CERNs physics programme

Introduction to CERN’s experiments & facilities

Christoph Rembser (CERN)

CERN: founded in 1954: 12 European States

"Science for Peace"

Today: 21 Member States

~ 2300 staff
~ 1400 other paid personnel
~ 12500 scientific users

Budget (2015) ~1000 MCHF

Member States: Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland and United Kingdom

Associate Member States: Pakistan, Turkey

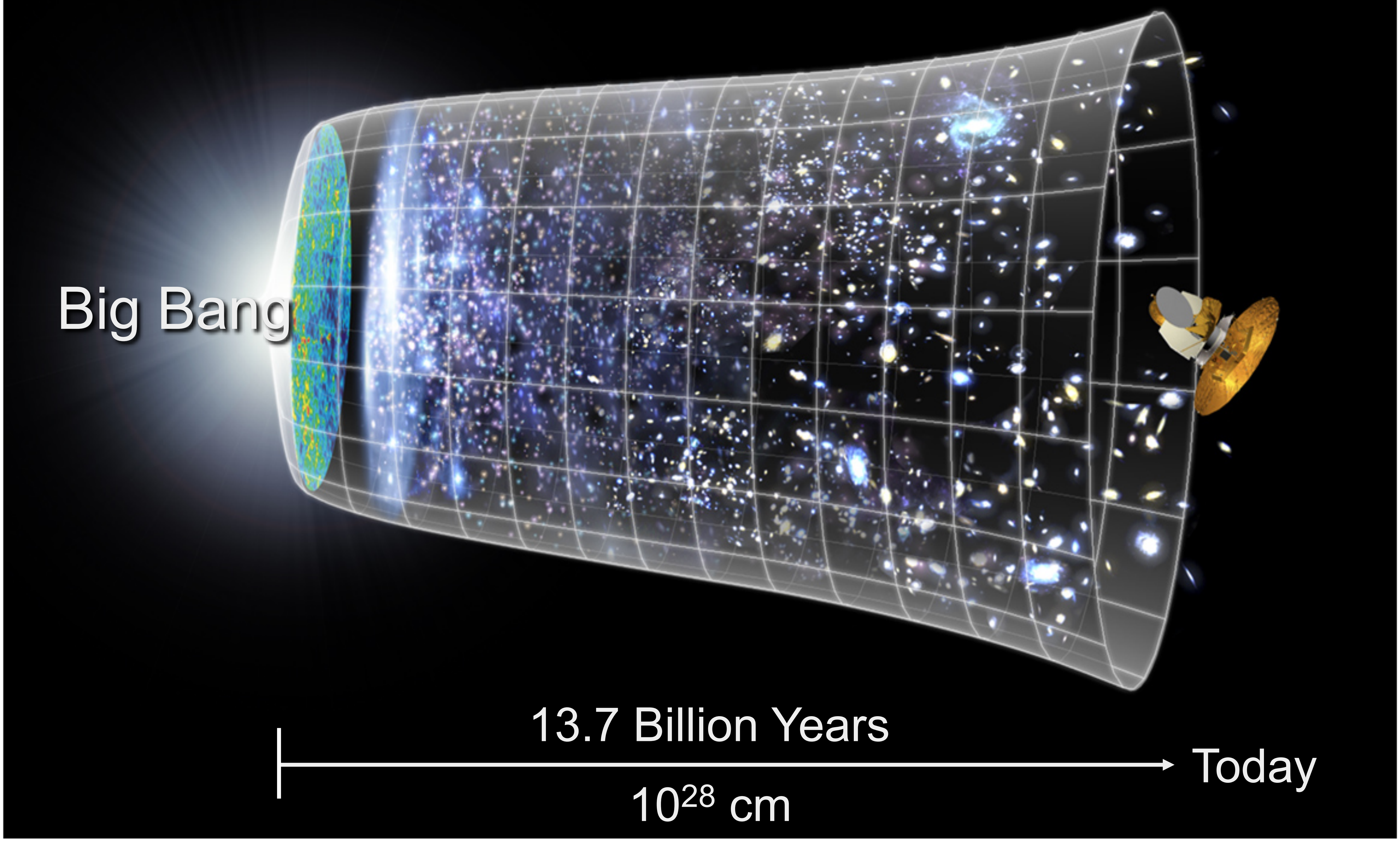
States in accession to Membership: Romania, Serbia

Applications for Membership or Associate Membership: Azerbaijan, Brazil, Croatia, Cyprus, India, Russia, Slovenia, Ukraine

Observers to Council: India, Japan, Russia, United States of America; European Union, JINR and UNESCO

Scientific Challenge

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



Particle physics, what we know/don't know

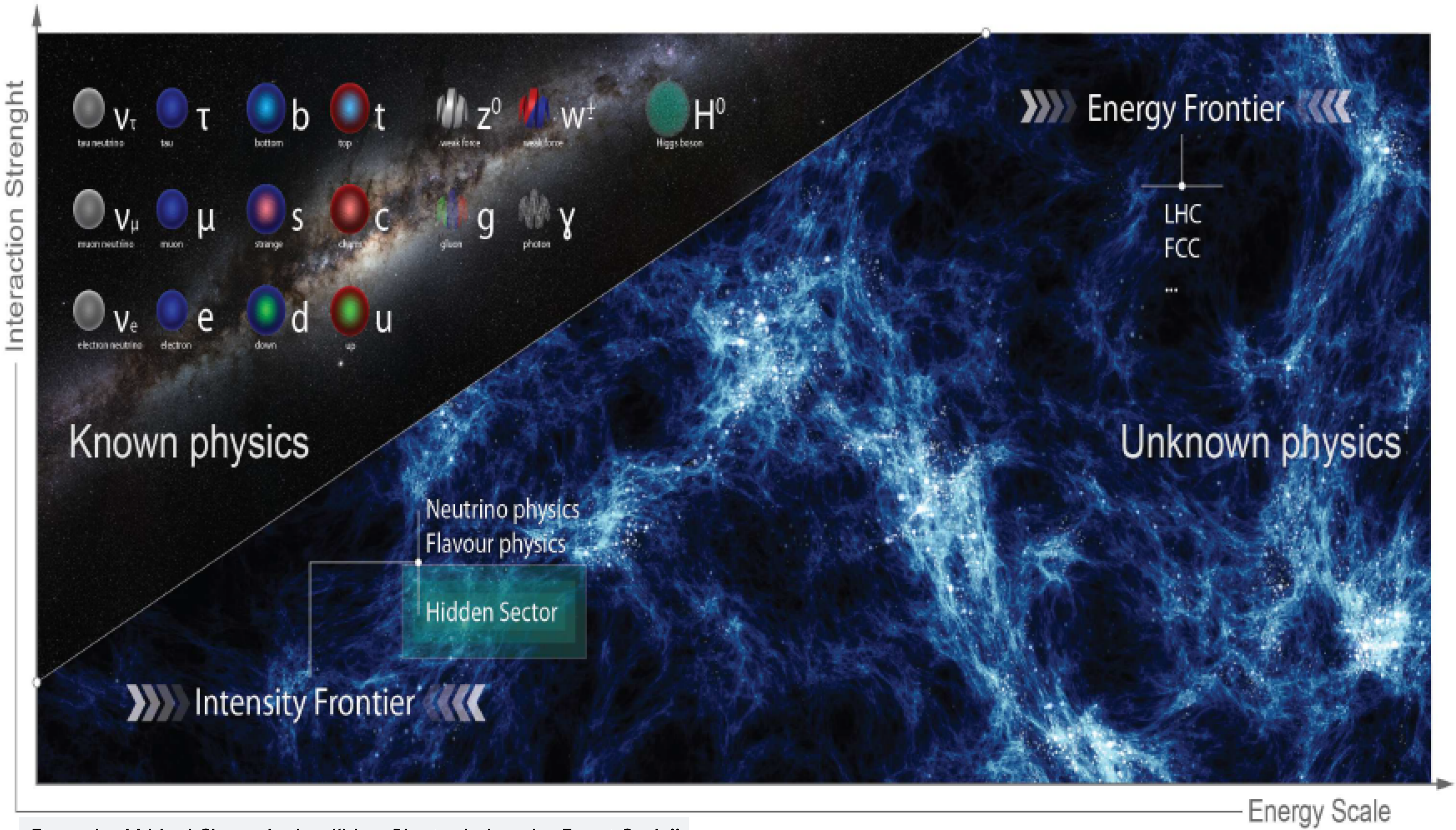


Figure by Mikhail Shaposhnikov "New Physics below the Fermi Scale" at the Physics Beyond Colliders Kickoff workshop

Particle Physics Landscape

Understanding of the "known": Hadronic matter
deconfinement, hadron structure, non-perturbative QCD
@CERN: *experiments at the PS and SPS*

High energy frontier
@CERN: *LHC*

Multidisciplinary
climate, medicine
@CERN: *experiments at the PS, SPS, AD*

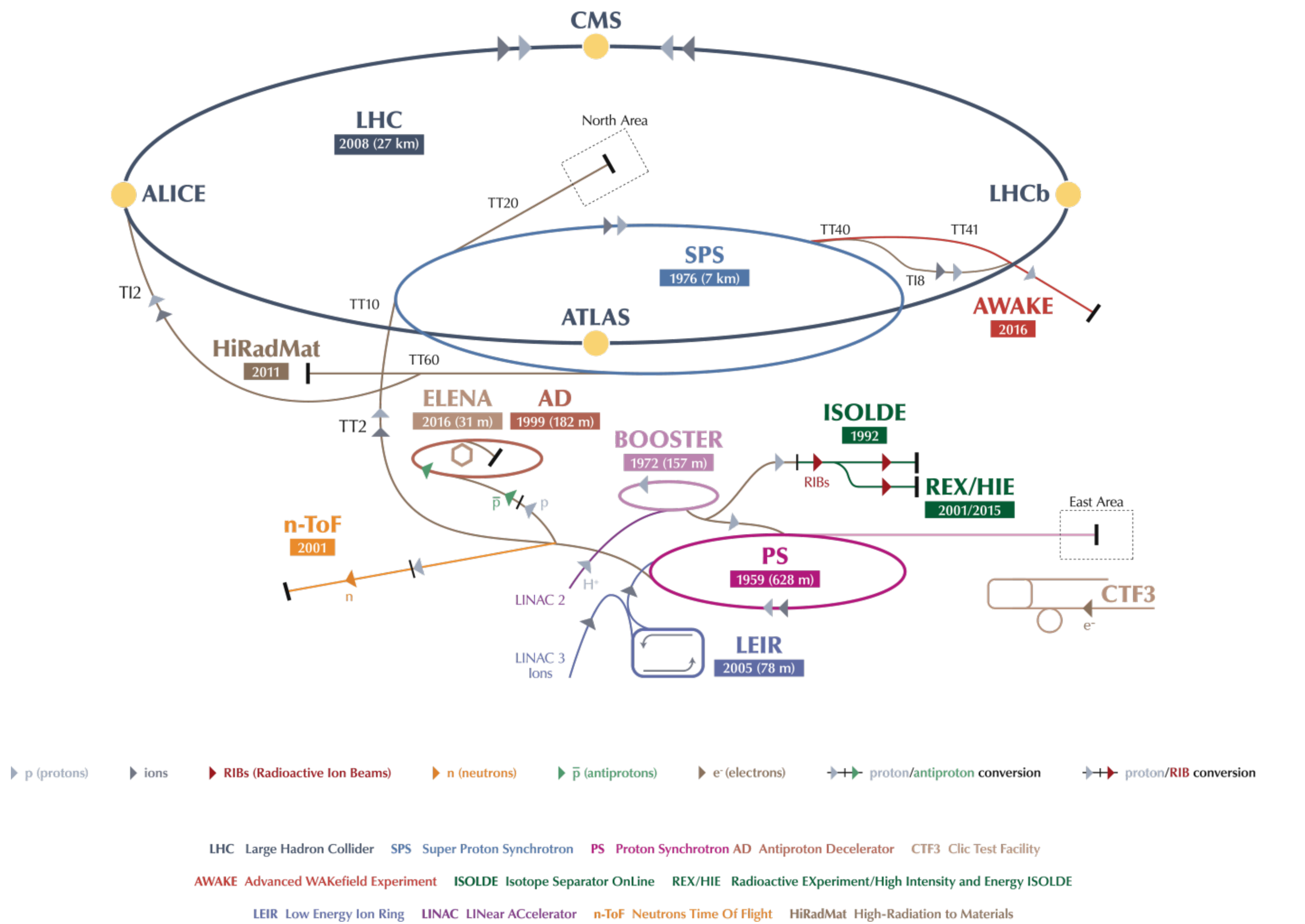
Intensity/precision frontier: low energy
heavy flavours, rare decays, antiprotons, isotopes
@CERN: *experiments at the PS, SPS and AD*

Non-accelerator
dark matter, double beta decay, astroparticles
@CERN: *searches using strong magnets*

Intensity frontier: Neutrinos
masses and mass hierarchy
@CERN: *R&D for neutrino detectors*

R&D for accelerators and detectors
@CERN: *everywhere*

The CERN accelerator complex



LINAC2, LINAC3, LINAC4

PROTONS

Proton LINAC2 (1978)

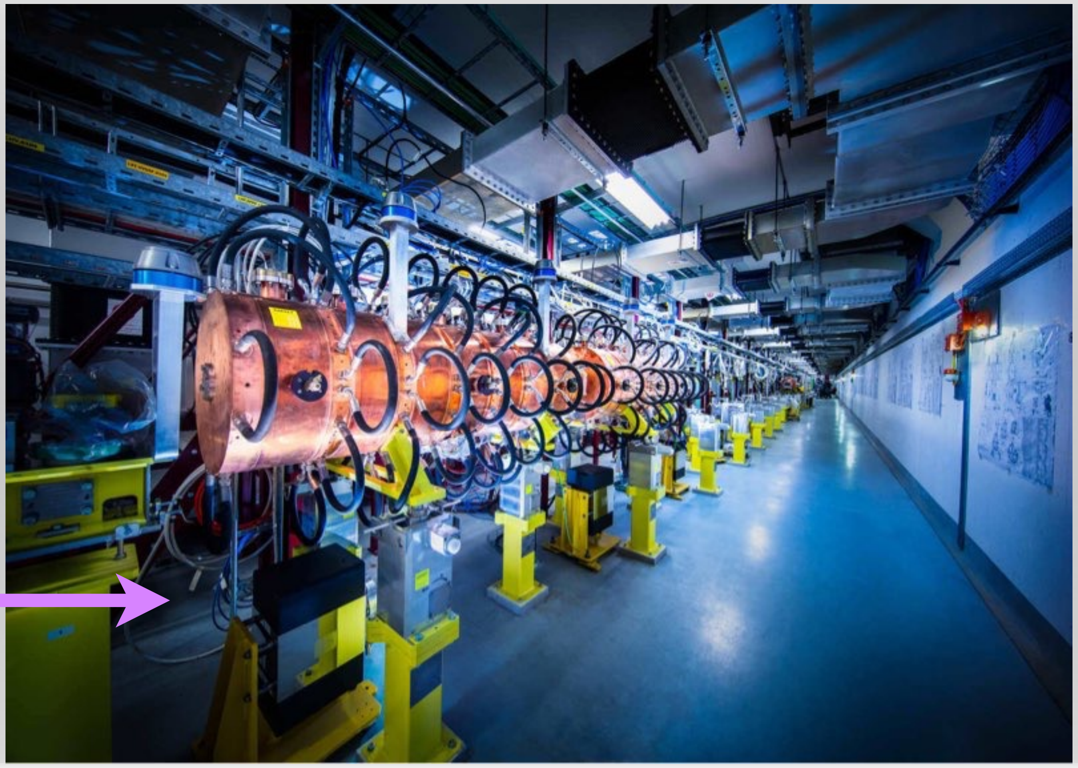
Protons accelerated to **50MeV**; typical intensities: **$8.8*10^{13}$ particles/cycle**

average availability: 98.4% (2016)

hand-over during LS2

H- LINAC4 (2020)

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

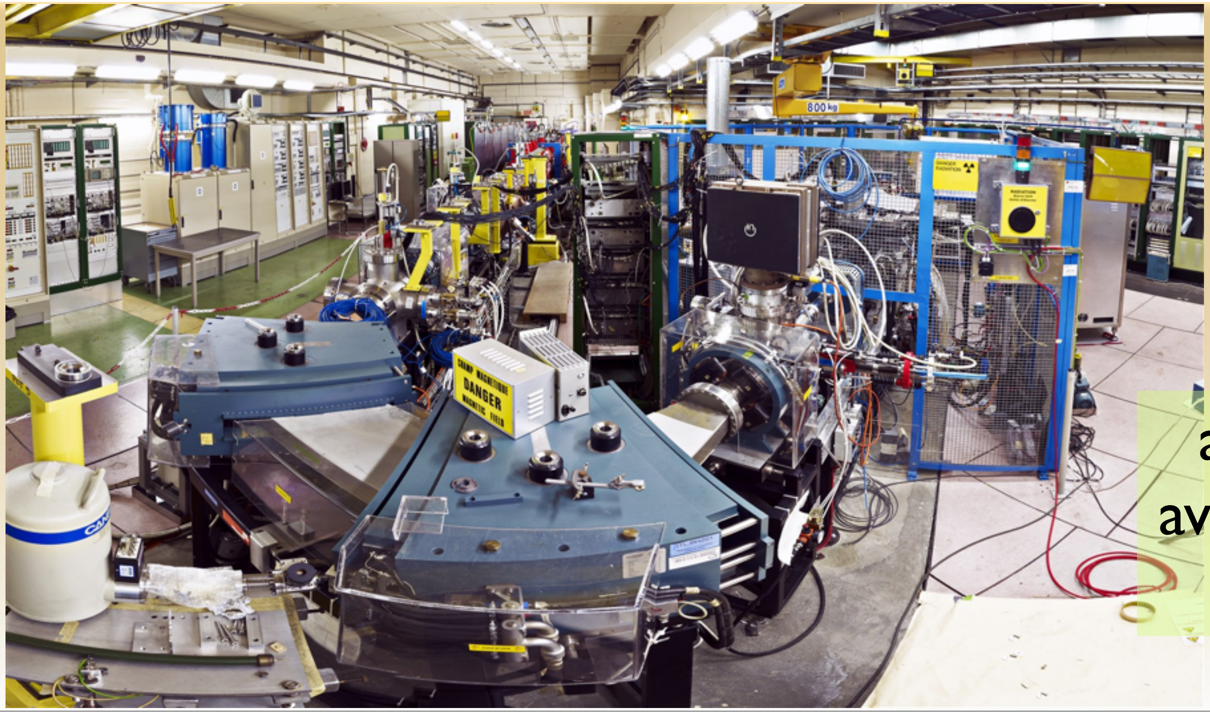


HEAVY IONS

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

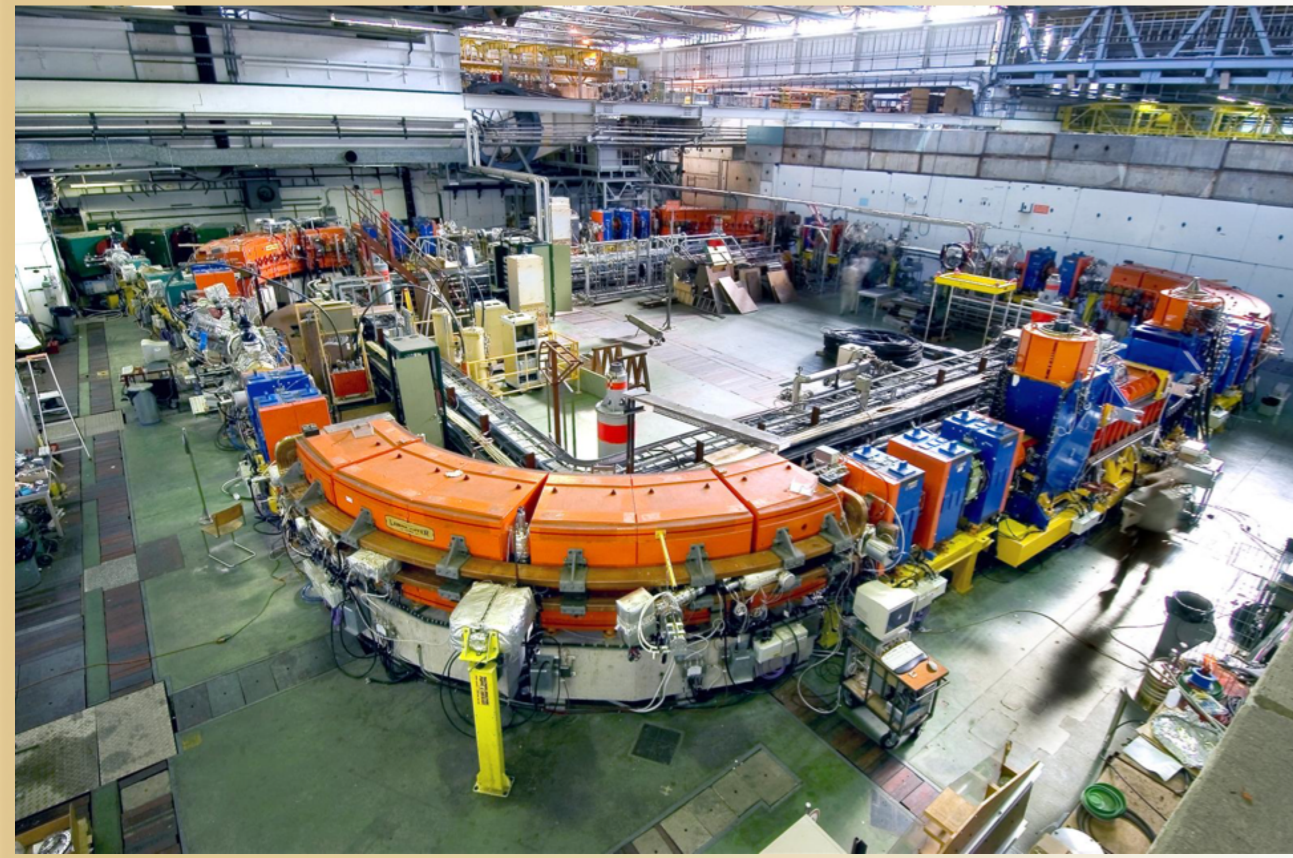
average availability: 95% (2016)

<u>PS Booster (1972):</u>

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



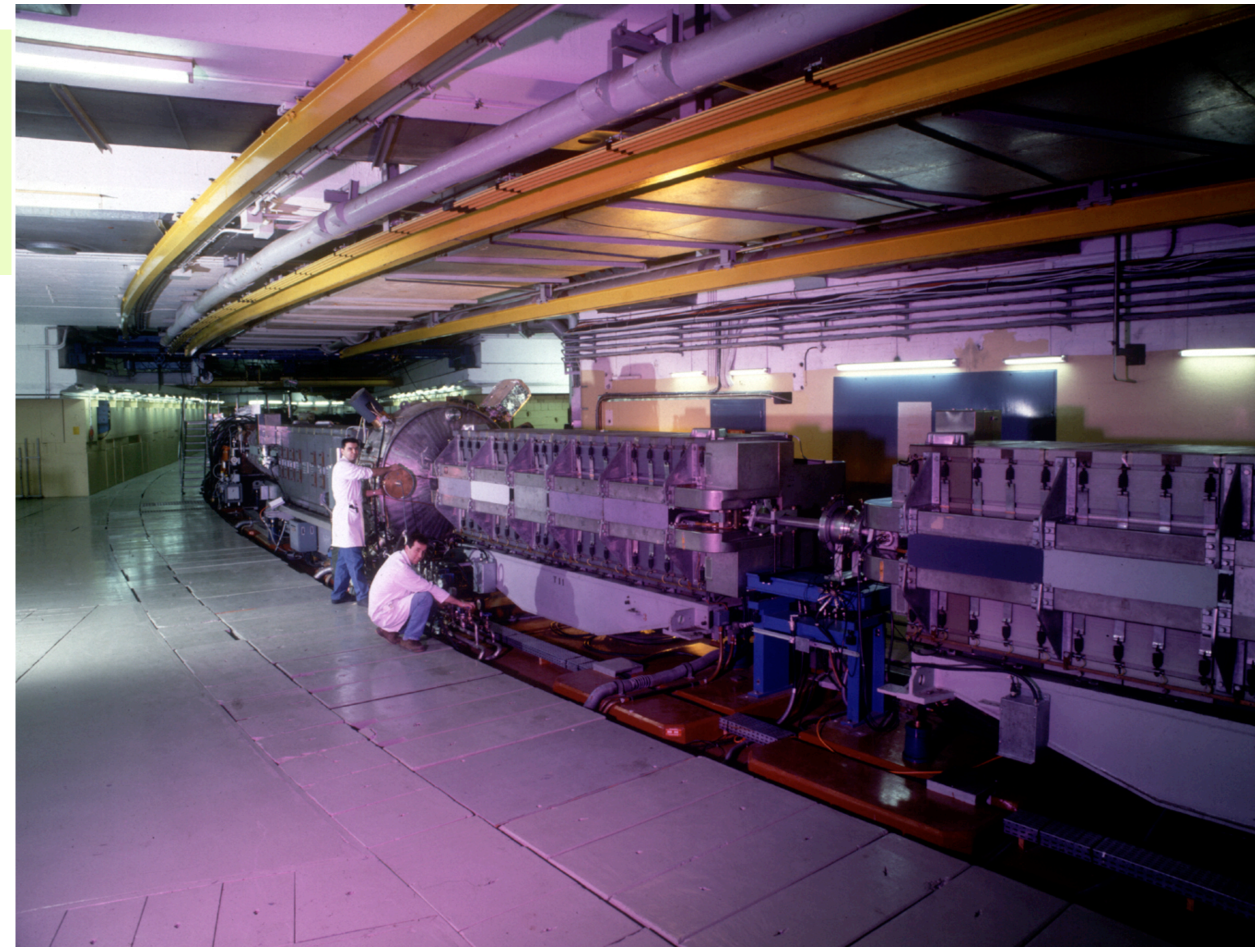
<u>LEIR (2005):</u>

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

average availability: 88% (2016)



Proton Synchrotron PS (1959):
filled by 2 batches from Booster, ramping protons from **14** to **26GeV**, maximum 1.4×10^{13} protons per pulse.

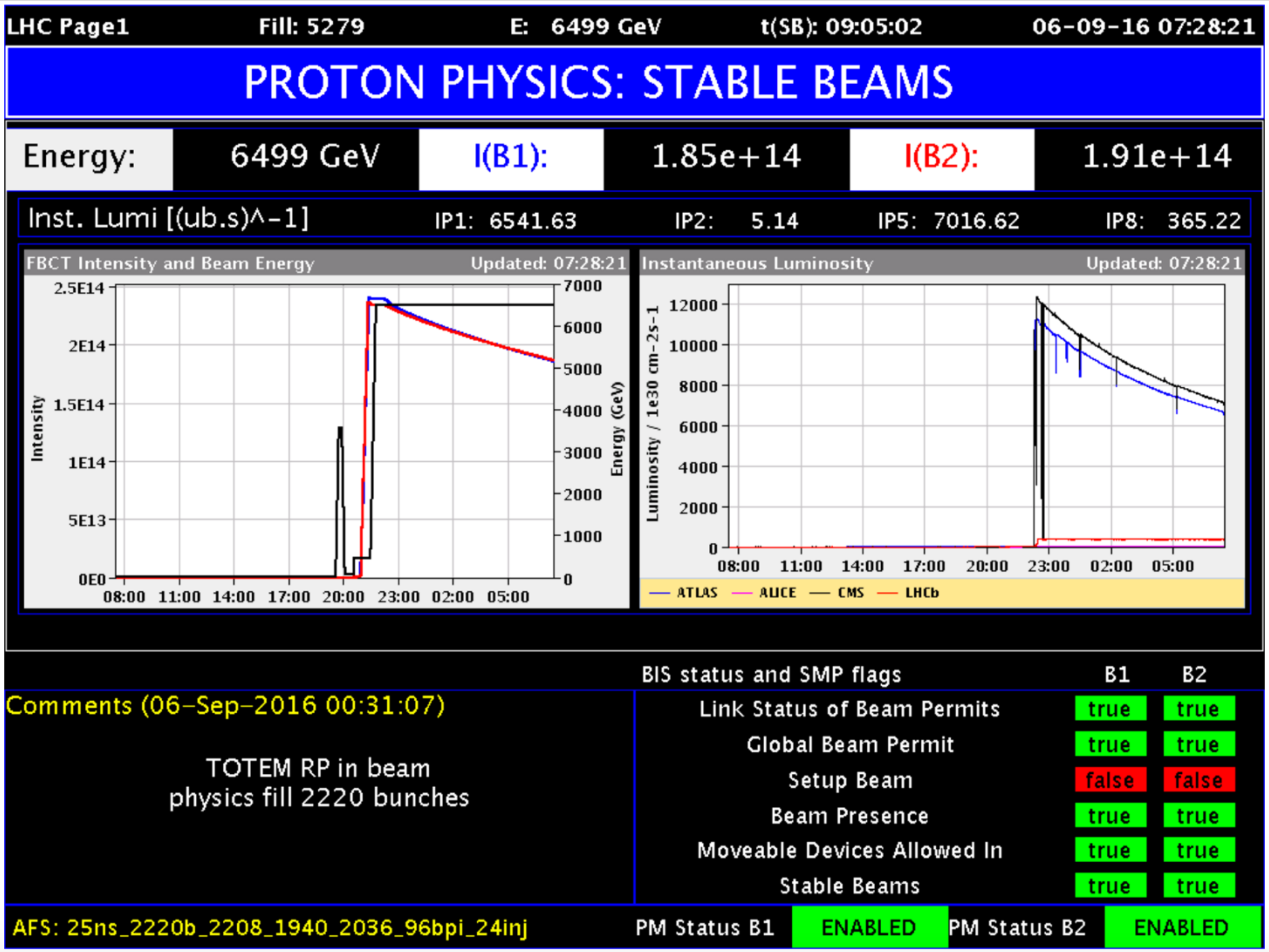
Superproton Synchrotron SPS (1976):
accelerates protons up to **400GeV** (FT) or **450GeV** (LHC) with intensities up to $\mathbf{9.5\,10^{9}}$ protons per bunch (FT) or $\mathbf{1.2\,10^{11}}$ protons per bunch (LHC25ns).

average availability: 85% (2016)

The LHC

Up to a few days ago…

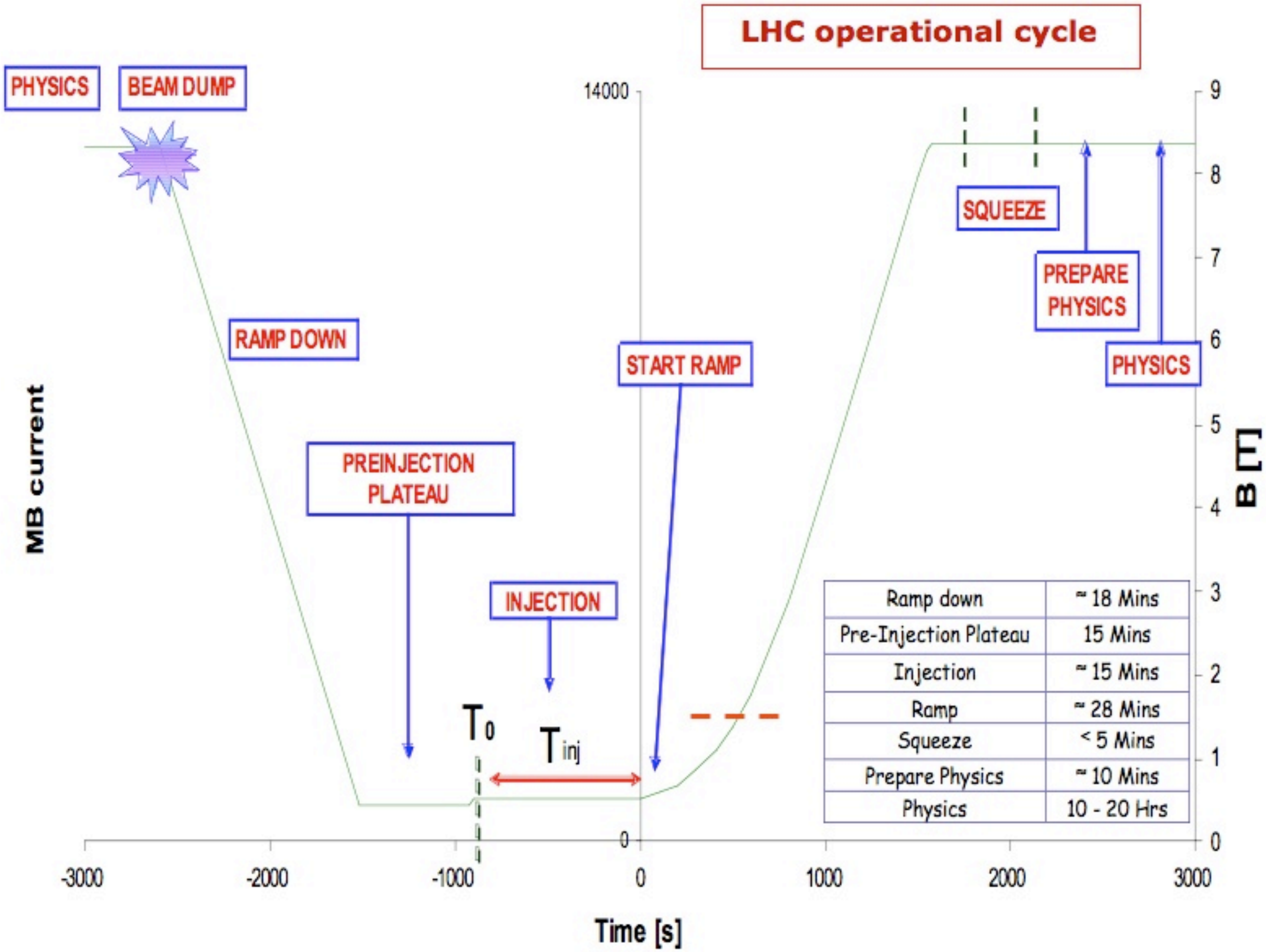
…the LHC was taking data - machine and experiments were performing extremely well!



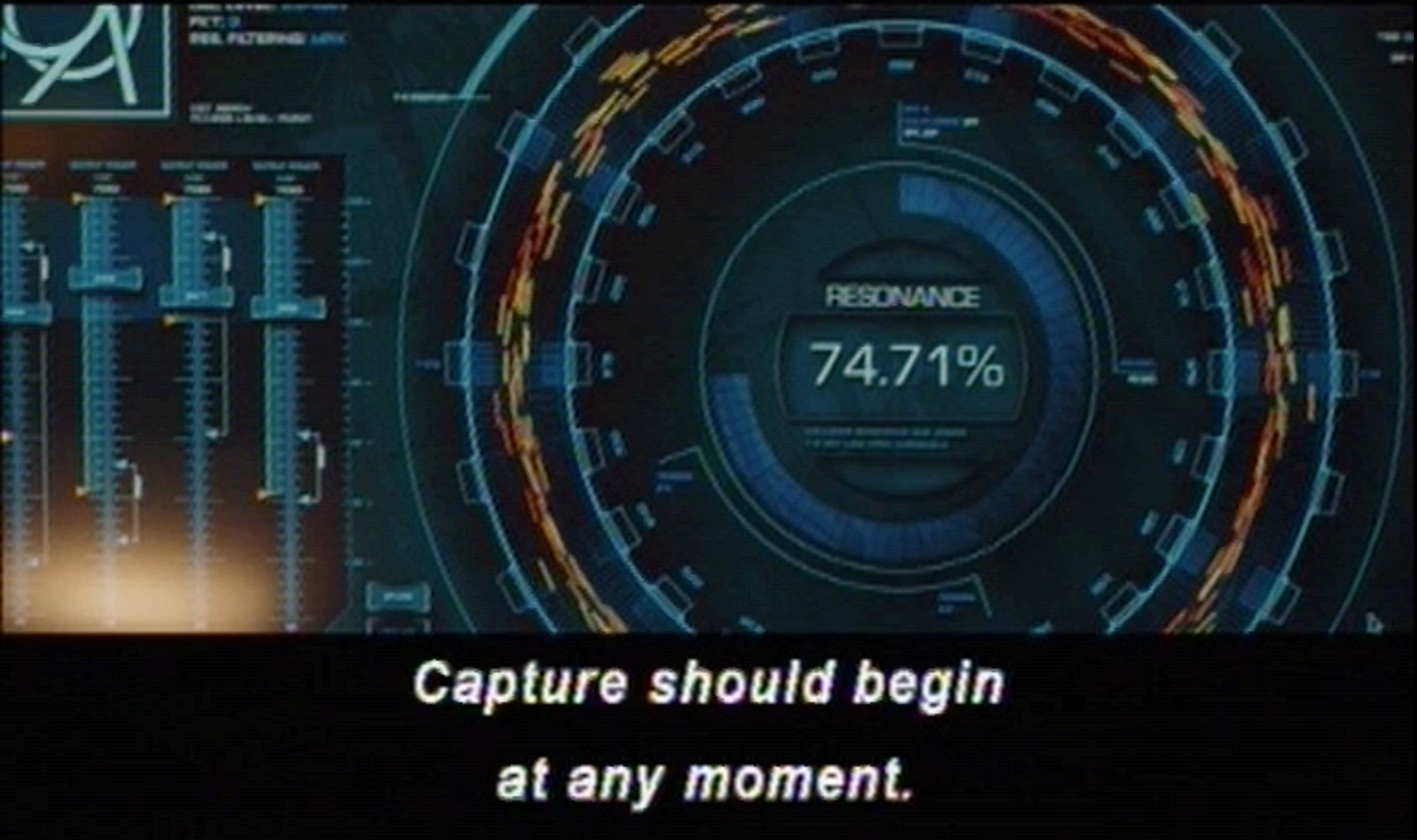
LHC: collisions 24/7

- 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)

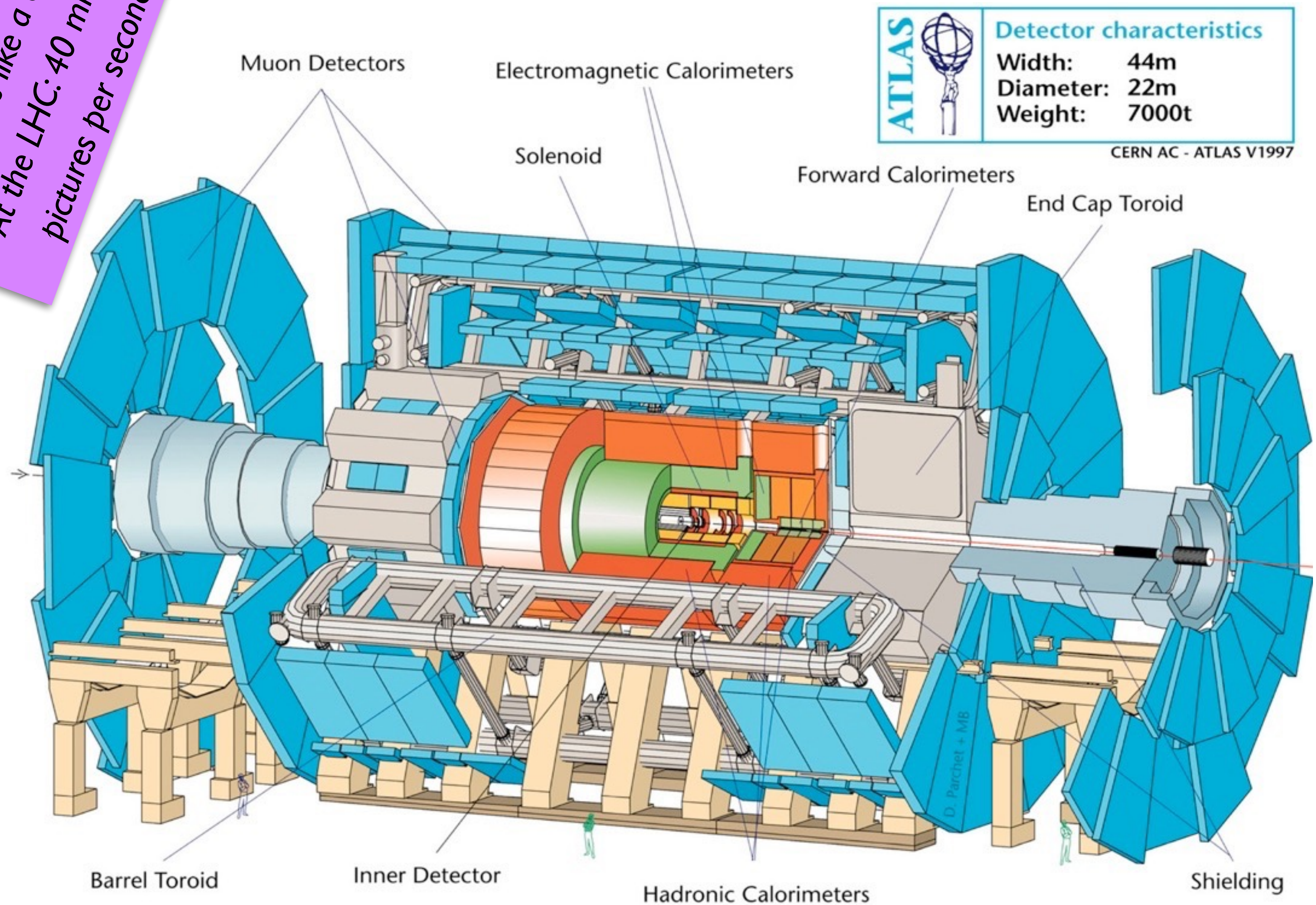


CERN und der Large Hadron Collider
(in dem Film "Illuminati")



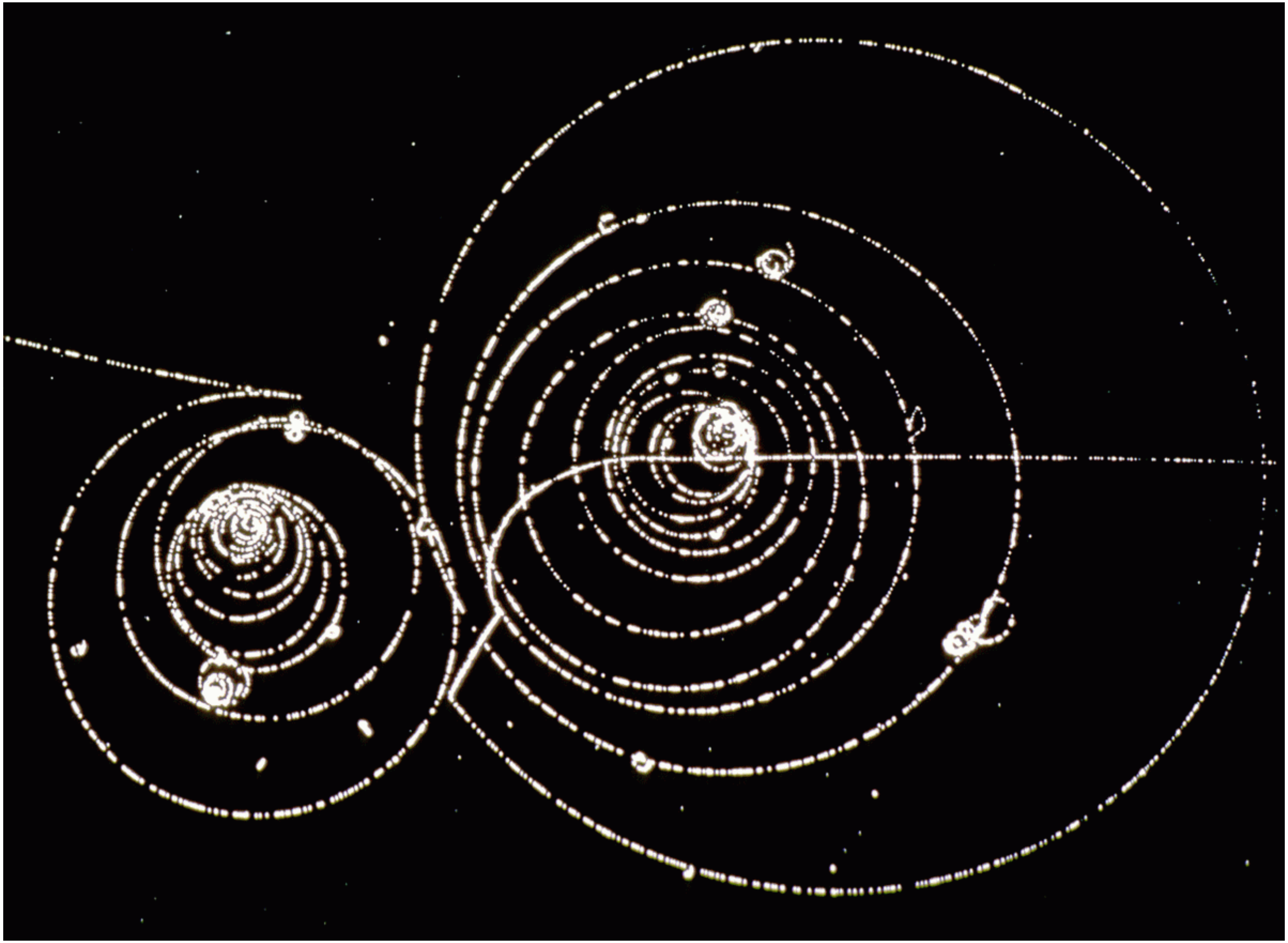
An LHC detector

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

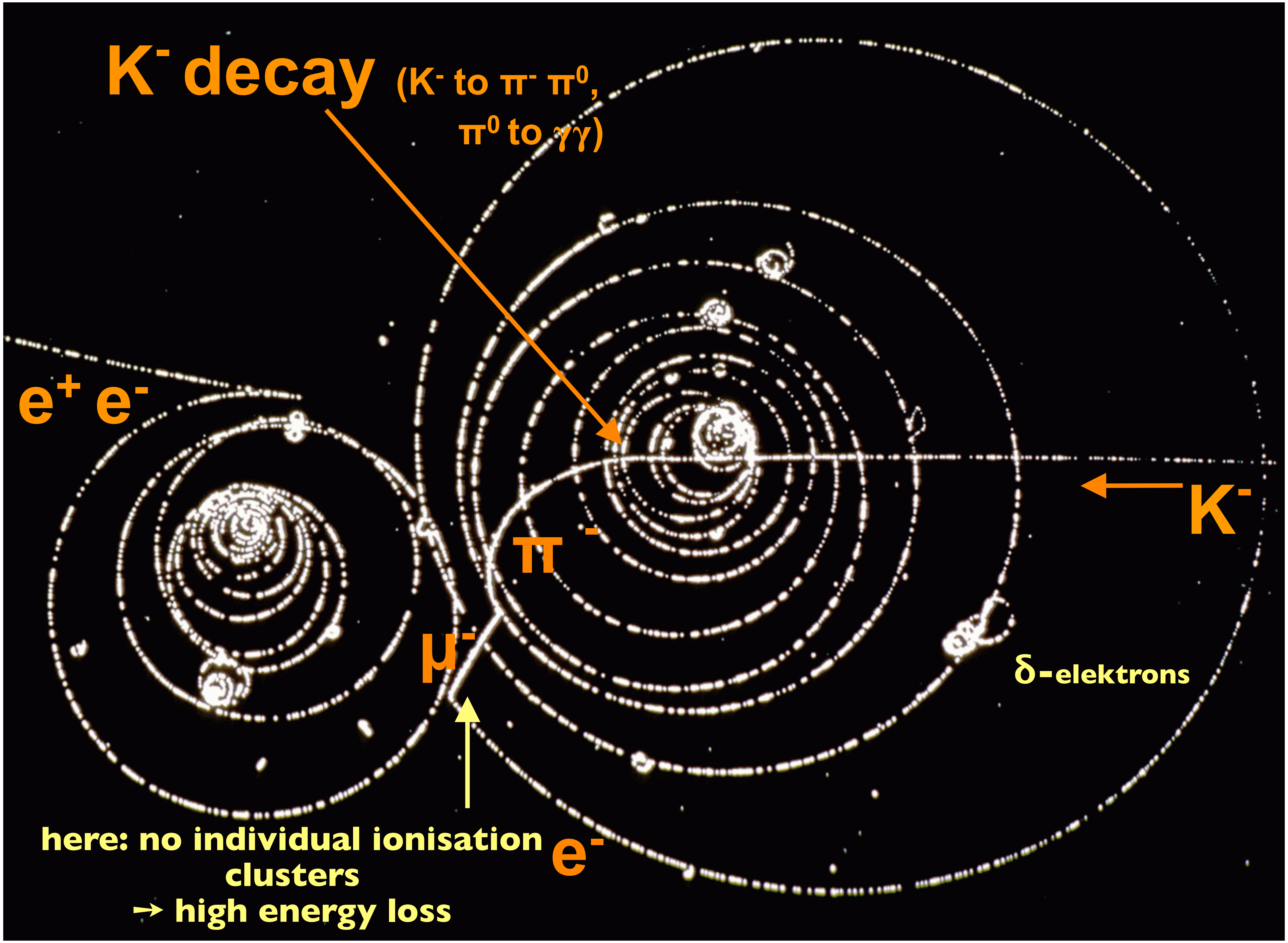


Taking pictures of particles

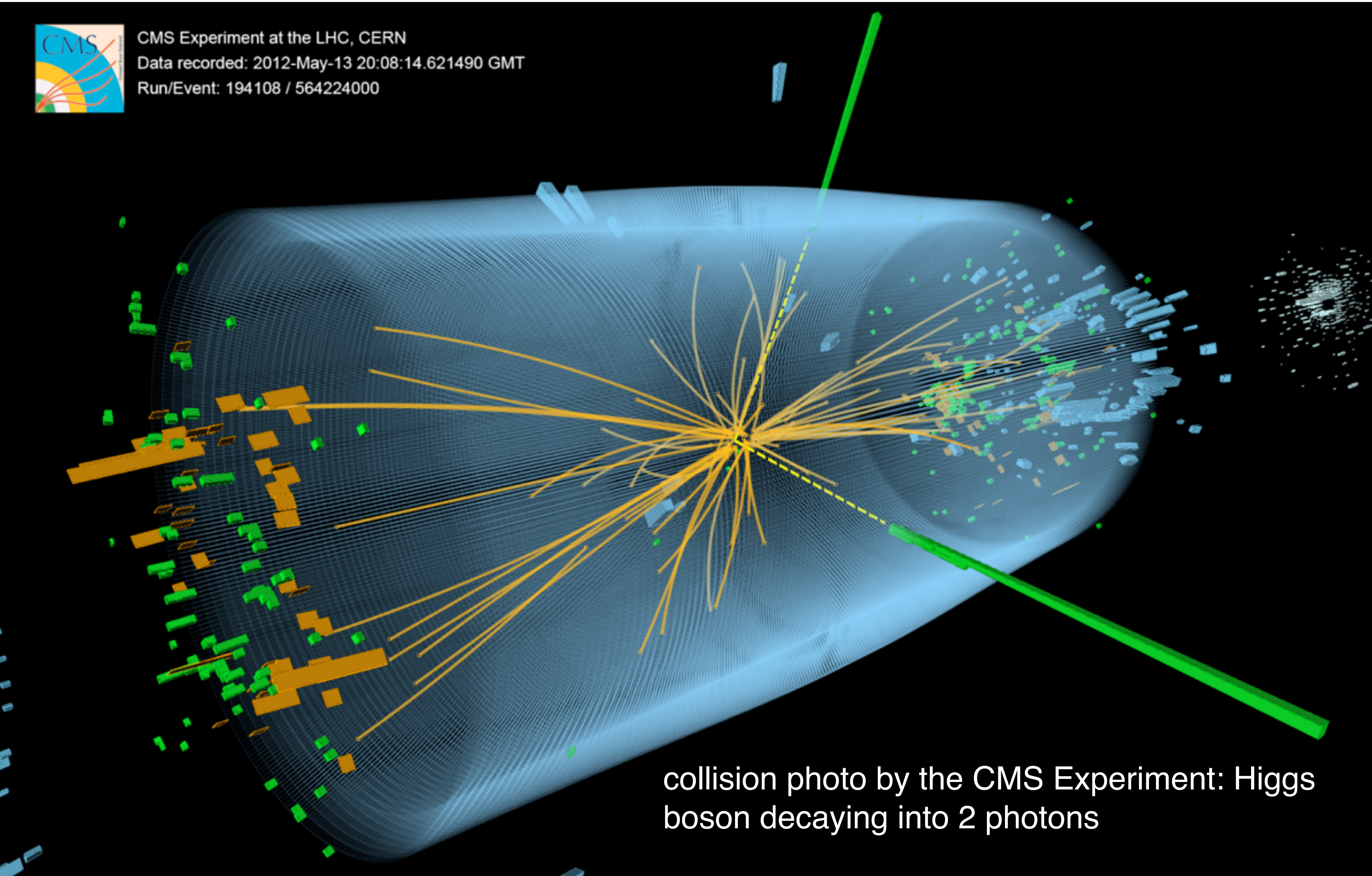
…what you see…



…what has happened



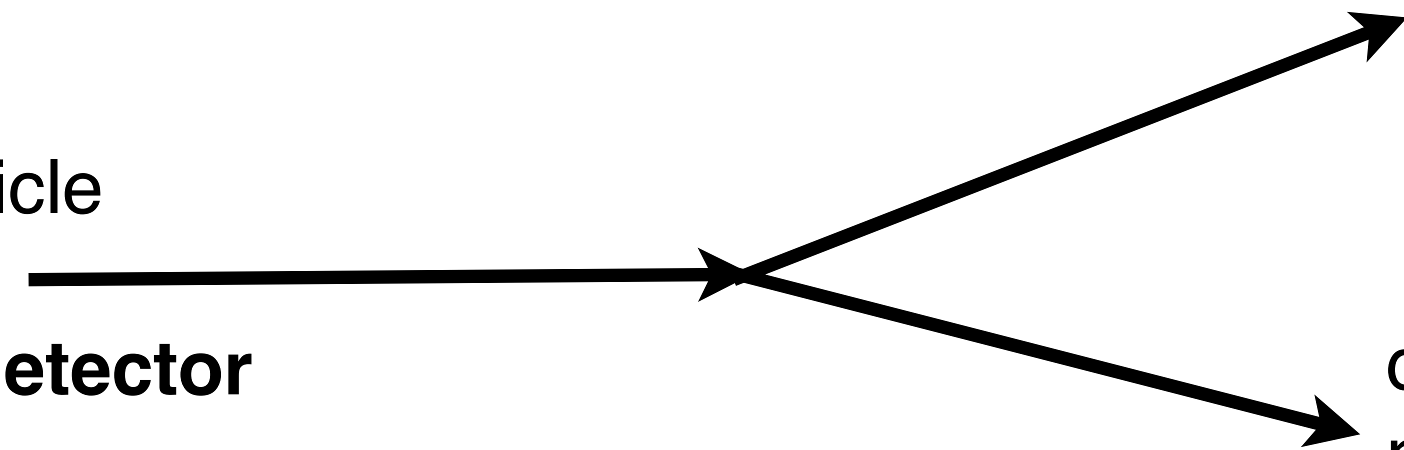
4. July 2012: CERN special seminar
“CERN experiments observe particle consistent with long-sought Higgs boson”



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

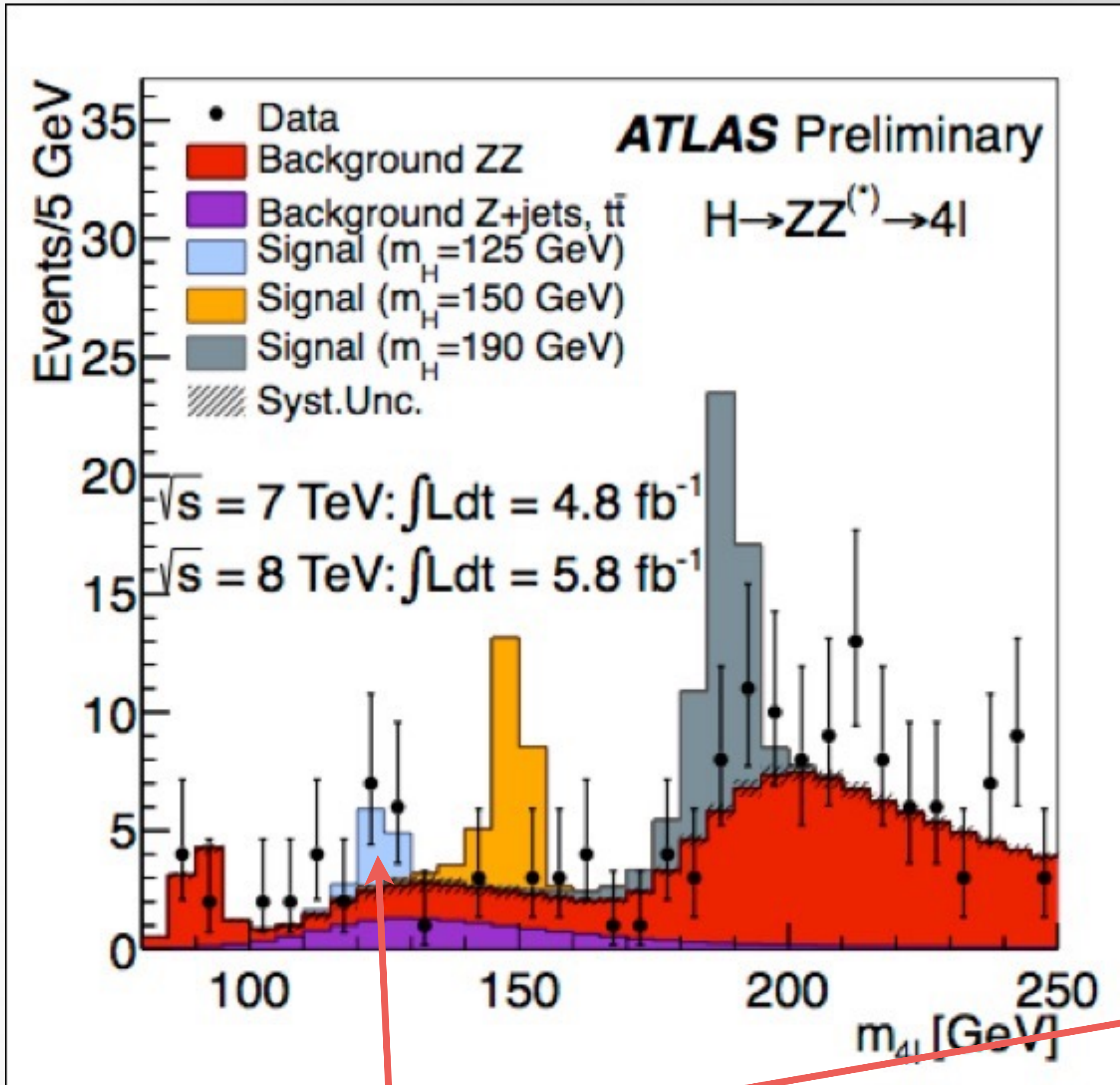
Decay particles (m, E, p)
are measured in detector!

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

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

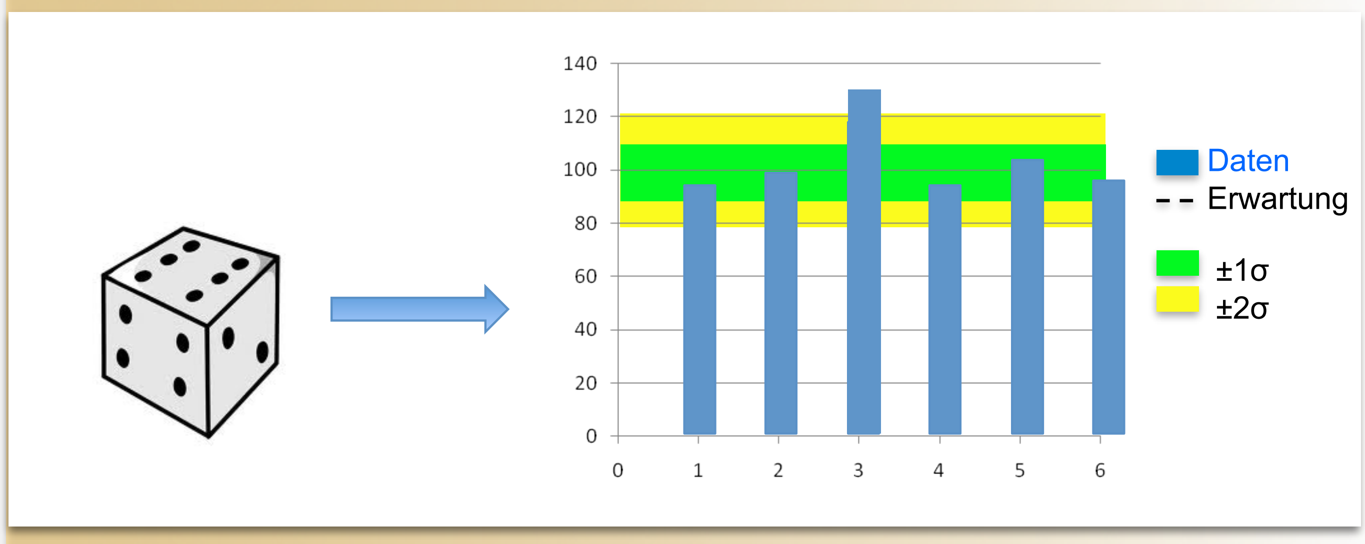
$$\begin{aligned} M^2 &= (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2 \\ &= m_1^2 + m_2^2 + 2\left(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2\right) \end{aligned}$$

Finding new particles: calculate invariant mass

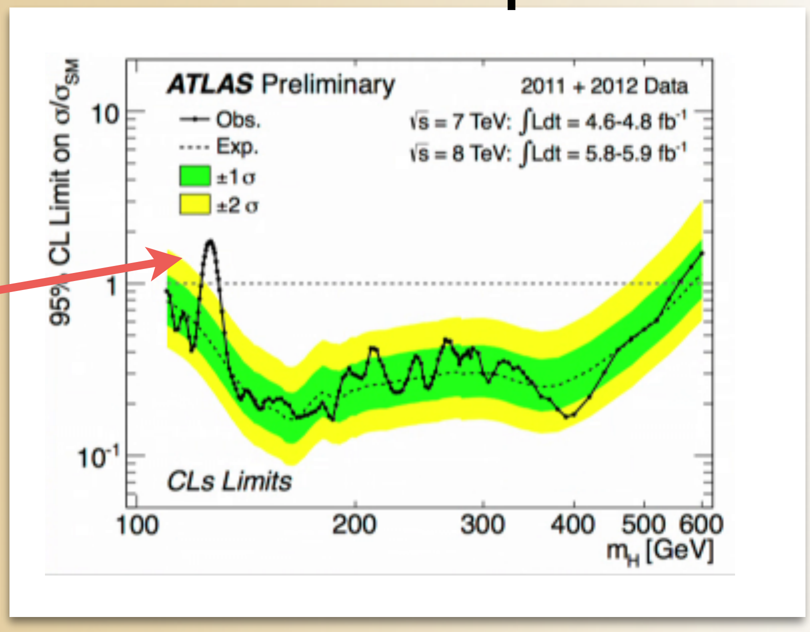


This is the Higgs particle!!!

Example: is the dice marked?

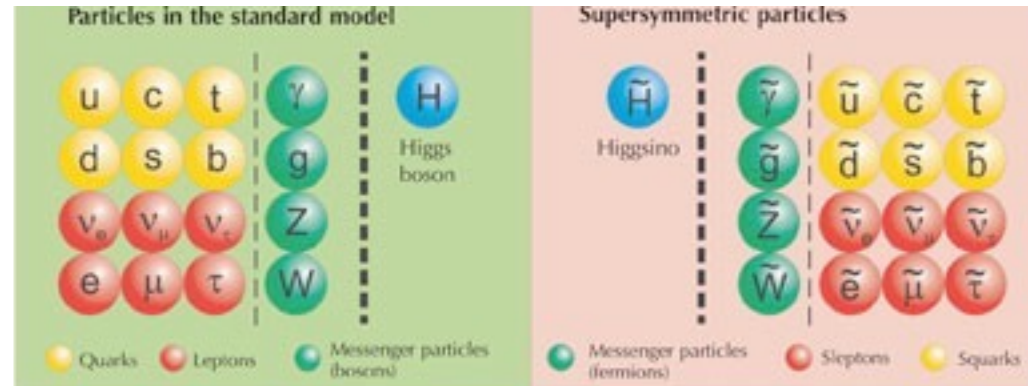


Is there a new particle?



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?

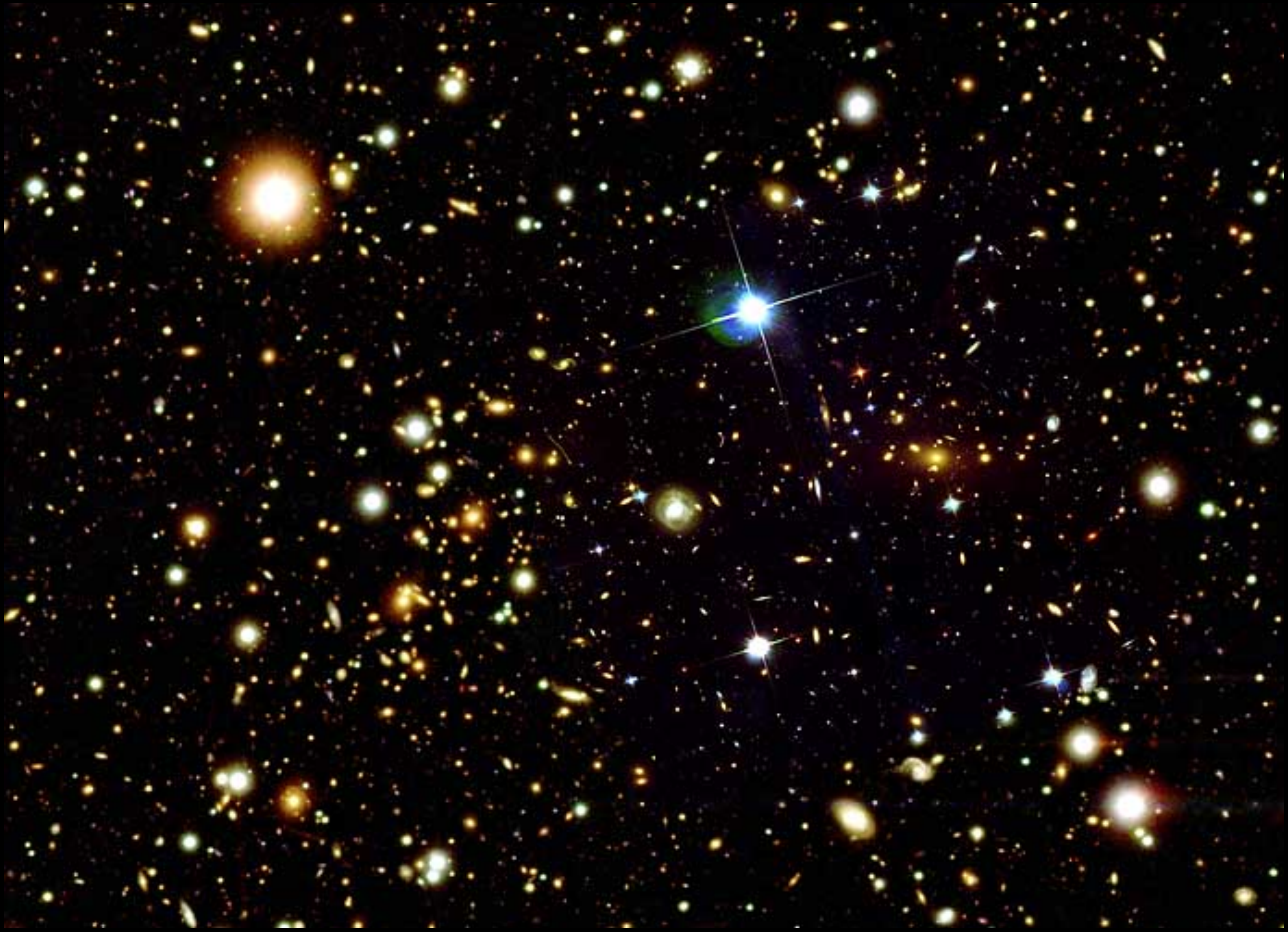
© Rocky Kolb

- What is Dark Energy?

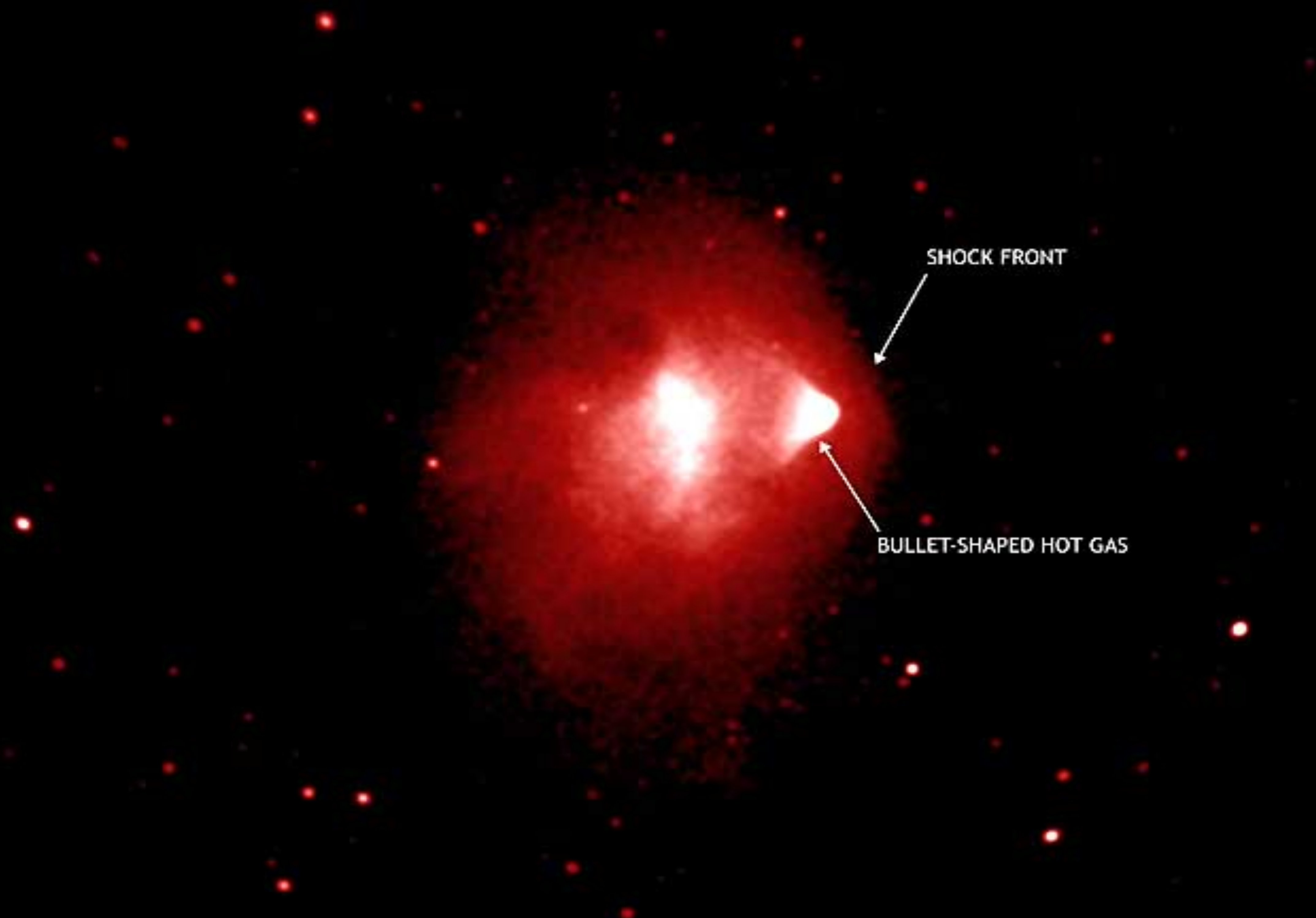
- Why did antimatter after Big Bang disappear?
- Are there an unknown unknowns?

My dream at the LHC: find **dark matter**

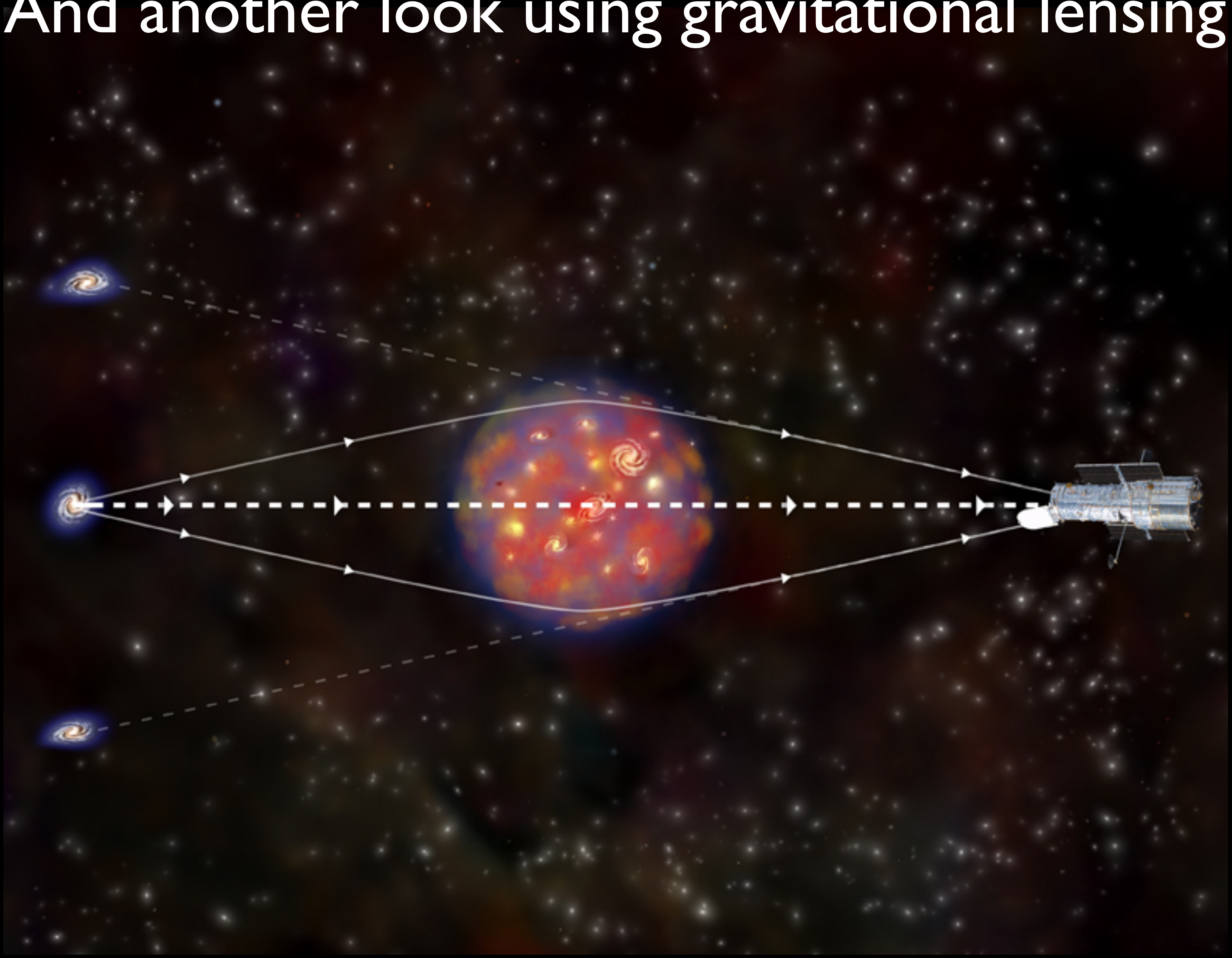
Why? Take a look at the stars (as here August 2006)



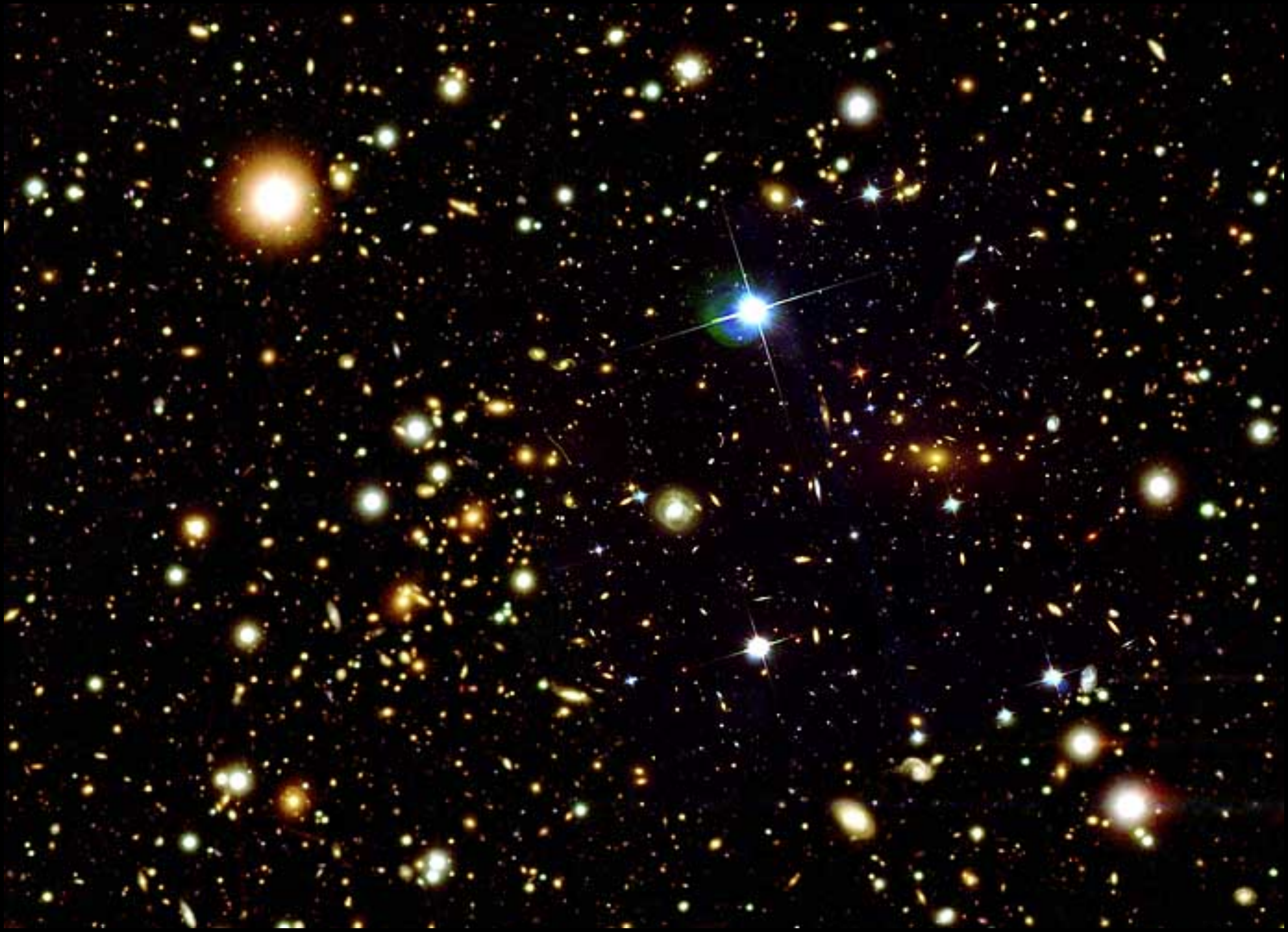
Take another look at same region.
This time at different wave length (hot gases)



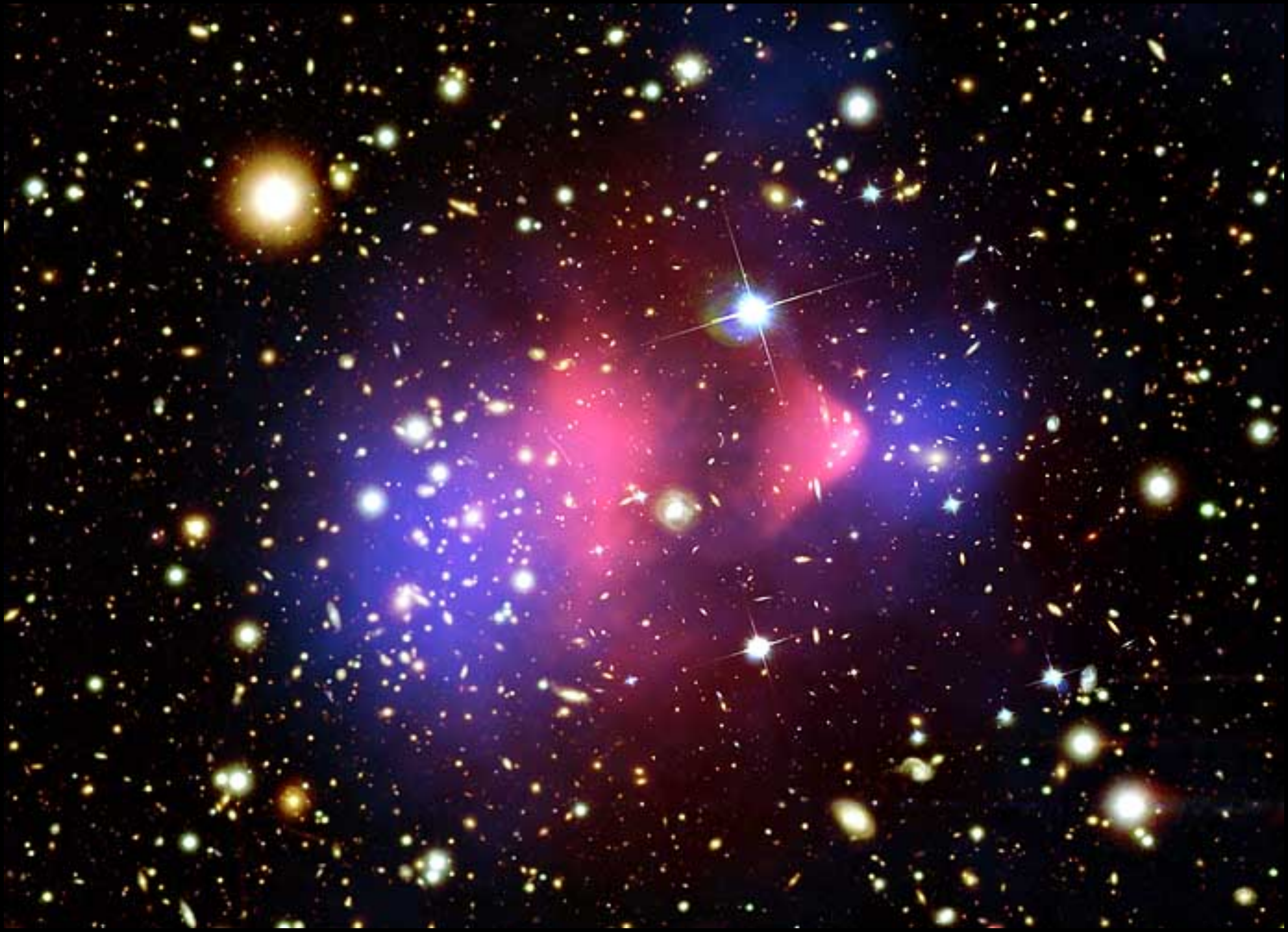
And another look using gravitational lensing



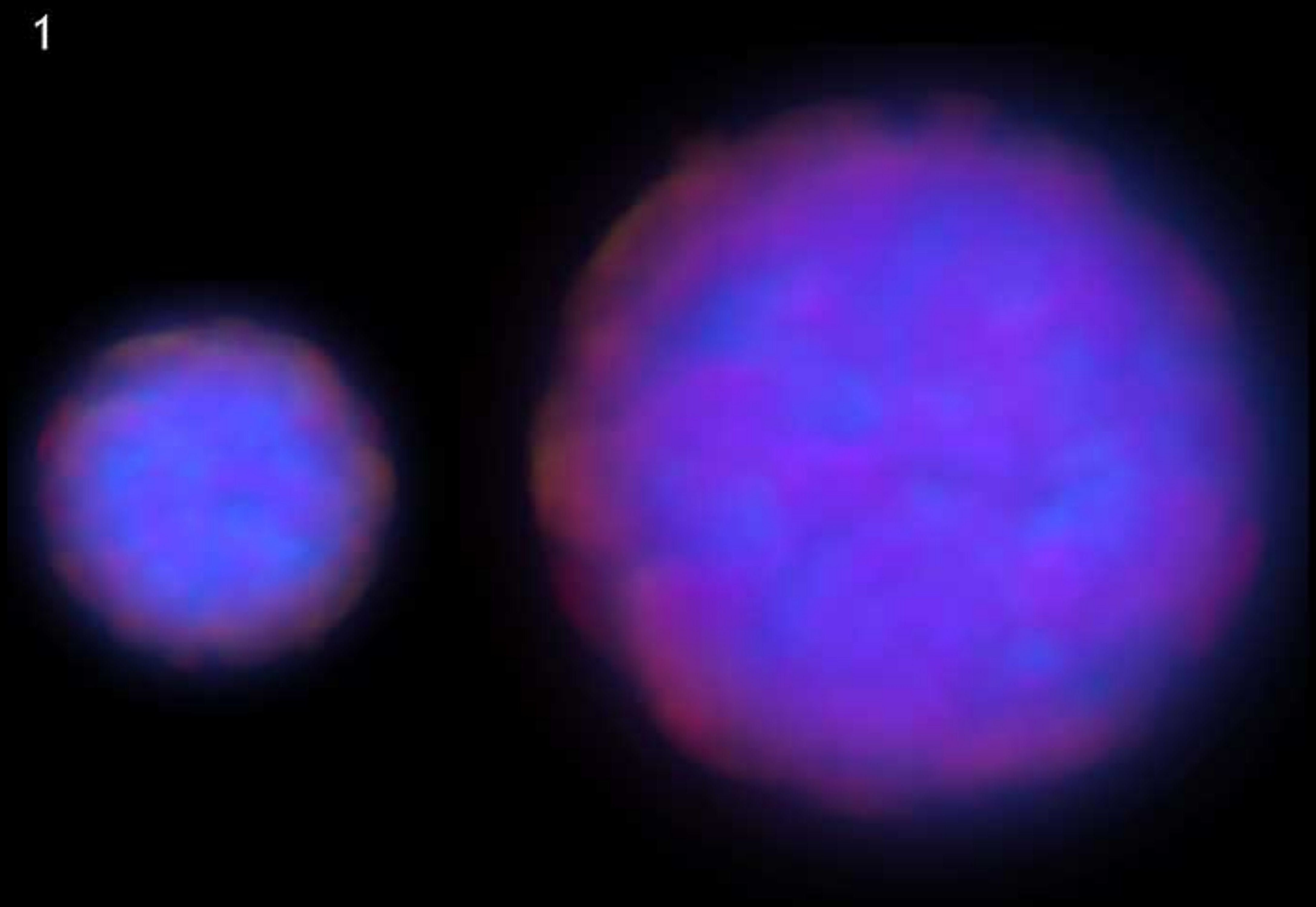
Now overlay all three pictures



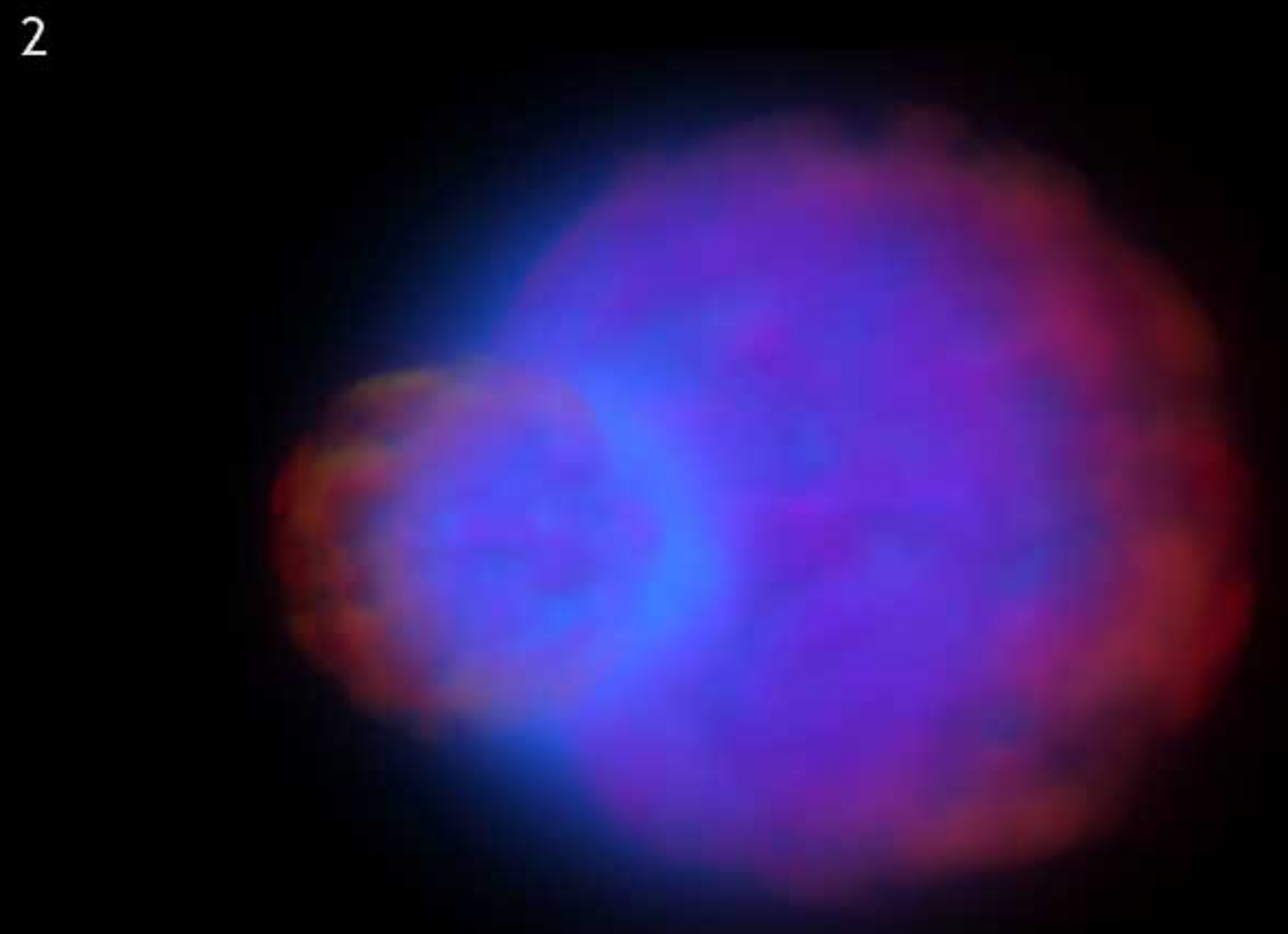
WHOW!



What could this be? A simulation of colliding galaxies (1)

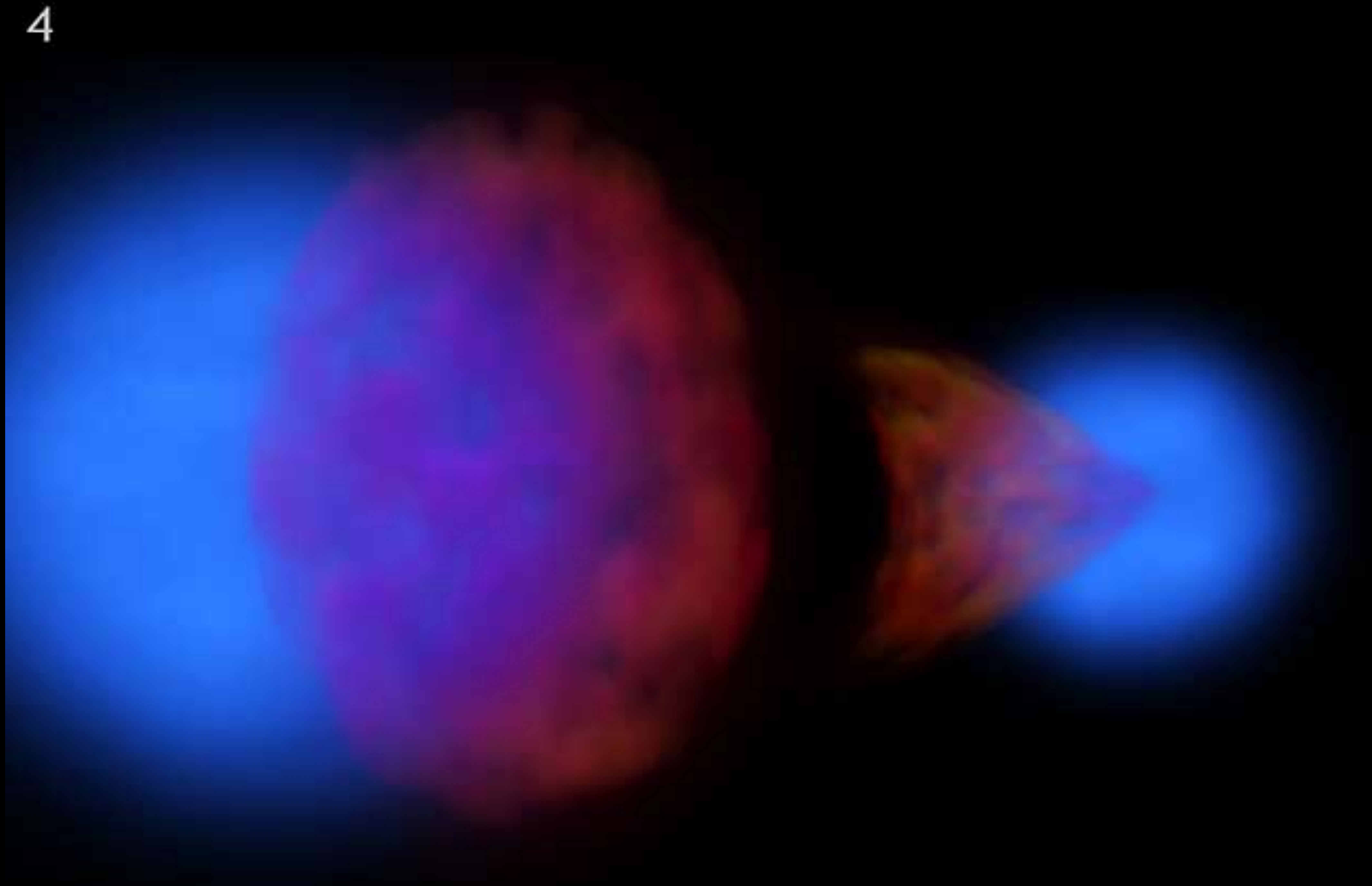


What could this be? A simulation of colliding galaxies (2)

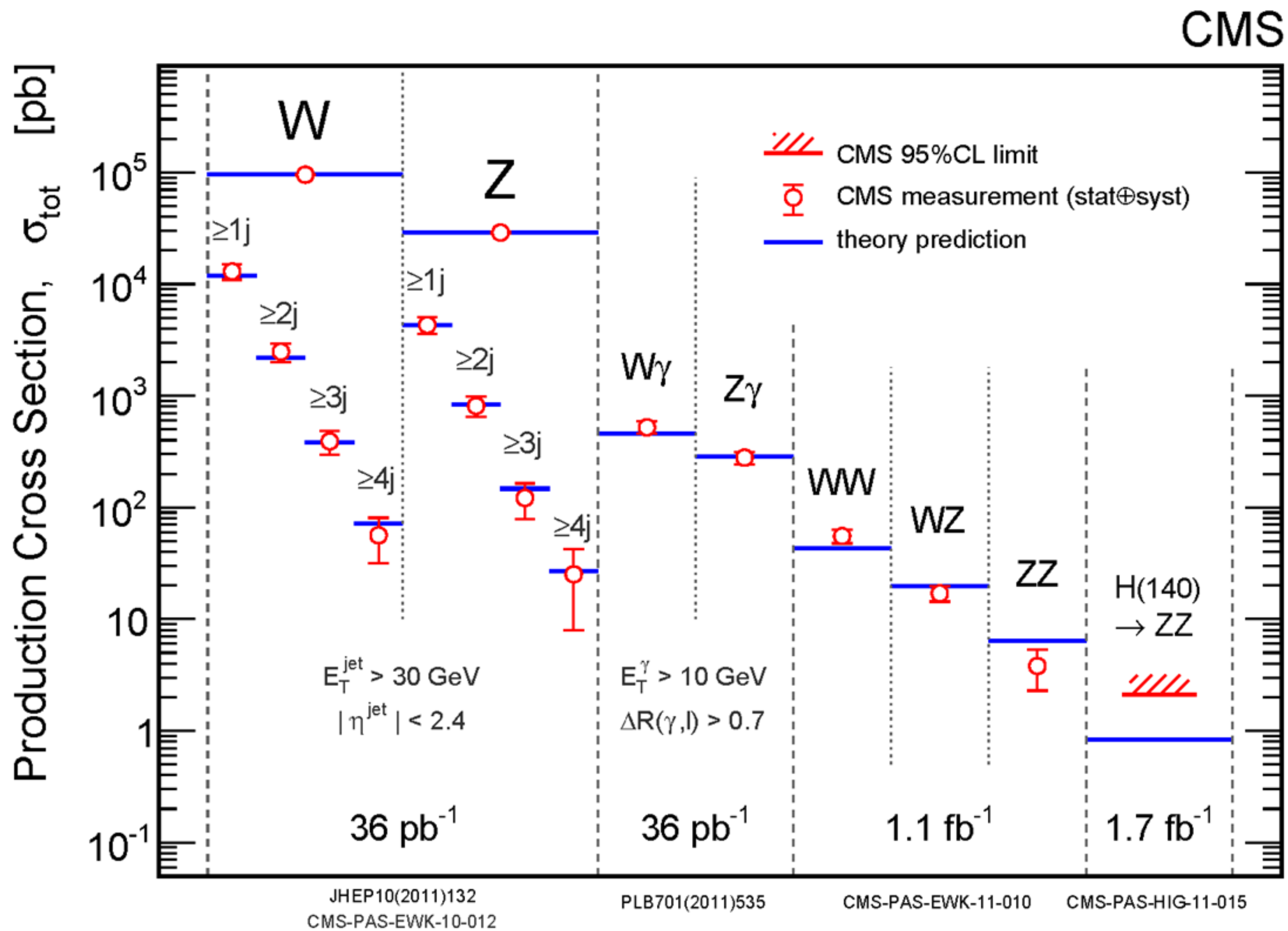


What could this be? A simulation of colliding galaxies (3)

What could this be? A simulation of colliding galaxies (4)

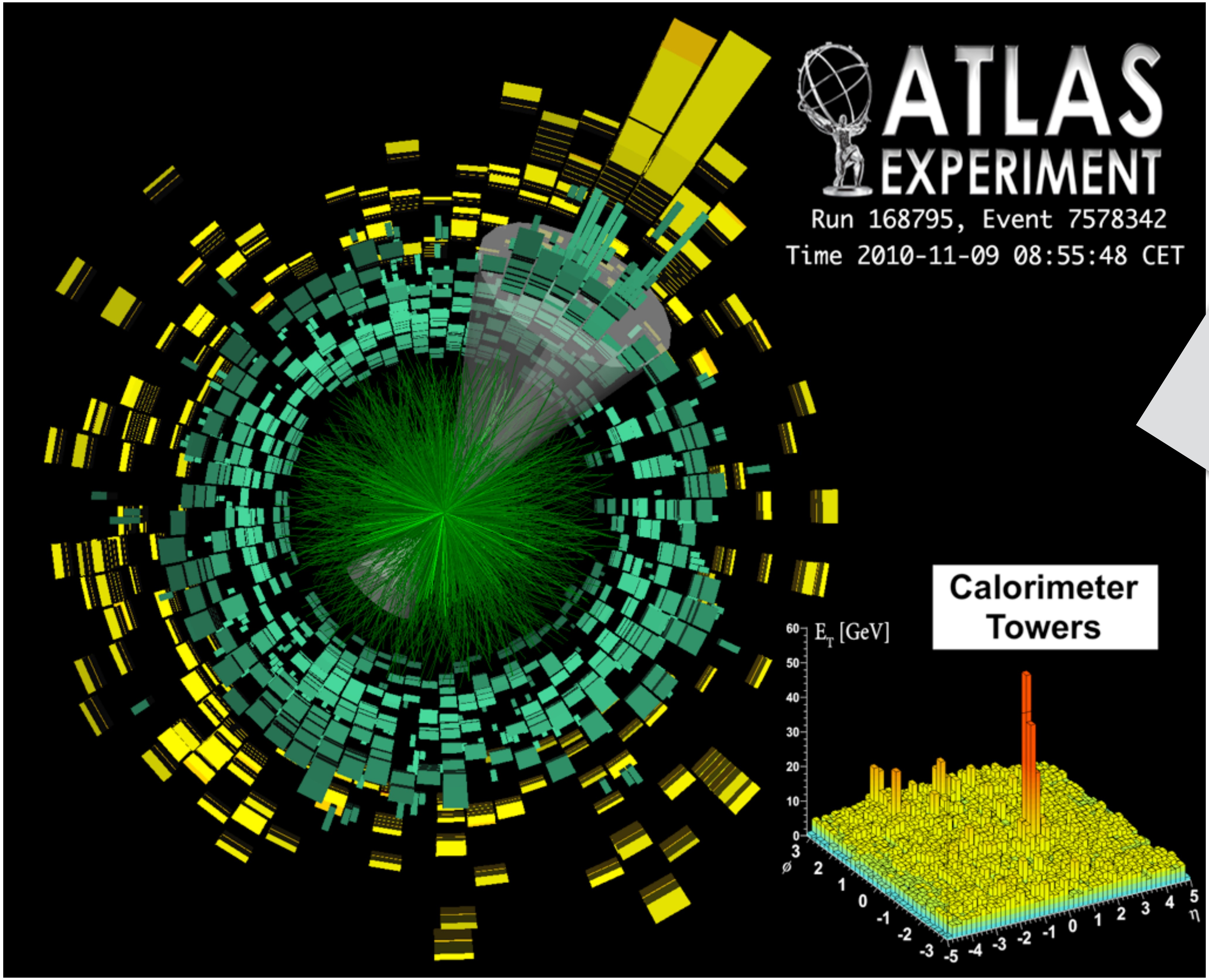


Probing the Standard Model at the LHC



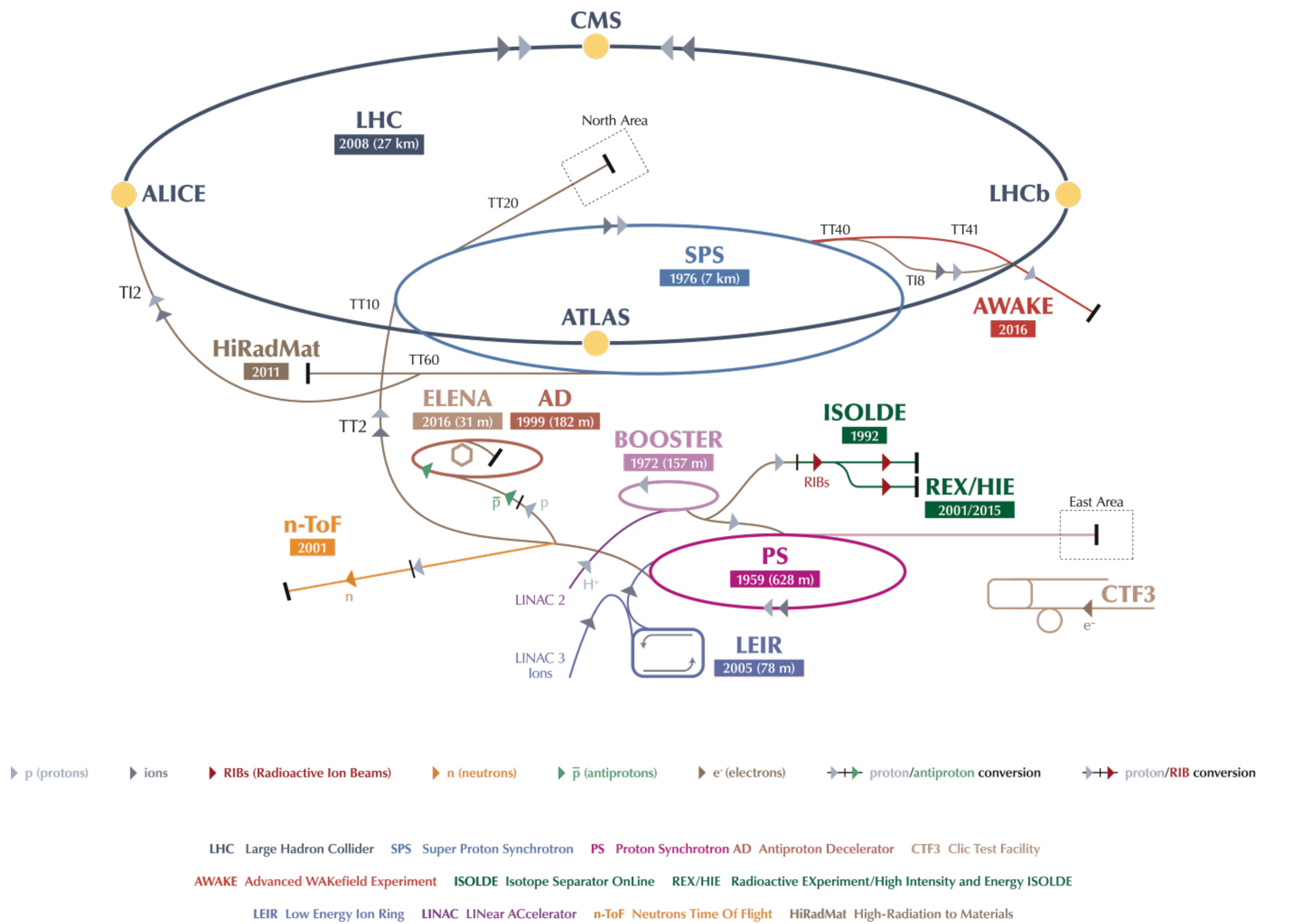
Testing the Standard Model is as important as directly searching for new phenomena!
Are there deviations? Hints for NEW PHYSICS!

Heavy ion physics at the LHC



Jet quenching in heavy ion collisions

The CERN accelerator complex

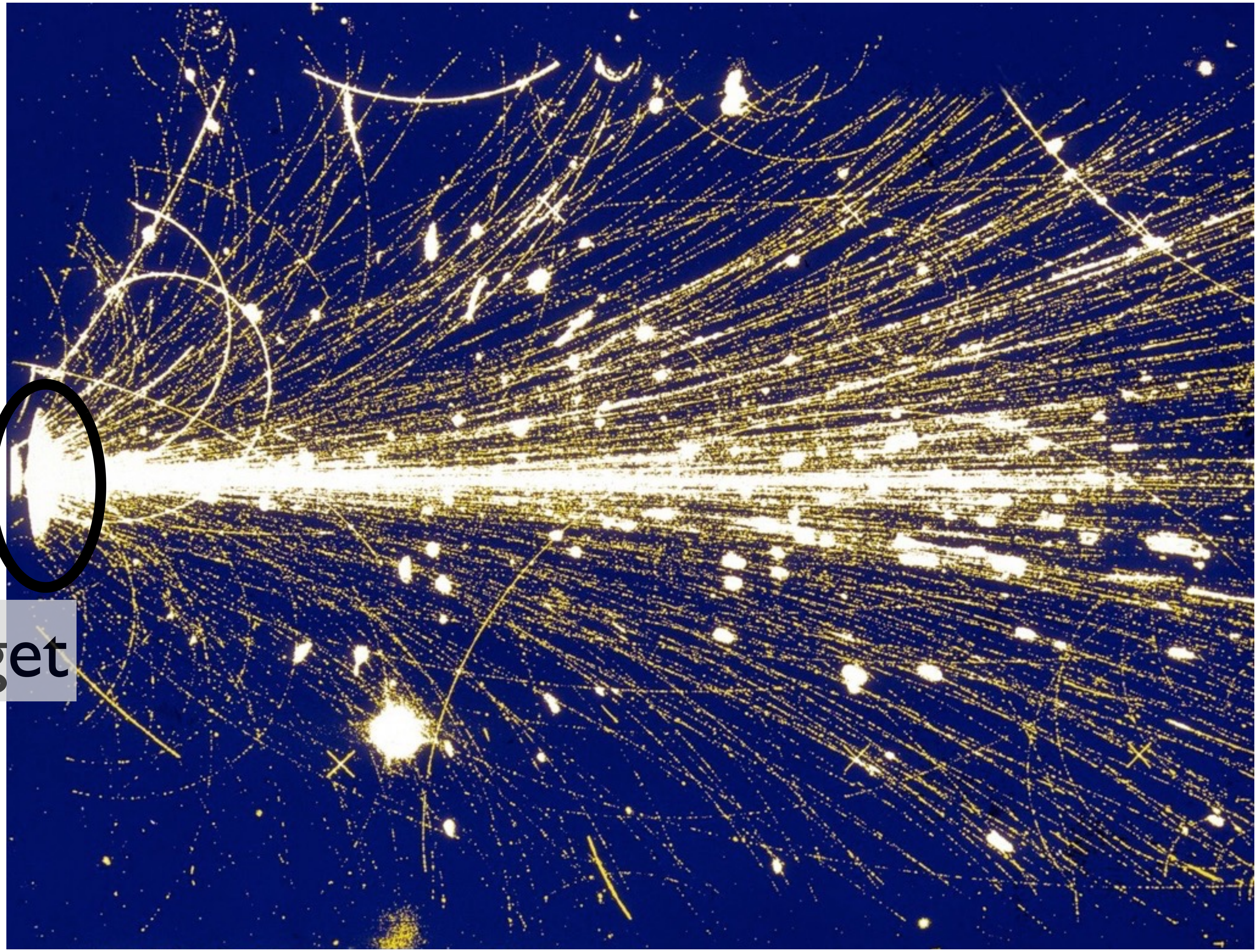


Experiments at the PS/SPS are called"fixed-target experiments"

Protons from the accelerator hit a target

beam

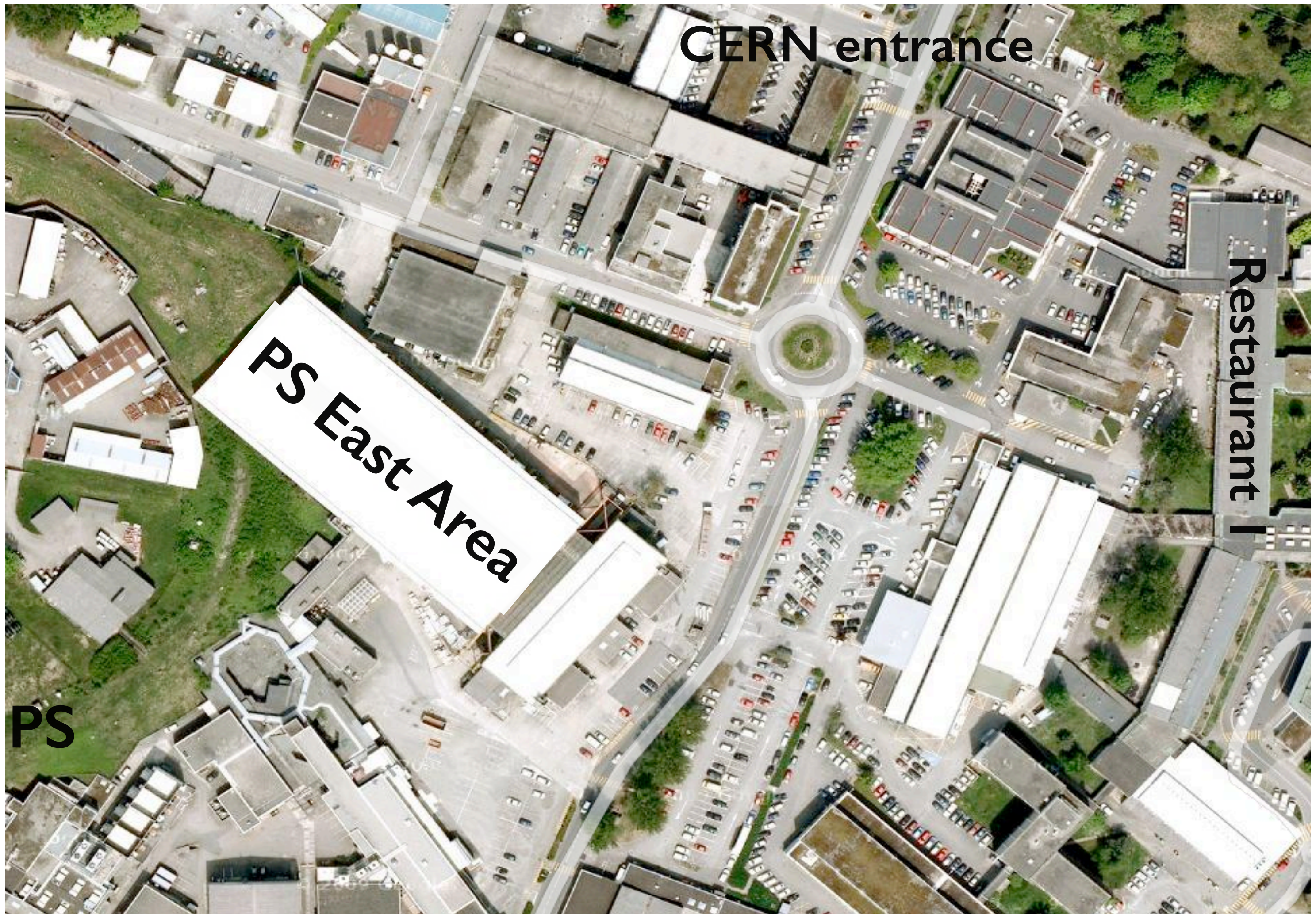
target



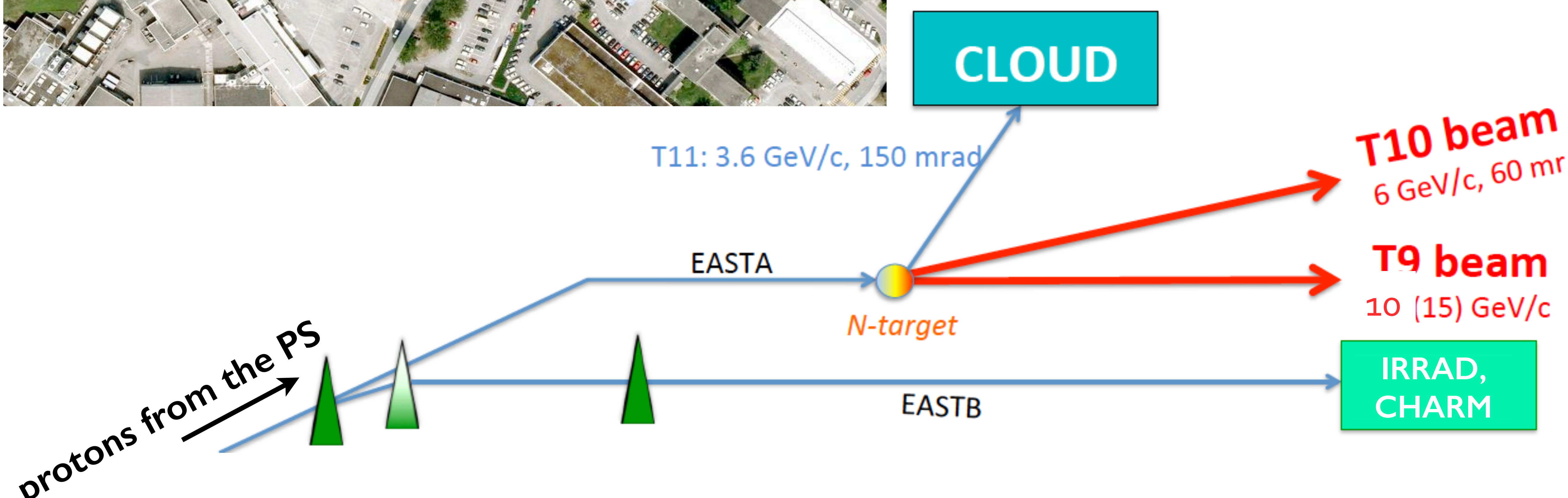
Picture: a collision of a sulphur ion onto a gold target, recorded by the NA35 experiment at the SPS in 1991

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

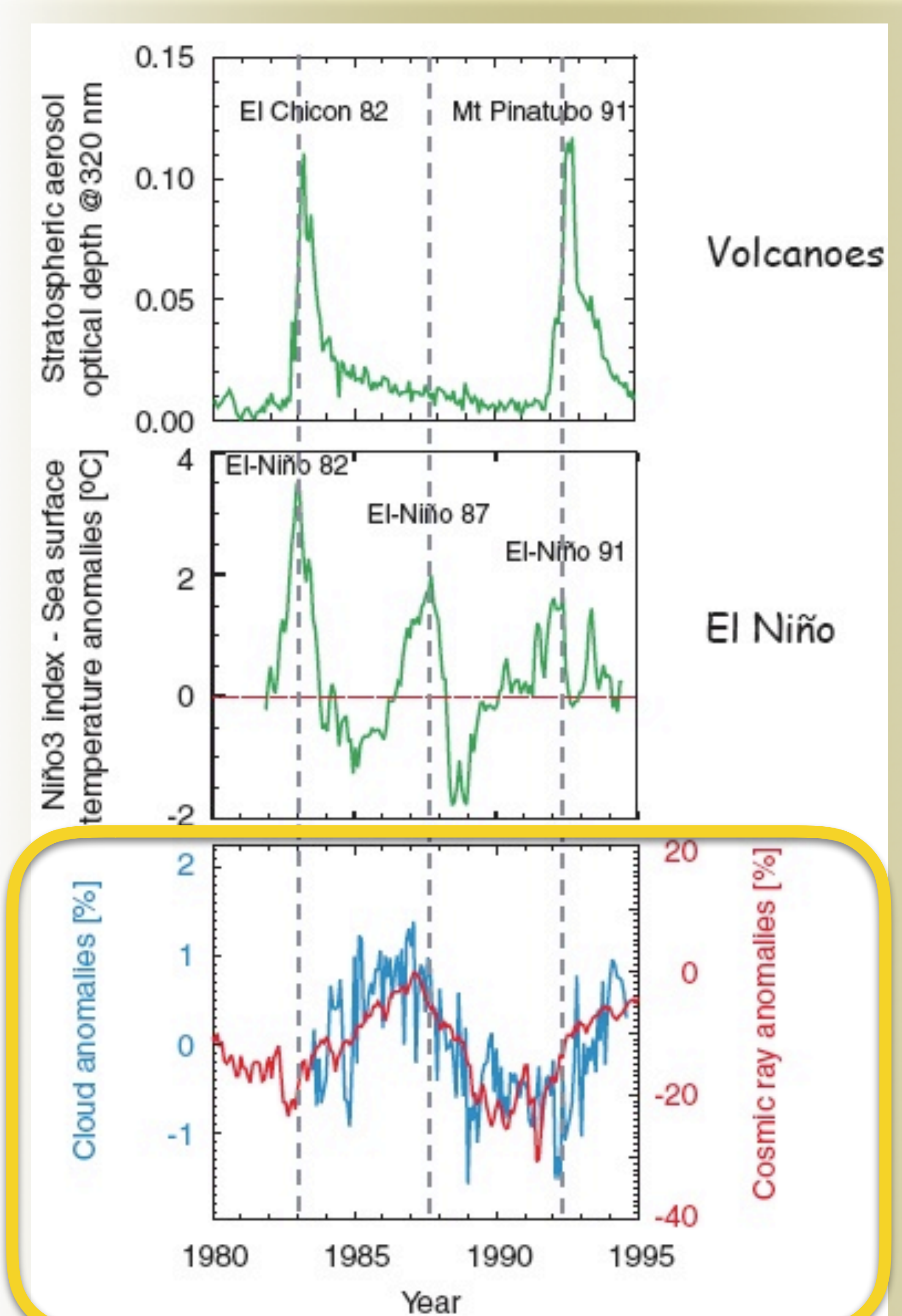
The PS East Area



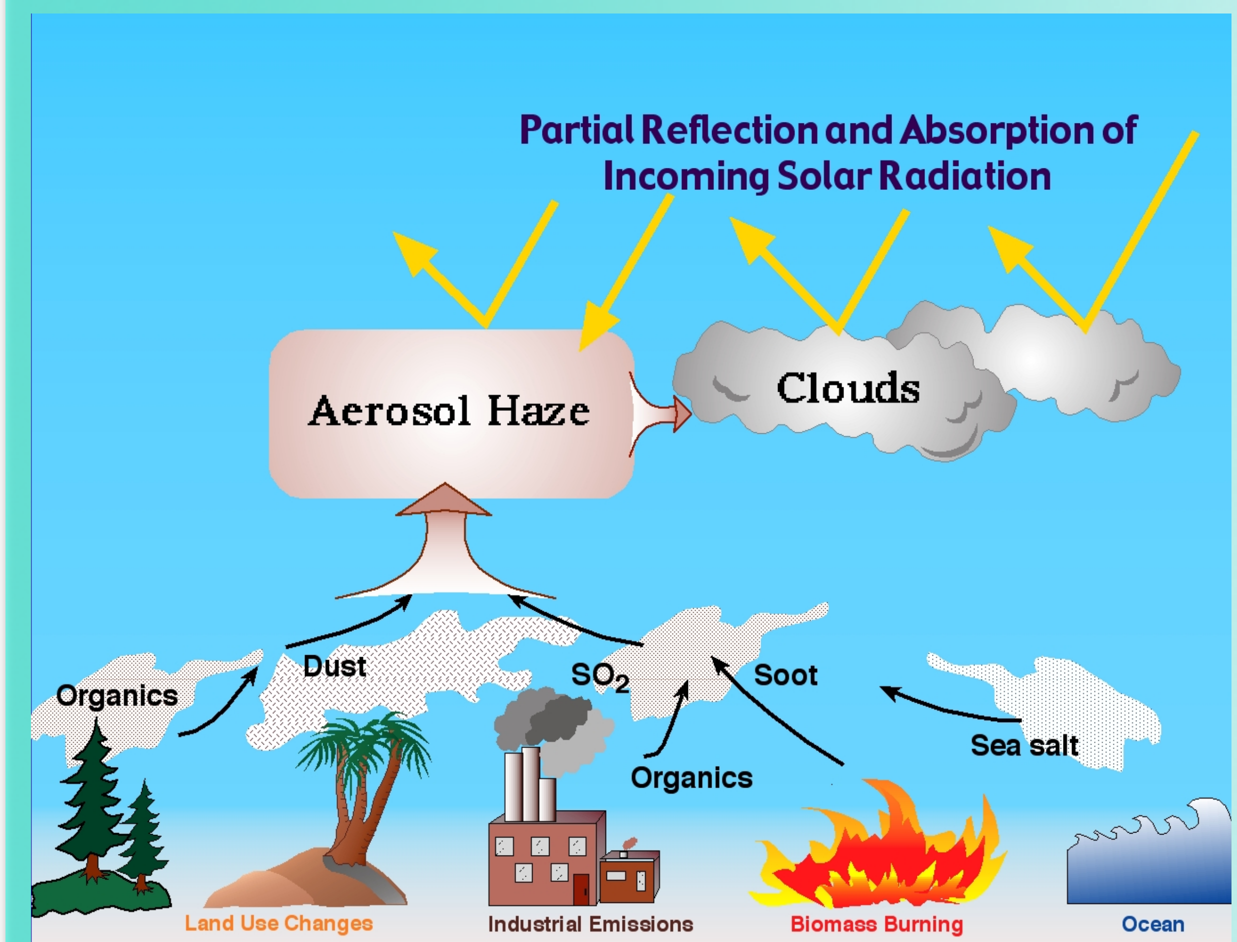
One of the oldest complexes at CERN, hosts 2 irradiation facilities IRRAD and CHARM, the CLOUD experiment and 2 flexible test beams and up to 2012 also the DIRAC experiment



@East Area: the CLOUD experiment



Understanding clouds → understanding of climate



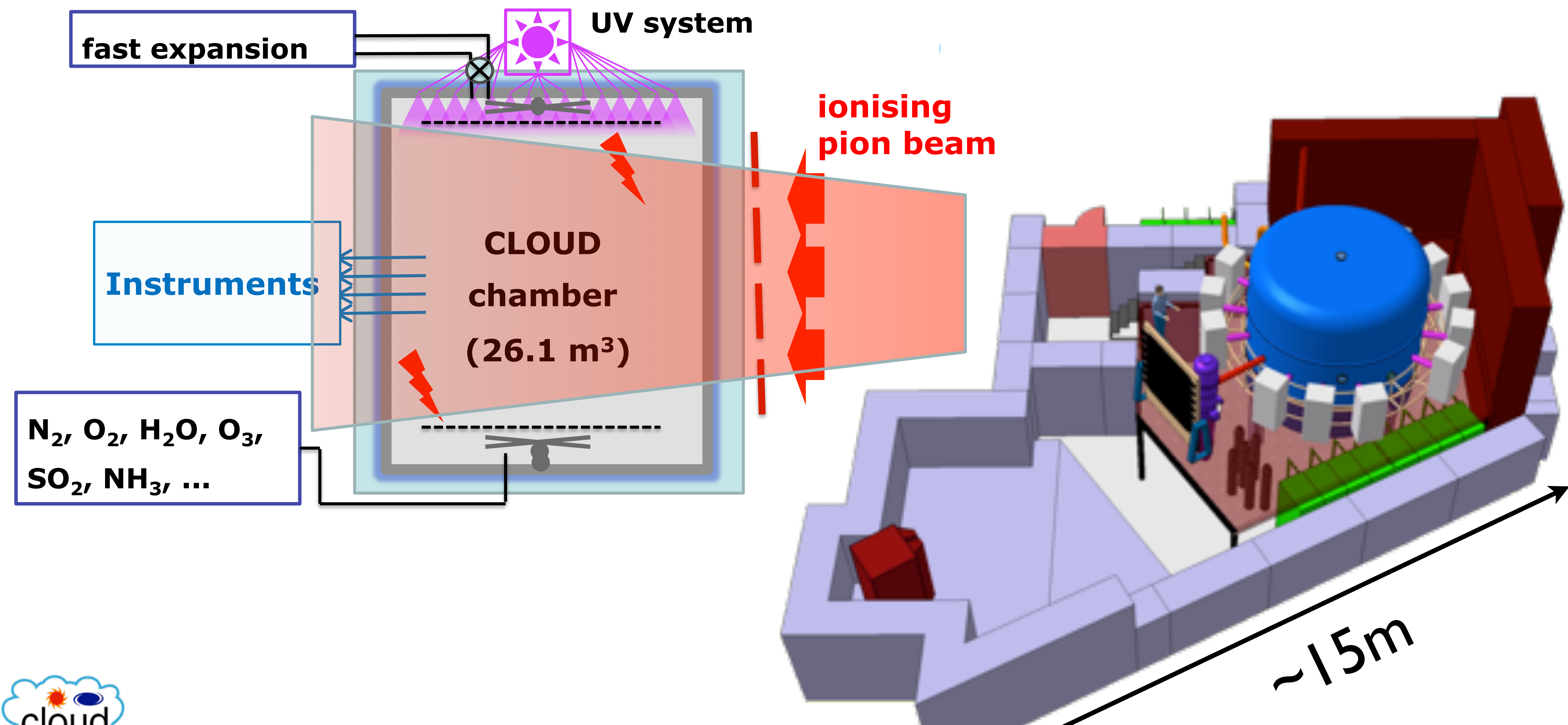
Direct effect:
Scattering and absorption of incoming sunlight by aerosol particles.

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

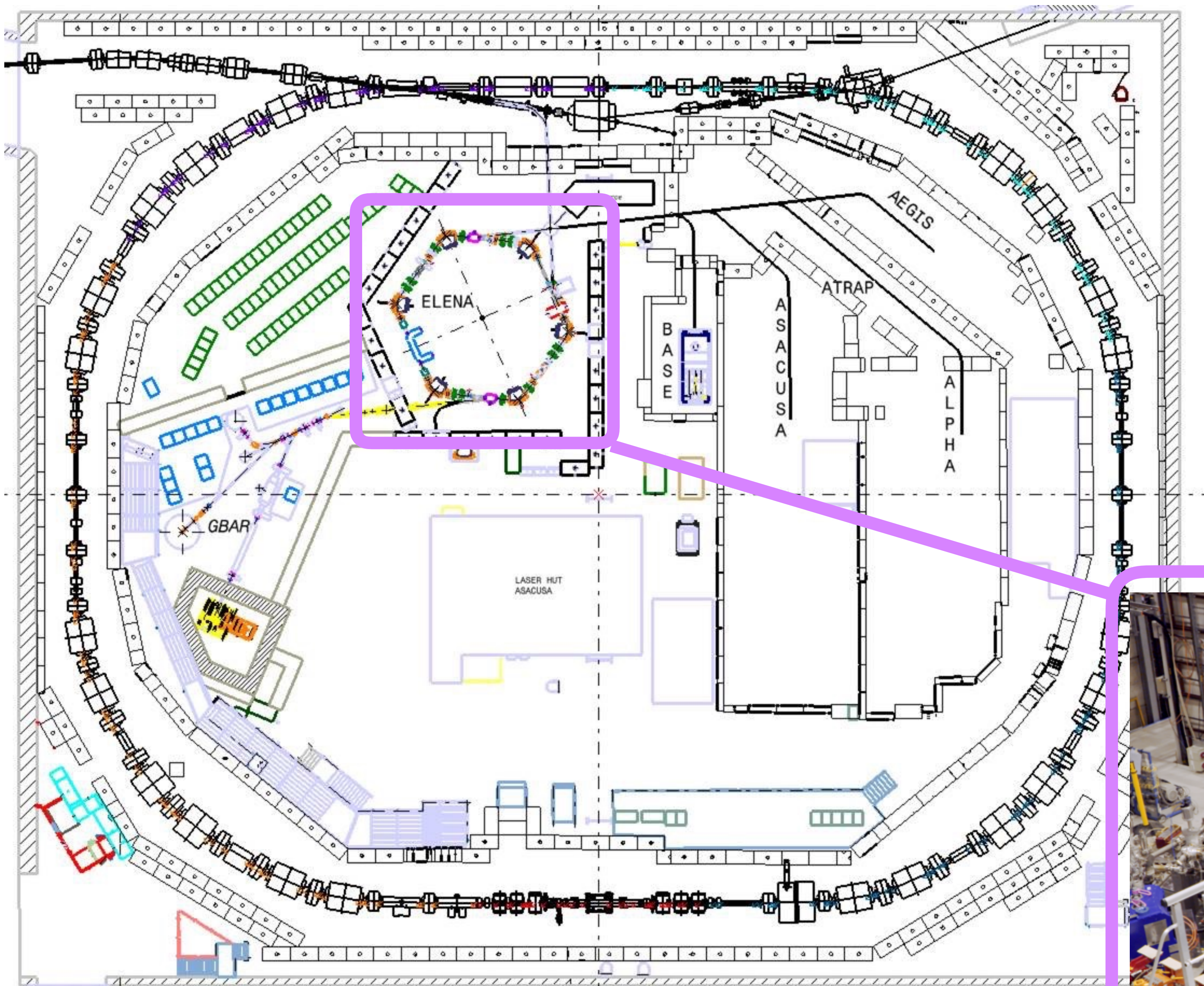
But how droplets and clouds form???

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.



Facilities at the PS: the Antiproton Decelerator AD



AD: low-energy antiprotons (5.3MeV/c, 3 107 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.

Experiments:
ATRAP (spectroscopy and p_bar magnetic moment), **ALPHA** (spectroscopy), **ASACUSA** (spectroscopy, atomic and nuclear collision cross sections), **BASE** (p_bar magnetic moment), **AeGIS** and **GBAR** (antimatter gravity experiments)

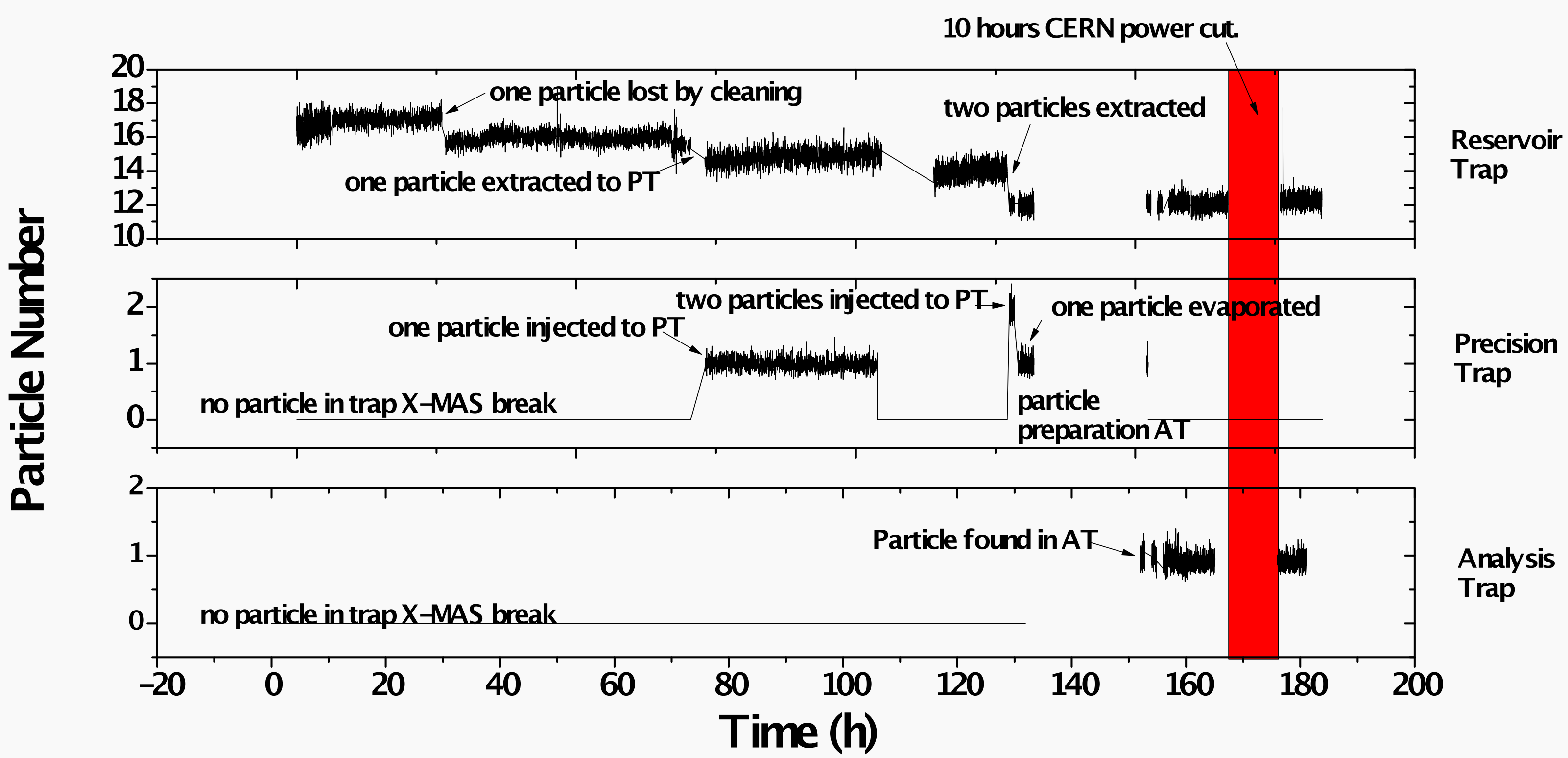
@AD: BASE

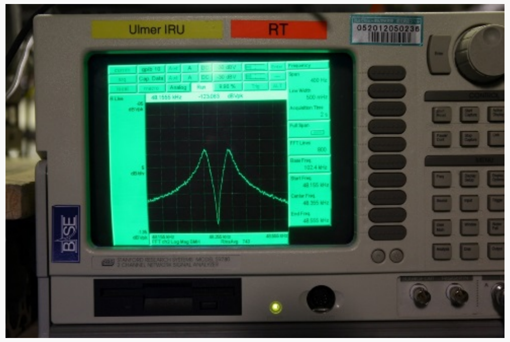
Precise comparisons of the fundamental properties of pbar and p by measuring the cyclotron and Larmor frequencies of single trapped (anti)protons (optionally H-).

Goal until 2018 : measurement of magnetic moment of the (anti)proton with precision of δg/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.

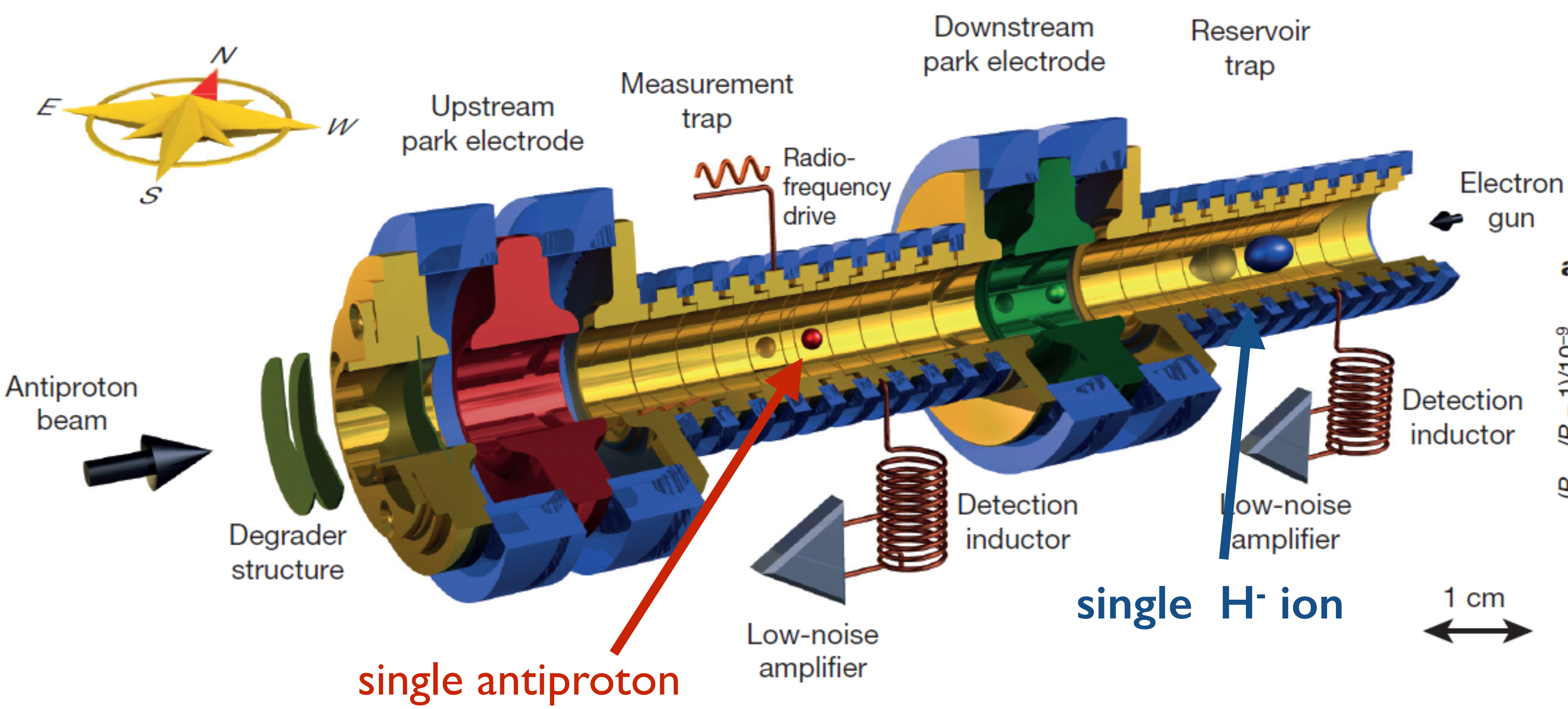
N.B.: currently BASE is still running with pbars caught in November 2015.



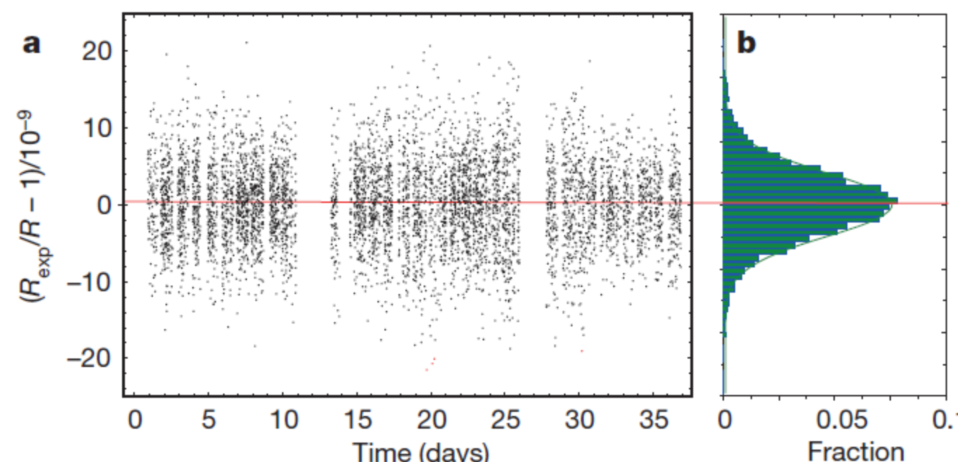


C. Smorra et al., A reservoir trap for antiprotons, Int. Journ. Mass. Spec. 389, 10 (2015).

@AD: BASE (2)



All measured antiproton-to-H- cyclotron frequency ratios as a function of time. 6,521 ratios were measured in 35days.



$$\frac{(q/m)_{\bar{p}}}{(q/m)_{p}} - 1 = -1(69) \times 10^{-12}$$

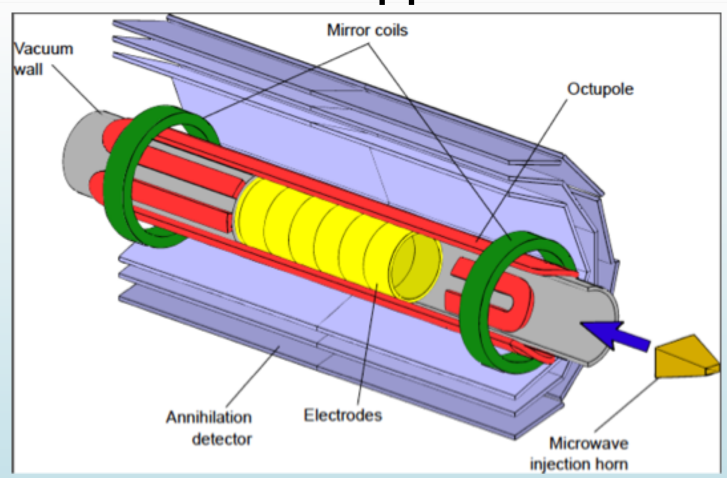
- FIRST measurement with the new apparatus: high precision comparison of the antiproton-to-proton charge-to mass ratio by comparing cyclotron frequencies of antiproton an hydrogen ions in a Penning trap.
- 69ppt comparison of the proton/antiproton Q/M ratio
  - ➡ succeeding Gabrielse, G. et al. "Precisionmass spectroscopy of the antiproton and proton using simultaneously trapped particles. Phys. Rev. Lett. 82, 3198–3201 (1999);
  - ➡ currently most precise test of CPT invariance with baryons.

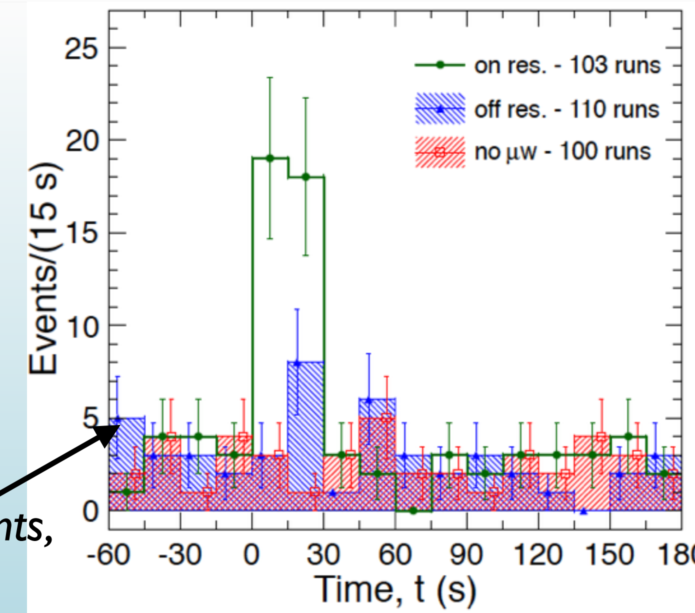
@AD: ASACUSA & ALPHA

ATRAP, ALPHA, and ASACUSA use 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, Nature 483, 439 (2012).

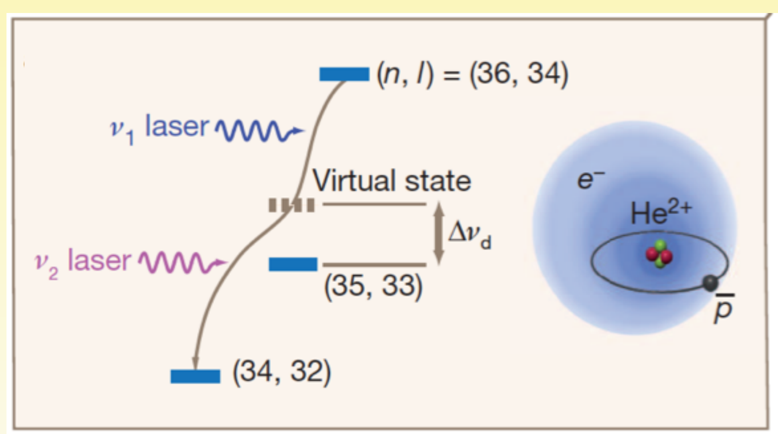
ALPHA apparatus

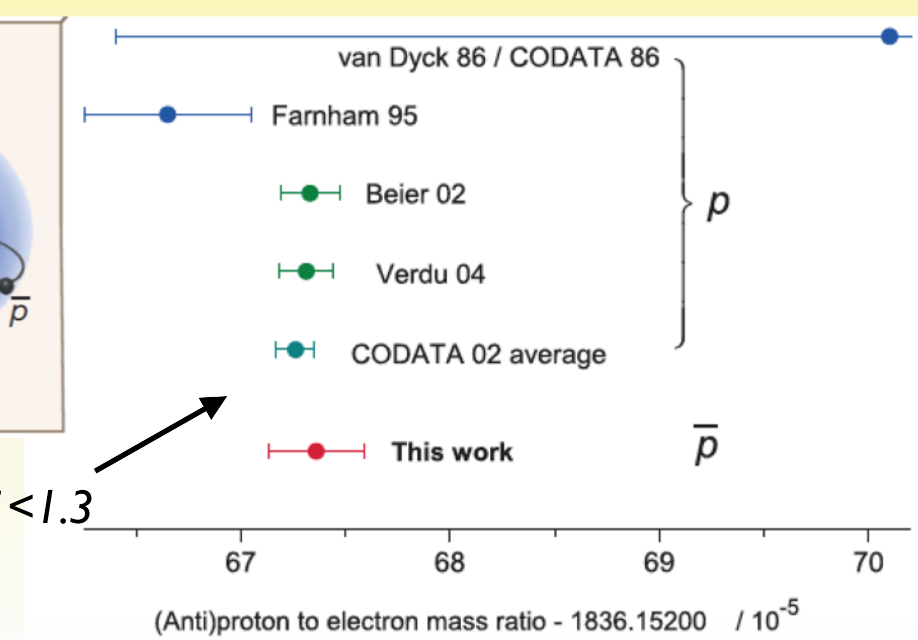




Number of 'appearance mode' annihilation events, microwave power is first applied at time t = 0.

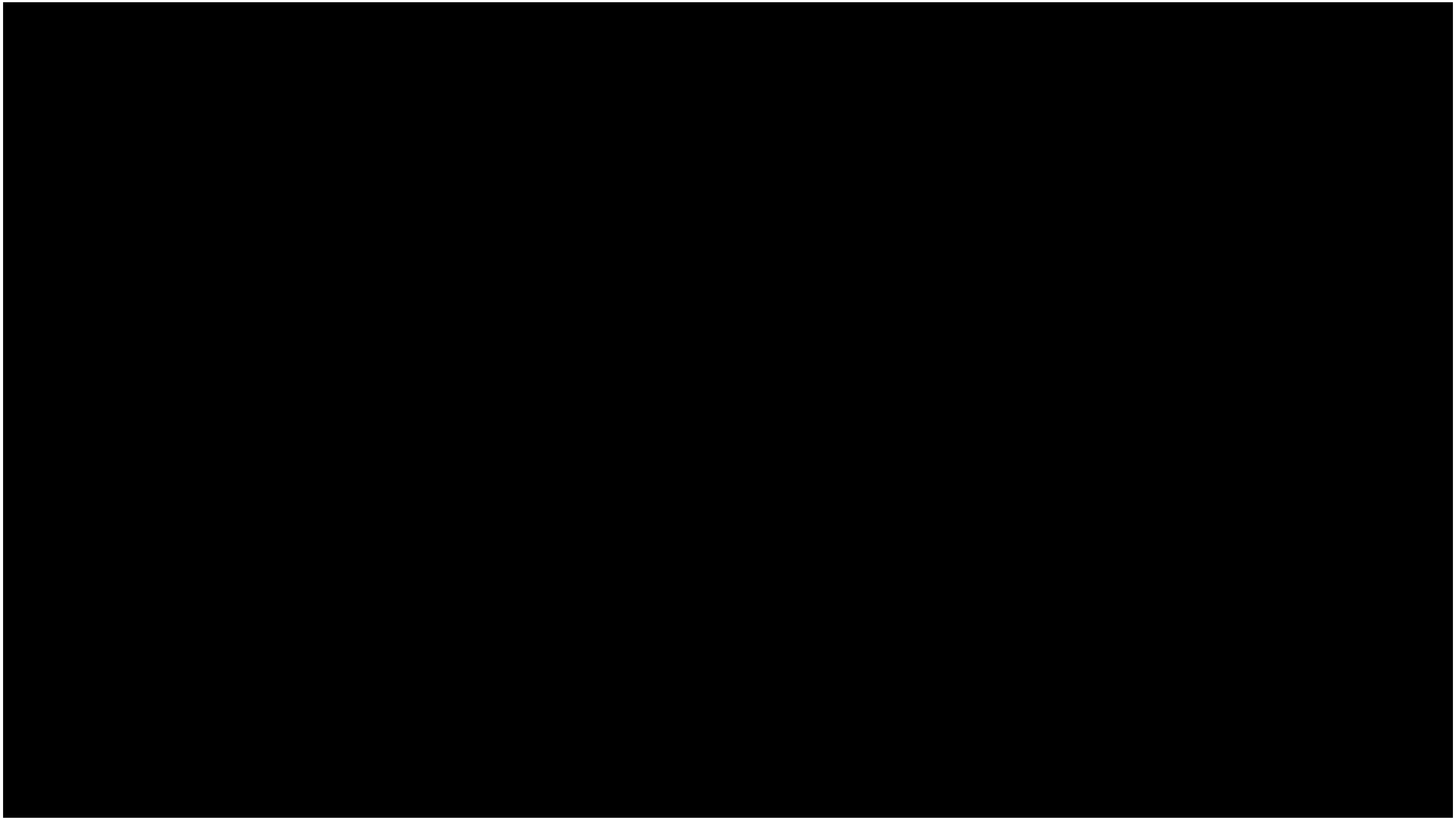
- **ASACUSA**: two-photon laser spectroscopy of antiprotonic helium and precise measurement of antiproton-to-electron mass ratio, Nature 475, 484–488 (2011).





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

The ALPHA experiment - manipulating antimatter

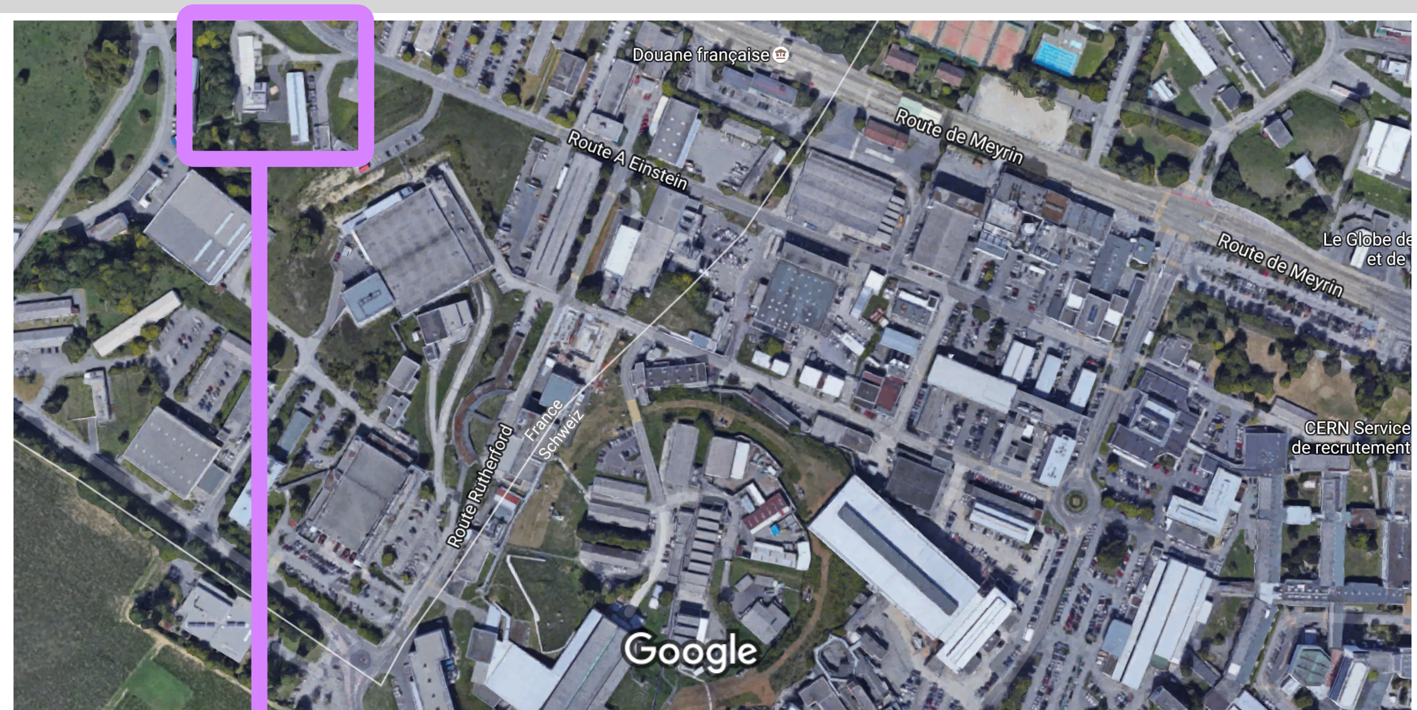


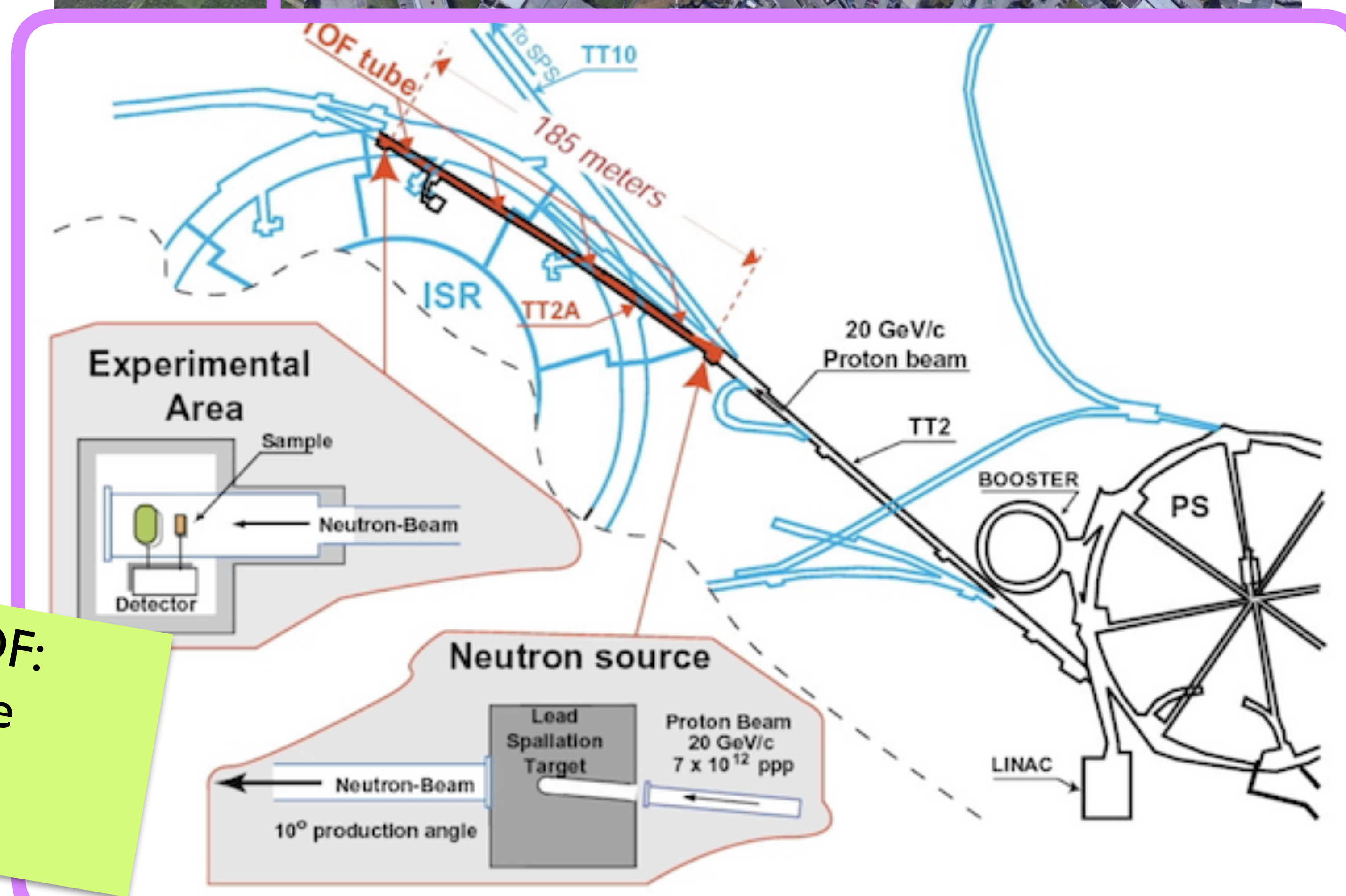
Facilities at the PS: nTOF

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/



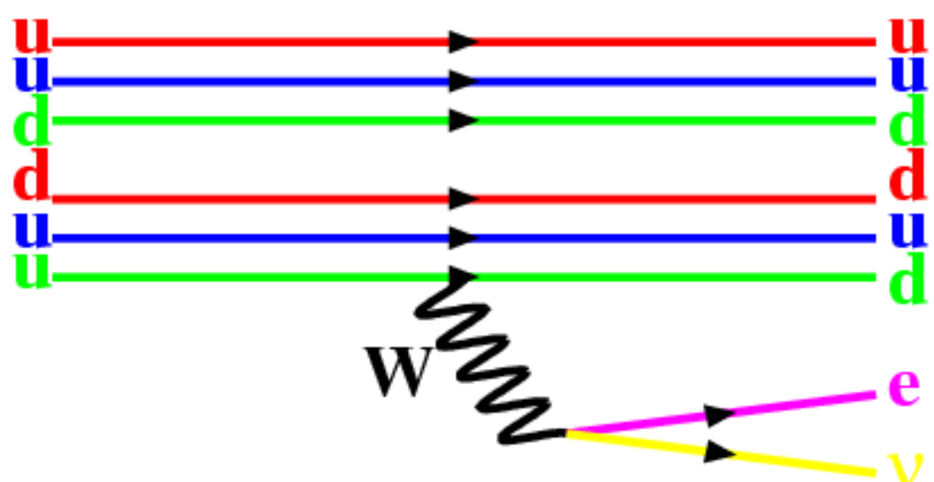


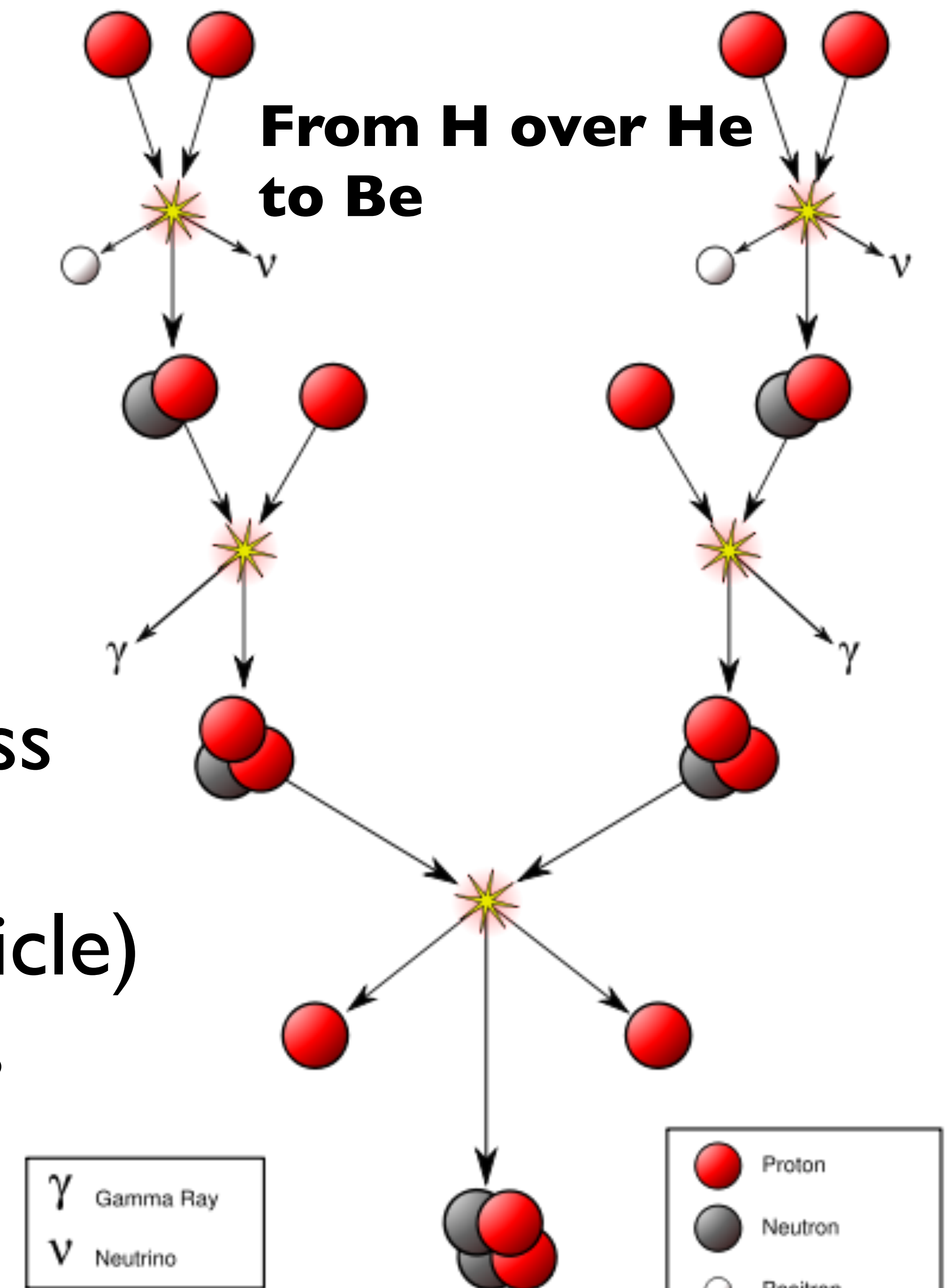
Scientific questions investigated by nTOF:
e.g. how heavy elements in the universe are formed?
(→ study fast neutron capture)

Elements in the universe

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

β+ decay of a proton to a neutron

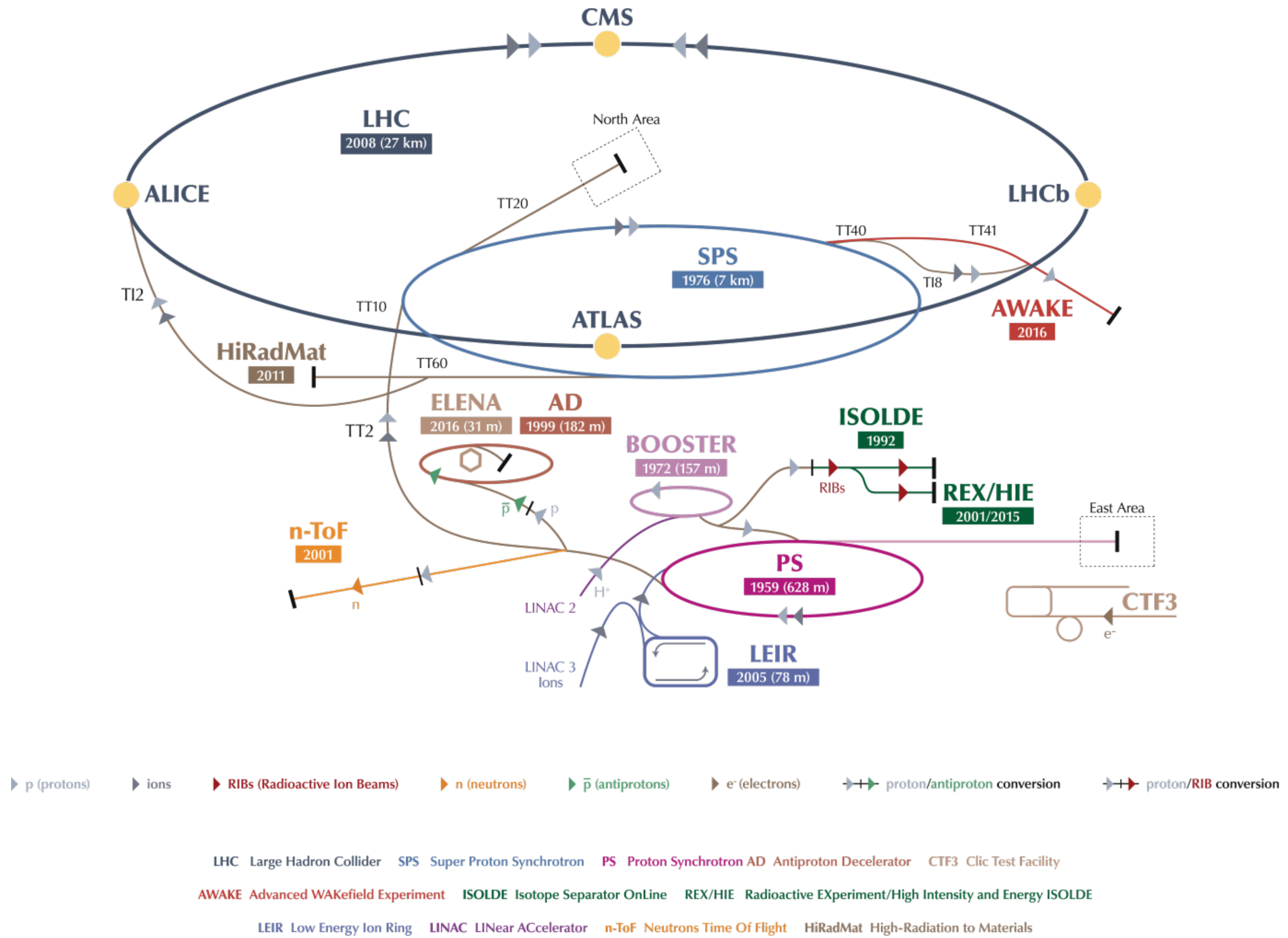




For elements bigger than Fe(26 protons, 30 neutrons) this process stops
➙ difficult for a proton (=charged particle) to enter the atom and reach nucleus

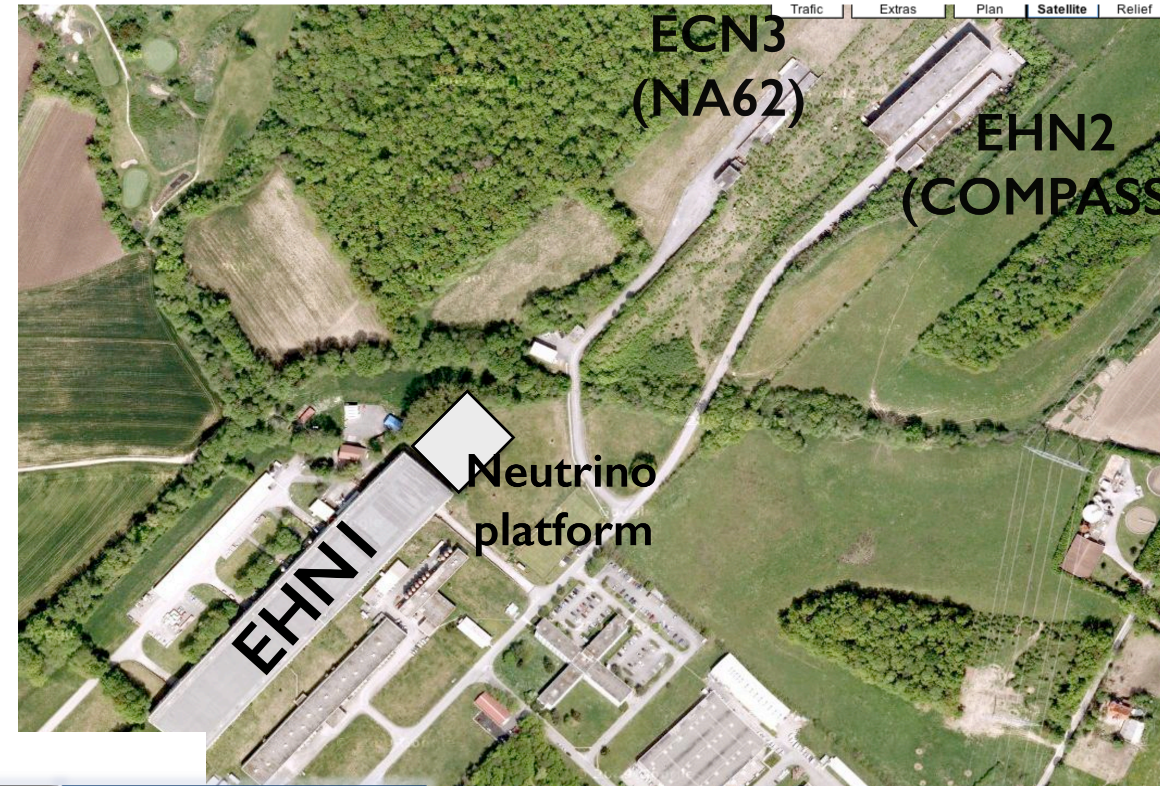
Where and how are heavy elements produced?

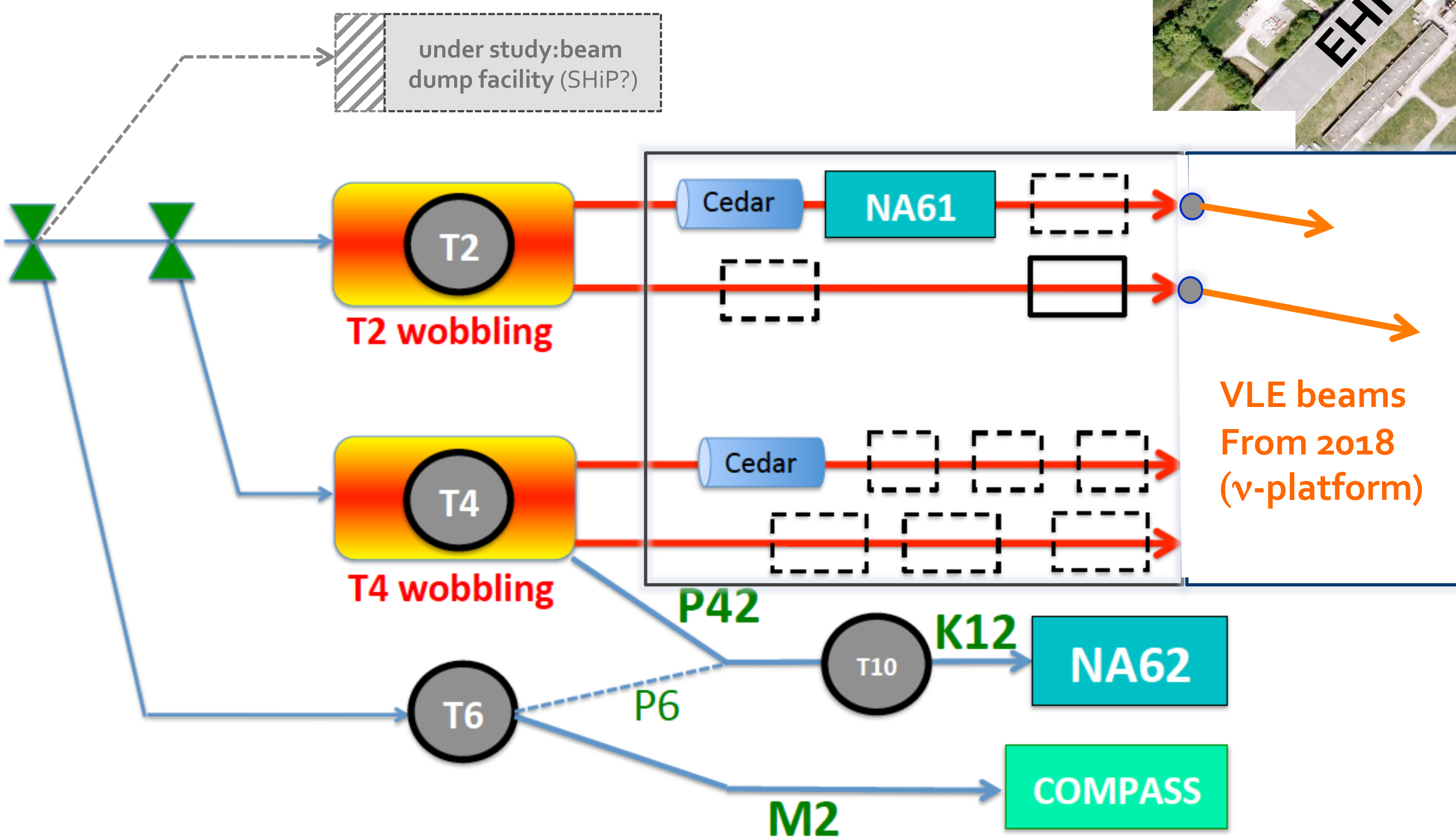
The CERN accelerator complex



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 or T6. Particles are transported to the user areas.
Also ions can be sent to the area.





Experiments in the North Area:

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

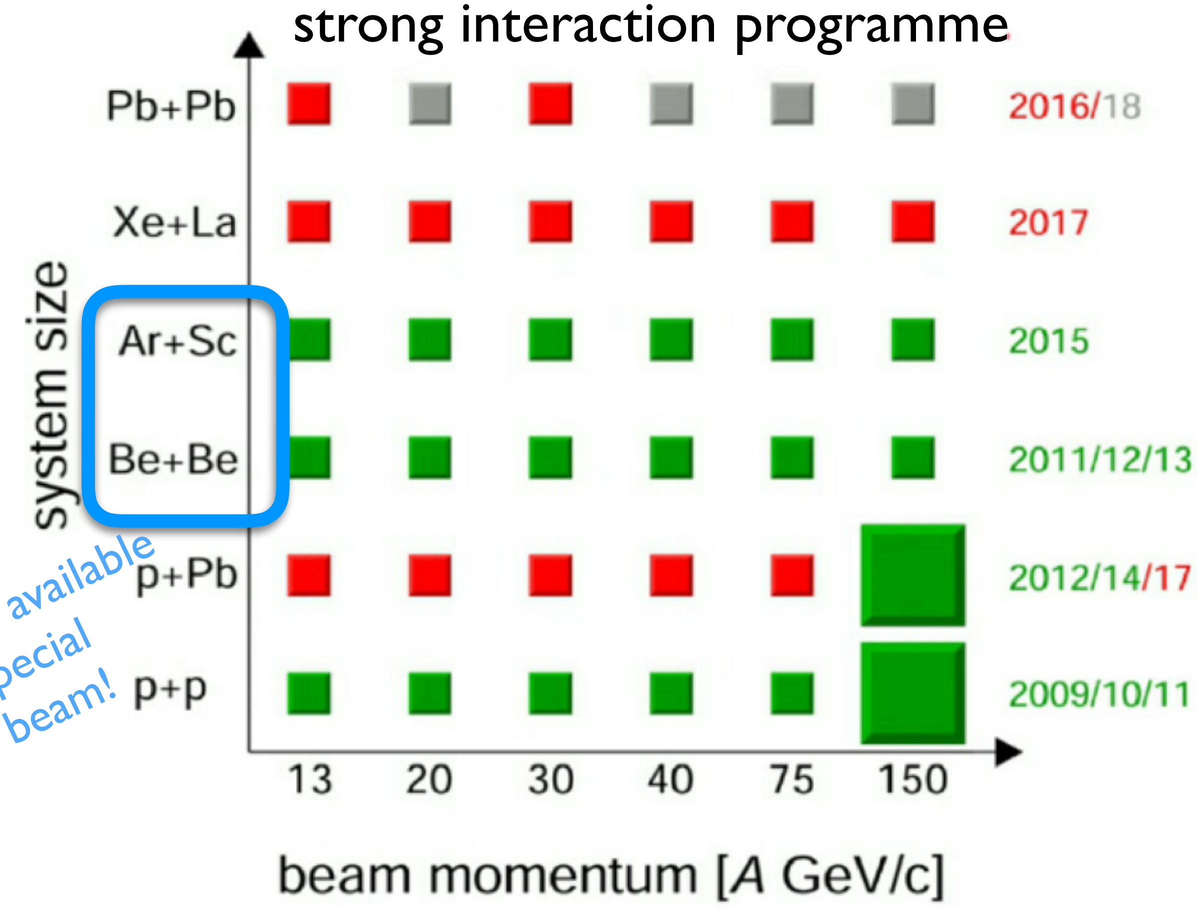
@SPS: NA61

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);

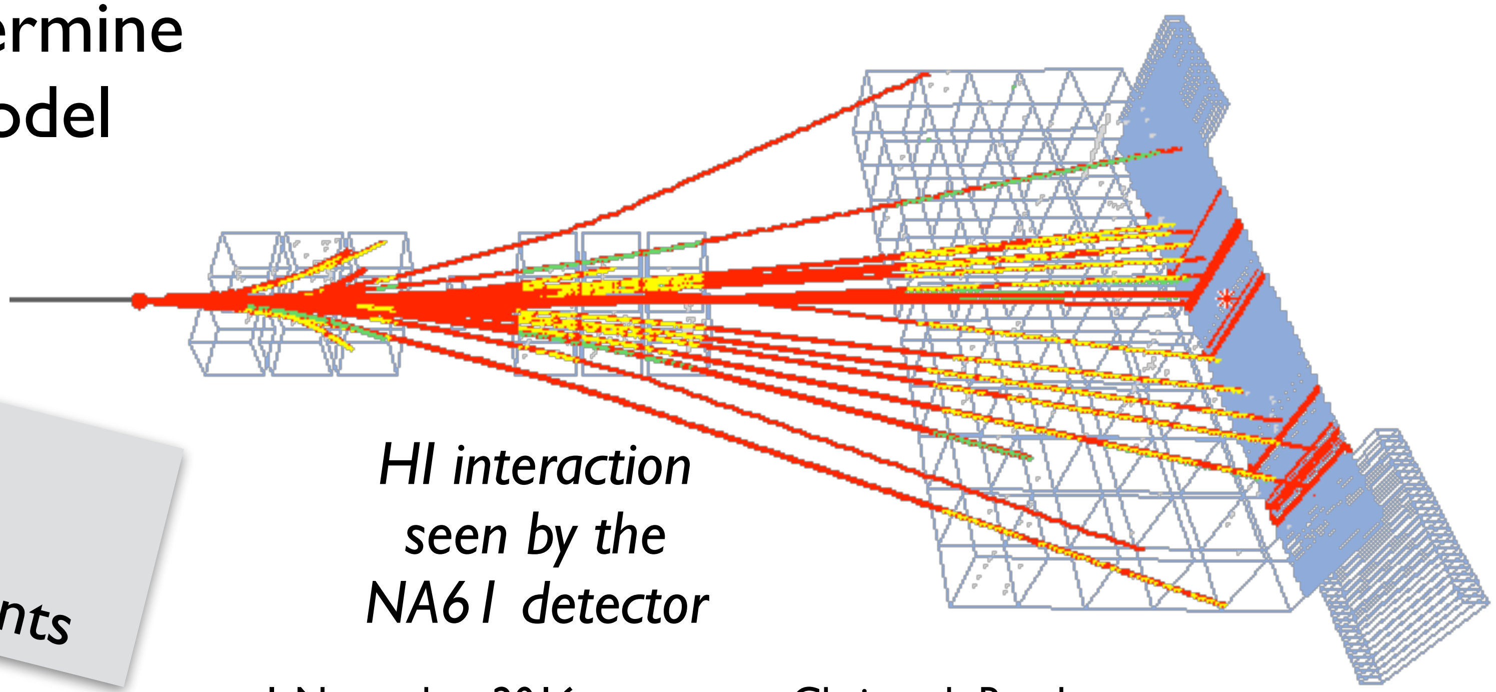
- **Neutrinos and cosmic ray** programme: Hadron-nucleus interactions to determine neutrino beam properties and to model cosmic ray showers

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

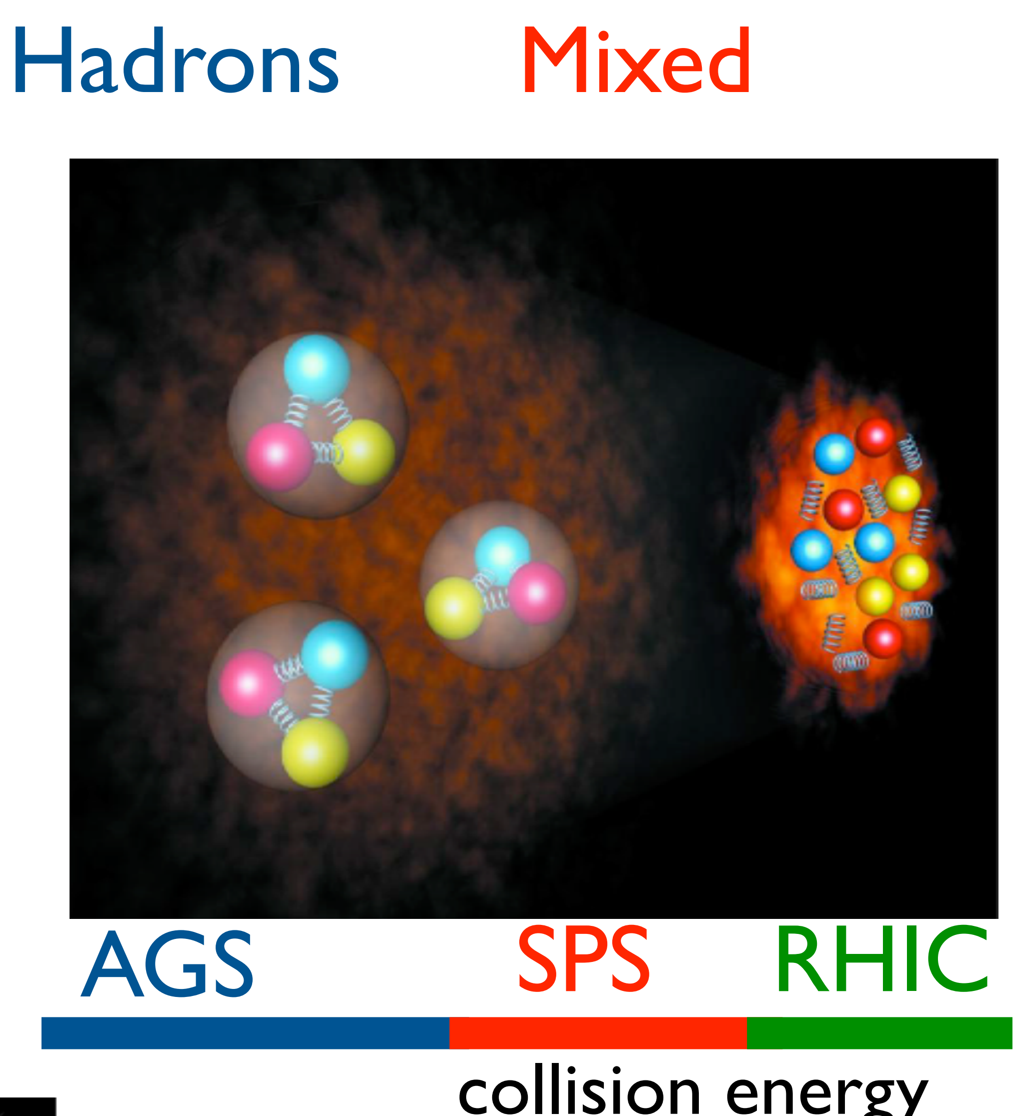
SHINE NA61

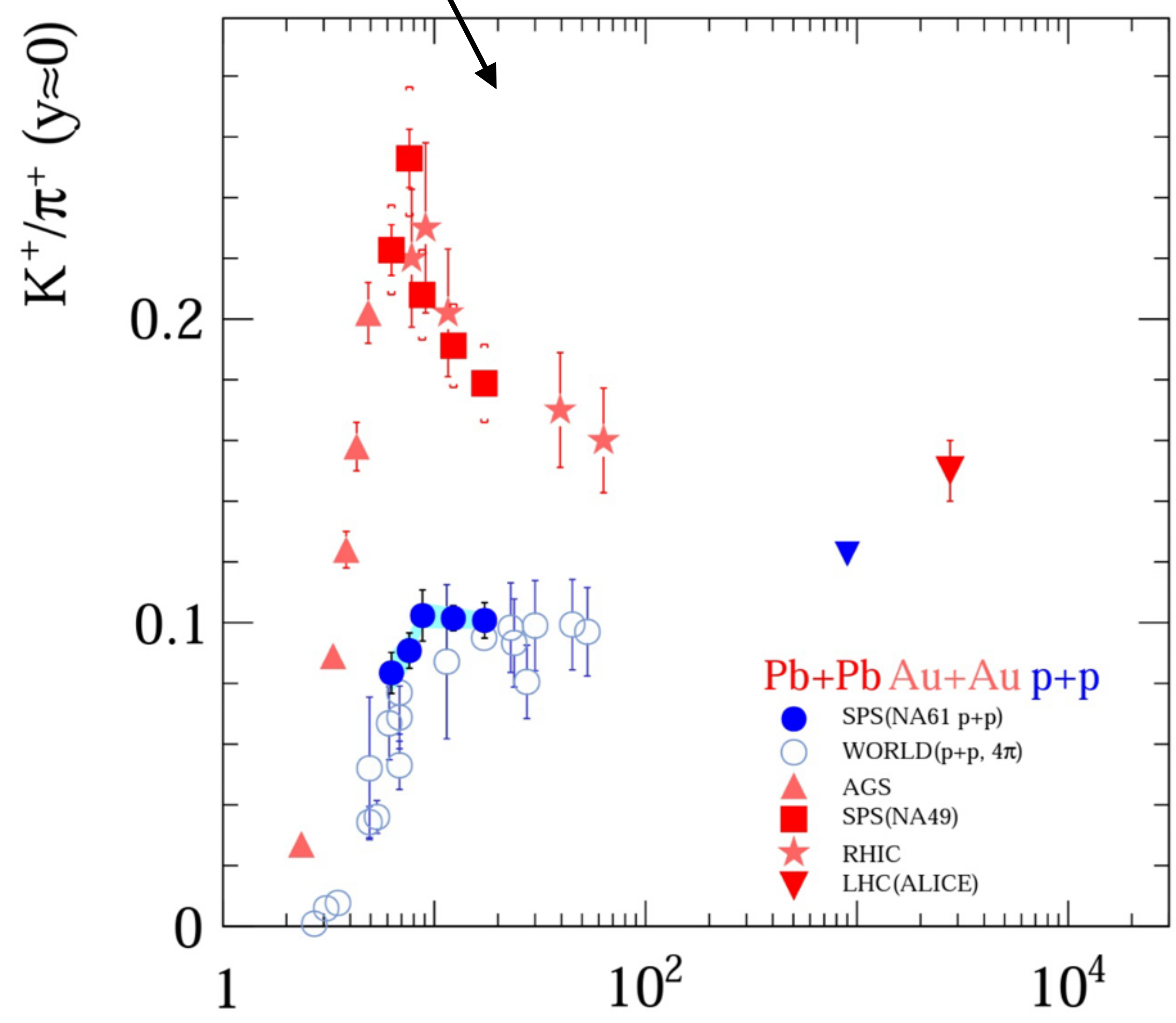
NA61: Study of properties of onset of deconfinement

Example:

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

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



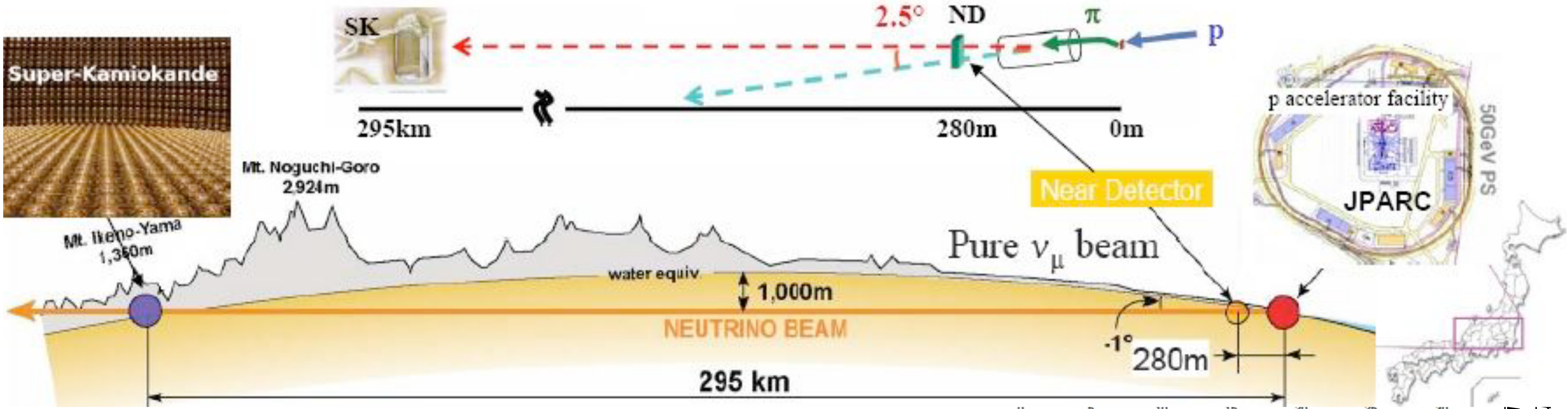


see CERN-SPSC-2014-031

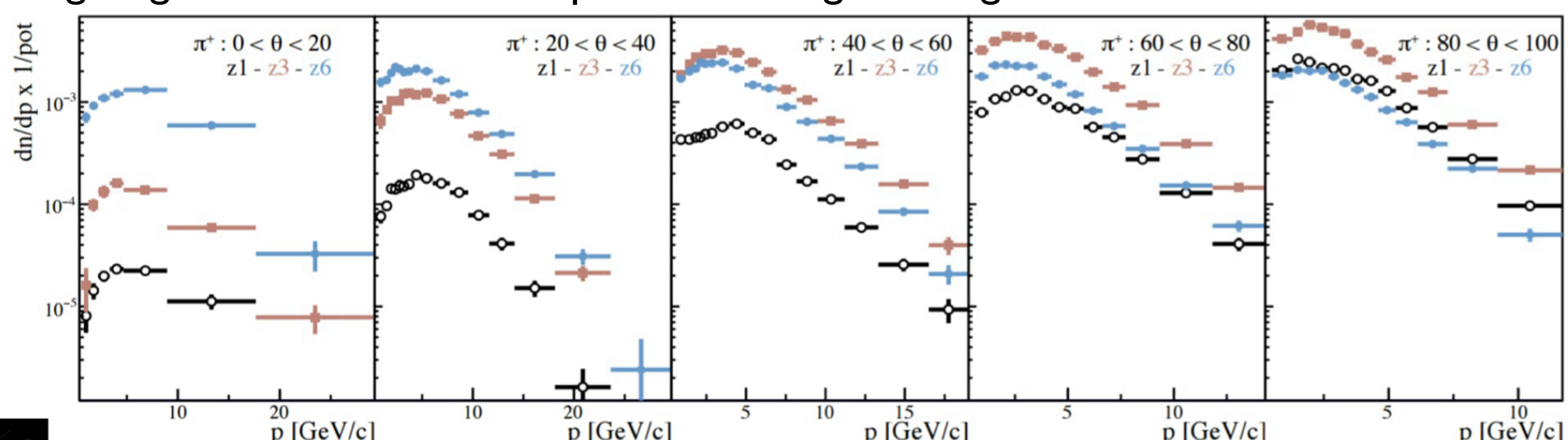
Hadron production data for neutrino experiments

Example:

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



long target → rates at various positions along the length:



nspirehep.net/record/1431983?ln=en,

nspirehep.net/record/1121706?ln=en

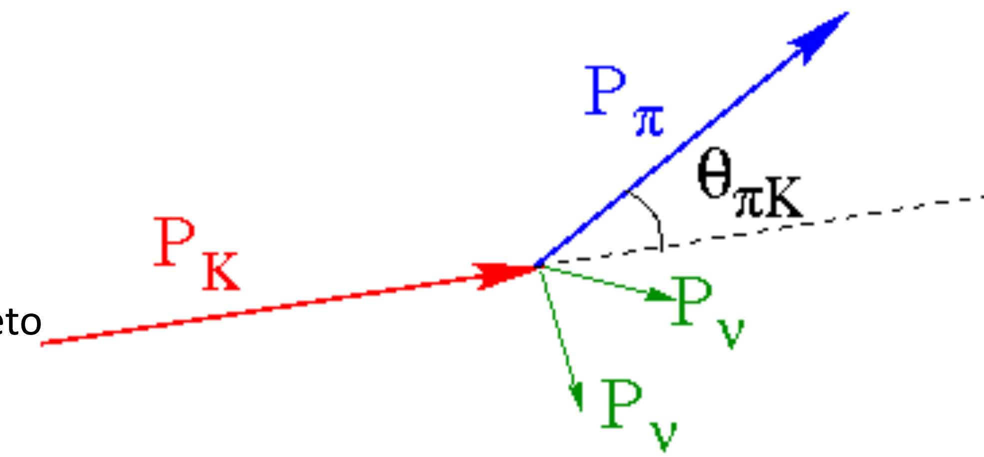
Rare decays: NA62 measures BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)

Kaons are special: the theoretical predictions are precise

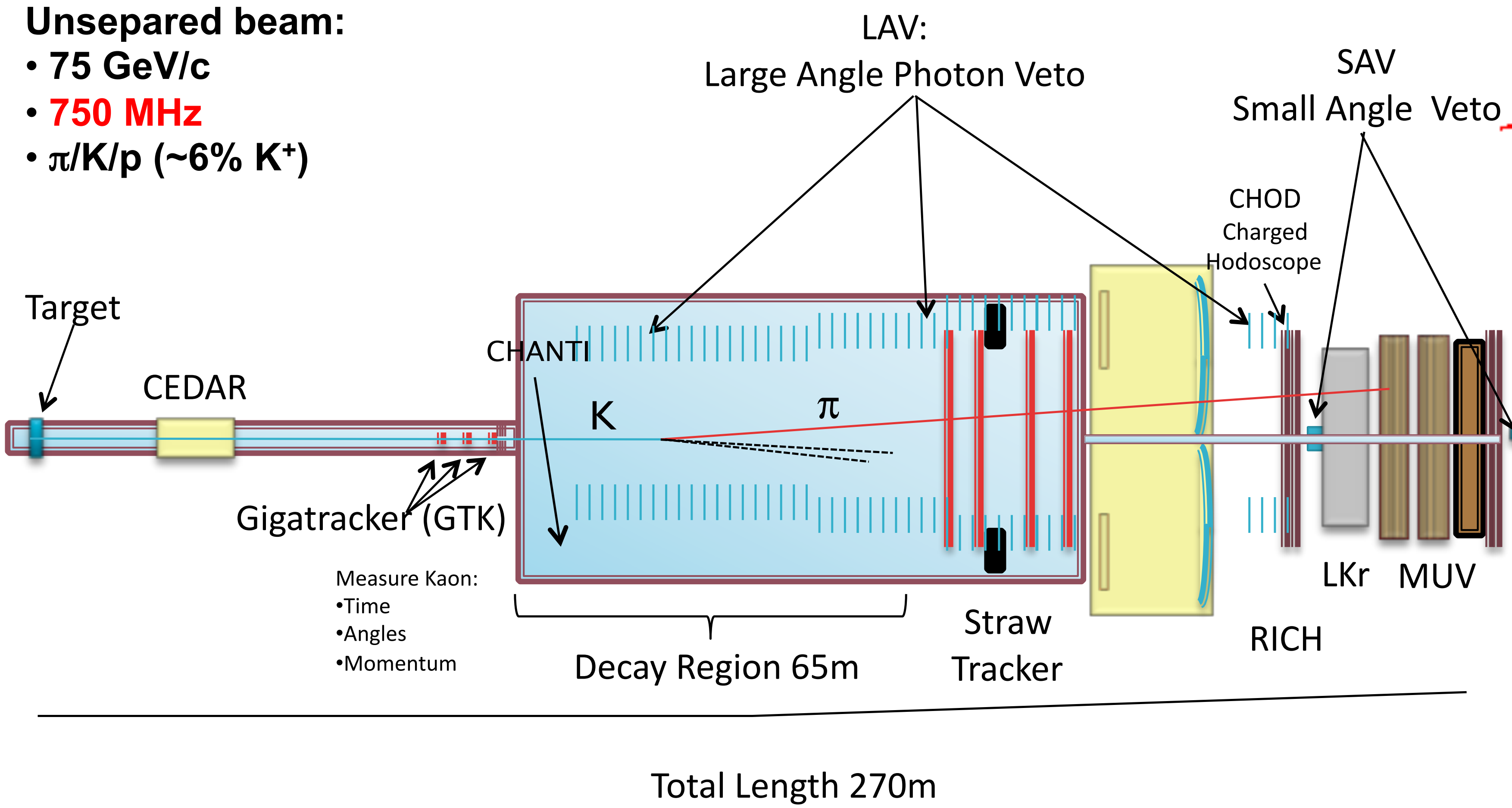
$$Br(K^+ \rightarrow \pi^+ \nu\bar{\nu})_{TH} = (8 \pm 1) \times 10^{-11}$$ Buras et al. (2015)

…and the experimental window of opportunity is largely unexplored

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



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



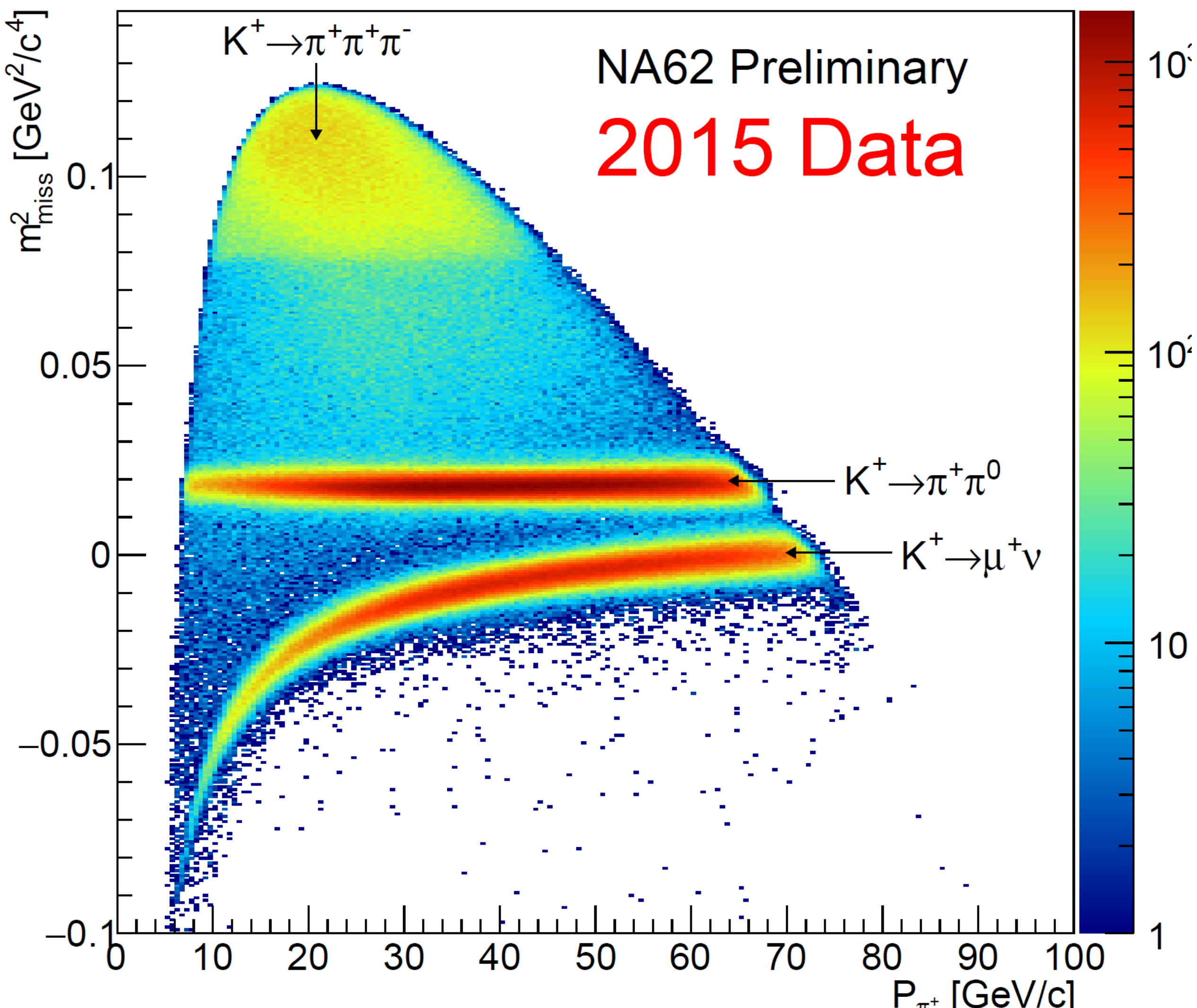
Beam line:
- CEDAR: K ID
- Gigatracker: beam particle ID
- CHANTI: Charged particle veto

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

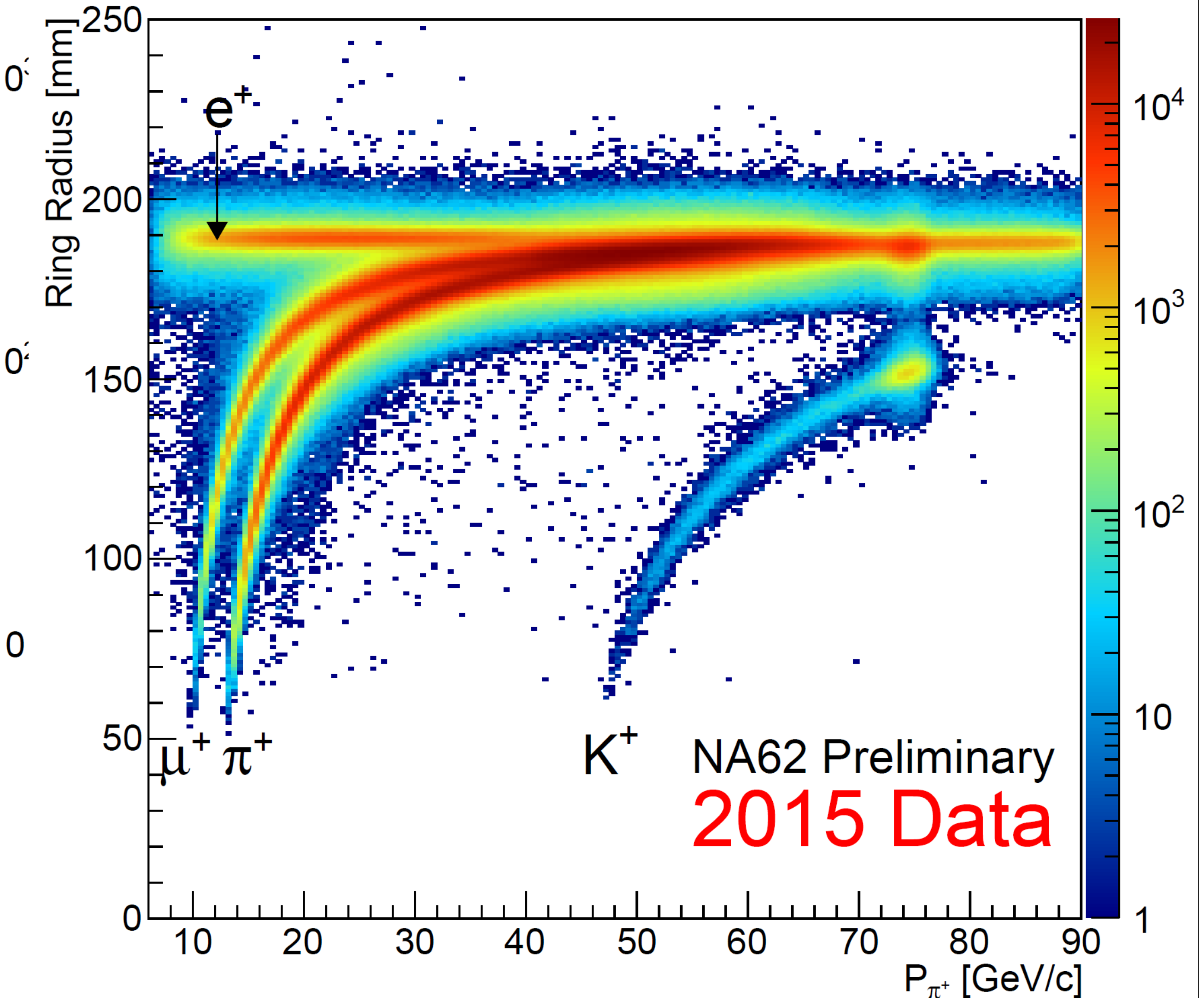
- K+ rate: 11 MHz

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

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

NA62 collaboration: ~230 authors incl. ~20 students

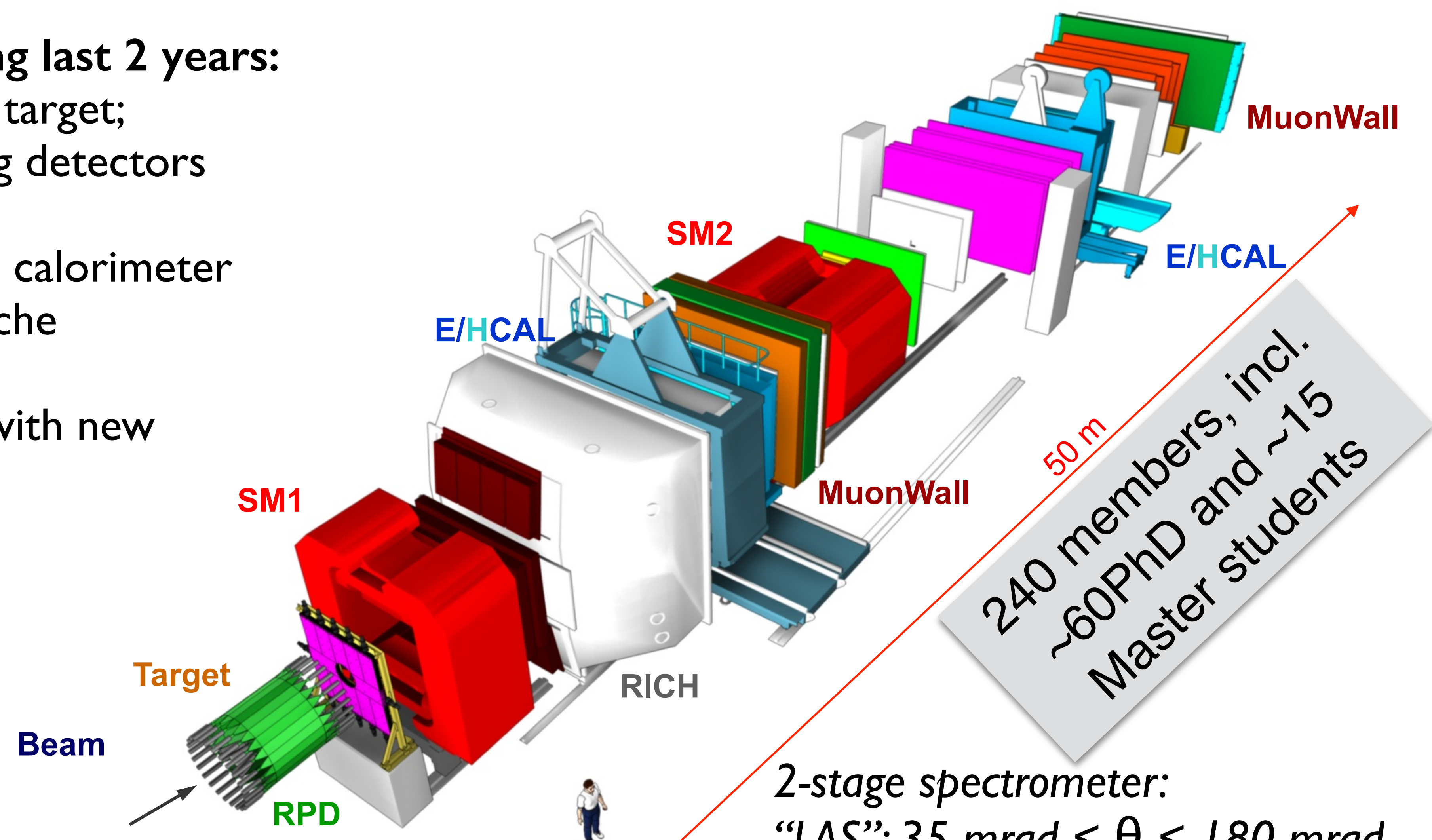
N.B.: one of my favourite photos…

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 ECal0 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-Fl based Vertex detector for first ever polarized Drell-Yan data set (successfully collected in 2015).

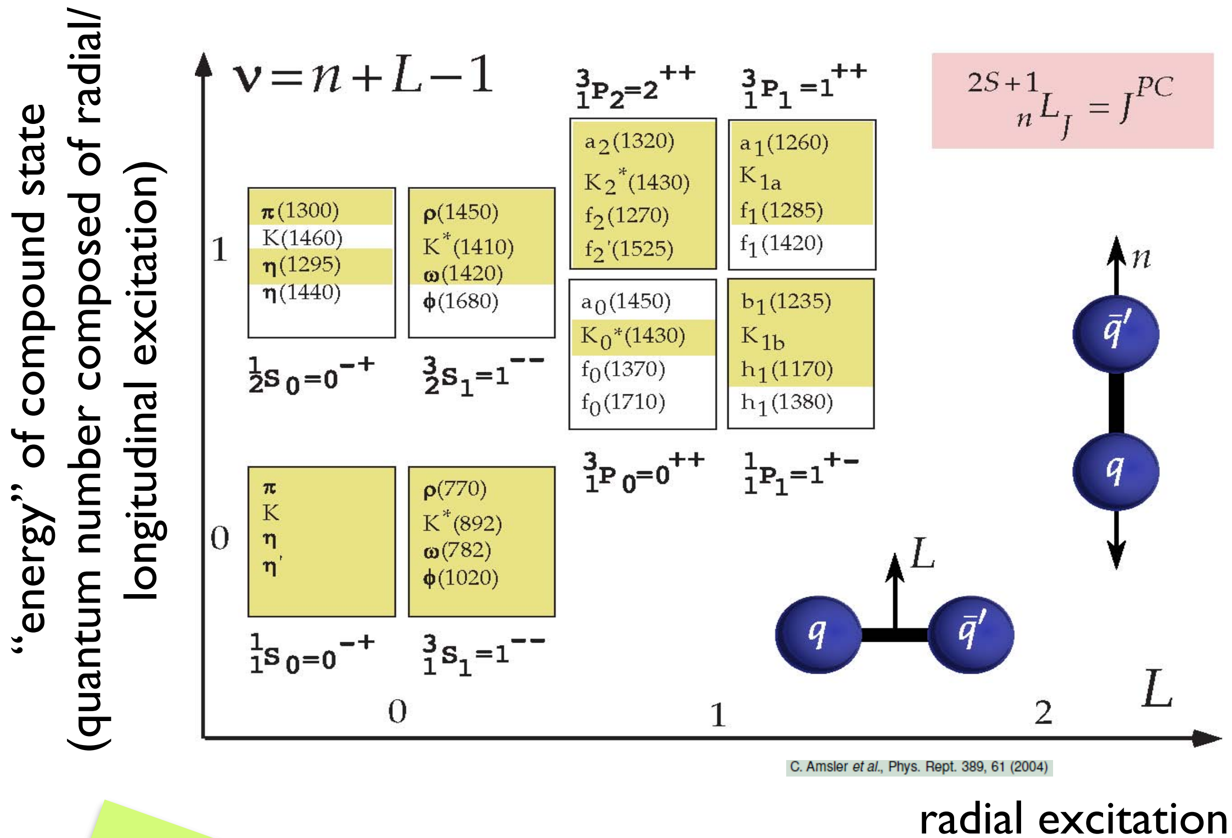


[COMPASS, P. Abbon et al., NIM A 577, 455 (2007)]

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

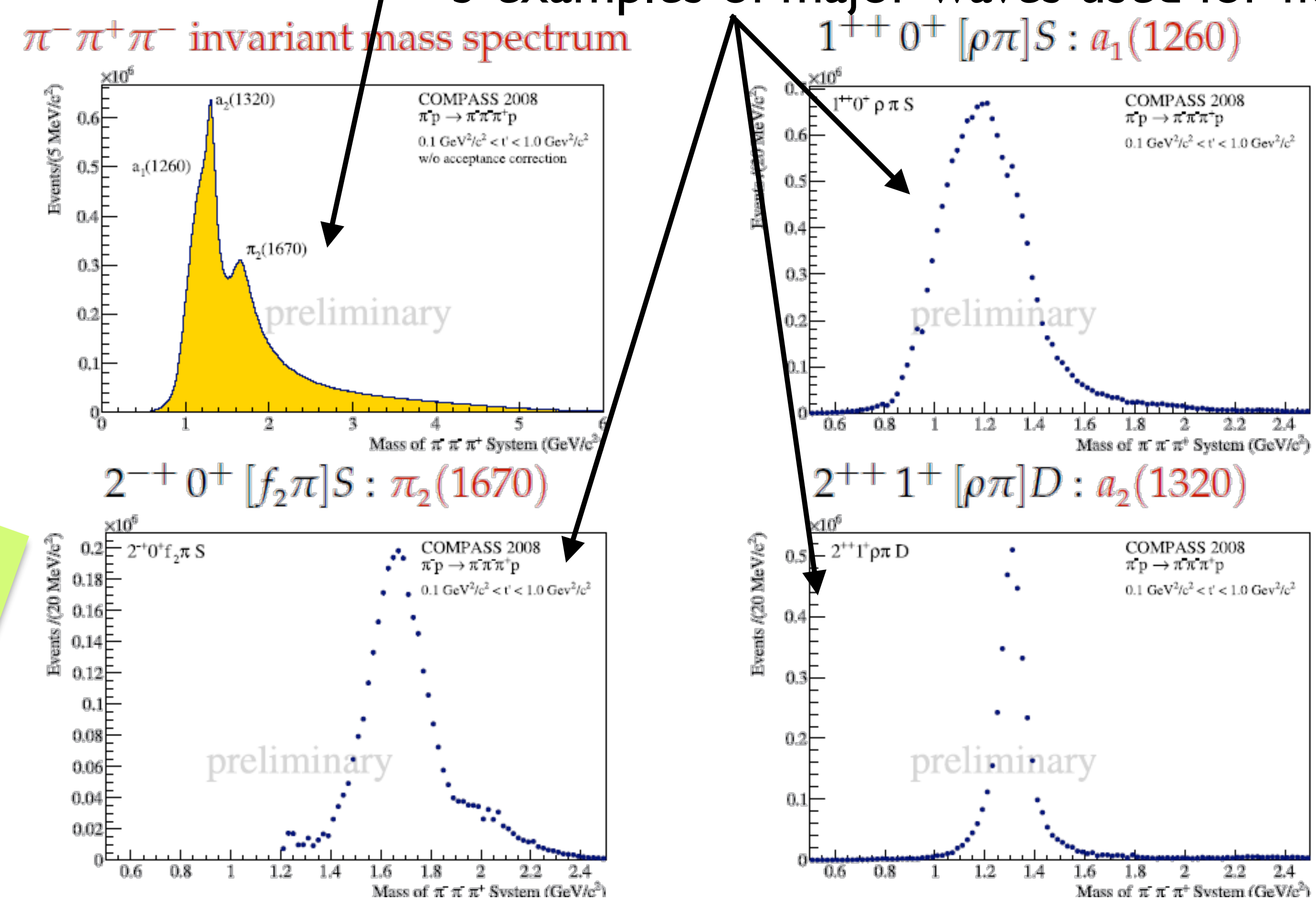
Example COMPASS hadron spectroscopy

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



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

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



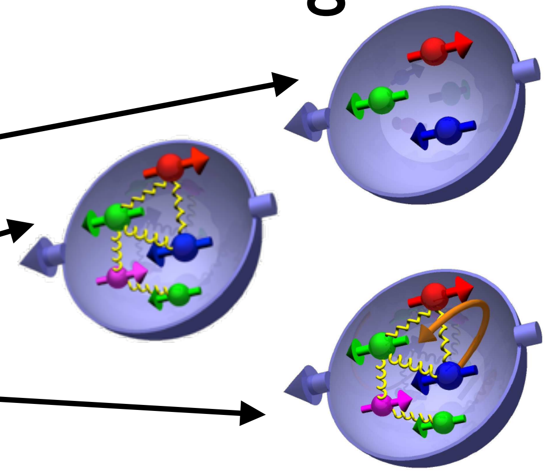
Discovery of the a₁(1420) axial-vector meson (was not predicted by Lattice QCD calc.) see Phys. Rev. Lett. 115, 082001

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 Δq_v
- QCD: sea quarks and gluons Δq_s, ΔG
- 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.

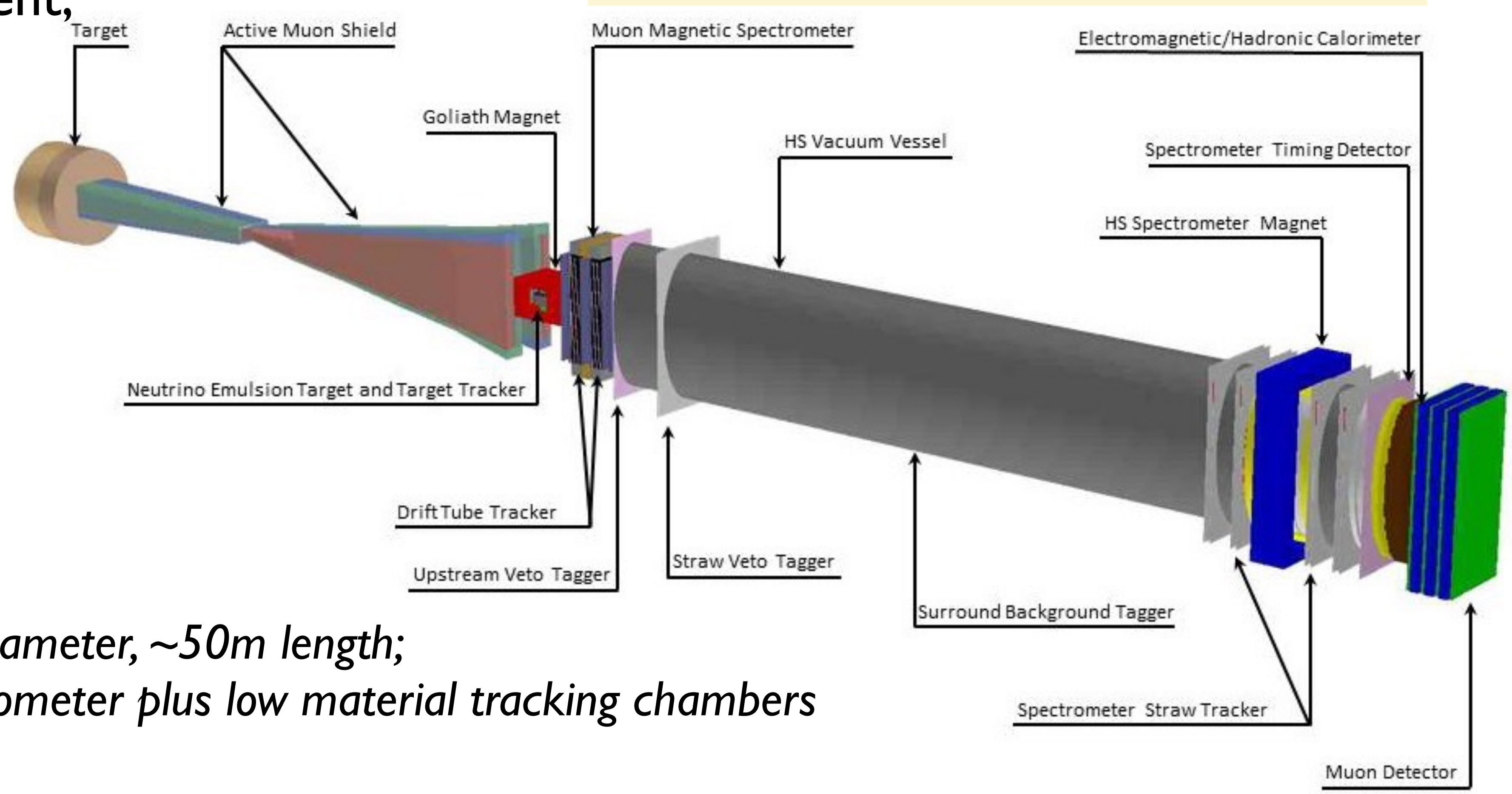
- Currently ongoing, DVCS run (nucleon tomography):

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.

Proposal in SPSC review: SHiP

- General purpose beam dump facility with 400 GeV protons from the SPS, to explore the domain of hidden particles with masses below O(10) GeV. Also ideal for ν_τ physics (DS→τ ν_τ);
- BSM theories with a new energy scale;
  - R-parity violating SUSY, s-goldstinos (that have escaped detection);
  - Models with a dark sector (vector-, Higgs-, neutrino- and axion-portals);
- BSM theories with no new physics between Fermi and Planck scales (nMSM);
  - Explains all experimental shortcomings of the SM at once by adding 3 heavy neutral leptons;
- Neutrino physics;
  - ν_τ cross section measurement;
  - First observation of anti-ν_τ.

see http://ship.web.cern.ch/ship/

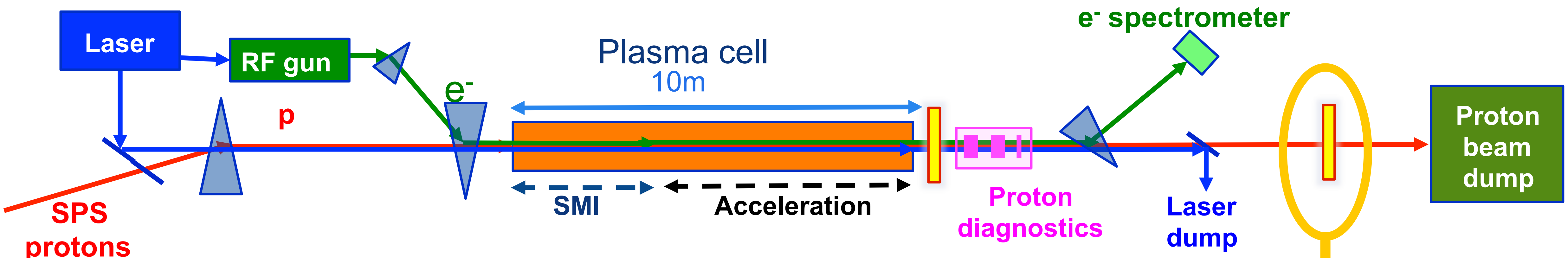


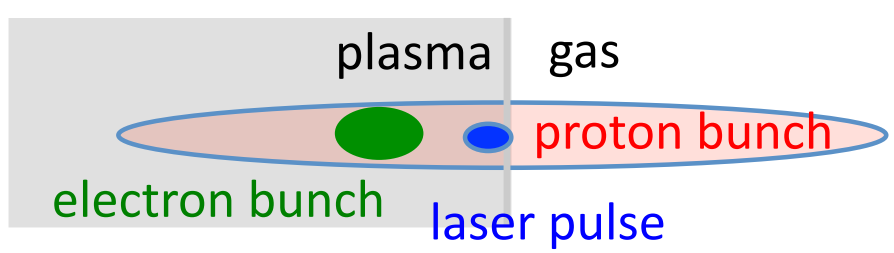
Long vacuum vessel, ~5m diameter, ~50m length;
~10m long magnetic spectrometer plus low material tracking chambers

Facilities@SPS: AWAKE

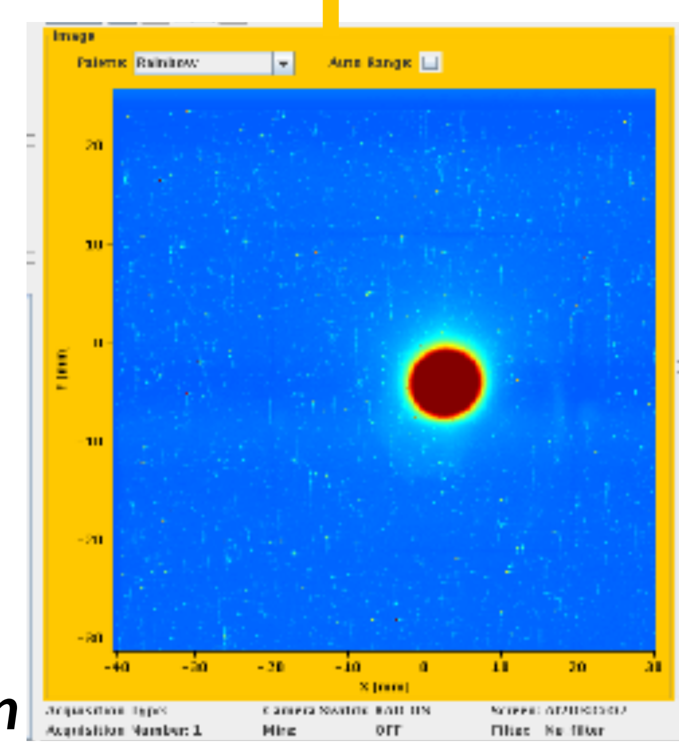
Advanced Proton Driven Plasma Wakefield Acceleration experiment in former CNGS tunnel

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



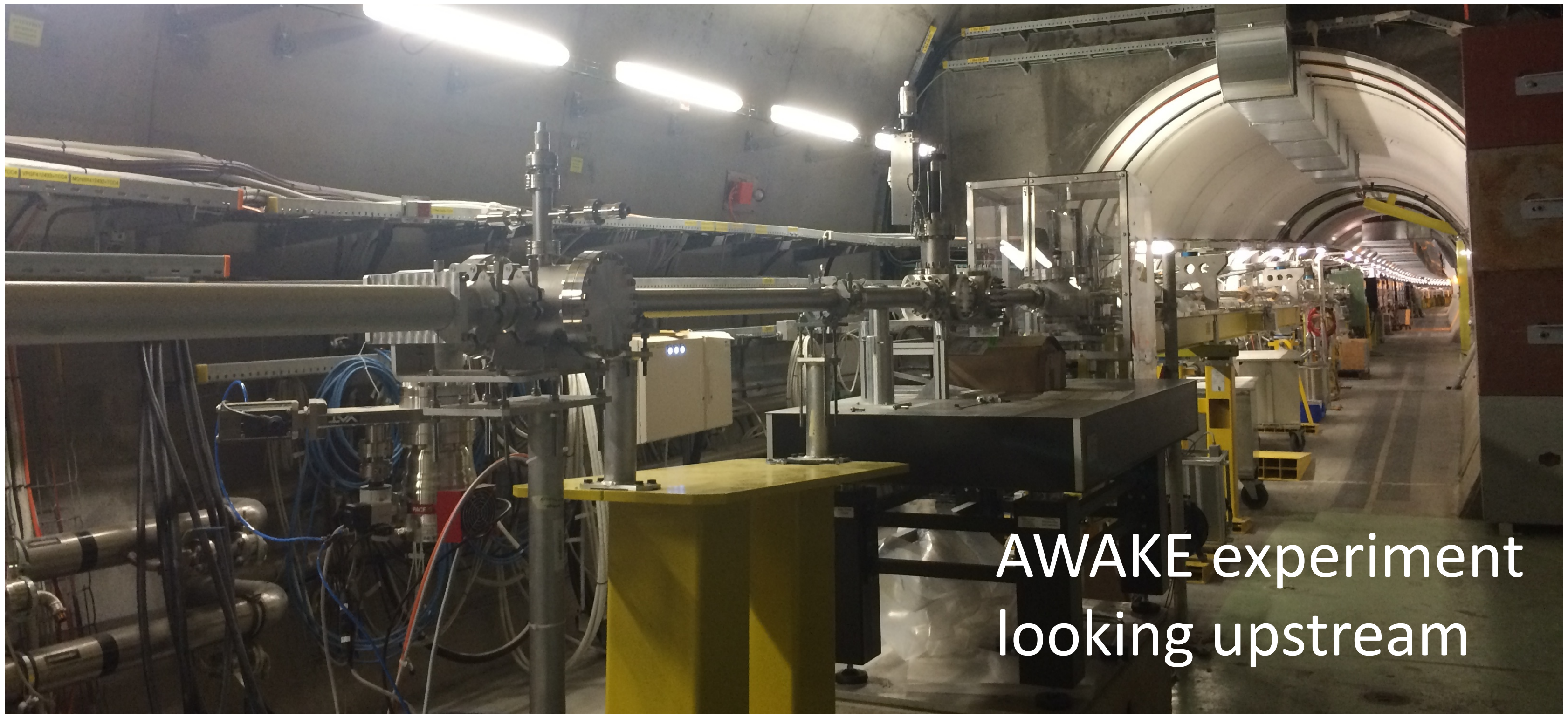


- 16 June 2016 first proton beam extraction from SPS to AWAKE



Beam TV screen image of the proton beam

Facilities at the SPS: AWAKE (2)

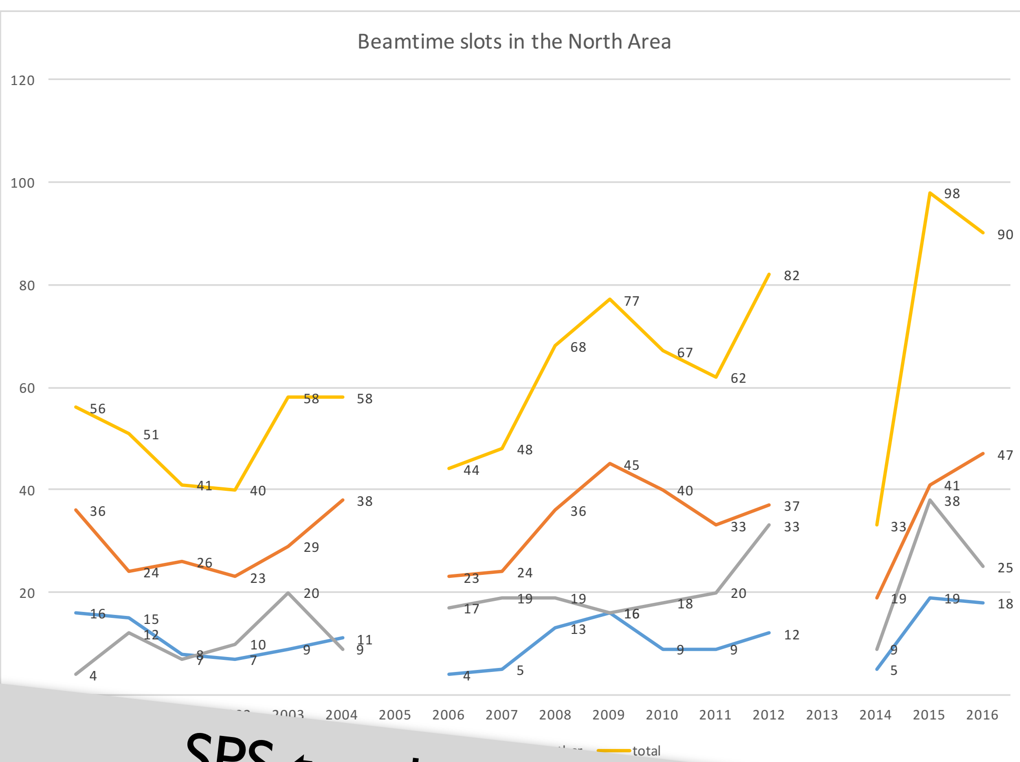


AWAKE Collaboration:
~90 authors
~15 master/PhD students

- Until LS2: demonstrate modulation of a proton bunch and generation of strong fields in a plasma driven by a proton bunch;
- Plans beyond LS2:
  → Demonstrate acceleration of electrons while preserving electron beam quality;
  → Demonstrate scalability of the AWAKE concept (develop solutions for sustaining gradients of significant distances, keep stable acceleration, design scalable length plasma sources and study pre-bunching of the proton beam.
- After LS3: First application of SPS proton beam driven plasma wakefield accelerator →50-100GeV/c electrons, used for fixed target experiments or for low-luminosity version of LHeC.

Irradiation & 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 beams increasing,
PS test beams ~constant 35-50

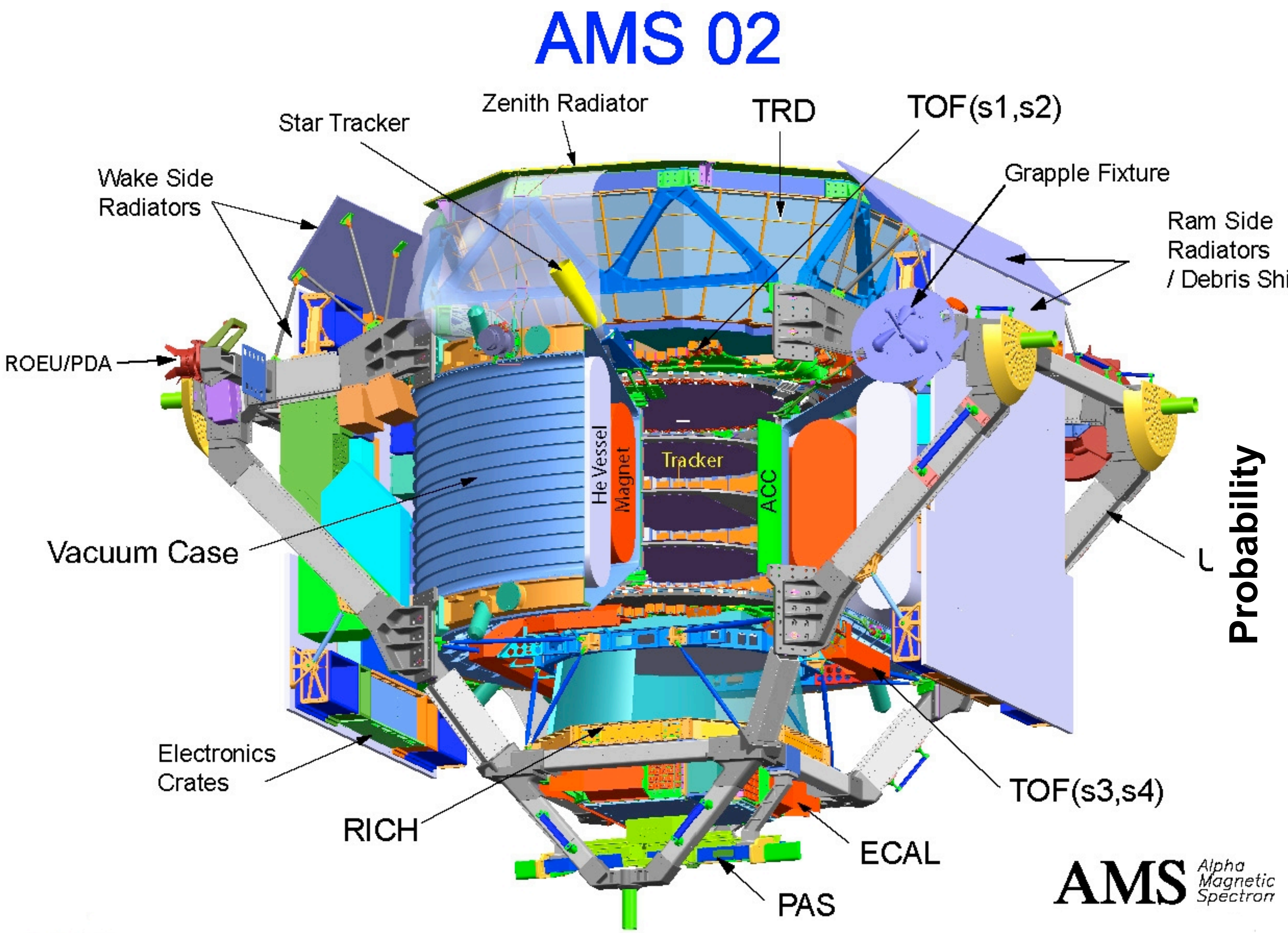
Test beams* in the world, status September 2016

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 Cherencov, scintillators, MWPCs, delay wire chambers, scintillators, magnet, movable platform	9 months per year, continous except winter shutdown Duty cycle depends on PS / SPS / LHC operation mode and is typical * PS ~1-3% * SPS: 20-40%	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 fragmentec 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		
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	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: 2kHz)		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	Cherencov, 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/ contact: Mandy Rominsky (rominsky@fnal.gov) Erik Ramberg (ramberg@fnal.gov)
IHEP Bejing (CN)	2	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 Cherencov, CAMAC system, platform	Availability: 3 mouths 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 ax. current 2 - 5 nA, rate <10^9 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/

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

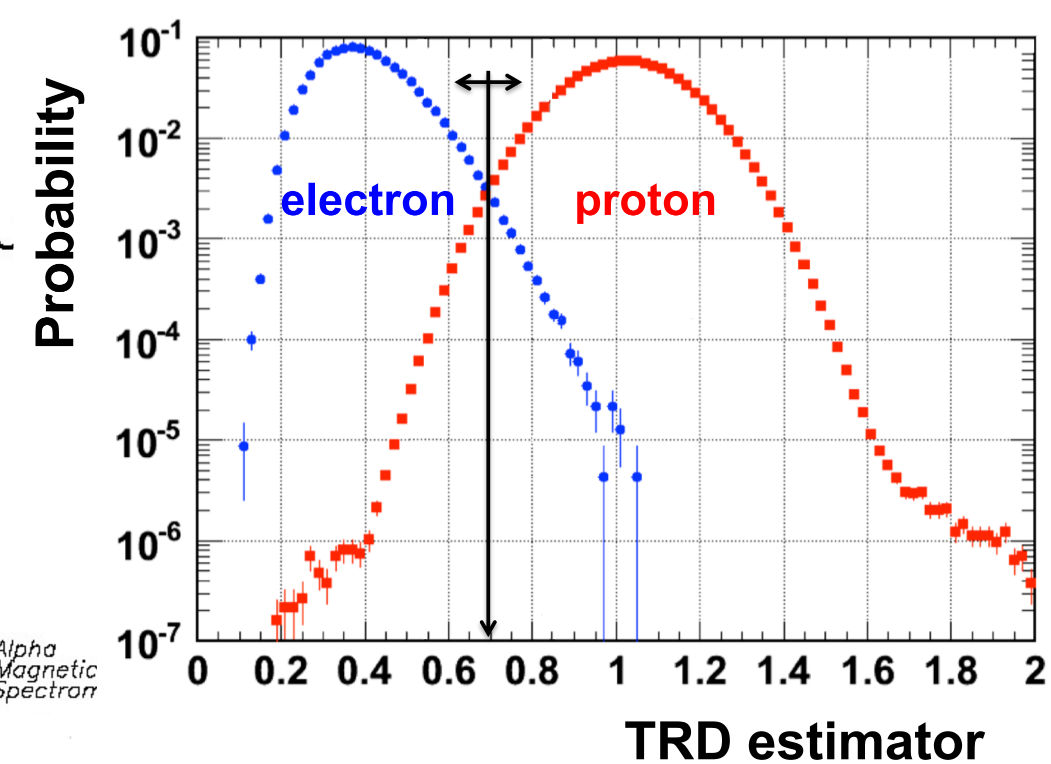
CR, Aug 2016

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))



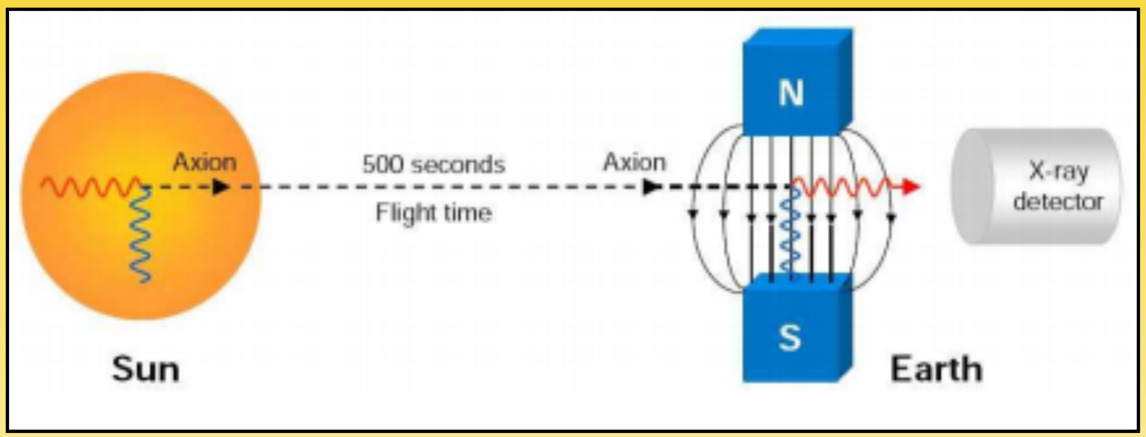
...needs down to earth calibration

Non-accelerator experiments

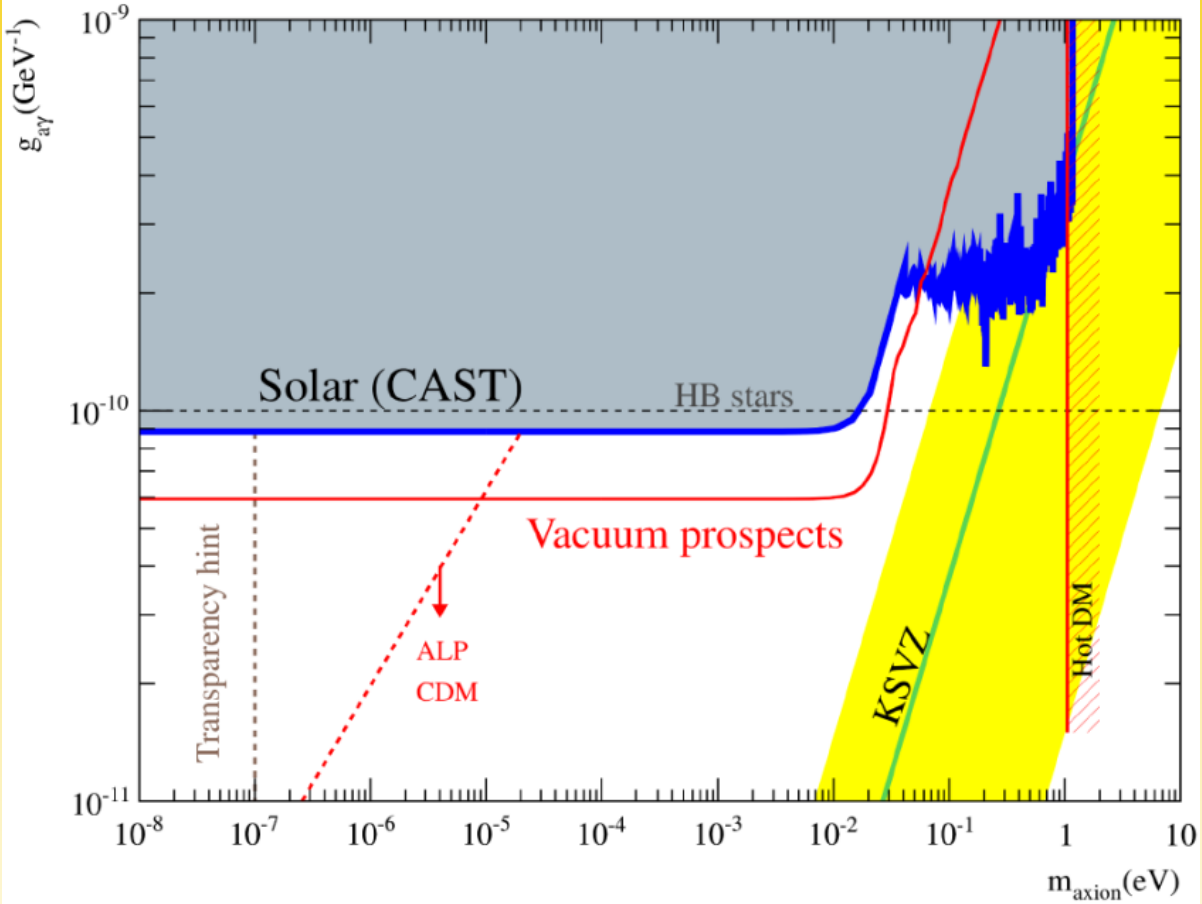
Two world-class experiments on CERN site searching for axions and axion-like particles.
Experiments benefit from CERN expertise on cryogeny, magnets, detector technology:

- **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



Best limit for **axion**-photon coupling



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

Beamline4schools: idea

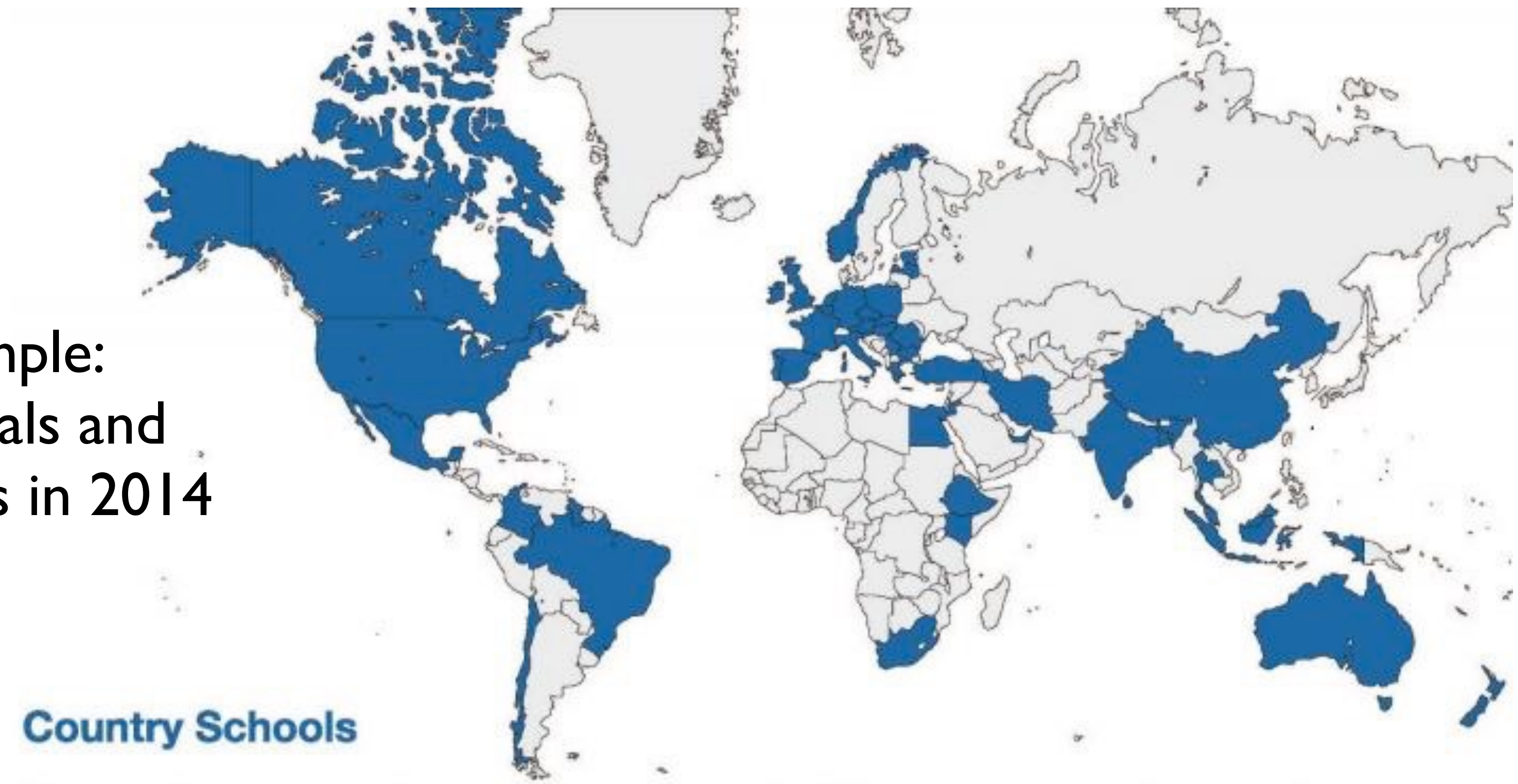
- Worldwide competition among schools for beam time at CERN
  - ➡ class to phrase scientific question, to work out / design / build an experiment which uses particle beams and to write / submit a proposal;
  - ➡ a committee selects best 16 proposals;
  - ➡ PS and SPS Experiments Committee (SPSC) decides 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

BL4S - participants and proposals

2014, 2015, 2016: ~1000 teams from >65 countries signed up; 562 proposals were submitted

Example: proposals and countries in 2014



Team Beamline Thailand:
" We want to throw out that lump of a book, kick the classroom door open and go out to see real things."

Country Schools

Italy	68	France	4	Bangladesh	1	Malta	1
Spain	35	Hungary	4	Belgium	1	Mauritius	1
United Kingdom	30	Switzerland	4	Bulgaria	1	New Zealand	1
United States	24	Colombia	3	Chile	1	Norway	1
Germany	10	Mexico	3	China	1	Oman	1
Greece	10	Slovakia	3	Czech Republic	1	Qatar	1
India	10	Brazil	2	Estonia	1	Serbia	1
Poland	9	Iran	2	Ethiopia	1	UAE	1
Canada	8	Ireland	2	Indonesia	1		
Portugal	8	Slovenia	2	Israel	1		
Netherlands	6	South Africa	2	Jordan	1		292
Romania	6	Thailand	2	Kenya	1		
Turkey	6	Australia	1	Lebanon	1		
Singapore	5	Austria	1	Malaysia	1		

The winners

2014:
Odysseus' Comrades from Greece
Dominicuscollege from the Netherlands

2015:
Leo4G from Italy
Accelerating Africa from South Africa

2016:

Relatively Special from the UK: Test the validity of the Lorentz factor by measuring the effect of time dilation due to special relativity on the decay rate of pions.

'My Mum asked me "What is your team doing in the competition?" To which I replied, "Oh, just proving Einstein's Special Theory of Relativity" ' - Achintya Singh, member of 2016 winning team

Pyramid hunters from Poland: Try to examine the internal structure of the Chephren pyramid using muon tomography

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 2017: PROPOSAL SUBMISSION IS NOW OPEN!

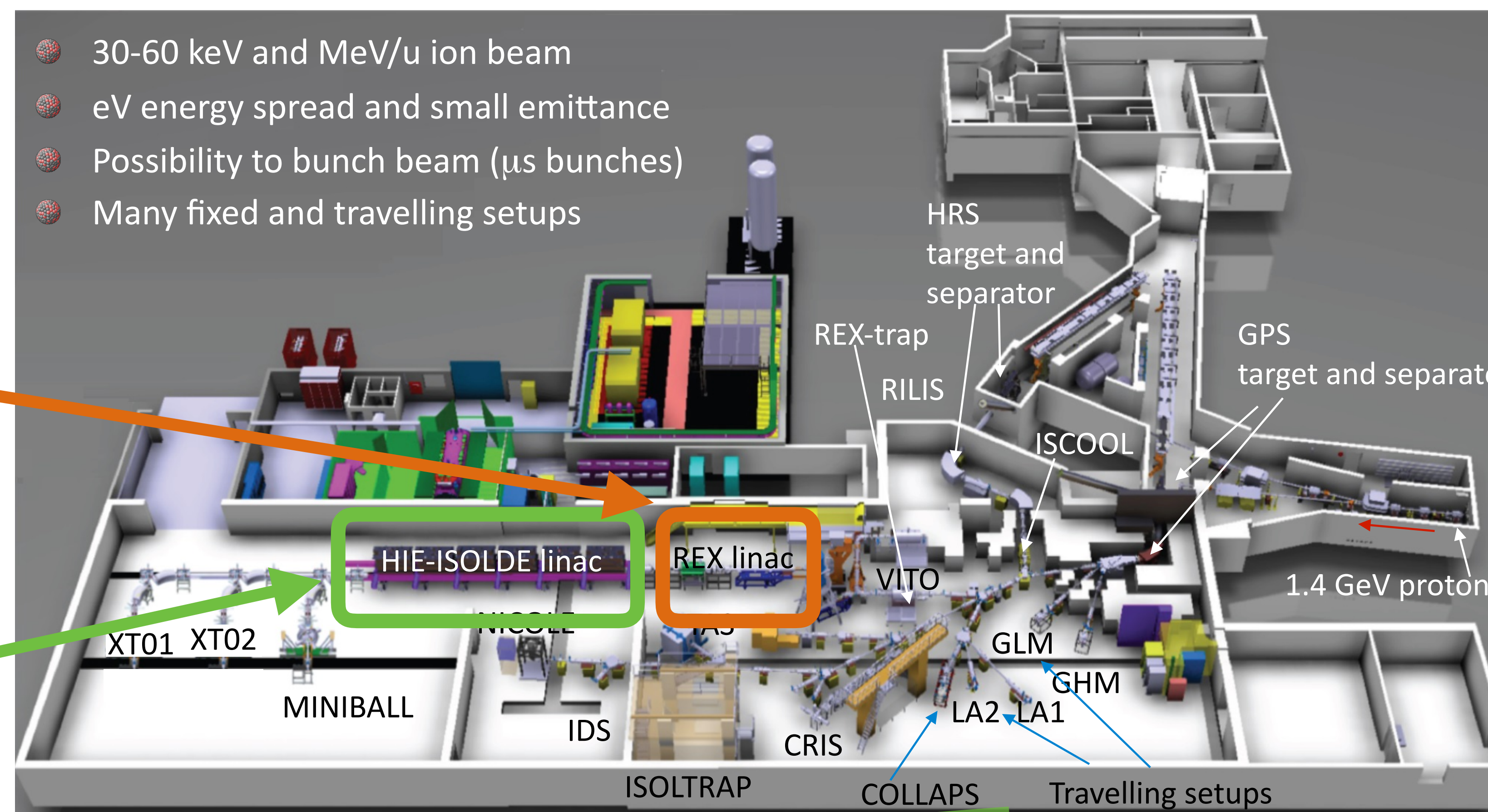
Summary

- There is a rich physics programme at the CERN accelerators:
  - ➡ using unique experimental facilities;
- The LHC collider is exploring new territory at the energy fronteer:
  - ➡ 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

Experimental facility at the Booster: ISOLDE

- ISOLDE (Isotope Separator On Line DEvice): radioactive ion beams (>1000 isotopes, more than 70 chemical elements) for experiments in nuclear and atomic physics, solid-state physics, materials and life sciences, see http://isolde.web.cern.ch/ ;
- REX-ISOLDE: post-accelerated nuclei covering mass range from He to U for reaction studies and Coulomb excitation with energies up to 3 MeV/u;
- HIE-ISOLDE: post-accelerating radioactive ion beams with up to 10 MeV/u.

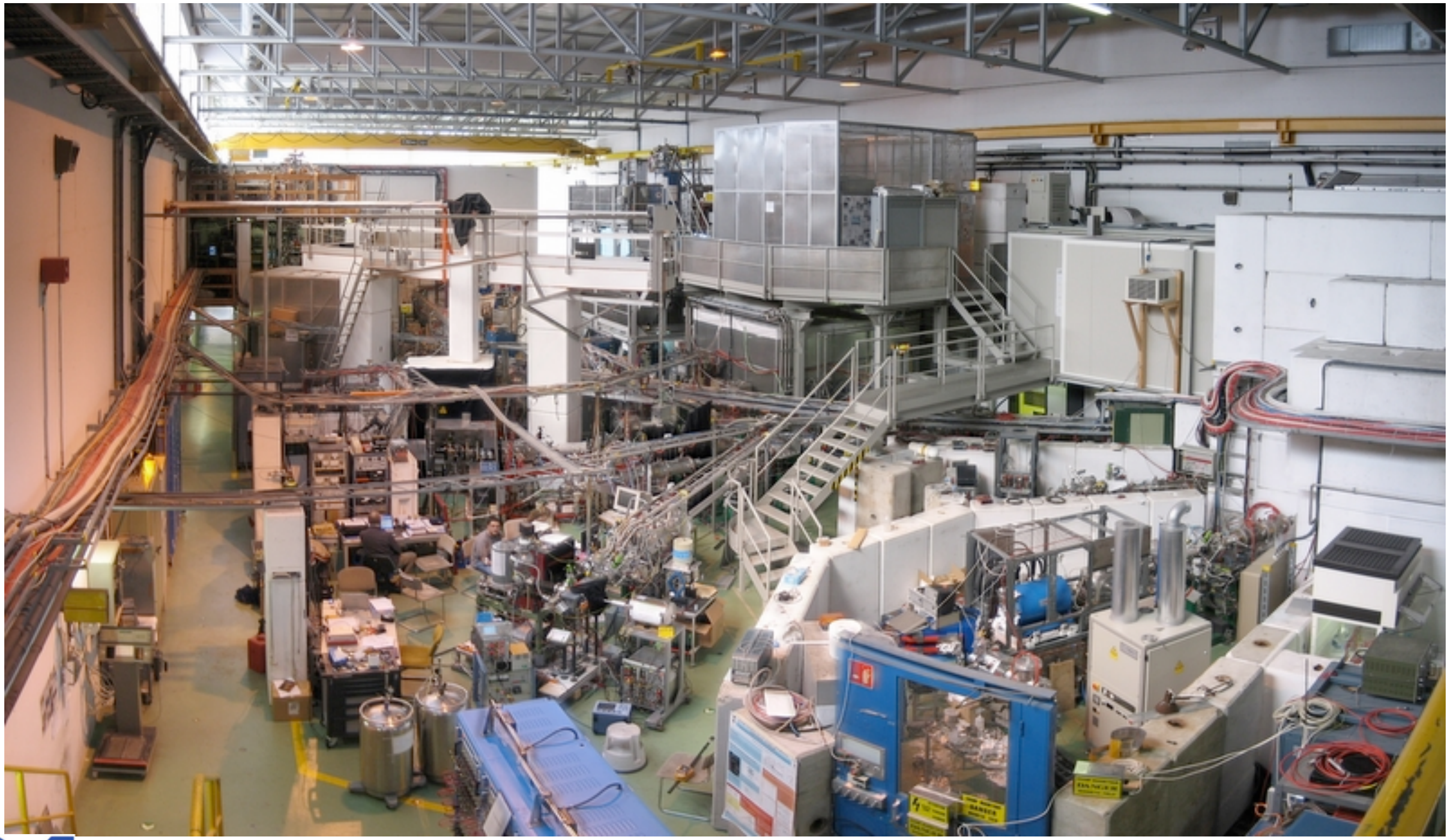


Hie-isolde running last year. Starting physics this week, might accelerate radioactive beam at 5MeV/u even this weekend.

Search for new physics at ISOLDE

- An example: are there supersymmetric (SUSY) particles?

  Indirect search: measuring electromagnetic dipole moment of an atom.
  Expect strong contributions if there is SUSY:
  ^{225}Ra EDM to the 10^{-27} e . cm level
  Current experimental limits e.g. $|d_{Tl}| < 9 \times 10^{-25}$ e · cm or $|d_n| < 3 \times 10^{-26}$ e · cm



@SPS(and LHC): UA9 crystal channeling

Bent crystals allow deflecting particles by coherent interaction:

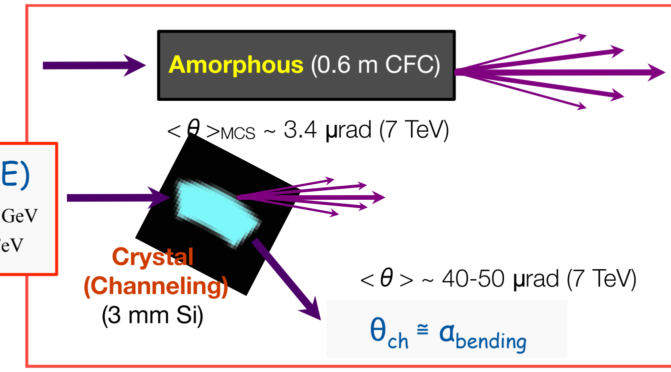
- ➡ large angle deflection also at high energy,
- ➡ reduced interaction probability (e.g. diffractive events);
- ➡ reduced impedance (less secondary collimators,…)

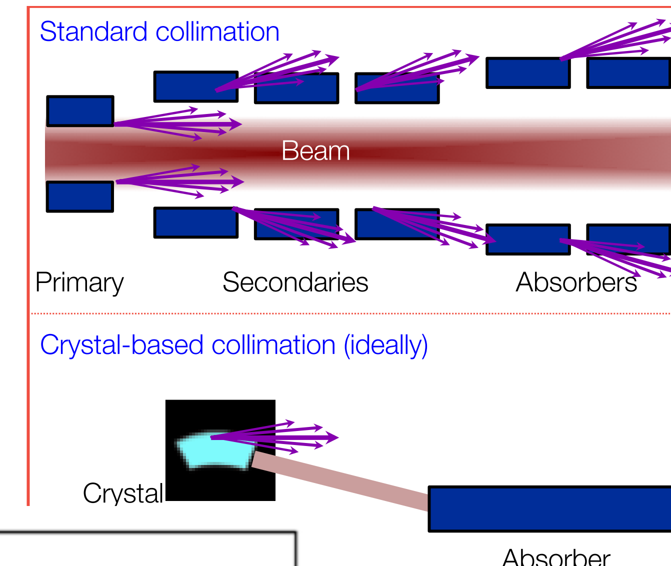
BUT

- ➡ small angular acceptance,
- ➡ concentration of the losses on a single absorber.

$$\theta_c \cong \sqrt{(2U_0/E)}$$

$$\theta_c = \begin{cases} 10\,\mu rad @ 270\text{ GeV} \\ 2\,\mu rad @ 7\text{ TeV} \end{cases}$$

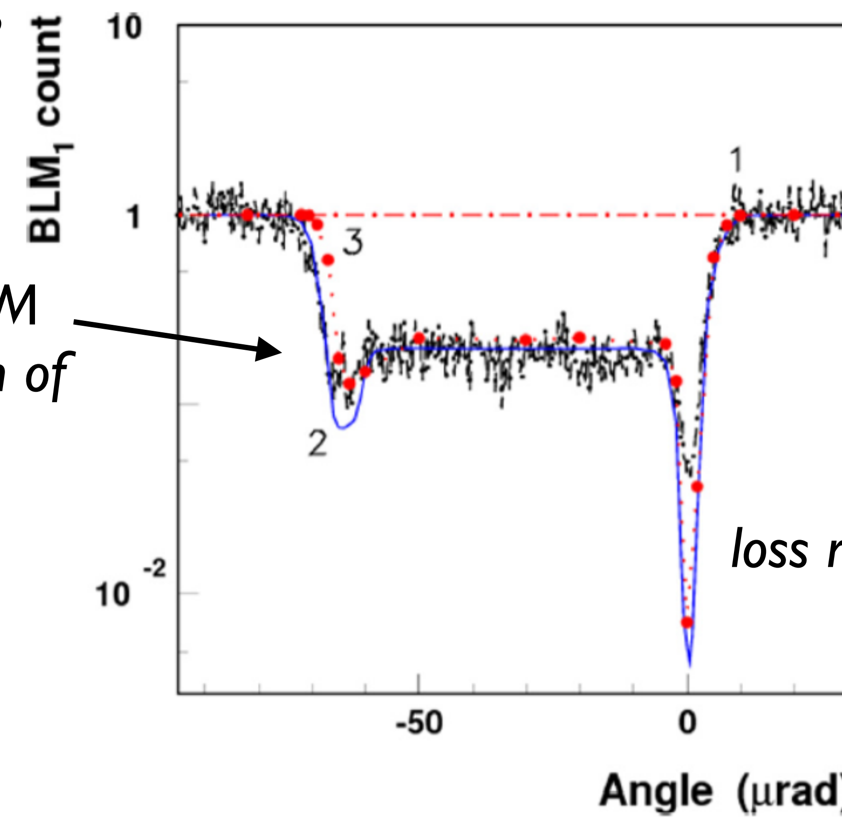




Very successful MDs during 2015/2016:

- ➡ Channeling observed for the first time at the LHC with protons and ions at 450 GeV;
- ➡ Channeling observed with protons at 6.5 TeV, see Physics Letters B758(2016)129–133;

The dependence of the beam losses observed with the BLM downstream of crystal (curve 1) for the LHC coasting beam of 6500GeV/c protons. Curves 2 and 3 are simulations,

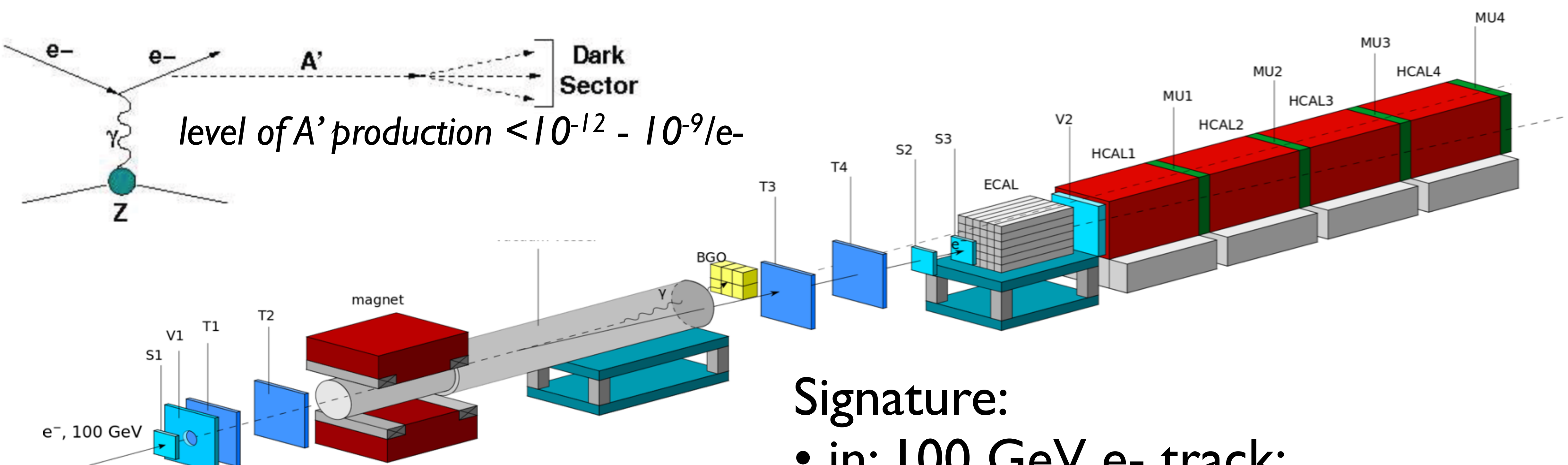


loss reduction about ~24

@SPS: NA64

Search for dark sector physics in missing-energy events with an active beam dump experiment;

- ➡ Test run in 2015 to validate detector;
- ➡ 2016: direct search for massive dark photons (A') which decay predominantly invisibly into lighter dark matter particles.



level of A' production <10^{-12} - 10^{-9}/e-

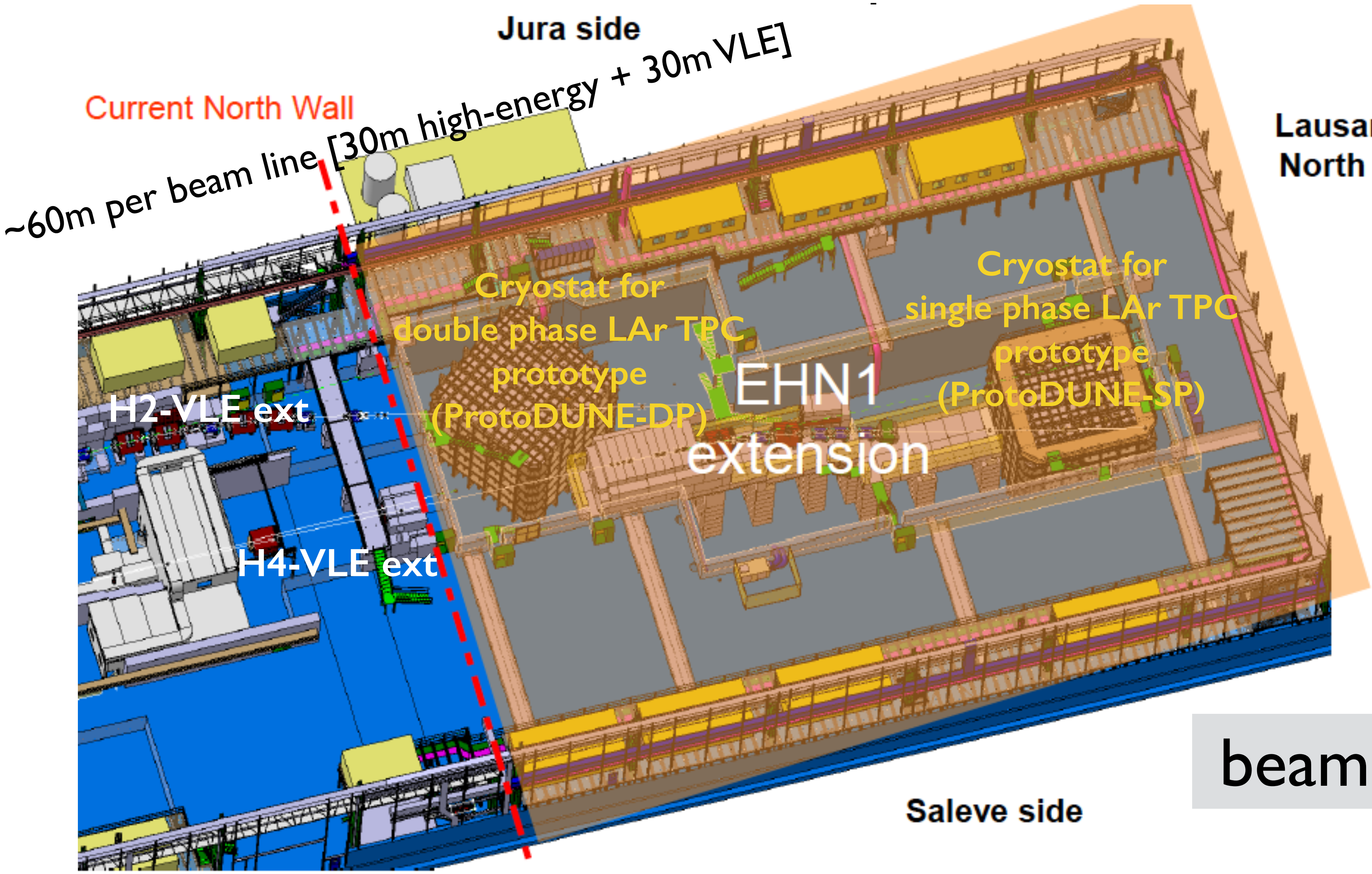
Signature:
- in: 100 GeV e- track;
- out: < 50 GeV e-m shower in ECAL;
- no energy in the Veto and HCAL.

Irradiation & test beam facilities

- At the PS/East Area:
  - ➡ **IRRAD**: primary proton irradiation, beam parameters: proton beam momentum 24GeV, max. $5*10^{11}$ protons per spill, up to10^{18} protons per year, see https://irradiation.web.cern.ch/irradiation/ ;
  - ➡ **CHARM** (Cern High energy AcceleRator Mixed field facility): downstream of IRRAD, proton beam on target creates any radiation environments found in the accelerator chain, see http://charm.web.cern.ch/CHARM/ ;
- At the SPS:
  - ➡ **HiRadMat** (High-Radiation to Materials): high-intensity pulsed beams to test material samples as well as accelerator component assemblies can be tested, see https://espace.cern.ch/hiradmat-sps/Wiki%20Pages/Home.aspx ;
  - ➡ **GIF++** (Gamma Irradiation Facility): located in the North Area. Combines 15 TBq ^{137}Cs source with a high-energy particle beam from the SPS H4 beam line to allow detector tests in high multiplicity environment and detector ageing tests, see https://gif-irrad.web.cern.ch/gif-irrad/ ;
  - ➡ **CERF** (CERN-EU high-energy Reference Field): located in the North Area providing a neutron field for characterisaion of dosimetry at commercial flight altitudes and in space, see https://cerf-dev.web.cern.ch/ .

Irradiation & test beam facilities (3)

The **neutrino platform** at CERN is currently constructed to develop and prototype the next generation of neutrino Liquid Argon (LAr)

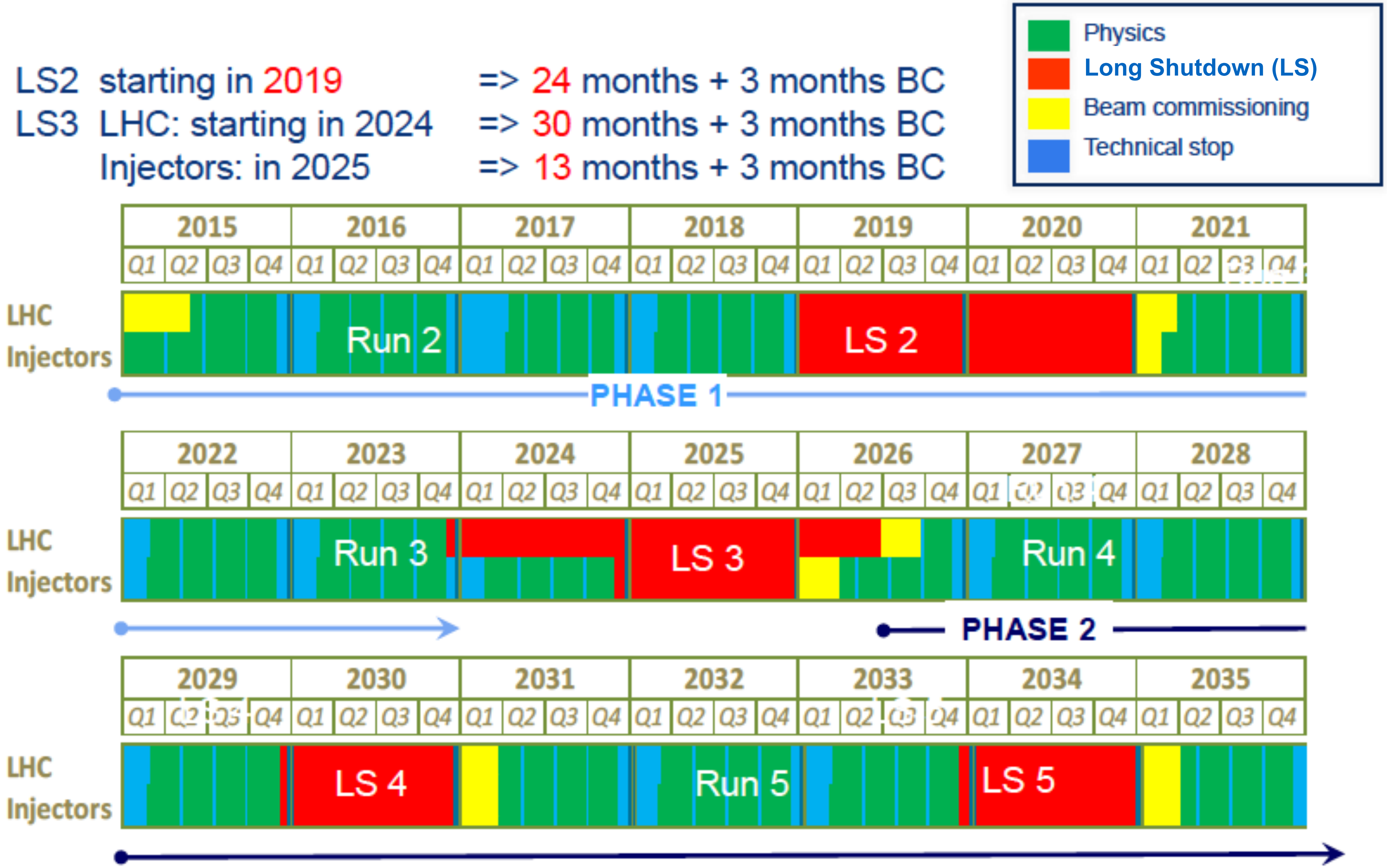


beams available 2018

H2 extension: 1(0.5)÷12 GeV tertiary beam, H4 extension: 1(0.2)÷7(10)GeV tertiary beam
Beam characteristics:
Secondary beam of 80Gev (π/p, or e) produces the tertiary low−energy beams on a secondary target
VLE beams: mixed hadrons (π±, μ±, K±, p), ~pure electron (e±) beams

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



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