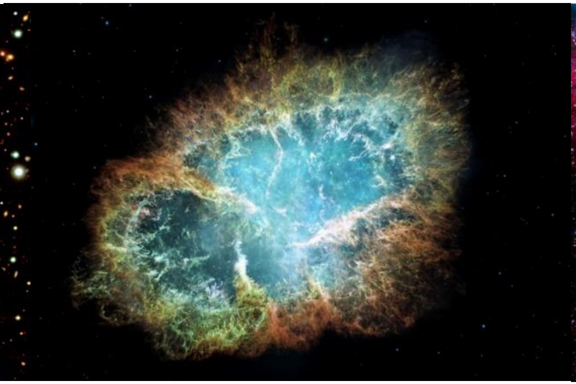
Structural Instruments 2014-2020

Operational Programme Competitiveness

Extreme Light Infrastructure – Nuclear Physics (ELI-NP) – Phase II

Project co-financed by the European Regional Development Fund

Extreme Light and the Dark Matter

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Extreme Light Infrastructure (ELI)

2006: ELI on ESFRI Roadmap

2007-2010: ELI-PP (FP7)

- ELI-Beamlines (Czech Republic)
- ELI-Attoseconds (Hungary)
- ELI-Nuclear Physics (Romania)
- ELI-Ultra-high intensity – TBD

2009: Approved by Competitiveness Council

2010: ELI-DC formation decided

2012: Start construction on the ELI-NP site

2013: Establishment of ELI-DC

2016: Completion construction works ELI-NP

2019: Completion and testing of the 10PW laser at ELI-NP

2020: Completion of 10PW laser beam transport

- First experiments at 100TW beams at ELI-NP
- Start of the IMPULSE project

2021: Establishment of ELI-ERIC

- First experiments at 1PW beams at ELI-NP

ELI-NP Light Source

Very high intensity lasers – IR, 810nm

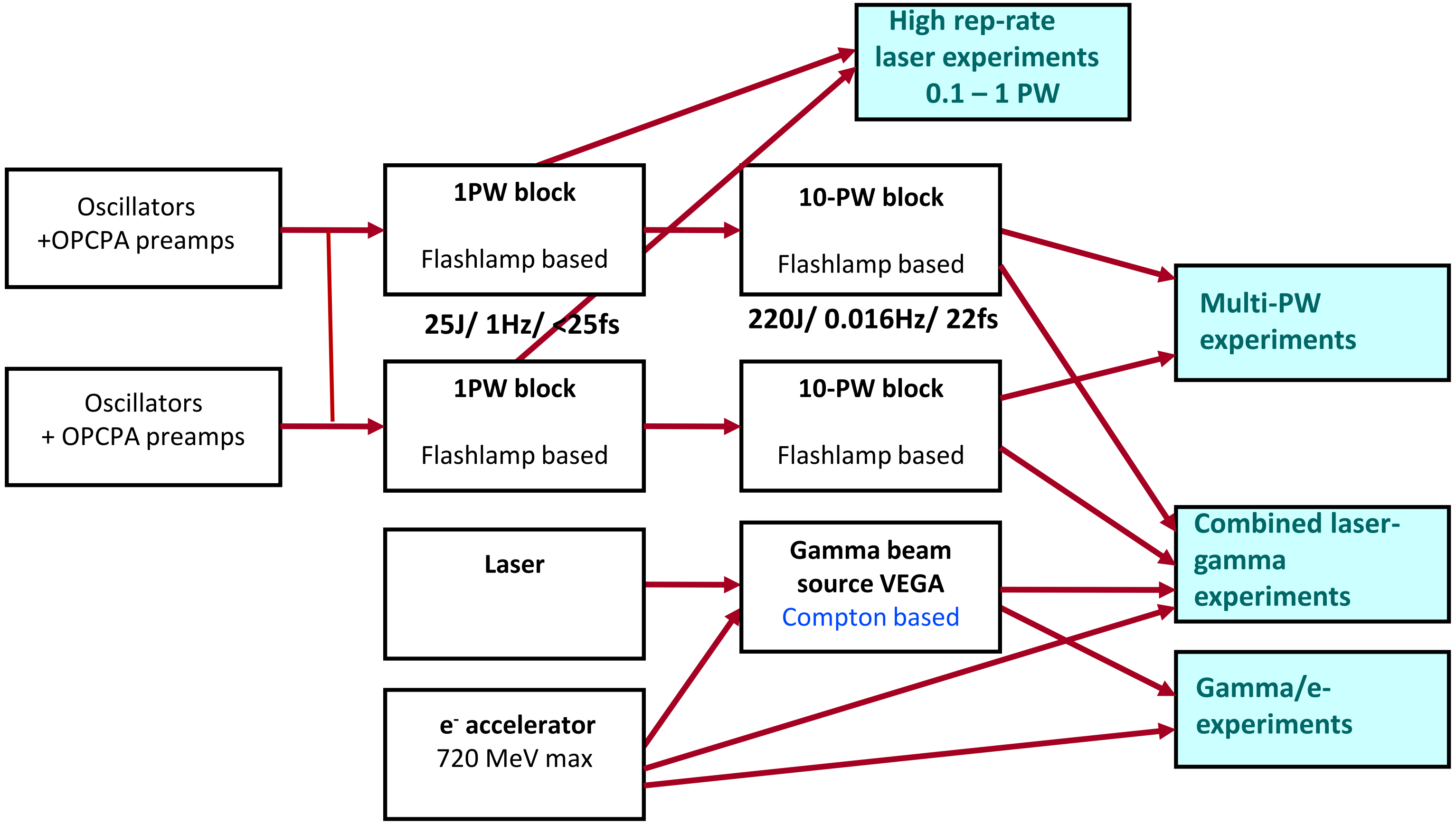
- 2 arms of 10PW each
- <25fs pulse duration

Brilliant Gamma Beam – invisible light

- Compton backscattering of laser light off accelerated electrons
- Wide energy range: 1 to 20MeV
- Very good bandwidth: < 0.5%

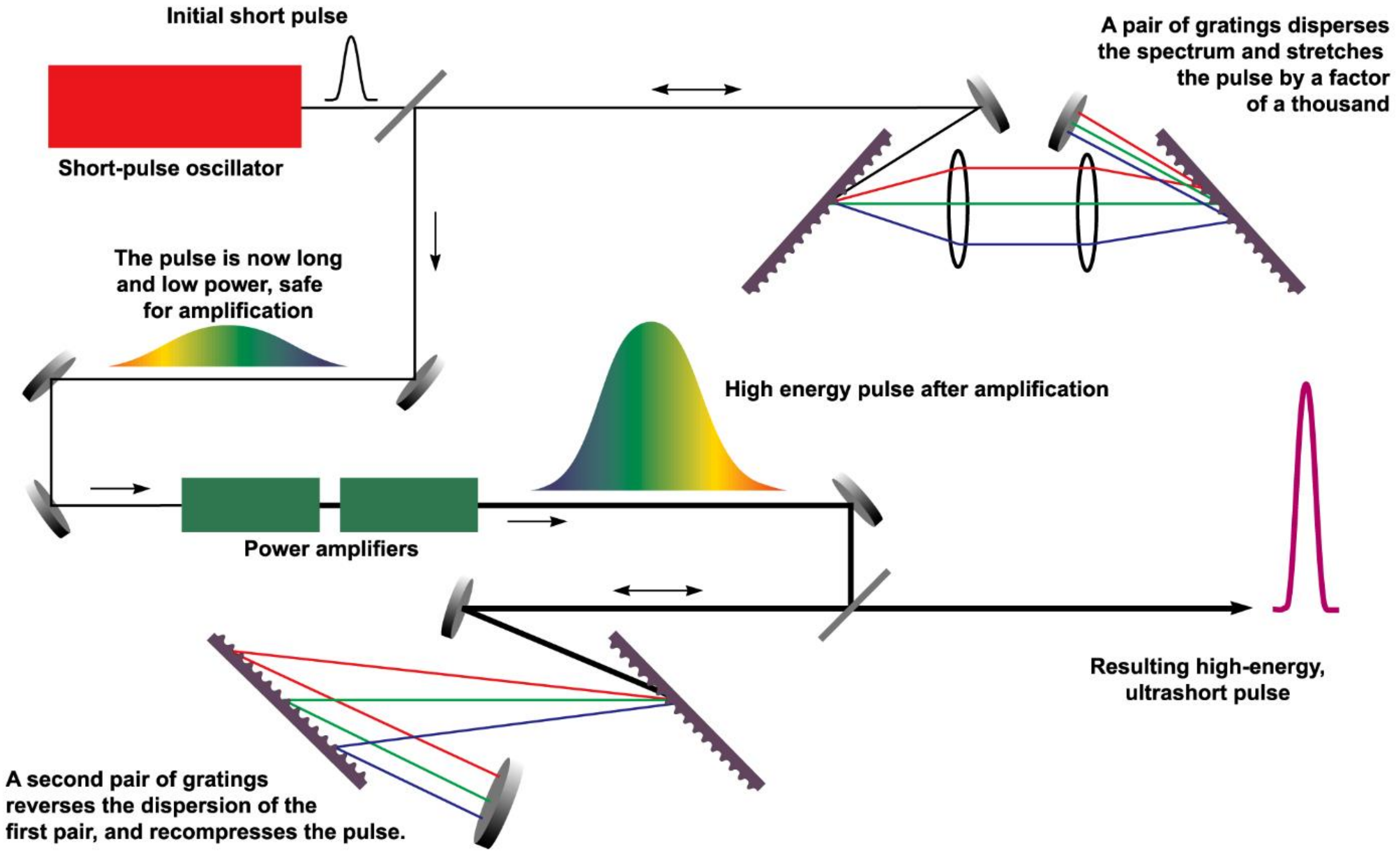
Equipment beyond State of the Art

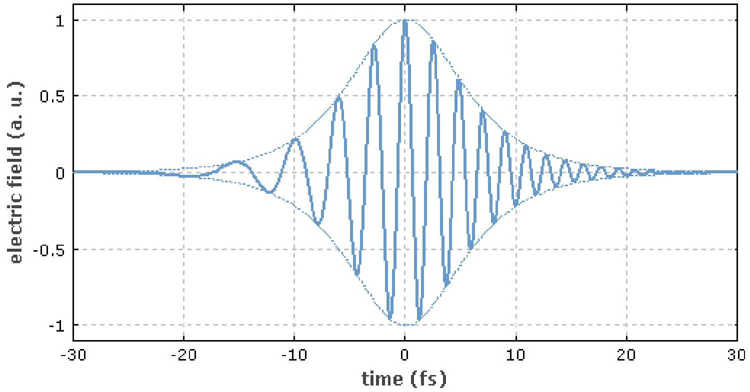
User facility – open access

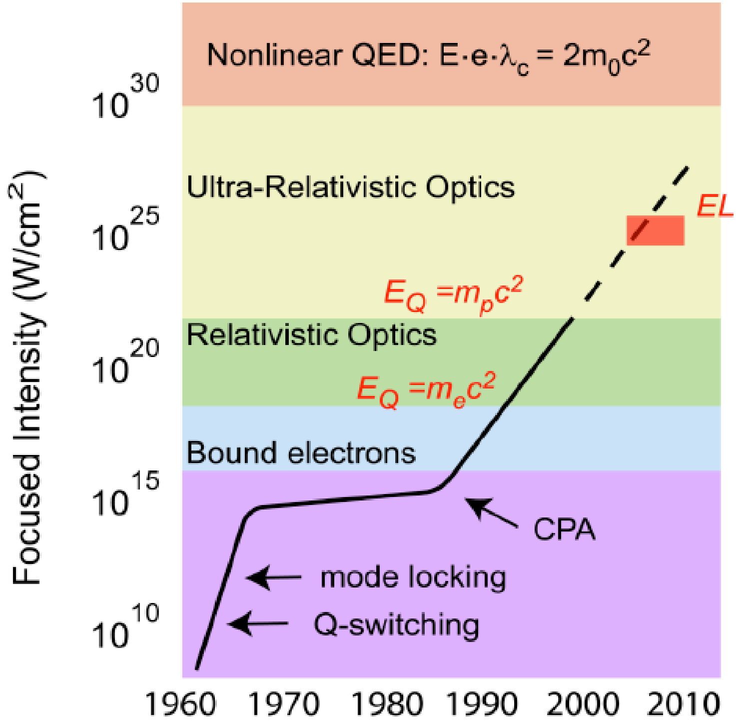


Chirped Pulse Amplification (CPA)

A pulse can acquire a chirp e.g. during propagation in a transparent medium due to the effects of chromatic dispersion and nonlinearities







Gerard Mourou 1985: Chirped Pulse Amplification (CPA)

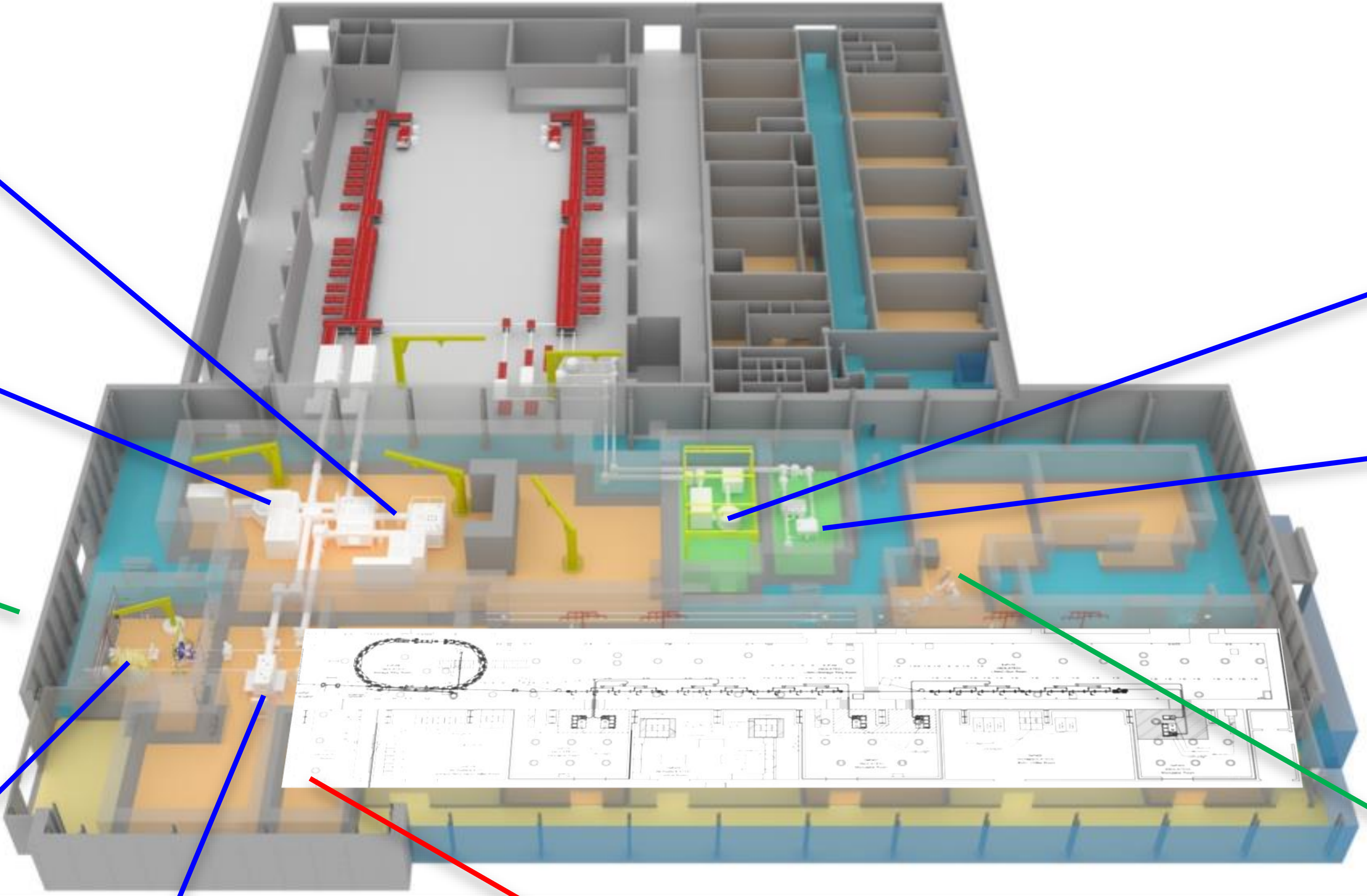
Layout of the ELI-NP facility

E1 10 PW @ 1/min
Laser driven
Nuclear Physics

E6 10 PW @ 1/min
High Field QED

E9 γ beams
Photonuclear
Reactions

E8 γ beams
Photonuclear
Reactions



E7 10 PW + γ
High Field QED

ERA positrons
Material Studies

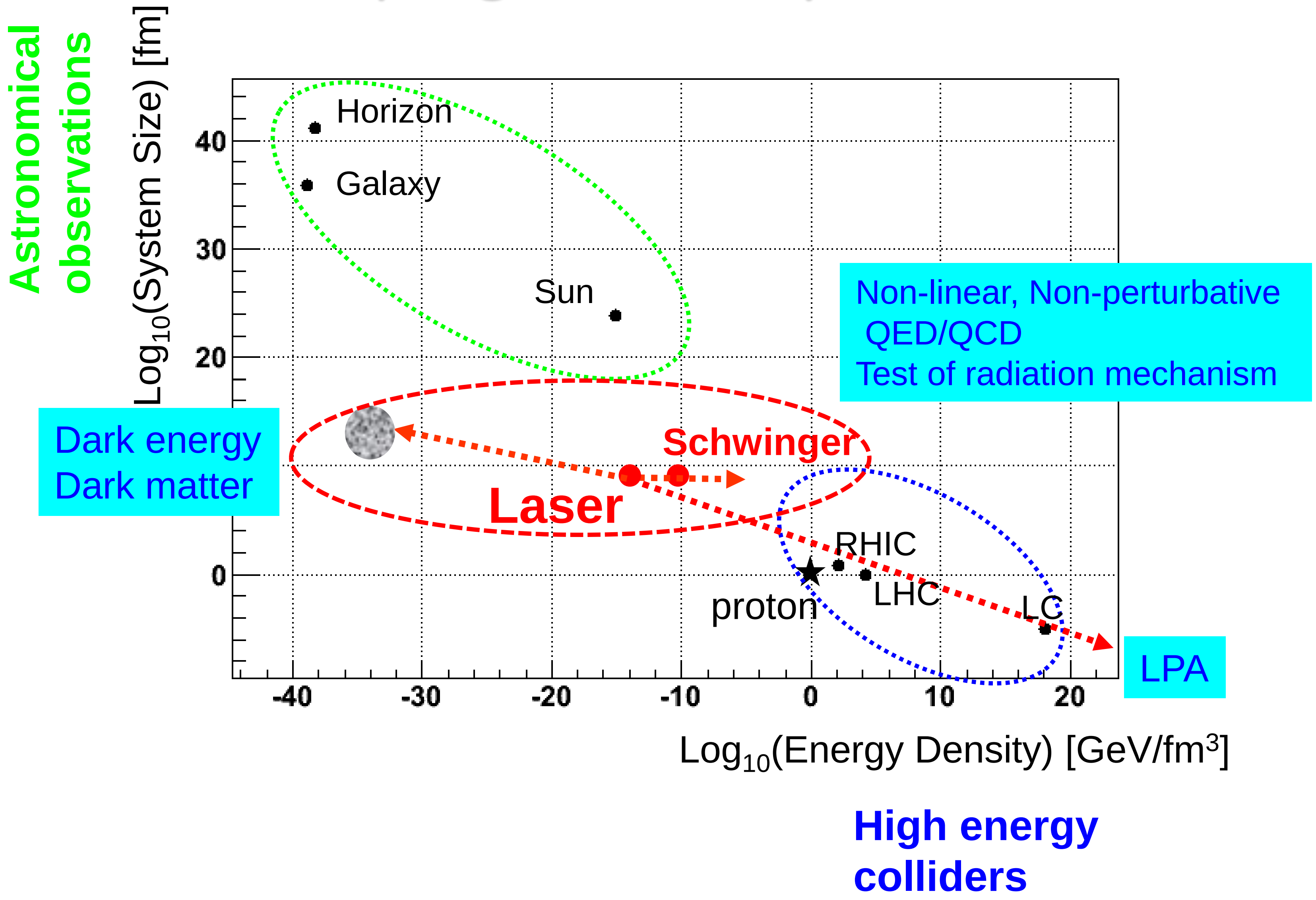
E5 1 PW @ 1 Hz
Material Studies

E4 0.1PW@10 Hz
High Field QED

E3 X rays
Test/develop
instrumentation
and technology

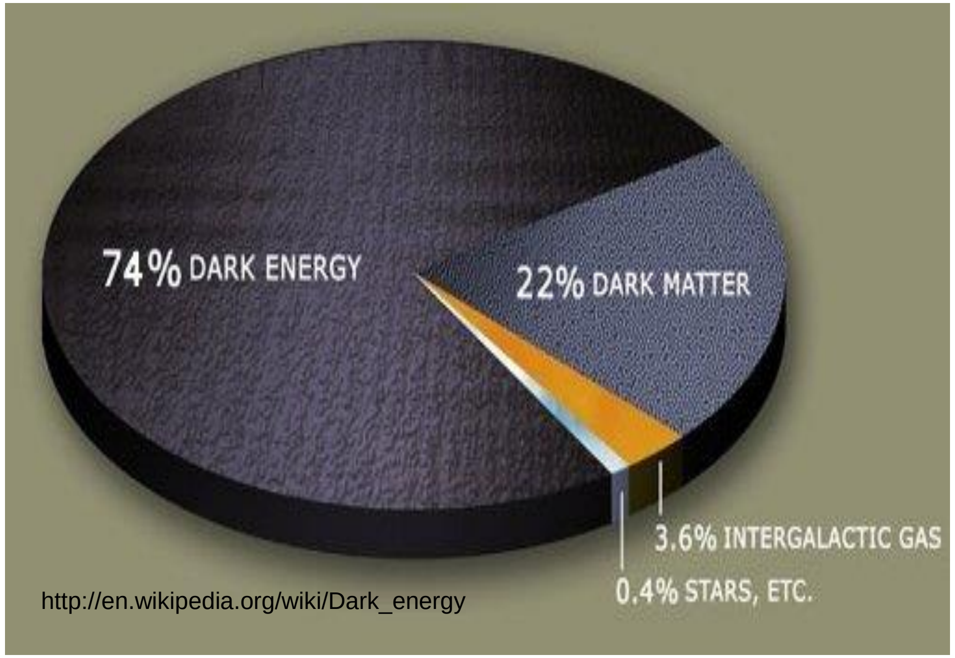

eli
nuclear physics
THALES

Three major directions to be explored by high-intensity lasers



Courtesy of Prof. K. Homma @ ELI-NP School 2015

Dark Components of the Universe



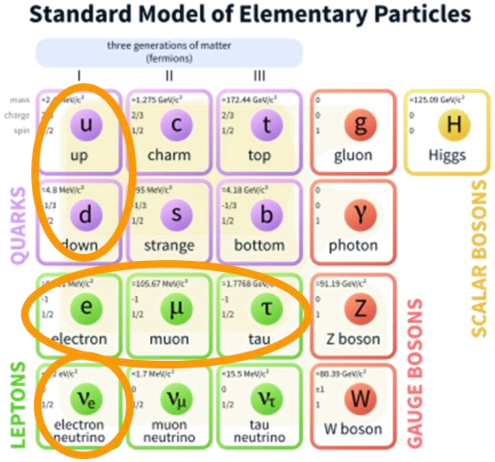
<u>Dark Matter Candidates</u>

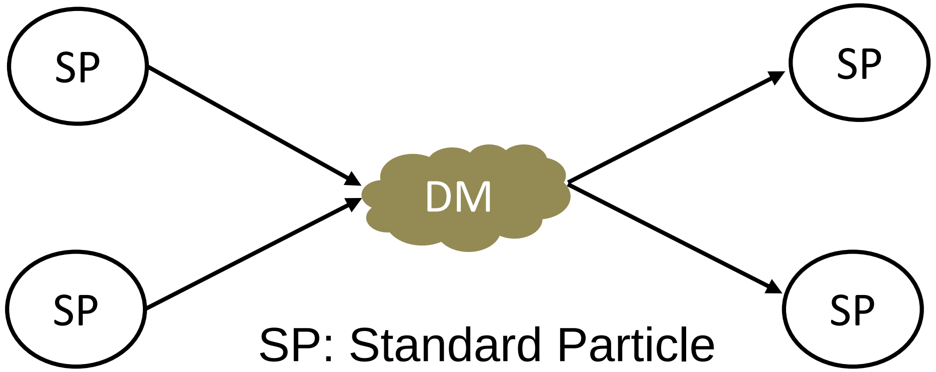
Heavy Dark Matter at m > 100 GeV

- SUSY particle (e.g. Neutralino)
- Kaluza-Klein Mode

Light Dark Matter at m < 1 eV

- Axion
- Dilaton





SP: Standard Particle
DM: Dark Matter

<u>Experimental Approach</u>

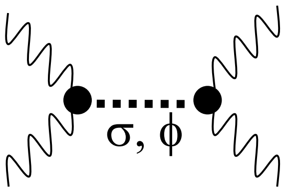
<u>= Direct Production + “Stimulated” Decay in Lab.</u>

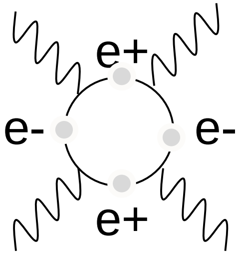
- Controllable initial condition
- Direct measurement of decay products

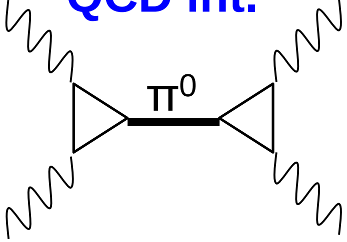
Courtesy of Prof. K. Homma @ ELI-NP School 2015

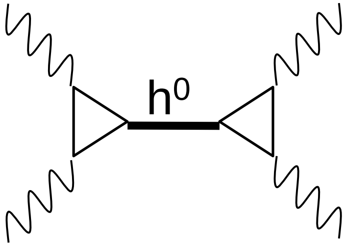
Photon-Photon interactions in different energy scales

Laser-Laser quantum interaction		High-energy particle interactions	
Very light field in the context of dark energy / matter	**Interactions via QED (+QCD)**	**Chiral symmetry QCD int.**	**Gauge symmetry Electroweak int.**







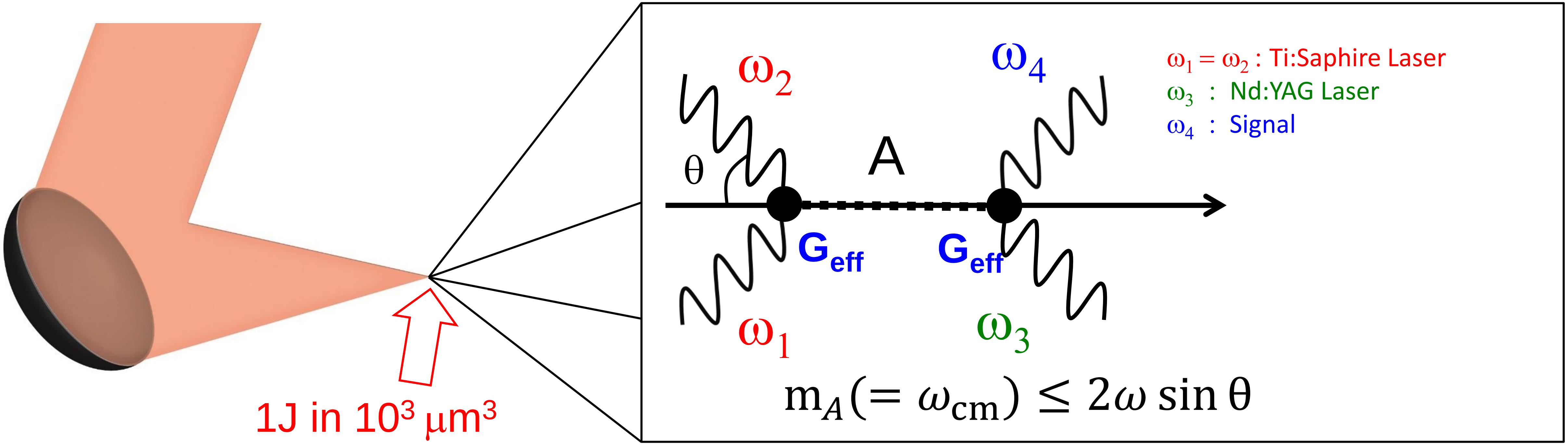


Undiscovered !	Not verified !	pseudoscalar	scalar
Below 1eV	Below 1 MeV	135 MeV	126 GeV

Photon-photon center of mass energy

Courtesy of Prof. K. Homma @ ELI-NP School 2015

Dark Matter (Axion) Search at ELI-NP



Dark Matter Production <-> Four-wave mixing process in the vacuum

Key Essences of our approach

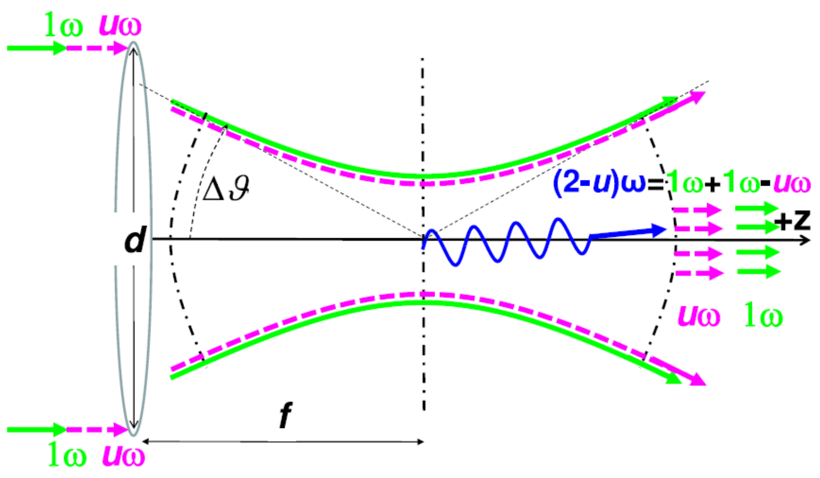
Observable: Wavelength shift of the light -> Blue light in our case

Advantages: High photon density against small coupling -> Laser Intensity + Repetition Rate

Challenges: Suppressing Atomic four-wave mixing -> Control of Ultra-high Vacuum

High statistics data -> Control of high-intensity laser system

Four-wave mixing



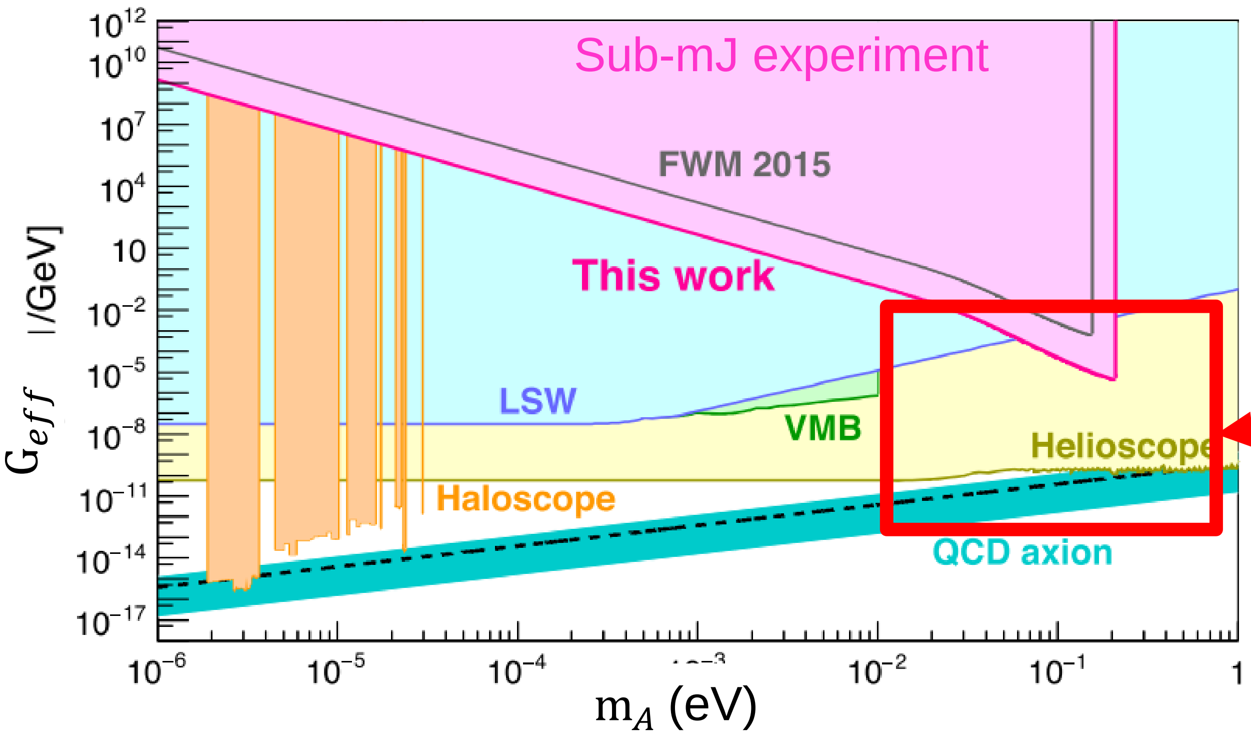
Search for resonance states at very low energies. There are theoretical rationales to expect sub-eV particles.

- Quasi-parallel colliding system (QPS) between two incident photons
- Signature is produced via the four-wave mixing process
- mixing two-color waves with different frequencies 1ω and uω in advance
- **SAPPHIRES** collaboration:
  - Japan: K. Homma (Univ. Hiroshima), S. Sakabe (ICR Kyoto) & students
  - Romania: Y. Nakamiya, O. Tesileanu, L. Neagu, M. Rosu, V. Rodrigues, C. Chiochiu, J. Tamlyn
- **Experiment in operation (HPLS alignment beam) for the first beamtime session**

DM experiment at ICR Kyoto: Recent Results

Nuclear Physics

- Preparatory experiments have started 5 years ago in ICR Kyoto
- Pulse energies up to 10mJ range
- In 2019 a UHV interaction chamber was installed
- Nd:YAG and OPA tested, published results



PTEP

Prog. Theor. Exp. Phys. **2020**, 073C01 (19 pages)
DOI: 10.1093/ptep/ptaa075

Extended search for sub-eV axion-like resonances via four-wave mixing with a quasi-parallel laser collider in a high-quality vacuum system

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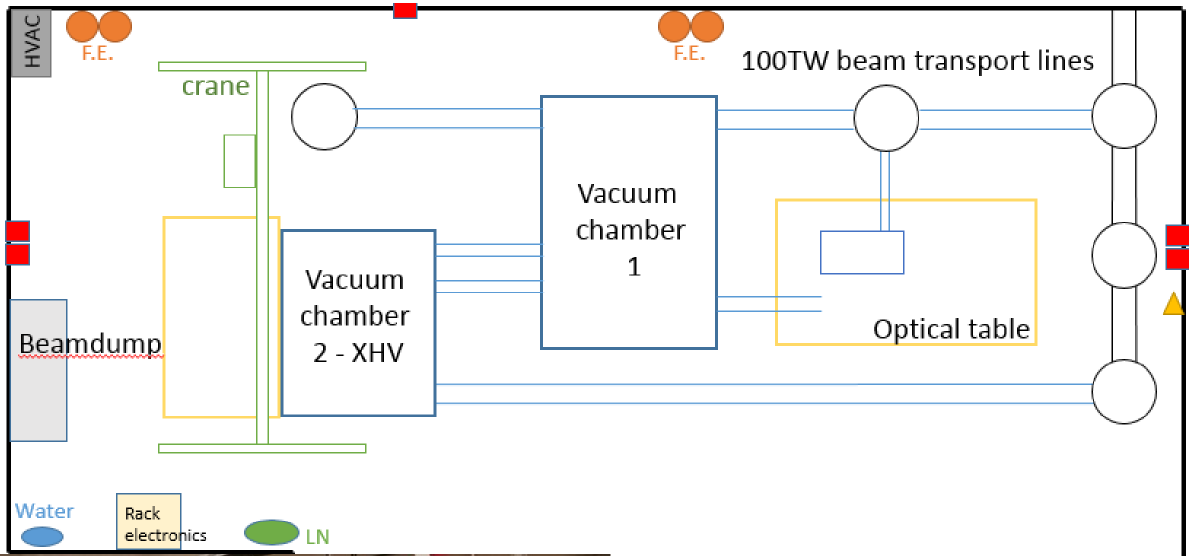
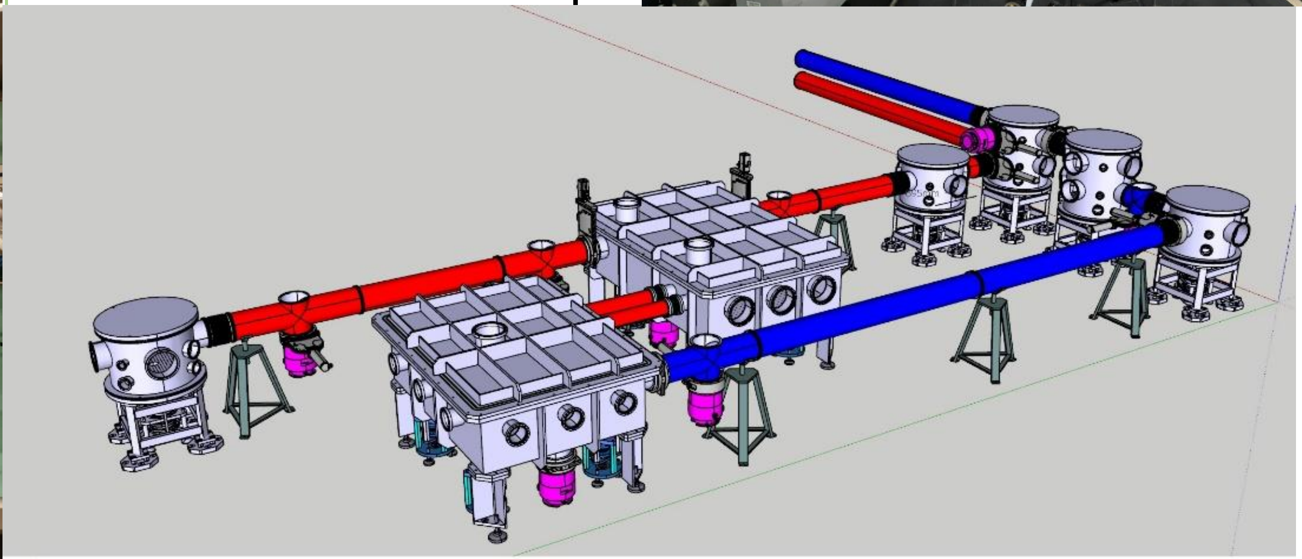
Received January 21, 2020; Revised March 23, 2020; Accepted April 21, 2020; Published July 2, 2020

Target at ELI-NP

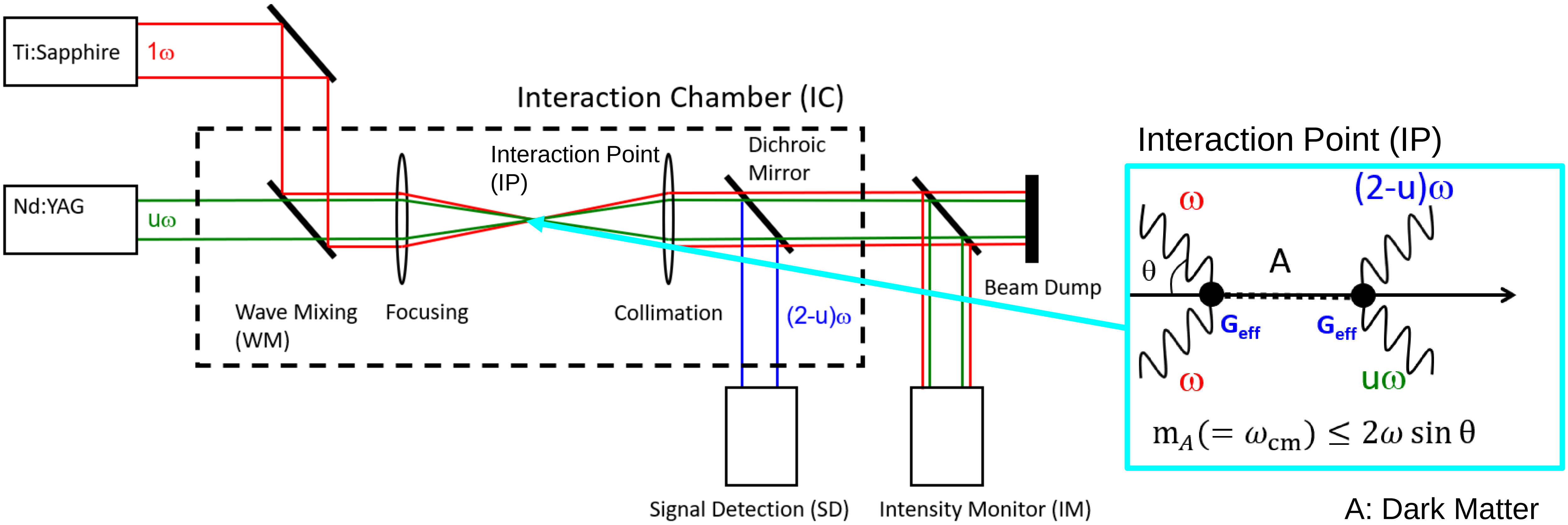
With increased energy per pulse and better vacuum conditions (differential pumping)

E4 experimental area





Overview of DM experiment – Beamtime 1



Aims for the current beamtime in E4

1. Establish spatial overlap and timing synchronization between Ti:Sapphire and Nd:YAG
2. Measurements with 2mJ (Ti:Sap.) + 2mJ(Nd:YAG) for system calibration
3. Measurements with 50mJ (Ti:Sap.) + 50mJ (Nd:YAG) for systematic background studies
4. Measurements with 1J(Ti:Sap.) + 50mJ (Nd:YAG)

Four-wave Mixing in Vacuum

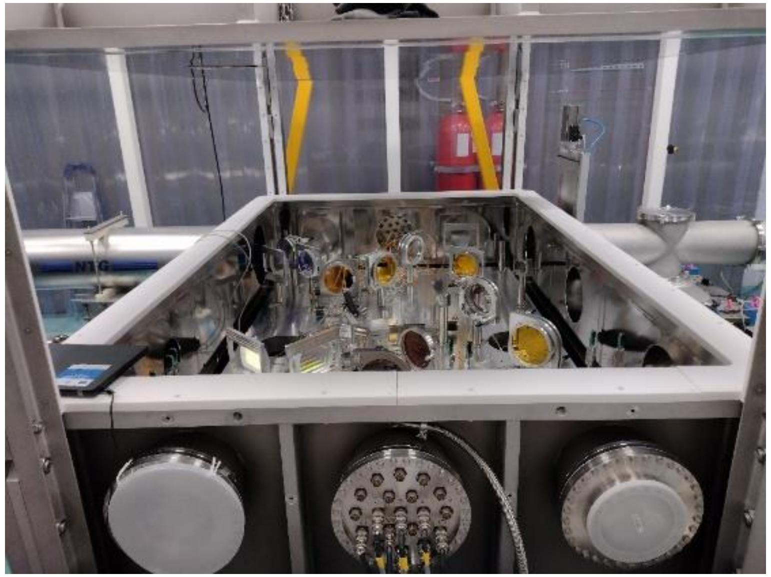
Experimental challenges

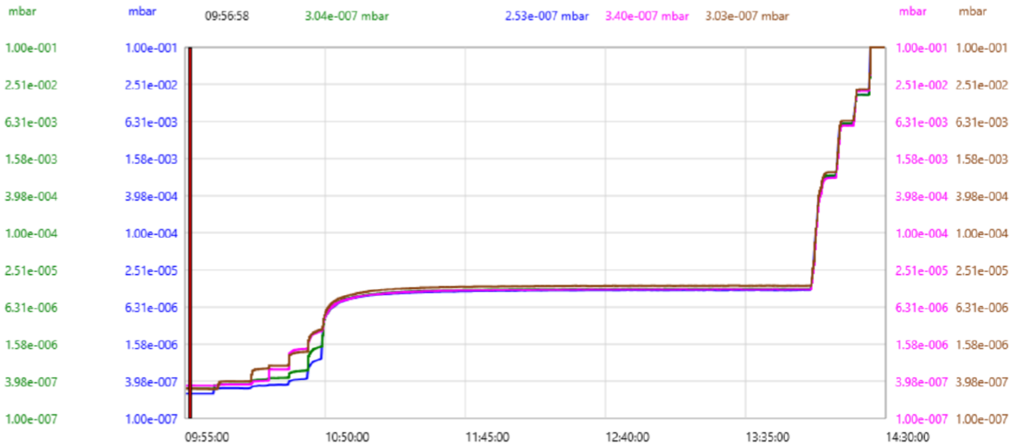
- Detailed background study is needed because of:
  - Four-wave mixing at the optical elements
  - Four-wave mixing on the atoms of the residual gas
- Extremely high sensitivity to be achieved in order to detect the 4wm signature – 5 layers of dichroic mirrors to separate signal from background
- Precise timing synchronization between two short laser pulses (20fs – 10ns in the initial, HPLS+Nd:YAG configuration, then 20fs-50fs level when using OPA for the second beam) and spatial overlap in the focus
- For minimizing background, ultra-high vacuum (UHV) levels should be ensured
- For the study of the background dependence with pressure, a precise control of pressure needed

Four-wave Mixing in Vacuum

Experimental setup

- VE1 high vacuum chamber:
  - Overlap and focusing of the two laser beams
  - Motorized linear stages and mirror mounts (>100 channels)
  - Needle valve for fine vacuum level control
  - Dichroic mirrors for signal-background separation
  - Focus monitor (in vacuum camera with DM feedback)

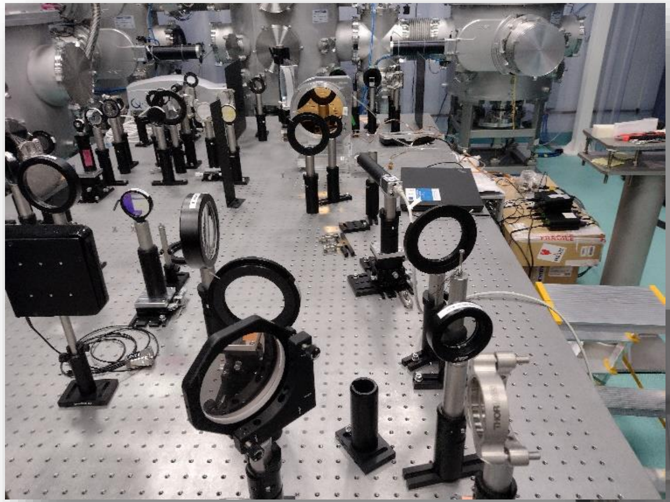


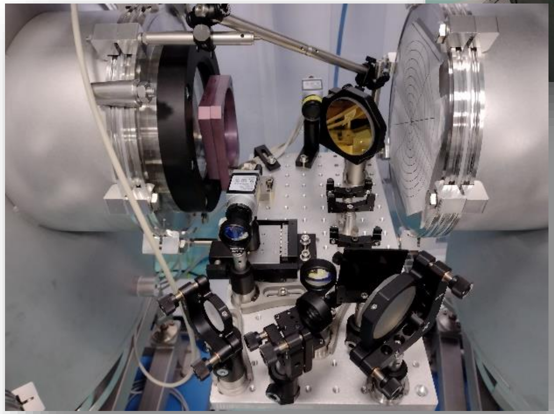


Four-wave Mixing in Vacuum

Experimental setup

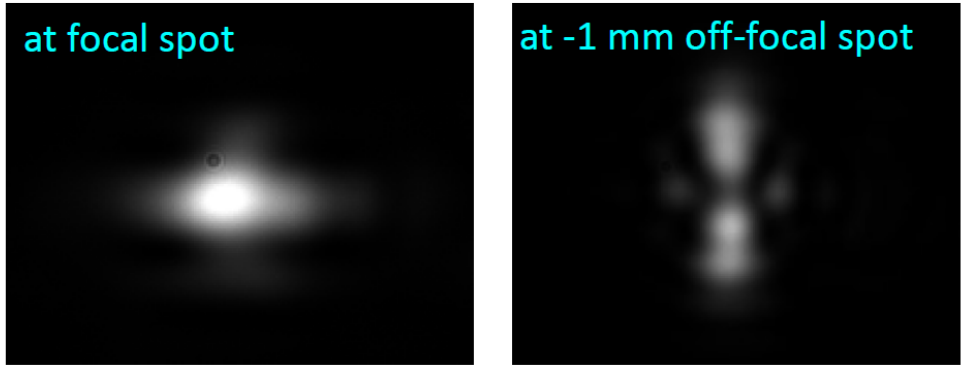
- Upstream optical table:
  - Nd:YAG laser installed
  - He:Ne laser for alignment installed
  - OAP testbench in air
- Signal detection optical table:
  - Photomultiplier tubes aiming for 1-photon level detection
  - Light shielding important
- Pulse imaging at TB1 (turning-box) vacuum chamber



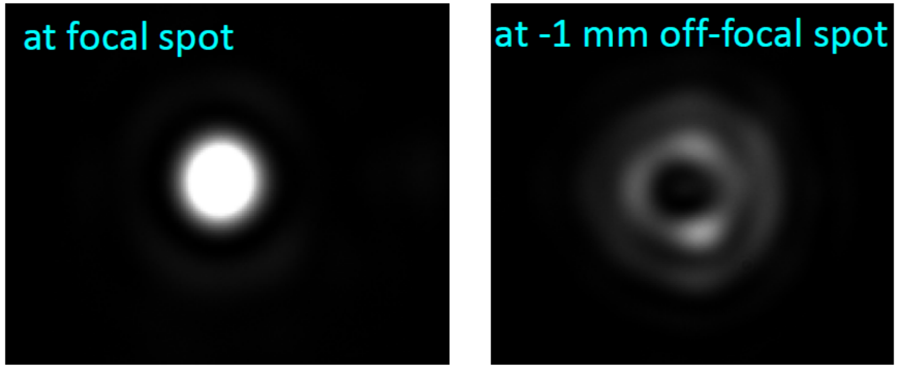


Focusing optimization

- Highest intensities needed for the experimental search
- Aim: Achieve best focus and spatial overlap of the two laser pulses
- Large distance from the laser bay (>20m to E4 entrance) and 4 flat mirrors and one beam combiner
- Deformable mirror in HPLS before pulse compressor
- Nd:YAG beam expanded to a diameter comparable to the HPLS laser beam
- Alignment with He:Ne laser (633nm), overlap with HPLS (Ti:Sapph) beam (810nm) and Nd:YAG beam (1064nm)



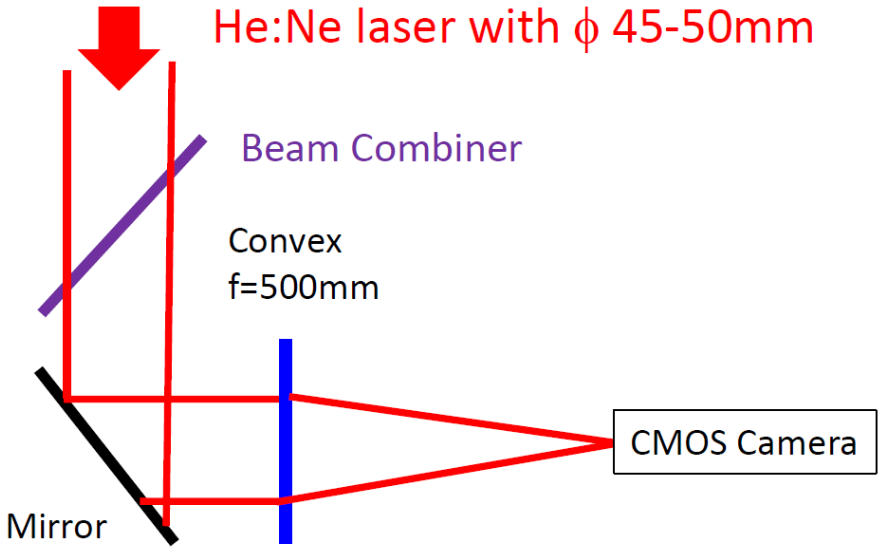
Before Adjustment

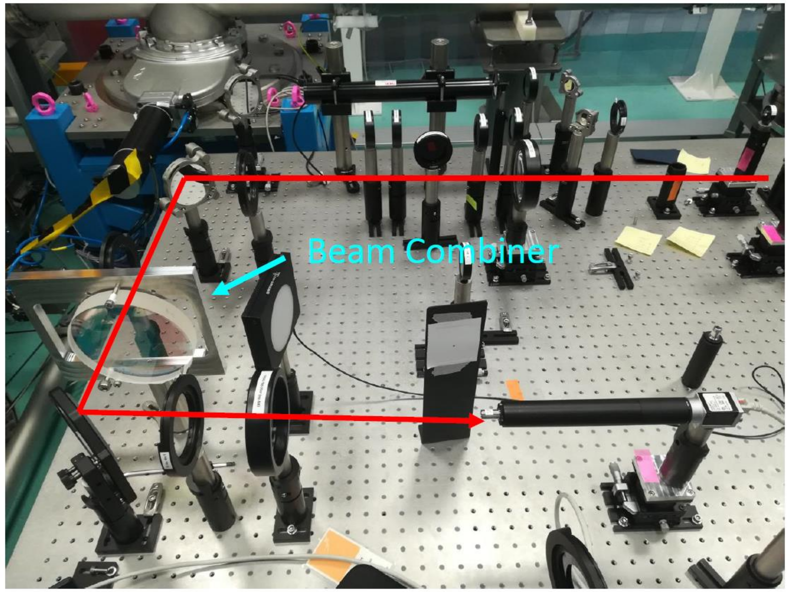


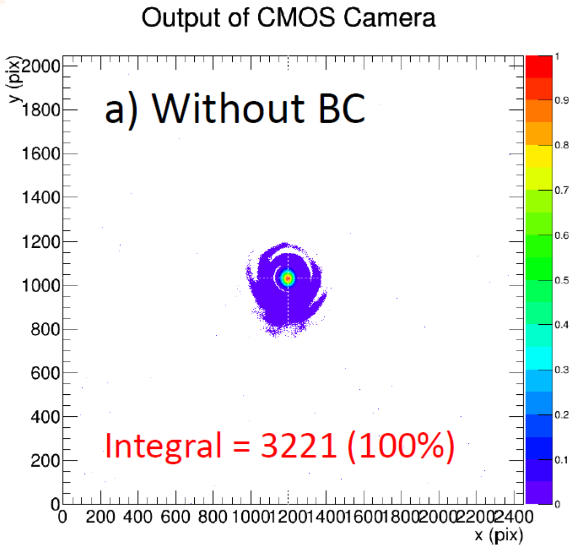
After Adjustment

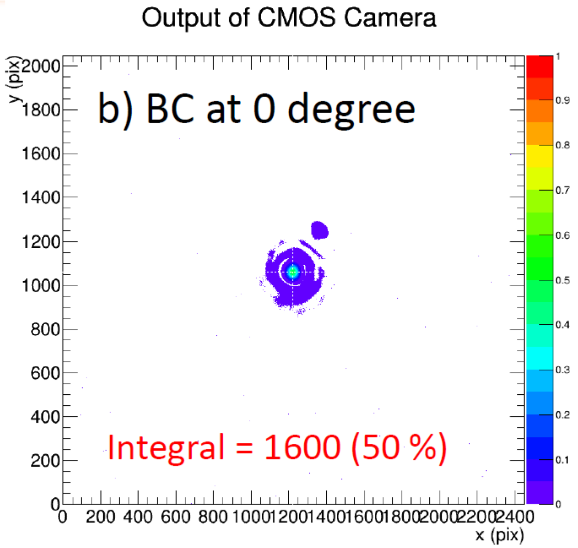
Focusing optimization

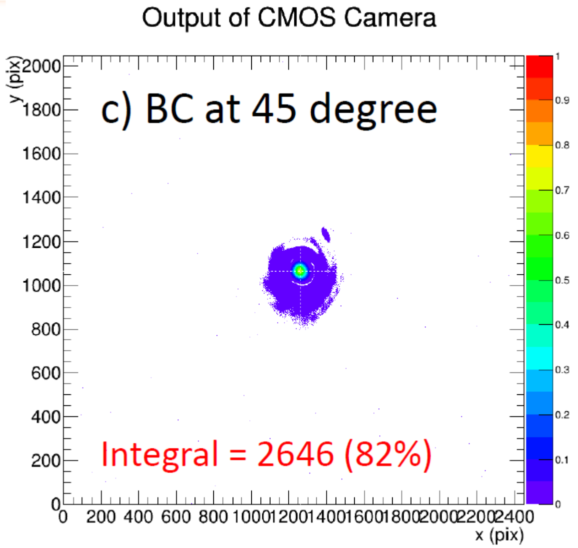
- Testing of beam combiner





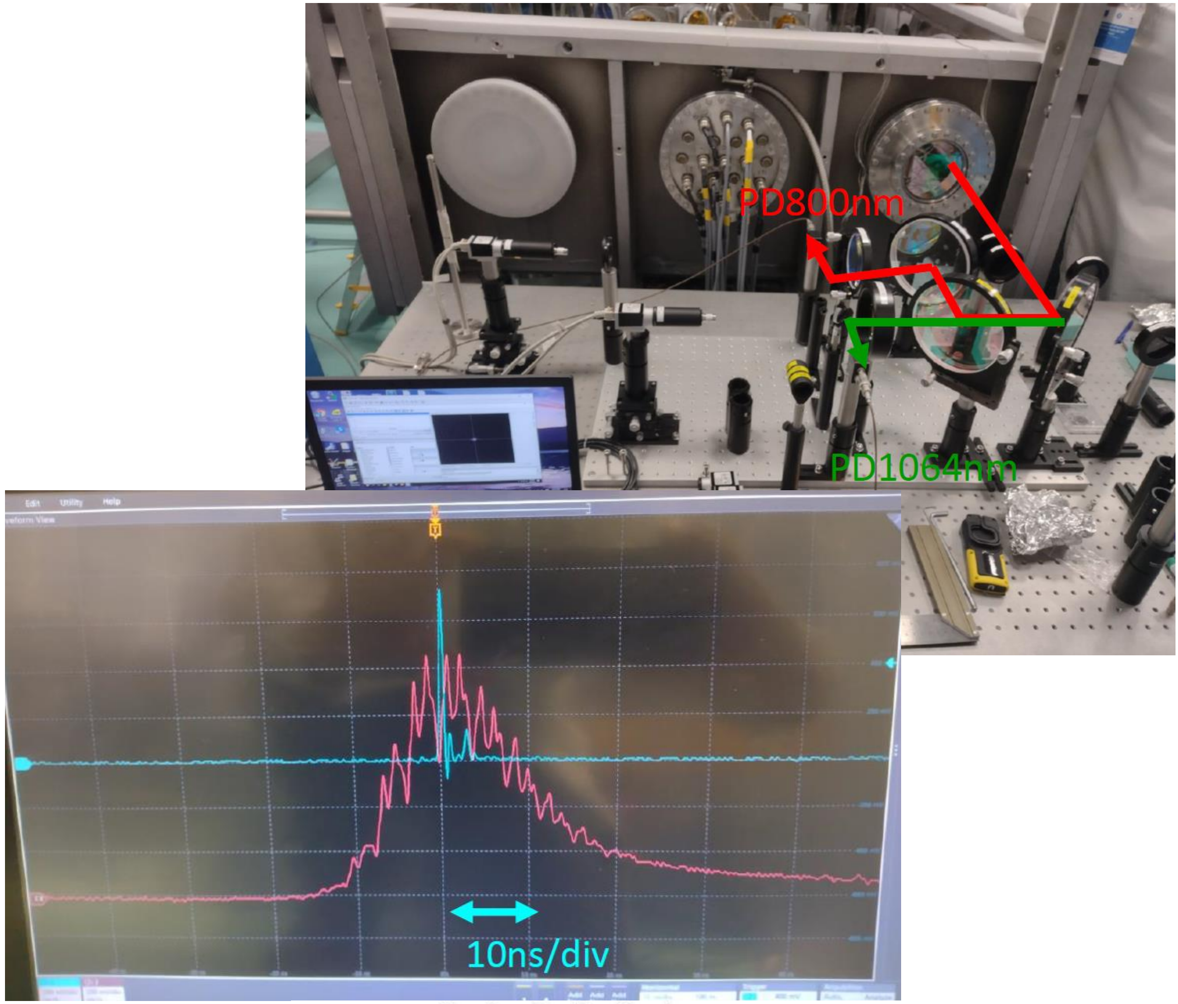


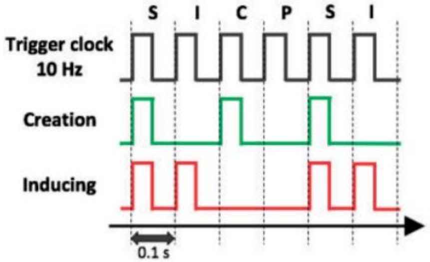




Timing adjustment

- Fast photodiodes used for timing measurement; fast oscilloscope for data acquisition
- Aim: Achieve temporal overlap of the fs pulse with the maximum area of the ns pulse
- Adjustment of the relative delay between the triggers for the two laser pulses
- HPLS pulse: 22-100fs, 800nm
- Nd:YAG pulse: 10ns, 1064nm
- Measurement of the timing jitter
- Setup on the laser diagnostics bench





Pattern	Pulse Combination
S	Creation + Inducing + Pedestal
I	Inducing + Pedestal
C	Creation + Pedestal
P	Pedestal

Progress and Perspectives

- First beamtime ongoing, ending mid-August; expectations: tuning of the system, first background measurements
- Second beamtime session foreseen for Septmber-October; expectations: background measurements at increased energy of the Ti:Sap and Nd:YAG laser pulses
- Third beamtime (Nov-Dec) will be performed in the UHV interaction chamber – improved vacuum for lower background; expectations: tests for highest vacuum achievable (with/w.o. bake-out), background measurements at high vacuum, tuning detection systems and signal to noise ratio
- Fourth beamtime (Q1 2022, last for commissioning experiment), in UHV chamber; expectations: final tuning, longer measurement sessions for significant 4wm signal in vacuum
- Letter of Intent submitted to ELI-NP by the **SAPPHIRES** collaboration for the continuation of the DM search experiments at the 100TW and then at 1PW areas at improved vacuum / increased energy per pulse conditions

Laser Driven Astrophysics, Particle Physics and Cosmology

Create extreme conditions plasma environments similar to astrophysical context – massive stars, supernovae, etc for the study of plasma dynamics and nucleosynthesis

- Production of extremely neutron-rich isotopes
- Electron screening effects in hot plasmas
- Study of nuclear reactions departing from excited states
- Dynamics of astrophysical plasmas
- Possibility to employ also gamma photons / accelerated electron beams together with high power lasers in experiments

Studies of particle physics and dark components of the Universe relevant for Cosmology

- Laboratory searches for dark fields
    - Weakly Interacting Massive Particles (WIMPS) such as super symmetric particles: direct production by particle colliders
    - Weakly Interacting Sub-eV Particles (WISPS) such as QCD axions
- Photon-photon interactions
- Vacuum properties – pair creation, birefringence

Astrophysical plasma in laboratory

- Scaling laws for MHD systems (D. D. Ryutov et al., ApJ. Suppl. 127, 465 (2000))
- Two types of astrophysically-relevant plasma can be produced in laboratory:
  - Thermal plasma (equil, dense): long pulse (ns) lasers
  - Kinetic plasma (out of equil, maximum E field): short-pulse lasers (ps-fs)
- Three possible approaches:
  - Study of fully scalable phenomena (e.g., extragalactic or stellar jets)
  - Investigate physics (e.g. strong turbulence)
  - Test models / numerical codes for certain non-ideal processes
- Accretion-ejection mechanisms: first experiments done with radial wire array (JETSETS FP6 projects, Lebedev et al 2005), proposal to continue at laser infrastructures (simulations A. Ciardi et al., Phys. Rev. Lett. 110, 025002, B. Albertazzi et al., Science 346, 325)

Astrophysics-related experiments with the ELI-NP Gamma Beam

- Larger energy range allows going further above the neutron separation threshold
- Better statistics or faster experiments due to superior intensity
- Energy bandwidth to approach with high precision the neutron separation energy – s-process studies
- Inverse reactions (γ,n) for determination of nuclear parameters: the single studies on long-lived branching points (e.g. 147Pm, 151Sm, 155Eu) showed that the recommended values of neutron capture cross sections in the models differ by up to 50% from the experimentally determined values; total (γ,n) cross-section measurements: 4π high efficiency n detector (3He)
- (γ,p) and (γ,α) reactions relevant for p-process nucleosynthesis – necessity of a broad database of measurements, requires short exposure times

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"Investing in Sustainable Development"

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Thank you!

www.eli-np.ro