# CERN's Physics Programme

## Introduction to CERN’s Experiments & Facilities

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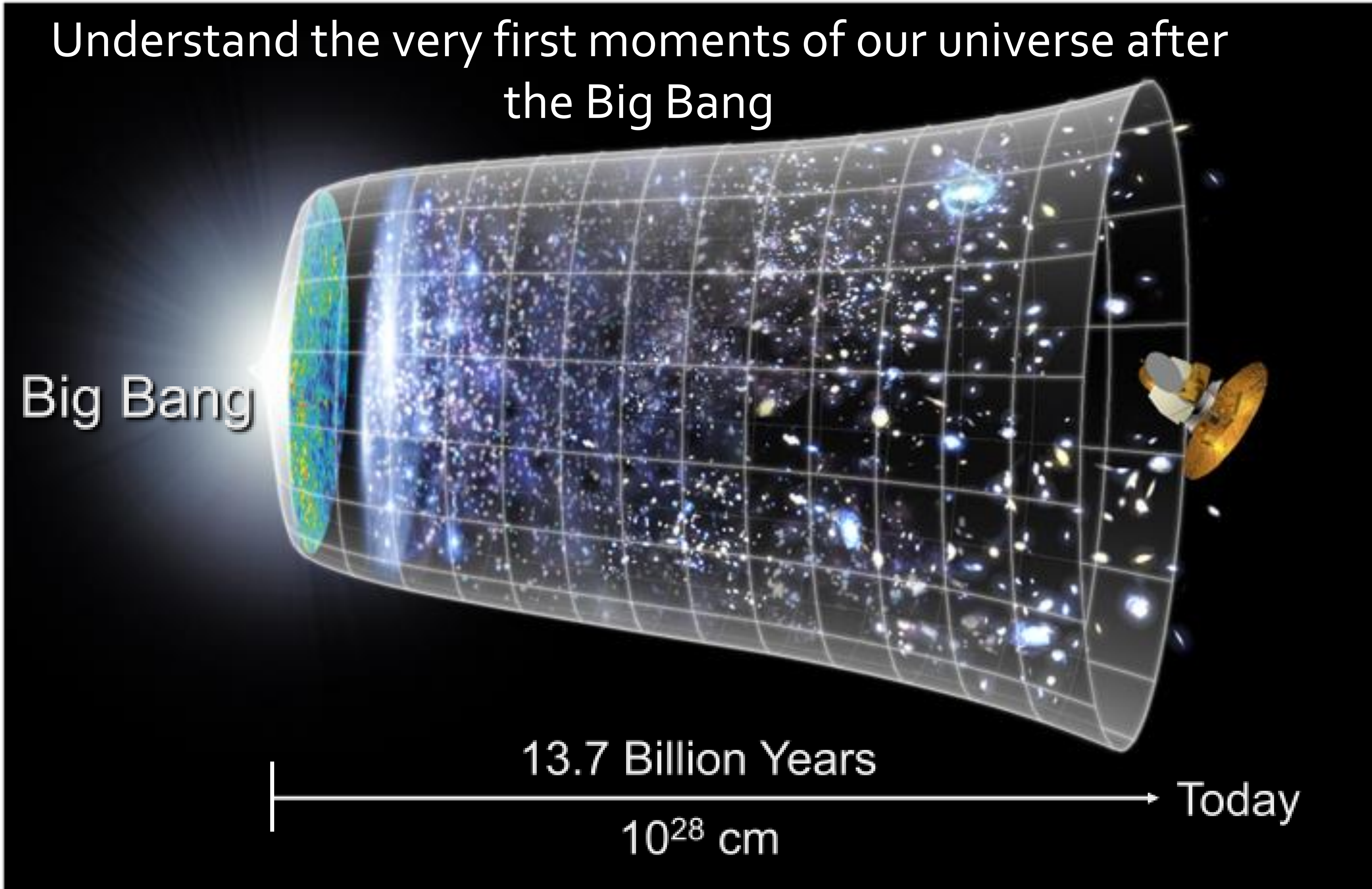
ENGINEERING DEPARTMENT

Experimental Physics Department

# Scientific Challenge

Understand the very first moments of our universe after the Big Bang



# Particle physics
## What we know and what we do not know

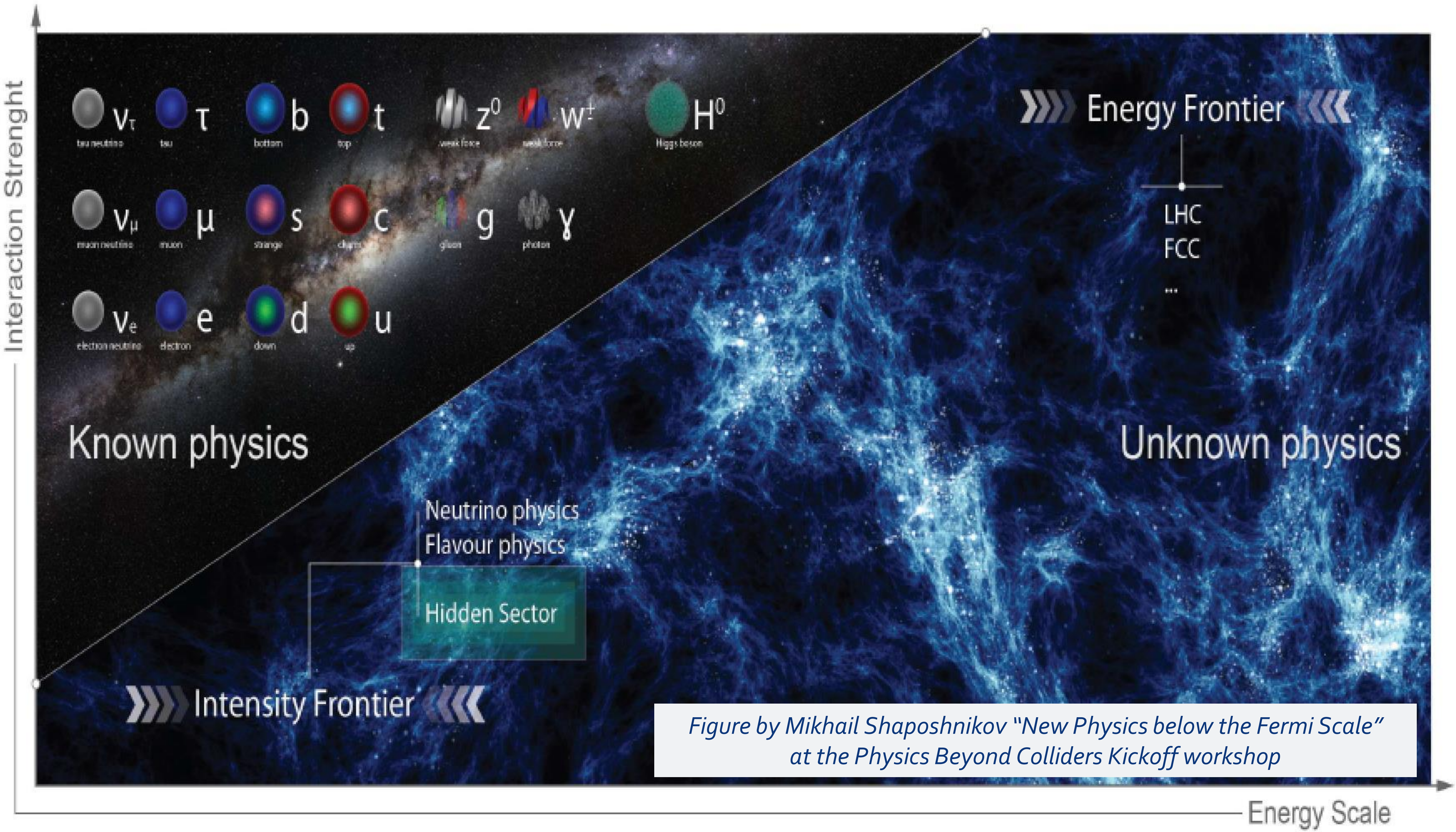
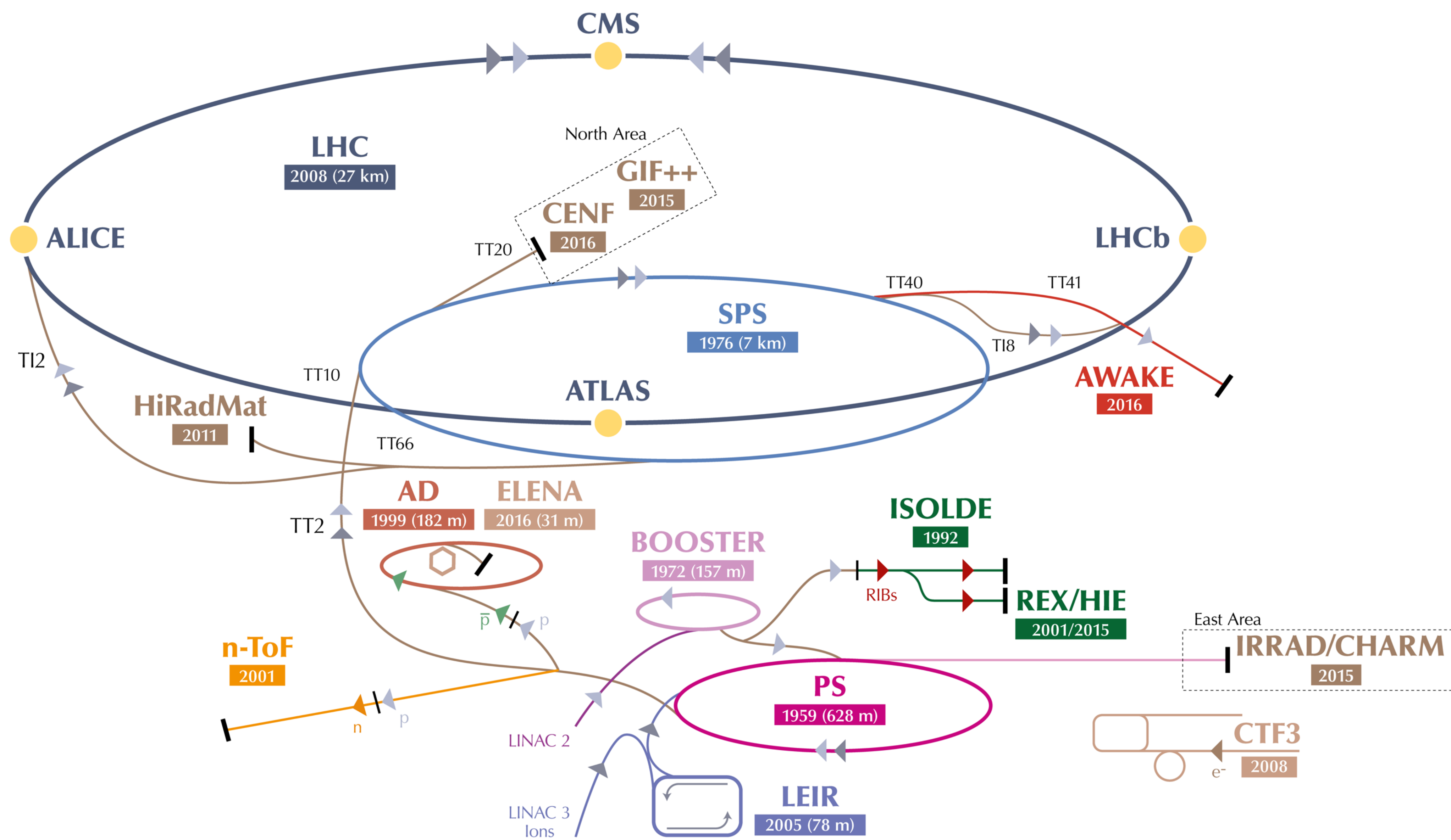



*Figure by Mikhail Shaposhnikov "New Physics below the Fermi Scale" at the Physics Beyond Colliders Kickoff workshop*

# The CERN accelerator complex




p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) $\bar{p}$ (antiprotons) $e^-$ (electrons)

**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

**CHARM** Cern High energy AcceleRator Mixed field facility **IRRAD** proton IRRADiation facility **GIF++** Gamma Irradiation Facility

**CENF** CErn Neutrino platForm

# Injectors: LINACs

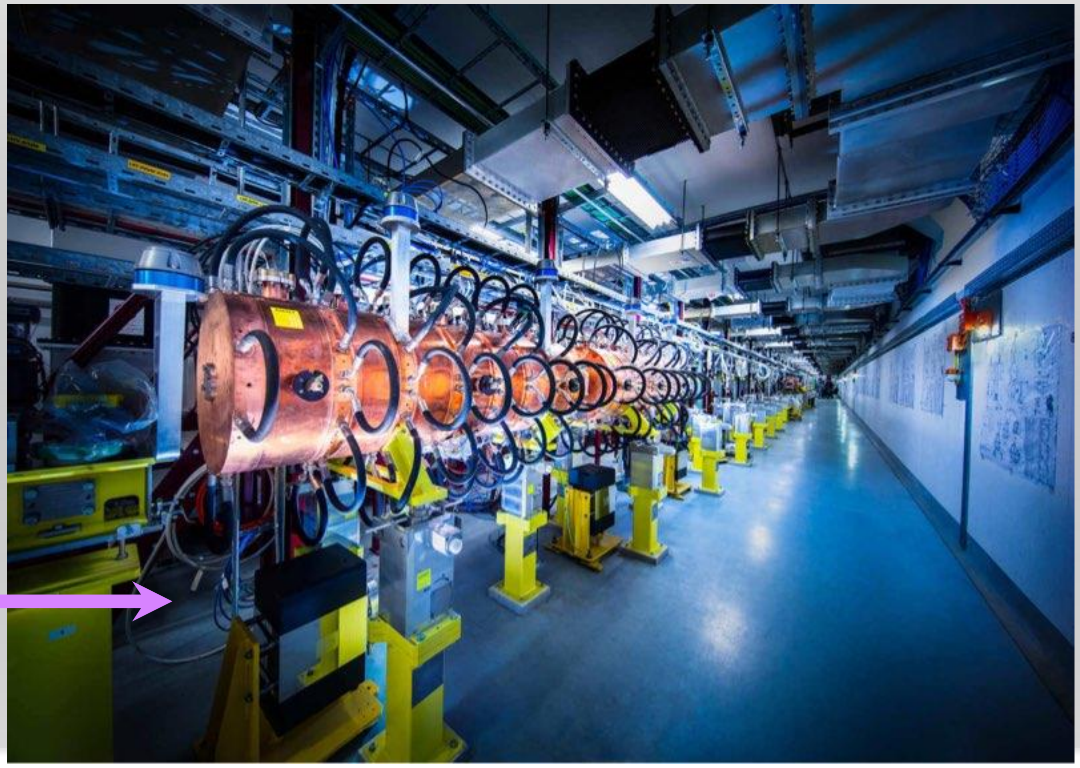
PROTONS

**Proton LINAC2 (1978)**

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

**$H^-$ LINAC4 (2020)**

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



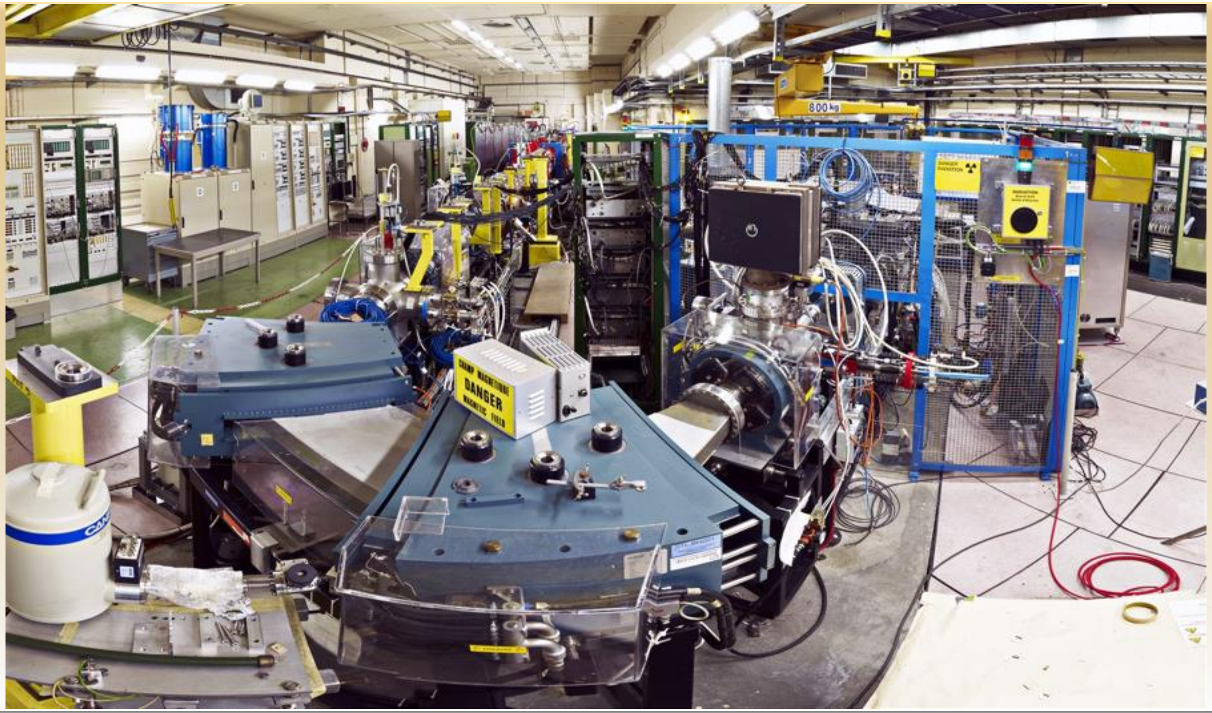
hand-over during LS2 (2019/20)

HEAVY IONS

**Heavy ion LINAC3 (1994)**

~$9 \times 10^8$ 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.



# Injectors: PS Booster and LEIR

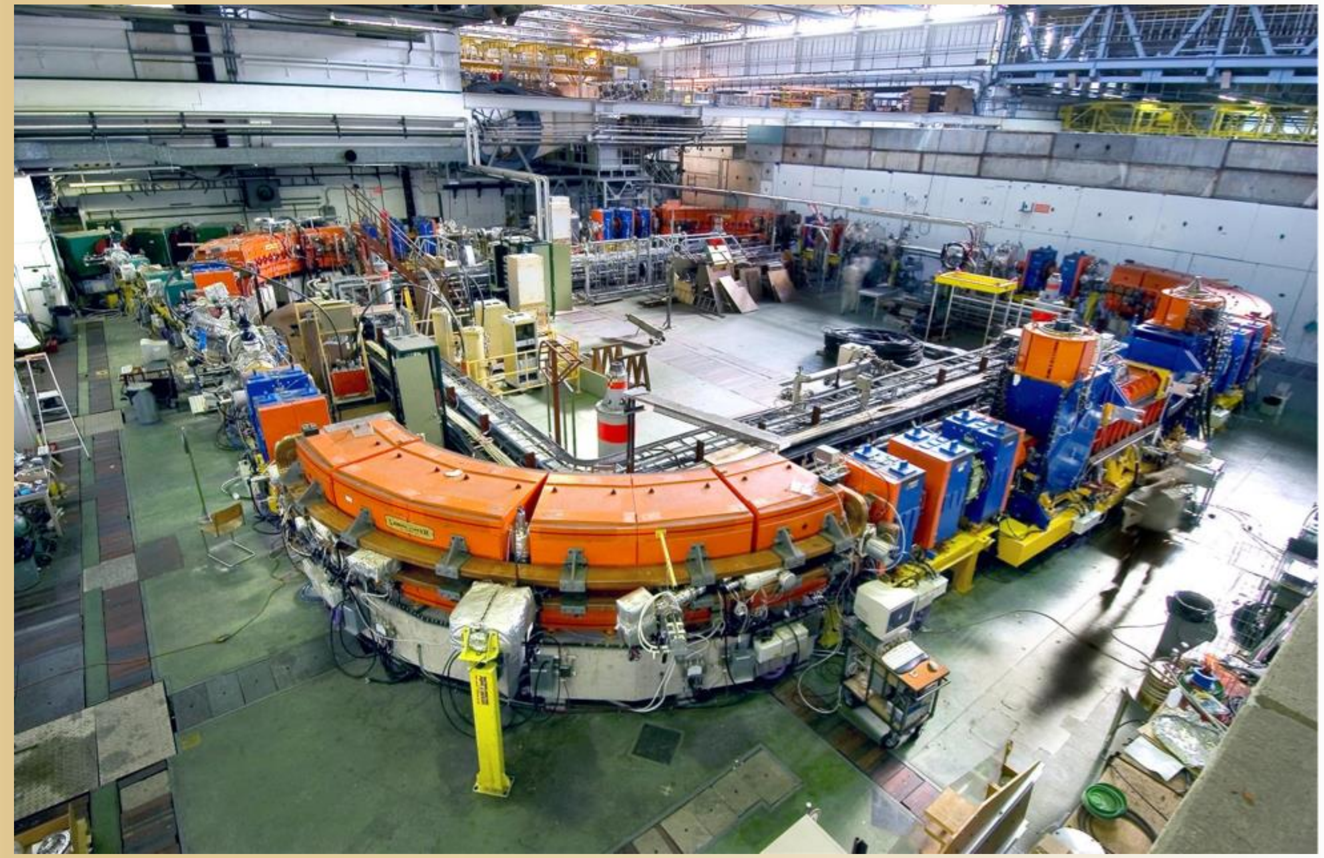
## PROTONS


**PS Booster (1972):**

4 superimposed rings accelerate 4 bunches, all together max. $3.4 \times 10^{12}$ 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



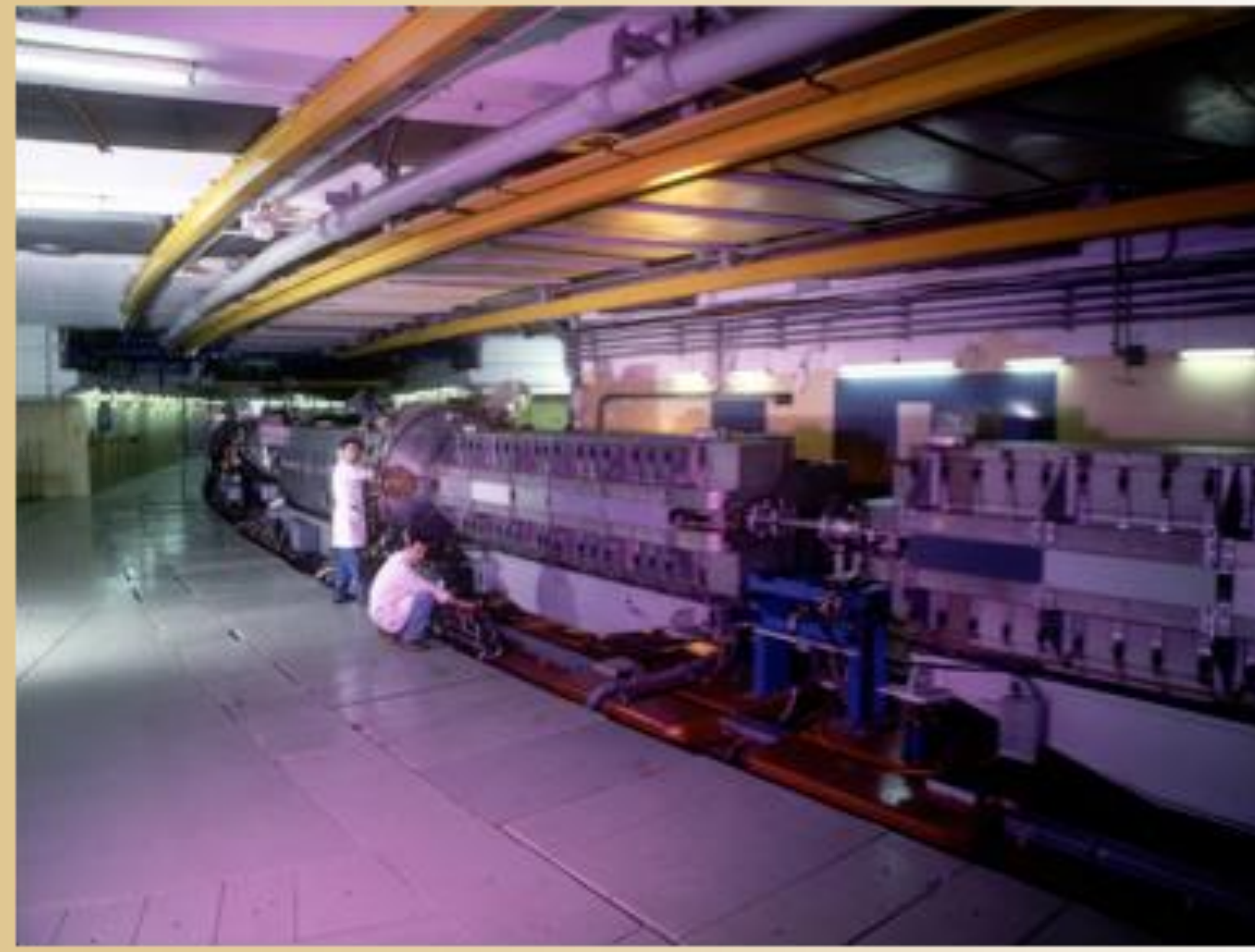
**LEIR (2005):**

Accelerates 4 bunches of $2.2 \times 10^8$ 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

**Superproton Synchrotron SPS (1976):**
accelerates protons up to **400GeV** (FT) or **450GeV** (LHC) with intensities up to **$9.5 10^9$** protons per bunch (FT) or **$1.2\times10^{11}$** protons per bunch (LHC25ns).

**Proton Synchrotron PS (1959):**
filled by 2 batches from Booster, ramping protons from **14** to **26GeV**, maximum $1.4\times10^{13}$ protons per pulse.

# Beams to all experiments: A Complicated Ballet

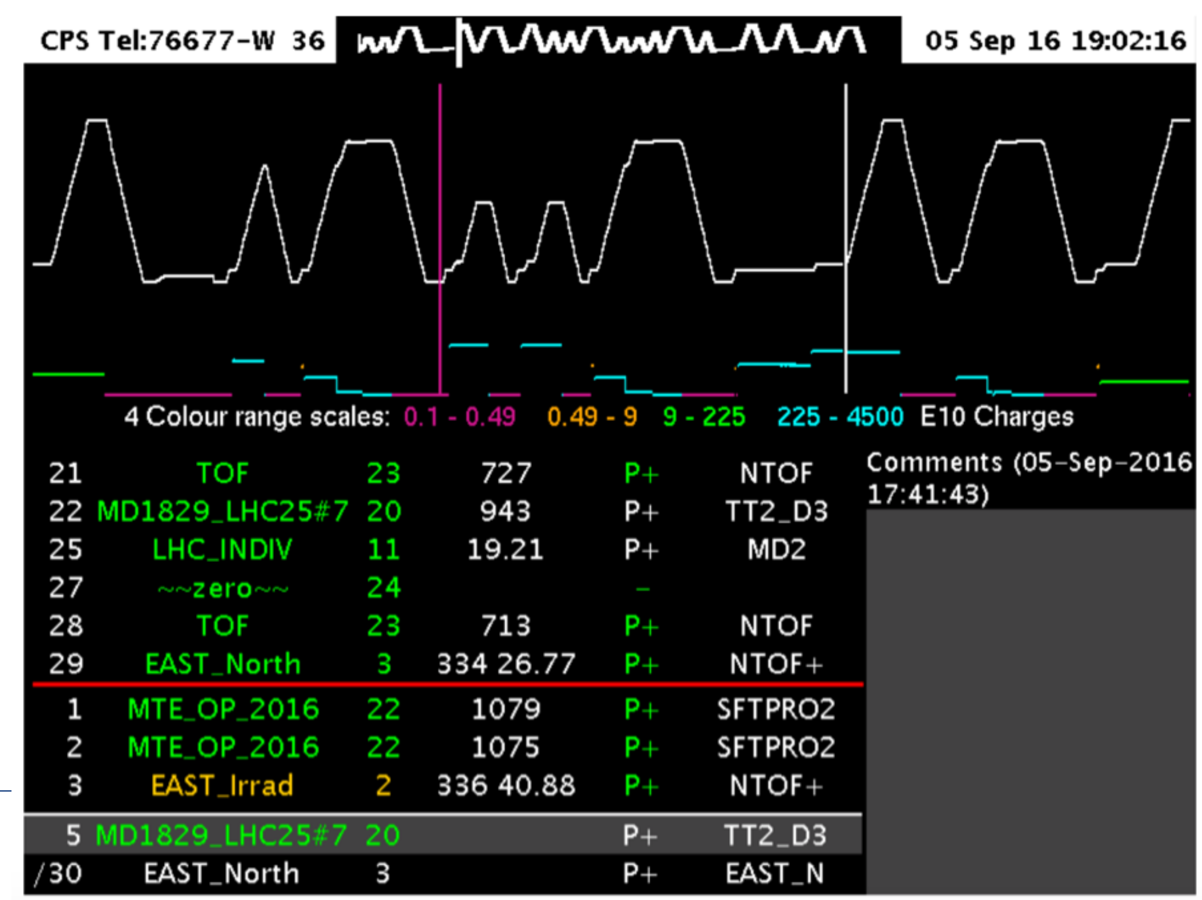
To bring beam to all experiments and tests requires complex planning:
**Supercycles** are prepared with variable length and variable composition

SPS

*Example: one (of many) Supercycles in 2016:*


Booster

*Supercycles define operation e.g. of the PS:*



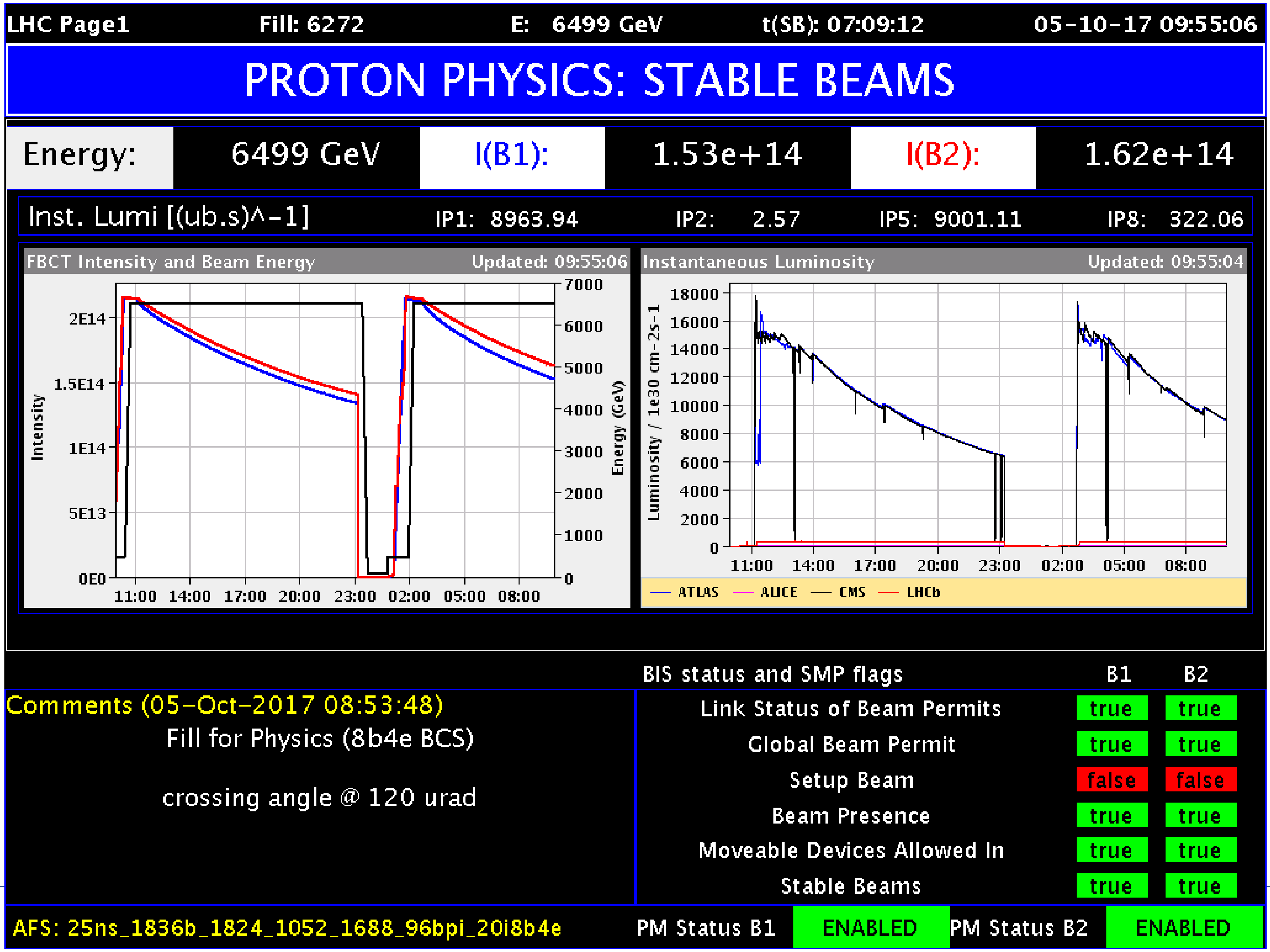

Keep in mind: The number of protons for experiments is limited.

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

# The Large Hadron Collider (LHC)

# Flagship machine at CERN: The LHC

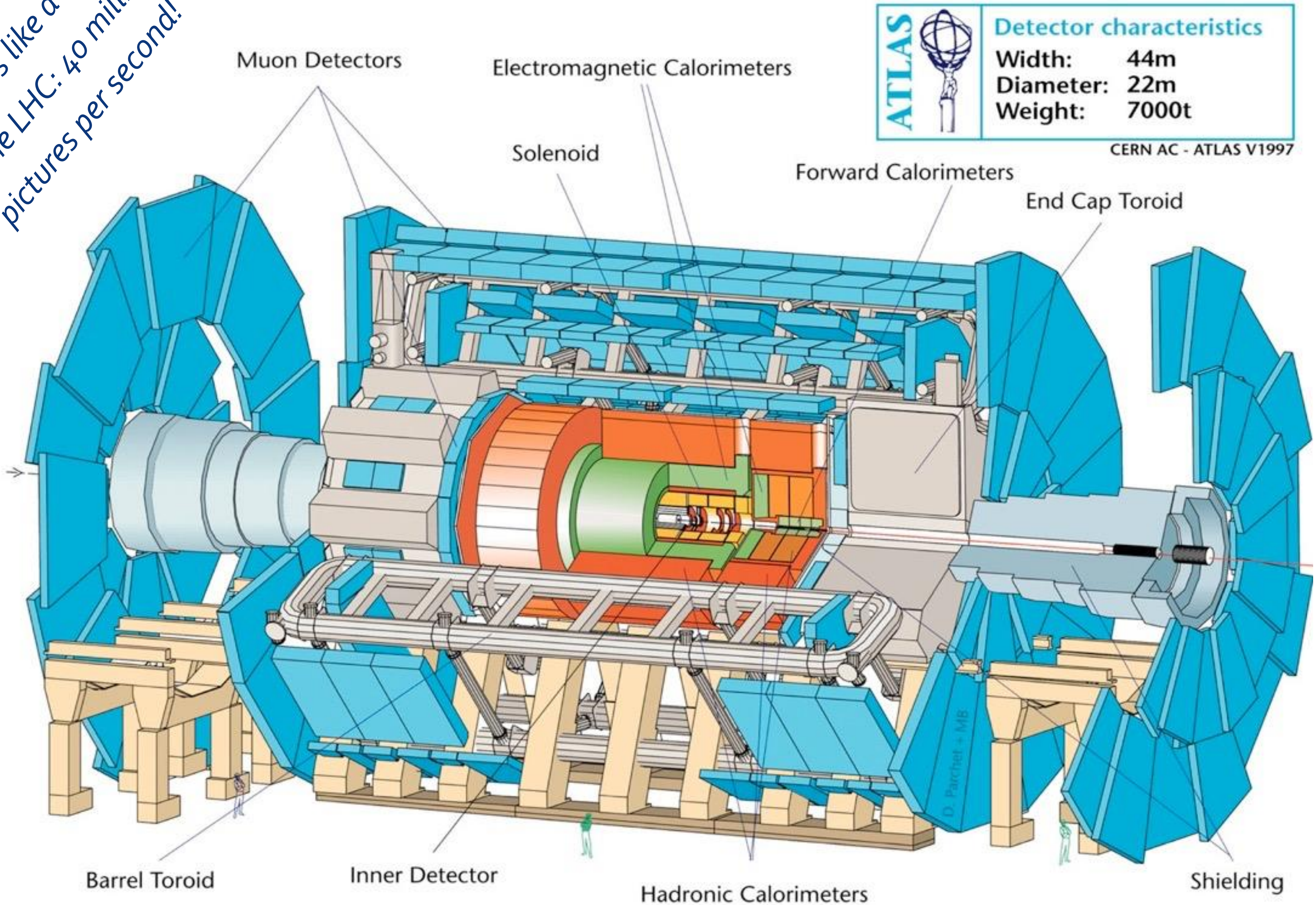
Almost all year, the LHC is taking data - machine and experiments are performing extremely well.



# CERN and the Large Hadron Collider (in the movie "Angels & Demons")

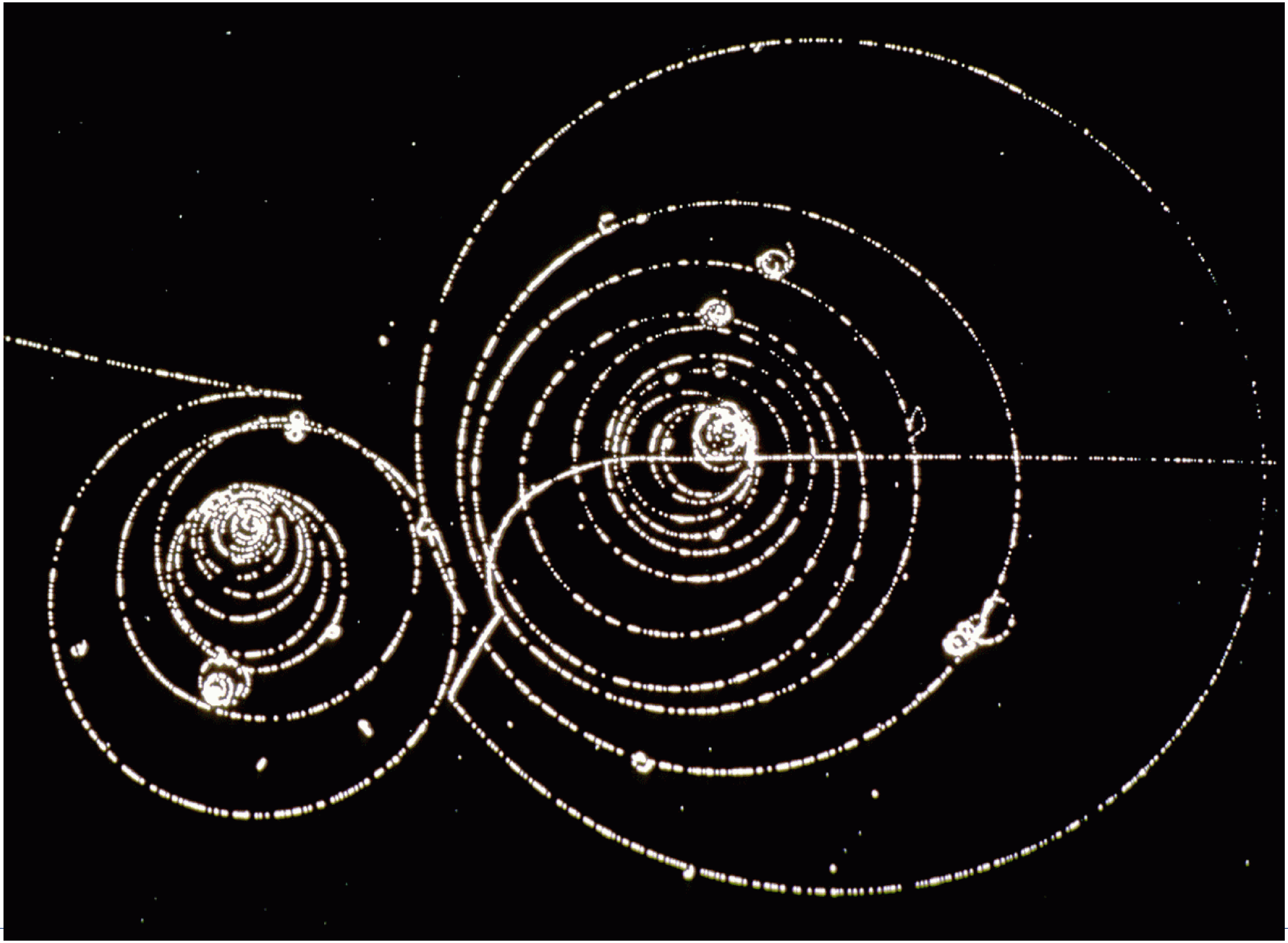
# An LHC detector

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

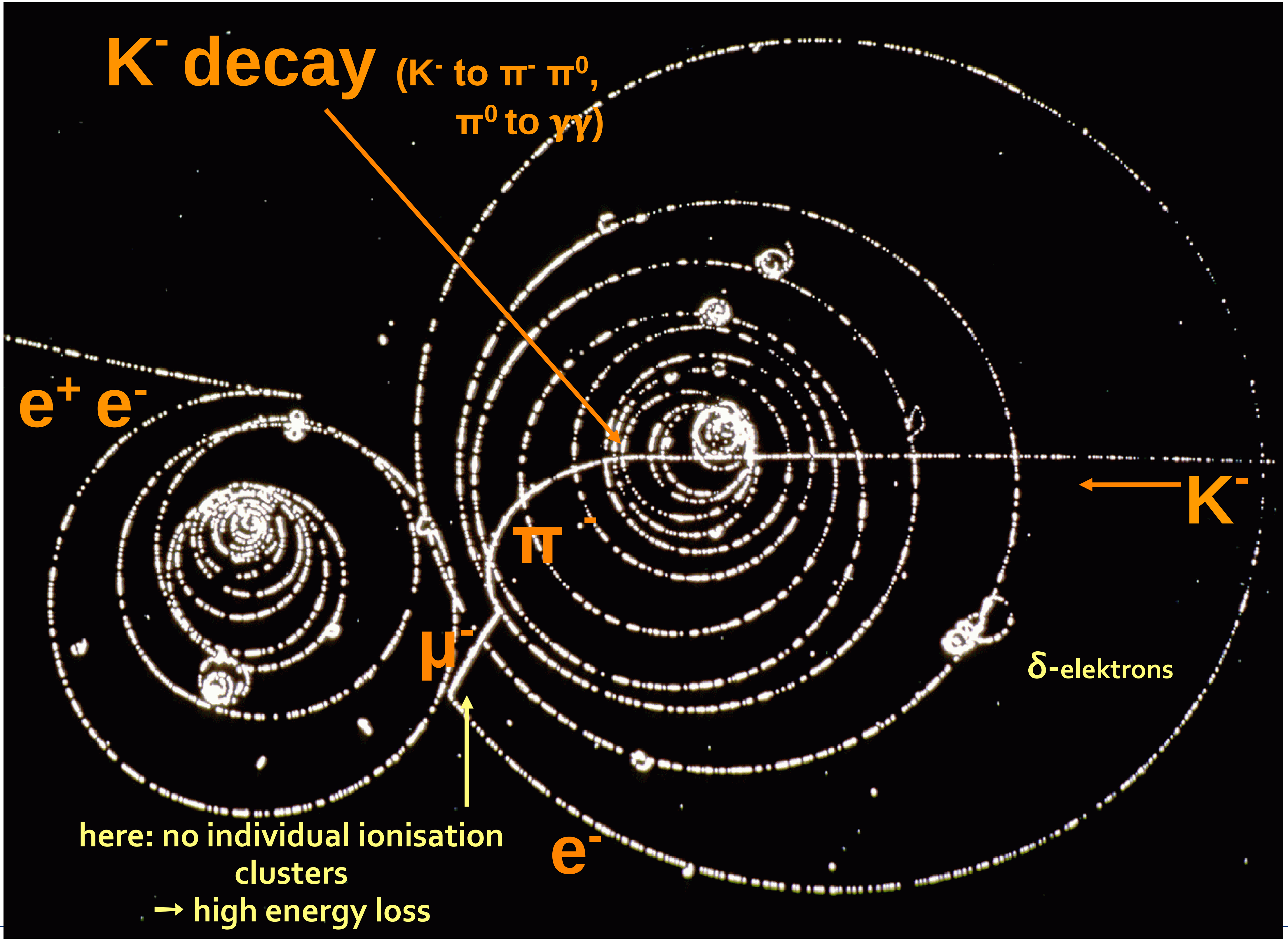


# Taking pictures of particles

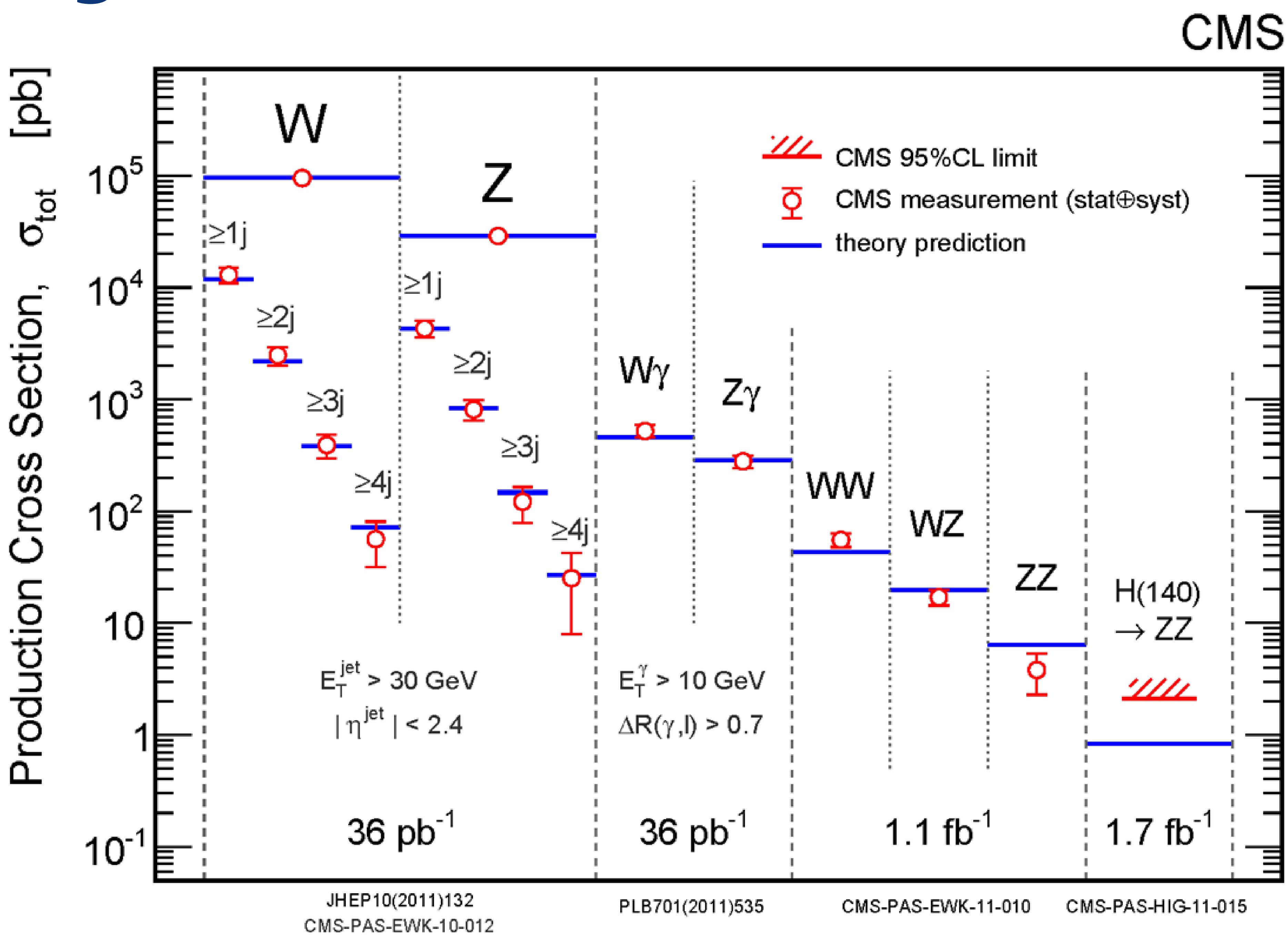
# …what you see…



# …what has happened

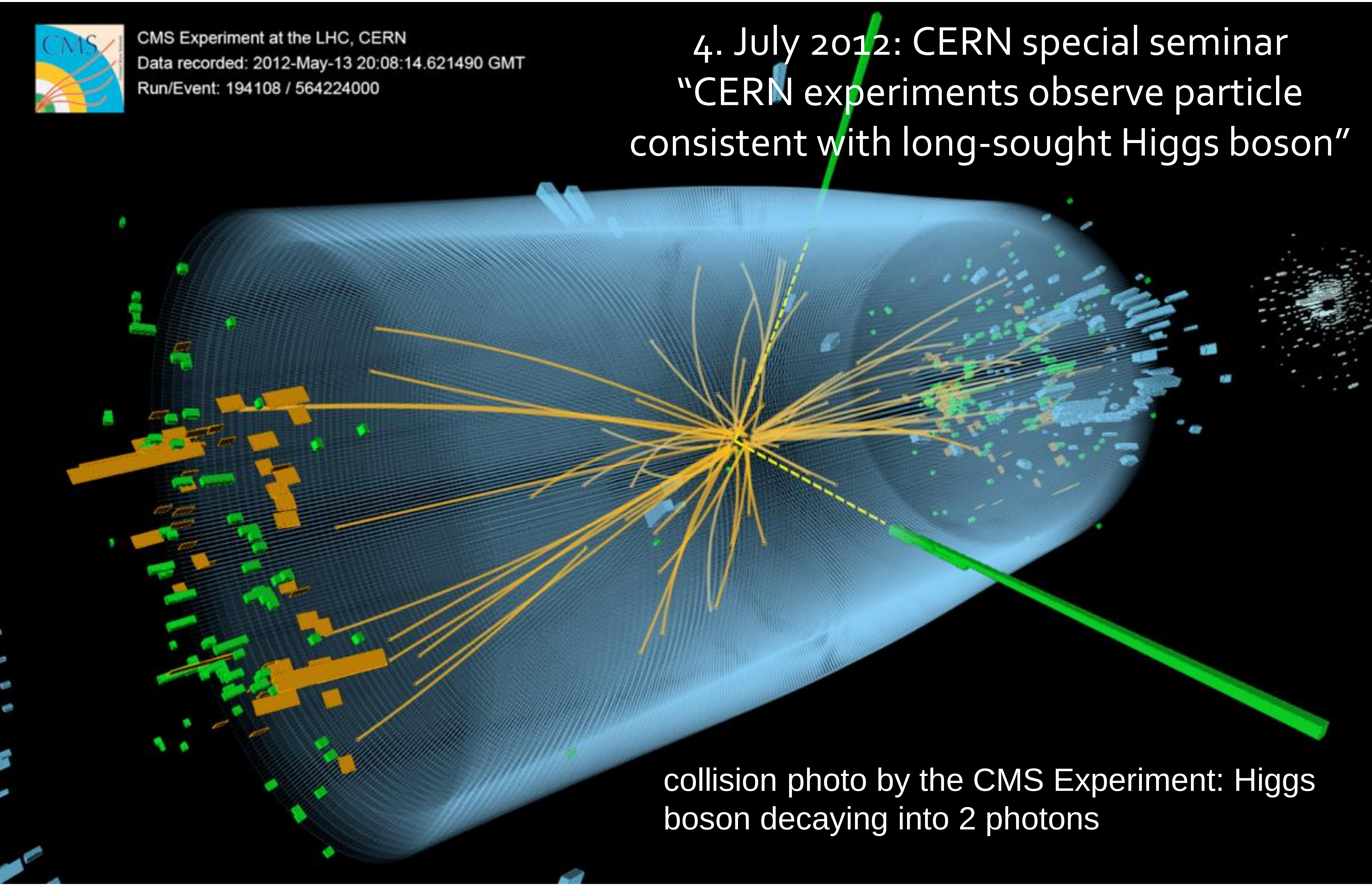


# Probing the Standard Model at the LHC




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

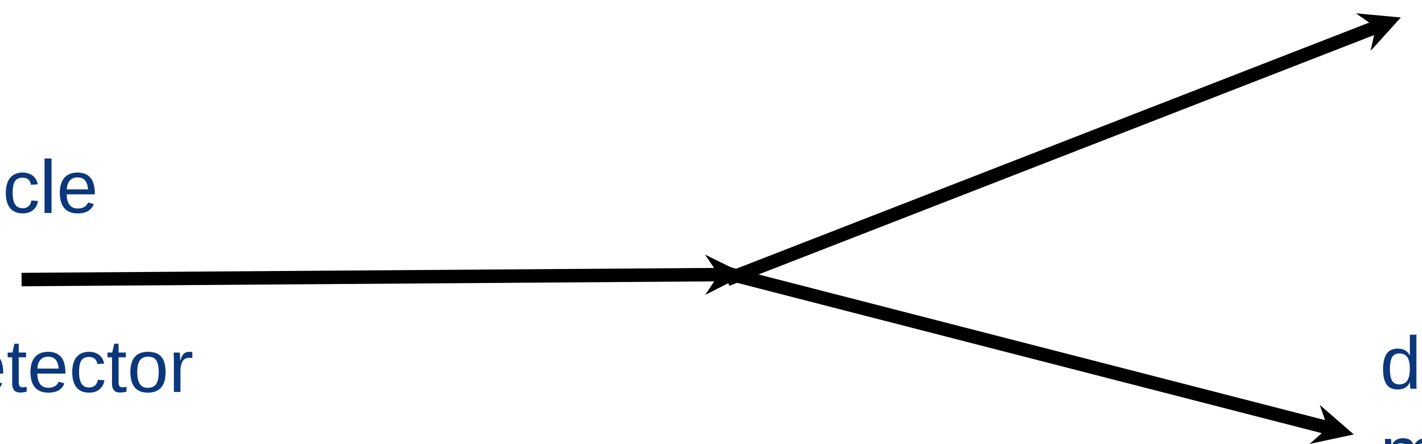
# Higgs Boson




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



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

decaying particle
mass M
not seen in detector

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

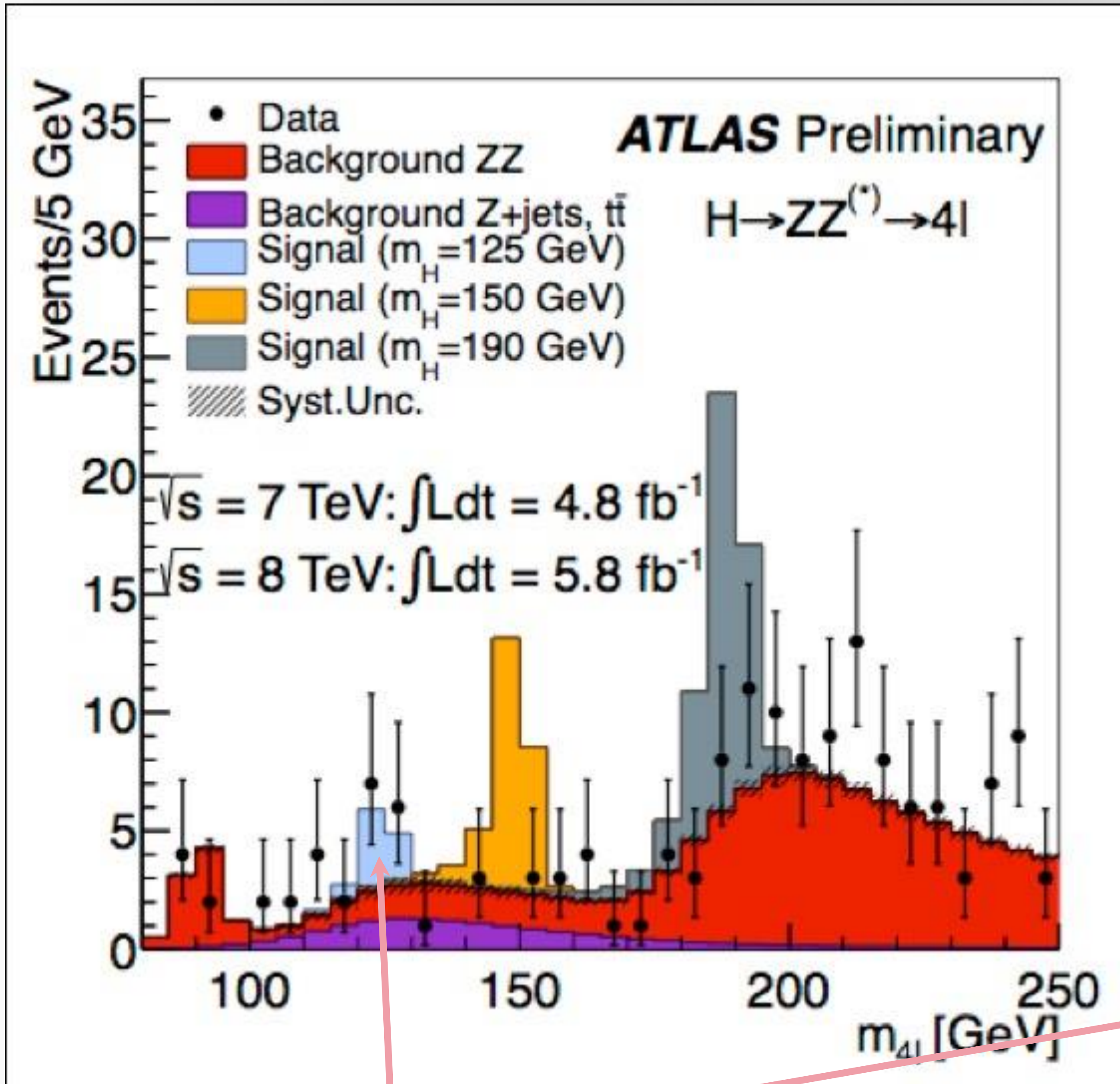
Decay particles (m, E, p)
are measured in detector!

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

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

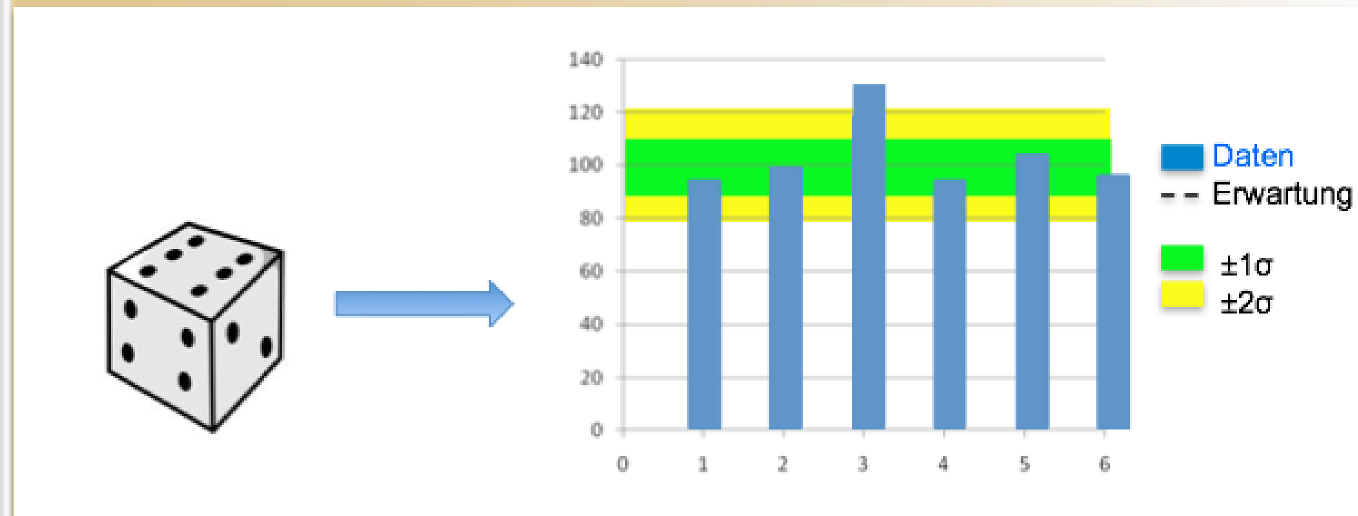
$$\begin{aligned} M^2 &= (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2 \\ &= m_1^2 + m_2^2 + 2\,(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2) \end{aligned}$$

# Finding new particles: calculate invariant mass

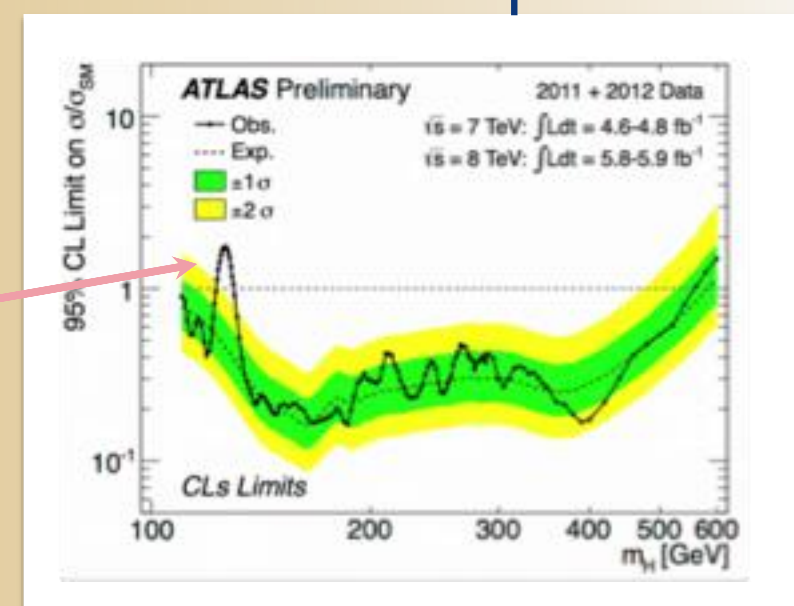



This is the Higgs particle!!!

Example: is the dice marked?

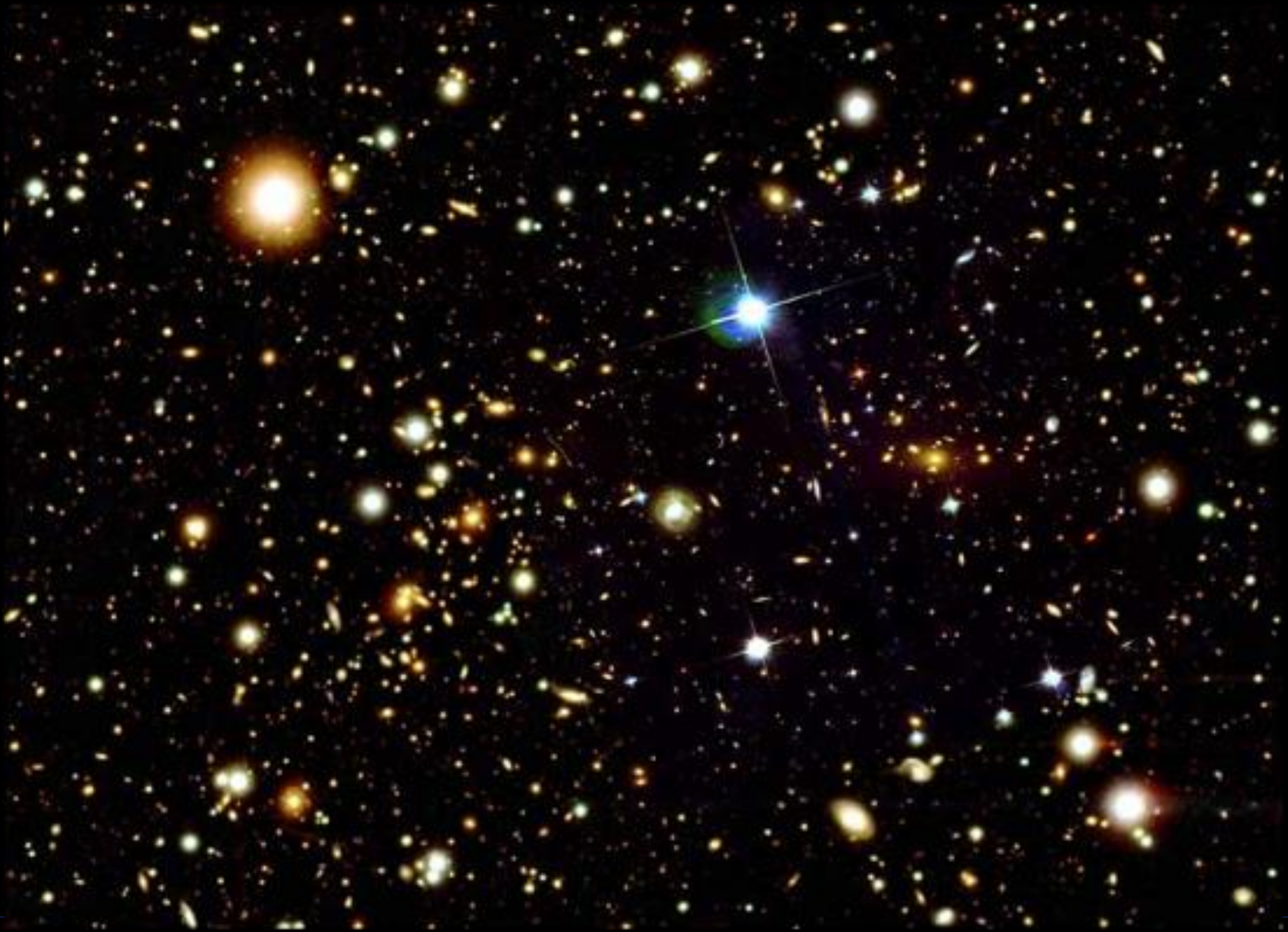



Is there a new particle?

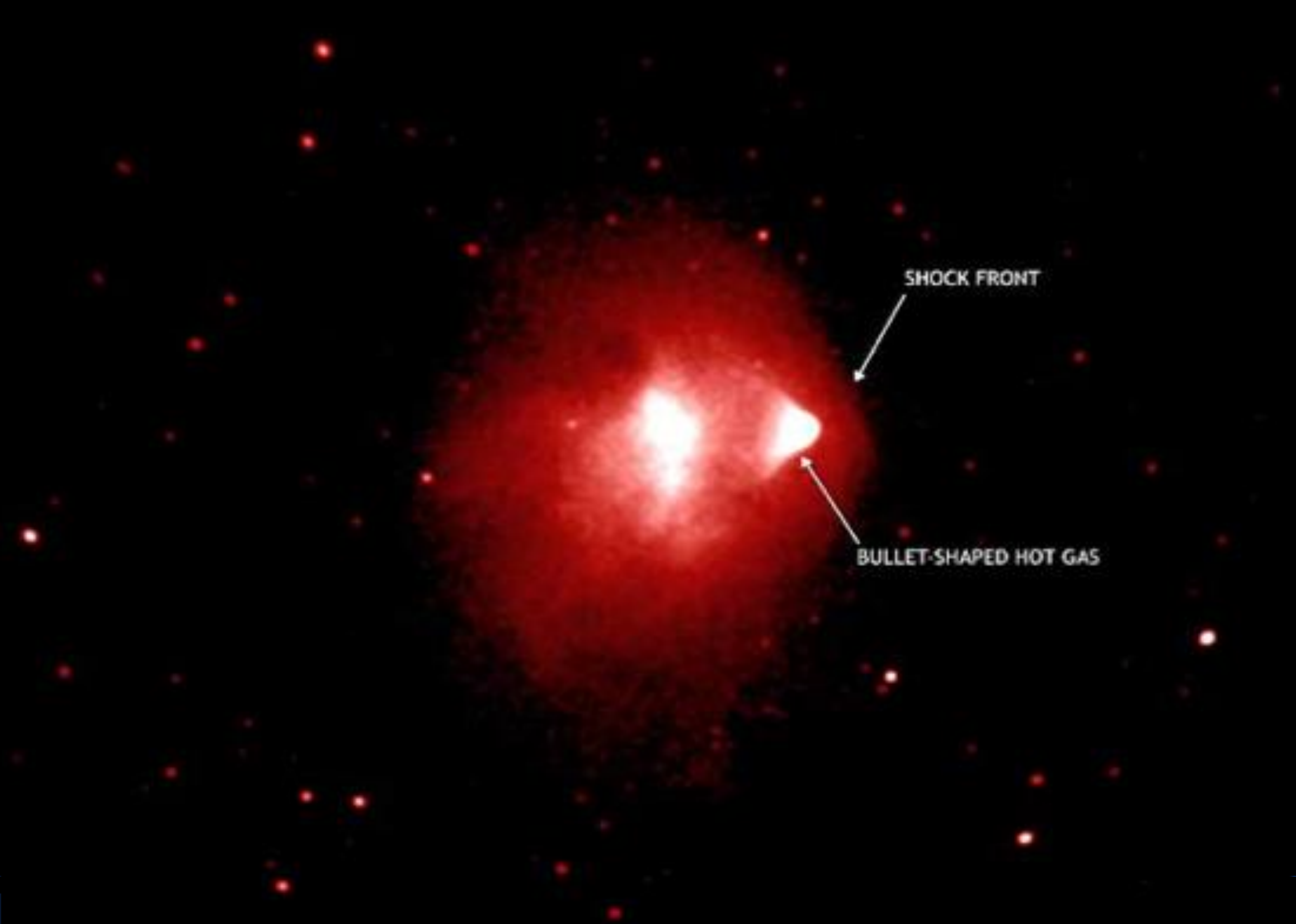


# My dream at the LHC: find dark matter

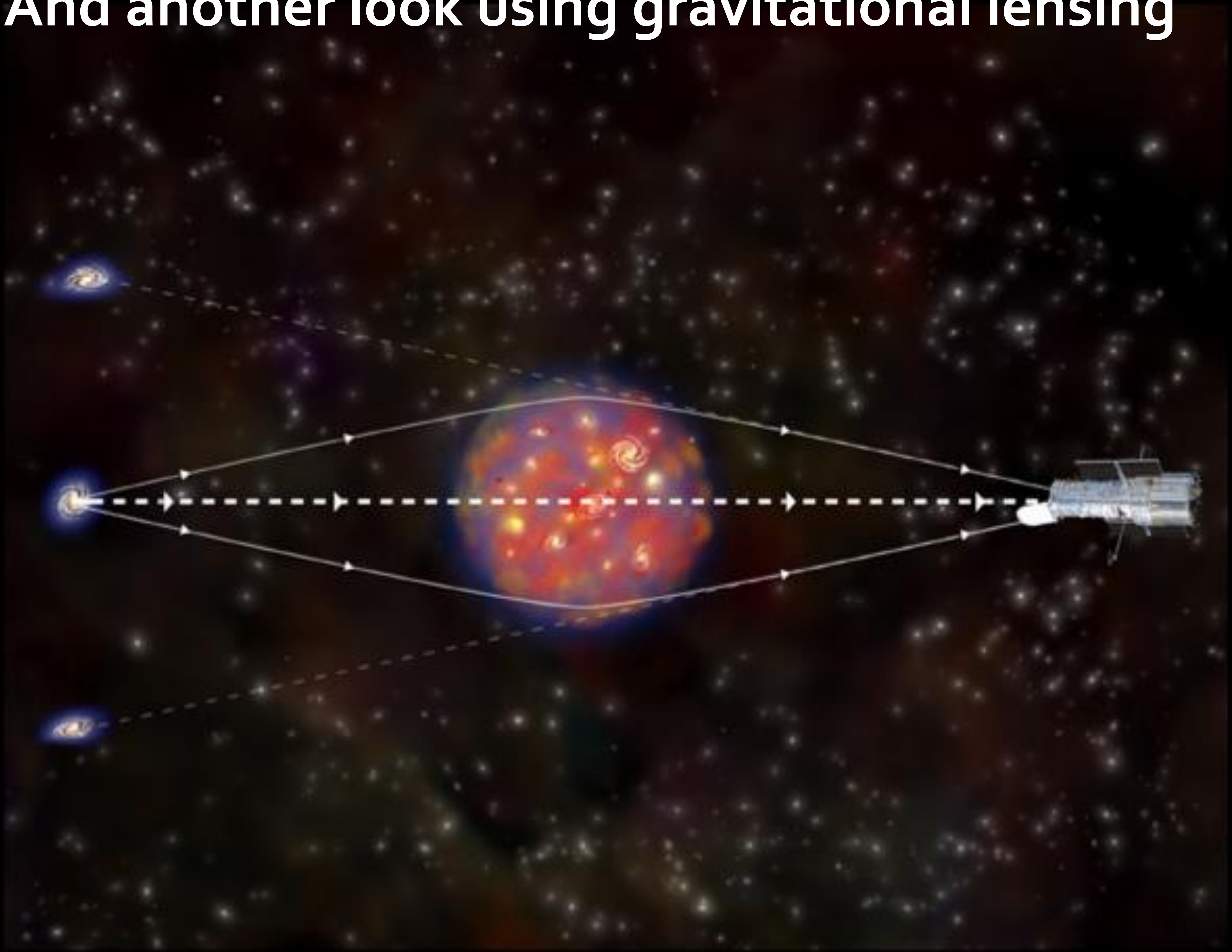
Why? Take a look at the stars (as here August 2006)



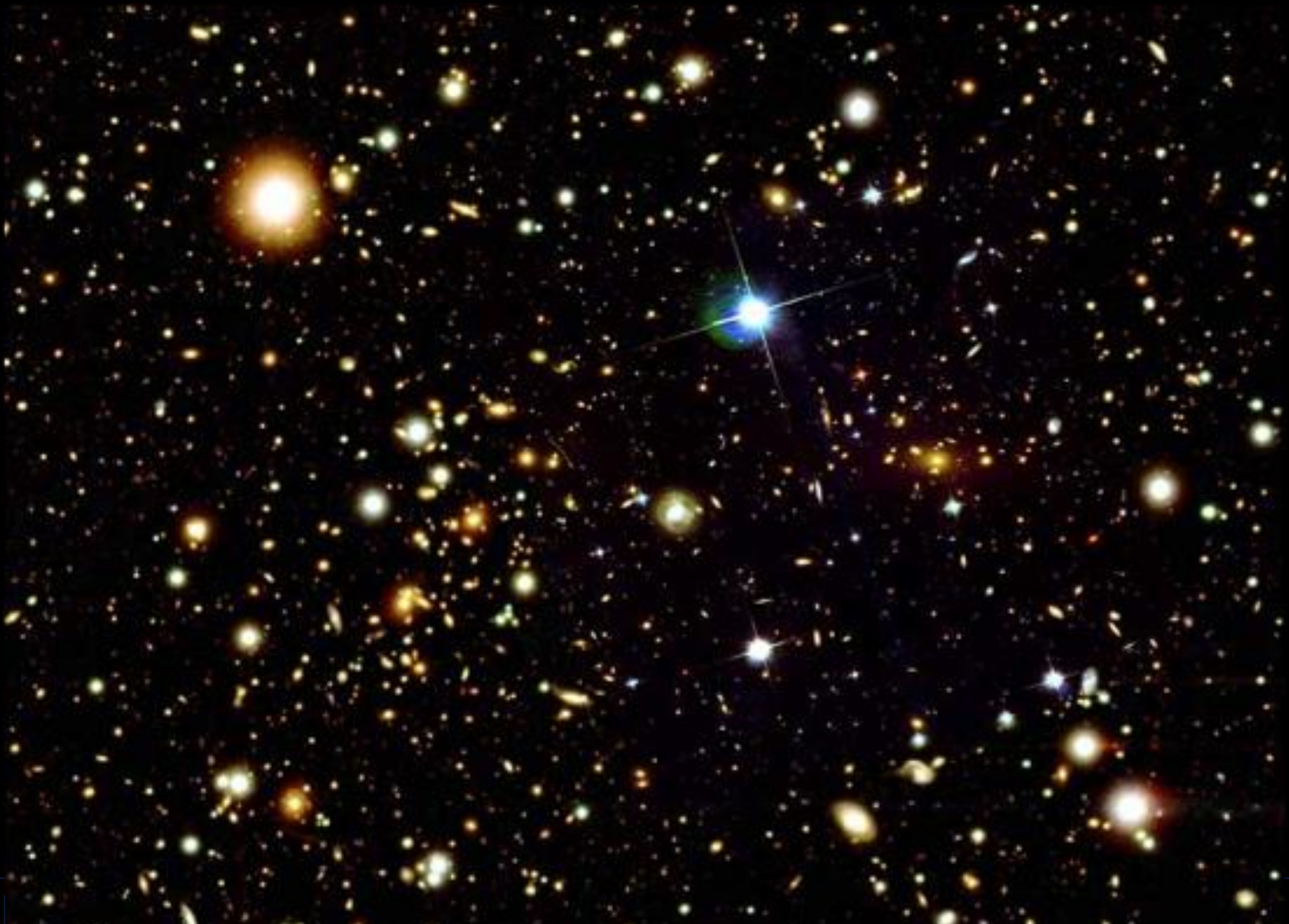
# Take another look at same region.
# This time at different wave length (hot gases)



# And another look using gravitational lensing

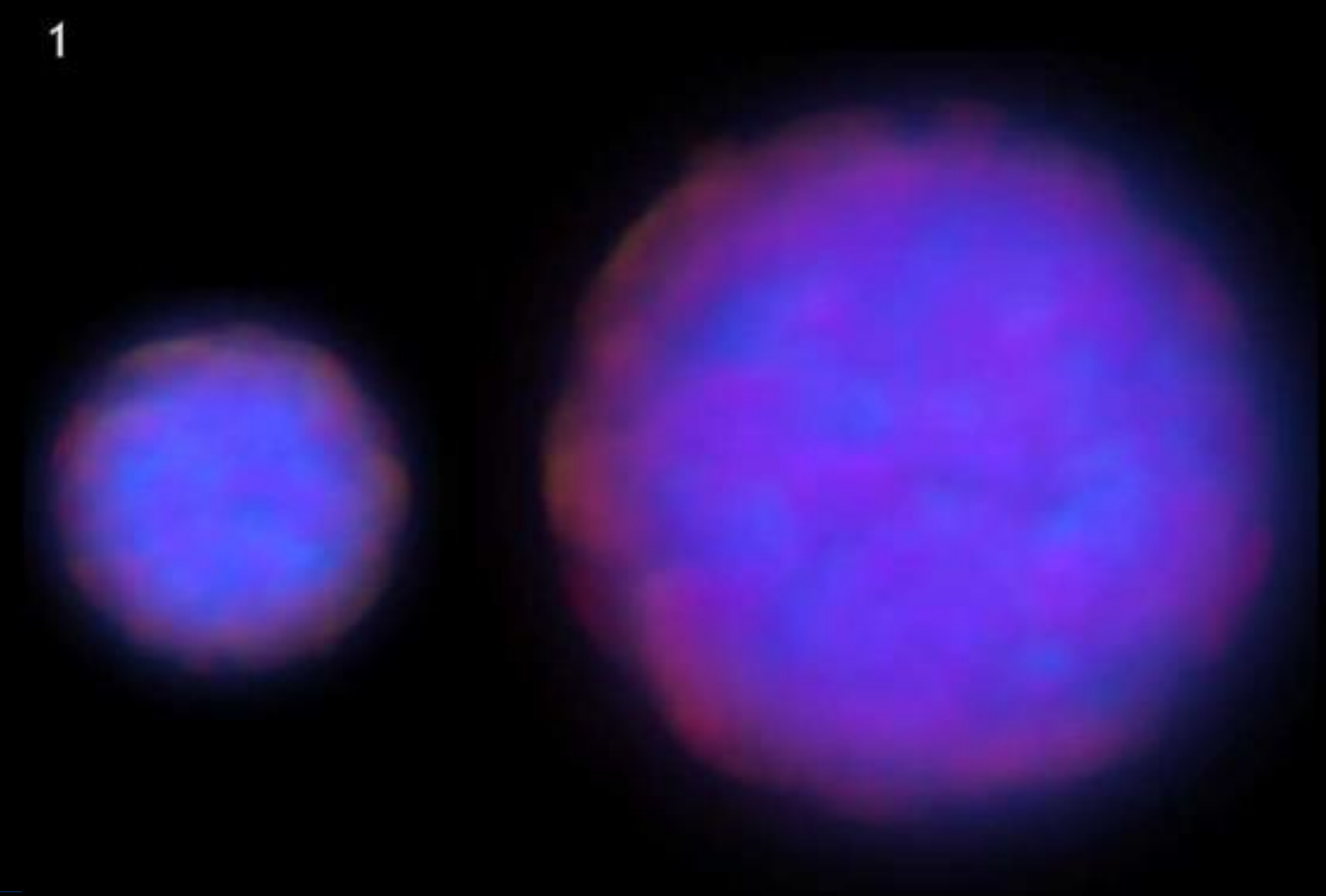


# Now overlay all three pictures



# WHOW!

# What could this be? A simulation of colliding galaxies



## What could this be? A simulation of colliding galaxies

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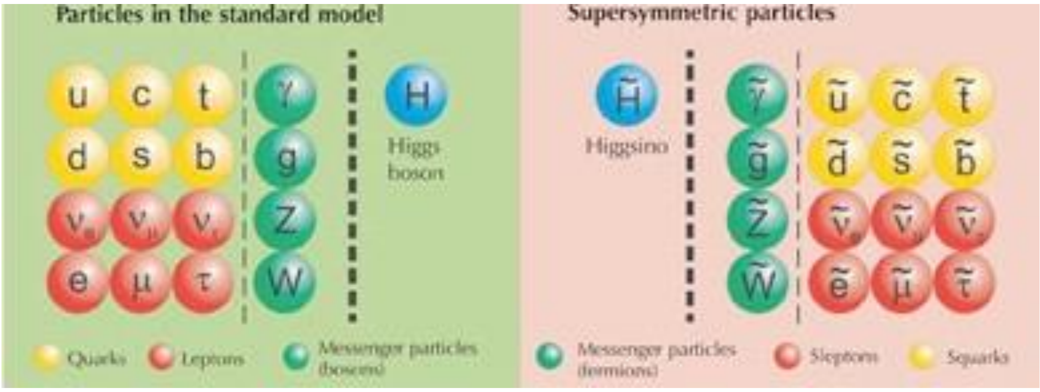
# Finding the Higgs particle at the LHC is just the start…

With the particles of the Standard Model we only know 5% of our universe.

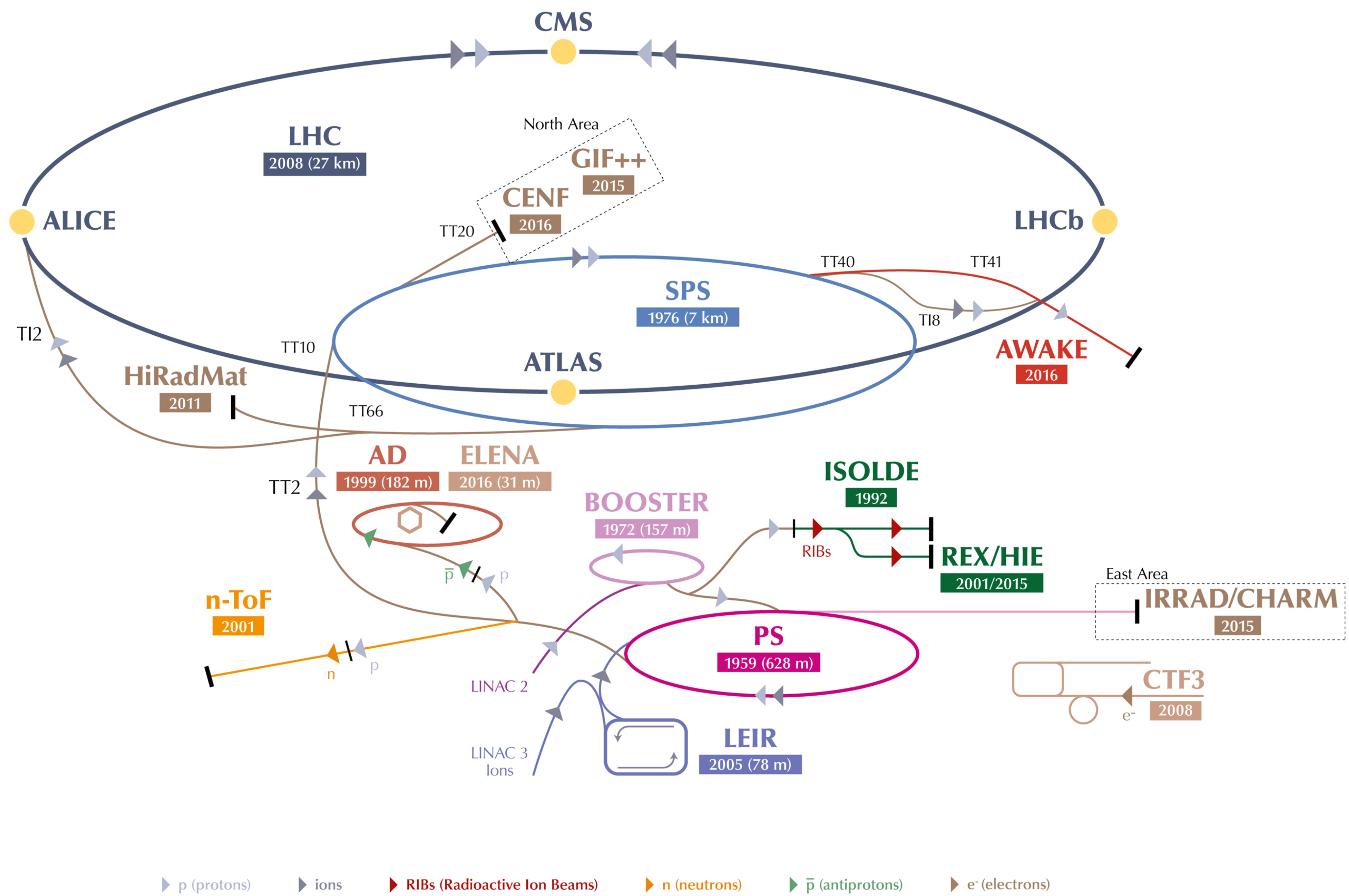



- What is Dark Matter?
- What is Dark Energy?

© Rocky Kolb

- Why did antimatter after Big Bang disappear?
- Are there an unknown unknowns?

# The CERN accelerator complex

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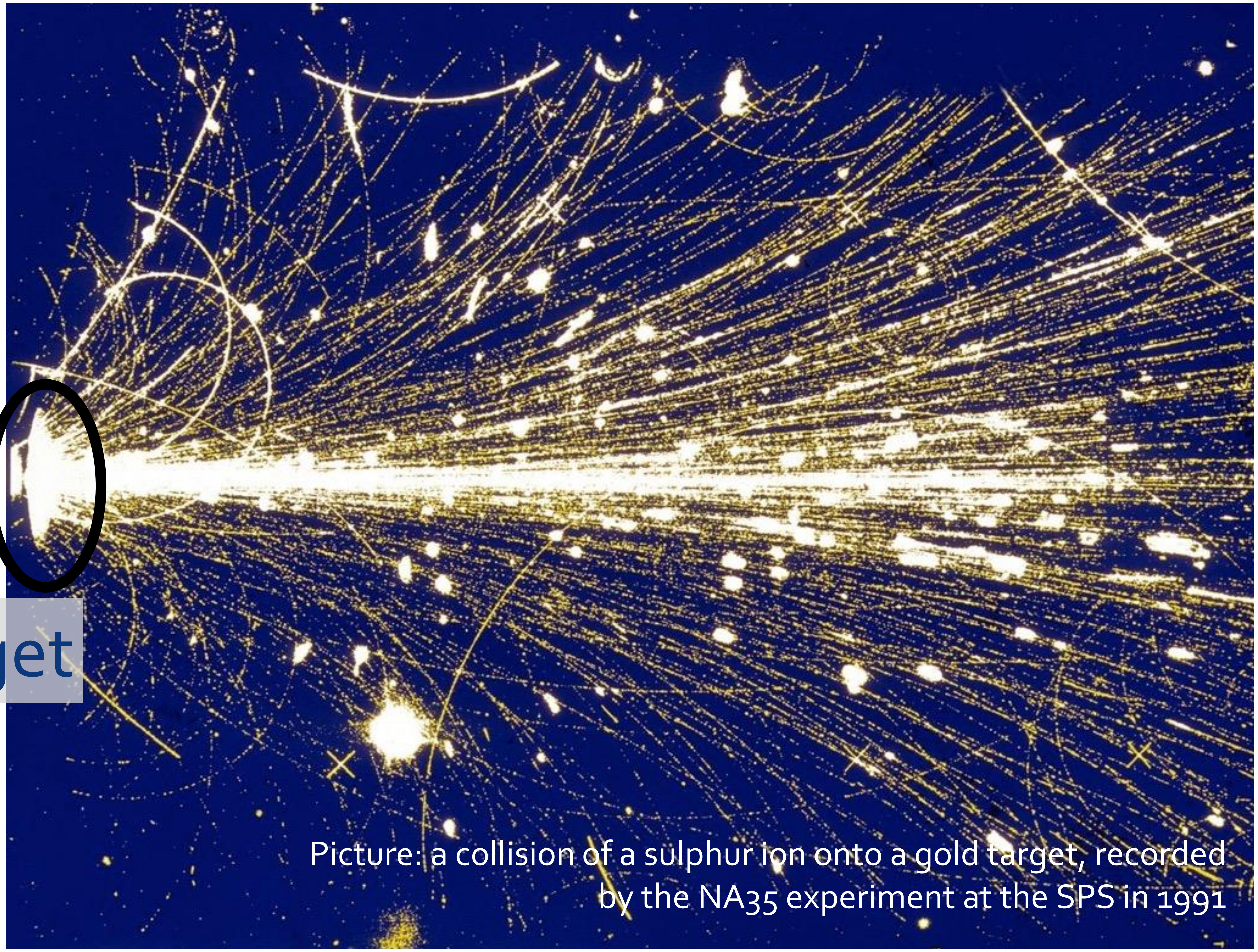
# Fixed-target experiments at the PS/SPS: "Physics beyond Colliders"

Protons from the accelerator hit a target

beam

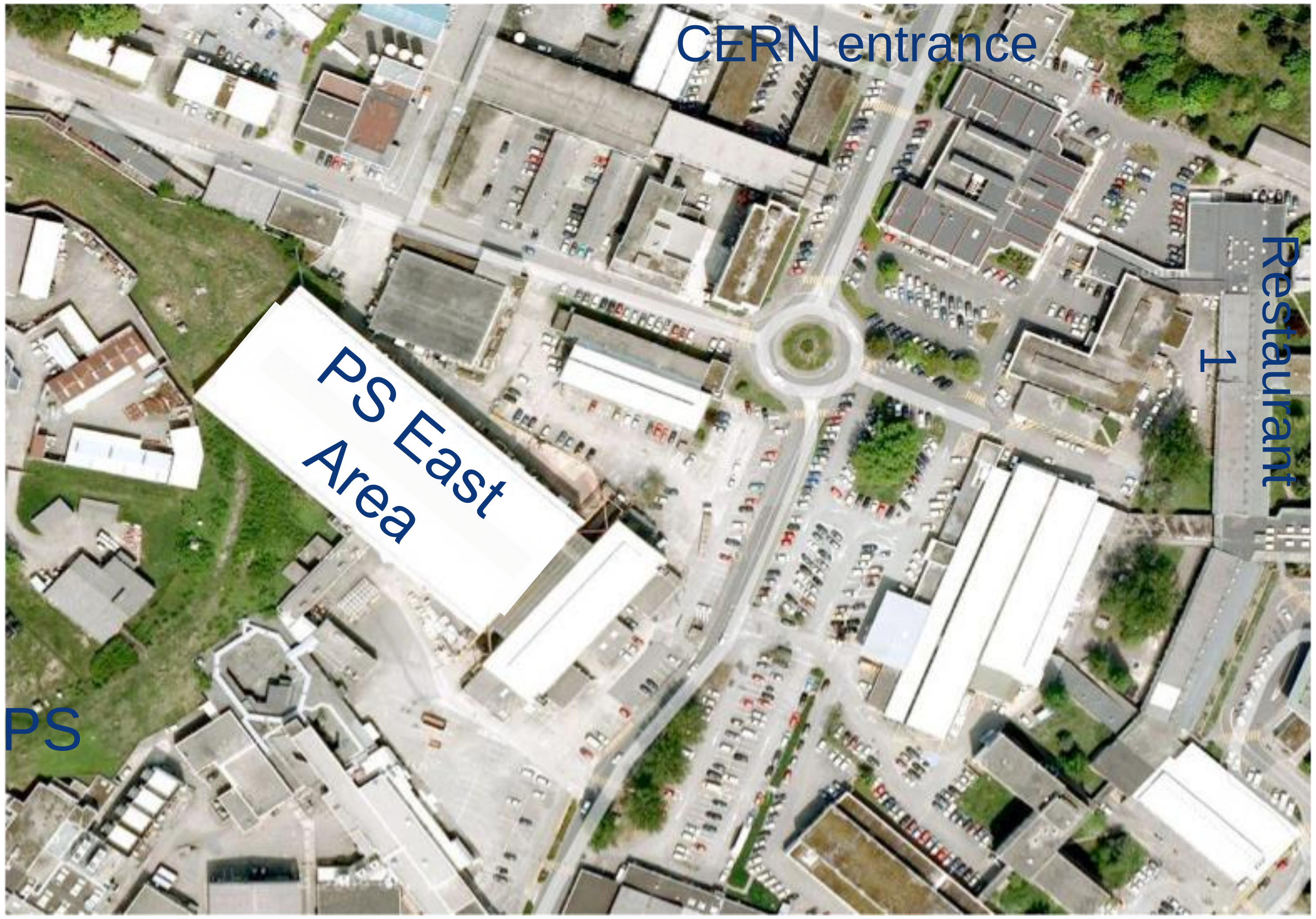
target



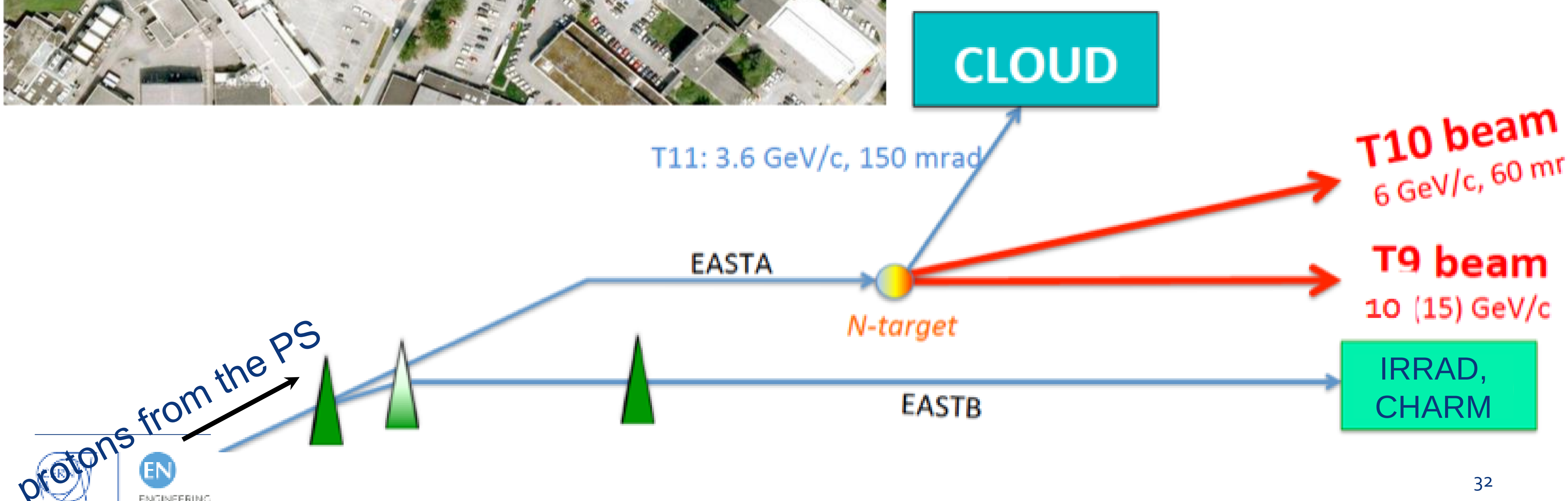
Picture: a collision of a sulphur ion onto a gold target, recorded by the NA35 experiment at the SPS in 1991

Spray of secondary, tertiary particles get out of the target. Particles (electrons, muons, pions, antiprotons…) are selected using magnets and/or absorption foils

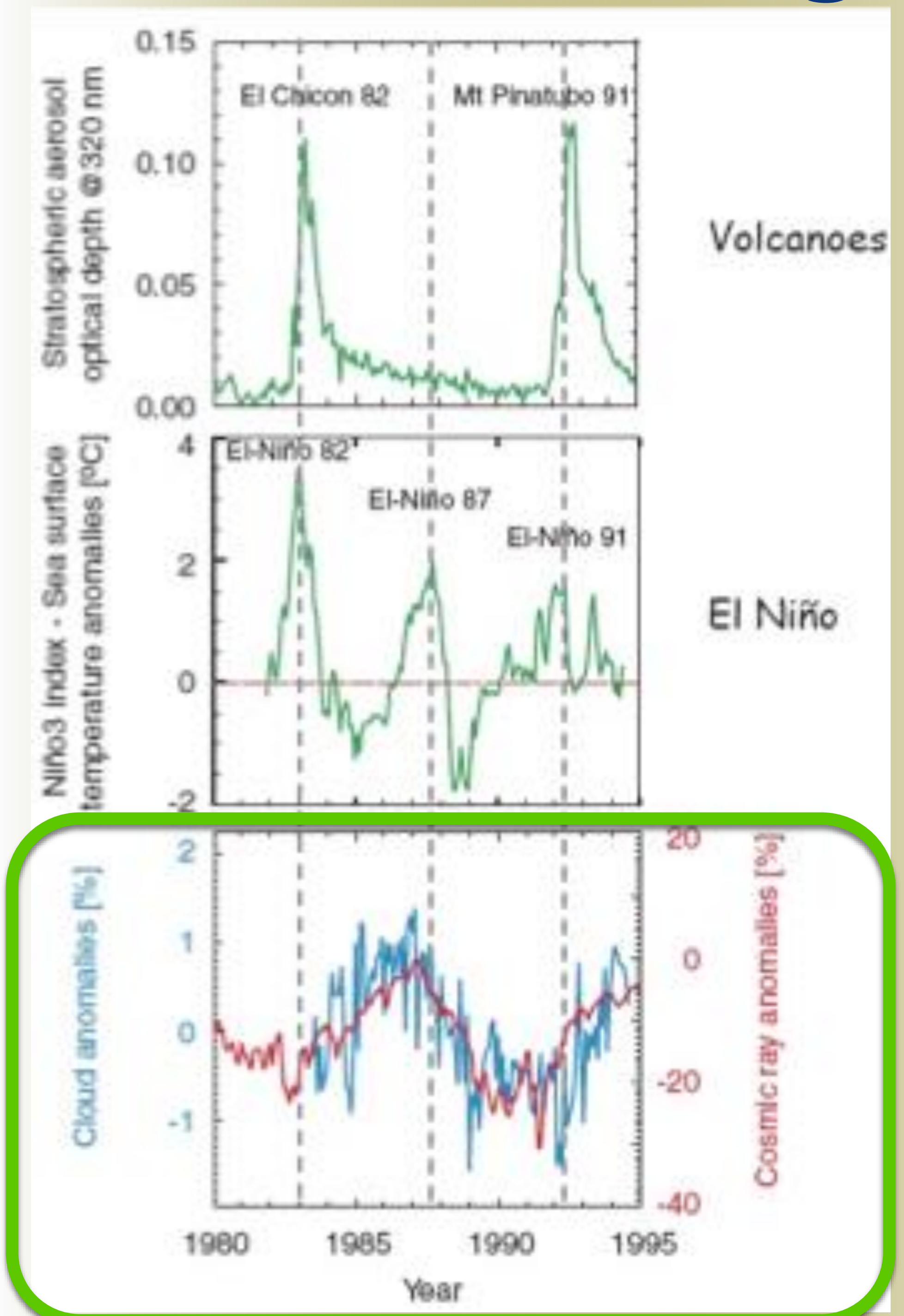
# The PS East Area

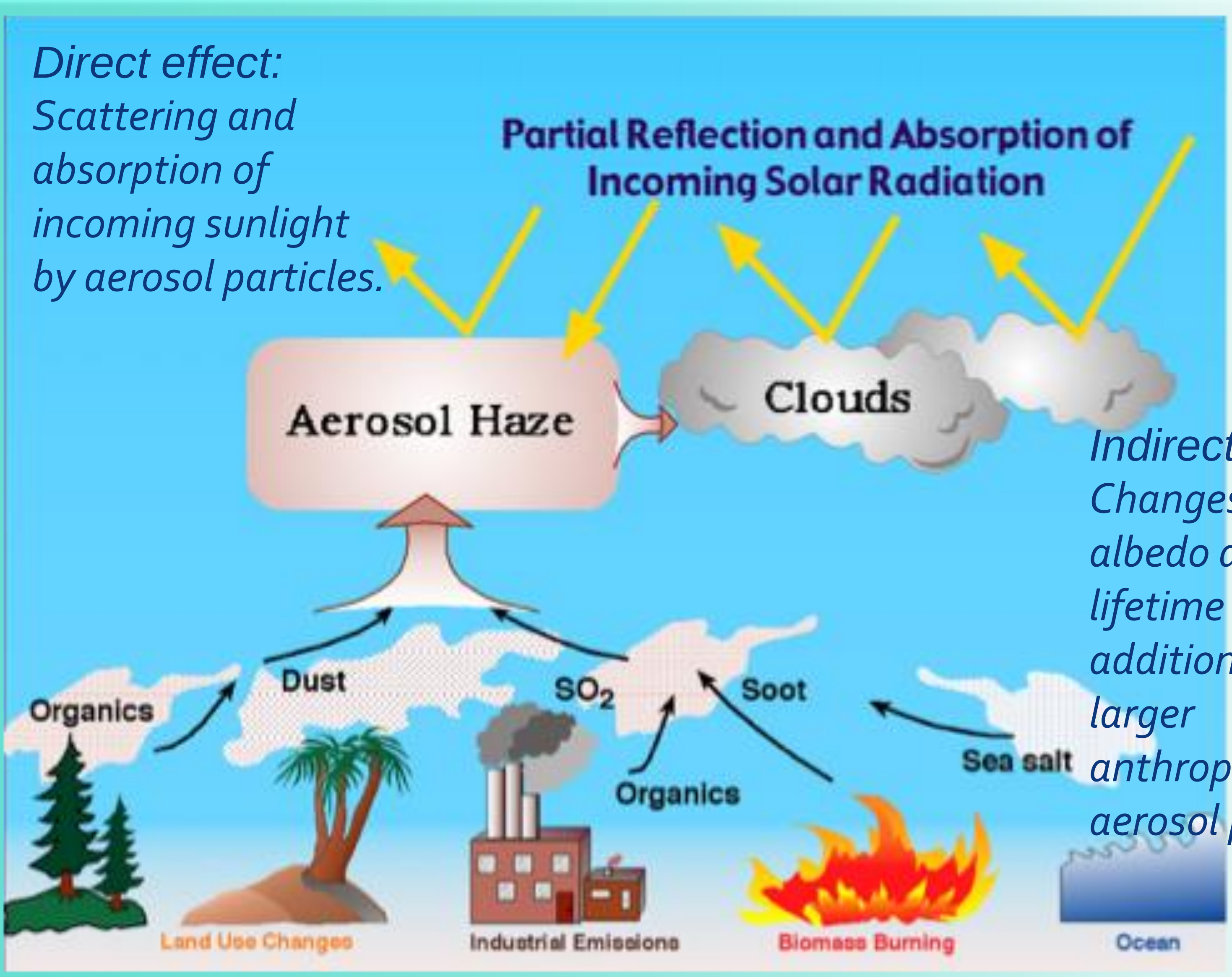



One of the oldest complexes at CERN, hosts 2 irradiation facilities IRRAD and CHARM, the CLOUD experiment and 2 flexible test beams and up to 2012 also the DIRAC experiment



# Understanding clouds means understanding of climate



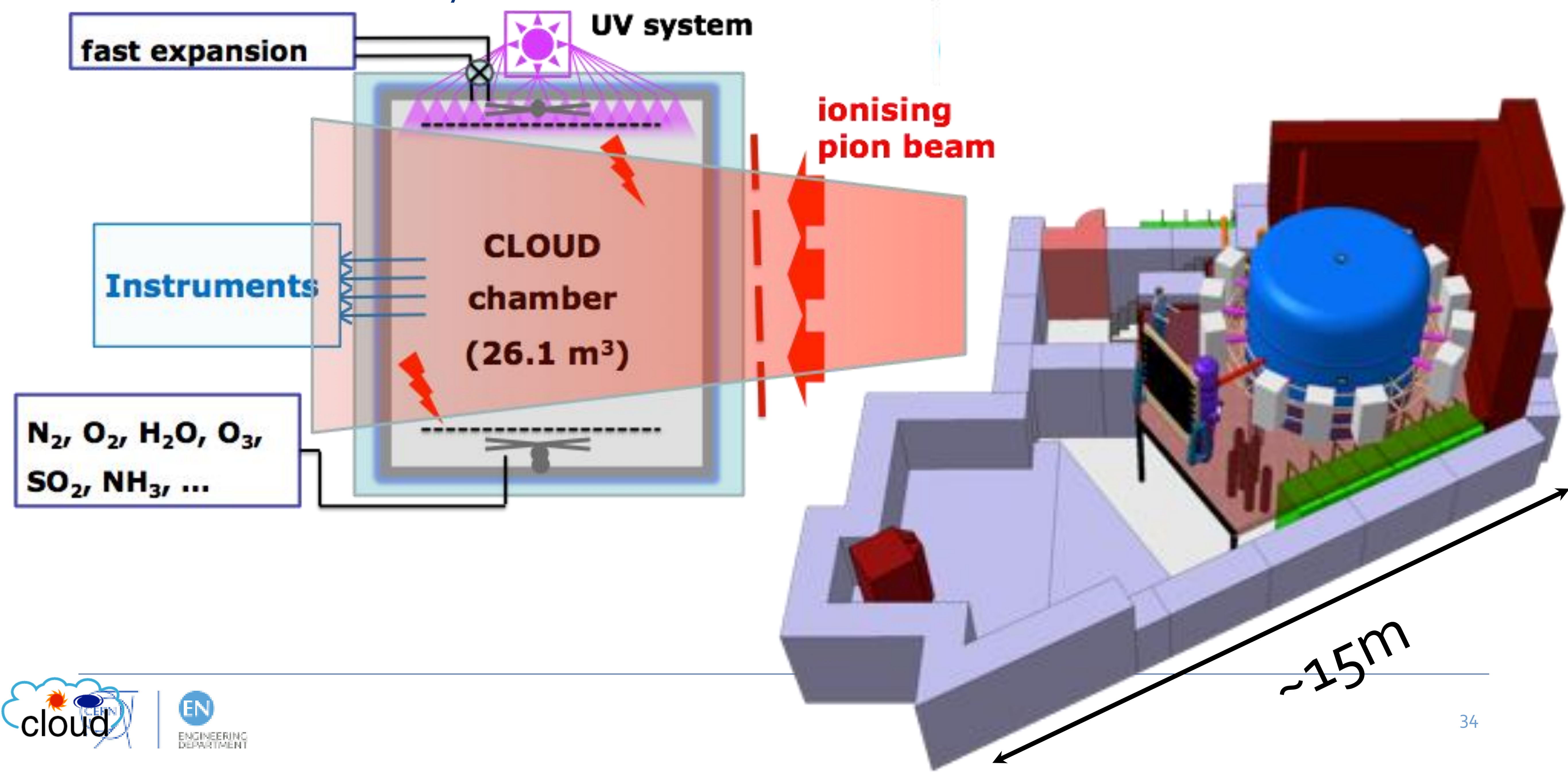

*Direct effect:*
*Scattering and absorption of incoming sunlight by aerosol particles.*

*Indirect effect*
*Changes of cloud albedo and cloud lifetime through additional and larger anthropogenic aerosol particles.*

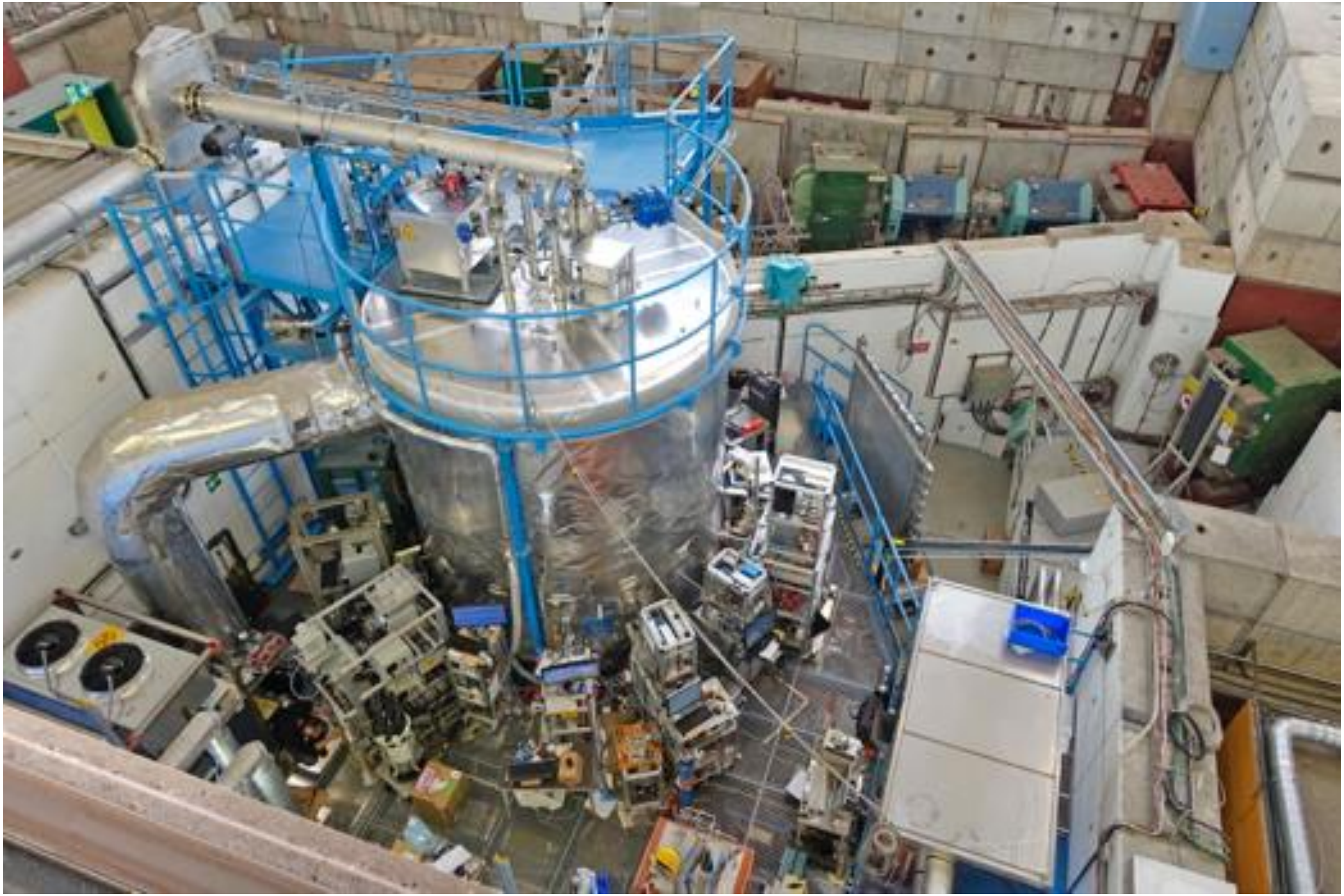
But how do droplets and clouds form???

# CLOUDs at CERN

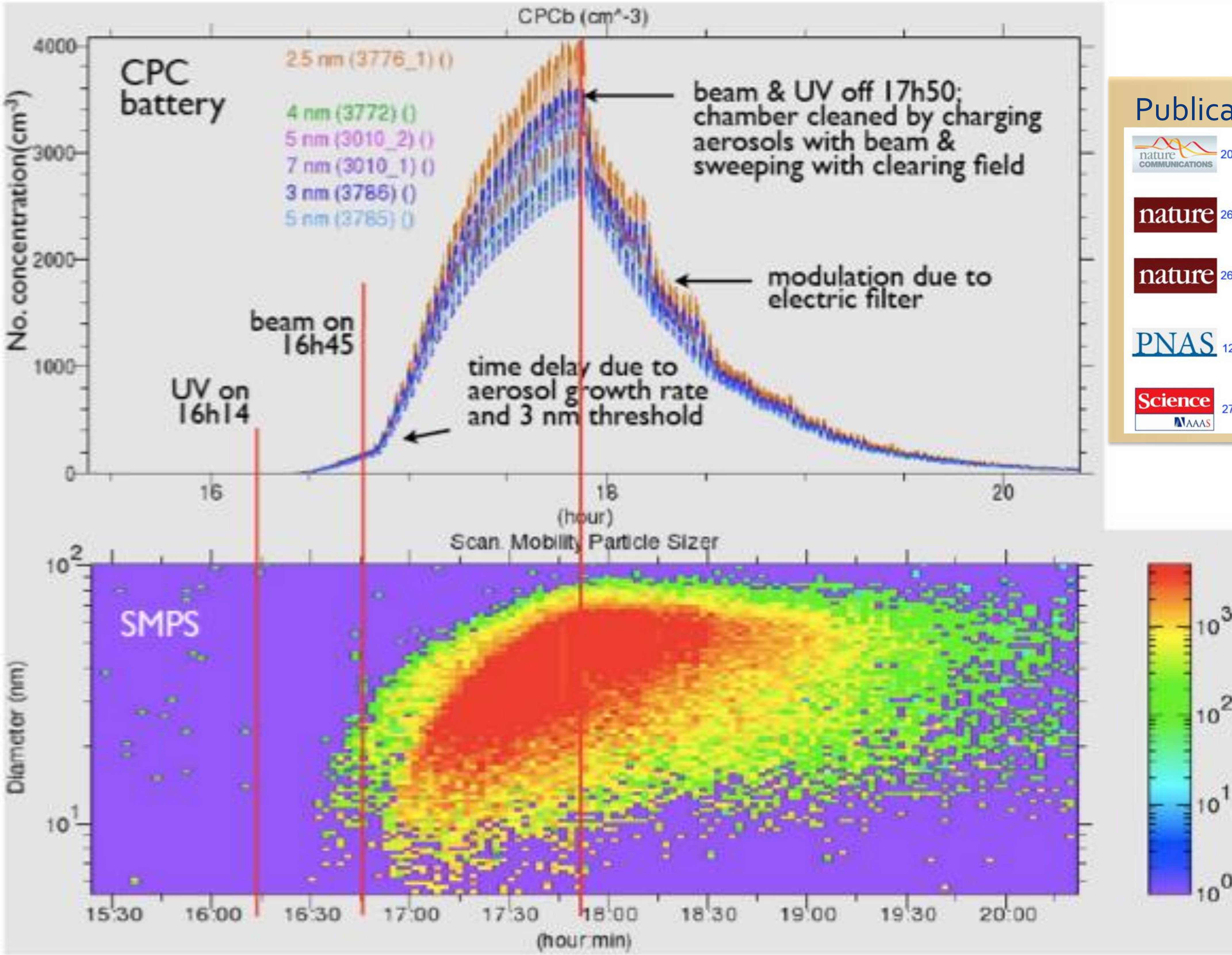
- Simulate atmosphere in a cloud chamber (incl. gas composition, temperature, pressure…)
- use 3.6 GeV pions from the PS, spread over 1.8x1.8m, 1-100kHz rate, to simulate cosmic rays.



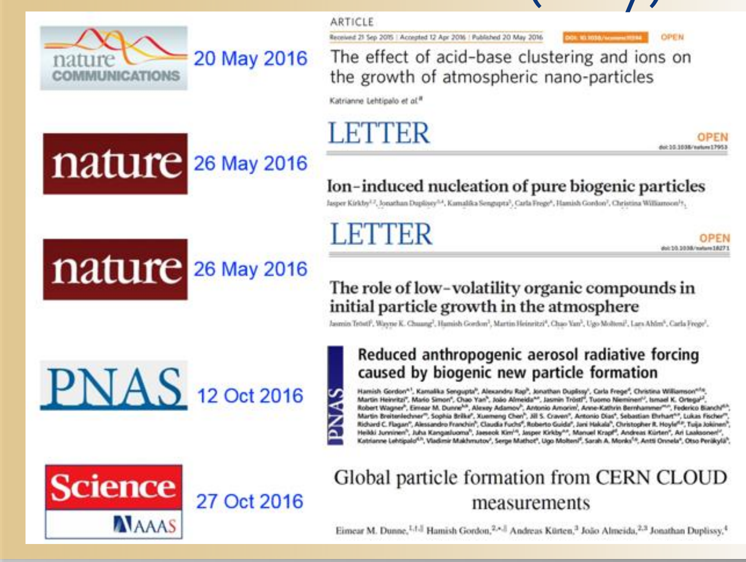
# The CLOUD experiment in T11



# A typical CLOUD run




Publications in 2016(only)



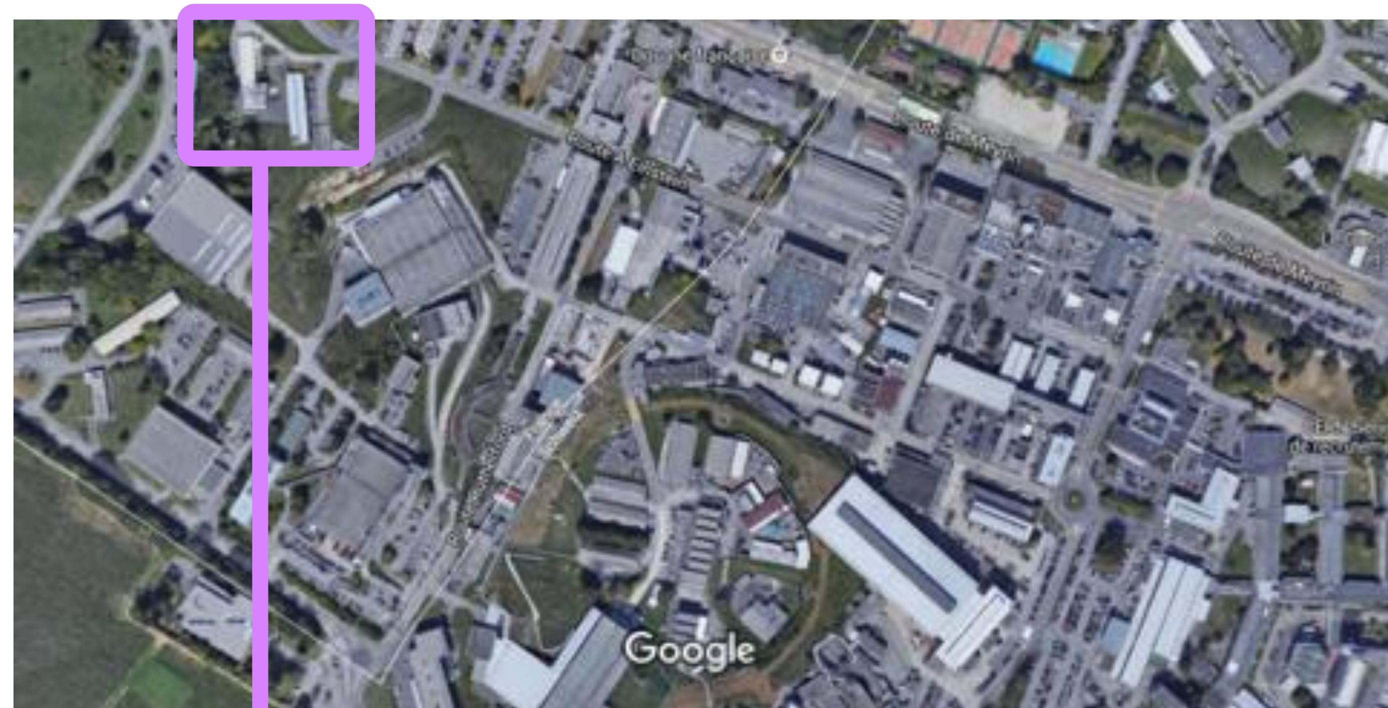
# Facilities at the PS: nTOF

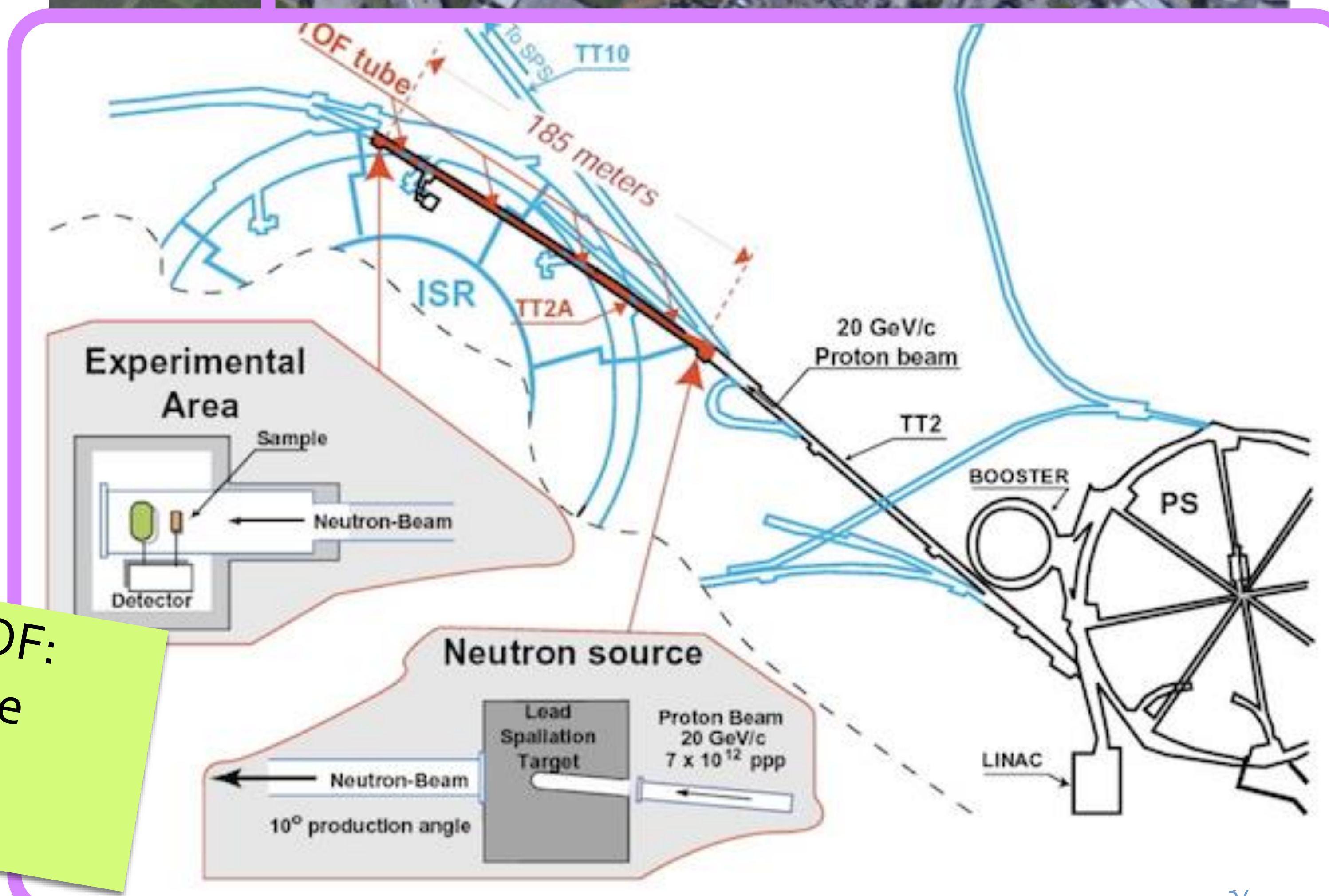
nTOF (neutron time-of-flight):
facility providing neutrons generated by PS proton beam at 20GeV hitting a lead spallation target.
The initially fast neutron spectrum is slowed down by the lead target and by water slab, creating a wide neutron spectrum, spanning an energy range from meV up to GeV.

Experimental area at a distance of 185 m from the target.

More info:https://ntof-exp.web.cern.ch/ntof-exp/

Scientific questions investigated by nTOF:
e.g. how heavy elements in the universe are formed?
(→ study fast neutron capture)

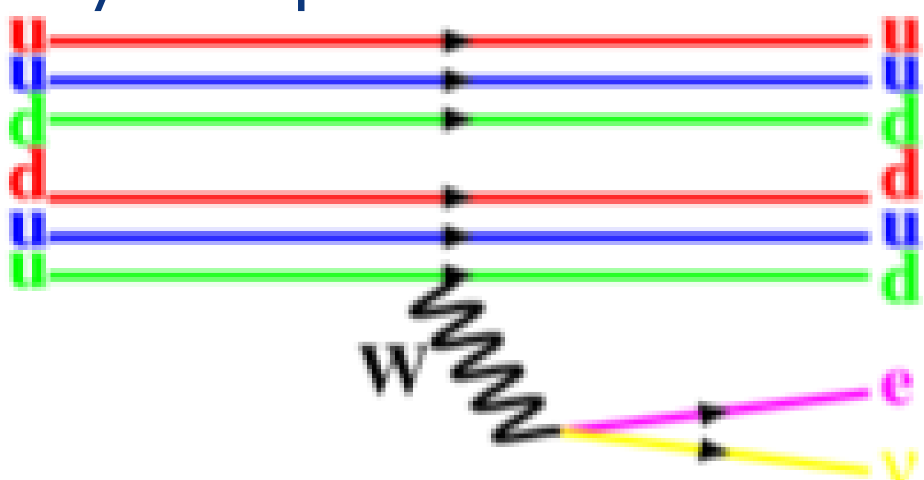


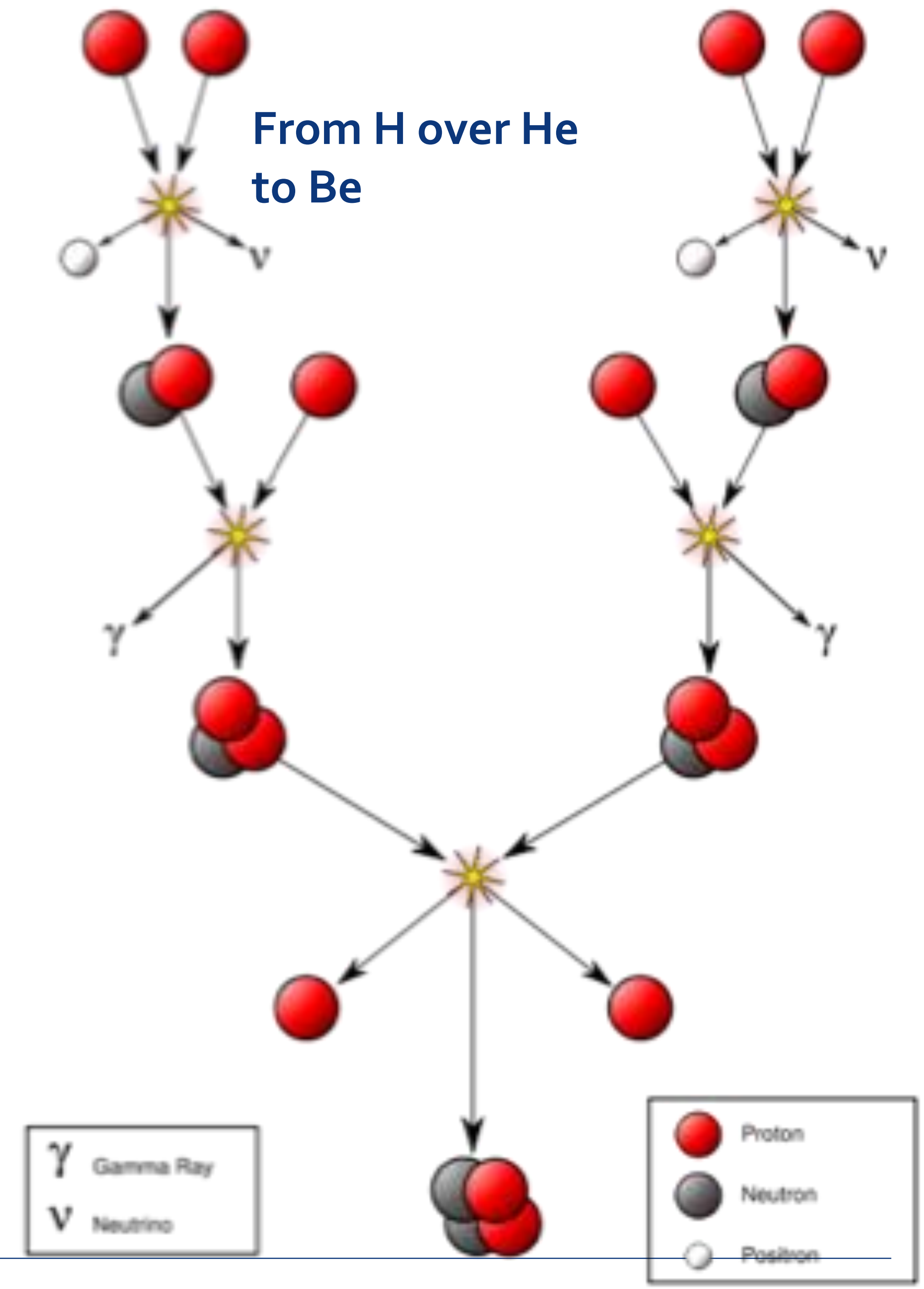
# Elements in the universe

Elements up to iron are produced in stars by fusion
→ fundamental process:

β+ decay of a proton to a neutron



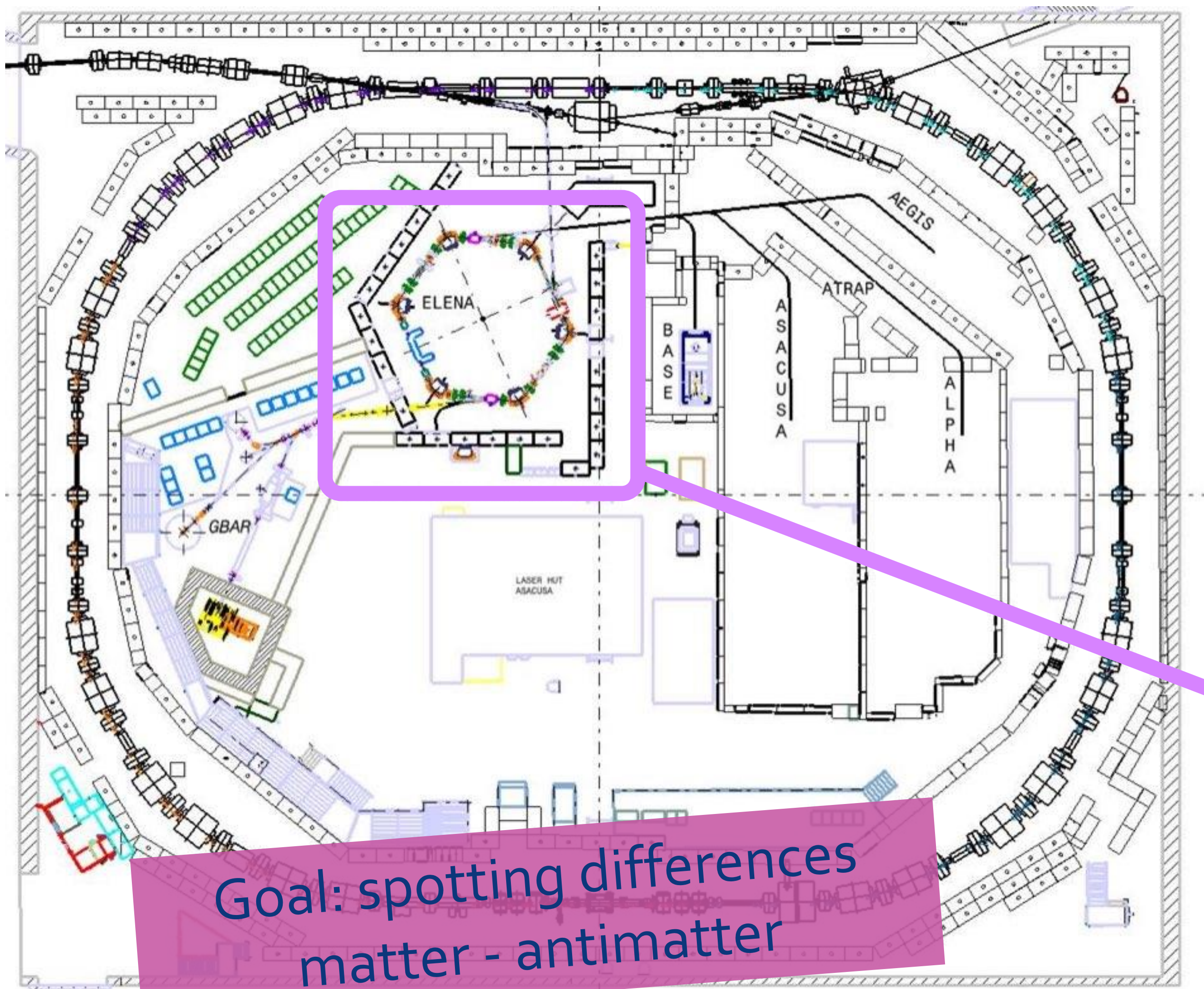

From H over He to Be




For elements bigger than Fe(26 protons, 30 neutrons) this process stops
→ difficult for a proton (=charged particle) to enter the atom and reach nucleus

Where and how are heavy elements produced?

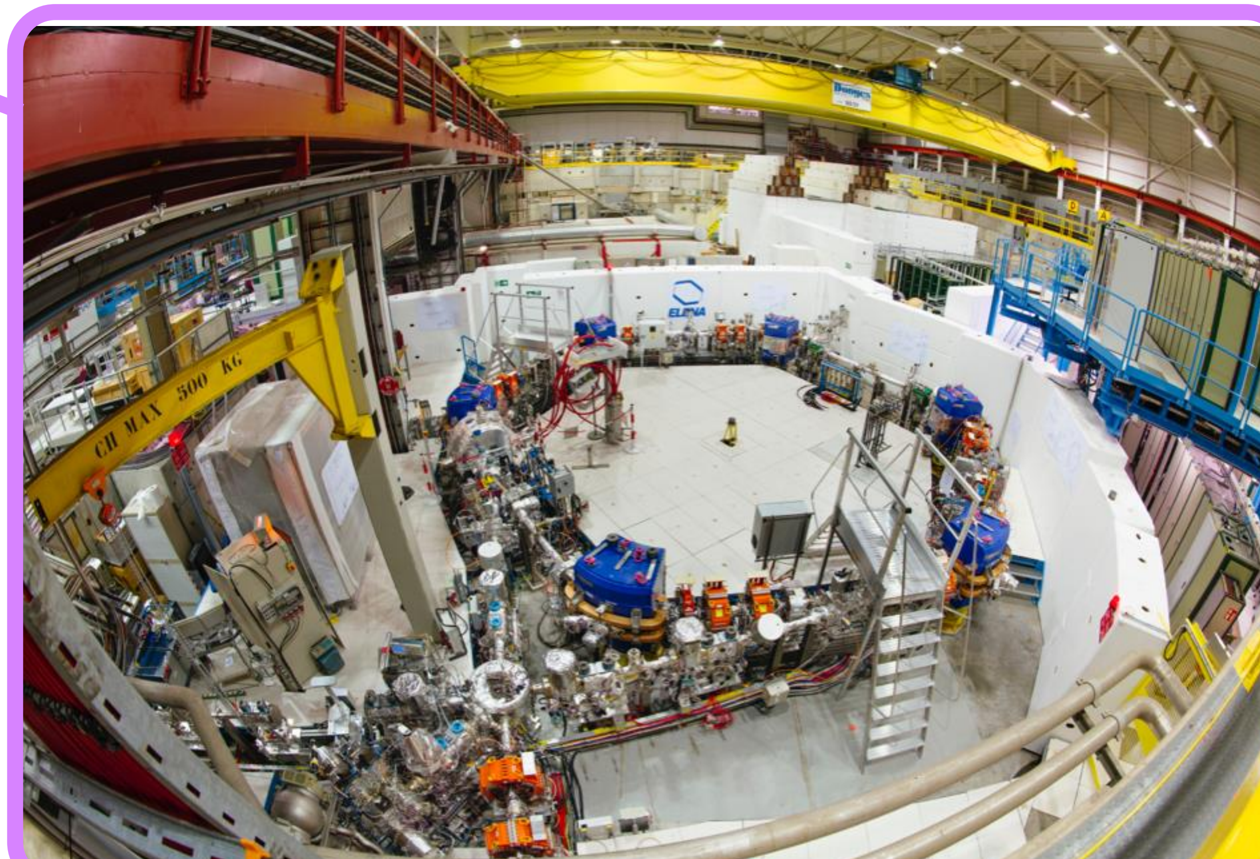
# At CERN PS: the Antiproton Decelerator AD




Goal: spotting differences matter - antimatter

AD: low-energy antiprotons (5.3MeV/c, $3 \times 10^7$ per cycle) for studies of antimatter.

Upgrade: additional ELENA (Extra Low ENergy Antiproton) ring providing 100 keV antiprotons.
Experiments: ~100 times more particles per unit time.




AD Experiments:
ATRAP (spectroscopy and antiproton magnetic moment), ALPHA (spectroscopy), ASACUSA (spectroscopy, atomic and nuclear collision cross sections),
BASE (antiproton magnetic moment), AeGIS, GBAR and ALPHA-g (antimatter gravity experiments)

# The BASE experiment

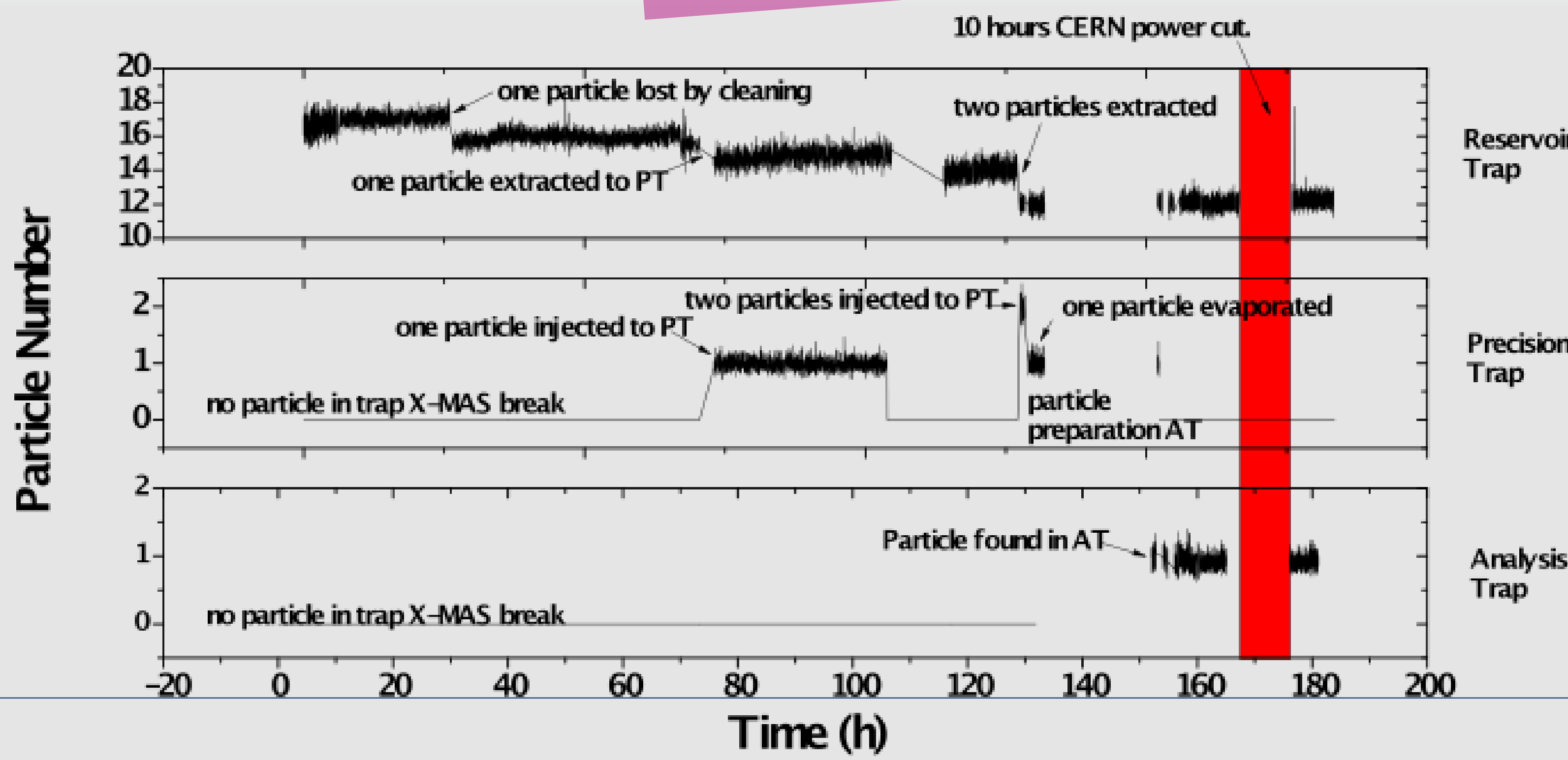
Precise comparisons of the fundamental properties of antiproton and p by measuring the cyclotron and Larmor frequencies of single trapped (anti)protons (optionally H-).

Goal until 2018 : measurement of magnetic moment of the (anti)proton with precision of $\delta g/g$ 10−9 (~factor1000 w.r.t. ATRAP measurement, Phys. Rev. Lett. 110, 130801 – March 2013);

- ➞ Letter of Intent to SPS and PS Experiments Committee (SPSC) June 2012, Technical Design Report to SPSC January 2013;
- ➞ Recommended by SPSC and approved by the CERN Research Board: June 2013
- ➞ Operation and first results: 2014.

Example on how fast things can move forward!

*N.B.: in 2016 BASE was performing experiments with antiprotons caught in November 2015.*



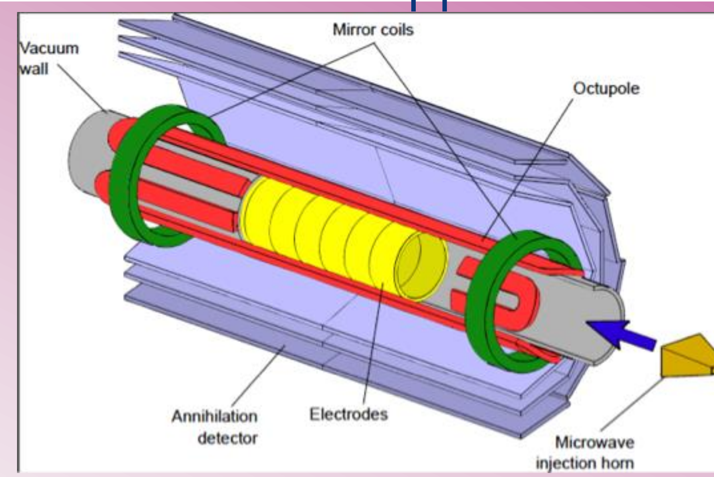

C. Smorra et al., A reservoir trap for antiprotons, Int. Journ. Mass. Spec. 389, 10 (2015).

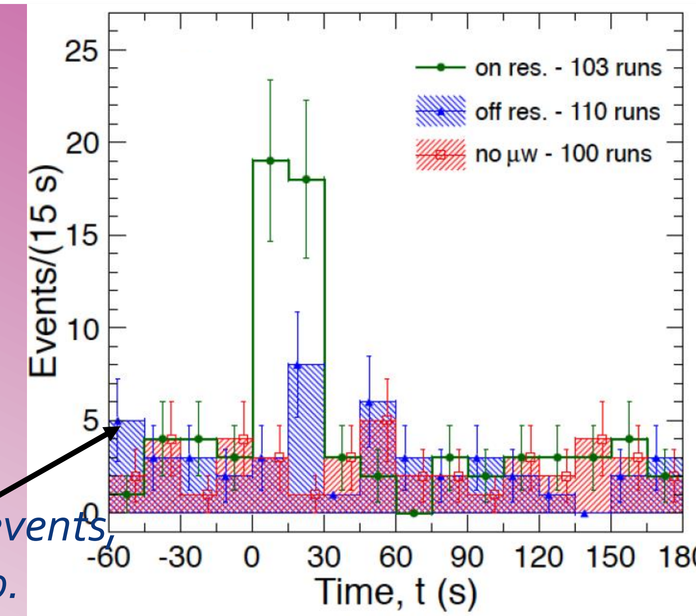
# ASACUSA, ALPHA, ATRAP: spectroscopy

Essentially similar methods but
ATRAP and ALPHA: anti-hydrogen at rest;
ASACUSA: beam of anti-hydrogen for hyperfine transition studies in low magnetic fields.
Examples:

- ALPHA: very first spectroscopy of an anti-matter atom demonstrating the observation of resonant quantum transitions in anti-hydrogen by manipulating the internal spin state;

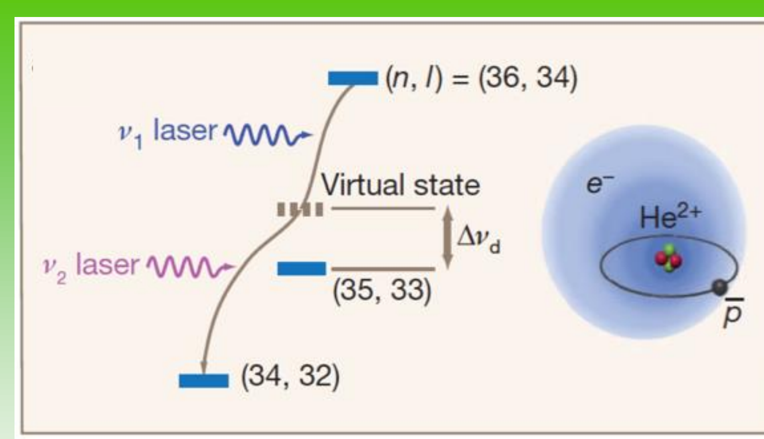
ALPHA apparatus

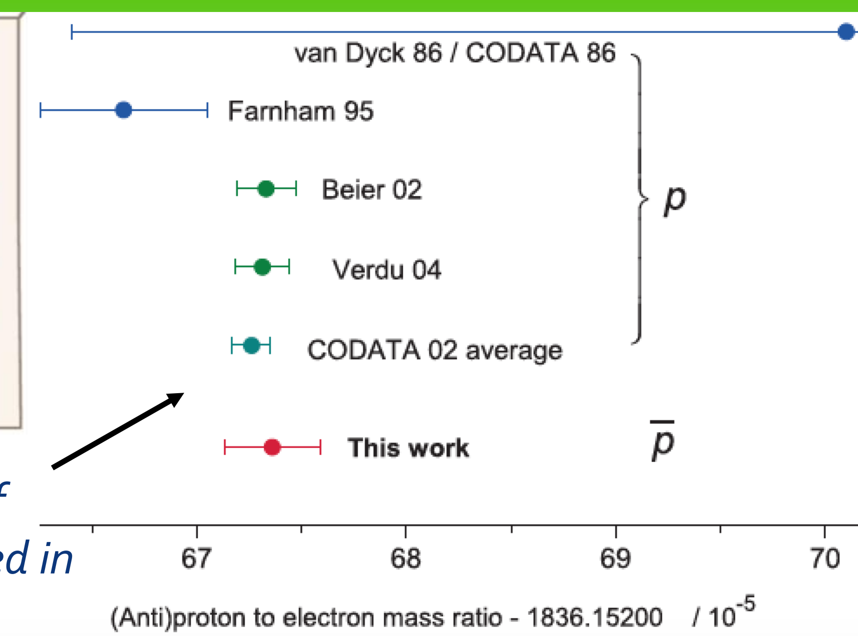



*Number of 'appearance mode' annihilation events, microwave power is first applied at time t = 0.*

- ASACUSA: two-photon laser spectroscopy of antiprotonic helium and precise measurement of antiproton-to-electron mass ratio;



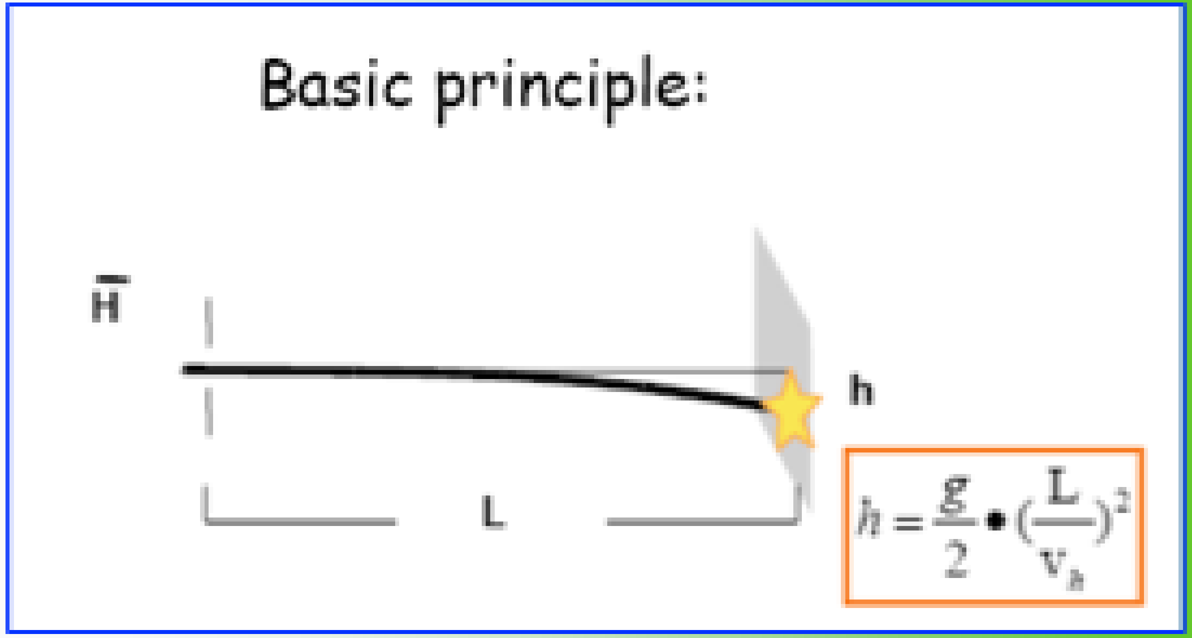

*Agreement within a fractional precision of <1.3 p.p.b. with the p-to-e values measured in previous experiments.*

# The ALPHA experiment

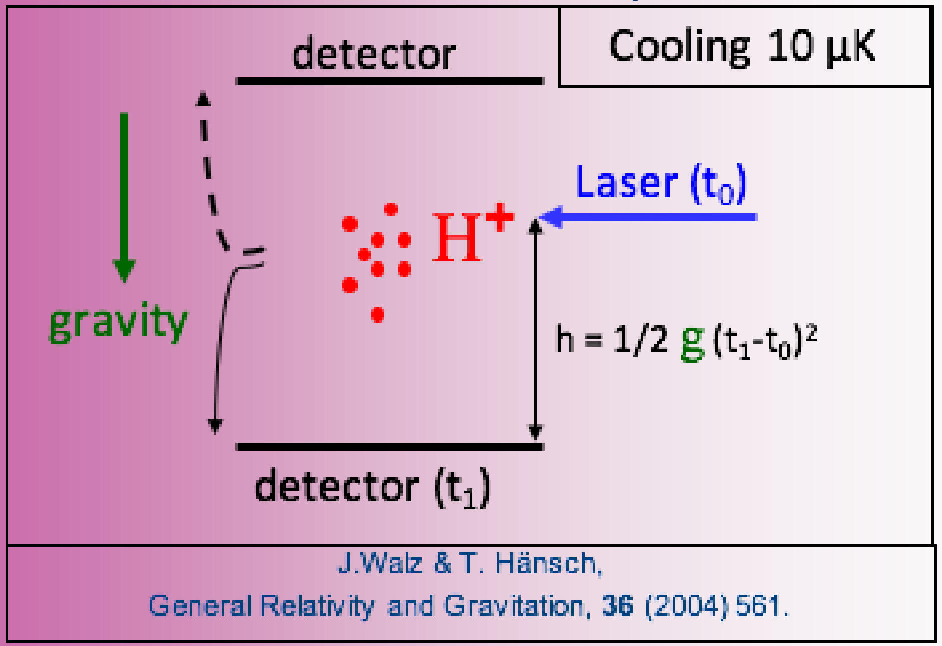
# Antimatter gravity: AeGIS, GBAR, ALPHA-g

- Comparing the behaviour of hydrogen and anti-hydrogen in the earths gravitational field


AeGIS:
measure deflection of anti-hydrogen beam




GBAR, ALPHA-g:
measure differences in number of annihilations in bottom and top detectors



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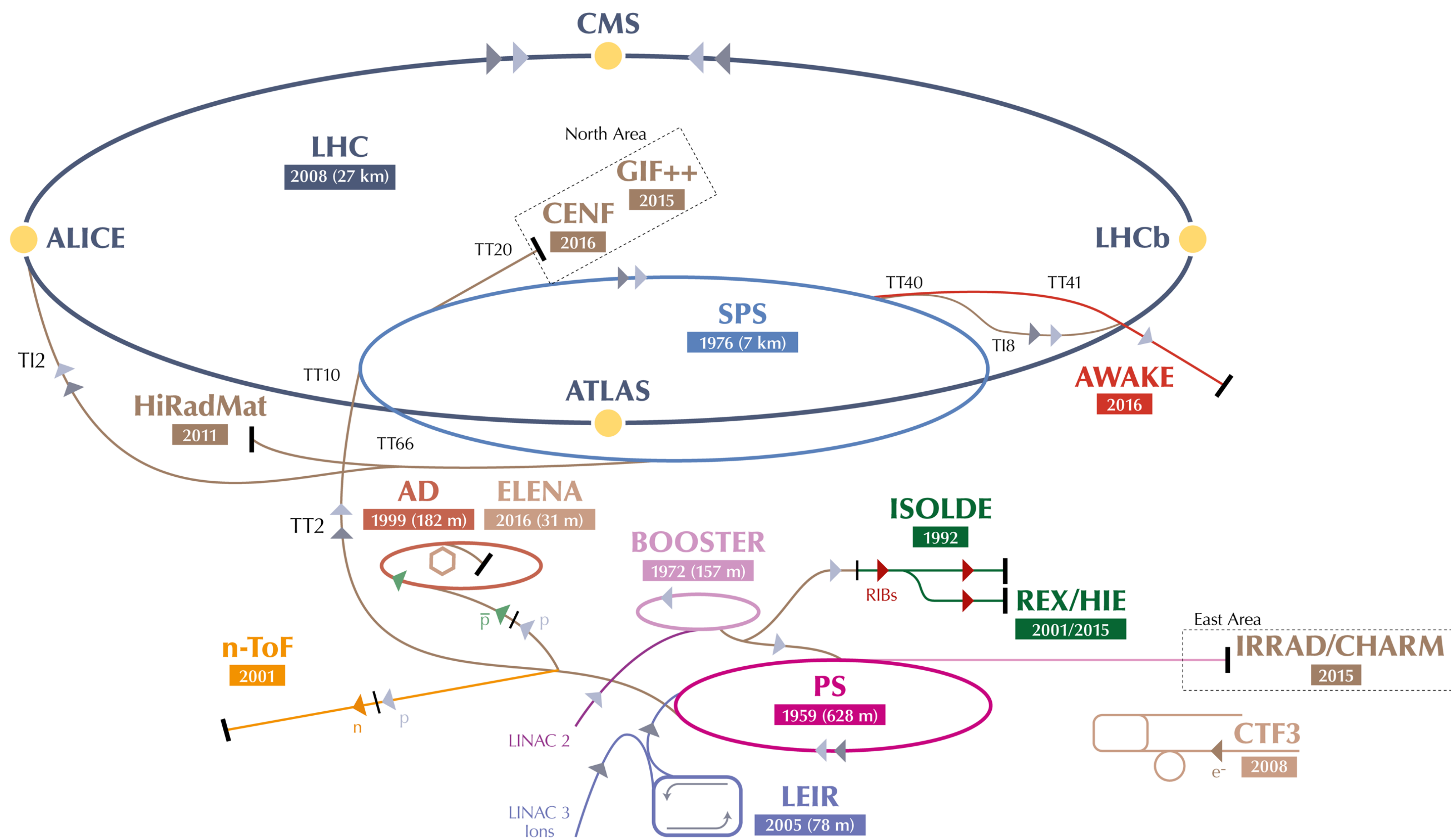


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**LHC** Large Hadron Collider **SPS** Super Proton Synchrotron **PS** Proton Synchrotron **AD** Antiproton Decelerator **CTF3** Clic Test Facility

**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

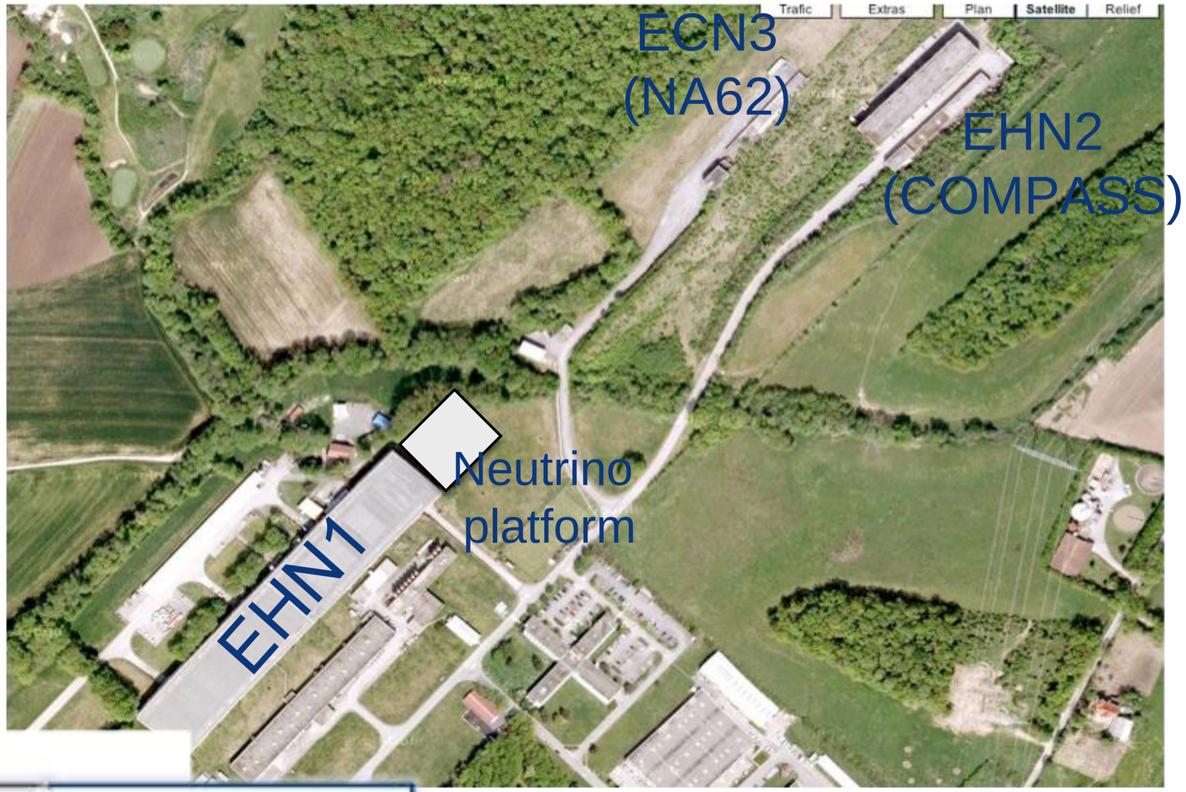
**CHARM** Cern High energy AcceleRator Mixed field facility **IRRAD** proton IRRADiation facility **GIF++** Gamma Irradiation Facility

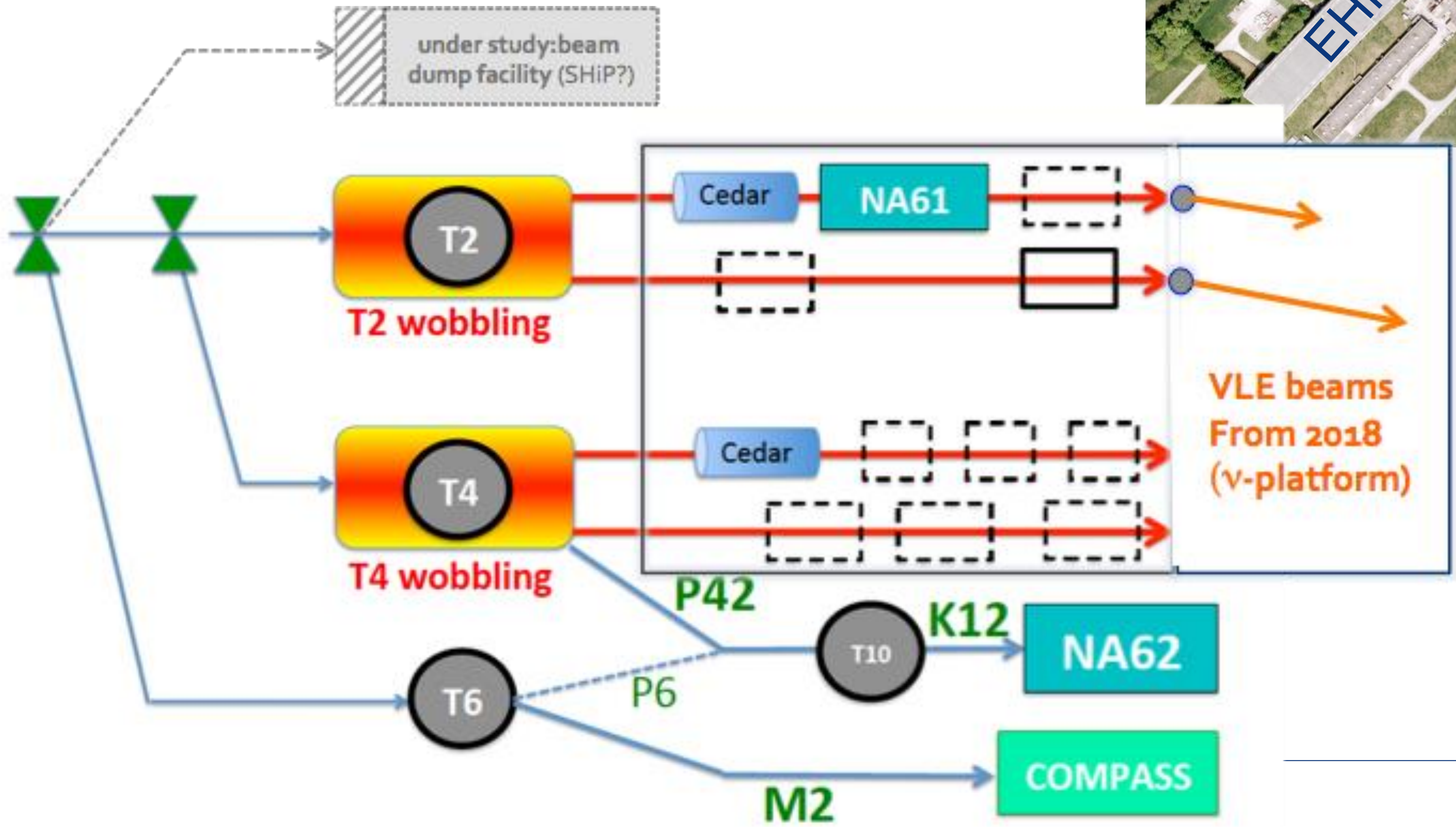
**CENF** CErn Neutrino platForm

CERN | EN ENGINEERING DEPARTMENT

# The SPS North Area

The North Area beams H2, H4, H6, H8, P42, K12 and M2 are produced by a high-intensity primary proton beam, impinging on each of the three primary targets T2,T4,T6 and T10. Particles are transported to the user areas and also ions can be sent to the areas.




Experiments in the North Area:

- EHN1:
  - NA61;
  - NA63;
  - NA64;
  - UA9;
- Neutrino platform:
  - ProtoDUNE-DP;
  - ProtoDUNE-SP;
- EHN2:
  - COMPASS
- ECN3:
  - NA62

# EHN1 Experimental Area

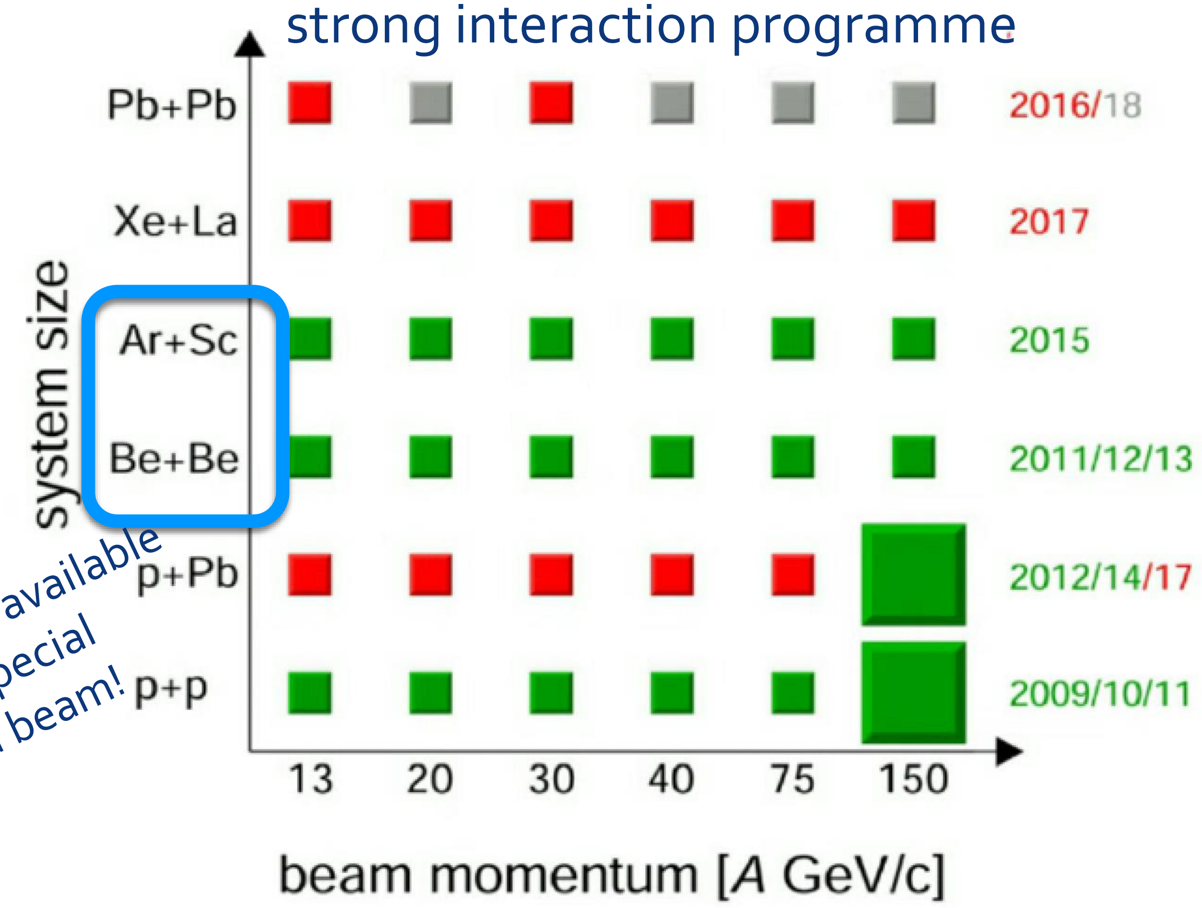
# @SPS: NA61

NA61 measures the production of hadrons in different types of collisions

- Strong interactions programme: Nucleus-nucleus (heavy-ion) collisions to investigate properties of the transition line between quark-gluon plasma and hadron gas (deconfinement);

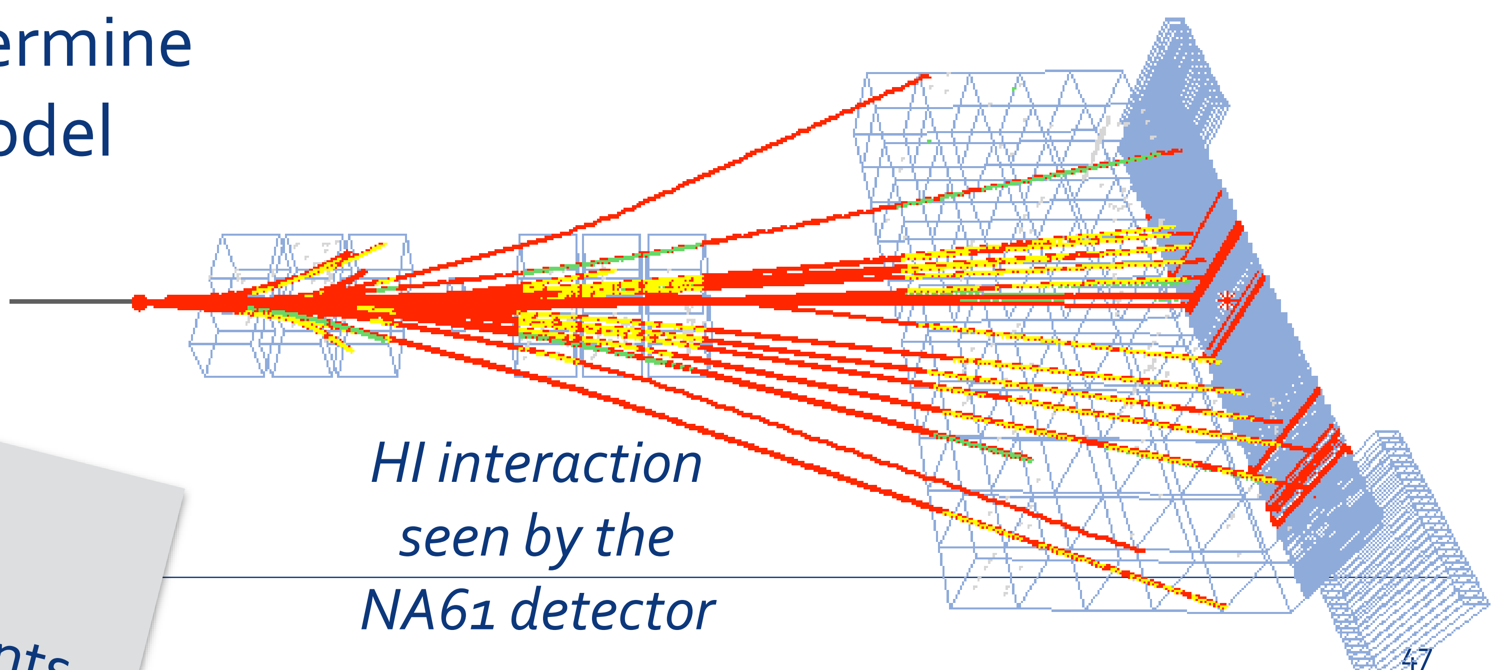
- Neutrinos and cosmic ray programme: Hadron-nucleus interactions to determine neutrino beam properties and to model cosmic ray showers

NA61 data set of strong interaction programme




Note: some special available because of special fragmented beam!

NA61/Shine
Data taking since 2007
150 authors incl. ~25 students



*HI interaction seen by the NA61 detector*

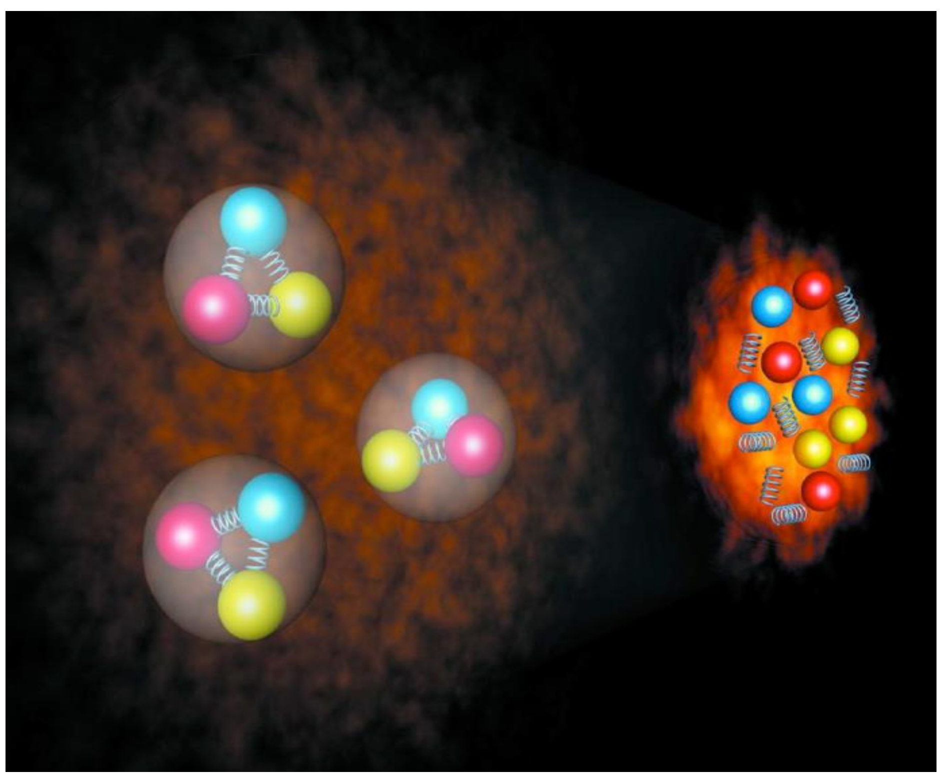
# NA61: Study of properties of onset of deconfinement

Example:

For Pb+Pb, sharp peak ("horn") in energy dependent $K^+/\pi^+$ ratio due to onset of deconfinment expected (APPB 30, 2705 (1999)).

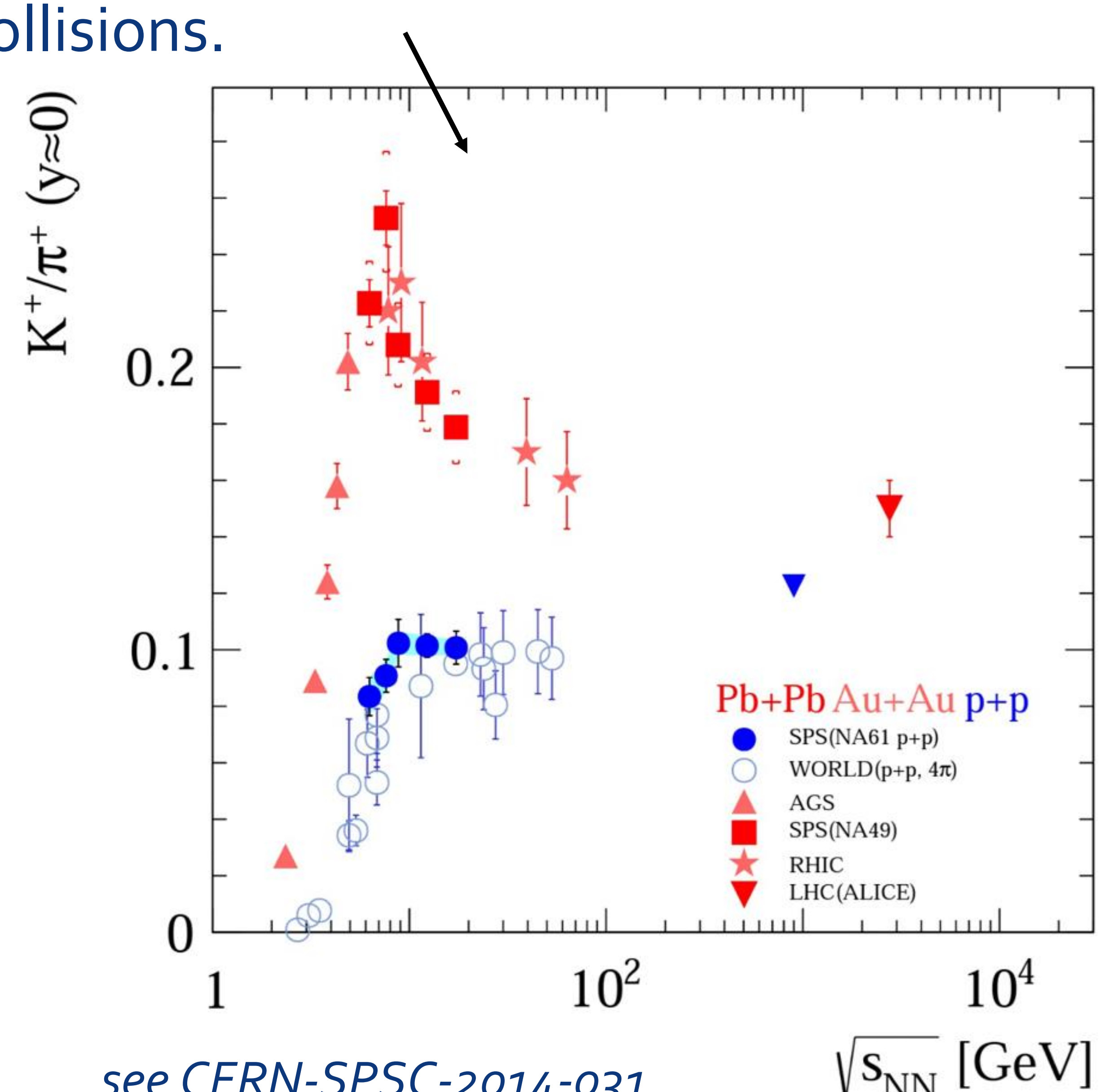
Measurement of energy dependence of the $K^+/\pi^+$ ratios at mid-rapidity for p+p interactions and central Pb+Pb/Au+Au collisions.

Hadrons Mixed



AGS SPS RHIC

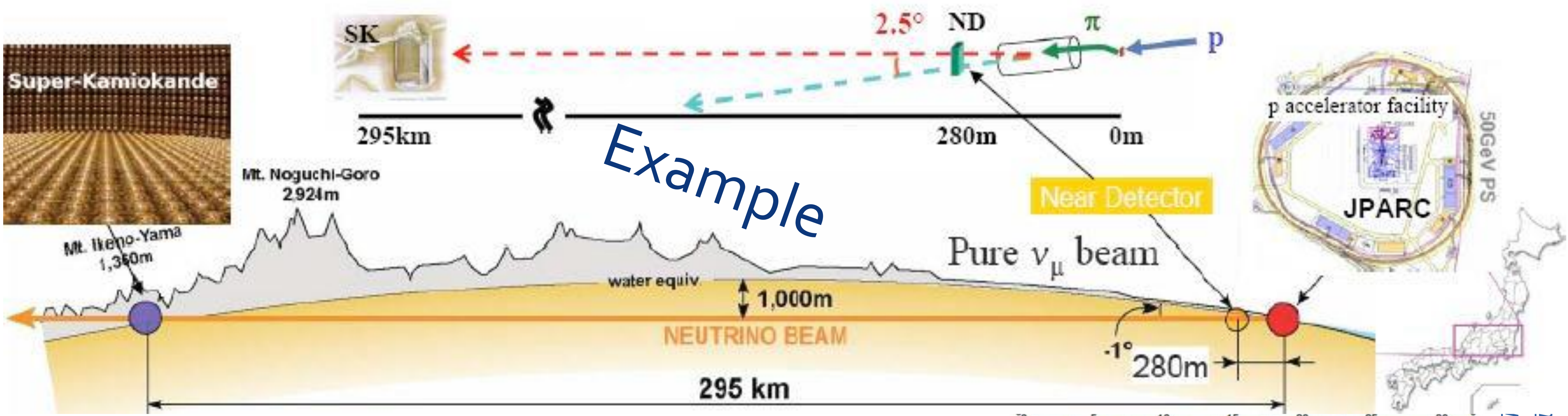
collision energy



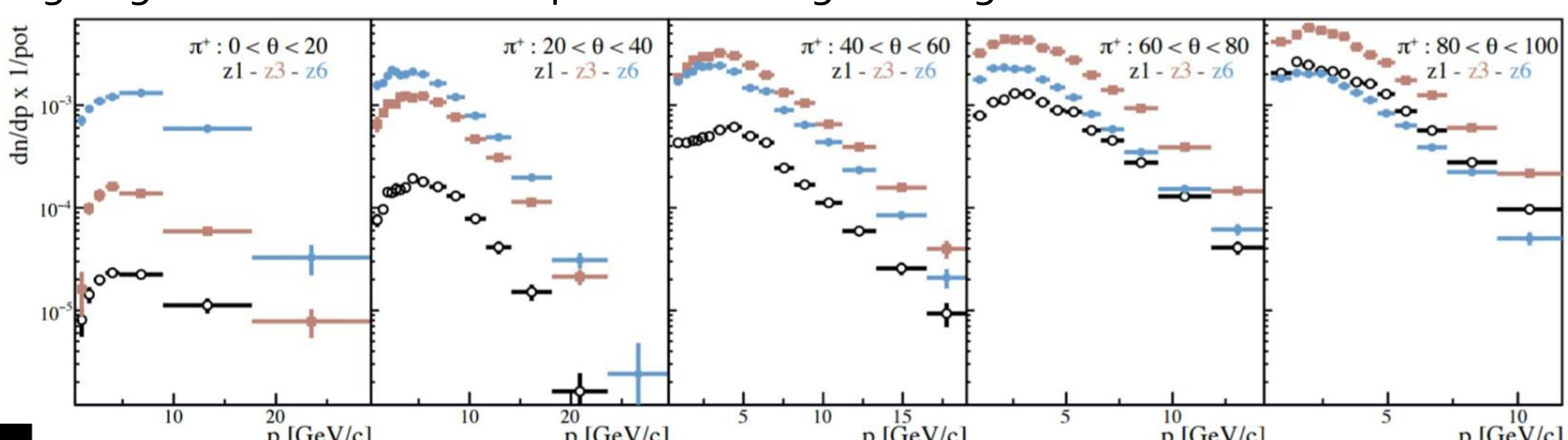

*see CERN-SPSC-2014-031*

# Hadron production data for neutrino experiments

Use a T2K replica target [graphite, 90 cm long, 2.6 cm diameter]




long target → rates at various positions along the length:



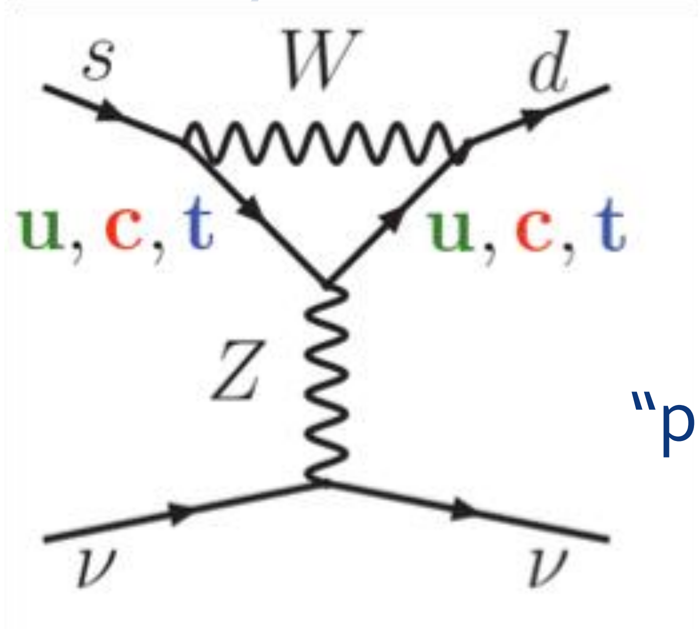

inspirehep.net/record/1431983?ln=en, inspirehep.net/record/1121706?ln=en

SHINE NA61

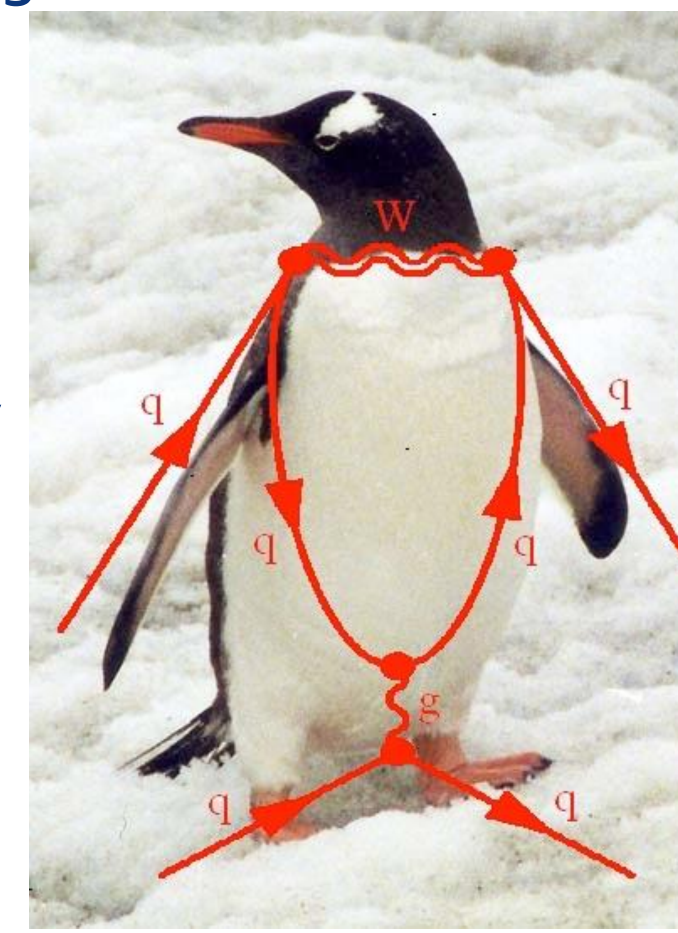
# Probing the Standard Model

- NA62 is searching for ultra-rare kaon decays

$$\boxed{K \to \pi \nu \bar{\nu}}$$

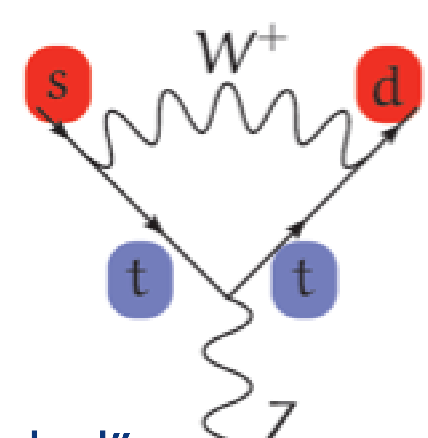



...so-called "penguin graph"

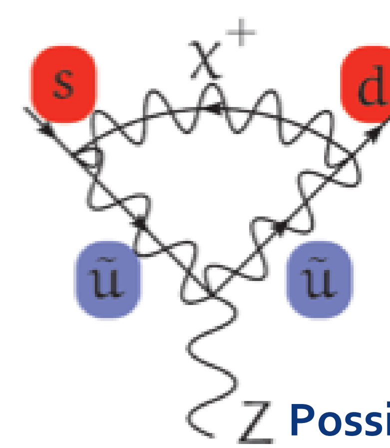



The contribution to
these processes due to the Standard Model is strongly suppressed ($<10^{-10}$) and
calculable with excellent precision (~%)

| |
|---|
| They are very sensitive to possible contributions from New Physics |




"Standard" Penguin




Possible "Super-Symmetric" Penguin

# Rare decays: NA62 measures BR($K^+ \rightarrow \pi^+ \nu\nu$)

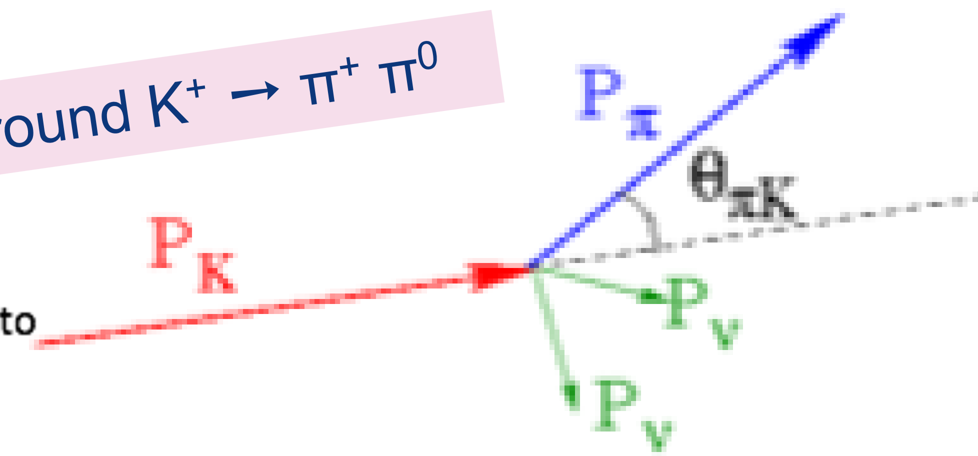
Kaons are special: the theoretical predictions are precise

$$Br(K^+ \rightarrow \pi^+ \nu\bar{\nu})_{TH} = (8 \pm 1) \times 10^{-11} \quad \text{Buras et al. (2015)}$$

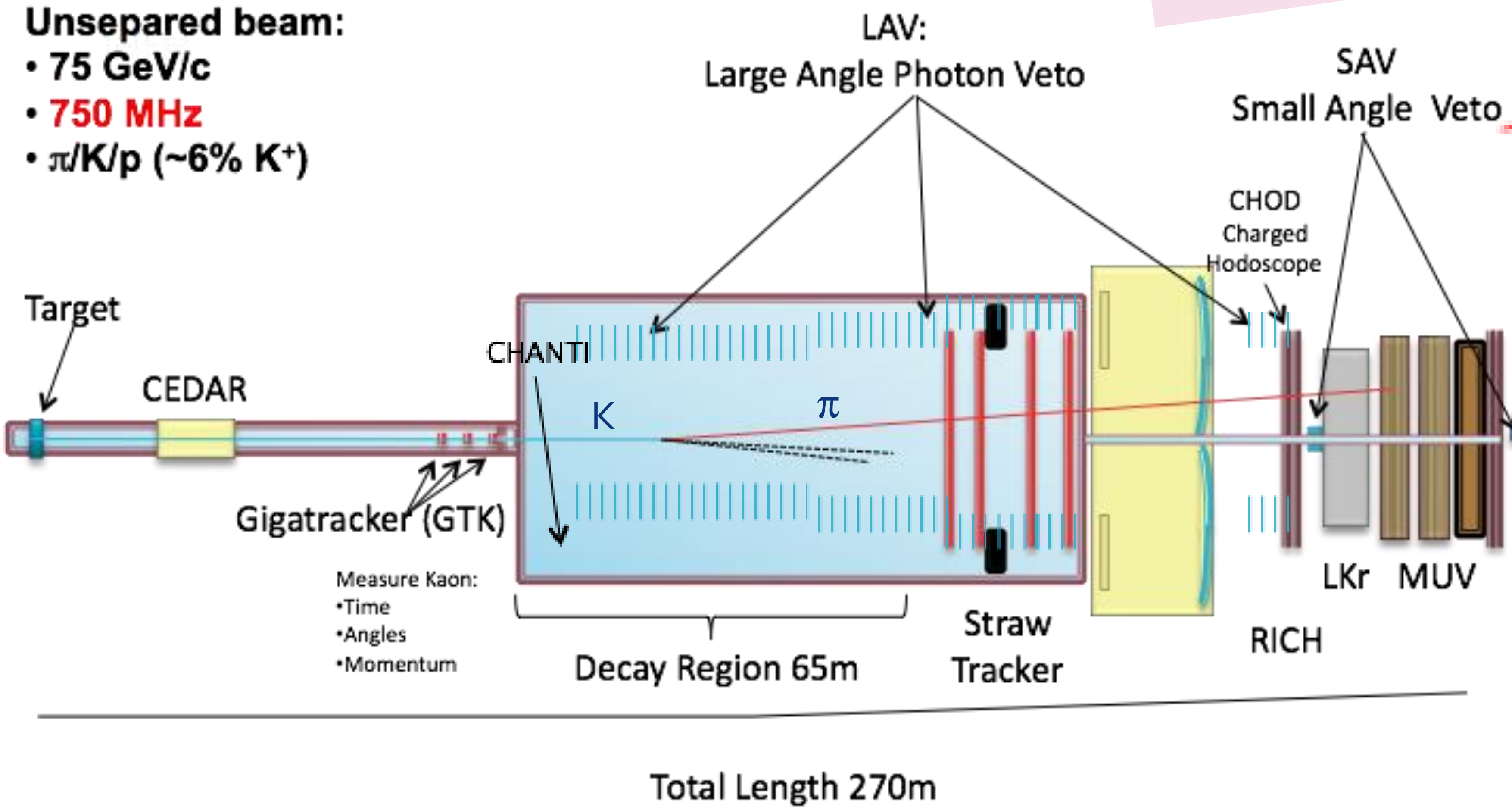
...and the experimental window of opportunity is largely unexplored

$$Br(K^+ \rightarrow \pi^+ \nu\bar{\nu})_{EX} = (17.3^{+11.5}_{-10.5}) \times 10^{-11} \quad \text{BNL E787/E949 (2009)}$$

Main background $K^+ \rightarrow \pi^+ \pi^0$




**SPS primary p: 400 GeV/c**
**Unsepared beam:**
- **75 GeV/c**
- **750 MHz**
- **$\pi$/K/p (~6% $K^+$)**



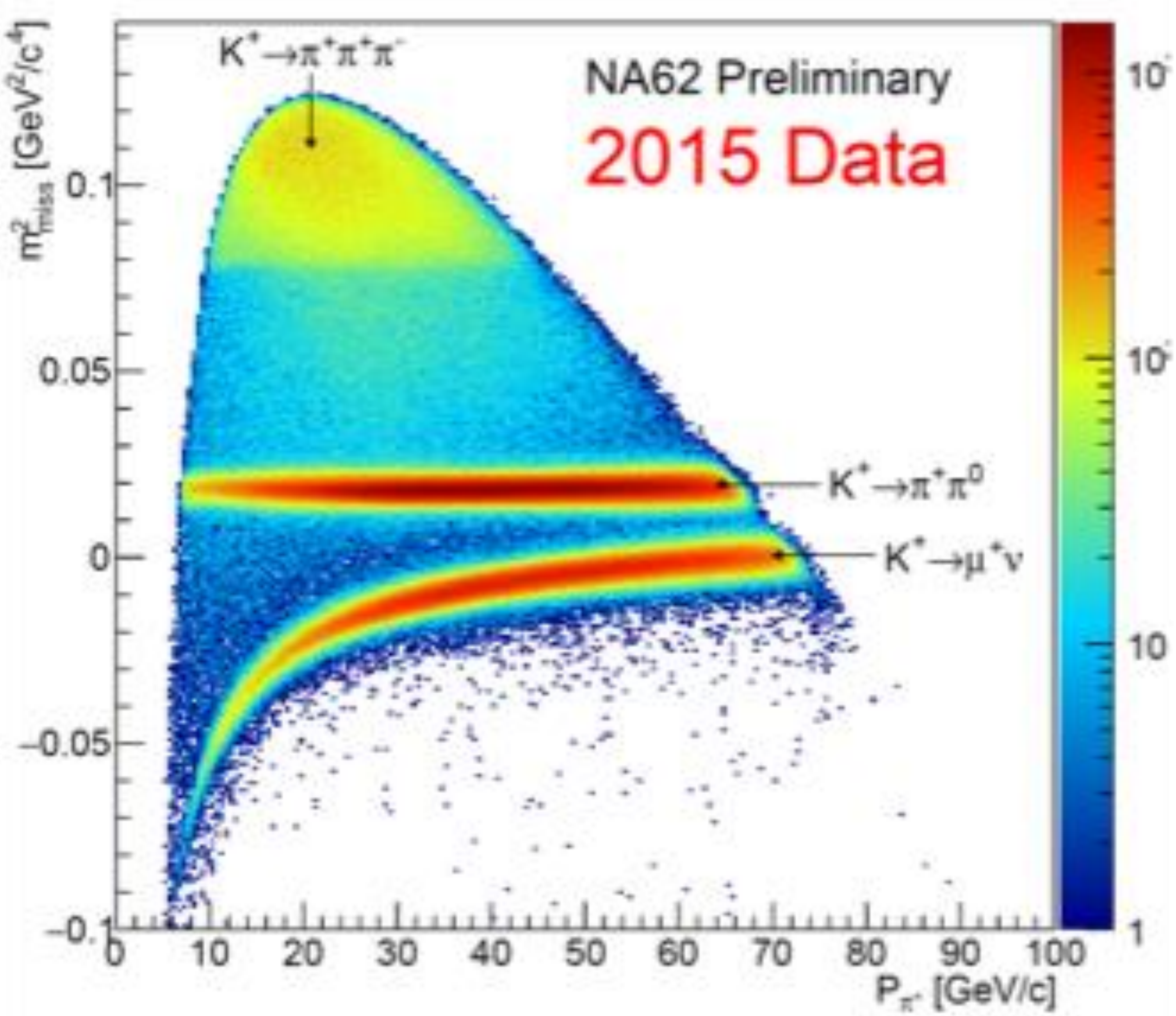

Beam line:
- CEDAR: K ID
- Gigatracker: beam particle ID
- CHANTI: Charged particle veto

Detector region:
- pion tracks: straws
- particle ID: LKr, RICH
- muon rejection: MUV
- photon rejection: LKr, LAV, SAV

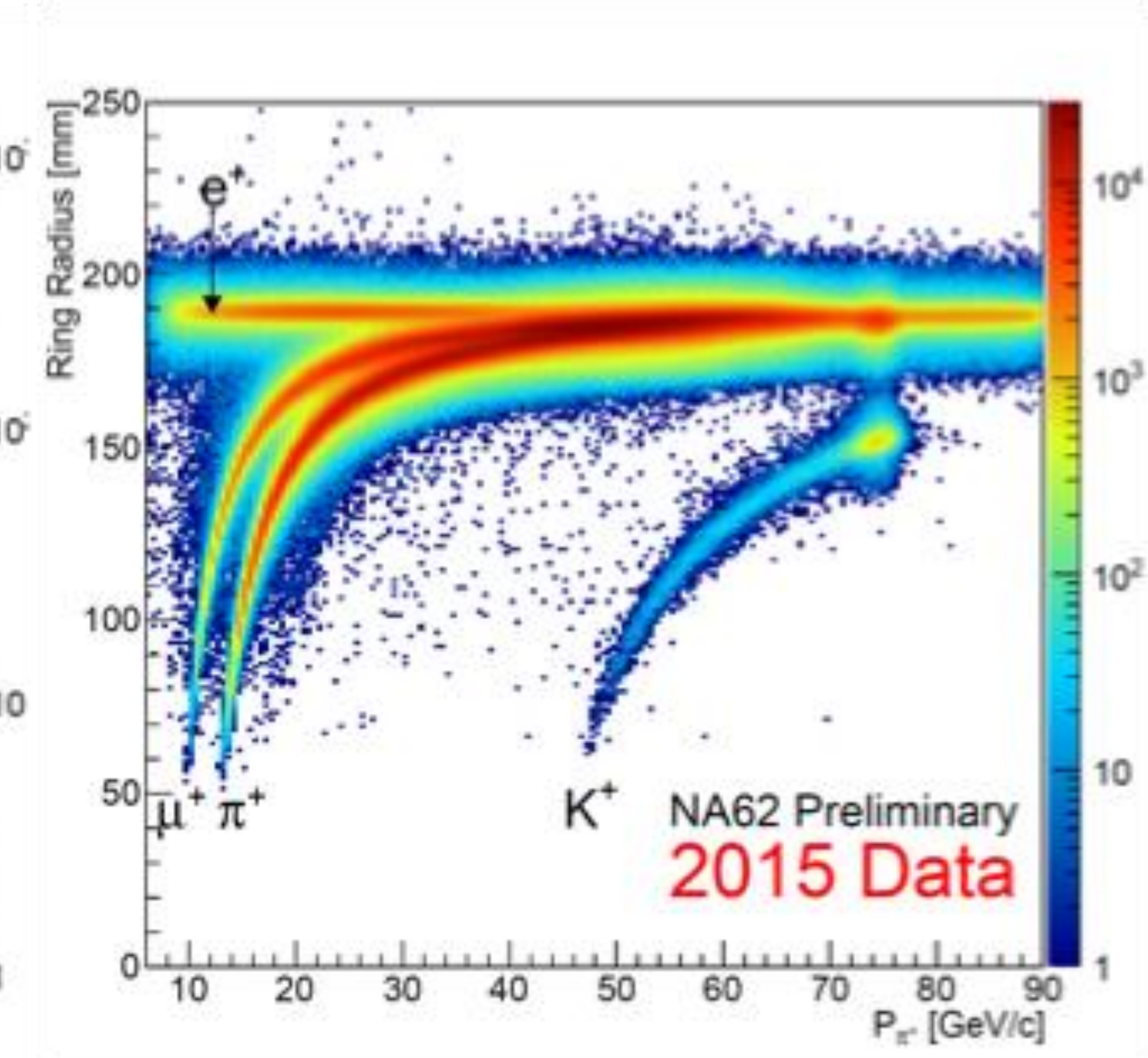
Data taking in progress and foreseen until LS2 (end of 2018)

# The NA62 experiment

# A glimpse of NA62 data




The squared missing mass, reconstructed under the hypothesis that the charged track is a pion, vs. track momentum for decays of particles tagged to be kaons



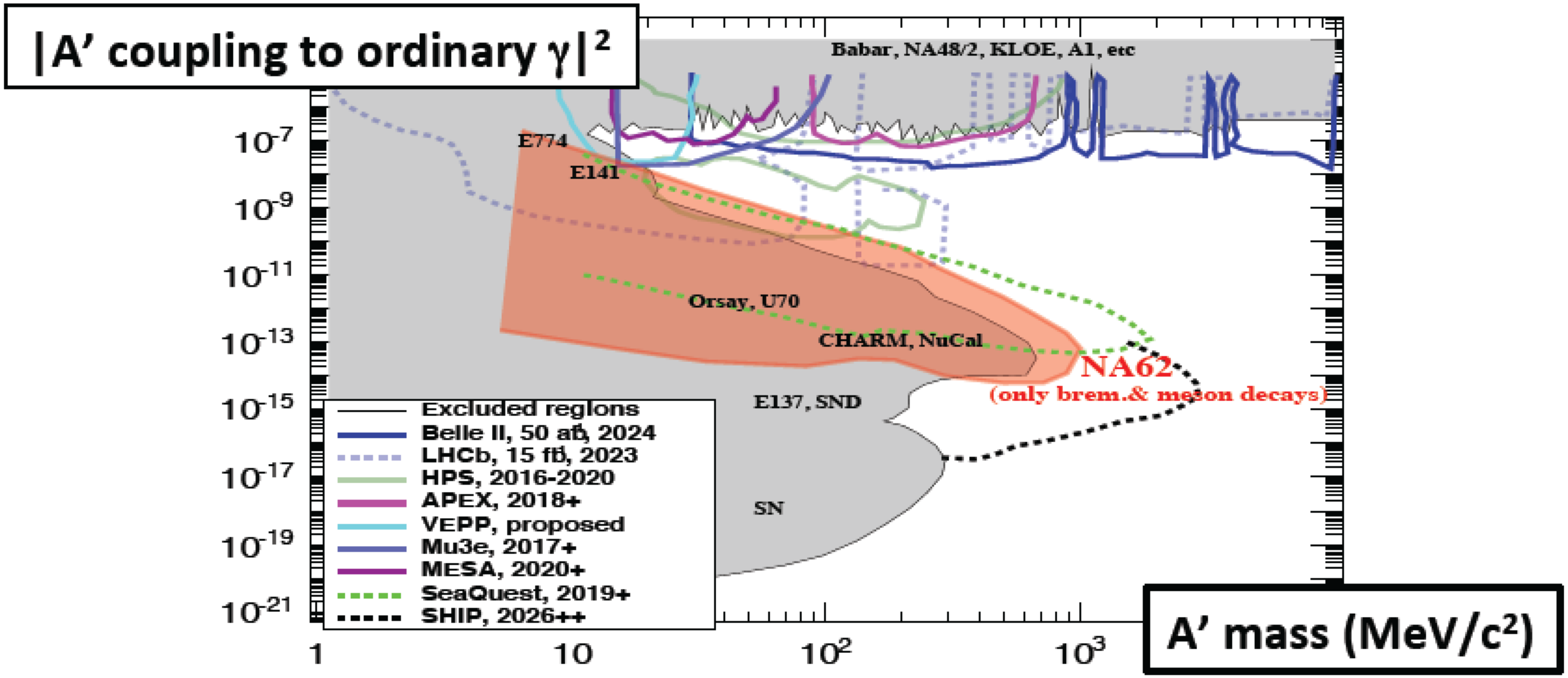

The particle identification of the combined tracking and RICH spectrometers

# Preparations…

Excavation work for the new Beam  Dump.

# Possible future: NA62 operating as beam dump experiment

Search for visible decays of dark photons A’




90%-CL exclusion plot with assumption of $2 \times 10^{18}$ protons on target @400GeV for the search for displaced, leptonic decays dark photons to ee and μμ, including trigger/acceptance/selection efficiency and zero-background assumption. Even higher sensitivity when including including direct QCD production of A’ and when including A’ production in the dump (only target considered here).

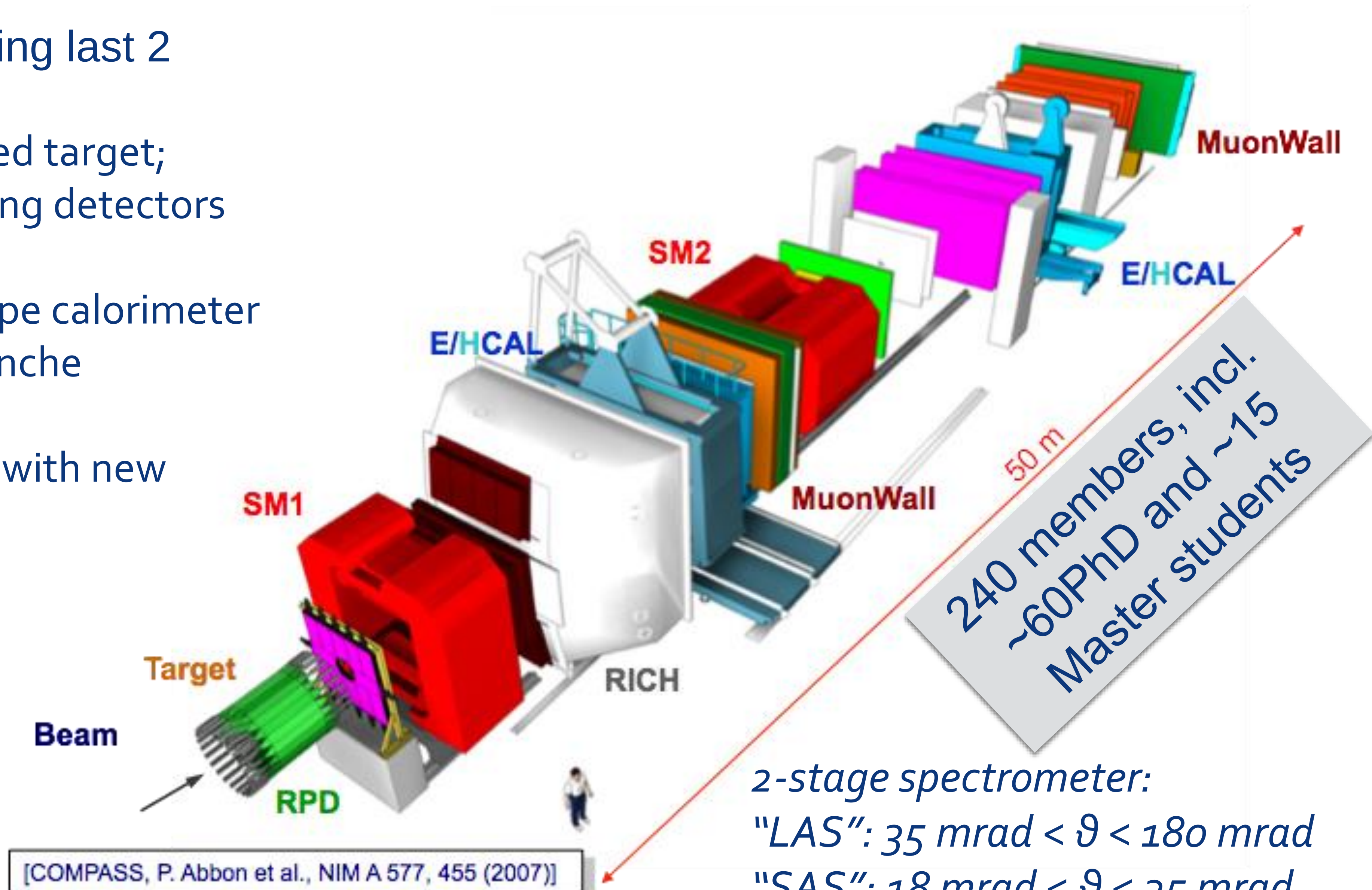
# @SPS: COMPASS

Study of hadron structure and hadron spectroscopy with high intensity muon and hadron beams.

Data taking started summer 2002, since 2010 measurements to study the structure of hadrons in Deep Virtual Compton Scattering (DVCS), Hard Exclusive Meson Production, semi-inclusive deep inelastic scattering, Polarized Drell-Yan and Primakoff reactions.

Main spectrometer upgrades during last 2 years:

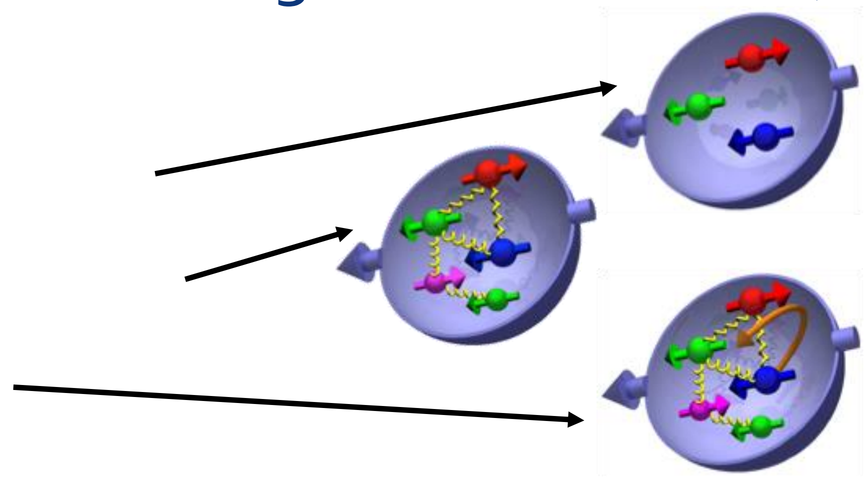
1. Superconducting magnet polarised target;
2. New system of MicroMega tracking detectors with pixelized central parts;
5. New high granularity shashlyk-type calorimeter ECalo read out by micro-pixel avalanche photodiodes
6. Recoil proton detector upgraded with new internal scintillating barrel;
7. RICH1 detector upgrade with novel photon detectors: Micro-Megas + thick GEM hybrid - curr. 1/4 of detector replaced;
8. New Sci-FI based Vertex detector for first ever polarized Drell-Yan data set (successfully collected in 2015).




*2-stage spectrometer:*
*"LAS": 35 mrad < ϑ < 180 mrad*
*"SAS": 18 mrad < ϑ < 35 mrad*
*~350 tracking planes*

# Example: COMPASS hadron structure

Internal dynamics of the objects as protons is not understood, i.e. if it comes to spin (contribution of gluons and orbital angular momentum)



Contributions to the spin of the proton

- naive QPM: only valence quarks $\Delta q_v$
- QCD: sea quarks and gluons $\Delta q_s$, $\Delta G$
- orbital angular momentum $L_q$, $L_g$

Spin of proton = 1/2, with $\Delta\Sigma = \Delta u + \Delta d + \Delta s$:

$$1/2 = 1/2 \cdot \Delta\Sigma + 1 \cdot \Delta G + \langle L_z \rangle$$

COMPASS: $\Delta\Sigma \sim 0.25$, $\Delta G \sim 0.06$, spin crisis not yet over!

For full story: PLB 633 (2006) 25–32; PLB 718 (2013) 922; PLB 753 (2016) 573; CERN-PH-EP-2015-328.

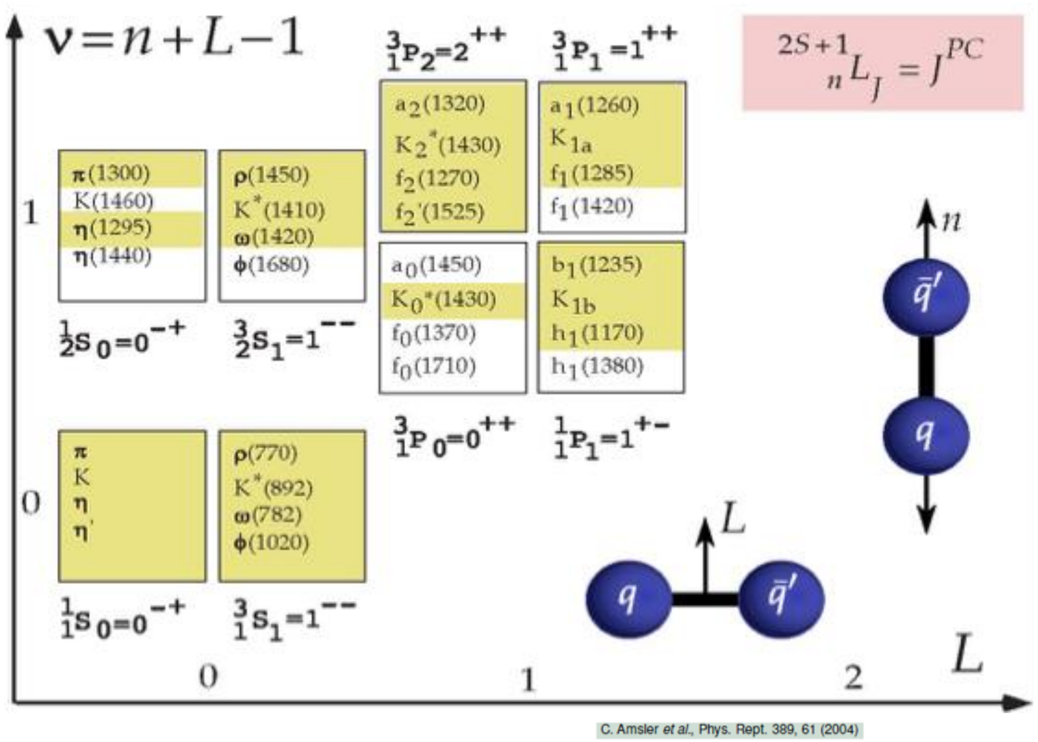
## DVCS run (nucleon tomography):

studies of 3-dim $(x, k_T, b_T)$ structure of the nucleon described by transverse-momentum-dependent (TMD) PDFs instead of a 1-dim (x) structure
($k_T$ intrinsic transv. momentum of the struck quark, $b_T$ impact parameter), as described in http://arxiv.org/pdf/1507.05267 → interesting e.g. for LHC.

# Example COMPASS hadron spectroscopy

## What is the hierarchy or spectrum of particles that quarks and gluons can form?

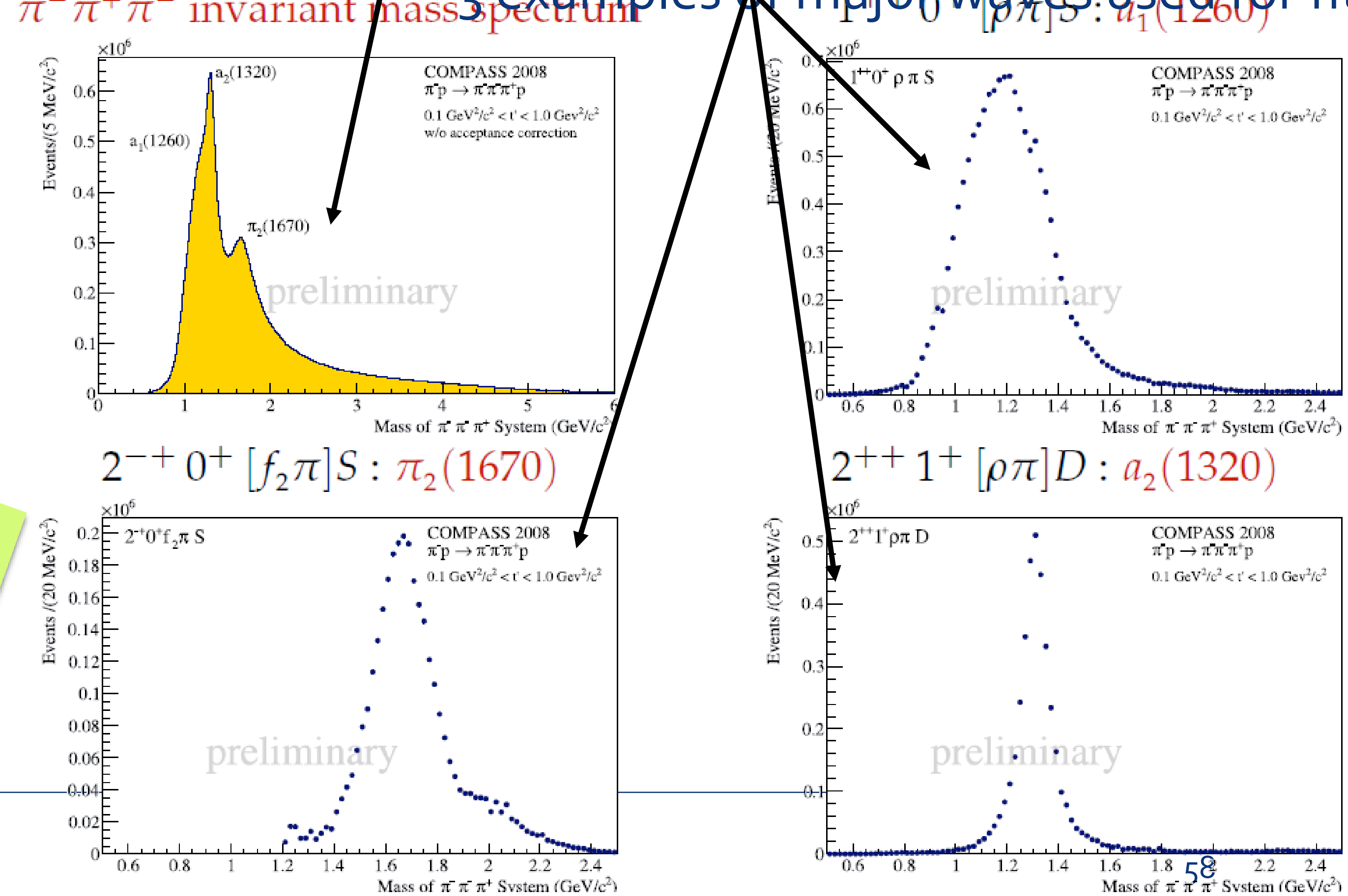
"energy" of compound state (quantum number composed of radial/longitudinal excitation)




radial excitation


Art taken from Urs Wehrli: "Kunst aufgeräumt"
Idea: Stephan Paul

partial wave analysis of measured spectrum,
3 examples of major waves used for fit




Discovery of the
$a_1(1420)$ axial-vector meson
(was not predicted by Lattice QCD calc.)
see Phys. Rev. Lett. 115, 082001

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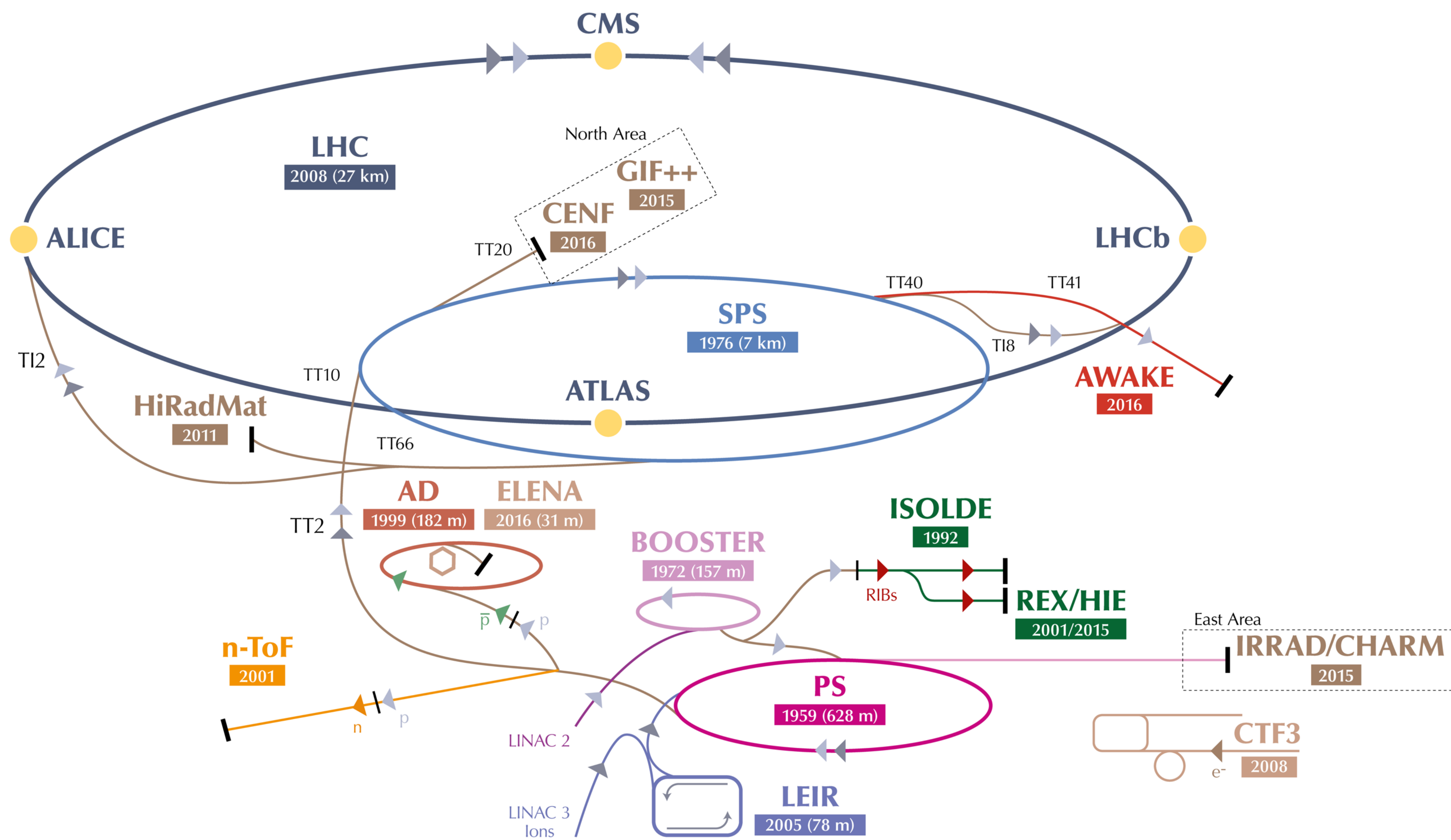
# The CERN accelerator complex




p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) p̄ (antiprotons) e⁻ (electrons)

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

CHARM Cern High energy AcceleRator Mixed field facility IRRAD proton IRRADiation facility GIF++ Gamma Irradiation Facility

CENF CErn Neutrino platForm

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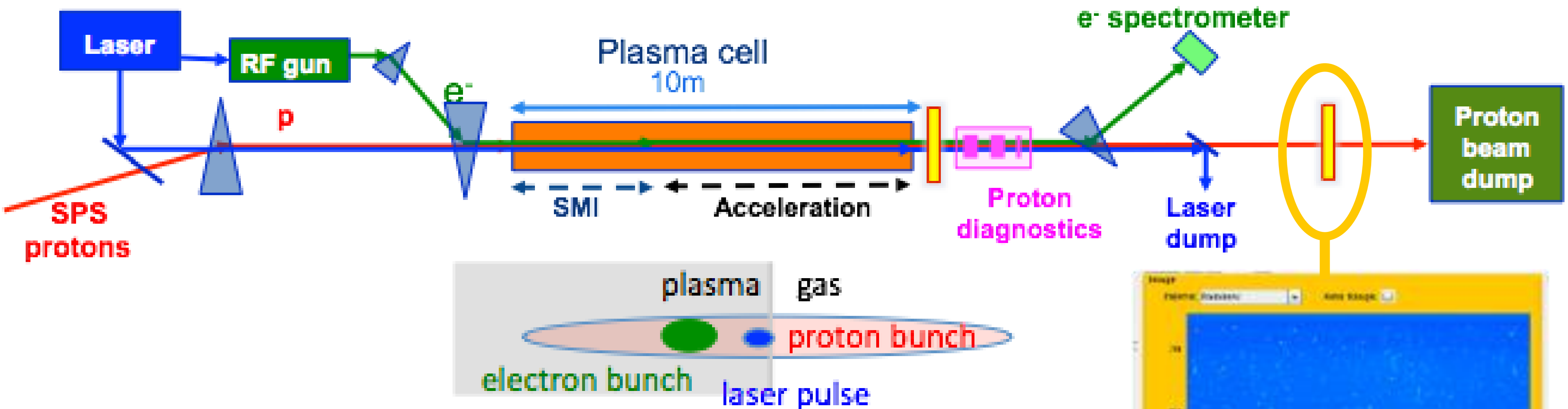
# Towards novel accelerators: AWAKE

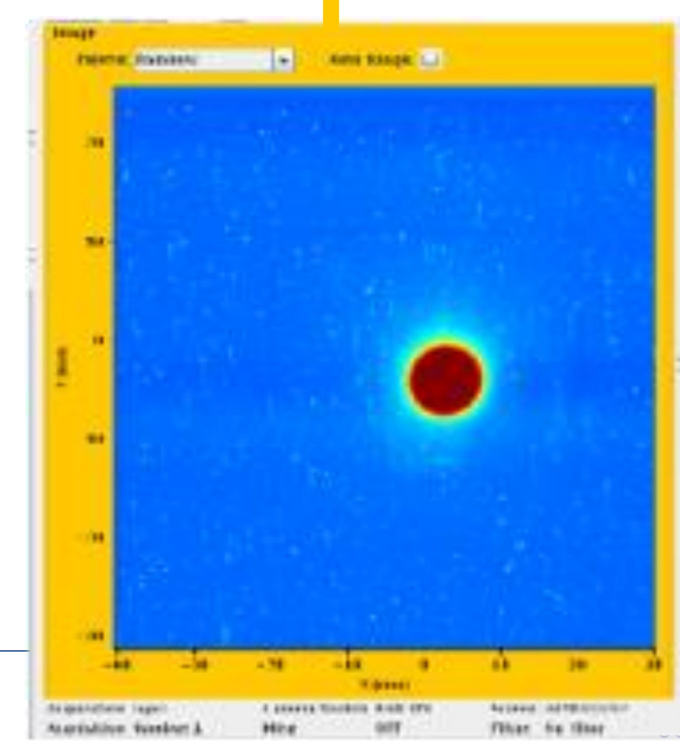
Advanced Proton Driven Plasma Wakefield Acceleration experiment in former CNGS tunnel

Goal: proof-of-principle of the approach to accelerate electron beam to TeV energy regime in a single plasma section



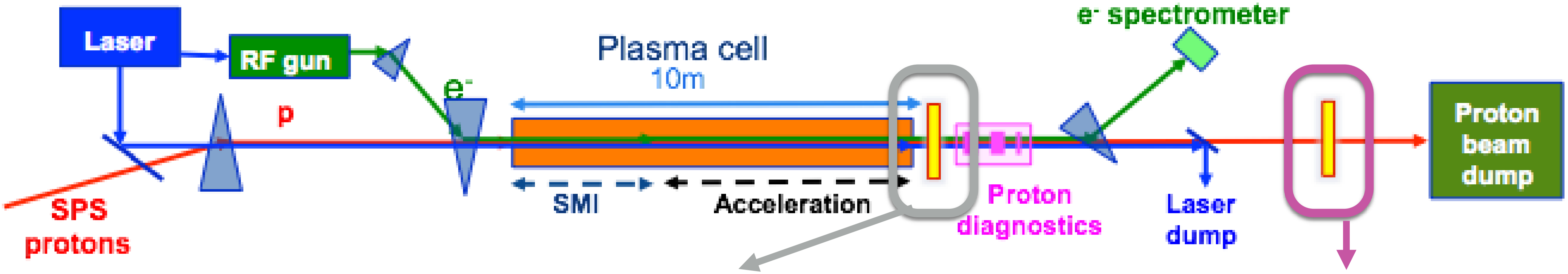

- 16 June 2016 first proton beam extraction from SPS to AWAKE

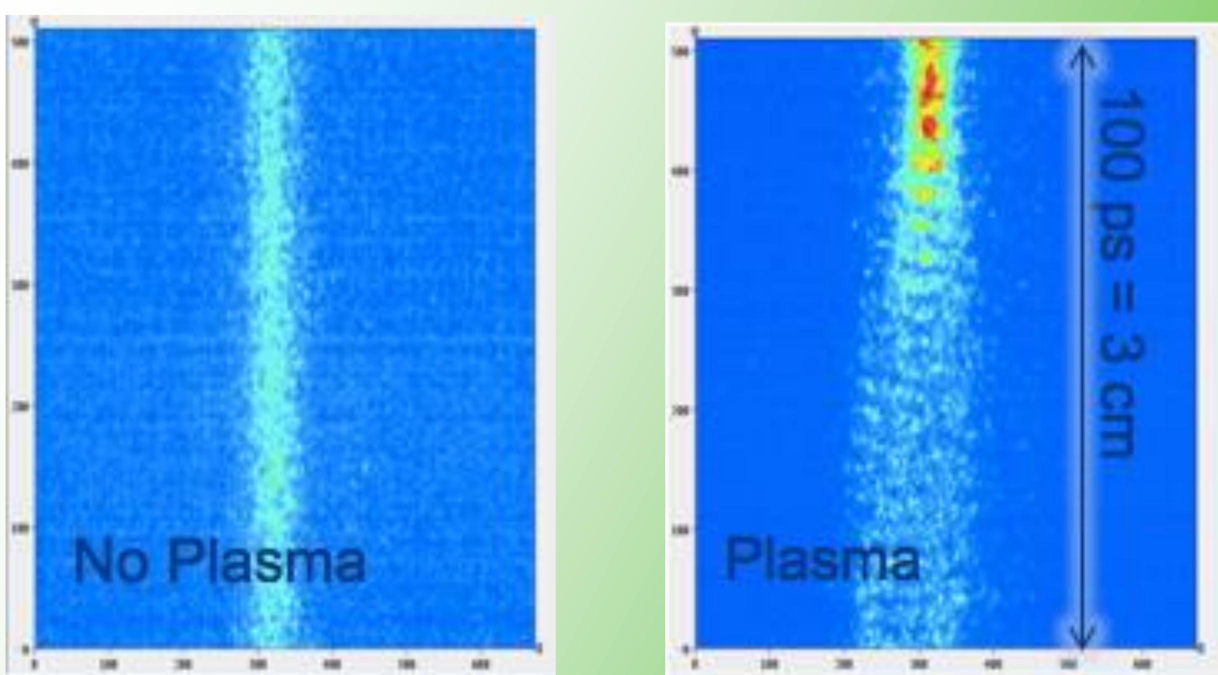
*Beam TV screen image of the proton beam*



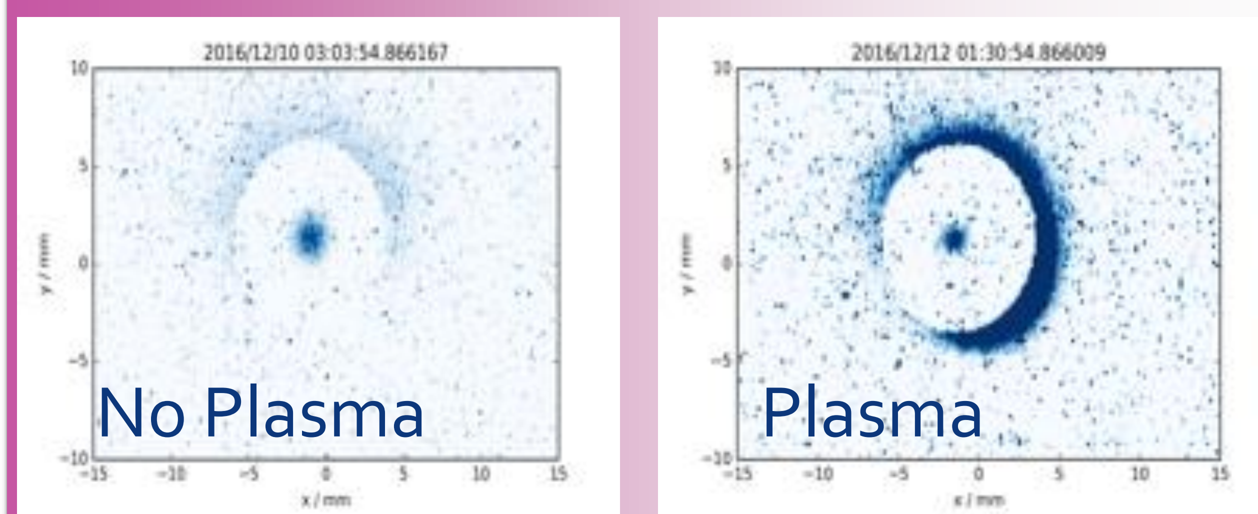
# AWAKE 12/2016: self modulation observed

Observed the strong modulation of high-energy proton bunches in plasma; first ever demonstration of strong plasma wakes generated by proton beams!




Camera signal:
Observation of self-modulation of proton beam in plasma




BeamTV screen: Compare transverse size of beam with and without plasma fields!
Growth of tails governed by the transverse fields in the plasma clearly seen! Only possible with very strong electric fields!

# Accelerators for the future

Cool technology!

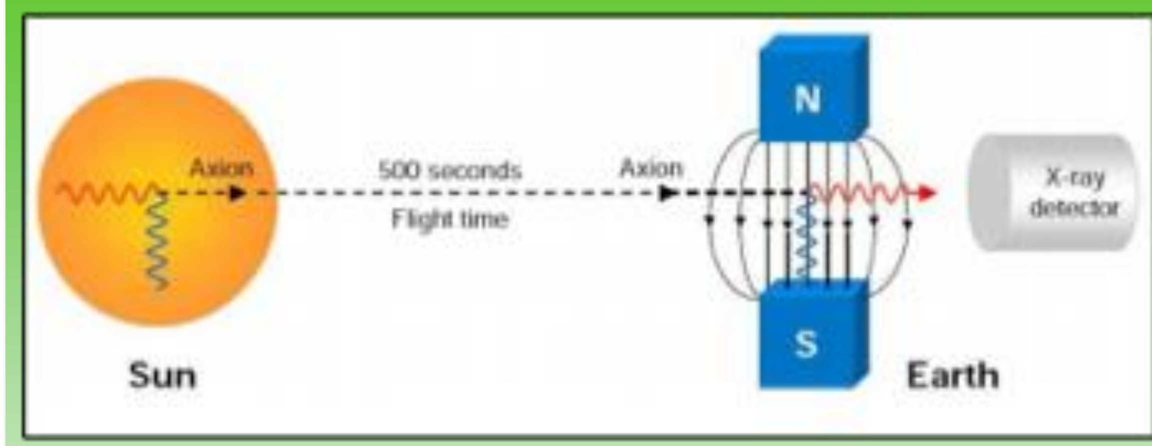
(First application of proton beam driven plasma wakefield accelerator (50-100GeV/c electrons) for fixed target experiments after 2023?)

# Non-accelerator experiments

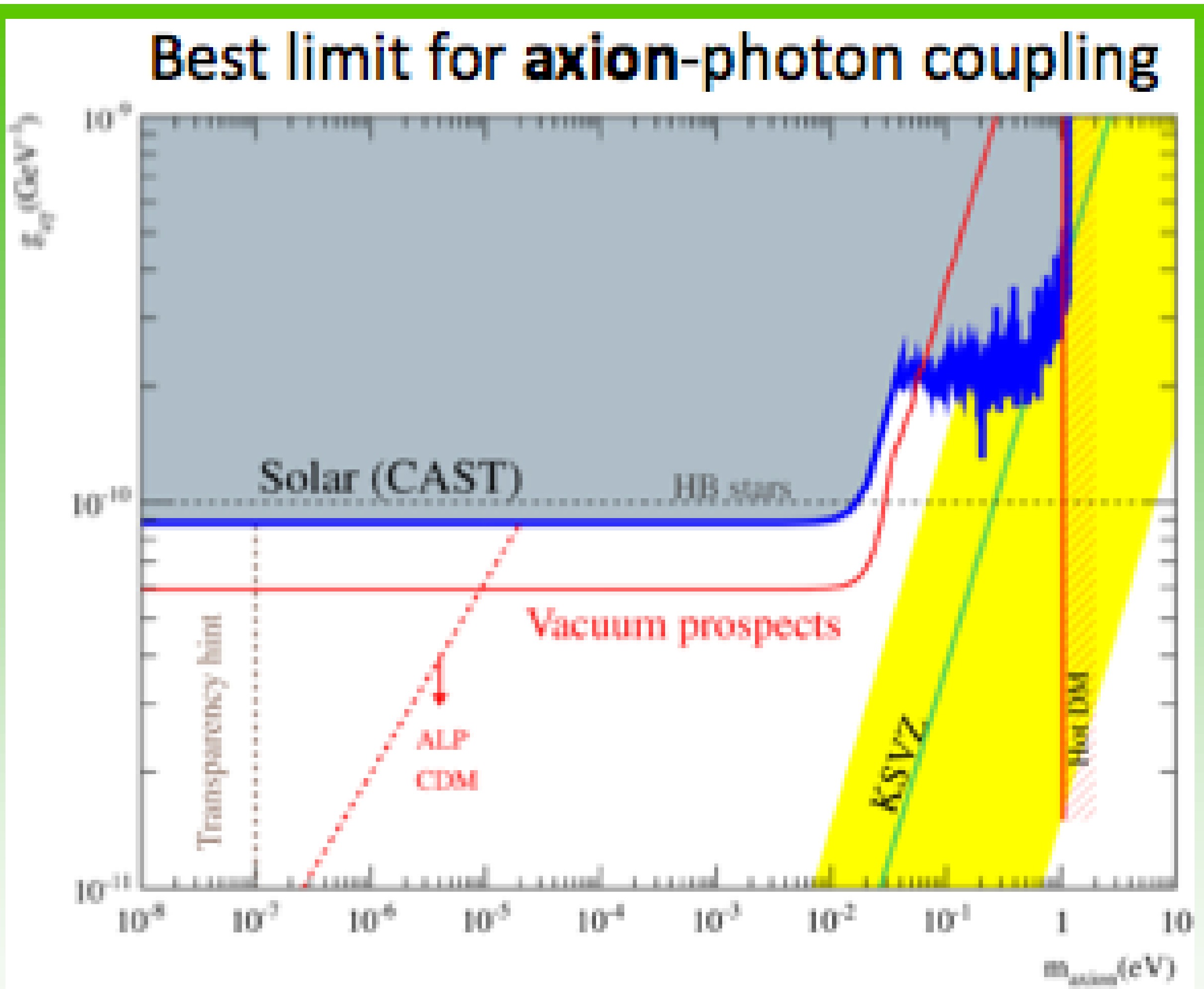
Two world-class experiments on CERN site searching for axions and axion-like particles.
Experiments benefit from CERN expertise on cryogeny, magnets, detector technology:

- CAST (A Solar Axion Search Using a Decommissioned LHC Test Magnet)
- OSQAR (Optical Search for QED vacuum magnetic birefringence, Axions and photon Regeneration)

*Example: CAST solar axion search*

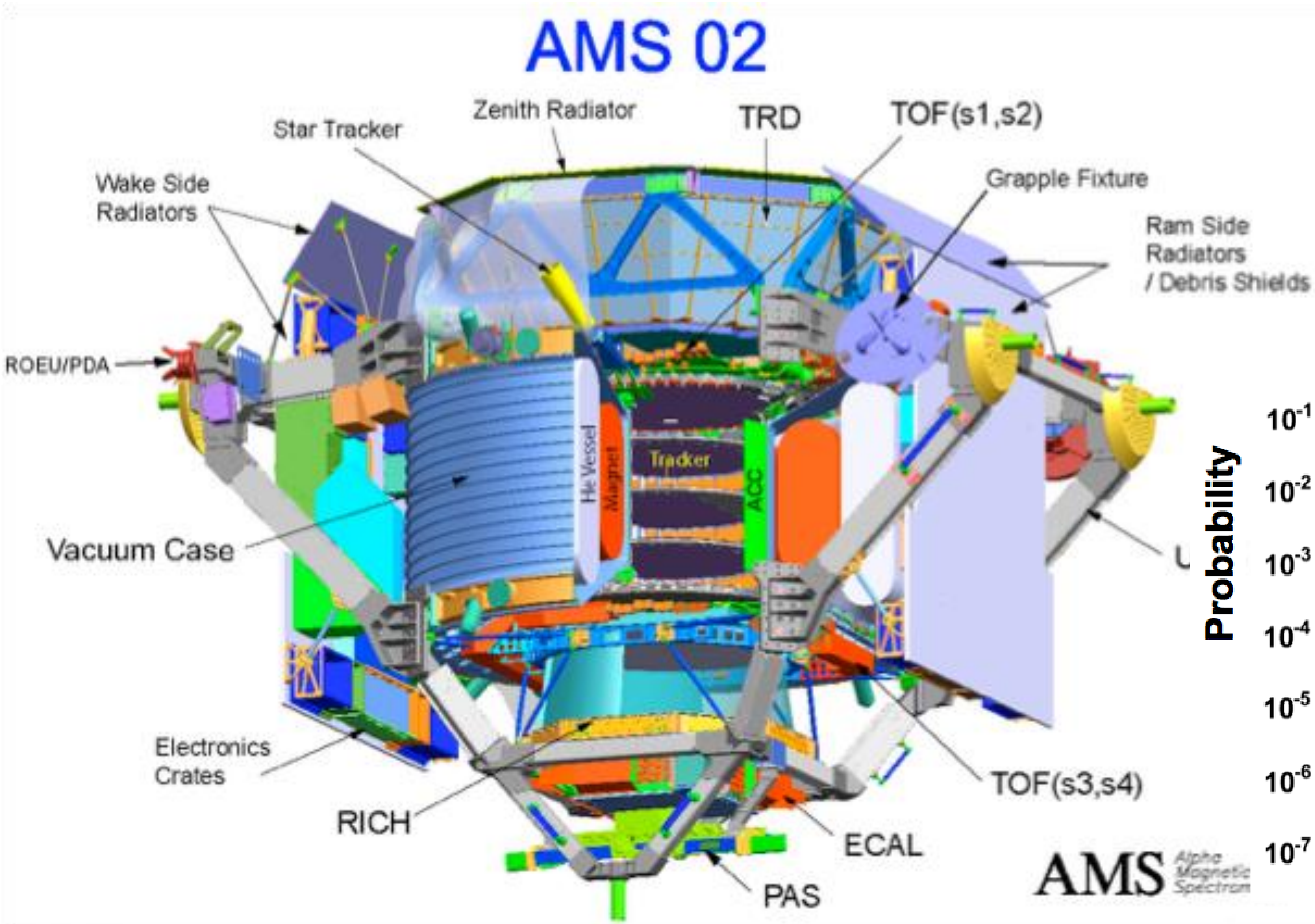



CAST: ~45 collaborators incl. 3 PhD students



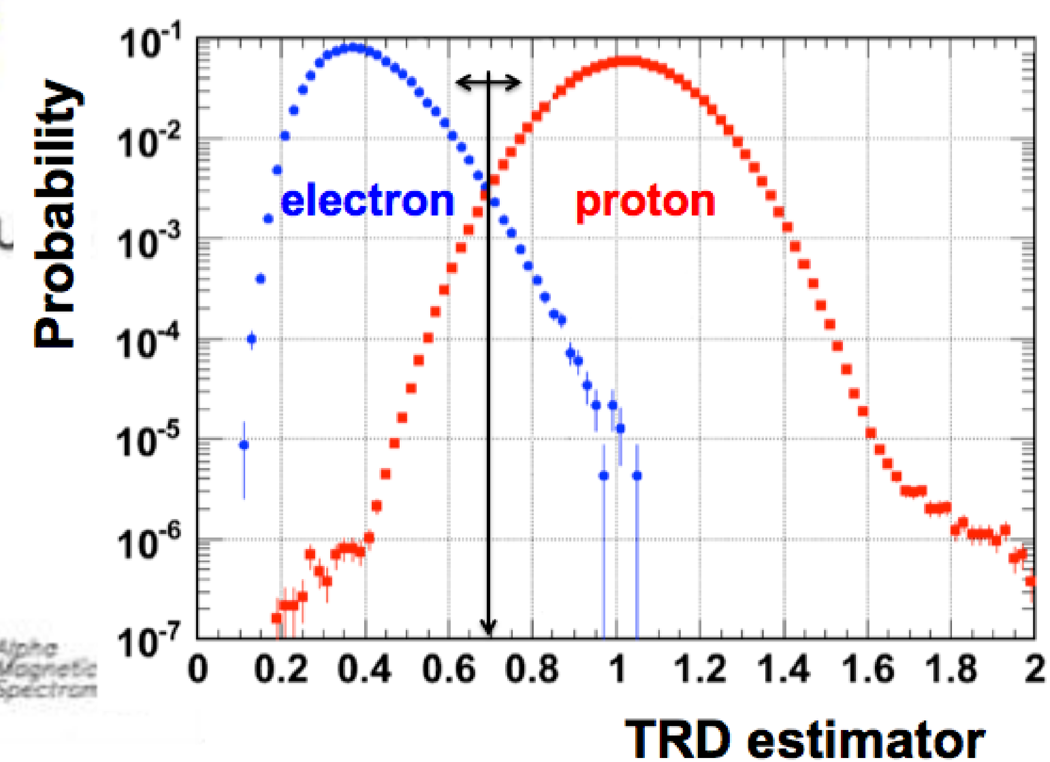

CAST in 2016: search for solar Chameleons using a novel force sensor with thin membrane inside a resonant Fabry-Perot cavity (KWISP)

# AMS: search for antimatter in space…




Example:
excellent particle identification in TRD - only achieved because of excellent calibration in SPS test beams:

**TRD estimator = $-\ln(P_e/(P_e+P_p))$**

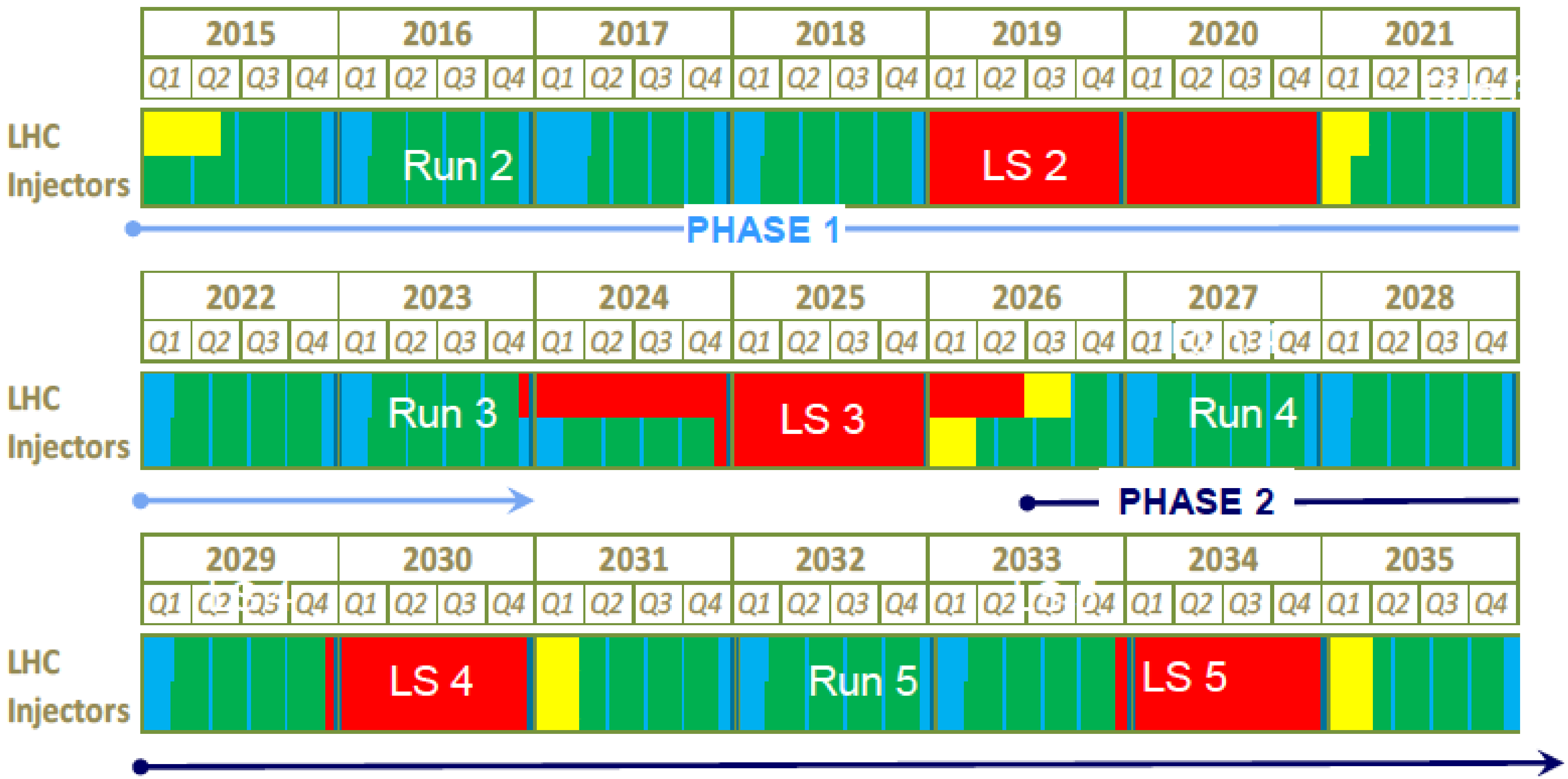



…needs down to earth calibration

# LHC roadmap
## according to MTP 2016-2020*

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC

- Physics
- Long Shutdown (LS)
- Beam commissioning
- Technical stop




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

# Summary

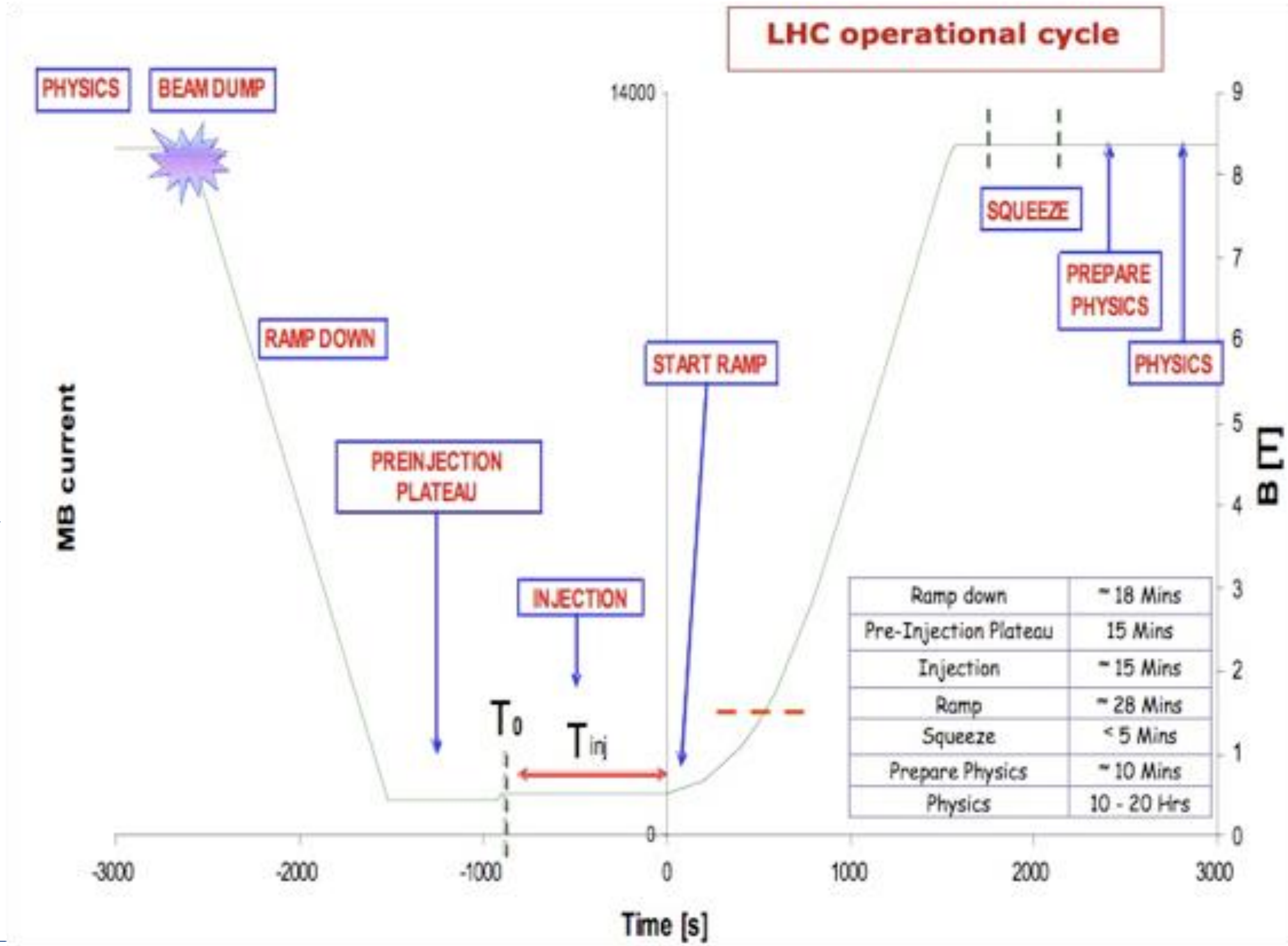
- There is a rich physics programme at the CERN accelerators using unique experimental facilities
- The LHC collider is exploring new territory at the energy frontier:
  - solving riddle of dark matter and dark energy?
  - probing the successful Standard Model
- Non-collider experiments vital part of CERN's physics landscape: exploration and understanding
  - of novel phenomena
  - using high statistics
  - investigating rare processes
  - and investigating structure and property of matter (antimatter)
- CERN's experiments provide excellent ground for educating future experimental particle physicists!

# Backup & additional slides

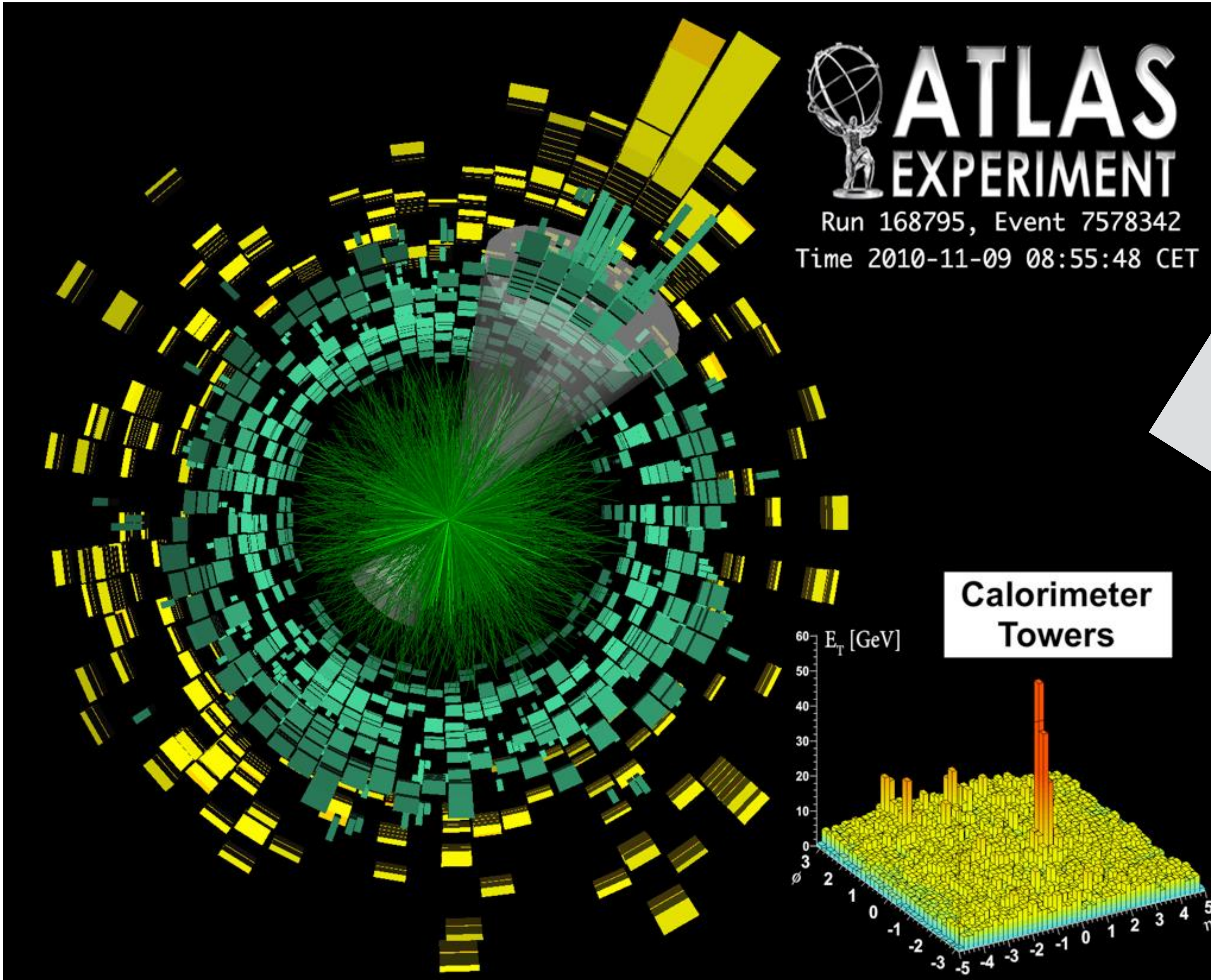
# LHC: collisions 24/7

- The LHC is running 24/7 for 9 months per year: 40 million collisions per second!

If number of protons has decreased too far, the LHC is filled again (~once per day)



# Heavy ion physics at the LHC




Jet quenching in heavy ion collisions

# NA62 physics besides $K^+ \to \pi^+ \nu\nu$

**Standard kaon physics**

- Precision measurements of dominant $K^+$ BRs
- ChPT studies: $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+ e^-$, $K_{e4}$
- Precision test of lepton universality: $R_K = \Gamma(K \to e\nu(\gamma))/\Gamma(K \to \mu\nu(\gamma))$

**Searches for lepton-flavor or -number violating decays**

- $K^+ \to \pi^+ \mu e$, $K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^- \ell^+ \ell^+$

**Searches for heavy neutrinos**

- $K^+ \to \ell^+ \nu_h$ (inclusive)
- $\nu_h$ from upstream $K$, $D$ decays with $\nu_h \to \pi\ell$

**Searches for long-lived dark sector particles**

- Dark photon $\gamma'$ produced in $\pi/\rho$ decays in target, with $\gamma' \to \ell^+\ell^-$
- Axion-like particle $A^0$ produced in target/beam dump, with $A^0 \to \gamma\gamma$

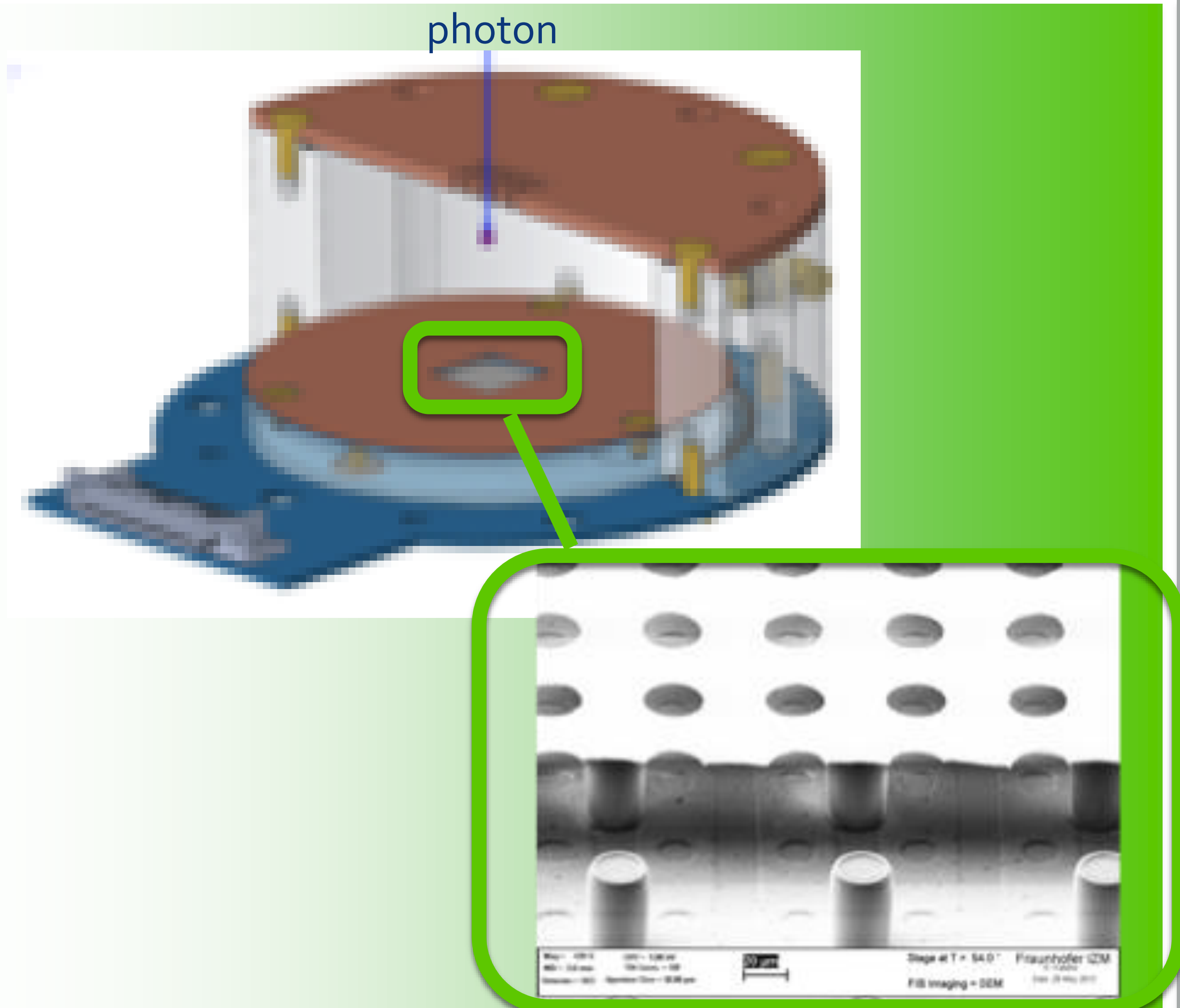
**$\pi^0$ decays**

- $\pi^0 \to$ invisible; $\pi^0 \to 3\gamma$, $4\gamma$; $\pi^0 \to \gamma\gamma'$

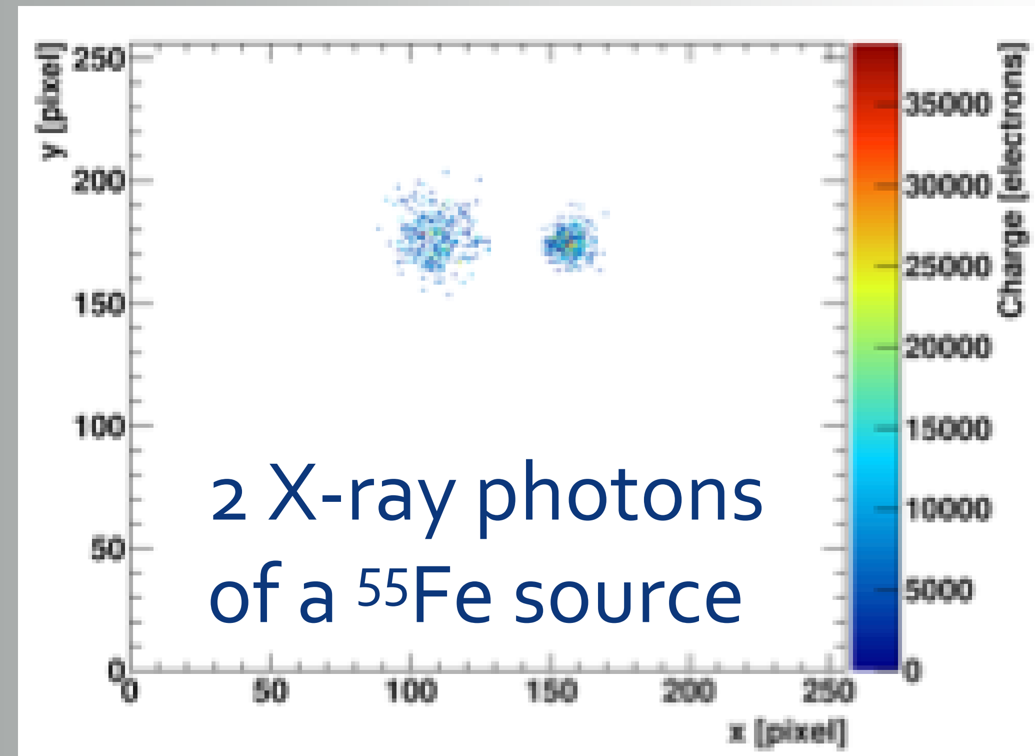
NA62 collaboration:
~230 authors incl.
~20 students

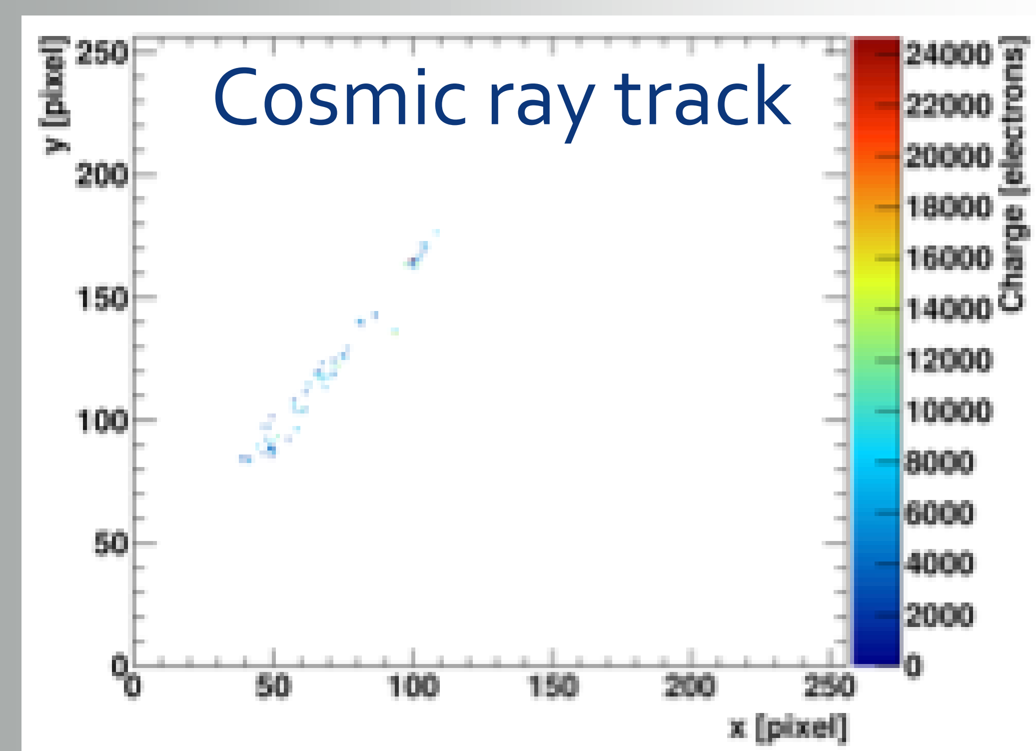
Slide from
Search for $K^+ \to \pi^+\nu\bar{\nu}$ at NA62 – M. Moulson (Frascati) – ICHEP 2016 – Chicago – 6 August 2016

# CAST - a chance for new detectors



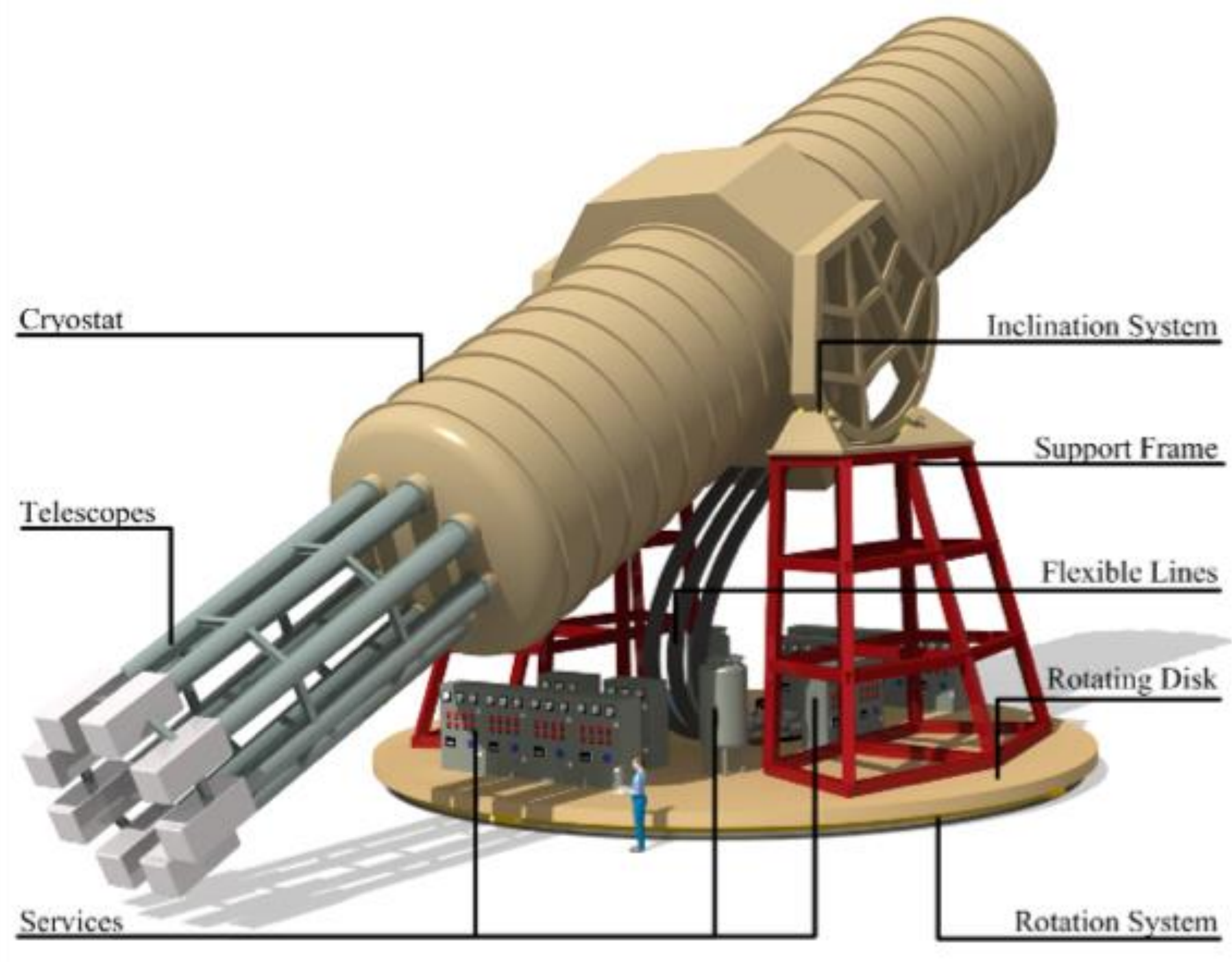

E.g. **InGrid Detectors**
- Micromegas built on top of a CMOS ASIC bump bond pads of the ASIC are used as charge collection pads;
- built and operated by Uni Bonn;
- excellent low background/low noise detector for detecting single photons!



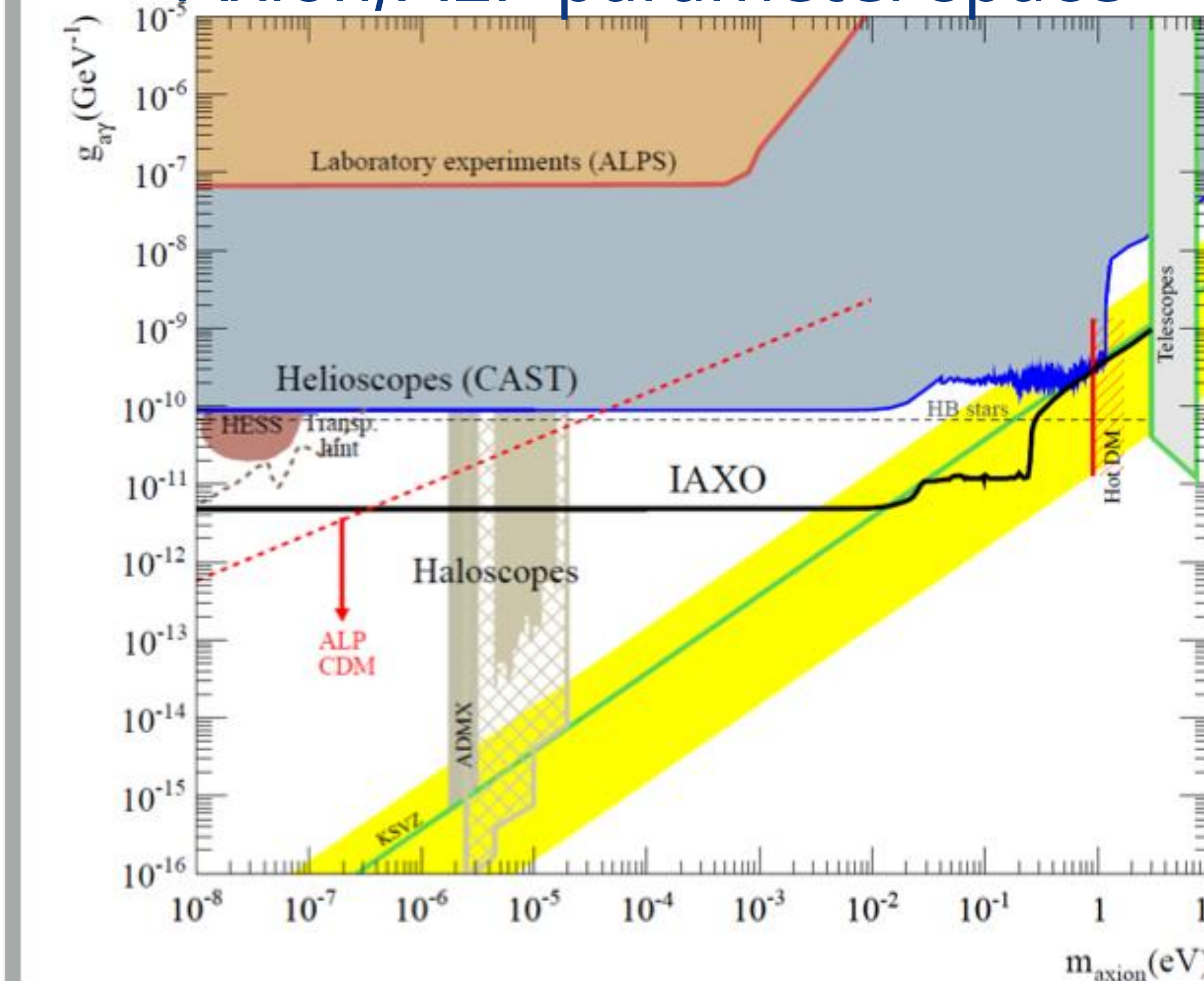
# Next step: IAXO?

## IAXO – Conceptual design




- Large toroidal 8-coil magnet *L* = ~20 m;
- 8 bores: 600 mm diameter each;
- 8 x-ray telescopes + 8 detection systems;
- Rotating platform with services.

## Axion/ALP parameter space



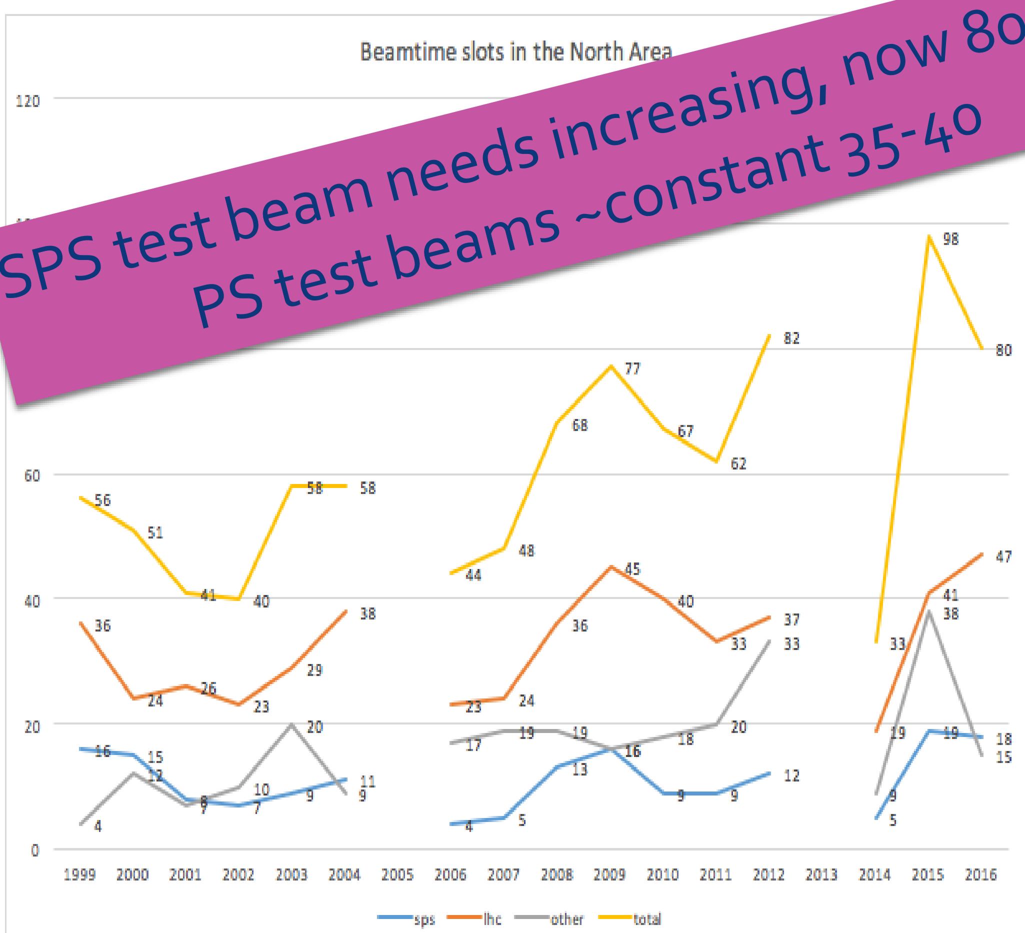

### Currently TDR in progress

- demonstration coil magnet;
- prototype x-ray optics;
- prototype low background detector setup is testing different technologies for detector;
- Studies to refine IAXO physics case and additional physics potential;
- Consolidate  and structure collaboration.

# Test beam facilities

<u>PS and SPS test beams in the East and North Areas</u> provide world-wide unique opportunities to develop novel technologies, to test and calibrate particle detectors

SPS test beam needs increasing, now 80-100
PS test beams ~constant 35-40




| Test beams* in the world, status September 2017 | | | | | | |
|---|---|---|---|---|---|---|
| Laboratory | Number of beam lines | Particles | Energy range | Diagnostics etc. | Availability | Information, contacts & comments |
| CERN / PS (CH) | 2 | e, h, μ (sec.) | 0.5 - 10 GeV/c | Threshold Cherenkov, scintillators, MWPCs, delay wire chambers, scintillators, magnet, movable platform | 9 months per year, continuous except winter shutdown. Duty cycle depends on PS / SPS / LHC operation mode and is typical * PS ~1-3% * SPS: 20-40% No PS and SPS test beams in 2019 and 2020 | Contact beam time request and scheduling: Sps.Coordinator@cern.ch http://sps-schedule.web.cern.ch/sps-schedule/ contact beam lines: sba-physicists@cern.ch http://sba.web.cern.ch/sba/ |
| CERN / SPS (CH) | 4 | p (prim.) e, h, μ (sec.) e, h (tert.) Pb ions (prim) other ion species (out of fragmented primary Pb ions) | 400 GeV/c 10 - ≈400 GeV/c 10 - 200 GeV/c 20 - 400 GeV/c proton equivalent (z=1) | Delay wire chambers, filament scanners, XEMC calorimeters, Threshold & CEDAR, hodoscopes, magnet, movable platform | | |
| CERN / CLEAR (CH) | 1 | e- | 50-250 MeV/c | | 8 -9 months per year | Contact: CLEAR-info@cern.ch https://clear.web.cern.ch |
| DAFNE BTF Frascati, (IT) | 1 | e+/e- both primaries and secondaries | 25-750 MeV/c Rep Rate 50Hz 1–40 ns 1 to $10^{10}$ p/pulse | Calorimeter, silicon pixel, remote trolley, gas system, HV, trigger | depending on DAFNE schedule, from 25 to 35 weeks/year Not available in the first half of 2018 | Contact: btf@lnf.infn.it, paolo.valente@lnf.infn.it info at: http://www.lnf.infn.it/acceleratori/btf http://www.lnf.infn.it/acceleratori/padme |
| DESY (D) | 3 | e+, e- (sec.) e- (prim., planned for 201X) | 1 - 6 GeV/c 6.3 GeV/c | Trigger systems and beam telescopes, magnet (~1T) | 10 months per year, Duty cycle ~ 50% | Contact: Testbeam-Coor@desy.de http:// testbeam.desy.de |
| ELPH (Sendai) (JP) | 2 | photons (tagged) e+, e- (conv.) | 0.7-1.2 GeV/c 0.1-1.0 GeV/c beam rate < 500kHz (typical rate: 3kHz) | | 2 months/year | contact: Toshimi Suda (suda@lns.tohoku.ac.jp) info: http://hayabusa1.lns.tohoku.ac.jp/en/users/?id=a5 |
| FERMILAB/FTBF (US) | 2 | p (prim.) e, h, μ (sec.) h (tert.) | 120 GeV/c 1-66 GeV/c 200-500 MeV/c | Cherenkov, TOF, pb-glass calorimeters, MWPC, Si Tracker, see website for more | 24 hrs/day 6% duty cycle | Contact: FTBF_Co@fnal.gov http://ftbf.fnal.gov/ more contacts: Mandy Rominsky (rominsky@fnal.gov) Erik Ramberg (ramberg@fnal.gov) |
| IHEP Beijing (CN) | 3 | e (prim.) e (sec.) p, π (sec.) | 1.1 - 2.5 GeV/c 100 - 300 MeV/c 0.4 - 1.2 GeV/c | MWPC, TOF Cherenkov, CAMAC system, platform | Availability: 3 months per year, duty cycle depends on BEPCII operation mode | Contact: Hu Tao (hut@ihep.ac.cn) |
| IHEP Protvino (RU) | 5 | p (prim), p, K, π, μ, e (sec.) C-12 (prim) | 70 GeV/c 1-45 GeV/c 6-300 GeV/c | Cherenkov, TOF, MWPC | two months per year duty cycle (U-70 machine): 15-30% | contact: Alexandre Zaitsev (alexandre.zaitsev@cern.ch) |
| KEK / JPARC (JP) | | | | | | No dedicated lines for test beams contact: Masaharu Ieiri (masaharu.ieiri@kek.jp) http://j-parc.jp/researcher/Hadron/en/index.html |
| KEK / Tsukuba (JP) | | | | | | Fuji beam line in KEKB main ring unavailable until Super KEKB will resume operation http://www.kek.jp/ja/Facility/IPNS/K11BeamLine/ |
| PSI / piE1, piM1, etc. (CH) | 2-4 | π+-, μ+-, e+-, p | 50-450 MeV/c, rate <$10^9$ sec$^{-1}$ 20nsec structure continuous beam at very high rate | | 6-8 months per year | Beam time allocated by programme committee (twice per year) Contact: Davide Reggiani (davide.reggiani@psi.ch) |
| PSI / PIF (CH) | 1 | p | 5 - 230 MeV/c max. current 2 - 5 nA, rate <$10^{10}$ sec$^{-1}$, typ. flux $10^8$ cm$^{-2}$ sec$^{-1}$ for wide beam, energy, beam spot and flux selectable by user | | 11 months per year, mostly during weekends | Contact: Wojtek Hajdas (wojtek.hajdas@psi.ch) |
| SLAC (US) | 1 | e (prim.) e (sec.) | 2.5 - 15 GeV/c 1 - 14 GeV/c | | 9 months per year, 50% duty cycle | Contact: Carsten Hast (hast@slac.stanford.edu) https://slacportal.slac.stanford.edu/sites/ard_public/tfd/ |
| SPRING-8, Compton Facility (JP) | 1 | photons (tagged) e+, e- (conv.) | 1.5 - 3.0 GeV/c 0.4 - 3.0 GeV/c | | >60 days per year | Contact: Takashi Nakano (nakano@rcnp.osaka-u.ac.jp) http://www.spring8.or.jp/en/ |
| University of Bonn ELSA (D) | 1 | e- | Energy range: 1.2 - 3.2 GeV/c rate: ~1 kHz - 1 GHz | Trigger, beam telescope | upon request, ~30 days/year | Contact: Daniel Elsner elsner@physik.uni-bonn.de http://www-elsa.physik.uni-bonn.de/elsa-facility_en.html |
| University of Mainz MAMI (D) | 2 | e- gamma | Energy range for e- and gamma beam: < 1.6 GeV/c e- intensity < 100muA | energy tagged photon beam | upon request, ~30 days/year | Contact: Susanne Fischer fischer@kph.uni-mainz.de http://www.kph.uni-mainz.de/eng/index.php |

*beam lines with beams of energies higher than 100 MeV/c