The Mission of CERN

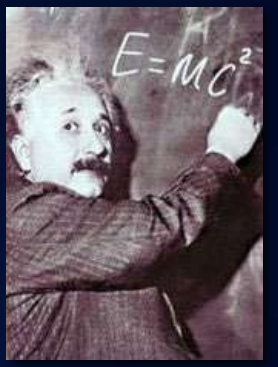
- **Push forward** the frontiers of knowledge

  E.g. the secrets of the Big Bang ... what ... the matter like within the first moments of the Universe's existence?

- **Develop** new techno... accelerators and d...

  Information technology

  Medicine - diagnosis and therapy

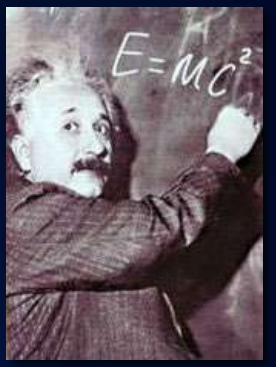


EXPERIMENT

The Mission of CERN

- **Push forward** the frontiers of knowledge

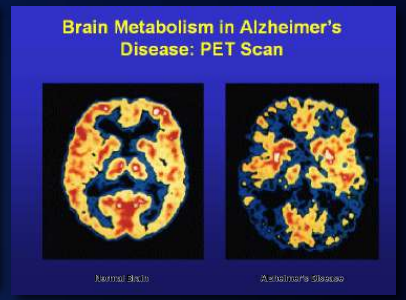
  E.g. the secrets of the Big Bang …what was the matter like within the first moments of the Universe's existence?



- **Develop** new technologies for accelerators and detectors

  Information technology - the Web and the GRID

  Medicine - diagnosis and therapy



- **Train** scientists and engineers of tomorrow

- **Unite** people from different countries and cultures

CERN was founded 1954: 12 European States

"Science for Peace"

Today: 21 Member States

~ 2300 staff
~ 1600 other paid personnel
~ 10500 users

Budget (2014) ~1000 MCHF

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

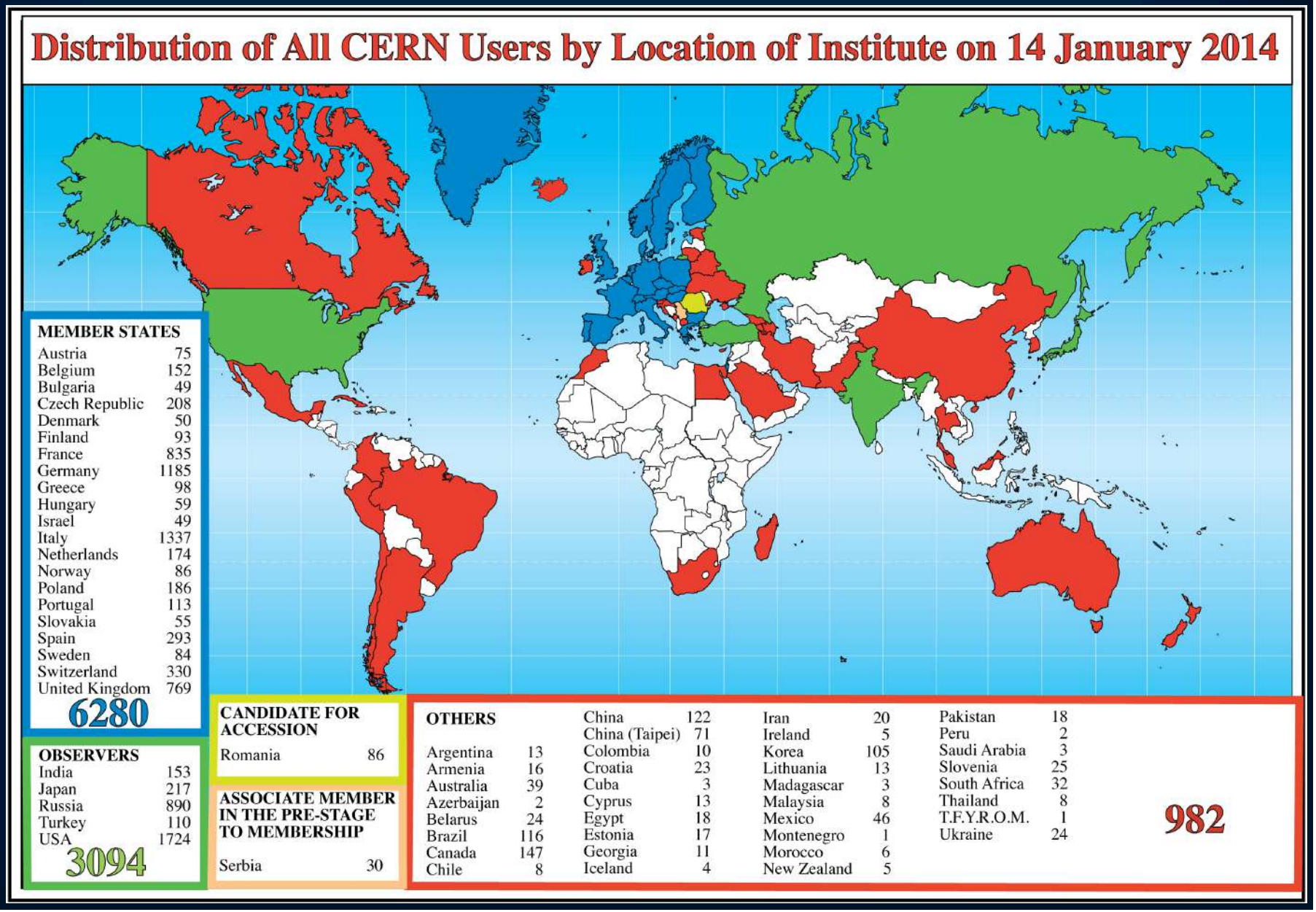
Candidate for Accession: Romania

Associate Member in Pre-Stage to Membership: Serbia

Applicant States for Membership or Associate Membership: Brazil, Cyprus, Pakistan, Russia, Slovenia, Turkey, Ukraine

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

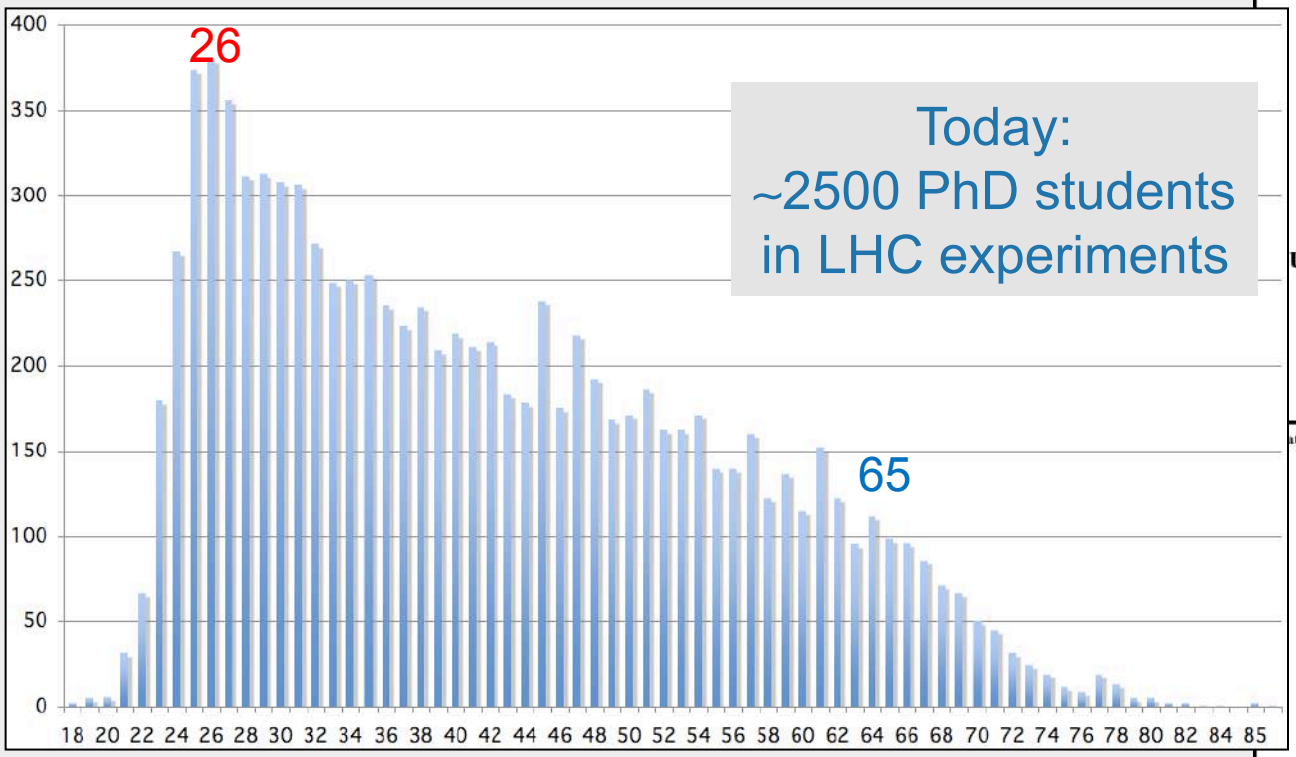
Science is getting more and more global



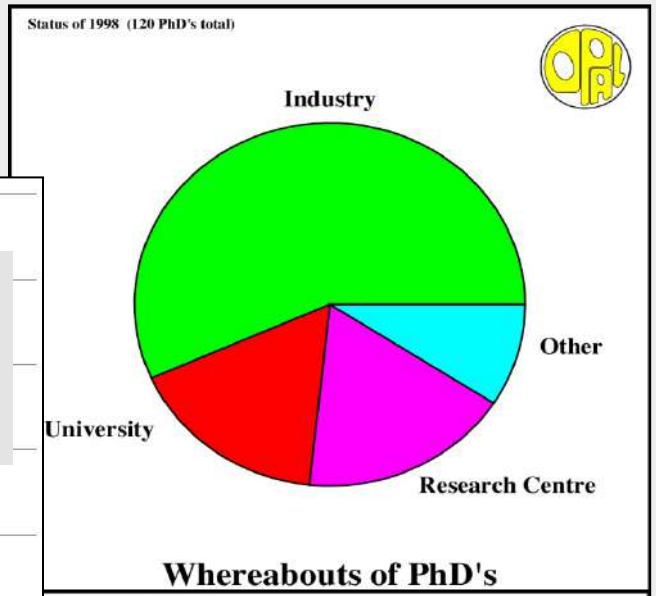
Age Distribution of Scientists

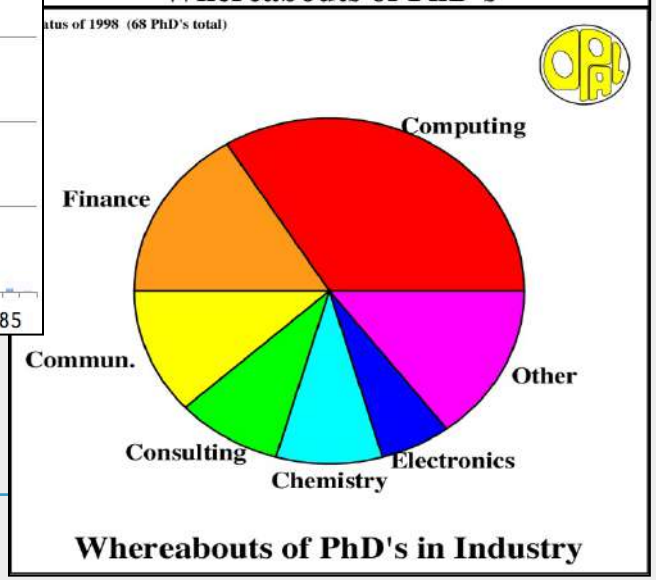
- and where they go afterwards

Survey in March 2009



Today:
~2500 PhD students
in LHC experiments





They do not all stay: where do they go?

A peculiar ant colony, probably worth of a closer look

How Do We Manage This?

Contrary to popular belief, our community is rather elementary:

- It has simple rules, honed by centuries of practice
- It shares a common vision and a common set of values
- It is based on **collaboration** AND **competition**

Science is intrinsically **not democratic** (can't decide who is right by vote!) and therefore it has to be performed **with the most democratic tools:**

- Freedom of expression
- Peer reviewing
- Independency from political orientation, religion, social status, etc…

The scientists/engineers

Despite the usual cinematographic representation, in general we DO NOT

- Wear white lab coats
- Live in ivory towers
- Find a revolutionary result every second day (scientist=genius)

We are a pragmatic community capable to address in a very material way grand and (apparently) immaterial questions, knowing that for every answer we might find, we will open more and unpredicted questions.

(we definitely prefer to be Ministers of Doubt than Kings of Truth: ubi dubium, ibi libertas)

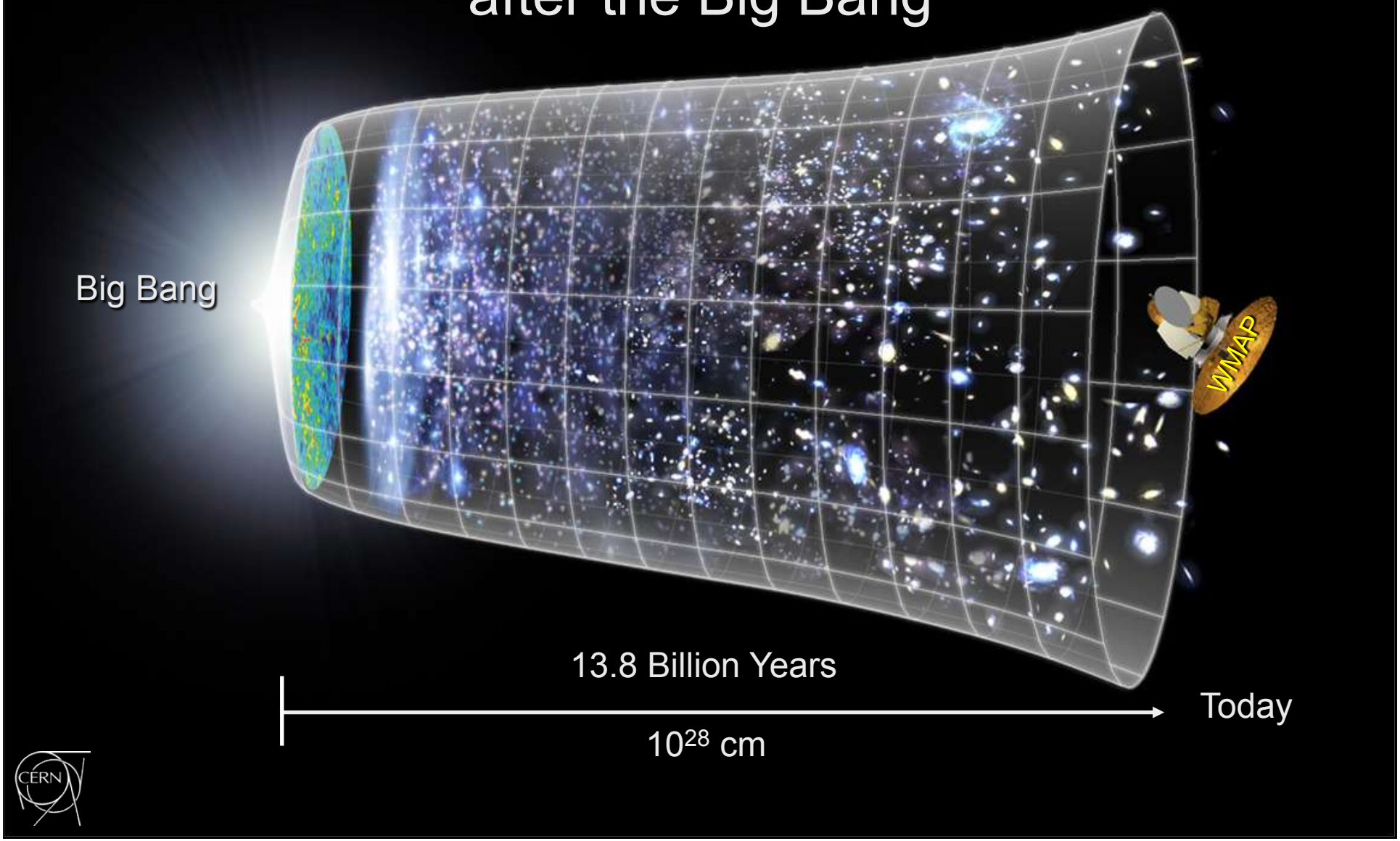
How can you manage such a community?

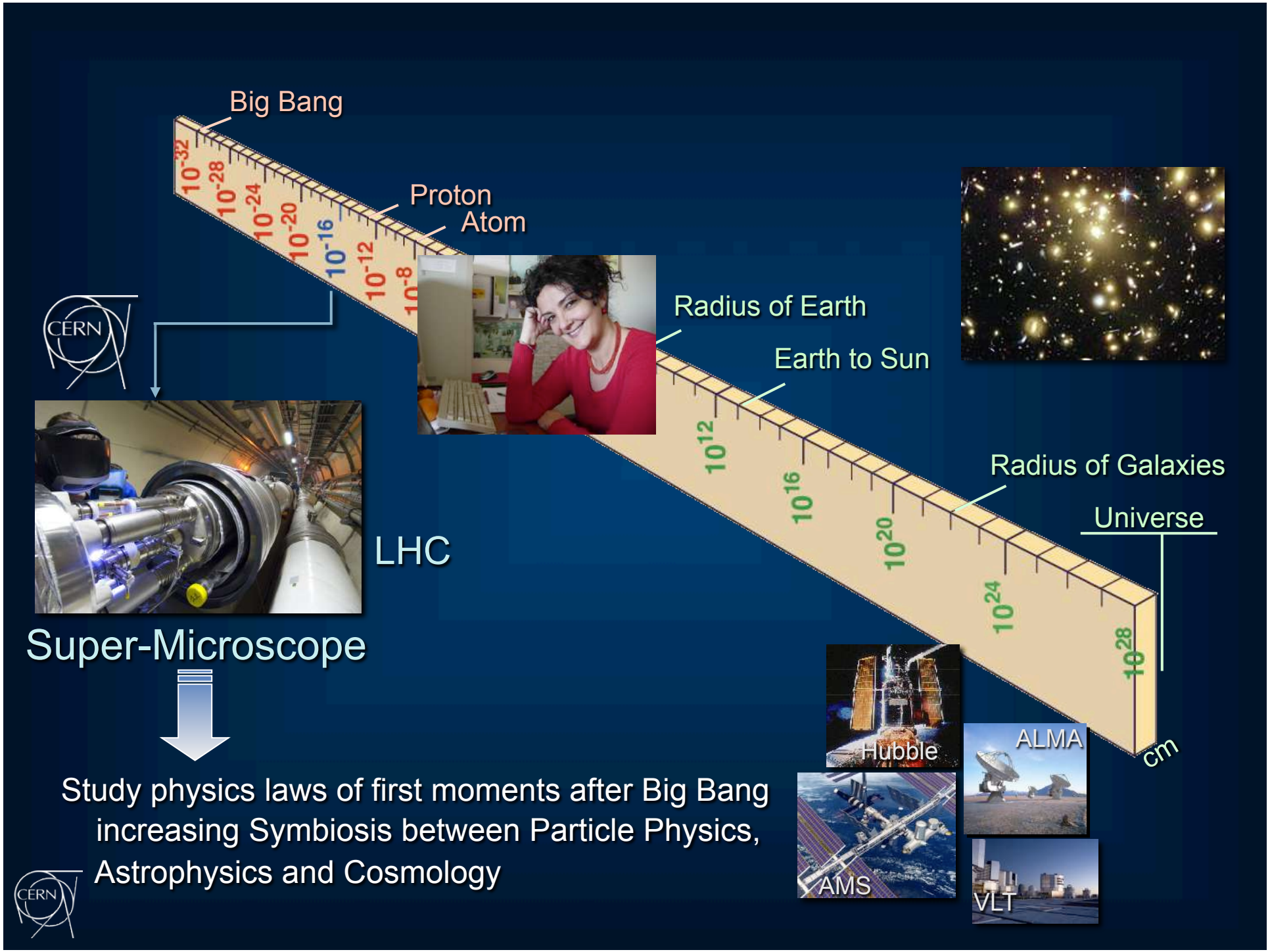
Need individualized, enabling and integrated structures **within supporting infrastructure to:**

- Allow everybody to keep his/her 5% of dream (i.e. the own original contribution to the advancement of Science), while operating in a very large symphony orchestra.
- Encourage the emergence of gifted performers/soloists
- Foster a leadership based on credibility and consensus more than on authority

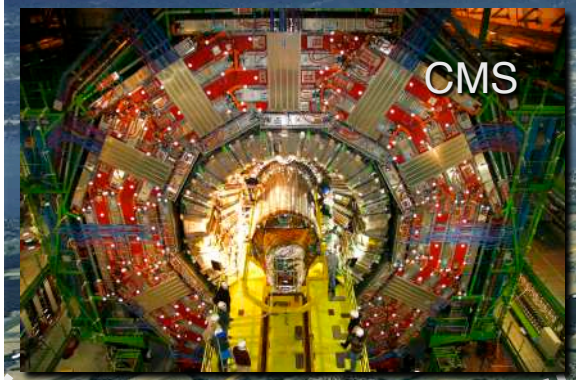
Our Scientific Challenge:

to understand the very first moments of our Universe after the Big Bang



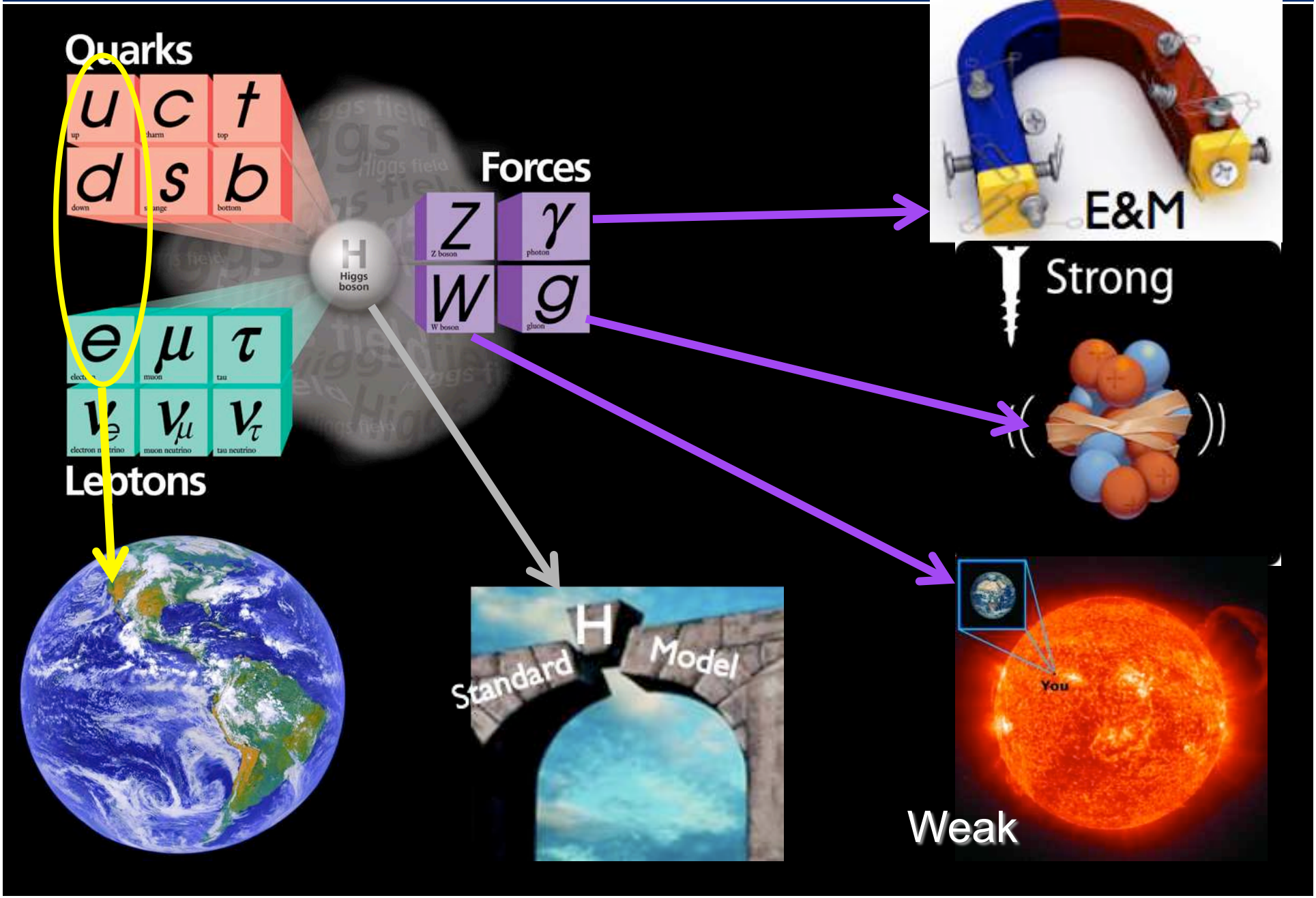

Big Bang
Proton
Atom
Radius of Earth
Earth to Sun
Radius of Galaxies
Universe
cm
LHC
Super-Microscope
Hubble
ALMA
AMS
VLT
Study physics laws of first moments after Big Bang
increasing Symbiosis between Particle Physics,
Astrophysics and Cosmology

Enter a New Era in Fundamental Science

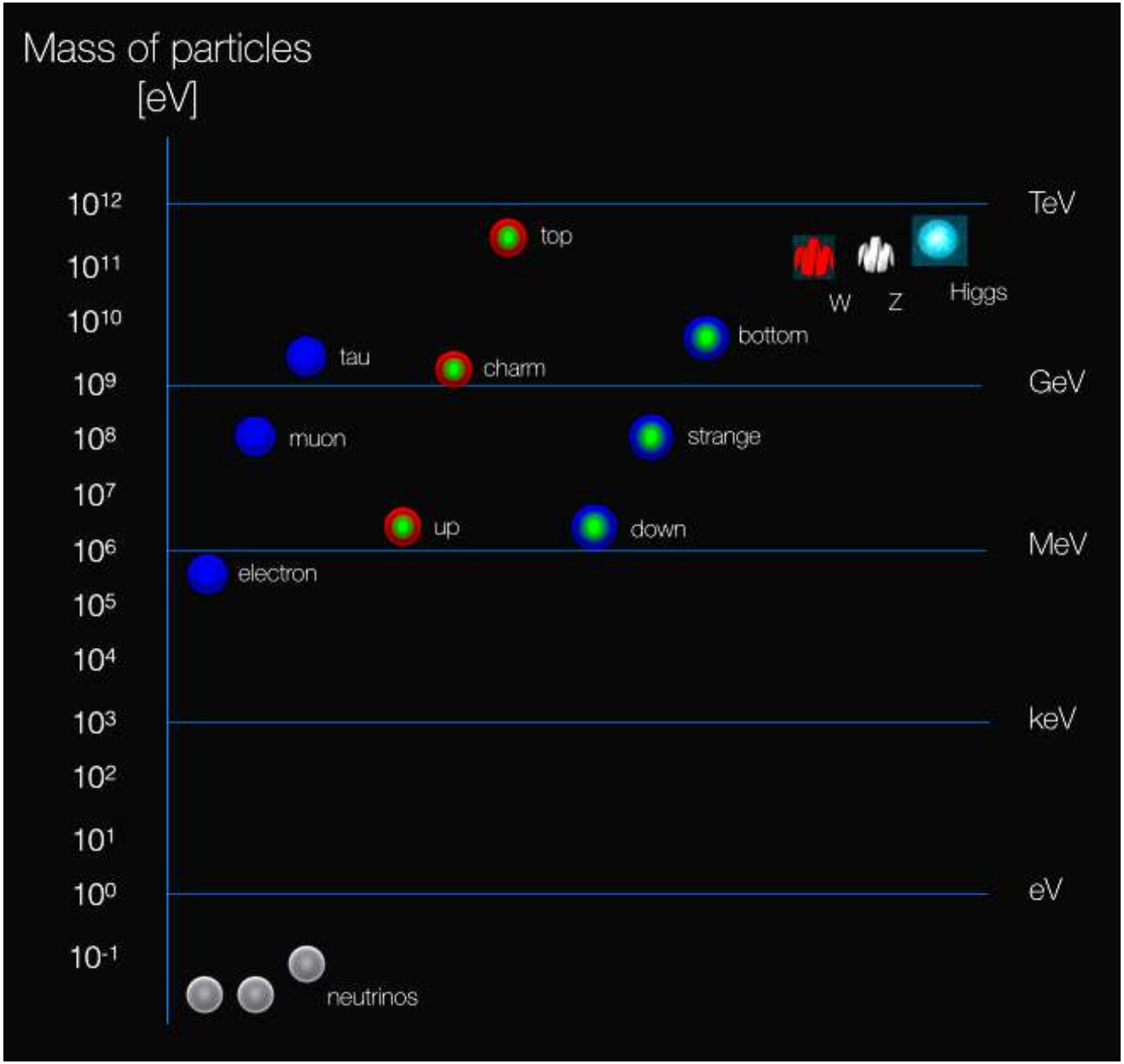


Since March 2010 exploration of a new energy frontier
in p-p and Pb-Pb collisions

The Standard Model



How do particles obtain their mass ?



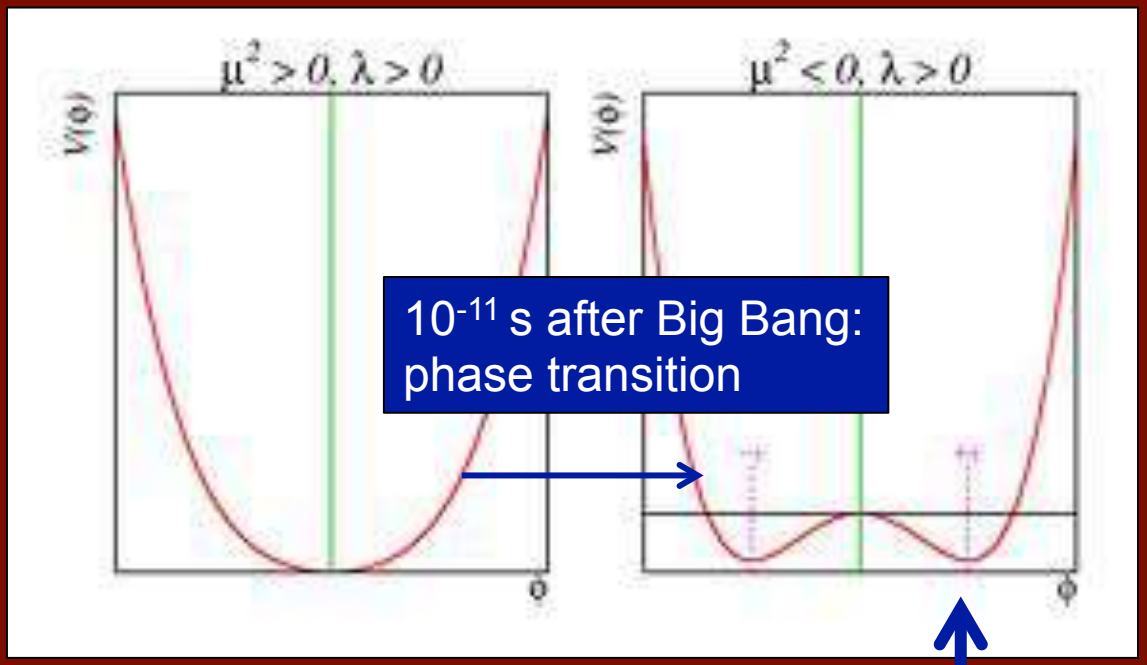
The mystery of mass

Massless particles have to move with the speed of light

THEY CANNOT FORM SOLID OBJECTS

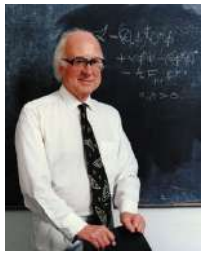
How does the Higgs mechanism work ? An over-simplified picture …

At the time of the Big Bang particles were all massless (→ were moving at speed of light) and Higgs field was there as an "non-interacting ether" (minimum of Higgs potential = 0).



About 10^{-11} s after the Big Bang → temperature became low enough for phase transition (→ minimum of Higgs potential became negative) → ether becomes "molasses" → particles interacting with "molasses" acquire a mass and are slowed down

The Brout-Englert-Higgs (BEH) field idea



Sir Peter Higgs

The ‘cocktail party’ explanation of the Higgs mechanism

A cocktail party ...

The BEH field ....

... a massless particle enters...

.. but the guests cluster around and slow down its movement...

The ‘Higgs boson’

A rumour is spreading among the guests ...

. they cluster together to exchange the information among themselves...

The BEH field ...

... is excited by an energy concentration and forms an excitation by self-interaction ...

The Higgs mechanism

Exciting the Brout-Englert-Higgs field: the “Higgs boson”

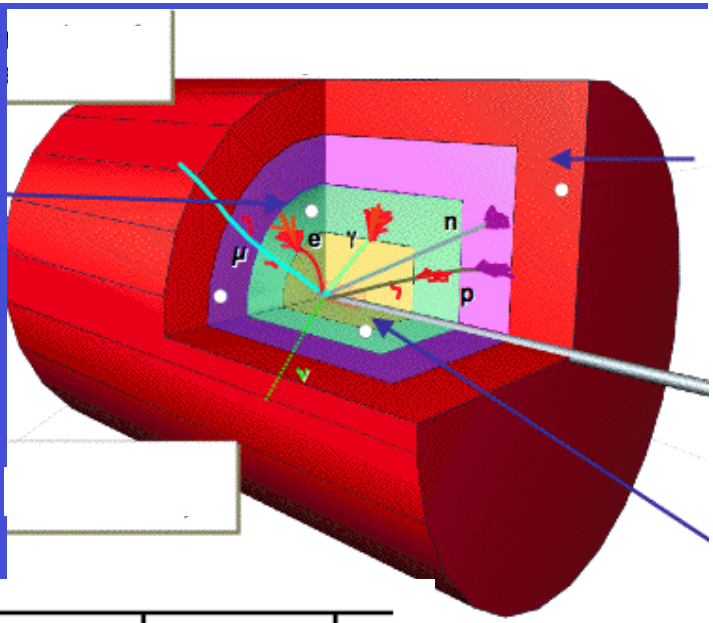
.. but this happens on average once per 10,000,000,000 (10^{10}) collisions !

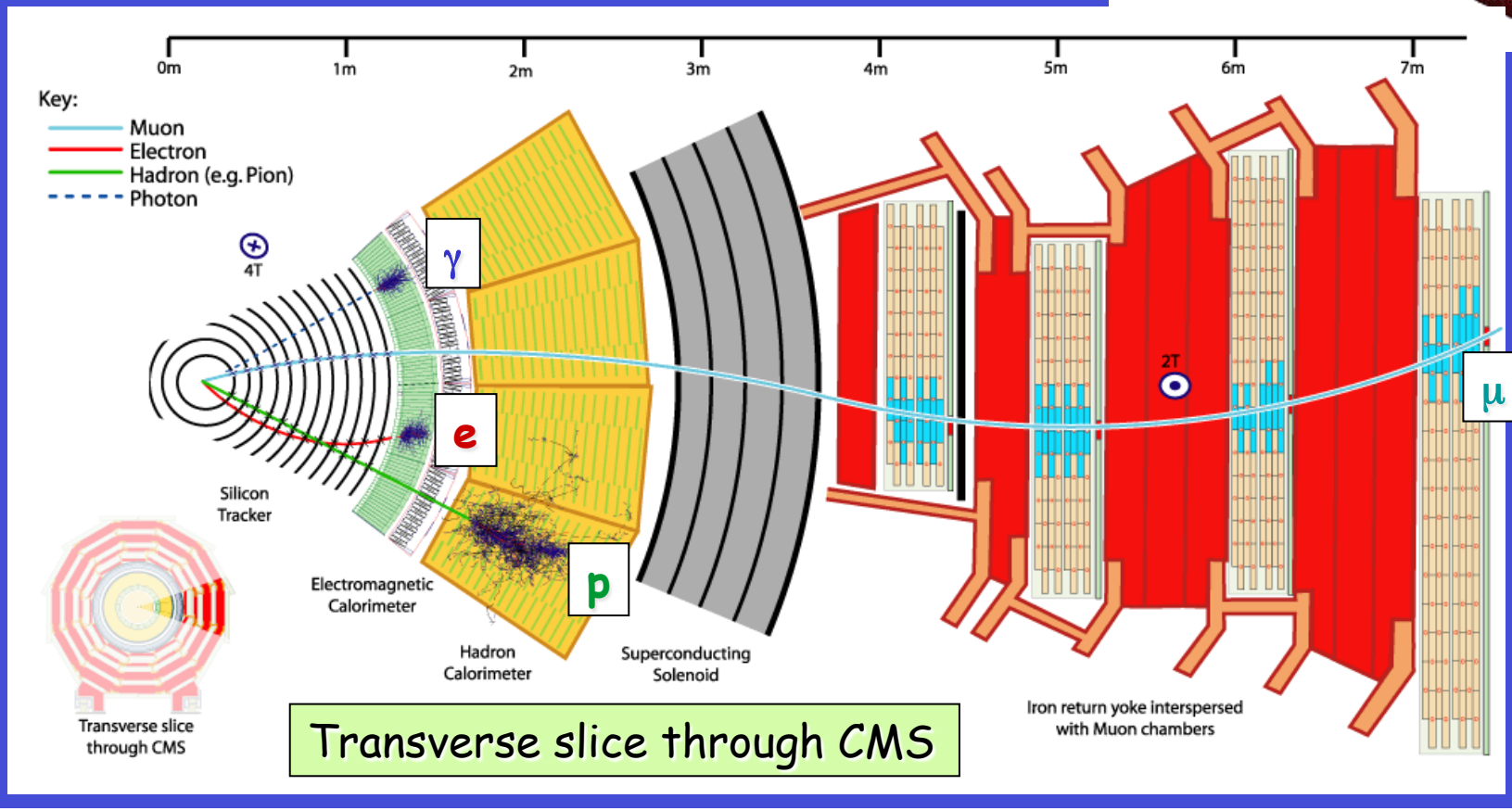
The Higgs boson can decay in two photons ...

but only with a probability of 0.2 %

Detectors for particle physics

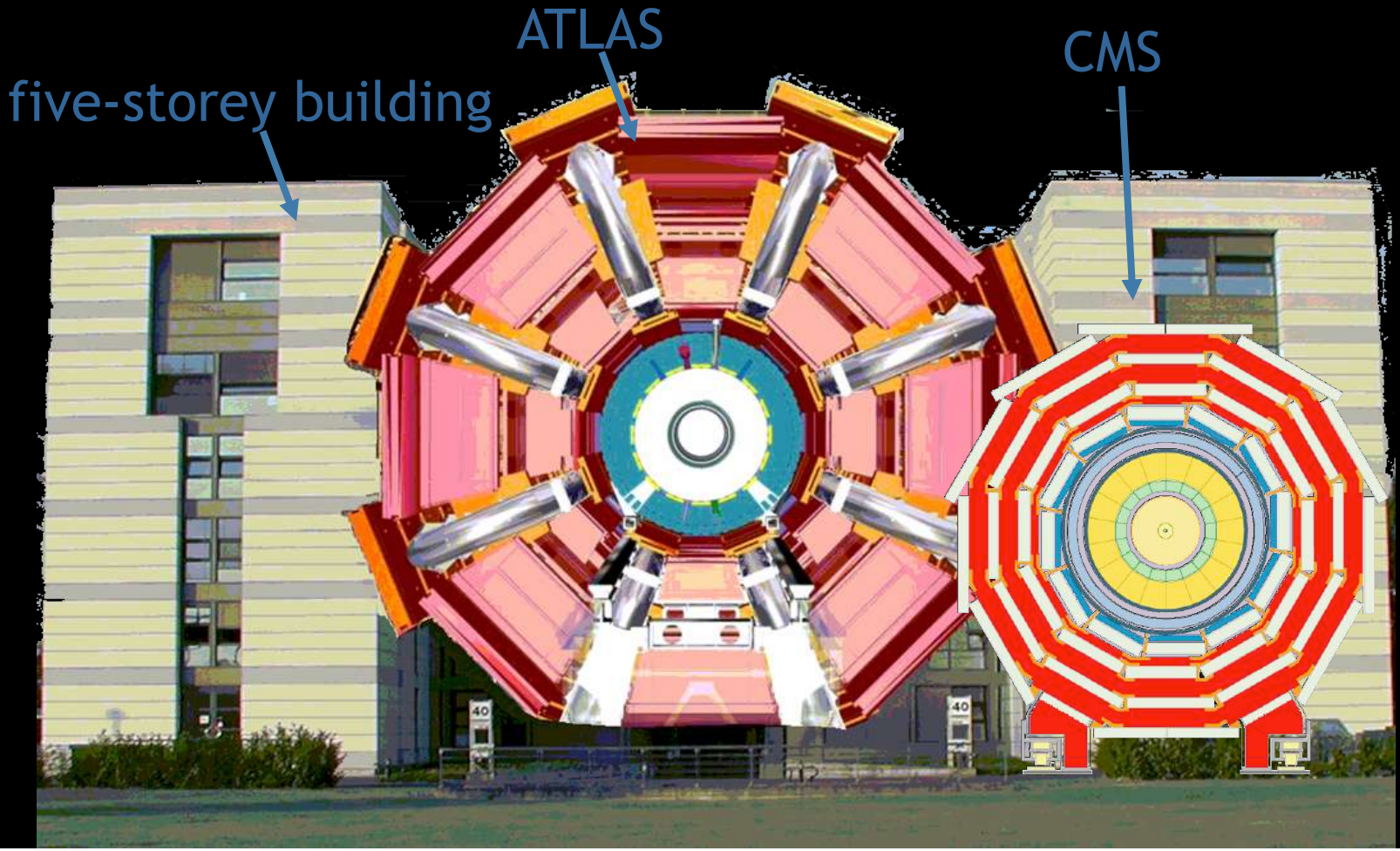
Cover the whole angular range around the collision point to detect as many particles produced in the collision as possible.

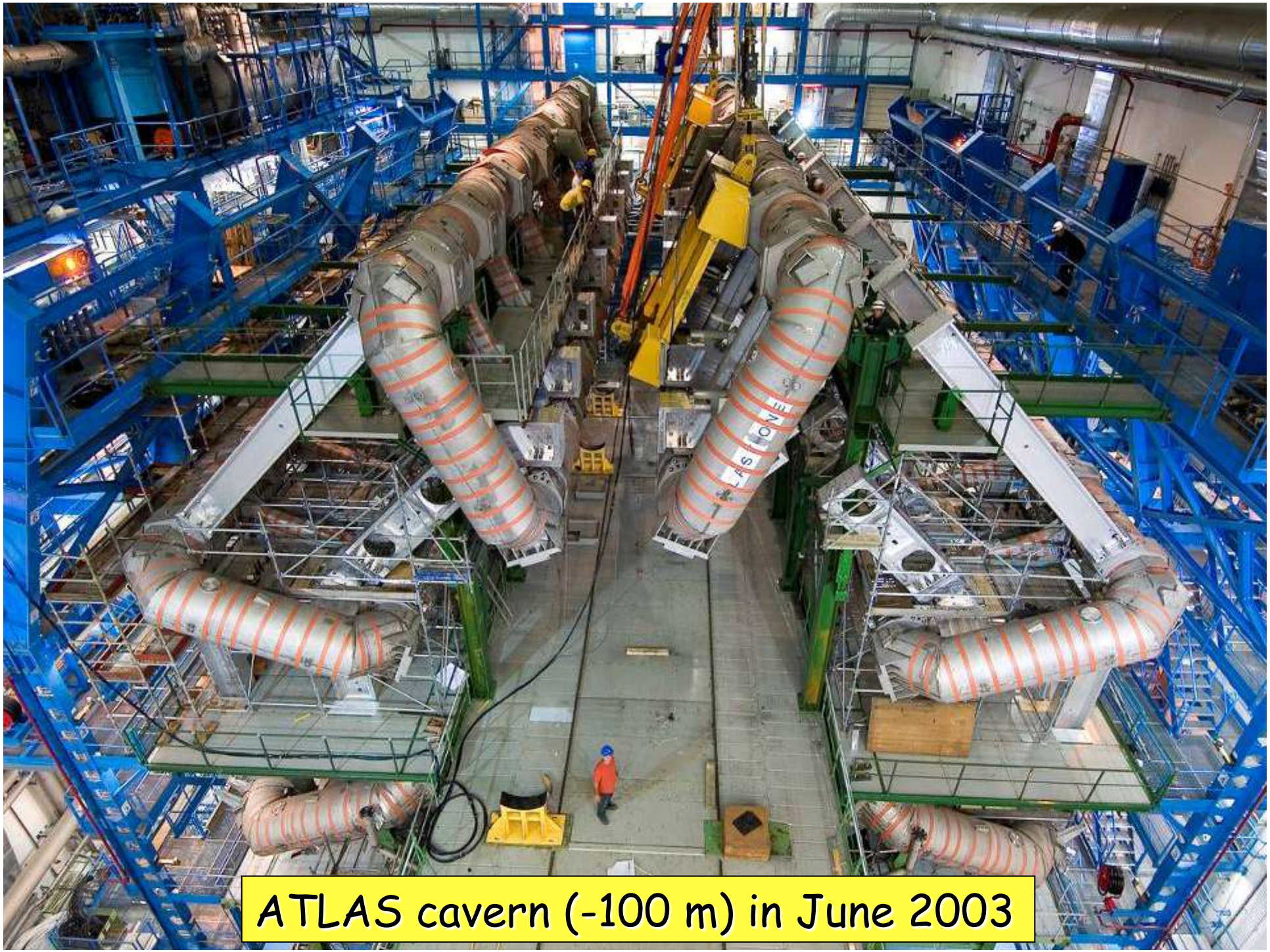




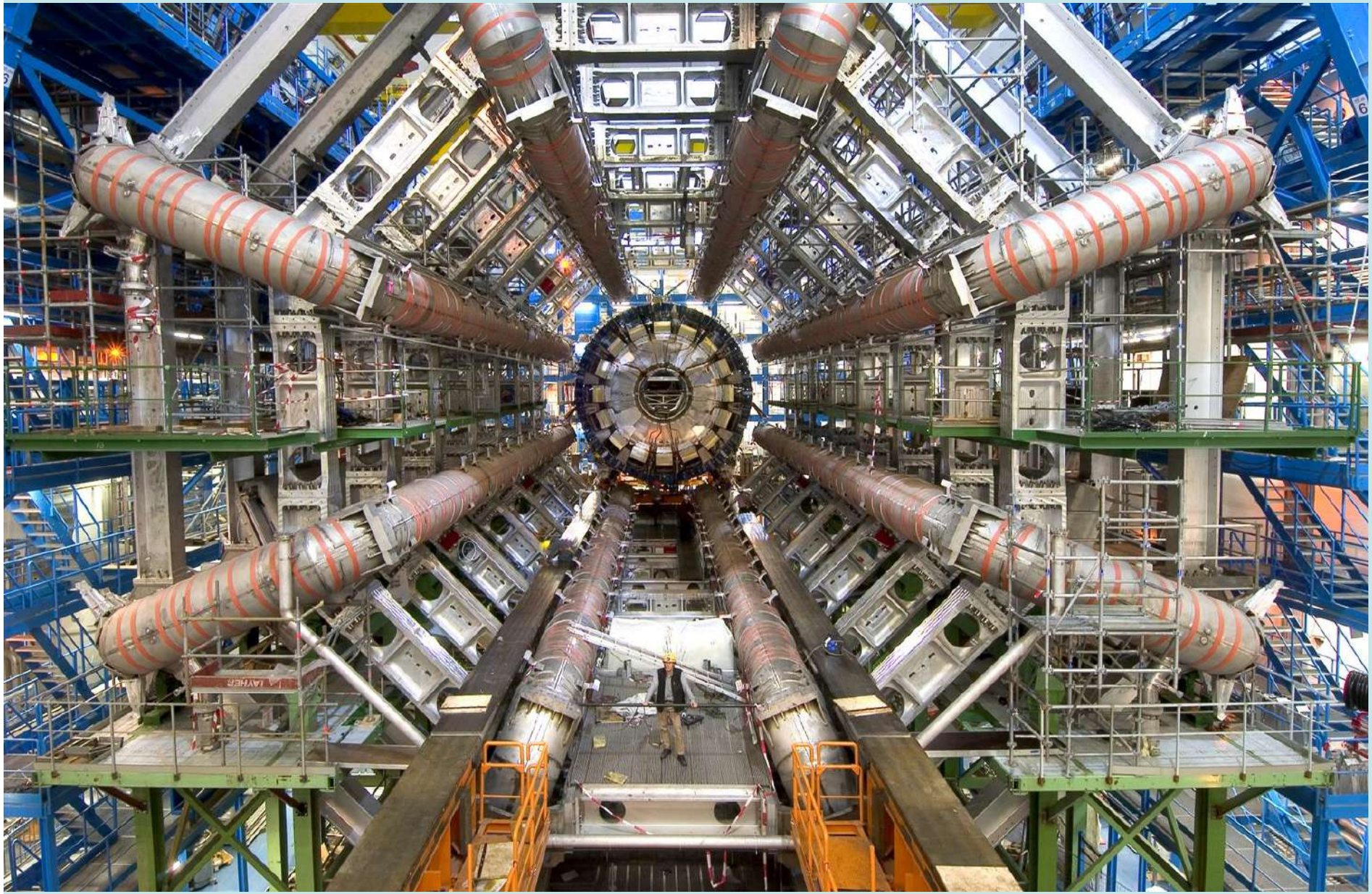
Transverse slice through CMS

The LHC experiments: about 100 million "sensors" each [think your 6MP digital camera... ...taking 40 million pictures a second]

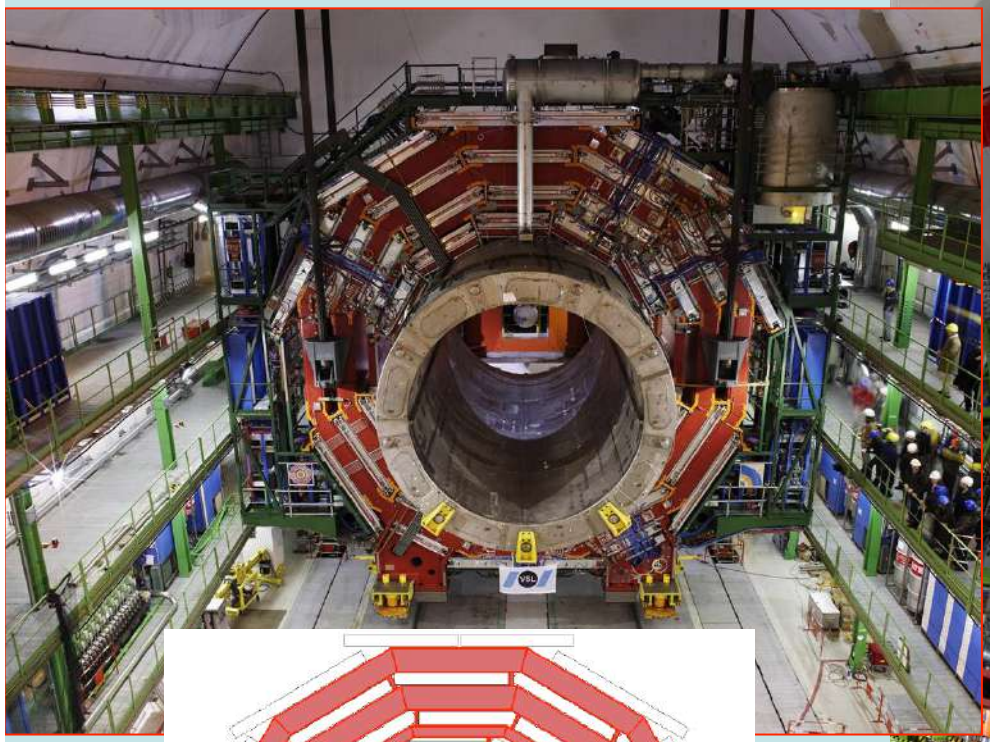


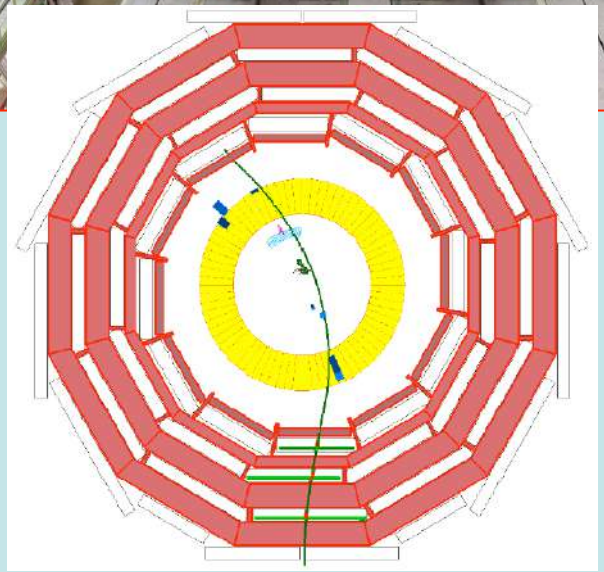

ATLAS cavern (-100 m) in June 2003

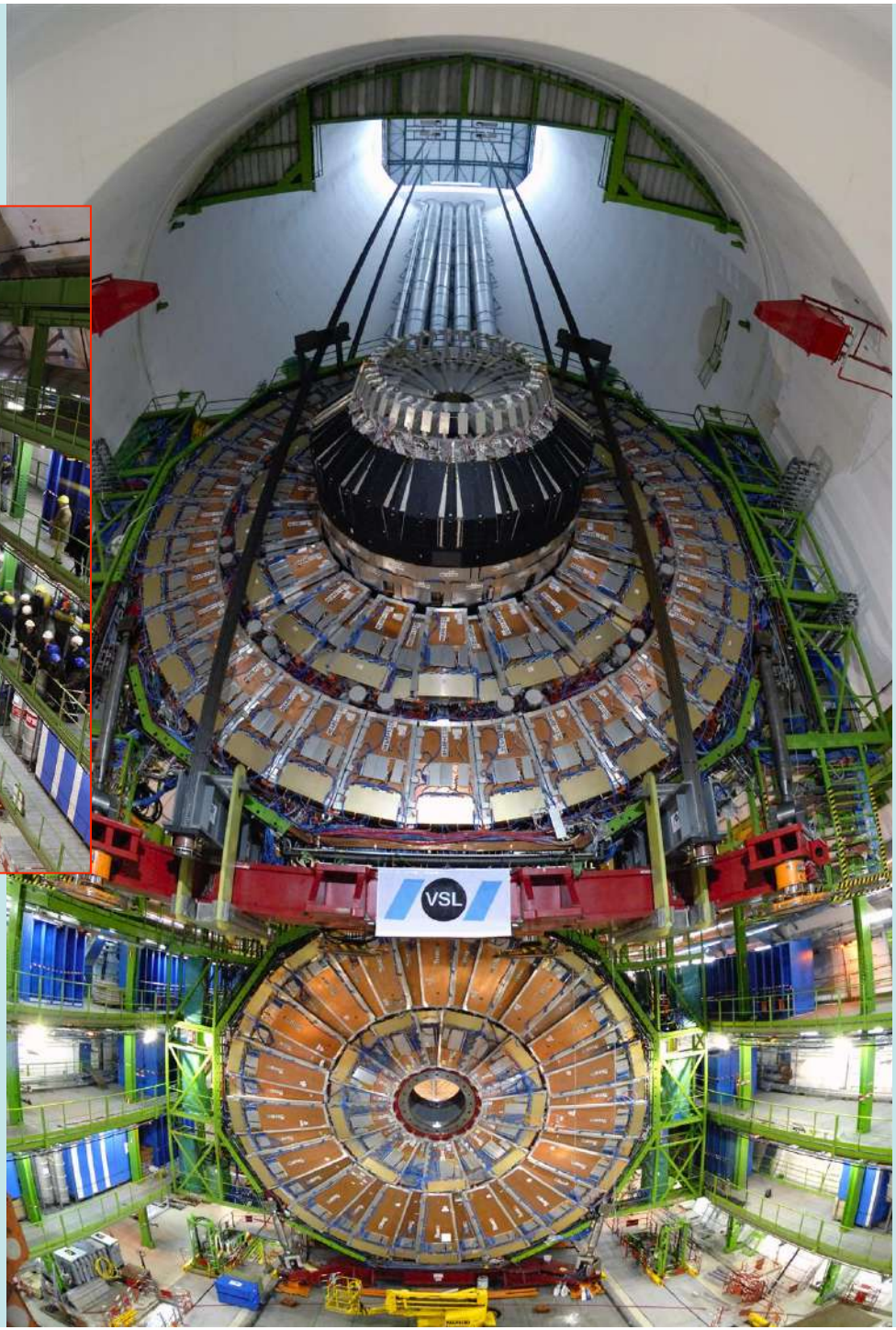
October 2005: Barrel toroid magnet system in place



The CMS experiment



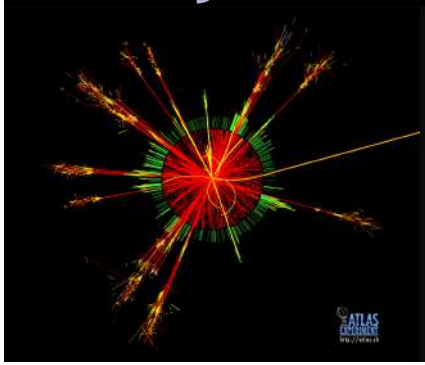


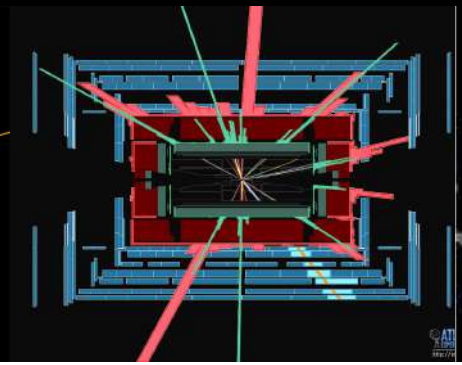


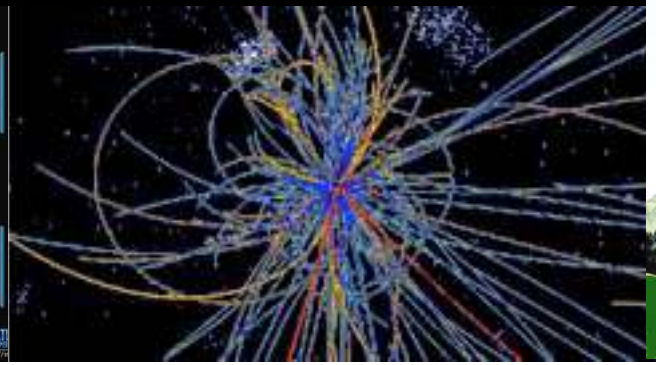
The LHC data

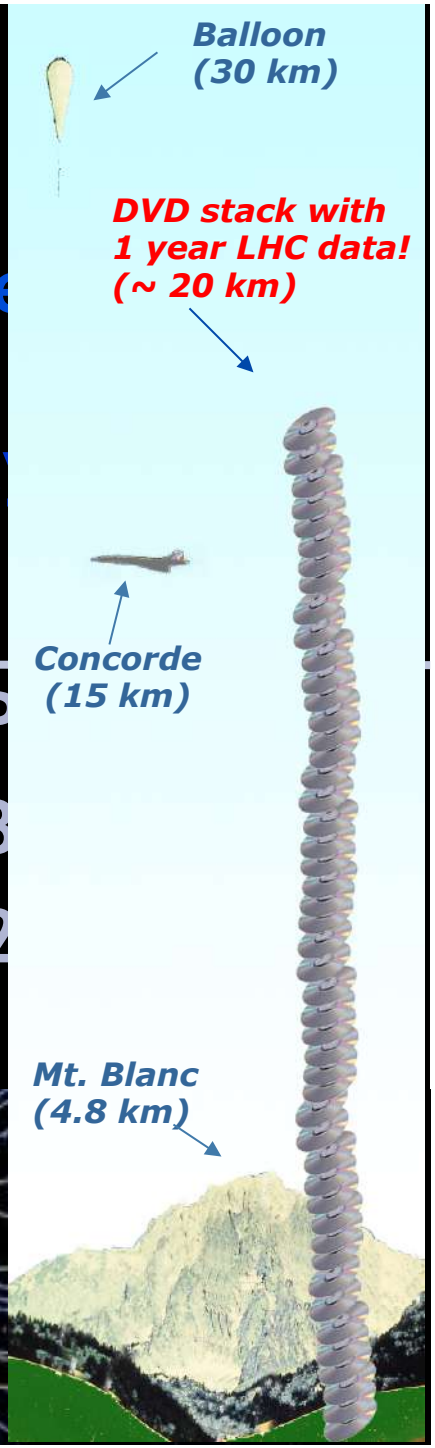
- 40 million events (pictures) per second
- Select (on the fly) the ~500 interesting e
  second to write on tape
- "Reconstruct" data and convert for anal
  "physics data" [→ the grid…]

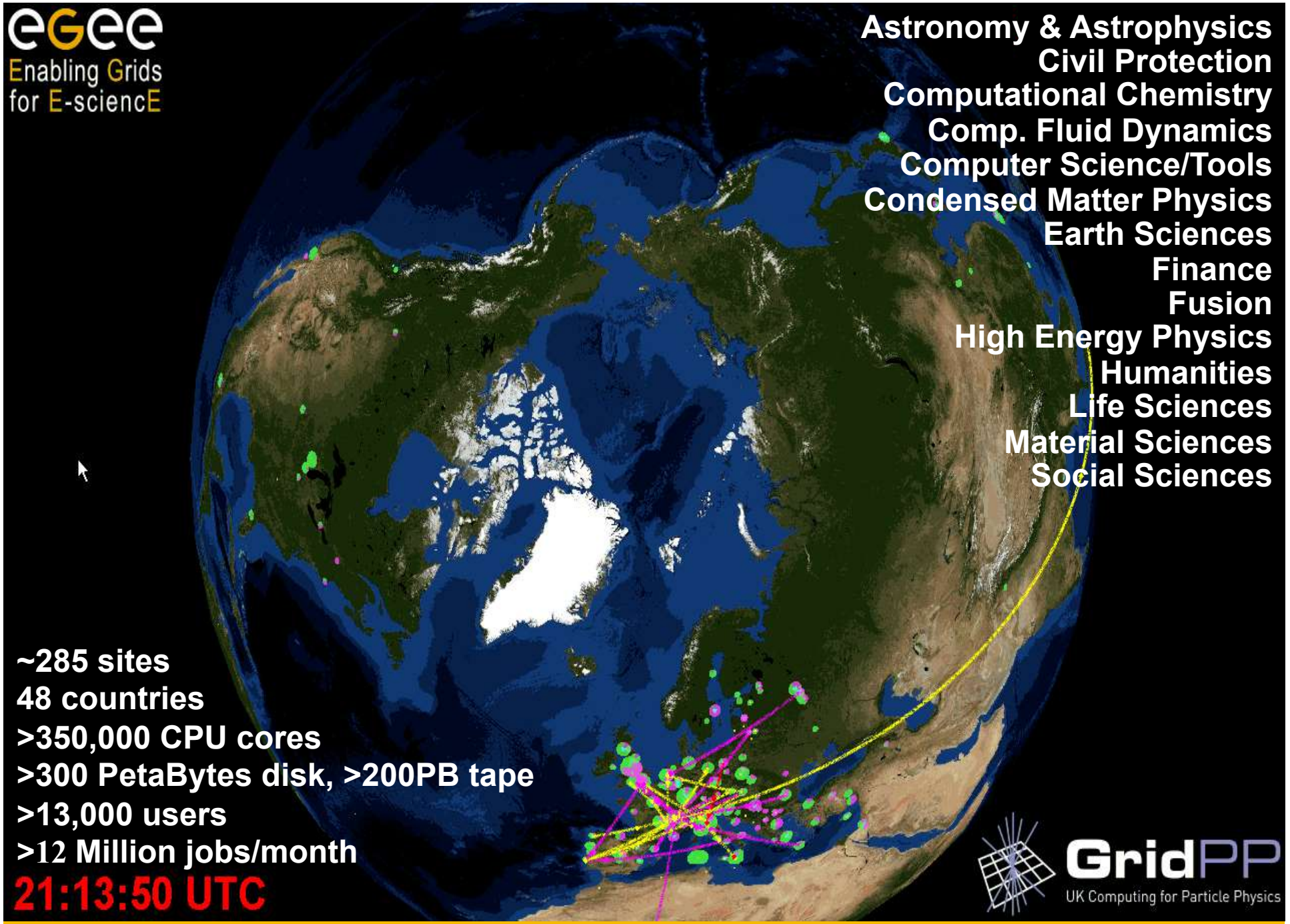
(x4 experiments x15 years)	Per event	P
Raw data	1.6 MB	3
Reconstructed data	1.0 MB	2
Physics data	0.1 MB	



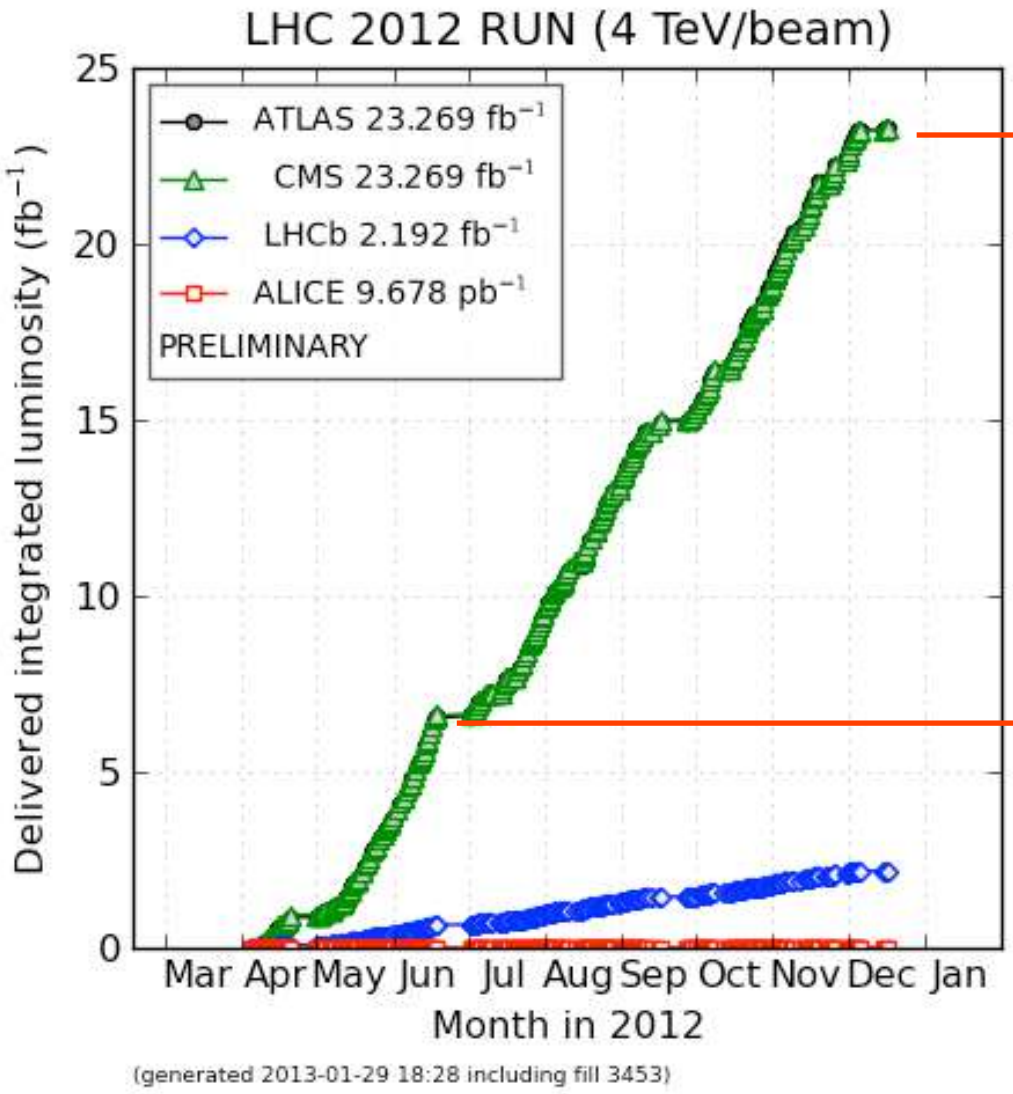







eGee
Enabling Grids
for E-sciencE
Astronomy & Astrophysics
Civil Protection
Computational Chemistry
Comp. Fluid Dynamics
Computer Science/Tools
Condensed Matter Physics
Earth Sciences
Finance
Fusion
High Energy Physics
Humanities
Life Sciences
Material Sciences
Social Sciences
~285 sites
48 countries
>350,000 CPU cores
>300 PetaBytes disk, >200PB tape
>13,000 users
>12 Million jobs/month
21:13:50 UTC
GridPP
UK Computing for Particle Physics

The CERN hunt for the Higgs boson

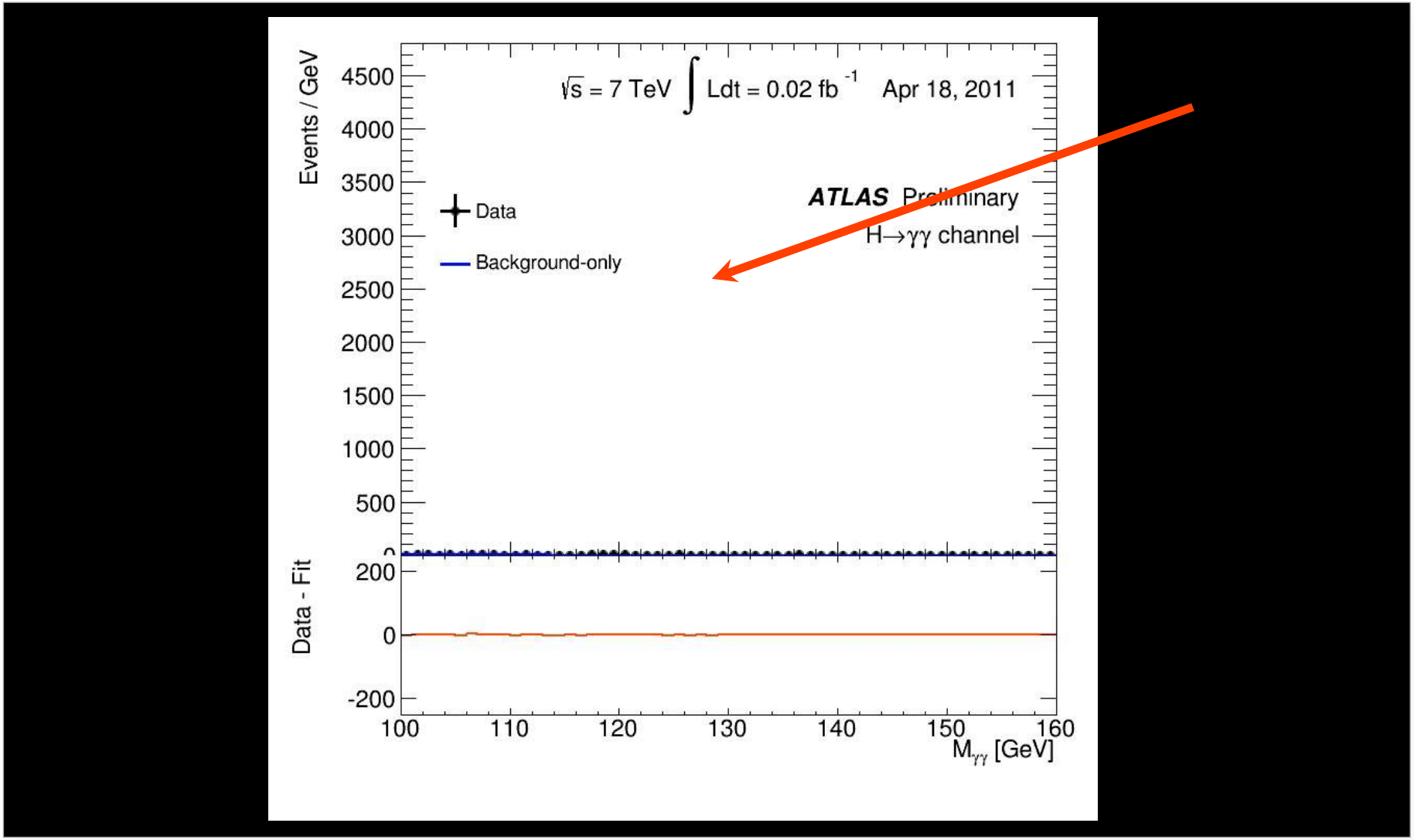


15.12.2012

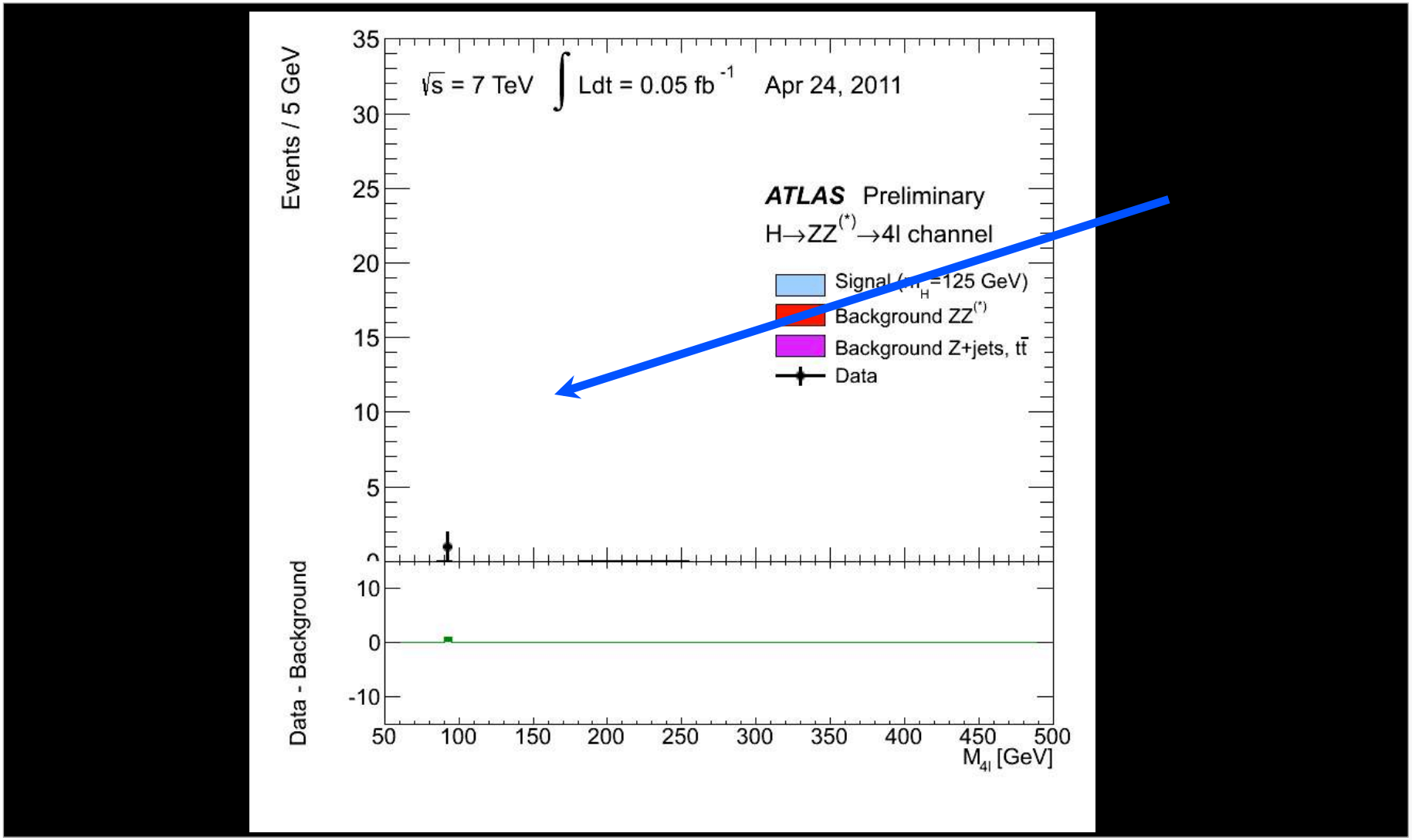
3,000,000,000,000,000 ($3 \cdot 10^{15}$)
(3000 trillion events !)

4.7.2012

The evolution of the histogram with two-photon events

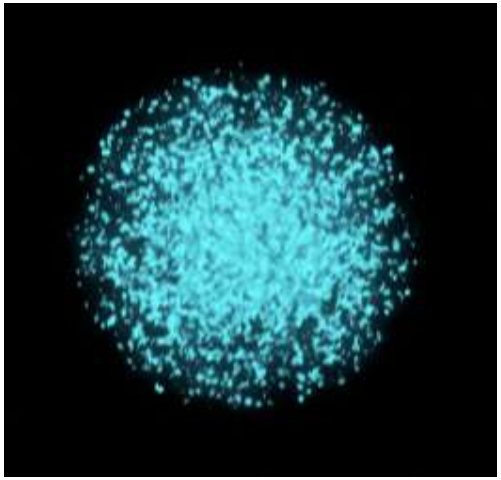


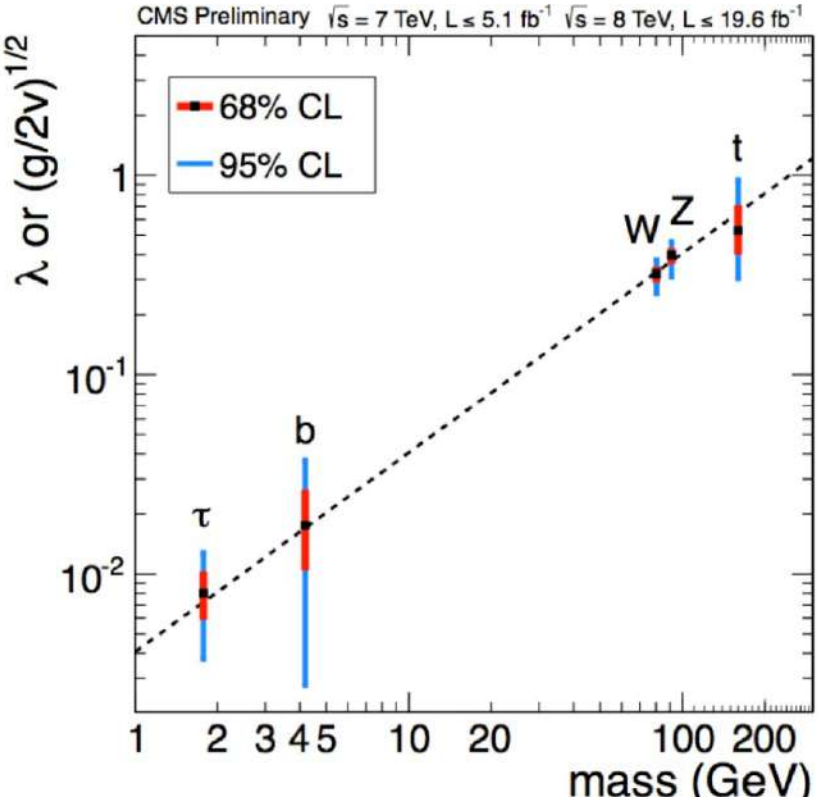
The evolution of the histogram with four leptons



Status 2014: the new particle is the Higgs boson

proportional to the mass of the decay particles





Theoretical expectations compatible with observations

What does this mean?

- the Higgs boson exists, therefore ...

- the Brout-Englert-Higgs field exists

- we know how particles obtain their mass

- the “Standard model” is complete

Even more:

- empty space is not ‘empty’

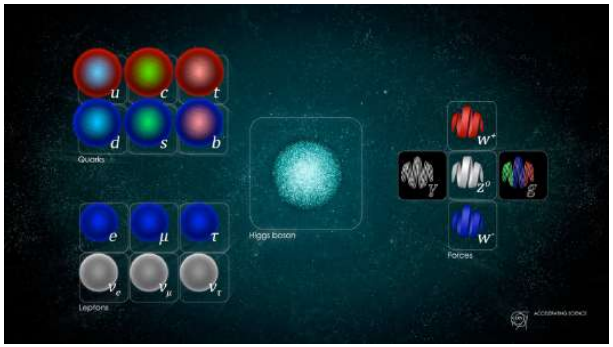
- perhaps a connection to ‘dark energy’ ?

Nobel Prize in Physics 2013

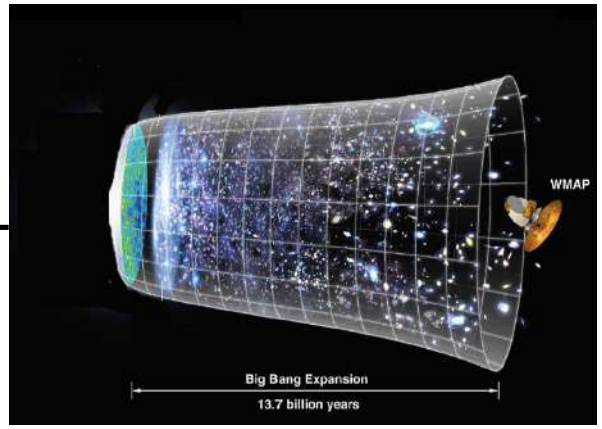
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

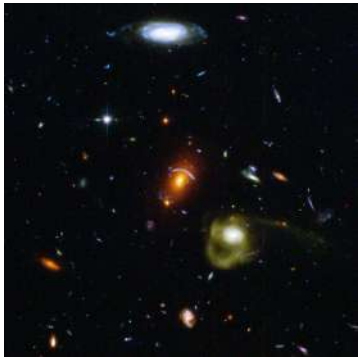
CERN

Particle physics + Cosmology = Universe ?



+

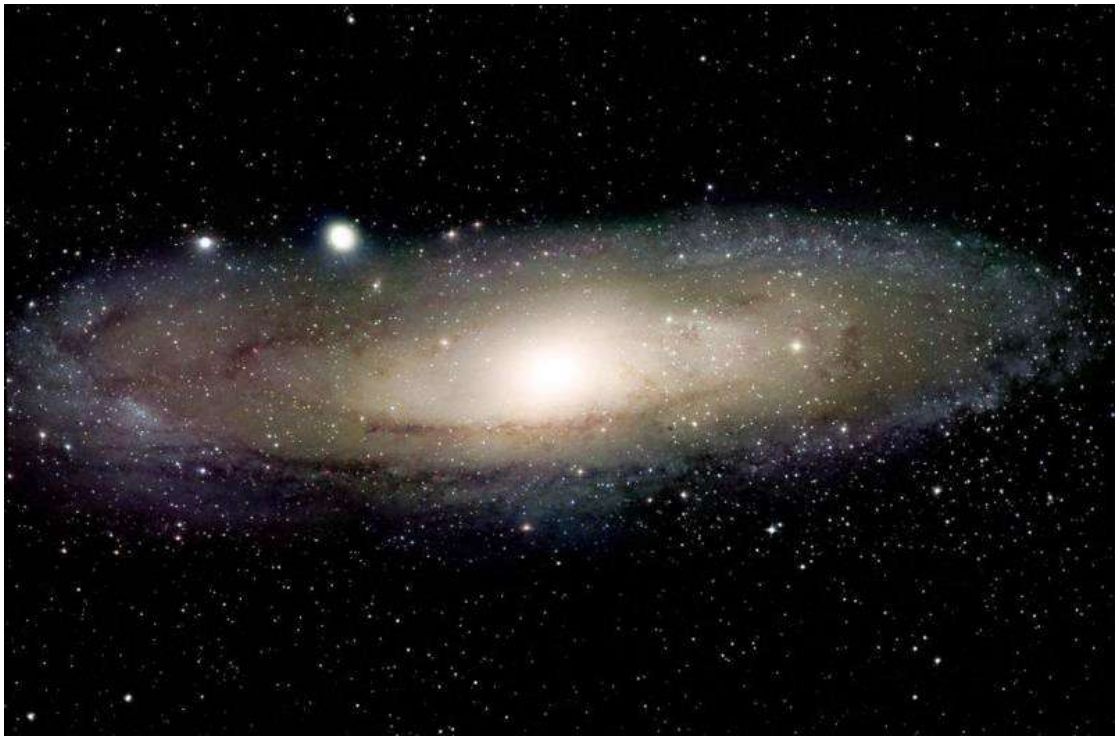




No !

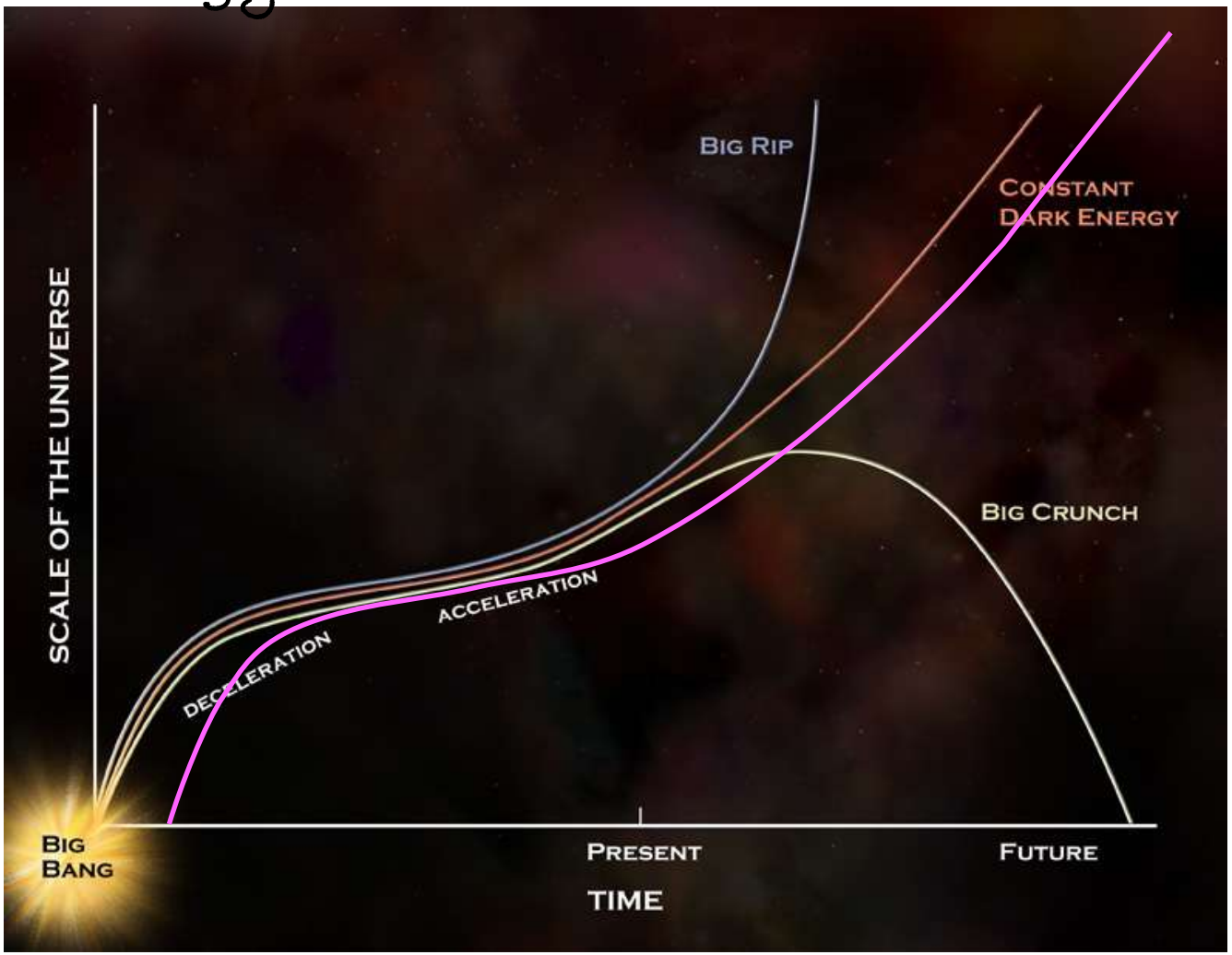
Less than 5% of the energy content of the universe are understood!

Dark matter …?



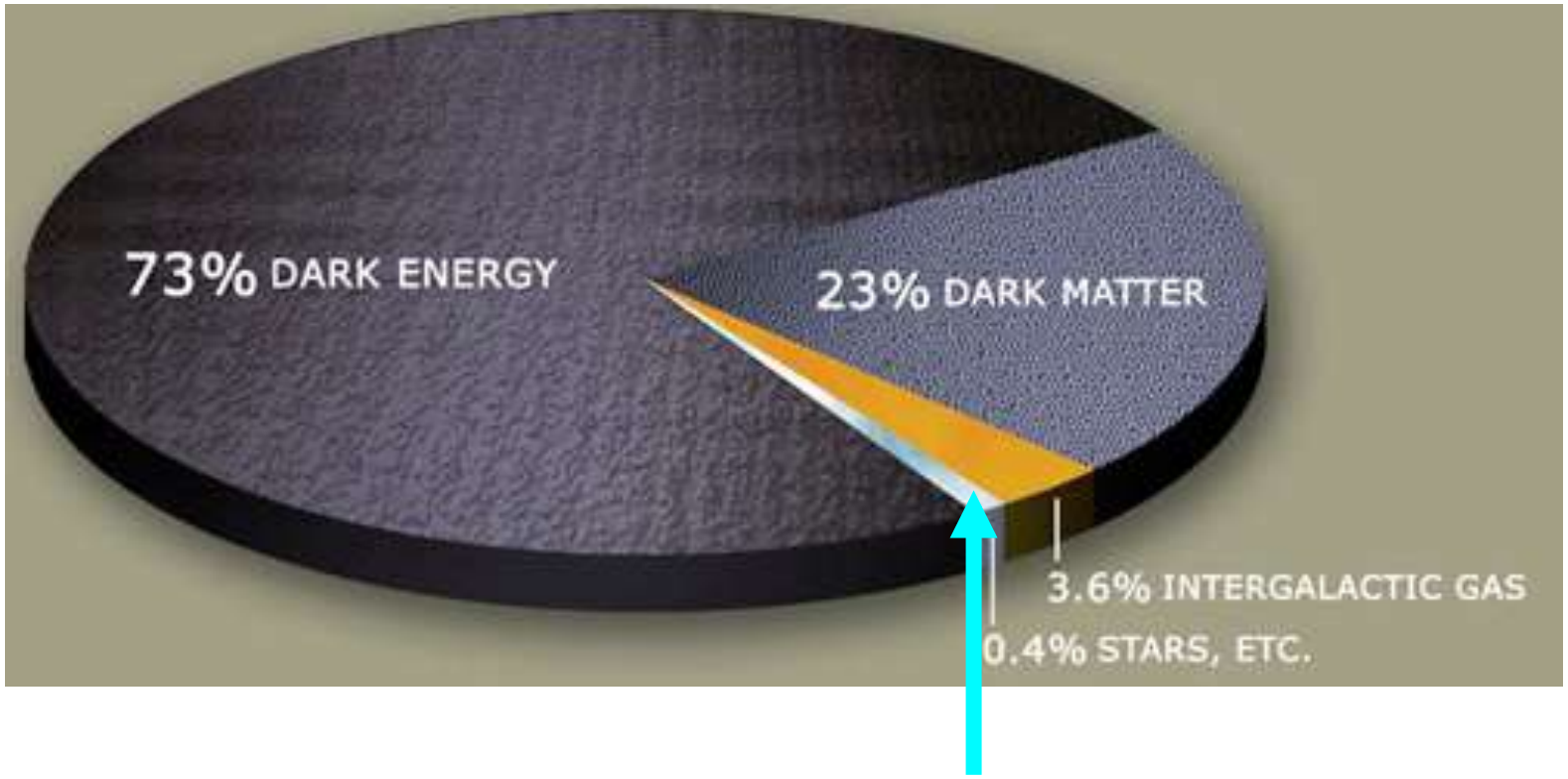
Galaxies rotate too fast

Dark energy ...?

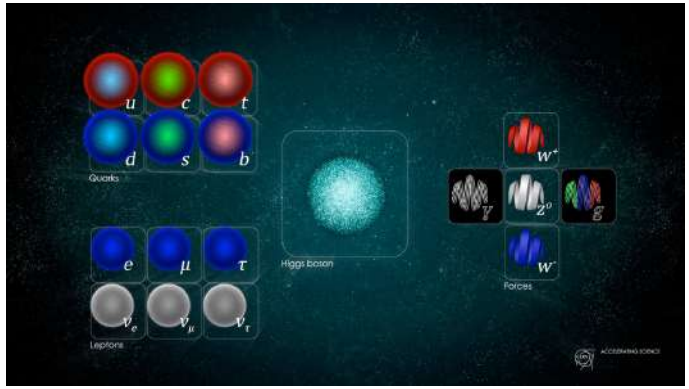


The expansion of the Universe accelerates ...

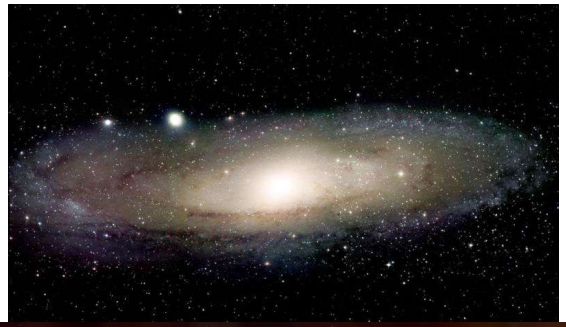
The “dark Universe”: 96 % of its energy content are hidden in ‘dark energy’ and ‘dark matter’



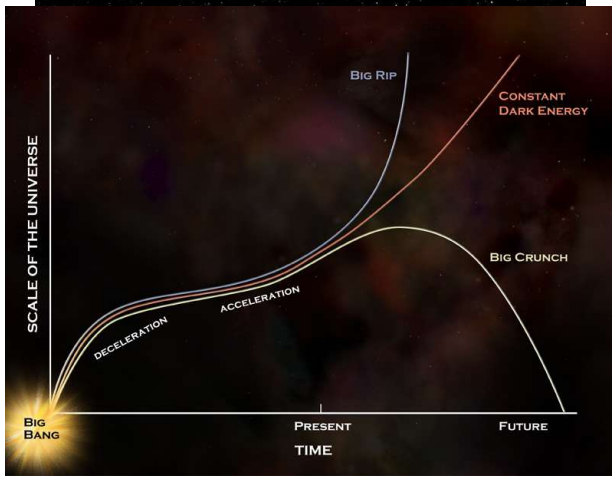
The big questions:



Is the Higgs boson alone?
Connection to ‘dark energy’ ?



What is dark matter?



What is dark energy?

BUT, despite its success….

…. we know that the Standard Model is not complete because:

- It doesn't solve the hierarchy problem
- It has no explanation for dark matter/dark energy
- Its mechanisms of CPV are too small to explain matter/antimatter imbalance
- It cannot provide a QFT of gravitation
- ….etc

Solutions?

Standard Model

For all proposed solutions:
new particles should appear
at **TeV** scale or below

Selected NP
Since 1957

Technicolor
New (strong) interactions produce EWSB

Extensions of the SM gauge group :
Little Higgs / GUTs / ...

Supersymmetry
New particles at ≈ TeV scale, light Higgs
Unification of forces
Higgs mass stabilized
No new interactions

cessful for ever ??

Extra Dimensions
New dimensions introduced
$m_{Gravity} \approx m_{elw}$ → Hierarchy problem solved
New particles at ≈ TeV scale

CERN

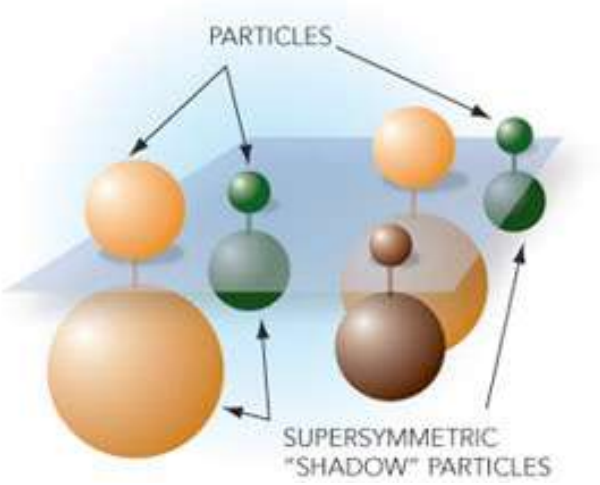
SUPERSYMMETRY - connection to Dark Matter ?

A connection between particles (spin 1/2) and fields (spin 1) ?

FERMIONS (quarks, electrons, neutrinos) interact through the exchange of BOSONS (gluons, photon, W/Z bosons)

"SUPERSYMMETRY" predicts a complete symmetry between FERMIONS AND BOSONS: each fermion has a boson partner, and vice versa:

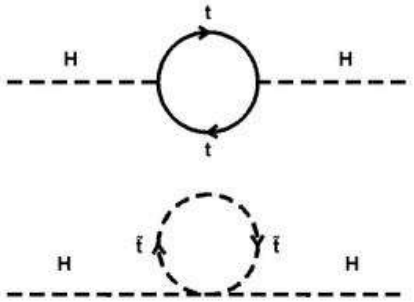
Spin 1/2	Spin 0, Spin 1
electron	selectron (S=0)
quark	squark (S=0)
photino	photon (S=1)
gluino	gluon (S=1)
gaugino (Wino, Zino)	W, Z (S=1)



But: no such SUSY partner has ever been seen. So ...
if they exist, they must have a large mass (> 1 TeV)

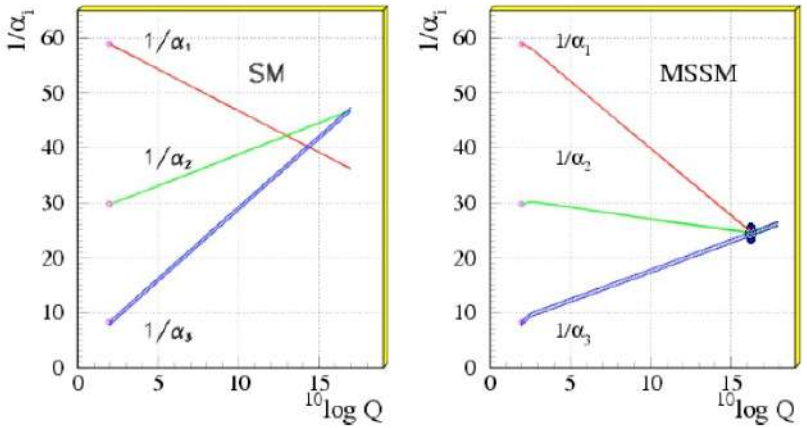
Why SUSY?

1) A fundamental space-time-symmetry



2) "Protection of the Higgs boson mass (M ~ 10^2 GeV)
from vacuum fluctuations up to Planck mass (~10^{19} GeV)

3) Predicts unification of electroweak and strong interaction at ~10^{17} GeV

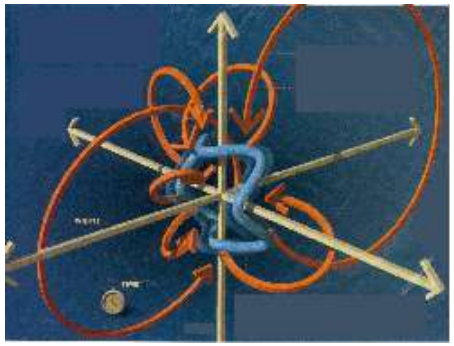


4) May explain the cosmological matter-antimatter asymmetry

5) **Lightest supersymmetric particle = dark matter ??**

MORE MYSTERIES

What is a particle?

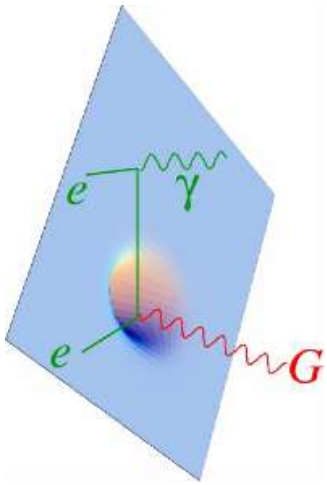


Superstrings in 9+1 dimensions?

Little strings of string energy vibrating in a 9+1 dimensional space ?
L ~10^{-35} m (Planck length)
Standard model particles: different vibration modes, open/closed strings
GRAVITON-like particle contained (unification of SM and gravity?)

BUT: why did 6 dimensions disappear? how did they disappear?
is there a unique way to go from 10 to 4 dimensions?

Extra dimensions ?

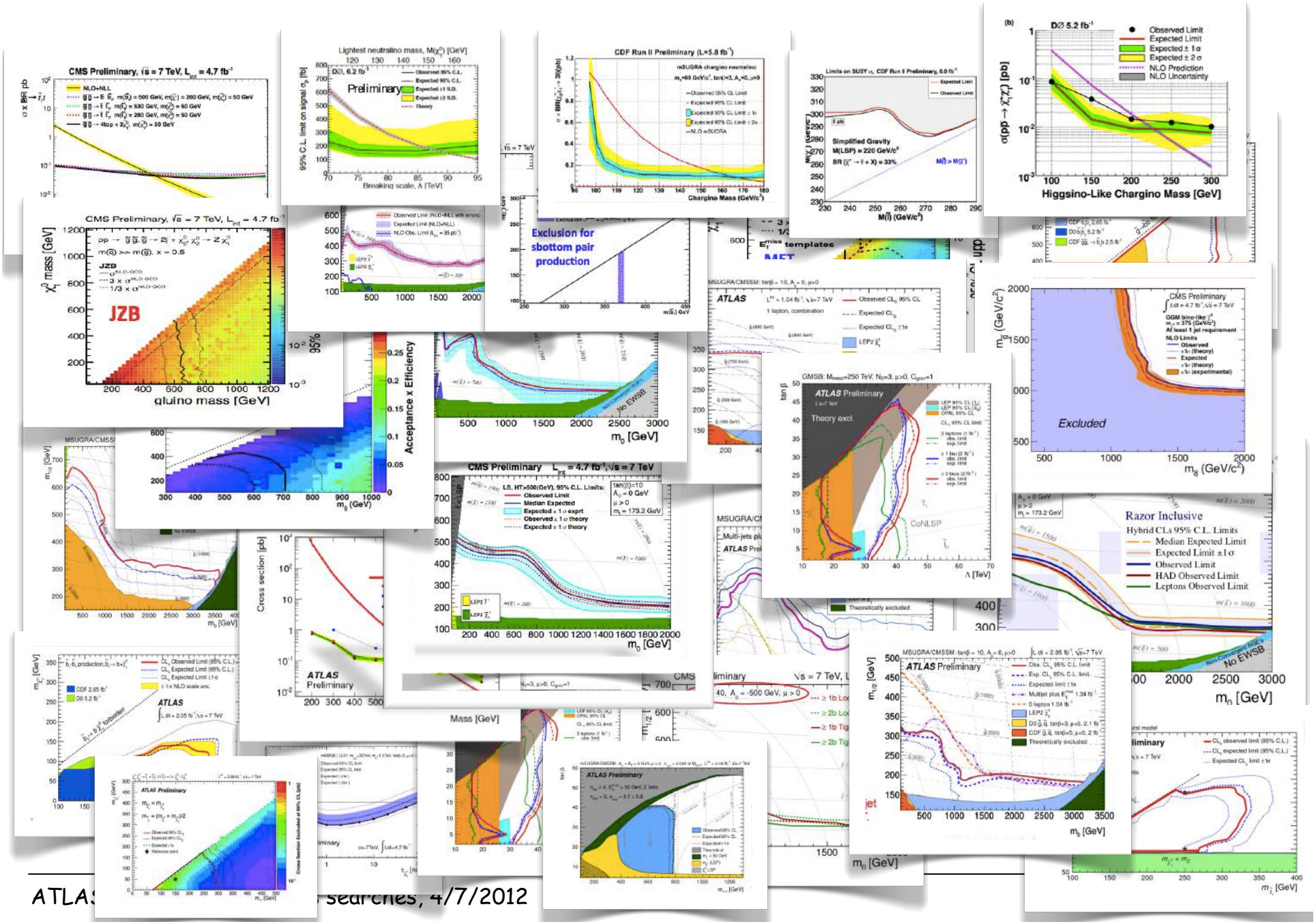


More than 3 macroscopic dimensions of space?

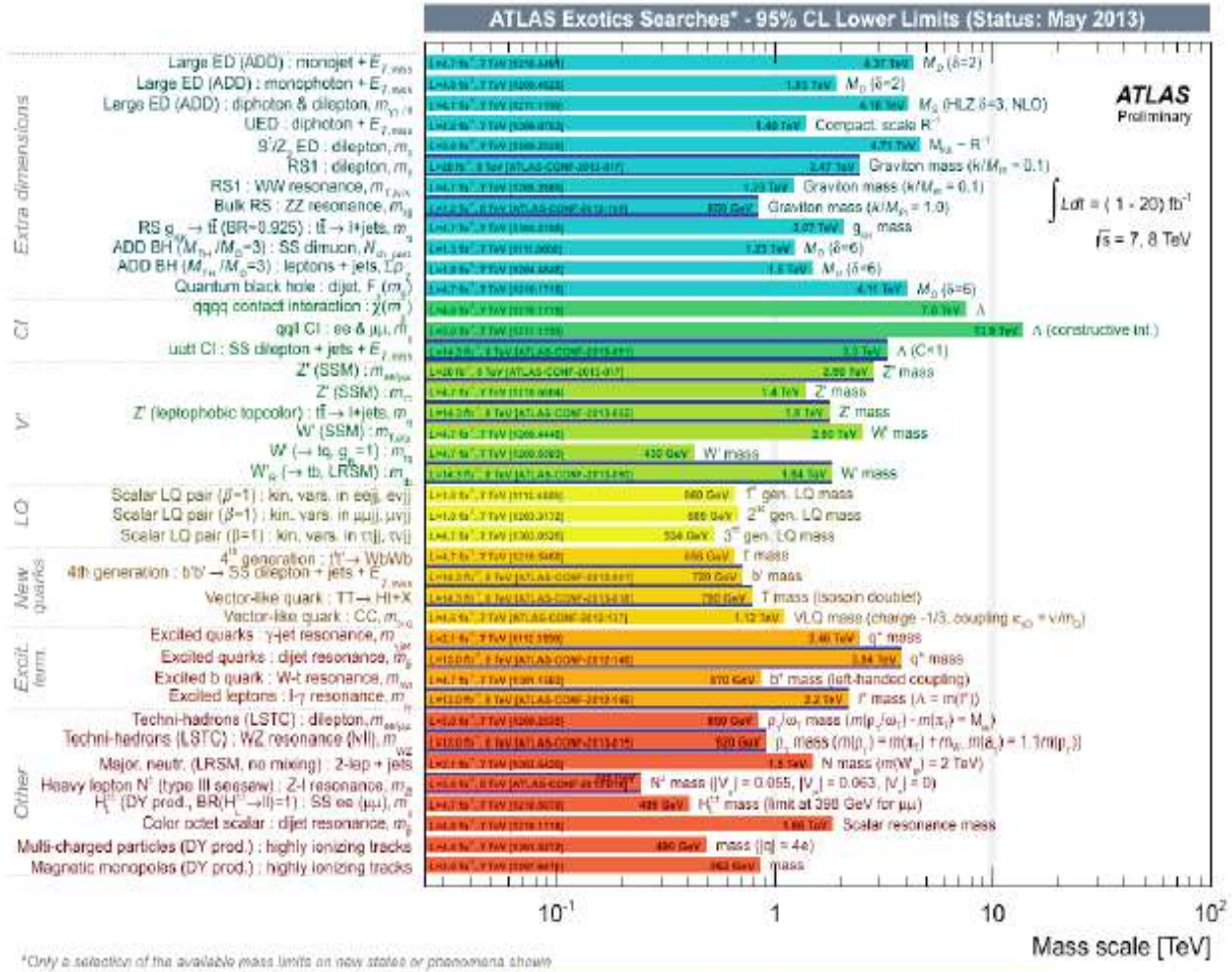
Is the graviton propagating in 4- or more dimensions of space?

Micro-black holes ?

BSM: we have searched....



...and exotics


ATLAS Exotics Searches* - 95% CL Lower Limits (Status: May 2013)
ATLAS
Preliminary
∫Ldt = (1 - 20) fb⁻¹
√s = 7, 8 TeV
Extra dimensions
CI
V'
LQ
New quarks
Excit. ferm.
Other
Large ED (ADD) : monojet + E_T,miss
Large ED (ADD) : monophoton + E_T,miss
Large ED (ADD) : diphoton & dilepton, m_γγ/ll
UED : diphoton + E_T,miss
S¹/Z₂ ED : dilepton, m_ll
RS1 : dilepton, m_ll
RS1 : WW resonance, m_WW/lνjj
Bulk RS : ZZ resonance, m_ll
RS g_KK → tt̄ (BR=0.925) : tt̄ → l+jets, m_tt
ADD BH (M_th /M_D=3) : SS dimuon, N_ch_particles
ADD BH (M_th /M_D=3) : leptons + jets, ΣpT
Quantum black hole : dijet, F (m_jj)
qqqq contact interaction : χ(m_jj)
qqll CI : ee & μμ, m_ll
uutt CI : SS dilepton + jets + E_T,miss
Z' (SSM) : m_ee/μμ
Z' (SSM) : m_ττ
Z' (leptophobic topcolor) : tt̄ → l+jets, m_tt
W' (SSM) : m_T,eν/μν
W' (→ tq, g_q =1) : m_tq
W'_R (→ tb, LRSM) : m_tb
Scalar LQ pair (β=1) : kin. vars. in eejj, evjj
Scalar LQ pair (β=1) : kin. vars. in μμjj, μνjj
Scalar LQ pair (β=1) : kin. vars. in ττjj, τνjj
4th generation : t't' → WbWb
4th generation : b'b' → SS dilepton + jets + E_T,miss
Vector-like quark : TT → Ht+X
Vector-like quark : CC, m_C
Excited quarks : γ-jet resonance, m_q*
Excited quarks : dijet resonance, m_q*
Excited b quark : W-t resonance, m_b*
Excited leptons : l-γ resonance, m_l*
Techni-hadrons (LSTC) : dilepton, m_ee/μμ
Techni-hadrons (LSTC) : WZ resonance (lνll), m_WZ
Major. neutr. (LRSM, no mixing) : 2-lep + jets
Heavy lepton N (type III seesaw) : Z-l resonance, m_N
H_L^±± (DY prod., BR(H_L^±±→ll)=1) : SS ee (μμ), m_H
Color octet scalar : dijet resonance, m_S
Multi-charged particles (DY prod.) : highly ionizing tracks
Magnetic monopoles (DY prod.) : highly ionizing tracks
M_D (δ=2)
M_D (δ=2)
M_D (HLZ δ=3, NLO)
Compact. scale R⁻¹
M_KK ~ R⁻¹
Graviton mass (k/M_Pl = 0.1)
Graviton mass (k/M_Pl = 0.1)
Graviton mass (k/M_Pl = 1.0)
g_KK mass
M_D (δ=6)
M_D (δ=6)
M_D (δ=6)
Λ
Λ (constructive Int.)
Λ (C=1)
Z' mass
Z' mass
Z' mass
W' mass
W' mass
W' mass
1st gen. LQ mass
2nd gen. LQ mass
3rd gen. LQ mass
t' mass
b' mass
T mass (isosoin doublet)
VLQ mass (charge -1/3, coupling κ_VQ = v/m_VQ)
q* mass
q* mass
b* mass (left-handed coupling)
l* mass (Λ = m(l*))
ρ_T/ω_T mass (m(ρ_T/ω_T) - m(π_T) = M_W)
ρ_T mass (m(ρ_T) = m(π_T) + m_W, m(a_T) = 1.1m(ρ_T))
N mass (m(W_R) = 2 TeV)
N mass (|V_eN| = 0.055, |V_μN| = 0.063, |V_τN| = 0)
H_L^±± mass (limit at 398 GeV for μμ)
Scalar resonance mass
mass (|q| = 4e)
mass
10⁻¹
1
10
10²
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown

Conclusions: Executive Summary

The LHC leaves us with the deepest mathematical pb:

Dissertori, ECFA '13

$$\infty \cdot 0 = ?$$

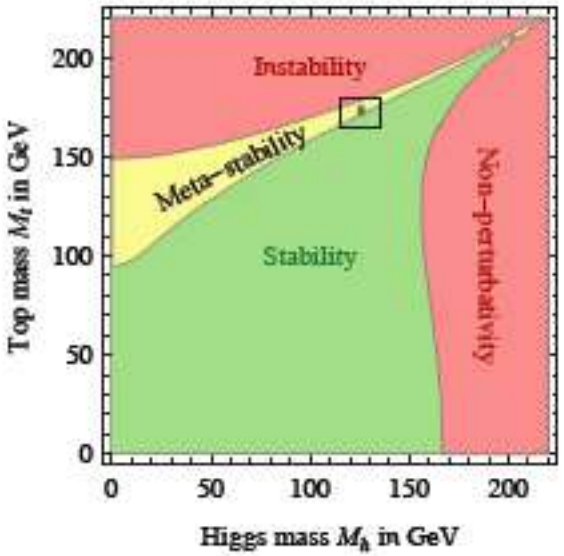
number of already performed BSM searches

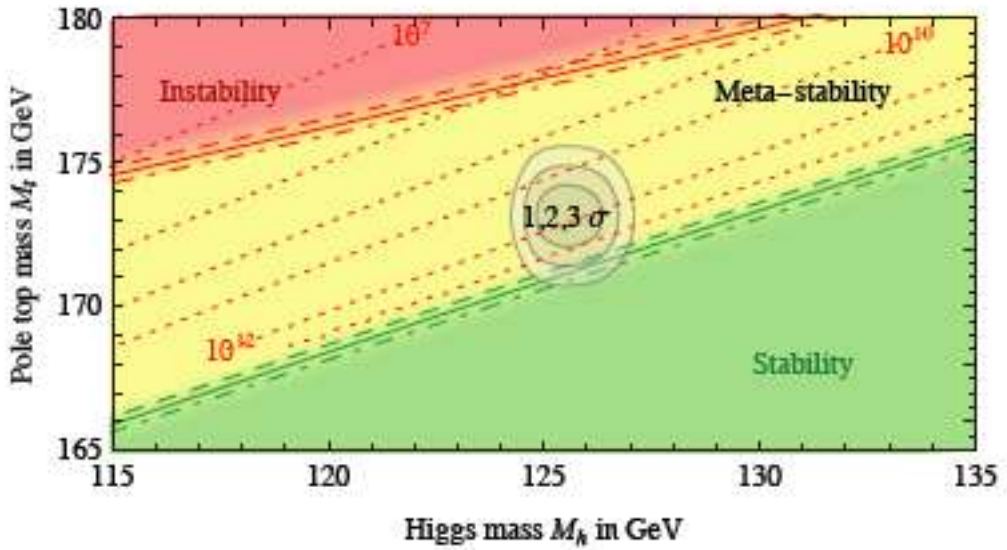
number of significant/ interesting/exciting deviations from SM predictions

general state of (our) mind (?)

Understanding the scalar sector of the SM
will help us grasping what lays beyond the SM

Higgs mass and vacuum stability





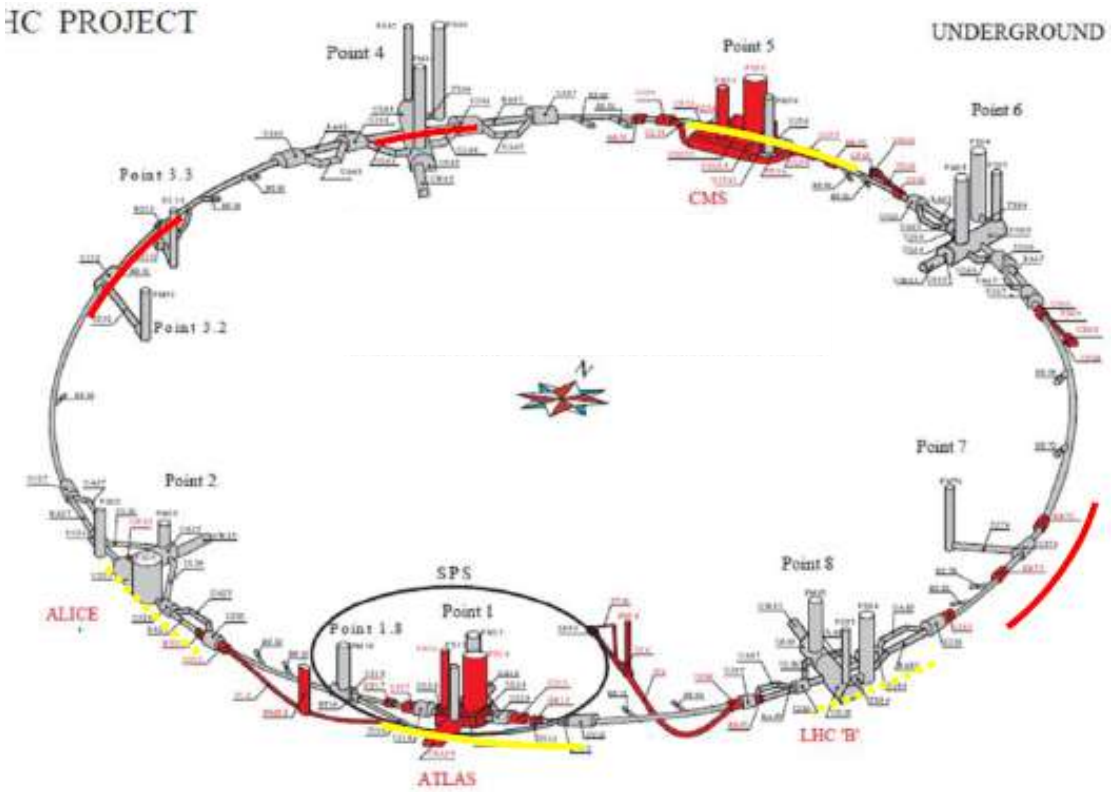
Looking for BSM effects

- …with searches
- ….with precision measurements
- …with rare (and reliably predicted) decays

Extending the reach…

- Weak boson scattering
- Higgs properties
- Supersymmetry searches and measurements
- Exotics
- t properties
- Rare decays
- CPV
- ..etc

The HL-LHC Project



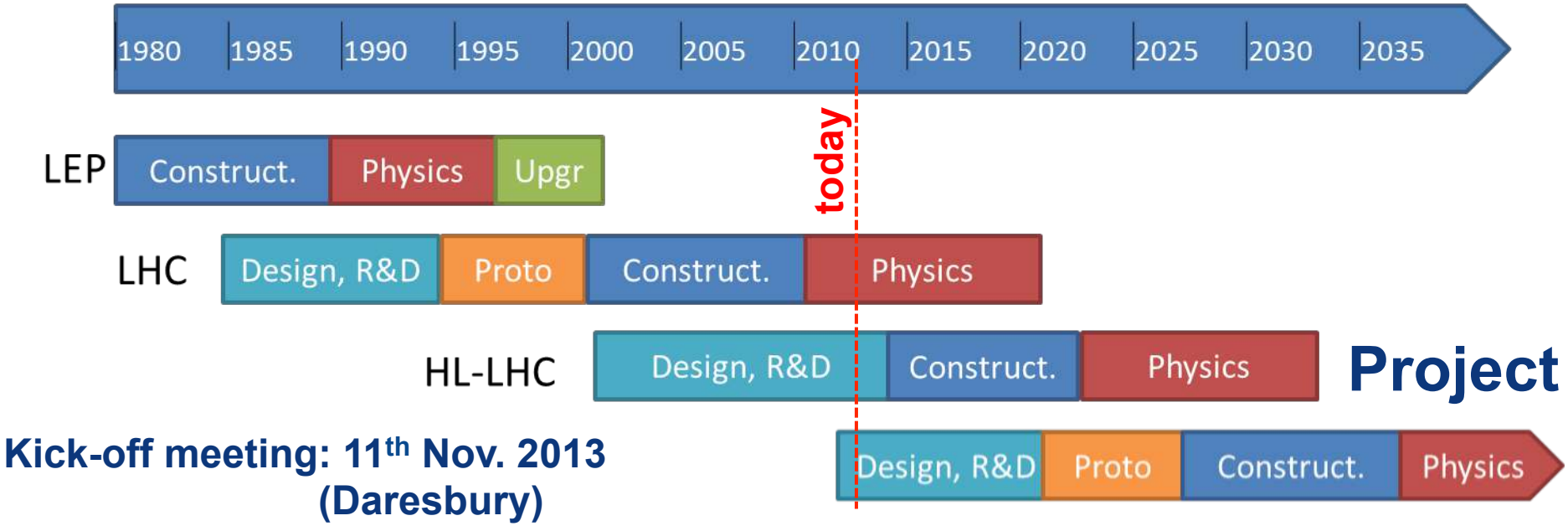
- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

Experiments from LHC to HL-LHC

- An extensive and rich physics program
- Maintain full sensitivity for discovery
  - And precision measurements at low p_T
- Pileup
  - <PU> ≈ 50 events per crossing by LS2
  - <PU> ≈ 60 events per crossing by LS3
  - <PU> ≈ 140 events per crossing by HL-LHC
    - Lumi-leveling at $5x10^{34}cm^{-2}s^{-1}$
- Radiation damage
  - Requires work to maintain calibration
  - Limits performance-lifetime of the detectors
    - Light loss (calorimeters)
    - Increased leakage current (silicon detectors)

"CERN should undertake design studies for accelerator projects in a global context, with emphasis on ***proton-proton*** *and electron- positron* ***high-energy frontier machines.***"



Kick-off meeting: 11th Nov. 2013 (Daresbury)

FCC Study : p-p towards 100 TeV

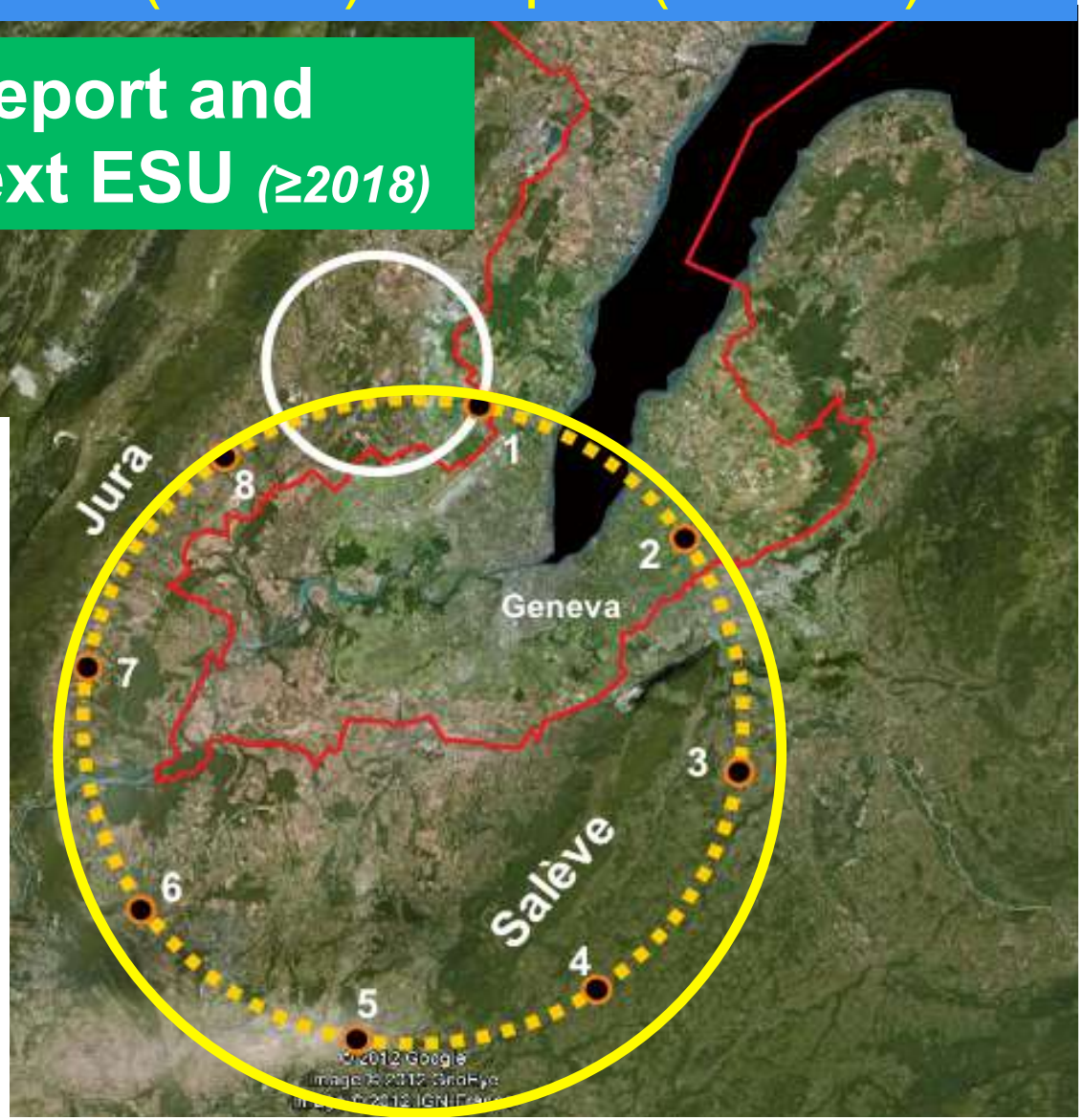
Kick-off meeting: mid-February 2014

FCC: Future Circular Colliders

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements

with possibility of e+-e- (TLEP) and p-e (VLHeC)

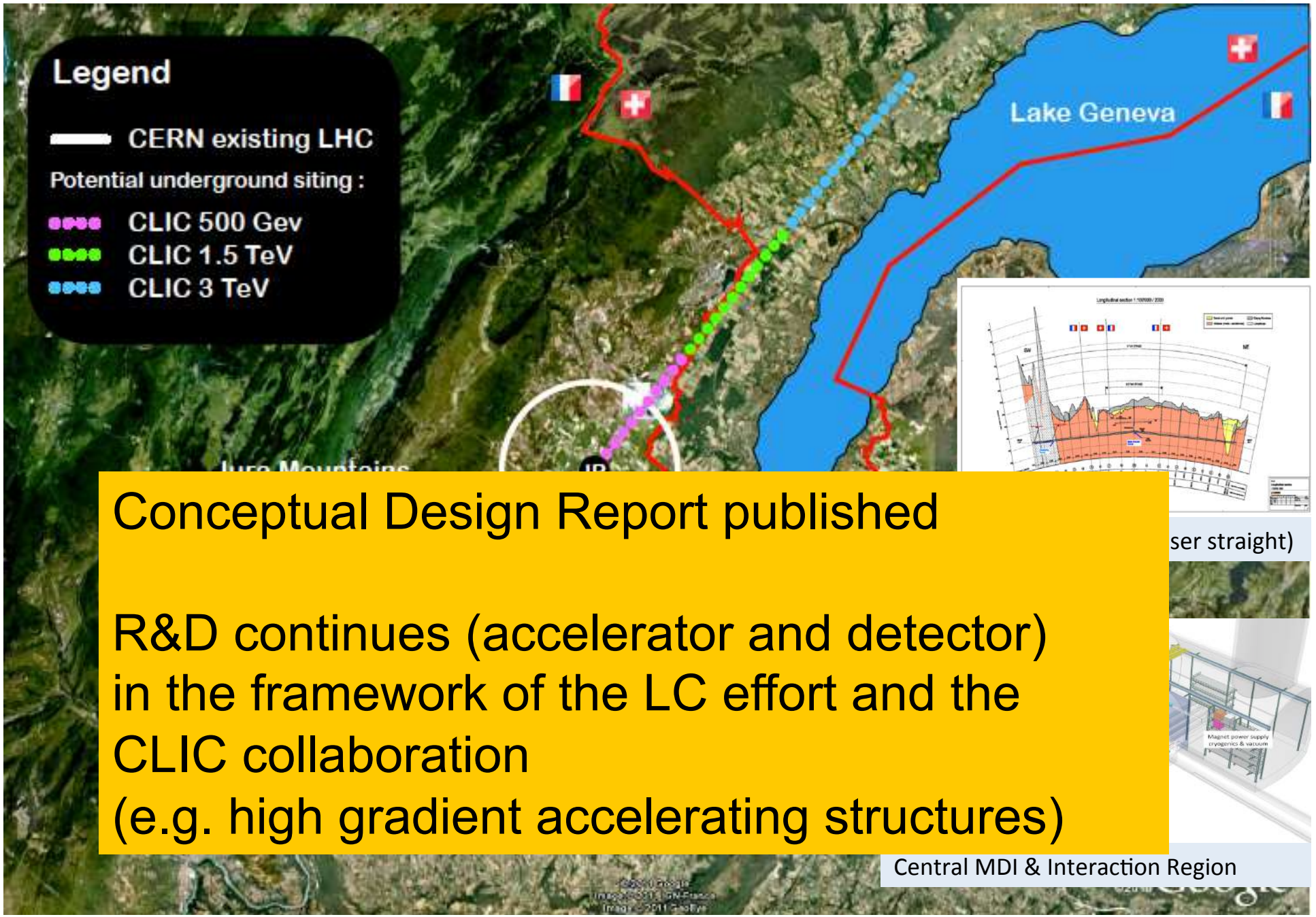
Conceptual Design Report and cost review for the next ESU ***(≥2018)***



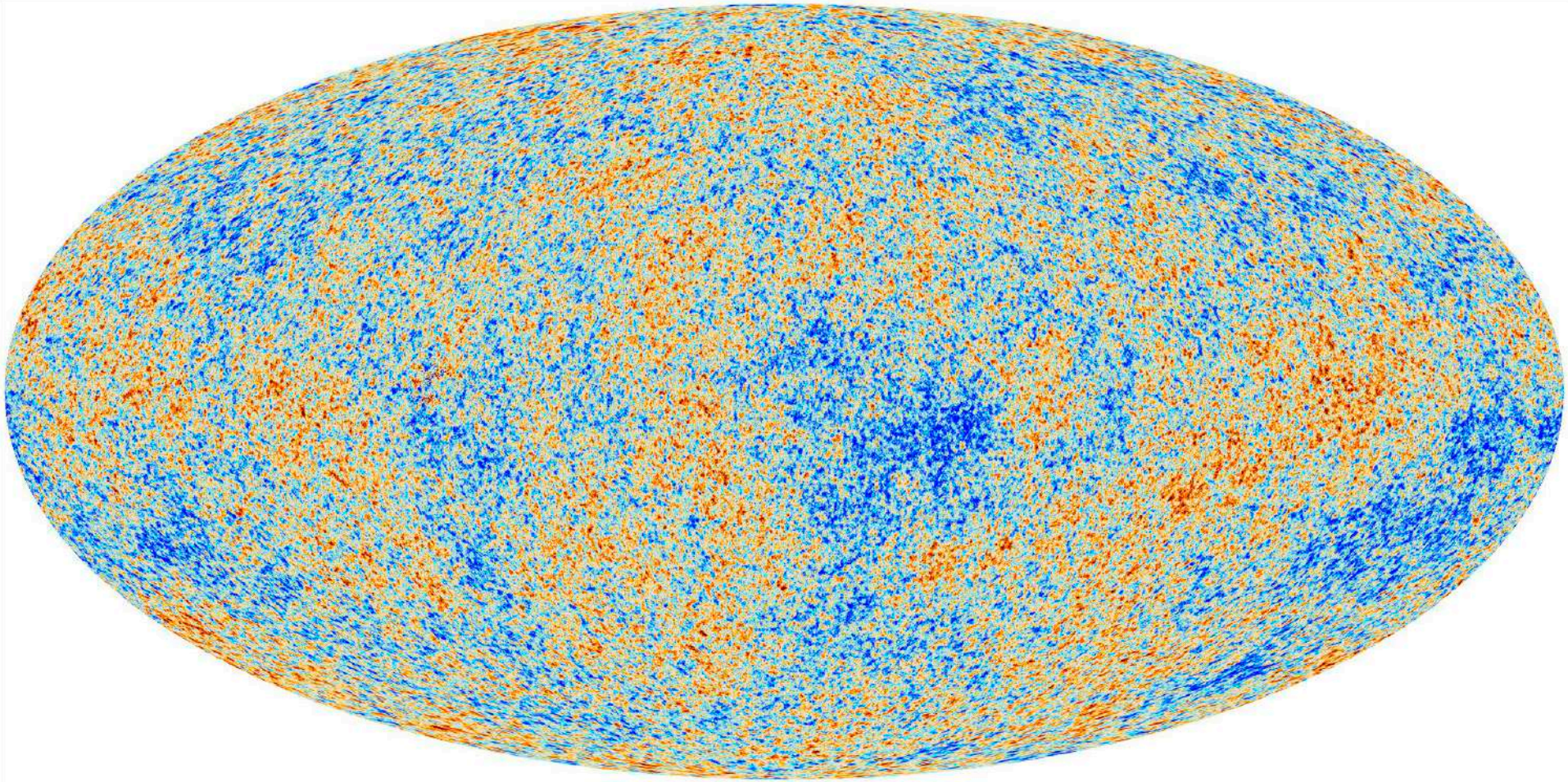
FCC Design Study Kick-off Meeting: 12-14. February 2014 in Geneva area

- ***Establishing international collaborations***
- ***Set-up study groups and committees***

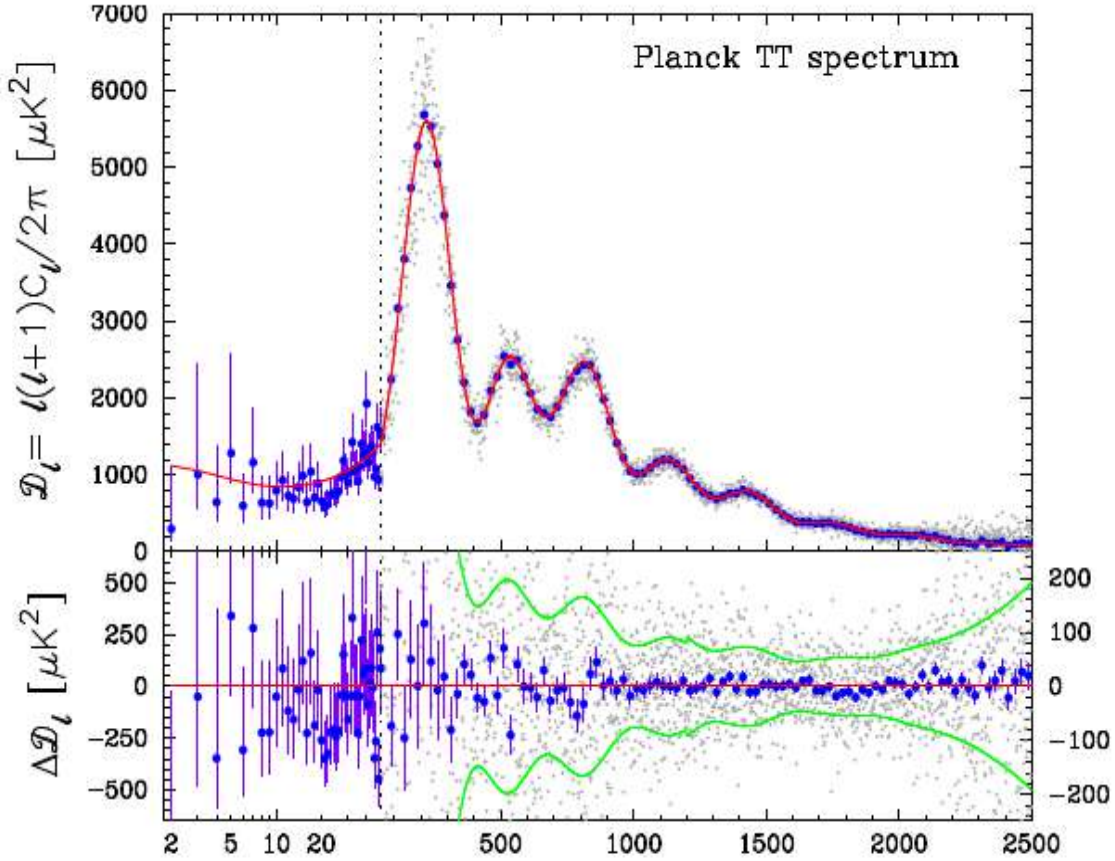
CLIC near CERN



Planck CMB (2013)



CMB power spectrum (Planck 2013)



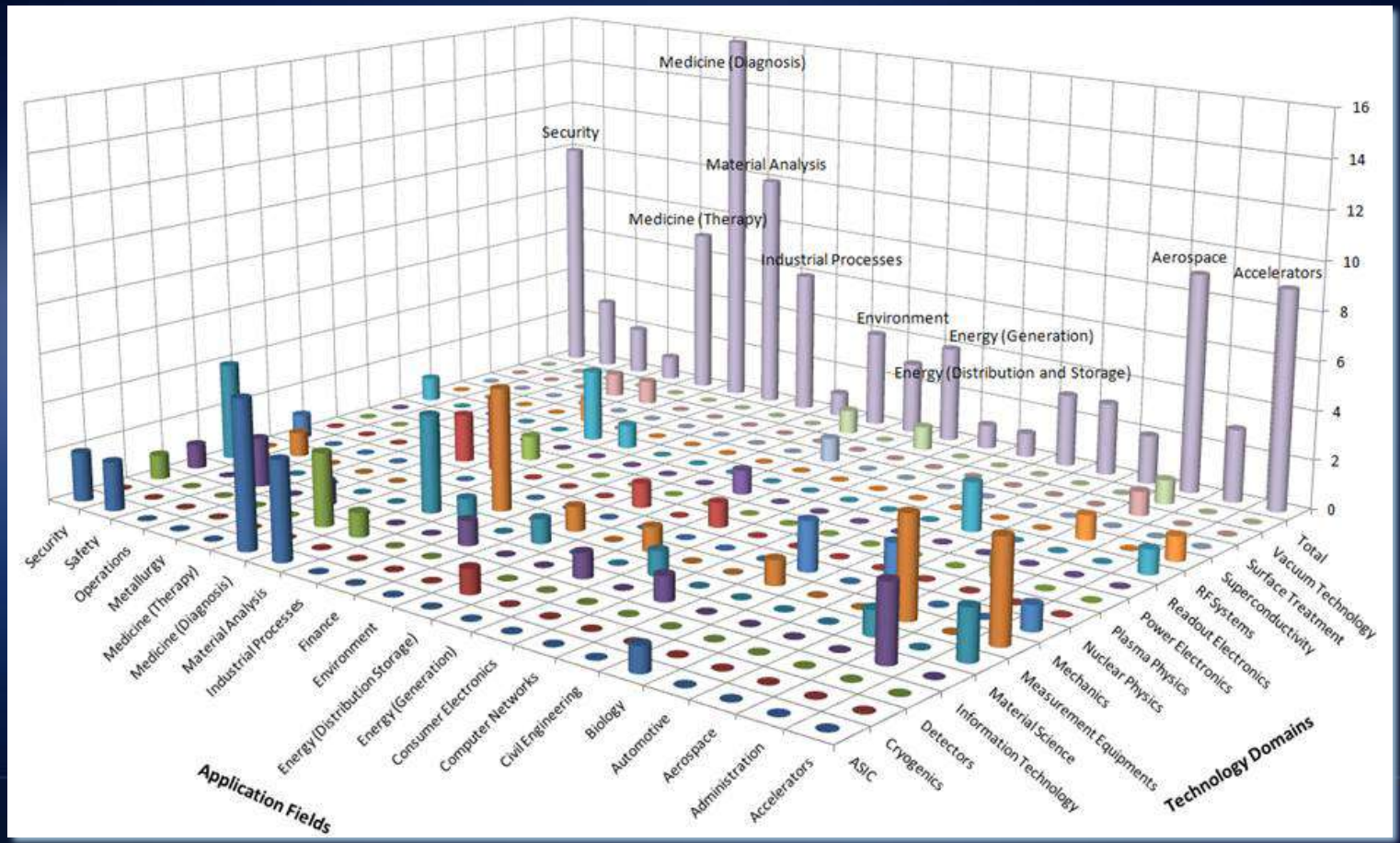
output of Planck likelihood - foregrounds subtracted

Hybrid method : map based ML (low ℓ) / pseudo-spectra (high ℓ) of masked raw maps

Innovation
Education
CERN
uniting people
Research

Only abstract speculations???

Cutting edge Research Infrastructures play a key role in a knowledge driven society



EXPERIMENT

Medical Application as an Example of Particle Physics Spin-off

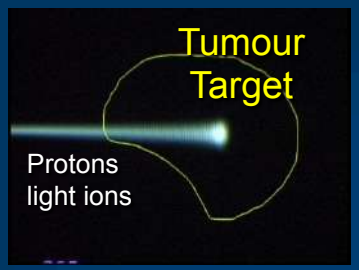
Combining Physics, ICT, Biology and Medicine to fight cancer

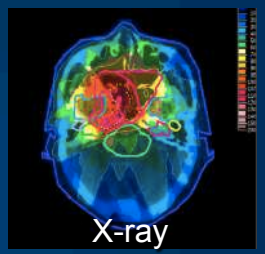
Accelerating particle beams

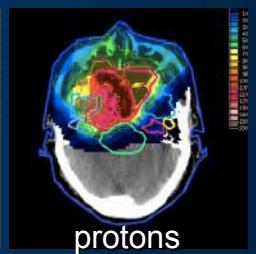
~30'000 accelerators worldwide

~17'000 used for medicine

Hadron Therapy



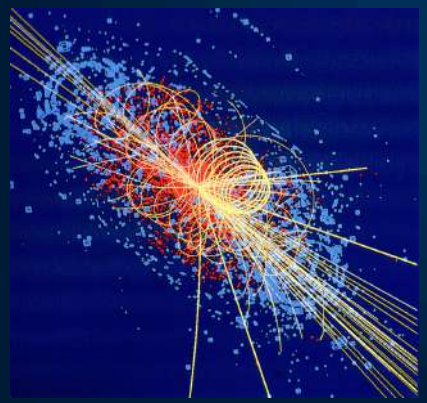




Leadership in Ion Beam Therapy now in Europe and Japan

>70'000 patients treated worldwide (30 facilities)

>21'000 patients treated in Europe (9 facilities)

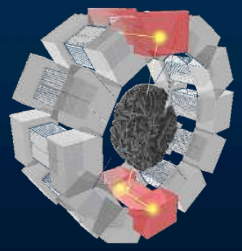


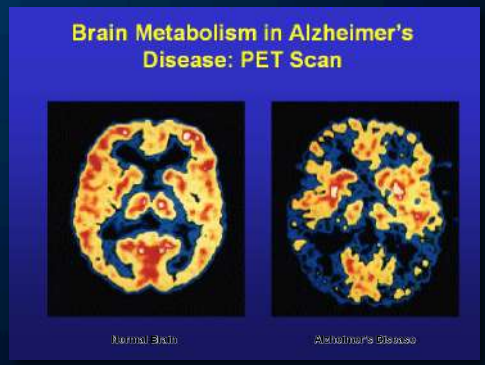
Detecting particles

Imaging

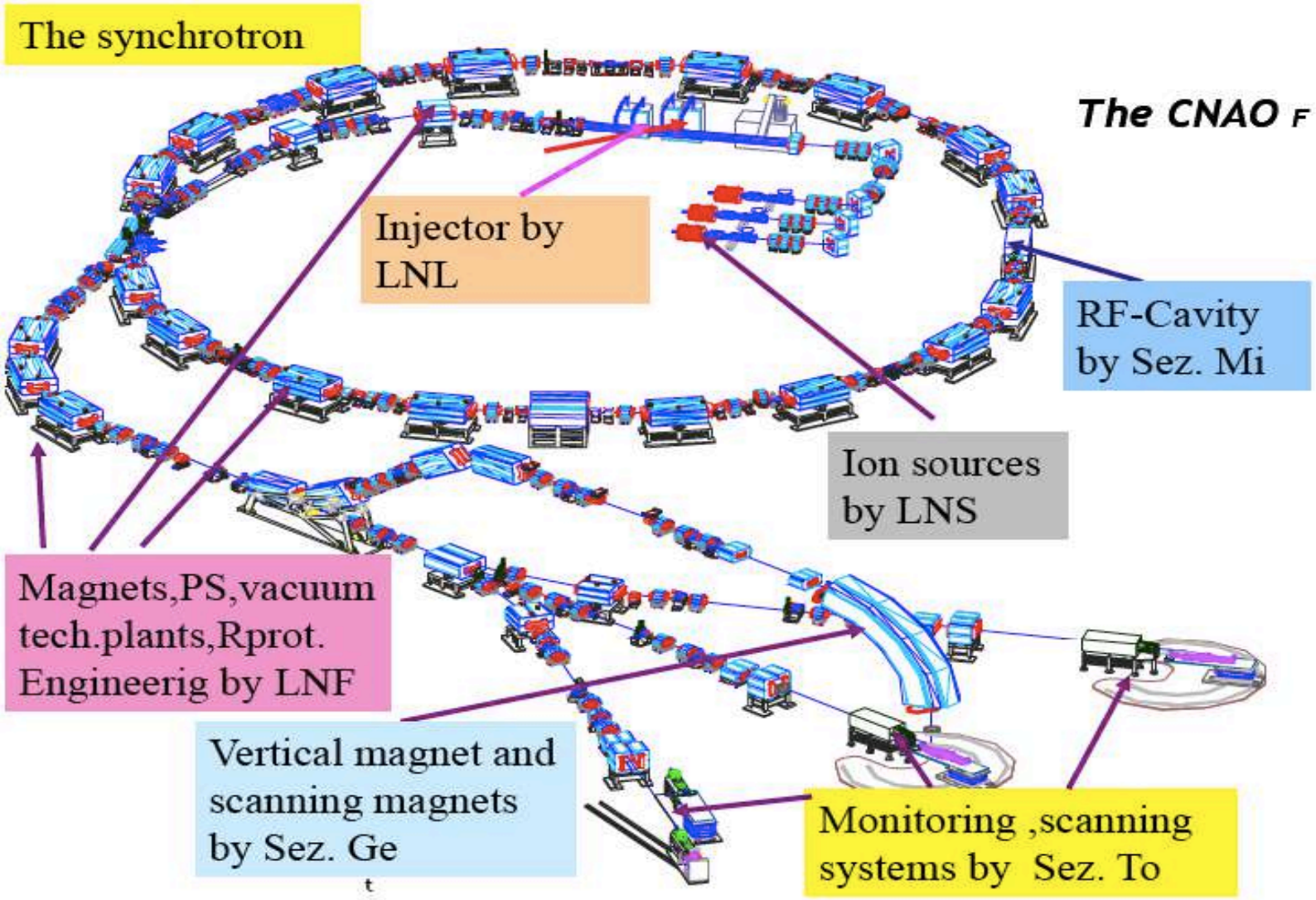
PET Scanner

Clinical trial in Portugal for new breast imaging system (ClearPEM)





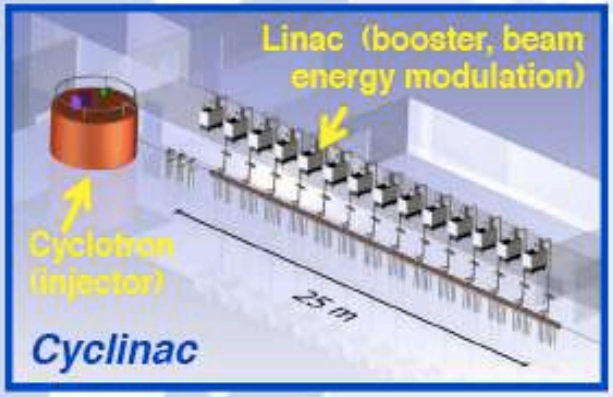
CNAO in Pavia



Novel accelerator and gantry studies

Objective:

Development of a linear accelerator (linac) for a carbon ion cyclinac (CABOTO)

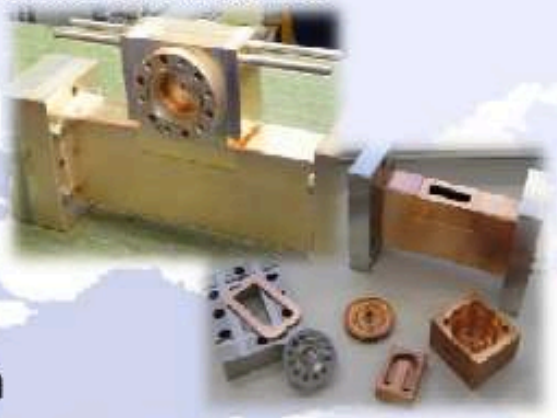


Motivation...

To deliver a **compact, dedicated accelerator**, providing the best possible treatment modalities for hadron therapy at the **lowest cost**

The challenge!

Machine **dimensions** could be **reduced** if high gradients could be achieved in the linac without compromising machine **reliability**



Work description:

- **Performance optimization** of CABOTO
- **Tests** of single-cell **accelerating cavites** to determine the highest reliable operational gradient for CABOTO
- **Comparison** between **RF linacs and FFAGs** for hadron therapy

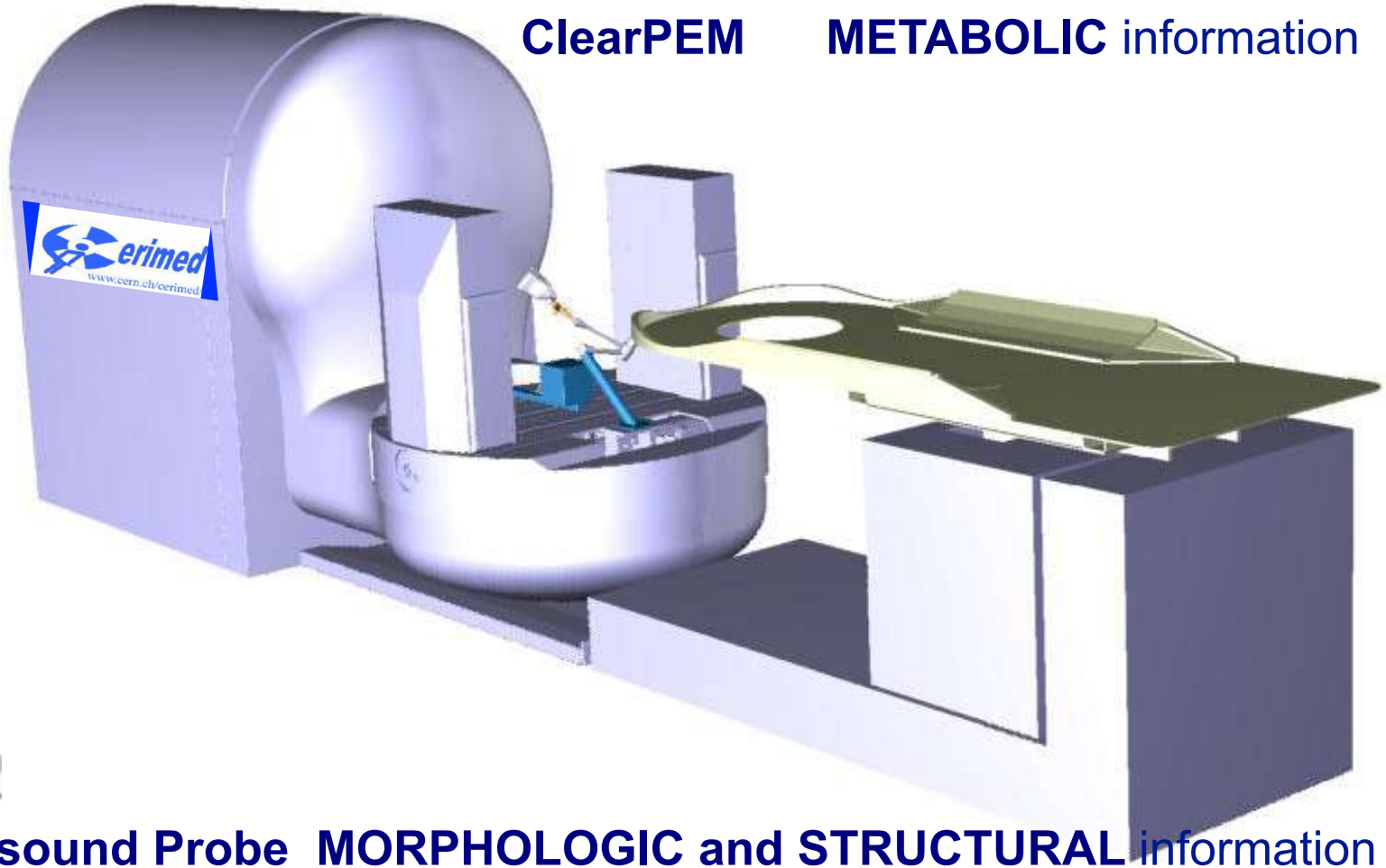
Silvia Verdú Andrés

TERA

PARTNER

ClearPEM-Sonic a collaborative project between physicians and physicists

ClearPEM **METABOLIC** information

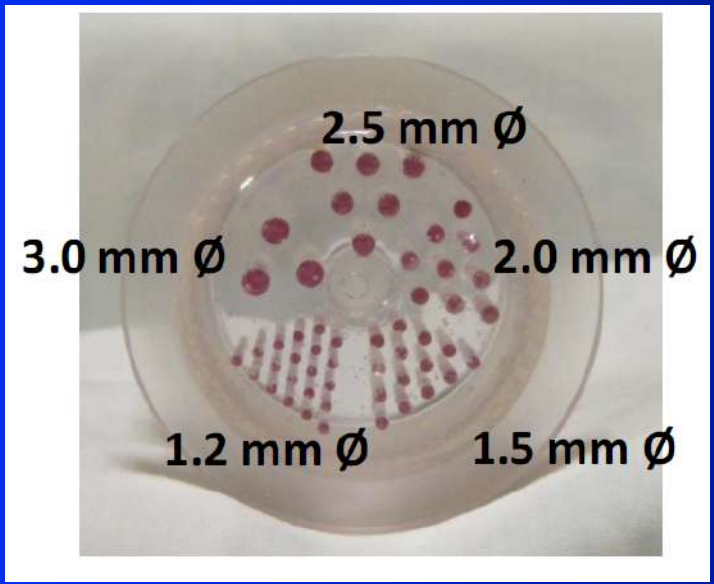


Ultrasound Probe **MORPHOLOGIC and STRUCTURAL** information

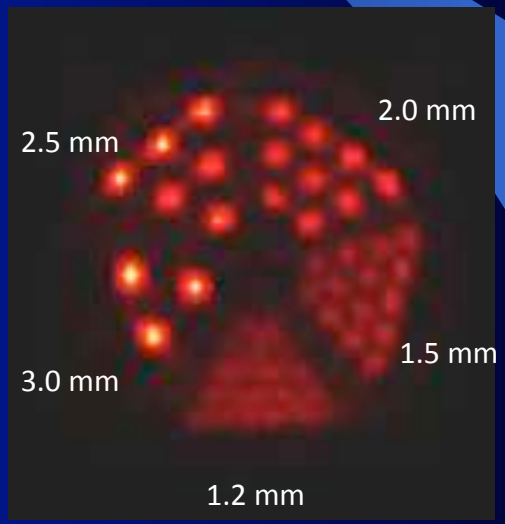
Objective: Detect 1 to 2mm tumors and define their cancerous status

Derenzo phantom

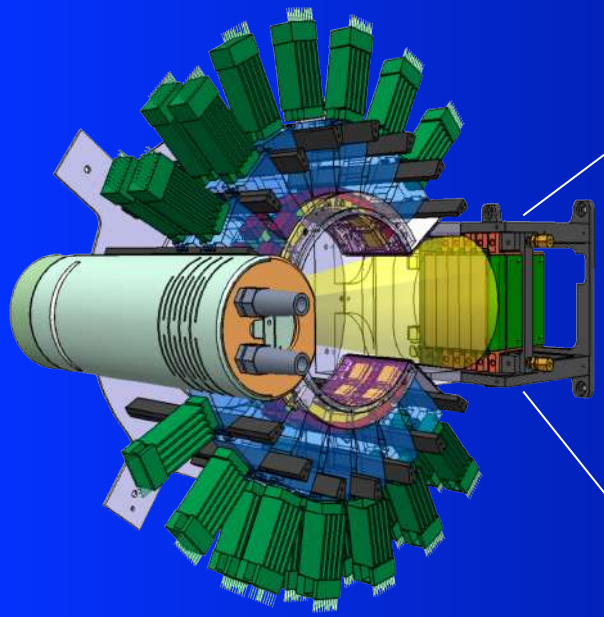
Excellent resolution (< 1.5mm)
compared to
5mm for the best commercial PET scanners

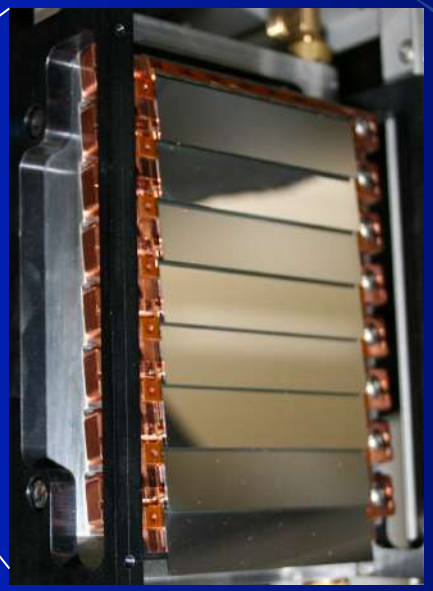


OSEM 3D



ClearPET-XPAD





ClearPET/XPAD

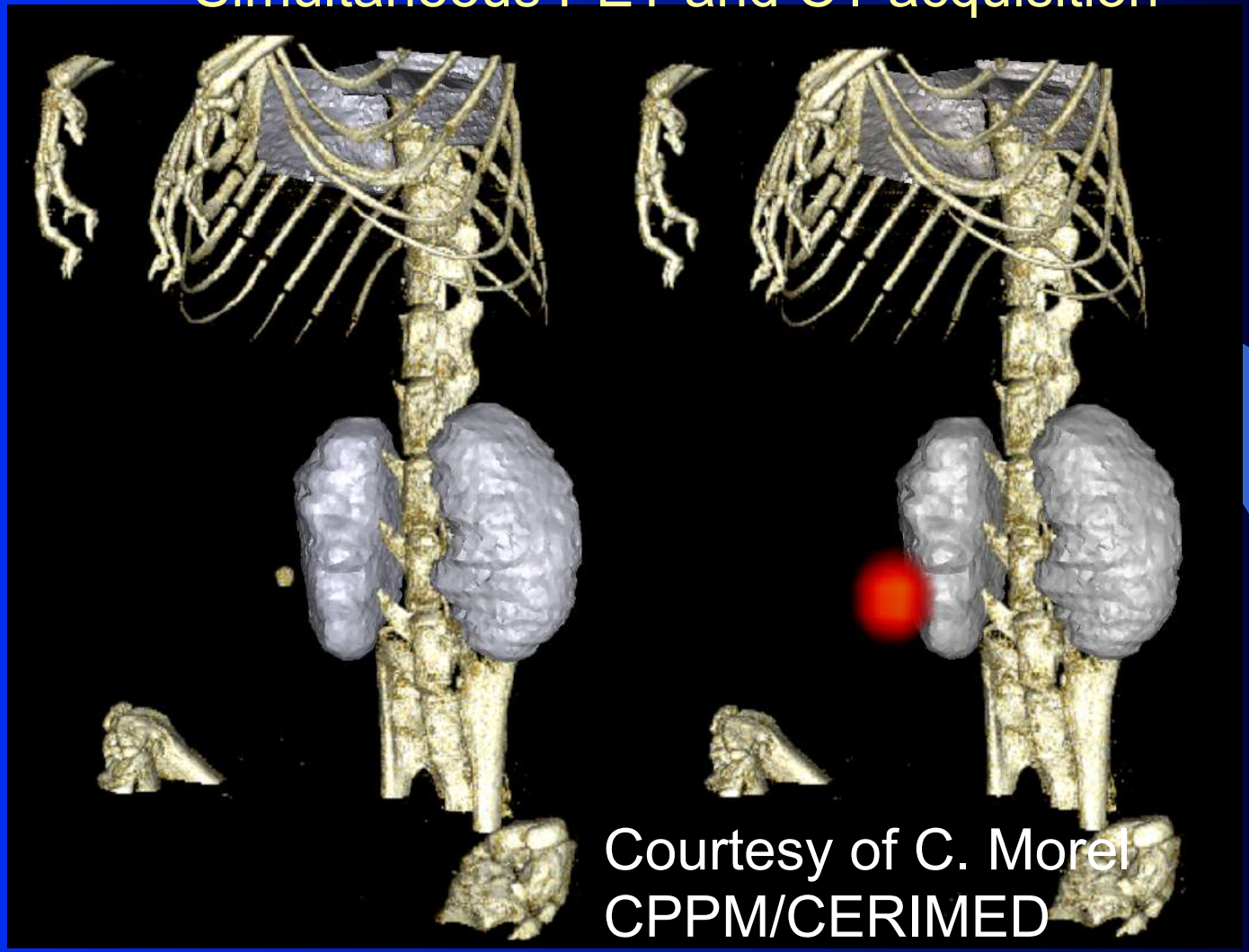
- Simultaneous hybrid PET/CT imaging system

Courtesy of C. Morel CPPM/CERIMED

- RTW X-ray tube
  - Mo target, 50 µm spot size, 50 W
  - Nb/Mo additional filter
  - Threshold 3-35 keV
- XPAD3/Si Hybrid pixel camera
  - X-ray photon counting mode
  - 500 µm silicon sensor thickness
  - 78 x 75 mm² detector
  - 130 x 130 µm² pixel size
- PET FOV
  - 55mm axial
  - 111mm transverse
- 35 mm transverse FOV
  - 59mm axial
  - 38mm transverse

ClearPET-XPAD

Simultaneous PET and CT acquisition

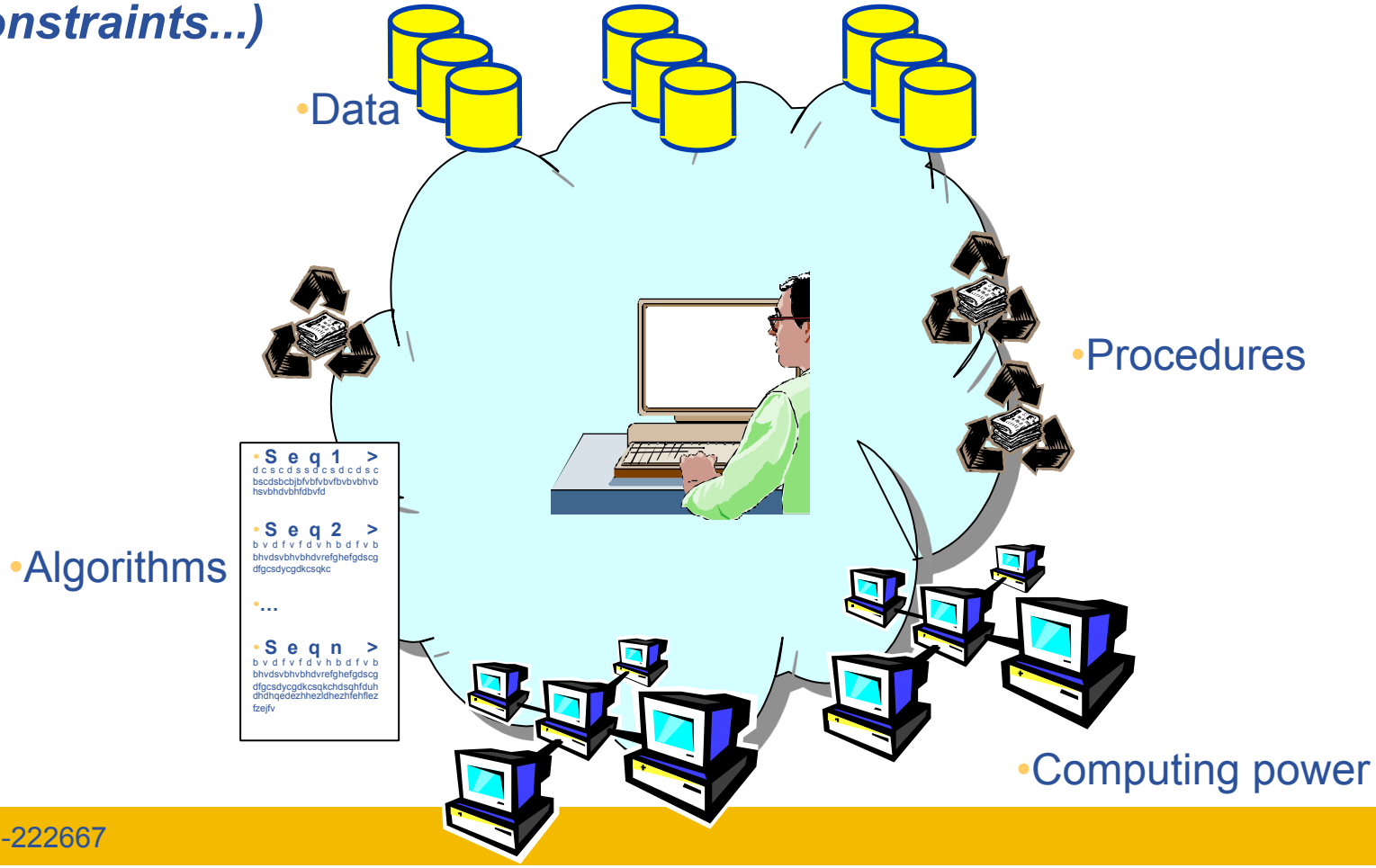


Courtesy of C. Morel
CPPM/CERIMED

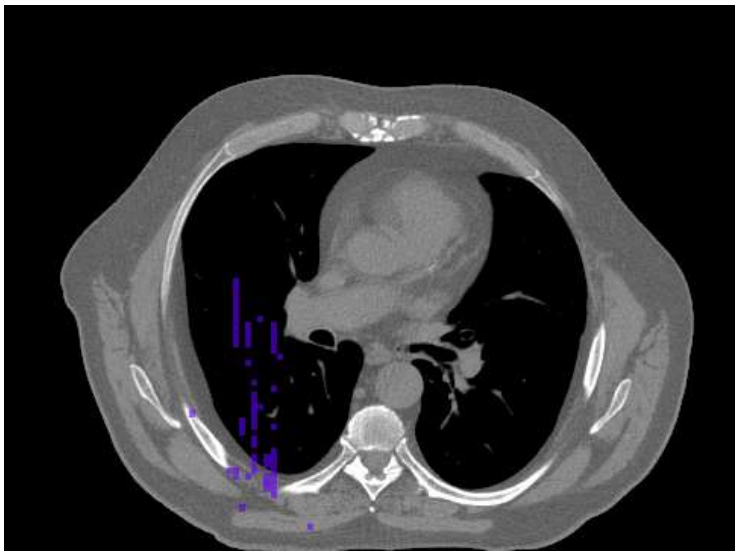
^{22}Na source surgically inserted in the belly of a dead mouse

Why grids for e-Health?

- ***Sharing computing resources and algorithms***
  - ***Research (populations studies, models design, validation, statistics)***
  - ***Complex analysis (compute intensive image processing, time constraints...)***



ThIS: Therapeutic Irradiation Simulator

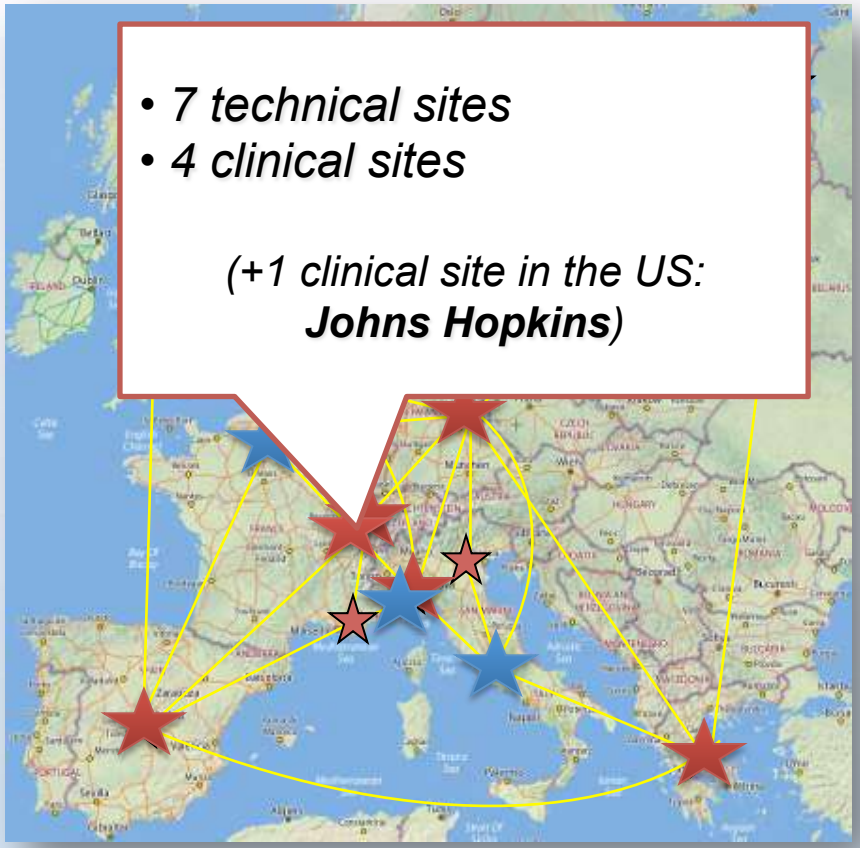


- **Cancer treatment by irradiation of patient with beams of photons, protons or carbons**
- **CT image (482x360x141)**
- **3D dose distribution, 700h CPU**

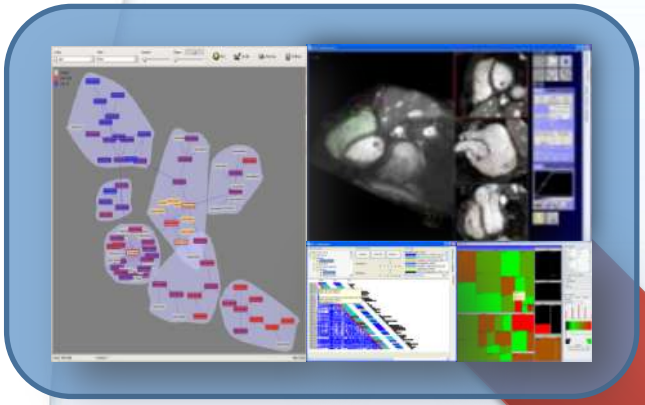
- **Offer an open platform to researchers for Monte Carlo simulations optimisation**
- **Offer a fast and reliable simulation tool for researchers in medical physics and medical imaging for treatment control**
- **Produce a reference dataset for non-conventional therapies (hadrontherapy).**

Health-e-Child Network

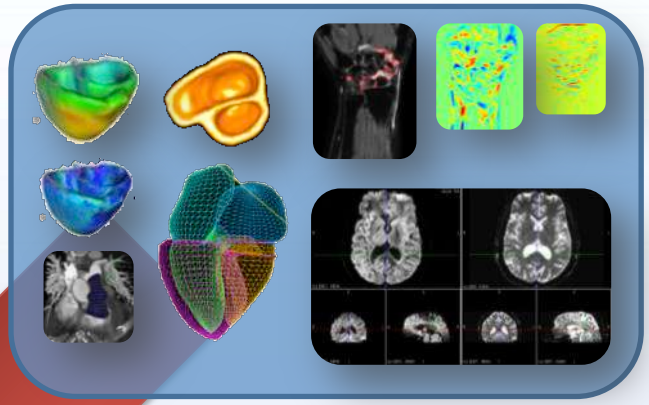
- *4 paediatric hospitals*
  - *IGG - Gaslini, Genoa, Italy*
  - *GOSH, London, UK*
  - *NECKER, Paris, France*
  - *OPBG, Rome, Italy*
- *Strong interdisciplinary team across*
  - *Countries and languages*
  - *Technical and clinical fields*
- *Research on three paediatric areas*
  - *Arthritis*
  - *Cardiac Disorders*
  - *Brain Tumours*



Decision Support



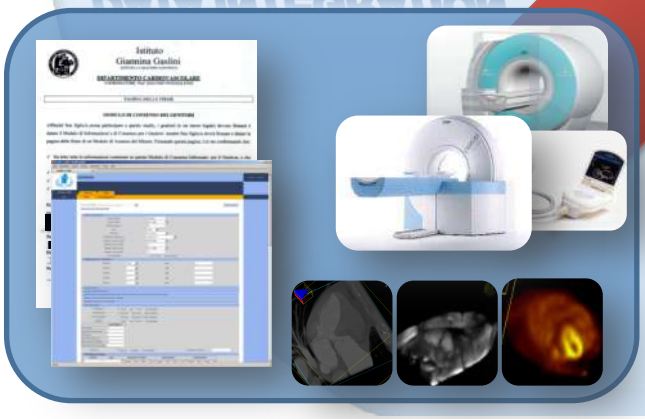
MEDICAL DSS



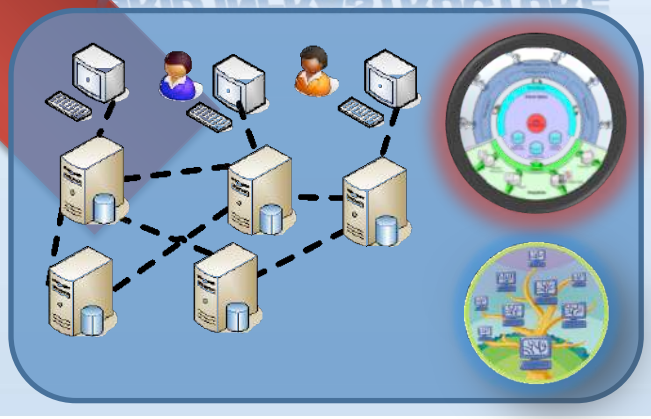
DISEASE MODELS

Virtual Physiological Child

DATA INTEGRATION



GRID INFRASTRUCTURE



In summary

An exciting period in front of us:

- We have finished the inventory of the “known unknown”…
- …but we have a vast space to explore, and tools to do it exhaustively.
- We have a solid physics program for the next 20 years
- Big surprises, and even a paradigm change might be around the corner

In summary

Experimental results will be dictating the agenda of the field.

We will need:

- Flexibility
- Preparedness
- Visionary ideas

- ...and a bit of luck!

Thank you!