Gamma Factory concepts and beams for the dark sector

ARIES, APEC & iFAST SMART PAF Brainstorming and Strategy Workshop, March-April 2022

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The Gamma Factory proposal for CERN†

Abstract

This year, 2015, marks the centenary of the publication of Einsteins Theory of General Relativity and it has been named the International Year of Light and light-based technologies by the UN General Assembly It is thus timely to discuss the possibility of broadening the present CERN research program by including a new component based on a novel concept of the light source which could pave a way towards a multipurpose Gamma Factory. The proposed light source could be realized at CERN by using the infrastructure of the existing accelerators. It could push the intensity limits of the presently operating light-sources by at least 7 orders of magnitude, reaching the flux of the order of 10^{17} photons/s, in the particularly interesting γ-ray energy domain of $1 \leq E_{photon} \leq 400$ MeV. This domain is out of reach for the FEL-based light sources. The energy-tuned, quasi-monochromatic gamma beams, together with the gamma-beams-driven secondary beams of polarized positrons, polarized muons, neutrons and radioactive ions would constitute the basic research tools of the proposed Gamma Factory. The Gamma Factory could open new research opportunities at CERN in a vast domain of uncharted fundamental physics and industrial application territories. It could strengthen the leading role of CERN in the high energy frontier research territory by providing the unprecedented-brilliance secondary beams of polarized muons for the TeV-energy-scale muon collider and for the polarized-muon-beam based neutrino factory.

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† An Executive Summary of the proposal addressed to the CERN management.

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Gamma Factory

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Today :

~ 100 physicists

40 Institutes

13 countries

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A potential place of Gamma Factory in the future CERN research programme

- *The **next** CERN **high-energy frontier** project may take **long time** to be approved, built and become operational, … unlikely before 2045 (FCC-ee) or 2050+ (μ-collider)*
- *The **present** LHC **research programme** will certainly reach **earlier** (~2035?) its discovery **saturation** (little physics gain by a simple extending its pp/pA/AA running time)*
- *A strong **need** will certainly arise for a **novel** multidisciplinary programme which could **re-use** ("co-use") the **existing** CERN facilities (including LHC) in **ways** and at **levels** that were **not** necessarily **thought** of when the machines were **designed***

***The Gamma Factory** research programme (2035-????) could fulfil such a role. It can exploit **the existing world unique opportunities** offered by the CERN accelerator complex and CERN's scientific infrastructure **(not available elsewhere**) to conduct new, diverse, and vibrant research.*

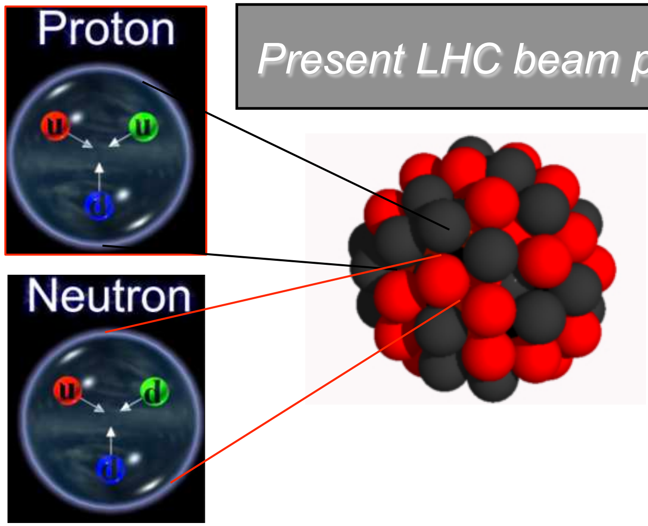
The Gamma Factory in a nutshell

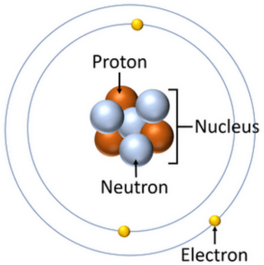
- *The infrastructure and the operation mode of the CERN accelerators allowing to:*

    - *produce, accelerate, cool, and store beams of highly ionised atoms*
    - *excite their atomic degrees of freedom by laser photons to form high intensity secondary beams of gamma rays*
    - *produce plug-power-efficient diverse tertiary beams*

- *The research programme in a broad domain of science enabled by the "Gamma Factory tools"*

Present LHC beam particles:

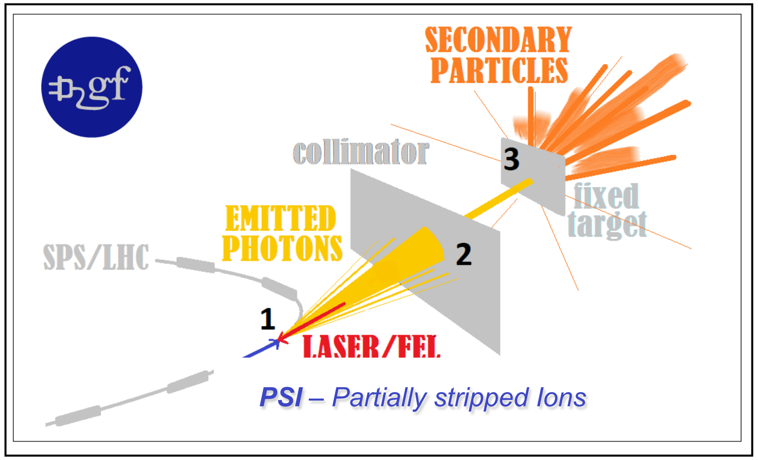




Future LHC beam particles:

Partially Stripped Ions (highly ionized atoms)

The Gamma Factory proposal for CERN
Mieczyslaw Witold Krasny (Paris U., VI-VII) (Nov 24, 2015)
e-Print: 1511.07794 [hep-ex]



Atomic beams in the LHC (Hydrogen-like Lead)

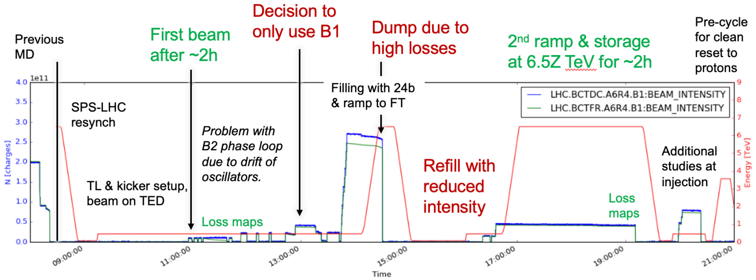
symmetry dimensions of particle physics — topics — follow

A joint Fermilab/SLAC publication

LHC accelerates its first "atoms"

07/27/18 | By Sarah Charley

Lead atoms with a single remaining electron circulated in the Large Hadron Collider.



CERN-ACC-NOTE-2019-0012

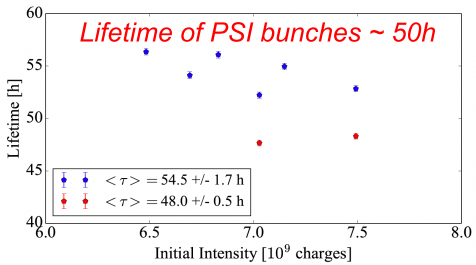
8 May 2019

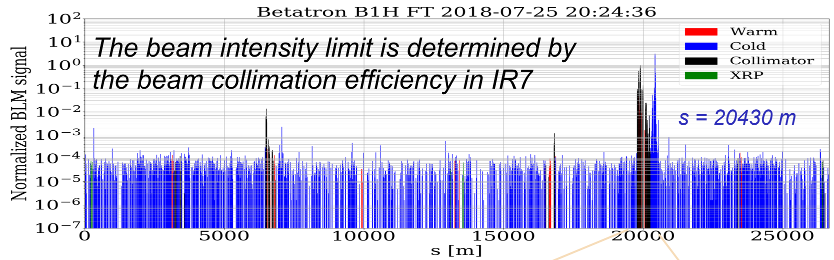
Michaela.Schaumann@cern.ch

MD3284: Partially Stripped Ions in the LHC

M. Schaumann, A. Abramov, R. Alemany Fernandez, T. Argyropoulos, H. Bartosik, N. Biancacci, T. Bohl, C. Bracco, R. Bruce, S. Burger, K. Cornelis, N. Fuster Martinez, B. Goddard, A. Gorzawski, R. Giachino, G.H. Hemelsoet, S. Hirlaender, M. Jebramcik, J.M. Jowett, V. Kain, M.W. Krasny, J. Molson, G. Papotti, M. Solfaroli Camillocci, H. Timko, D. Valuch, F. Velotti, J. Wenninger

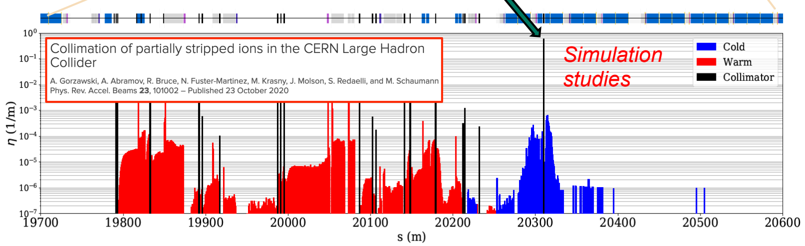
CERN, CH-1211 Geneva 23





Mitigation strategies:

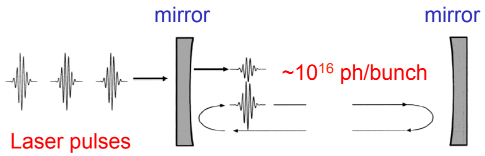
1. *Dispersion suppressor collimator (TCLD)*
2. *Crystal collimation*
3. *Laser collimation*

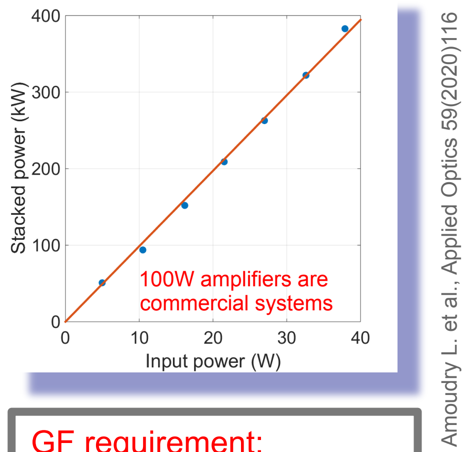


A dedicated LHC MD with crystal collimation of the PSI (H-like Pb) beam is a natural next step…

Fabry-Pérot (FP) resonators
and their integration in the electron storage rings

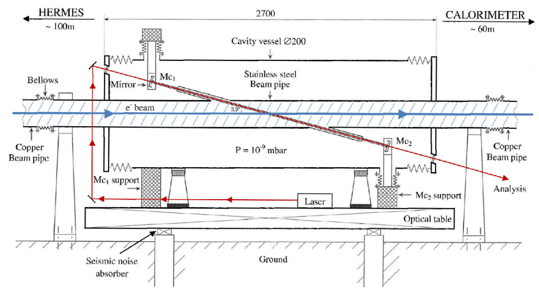
Fabry-Pérot resonator



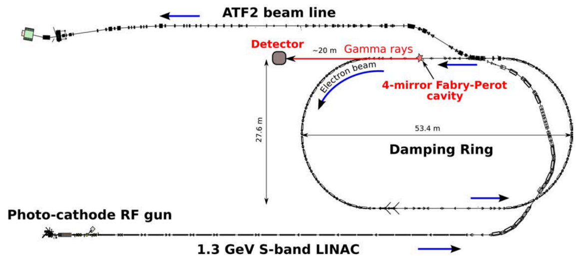


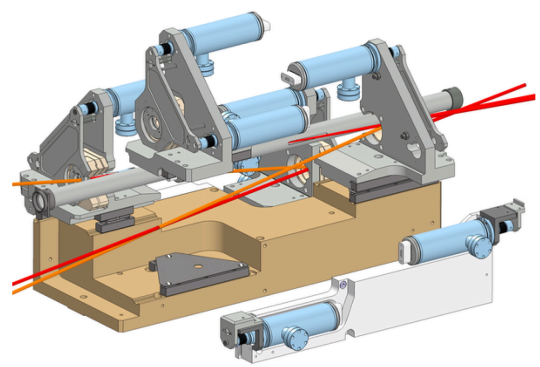
GF requirement:
< 5mJ pulses @ 40MHz,
(200kW photon beam)

HERA storage ring



KEK – ATF ring





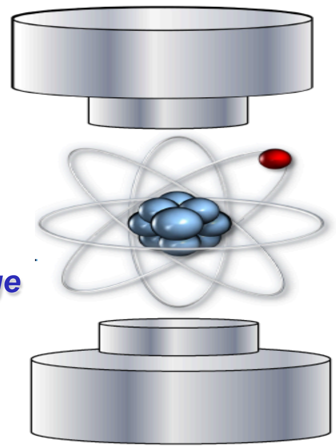
Towards the first integration of the FP resonator in the hadron storage ring →

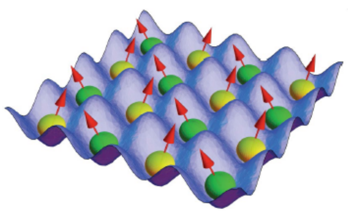
GF research tools made from light

1.Atomic traps of highly-charged, “small-size” atoms

Atomic rest-frame

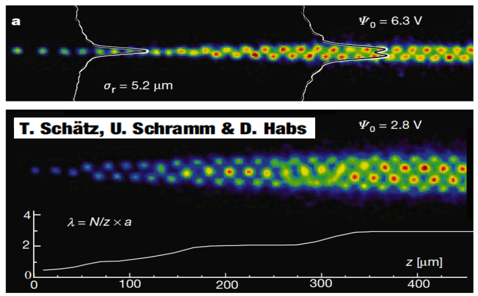
Trapped stationary atoms
Exposed to pulsed magnetic and electric fields of the storage ring





Crystalline beams?

letters to nature



__Opening new research opportunities:__

- *Highly-charged atoms – very strong (~10^{16} V/cm) electric field (QED-vacuum effects)*
- *Small size atoms (electroweak effects)*
- *Hydrogen-like and Helium-like atomic structure (calculation precision and simplicity)*
- *Atomic degrees of freedom of trapped highly-charged atoms can be resonantly excited by lasers*
- *Circular, repetitive relativistic motion of the GF atomic traps → Lorentz invariance tests and gravitational wave detection*

adp annalen der physik
Feature Article | Open Access

Atomic Physics Studies at the Gamma Factory at CERN

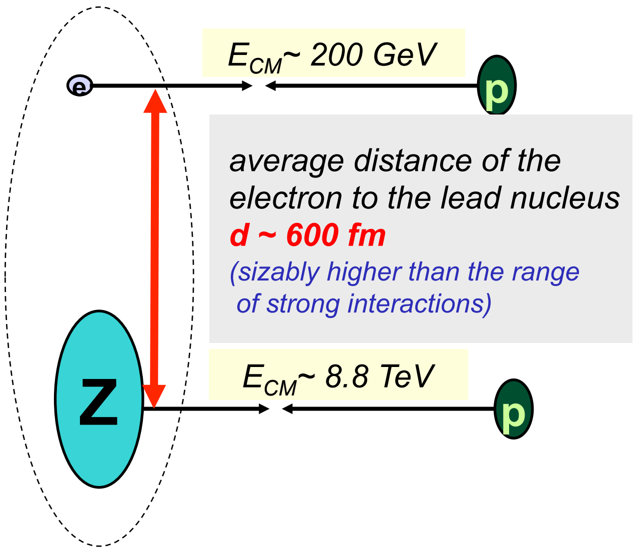
Dmitry Budker, José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczyslaw Witold Krasny, Alexey Petrenko, Szymon Pustelny, Andrey Surzhykov, Vladimir A. Yerokhin, Max Zolotorev ... See fewer authors ^

First published: 09 July 2020 | https://doi.org/10.1002/andp.202000204

2.Electron beam for ep collisions at LHC

(in the ATLAS, CMS, ALICE and LHCb interaction points)

Hydrogen-like lead



Atomic beams can be considered as ***independent electron and nuclear beams*** *as long as the incoming proton scatters with the momentum transfer q >> 300 KeV!*

Opens the possibility of collecting, by each of the LHC detectors, over one day of the ***Pb+81–p*** *operation, the effective ep-collision luminosity comparable to the HERA integrated luminosity in the first year of its operation (1992) – in-situ diagnostic of the emittance of partonic beams at the LHC!*

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Nuclear Instruments and Methods in Physics Research A 540 (2005) 222–234

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Electron beam for LHC

Initial studies:

Mieczyslaw Witold Krasny

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Received 14 September 2004; received in revised form 19 November 2004; accepted 23 November 2004
Available online 22 December 2004

Very recent important development:

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 101002 (2020)

Editors' Suggestion

Collimation of partially stripped ions in the CERN Large Hadron Collider

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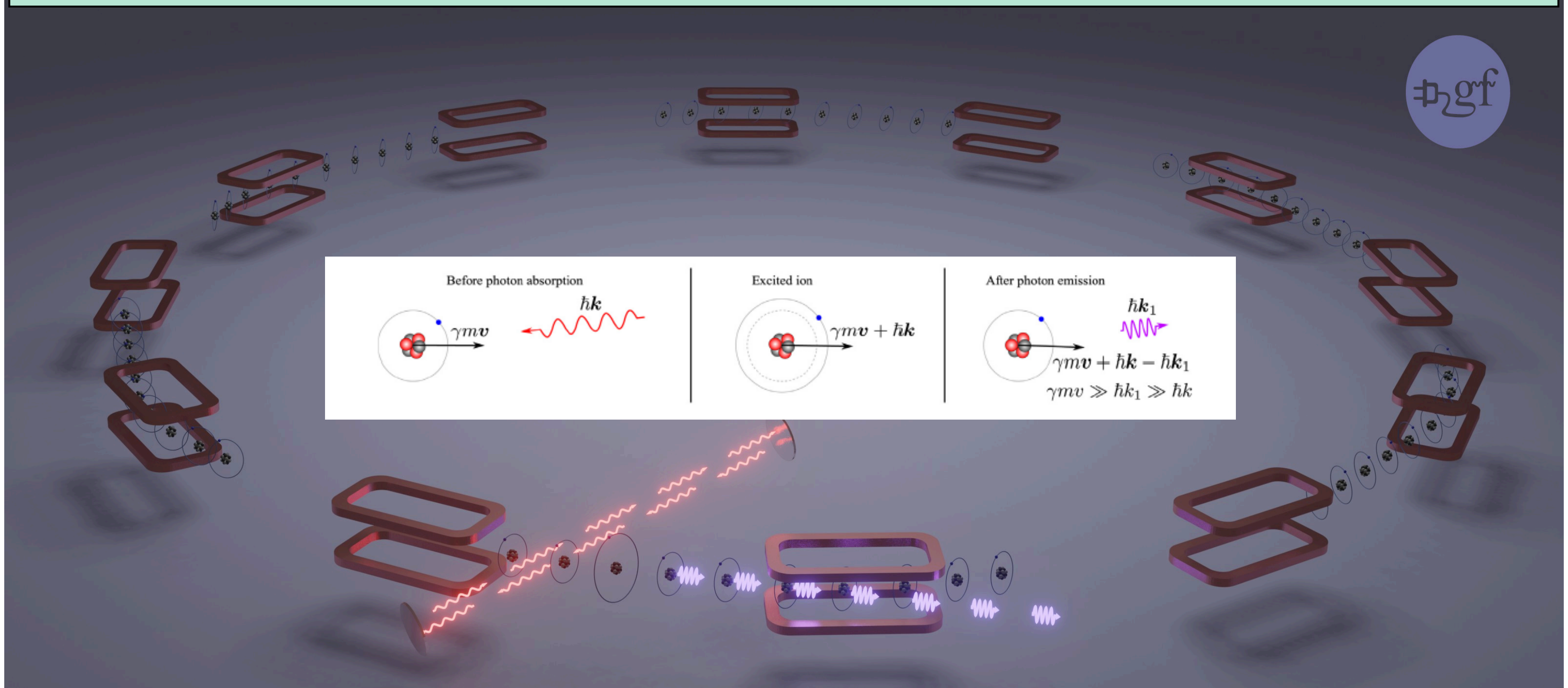
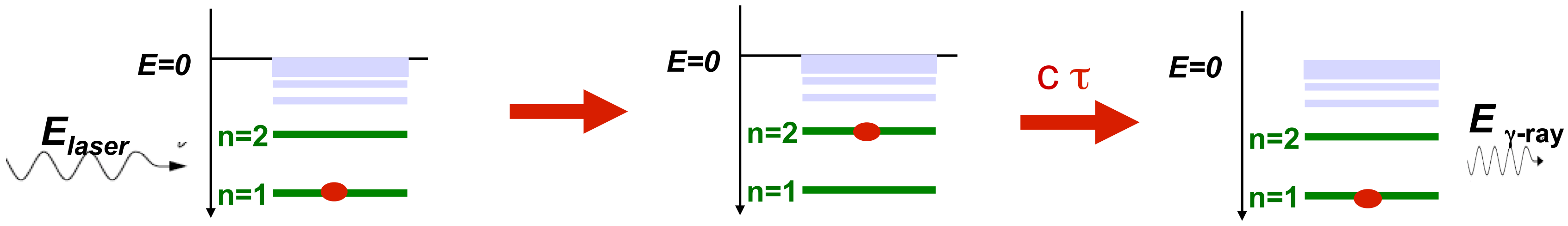
(Received 3 August 2020; accepted 5 October 2020; published 23 October 2020)

3.Gamma Factory γ-source



Novel technology: Resonant scattering of laser photons on ultra-relativistic atomic beam

Source properties



1. Point-like:

➢ *For high-Z, hydrogen- and helium-like atoms:* ***decay length ($c\tau\gamma_L$) << 1 cm***

2. High intensity:

➢ ***Resonant*** *process. A leap in the intensity by* ***6–8 orders of magnitude*** *w.r.t. electron-beam-based Inverse Compton Sources (ICS) (at fixed γ_L and laser power)*

Source properties

High energy atomic beams play the role of **high-stability light-frequency converters**:

$$\nu^{max} \longrightarrow (4\,\gamma_L^{\,2})\,\nu_{Laser}$$

for photons emitted in the direction if incoming atoms, $\gamma_L = E/M$ is the Lorentz factor for the ion beam

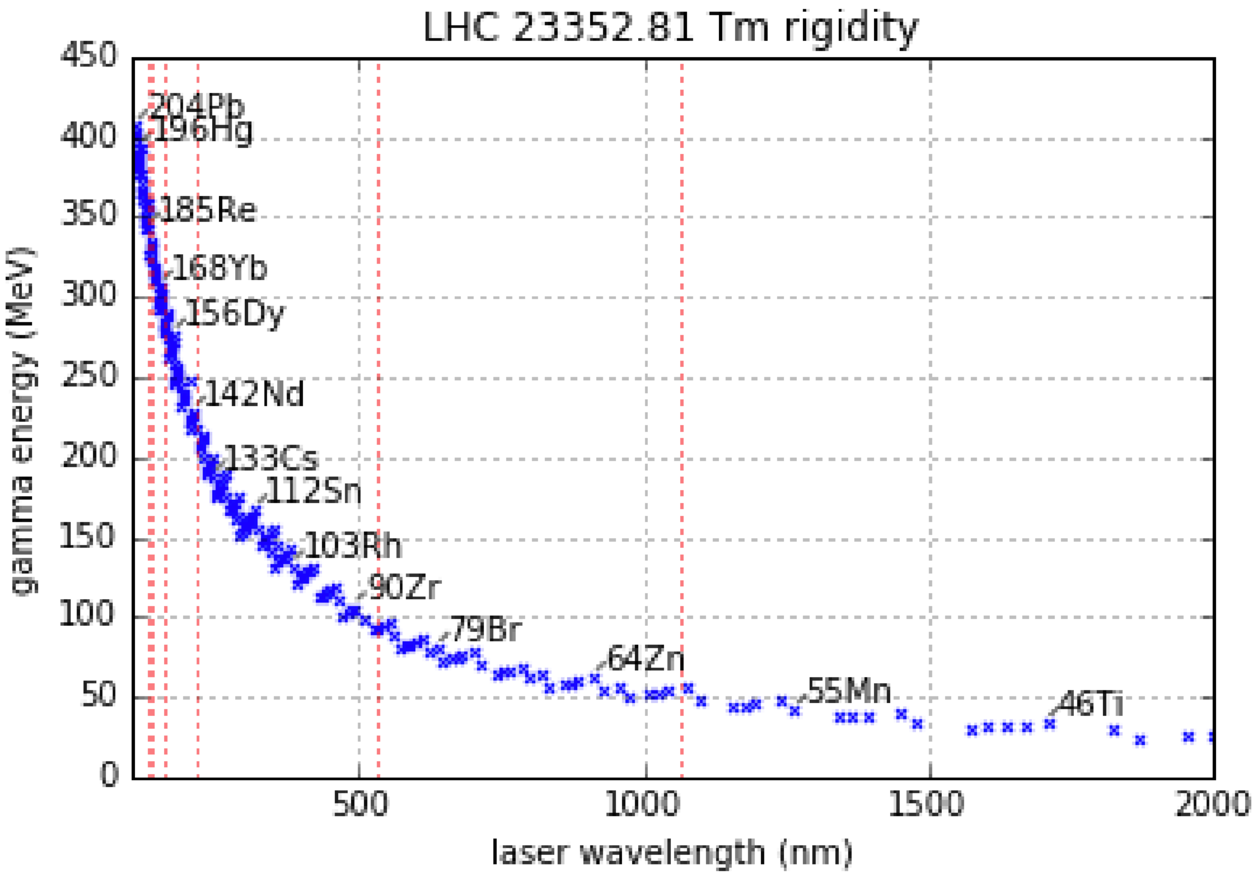
3.Tuneable energy and polarisation:

- *The tuning of the beam energy (SPS or LHC), the choice of the ion, the number of left electrons and of the laser type allow to tune the γ-ray energy at CERN in the energy range of 10 keV – 400 MeV (extending, by a factor of **~1000**, the energy range of the FEL X-ray sources); polarisation tuning via laser photon polarisation tuning and the use of helium-like atoms*

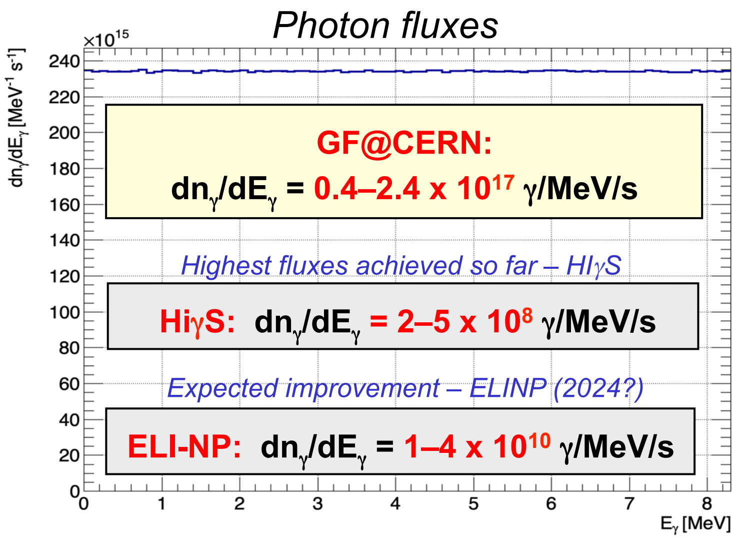
4. Plug power efficient:

- *Atoms loose a tiny fraction of their energy in the process of the photon emission. Important: No need to refill the driver beam. The RF power is fully converted to the power of the photon beam*

Radial n=1→ n=2 atomic excitation, maximal energy, zero crossing amgle



A concrete example: Nuclear physics application: He-like, LHC Calcium beam, $(1s \rightarrow 2p)_{1/2}$ transition, TiSa laser

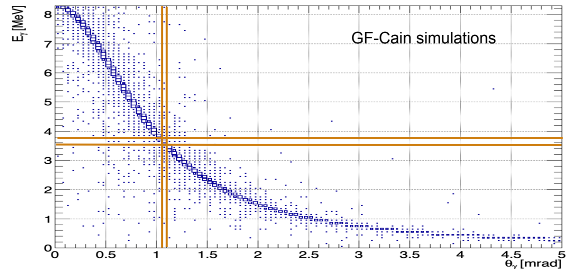


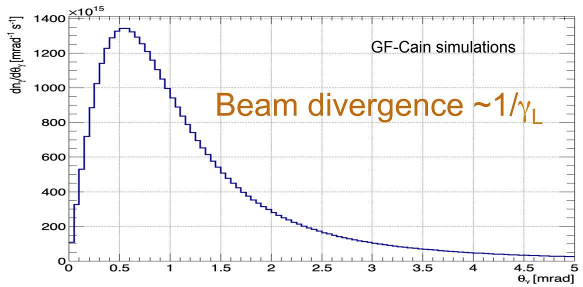
laser pulse parameters

- Gaussian spatial and time profiles,
- photon energy: E_photon = 1.8338 eV
- photon pulse energy spread: sigma_{omega}/omega = 2 x 10^{-4},
- photon wavelength: lambda = 676 nm,
- pulse energy: W_{l} = 5 mJ,
- peak power density 1.12 x 10^13 W/m^2
- r.m.s. transverse beam size at focus: sigma_{x} = \sigma_{y } = 150 um (micrometers),
- Rayleigh length: R_{L,x} = R_{L,y} = 7.5 cm,
- r.m.s. pulse length: l_{l} = 15 cm.

5. Highly-collimated monochromatic γ–beams:

- *the beam power is concentrated in a narrow angular region (facilitates beam extraction)*
- *the $(E_\gamma, \Theta_\gamma)$ correlation can be used (collimation) to "monochromatize" the beam*

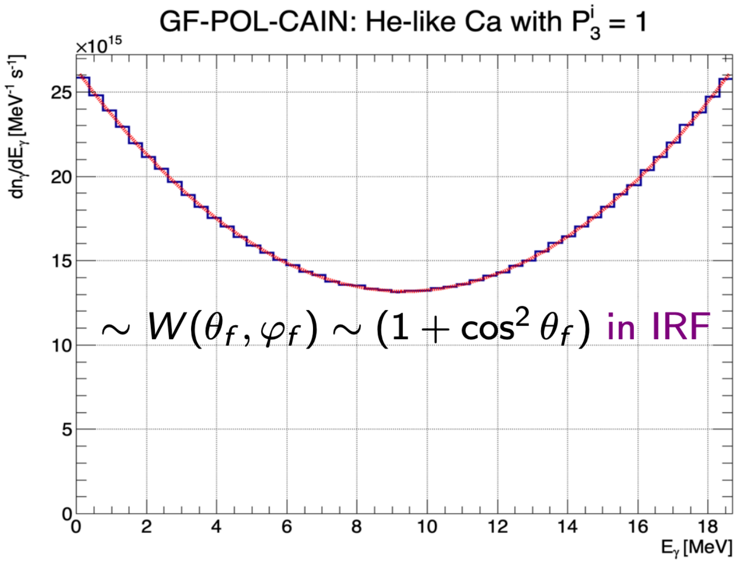




$nS_0 \to n'P_1 \to nS_0$: Helium-like Calcium $\to$ RIB @ LHC

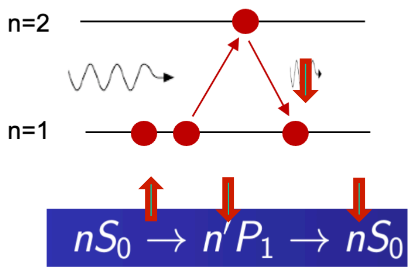
- **PSI beam:** ${}^{40}_{20}\mathrm{Ca}^{18+}$ with transition: $1s^2\ {}^1S_0 \to 1s^1 2p^1\ {}^1P_1$
  - transition energy and lifetime: $\hbar\omega_0 = 3902.3775\,\mathrm{eV}$, $\tau_0 = 6\,\mathrm{fs}$
  - ion mass: $M_i = 37.332\,\mathrm{GeV/c^2}$
  - ion energy and relative spread: $E_i = 89.4093\,\mathrm{TeV}$, $\sigma_E = 2 \times 10^{-4}$
  - relativistic factor: $\gamma_i = 2394.9782$
  - number of ions per bunch $N_i = 3 \cdot 10^9$
  - Twiss parameters: $\alpha_x = \alpha_y = 0$, $\beta_x = \beta_y = 50\,\mathrm{m}$
  - geometric emittance: $\epsilon_x = \epsilon_y = 3 \cdot 10^{-10}\,\mathrm{m} \times \mathrm{rad}$
  - r.m.s transverse beam size: $\sigma_x = \sigma_y = 0.1225\,\mathrm{mm}$
  - r.m.s. bunch length $\sigma_z = 15\,\mathrm{cm}$
- **Laser:** Er:glass – Gaussian spatiotemporal profile, beam angle: $0°$
  - photon energy and rel. spread: $E_\gamma = 0.8147\,\mathrm{eV}$, $\sigma_\omega = 2 \times 10^{-4}$
  - photon wavelength: $\lambda_\gamma = 1521.84\,\mathrm{nm}$
  - pulse energy: $W_l = 0.5\,\mathrm{mJ}$ $(2\,\mathrm{mJ})$
  - peak power density: $P_{00} = 2.822 \cdot 10^{13}\,\mathrm{W/m^2}$
  - r.m.s. transverse beam size at focus: $\sigma_x = \sigma_y = 0.15\,\mathrm{mm}$
  - Rayleigh length: $R_{L,x} = R_{L,y} = 41.81996\,\mathrm{cm}$
  - r.m.s. pulse duration: $\sigma_t = 50\,\mathrm{ps}$ $(\sigma_t = 500\,\mathrm{ps})$

circular laser photon polarisation

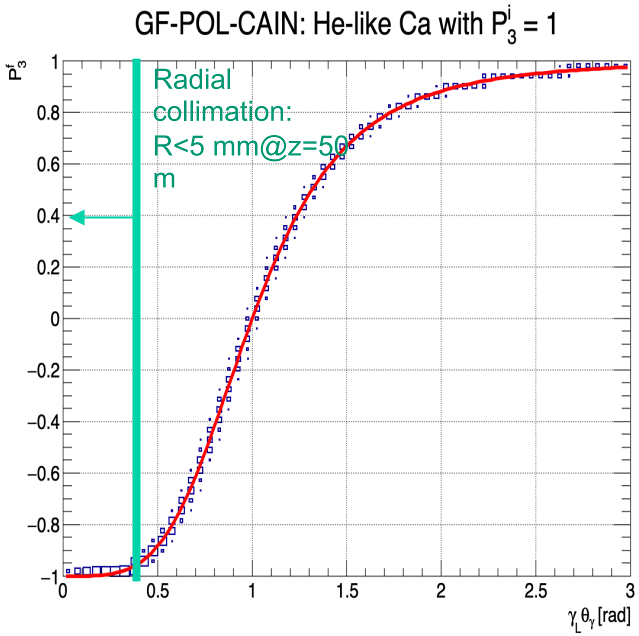


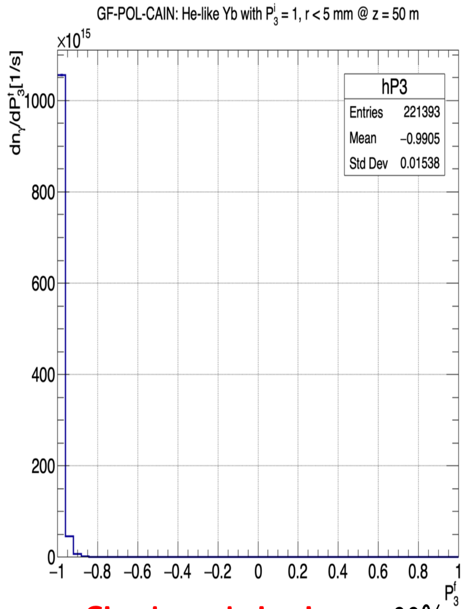
An example: He-like, Calcium beam, Er:glass laser (1522 nm) - circular polarisation

A trick: $1s^2\ ^1S_0 \rightarrow 1s^1\ 2p^1\ ^1P_1$ transition in He-like atoms



Closed transition in Helium-like atoms (n=1, n' =2) preserve initial polarisation of the laser light

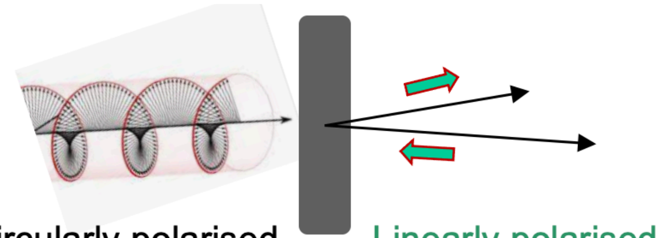


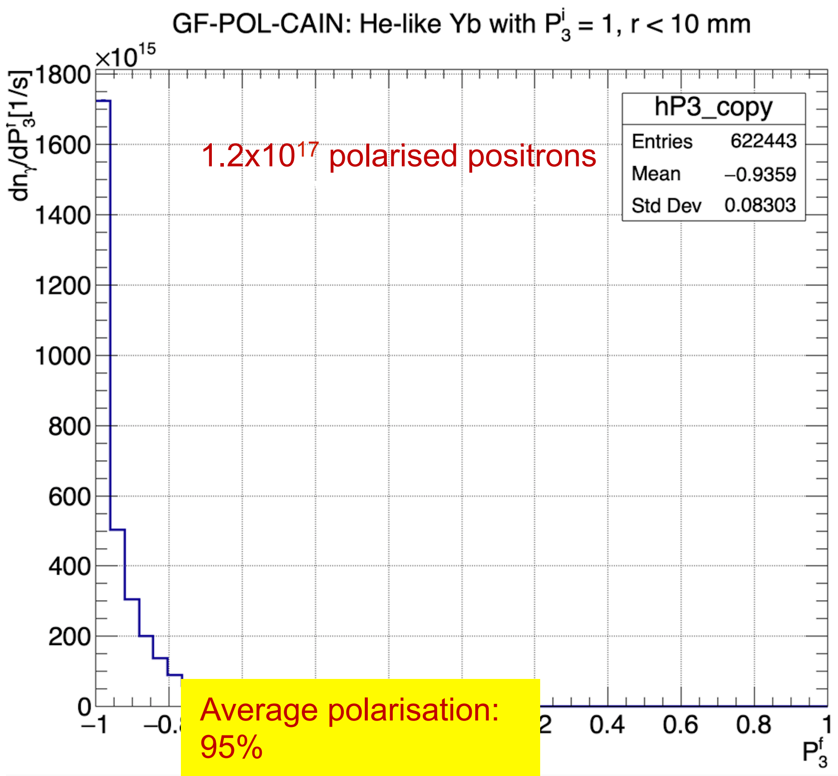


→ Circular polarization ≈ 99%

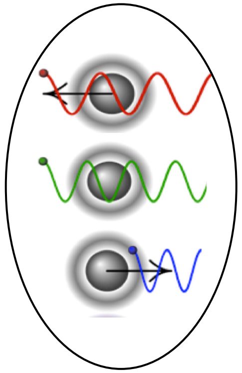
For more details see presentations at our recent, November 2021, Gamma Factory workshop: https://indico.cern.ch/event/1076086/

Polarized lepton source from polarized gamma beams

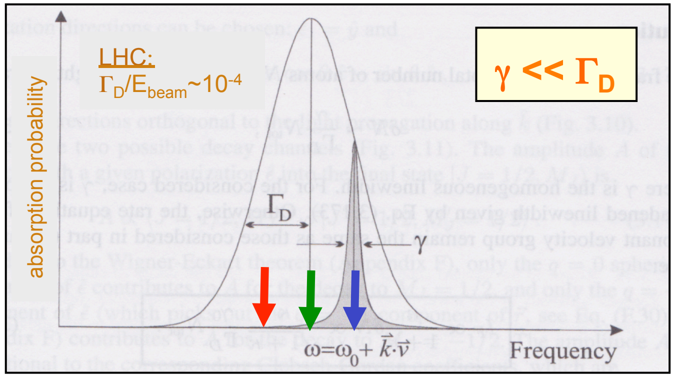


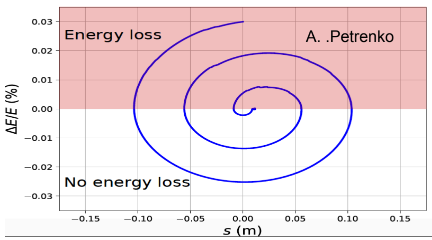


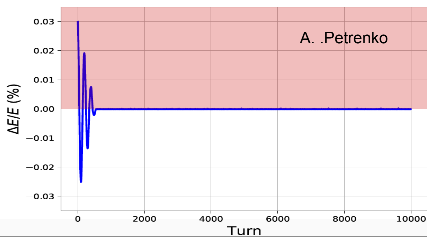
4.Doppler laser cooling methods of high energy beams



Bunch

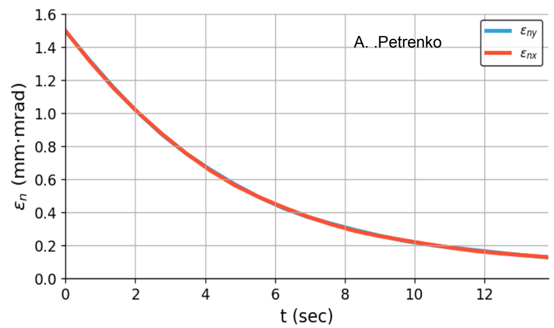






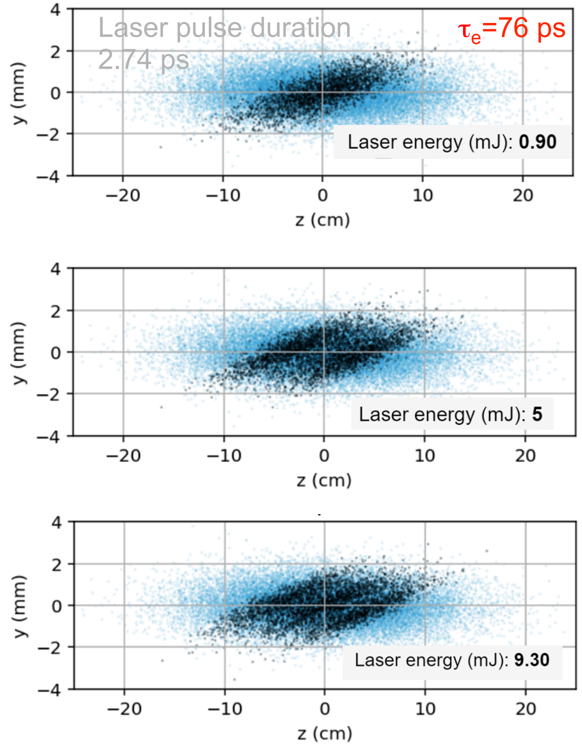
***Beam cooling speed**: the laser wavelength band is chosen such that only the ions moving in the laser pulse direction (in the bunch rest frame) can resonantly absorb photons.*

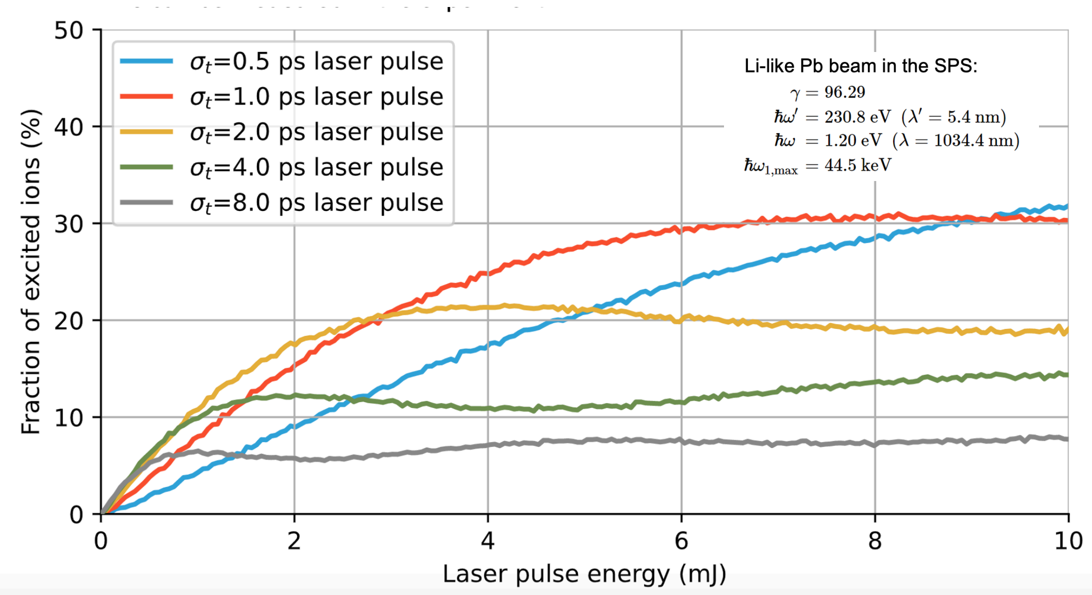
Opens a possibility of forming at CERN hadronic beams of the required longitudinal and transverse emittances within a seconds-long time scale



Simulation of laser cooling of the lithium-like Ca(+17) bunches in the SPS: transverse emittance evolution.

5. Atomic Quantum interference effects



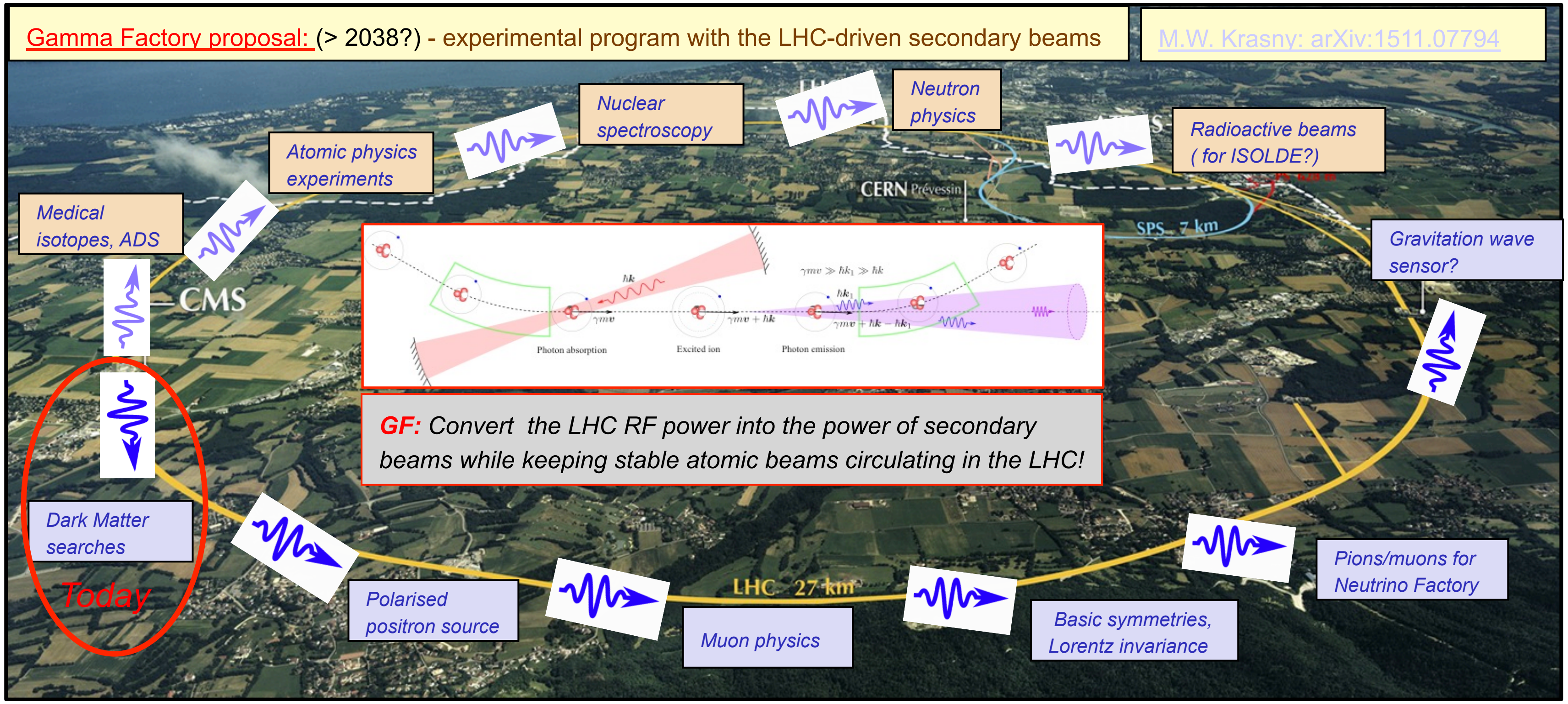


Clear imprint of Quantum-Mechanical interference effects (Rabi oscillations) on the observables which will me measured in the GF-PoP@SPS experiment!

6.Tertiary beams' sources – Intensity/quality targets

- ***Polarised positrons*** – potential gain of up to *a factor of 10^4* in intensity w.r.t. the KEK positron source, satisfying both the LEMMA and the LHeC requirements
- ***Pions*** – potential, gain by *a factor of 10^3, gain* in the spectral density ($dN_\pi/dEdp_TdP$ [MeV^{-2} x MW^{-1}]) with respect to proton-beam-driven sources at KEK and FNAL (P is the driver beam power)
- ***Muons*** – potential gain by *a factor of 10^3* in intensity w.r.t. the PSI muon source, charge symmetry ($N\mu^+ \sim N\mu^-$), polarisation control, no necessity of the muon beam cooling (to be proven)?
- ***Neutrinos*** – fluxes comparable to NuMAX but: (1) *Very Narrow Band Beam*, driven by the small spectral density pion beam and (2) unique possibility of creating *flavour- and CP-tuned beams* driven by the beams of polarised muons
- ***Neutrons*** – potential gain of up to *a factor of 10^4* in intensity of primary MeV-energy neutrons per 1 MW of the driver beam power
- ***Radioactive ions*** – potential gain of up to *a factor 10^4* in intensity w.r.t. e.g. ALTO

The LHC as a driver of secondary beams (operation mode)

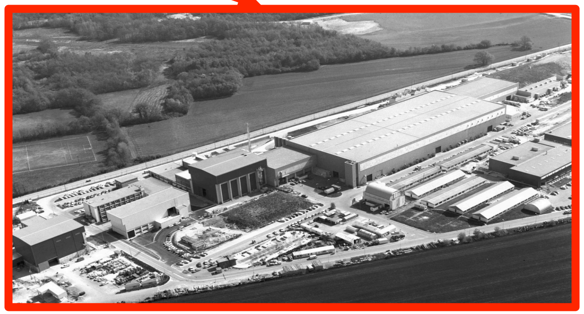


The SPS as a driver of secondary beams

1974-2021: 47 years of the experimental program with the SPS extracted beams

North Area

West Area



Energy footprint: Comparison of the DESY-XFEL and the CERN GF photon sources

DESY-XFEL

- Wall-pug power – 19 MW
- Driver beam power consumption – 600 kW
- Photon beam power 600 W
- **beam power efficiency ~ 0.1 %**
- **overall plug-power consumption efficiency ~ 0.003 %**
  (thanks to Andrea Latina for these numbers)

CERN-GF

- wall-pug power – 200 MW (total CERN)
- wall-pug power – 125 MW (LHC)
- beam lifetime 10 h
- **driver beam power consumption = photon beam power**
  (power to ramp the beam to requite energy negligible)
- **beam power efficiency ~ 99 %**
- **overall energy spending efficiency ~1%**
  (for 2 MW GF photon beams)

CERN **GF photon source** energy footprint is expected to be smaller, by a factor of 300, than the **DESY-XFEL** photon source…

…for the fixed power of the produced photon beam

Research with the Gamma Factory research tools

- ***particle physics*** *(studies of the basic symmetries of the universe,* ***dark matter searches****, precision QED and EW studies, vacuum birefringence studies, Higgs physics in $\gamma\gamma$ collision mode, rare muon decays, precision neutrino physics, …).*
- ***accelerator physics*** *(beam cooling techniques, low emittance hadronic beams, plasma wake field acceleration, high intensity polarized positron and muon sources, beams of radioactive ions and neutrons, very narrow band, and flavour-tagged neutrino beams).*

- ***nuclear physics*** *(confinement phenomena, nuclear spectroscopy, nuclear photo-physics, fission research, gamma polarimetry, physics of rare radioactive nuclides,…).*
- ***atomic physics*** *(electronic and muonic atoms, pionic and kaonic atoms).*
- ***applied physics*** *(accelerator driven energy sources, cold and warm fusion research, medical isotopes' and isomers' production, …).*

adp annalen der physik

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March 2022

Issue Edited by: Dmitry Budker, Mikhail Gorchtein, Mieczyslaw Witold Krasny, Adriana Pálffy, Andrey Surzhykov

EDITORIAL

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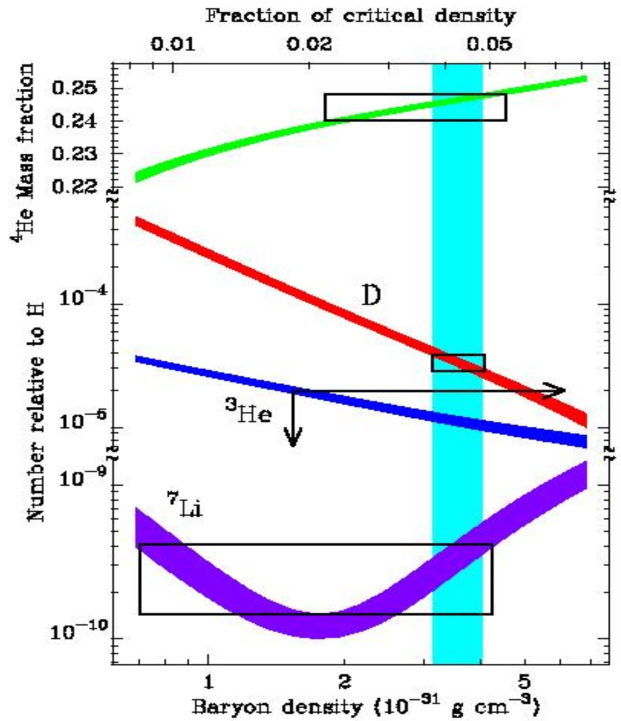
From Einstein to CERN's Gamma Factory – the Story of *Annalen der Physik* Continues

Gamma Factory light on the dark sector

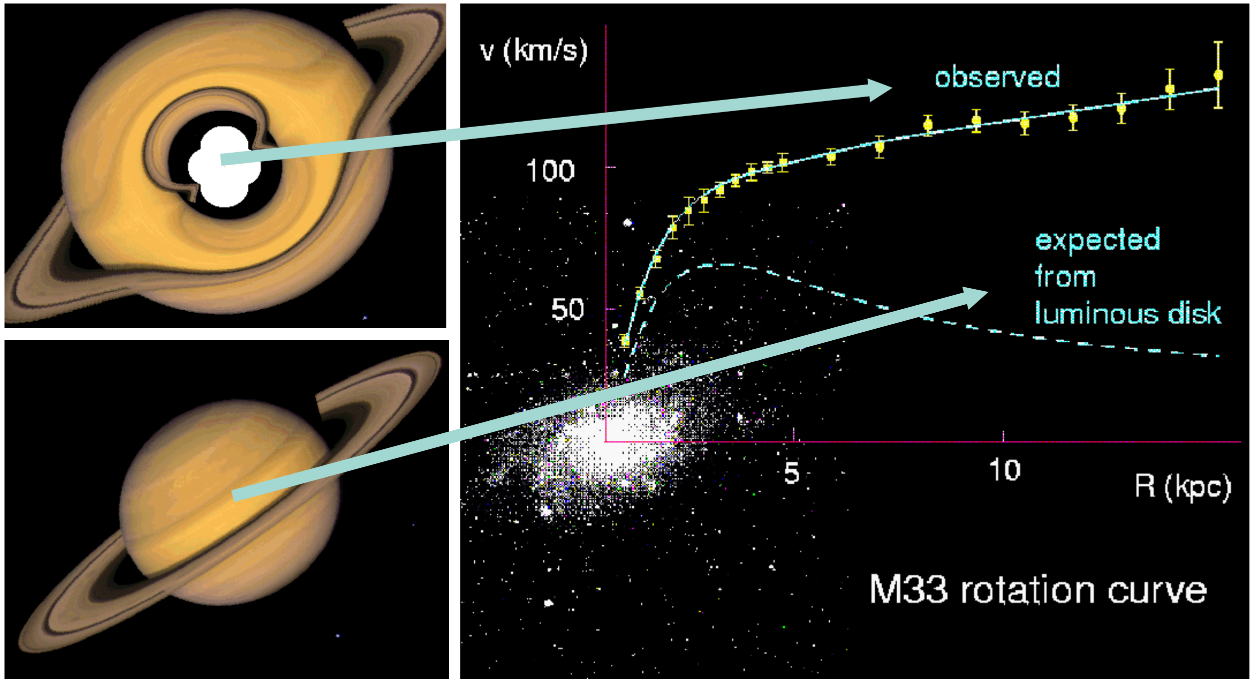
The mass of the Universe

indirect measurement method



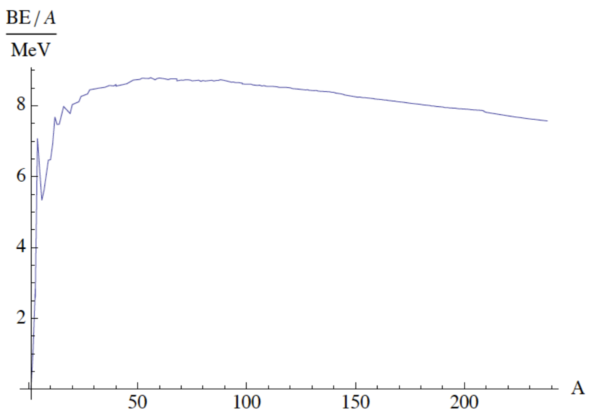
The mass of the Universe

direct measurement method



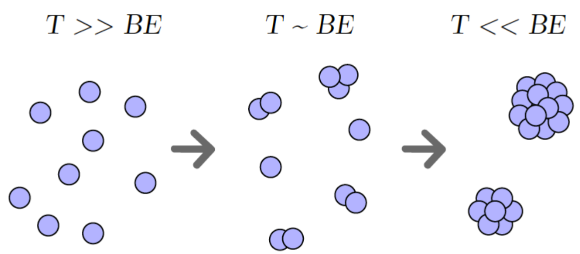
The example of dark nuclei

SM nuclei

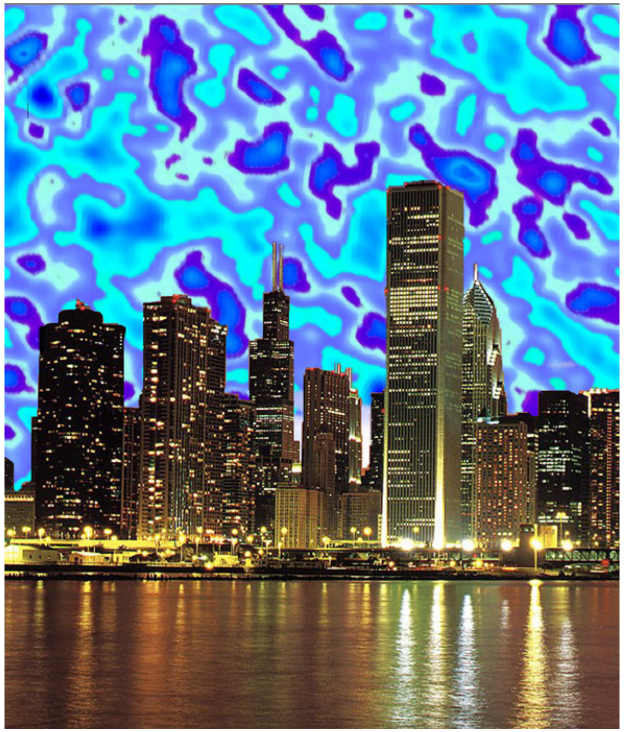


Dark nucleosynthesis

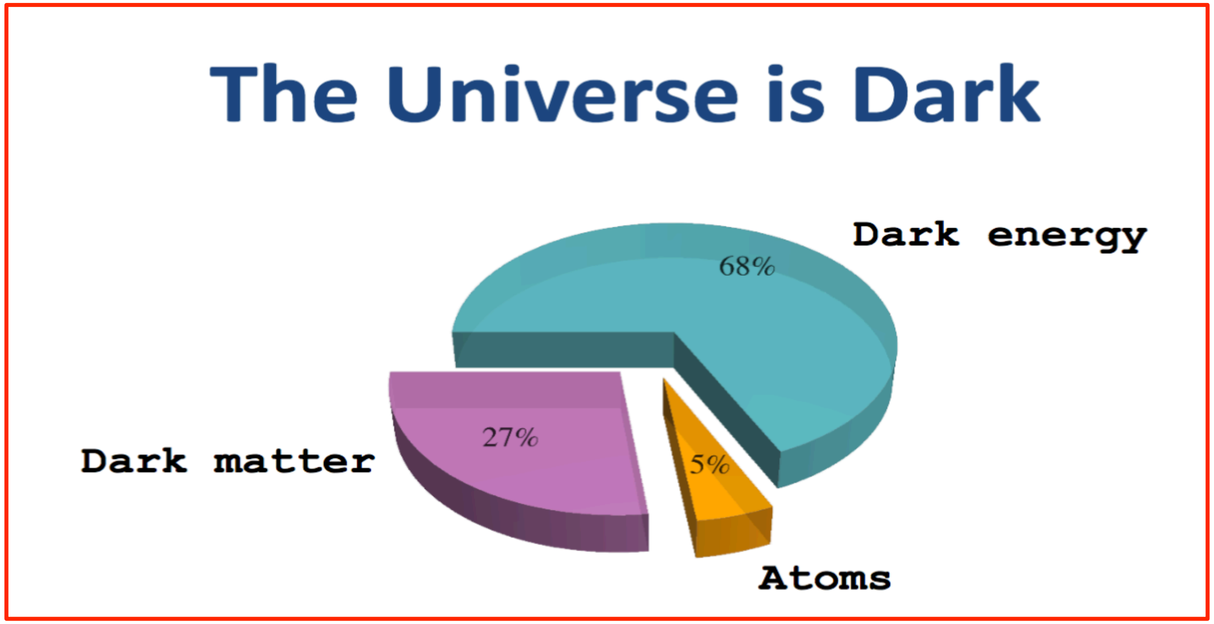
Free energy $F = E - TS$:
large $T \Rightarrow$ everything dissociated
small $T \Rightarrow$ large states favoured



Measuring dark energy



The result



The guiding puzzle for new ideas

- Why the dark energy, dark matter and visible matter are “almost” equally abundant?
- Does it tell us that the dark matter has similar properties as the normal matter (dark atoms, dark molecules, dark nuclei…) but “refuses” to communicate with normal matter?

The dark matter messengers

- "Higgs" portal (matter and dark matter in the same superconducting medium)
- Neutrino portal
- Dark photon portal

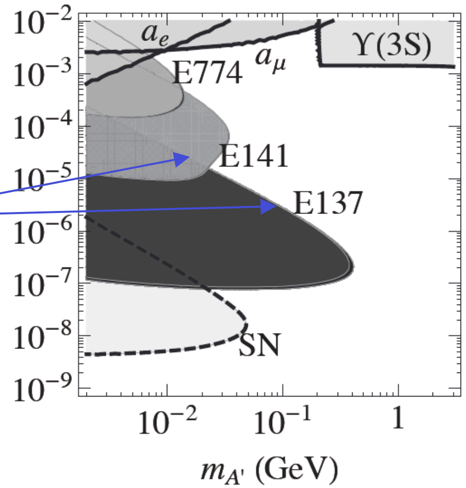
  (Z/γ mixing in the SM and photon/dark photon mixing)
- Axion and Axion Like portals

Dark Gauge Forces

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \epsilon_Y F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{,\mu\nu} F'_{\mu\nu} + m_{A'}^2 A'^{\mu} A'_{\mu}, \quad (3)$$

where $\mathcal{L}_{\rm SM}$ is the Standard Model Lagrangian, $F'_{\mu\nu} = \partial_{[\mu} A'_{\nu]}$, and A' is the gauge field of a massive dark $U(1)'$ gauge group [1]. The second term in (3) is the kinetic

Rejection regions of SLAC Experiments in the 80-ties
(more in tomorrow's talk)



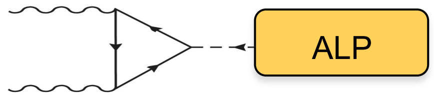
SLAC-PUB-13650
SU-ITP-09/22

The dark matter detection in GF

- “Produce and detect” DM particles (photon beams)
- Detect the cosmic origin DM particles (fully and partially stripped ion beams)

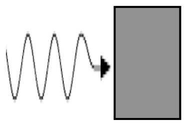
DM searches (and studies): Axion-Like-Particles (ALP) example

Collision schemes for ALP production:

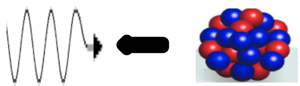


Search phase

γ_{GF} – B field
$m_{ALP} <$ 1 keV



γ_{GF} – A collisions (beam dump)
$m_{ALP} \sim$ 1 keV – 10 MeV



γ_{GF} – A collisions (LHC)
$m_{ALP} \sim$ 10 MeV – 10 GeV

"Production" phase

γ_{GF} – γ_{Laser} collisions
$m_{ALP} \sim$ 1–100 keV

γ_{GF} – γ_{GF} collisions (LHC)
$m_{ALP} \sim$ 100 keV – 800 MeV

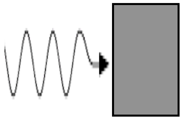
Concurrent, rich QED programme (e.g. vacuum birefringence studies)

Three principal advantages of the Gamma Factory photon beams:

- ***Large fluxes***: *~10^{25} photons on target over year (SHIP – 10^{20} protons on target).*
- ***Multiple ALP production schemes** covering a vast region of ALP masses **(sub eV – GeV)***
- ***Once** ALP candidate **seen** → a unique possibility to **tune** the GF beam **energy** to the **resonance**.*

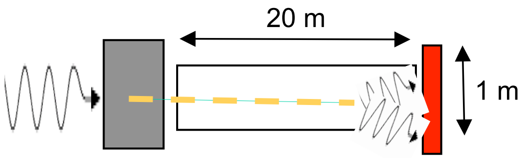
Gamma Factory APL-finding potential
(beam-dump search mode)

Search phase
Example: beam-dump mode

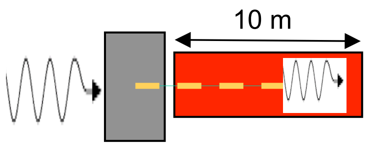


γ_{GF}–A collisions
1.6, 0.2, 0.02 GeV
beams (A,B,C)

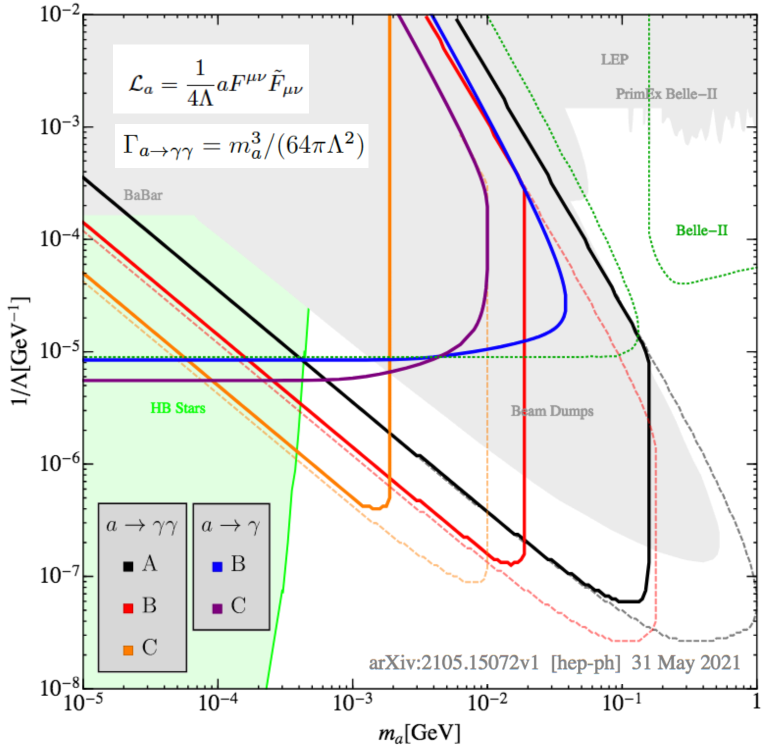
Two appearance modes:



- *decay: a →γγ (A,B,C)*



- *reconversion: aN →γN (B,C)*



Gamma Factory dark photon discovery potential
(beam-dump search mode)

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \varepsilon\, e \sum_f q_f \bar{f} \not{A}' f$$

$$\gamma e \rightarrow eX$$

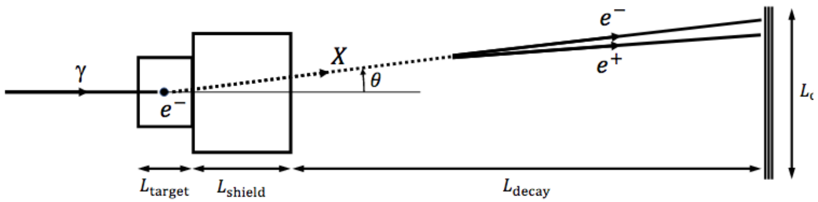


FIG. 1. **Experiment layout.** The experiment consists of a (graphite) target with thickn $L_{\mathrm{target}} = 1$ m, followed by a (lead) shield with thickness $L_{\mathrm{shield}} = 2$ m, an open air decay regi with length L_{decay}, and a tracking detector, centered on the beam axis, which we take to be circular disk with diameter L_{det}. The GF photon beam enters from the left and produces an particle through dark Compton scattering $\gamma e \to eX$. The X particle is produced with an angl relative to the GF beamline and decays to an e^+e^- pair, which is detected in the tracking detect

Gamma Factory Searches for Extremely Weakly-Interacting Particles

Sreemanti Chakraborti,[1,*] Jonathan L. Feng,[2,†] James K. Koga,[3,‡] and Mauro Valli[2,§]

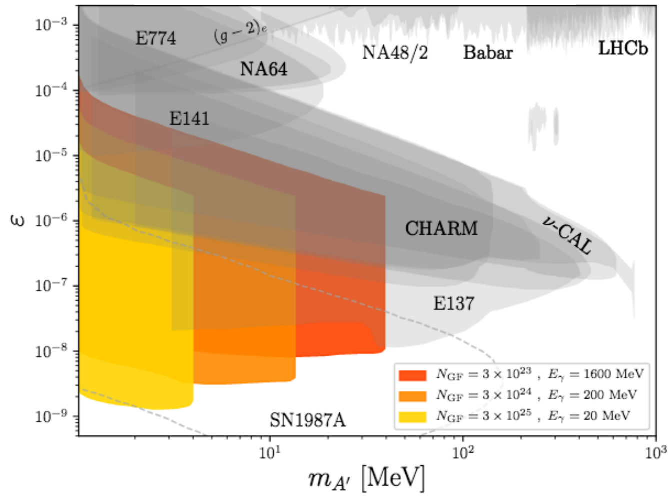


FIG. 3. **Dark photon sensitivity.** The sensitivity reach for the three sets of GF parameters $(E_\gamma, N_{\mathrm{GF}})$ indicated, each corresponding to a year of running, and detector parameters $L_{\mathrm{decay}} =$ 12 m and $L_{\mathrm{det}} = 3$ m. The contours are for 3 e^+e^- signal events and assume no background. The gray shaded regions are existing bounds from the terrestrial experiments indicated [32–42] (for further details, see also [43, 44]), from $(g-2)_e$ [45], and the dashed gray line encloses the region probed by supernova cooling, as determined in Ref. [46].

A comment on the possibilities to search for the cosmic origin DM particles with LHC-"stored" atomic clocks

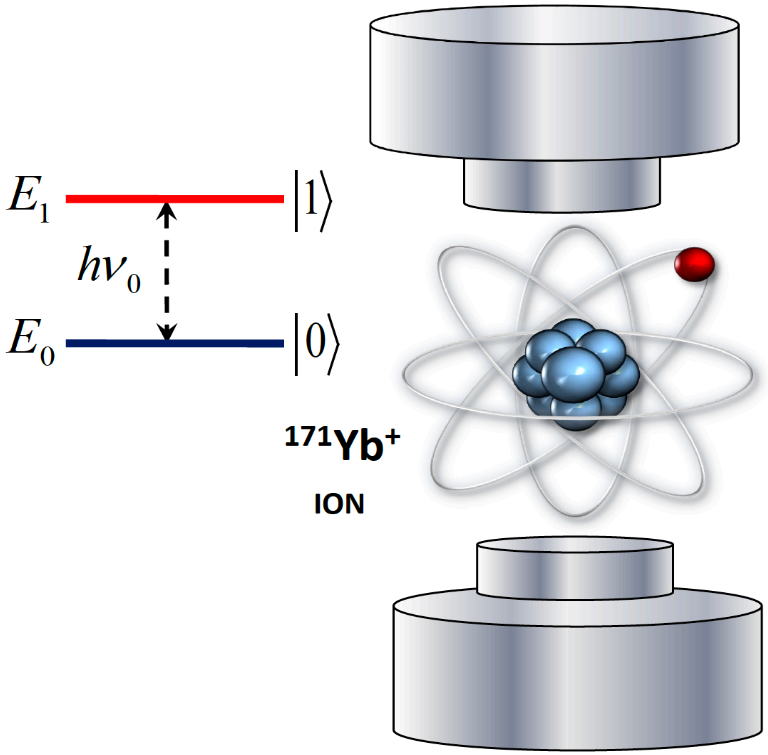
Ingredients for an atomic clock

1. Atoms are all the same and will oscillate at exactly the same frequency (in the same environment):
   You now have a perfect oscillator!

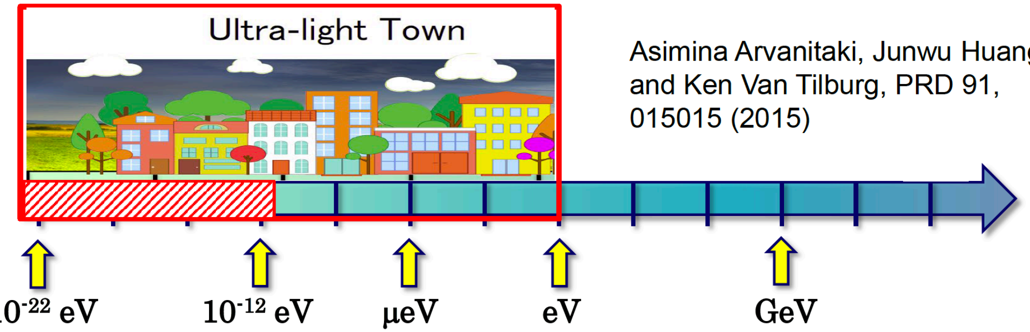
2. Take a sample of atoms (or just one)

3. Build a laser in resonance with this atomic frequency

4. Count cycles of this signal



How to detect ultralight dark matter with clocks?



Asimina Arvanitaki, Junwu Huang, and Ken Van Tilburg, PRD 91, 015015 (2015)

Dark matter field $\phi(t) = \phi_0 \cos\left(m_\phi t + \bar{k}_\phi \times \bar{x} + \ldots\right)$

couples to electromagnetic interaction and “normal matter”

It will make fundamental coupling constants and mass ratios oscillate

Atomic energy levels will oscillate so clock frequencies will oscillate

Can be detected with monitoring ratios of clock frequencies over time (or clock/cavity).

Need low energy, long-lived atomic (nuclear) transitions to search for low mass DM particles

Ultralight dark matter

$$\frac{\phi}{M^*}\mathcal{O}_{\rm SM} \longrightarrow \mathcal{L}_\phi = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} \ldots\right] \qquad \alpha = \alpha^{\rm SM} + \delta\alpha$$

Dark matter (ϕ) — **photons** ($F_{\mu\nu}F^{\mu\nu}$)

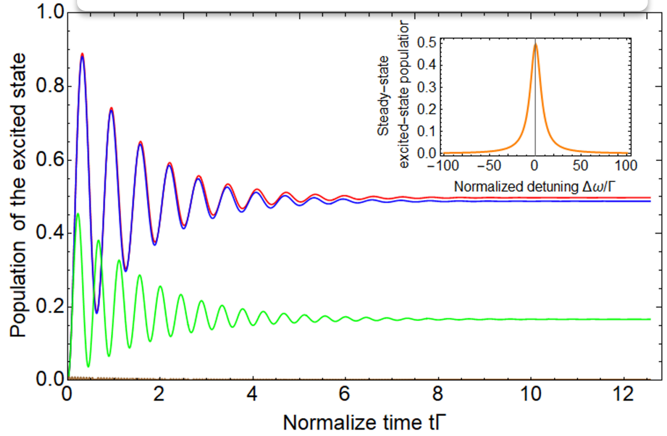
$$\phi(t) = \phi_0 \cos\left(m_\phi t + \bar{k}_\phi \times \bar{x} + \ldots\right)$$

Then, clock frequencies will oscillate!

DM virial velocities ~ 300 km/s

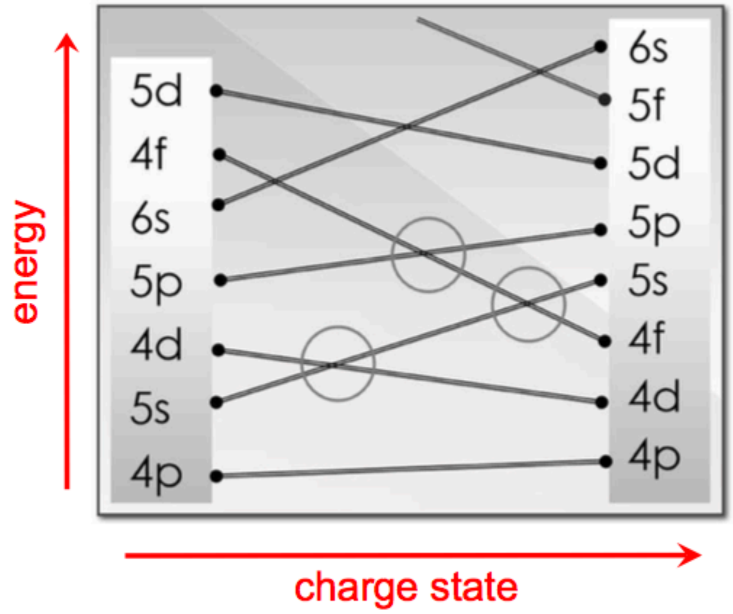
τ [s]	$f = 2\pi/m_\phi$ [Hz]	m_ϕ [eV]	
10^{-6}	1 MHz	4×10^{-9}	
10^{-3}	1 kHz	4×10^{-12}	
1	1	4×10^{-15}	One oscillation per second
1000	1 mHz	4×10^{-18}	
10^6	10^{-6}	4×10^{-21}	One oscillation per 11 days

GF PSI beams have sub picosecond lifetime



Excited state life time must be at least in microsecond range →

- *nuclear transitions*
- *energy level crossing for highly charged ions*
- *hyperfine splitting*



Isotope	$T^g_{1/2}$	E_e (keV)	I_g	I_e	λL	$T^{rad}_{1/2}$ (s)	$\alpha(K)$	$\alpha(L)$
^{229}Th	7880 y	0.008[a]	$5/2^+$	$3/2^+$	$M1$	5.19×10^{3}	-	-
^{235}U	7×10^{8} y	0.076	$7/2^-$	$1/2^+$	$E3$	7.03×10^{23}[b]	-	-
^{201}Hg	stable	1.565	$3/2^-$	$1/2^-$	$M1$	3.76×10^{-3}	-	-
^{205}Pb	1.7×10^{7} y	2.329	$5/2^-$	$1/2^-$	$E2$	9.07×10^{2}	-	-
^{181}Ta	stable	6.238	$7/2^+$	$9/2^-$	$E1$	4.34×10^{-4}	-	-
^{239}Pu	2.4×10^{4} y	7.861	$1/2^+$	$3/2^+$	$M1$	2.04×10^{-7}	-	-
^{169}Tm	stable	8.410	$1/2^+$	$3/2^+$	$M1$	1.07×10^{-6}	-	-
^{83}Kr	stable	9.406	$9/2^+$	$7/2^+$	$M1$	2.80×10^{-6}	-	14
^{187}Os	stable	9.756	$1/2^-$	$3/2^-$	$M1$	9.01×10^{-7}	-	-
^{137}La	6×10^{4} y	10.560	$7/2^+$	$5/2^+$	$M1$	1.04×10^{-5}	-	93.2
^{45}Sc	stable	12.400	$7/2^-$	$3/2^+$	$(M2)$	1.96×10^{2}	362	54
^{235}U	-[c]	13.034	$1/2^+$[d]	$3/2^+$	M1	2.43×10^{-7}[e]	-	-
^{73}Ge	stable	13.284	$9/2^+$	$5/2^+$	$E2$	3.1×10^{-3}	299	666
^{57}Fe	stable	14.413	$1/2^-$	$3/2^-$	$M1$	9.32×10^{-7}	7.35	0.78
^{151}Eu	$\geq 1.7 \times 10^{18}$ y	21.541	$5/2^+$	$7/2^+$	$M1$	2.62×10^{-7}	-	21.7
^{149}Sm	stable	22.507	$7/2^-$	$5/2^-$	$M1$	2.24×10^{-7}	-	22.2[f]
^{119}Sn	stable	23.871	$1/2^+$	$3/2^+$	$M1$	1.07×10^{-7}	-	4.1
^{161}Dy	stable	25.651	$5/2^+$	$5/2^-$	$E1$	9.59×10^{-8}	-	1.79[f]
^{201}Hg	stable	26.272	$3/2^-$	$5/2^-$	$M1$	4.61×10^{-8}	-	55.9[f]
^{129}I	1.6×10^{7} y	27.793	$7/2^+$	$5/2^+$	$M1$	1.02×10^{-7}	-	4.06
^{229}Th	7880 y	29.190	$5/2^+$	$5/2^+$	$M1$	3.26×10^{-8}[g]	-	168[f]
^{40}K	1.2×10^{9} y	29.830	4^-	3^-	$M1$	5.47×10^{-9}	0.26[f]	0.023[f]
^{201}Hg	stable	32.145	$3/2^-$	$3/2^-$	$M1$	5.04×10^{-9}[h]	-	30.8[f]
^{237}Np	2.1×10^{6} y	33.196	$5/2^+$	$7/2^+$	$M1$	9.92×10^{-9}	-	131[f]
^{125}Te	stable	35.492	$1/2^+$	$3/2^+$	$M1$	2.15×10^{-8}	11.69	1.602
^{189}Os	stable	36.200	$3/2^-$	$1/2^-$	$M1$	1.09×10^{-8}	-	15.6
^{121}Sb	stable	37.129	$5/2^+$	$7/2^+$	$M1$	4.06×10^{-8}	9.36	1.227
^{129}Xe	stable	39.578	$1/2^+$	$3/2^+$	$M1$	1.25×10^{-8}	10.27	1.41
^{233}U	1.6×10^{5} y	40.351	$5/2^+$	$7/2^+$	$M1$[i]	1.03×10^{-7}	-	374[f]
^{243}Am	7364 y	42.20	$5/2^-$	$7/2^-$	$M1$	6.43×10^{-9}	-	110
^{229}Th	7880 y	42.435	$5/2^+$	$7/2^+$	$M1$	2.59×10^{-8}	-	99.3[f]
^{240}Pu	6561 y	42.824	0^+	2^+	$E2$	1.55×10^{-7}	-	658
^{246}Cm	4706 y	42.852	0^+	2^+	$E2$	1.31×10^{-7}	-	770[f]
^{248}Cm	3.5×10^{5} y	43.400	0^+	2^+	$E2$	1.22×10^{-7}	-	724[f]
^{234}U	2.5×10^{5} y	43.498	0^+	2^+	$E2$	1.80×10^{-7}	-	520
^{244}Pu	8.1×10^{7} y	44.2	0^+	2^+	$(E2)$	1.23×10^{-7}	-	560
^{242}Pu	3.7×10^{5} y	44.54	0^+	2^+	$E2$	1.20×10^{-7}	-	543[f]
^{238}U	4.5×10^{9} y	44.916	0^+	2^+	$E2$	1.26×10^{-7}	-	444
^{236}U	2.3×10^{7} y	45.242	0^+	2^+	$E2$	1.38×10^{-7}	-	429
^{235}U	7×10^{8} y	46.103	$7/2^-$	$9/2^-$	$M1$	7.15×10^{-10}	-	40
^{183}W	$\geq 6.7 \times 10^{20}$ y	46.484	$1/2^-$	$3/2^-$	$M1$	1.73×10^{-9}	-	6.46[f]
^{232}Th	1.4×10^{10} y	49.369	0^+	2^+	$E2$	1.15×10^{-7}	-	244
^{81}Kr	2.3×10^{5} y	49.57	$7/2^+$	$9/2^+$	$M1$	9.41×10^{-9}	1.117[f]	0.169[f]
^{235}U	-[c]	51.697	$1/2^+$[d]	$5/2^+$	$E2$	8.34×10^{-8}[e]	-	226
^{230}Th	7.5×10^{4} y	53.227	0^+	2^+	$E2$	8.08×10^{-8}	-	166.8
^{157}Gd	stable	54.536	$3/2^-$	$5/2^-$	$M1$	1.74×10^{-9}	9.50[j]	2
^{239}Pu	2.4×10^{4} y	57.275	$1/2^+$	$5/2^+$	$E2$	3.58×10^{-8}	-	161.1
^{237}Np	2.1×10^{6} y	59.540	$5/2^+$	$5/2^-$	$E1$	1.86×10^{-7}[h]	-	0.376[f]
^{155}Gd	stable	60.010	$3/2^-$	$5/2^-$	$M1$	2.04×10^{-9}	7.25	1.48

Conclusions

- *Gamma Factory can create, at CERN, a variety of novel research tools, which could open novel research opportunities in a very broad domain of basic and applied science*
- *Examples of such tools were presented in this talk*
- *The Gamma Factory research programme can be largely based on the existing CERN accelerator infrastructure – it requires "relatively" minor infrastructure investments*
- *Gamma Factory has a significant potential to produce, detect and investigate the properties of the keV/MeV mass-range DM particles (if they exist)*
- *Its potential to detect DM waves of cosmic origin remains to be demonstrated*