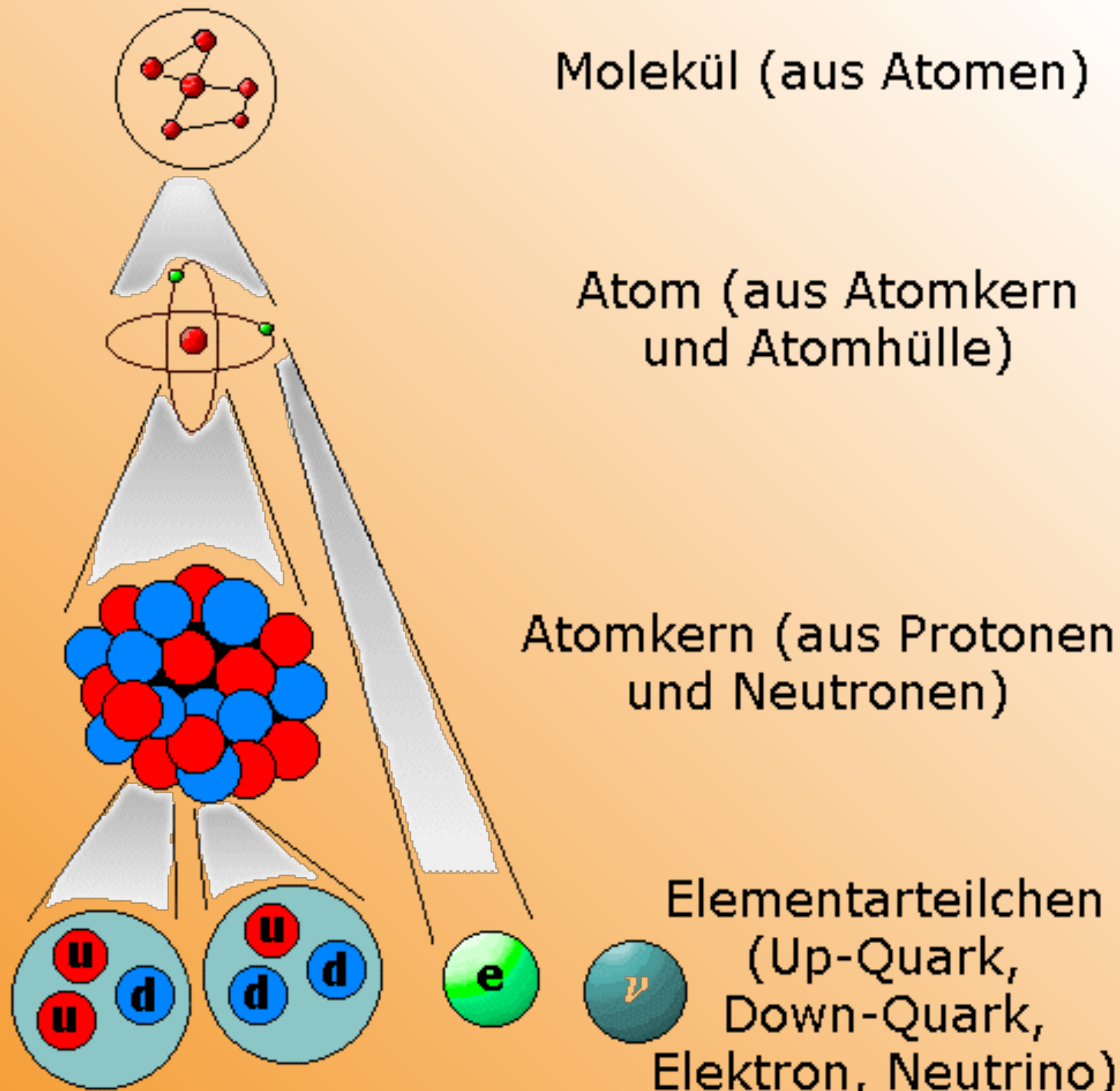
Die wunderbare Welt der Teilchen am CERN

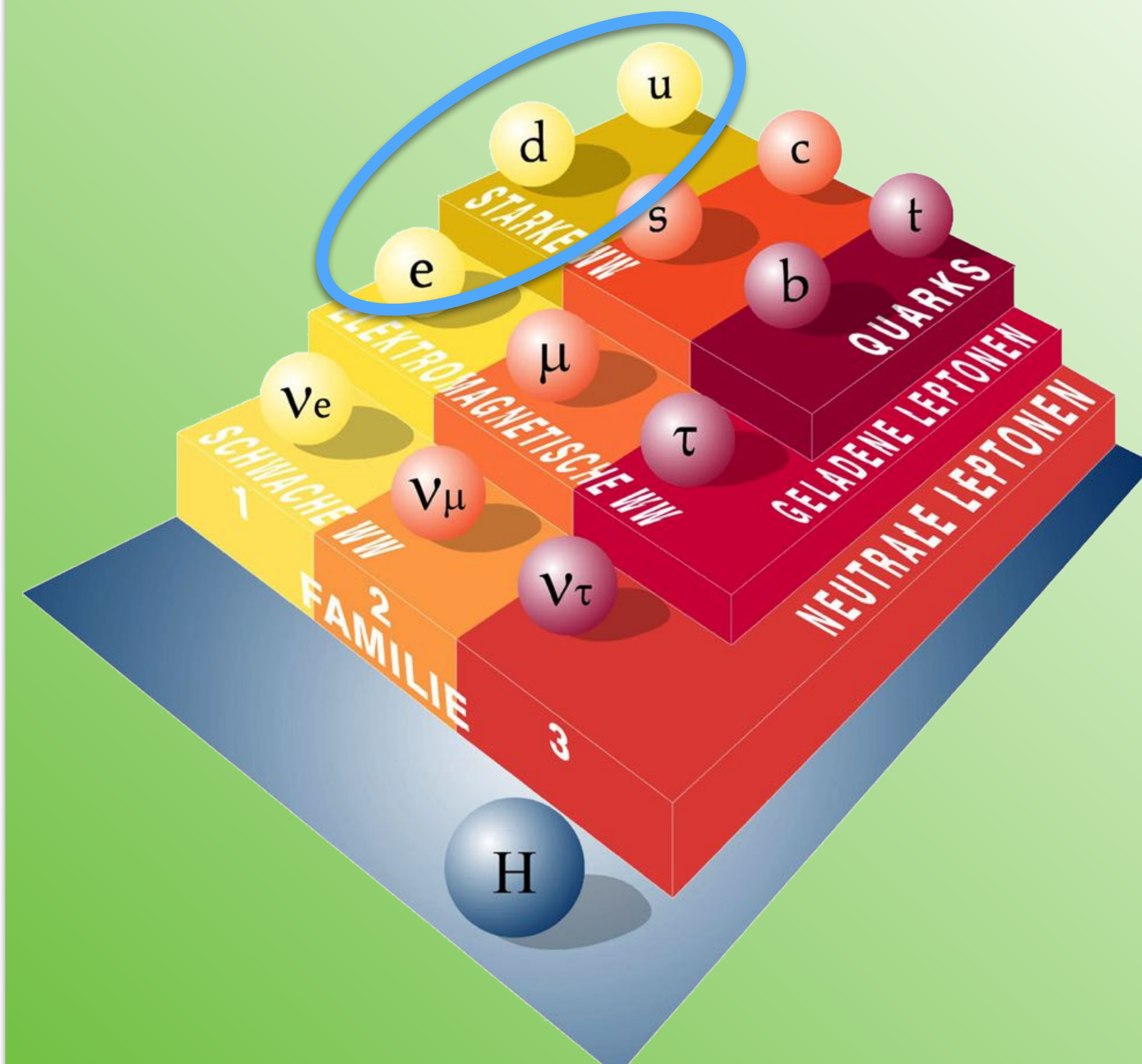
Christoph Rembser (CERN)

Woraus besteht die Welt? Elementarteilchen!

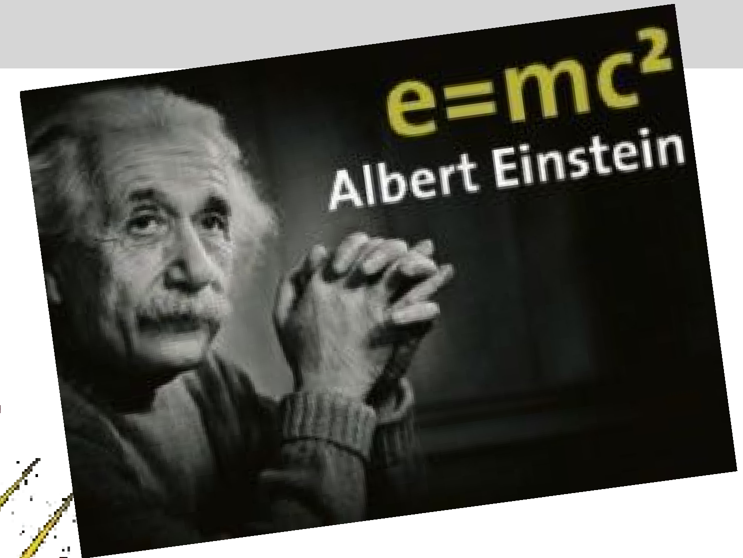


Elementarteilchen = Lego-Steine der Natur…

…es gibt 12 Lego-Steine, davon sind 3 stabil.

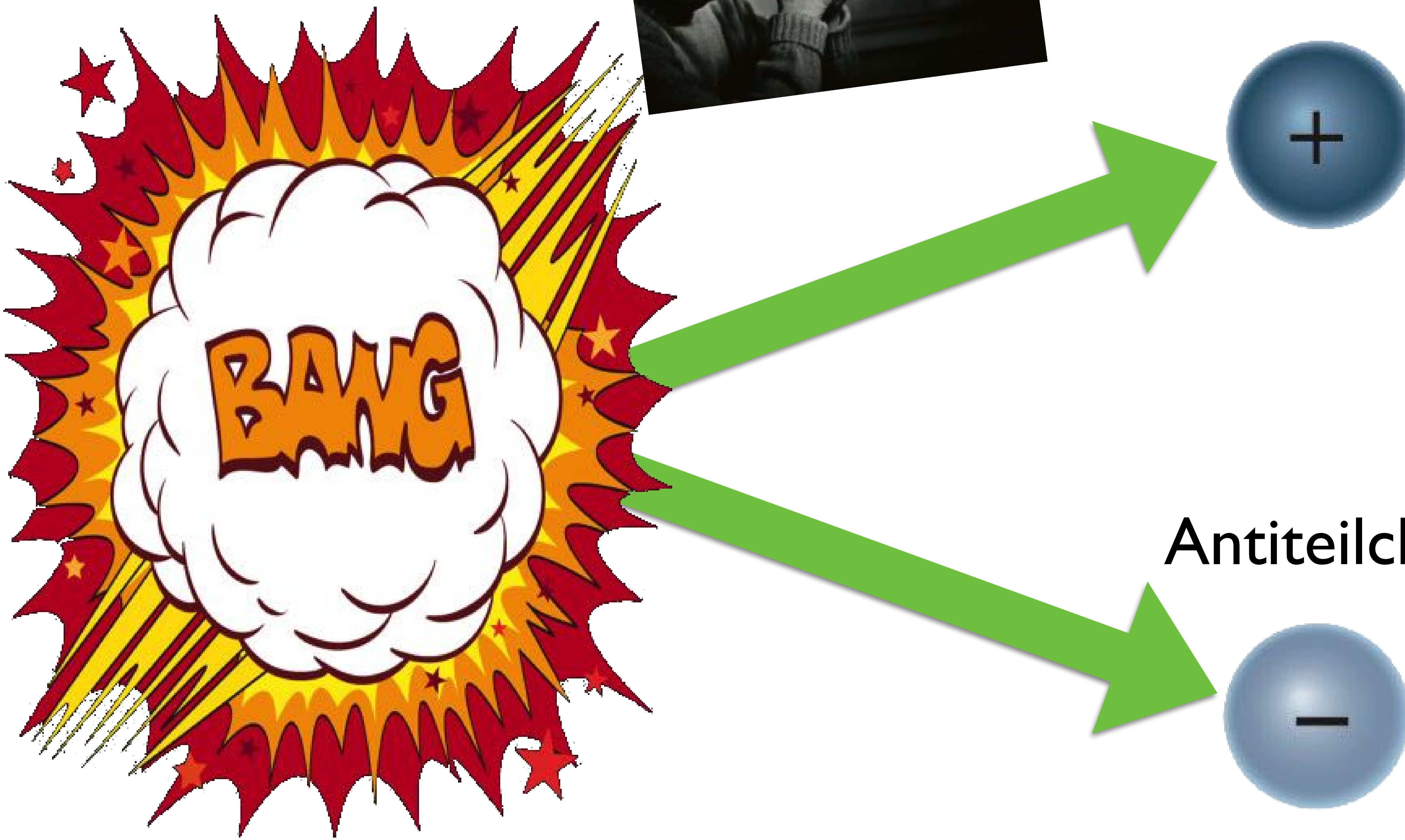


Elementarteilchen sind beim Urknall entstanden



Energie (Licht)

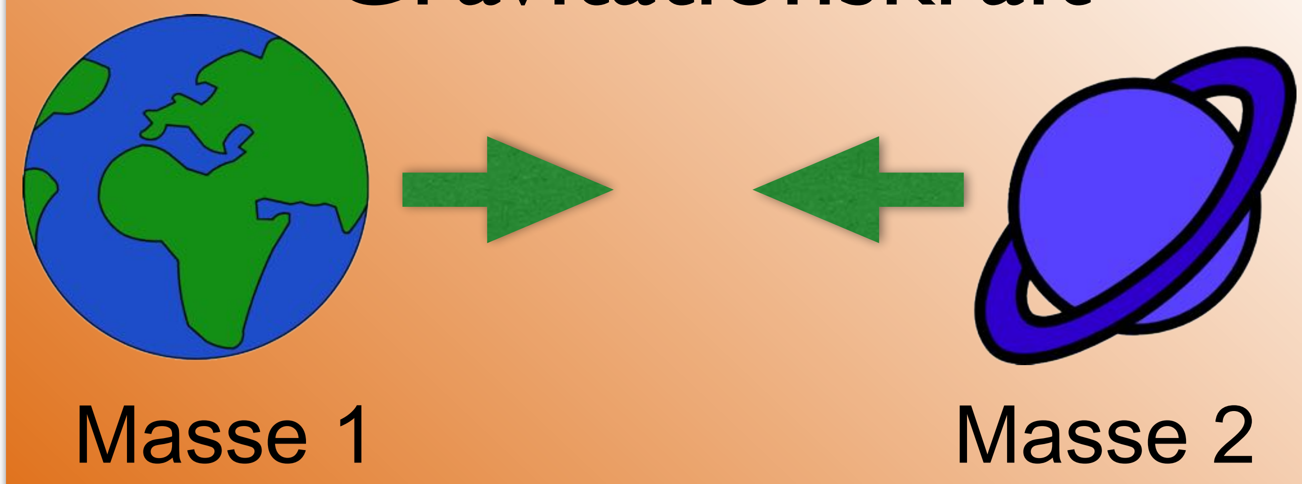
Teilchen



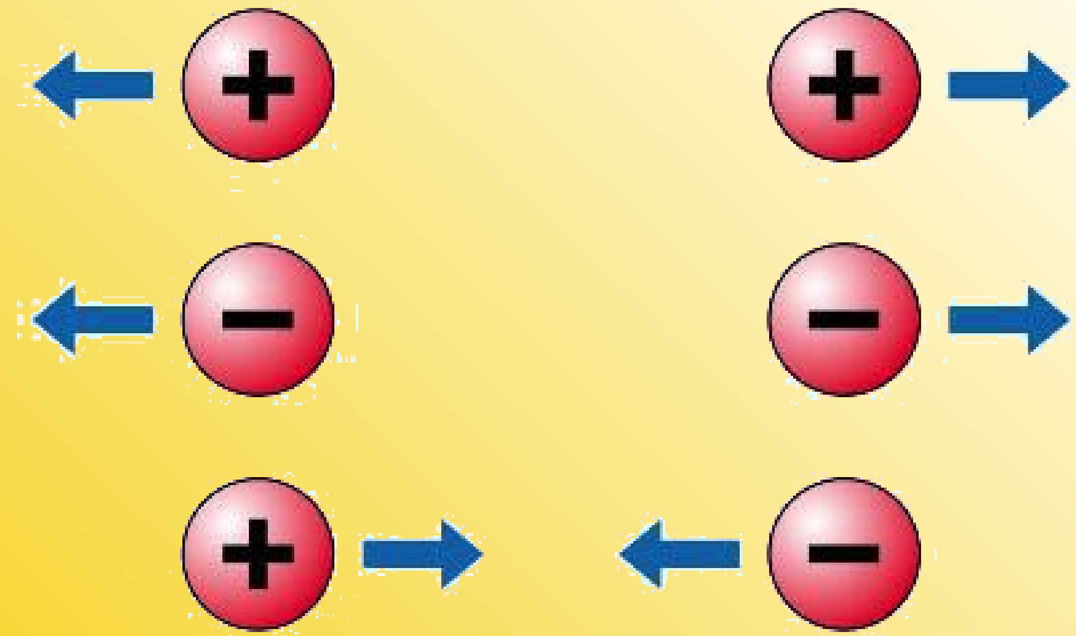
Antiteilchen

Kräfte: Regeln wie sich Elementarteilchen verhalten

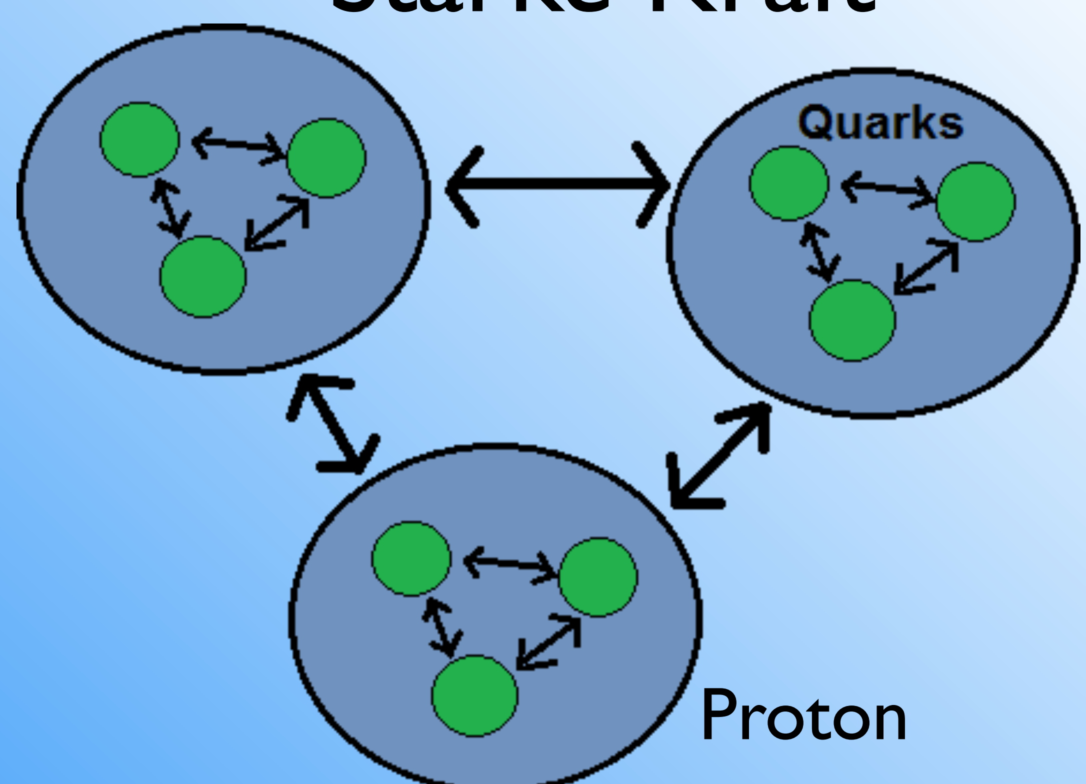
Gravitationskraft



Elektromagnetische Kraft

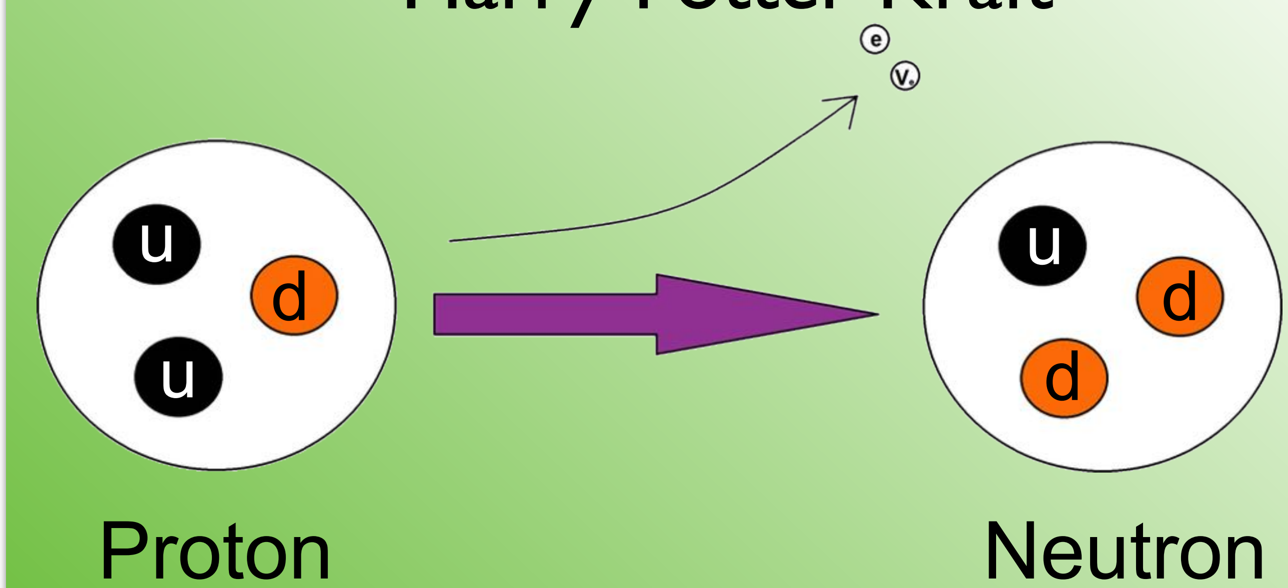


Starke Kraft

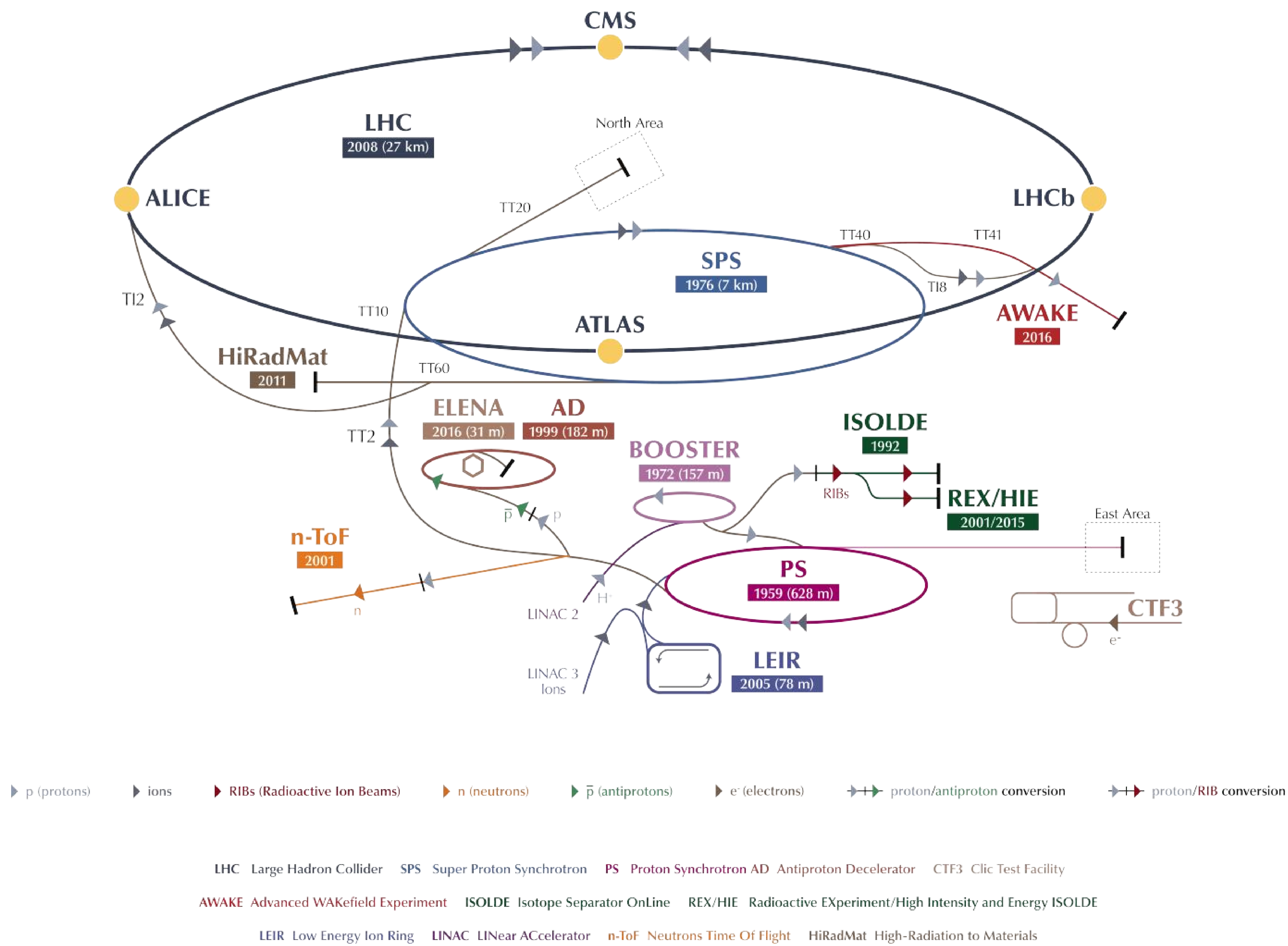


Schwache Kraft

“Harry-Potter Kraft”



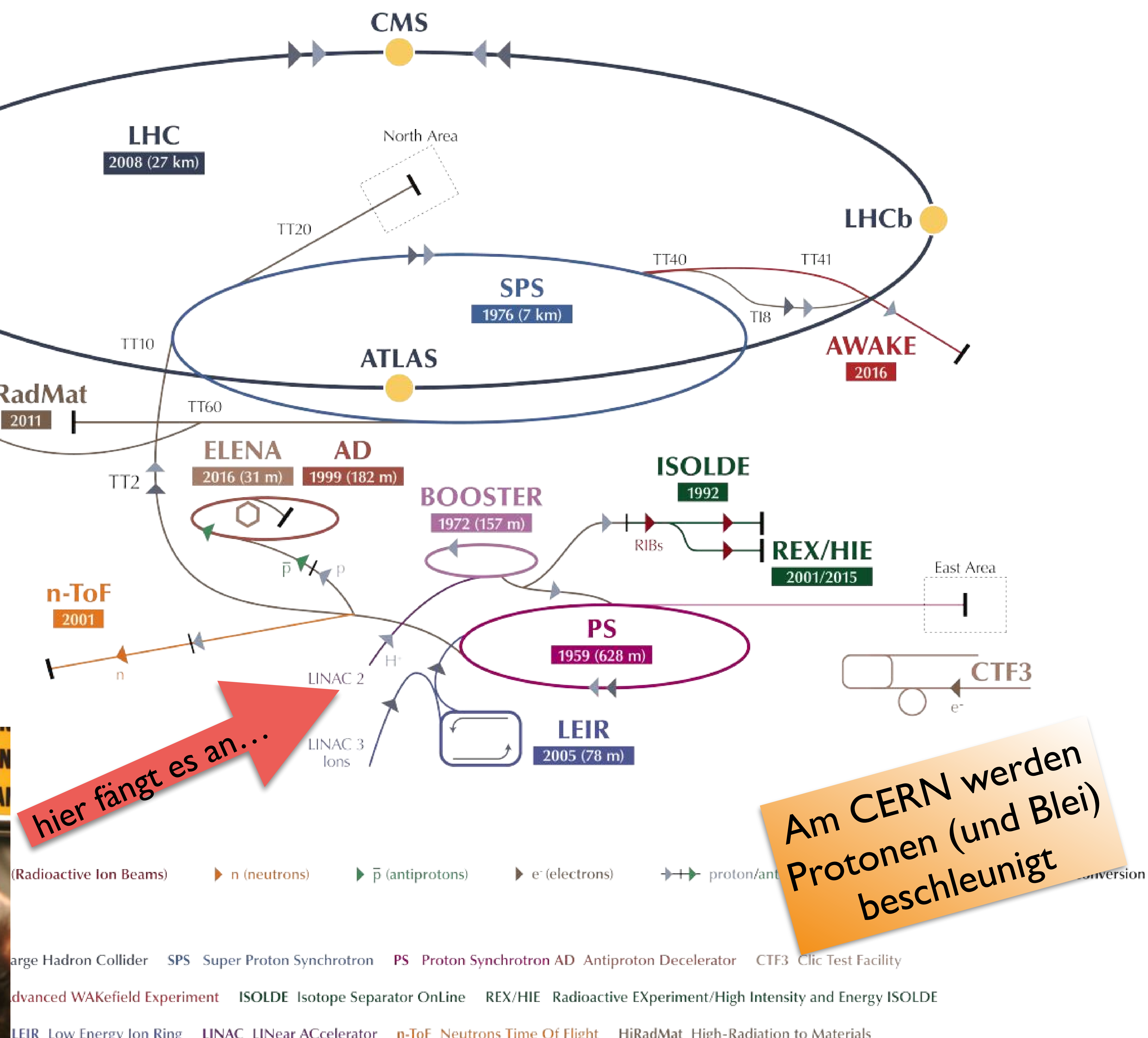
CERN Beschleuniger: Zeitreisen zum Urknall



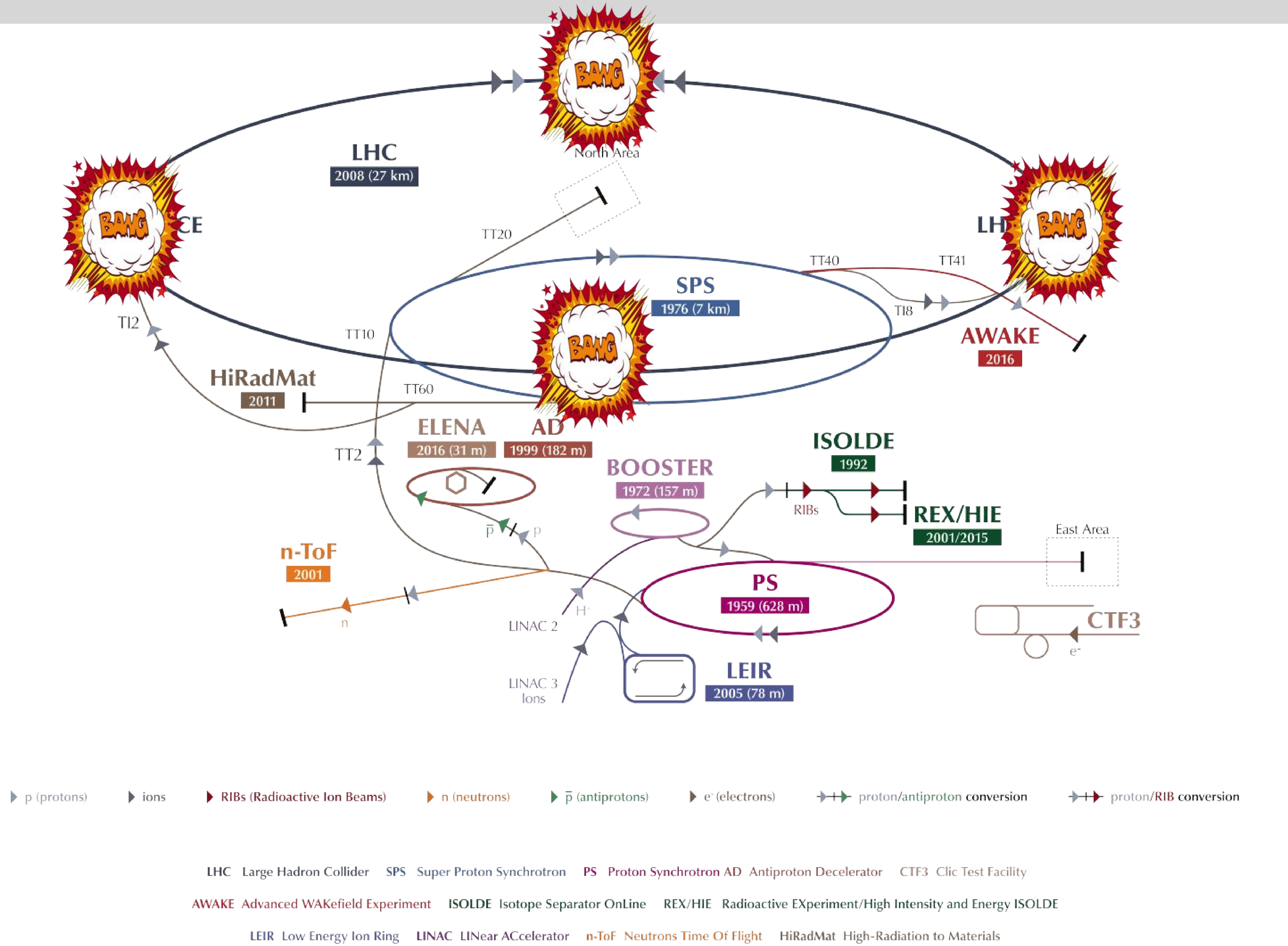
CERN, Genf/Schweiz

CERN, Genf/Schweiz

CERN Beschleuniger: Zeitreisen zum Urknall

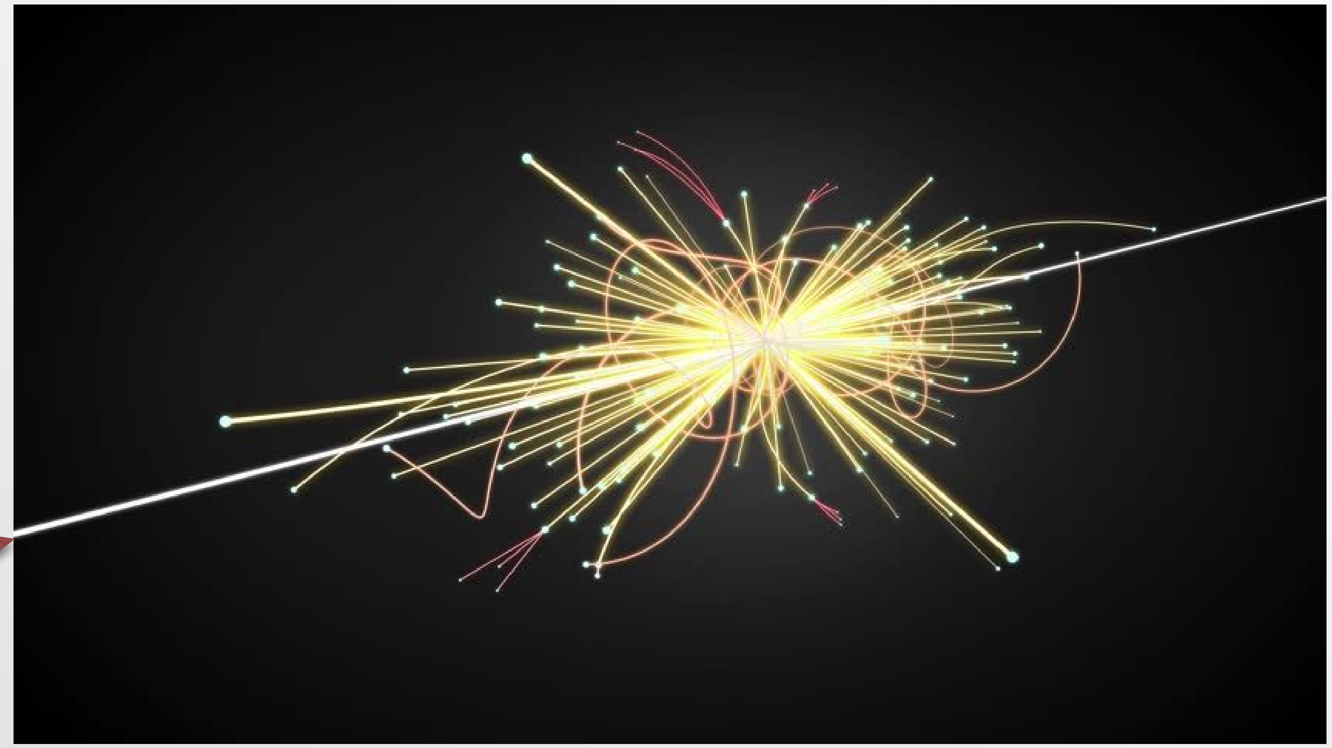


CERN Beschleuniger: Zeitreisen zum Urknall



So sehen Teilchenkollisionen aus

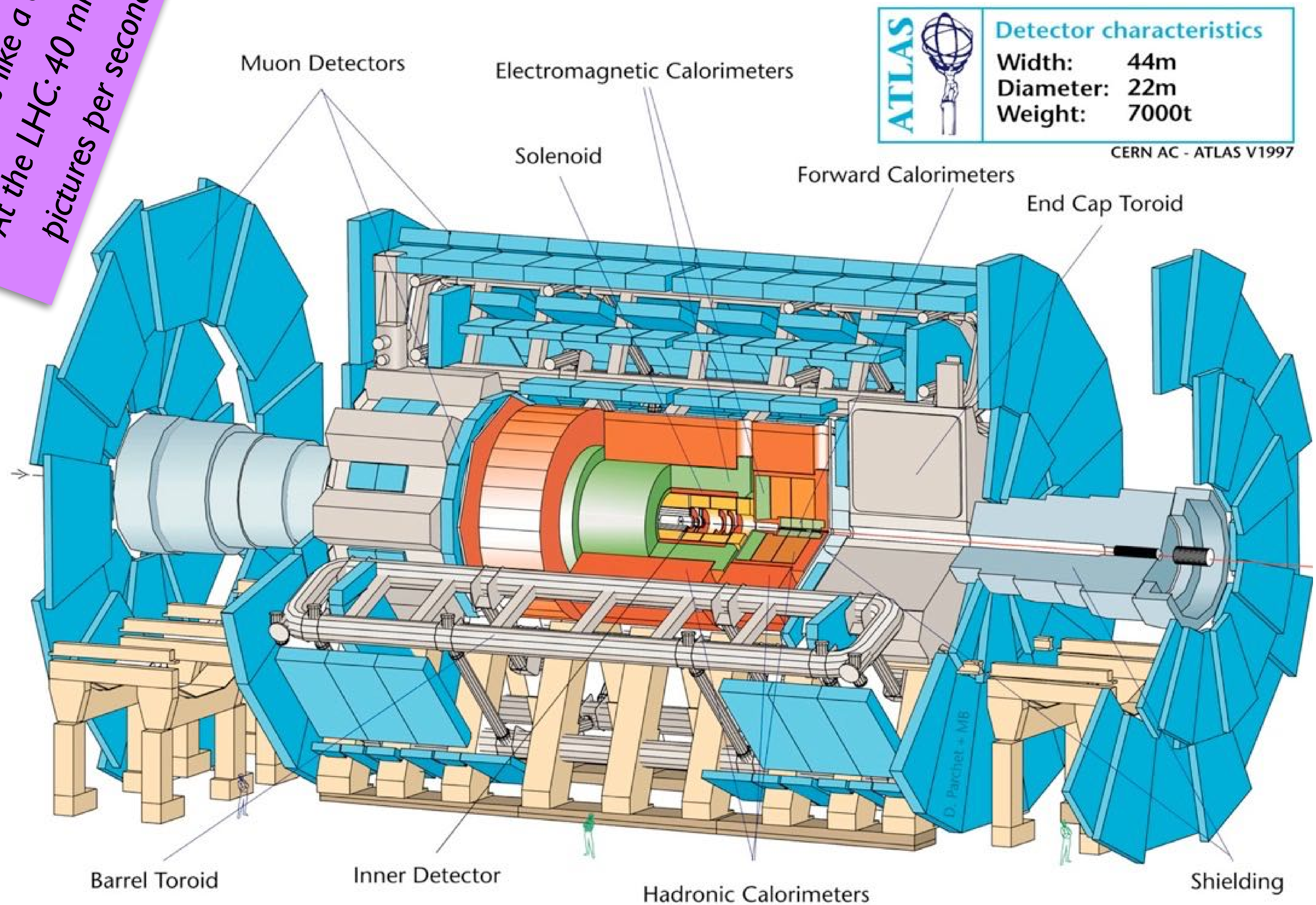
Kollider-
Experimente



Kollisionen à la Hollywood

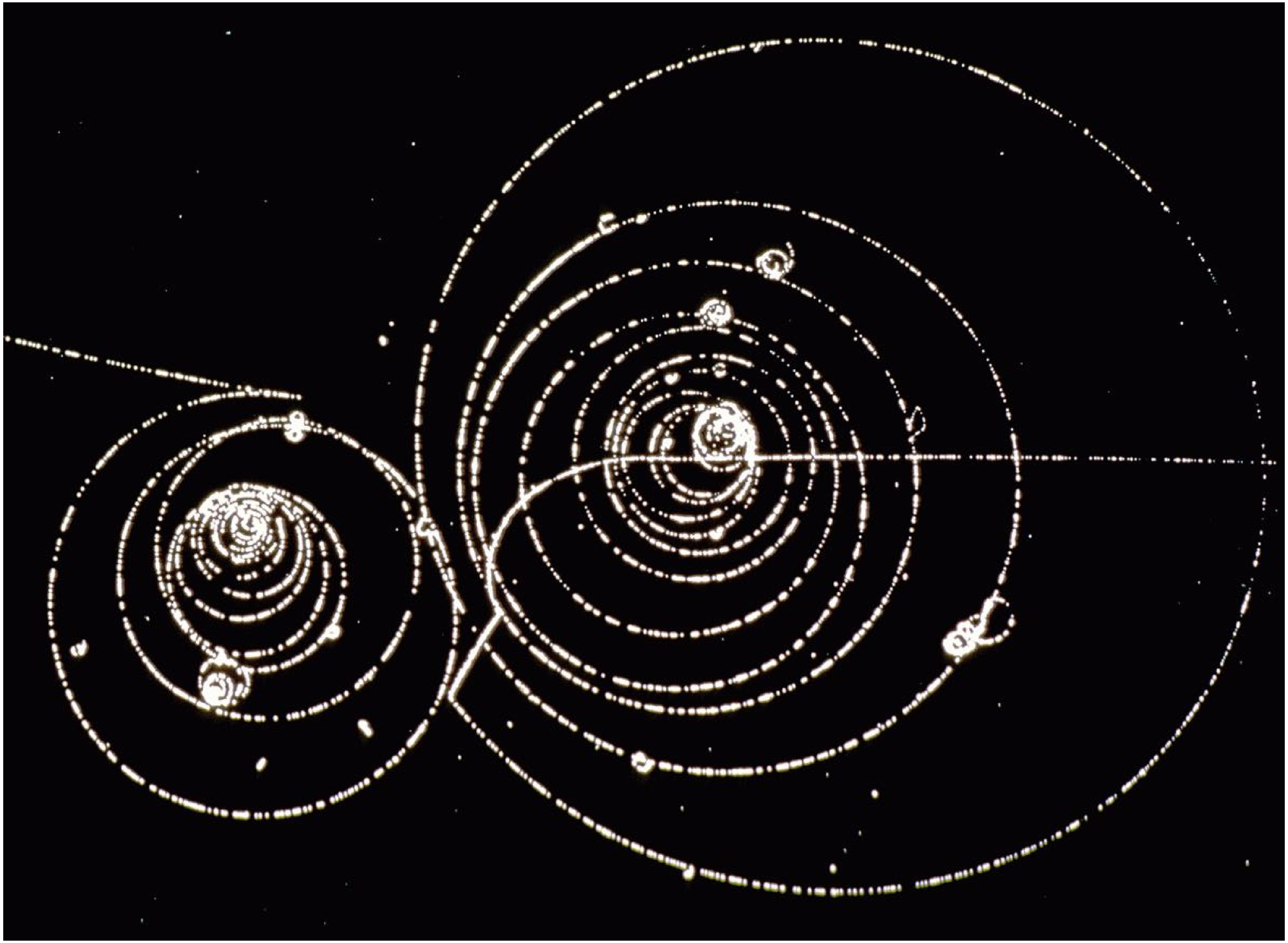
An LHC detector

A detector is like a camera!
At the LHC: 40 million pictures per second!

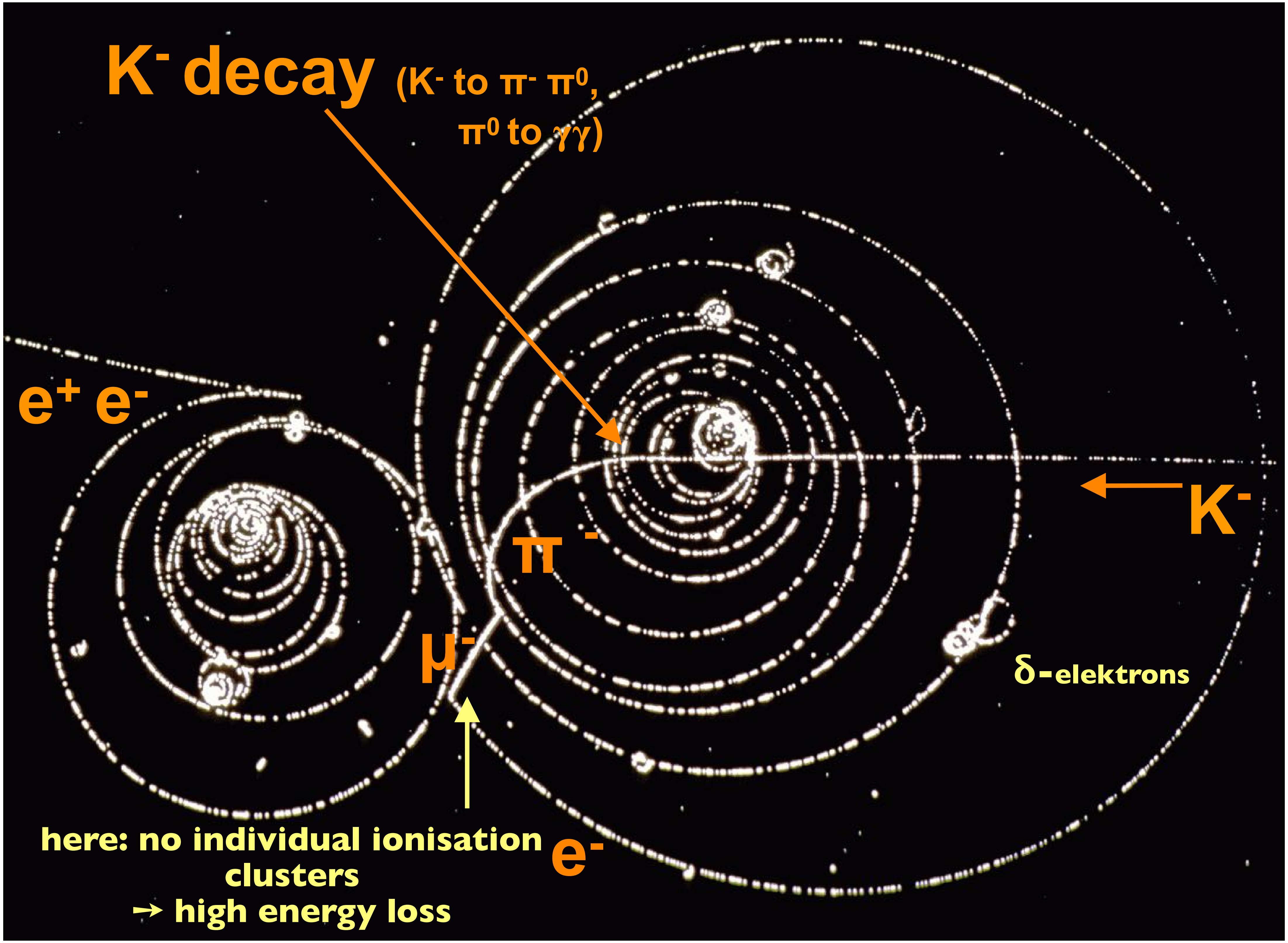


Taking pictures of particles

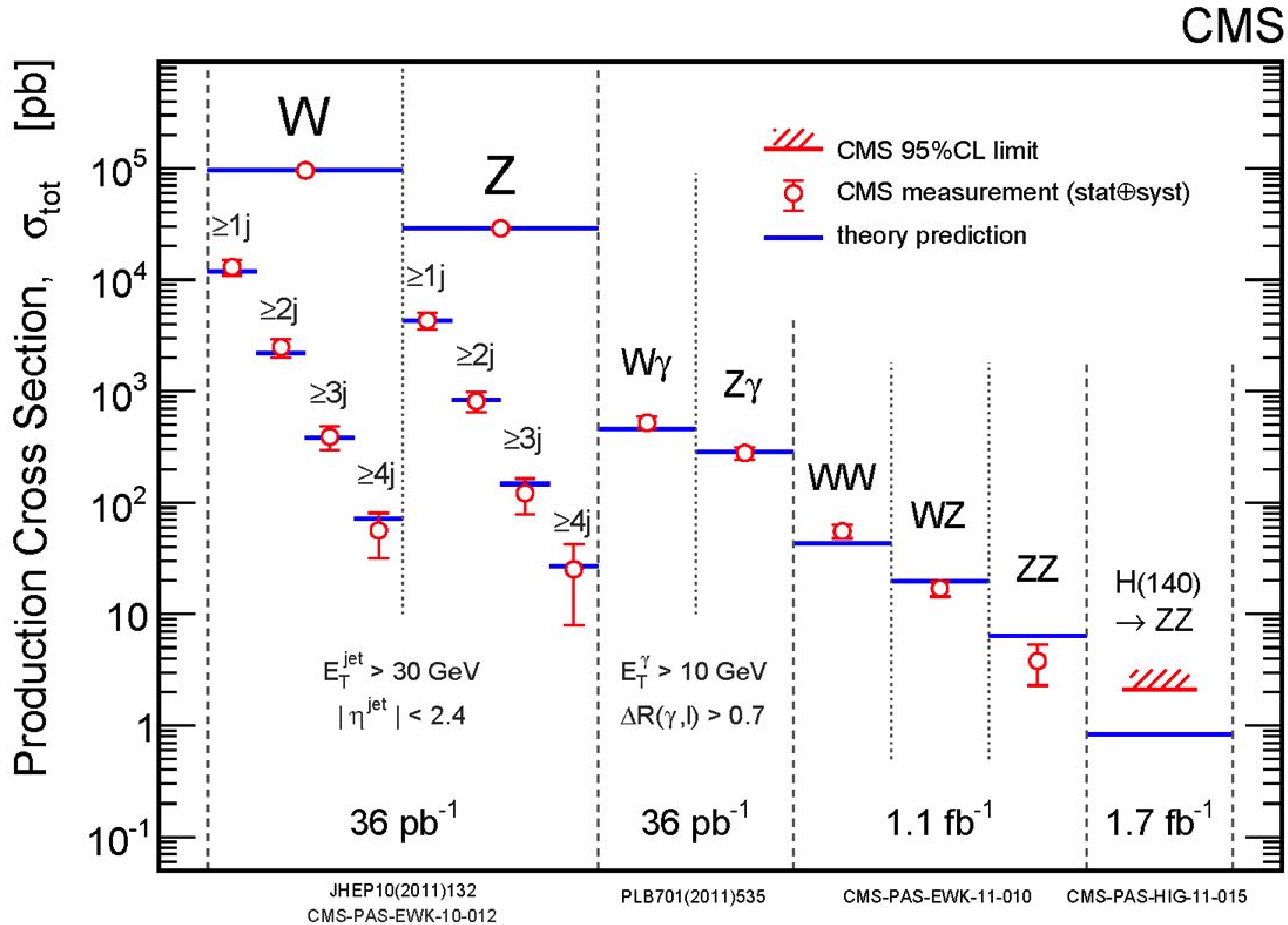
…what you see…



…what has happened

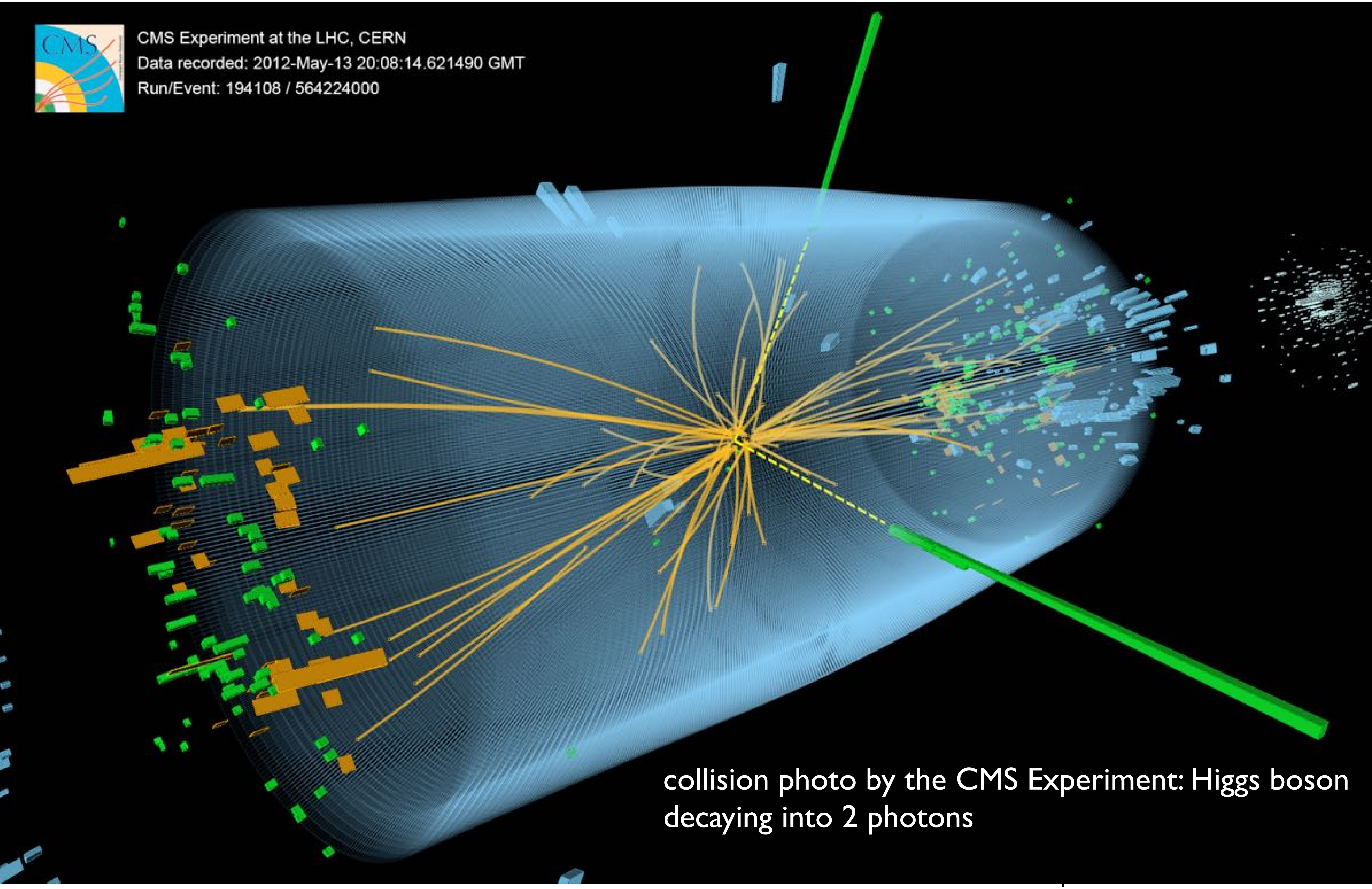


Probing the Standard Model at the LHC



Testing the Standard Model is as important as directly searching for new phenomena!
Are there deviations? Hints for NEW PHYSICS!

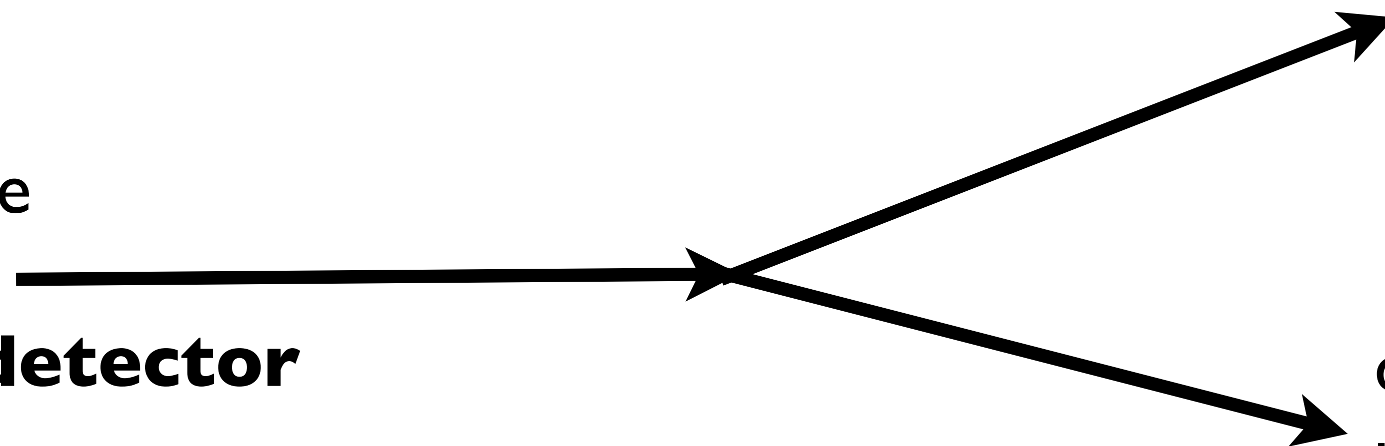
4. July 2012: CERN special seminar
“CERN experiments observe particle consistent with long-sought Higgs boson”



collision photo by the CMS Experiment: Higgs boson decaying into 2 photons

Mass of decaying particle can be calculated

decaying particle
mass M
not seen in detector



decay particle 1,
mass m1, energy E1,
momentum p1

decay particle 2,
mass m2, energy E2,
momentum p2

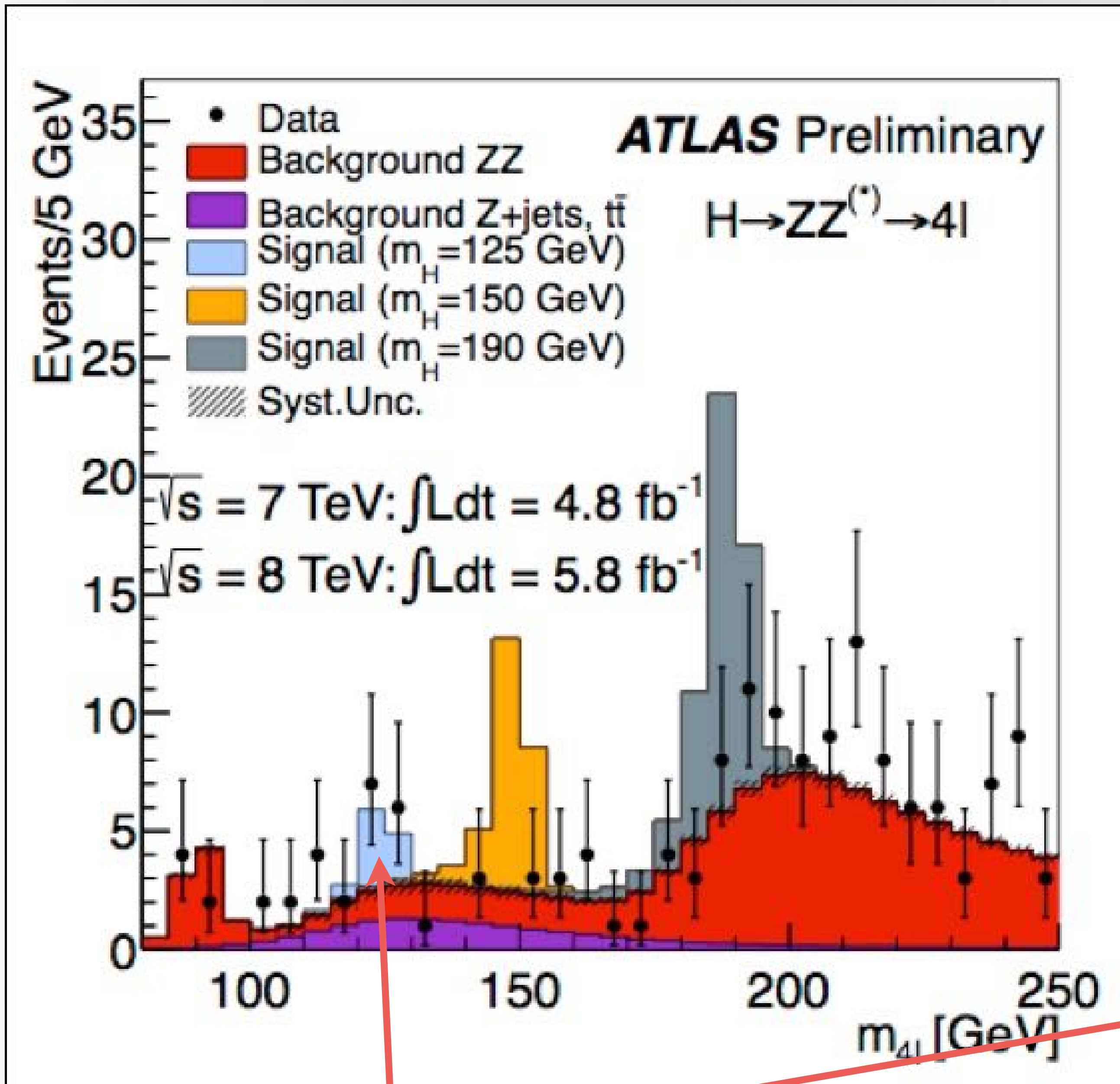
Decay particles (m, E, p) are measured in detector!

Calculation of particle mass M based on energy conservation and momentum conservation!

Basic relation: $m_0^2 = E^2 - \|\mathbf{p}\|^2$

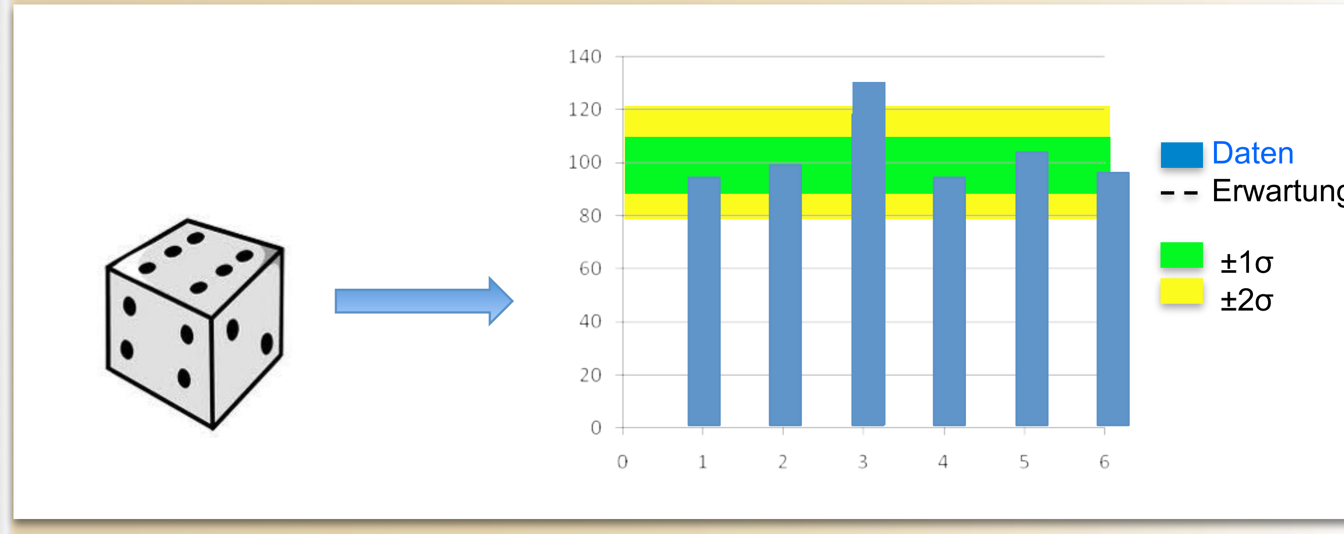
$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$
$$= m_1^2 + m_2^2 + 2\left(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2\right)$$

Finding new particles: calculate invariant mass

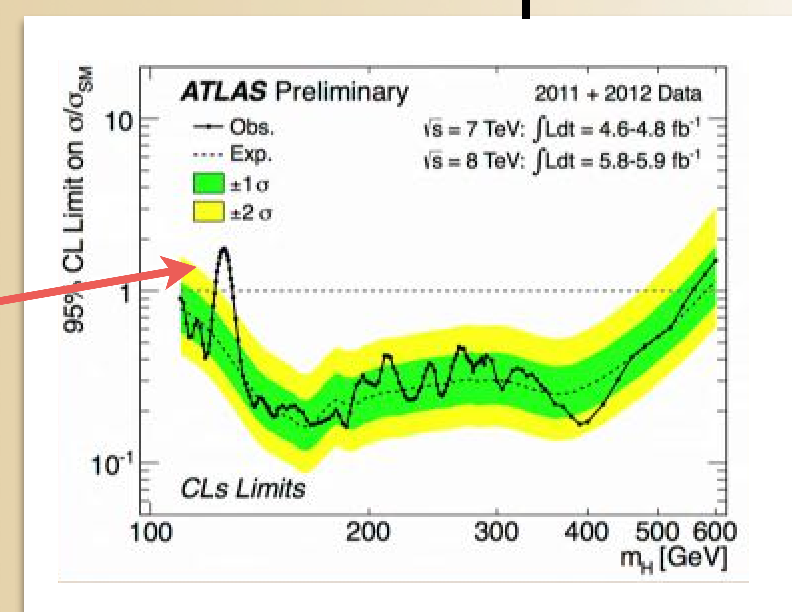


This is the Higgs particle!!!

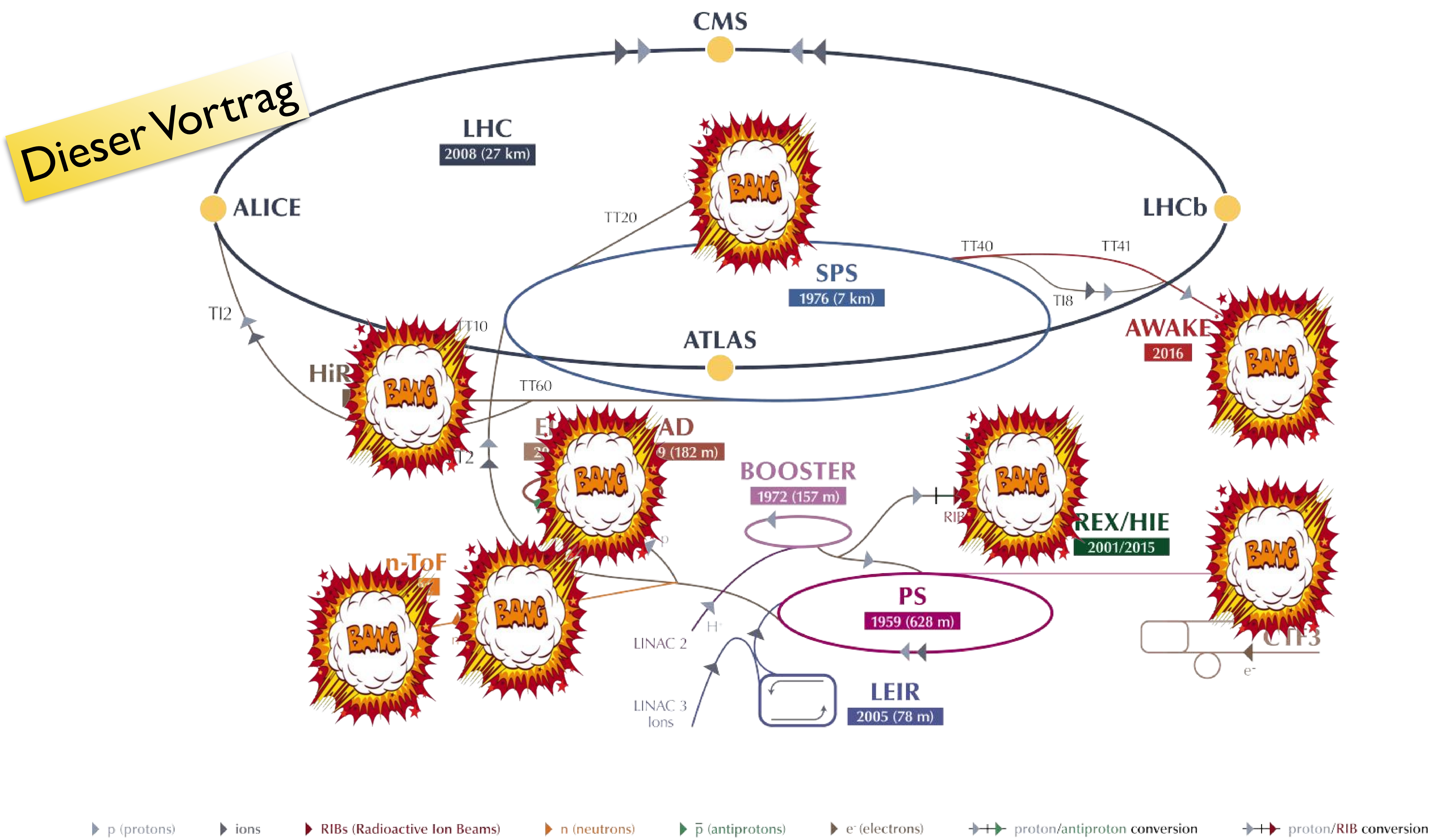
Example: is the dice marked?



Is there a new particle?



CERN Beschleuniger: Zeitreisen zum Urknall



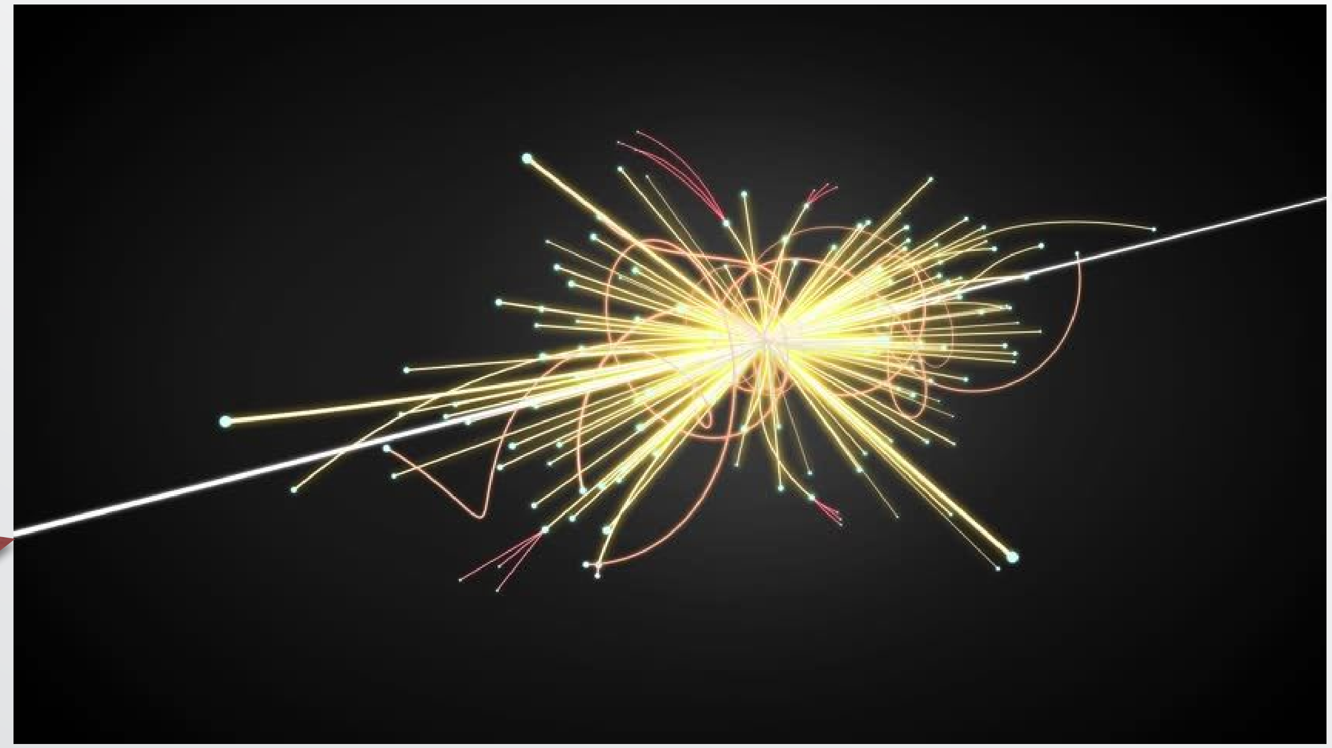
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron AD Antiproton Decelerator CTF3 Clic Test Facility

AWAKE Advanced WAKefield Experiment ISOLDE Isotope Separator OnLine REX/HIE Radioactive EXperiment/High Intensity and Energy ISOLDE

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

So sehen Teilchenkollisionen aus

Kollider-Experimente



Teilchenstrahl 1

Teilchenstrahl 2

Fixed-Target-Experimente

Teilchenstrahl

Target

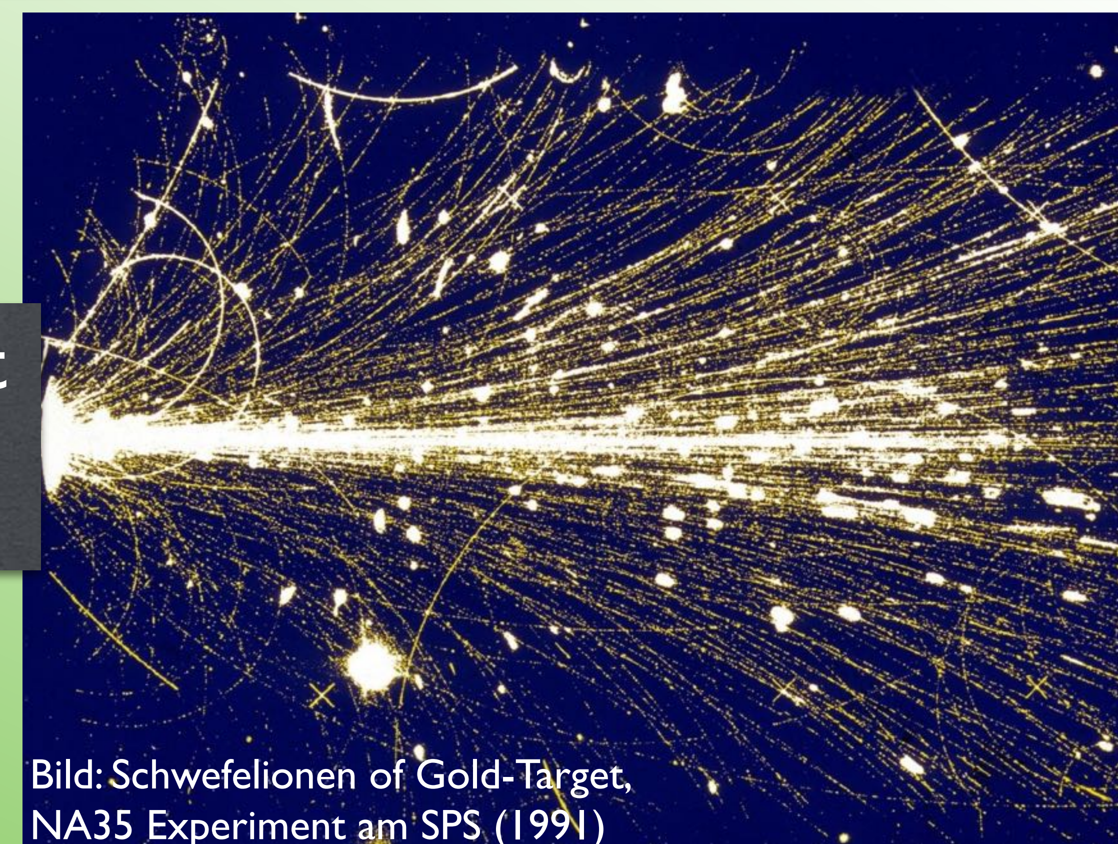
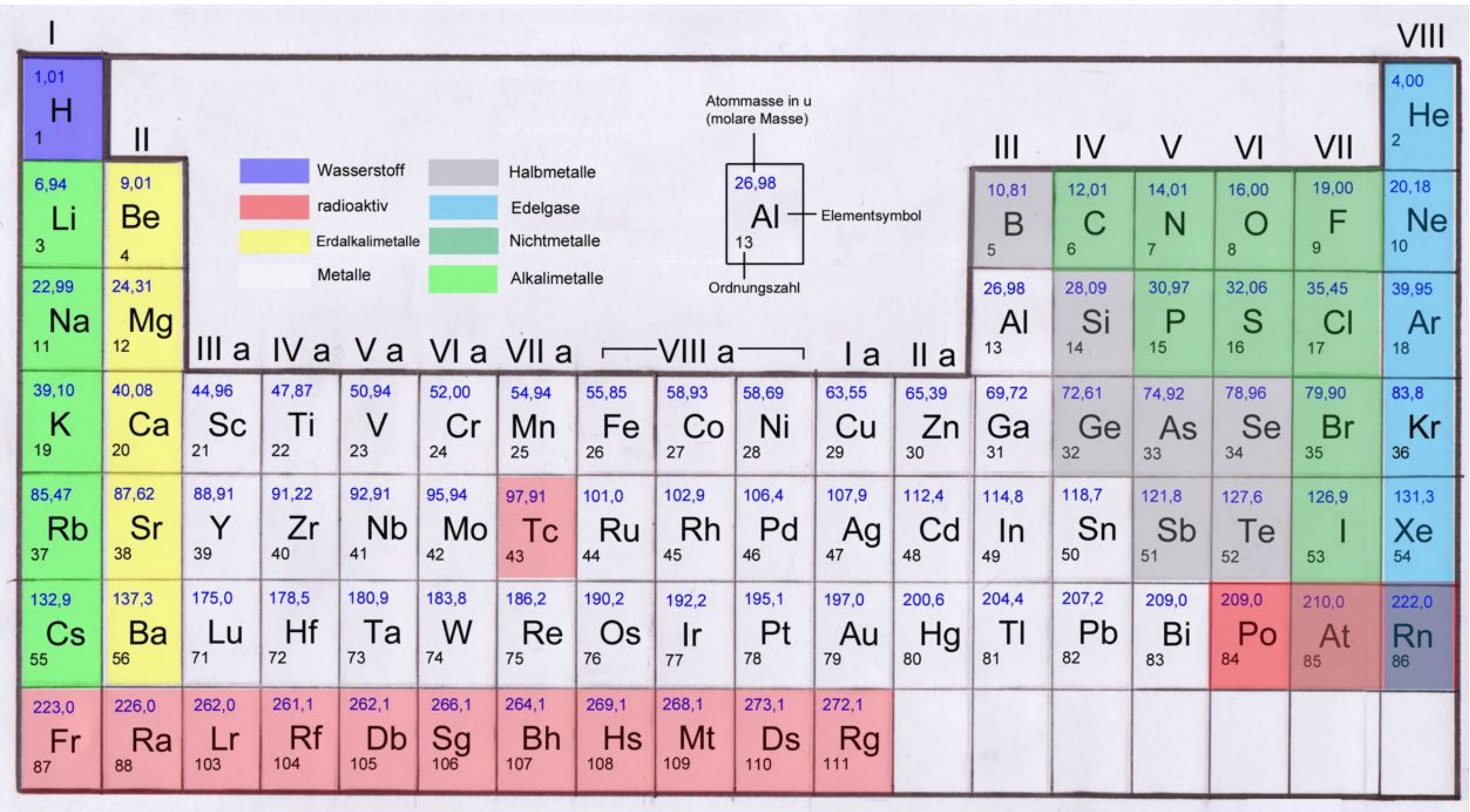


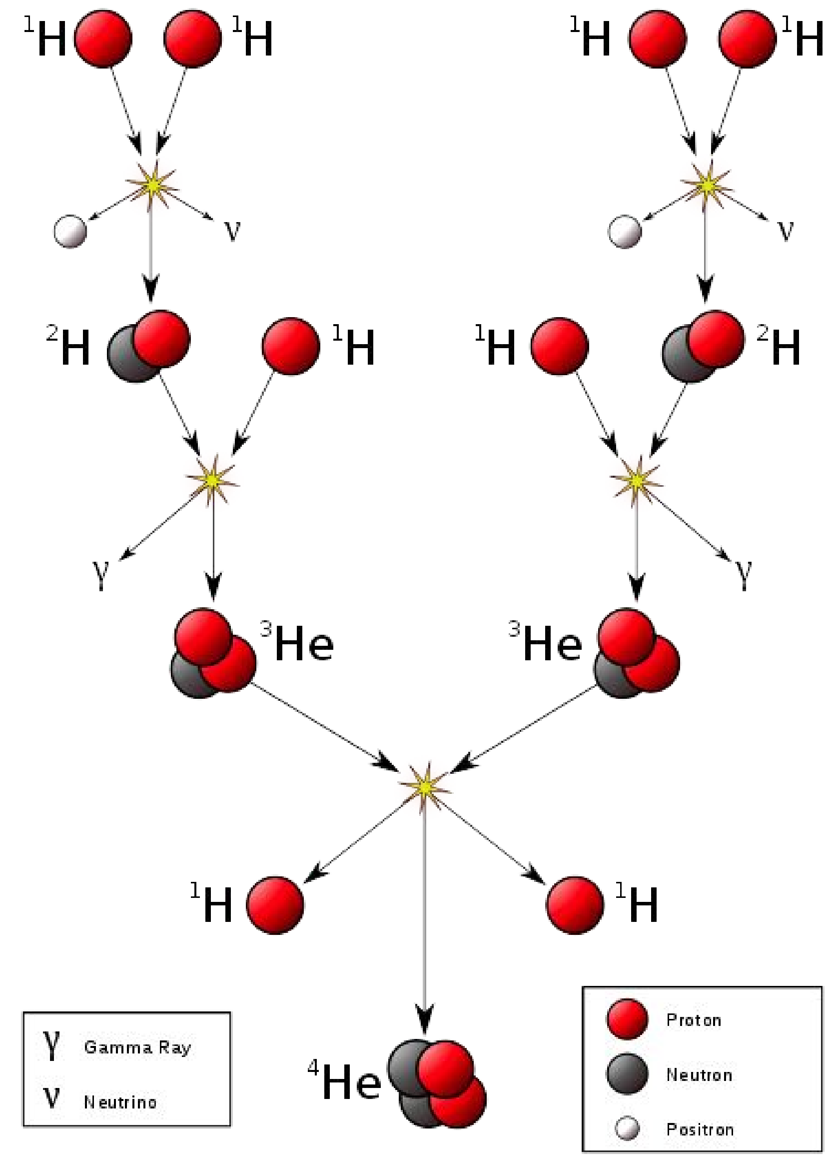
Bild: Schwefelionen of Gold-Target,
NA35 Experiment am SPS (1991)

Woher kommen die schweren Elemente im Universum?

Periodensystem der Elemente



Kernfusion in Sternen

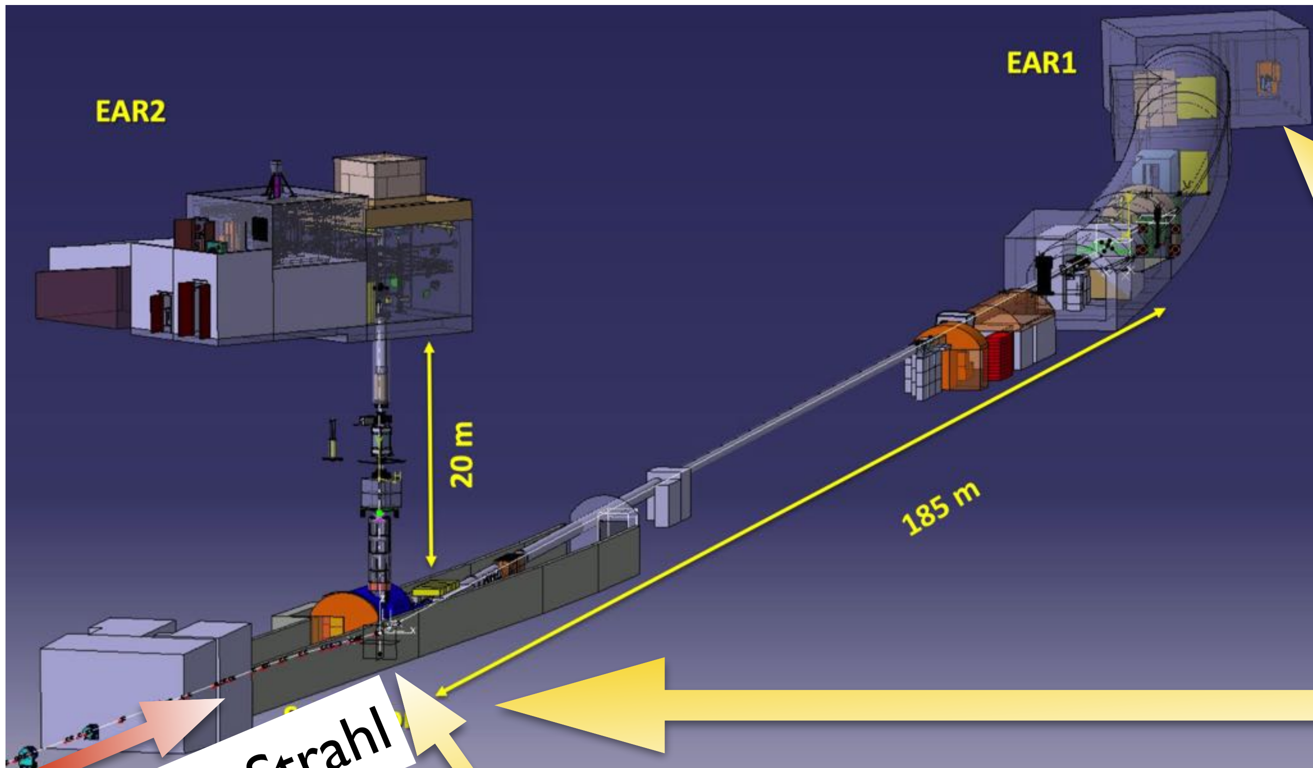


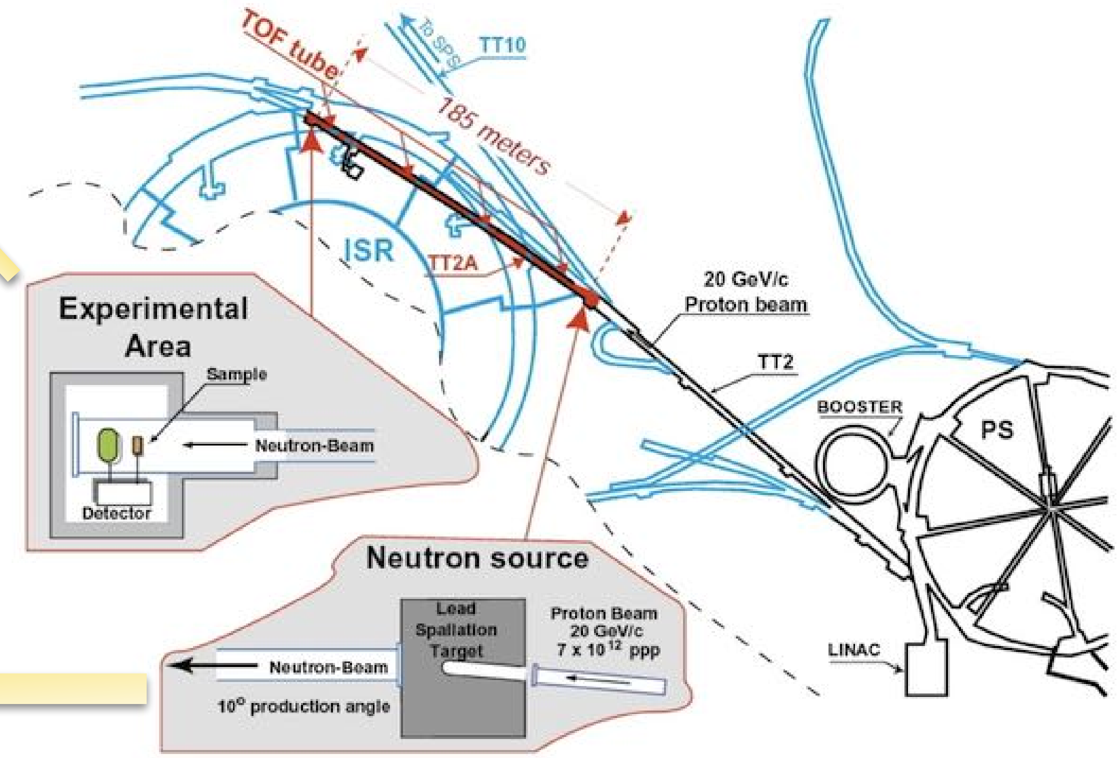
Kernfusion funktioniert bis hin zu Atommassen ~60

Woher kommen die schweren Elemente wie Gold, Blei?

Forschung mit Neutronen: n-TOF

n-TOF (neutron Time-of-Flight): typische unterirdische Experimentieranlage am CERN

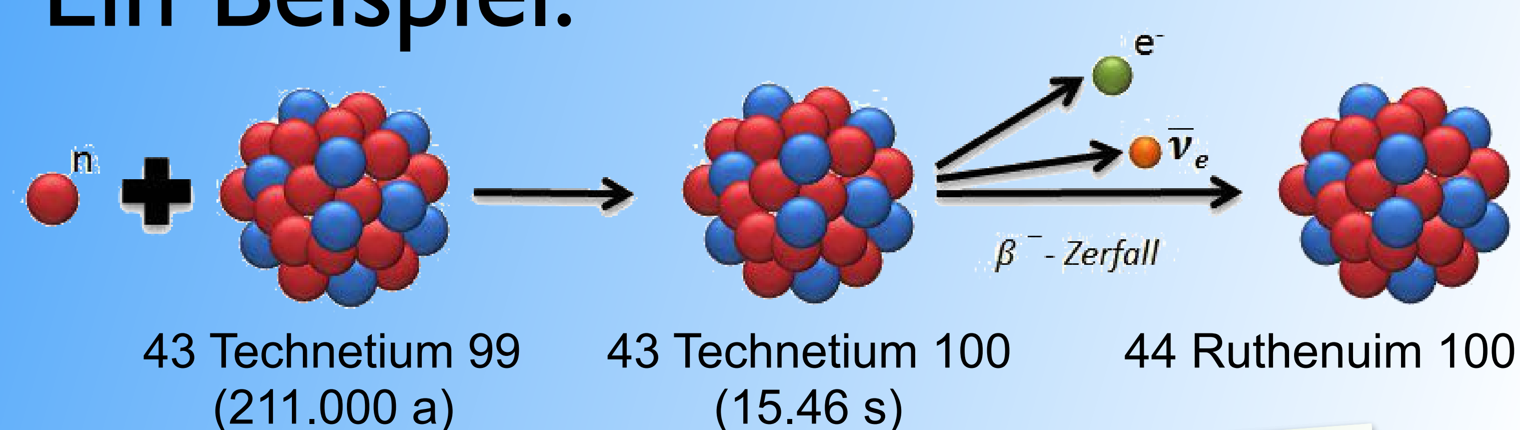




Protonen-Strahl

n-TOF Target

Ein Beispiel:



n-TOF: Simulation einer Supernova

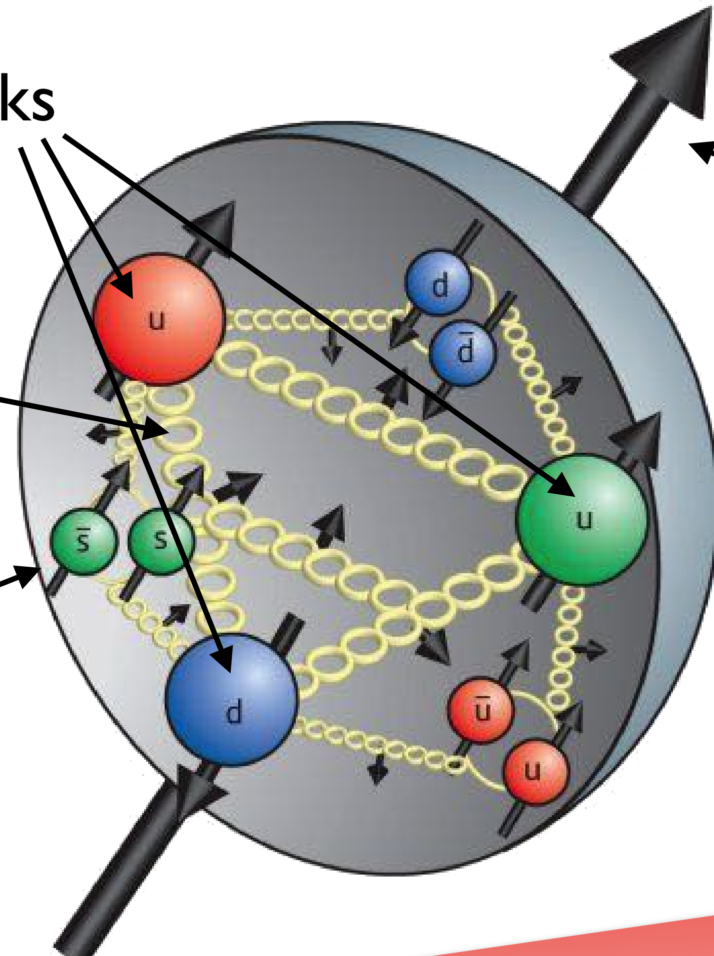
Verstehen wir das Proton?

Dank DESY: Struktur des Protons sehr gut bekannt.

drei quarks

Starke Kraft (Gluonen)
halten es zusammen

Genaues Hinsehen:
Suppe aus weiteren Gluonen
und kurzlebigen Paaren
aus quarks und Antiquarks

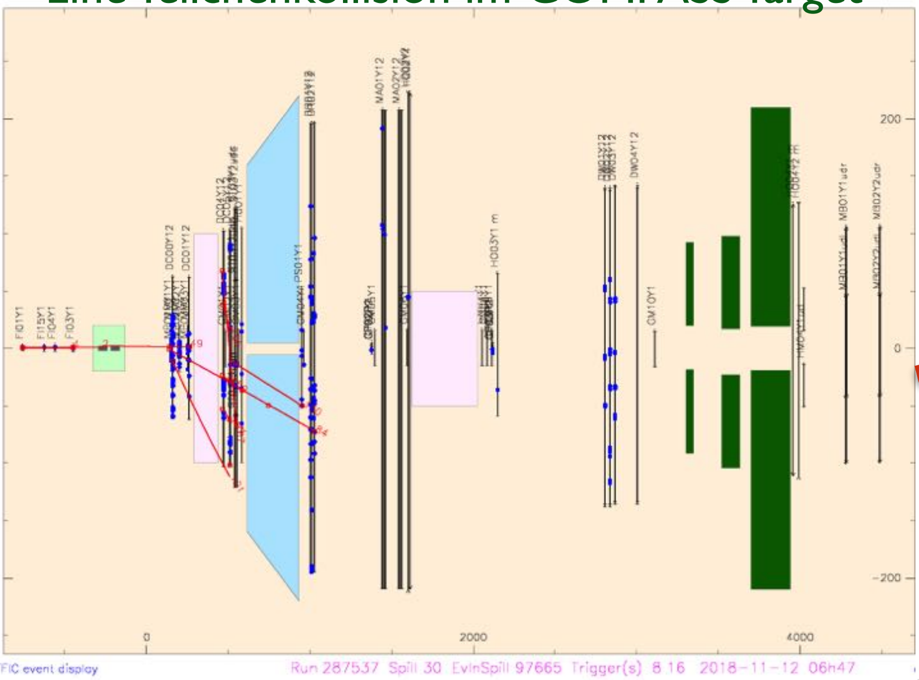


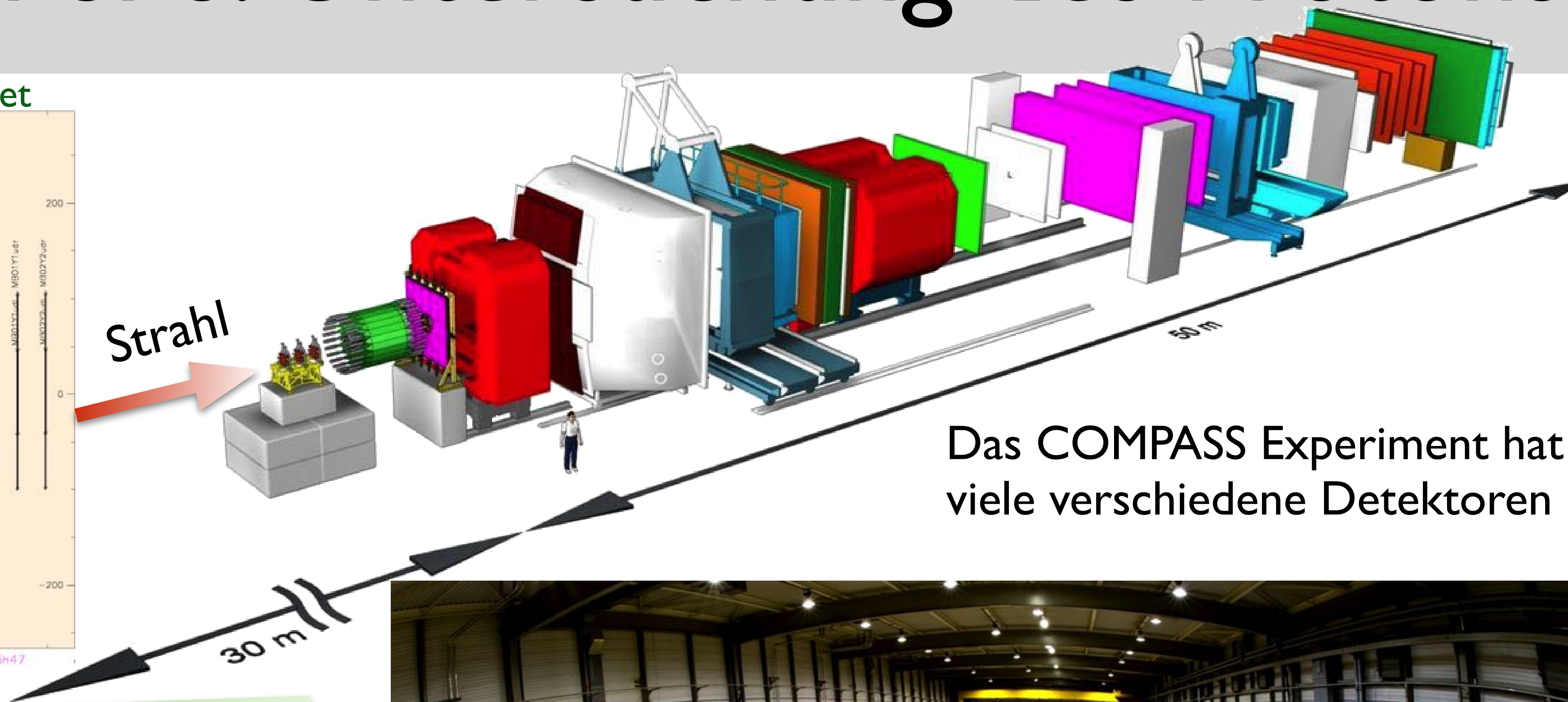
Eine weitere Eigenschaft:
spin
(Proton hat spin 1/2,
quarks haben ebenfalls spin 1/2)

Woher kommt der spin des Protons?
Was ist der "Radius" des Protons?
...

COMPASS am SPS: Untersuchung des Protons

Eine Teilchenkollision im COMPASS Target





Das COMPASS Experiment hat viele verschiedene Detektoren

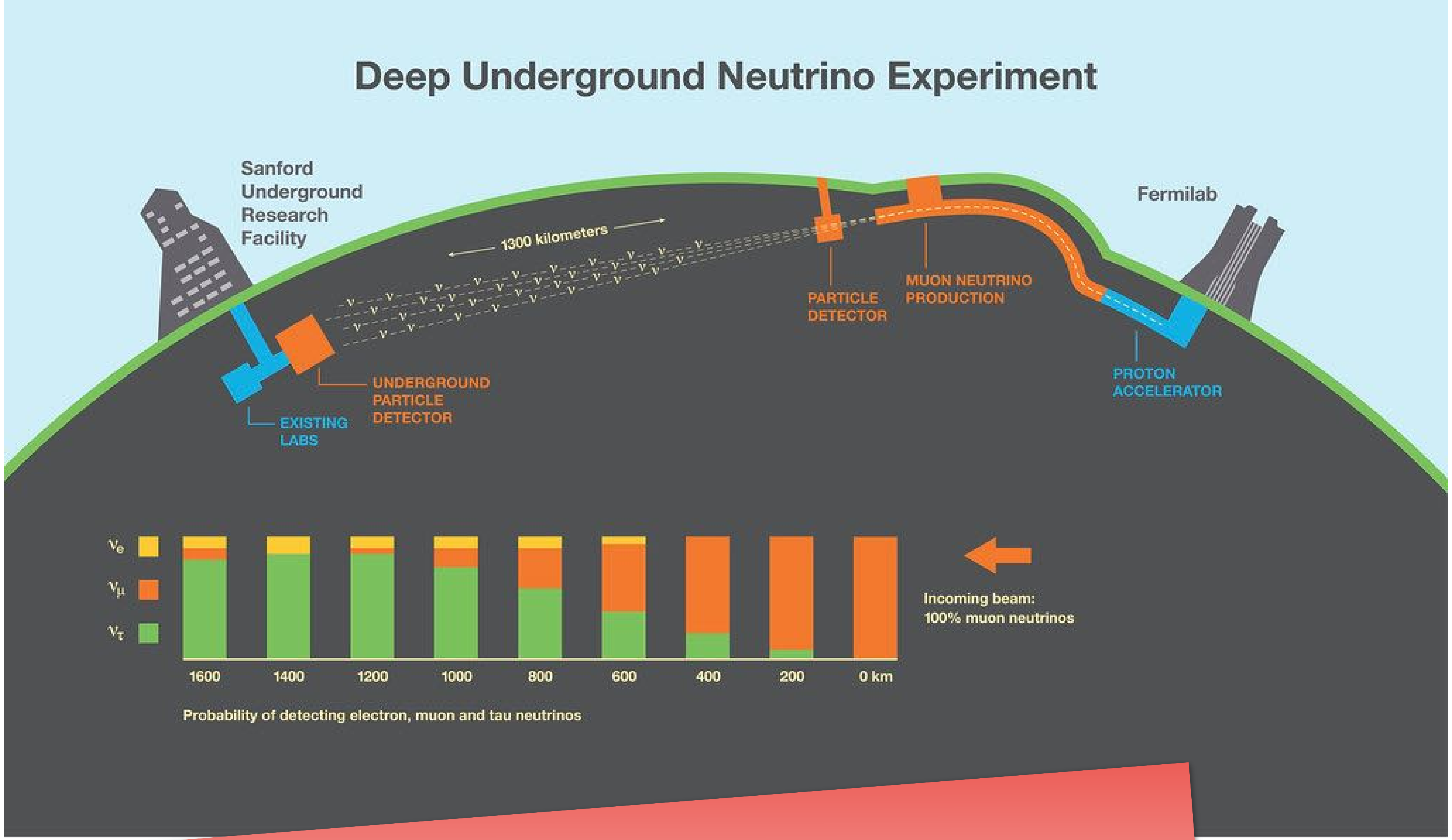
Ergebnis bisher:
Beitrag zum spin des Protons
- ➡ quarks 25%
- ➡ gluonen 6%

Wo ist der Rest????
→ "spin Krise"

Die Suche geht weiter.
Auch geplant:
Proton-Radius Messung

Wie verhalten sich Neutrinos?

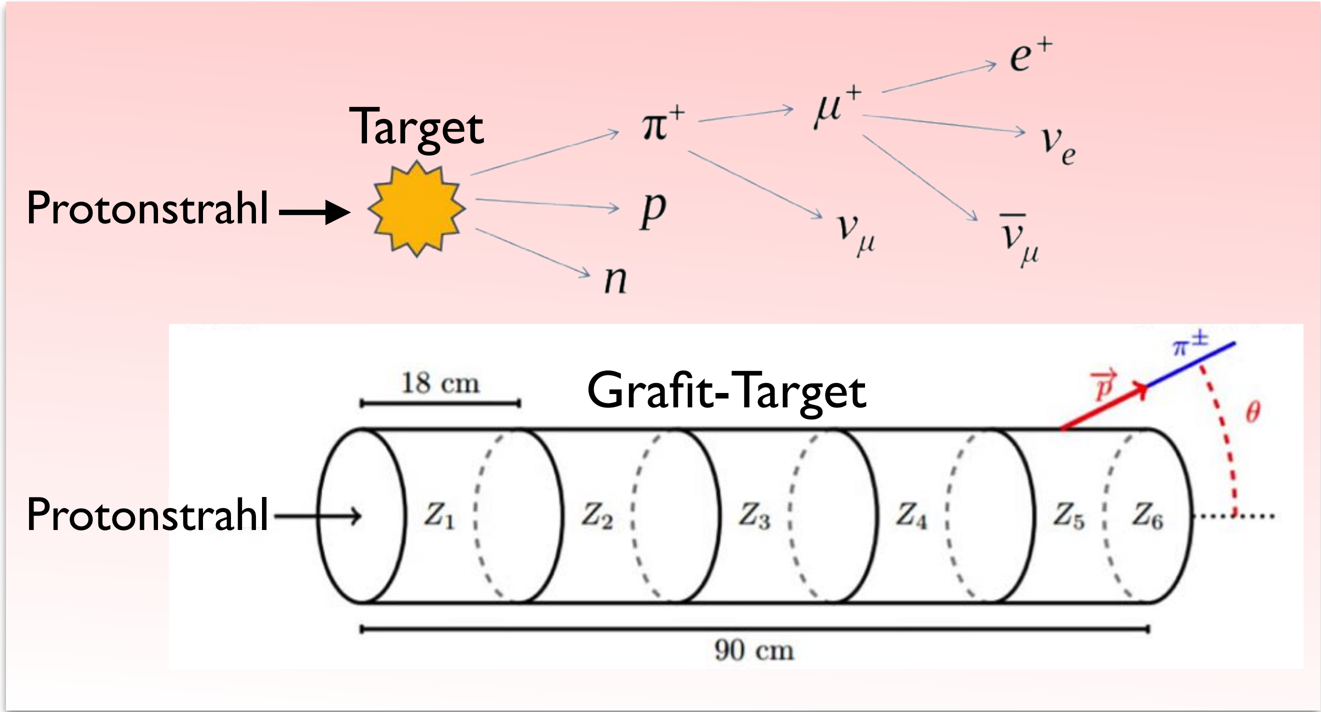
Das Experiment DUNE in Amerika will Neutrinos vermessen.

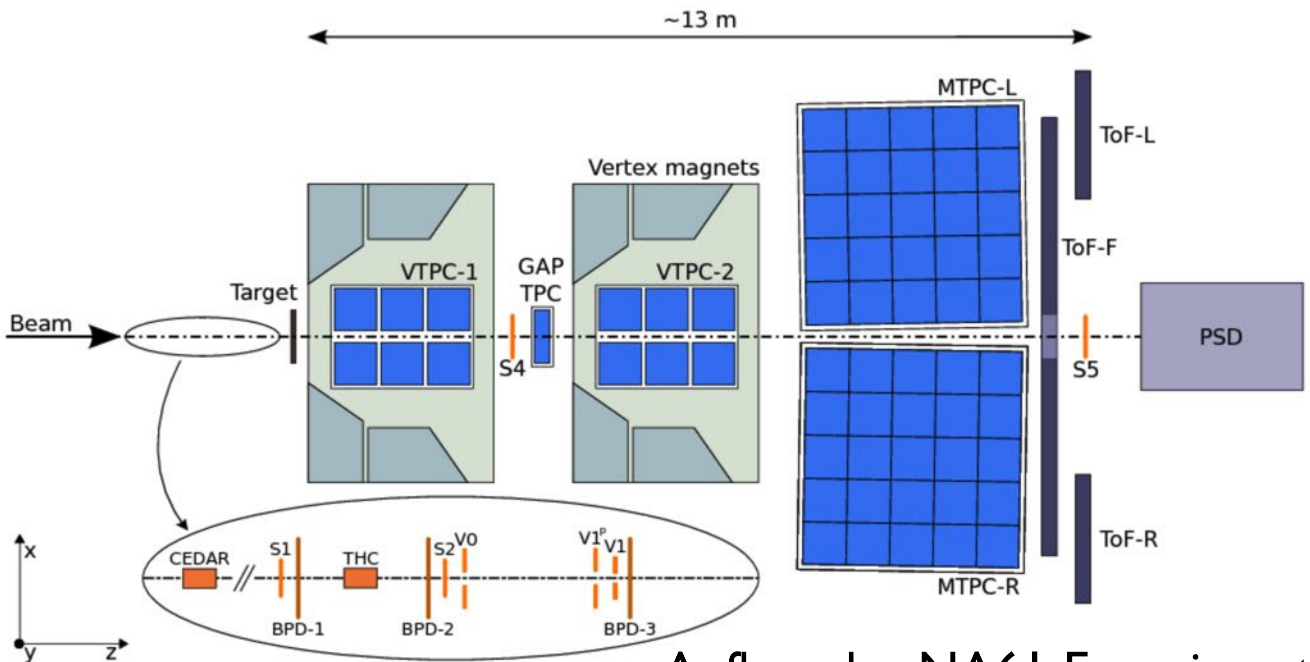


Um die Messungen zu verstehen:

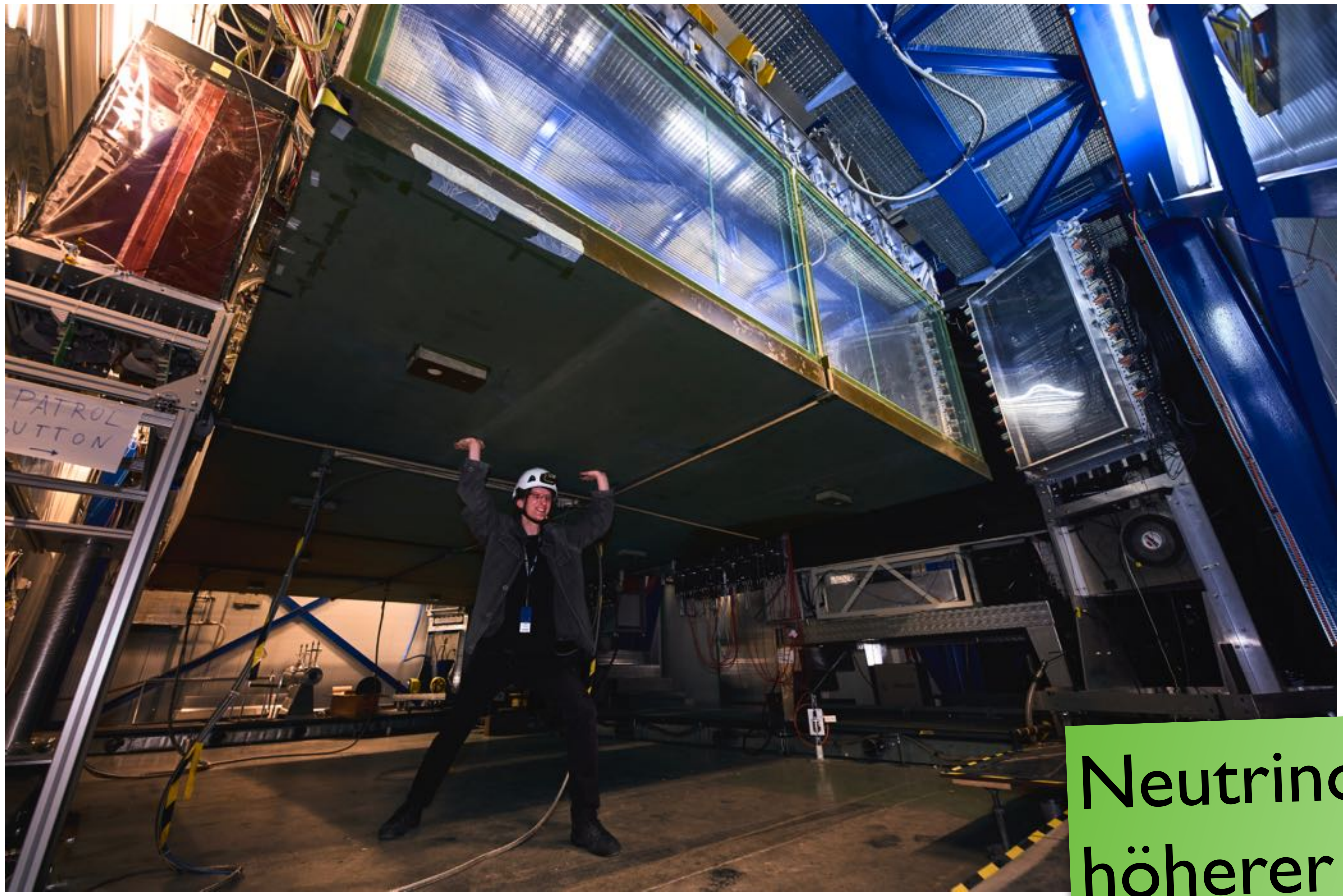
- ➡ wie viele Neutrinos werden im Fermilab produziert?
- ➡ wie viele Neutrinos gehen entlang der Flugstrecke in der Erde verloren?

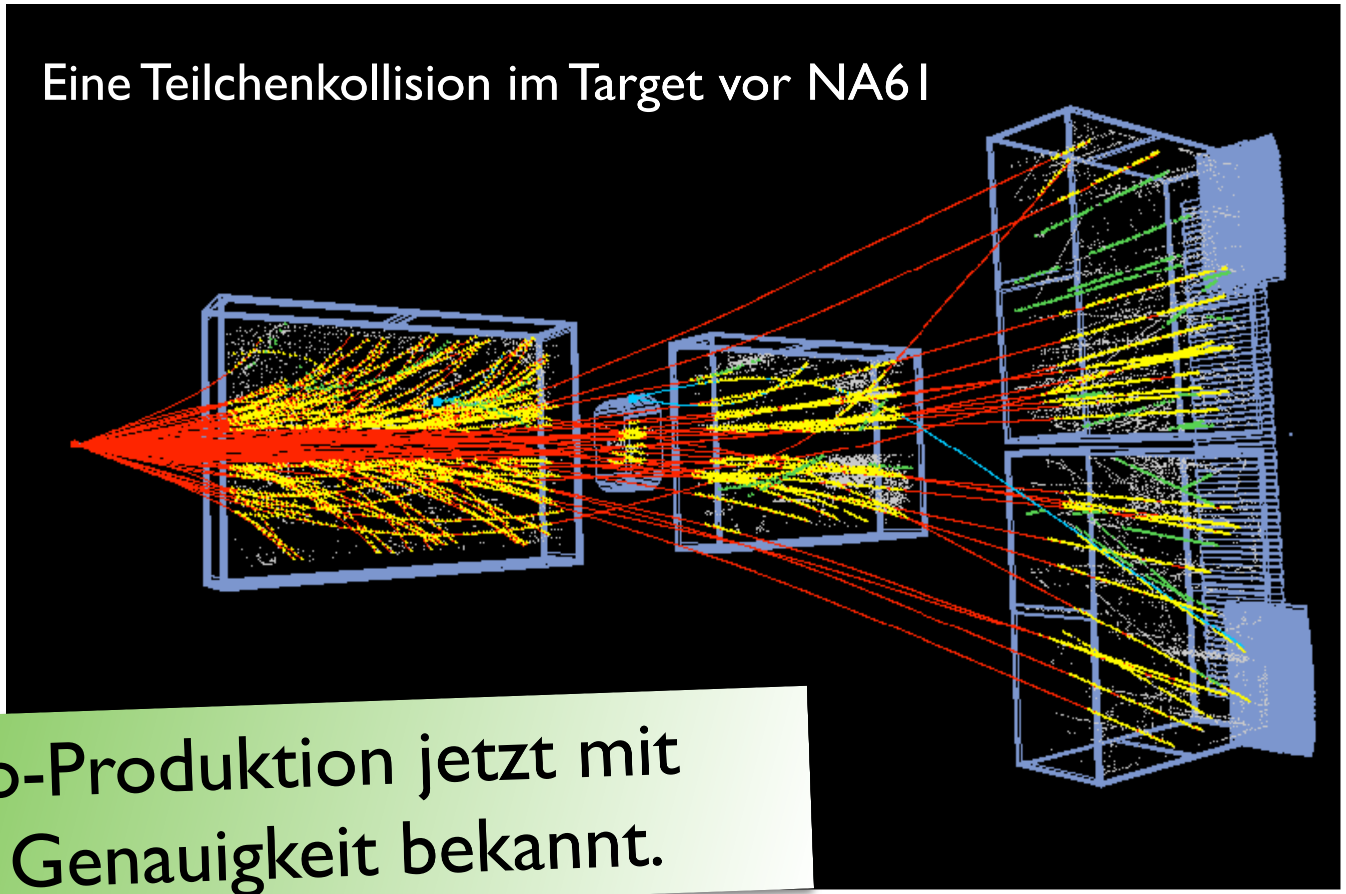
NA61 am SPS misst die Produktionsraten von Neutrinos





Aufbau des NA61 Experiments

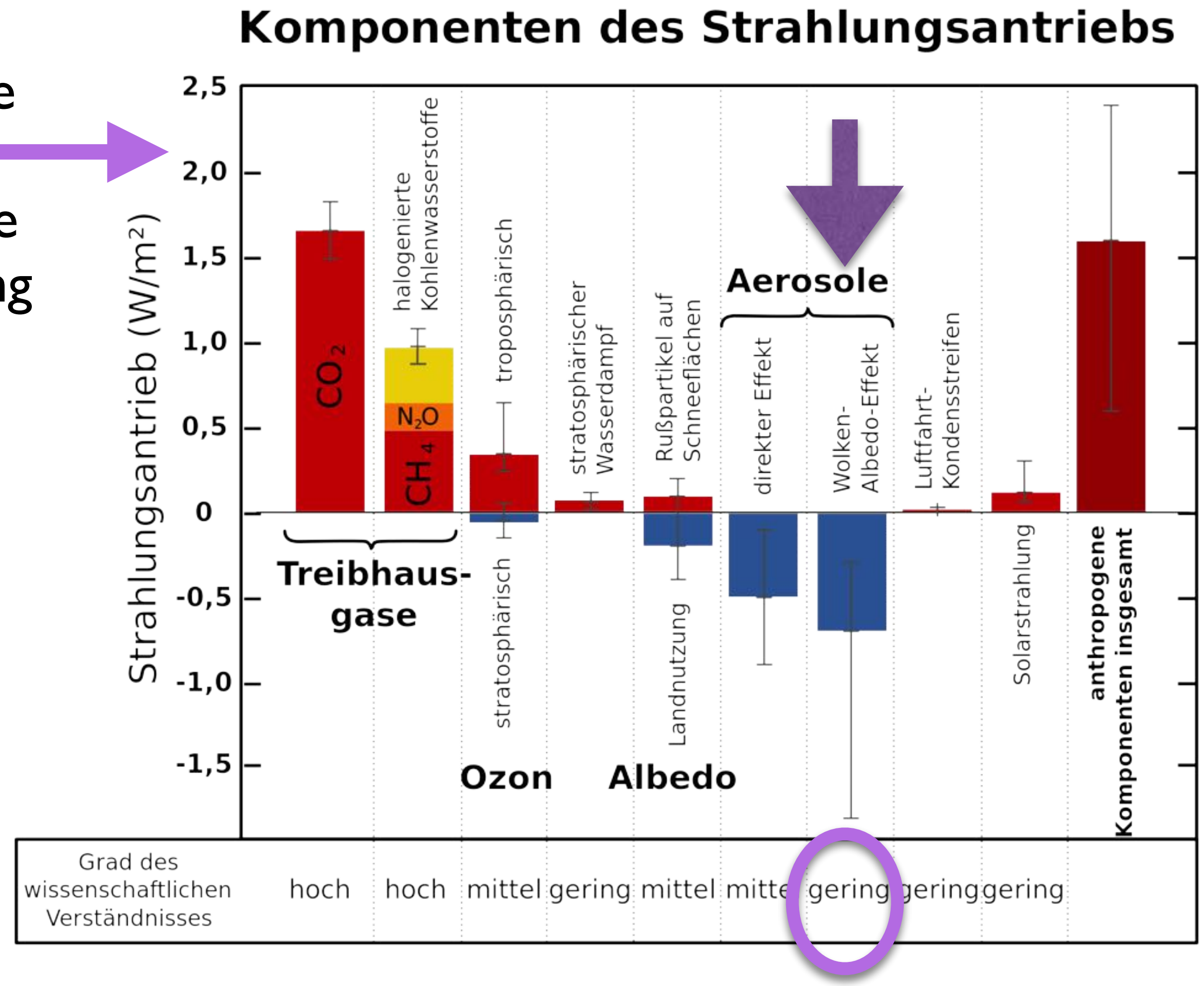


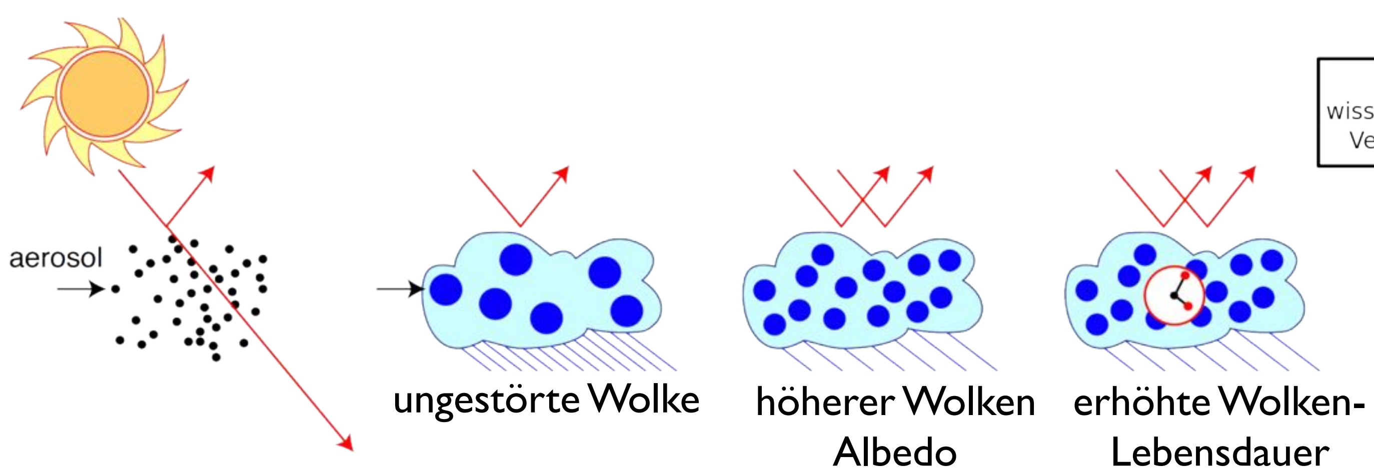


Neutrino-Produktion jetzt mit höherer Genauigkeit bekannt.

Ein wichtiges Thema

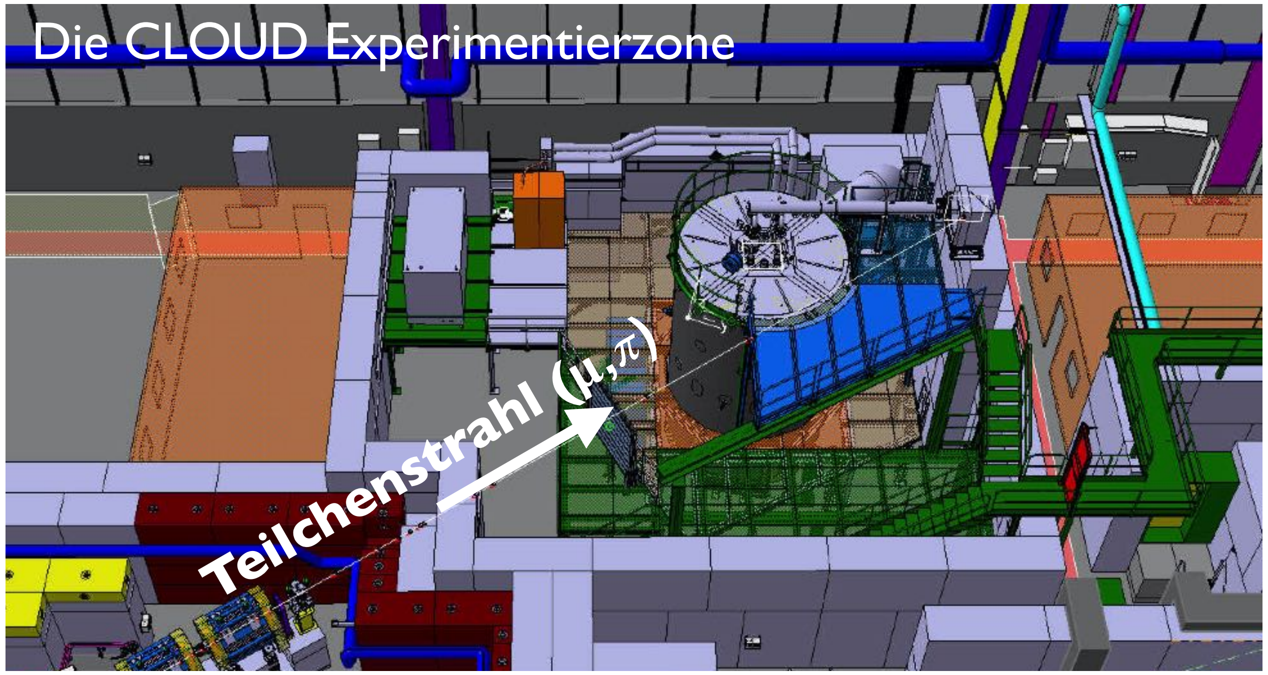
Strahlungsantrieb (radiative forcing) ist ein Maß für die Energiebilanz der Erde durch die von außen einwirkende Strahlung



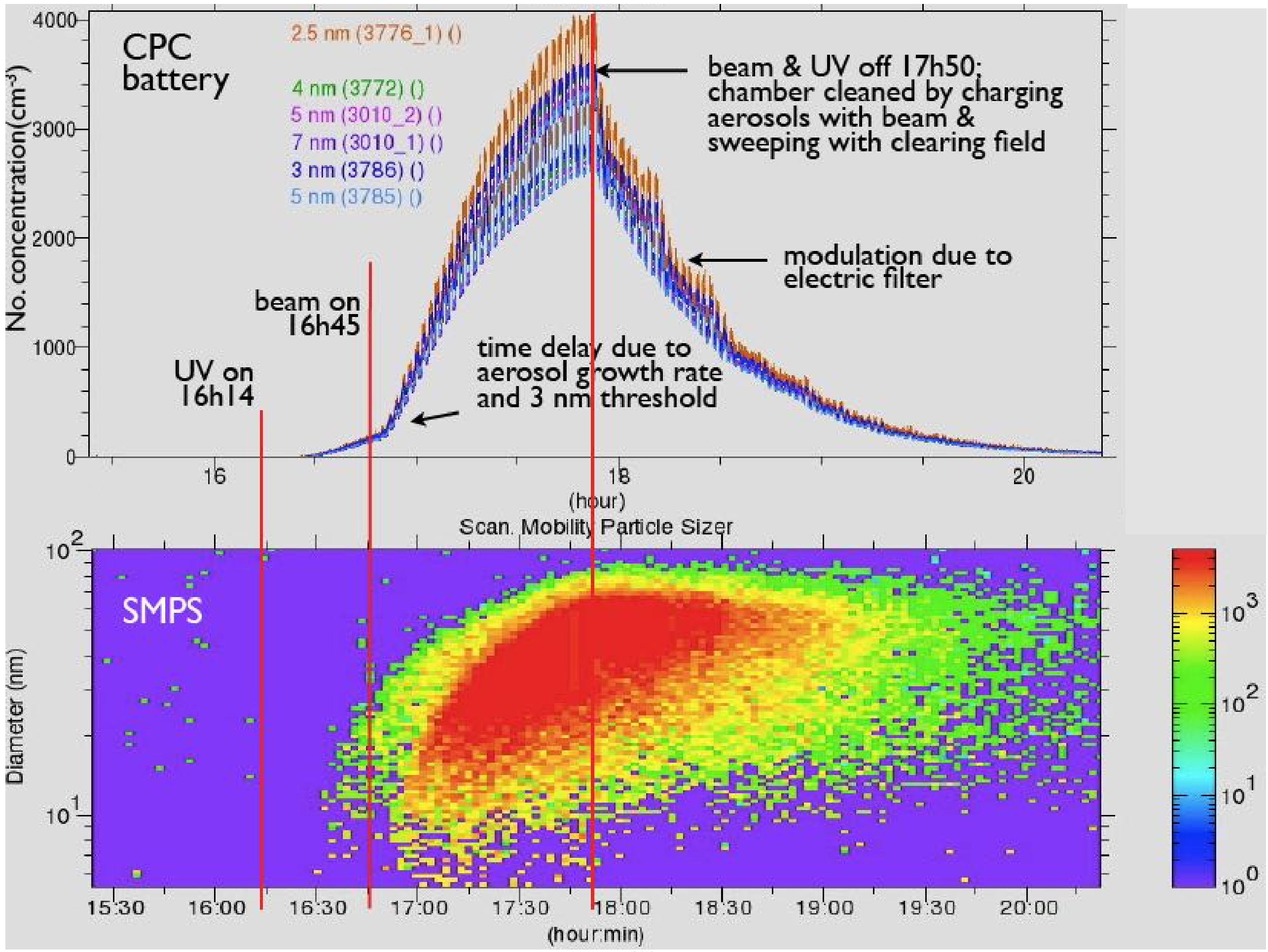


Verstehen wir Wolken? Wie bilden sie sich?

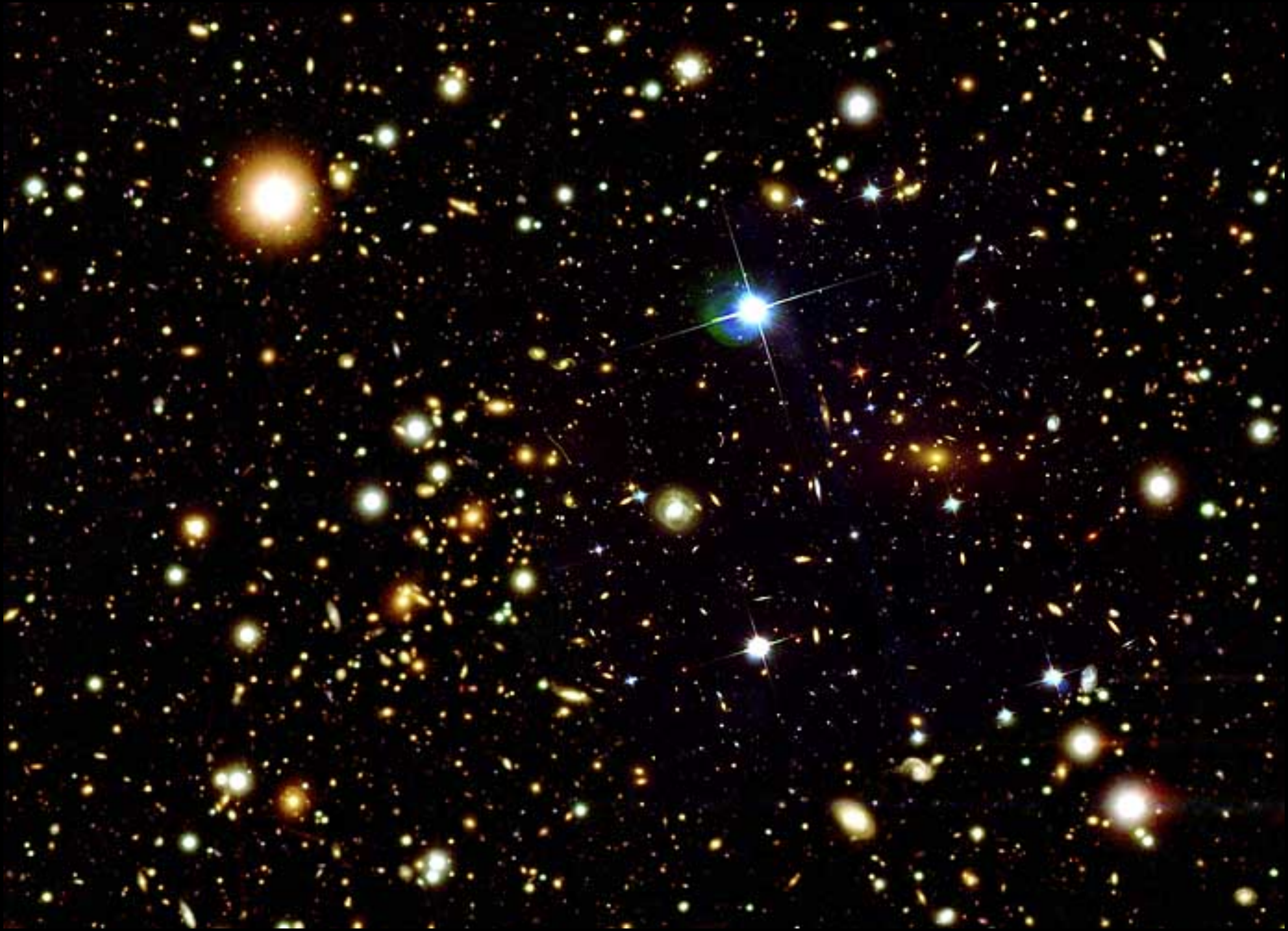
Wie entstehen Wolken? CLOUD am PS

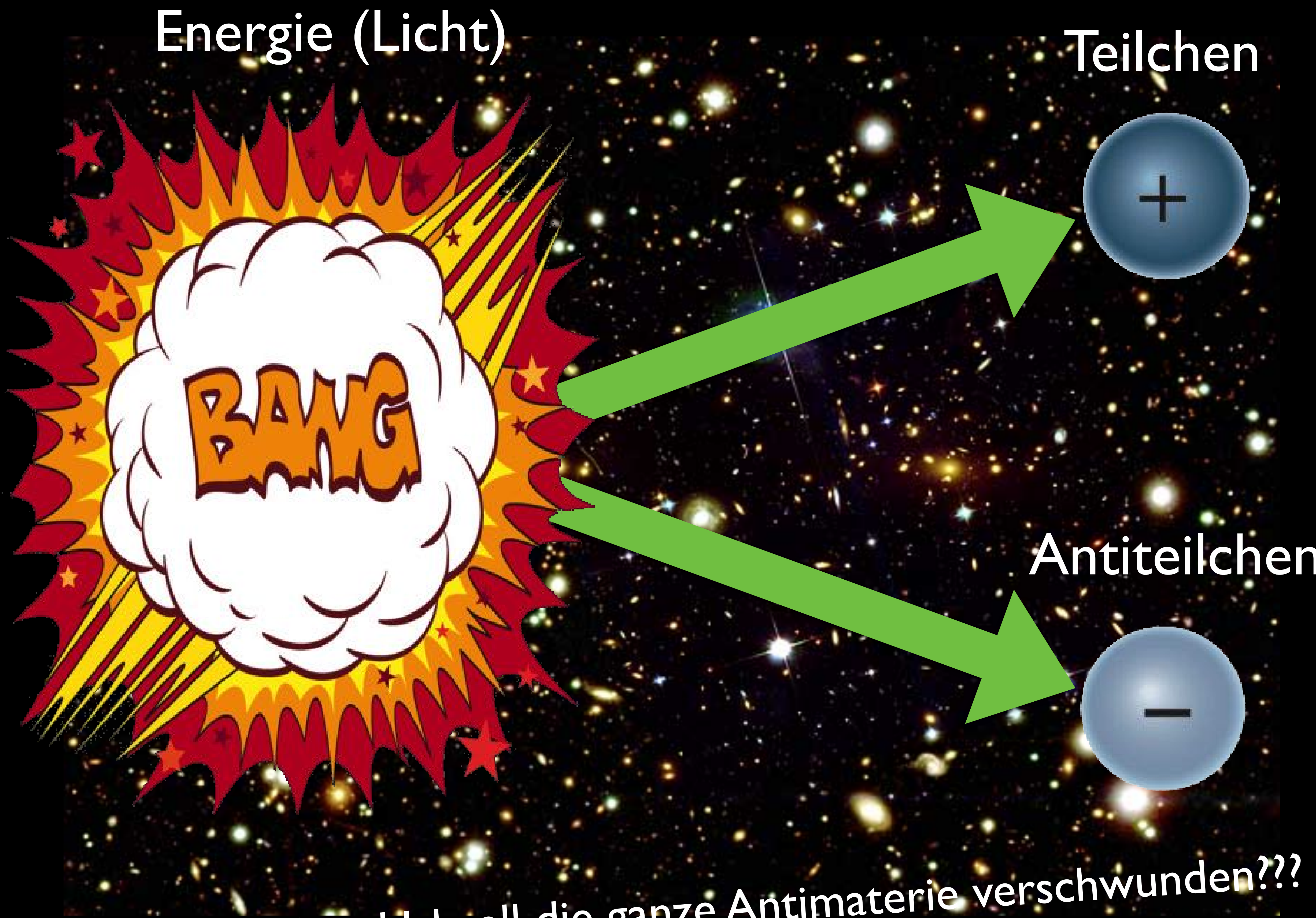


Ein typischer CLOUD run:
der Teilchenstrahl lässt Aerosole wachsen



Ergebnisse von CLOUD sind wichtig für die Klima-Simulation und -Vorhersage





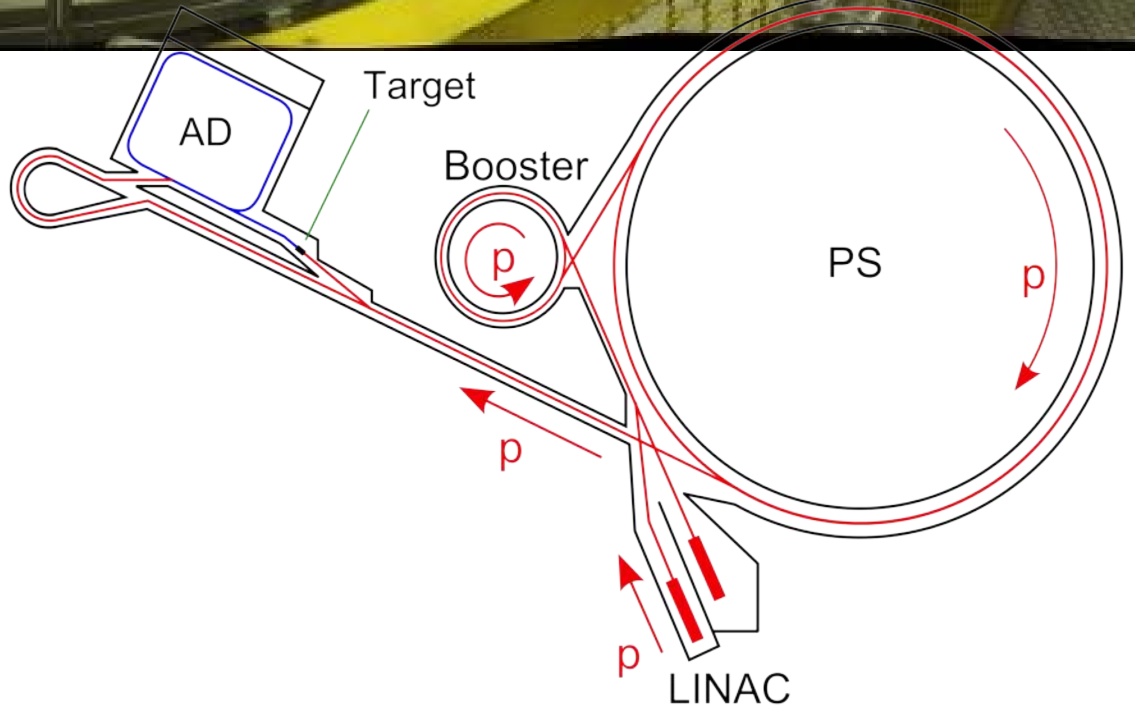
Wohin ist nach dem Urknall die ganze Antimaterie verschwunden???

Es muss Unterschiede zwischen Materie / Antimaterie geben

Experimente an CERN's Antiproton Decellerator AD

→ produzieren Antimaterie-Atome;

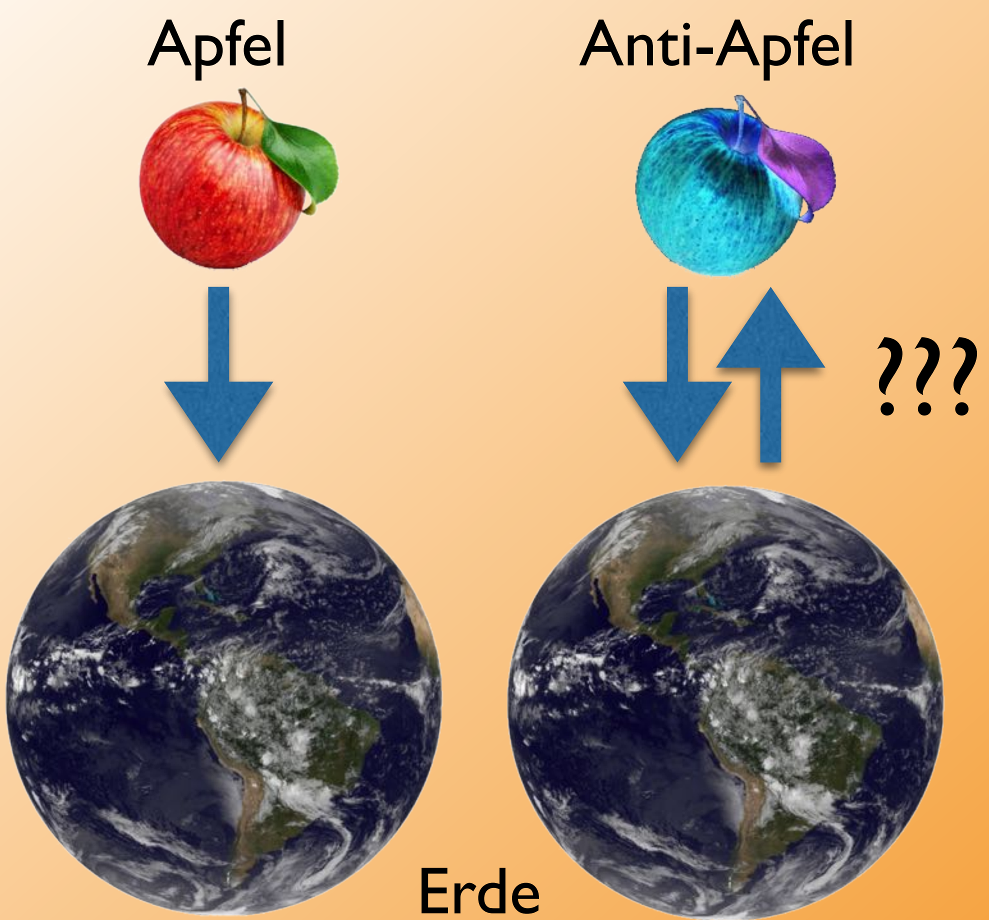
→ vergleichen sie mit Materie-Atomen.



Suche nach dem Materie-Antimaterie-Unterschied

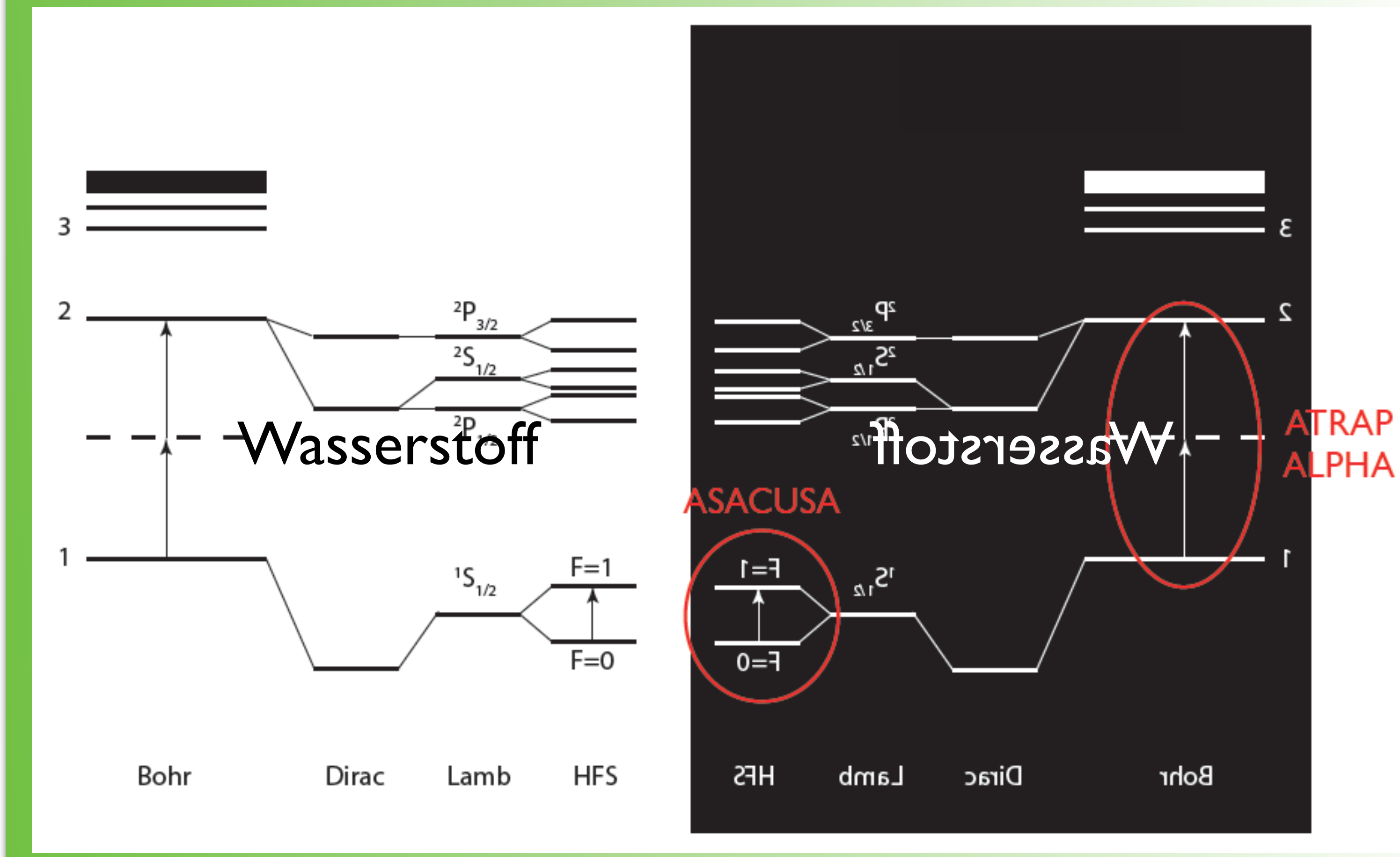
Zwei Ansätze:

Gravitationsmessung



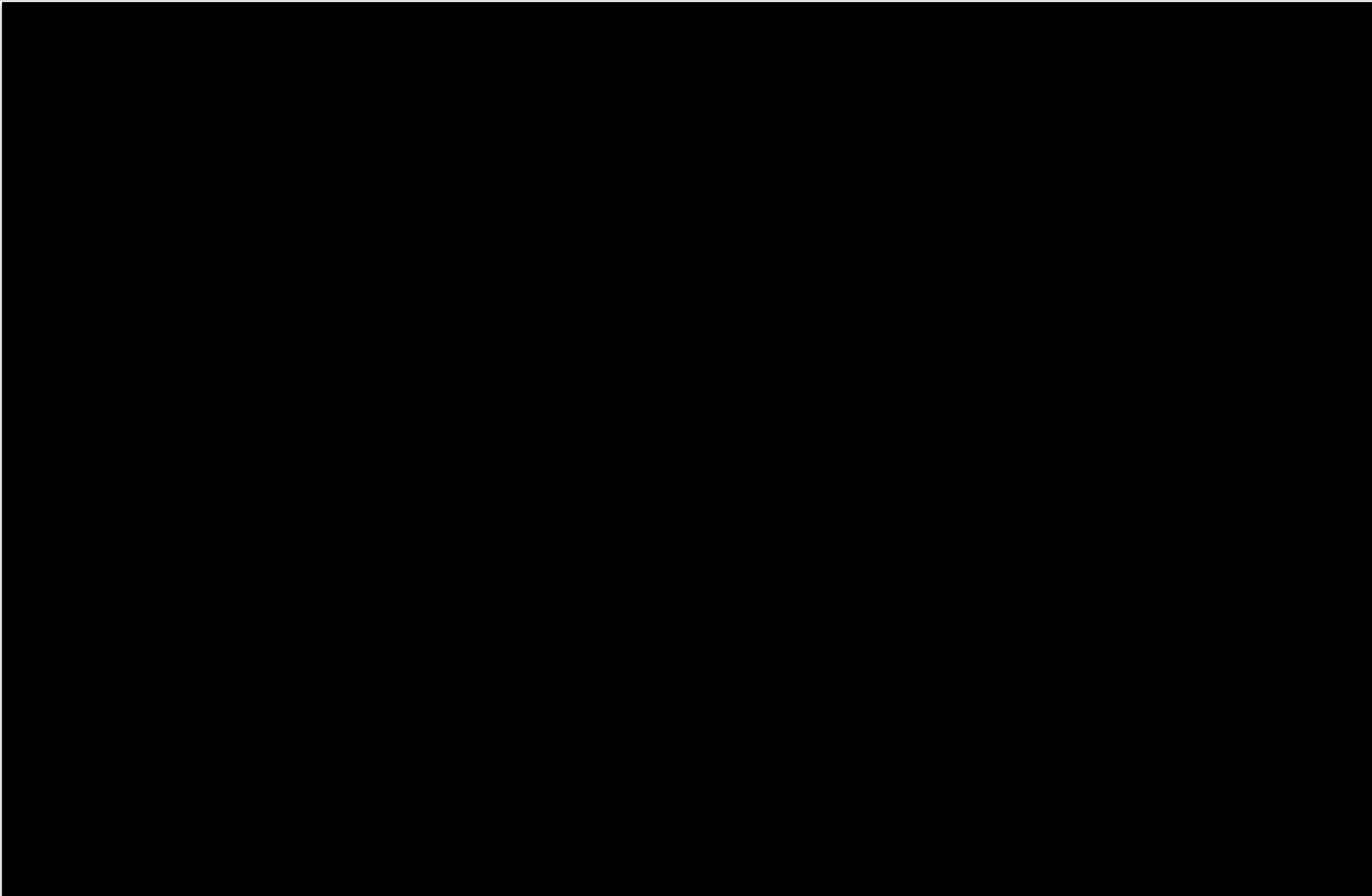
Experimente:
ALPHA-g, AeGIS, GBar

Spektroskopie



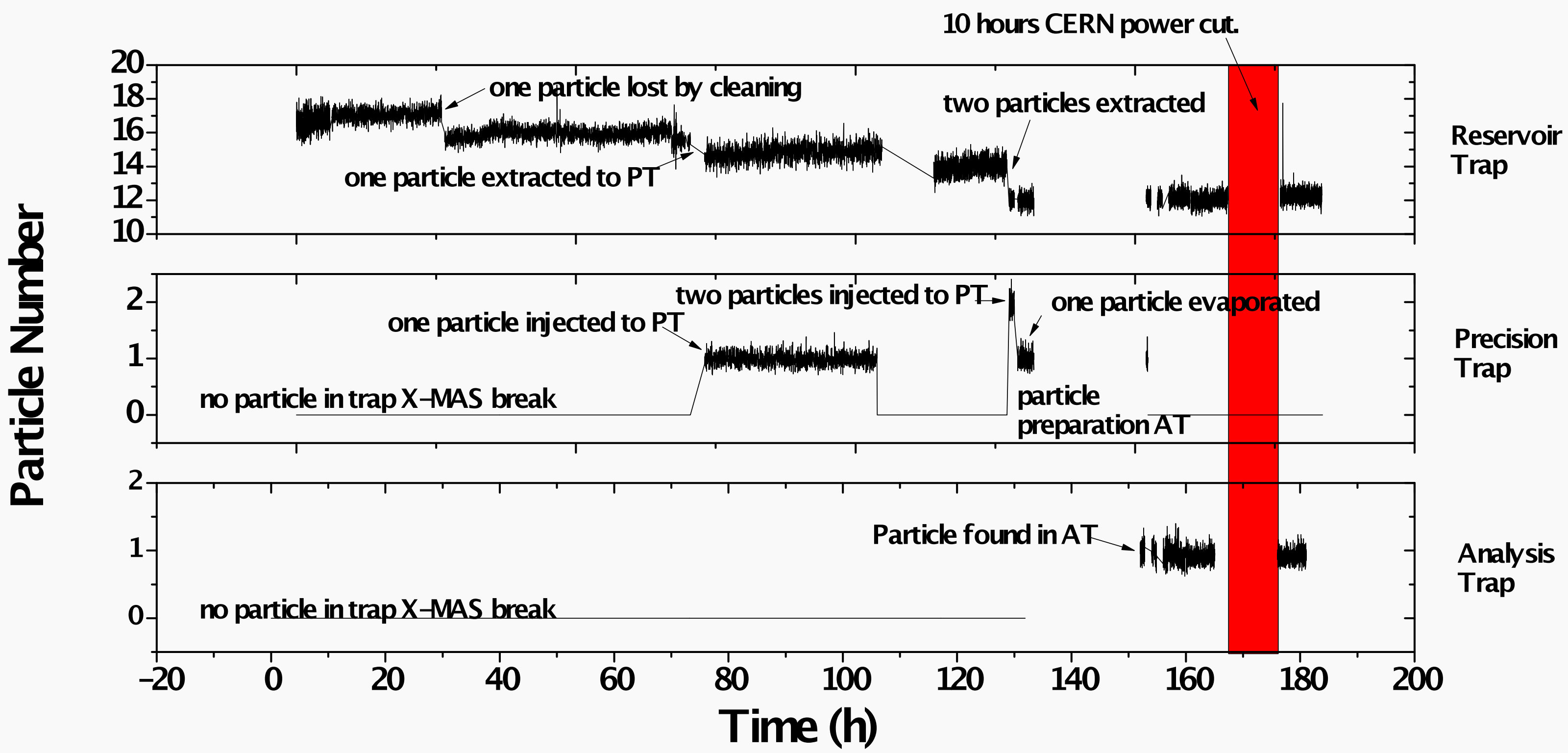
Experimente:
ALPHA, ATRAP, ASACUSA

The ALPHA experiment - manipulating antimatter

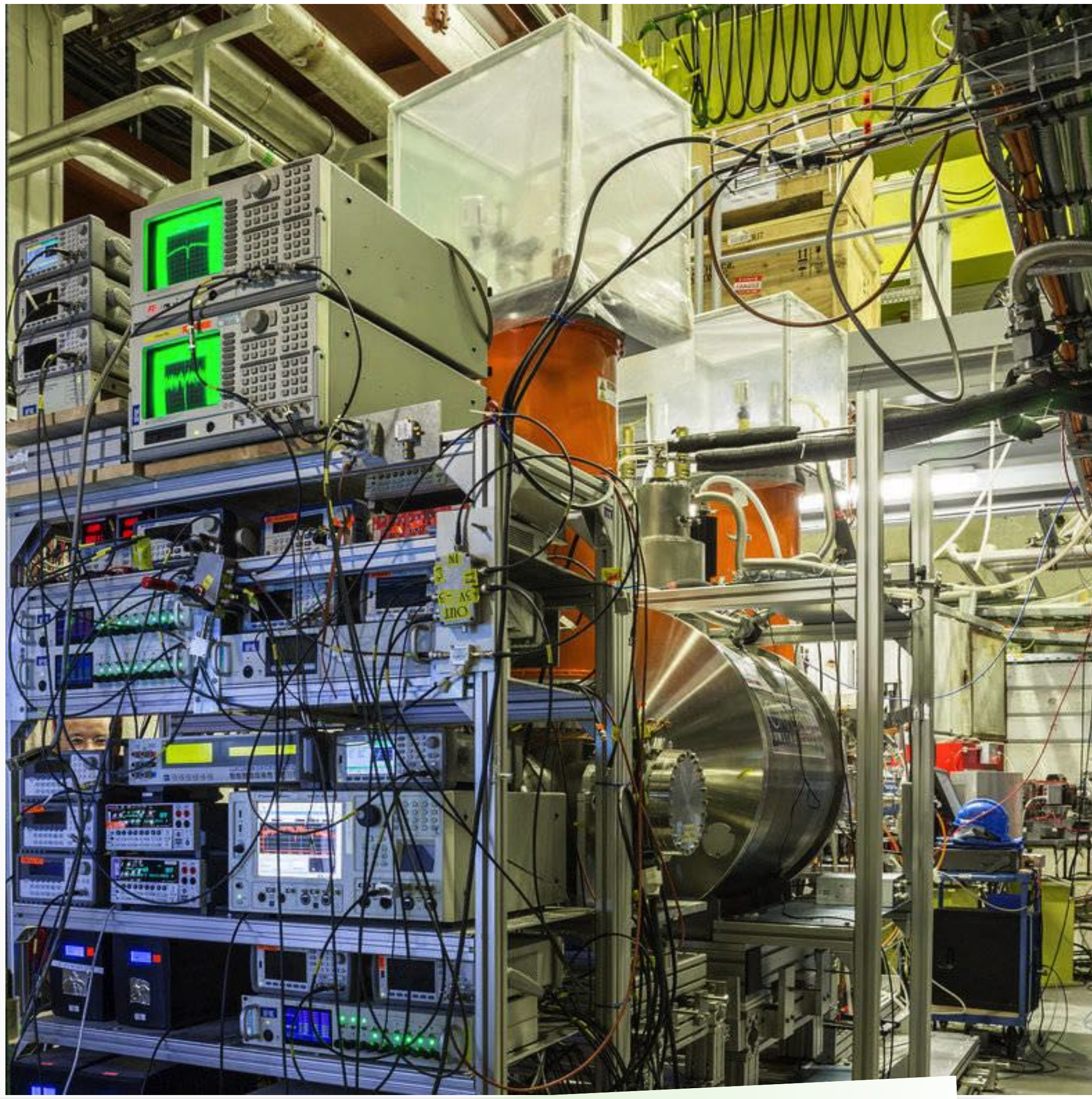


Das BASE Experiment am AD

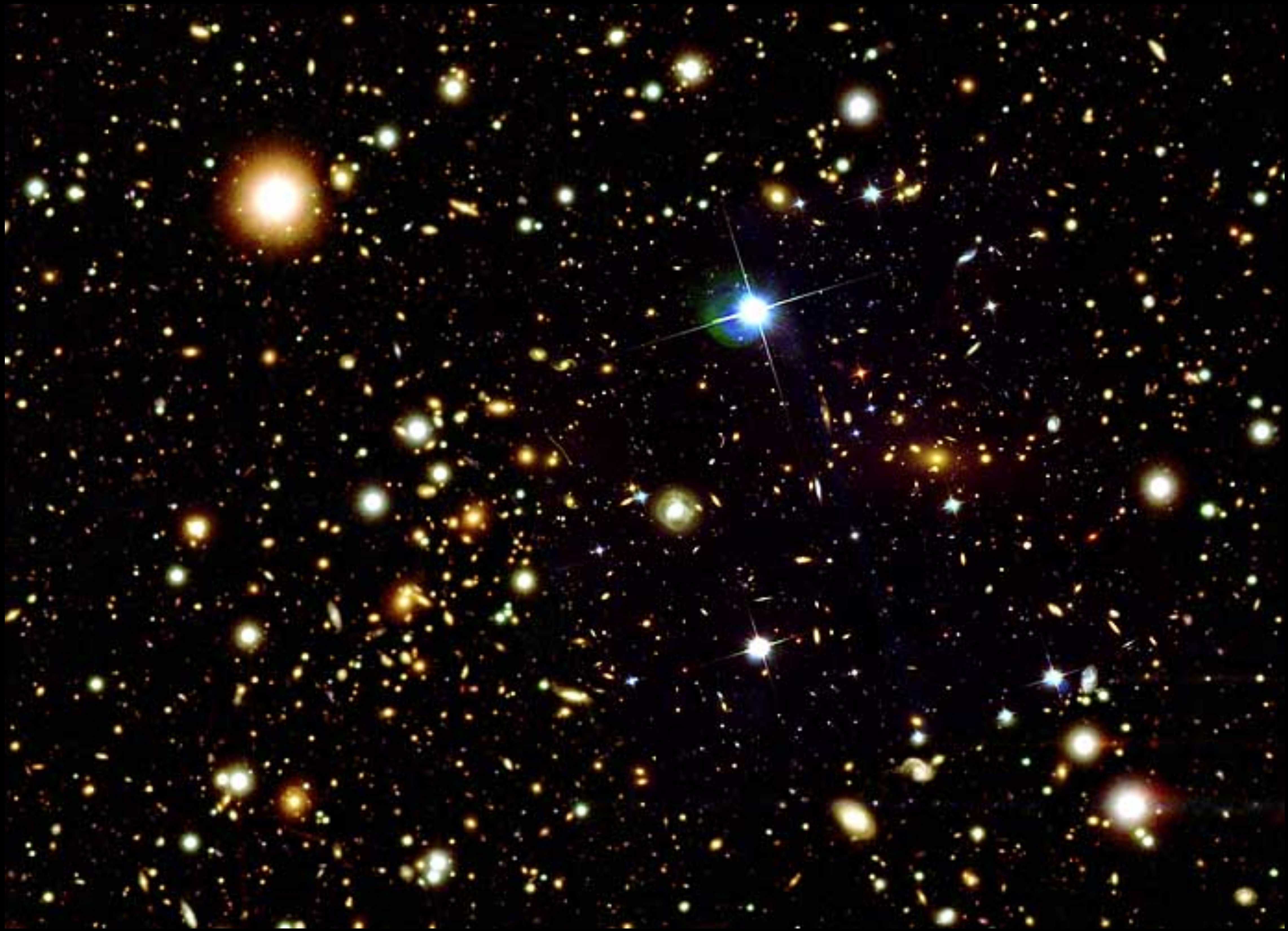
BASE: hochpräzise Messung/Vergleich des magnetischen Moments des Protons und des Antiprotons an einzelnen eingefangenen Protonen und Antiprotonen



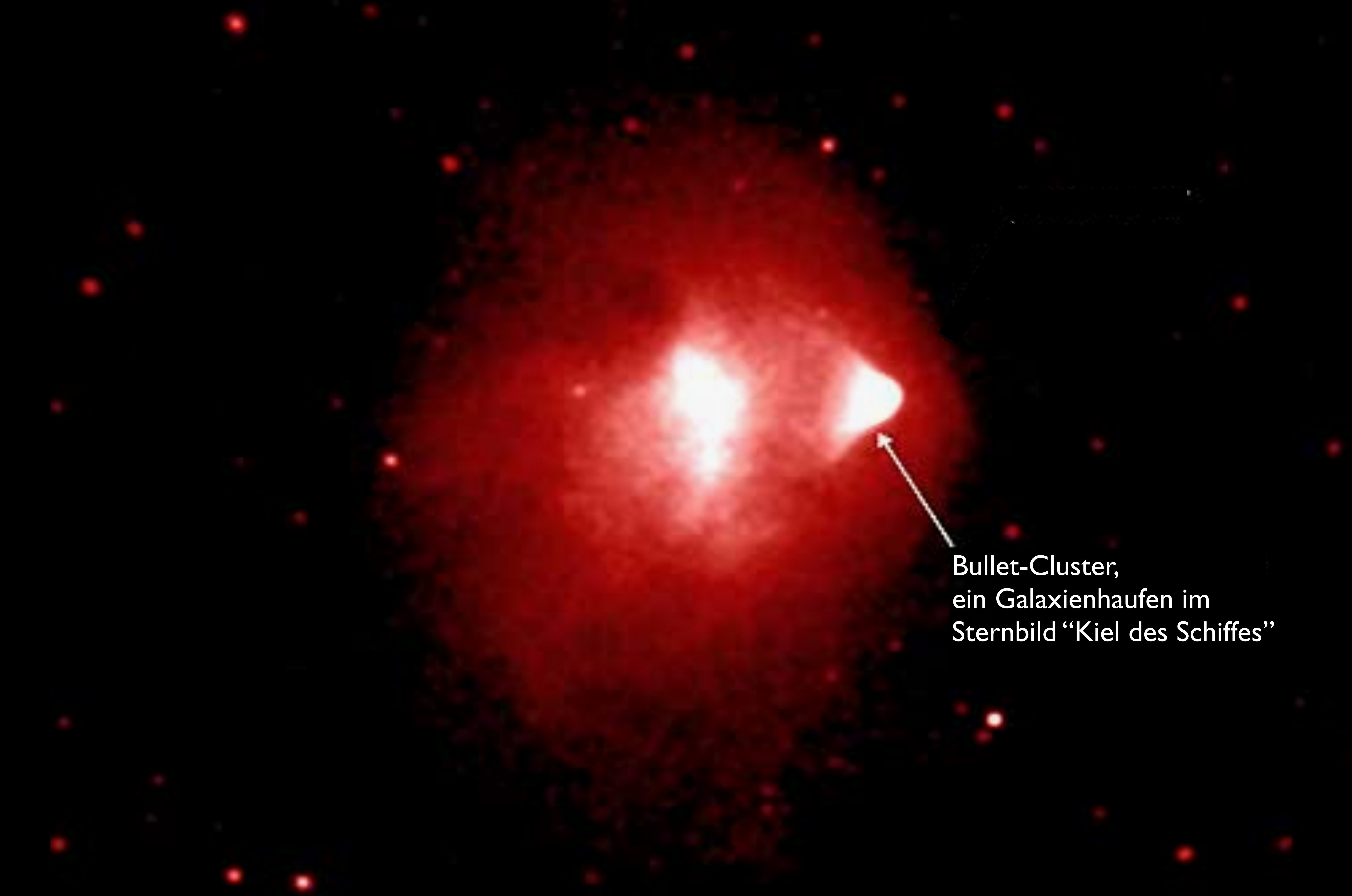
Beispiel wie BASE mit einzelnen Antiprotonen umgeht



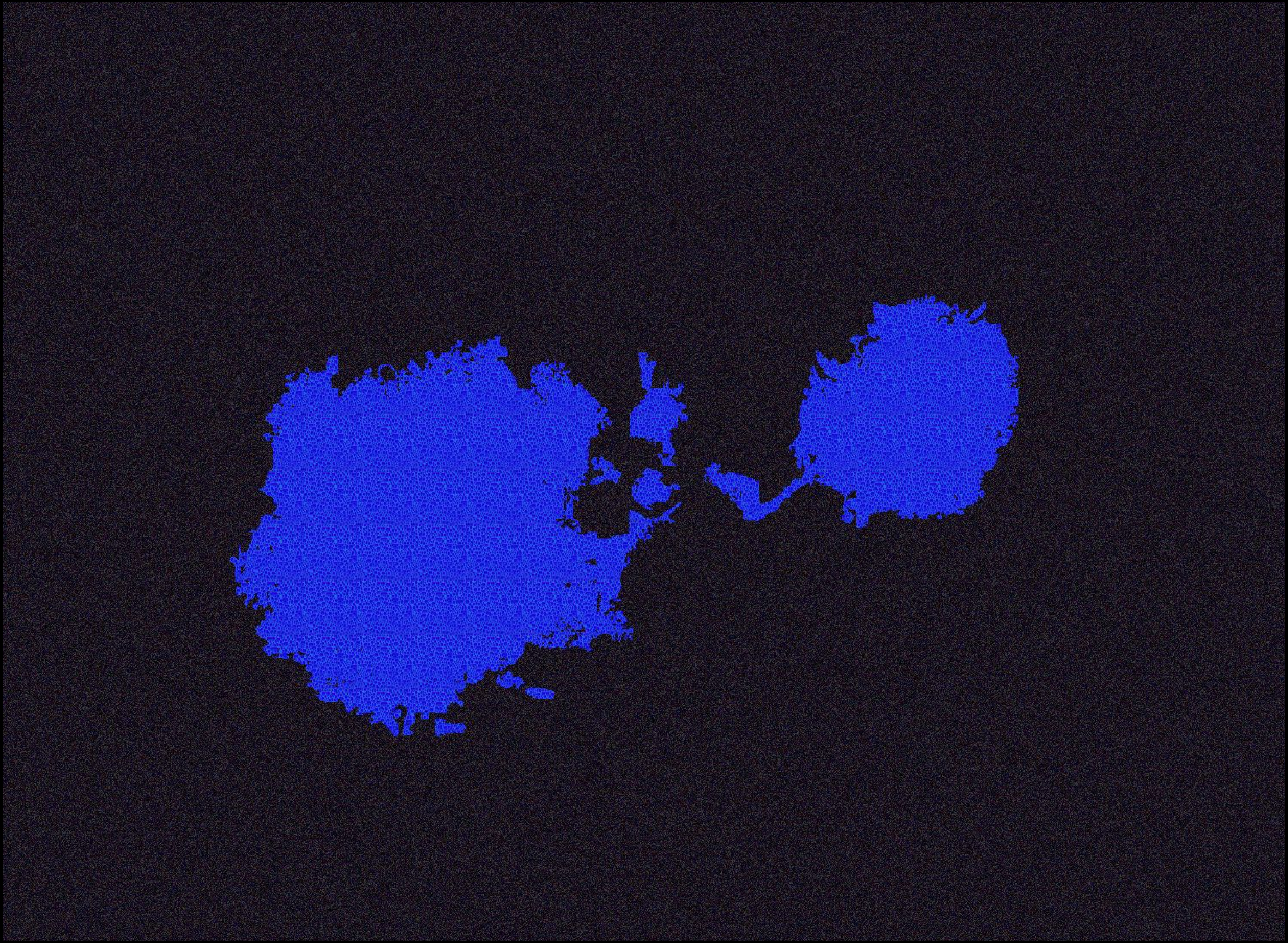
In den nächsten Jahren: spannende Ergebnisse vom AD!

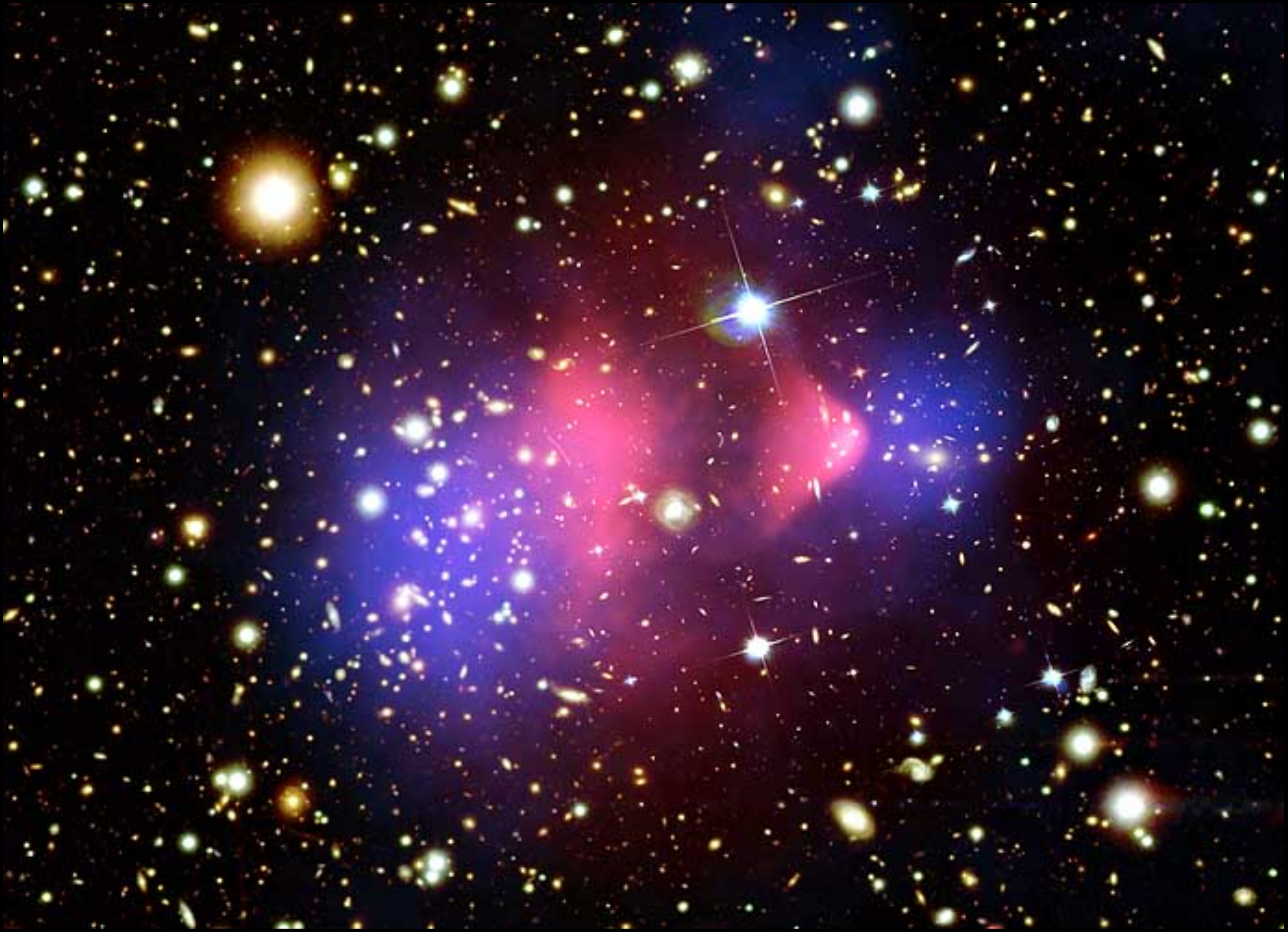


Nochmal hingeschaut, mit einem anderen Teleskop…

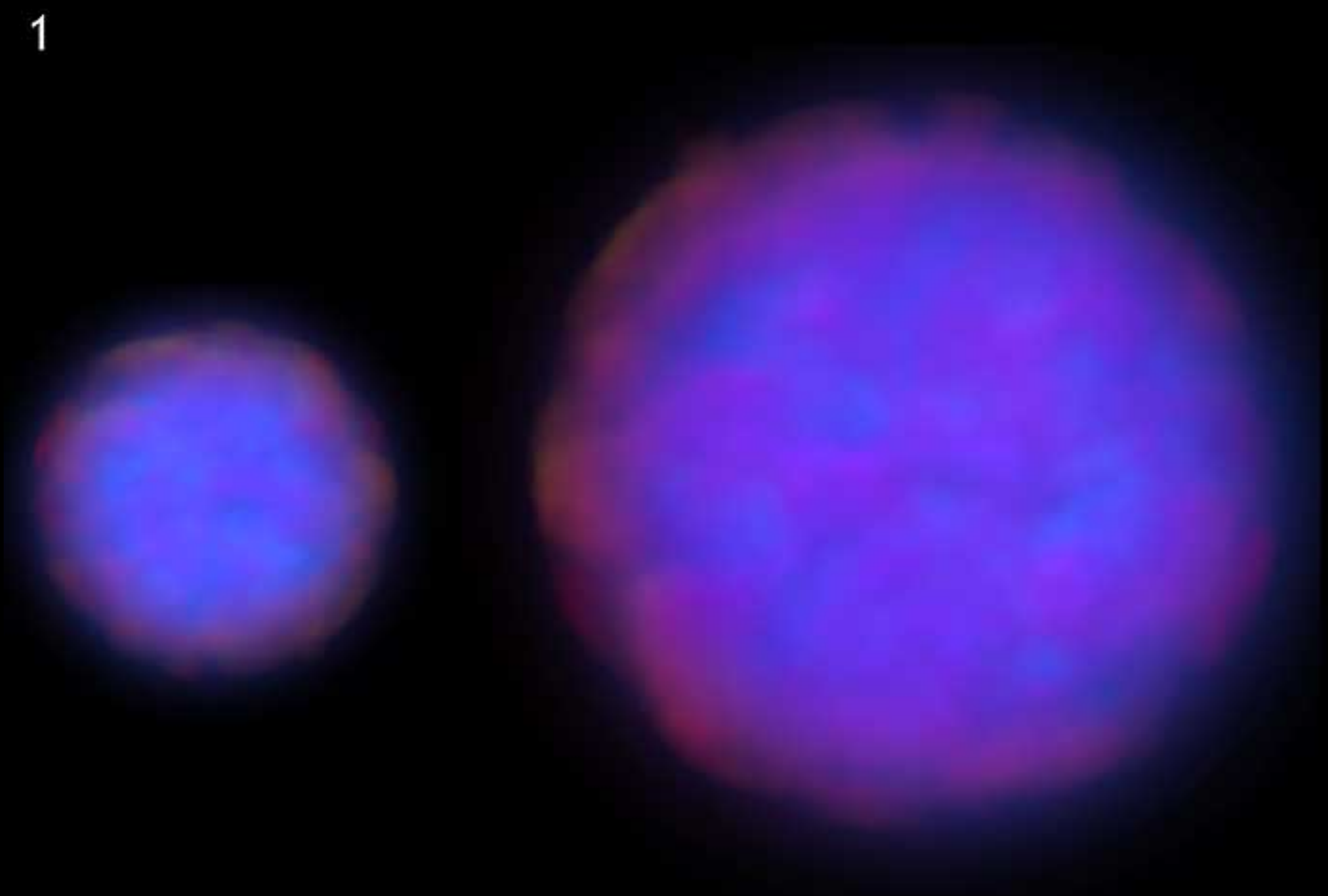


…und nochmal

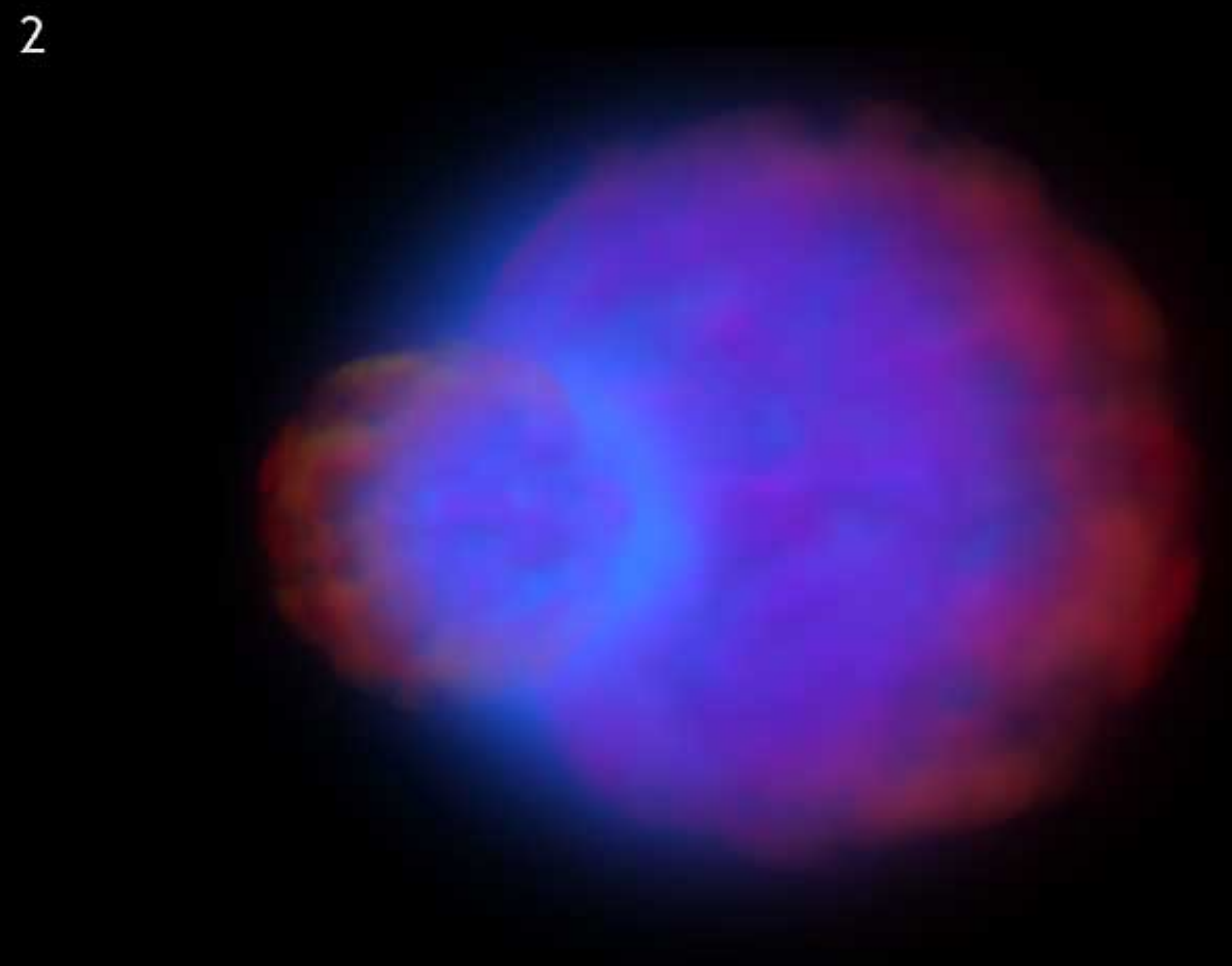




What could this be? A simulation of colliding galaxies



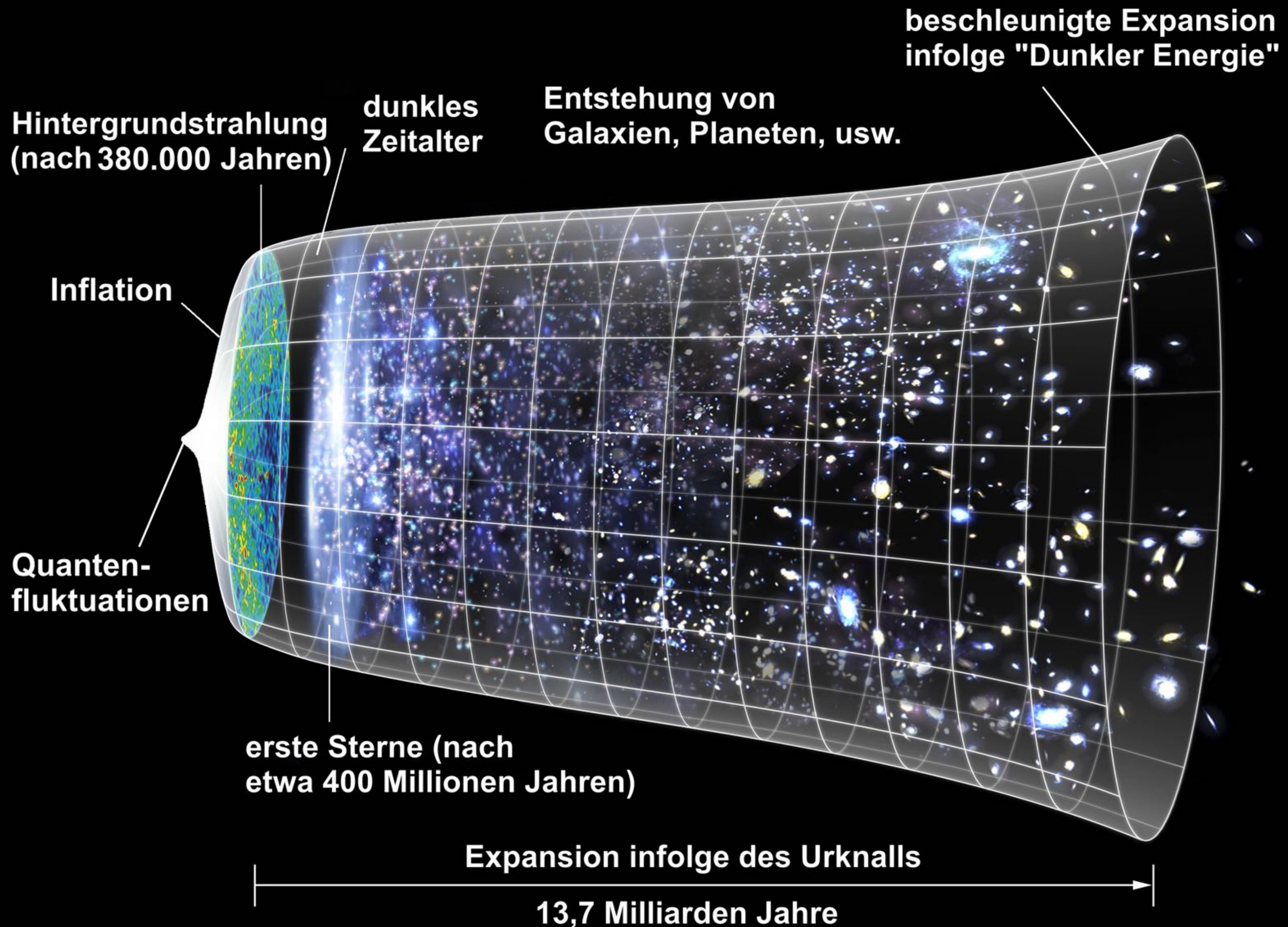
What could this be? A simulation of colliding galaxies



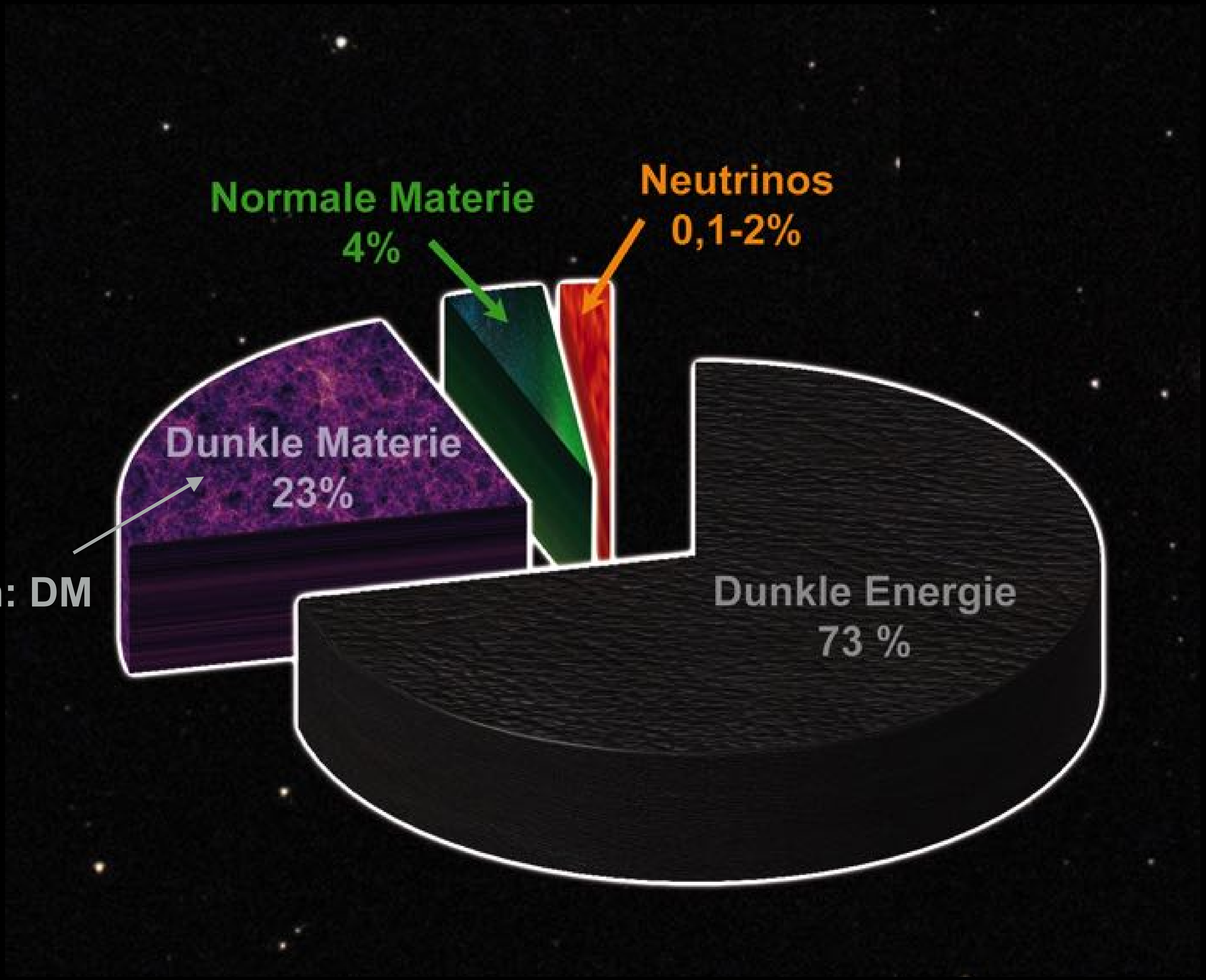
What could this be? A simulation of colliding galaxies

What could this be? A simulation of colliding galaxies

Die Entwicklung unseres Universums



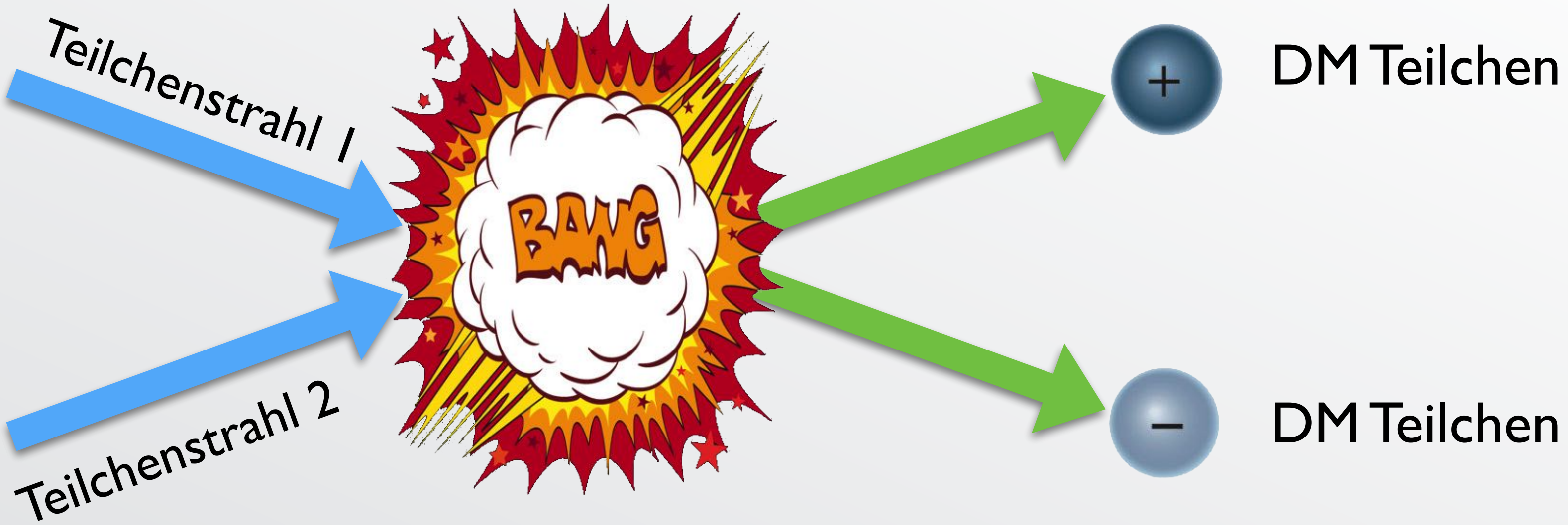
Inhalt des Universums



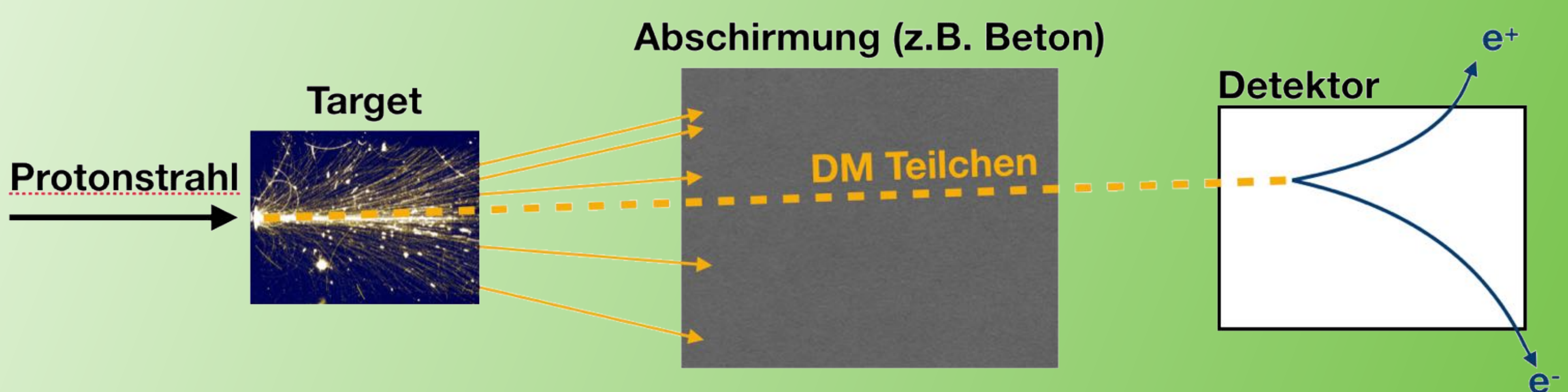
im folgenden: DM

Dunkle Materie könnte im Experiment produziert werden

Bei Kollider-Experimenten



Bei Fixed-Target Experimenten

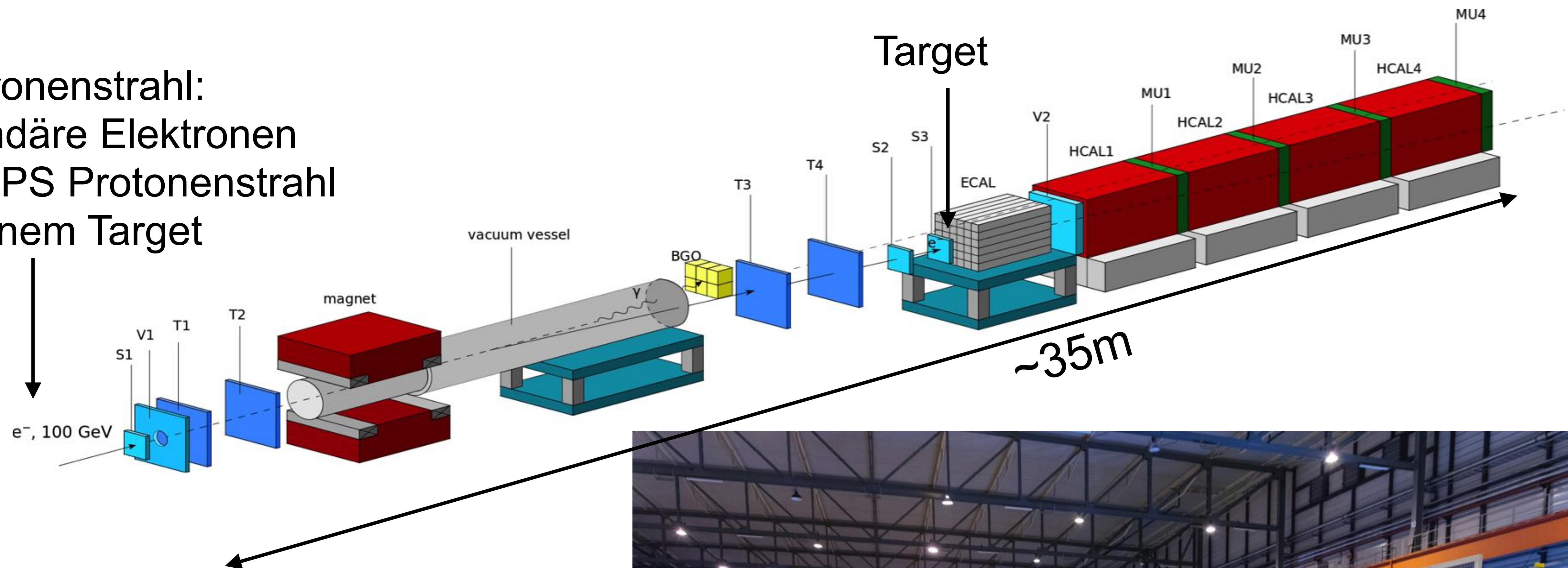


“Beam Dump Experimente”

Findet sich Dunkle Materie in den Teilchen die aus dem Beam Dump fliegen?

NA64 am SPS sucht nach neuen Teilchen

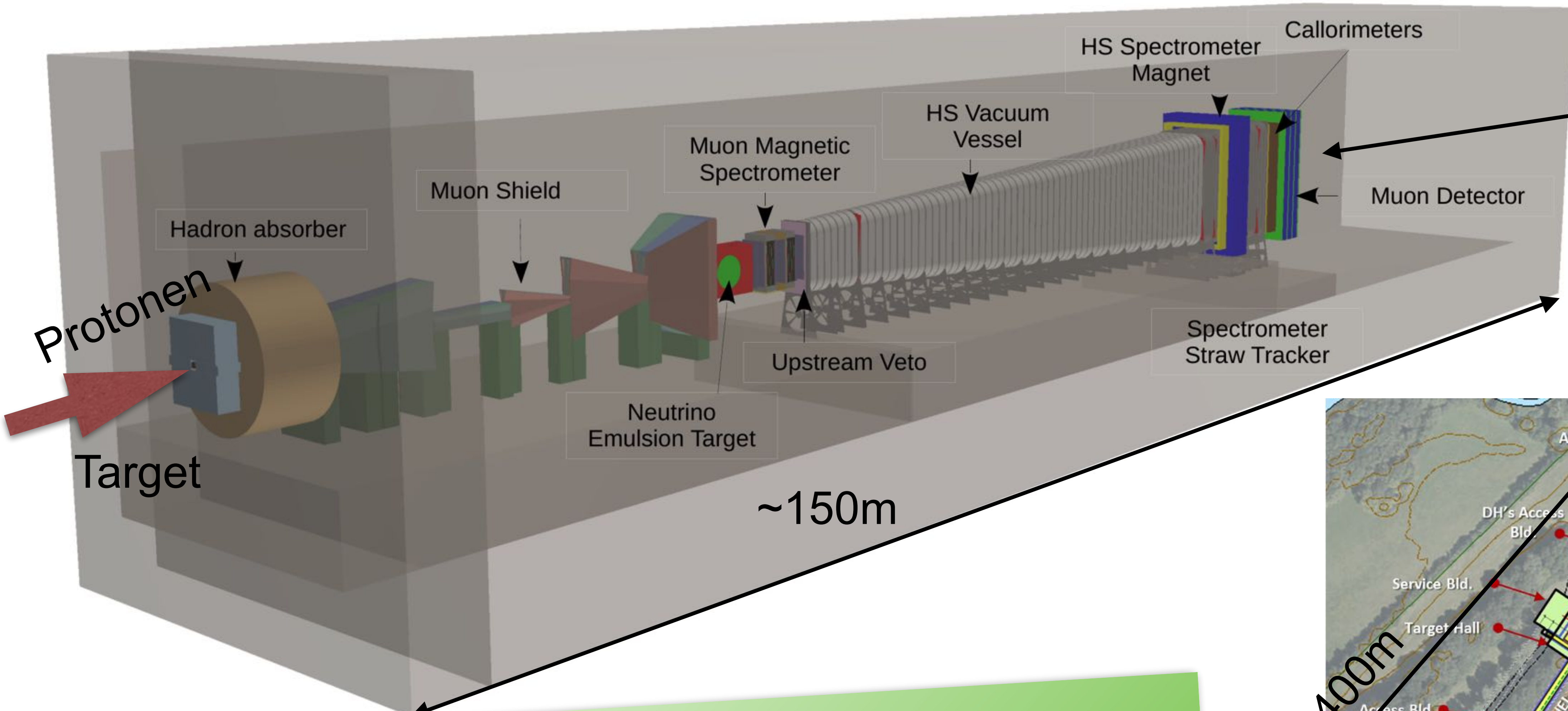
Elektronenstrahl:
sekundäre Elektronen
aus SPS Protonenstrahl
auf einem Target



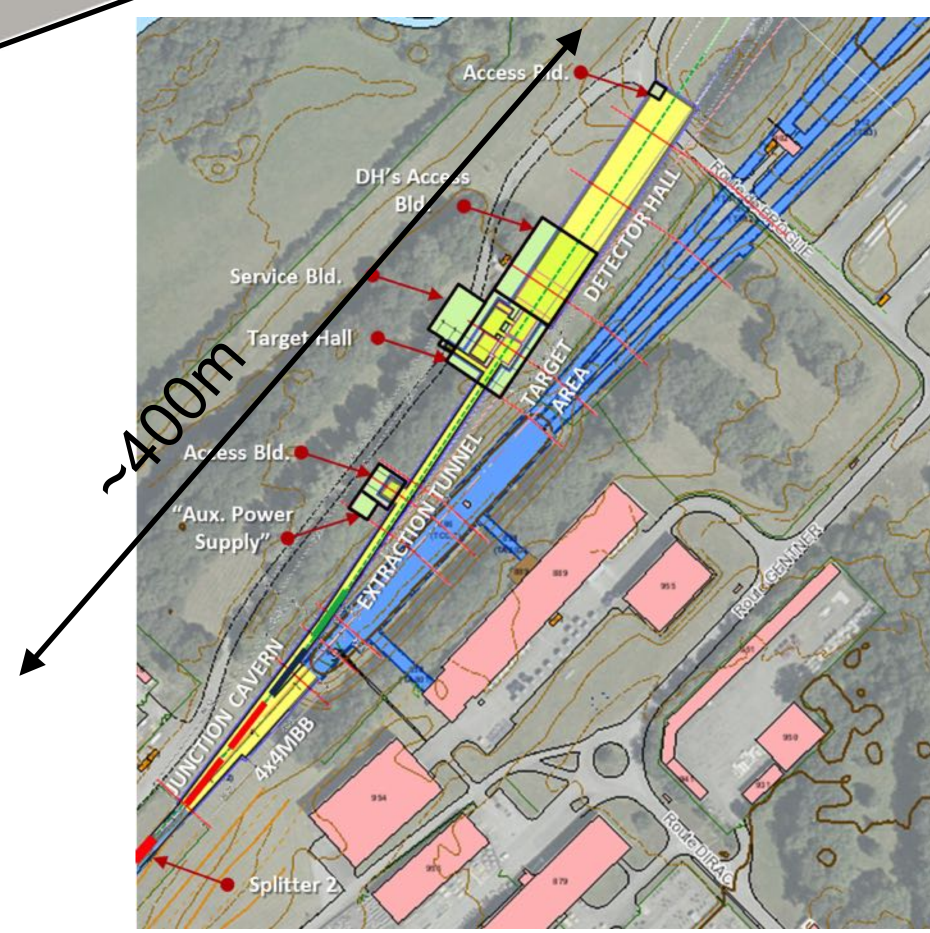
Bisher noch nichts gefunden…
aber 2021 geht es weiter.
Pläne für höhere Strahlintensität
und erweiterte Suche mit
Myonenstrahl

Eine Zukunftsstudie: SHiP

Gute Entdeckerchancen an Beam Dump Experimenten:
ein Vorschlag: SHiP (“Search for Hidden Particles”) am SPS



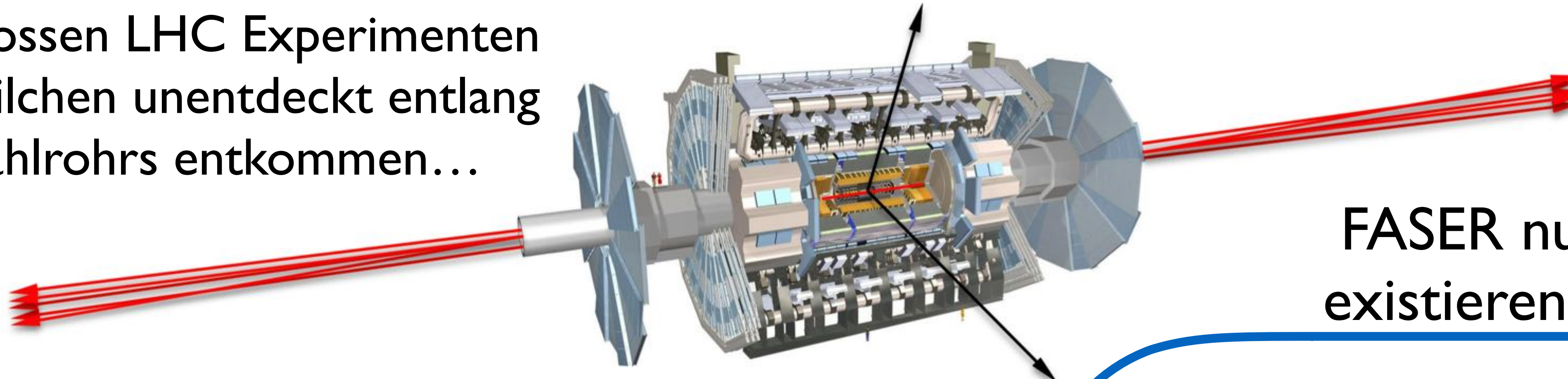
Viele neue, spannende Technologien



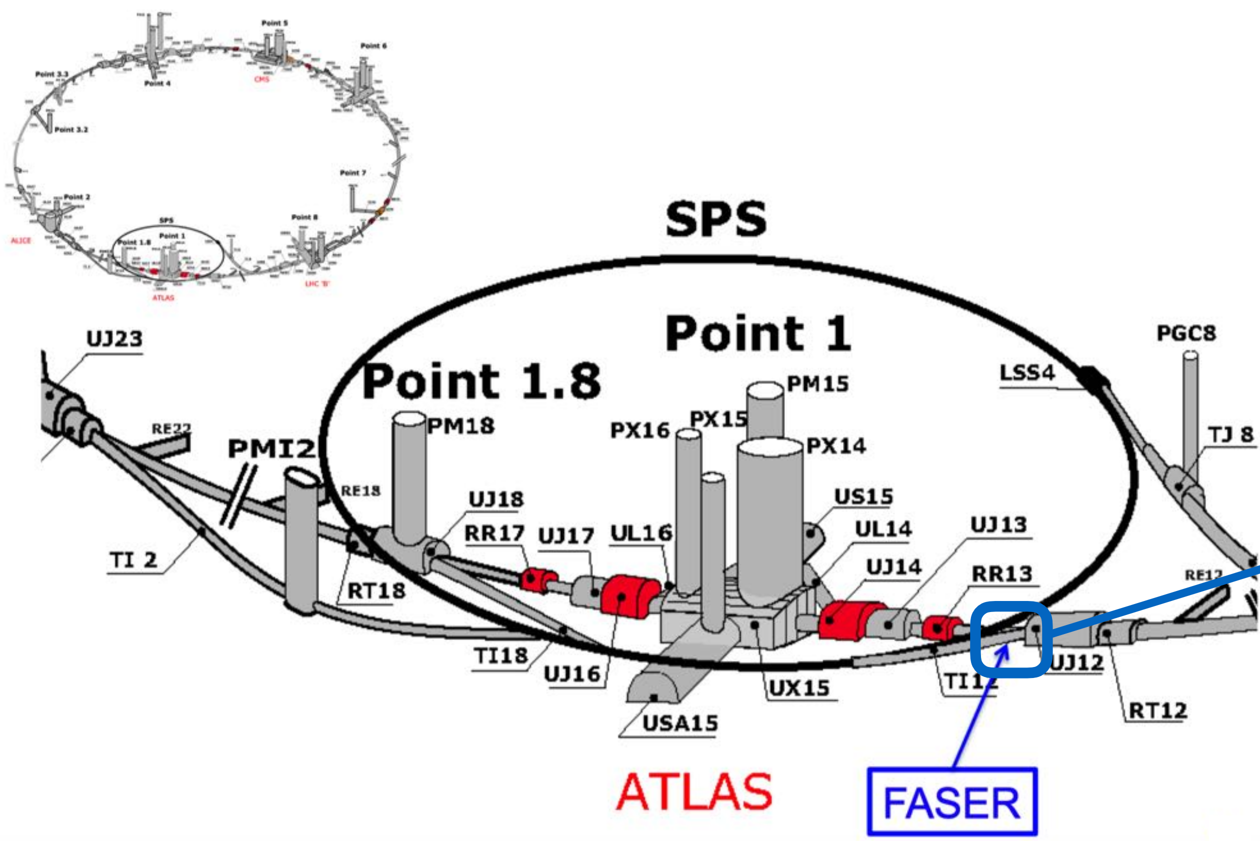
Beginn frühestens ~2030.
Zur Zeit diskutiert die internationale Gemeinschaft der Teilchenphysiker mögliche Zukunftsprojekte (*European Strategy for Particle Physics*). SHiP ist Teil der Diskussion.

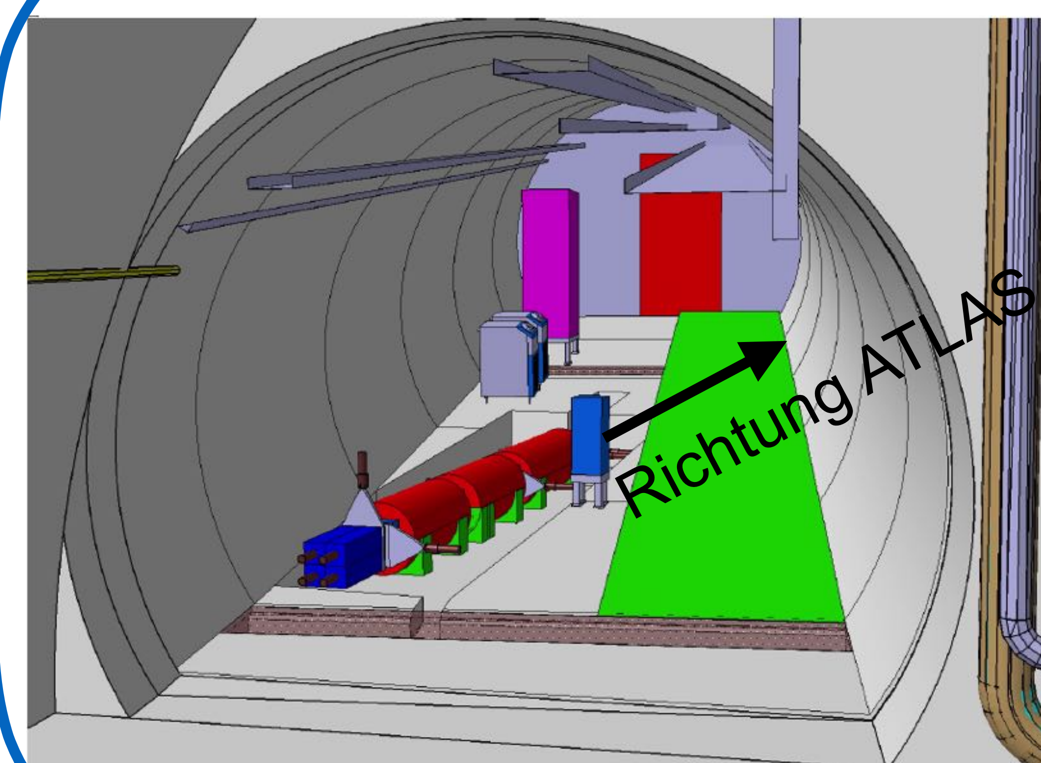
Eine “spontane” Idee: FASER

An den grossen LHC Experimenten können Teilchen unentdeckt entlang des Strahlrohrs entkommen…



FASER nutzt Prototypen existierender Detektoren

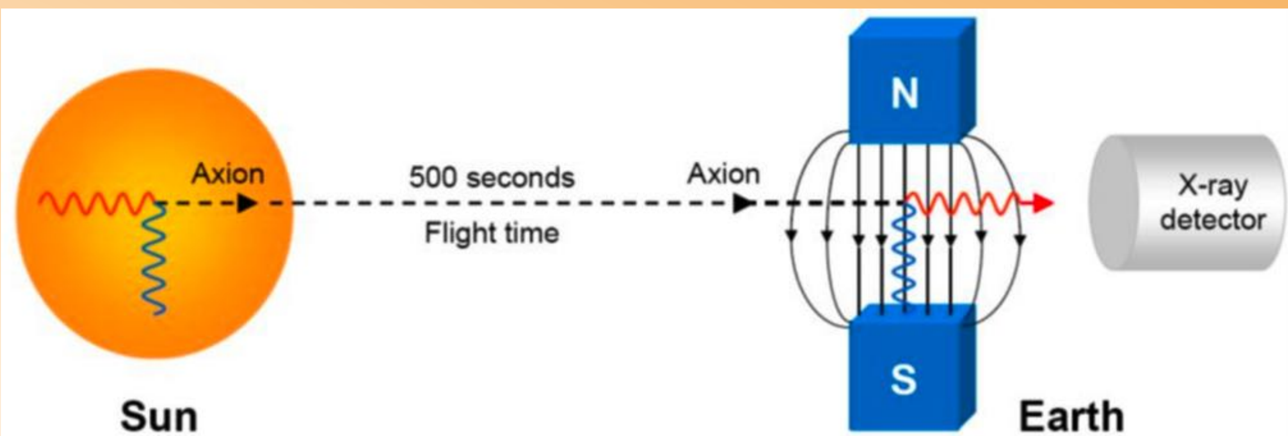




FASER wird gerade aufgebaut, Datennahme startet 2021

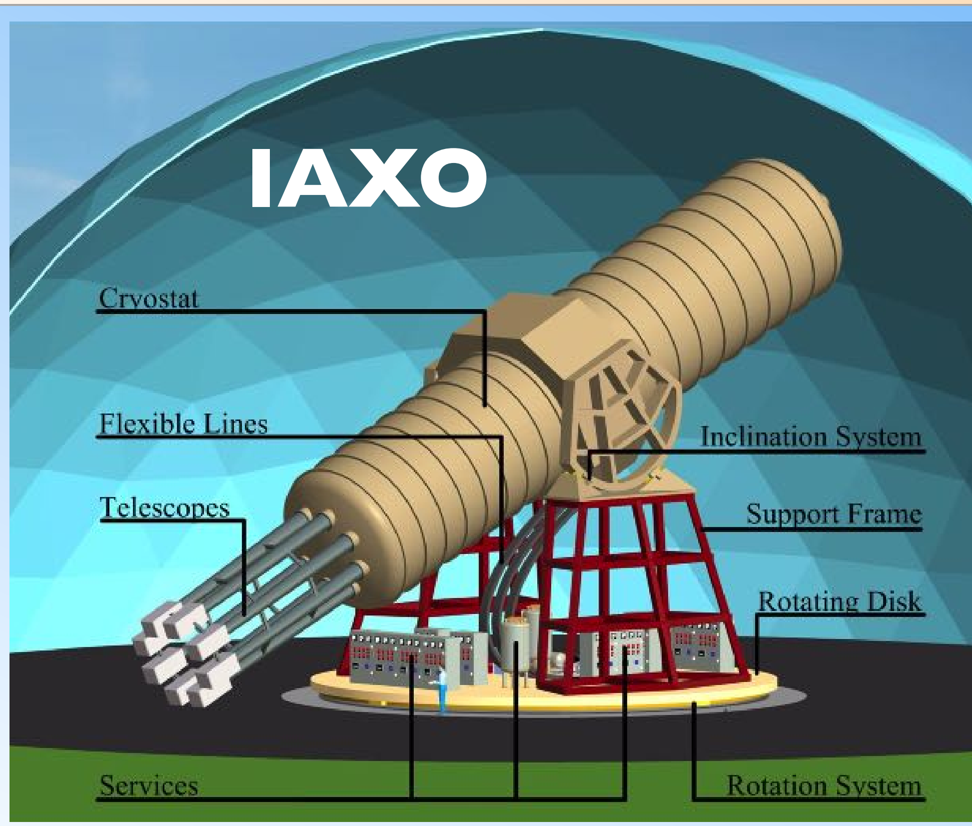
Dunkle Materie aus der Sonne zur Erde?

Suche nach Axiomen mit Helioskopen



CAST am CERN nutzt einen LHC Magneten

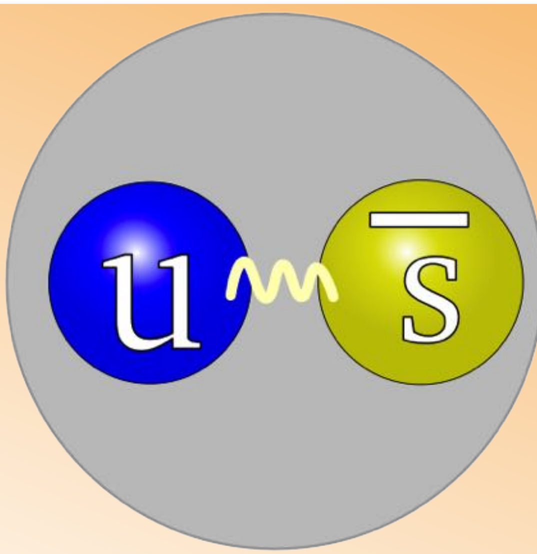
Zukünftige Axion Helioskope



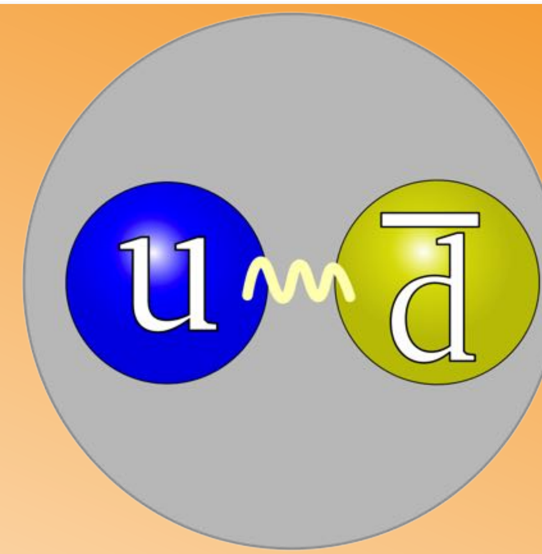
…vielleicht am DESY?

Spielregeln der Kräfte: Teilchenumwandlung durch Dunkle Materie?

Kommt in der Natur ständig vor: ein Kaon (Teilchen aus zwei quarks)…

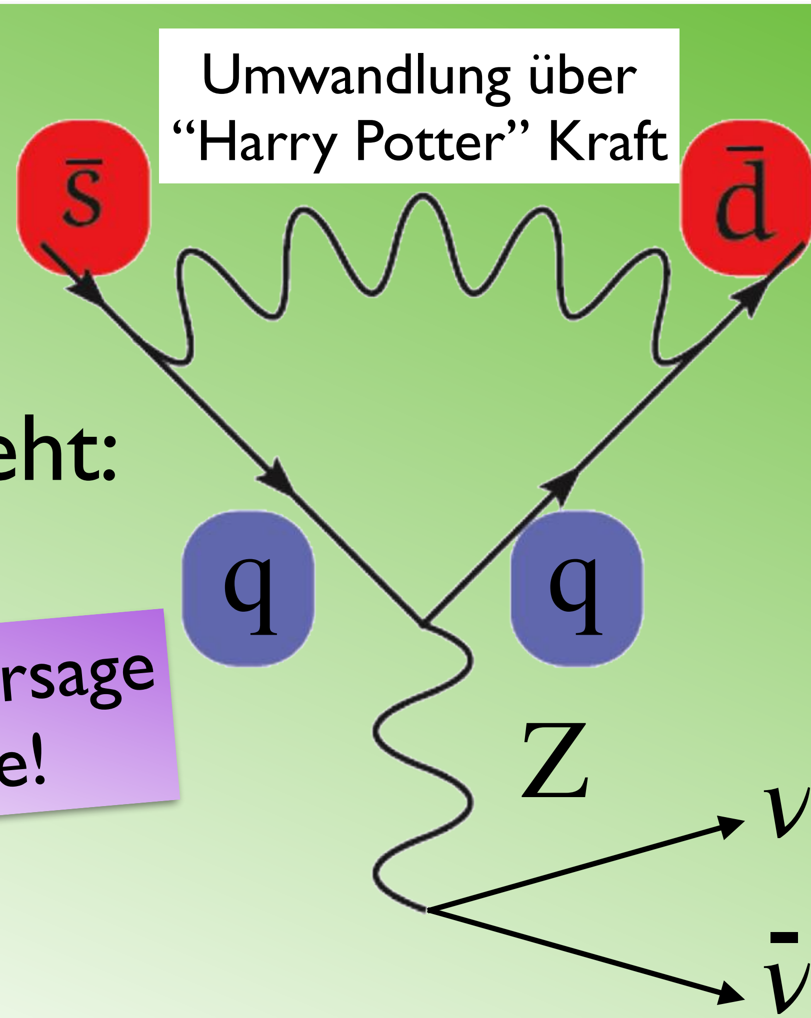


…wandelt sich in…



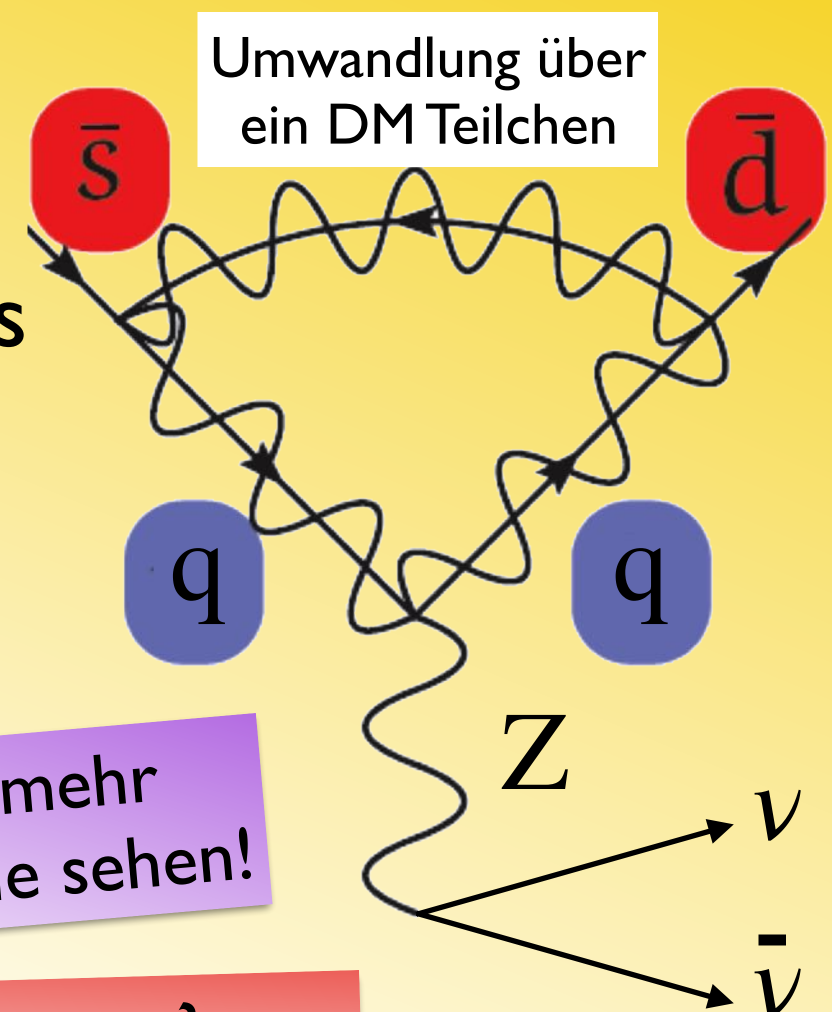
…ein Pion um

Wie das geht:



Präzise Vorhersage durch Theorie!

Dann muss auch das klappen!

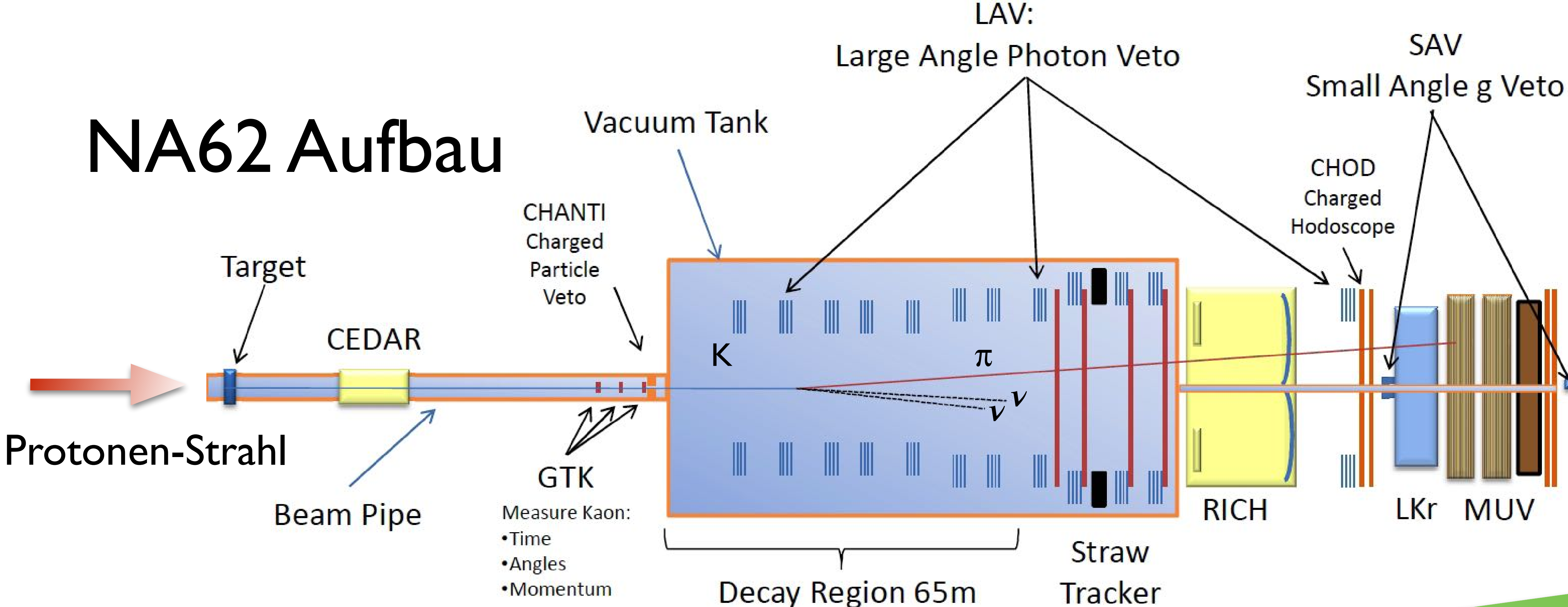


Man müsste mehr Kaon-Zerfälle sehen!

Finden sich mehr Kaon-Zerfälle als vorhergesagt?

Das NA62 Experiment

NA62 Aufbau

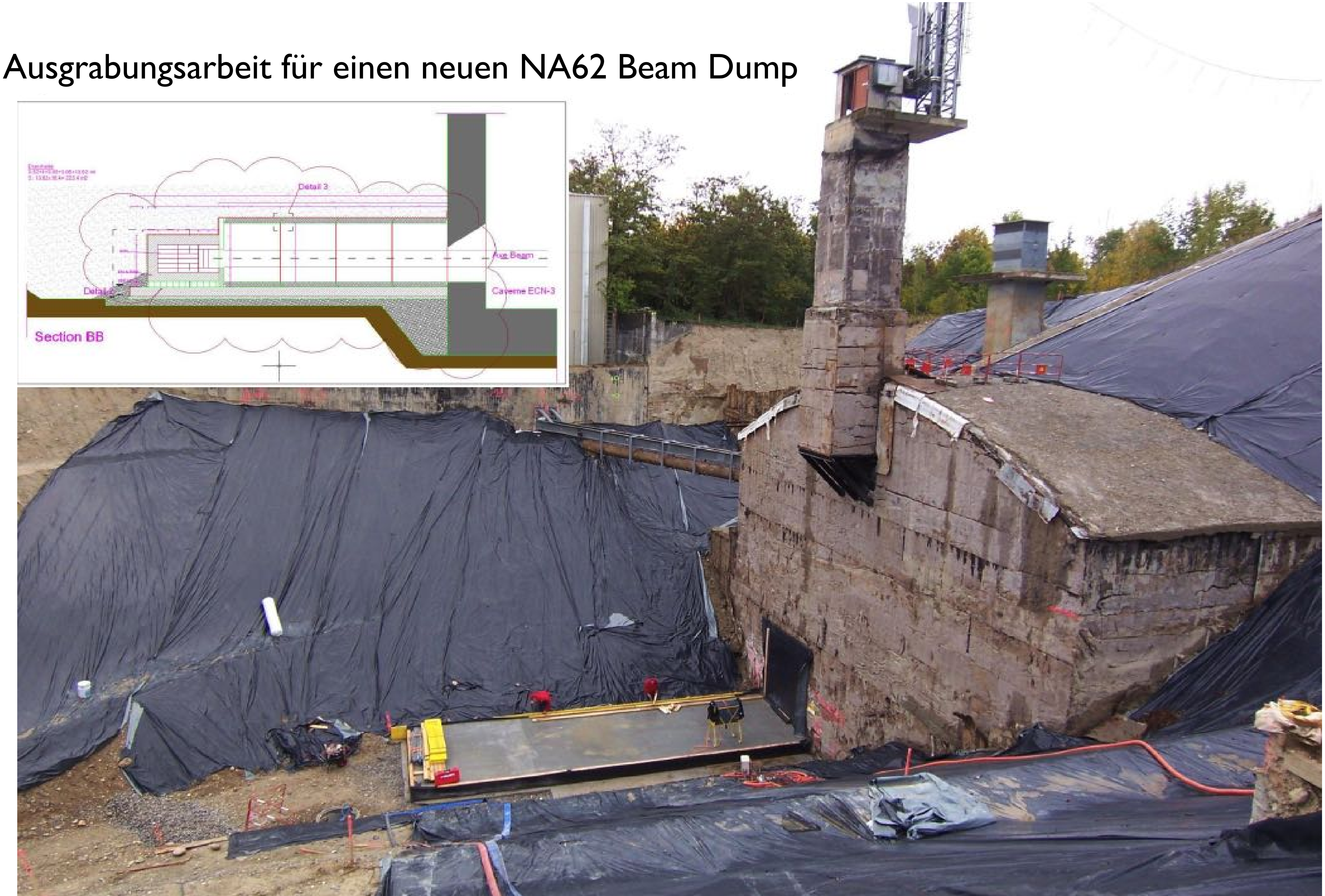


Frisch präsentiert (vorgestern): in Daten von 2017, werden 2.43 $K \rightarrow \pi\nu\nu$ Ereignisse erwartet, 1.65 “vorgetäuschte” Ereignisse. Gestehen werden 3 Ereignisse.
⇒keine Hinweise auf neue Teilchen.

NA62 macht weiter…

Grosse Infrastruktur am CERN…

Ausgrabungsarbeit für einen neuen NA62 Beam Dump



Der Baggerfahrer…

Rolf-Dieter Heuer, 2009 - 2015 CERN Generaldirektor, 2004 - 2009 DESY Forschungsdirektor

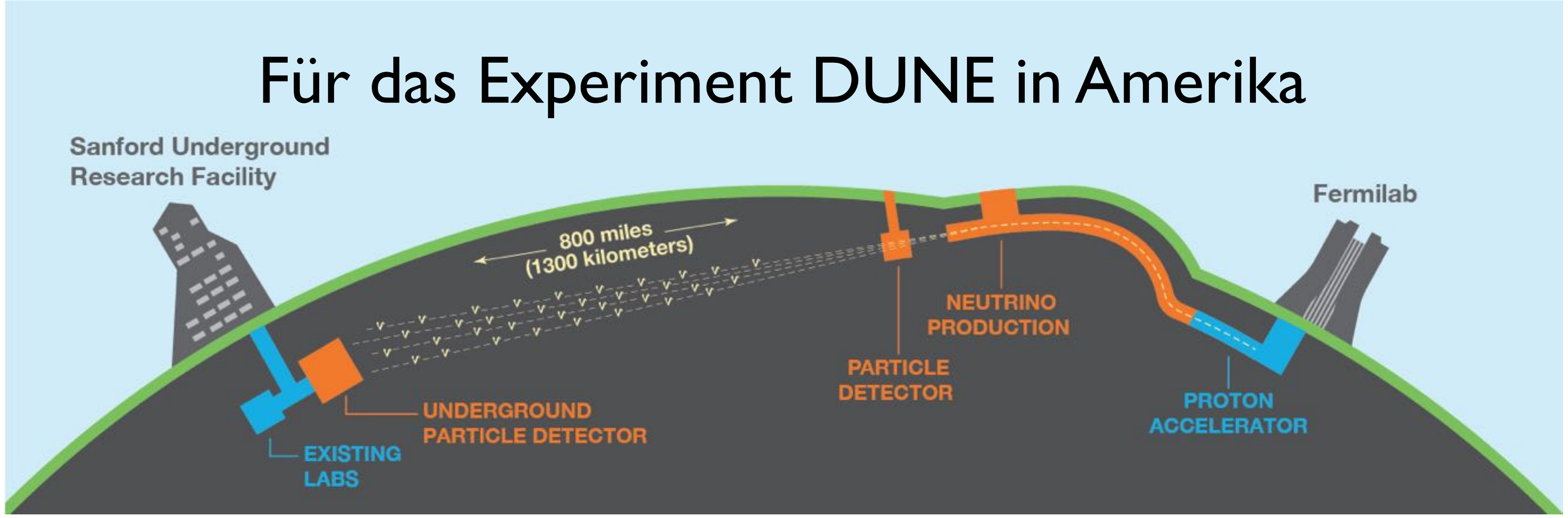
Die SPS Teststrahl-Halle

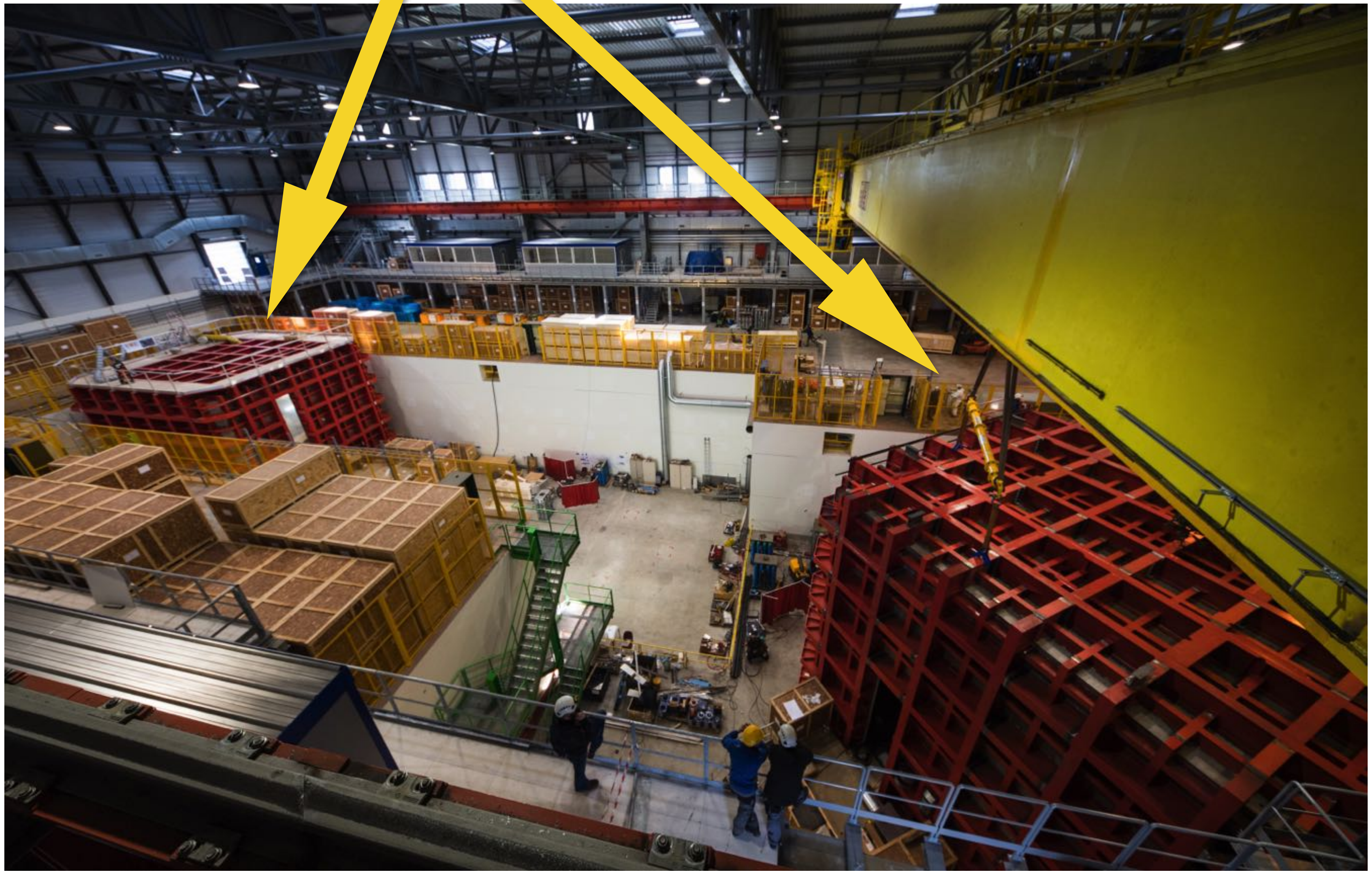
Prominenter Besuch, kalibriert an CERNs SPS

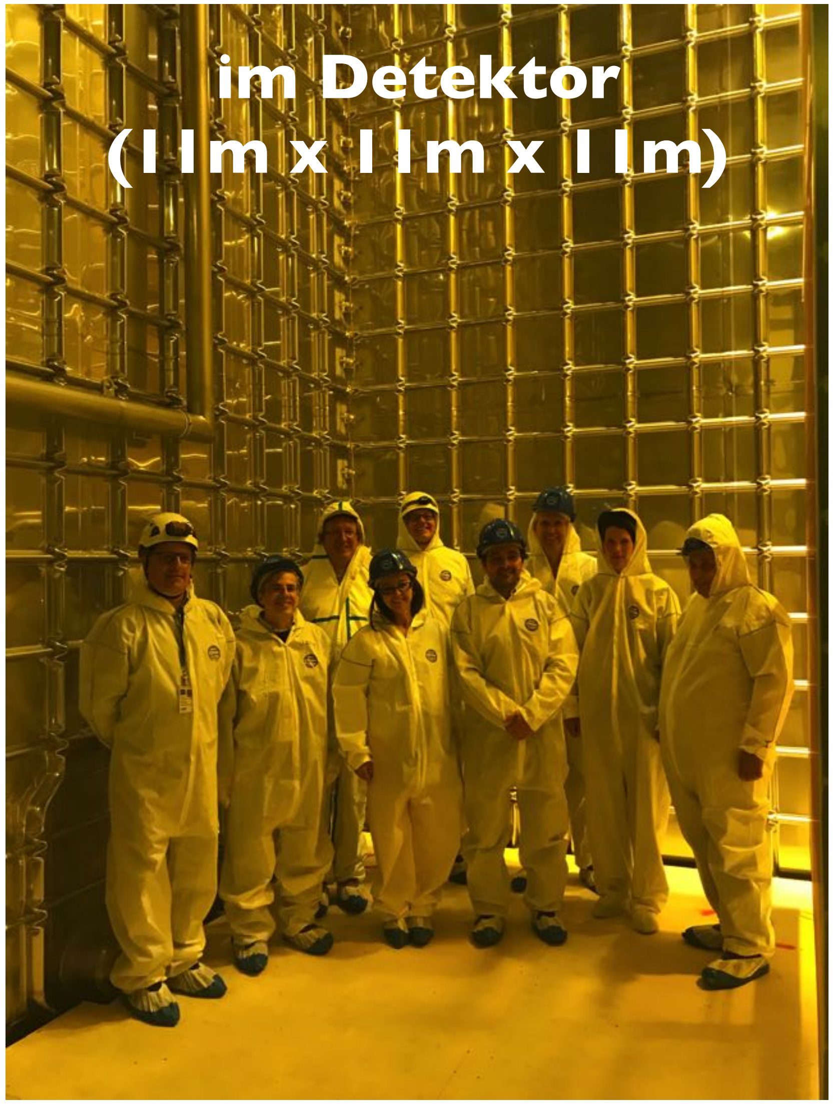
Alpha-Magnet-Spektrometer (AMS):
Teilchendetektor zur Untersuchung der kosmischen Strahlung.
Seit 2011 an der Internationalen Raumstation ISS

Detektorentwicklung für Neutrinoexperimente in Amerika, Japan

In der SPS Teststrahl-Halle sind 2 riesige Neutrino-Detektoren (Flüssig-Argon Spurkammern) aufgebaut und werden getestet.

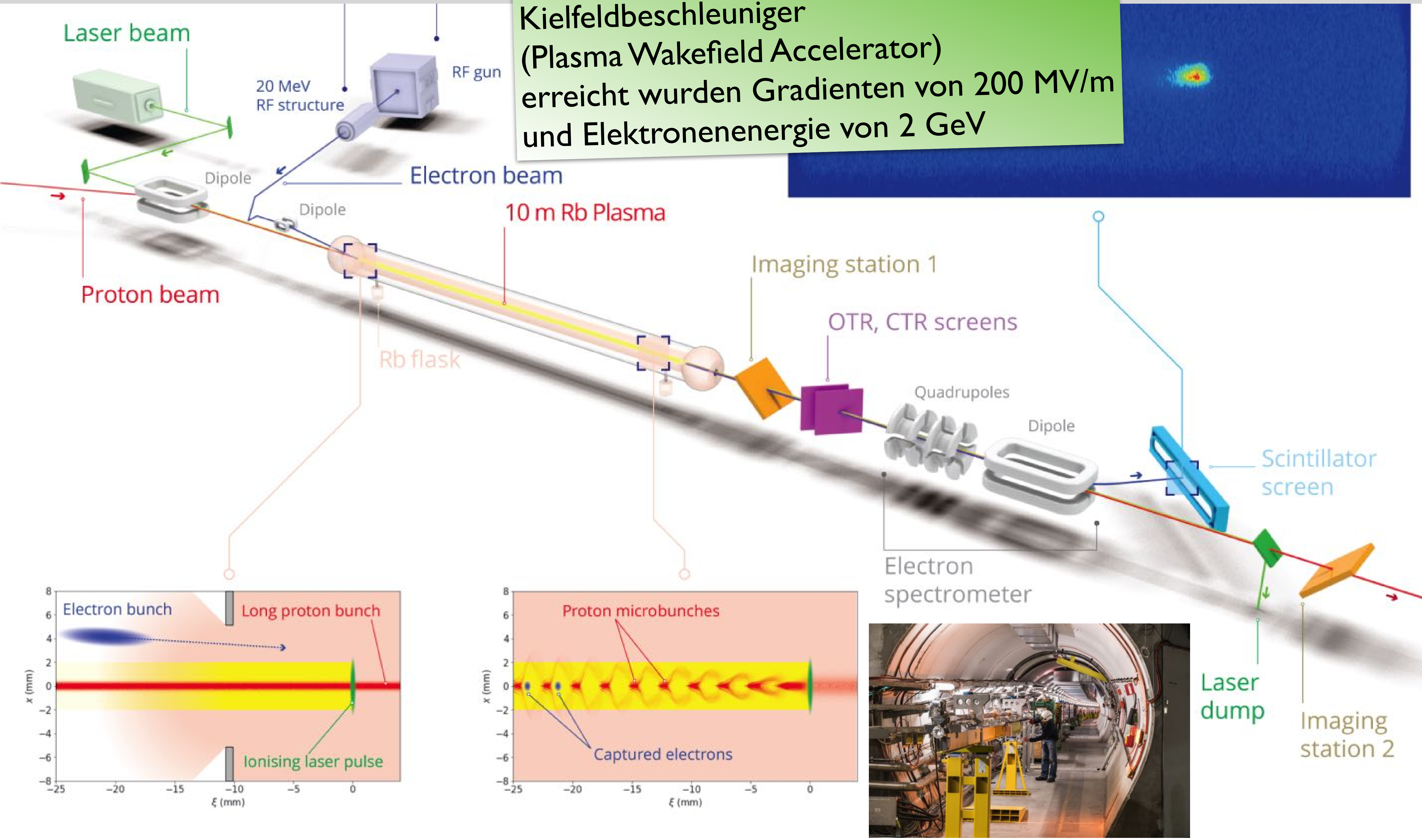






Beschleuniger für die Zukunft

Kielfeldbeschleuniger
(Plasma Wakefield Accelerator)
erreicht wurden Gradienten von 200 MV/m
und Elektronenenergie von 2 GeV



Beamline4schools: idea

- Worldwide competition among schools for beam time at CERN
  - ➡ class to phrase scientific question, to work out / design / build an experiment which uses particle beams and to write / submit a proposal;
  - ➡ a committee selects best 16 proposals;
  - ➡ PS and SPS Experiments Committee (SPSC) decides which experiment wins one week of beam time at a CERN accelerator;
  - ➡ class comes to CERN to do their experiment;
  - ➡ class writes up results (if possible results are published).

As close as possible to real science life

Beamline for schools BL4S

- CERN is offering high-school students from around the world the chance to create and perform a scientific experiment on a CERN accelerator beamline, see http://beamlineforschools.cern/ ;

deadline for 2019 was 2 days ago…

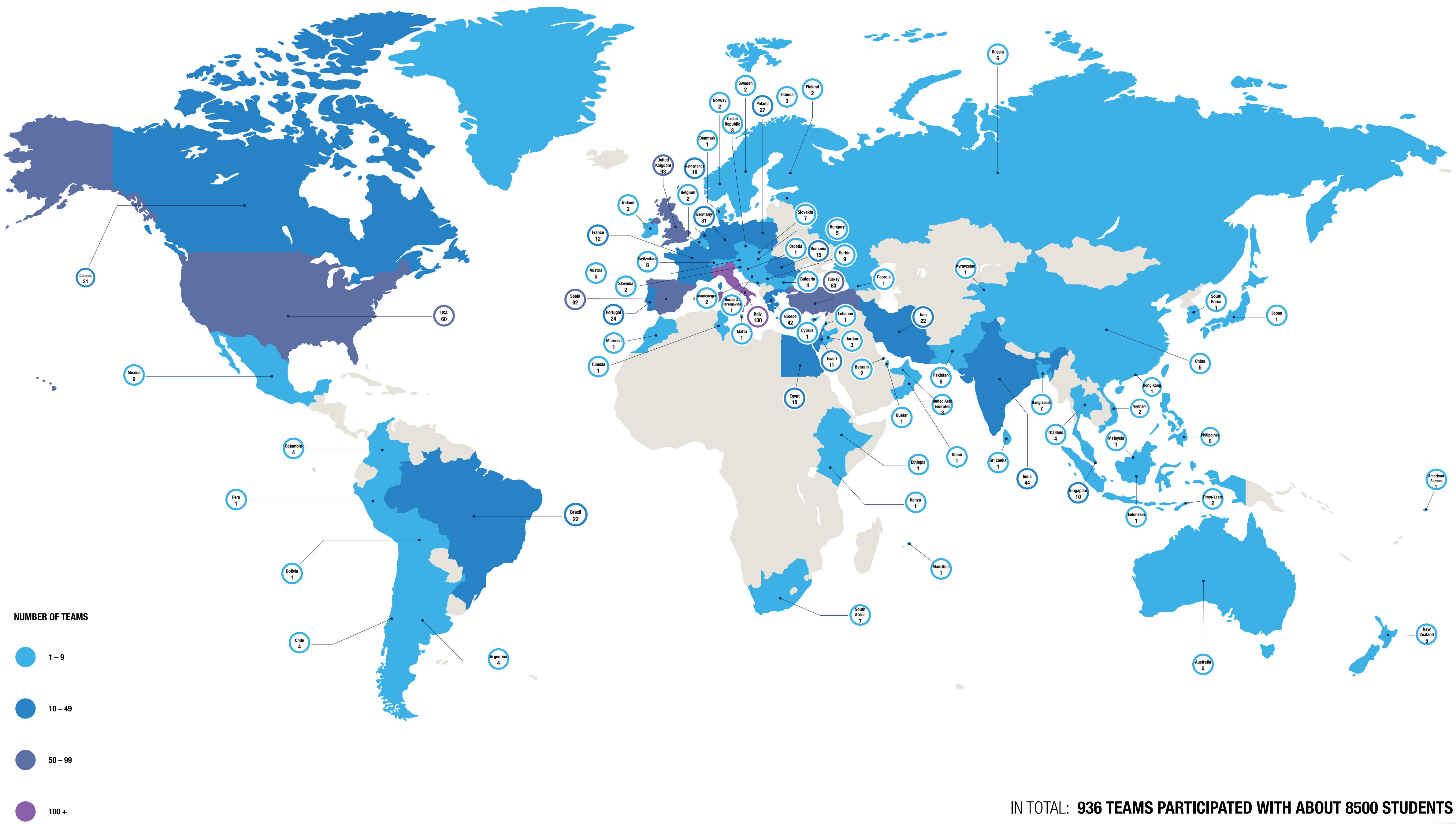
- Participants overview

	2014	2015	2016	2017	2018	2019
Proposals	292	119	150	180	195	~180
Different countries	50	28	37	43	42	50

- 2/3 boys, 1/3 girls;
- 57% from member states, 14% from associated member states, 29% from non member states;
- In total ~8500 students in 936 teams from 76 countries participated since 2014.

Beamline for Schools

participants 2014-2018



IN TOTAL: **936 TEAMS PARTICIPATED WITH ABOUT 8500 STUDENTS**

Project financed via the CERN & Society Foundation

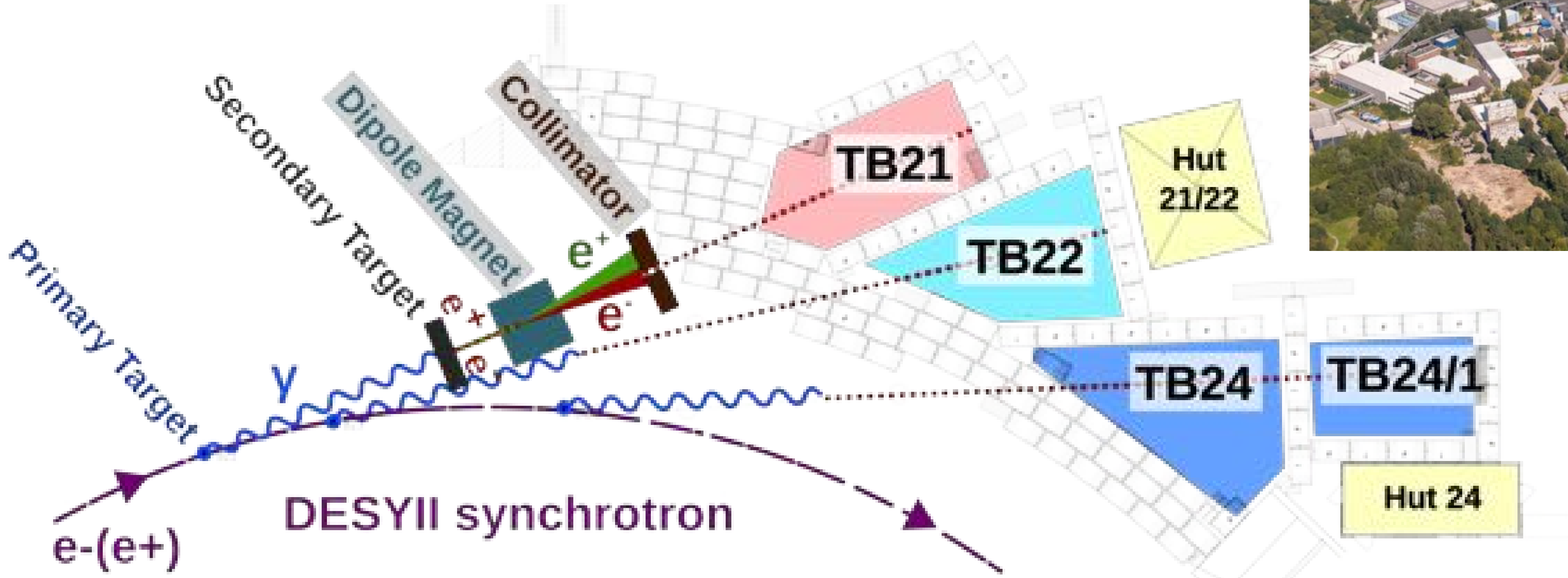
In 2019 six new countries:
Albania (6), Ecuador (1), Fiji (1), Réunion (1),
Sudan (1), Syria (1) and Uruguay (1)

Previous winners

- **2014:**
  Odysseus' Comrades (Greece): decay of charged pions;
  Dominicuscollege (Netherlands): growing their own crystals for a calorimeter;
- **2015:**
  Leo4G (Italy): customised web-cam as particle detector;
  Accelerating Africa (South Africa): production of high-energy gamma rays using a crystalline undulator;
- **2016:**
  Pyramid Hunters (Poland): muon absorption of limestone;
  Relatively Special (UK): effect of time dilation due to Special Relativity on the decay rate of pions;
- **2017:**
  Charging Cavaliers (Canada): search for particles with a fractional charge;
  TCO-ASA (Italy): building and testing a Cherenkov detector;
- **2018:**
  Beamcats (Philippines): pions for cancer therapy, Bragg peak measurement;
  Cryptic Ontics (India): study defl ection of protons and electrons in a magnetic fi eld.
- **2019:**
  Particle Peers (Netherlands): fundamental matter-antimatter differences - compare properties of particle showers from electrons and from positrons;
  DESY Chain (US): fundamental matter-antimatter differences - compare electrons and positrons in scintillators.

BL4S 2019 at DESY, today last day!

Electron / positron beam 1–6 GeV



BL4S - first publication by students

Phys. Educ. **51** (2016) 064002 (10pp) iopscience.org/ped

Building and testing a high school calorimeter at CERN

L Biesot[1], R Crane[1], M A G Engelen[1], A M A van Haren[1], R H B van Kleef[1], O R Leenders[1] and C Timmermans[2]

[1] Dominicus College, Nijmegen, The Netherlands
[2] Nikhef and Radboud University, Nijmegen, The Netherlands

E-mail: c.timmermans@science.ru.nl

CrossMark

Abstract
We have designed, built and tested a crystal calorimeter in the context of CERN's first beam line for schools competition. The results of the tests at CERN show that the light output of our calorimeter depends on the energy deposited by particles (electrons and muons) hitting the crystals. Our design can be reproduced by high schools around the world, as we have avoided the use of toxic chemicals.

Take part!

http://beamline-for-schools.web.cern.ch/

BEAMLINE FOR SCHOOLS COMPETITION 2020: PROPOSAL SUBMISSION IS NOW OPEN!

Designed by my 1998 Summer Student

Thank you very much!

Spare Slides

LINAC3, LINAC4

PROTONS

Proton LINAC2 (1978)

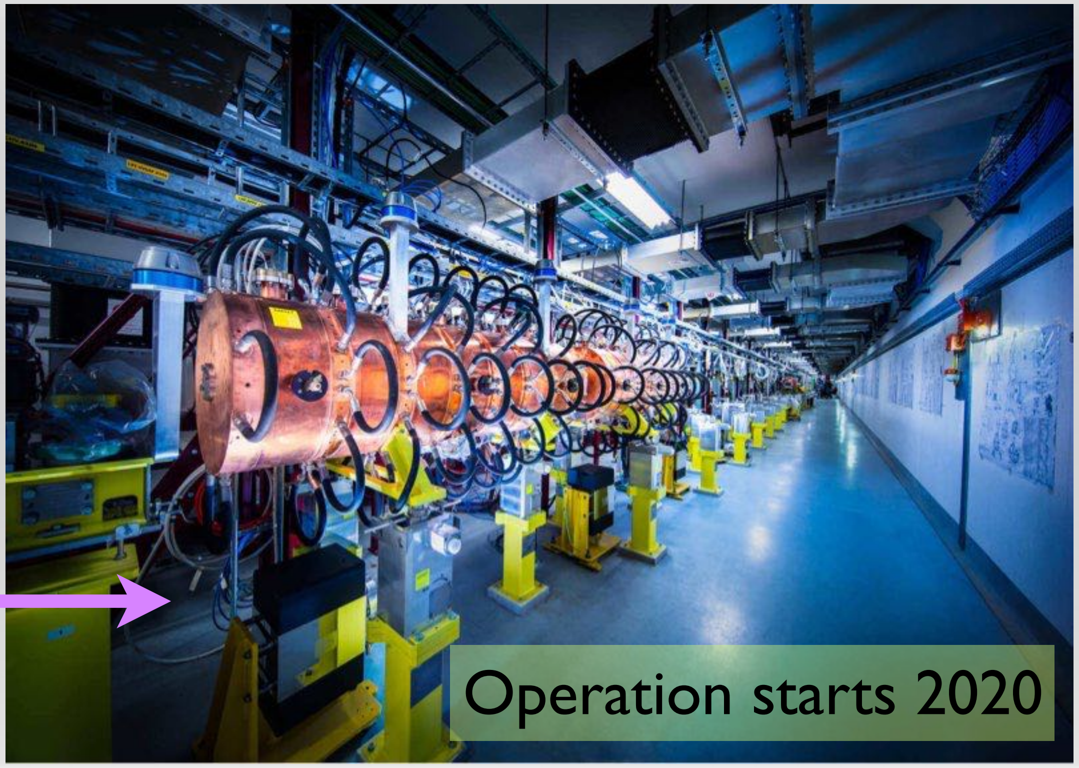
Protons accelerated to **50MeV**; typical intensities: **8.8*10^{13} particles/cycle**

switched off 2018

hand-over during LS2

H⁻ LINAC4 (2020)

H^- ions are accelerated to **160 MeV**; typical intensities: **6.5*10^{13} particles/s**



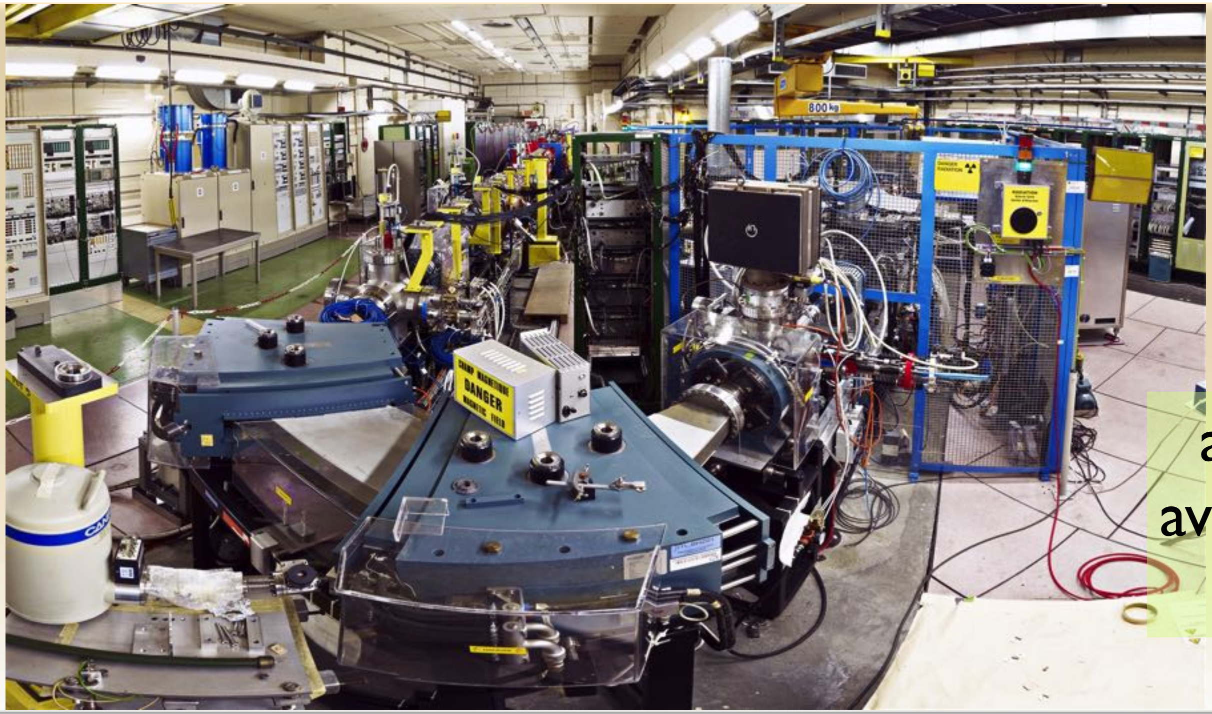
Operation starts 2020

HEAVY IONS

Heavy ion LINAC3 (1994)

~9×10^8 lead ions are accelerated to 4.2MeV/u.

Next to **Lead**, LINAC3 has delivered **Indium** (2000), **Oxygen** (2005), **Argon** (2015) and will deliver **Xenon** in 2017.



average availability: 97.8%

PS Booster and LEIR

PROTONS

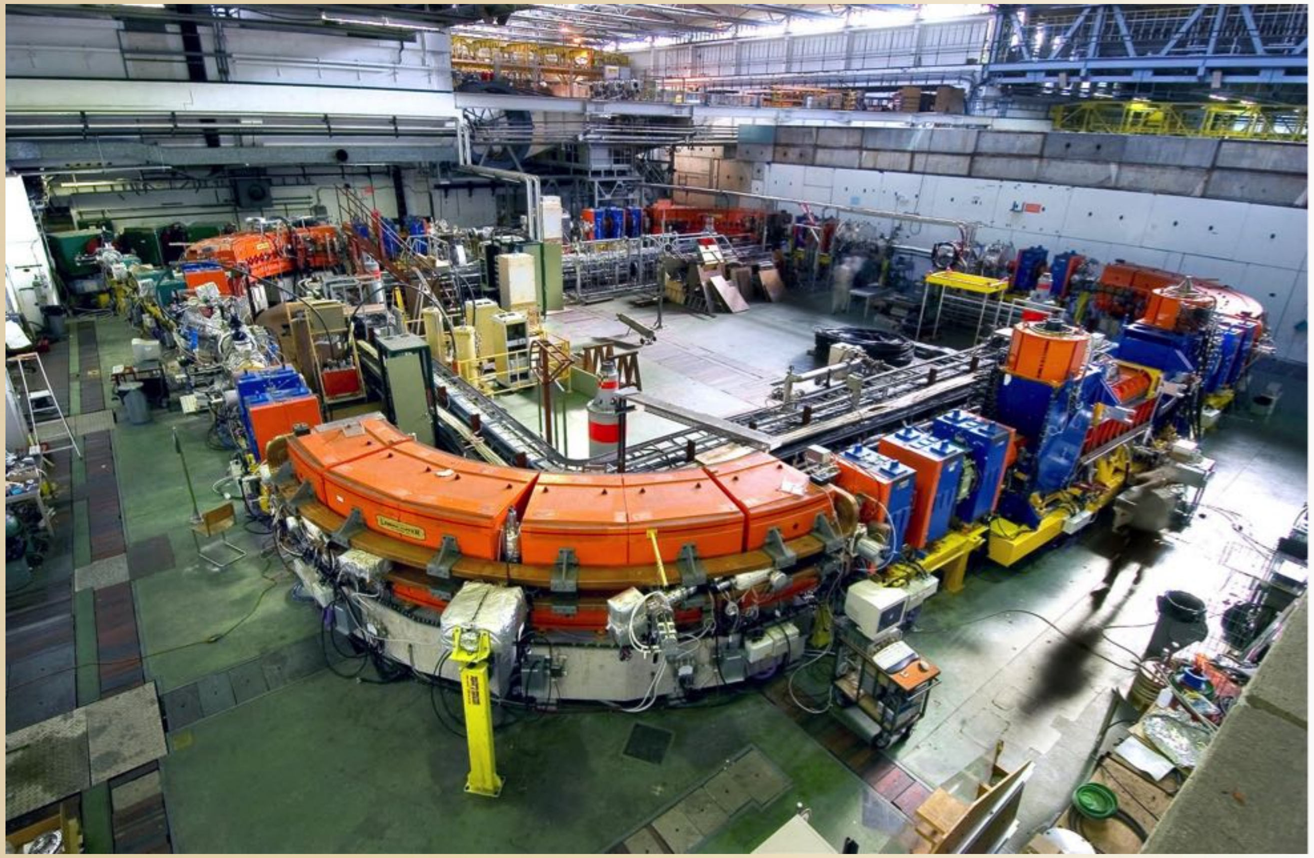
average availability: 95% (2016)

PS Booster (1972):

4 superimposed rings accelerate 4 bunches, all together max. 3.4 x 10^{12} protons in 1.2s up to **1 or 1.4 GeV** (2 GeV/c and no more 1 GeV/c after LS2).

A Booster cycle lasts **1.2 s**: defines the **heartbeat** of the CERN accelerator complex.

HEAVY IONS

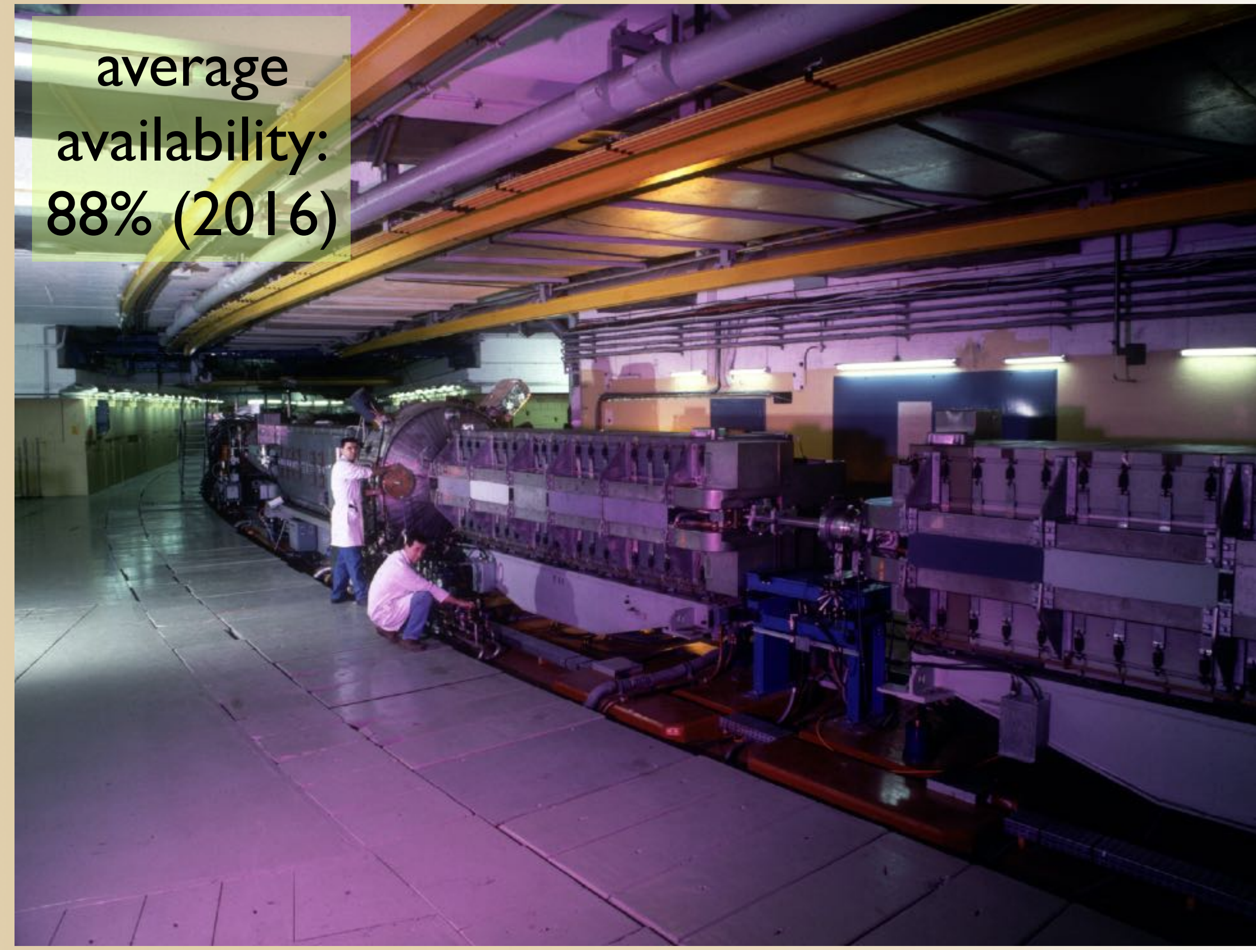


LEIR (2005):

Accelerates 4 bunches of 2.2x10^8 lead ions to **72 MeV/u** before passing them through to the PS.

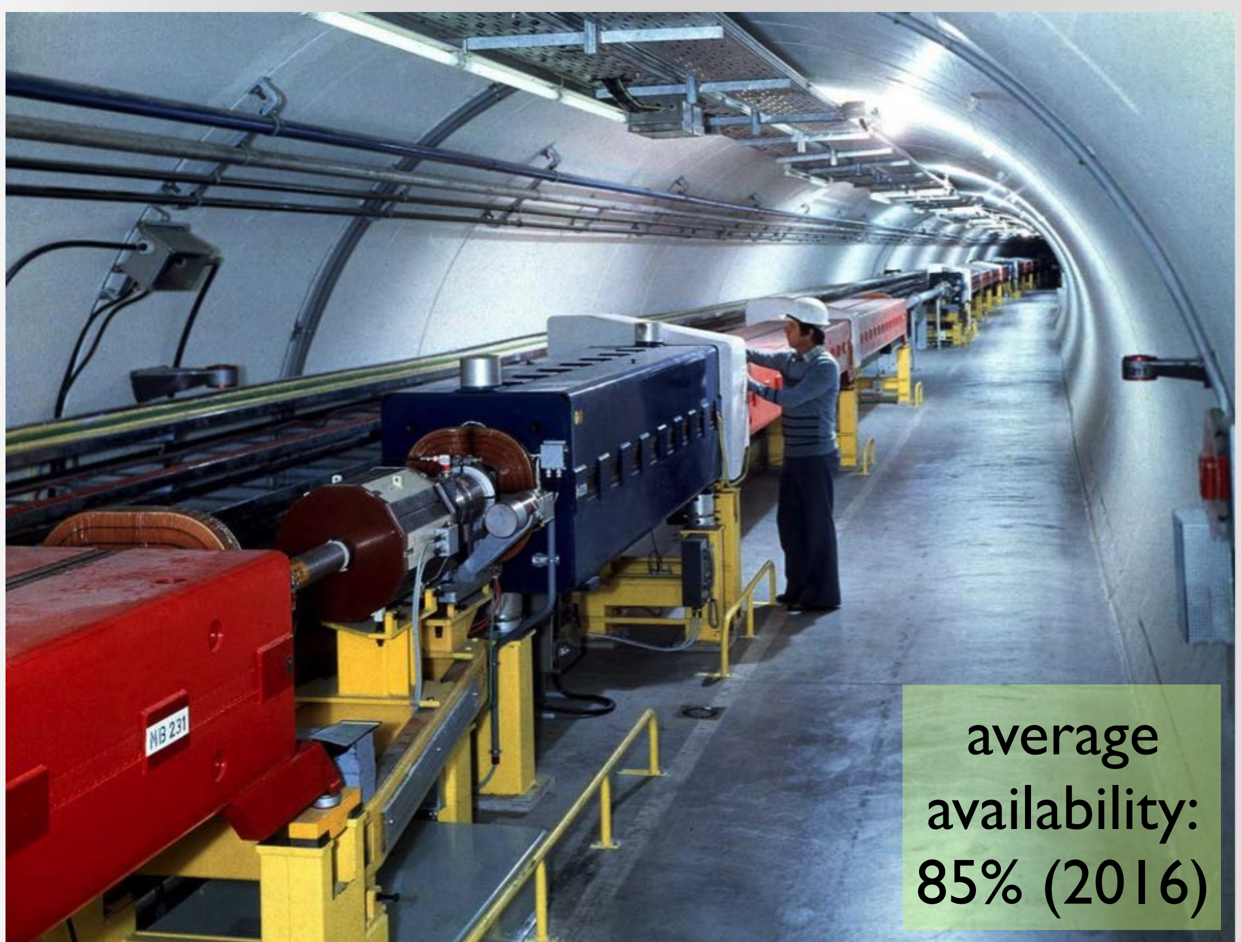
The PS and SPS

PS and SPS accelerate both, protons and ions



Proton Synchrotron PS (1959):
filled by 2 batches from Booster, ramping protons from **14** to **26GeV**, maximum 1.4x10^{13} protons per pulse.

Superproton Synchrotron SPS (1976):
accelerates protons up to **400GeV** (FT) or **450GeV** (LHC) with intensities up to **9.510**^{9} protons per bunch (FT) or **1.2x10**^{11} protons per bunch (LHC25ns).



Beams to all experiments: a complicated ballet

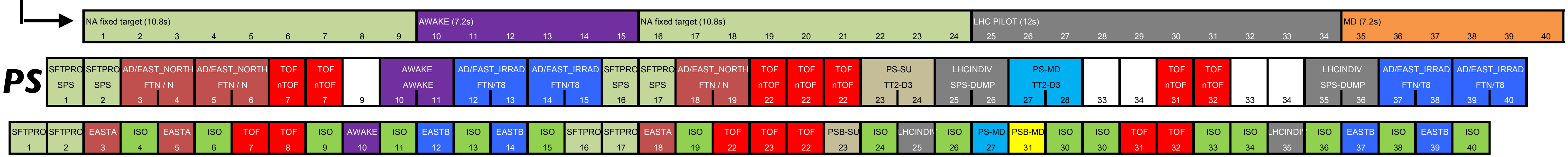
To bring beam to all experiments and tests requires complex planning

- ➡ **Supercycles** are prepared with variable length and variable composition;

Example: one (of many) Supercycles in 2016:

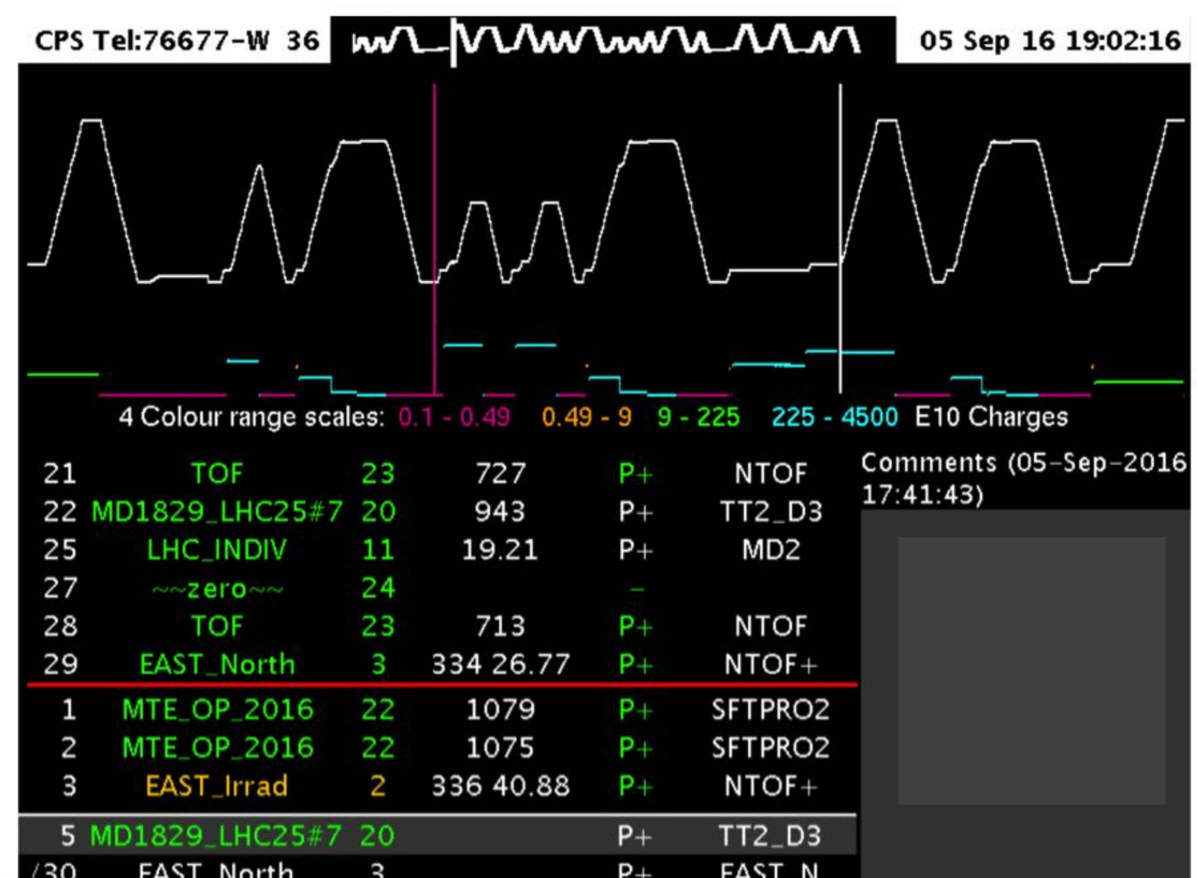
SPS

PS



Booster

Supercycles define operation e.g. of the PS:

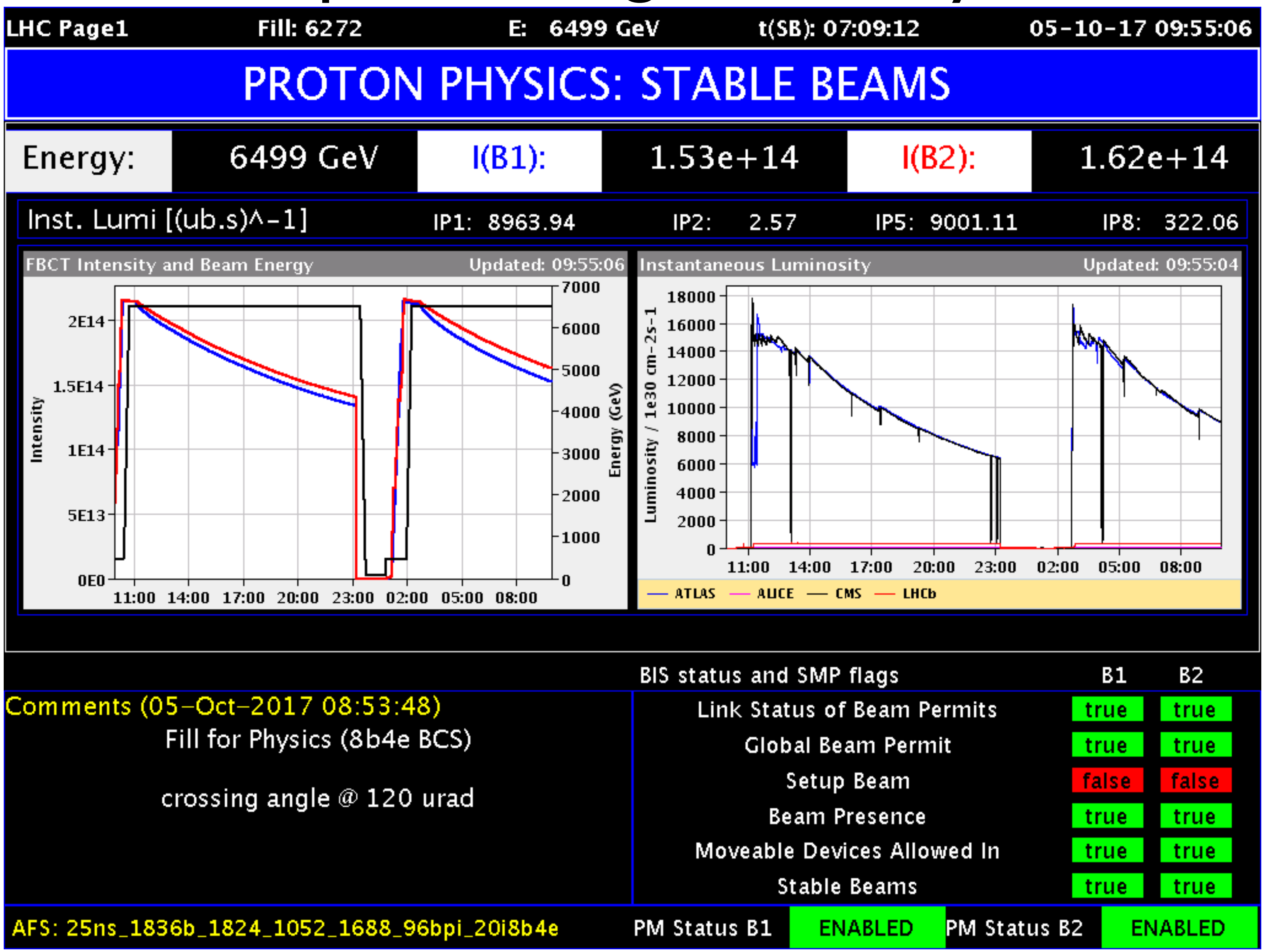


- **keep in mind:** the number of protons for experiments is limited;

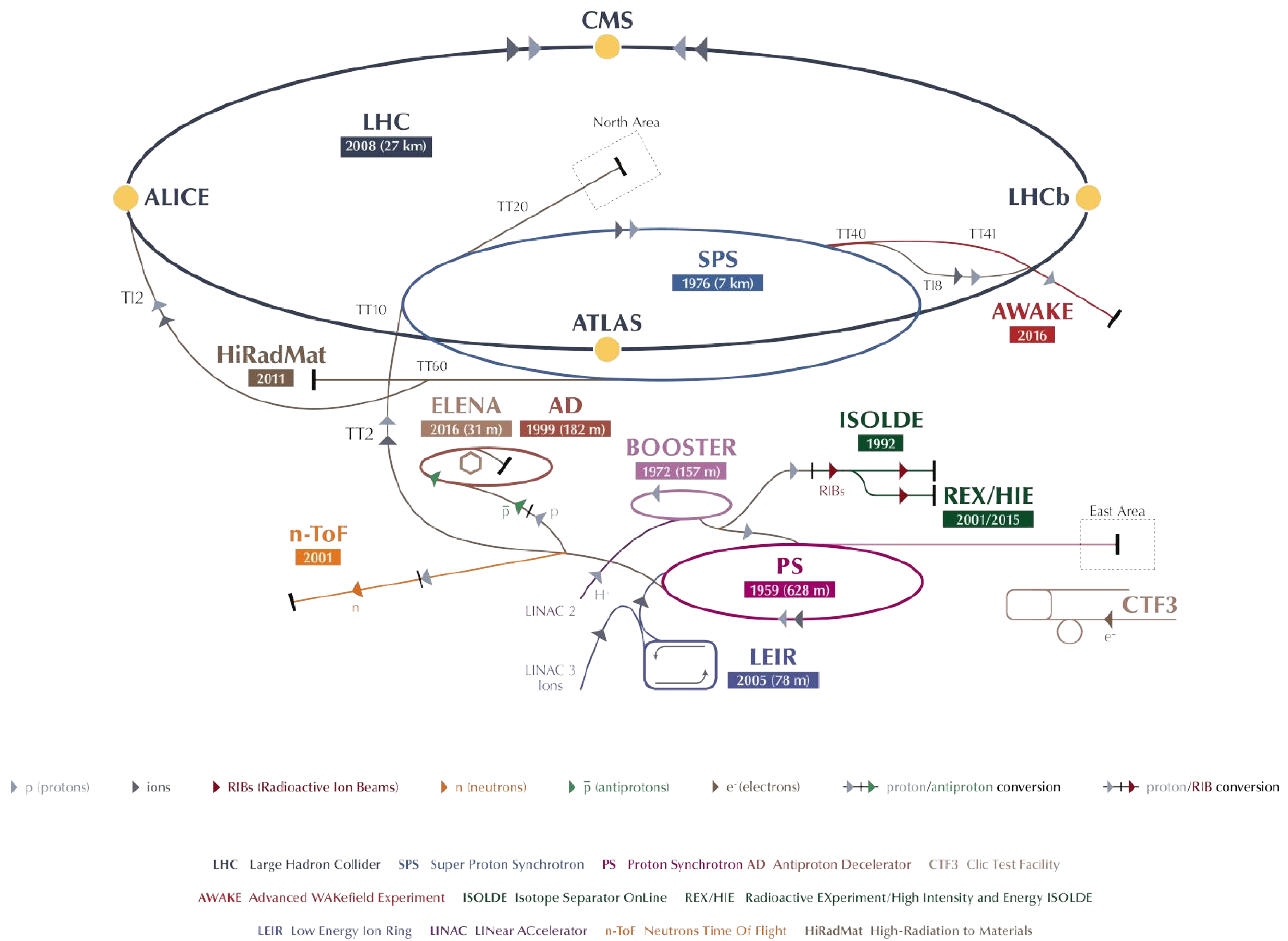
➡ lot of effort by the CERN accelerator teams to optimise the delivery rates

Flagship machine at CERN: the LHC

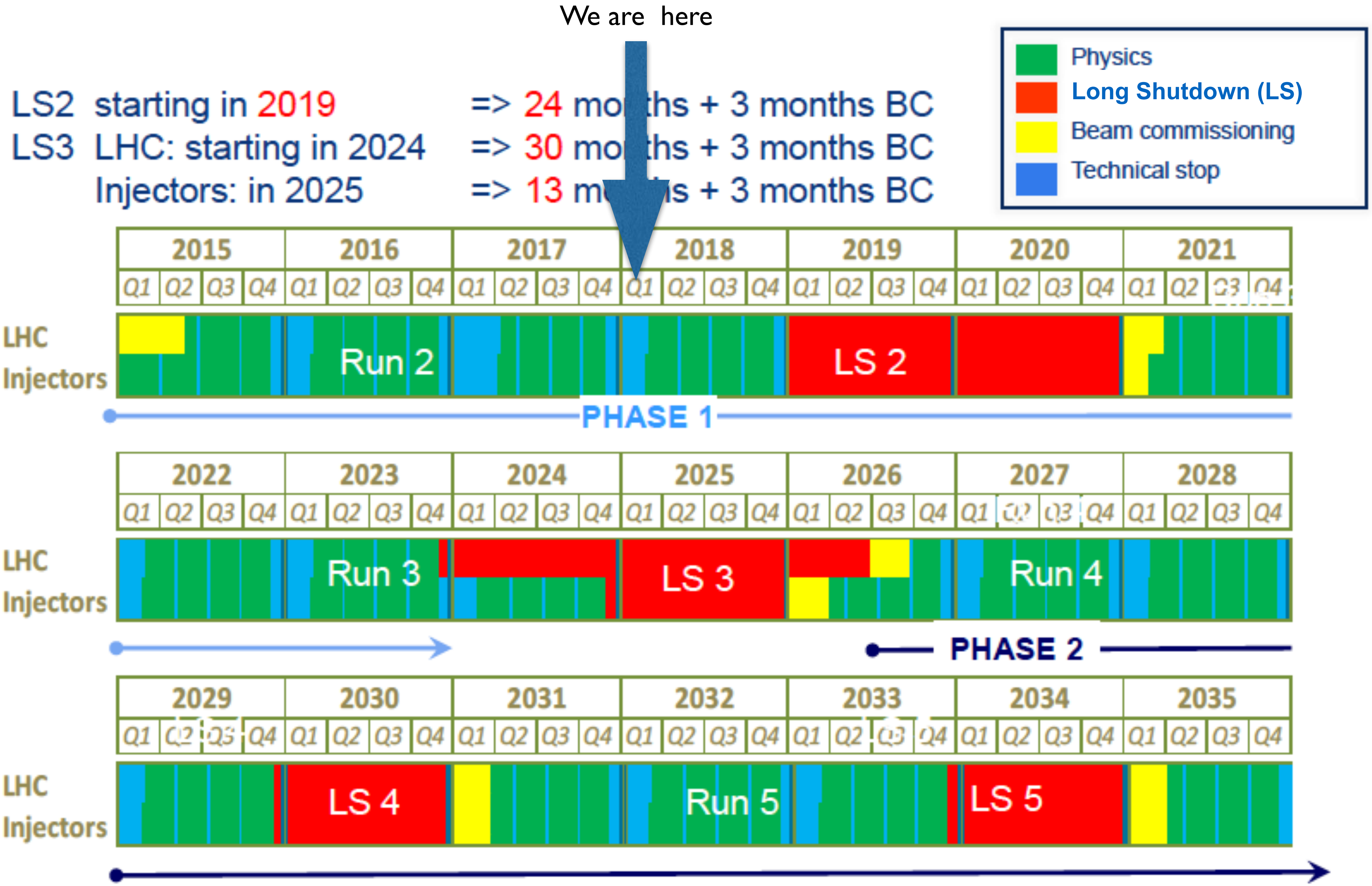
Almost all year, the LHC is taking data - machine and experiments are performing extremely well.



The CERN accelerator complex



LHC roadmap, according to MTP 2016-2020*



*outline LHC schedule out to 2035 presented by Frederick Bordry to the SPC and FC June 2015

New physics, experimentally

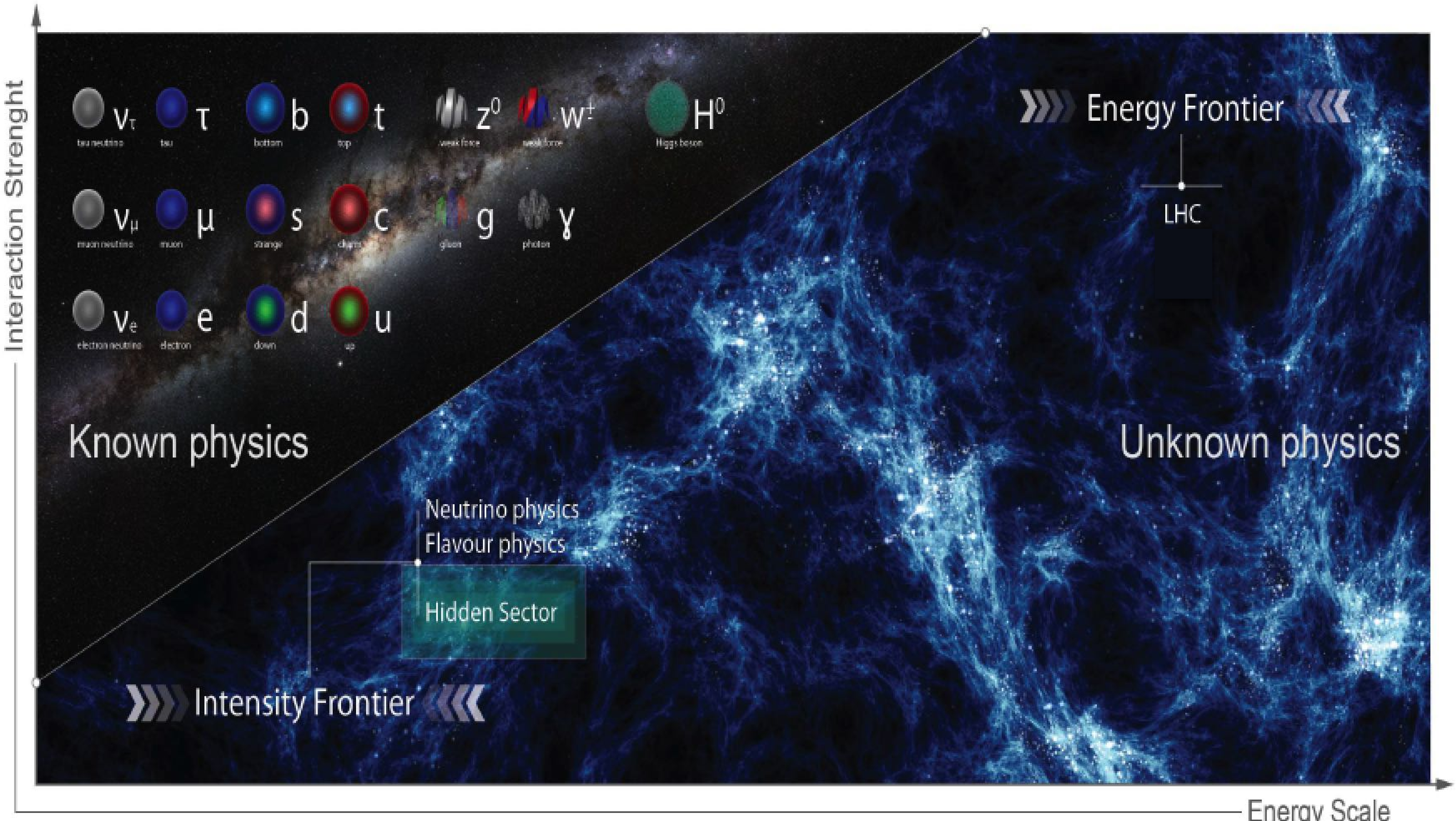


Figure by Mikhail Shaposhnikov "New Physics below the Fermi Scale"
at the Physics Beyond Colliders Kickoff workshop

*added by CR 19.11.2016