Probing the Quantum Vacuum at the High-Intensity Frontier

– DFG Research Unit FOR 2783 – An Overview (2019 –) –

Holger Gies

FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

hhu Heinrich Heine Universität Düsseldorf

LMU

HI JENA HELMHOLTZ

Felix Karbstein, Stefan Karsch, Carsten Müller, Gerhard G. Paulus, Hartmut Ruhl, Jörg Schreiber, Kai Sven Schulze, Matt Zepf

www.quantumvacuum.org

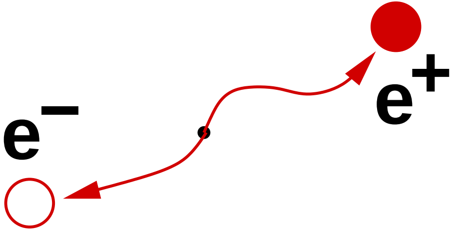
Strategy Meeting, Munich 20 June 2025

A view on the classical vacuum

Absence of anything

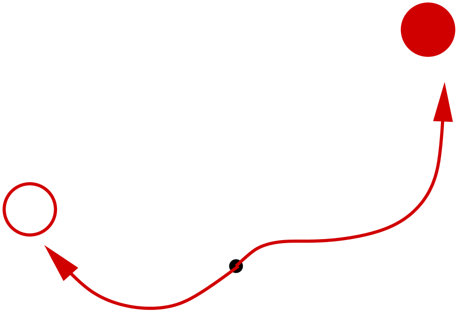
A view on the quantum vacuum

- Heisenberg's uncertainty principle, e.g. $\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$



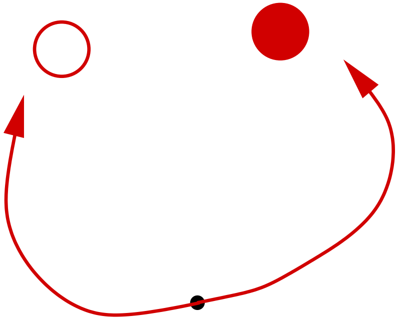
A view on the quantum vacuum

- Heisenberg's uncertainty principle, e.g. $\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$



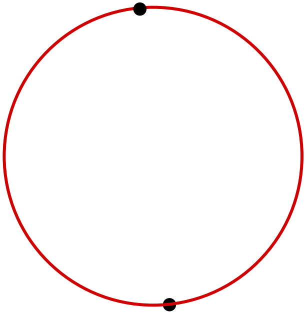
A view on the quantum vacuum

- Heisenberg's uncertainty principle, e.g. $\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$



A view on the quantum vacuum

▷ Heisenberg's uncertainty principle, e.g. $\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$

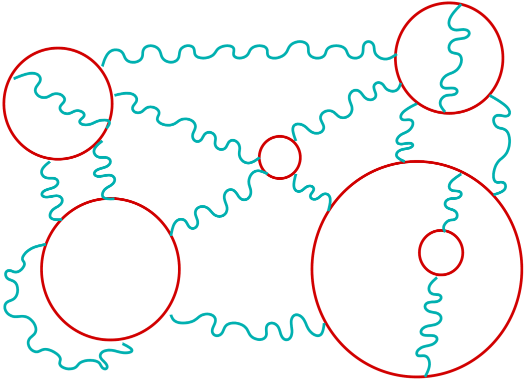


$$\lambda_\mathrm{C} = \frac{\hbar}{mc} \approx 3.9 \cdot 10^{-13}\,\mathrm{m}$$

$$\tau_\mathrm{C} = \frac{\lambda_\mathrm{C}}{c} \approx 1.3 \cdot 10^{-21}\,\mathrm{s}$$

A view on the quantum vacuum

▷ Heisenberg's uncertainty principle, e.g. $\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$

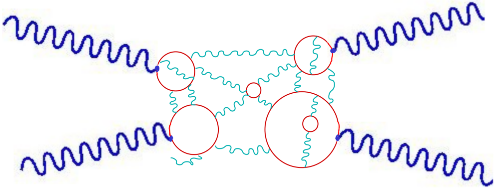


Quantum field theory: possibility of everything

Probing the quantum vacuum

▷ Quantum electrodynamics (QED): e.g., light-by-light scattering*

(Euler,Kockel 1935; Euler 1936)



$\Longrightarrow$ violation of Maxwell's superposition principle in vacuo

* 3) P. Debye, in einer mündlichen Diskussion mit Herrn Prof. Heisenberg.

Probing the quantum vacuum

▷ Heisenberg-Euler effective action

(Heisenberg,Euler 1936; Weisskopf 1936; Schwinger 1951)

Folgerungen aus der Diracschen Theorie des Positrons.

Von **W. Heisenberg** und **H. Euler** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

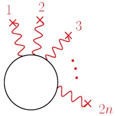
Aus der Diracschen Theorie des Positrons folgt, da jedes elektromagnetische Feld zur Paarerzeugung neigt, eine Abänderung der Maxwellschen Gleichungen des Vakuums. Diese Abänderungen werden für den speziellen Fall berechnet, in dem keine wirklichen Elektronen und Positronen vorhanden sind, und in dem sich das Feld auf Strecken der Compton-Wellenlänge nur wenig ändert. Es ergibt sich für das Feld eine Lagrange-Funktion:

$$\mathfrak{L} = \frac{1}{2}(\mathfrak{E}^2 - \mathfrak{B}^2) + \frac{e^2}{\hbar c}\int_0^\infty e^{-\eta}\frac{d\eta}{\eta^3}\left\{ i\eta^2(\mathfrak{E}\mathfrak{B})\cdot\frac{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)+\text{konj}}{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)-\text{konj}} + |\mathfrak{E}_k|^2 + \frac{\eta^2}{3}(\mathfrak{B}^2-\mathfrak{E}^2)\right\}.$$

$\Big(\mathfrak{E}, \mathfrak{B}$ Kraft auf das Elektron.

$$|\mathfrak{E}_k| = \frac{m^2c^3}{e\hbar} = \frac{1}{„137“}\,\frac{e}{(e^2/mc^2)^2} = \text{„Kritische Feldstärke“.}\Big)$$

Ihre Entwicklungsglieder für (gegen $|\mathfrak{E}_k|$) kleine Felder beschreiben Prozesse der Streuung von Licht an Licht, deren einfachstes bereits aus einer Störungsrechnung bekannt ist. Für große Felder sind die hier abgeleiteten Feldgleichungen von den Maxwellschen sehr verschieden. Sie werden mit den von Born vorgeschlagenen verglichen.

$$S_{\text{eff,HE}}[F] = \sum_{n=0}^{\infty}$$ 

▷ strong field nonlinearities

▷ quantum vacuum

$\simeq$ medium

▷ critical field:

$$E_{cr} \simeq 1.3 \times 10^{18}\, V/m$$

▷ vacuum instability:

pair production

Probing the quantum vacuum

- ▷ Heisenberg-Euler effective action

(Heisenberg,Euler 1936; Weisskopf 1936; Schwinger 1951)

Folgerungen aus der Diracschen Theorie des Positrons.

Von **W. Heisenberg** und **H. Euler** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

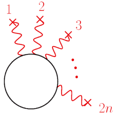
Aus der Diracschen Theorie des Positrons folgt, da jedes elektromagnetische Feld zur Paarerzeugung neigt, eine Abänderung der Maxwellschen Gleichungen des Vakuums. Diese Abänderungen werden für den speziellen Fall berechnet, in dem keine wirklichen Elektronen und Positronen vorhanden sind, und in dem sich das Feld auf Strecken der Compton-Wellenlänge nur wenig ändert. Es ergibt sich für das Feld eine Lagrange-Funktion:

$$\mathfrak{L} = \frac{1}{2}(\mathfrak{E}^2-\mathfrak{B}^2) + \frac{e^2}{\hbar c}\int_0^\infty e^{-\eta}\frac{d\eta}{\eta^3}\left\{ i\eta^2(\mathfrak{E}\mathfrak{B})\cdot\frac{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)+\text{konj}}{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)-\text{konj}} + |\mathfrak{E}_k|^2 + \frac{\eta^2}{3}(\mathfrak{B}^2-\mathfrak{E}^2)\right\}.$$

$$\left(\begin{array}{l}\mathfrak{E}, \mathfrak{B} \quad \text{Kraft auf das Elektron.} \\ |\mathfrak{E}_k| = \frac{m^2c^3}{e\hbar} = \frac{1}{\text{„}137\text{“}}\,\frac{e}{(e^2/mc^2)^2} = \text{„Kritische Feldstärke“.}\end{array}\right)$$

Ihre Entwicklungsglieder für (gegen $|\mathfrak{E}_k|$) kleine Felder beschreiben Prozesse der Streuung von Licht an Licht, deren einfachstes bereits aus einer Störungsrechnung bekannt ist. Für große Felder sind die hier abgeleiteten Feldgleichungen von den Maxwellschen sehr verschieden. Sie werden mit den von Born vorgeschlagenen verglichen.

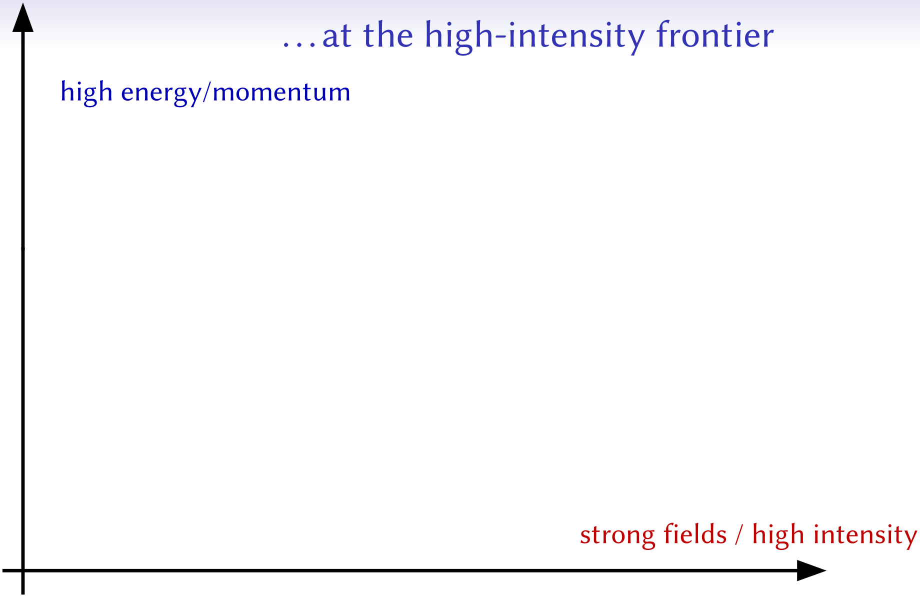
$$S_{\text{eff,HE}}[F] = \sum_{n=0}^{\infty}$$



- ▷ conceptual cornerstone of QFT

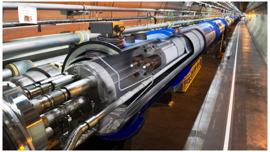
many predicted phenomena still
await their discovery

…at the high-intensity frontier



…at the high-intensity frontier

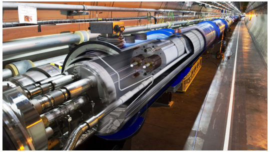
high energy/momentum

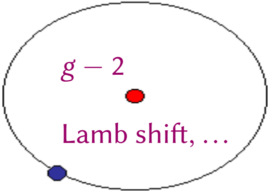


strong fields / high intensity

…at the high-intensity frontier

high energy/momentum





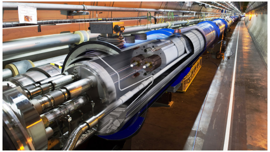
$g-2$

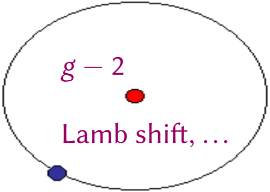
Lamb shift, …

strong fields / high intensity

…at the high-intensity frontier

high energy/momentum





Heisenberg-Euler regime

strong fields / high intensity

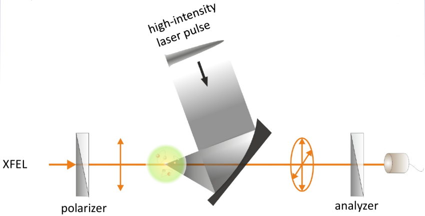
Theory		Experiment
T1 Vacuum birefringence	**Vacuum birefringence**	**E1** High-precision diamond X-ray polarimeters for the detection of vacuum birefringence
Quantum Field Theory		Laser Particle Physics
T2 Quantum vacuum nonlinearities in the all-optical regime	**Photon-scattering phenomena**	**E2** Spacetime resolved few-photon detection schemes for vacuum processes
Correlation functions		Precision metrology
T3 Electron-positron pair production	**Electron-positron pair production**	**E3** Towards pair production in the non-perturbative regime: Ultra-relativistic beams, laser characterisation & pair detection
Numerical simulations		High-intensity lasers

FOR 2783

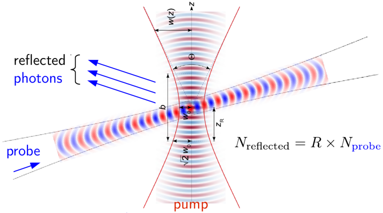
FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

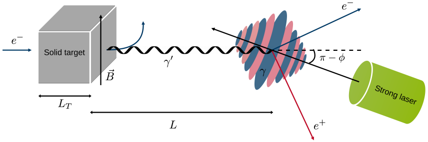
LMU



(Toll 1954; Heinzl et al. 2006)



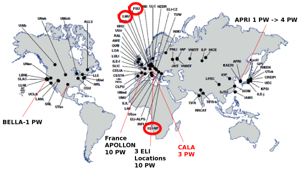
(Euler 1935; Gies, Karbstein, Seegert 2013)



(Breit, Wheeler 1934; Karsch, Zepf, E3 2018)

Why now? Why us?

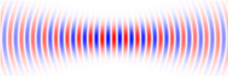
- Enabling high-intensity laser technology is coming online



ATLAS-3000 (M), Polaris/JETI (J), Draco/Penelope (HZDR), Arcturus (D), ELI (EU), NSF OPAL (USA), Apollon-Cilex (F), CoReLS (K), SEL (C), Gemini (UK), . . . , XFELs, . . . HED-HIBEF, . . .

- Theoretical description of QED in laser pulses, predictions of novel signatures from first principles

$\rightarrow$



- High-sensitivity detection schemes, precision metrology, in-house laser development, optimized beams

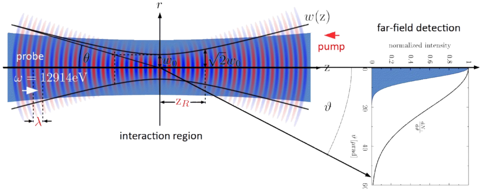
FOR 2783

T1
Vacuum birefringence

Vacuum birefringence

E1
High-precision diamond X-ray polarimeters for the detection of vacuum birefringence

T1: Vacuum Birefringence Theory

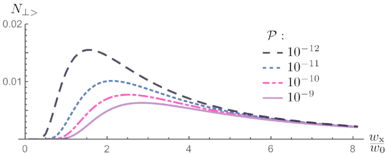


- accurate first-principle analysis
- discernibility criterion:

$$\frac{dN_{\text{signal}}}{d\cos\vartheta} \geq \mathcal{P}\,\frac{dN_{\text{bg}}}{d\cos\vartheta}$$

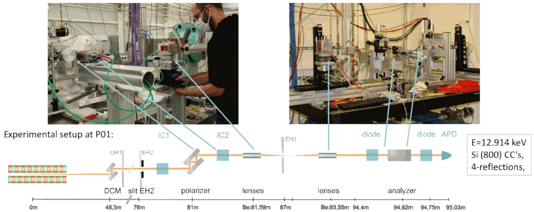
- first optimization for

HiBEF parameters:



(Karbstein,Mosman 2019; 2021; Karbstein et al. 2022)

E1: High Precision X-ray Polarimetry



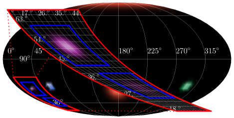
- new polarization purity $\mathcal{P}$ records
- first diamond quasi-channel-cut polarimeter
- high-definition polarimetry with suitable lenses
- first measurements at European XFEL, HiBEF

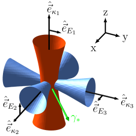
(Bernhard et al. 2020; Schmitt et al. 2021)

LoI (Biref@HIBEF, Ahmadiniaz'24), PoP-Exp (Smid et al.'25)

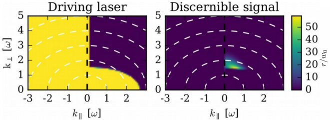
T2 Quantum vacuum nonlinearities in the all-optical regime — **Photon-scattering phenomena** — **E2** Spacetime resolved few-photon detection schemes for vacuum processes

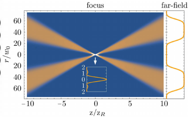
T2: Quantum-Vacuum Nonlinearities



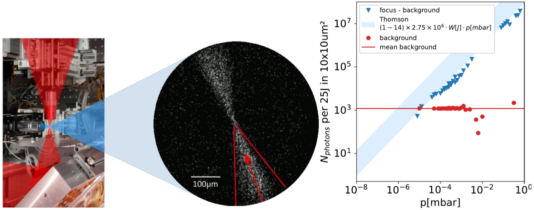


- analysis of multiple-beam scenarios (Gies,Karbstein,Klar'2021)
- discernible signals in full phase space
- numerical VE and HE solvers (Blinne et al.2019; Lindner,Ölmez,Ruhl 2021)
- enhanced signatures from tailored beams (Karbstein et al.'19'20; Maiwald'24)





E2: Spacetime-resolved Few Photon Detection



(Doyle et al. 2021)

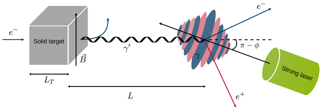
- first measurement of laser focus vacuum region
- time-gated background quantification
- identification of dominant background: geometric scattering
- design of scattering scenario using annular beams (Zepf et al. 1998; Schütze et al.'24)

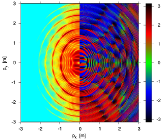
T3
Electron-positron pair production

Electron-positron pair production

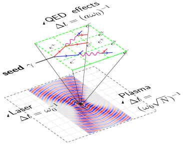
E3
Towards pair production in the non-perturbative regime: Ultra-relativistic beams, laser characterisation & pair detection

T3: Electron-Positron Pair Production

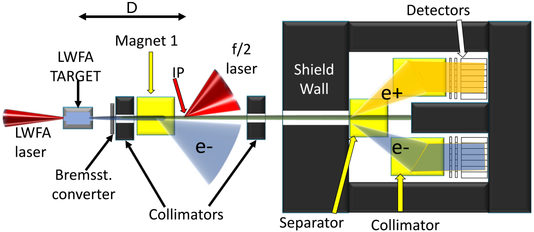




- linear Breit-Wheeler in focused pulse (Golub,Villalba-Chávez,Ruhl,Müller 2021)
- positron phase space distributions
- total pair yield and spectra for E3 (Salgado et al. 2021; Eckey et al.'24; Elsner et al. 2025)
- methods for nonperturbative pulse shape effects (Krajewska,Kaminski,Müller 2021)
- self-consistent numerical framework (Bild,Deckert,Ruhl 2019)

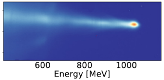


E3: Ultrarelativistic Beams, Laser Characterization & Pair Production



(Salgado et al. 2021)

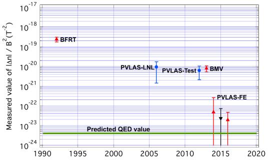
- e^- beam development (v.Grafenstein'23)
- γ beam characterization
- highly sensitive $e^\pm$ detectors in the presence of strong backgrounds
- design + bunker for CALA



Competing quantum vacuum experiments

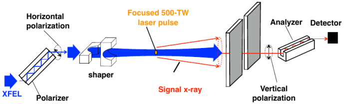
- magnet-based experiments:
  PVLAS (Ferrara), BMV (Toulouse), OVAL (Tokyo)

(Battesti et al.'2018)



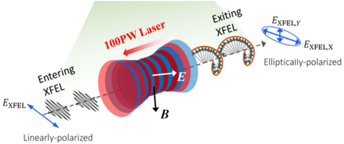
- @SACLA (Japan)

(Inada et al. 2017; Seino et al. 2020)



- @SEL (China)

(Shen et al. 2018)



- CLPU Madrid (Roso et al. 2021)
- FACET-II (Borysov et al. 2025)
- NSF-OPAL (Rinderknecht et al. 2025)

Quantum vacuum physics: emerging opportunities

▷ Quantum effective actions:

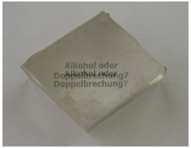
effective field theories near thresholds

▷ vacuum birefringence:

fundamental precision QED

$$\Delta n \simeq \frac{6}{45}\left(1+\frac{25}{4}\frac{\alpha}{\pi}+\dots\right)\frac{\alpha^2}{m^4}\, I$$

▷ quantum vacuum as a building block



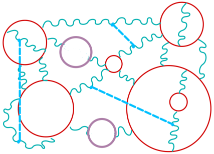
“The vacuum is a medium”

nonlinear phenomena

high-intensity metrology

▷ search for “new physics”

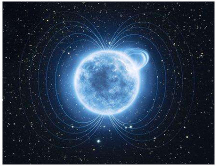
all fields contribute to the quantum vacuum



sensitivity to weakly interacting, light particles

axions, dark matter candidates …

▷ laboratory tests of astrophysical strong-field environments



(Mignani et al. 2016)

(Capparelli et al. 2017)

polarization properties of pulsars, magnetars, etc.

FOR 2783 objectives (resonating well with the referees)

▷ Probing the quantum vacuum at the high-intensity frontier

- understanding the ground state of nature

  "The vacuum is a medium"

- exploring uncharted territory of fundamental physics

  ... high amplitude vs. high energy

- establish ultra-intense lasers as instruments

  for "grand challenges"

$\Longrightarrow$ FOR2738: seizing the golden opportunity for first discoveries

and triggering the emergence of new fields

FOR 2783 objectives (resonating well with the referees)

▷ Probing the quantum vacuum at the high-intensity frontier

- understanding the ground state of nature

  "The vacuum is a medium"

- exploring uncharted territory of fundamental physics

  …high amplitude vs. high energy

- establish ultra-intense lasers as instruments

  for "grand challenges"

$\Longrightarrow$ SFB TR XY: seizing the golden opportunity for first discoveries

and triggering the emergence of new fields

Strong-field QED/QFT topics beyond FOR 2783

▷ Strong-field QED

- radiation reaction
- nonlinear Compton scattering
- Bethe-Heitler, Trident, spin-polarized, twisted beams …
- Schwinger pair production
- QED plasma physics

▷ Facilities/Instrumentation

- “better beams”
- stabilization, diagnostics
- detector R&D
- …

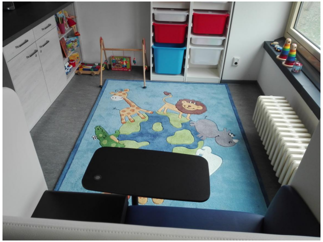
▷ Theory/Computational

- PIC, QED+plasma
- integration of our codes –> PIC
- QED/QFT beyond perturbation theory

▷ Application

- search for novel particles
- high-intensity metrology
- laboratory astrophysics
- plasma accelerators
- secondary pulsed beams
- …

Aspects of Coordination



- family-friendly working conditions

  child care, toddler-proof office space,
  home-office equipment, kid's corners

- gender equality measures
  - Physik für Schülerinnen, Girls' Day, Photon Lab
  - pro-active head-hunting of ESRs
  - funding of dissemination tours

  ...increase individual visibility