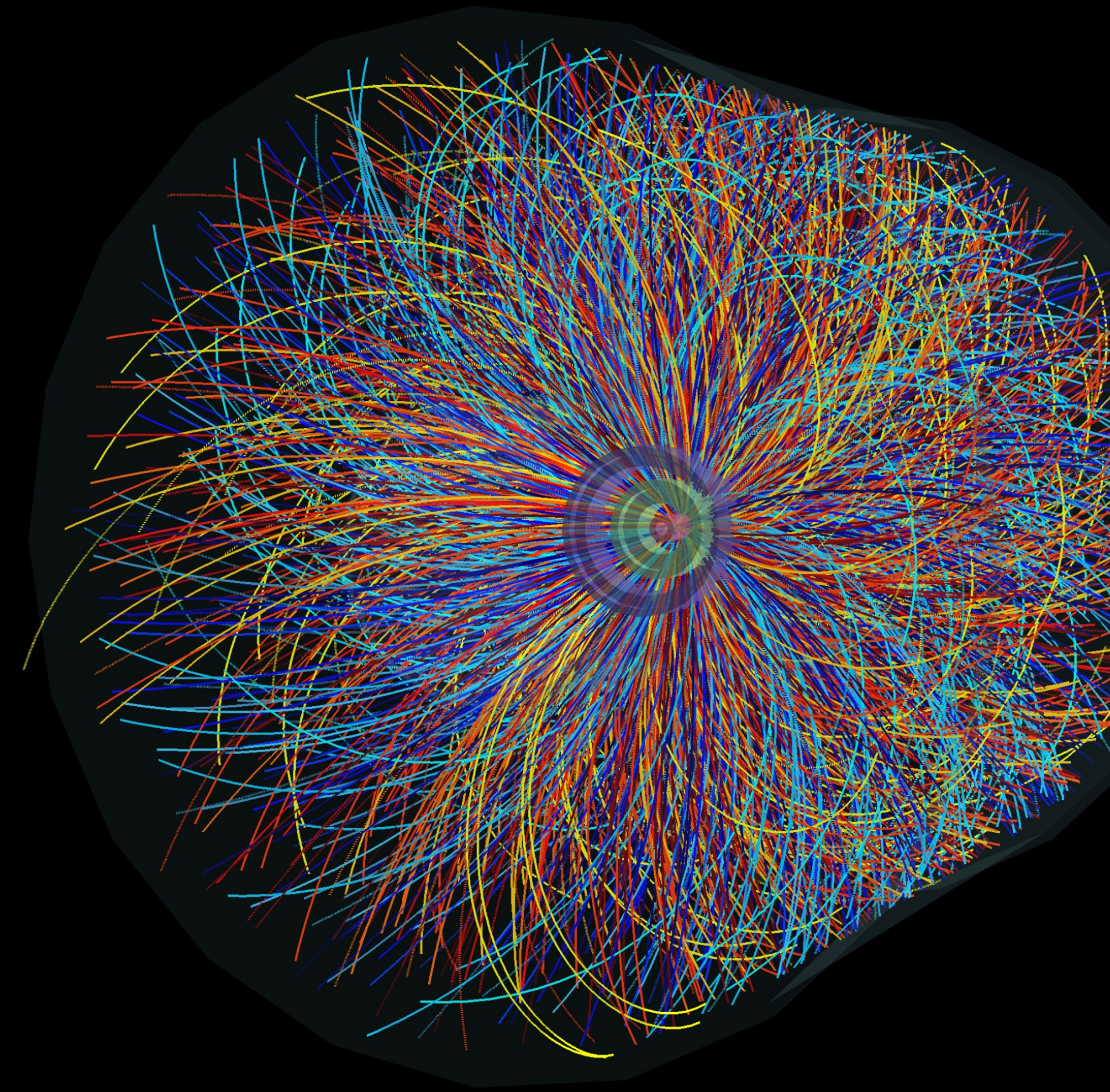


# Un infiniment petit vu grand

L'interaction forte, vue à l'échelle de l'infiniment petit  
(*collisions pp, Pb-Pb, ...*)  
avec des installations de très grande échelle  
(*LHC*)





# Prologue





# Un monde de glace





glaçons élémentaires





Phase liquide à une certaine température



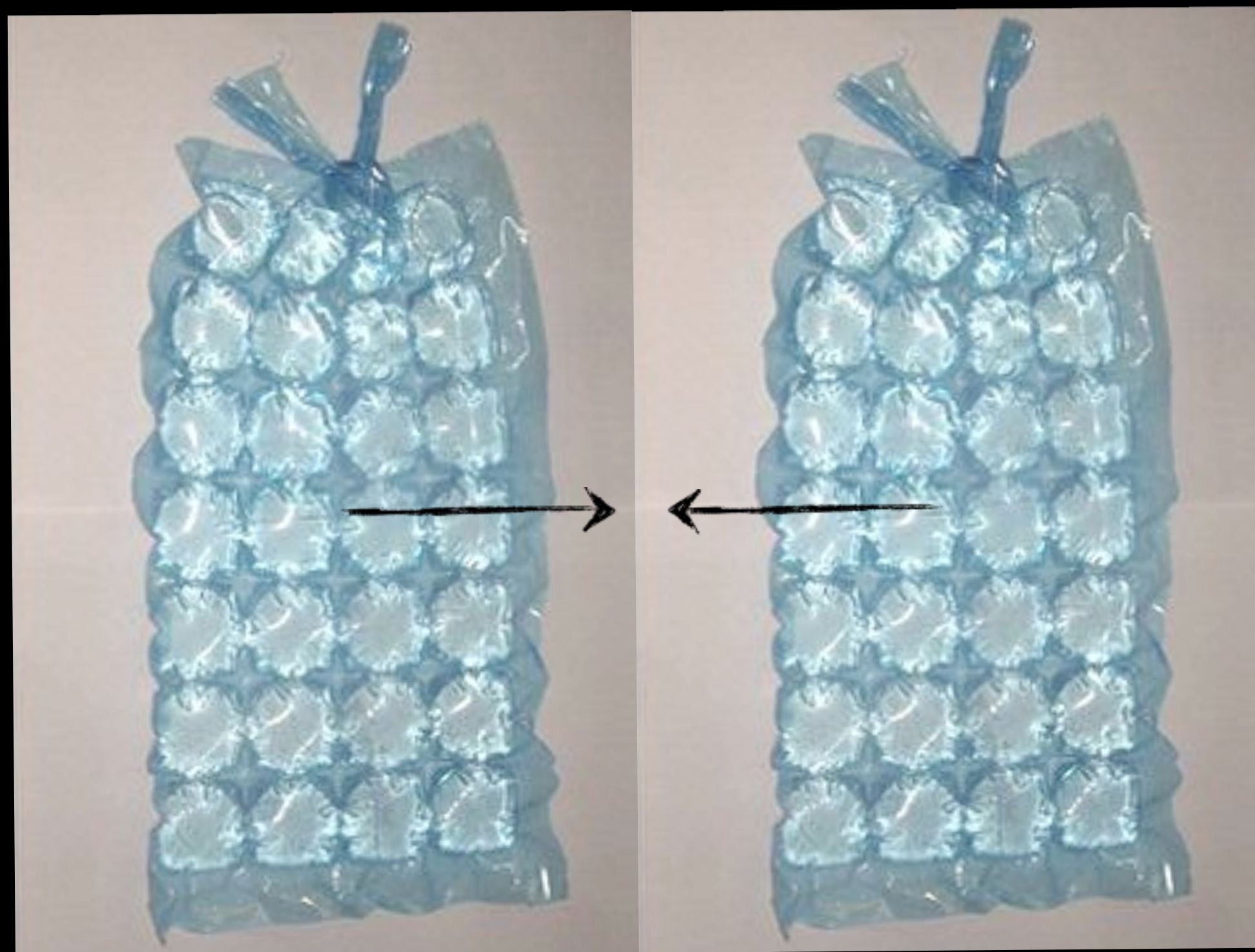


*Idée : chauffer la glace en frappant deux glaçons*



Prenons  $\approx$  100 millions de glaçons





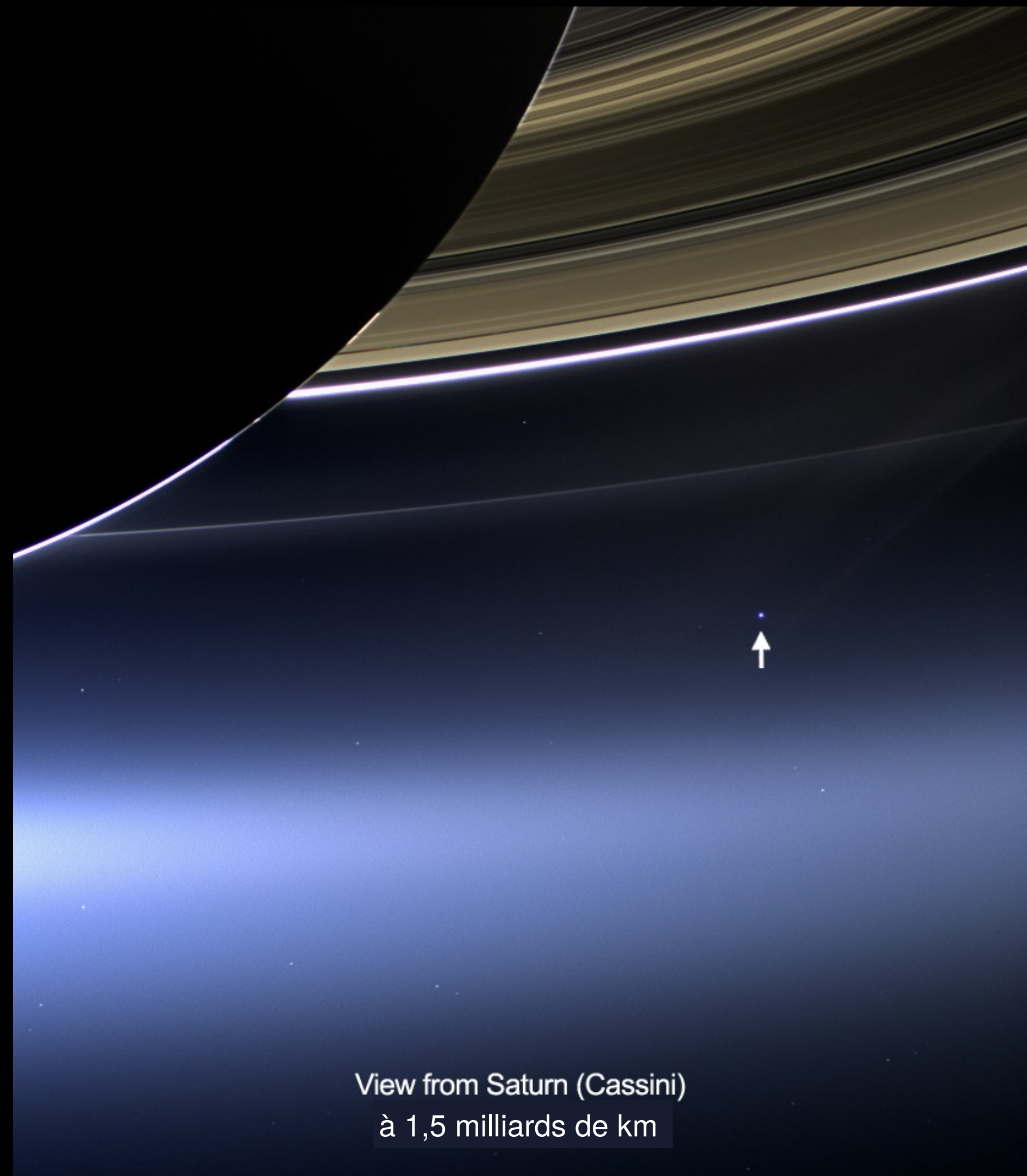
3 millions de fois par seconde





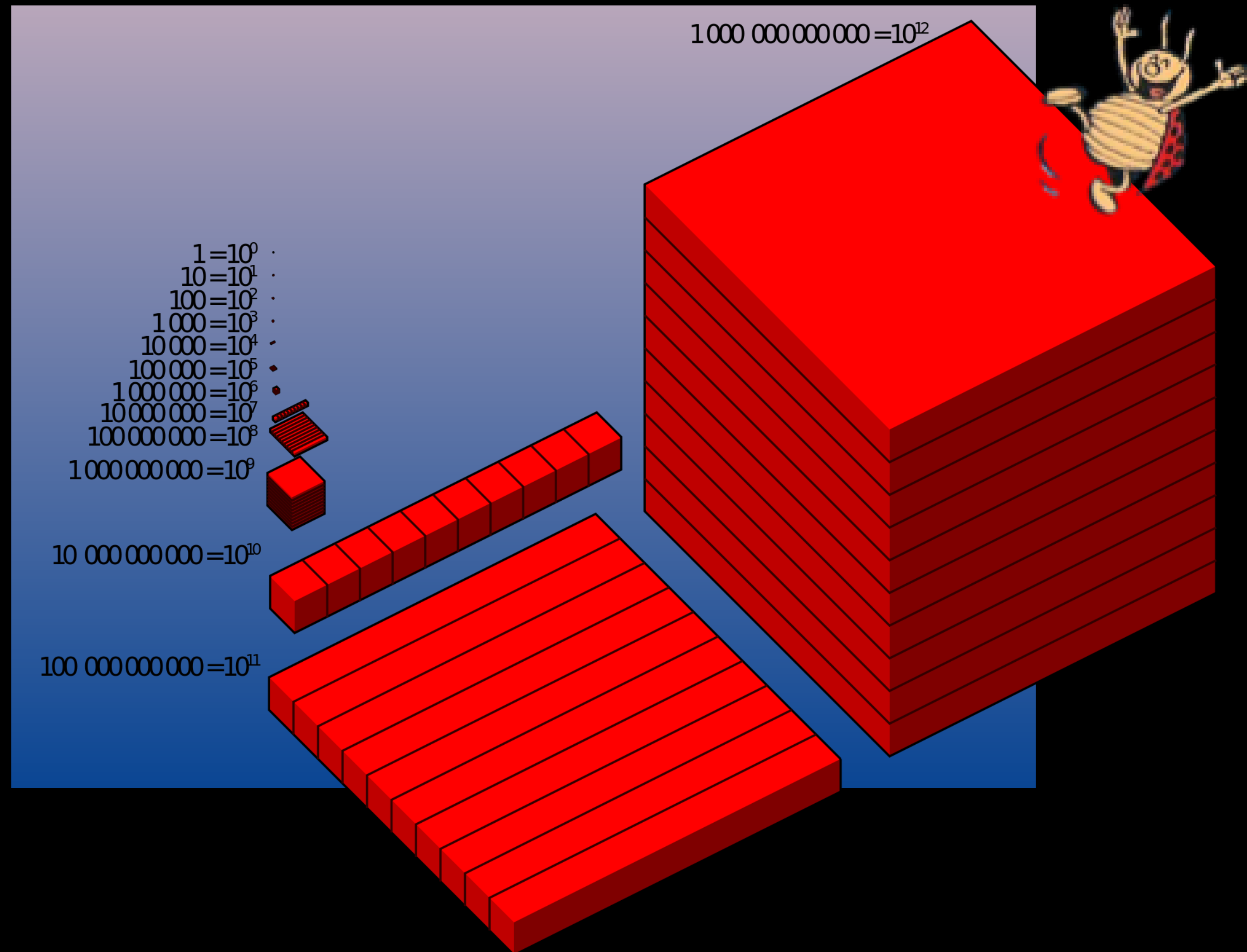
8000 collisions glaçon-glaçon par seconde





View from Saturn (Cassini)  
à 1,5 milliards de km

# Observateur sur Saturne



etc...

dimensions  $\times 10^{13}$



Mille millions de mille  
milliards de mille  
sabords de tonnerre de  
Brest !



$10^{10}$  ?  $10^{24}$  ?  $10^{-5}$  ?

Acte I: soit de la matière...





# La matière dans l'Univers



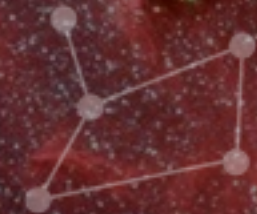
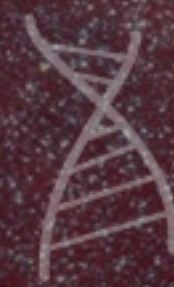
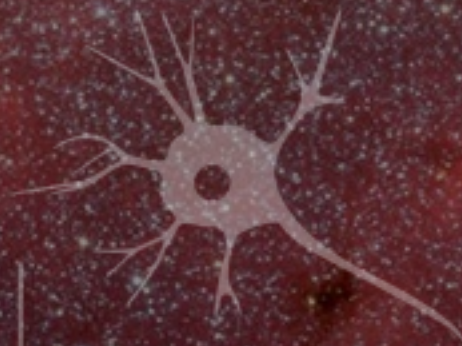
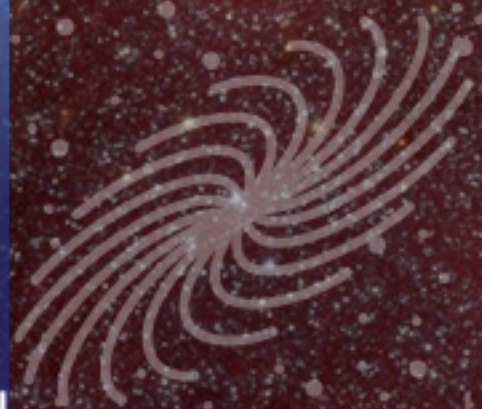
13,819 milliards  
d'années





# UNIVERS

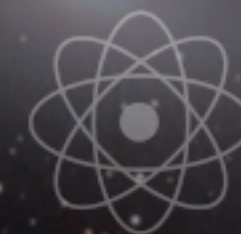
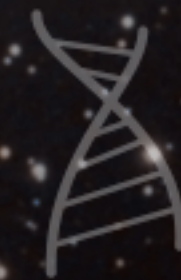
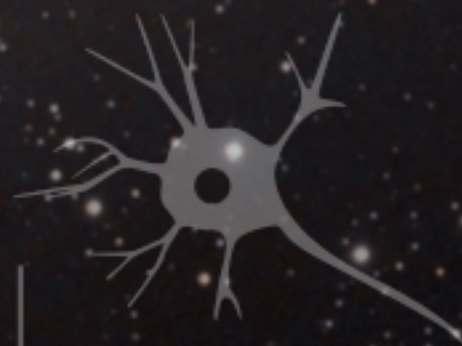
$>10^{26}$  m





# GALAXIE

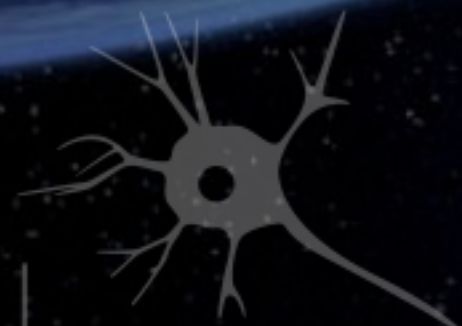
$\approx 10^{21}$  m





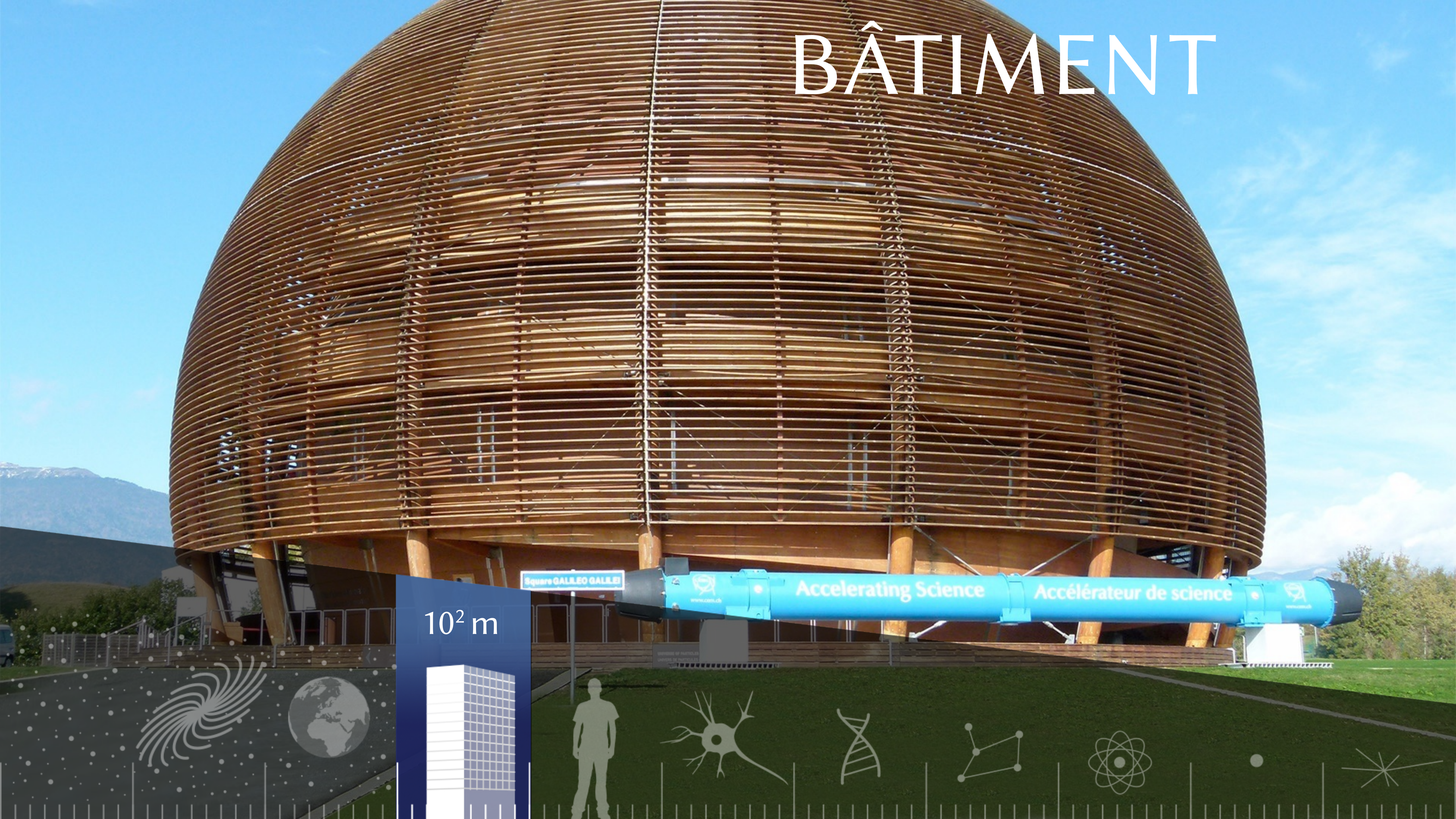
# SYSTÈME SOLAIRE

$\approx 10^{12}$  m

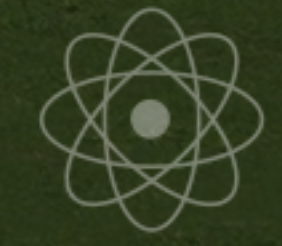
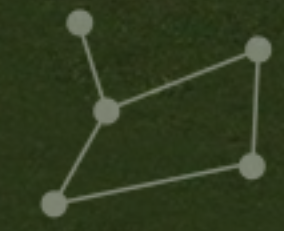
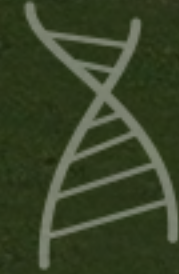
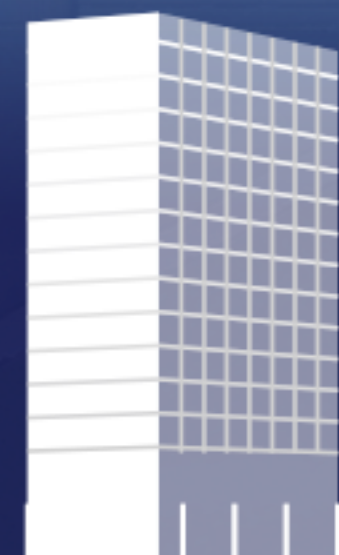




# BÂTIMENT



10<sup>2</sup> m





# HUMAIN



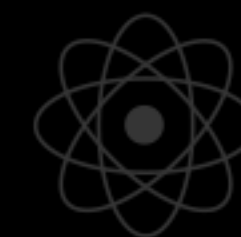
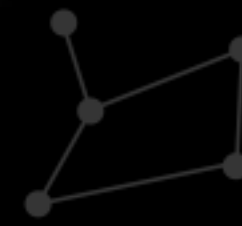
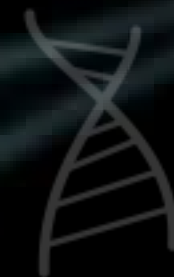
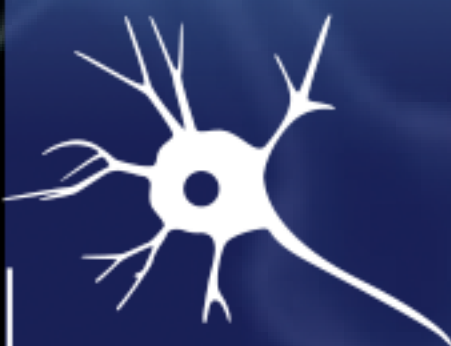
1,74 m





# NEURONES

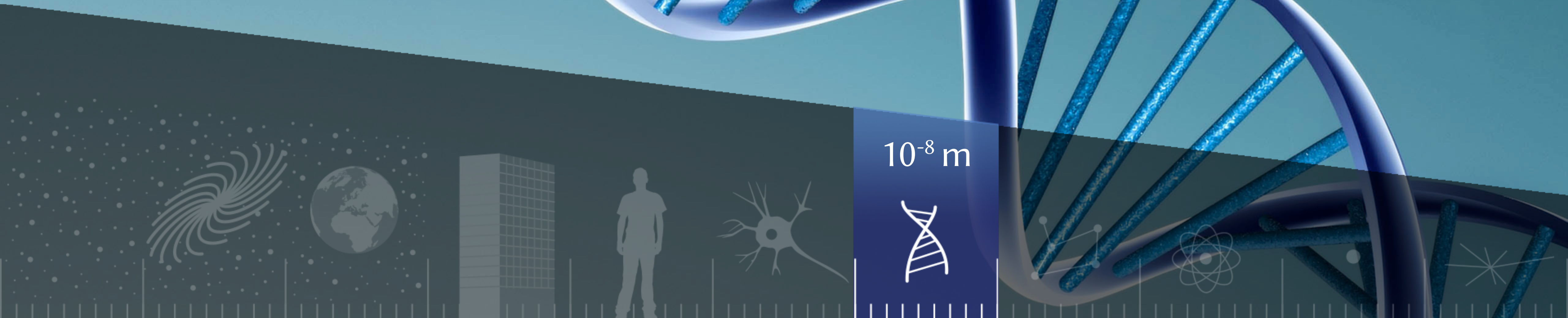
$10^{-5}$  m





ADN

$10^{-8}$  m





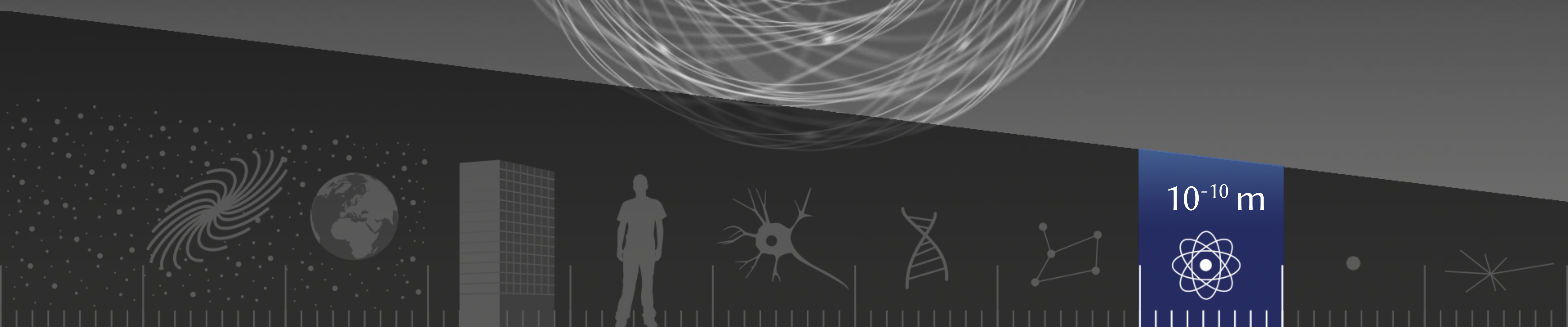
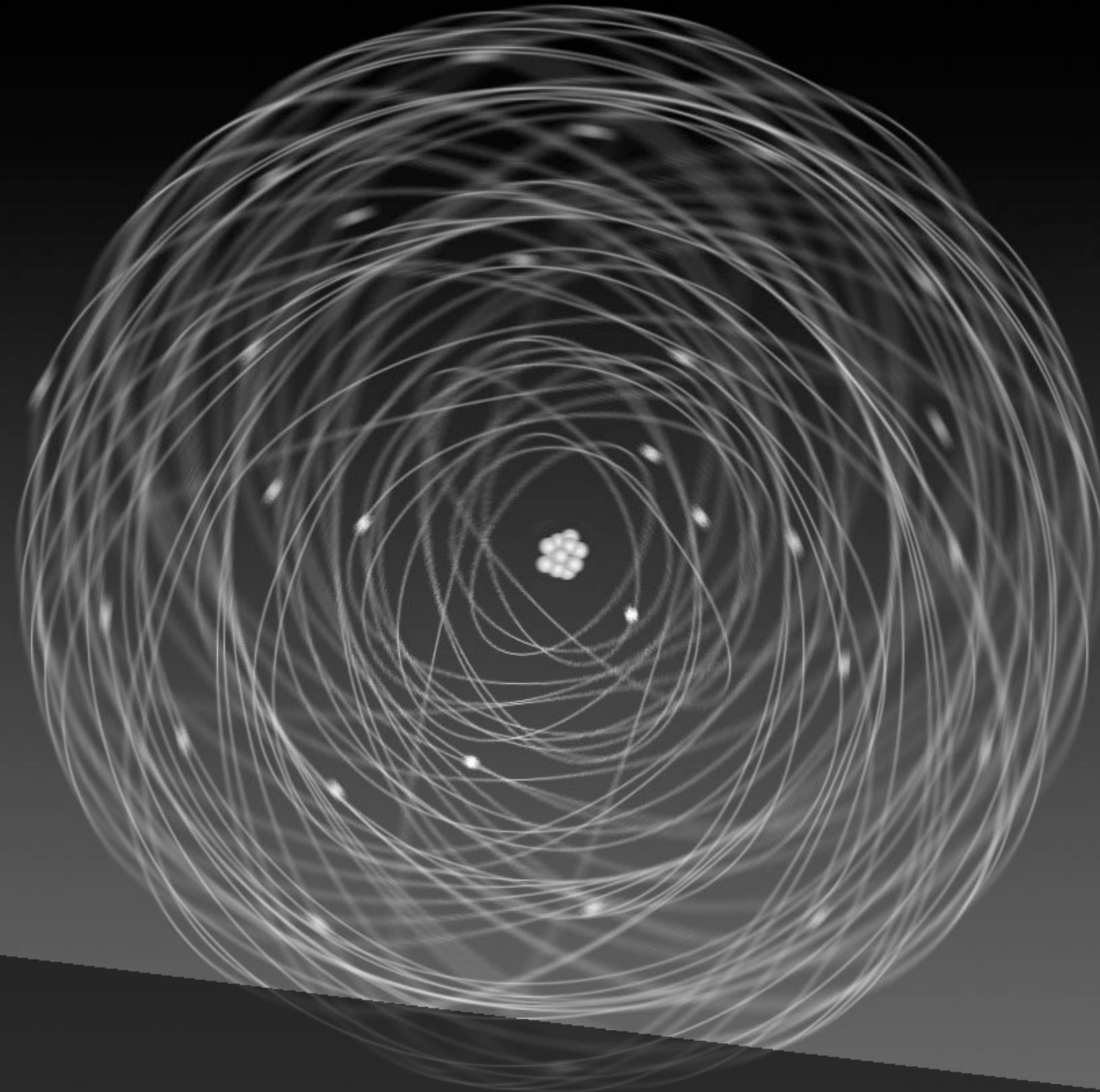
# MOLÉCULE

$10^{-9}$  m





# ATOMI

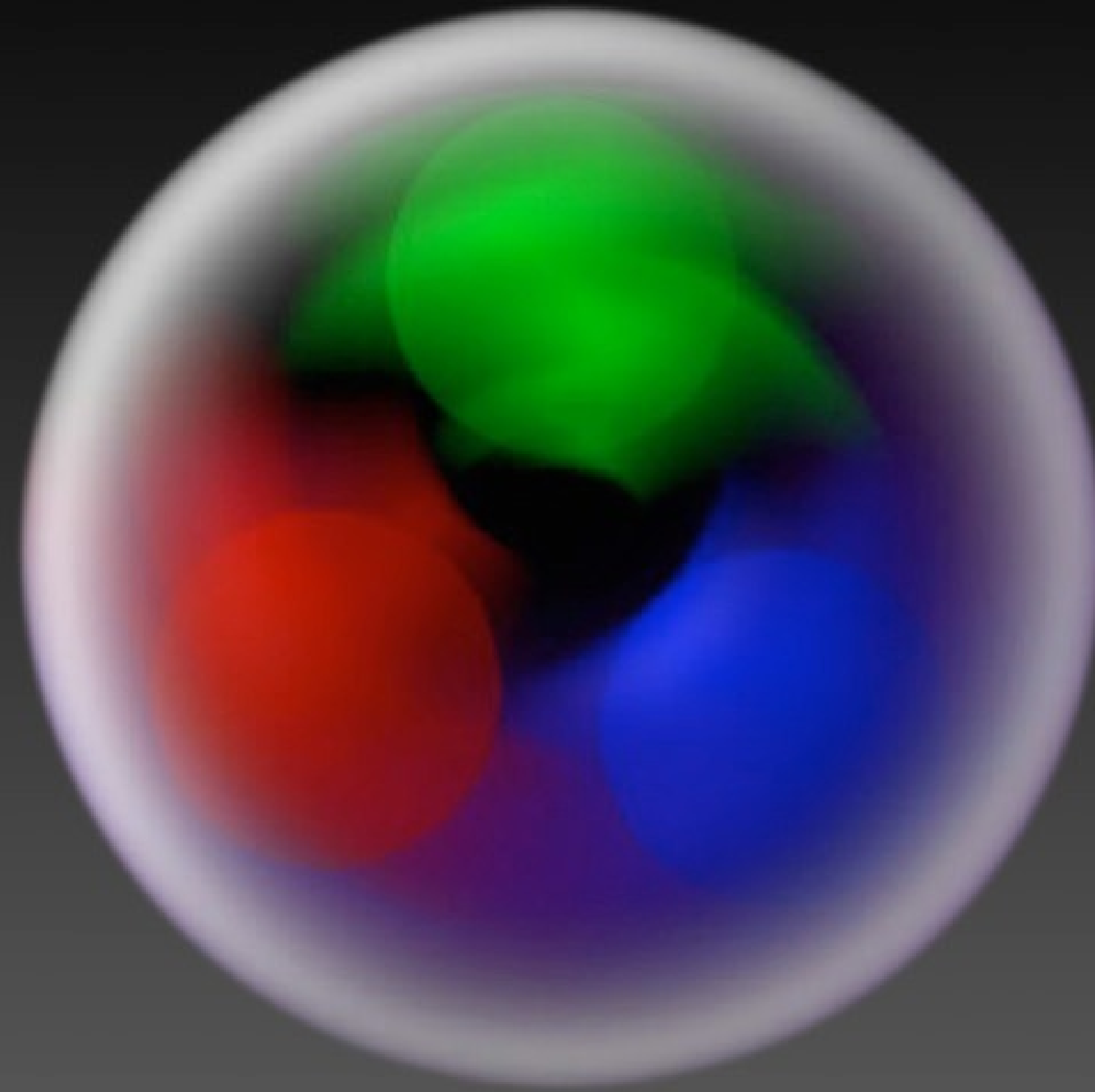


$10^{-10}$  m

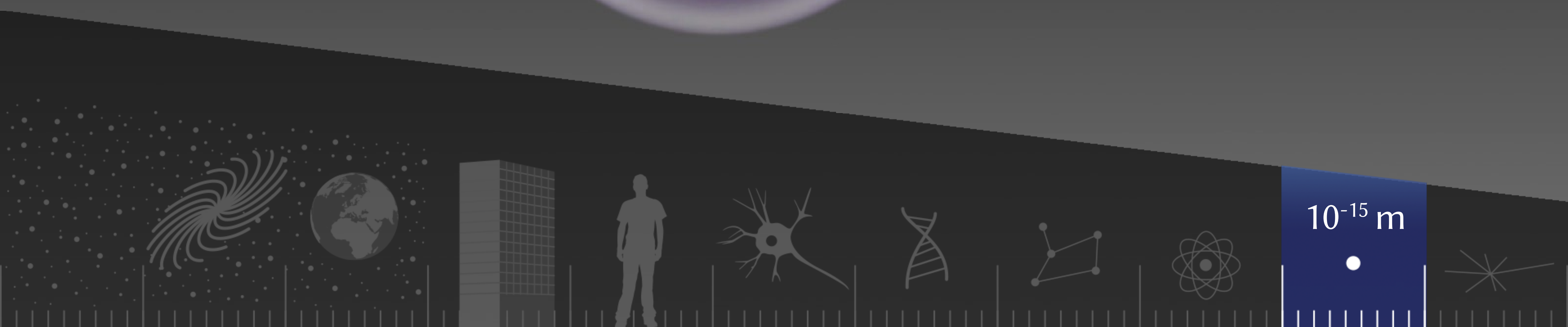




# PROTON

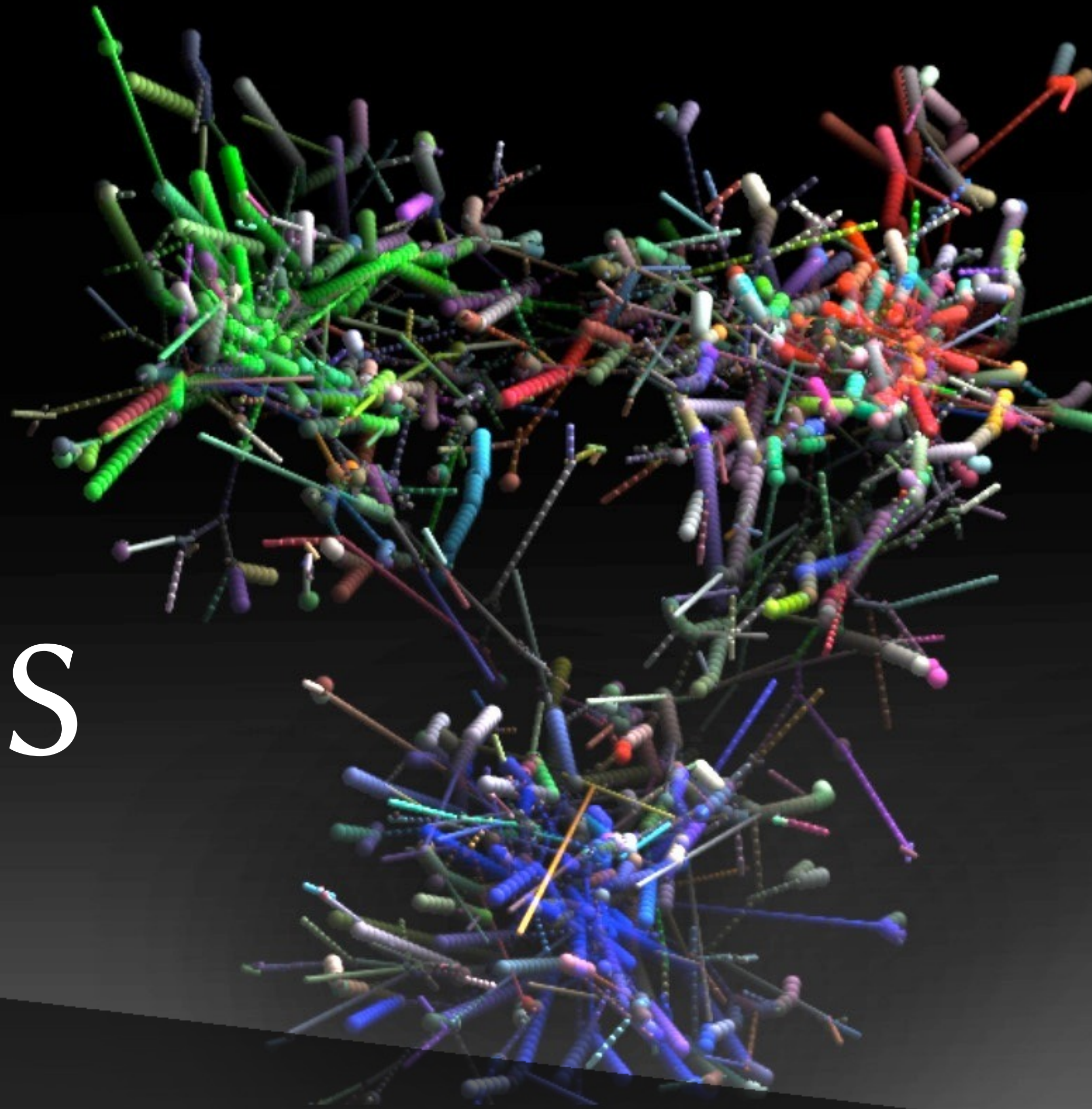


$10^{-15}$  m





# QUARKS



$< 10^{-18}$  m





# Un protocole pour établir de la matière

1. Soient quelques particules élémentaires (glaçons)





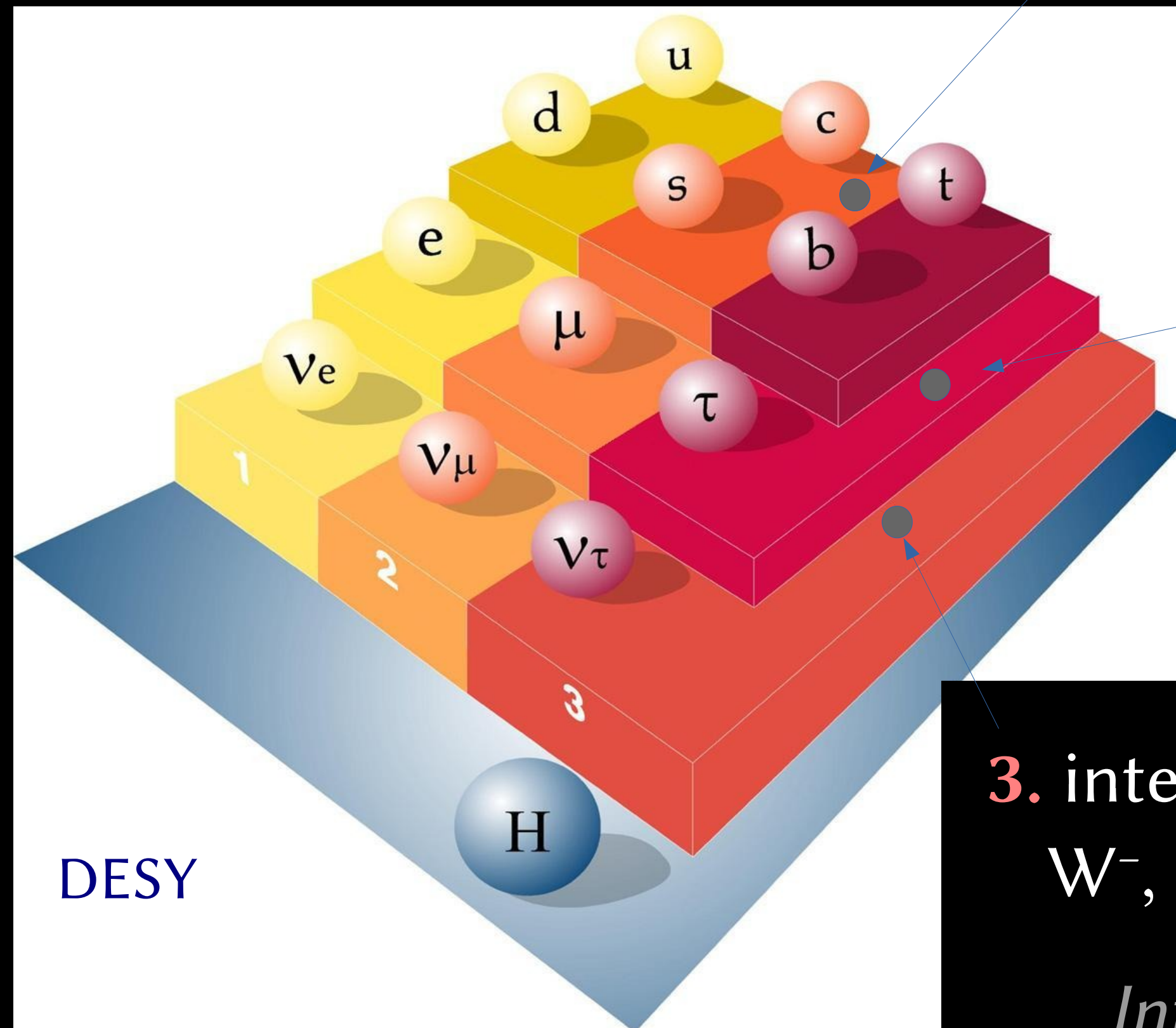


# Un protocole pour établir de la matière

1. Soient quelques particules élémentaires (« *glaçons* »)
2. Liez-les avec la (ou les) interaction(s) adéquates



# Bosons, Porteurs des interactions



1. interaction forte  
gluons

Intensité : **1**

Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
<b>g</b> gluon	0	0

2. interaction électromagnétique  
photons

Intensité :  $\approx 1/137$

Unified Electroweak spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
<b>γ</b> photon	0	0
<b>W<sup>-</sup></b>	80.39	-1
<b>W<sup>+</sup></b>	80.39	+1
W bosons		
<b>Z<sup>0</sup></b> Z boson	91.188	0

3. interaction (électro)faible  
W<sup>-</sup>, W<sup>+</sup>, Z<sup>0</sup>

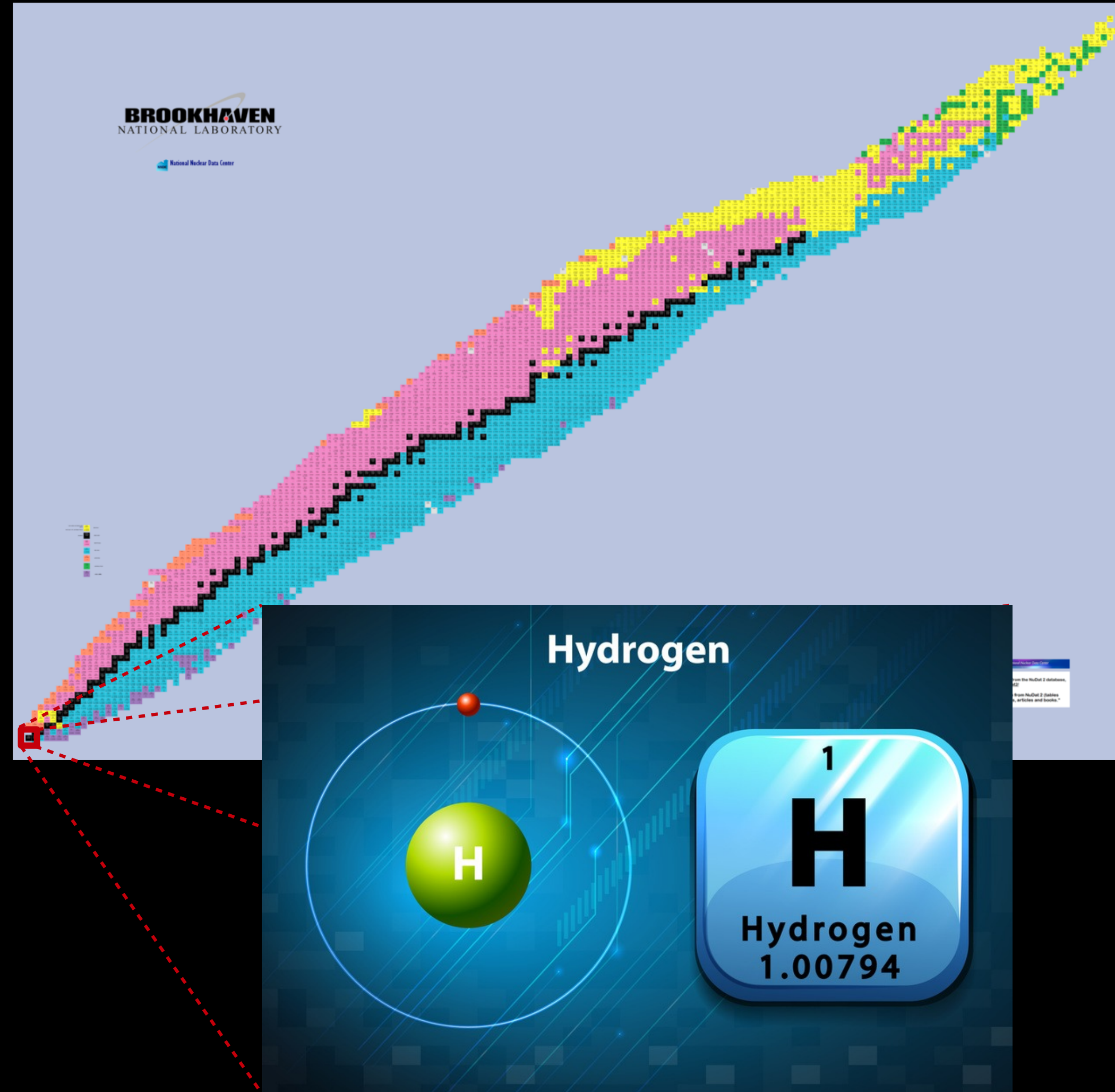
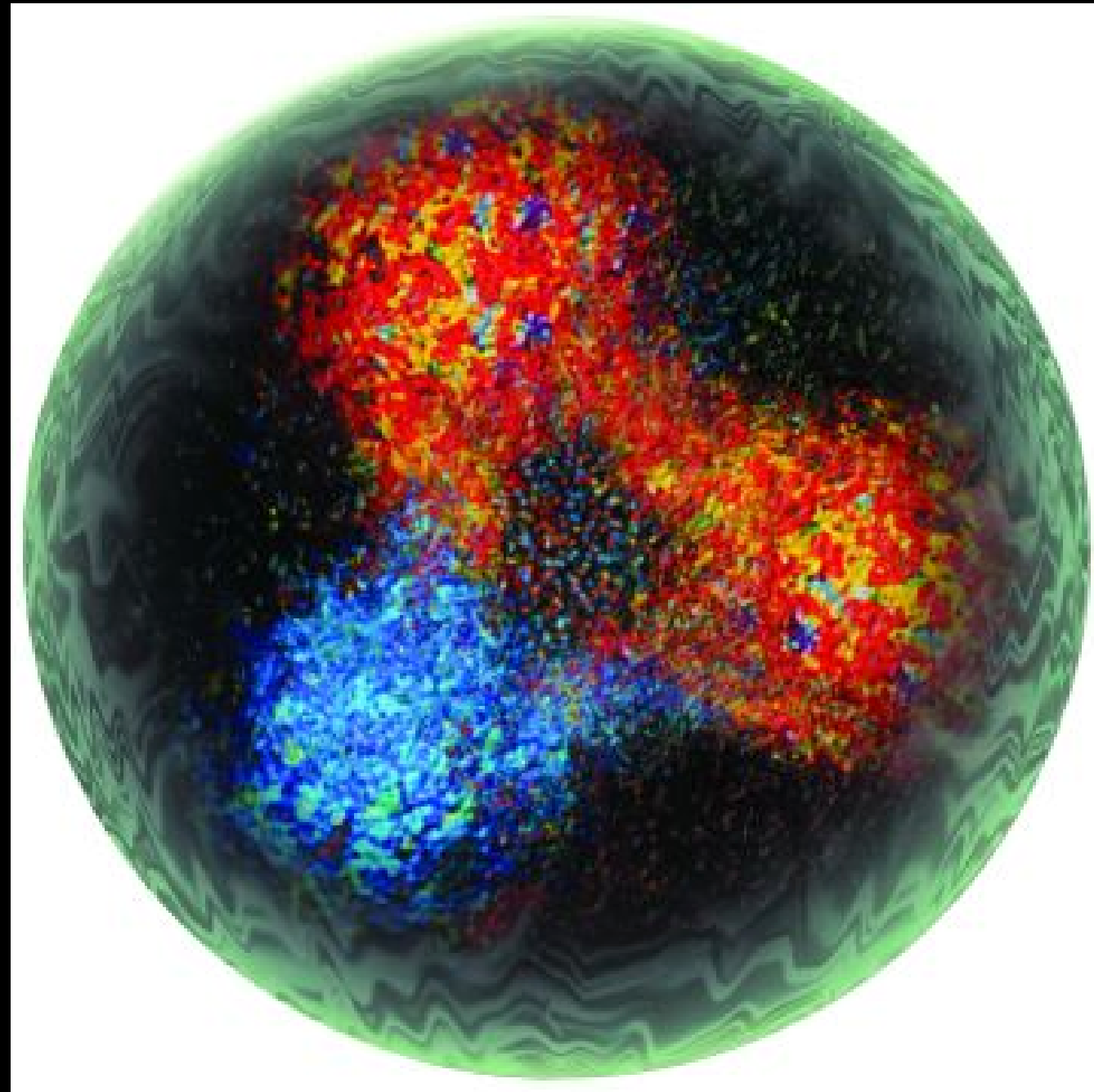
Intensité :  $\approx 10^{-5}$

4. interaction gravitationnelle  
graviton

Intensité :  $< 10^{-30}$

5. + masse : Brout-Englert-Higgs ...

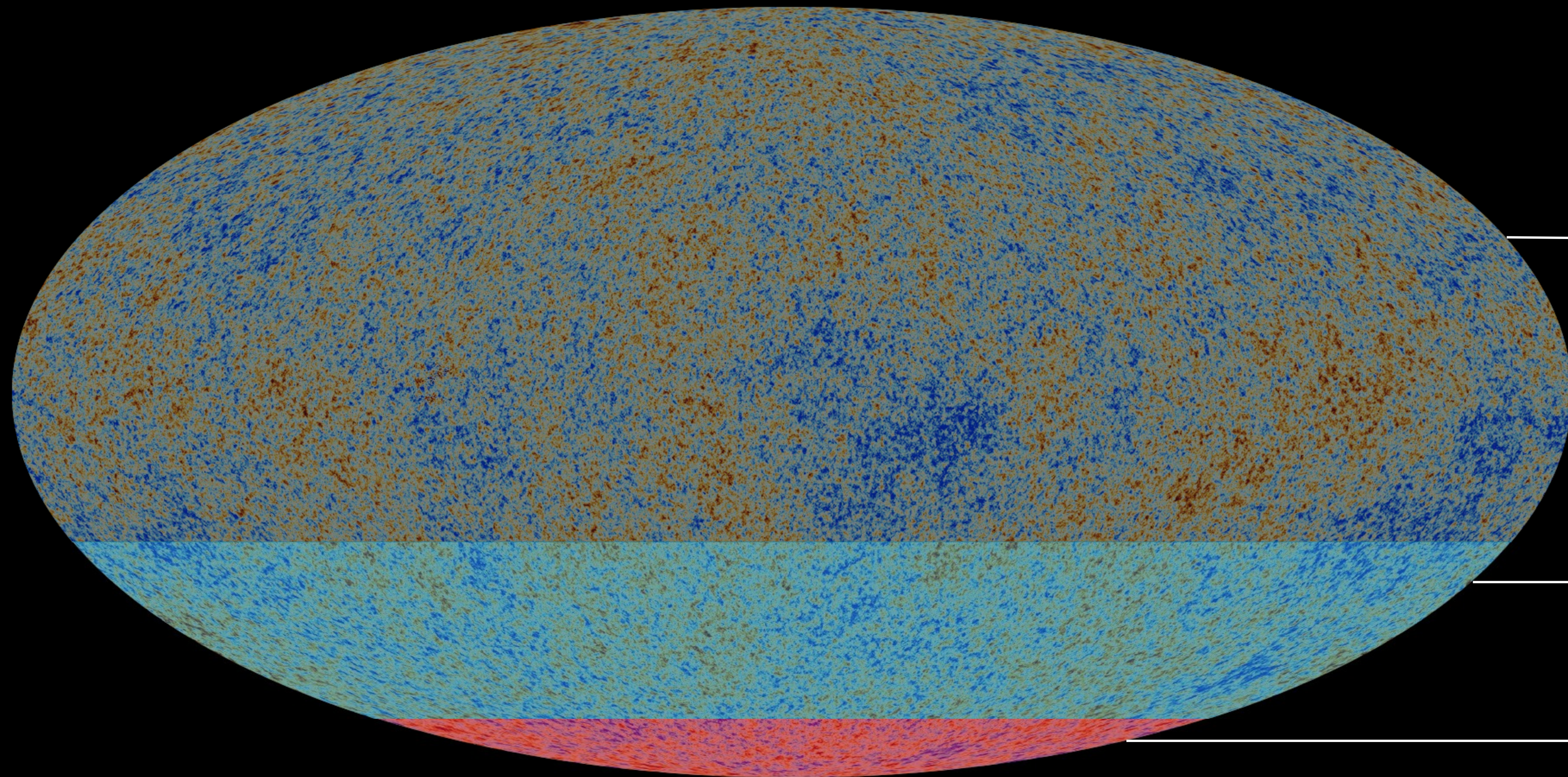




proton =  $uud$  + interaction forte (gluon)



# 380 000 ANS APRÈS LE BIG BANG

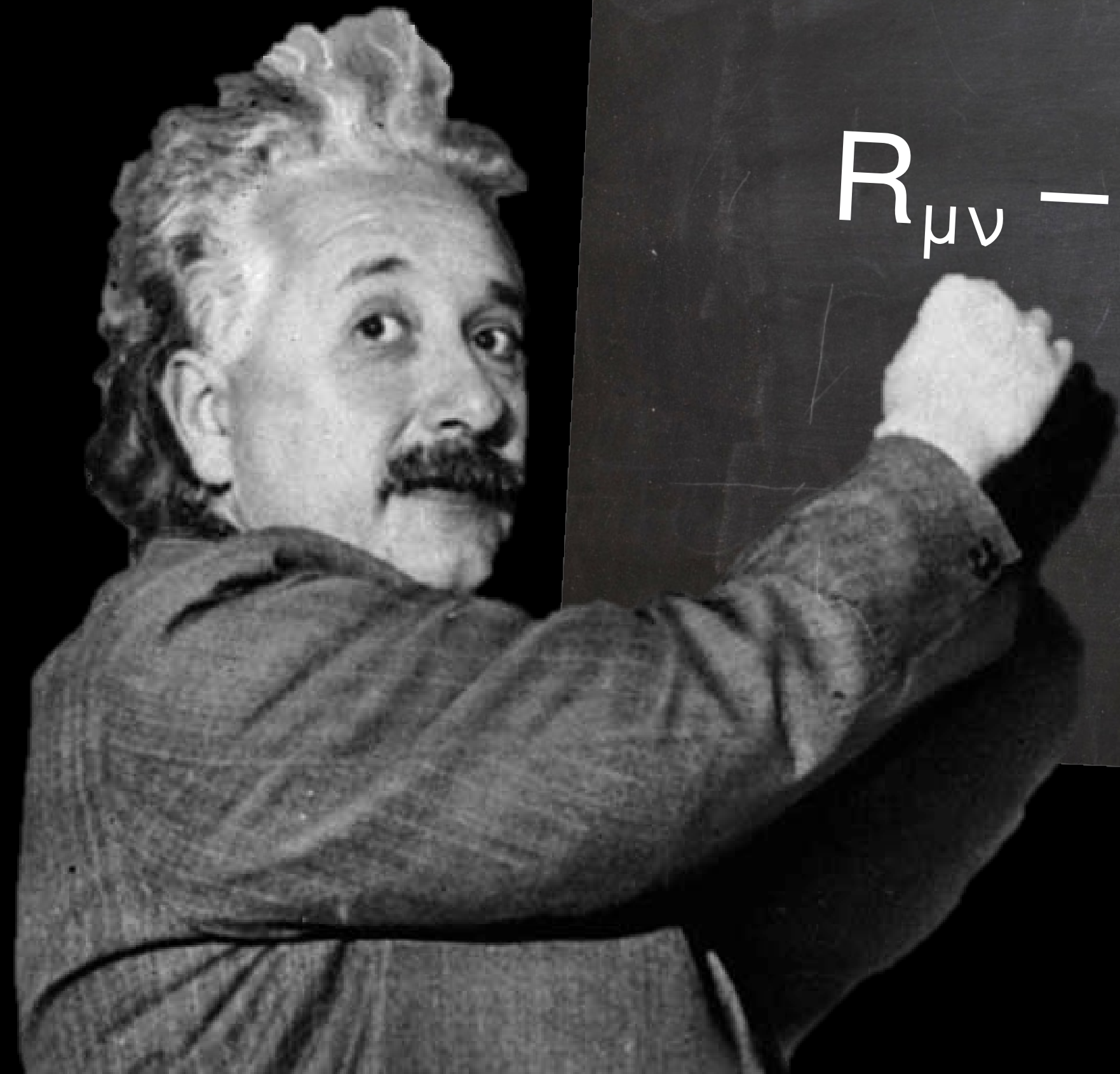


**69,2%**  
D'ÉNERGIE  
SOMBRE

**25,9%**  
DE MATIÈRE  
SOMBRE

**4,9%**  
DE MATIÈRE  
VISIBLE

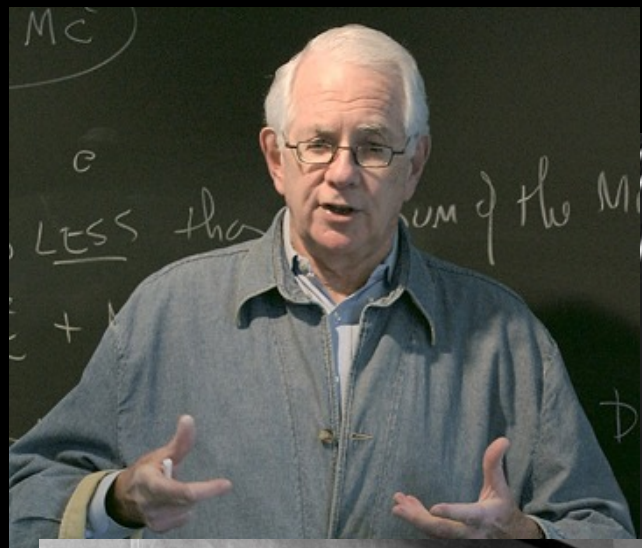




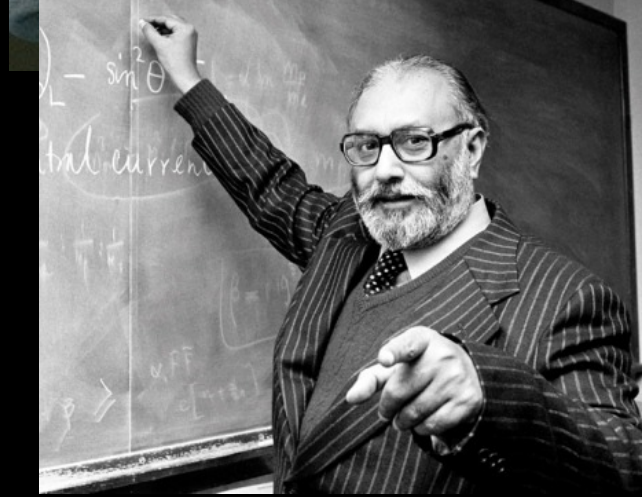
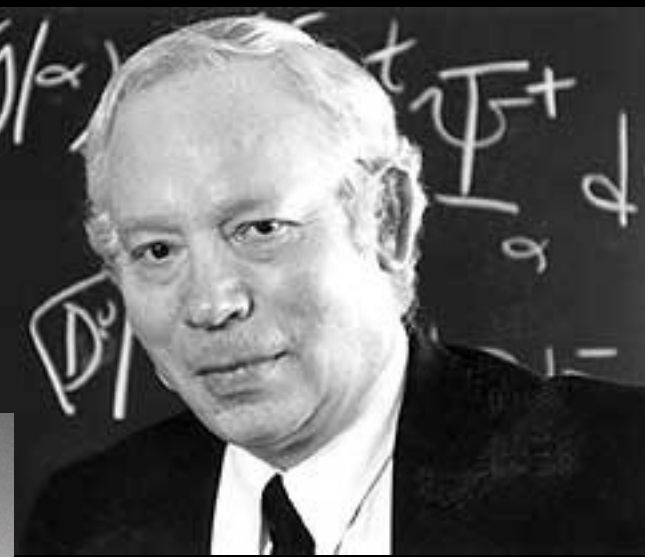
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi GT_{\mu\nu}$$







Glashow, Salam, Weinberg



Fermi



Feynman



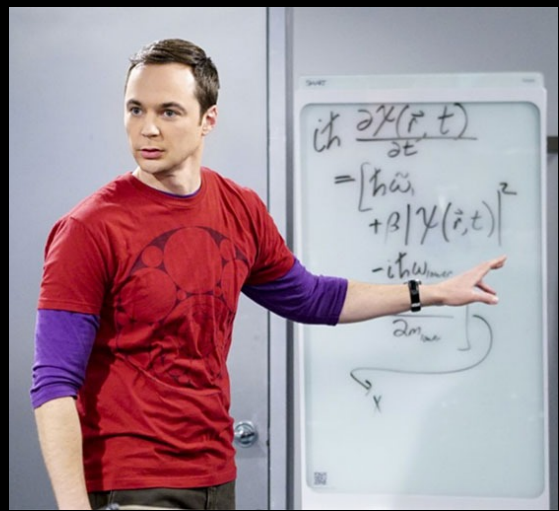
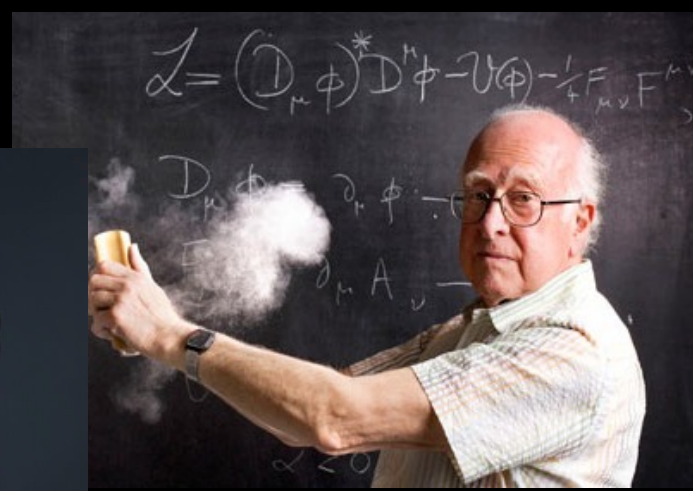
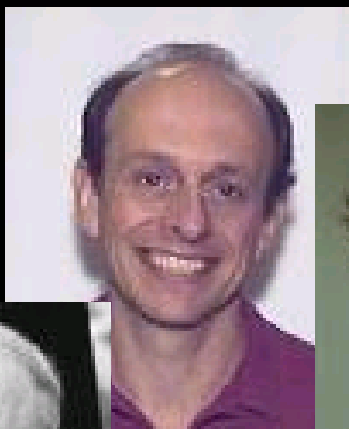
Brout, Englert, Higgs



Gell-mann



Gross, Wilczek, Politzer



Cooper

# Interactions forte, électromagnétique et faible en une formule ...

Théorie relativistes des champs quantiques:  
Le Lagrangien du Modèle Standard de la Physique de Particules

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
 & \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
 & \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[ \frac{2M^2}{g^2} + \right. \\
 & \left. \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\nu^- - \\
 & W_\nu^- \partial_\mu W_\mu^+)] - igs_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\mu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^+ W_\mu^- + \\
 & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^+ W_\mu^- + g^2 c_w^2 (Z_\mu^0 W_\nu^+ Z_\nu^0 W_\mu^- - Z_\mu^0 Z_\nu^0 W_\nu^+ W_\mu^-) + \\
 & g^2 s_w^2 (A_\mu W_\nu^+ A_\nu W_\mu^- - A_\mu A_\nu W_\nu^+ W_\mu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
 & \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
 & gMW_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
 & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
 & igs_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma^\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma^\partial \nu^\lambda - \bar{u}_j^\lambda (\gamma^\partial + m_u^\lambda) u_j^\lambda - \\
 & \bar{d}_j^\lambda (\gamma^\partial + m_d^\lambda) d_j^\lambda + igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \\
 & \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \\
 & \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_\lambda^2}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{g}{2} \frac{m_\lambda^2}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\
 & m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \\
 & \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \\
 & \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
 & \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W_\mu^- (\partial_\mu \bar{X}^- Y - \\
 & \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
 & igMs_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

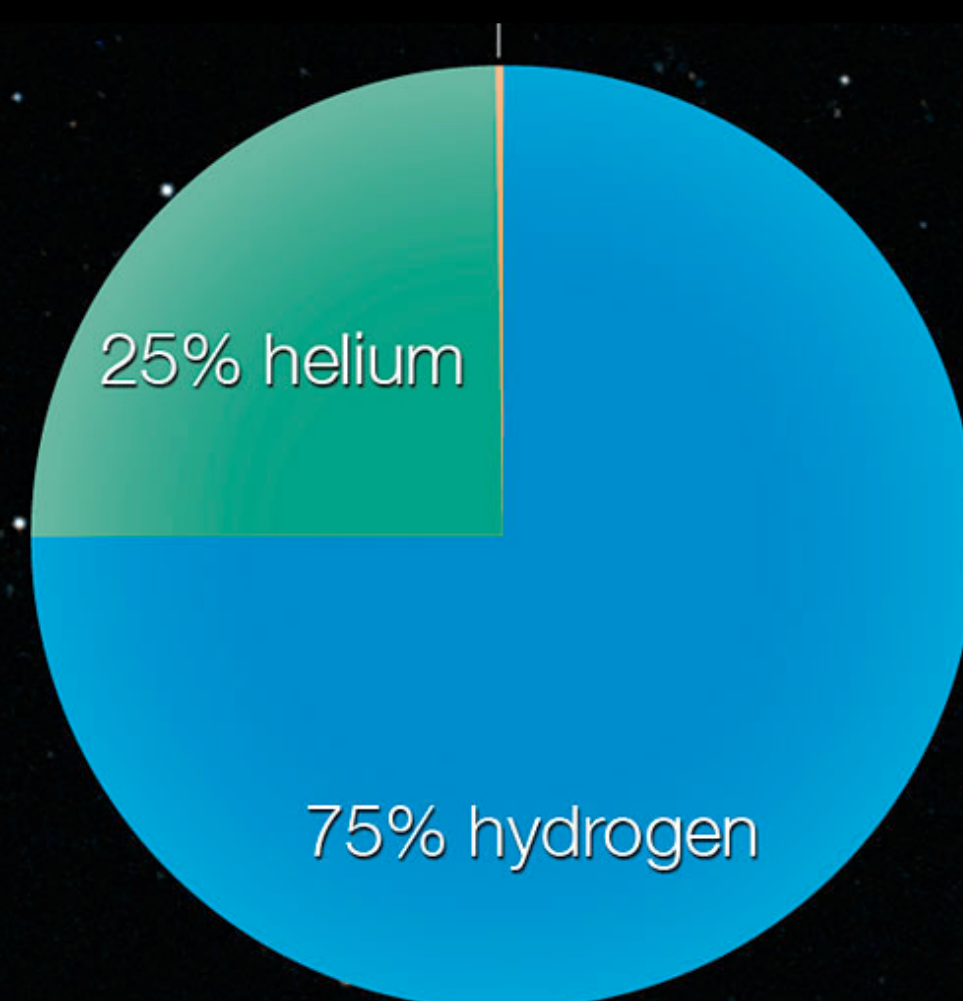




# Acte II: l'origine de la matière ?





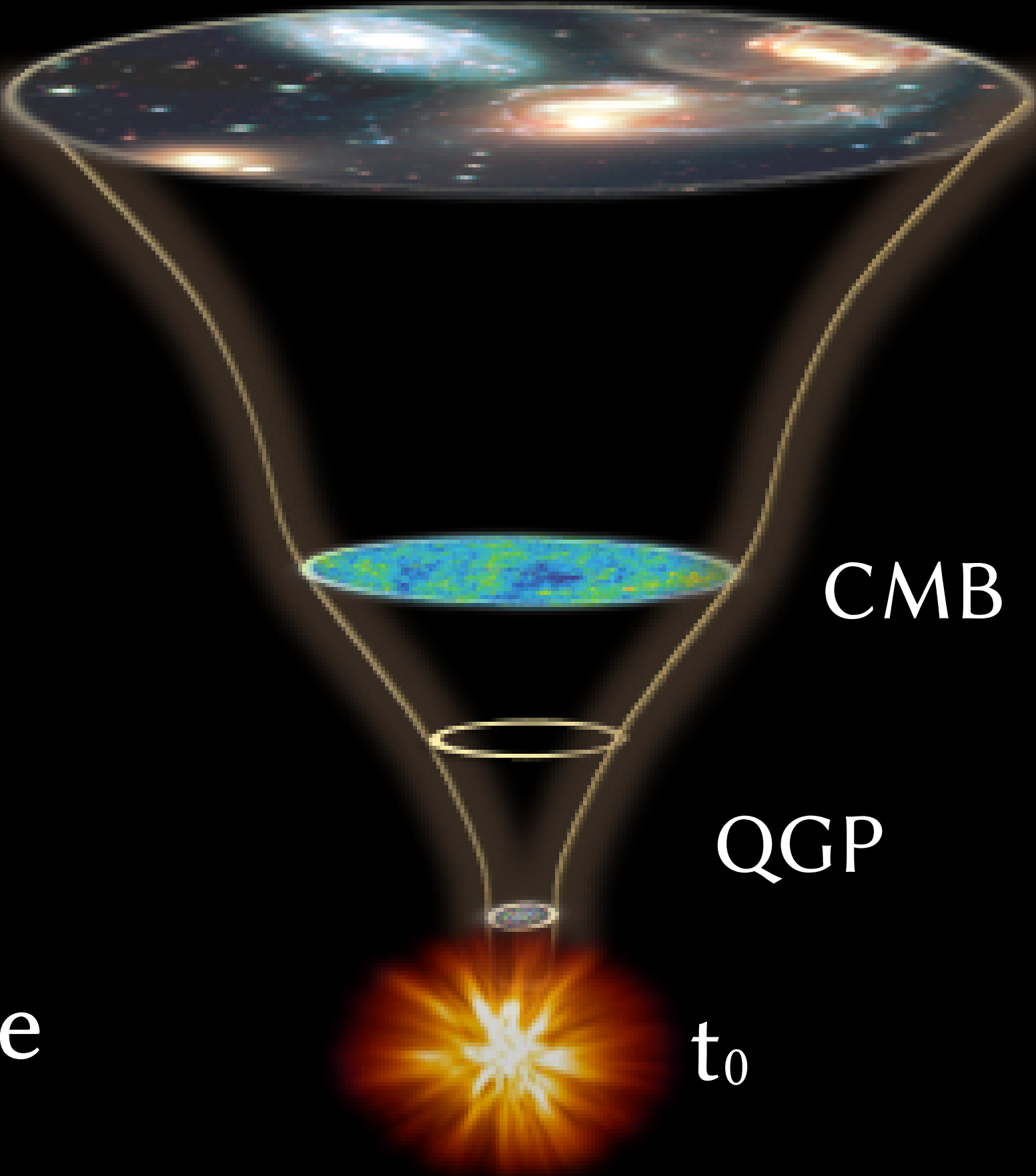
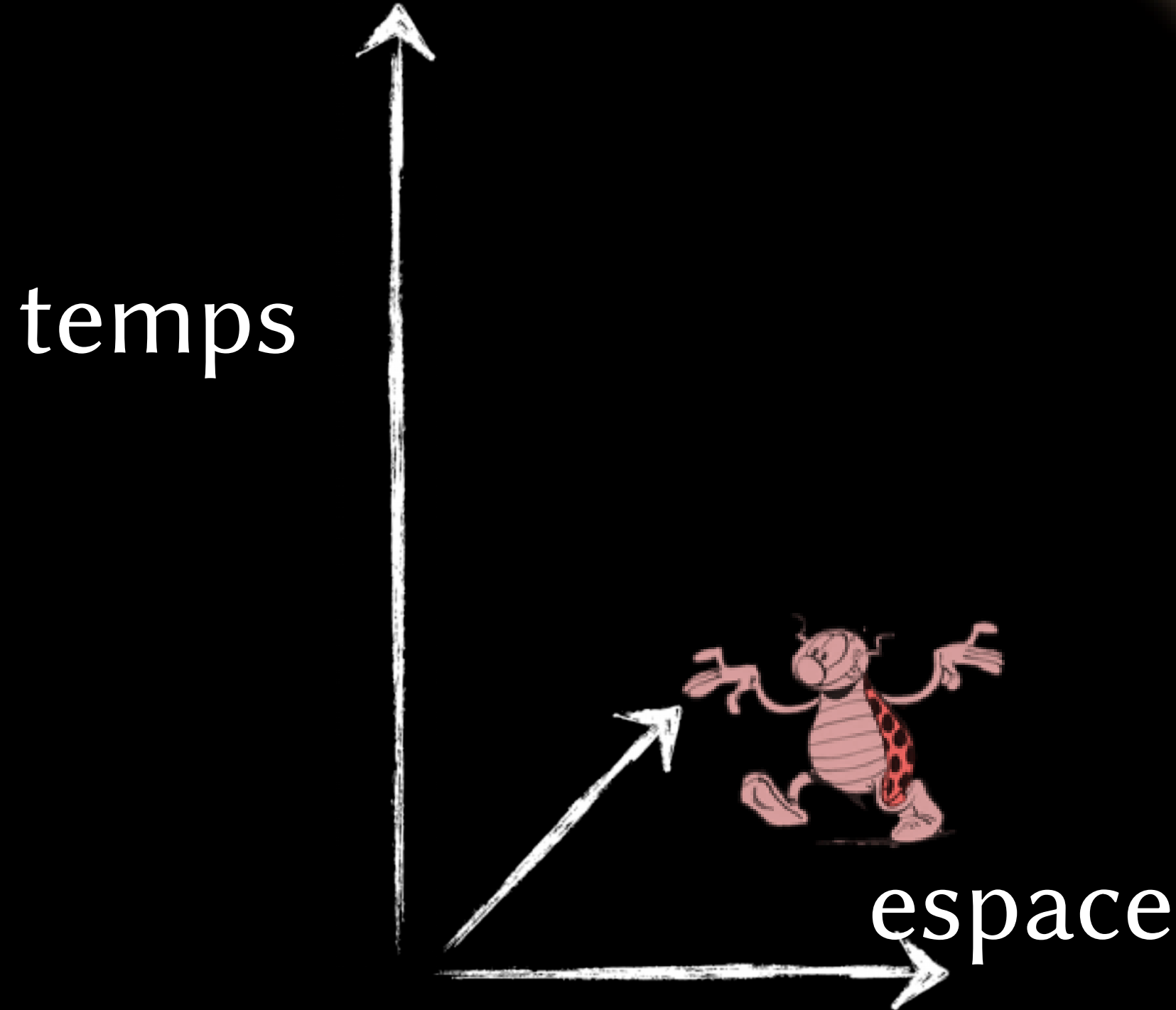


La cosmologie du Big Bang démarre il y a **13,7 milliards d'années**

- ▶ **3 minutes** plus tard, 99 % de la matière actuelle est synthétisée à partir des particules élémentaires
- ▶ **100 millions d'années** plus tard les éléments lourds (C, O, Fe,...) sont synthétisés dans le cœur des étoiles



# Big Bang



$t_0 + 13,7 \times 10^9$  années

CMB

QGP

$t_0$



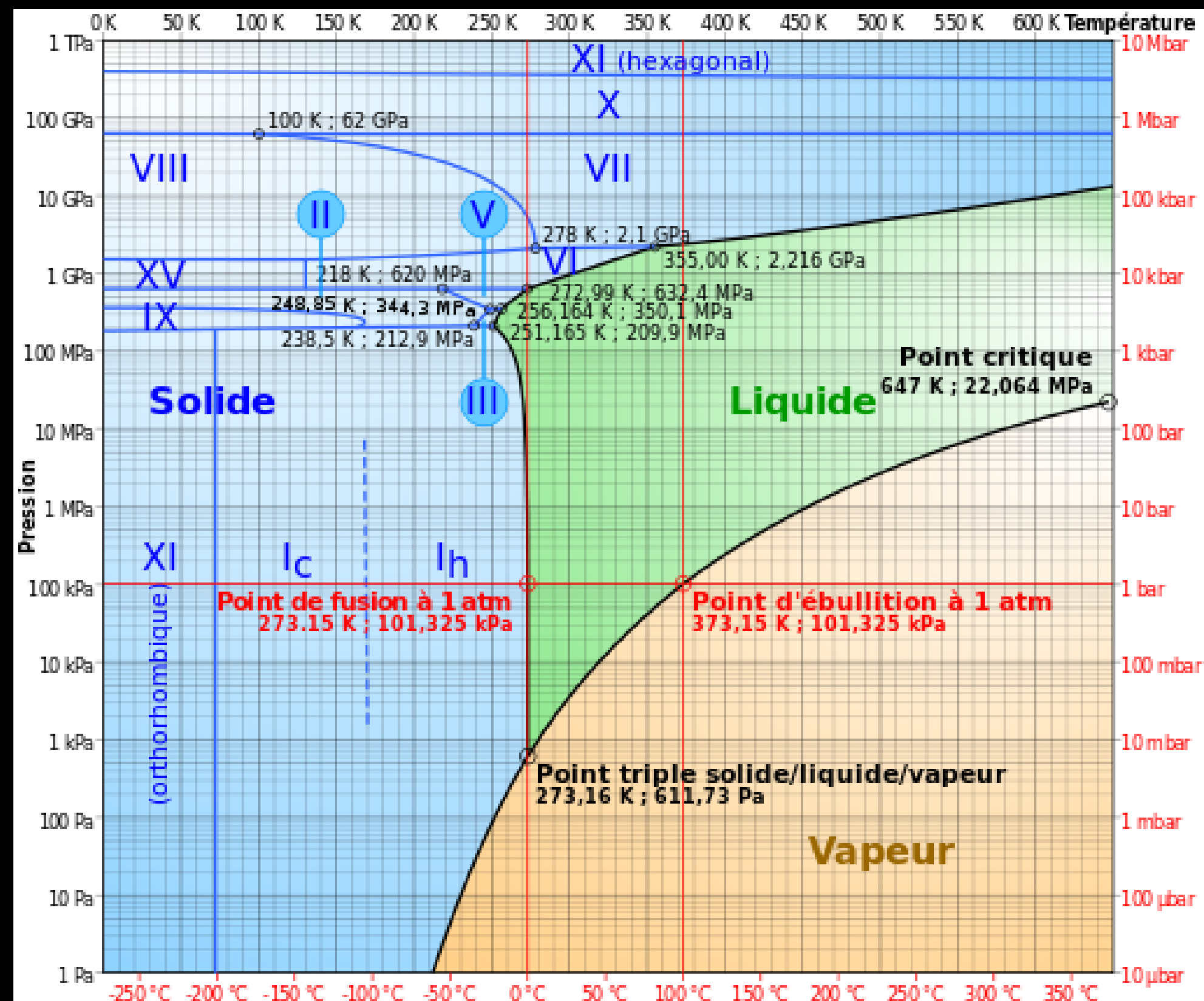
# Quelle matière primordiale ?

Un état de la matière à l'origine de la matière actuelle,



Un état de l'Univers qui court sur les premières  $\mu\text{s}$  après le Big Bang





# Diagramme des phases de l'eau



$$T_c = 160 \text{ MeV}$$
$$T_c \approx 2 \cdot 10^{13} \text{ }^\circ\text{C}$$

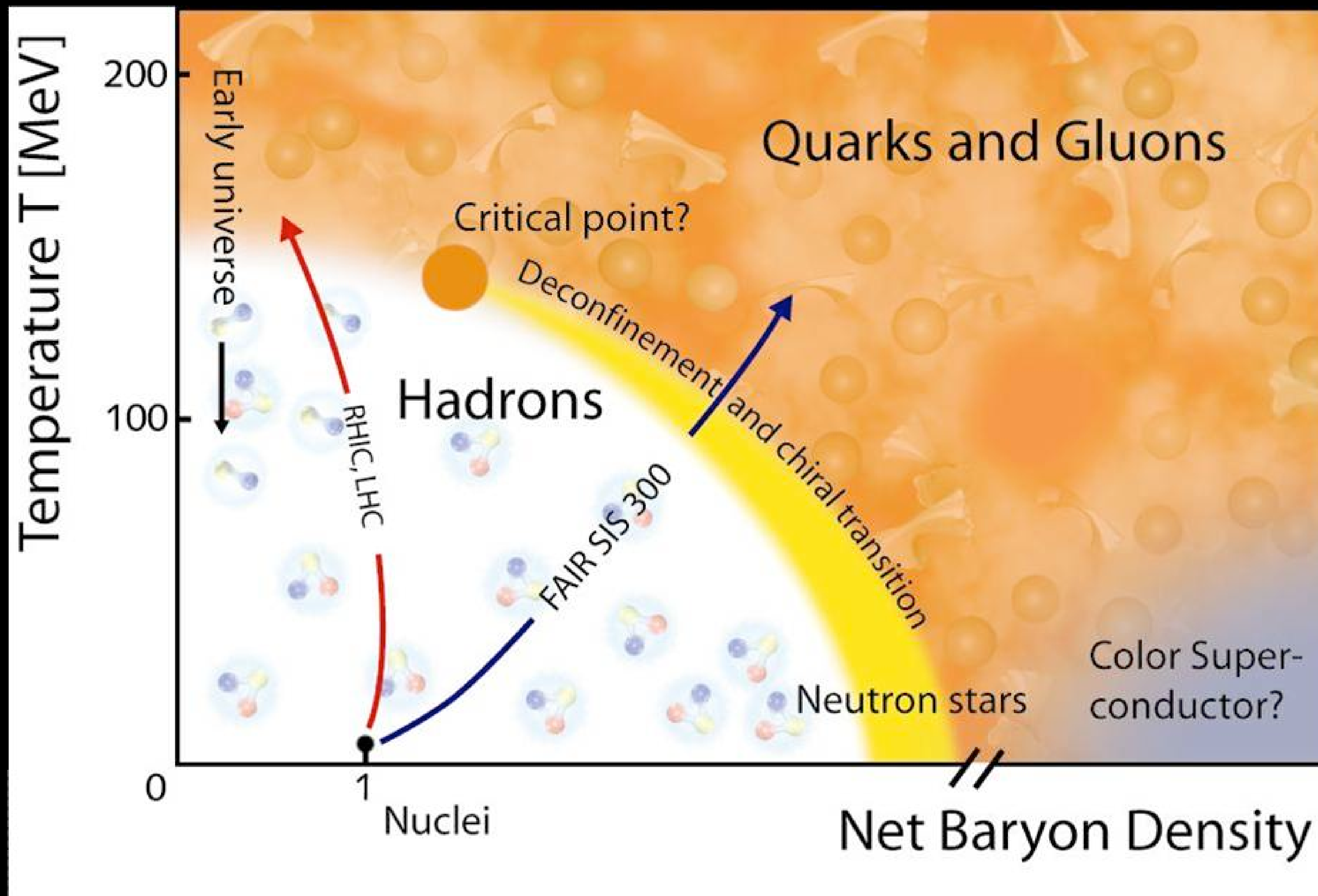


Diagramme de phase de la matière nucléaire



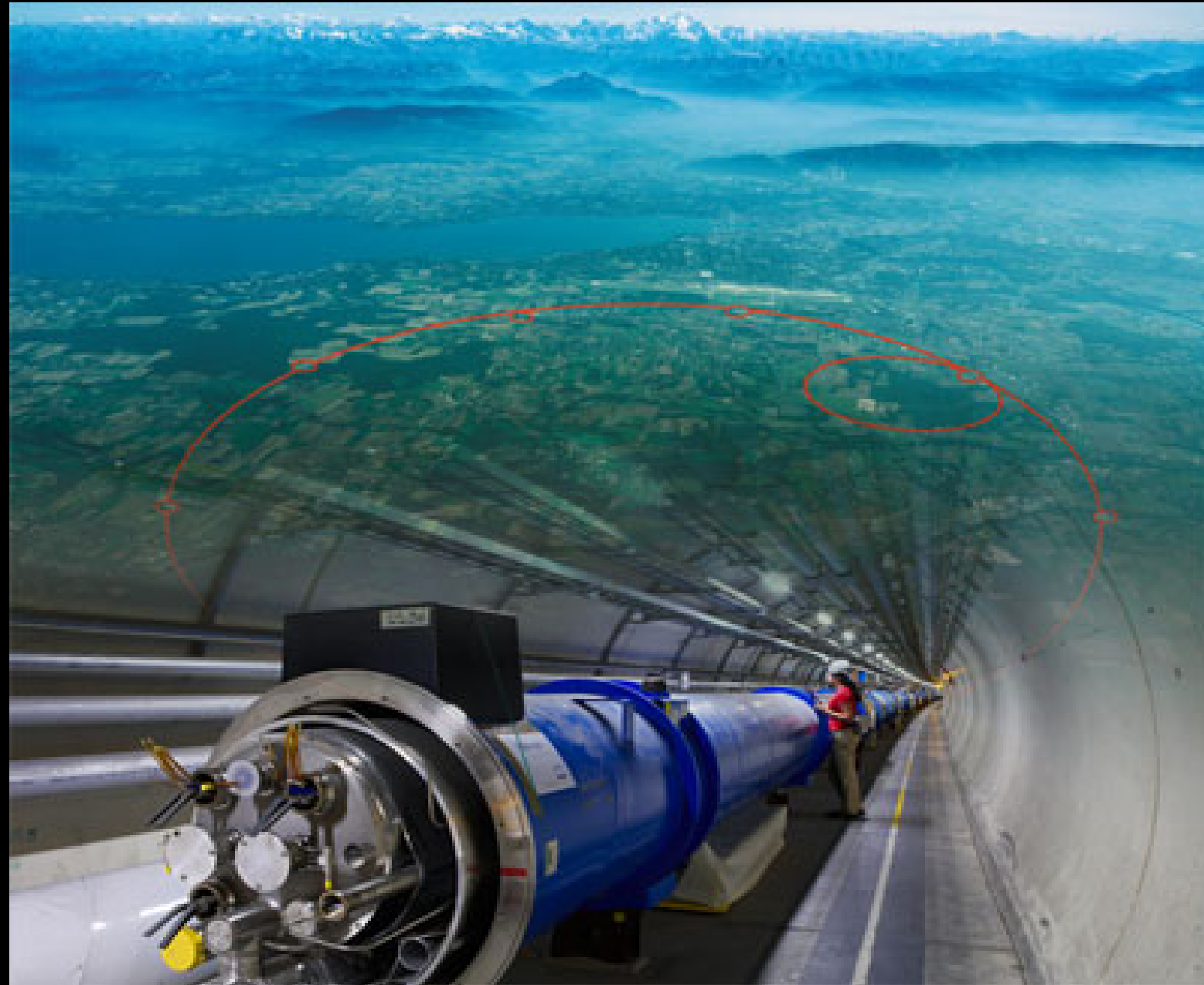


Acte III: recréer en laboratoire les  
conditions de la matière  
primordiale ...





# (...).1 – La machine LHC : 14 TeV dans quelques fm<sup>3</sup>



- The LHC en 1 chiffre :

≈ 1990 : « Pour avancer en physique des particules, disons que l'on a besoin de :

- collisions p-p at **2x 7 TeV** /

- collisions  $^{208}\text{Pb}^{82+} - ^{208}\text{Pb}^{82+}$  à **2x 2,76 TeV** »

→ 14 TeV ≈  $E_{\text{cin}}$  (moustique en vol) ...



*Tout ça pour ça ?!*

*Certes, mais ... 14 TeV ramené au volume d'un proton*

*i.e :  $E_{\text{cin}}$  (moustique en vol) in  $V(\text{moustique}) / (10^{12})^3$*

*→ clé : ≠ énergie mais plutôt la densité d'énergie.*



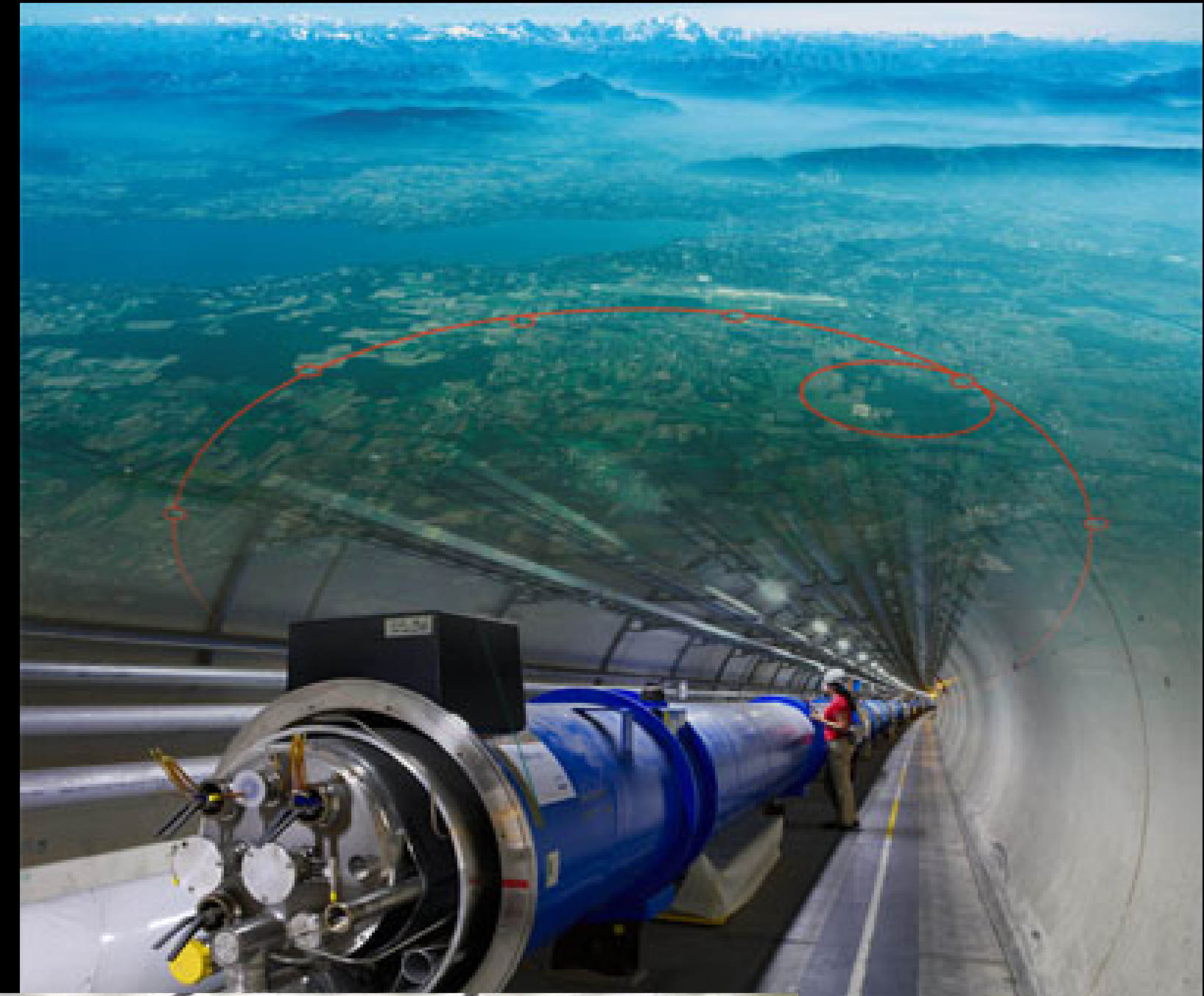
## (...).2 – La machine LHC : en 9 chiffres

CERN, LHC guide, CDS-2255762

Des faisceaux de protons à 7 TeV exigent ...

1. *vitesse* = 99,999 999 1 % de  $c_0$
2. *longueur* = anneau de 26,7 km de circonférence
3. *champs magnétiques* = 8,33 T
4. *courant de bobine* = 11 850 A
5. *température* = 1,9 K = -271,3° C
6. *pression* =  $10^{-13}$  atm
7. *énergie stockée par faisceau (pp)* = 346 MJ
- (8. *consommation électrique* = 120 MW)
9. *collisions (pp)* =  $400 \cdot 10^6 \text{ s}^{-1}$

...

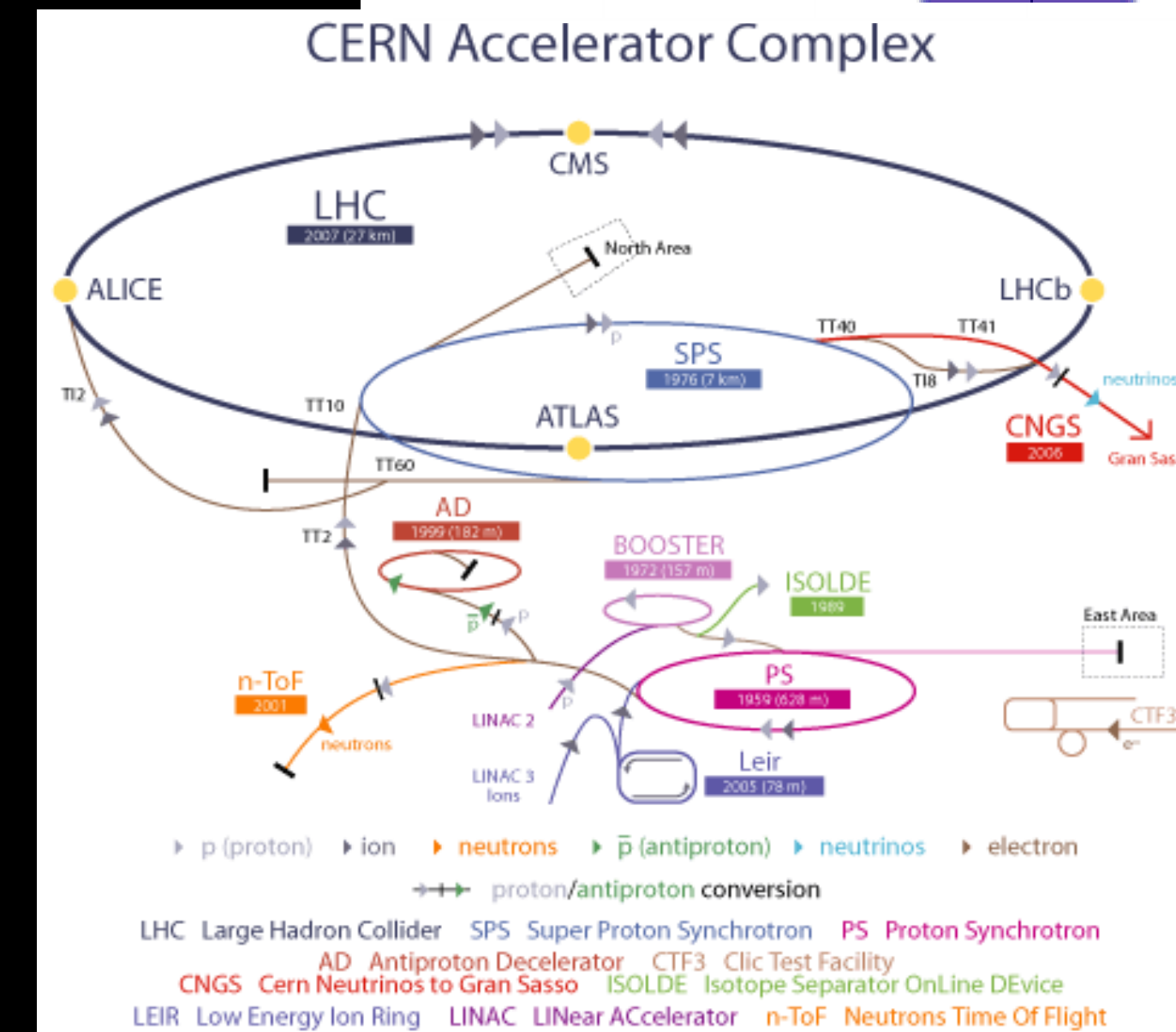
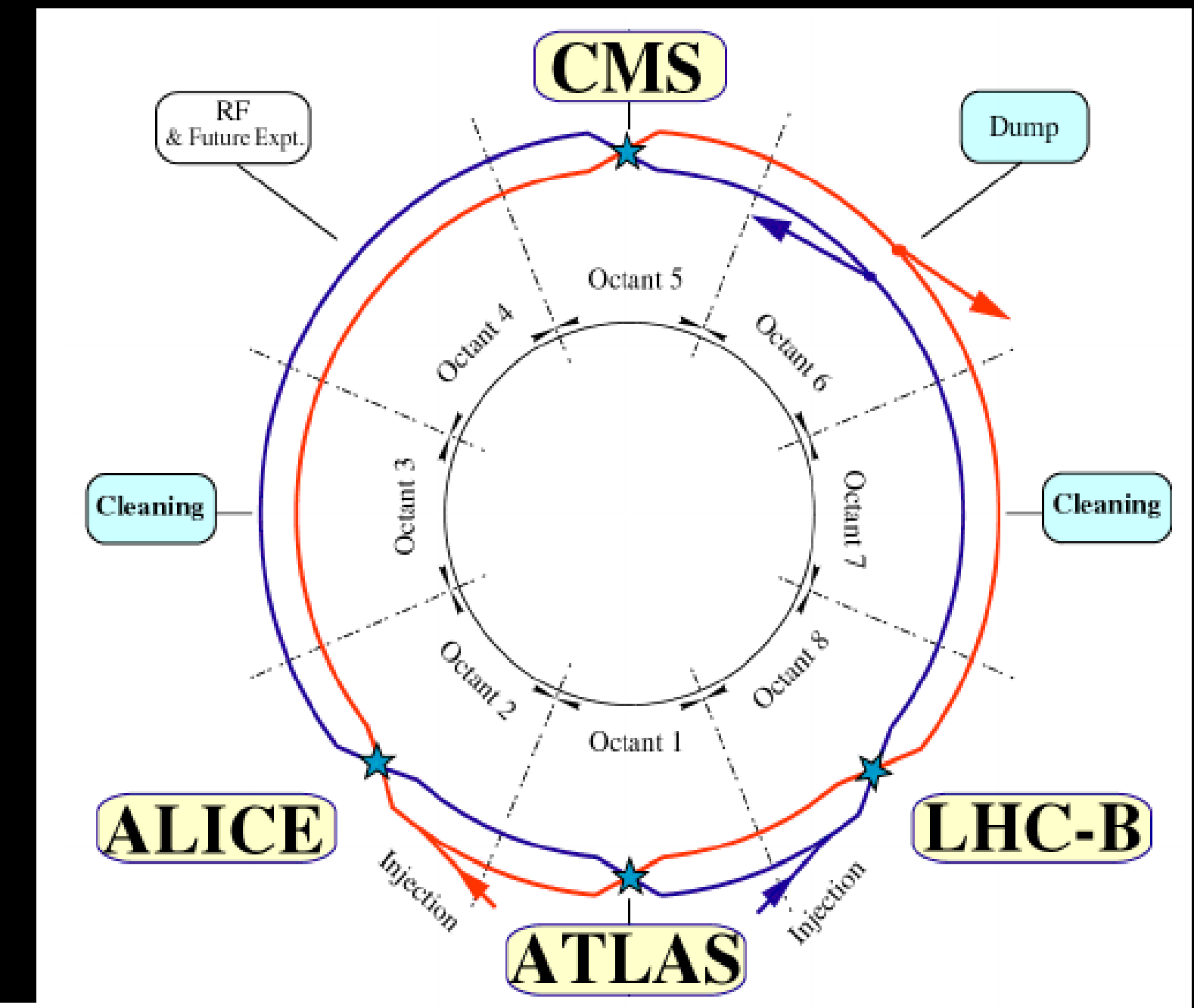




# (...).3 – La machine LHC : animations

*The LHC guide, 2017*

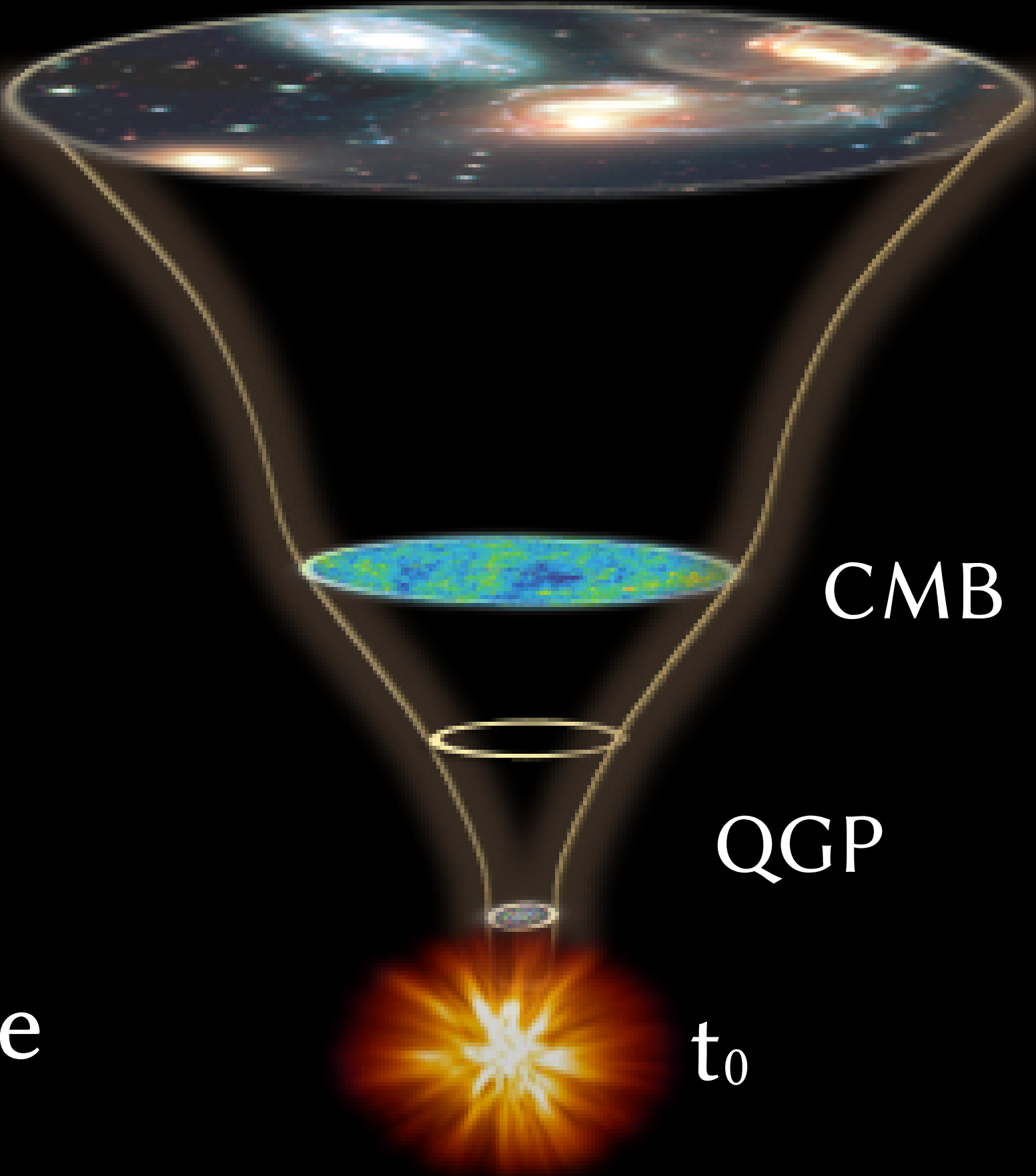
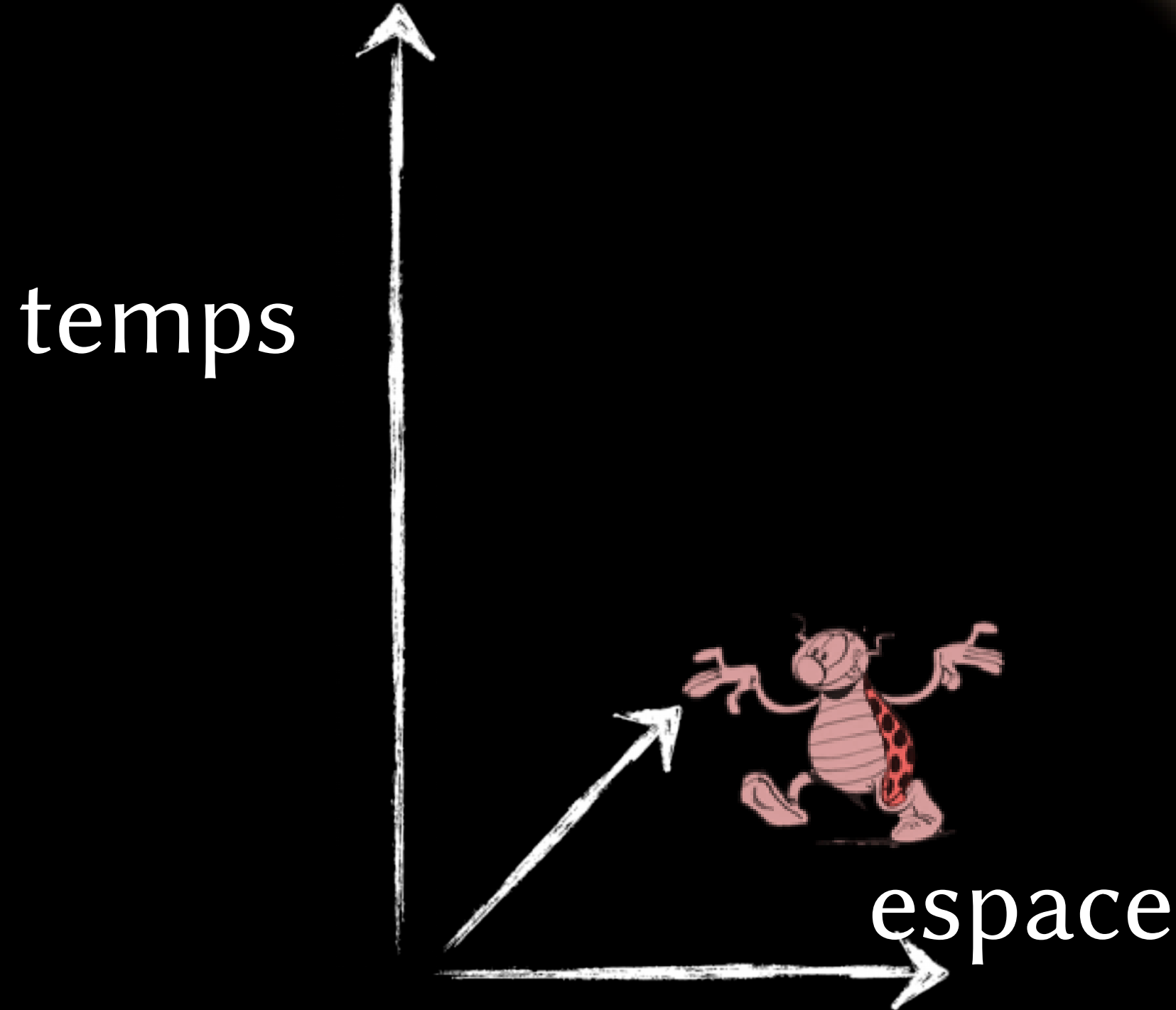
- CERN maps  
<https://maps.cern.ch/>
- LHC filling scheme viewer :  
[https://lpc.web.cern.ch/cgi-bin/filling\\_schemes.py](https://lpc.web.cern.ch/cgi-bin/filling_schemes.py)
- LHC From the Linac to the LHC : CDS Record - 1750702 (9min21s)  
CDS decomposition :
  - 01 – LHC proton source
  - 04 – LHC wire scanner
  - 05 – PS
  - 06 – SPS
  - 07 – Beam visualisation screen + pilot beam
  - 08 – LHC Dipole Magnets
  - 09 – LHC Quadripoles
  - 10 – RF Cavities
  - 11 – LHC collimators
  - 12 – CMS data collisions



TBD : LHC dump ?



# Big Bang



$t_0 + 13,7 \times 10^9$  années

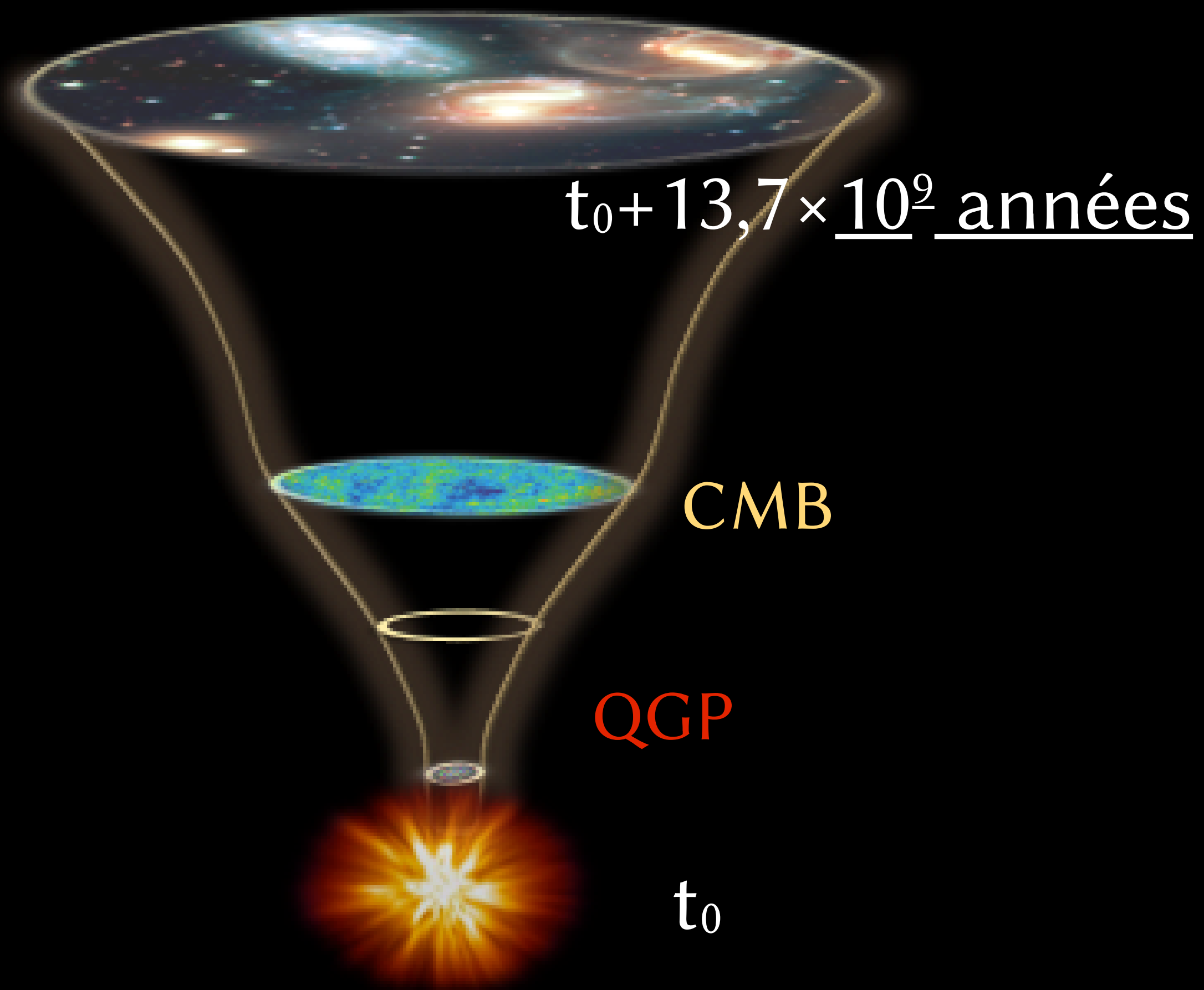
CMB

QGP

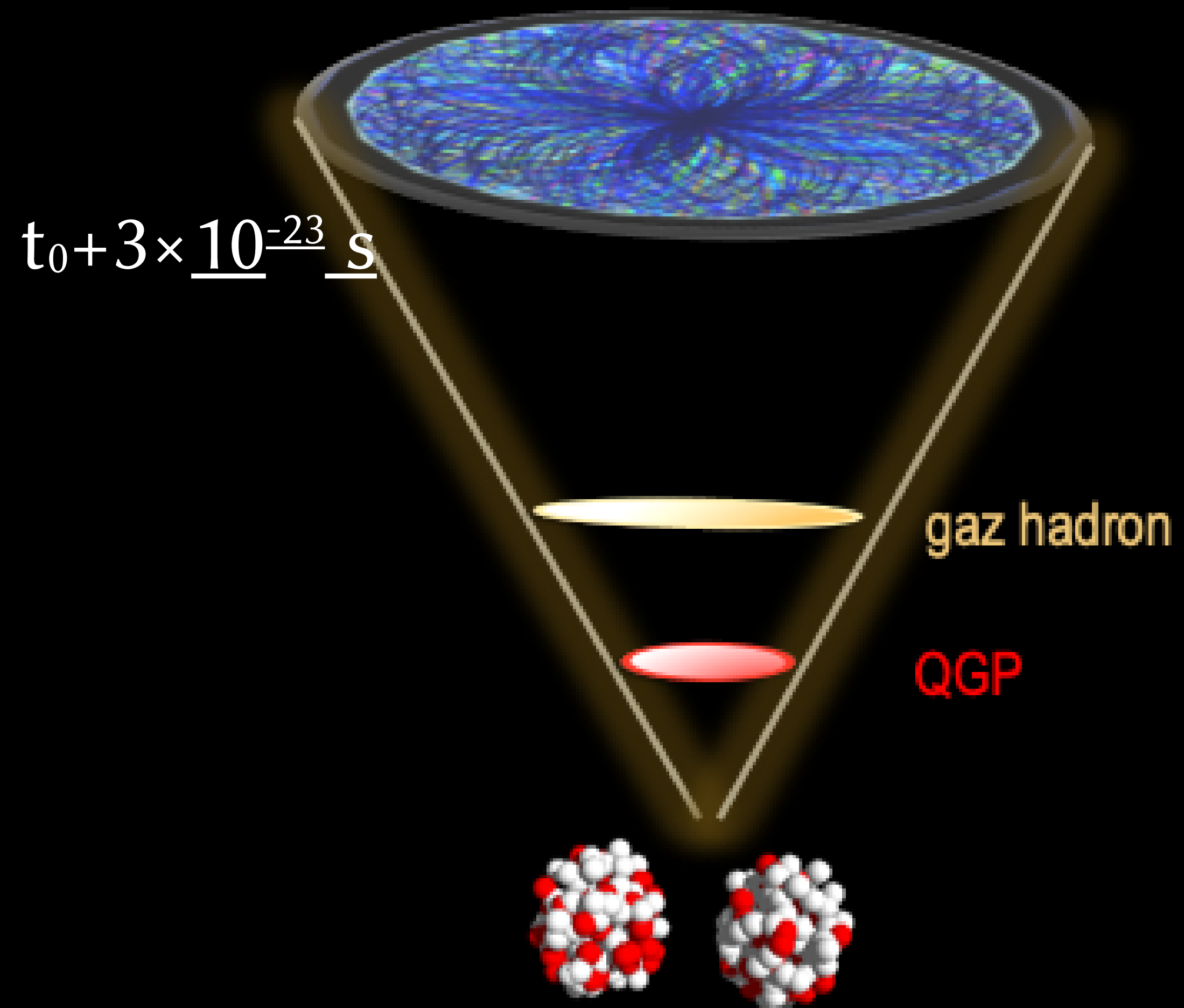
$t_0$



# Big Bang

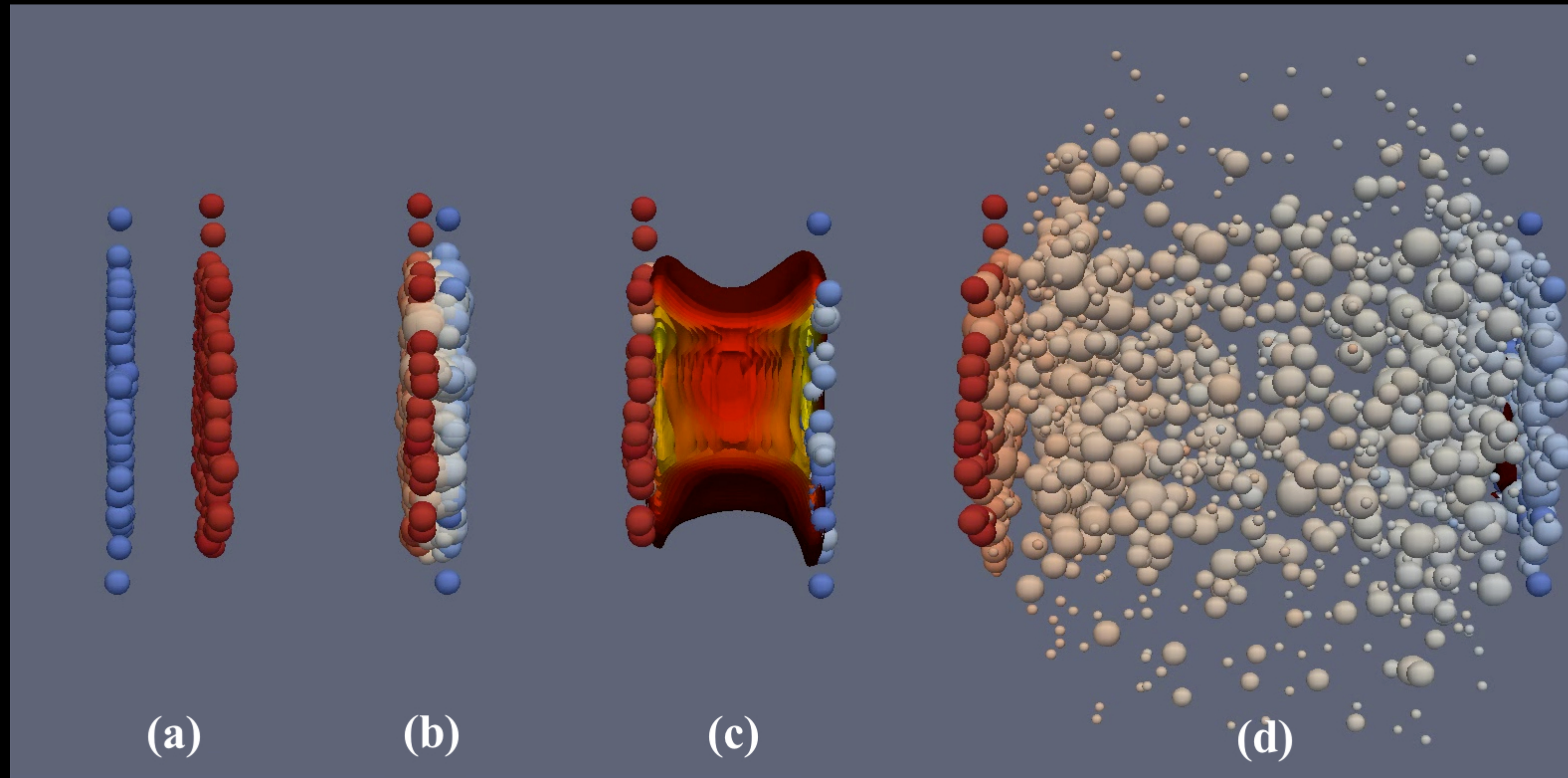


# Little Bang





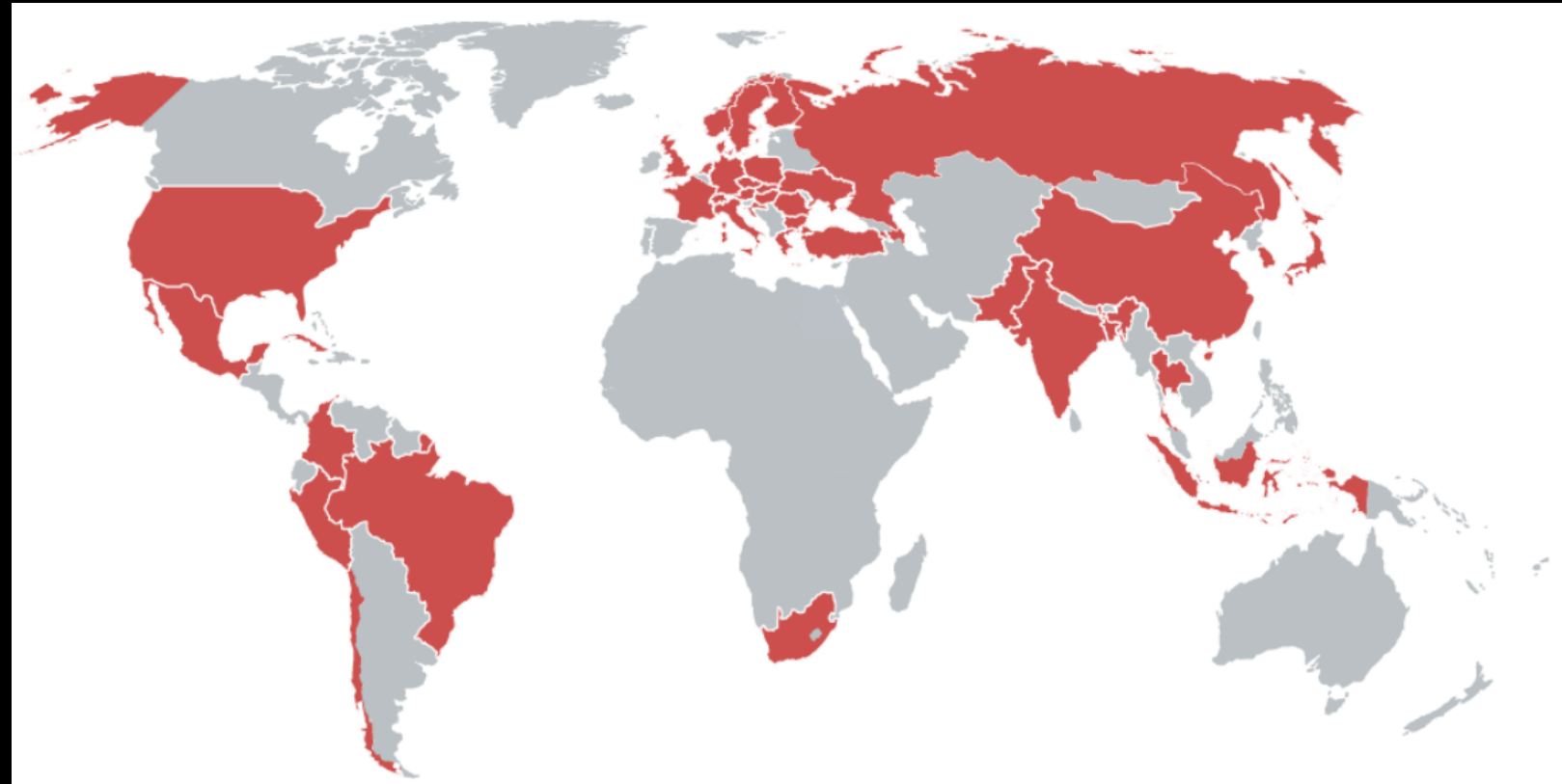
# De la matière primordiale pendant un laps de temps infiniment court (collisions glaçon-glaçon)



Madai.us : [video](#)

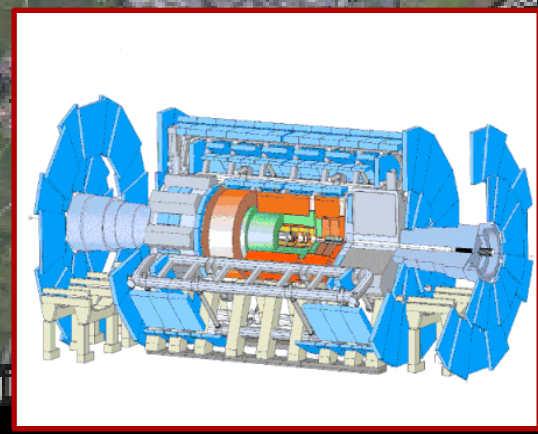
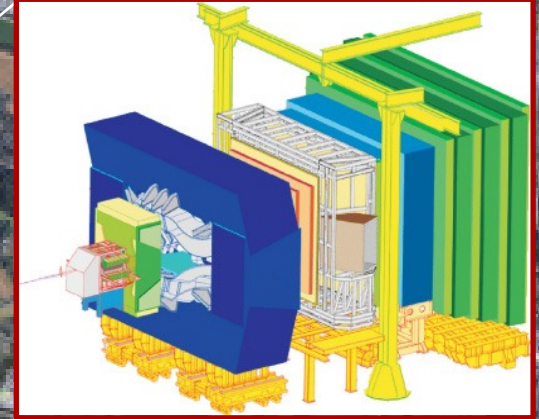
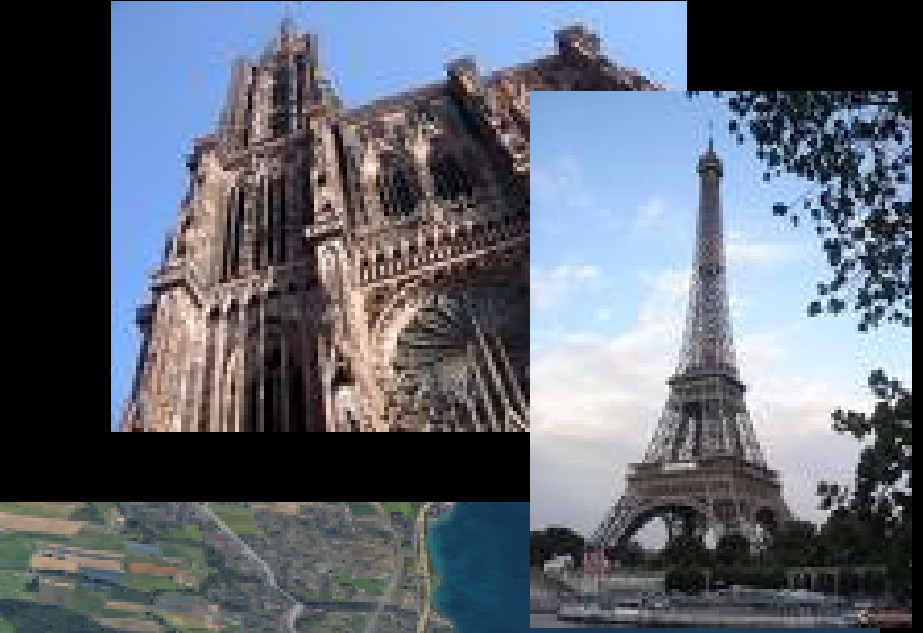
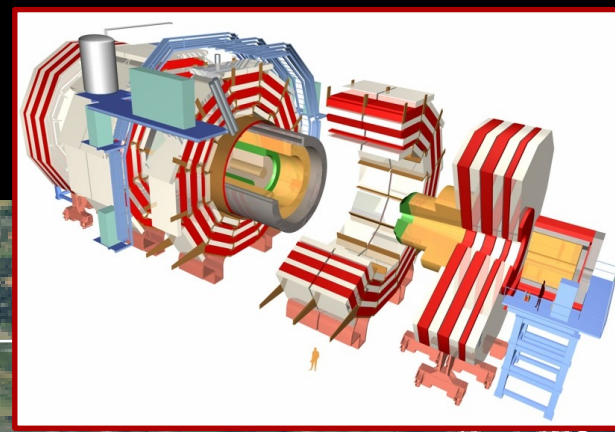
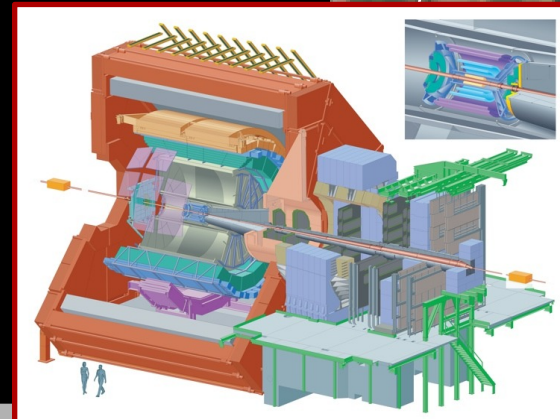






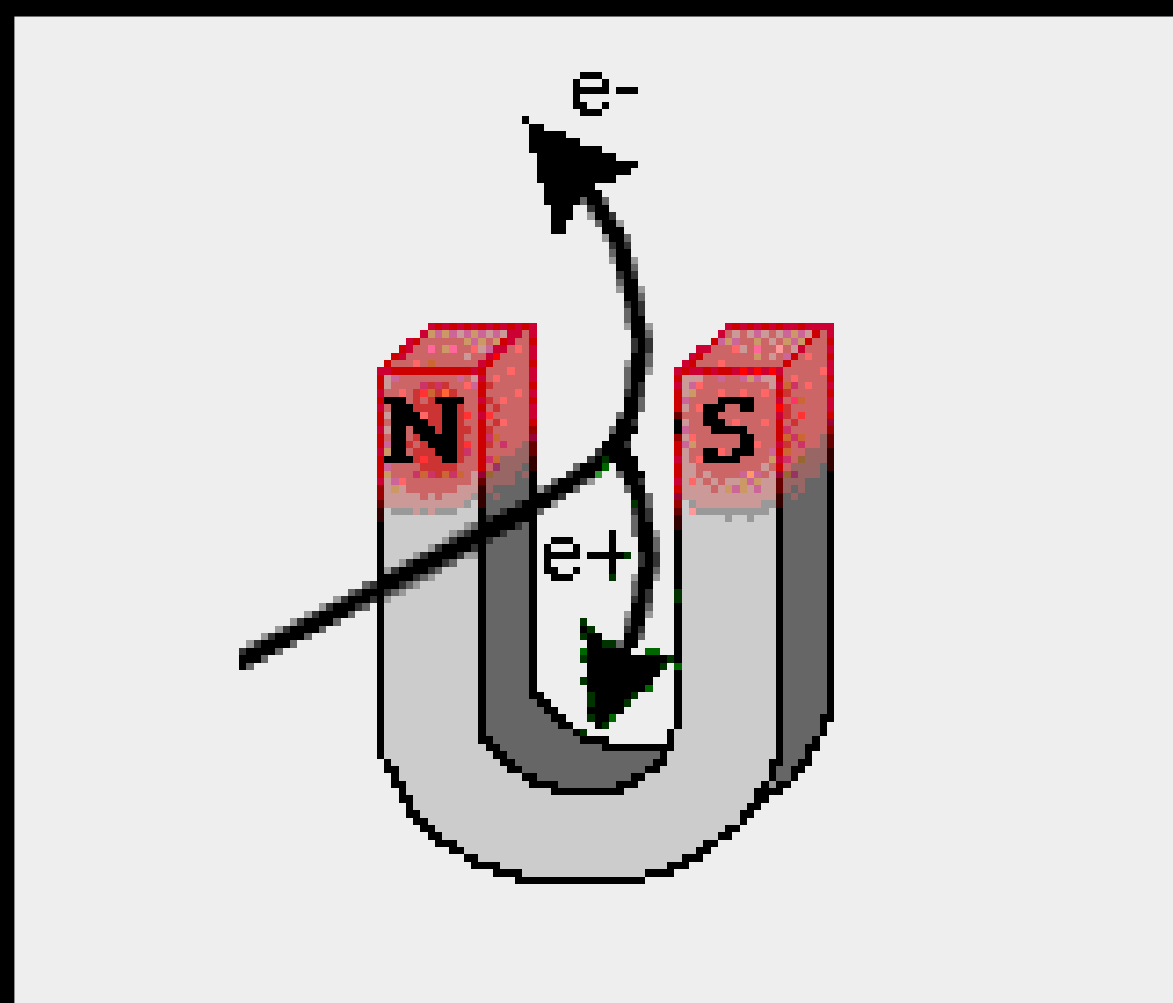
36 countries  
 147 institutes  
 $\approx 2.8 \times 10^3$  members  
 (1997-2018)  
 $\approx 830$  authors  
 (2018)

Dim :  $16 \times 16 \times 26 \text{ m}^3$   
 Mass : 10 000 t  
 Costs : 80 M€

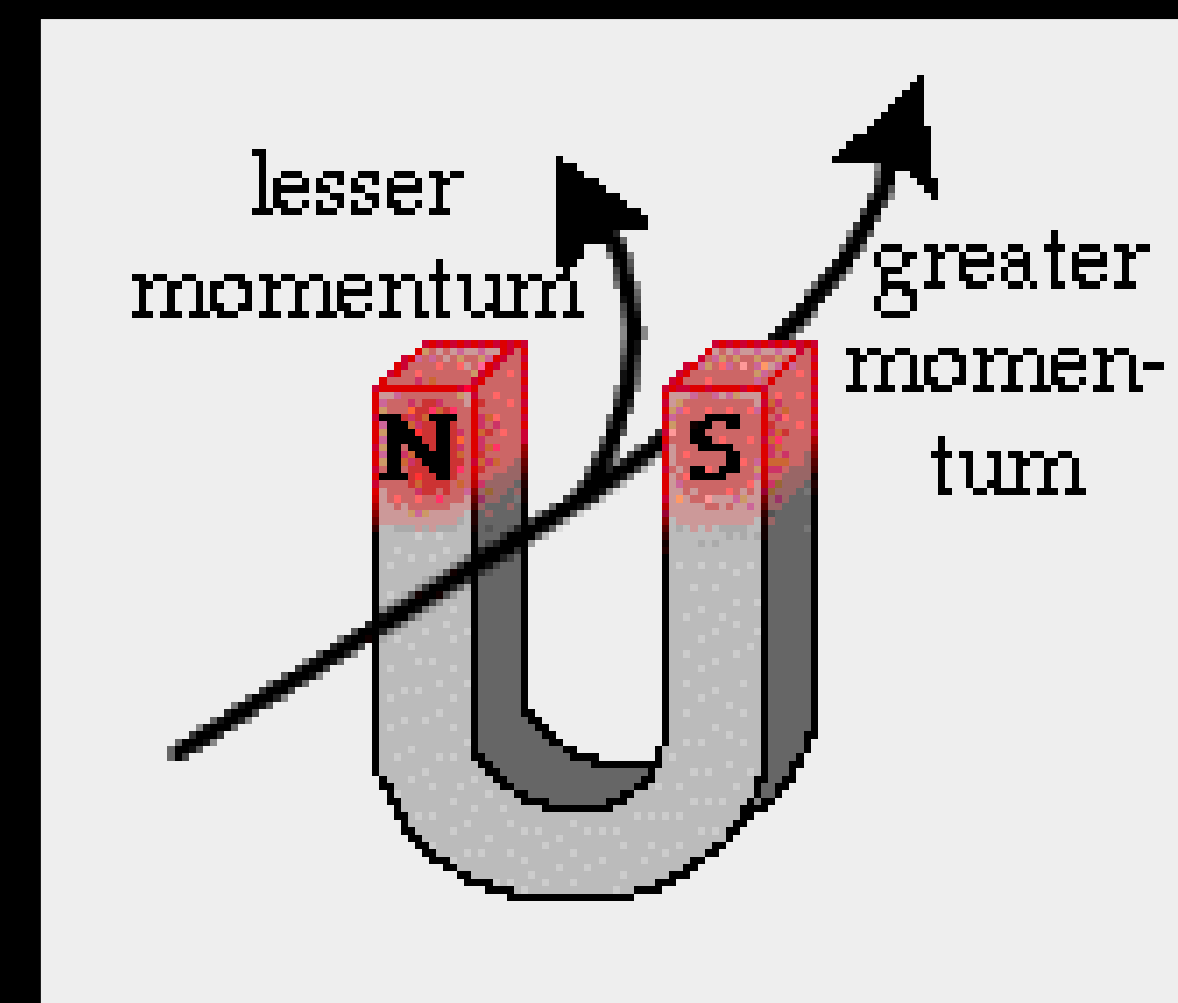
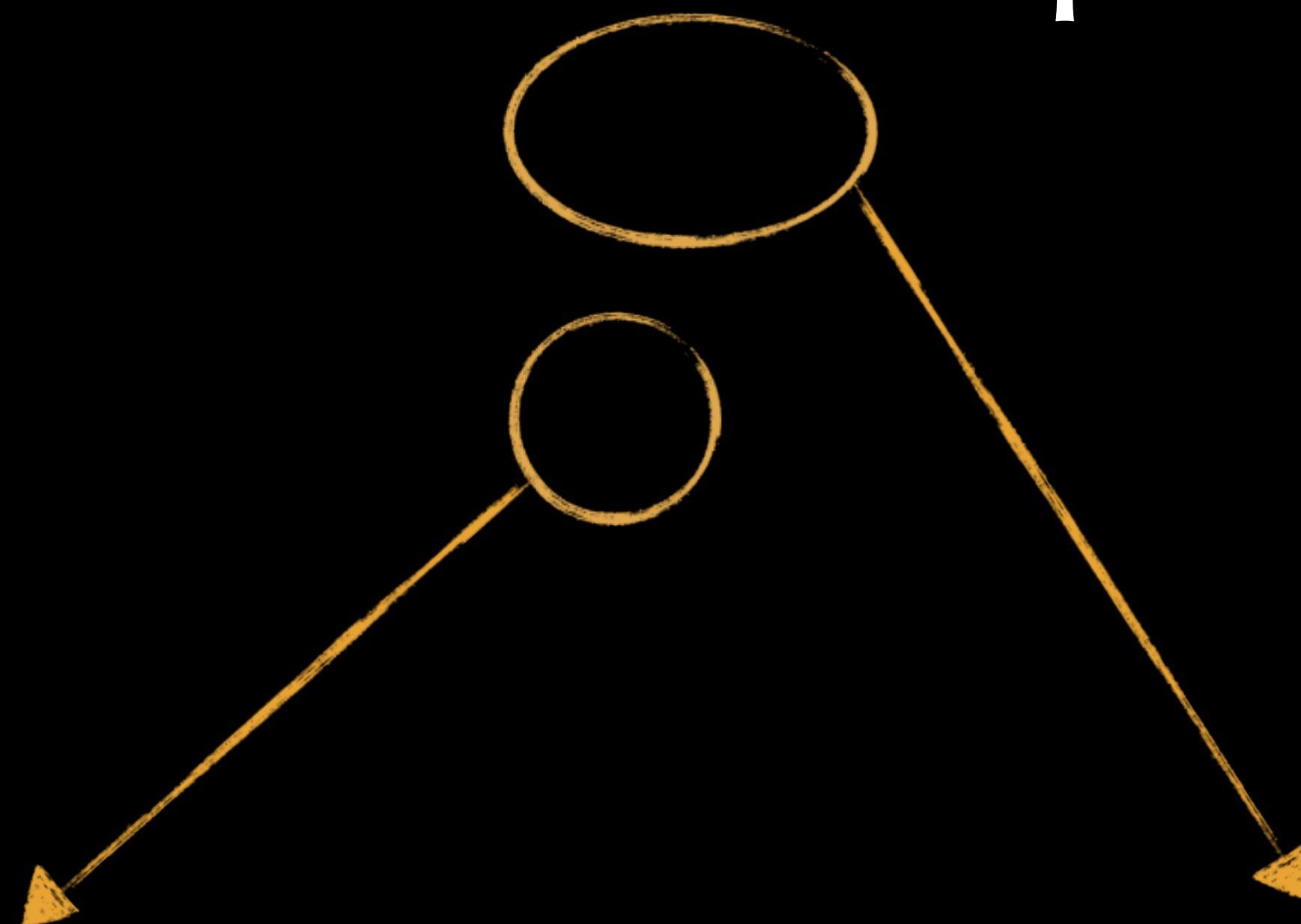




# Identification: un champ magnétique



Charge électrique  $\pm q$

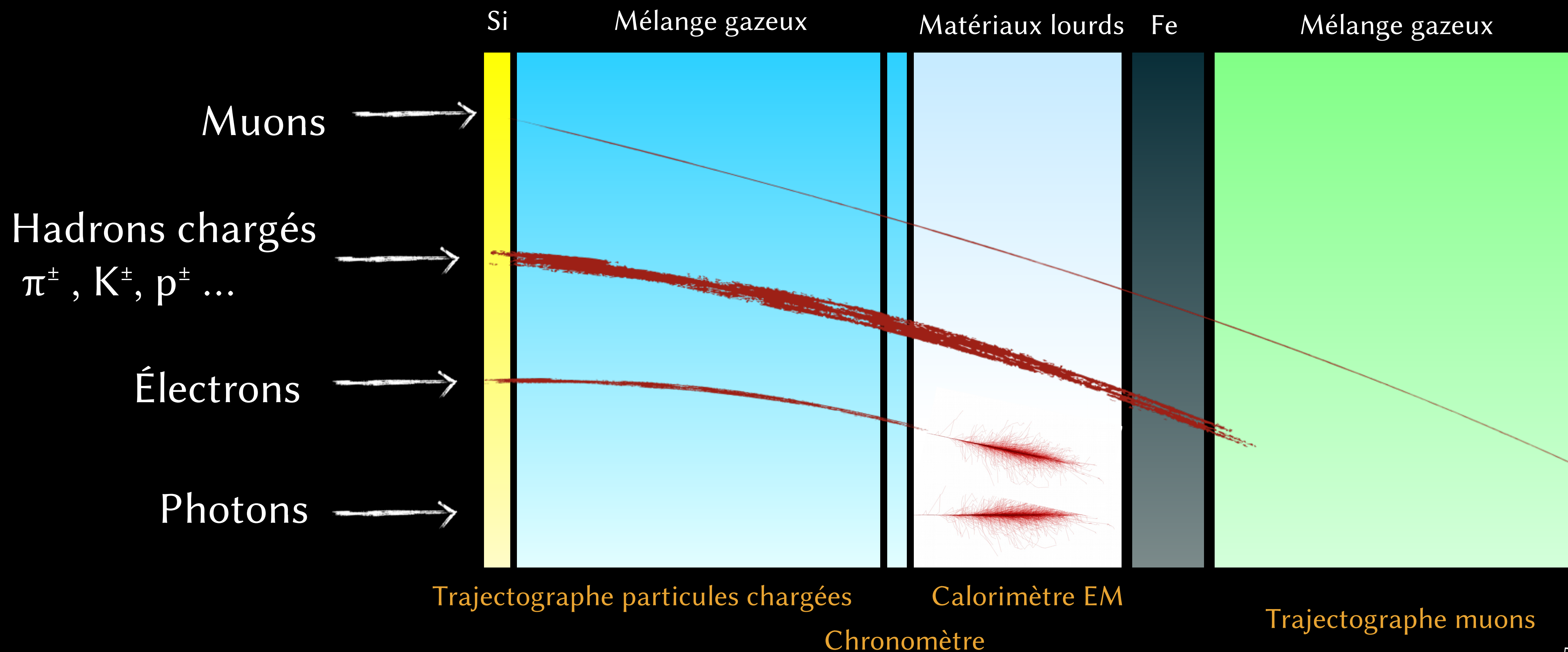


Quantité de mouvement,  
 $\gamma m \cdot v$

$$\frac{d\vec{p}}{dt} = q\vec{v} \wedge \vec{B} = \frac{q\vec{p}}{m\gamma} \wedge \vec{B} \rightarrow p = qBR$$

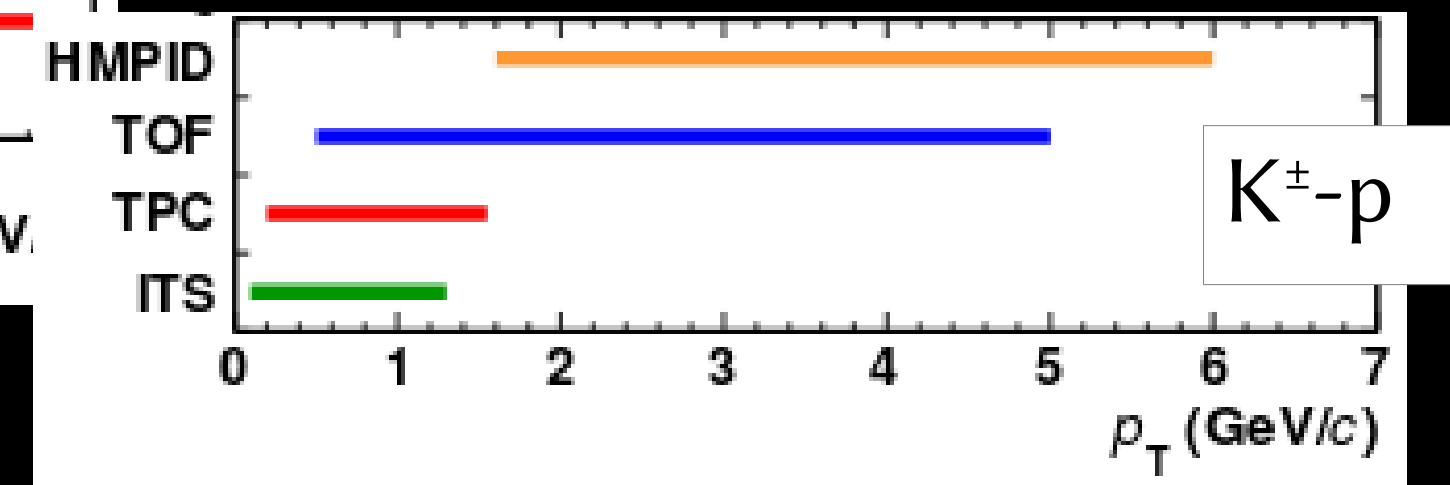
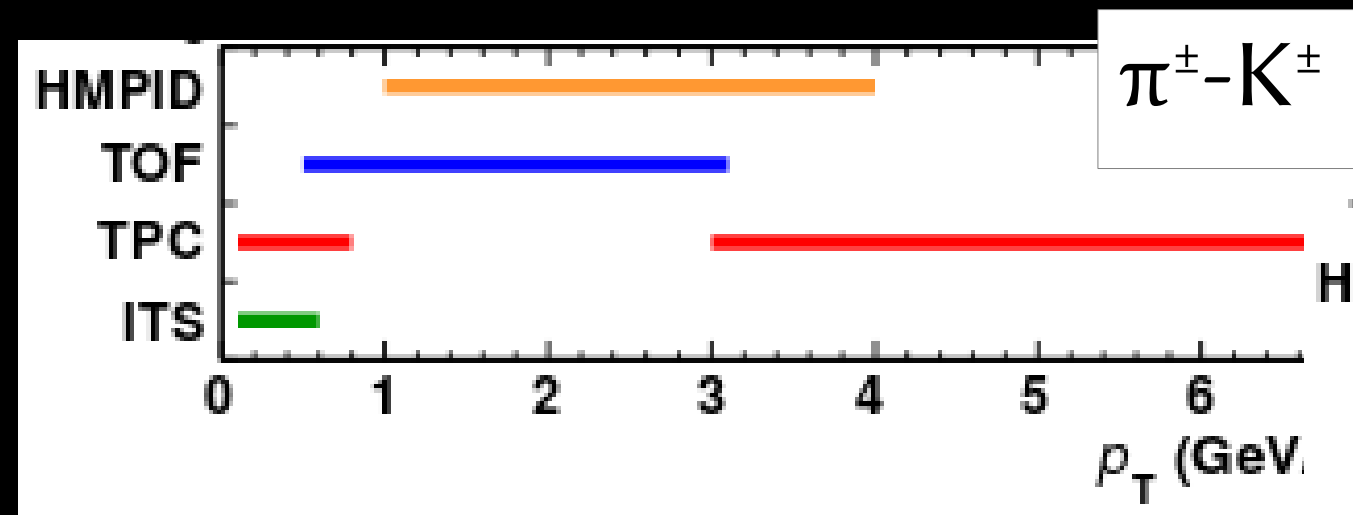
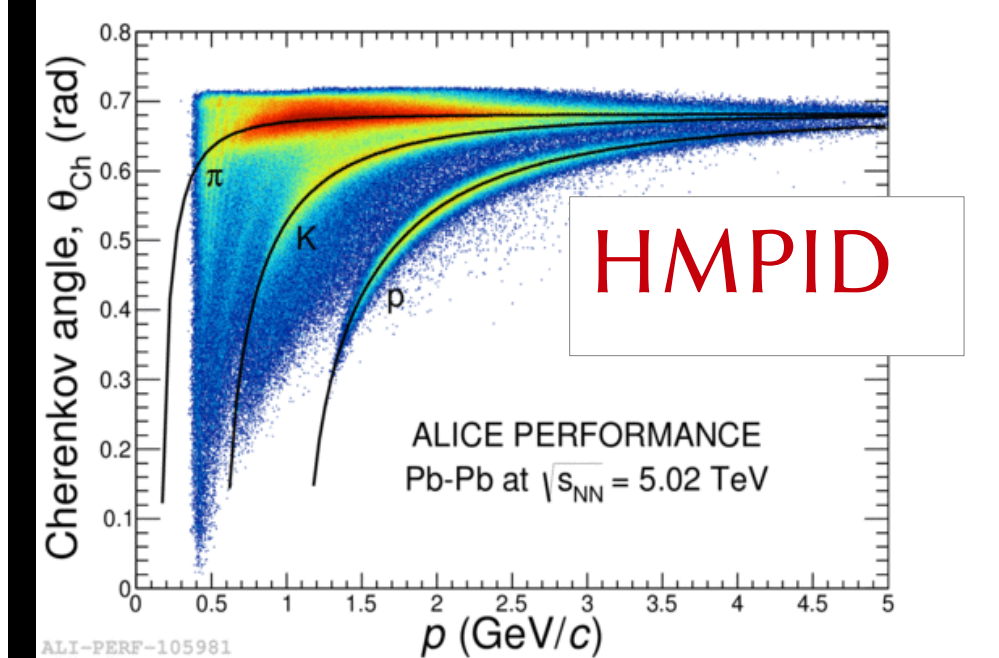
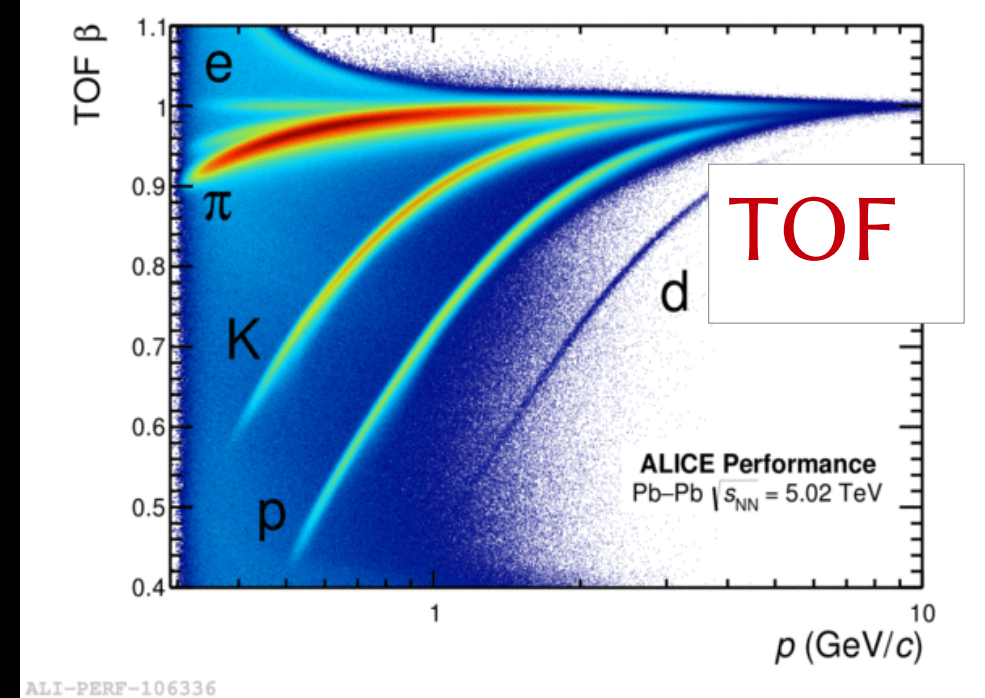
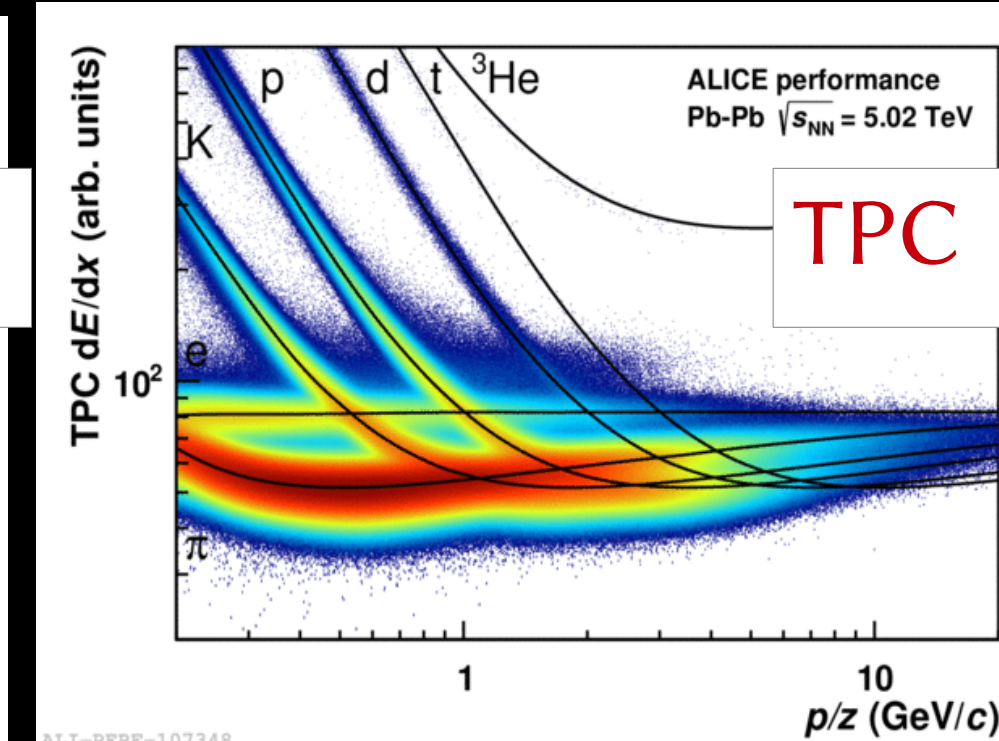
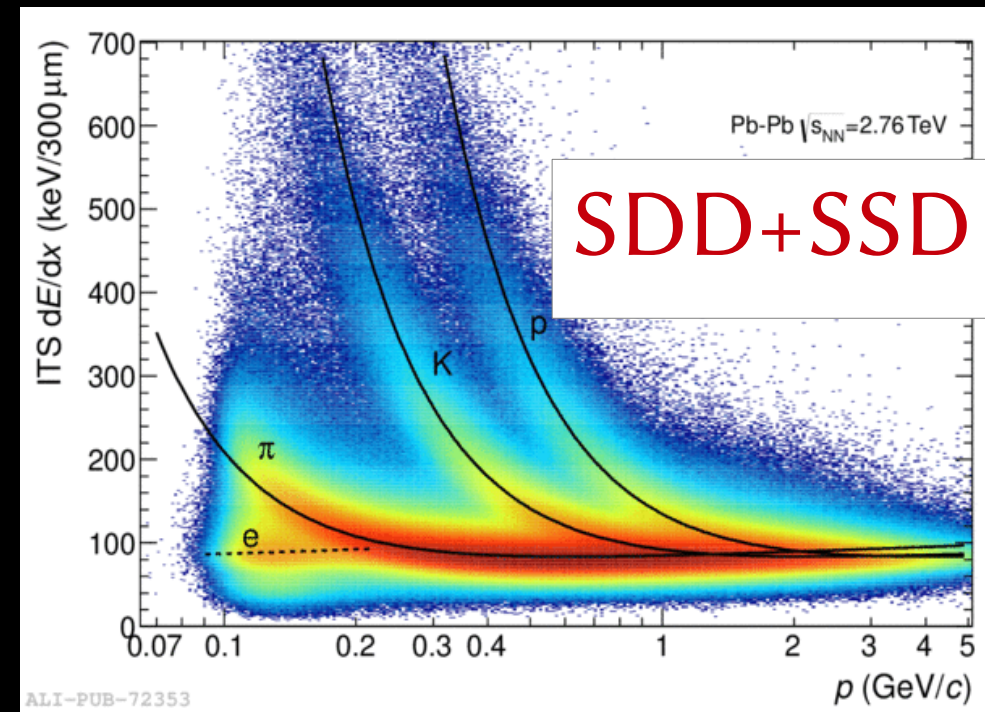
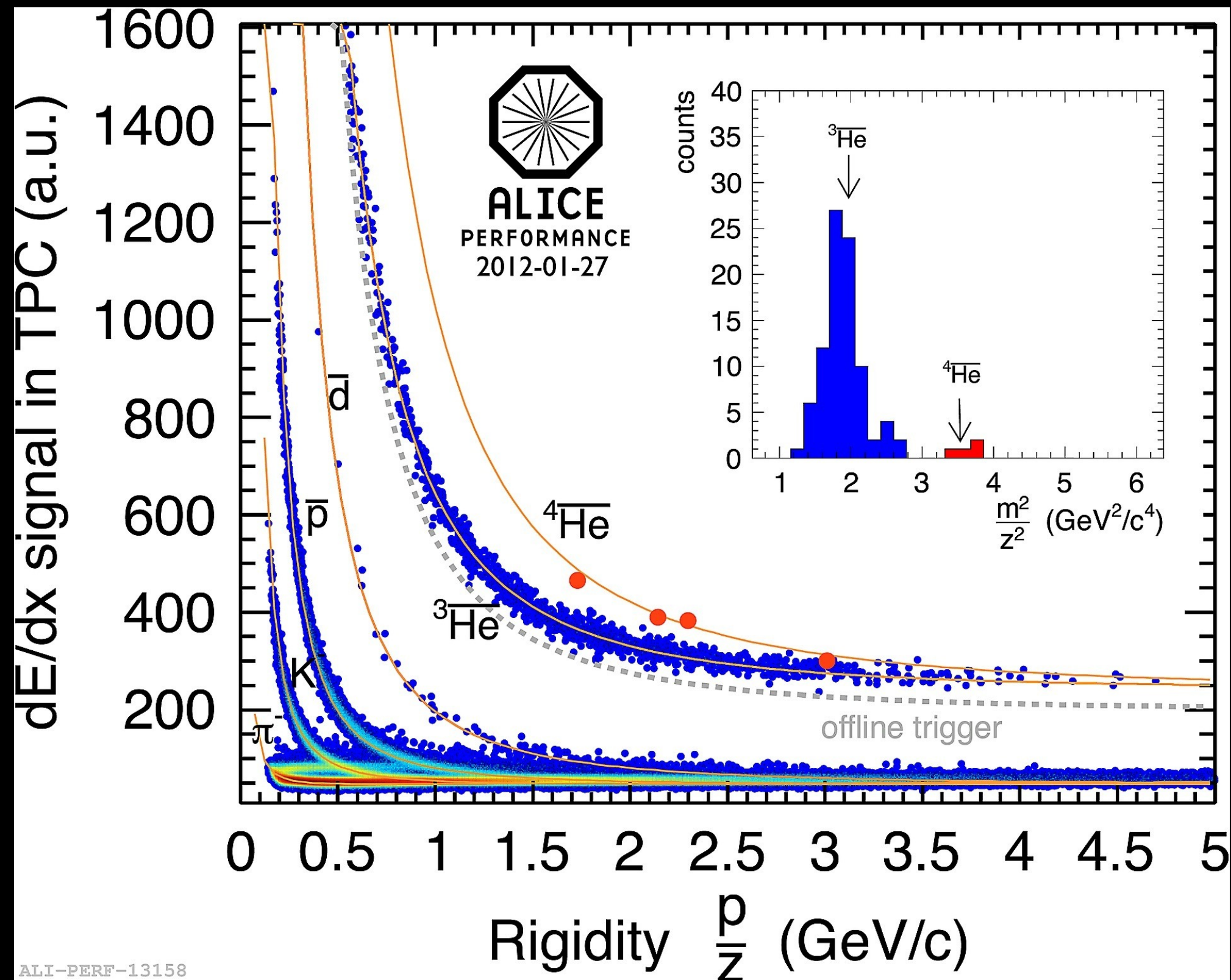


# Identification: interaction particule-matière



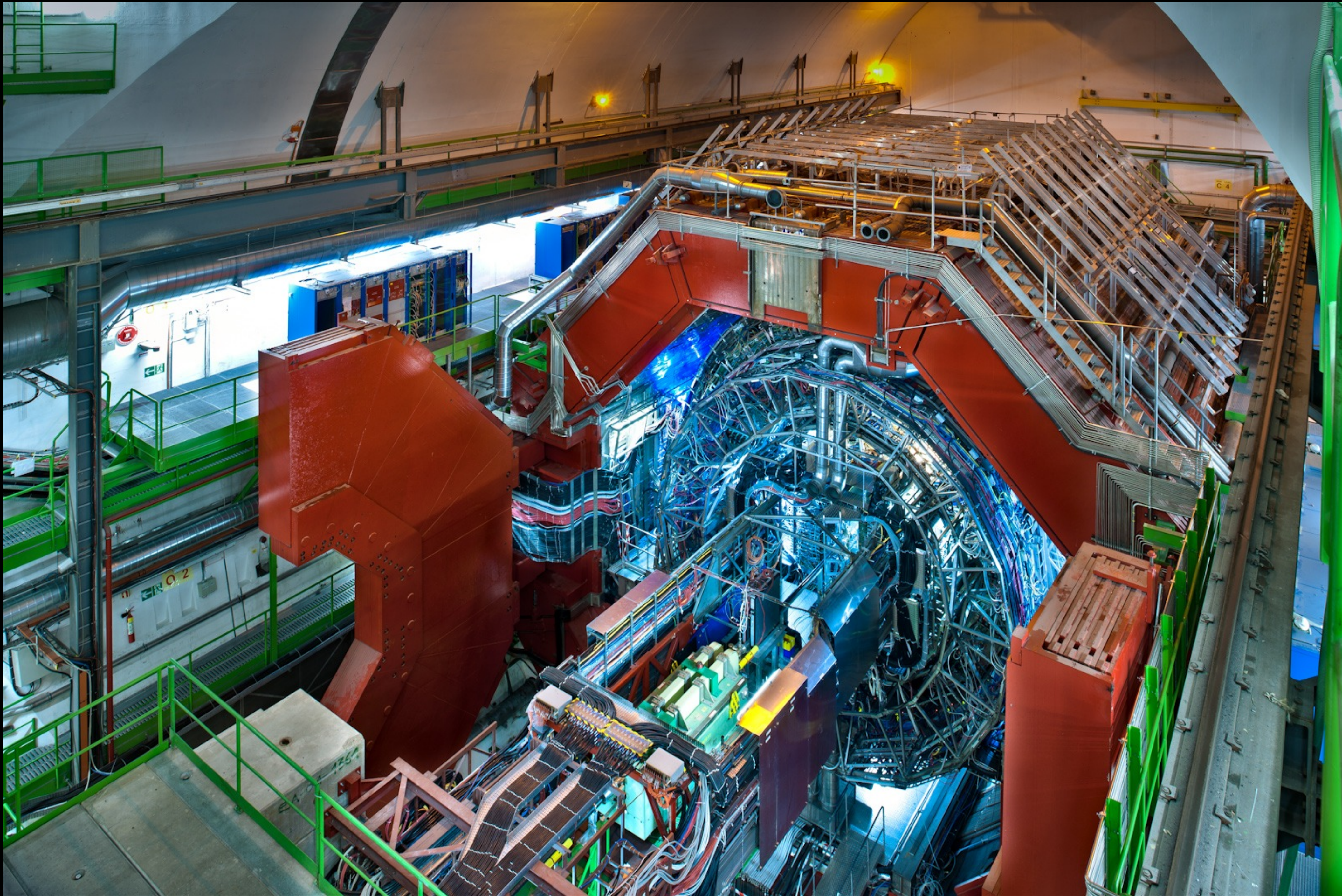


# Tous ensemble...



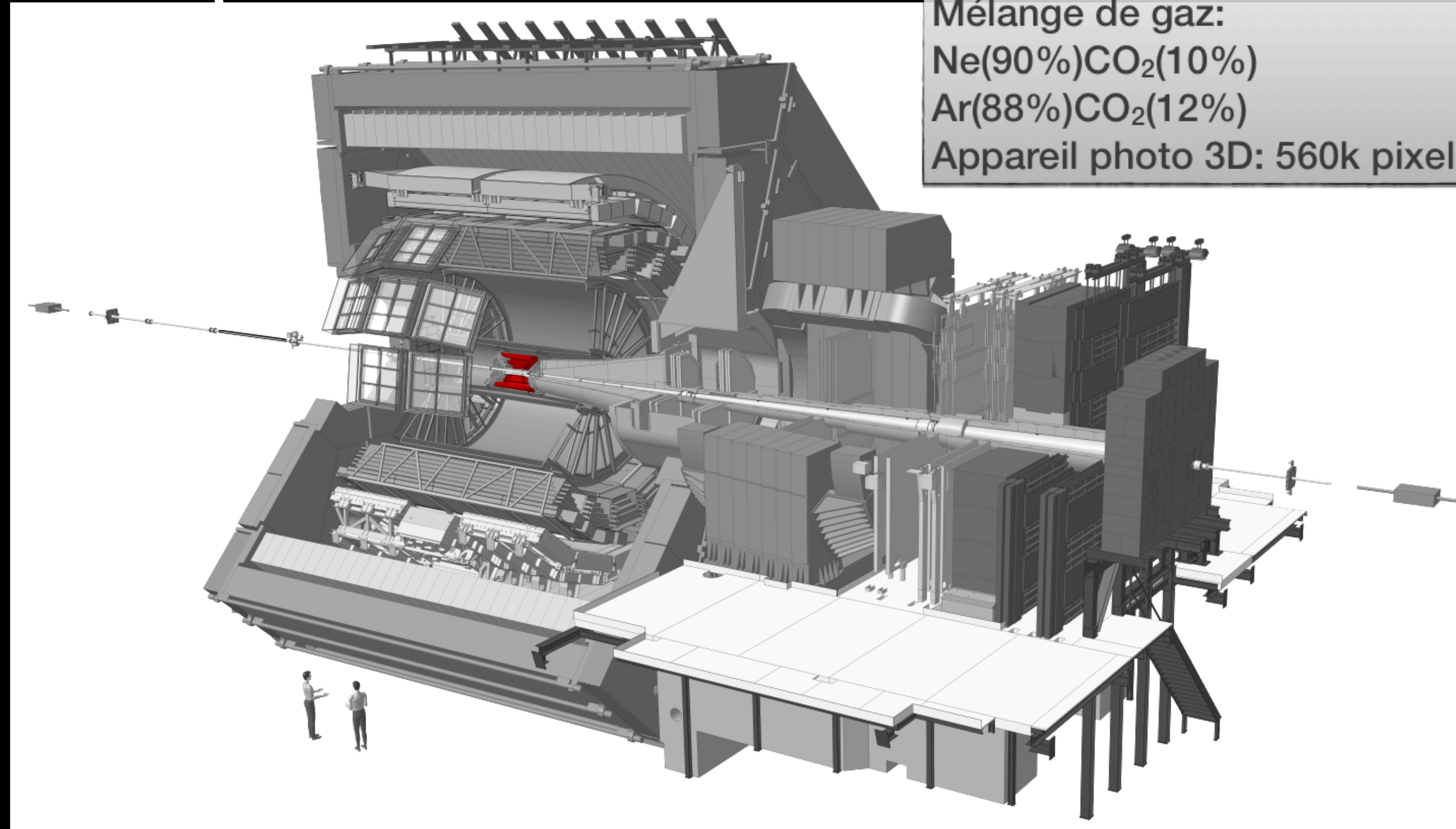
ALICE Perf., arXiv:1402.4476







# ALICE, un exemple



Mélange de gaz:

Ne(90%)CO<sub>2</sub>(10%)

Ar(88%)CO<sub>2</sub>(12%)

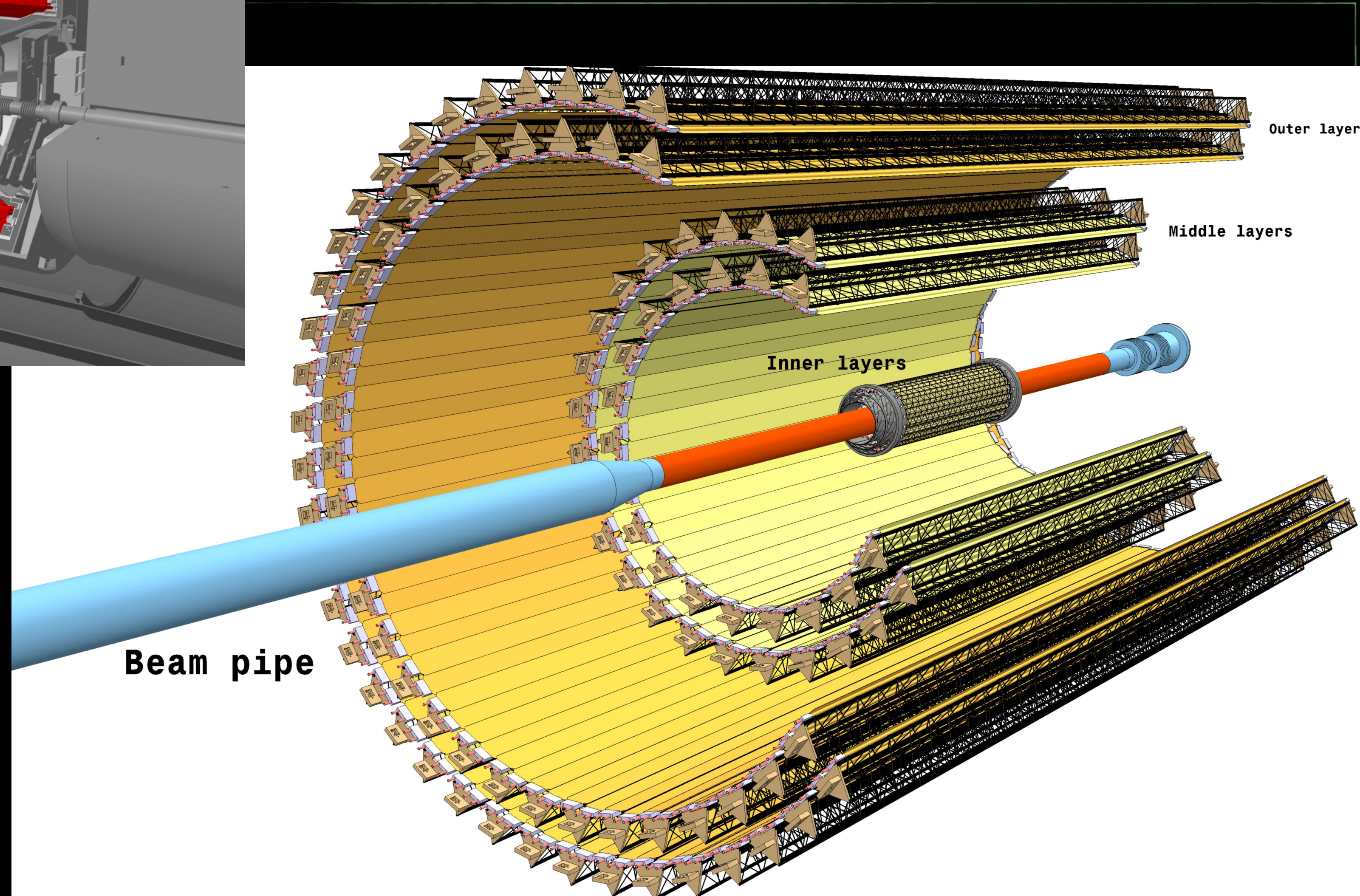
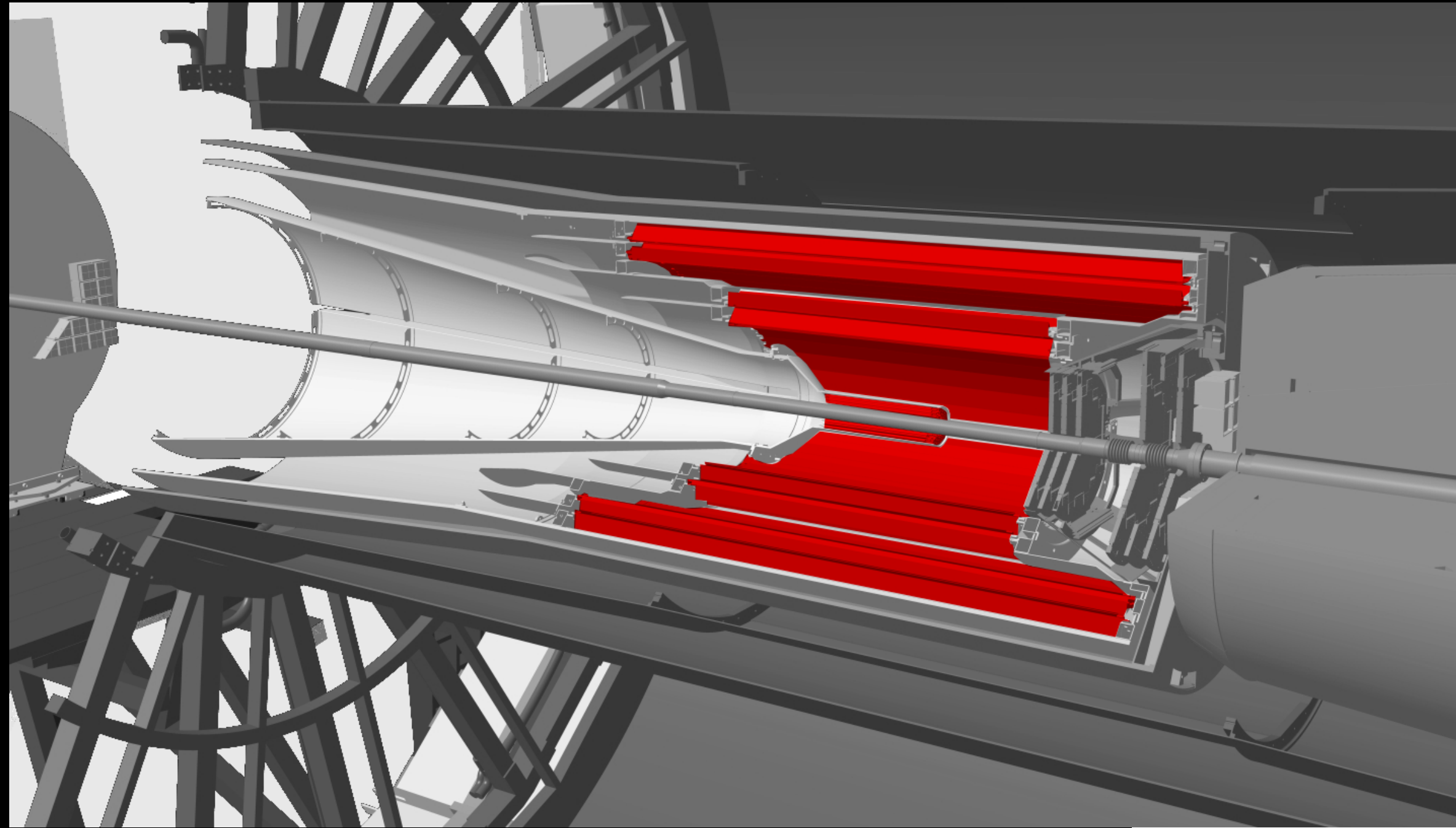
Appareil photo 3D: 560k pixels, 200 photos par seconde

► **Entourer** le point d'interaction

► Localisation: **segmenter** les éléments de détection en millions de cellules



# Silicium en vue pour 2021

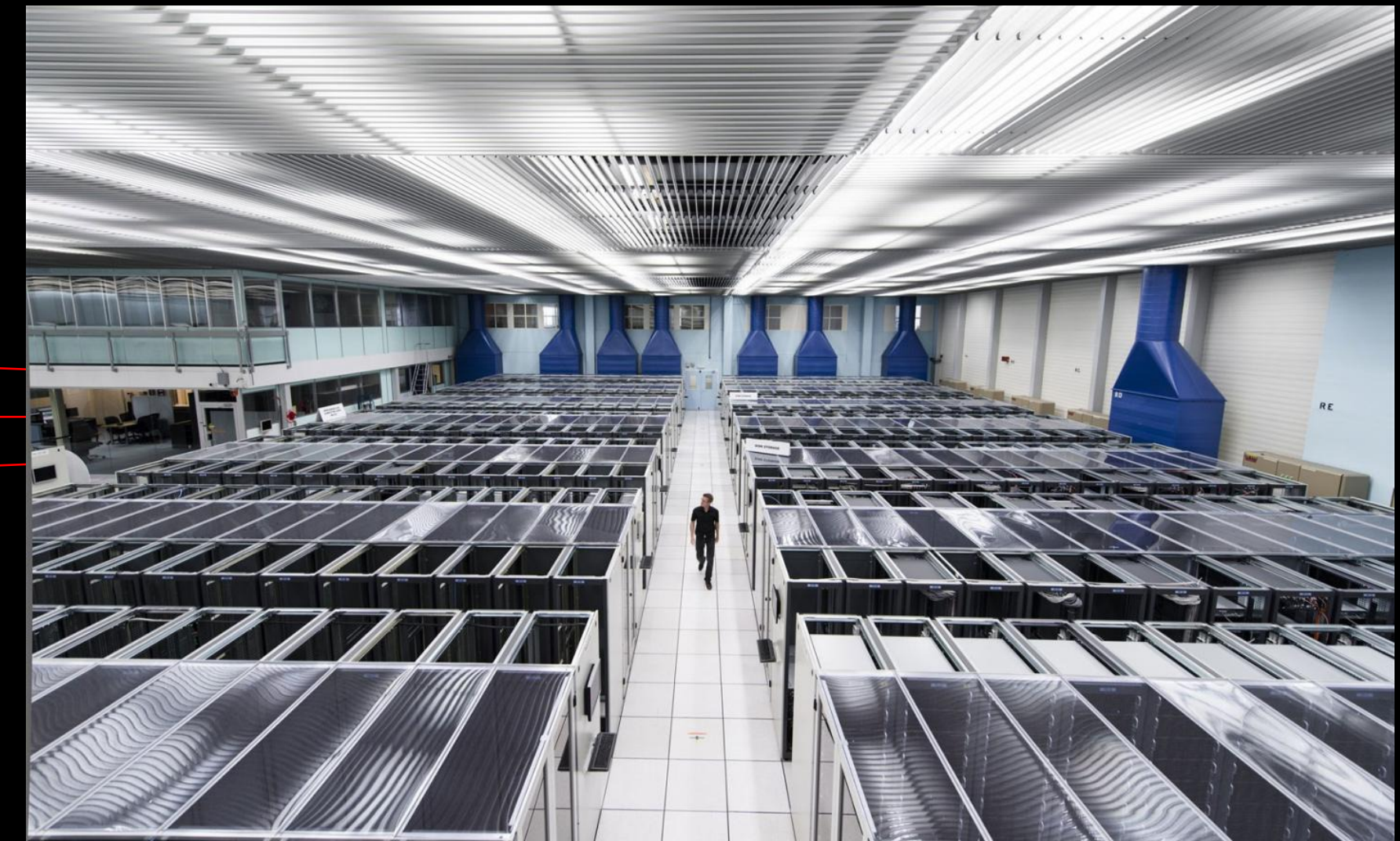
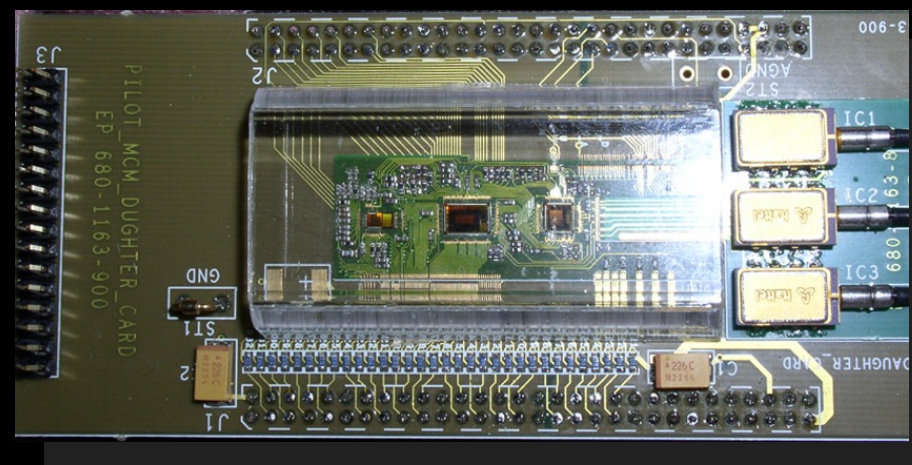
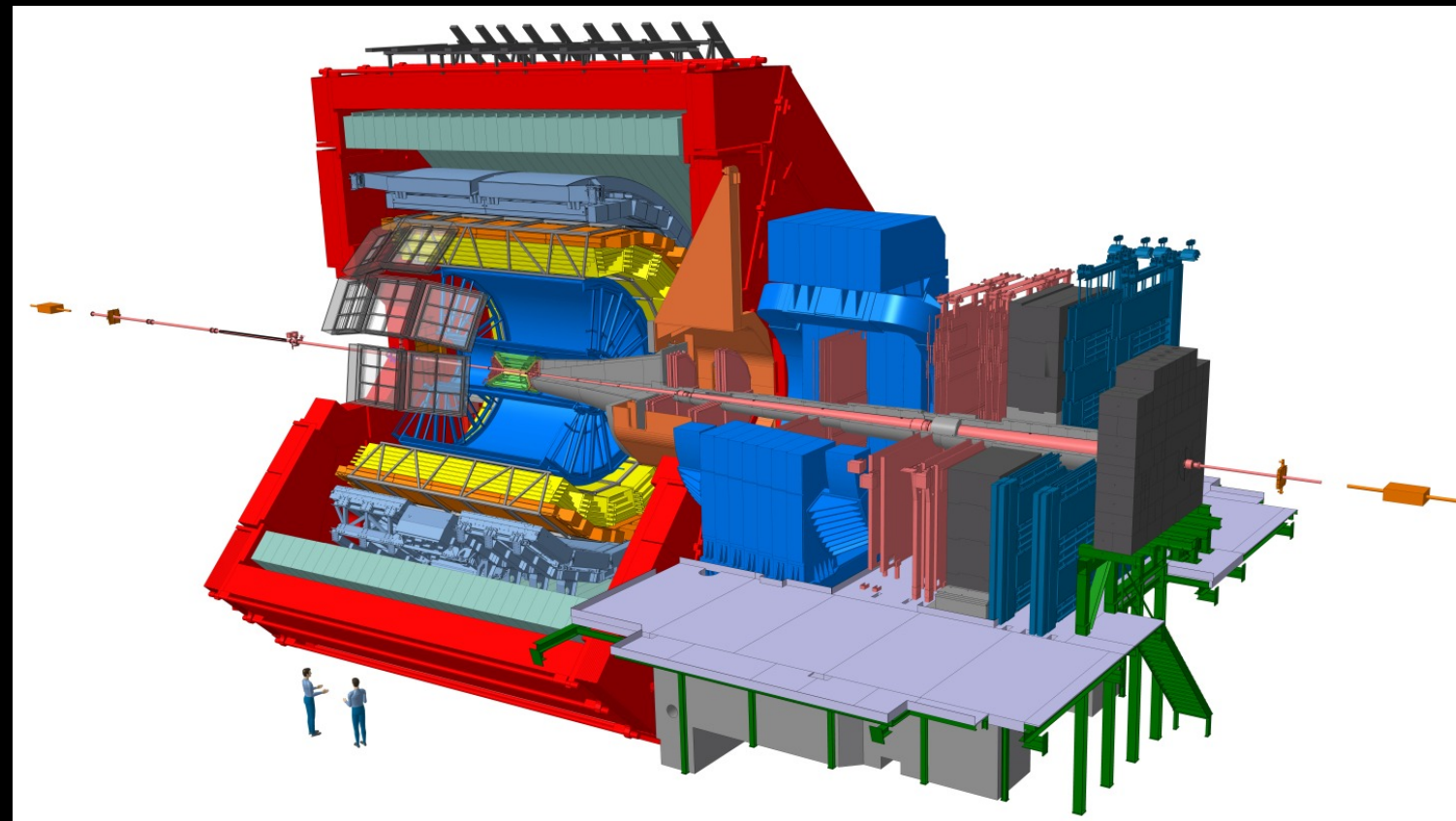


R..... 22 → 392 mm  
S..... 20 × 30  $\mu\text{m}^2$   
Pixels..... 12.6 Milliards  
400.000 photos par seconde



# Des volts aux octets

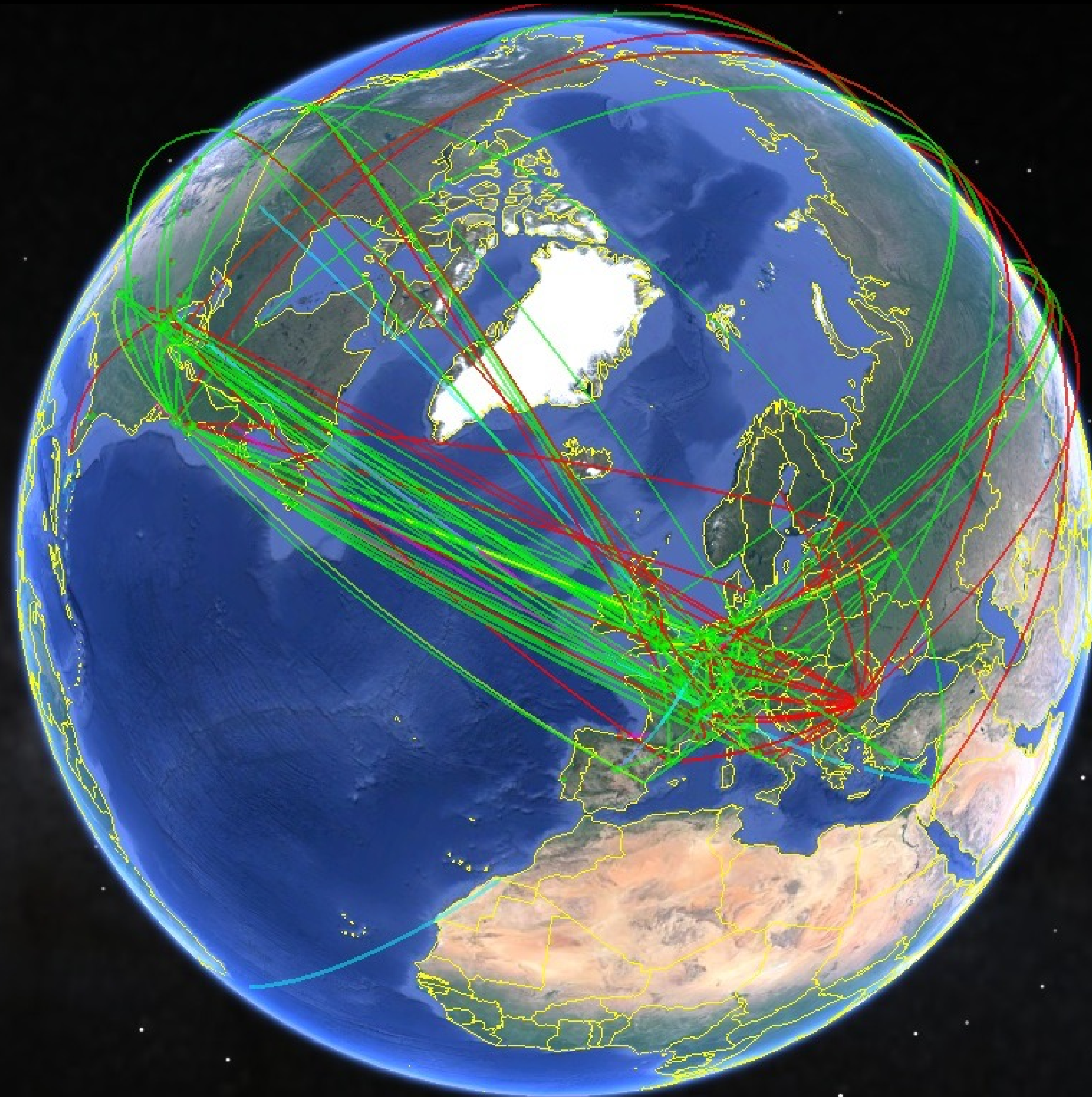
- Le signal de chaque cellule est mis en forme par des systèmes électroniques miniaturisés;
- Le signal électrique est numérisé;
- Les informations sont transmises par fibre optique aux ordinateurs



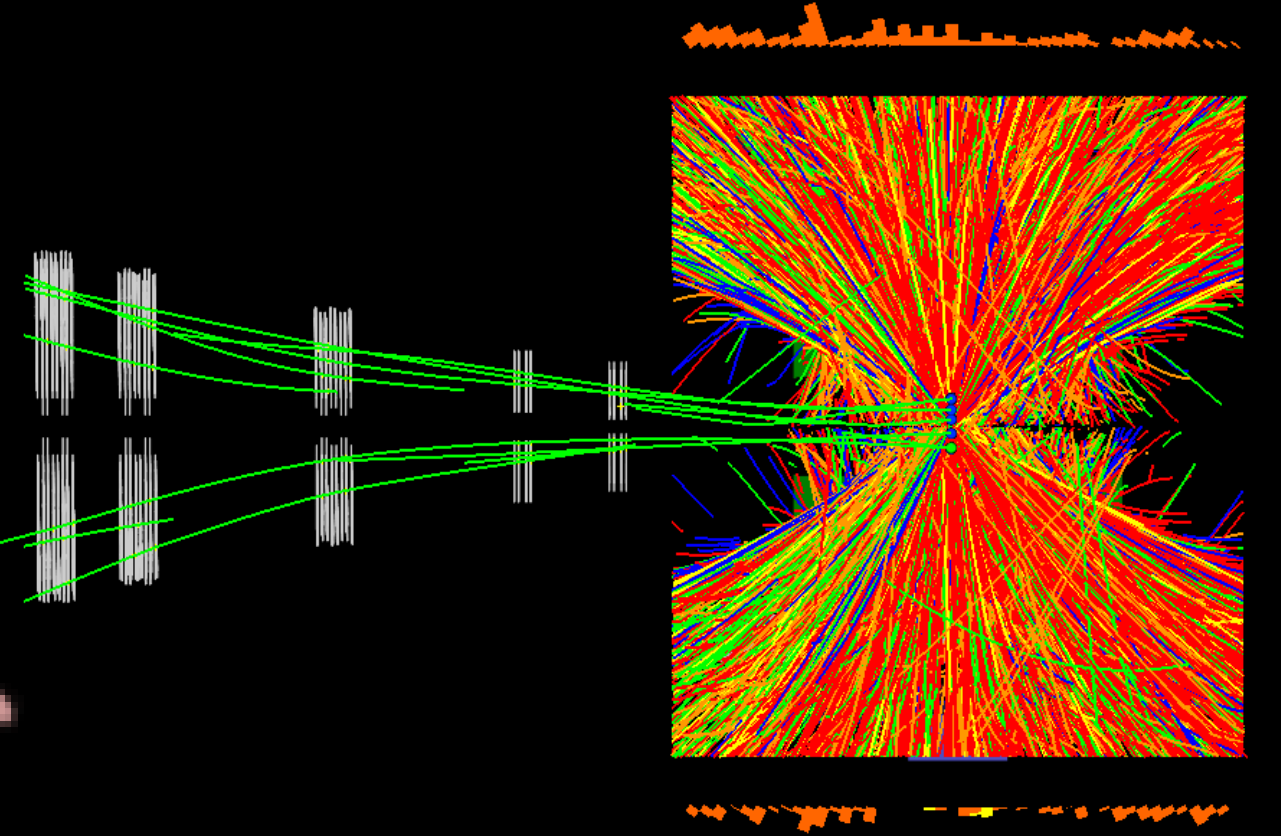
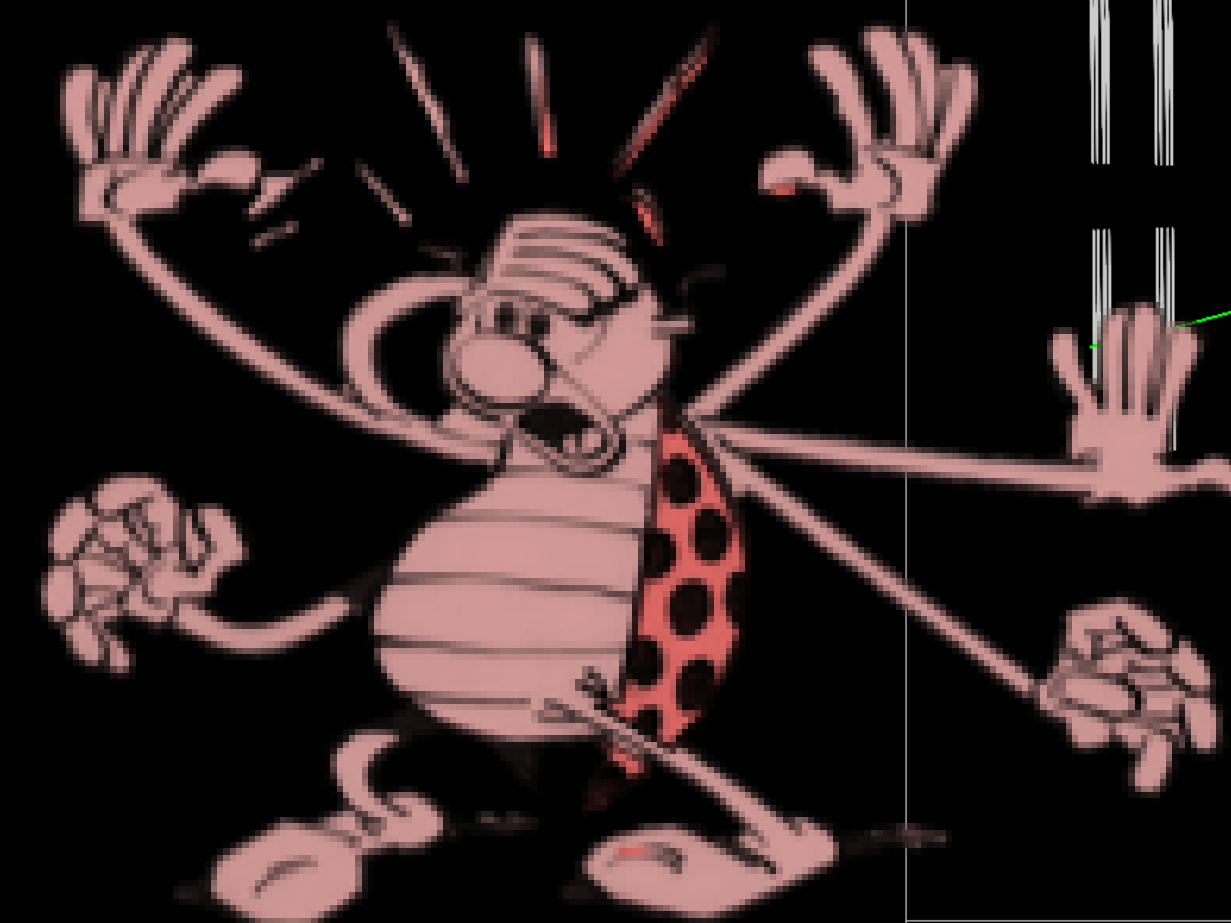
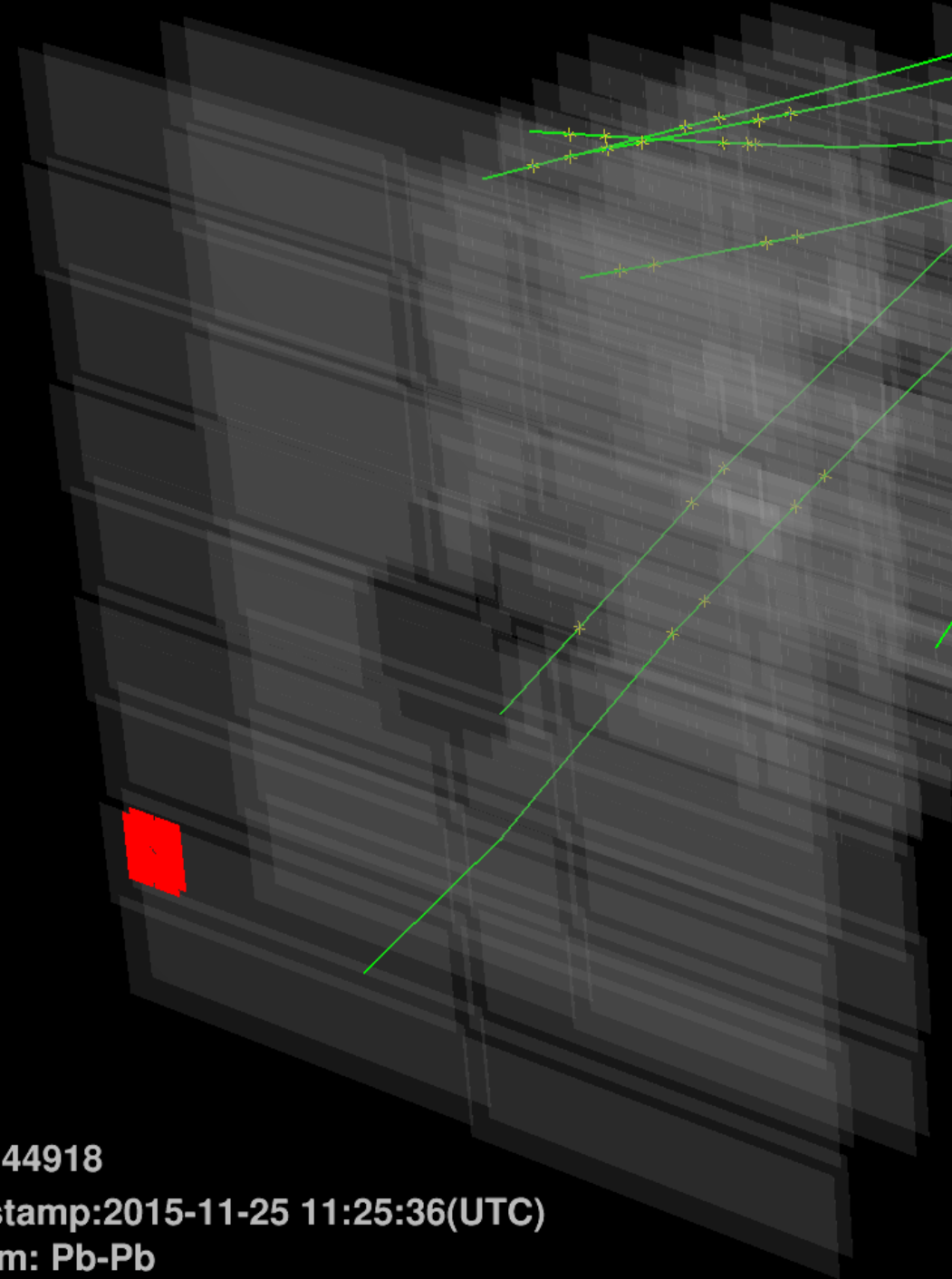
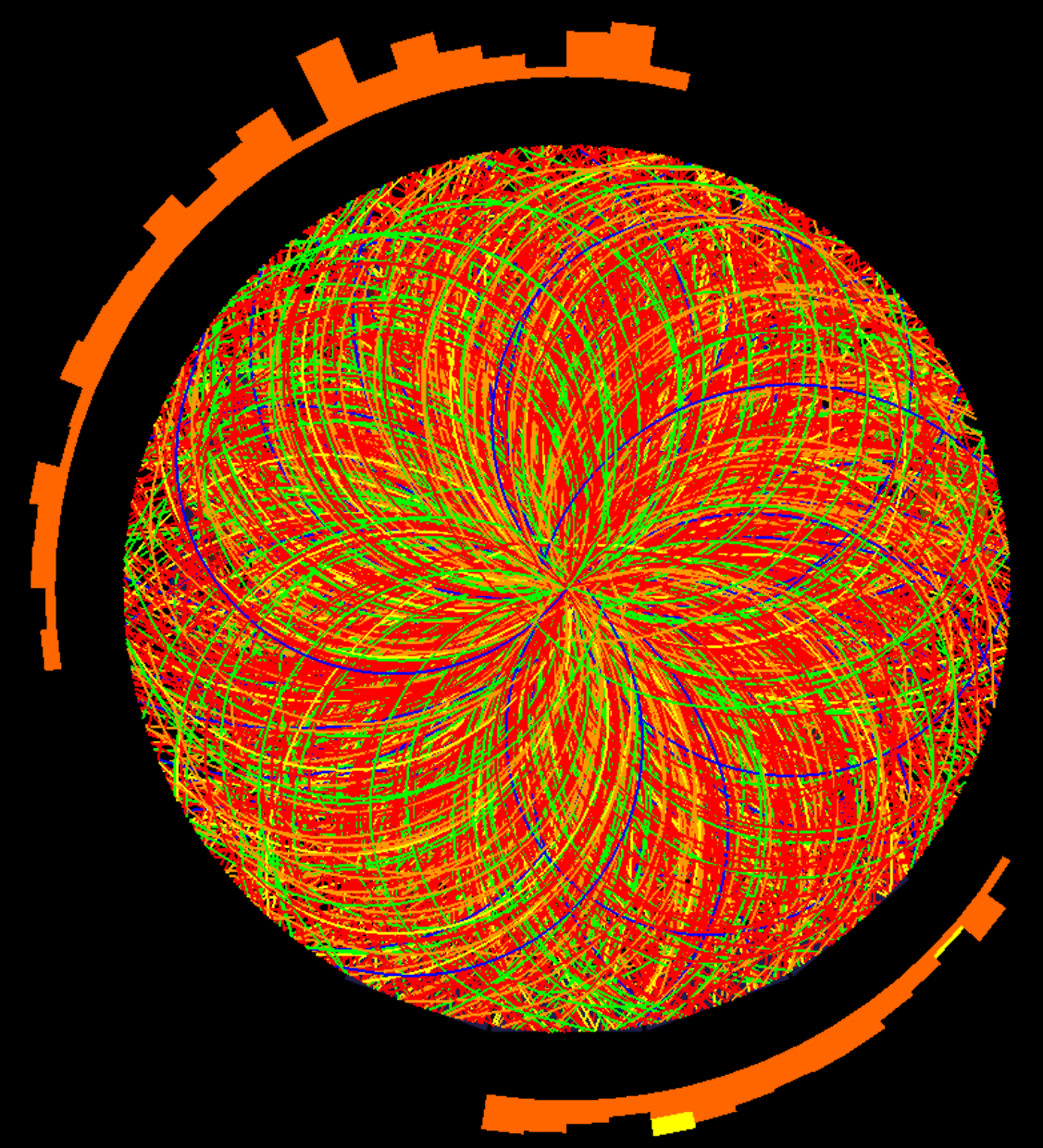
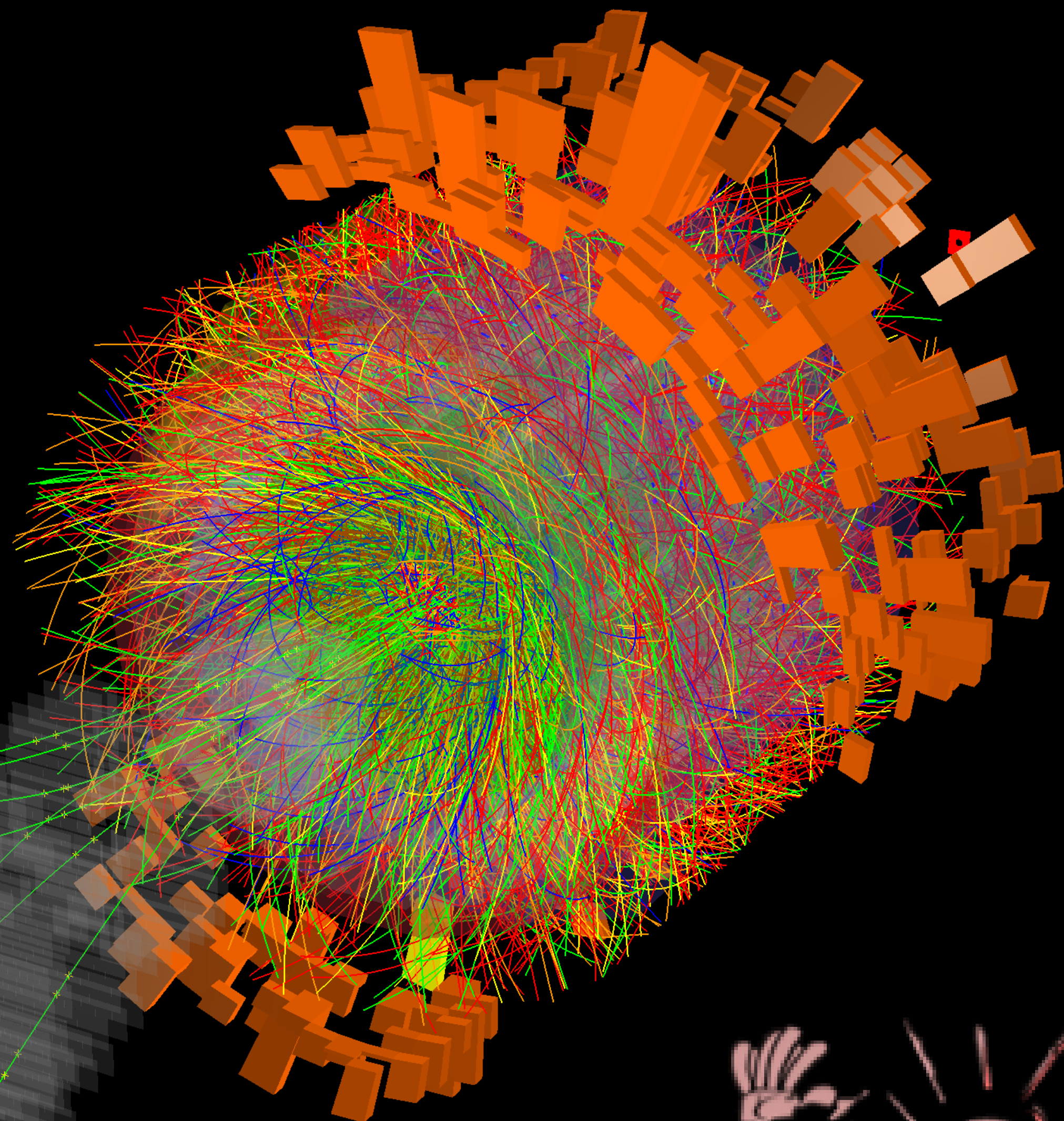


# Une grille de calcul mondiale

Running jobs: 214268  
Transfer rate: 42.74 GiB/sec







Run:244918  
Timestamp:2015-11-25 11:25:36(UTC)  
System: Pb-Pb  
Energy: 5.02 TeV



# Conclusion

- **Conclusions**

- Brief overview on some particle physics
- View via one machine + one associated experiment : LHC project + ALICE

- **Take-home messages**

- close link between infinitely small and infinitely large
- tight link between fundamental science and R&D :  
Fundamental questions + technological performances  
(NB : some CERN spin-offs : 1st touch screen, PET scanners, Web, ...)
- contrast between gigantism of the facilities + infinitely small scale of objects
- international components



