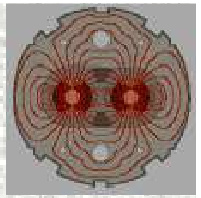


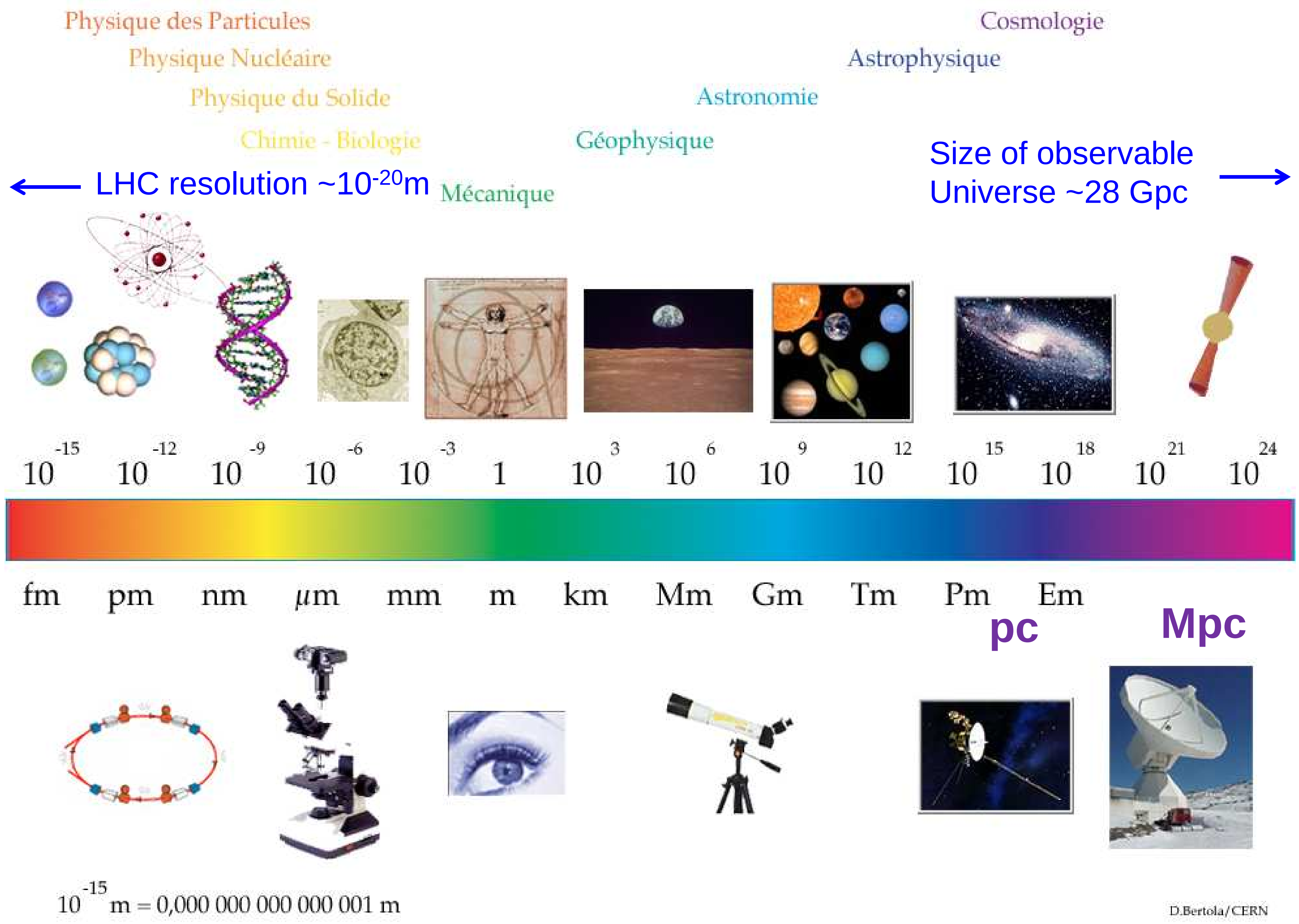
Od Velkeho Tresku k LHC

stvorenie Vesmiru v laboratoriu

Karel Šafařík (CERN)

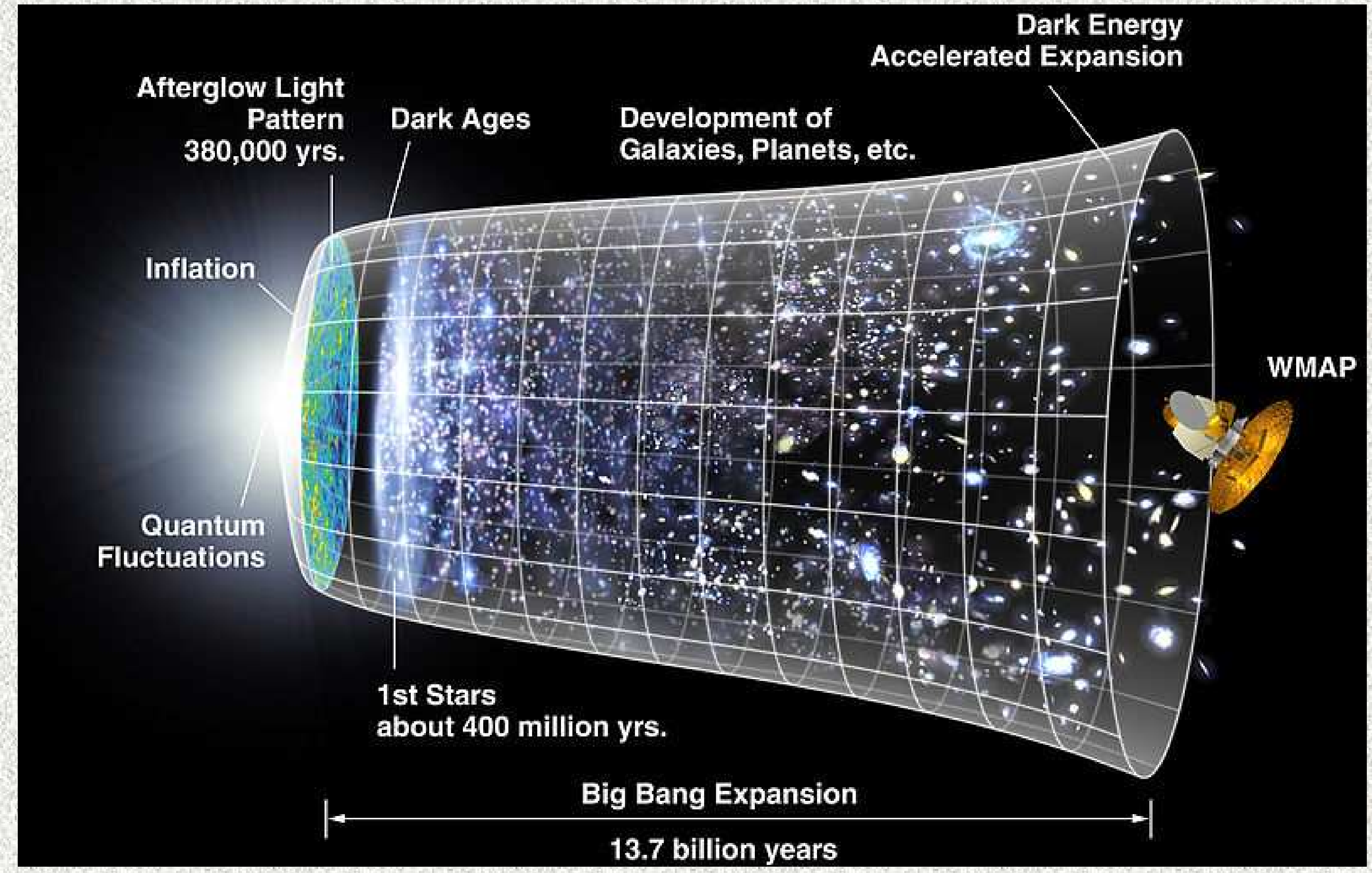
based on many talks of my friends

J.Ellis, J.Grygar, …



Physique des Particules
Physique Nucléaire
Physique du Solide
Chimie - Biologie
Mécanique
Géophysique
Astronomie
Astrophysique
Cosmologie
LHC resolution ~10^-20 m
Size of observable Universe ~28 Gpc
10^-15 10^-12 10^-9 10^-6 10^-3 1 10^3 10^6 10^9 10^12 10^15 10^18 10^21 10^24
fm pm nm µm mm m km Mm Gm Tm Pm Em
pc
Mpc
10^-15 m = 0,000 000 000 000 001 m
D.Bertola/CERN

Vesmir od Velkeho Tresku



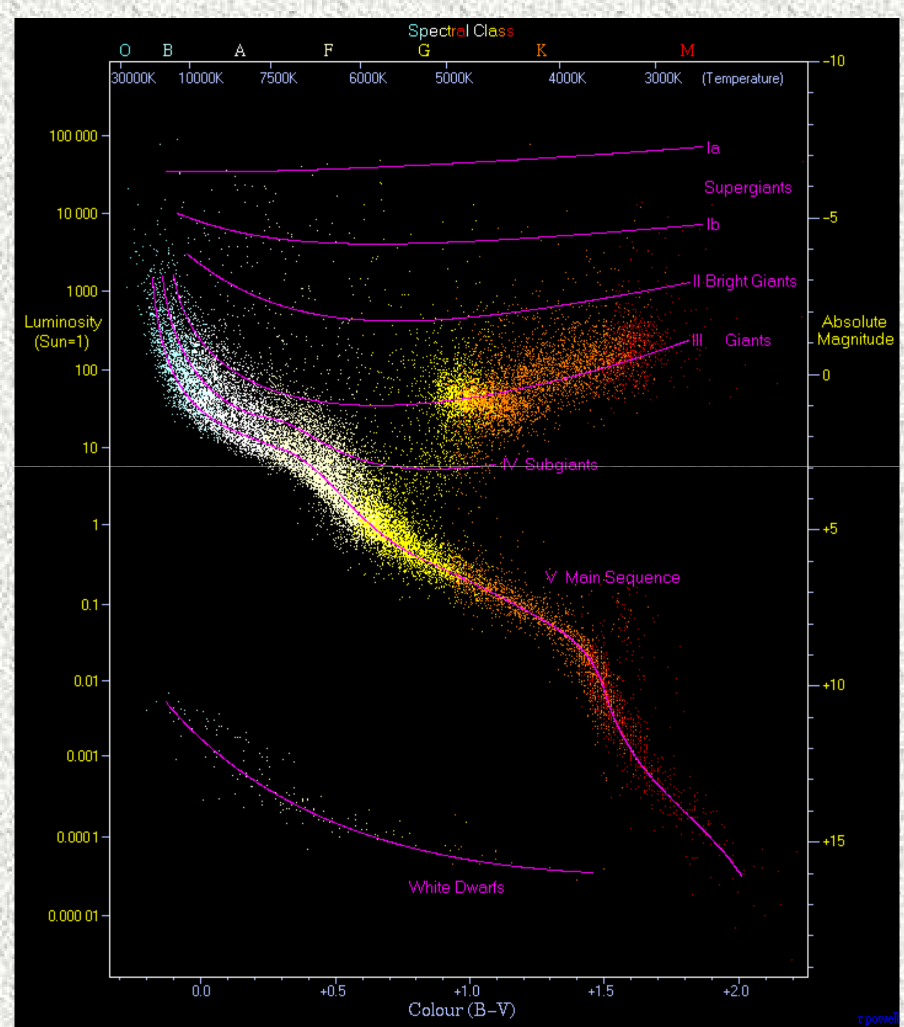
Cosmological 'Principle'

- 'Universe looks the same from any point'
  - isotropic and homogeneous
- (To be interpreted in average sense)
- Perfect Cosmological Principle?
- 'Universe looks same at all times and all places'
- Not correct: the Universe is expanding
- Olbers' Paradox
  - Why is the night sky not as bright as the surface of the Sun?
  - In an infinite, static Universe, every line of sight would end at the surface of a star
- Universe must be finite in time and/or space

Cosmological Distance Ladder

- Trigonometric parallax:
  motion of Earth around orbit
  → O(100) pc
- Spectroscopic Parallax:
  based on Hertzsprung-Russell diagram → 50 Kpc

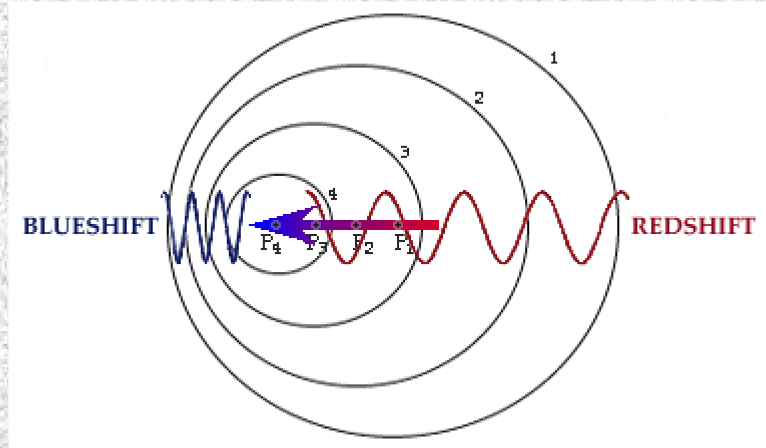
- Cepheid variables: → 4 Mpc
- Other 'Standard Candles':
  clusters, galaxies, radio sources, supernovae …
  weak lensing, microwave background, …



Cosmological Redshifts

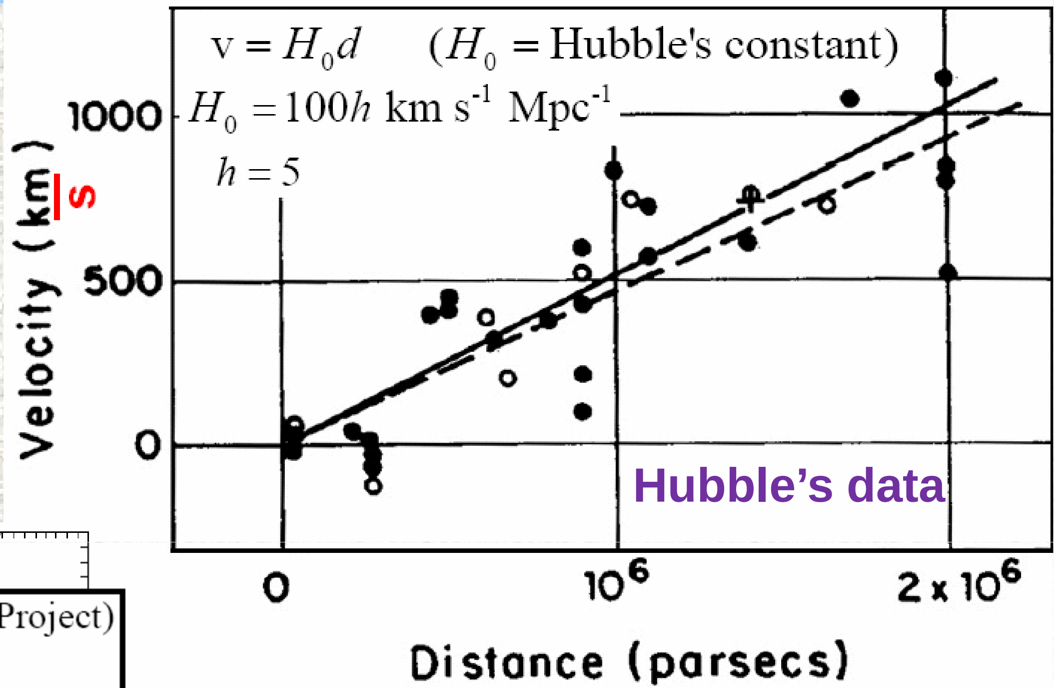
- Detectable effect on spectrum 'barcodes'
- for different elements, e.g., Sodium:

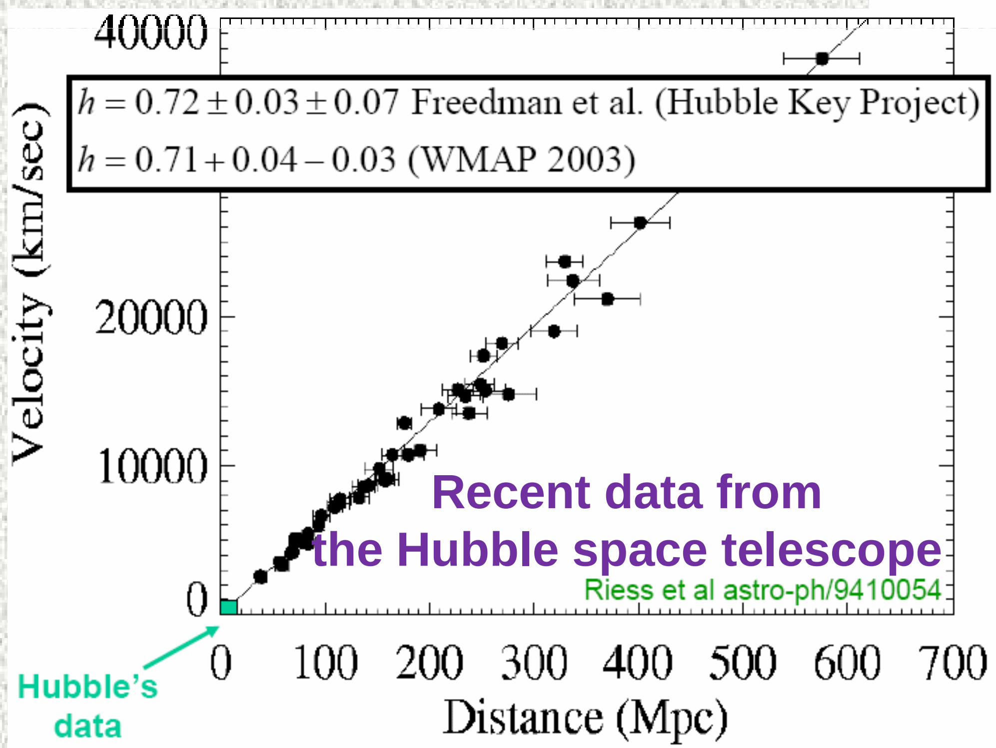
- Döppler effect

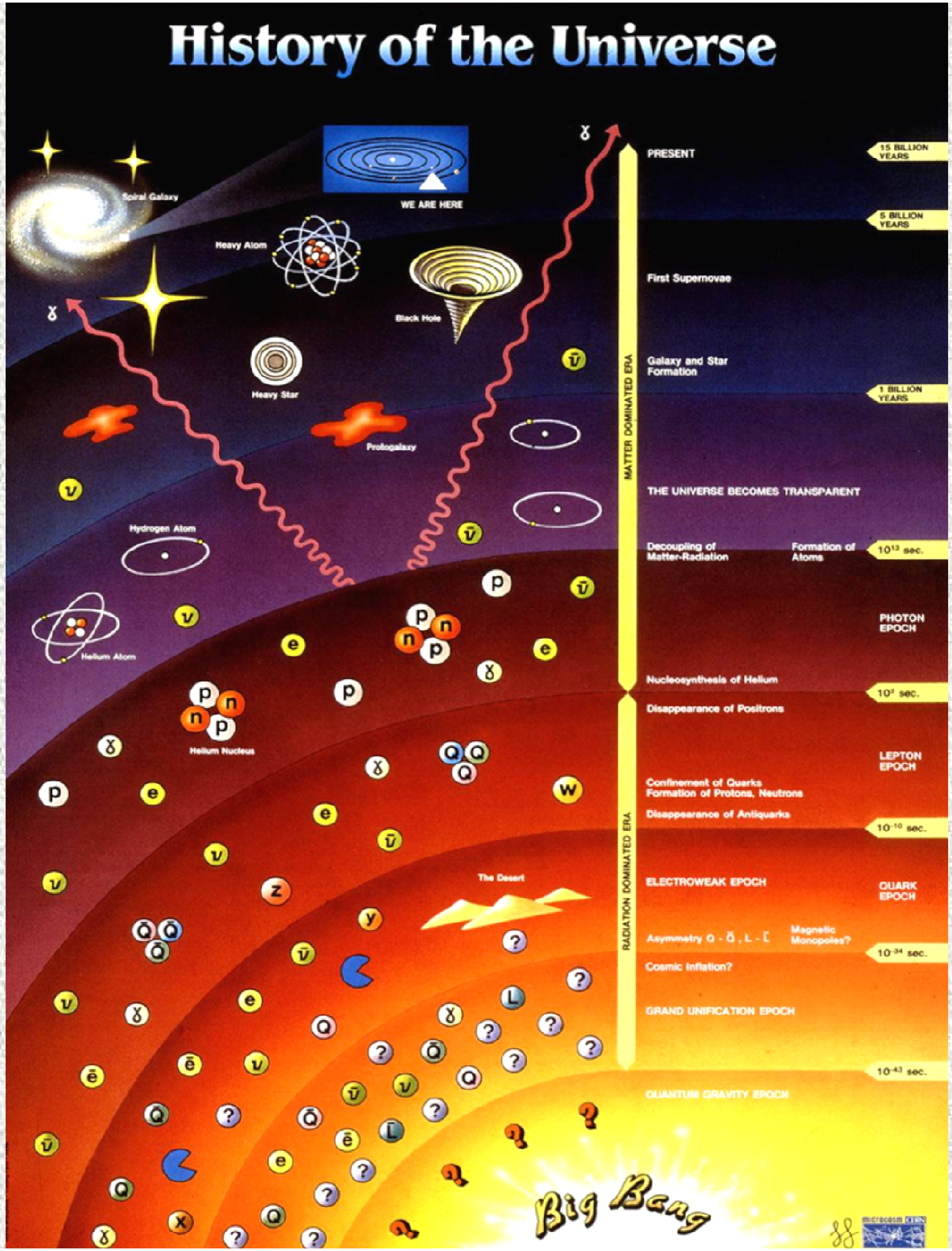


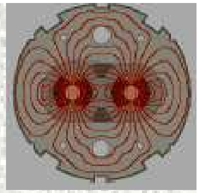
The expansion of the Universe

- **The Universe is expanding !**
- **Hubble constant = 70.4 km/s/Mpc ± 2 %**

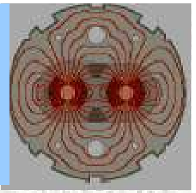


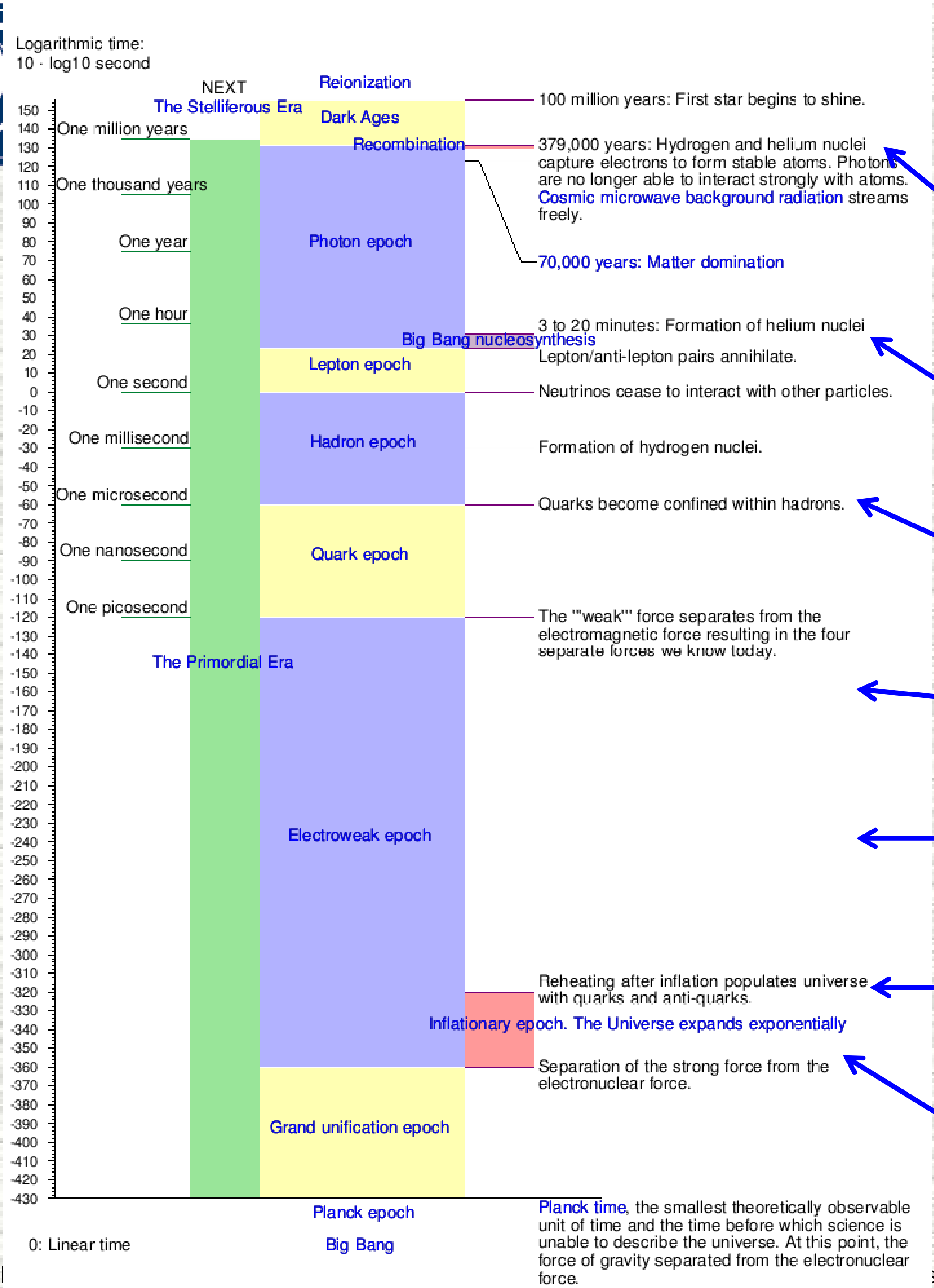



History of the Universe
Spiral Galaxy
WE ARE HERE
Heavy Atom
Black Hole
Heavy Star
Protogalaxy
Hydrogen Atom
Helium Atom
Helium Nucleus
The Desert
PRESENT
15 BILLION YEARS
5 BILLION YEARS
First Supernovae
Galaxy and Star Formation
1 BILLION YEARS
MATTER DOMINATED ERA
THE UNIVERSE BECOMES TRANSPARENT
Decoupling of Matter-Radiation
Formation of Atoms
PHOTON EPOCH
Nucleosynthesis of Helium
Disappearance of Positrons
LEPTON EPOCH
Confinement of Quarks Formation of Protons, Neutrons
Disappearance of Antiquarks
RADIATION DOMINATED ERA
ELECTROWEAK EPOCH
QUARK EPOCH
Magnetic Monopoles?
Cosmic Inflation?
GRAND UNIFICATION EPOCH
QUANTUM GRAVITY EPOCH
Big Bang



Big Bang





Cas $10^{-36}s$ 1ps 1μs 1s 1h 1r

atomy – vesmir je priehladny

atomove jadra (He, Li)

protony, neutrony

quarky, leptony

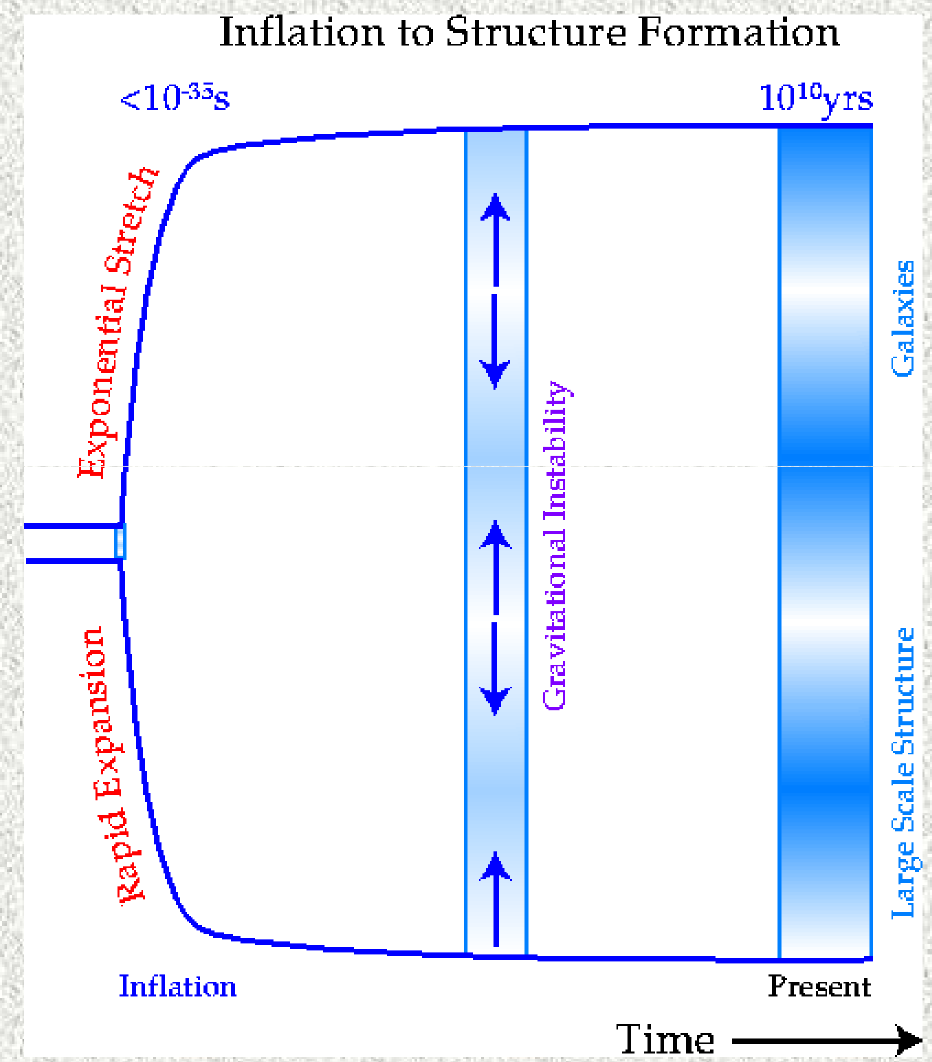
...?

asymetria hmota – antihmota

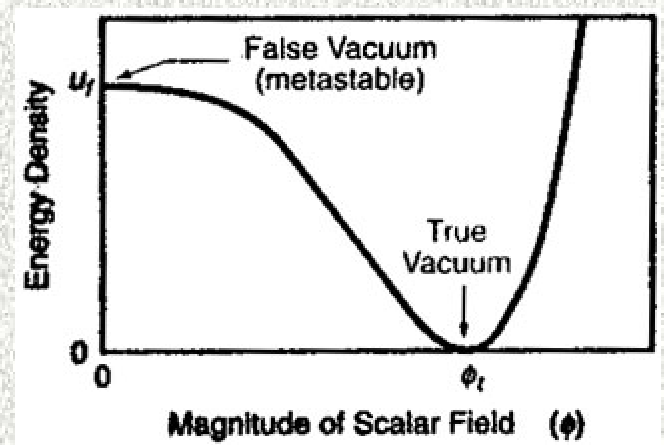
inflacia

LHC

Cosmological Inflation

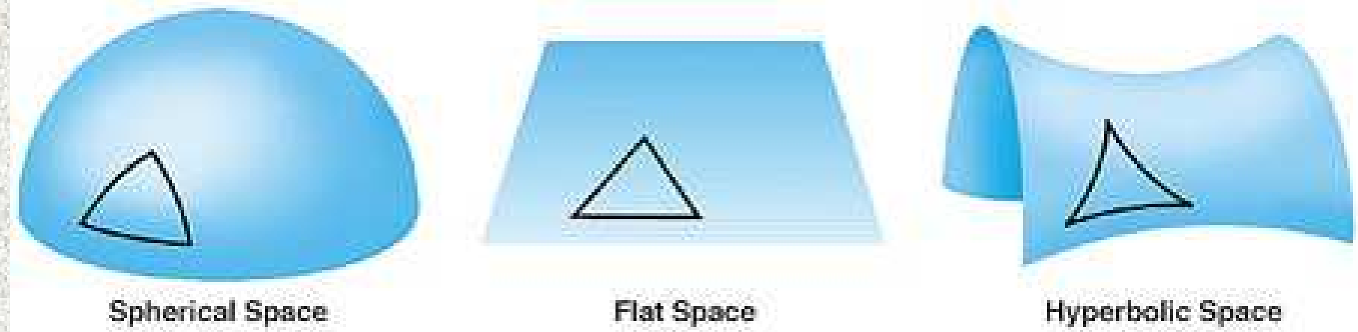


Basic idea: very early in the history of the Universe (between 10^{-36} – 10^{-33}s) the energy density was dominated by a constant piece V: would have caused an exponential expansion: size increased ~10^{26} times

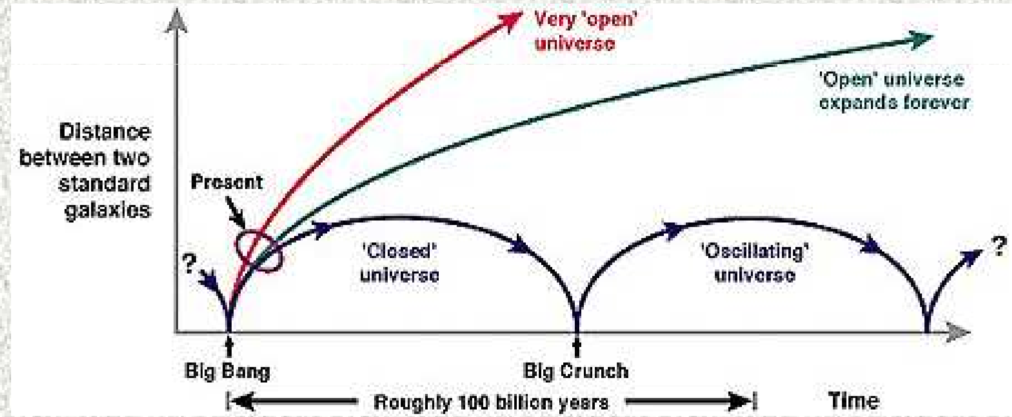


Geometry of the Universe

- Closed Universe? Flat Space? Open Universe?

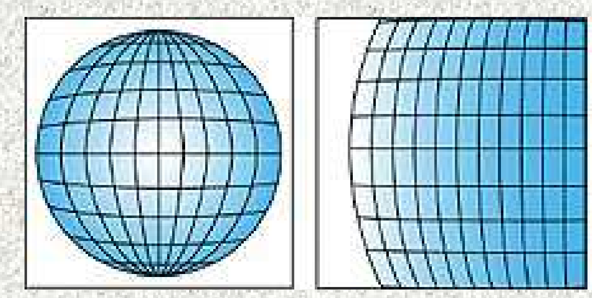


- Will the expansion reverse or continue?



- Inflation → Flat Universe

Exponential expansion makes Universe look nearly flat !

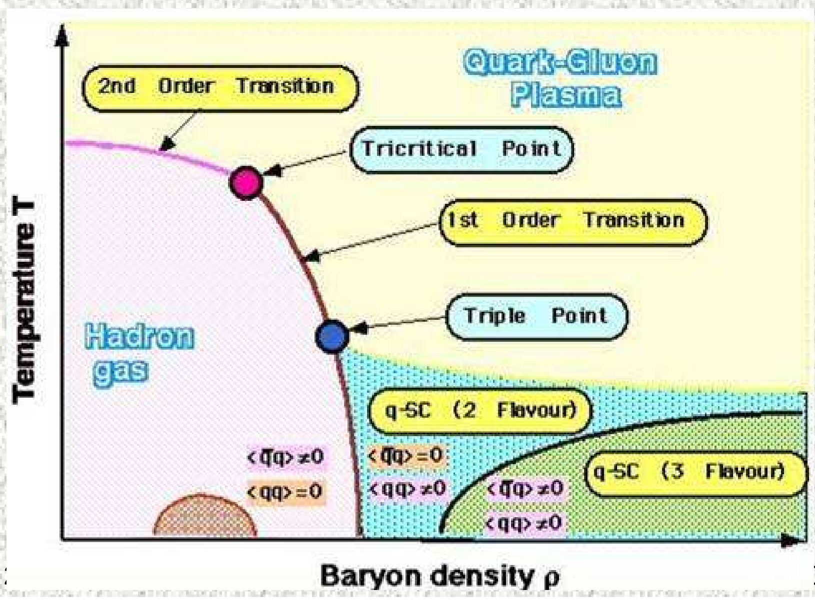


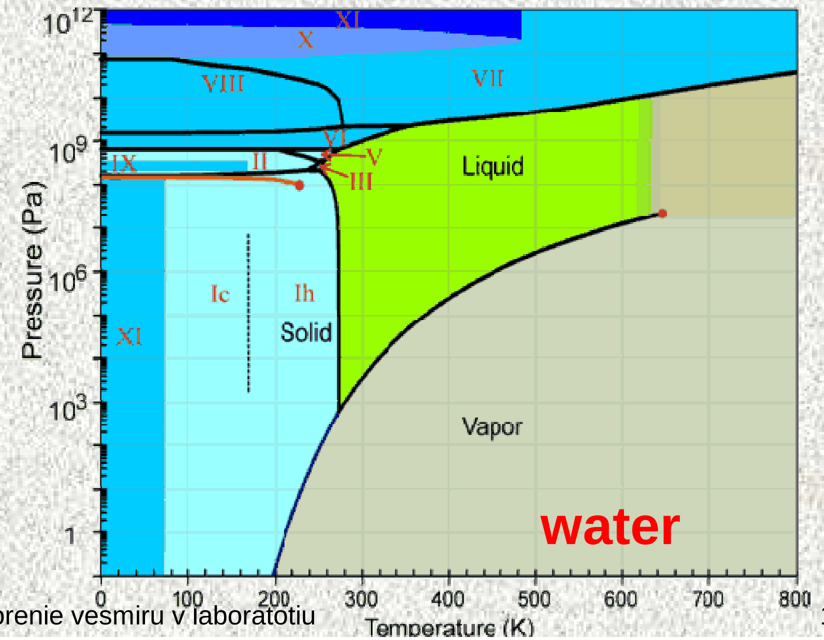
Matter and Antimatter

- **In Universe is only matter, practically no antimatter**
- **At the beginning we assume equal amount of matter and antimatter**
  - **slight violation of this symmetry, i.e. ~10^{-9} more of matter**
  - **matter and antimatter mostly annihilates -> giving photons**
  - **thus we observe 1 proton per 10^{9} photons**
- **need difference between matter, antimatter**
  - **charge symmetry broken in laboratory – a tiny effect**
- **need matter-creating interactions**
  - **present in unified theories – not yet seen**

Phase transitions

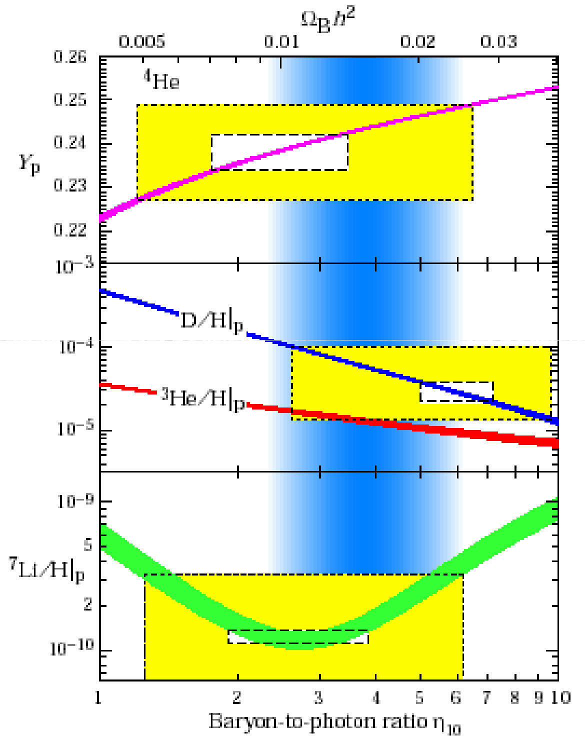
- Discontinuous or rapid change of matter thermodynamic properties, change of state of matter (phase)
- Phase transitions in early Universe creates fluctuations in the initial state
  - may influence the formation of different large scale structures
- Phase transitions in early Universe
  - Quark–Gluon Plasma phase transition: ~1ms, T~ 100 MeV ← Directly observable at LHC!
  - Electroweak phase transition: ~10^{-12}s, T~ 100 GeV
  - …?





Big Bang Nucleosynthesis

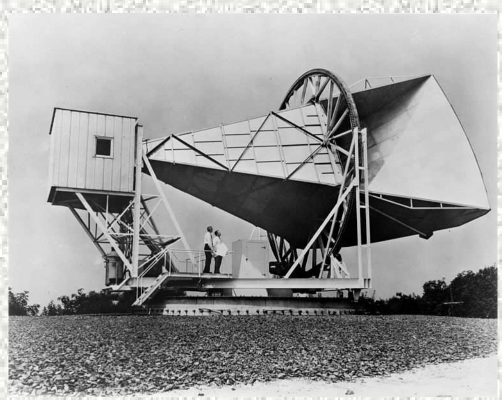
- Between 3 – 20 min the first elements build from protons and neutrons
- 75% of H, 25% of He^4, 0.01% of D, ~10^{-10} of Li, Be
- Exactly as predicted by Big Bang theory – depends on γ/p ration and temperature
- Problem – to few p/n to explain the density of the Universe
- All heavier elements produced much later in stars



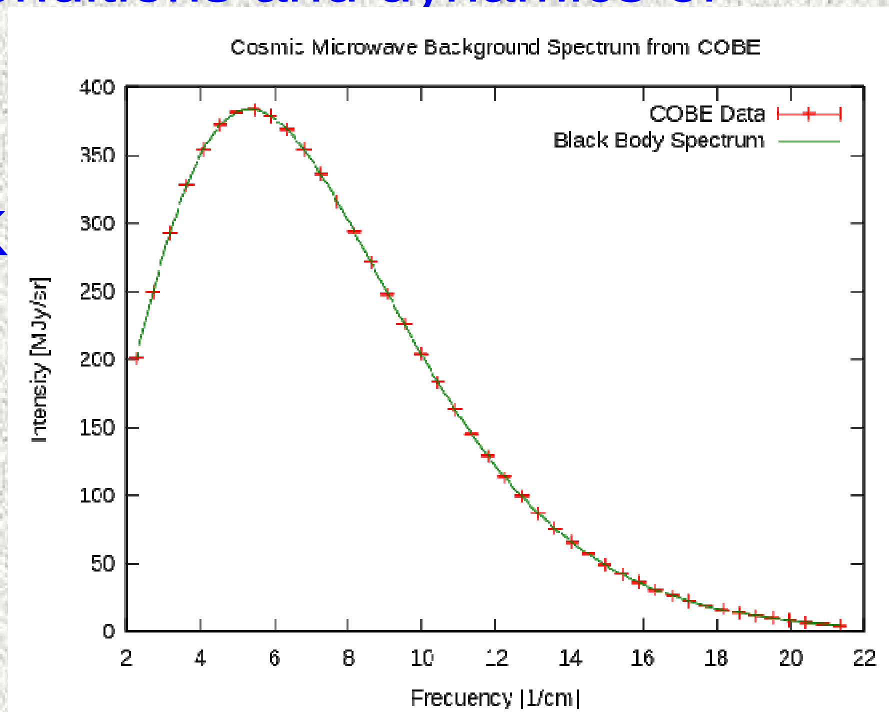
Cosmic Microwave Background

- definitive prediction of Big Bang theory
- after 380,000 years Universe became transparent for light, temperature was ~3000 K
- CMB is in thermal equilibration with matter in Universe – black body spectrum
- all deviations reflect initial conditions and dynamics of Universe evolution

Observed by Arno Penzias and Robert Wilson in 1964 T = 2.7 K

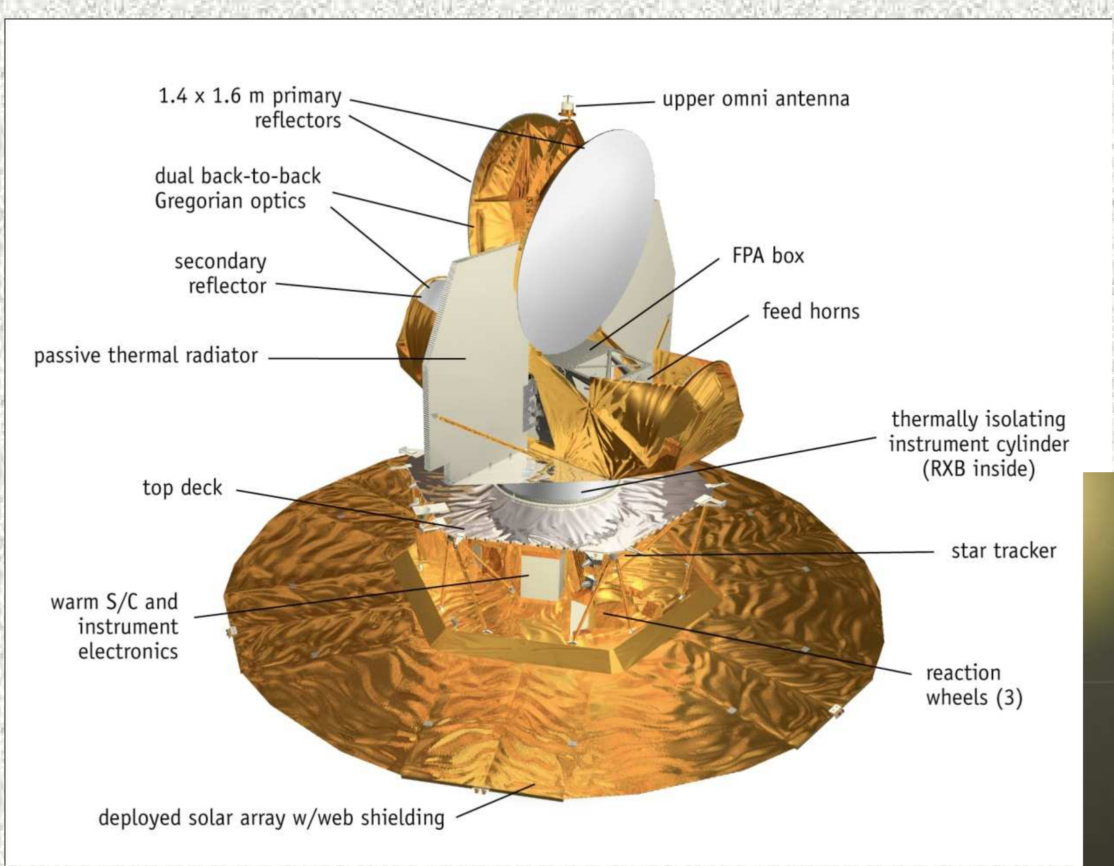


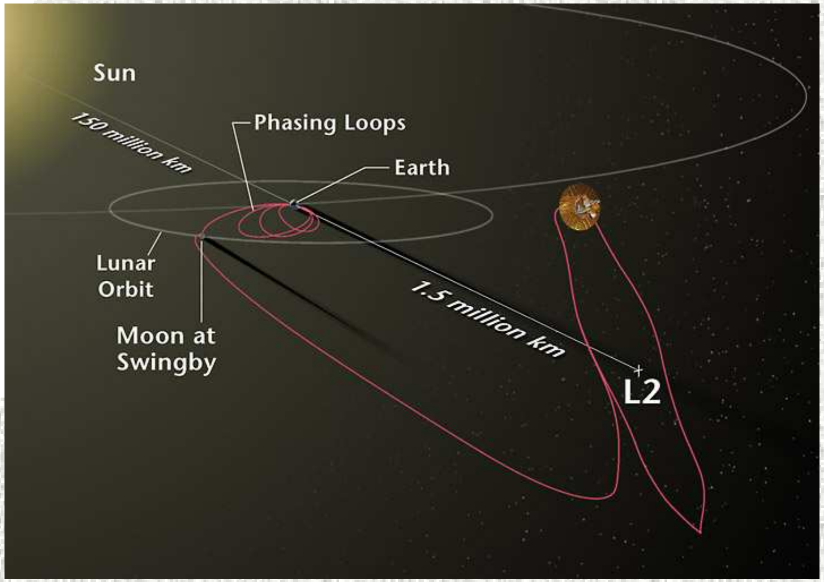
Horn antenna, in Holmdel, New Jersey



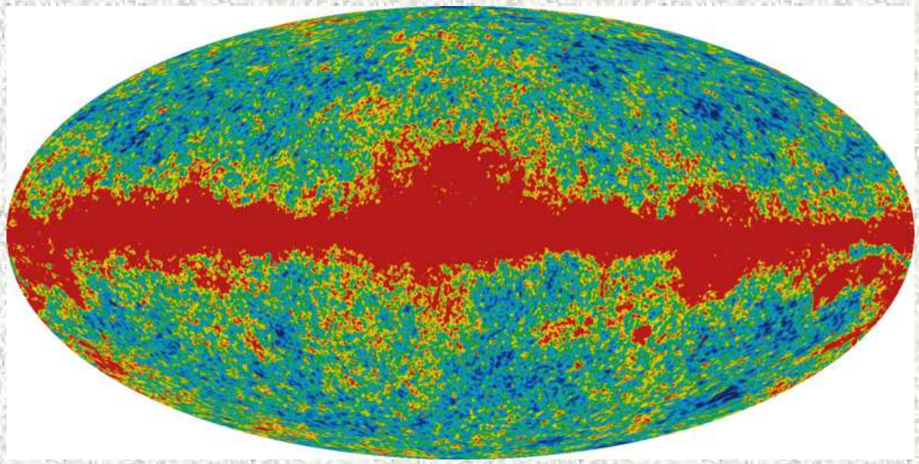
WMAP

- **Wilkinson Microwave Anisotropy Probe**



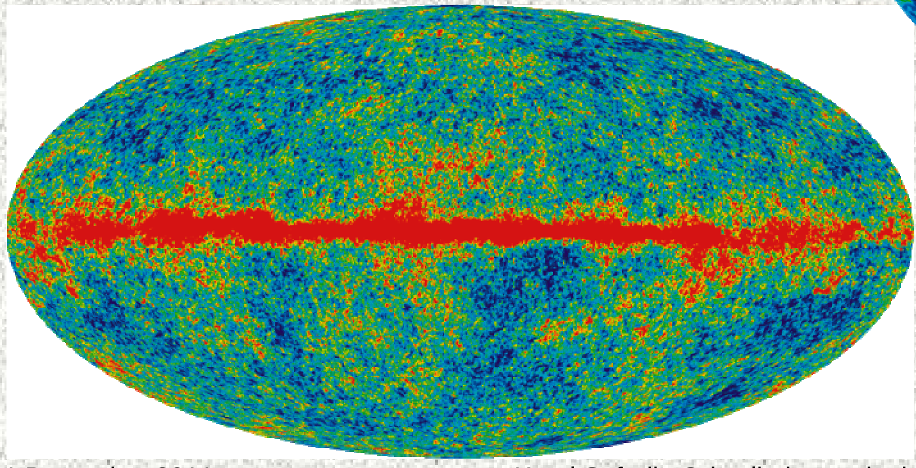


CMB maps

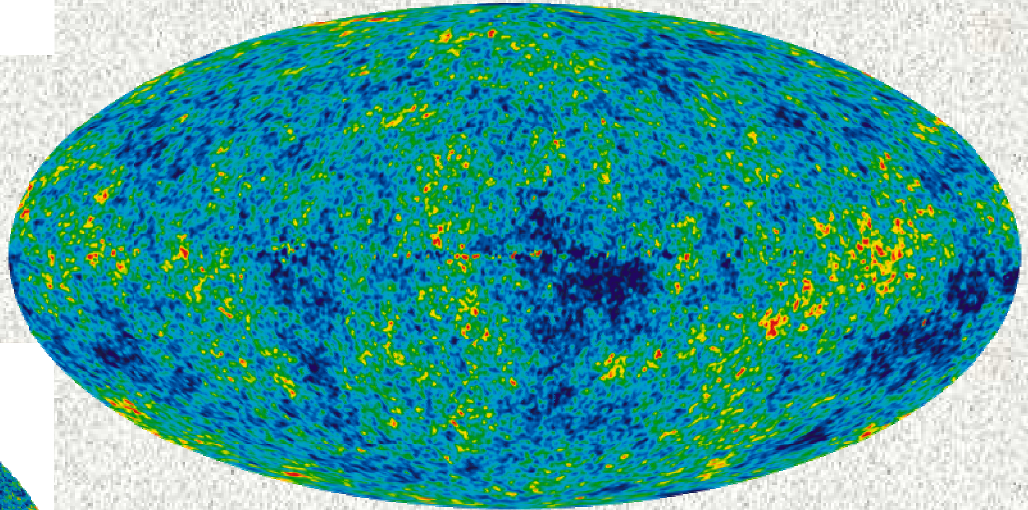


33 GHz with foreground

94 GHz with foreground



Final result, 7years data
foreground subtracted



Inhomogeneities ~$10^{-4} – 10^{-5}$

WMAP results

- CMB power spectrum

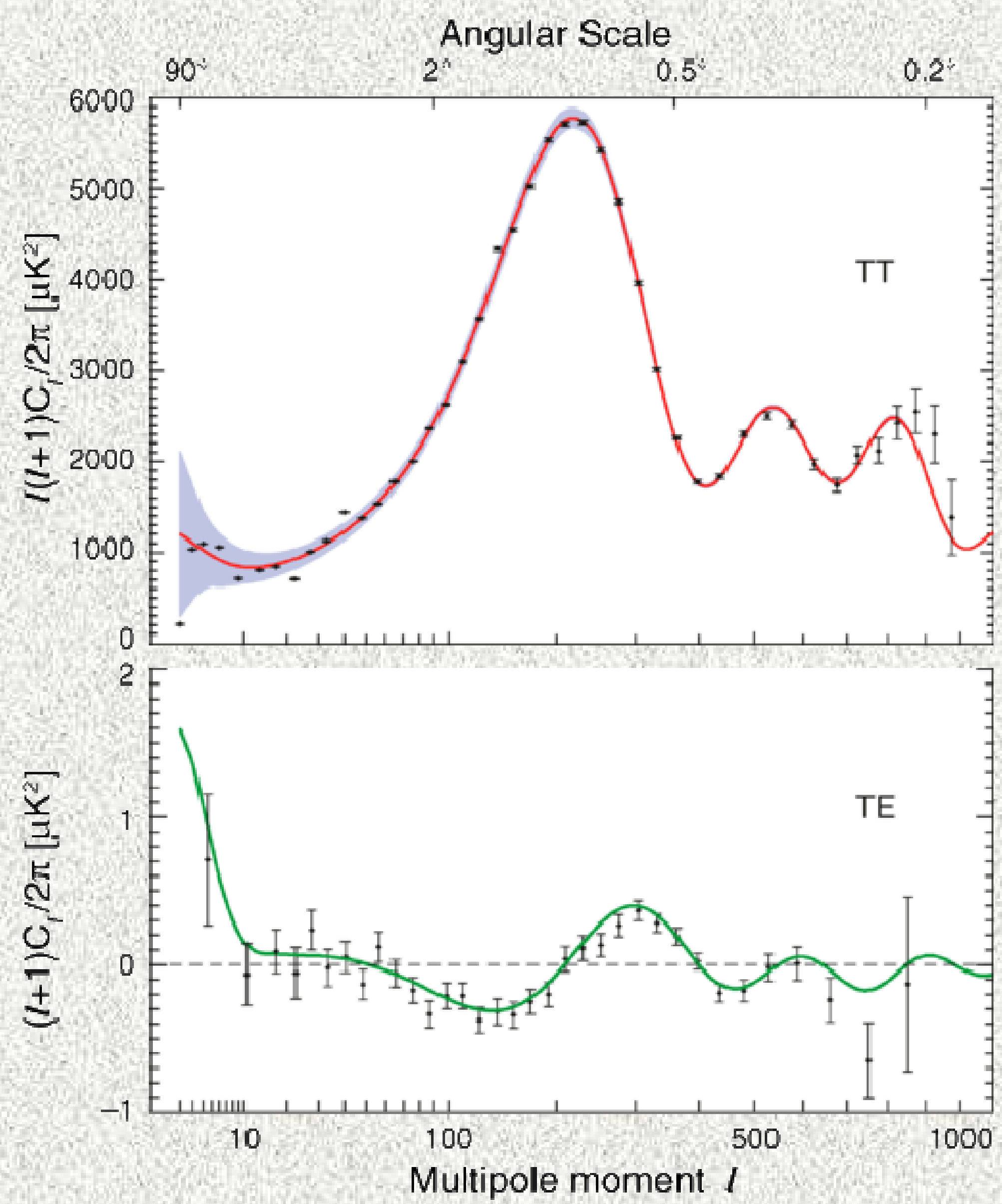
dipole moment gives our velocity 627±22 km/s

age of the Universe 13.75±0.11 x 10^9 years

total density of the Universe $1.0023^{+0.0056}_{-0.0054}$

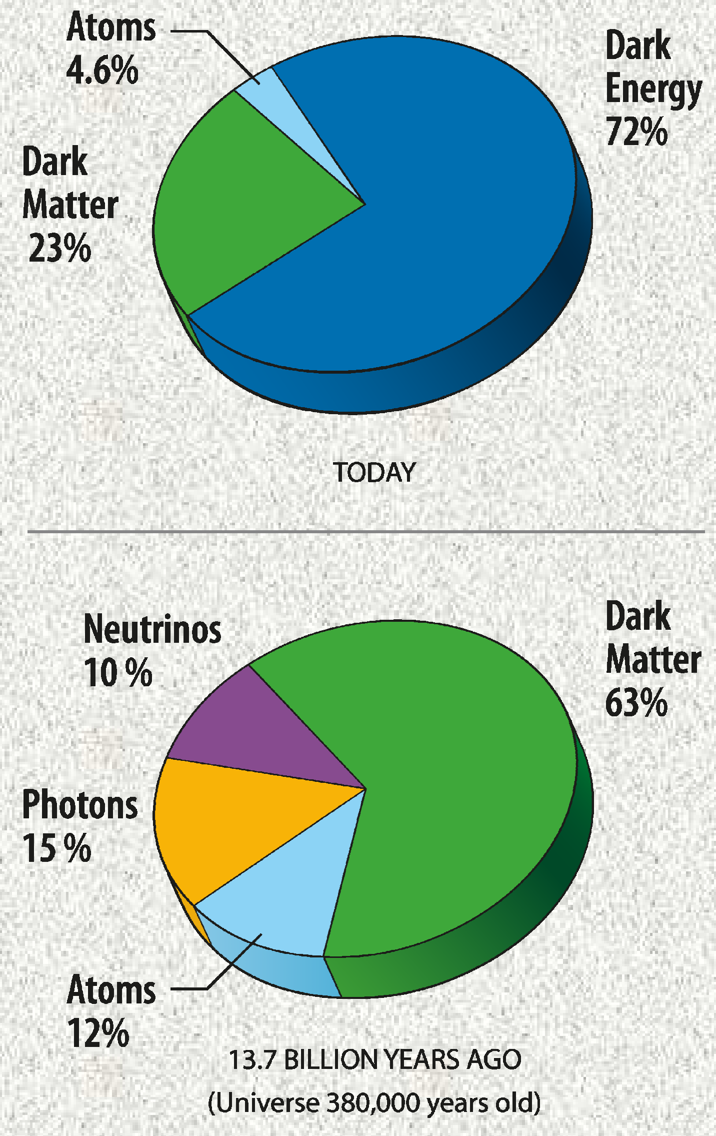
Hubble's constant $70.4^{+1.3}_{-1.4}$ (km/s) / Mpc

CMB temperature 2.725 K



Composition of matter

- today 72% of matter of the Universe – dark energy
- before ~7 x 10^9 years the Universe accelerated its expansion
- vacuum energy? scalar field? cosmological constant?
- 23% is (cold) dark matter, what is it?



Open Cosmological Questions

- Why is the Universe so big and old?
  - ~ 13,750,000,000 years
- Why is its geometry nearly Euclidean?
  - almost flat: density nearly critical
- Where did the matter come from?
  - 1 proton for every 1,000,000,000 photons
- How did structures form?
  - ripples + invisible dark matter?
- What is the dark matter?
- What is the dark energy?

- **Need particle physics to answer these questions**

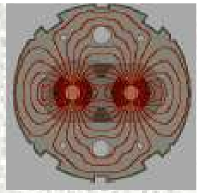
The‘Standard Model’

= Cosmic DNA

The matter particles

The fundamental interactions

gravitation **electromagnetism** **weak nuclear force** **strong nuclear force**



Vákum v QED a QCD
kvantová elektrodynamika: QED
kvantová chromdynamika: QCD

- **Energia páru nábojov spontánne narodených vo vákuu – kvantová fluktuácia (h = 1, c = 1):**

$$E_{kin} = p \sim 1/r \qquad (p \times r \geq 1)$$

$$E_{pot} = -\, q^2/(4\pi r) \qquad (q = e \text{ or } q = g_s)$$

$$E = E_{kin} + E_{pot} = (1/r)\times(1 - q^2/4\pi)$$

- **v QED toto je pravda pre lubovlonú "škálu" (už po Planckovu "škálu" ~ 10^{-20} fm)**

- **v QCD to je však správne len pre velmi malé vzdialenost', niekol'ko fm (10^{-13} cm)**

Prípad QED

- **v QED**

$$q^2 = e^2 = 4\pi\alpha_{em}$$

  - α_{em} sa mení zo vzdialenosťou (polarizácia vákua)
  - **kde pre velké vzdialenosti** $\alpha_{em} = 1/137$
  - **pri EW (elektro-slabej) škále (r = 2×10^{-3} fm)** $\alpha_{em} = 1/128$
  - **pri Planckovej "škále" (r = 10^{-20} fm)** $\alpha_{em} = 1/76$

- **To znamená, ze číselný faktor pred 1/r:** $(1 - q^2/4\pi)$ **sa mení zo vzdialonosťou, ale**
  - **len málo, medzi 0.987 – 0.993 (i.e. 0.6%) ak meníme vzdialenosť od Planckovej "škály" až po nekonečno…**

Prípad QCD

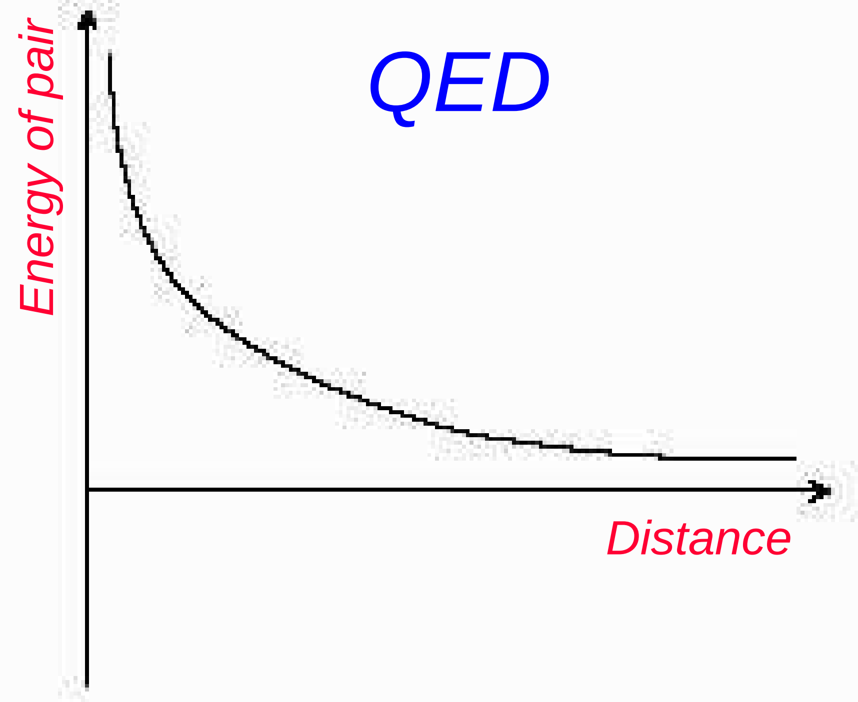
- **v QCD**

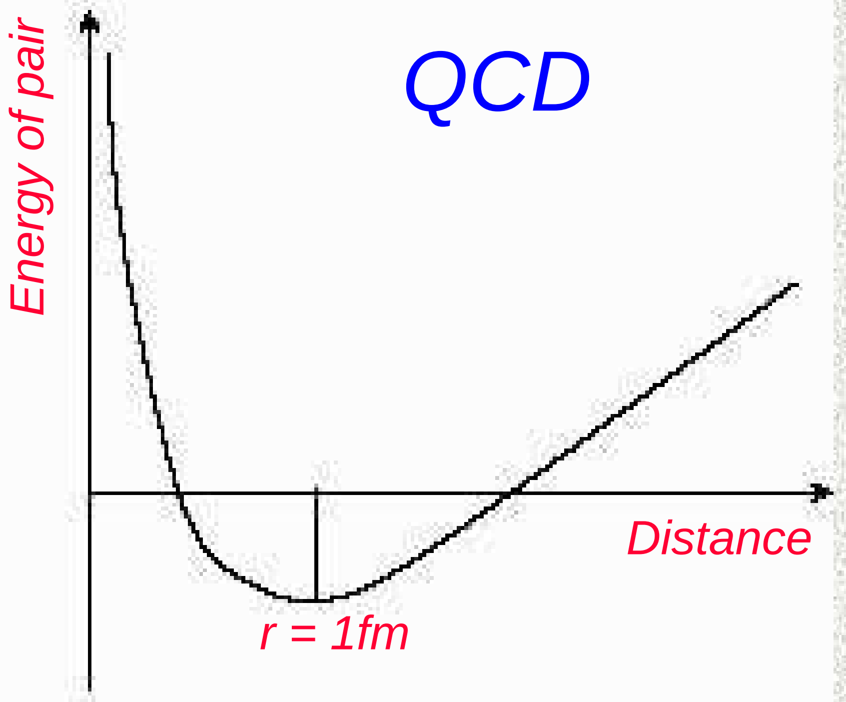
$$q^2 = g_s^2 = 4\pi\alpha_s$$

  - **kde α_s sa zmenšuje vel'mi rýchlo zo vzdialonost'ou (asymptotická sloboda)**
  - **pri Planckovej škále** $\alpha_s = 0.04$
  - **pri elektro-slabej skále** $\alpha_s = 0.118$
  - **pri $\Lambda_{QCD} \approx 0.2$GeV (r ≈ 1 fm)** $\alpha_s \approx 1$

- **numerický faktor** $(1 - q^2/4\pi) = 1 - \alpha_s$
  - **sa znižuje so vzdialenost'ou, pri Planckovej škále je 0.96**
  - **ale pozor, pre r ≈ 1 fm uz je záporný !**
- **pri vačších vzdialenostíach** je $E = \sigma \times r$ ($\sigma \approx 1$ GeV/fm)
  - **a tento faktor je opät' kladný**

QED versus QCD





Kinetická energia stále dominuje nad potenciálnou (pole je slabé)
virtual páry

Energia skrytá v poli prevázi pri nejakej vzdialenosti kinetickú
reálne páry – vakuový kondensát

Open Questions beyond the Standard Model

- Why do particles have mass?
- Why so many types of matter particles?
- Why the symmetry between matter – antimatter is violated?
- Are the fundamental forces unified?
- Quantum theory of gravity?

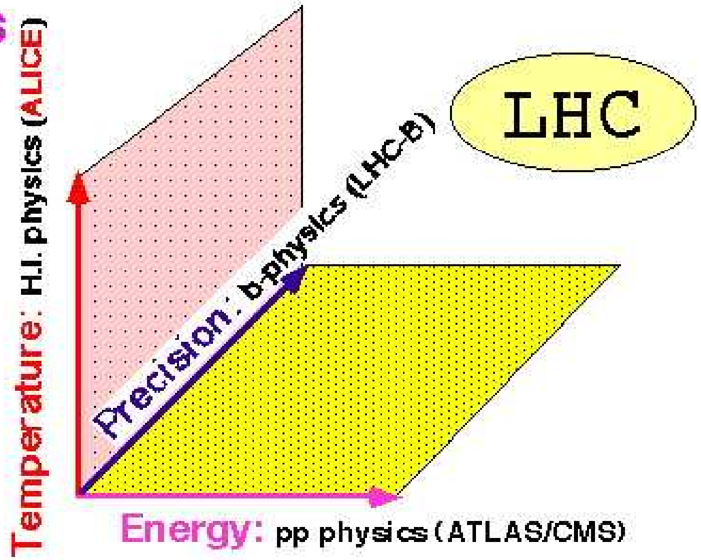
- **Large Hadron Collider !**

Chirálna symetria

- **Pre $m_q \to 0$ helicita kavarkov sa zachováva**
  - **pretože gluóny majú helicity ±1 QCD teória v tejto limite má $SU(3)_L \times SU(3)_R$ symetriu**
    - **QCD svet sa rozpadol na dva svety ktoré navzájom nekomunikujú – lavácky svet a pravácky**
  - **ak dáme do QCD vákua nehmotný lavotočivý kvark, on môže anihilovat' s lavotočivým anti-kvarkom z vákuového kondenzátu – tým sa ale oslobodí pravotočivý kvark**
    - **pre vzdialeného pozorovatela naš testový kvark spontánne zmenil helicitu a preto musel nejako získat' dynamickú hmotnost' !**
    - **QCD kvark—anti-kvarkový kondenzátate generuje dynamické kvarkové hmotnost a narušuje chirálnu symetriu**
  - **ak zvýšime teplotu kinetická energia nabitého páru (nad nejakou hodnotou) prevýši potenciálnu energiu**
    - **kvark—anti-kvark kondenzát zmizne z vákua**
    - **chirálna symetria sa obnoví nad nejakou kritickou teplotou**
    - **hodnota $<0|q\bar{q}|0>$ je "order parameter" fázového prechodu**

Physics at LHC

- **Common Questions**
  - generation of mass
    - elementary particles => Higgs => ATLAS/CMS
    - composite particles => QGP => ALICE
  - missing symmetries
    - SuperSymmetry: matter <-> forces => ATLAS/CMS
    - Chiral Symmetry: mass of light quarks => ALICE
    - CP Symmetry: matter <-> antimatter => LHC-B

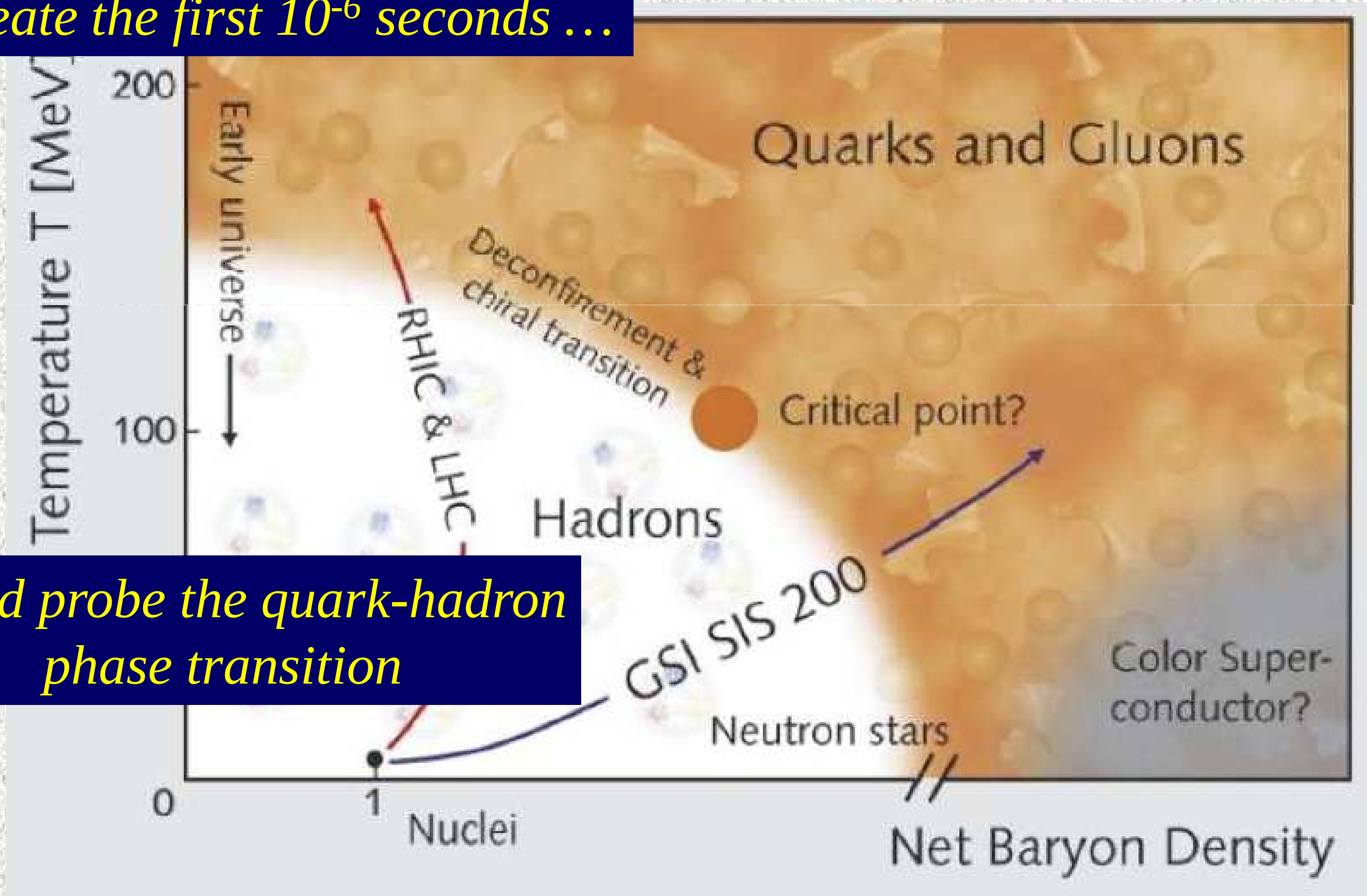


- **Different Approaches**
  - 'Concentrated Energy'
    => (single) high mass particles
  - 'Distributed Energy'
    => interaction between matter & vacuum
  - 'Borrowed Energy'
    => indirect effects of very high mass particles

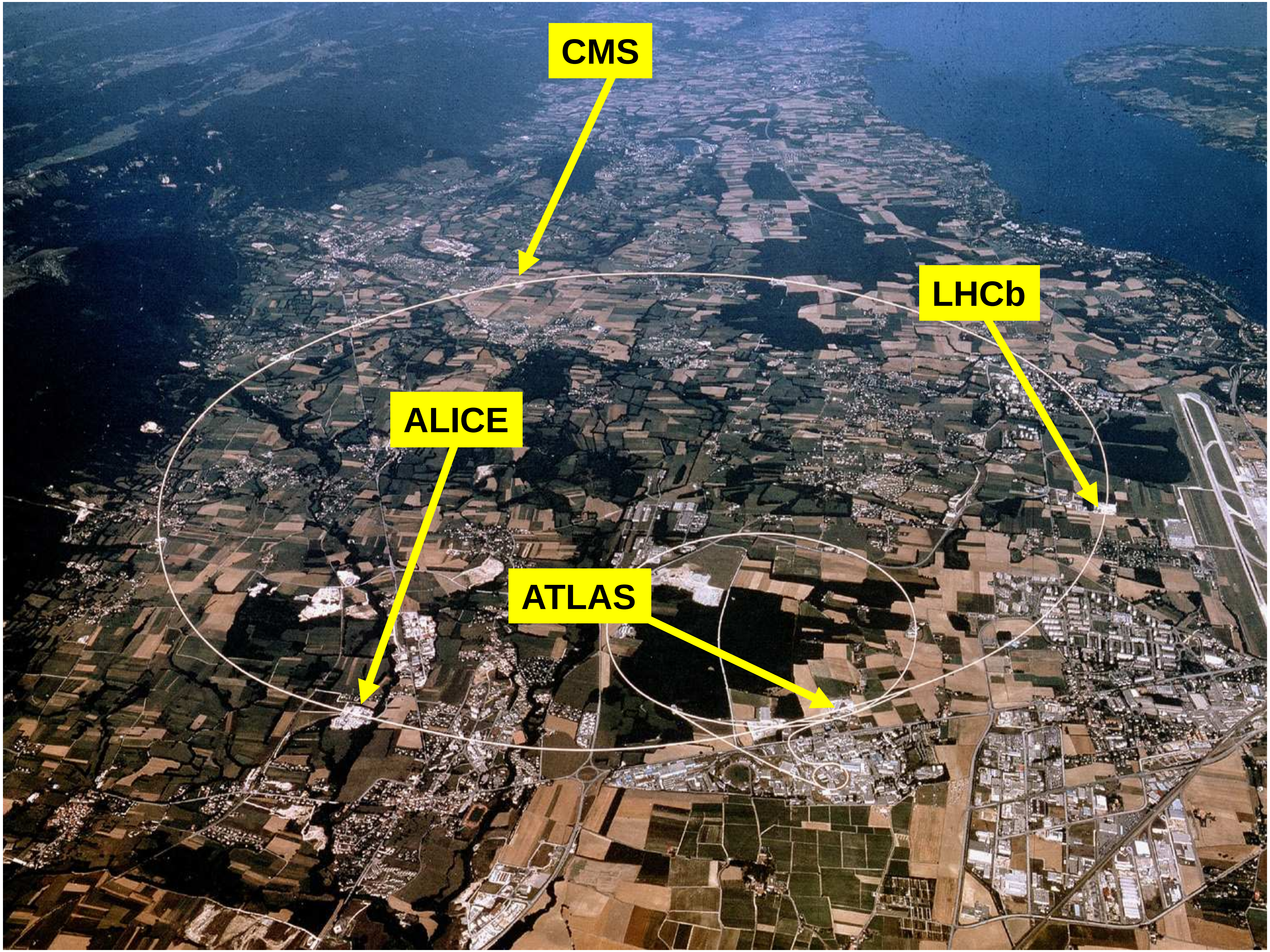
Collide heavy nuclei at high energies to create …

Hot and Dense Hadronic Matter

Recreate the first 10^{-6} seconds …

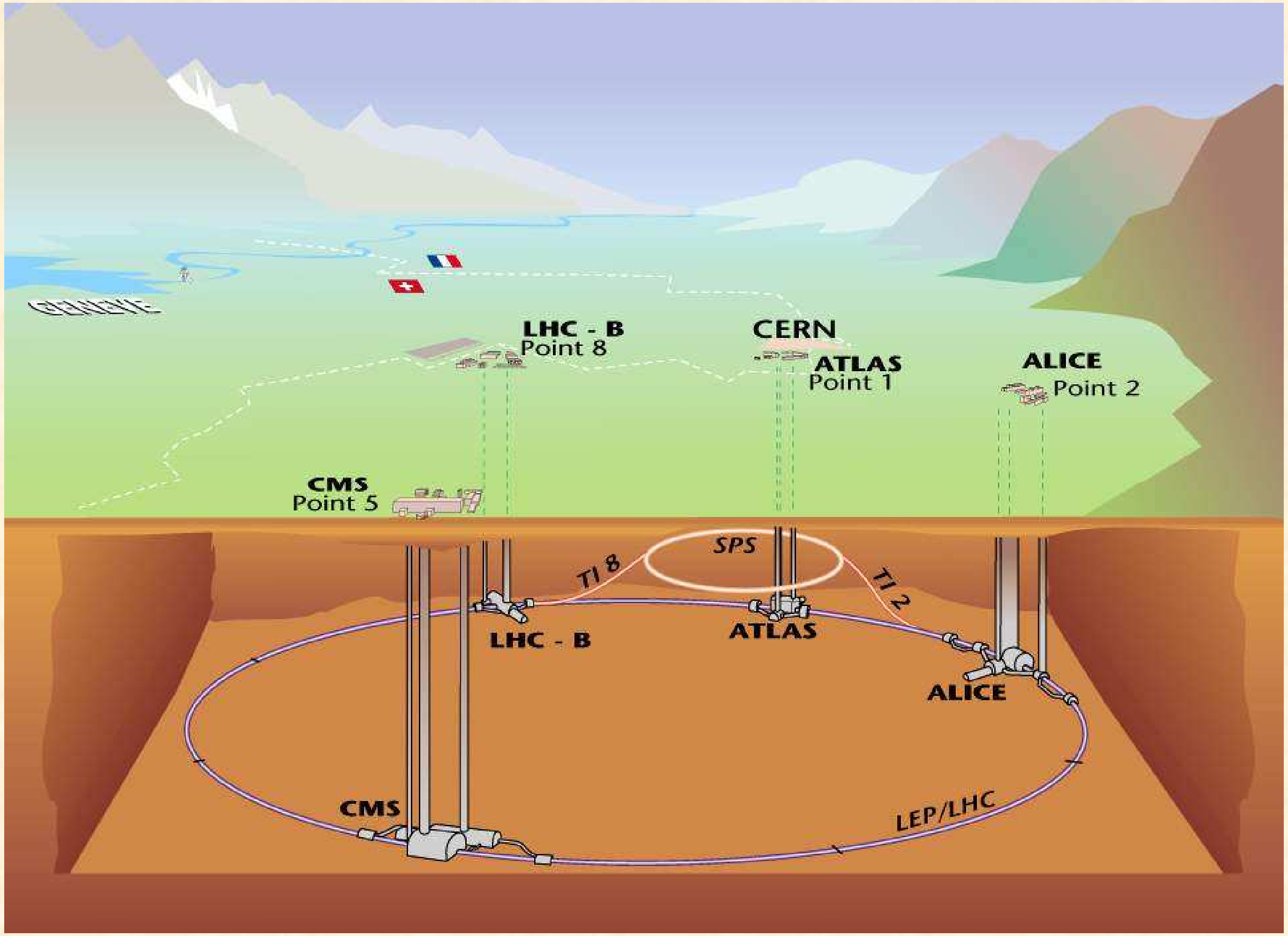


… and probe the quark-hadron phase transition



CMS
LHCb
ALICE
ATLAS

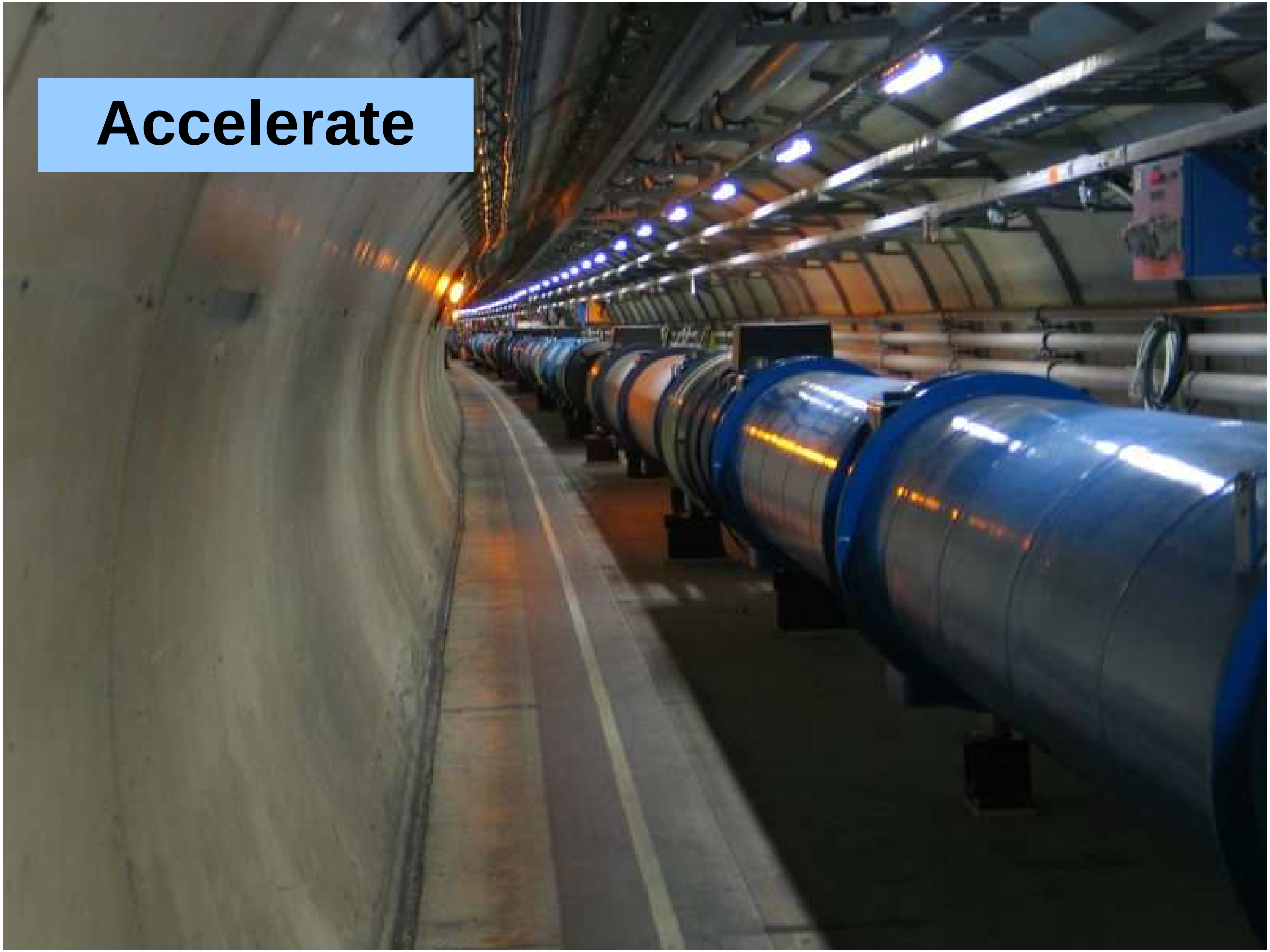
Large Hadron Collider (LHC)



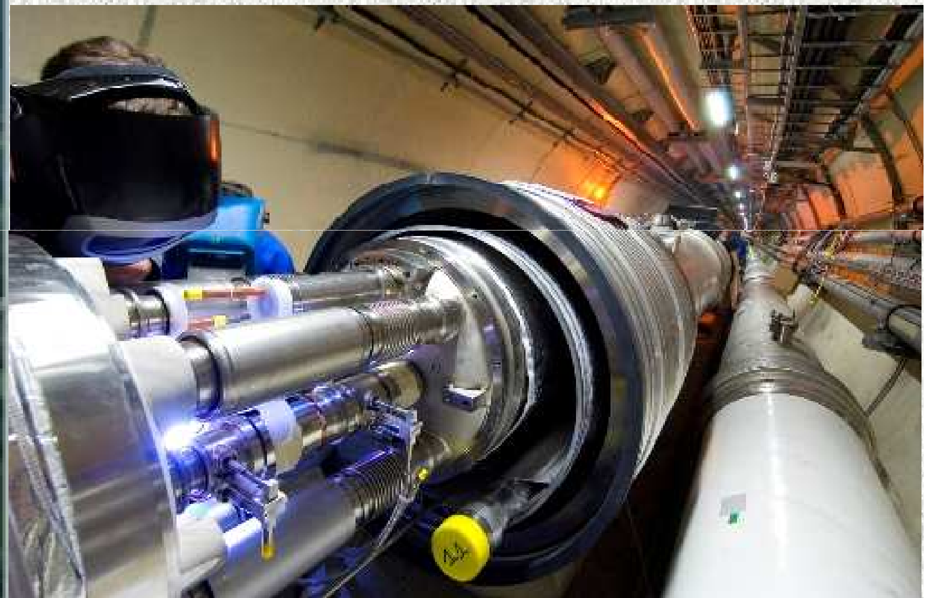
- **about 100 m underground**
- **27 km circumference**

- 11245 orbits per second
- pp collisions up to $\sqrt{s}$ = 14 TeV
- Pb-Pb collisions up to $\sqrt{s_{NN}}$ = 5.5 TeV

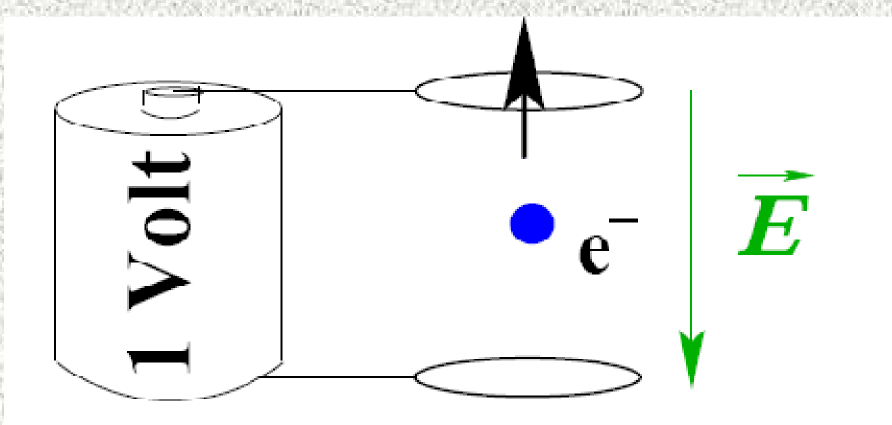
Accelerate



Úvod do urýchlovačov



Jednotky – elektrónvolt



Elektrónvolt, jednotka energie, oznacovaná ako eV, sa pouzivá pre malé energie:
1 eV je definovaný ako energia dodaná castici s nábojom jeden elektrón (t.j. okolo $1.602 \cdot 10^{-19}$ C) elektrickým polom s rozdielom potenciálov 1 Volt:
$1\ eV = 1.602 \cdot 10^{-19}$ joule

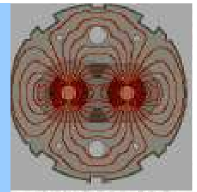
Úrýchlovanie

Vo fyzike castíc jednotka eV sa pouzivá taktiez ako jednotka hmotnosti, protoze hmotnost' a energia sú úzko spojené Einsteinovým vzt'ahom:
$E = mc^2$
kde m je hmotnost castice a c je rýchlost' svetla vo vákuu

Hmotnost' elektrónu je okolo 0.5 MeV

Celková energia

From Wikipedia



Prečo urýchlovače?
Prečo stále vyššia energia?

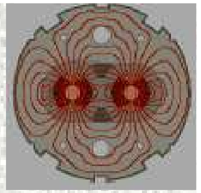
- častice – vlny (de Broglie)

- Rozlišovacia schopnosť je daná vlnvou dlžkou

  λ = h / p (h – Planckova konštanta)

  (napríklad elektrónový mikroskop má lepšie rozlíšenie než svetelný pre ktory $\lambda \sim$ few 10^2 nm $\leftrightarrow$ less than 1eV)

- 200 MeV $\leftrightarrow$ 1 fm (10^{-13} cm)
- 1 GeV $\leftrightarrow$ 0.2 fm
- 100 GeV $\leftrightarrow$ 2×10^{-16} cm (LEP)
- 10 TeV $\leftrightarrow$ 2×10^{-18} cm (LHC)



LHC energia

Pre A-A zrážky:

$E_{cms} = 5500\ A$ GeV

$E_{lab} = E_{cms}^2 / (2A\ m_N) = 1.61 \times 10^7\ A$ GeV

pre ióny olova $E_{lab\ Pb\text{-}Pb} = 3.35 \times 10^9$ GeV $= 3.35 \times 10^{12}$ MeV

dalej potrebujeme Harald Fritzsch Identity (definícia Anglo-Saxonskej libry $£_{AS}$)

$2 \times 10^{-30}\ £_{AS} = m_e$ (= 0.511 MeV)

a najaké iné definície (gravitacné zrýchlenie g, jednotka casu tr)

$g = 1$ in/tr^2 (1 s = 19.65 tr, trice)

(rýchlost' svetla c) $c = 6 \times 10^8$ in/tr

$m_e c^2 = 72 \times 10^{-14}\ £_{AS}$ in (= 0.511 MeV)

1 MeV $= 1.41 \times 10^{-12}\ £_{AS}$ in

Nakoniec

$E_{lab\ Pb\text{-}Pb} = 1\ £_{AS} \times 4.7''$ (= 0.45 kg $\times$ 12 cm)

LHC energia (pokracovanie)

A pre pp zrázky:

$E_{lab\ pp(14TeV)}$ = 0.15 $£_{AS}$ in ≈ ¼ $£_{AS}$ × ½'' = ⅛ $£_{AS}$ × 1'' = …

Pre tých ktorý neradi sedia na ióne olova (a lietajú vo vákuovej trubici LHC)

$E_{cms\ Pb\text{-}Pb} = 5500\ A\ \text{GeV} = 1.14 \times 10^{9}\ \text{MeV}$

(HFI, etc.)

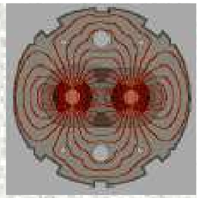
$E_{cms\ Pb\text{-}Pb} = 10^{-3}$ $£_{AS}$ × 1.6'' (= 0.45 g × 4 cm)

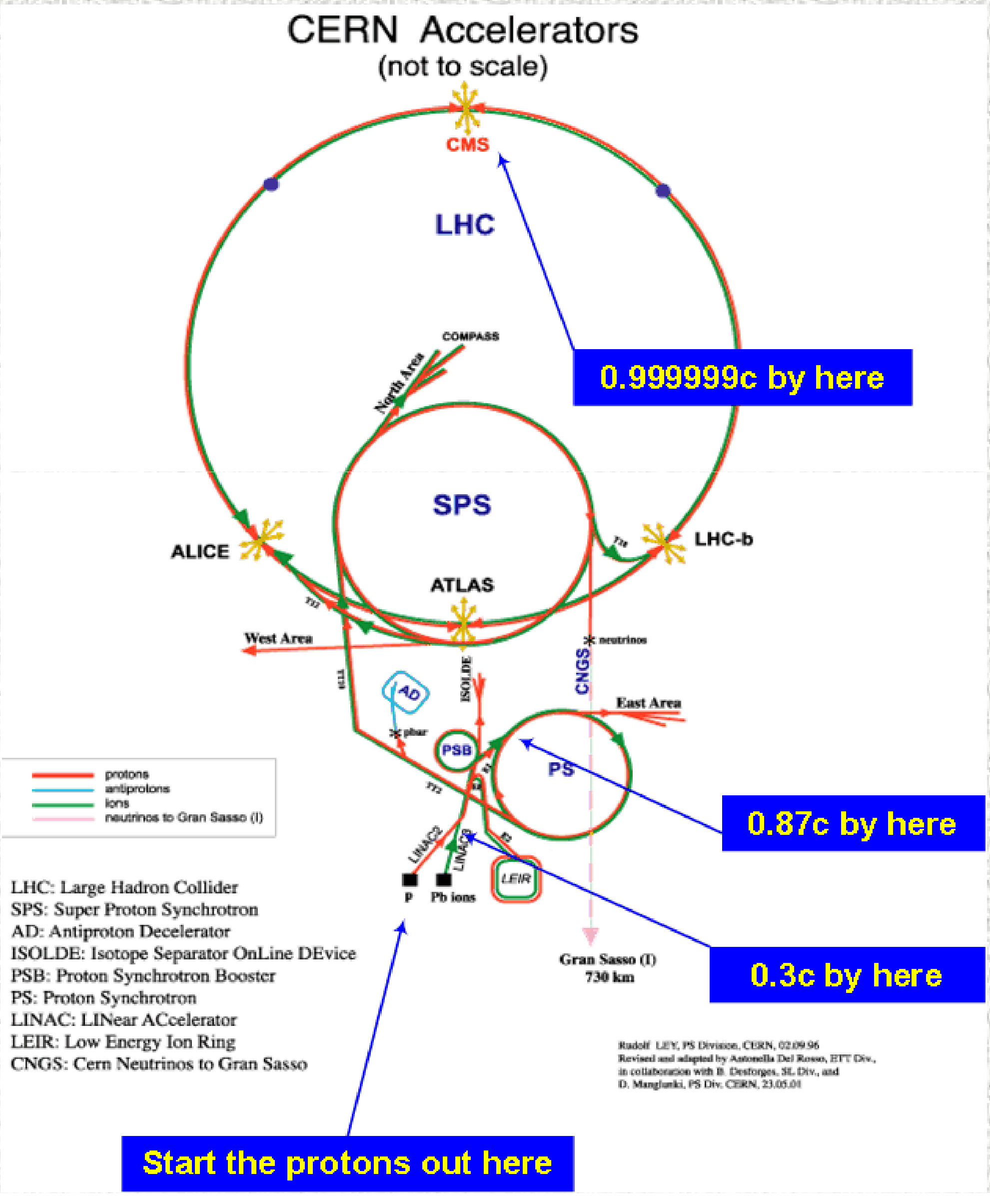
Stále, je to makroskopická energia !!! (zrážka by sa dala aj počut')

Ale rozmer oloveného jadra

je viac ako 10^{-13} menší !!!

Urýchlovače v CERNe





Energie:

Linac *50 MeV*

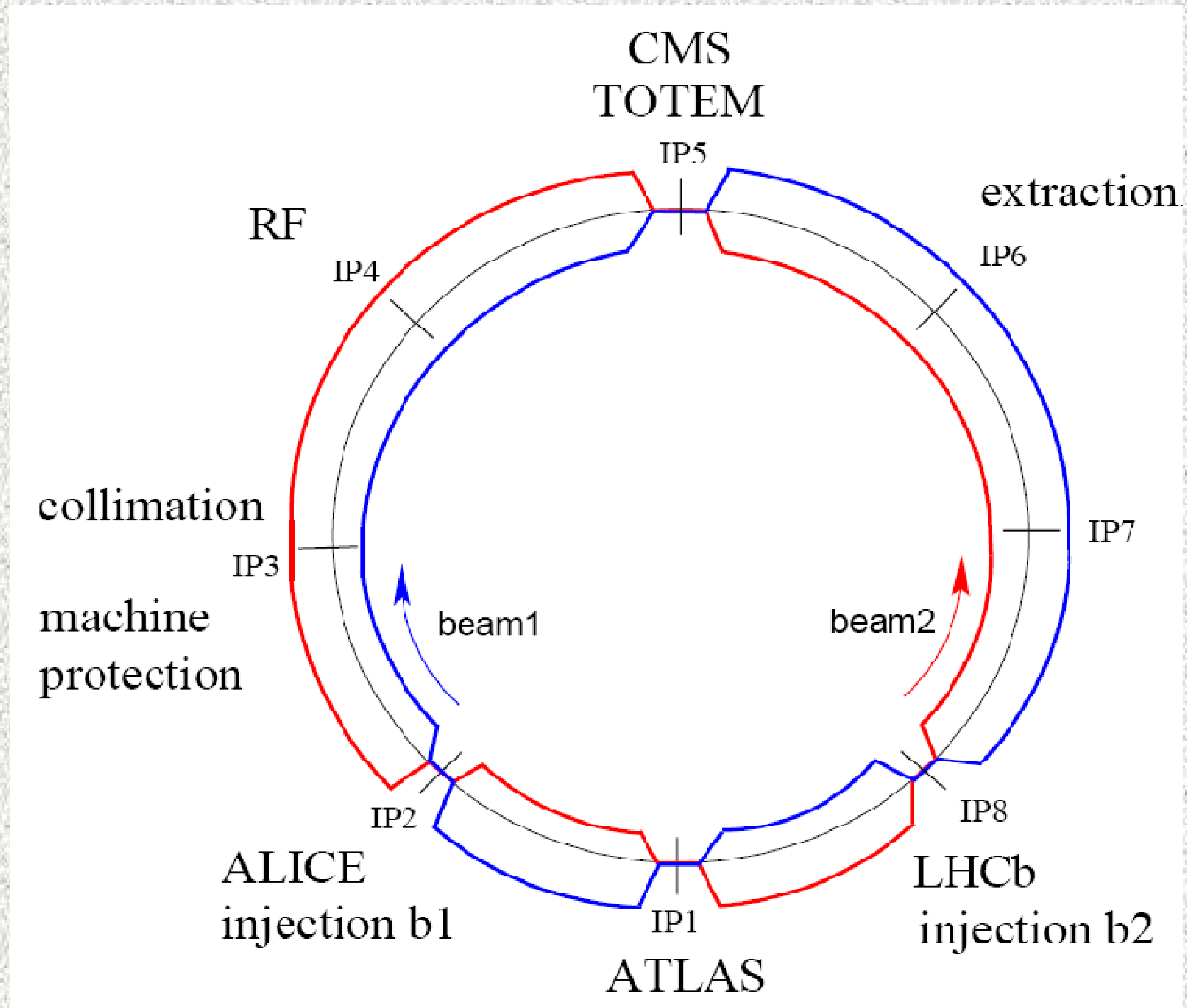
PSB *1.4 GeV*

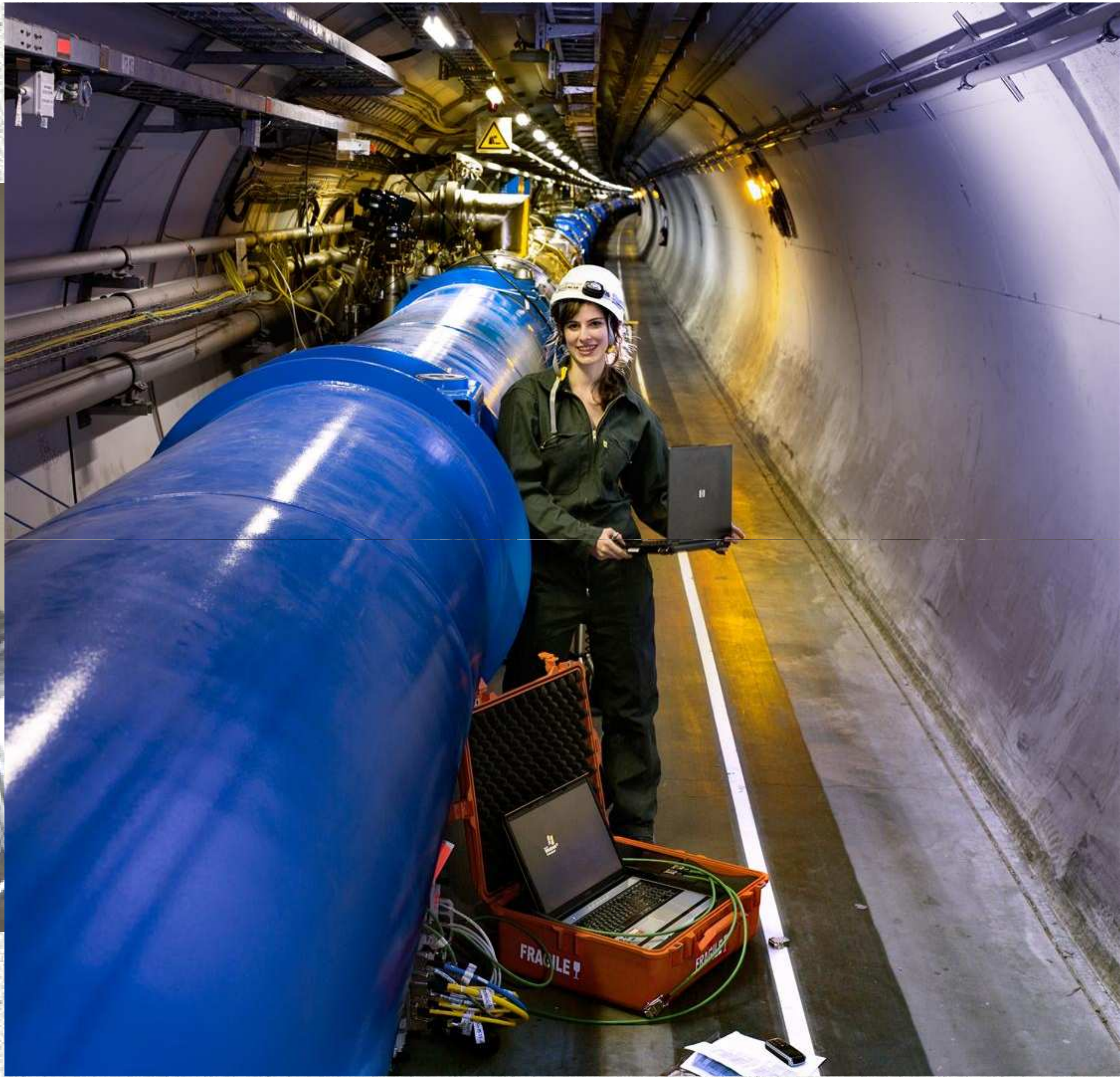
PS *28 GeV*

SPS *450 GeV*

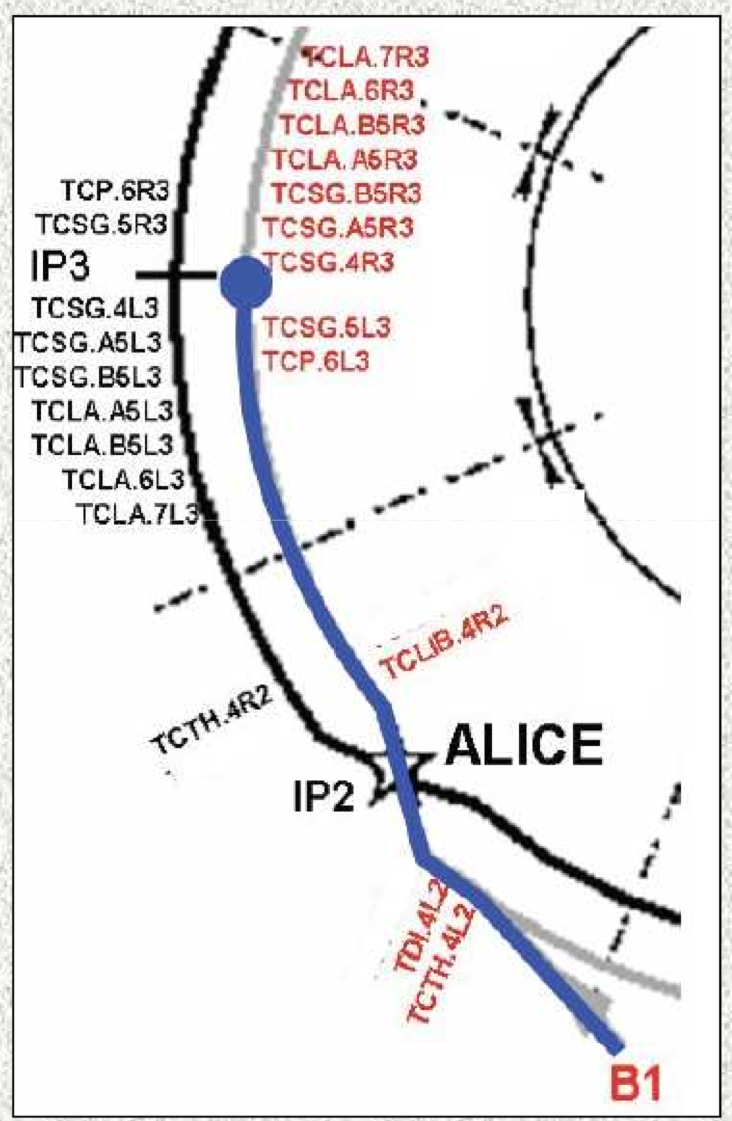
LHC *7 TeV*

LHC


CMS
TOTEM
IP5
extraction
IP6
RF
IP4
collimation
IP3
IP7
machine
protection
beam1
beam2
IP2
IP8
ALICE
injection b1
IP1
ATLAS
LHCb
injection b2


FRAGILE

08.08.08: Prvé častice v LHC !

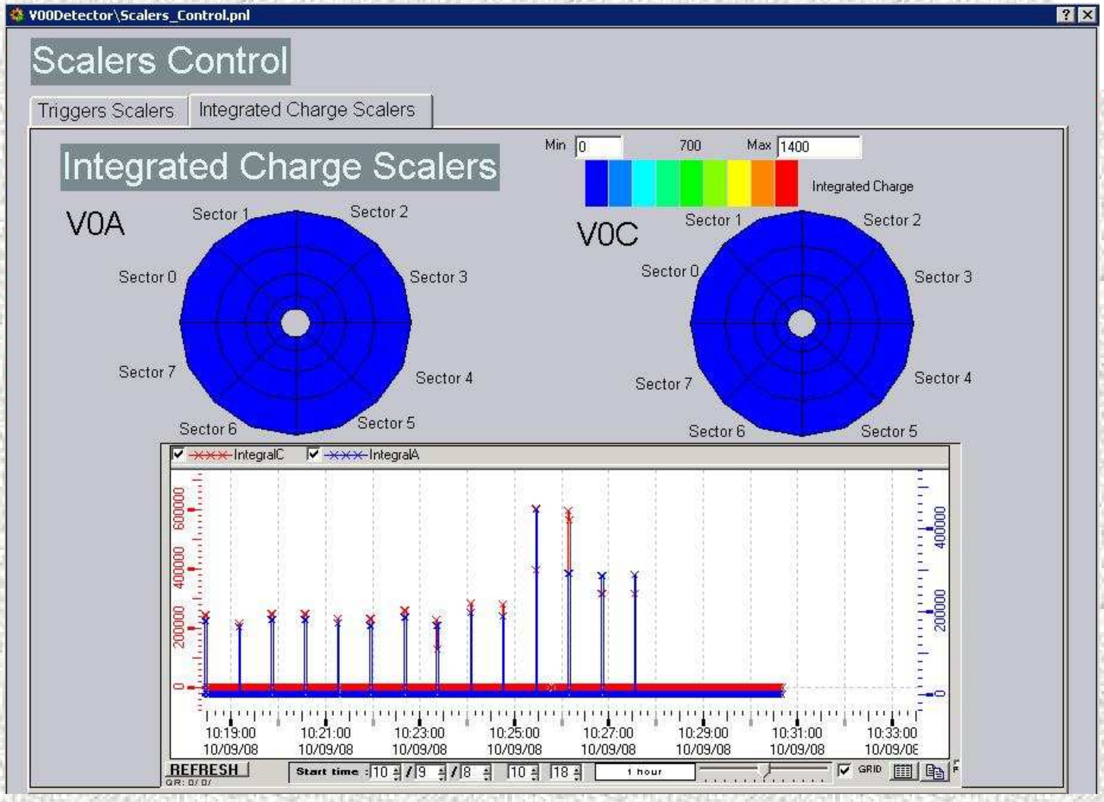


同一个世界 同一个梦想

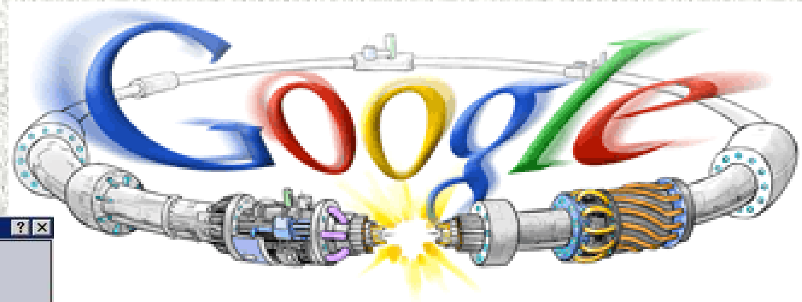
One World One Dream

10 septembra 2008: cirkulujúce zväzky!

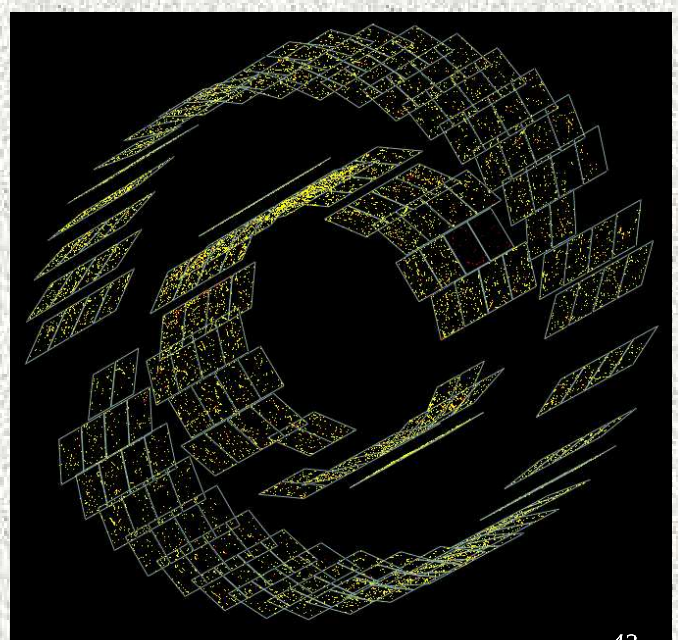
- **beam 1: 1st complete orbit ~ 10:30**



- **beam 2: 1st complete orbit ~ 15:00**

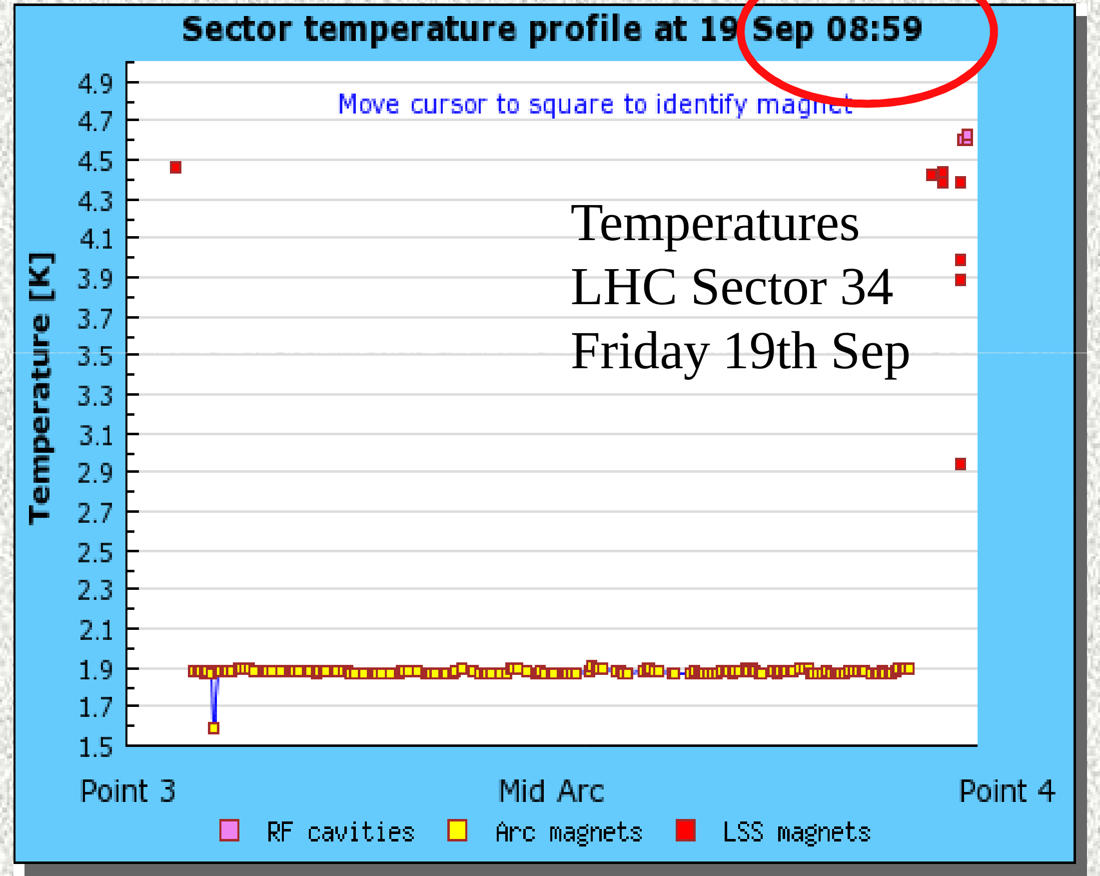


- *prvé signály z ALICE*



19 sepetembra 2008

…a boli sme len niekolko minút od štartu…

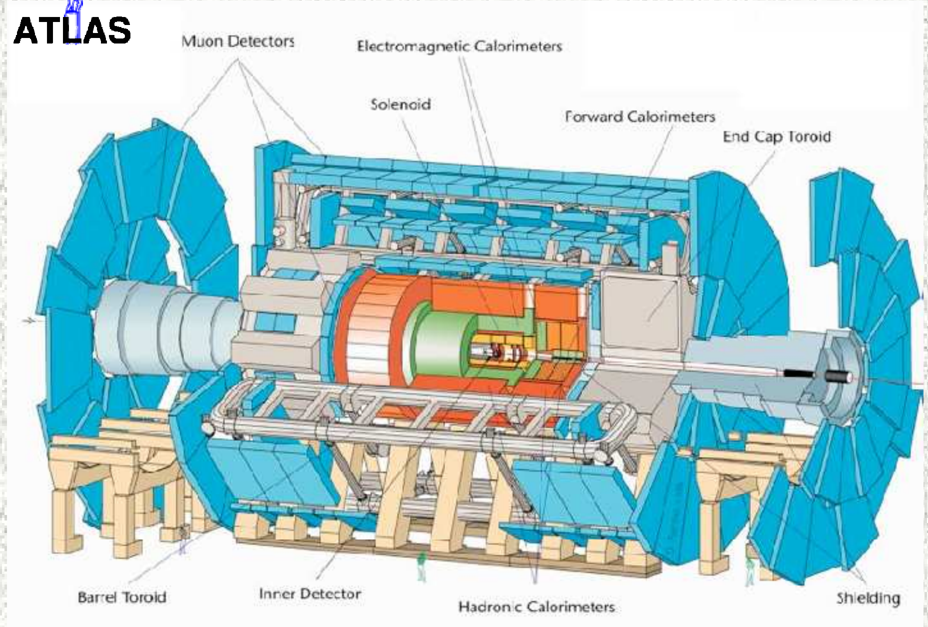


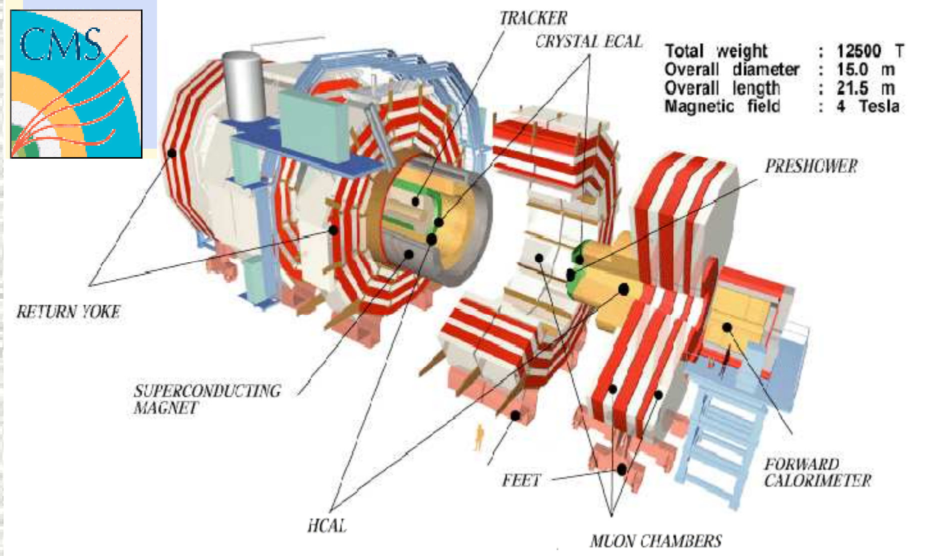
Jan Fiete Grosse-Oetringhaus

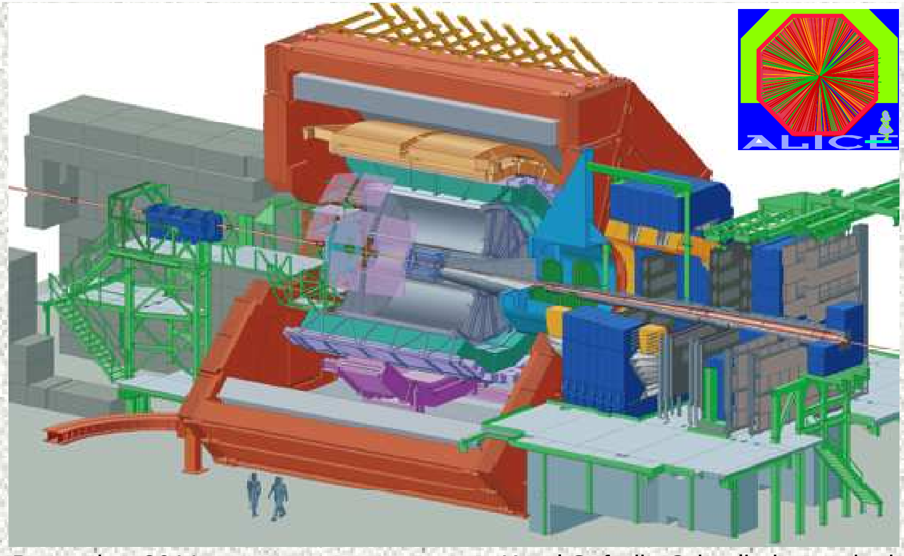
Prepojenie po havárii

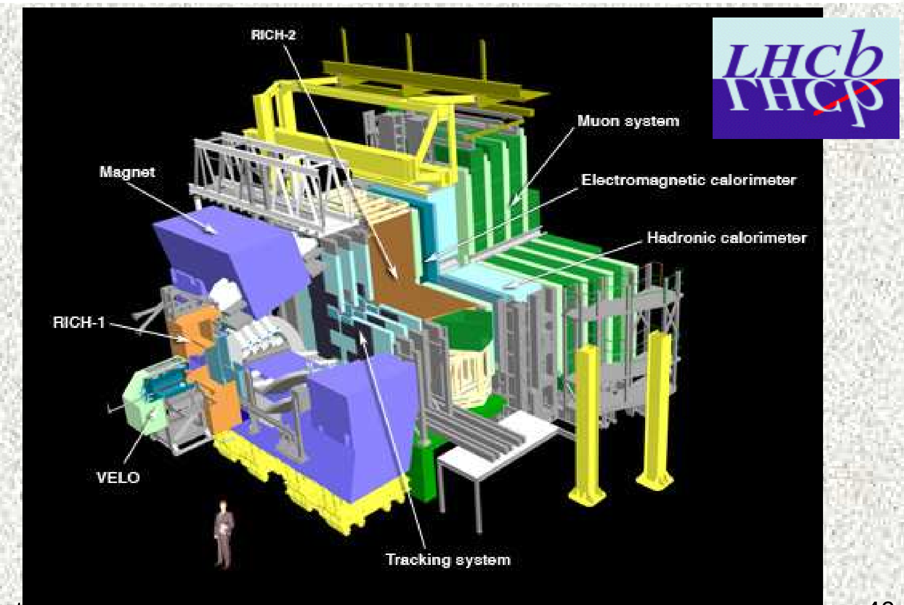
LHC start-up

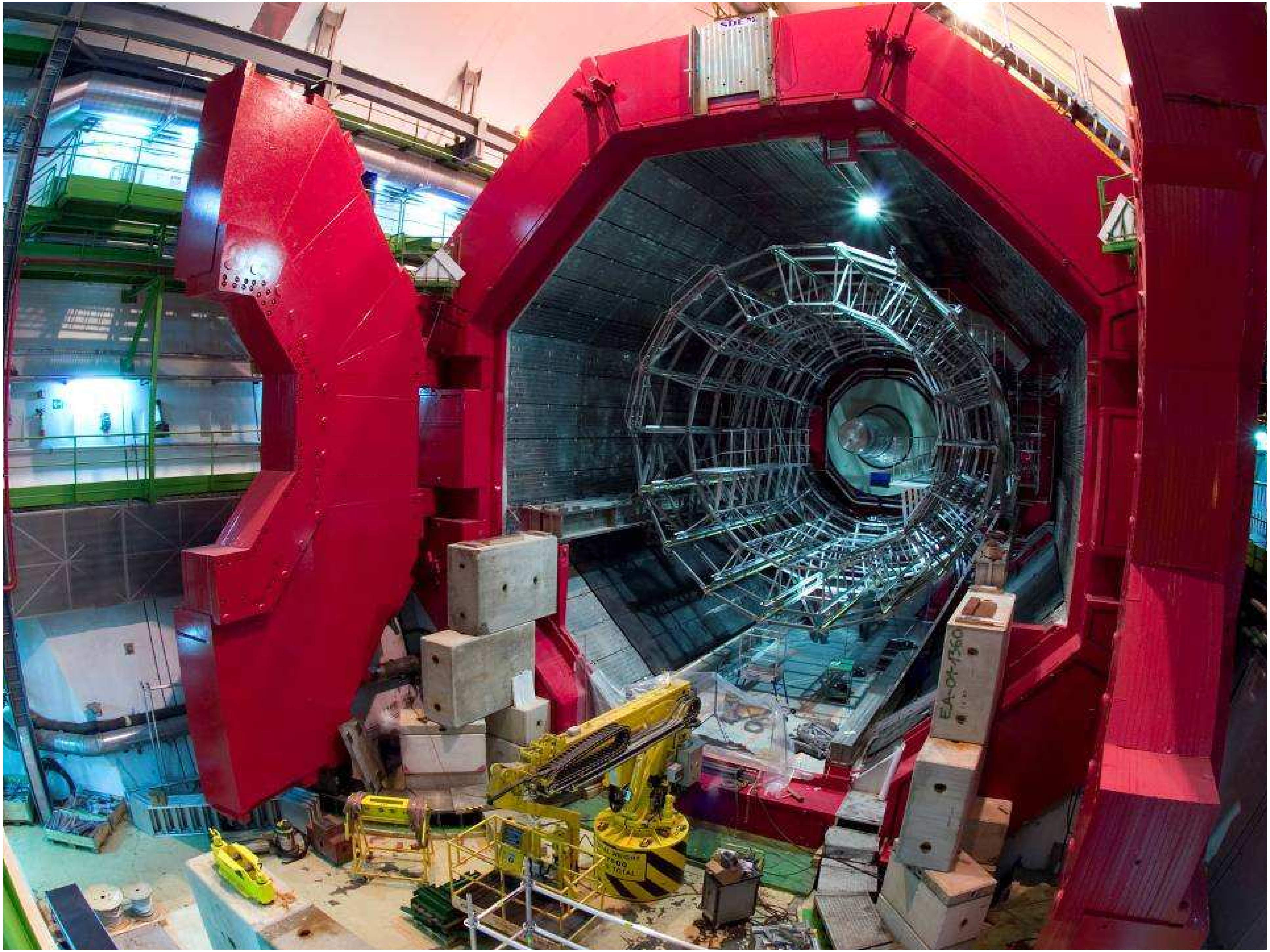
LHC detectors

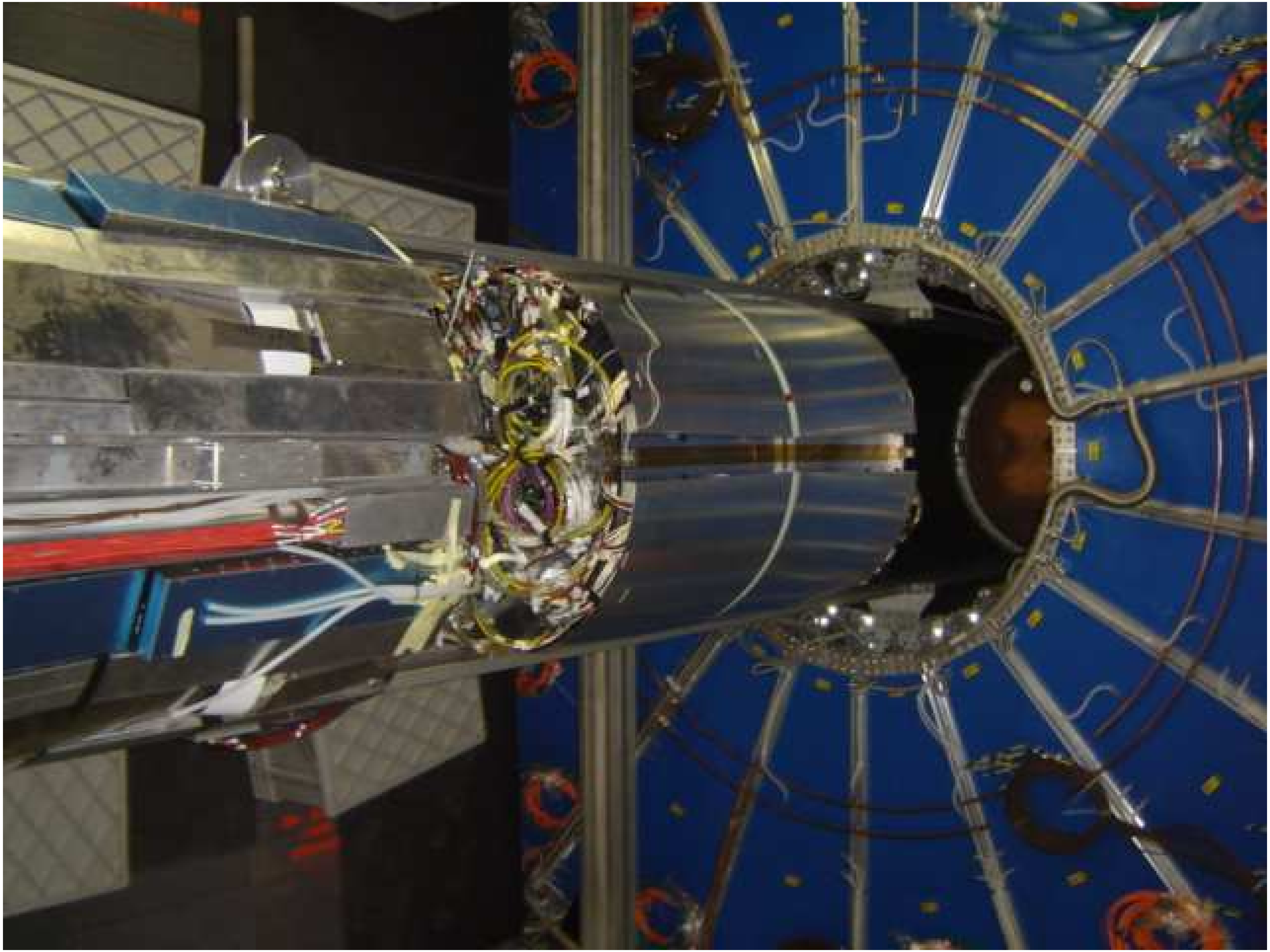




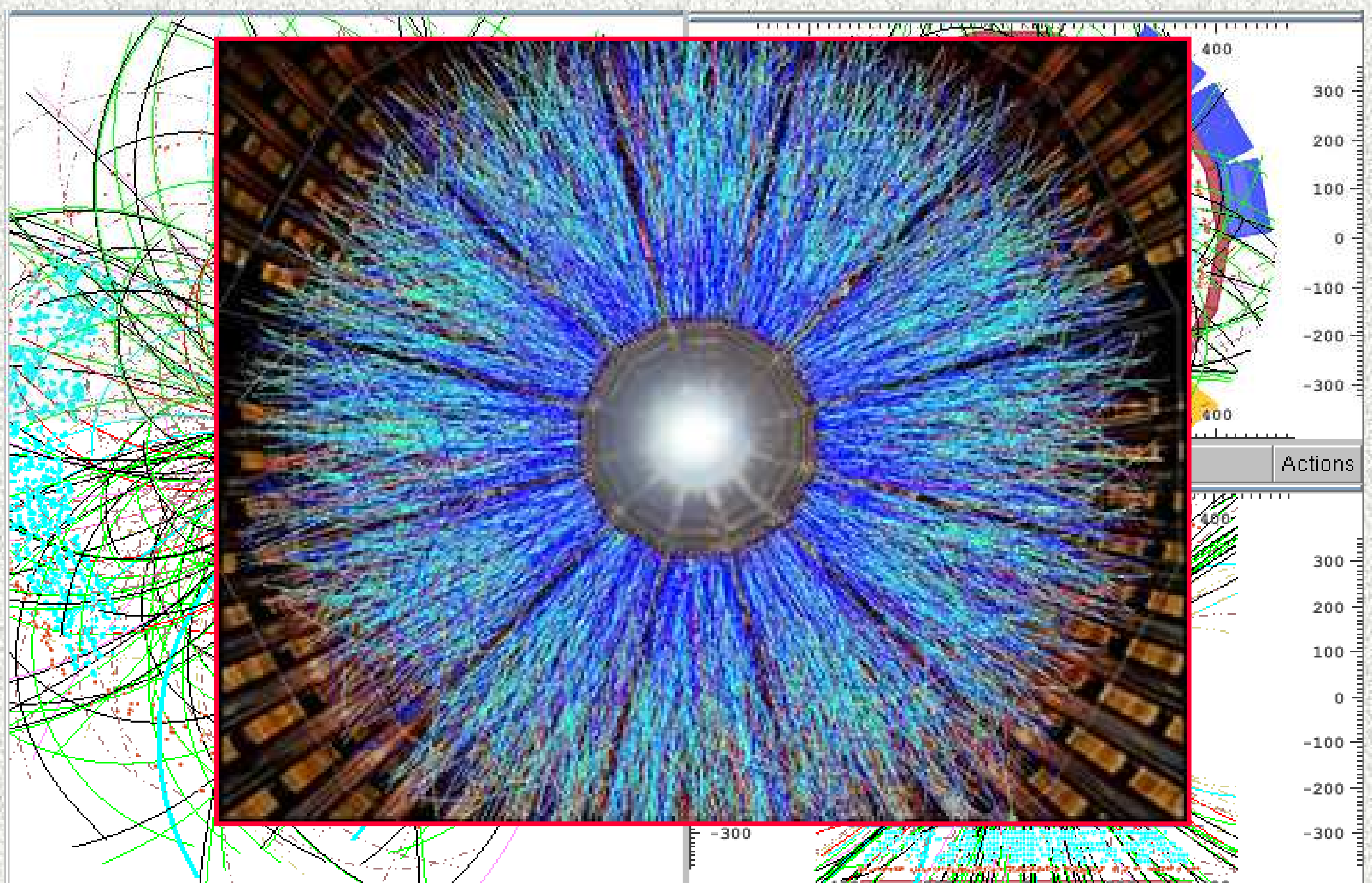






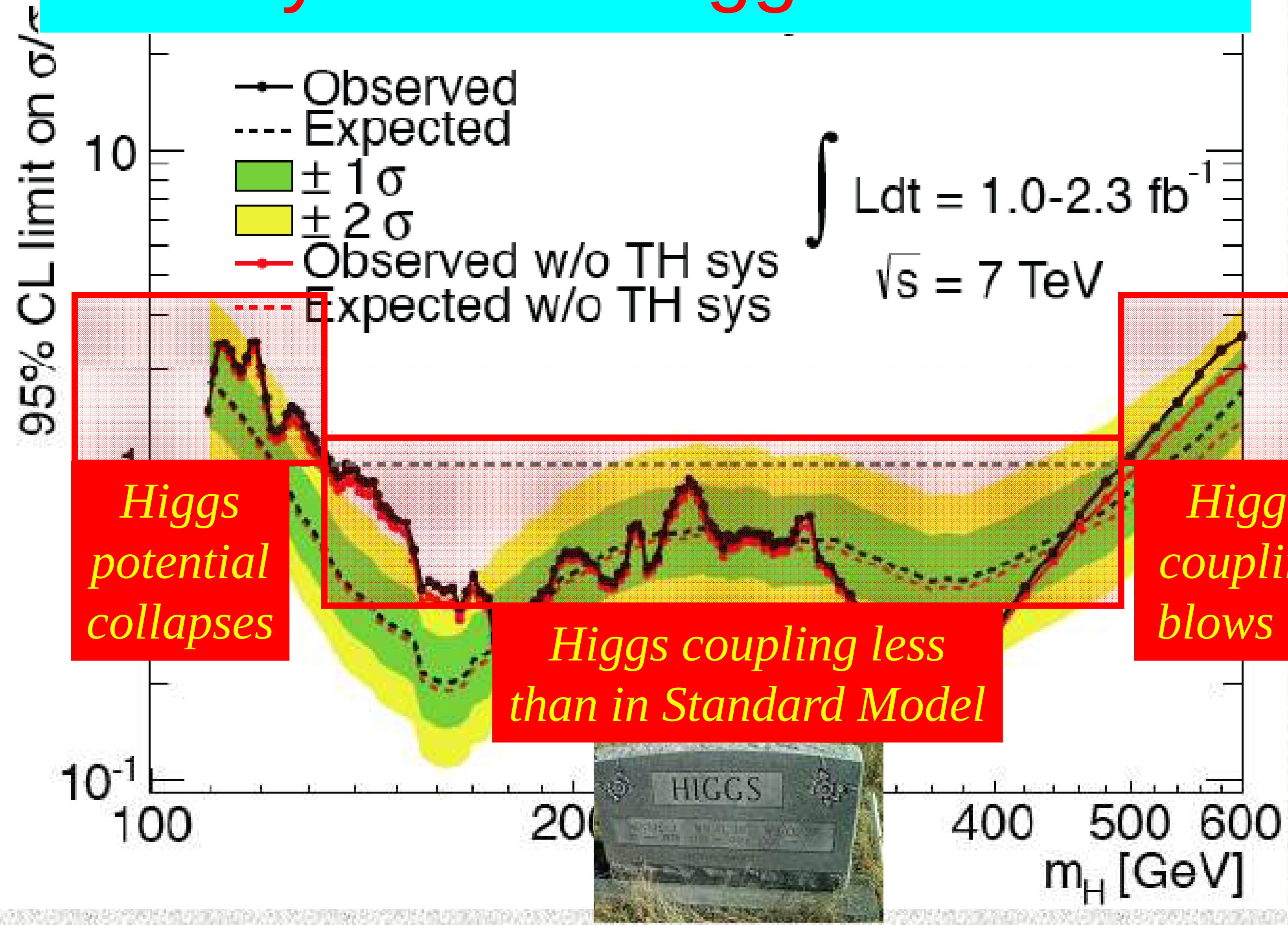


High-multiplicity event



No match for heavy ions, but not too bad for pp (>120 charged tracks in TPC)

There must be New Physics beyond the Higgs Boson



Higgs potential collapses

Higgs coupling less than in Standard Model

Higgs coupling blows up

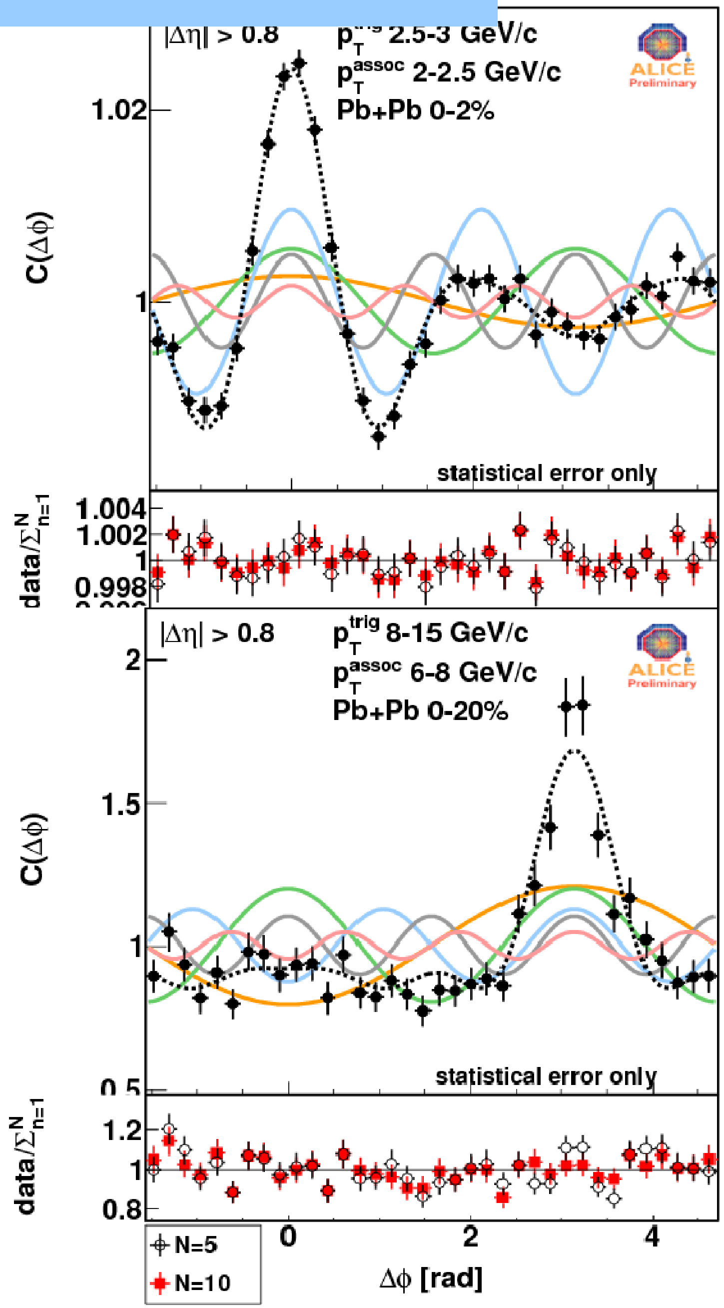
Fourier Decomposition

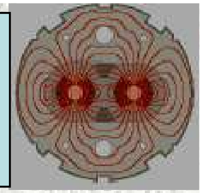
- **Fourier coefficients are calculated**

$$V_{n\Delta} = \langle \cos n\Delta\varphi \rangle = \frac{\int d\Delta\varphi C(\Delta\varphi) \cos n\Delta\varphi}{\int d\Delta\varphi C(\Delta\varphi)}$$

- **Strong near-side ridge + double-peaked structure (in very central events) on away side at low p_T**
  - **5 coefficients describe correlation well at low p_T**
- **Away-side peak dominates at high p_T**
  - **Higher coefficients improve description**

J.F.Grosse-Oetringhaus, ALICE

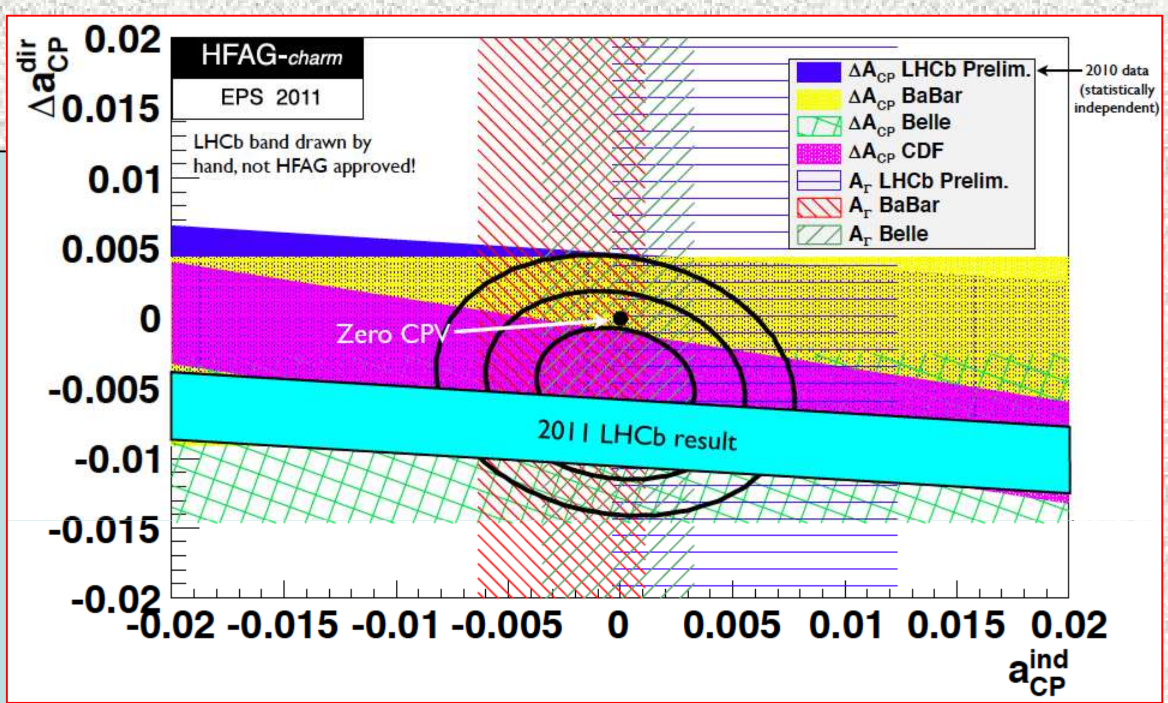




CP Violation in Charm

A new frontier opened up by LHCb

3.5 σ at the moment:



$$\Delta A_{CP} = [-0.82 \pm 0.21(\mathrm{stat.}) \pm 0.11(\mathrm{sys.})]\,\%$$

- 10 × larger than SM estimate, but difficult to calculate
- No consensus yet whether BSM required
- Are there more charming surprises in store?

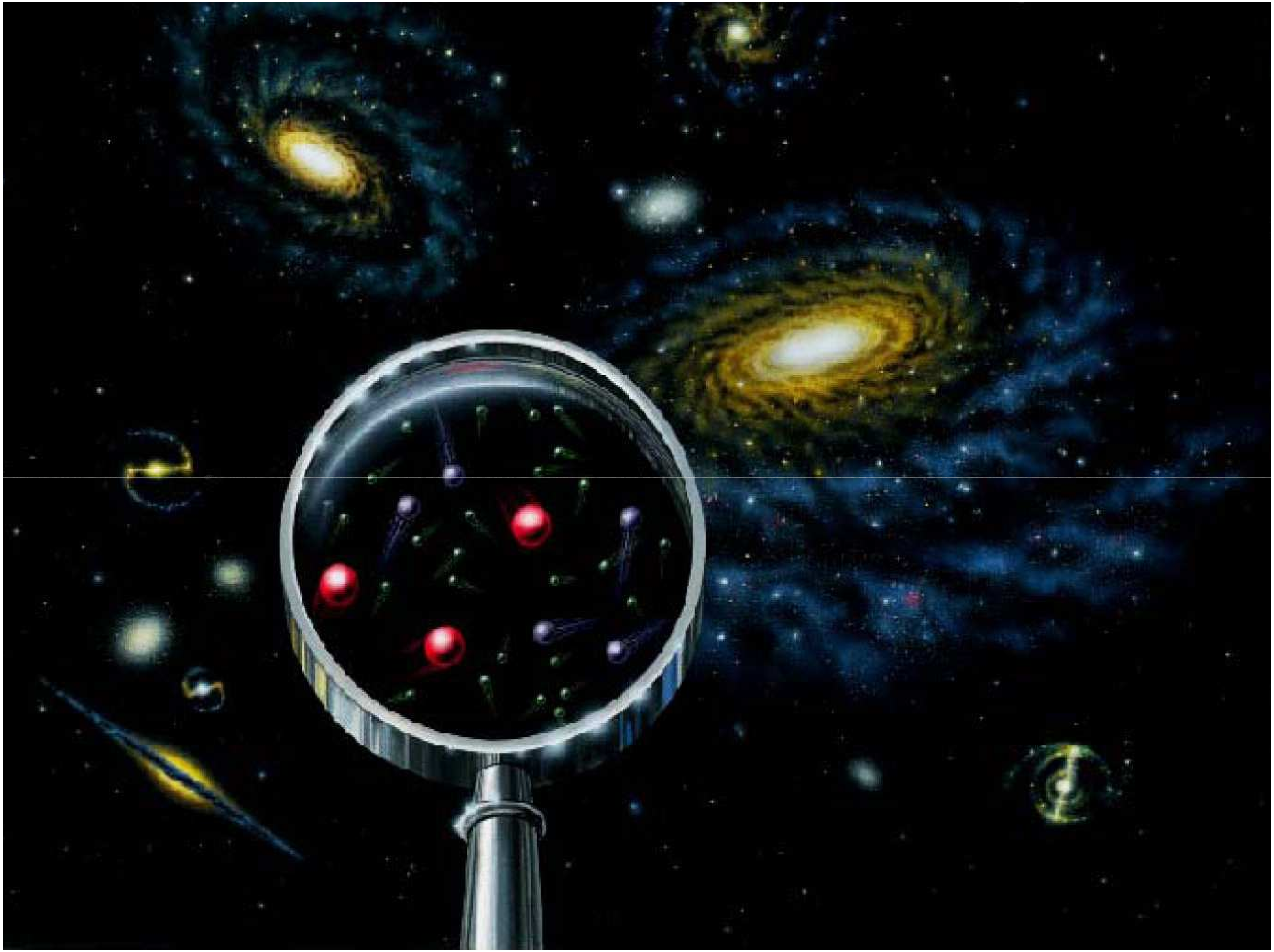
BANGS

Big Bang ↔ Little Bangs

- The matter content of the Universe
  - Dark matter
  - Dark energy
  - Origin of matter

- Experiments at particle colliders
  - Early Universe
  - Supersymmetry
  - Matter-antimattter asymmetry

Learn particle physics from the Universe
Use particle physics to understand the Universe



Zhrnutie

- **LHC a vsetky experimenty pracuju druhy rok perfektne**
  - **intezity zvazkov a mnozstvo zaznamenanych zrazok ovela nad ocakavanie**
  - **prve fyzikalne vysledky publikovane**
    - **presne potvrdenie stadartneho modelu**
    - **Higgsov bozon nenajdeny (zatial) – ak okolo 120 GeV velka sanca buduci rok**
    - **priame narusenie CP symetrie v charmovom sektore!**
    - **fluktacie v pociatocnom stave v zrazkach tazkych ionov**
- **Looking forward to explore the 'terra incognita' at LHC**

Hic sunt Leones !