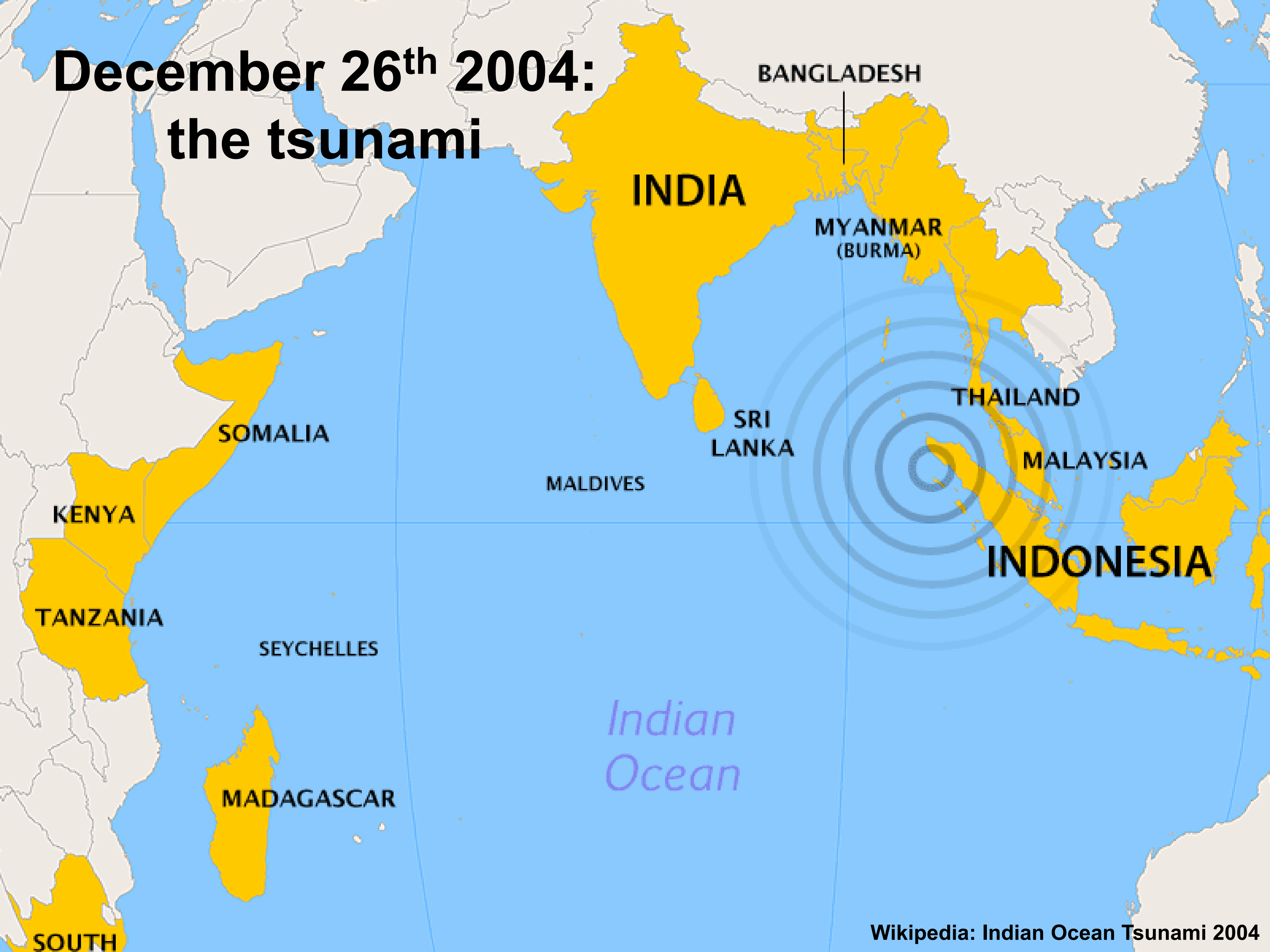
Nuclear matter at high density, the Quark Gluon Plasma

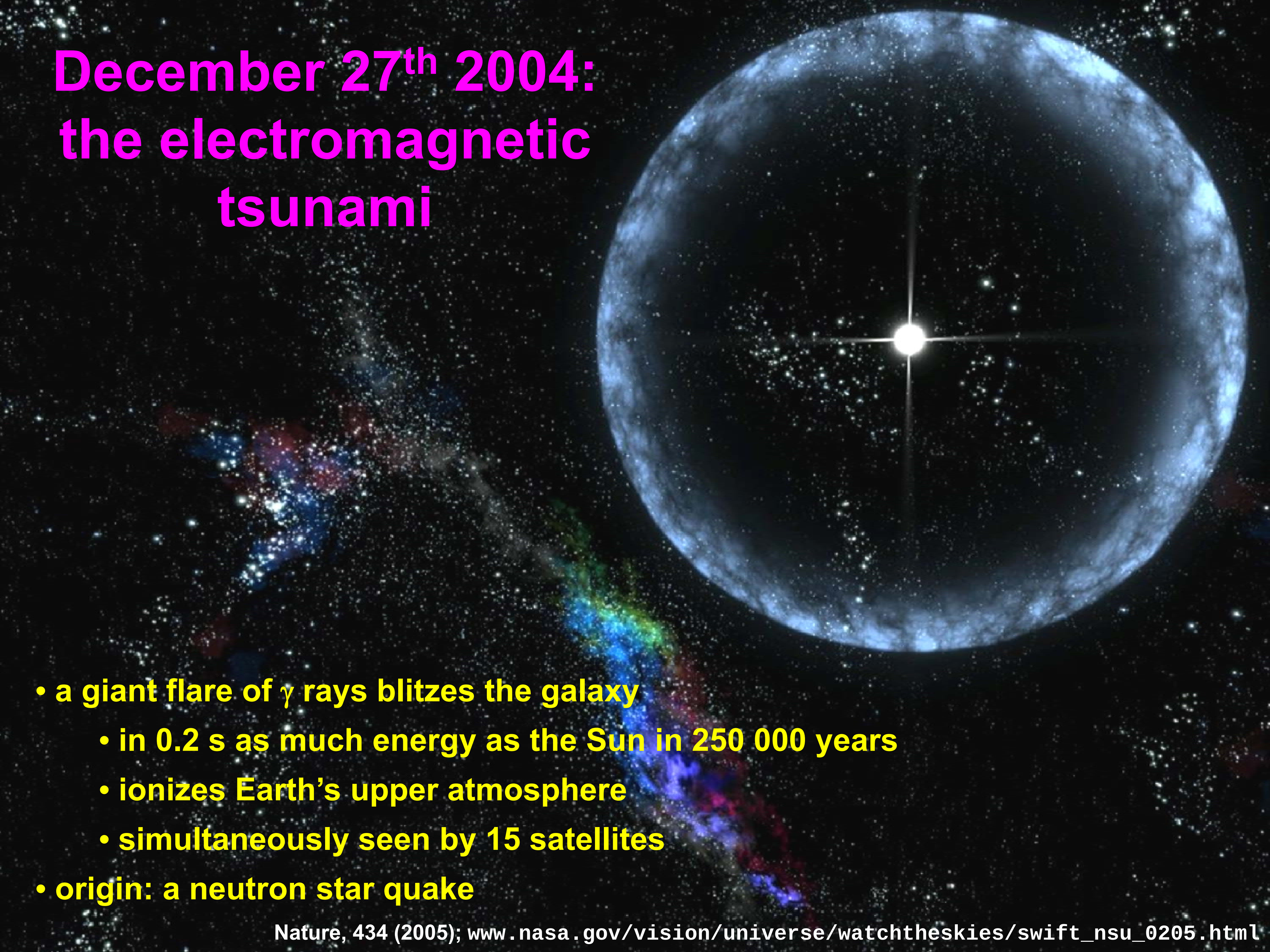
Philippe Crochet - LPC Clermont-Ferrand

December 26th 2004: the tsunami



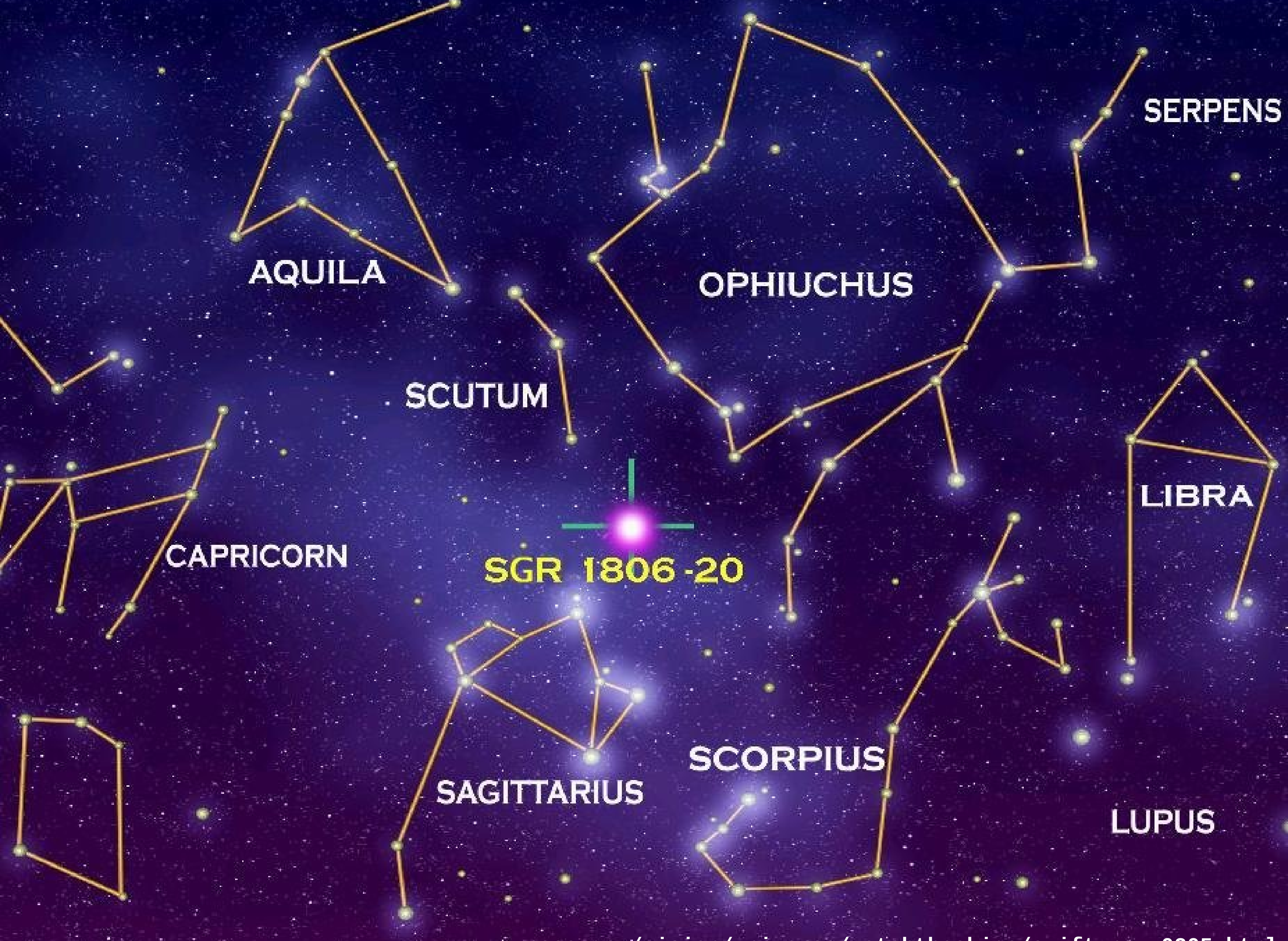
Wikipedia: Indian Ocean Tsunami 2004

December 27th 2004: the electromagnetic tsunami



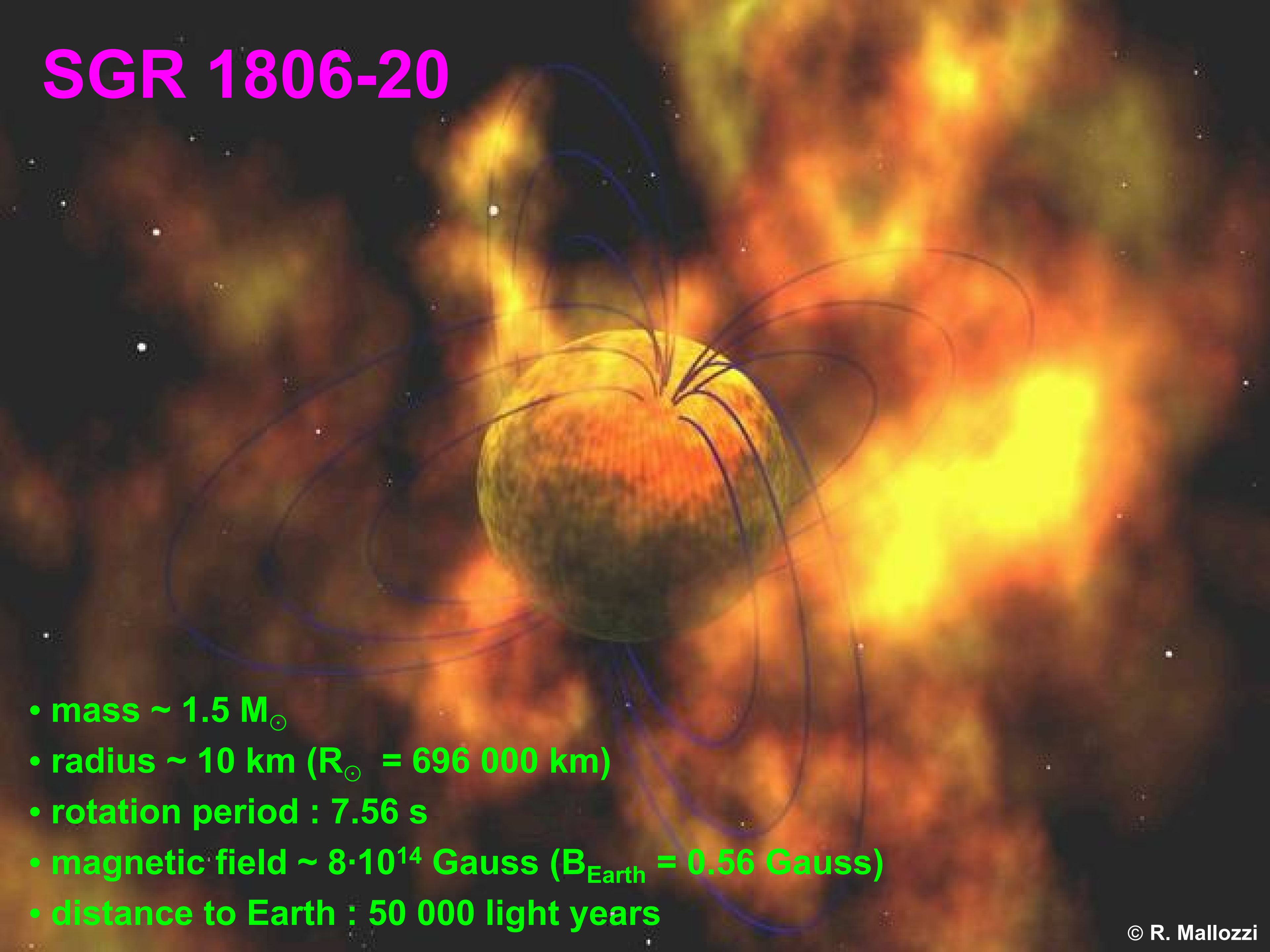
- a giant flare of γ rays blitzes the galaxy
    - in 0.2 s as much energy as the Sun in 250 000 years
    - ionizes Earth's upper atmosphere
    - simultaneously seen by 15 satellites
- origin: a neutron star quake

Nature, 434 (2005); www.nasa.gov/vision/universe/watchtheskies/swift_nsu_0205.html



www.nasa.gov/vision/universe/watchtheskies/swift_nsu_0205.html

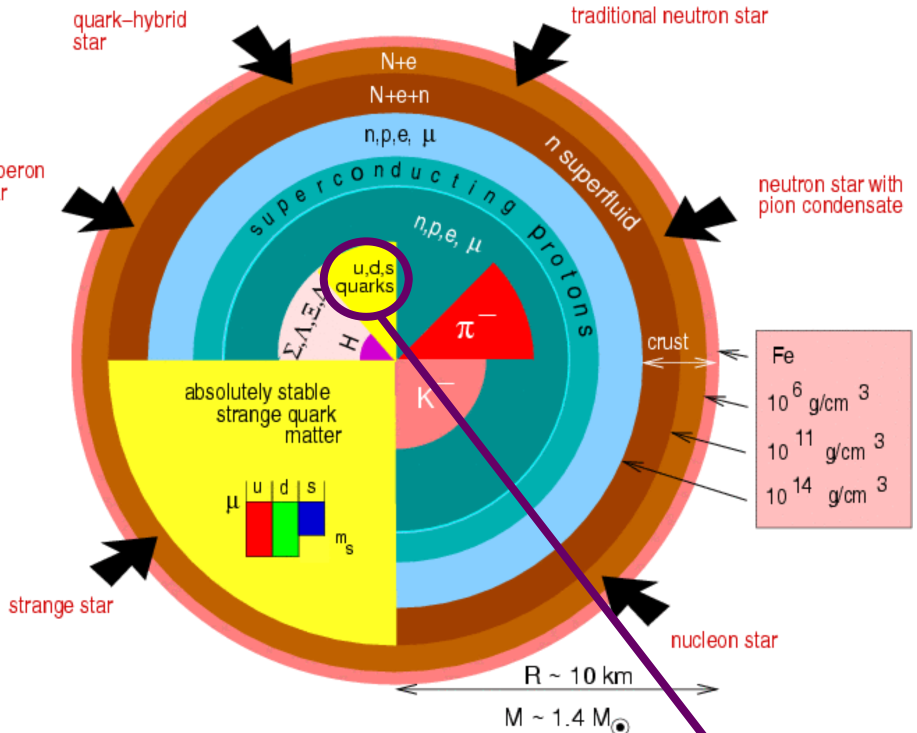
SGR 1806-20

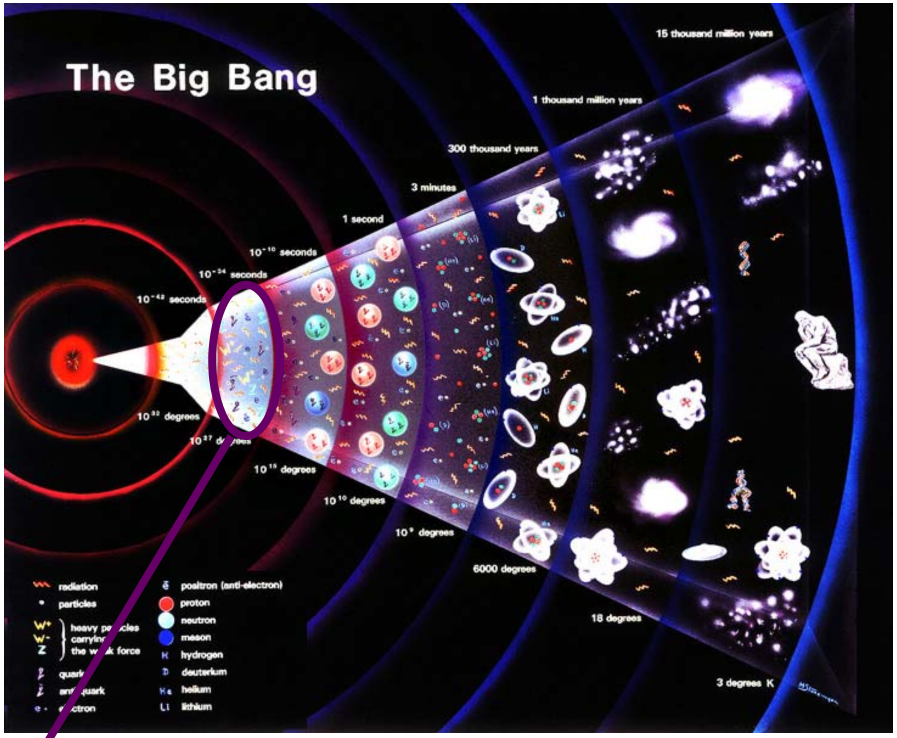


- mass ~ 1.5 $M_\odot$
- radius ~ 10 km ($R_\odot$ = 696 000 km)
- rotation period : 7.56 s
- magnetic field ~ $8 \cdot 10^{14}$ Gauss (B_{Earth} = 0.56 Gauss)
- distance to Earth : 50 000 light years

Neutron star, Big Bang and Quark Gluon Plasma

F.Weber, J. Phys. G 27 (2001) 465





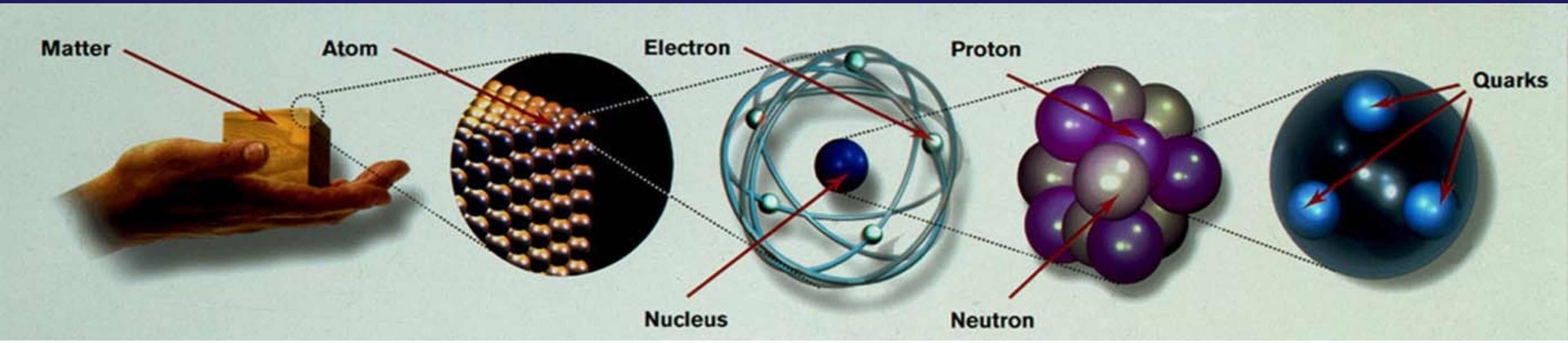
"When the energy density ε exceeds some typical hadronic value (~ 1 GeV/fm^3), matter no longer exists of separate hadrons (protons, neutrons, etc), but as their fondamental constituents, quarks and gluons. Because of the apparent analogy with similar phenomena in atomic physics we may call this phase of matter the QCD (or Quark Gluon) plasma."

E.V. Shuryak, Phys. Rept. 61 (1980) 71

Outline

- basics: elementary constituents, forces, thermodynamics
- how to produce and study the Quark Gluon Plasma in the lab?
- what do we know about the Quark Gluon Plasma?
- can we do better?

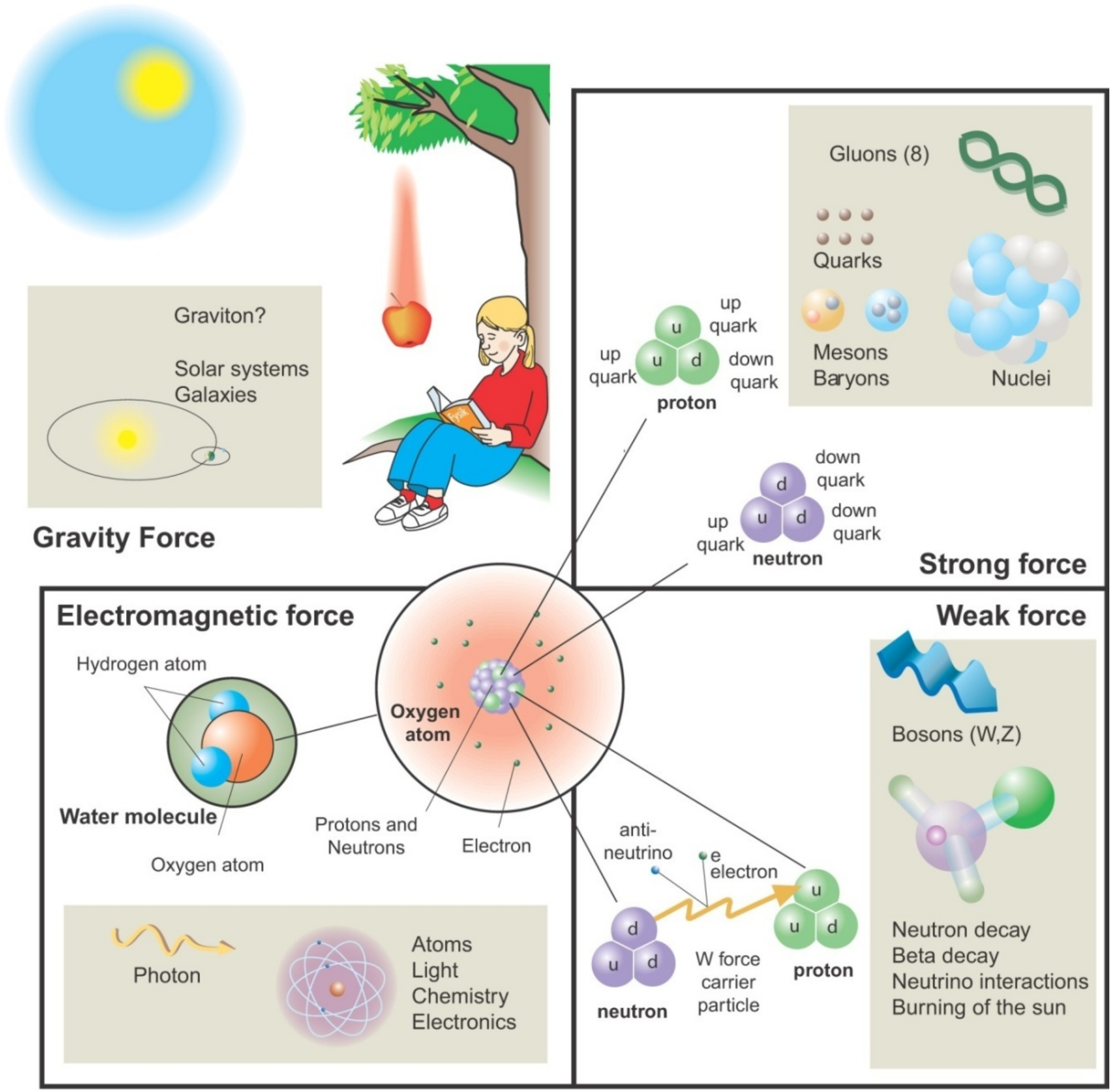
Elementary particles



Fermions			
Leptons		Quarks	
e electron	ν_e neutrino	u up	d down
μ muon	ν_μ neutrino	c charm	s strange
τ tau	ν_τ neutrino	t top	b bottom

+ anti-Fermions

Forces & force carriers



Bosons
g
8 gluons
γ
photon
Z^0, W^+, W^-
3 vector Bosons
G
graviton
H
Higgs Boson

`http://nobelprize.org/physics/laureates/2004/public.html`

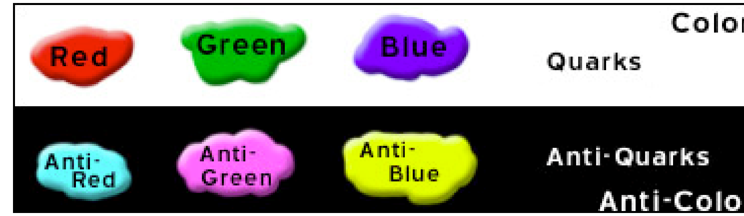
Putting everything together: the Standard Model

Fermions			
Leptons		Quarks	
e electron	ν_e neutrino	u up	d down
μ muon	ν_μ neutrino	c charm	s strange
τ tau	ν_τ neutrino	t top	b bottom

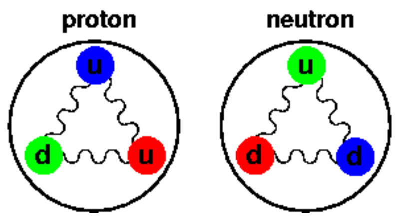
Bosons
g 8 gluons
γ photon
Z^0, W^+, W^- 3 vector Bosons
G graviton
H Higgs Boson

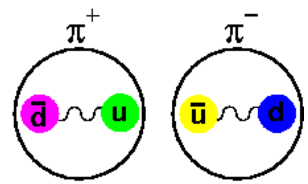
12 Fermions + 12 anti-Fermions + 14 Bosons = 38 particles
all predicted & "seen" except graviton and Higgs

Composite particles according to Quantum ChromoDynamics (QCD): theory of strong force (simplistic view here)

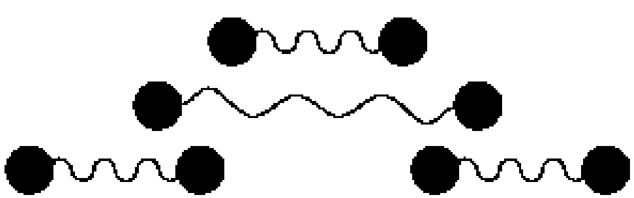


- **quarks are color-charged fermions**
- **3 colors: Red, Green and Blue**
- **anti-quarks are anti-color charged**
- **quarks are confined into hadrons (non-colored)**
- **hadrons = baryons (3 quarks) and mesons (1 quark & 1 anti-quark)**





- **quarks interact via gluons**
- **strong force is weak at small distances (asymptotic freedom) and becomes infinitely strong as the quarks move apart (confinement). Gross, Politzer, Wilczek, Nobel Price 2004. This prevents the separation of an individual quark.**



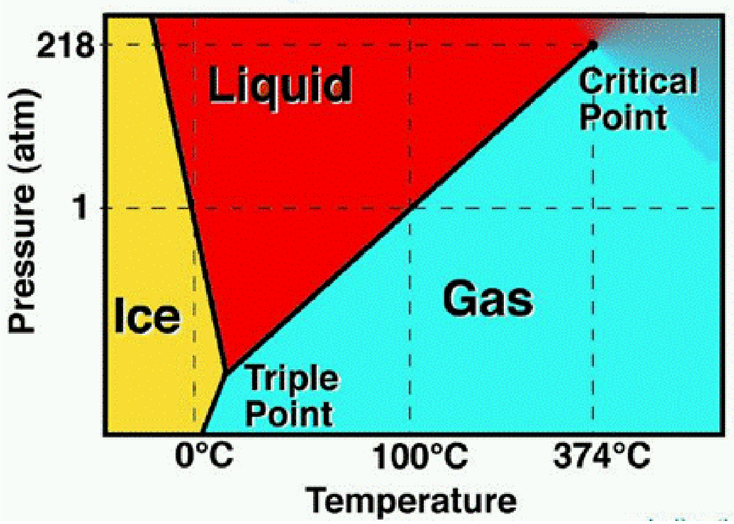
the particle zoo

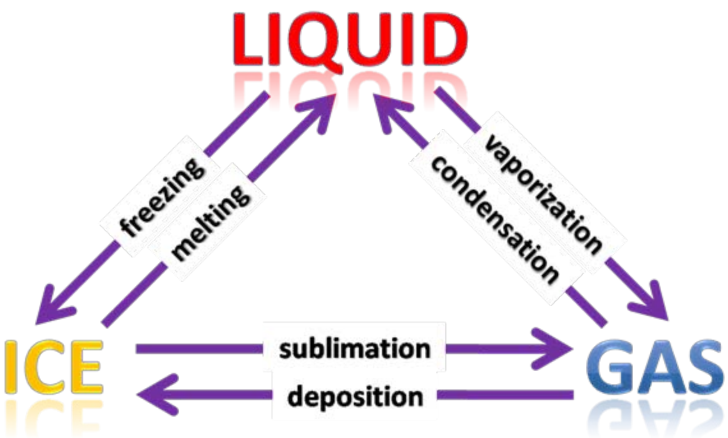
		unflavored	strange	charm	bottom
hadrons	baryons	$p(uud)$	$\Lambda(usd)$	$\Lambda_c^+(udc)$	$\Lambda_c^0(udb)$
		$n(udd)$	$\Sigma^+(uus)$	$\Sigma_c^0(ddc)$	$\Xi_b^0(usb)$
		$\Delta^0(udd)$	$\Xi^+(dss)$	$\Xi_c^+(usc)$	$\Xi_b^-(dsb)$
			$\Omega^-(sss)$	$\Omega_c^0(ssc)$	
		...	...	...	...
	mesons	$\pi^+(u\bar{d})$	$K^+(u\bar{s})$	$D^+(c\bar{d})$	$B^+(u\bar{b})$
		$\rho^+(u\bar{d})$	$K_s^0(d\bar{s})$	$D^0(c\bar{u})$	$B^0(d\bar{b})$
		$\phi(s\bar{s})$		$D_s^+(c\bar{s})$	$B_s^0(s\bar{b})$
				$J/\psi(c\bar{c})$	$\Upsilon(b\bar{b})$
		...	...	...	...

see the full list on http://pdg.lbl.gov

Phase diagram, phase transition & equation of state

• phase diagram: graphic representation that shows the equilibrium relationships between 2 (or more) thermodynamic variables for different states of matter





more phases: ferromagnetism, superfluidity, superconductivity…

• phase transition: transformation of a system from one state to another

• triple point: state of equilibrium between 3 states

• critical point: beyond this point, there no distinction between the states ("fluid" in the case of water), one goes from one state to another w/o transition ("cross-over")

• $1^{st}/2^{nd}$ order phase transition: phase transition with (w/o) mixed phase regime

• equation of state: thermodynamic equation describing states of matter under given sets of physical conditions i.e. mathematical representation of the phase diagram

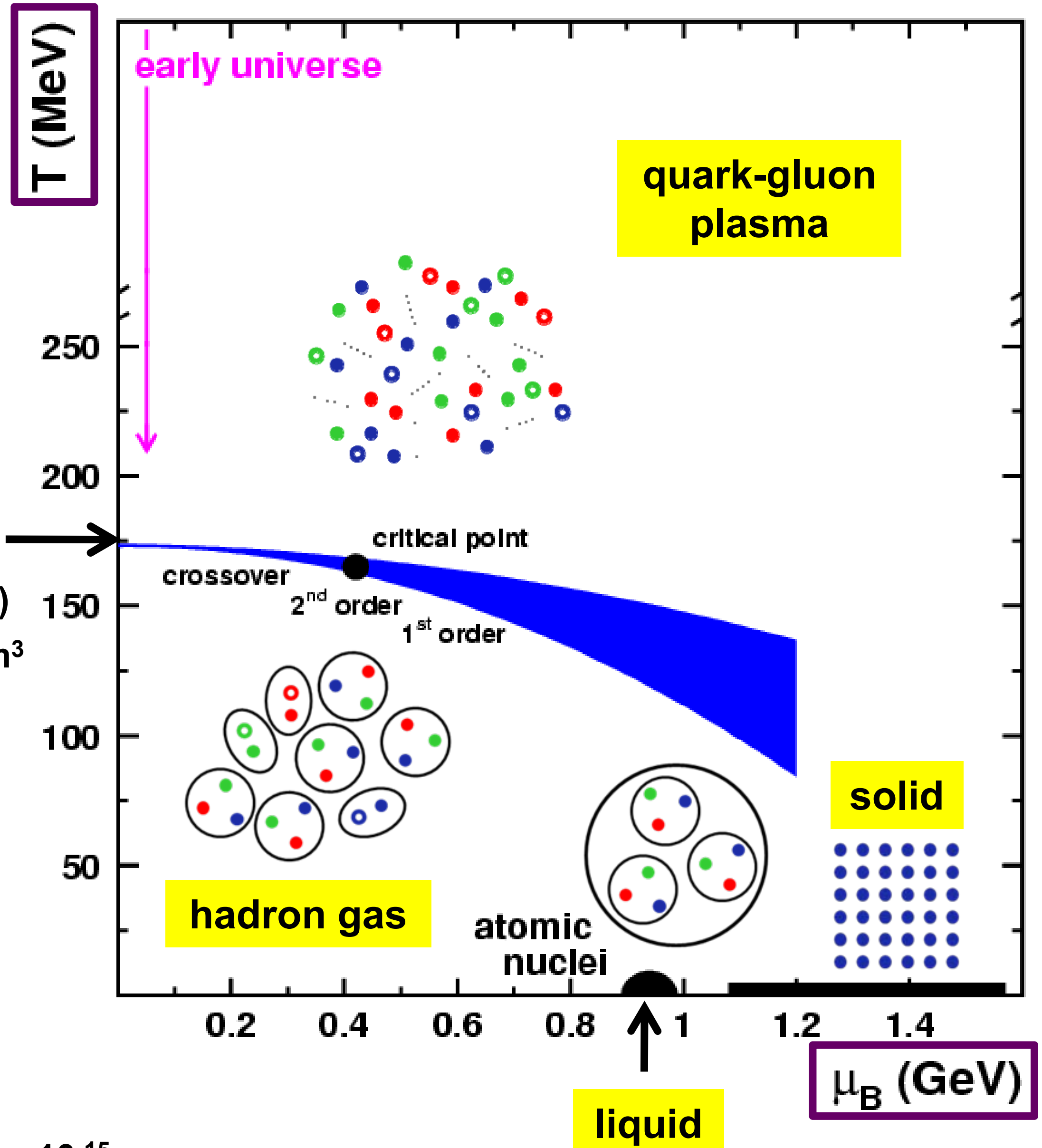
The nuclear matter phase diagram according to QCD

temperature

T_c = 173 ± 15 MeV

~ 10^{12} K ($T_\odot = 10^8$ K)

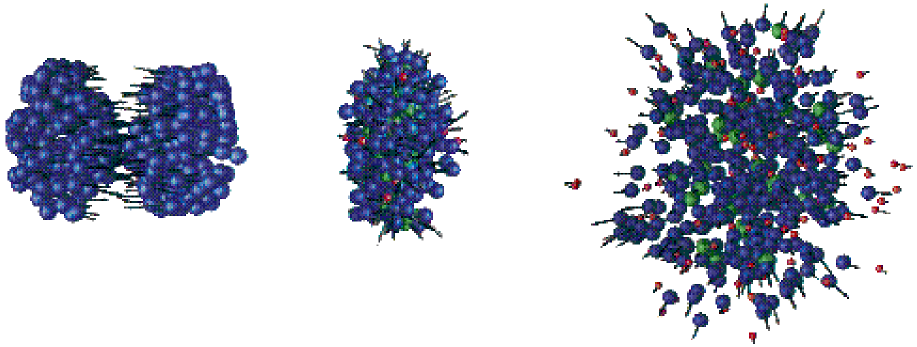
ε_c = 0.7 ± 0.3 GeV/fm^3

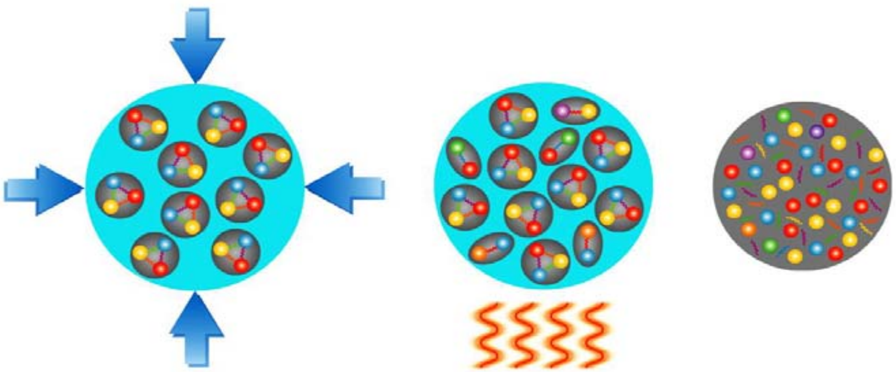


~ density

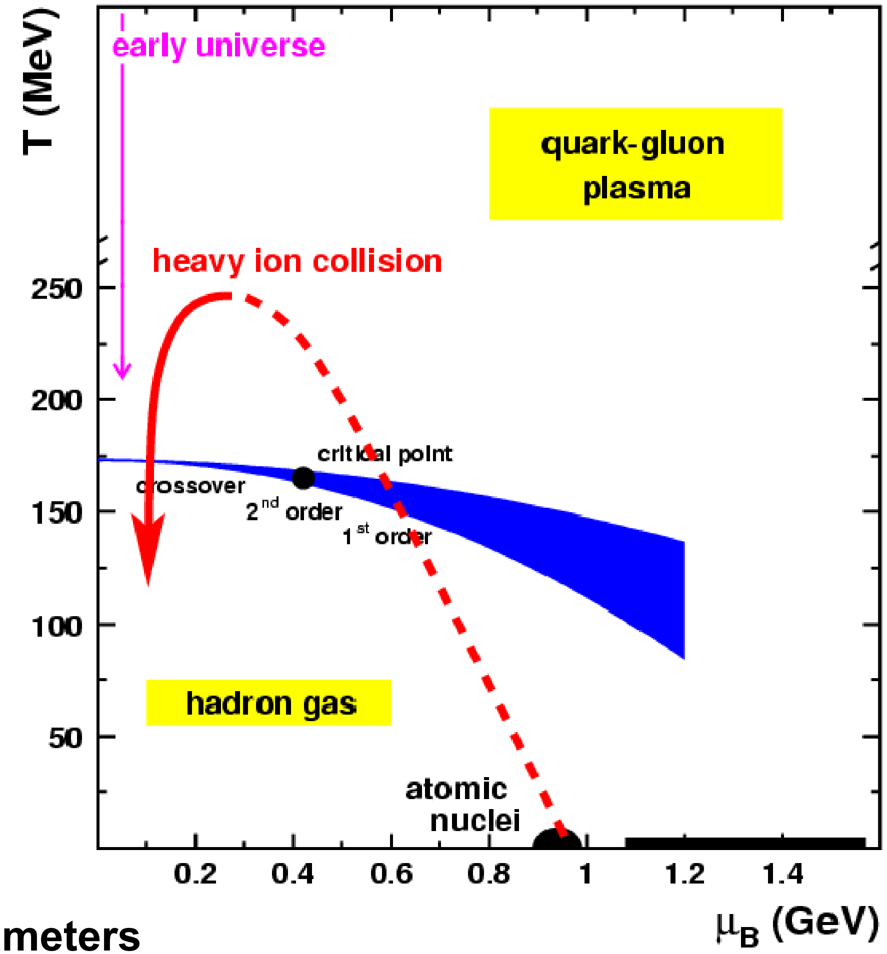
1 ev = $1.6 \cdot 10^{-19}$ J, 1 fm = 10^{-15} m

Recreating the QGP in laboratory with heavy ion collisions





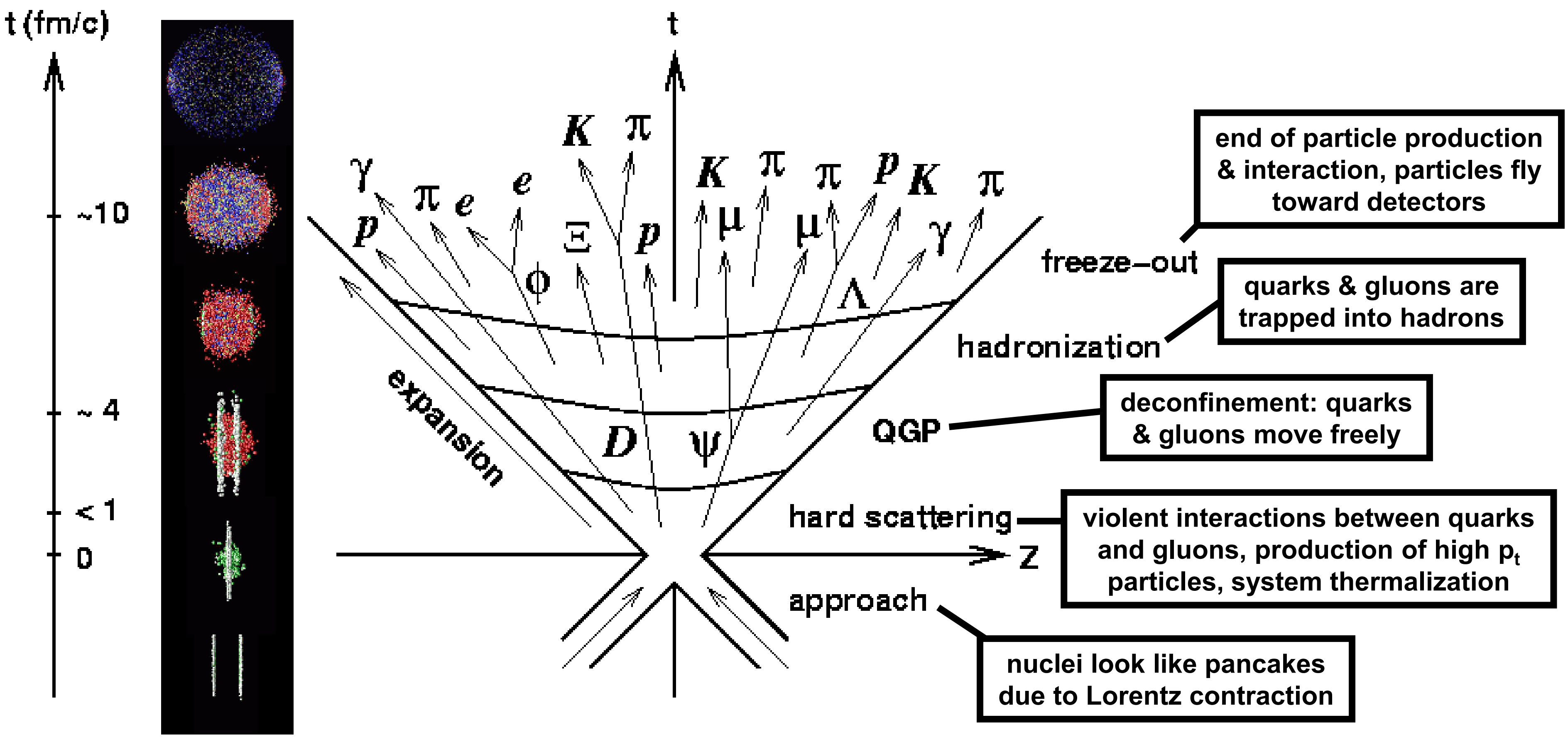
pressure + heat ⇒ QGP



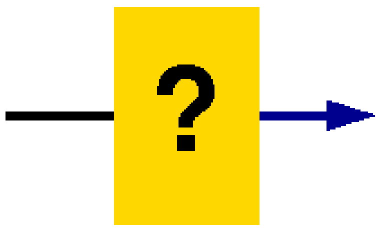
key parameters

- **beam energy: the higher the beam energy, the higher the temperature**
- **particule p_t: high/low p_t particles are produced at the beginning/end of the collision**

Space-time evolution of a heavy ion collision

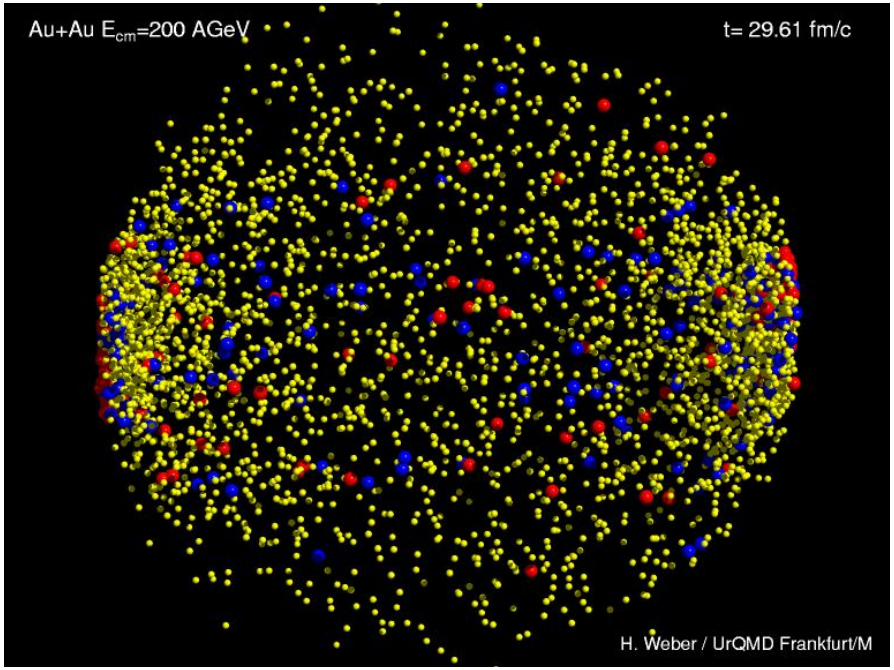


- 4 main “distinct” phases
- strategy: use produced particles as probes of the medium



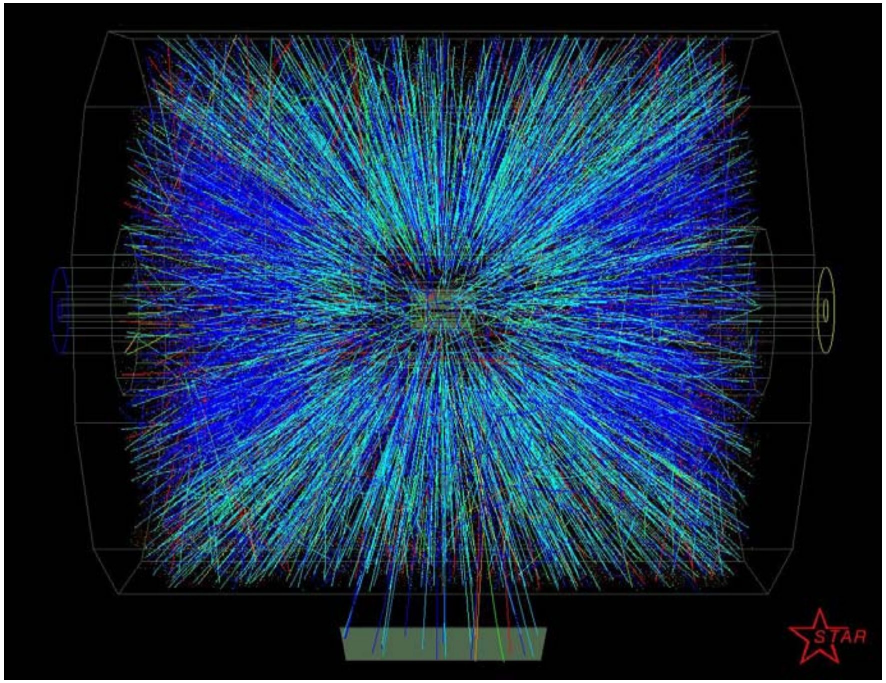
1 fm/c = 10^{-23} s, 1 fm = 10^{-15} m

Not that simple…



a simulated heavy ion collision

the same collision in real life

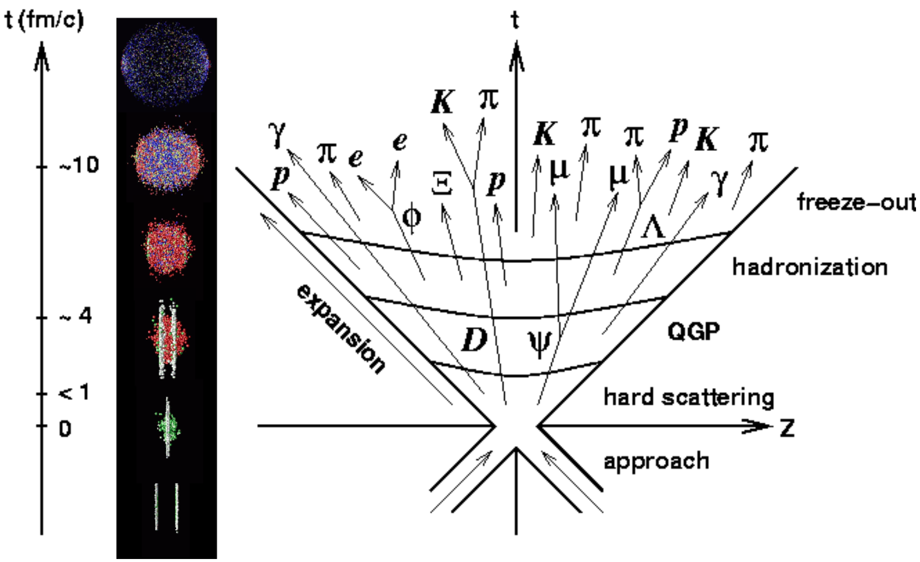


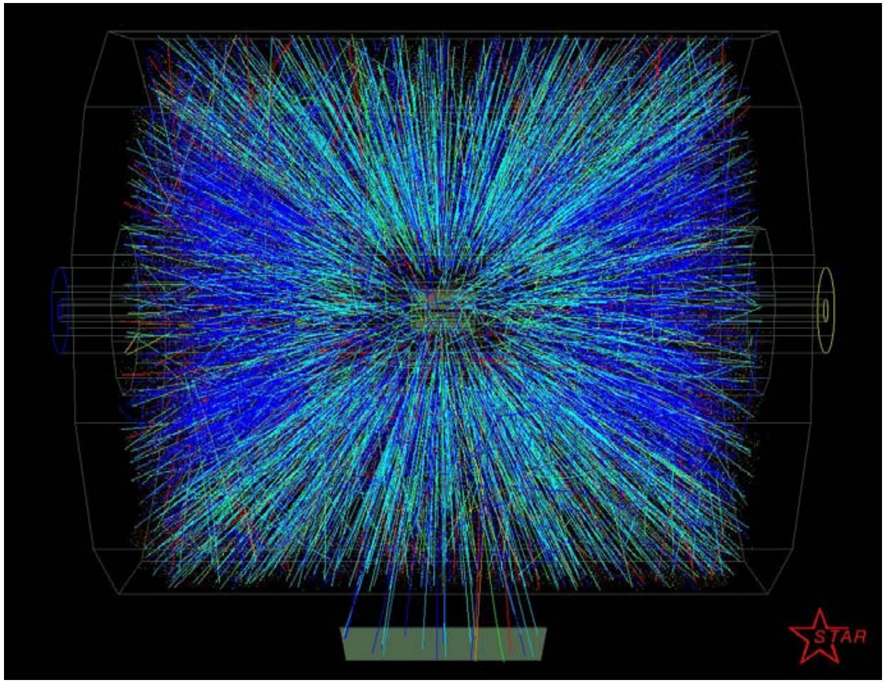
Even more difficult

- hostile environment (up to 30000 particles are produced in a collision)
- interesting collisions are often rare
- system life-time/size is extremely short/small

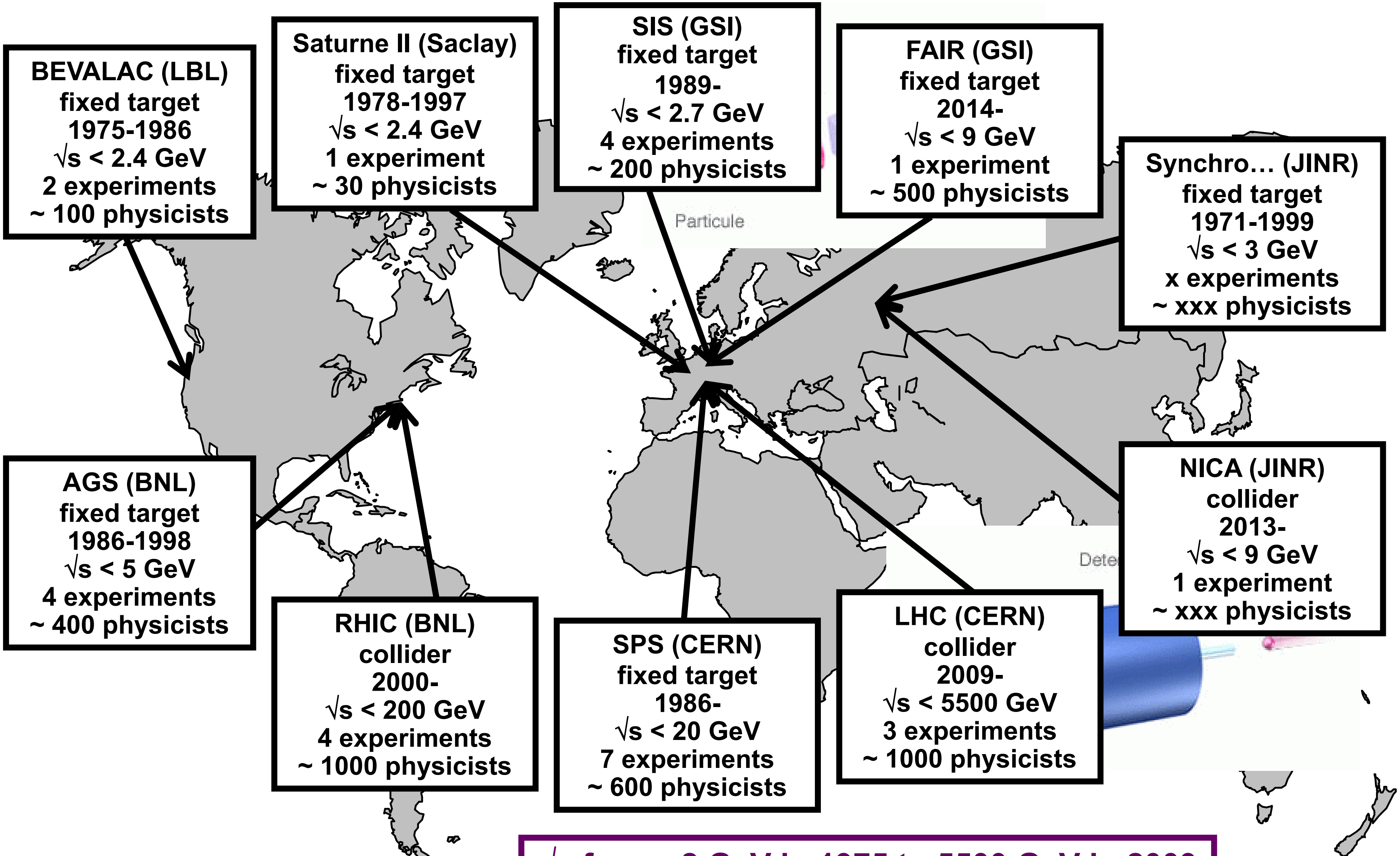
  ⇒ difficult to achieve a macroscopic description (e.g. temperature)

- QGP signals are mixed with signals from hadronic phase (wider in space & time)
- QGP signals can be destroyed during the collision (e.g. particle interaction)
- measurements are averaged over time
- measurements are not direct





1975-2009: 34 years of heavy-ion collisions

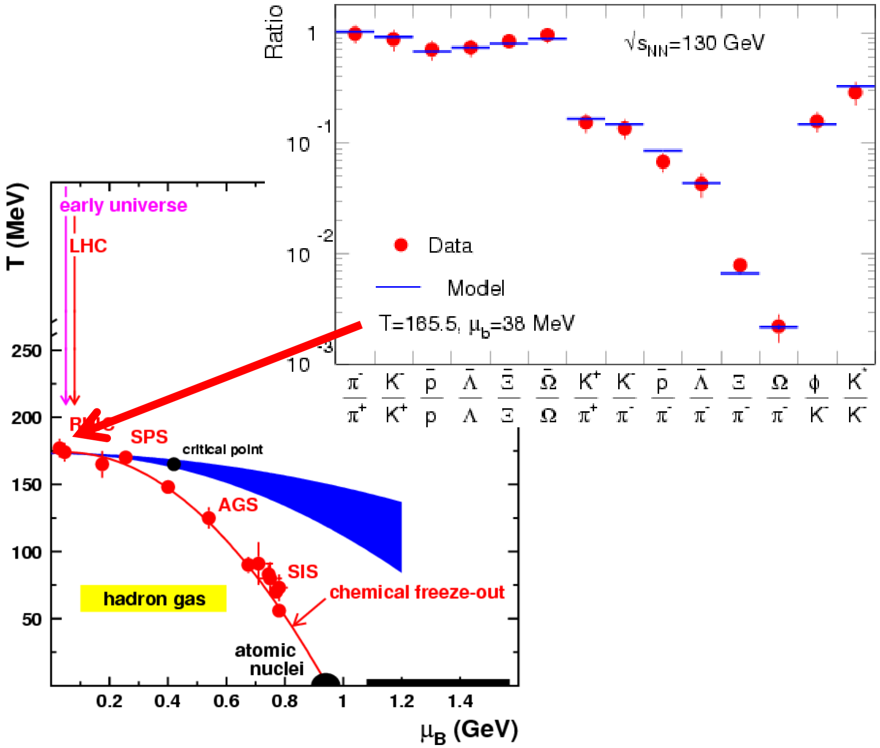


√s from ~2 GeV in 1975 to 5500 GeV in 2009

Do we reach the thermodynamic conditions of the QGP in HIC?

- **freeze-out temperature**

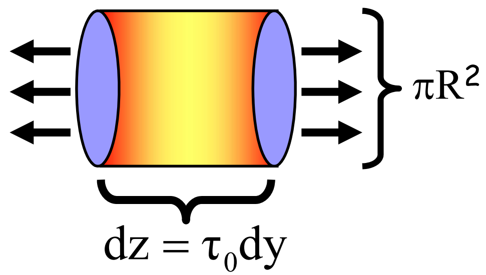
$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}$$

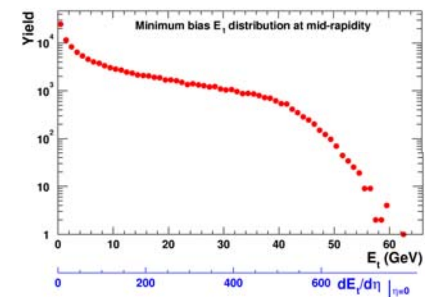


…coincides with critical value (173 MeV)

- **energy density**

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

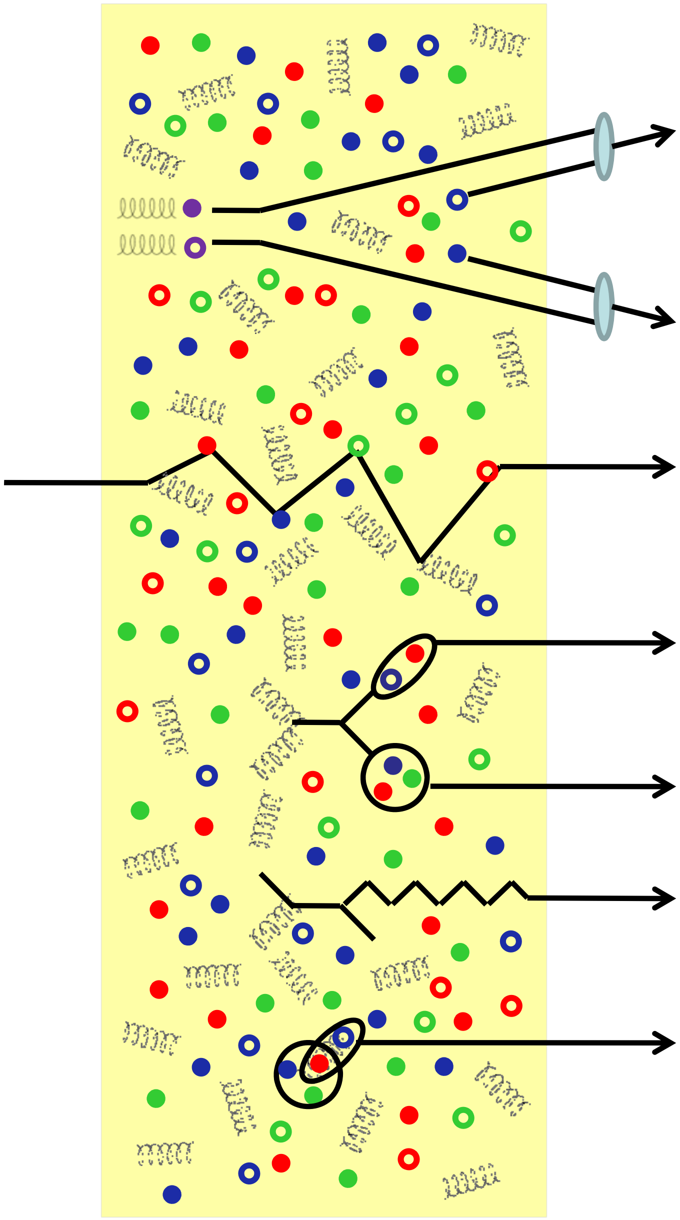




system	√s (GeV)	ε (GeV/fm³)
Pb+Pb	17	2.5
Au+Au	200	4.6

…larger than critical value (0.7 GeV/fm³)

QGP probes



suppression of heavy-quark mesons
screening of quarks-antiquarks pairs by quarks and gluons

suppression of energetic particles
radiative and collisional energy loss

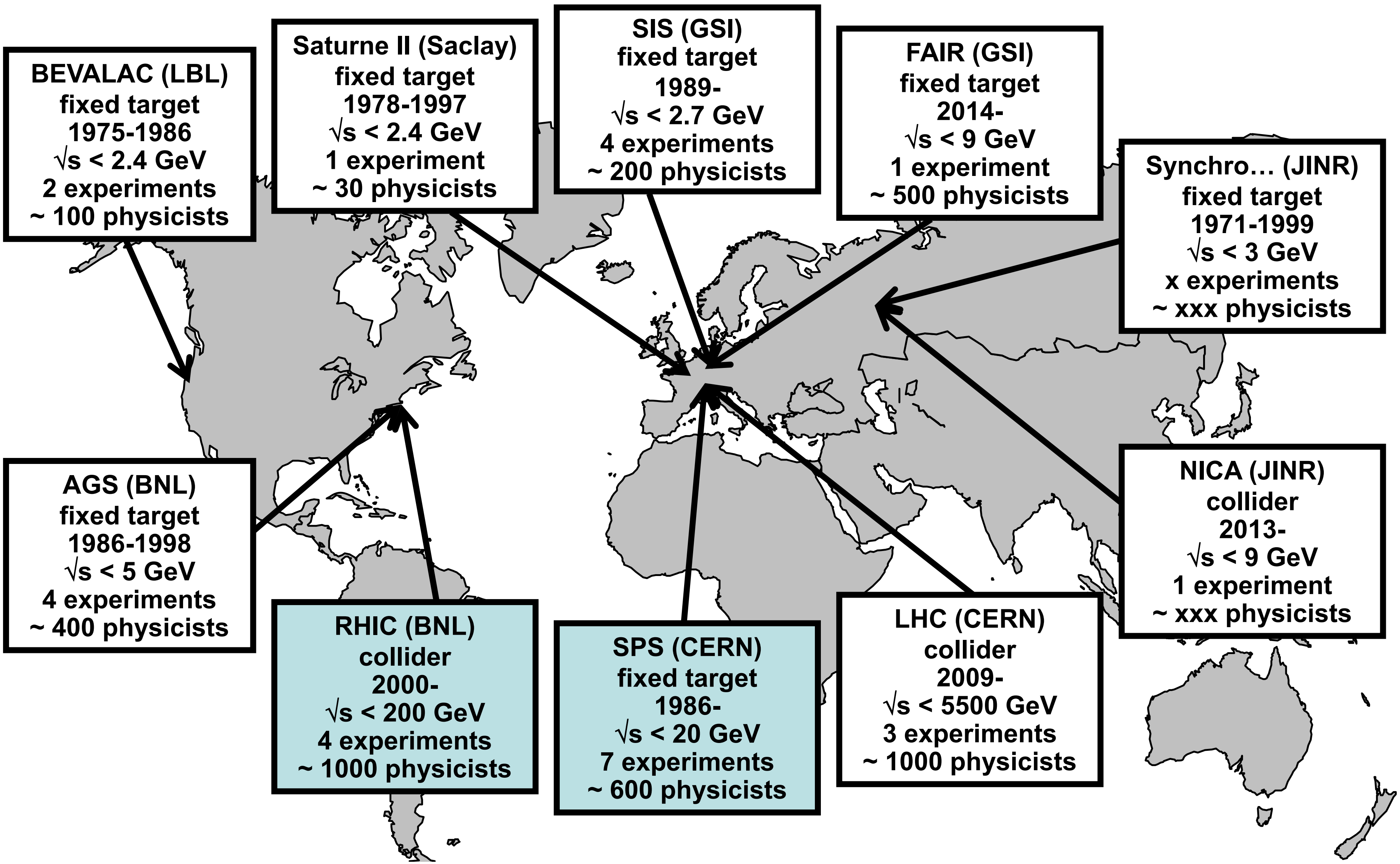
strangeness enhancement
$g+g \rightarrow s+\underline{s}$

photon production
$q+g \rightarrow q+\gamma$

modification of particle properties
high density effects

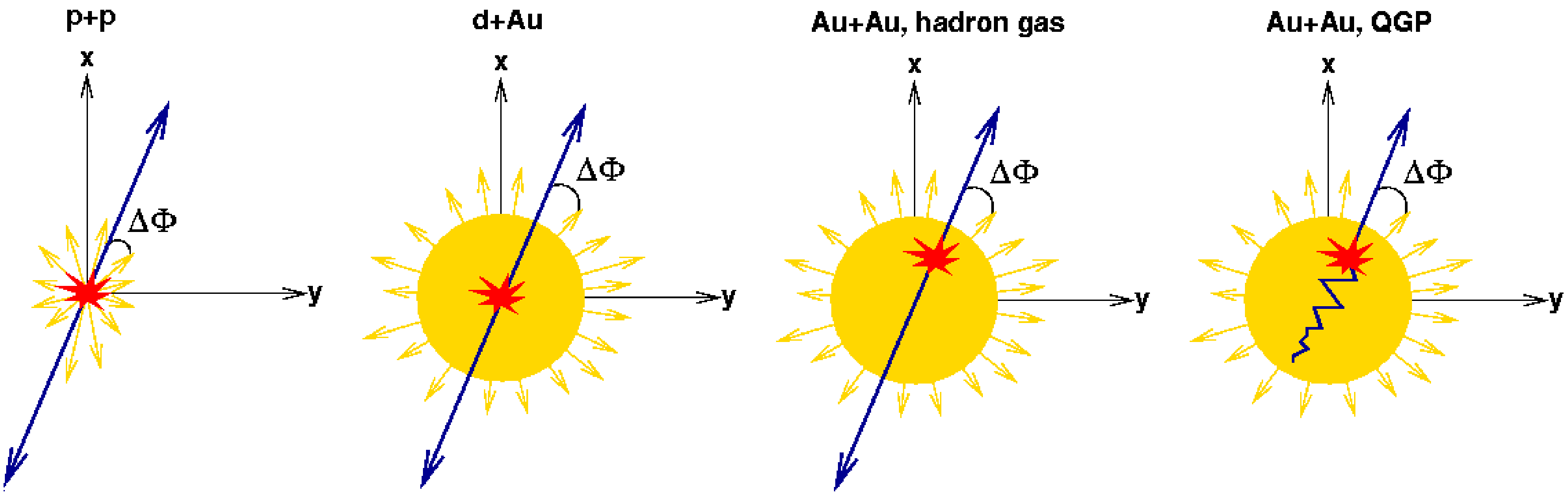
etc…

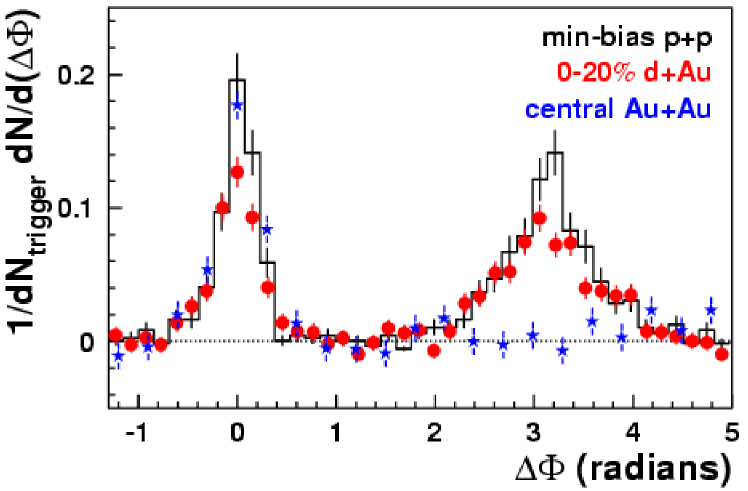
1975-2009: 34 years of heavy-ion collisions



First result: jet quenching

high p_t particles are, due to momentum conservation, produced by pair & back-to-back principle: use one particle to study the behaviour of the second one





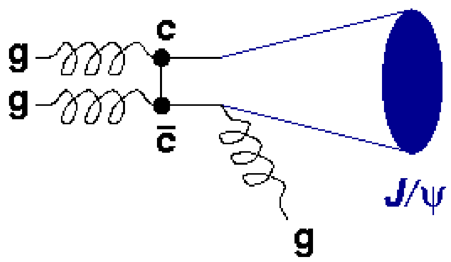
⇒ in each collision, one isolates the highest p_t particle and one builds up the difference in azimuth (ΔΦ) with all other particles

in contrast to p+p & d+A collisions, in Au+Au collisions, the particle going through the medium is absorbed by the medium

STAR collaboration, Phys. Rev. Lett. 91 (2003) 072304

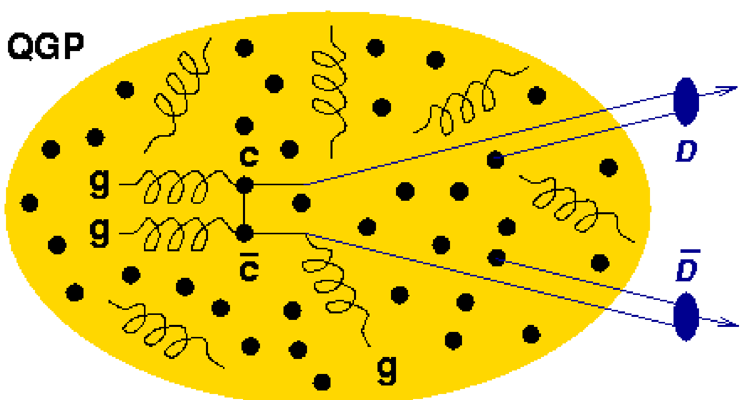
Second result: suppression of heavy-quark mesons

p+p

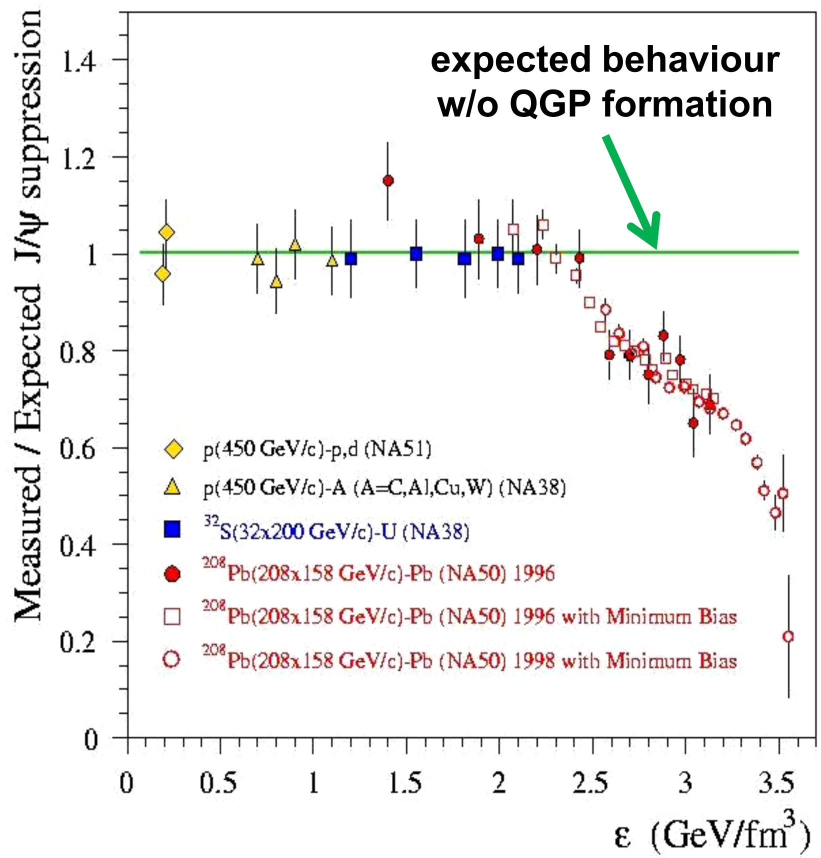


2 gluons fuse into a $c\bar{c}$ pair. After some time, the J/ψ is formed

QGP



the $c\bar{c}$ pair is screened by other quarks and gluons, the J/ψ cannot form



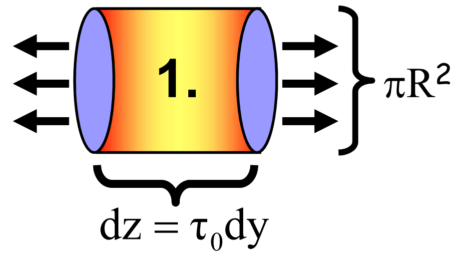
J/ψ yield decreases with increasing energy density

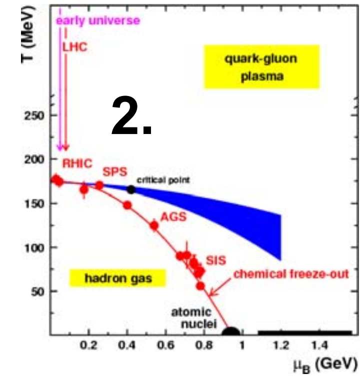
NA50 collaboration, Phys. Lett. B 477 (2000) 28

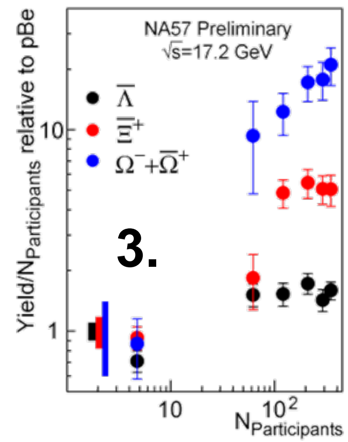
More results: SPS & RHIC findings in 8 plots

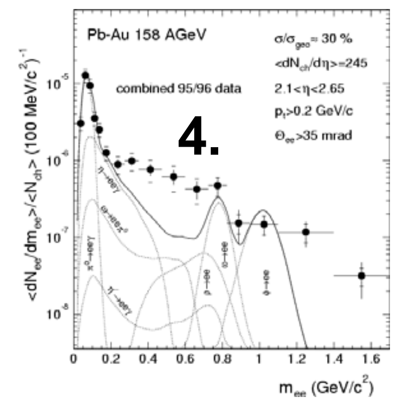
the medium produced in heavy-ion collisions:

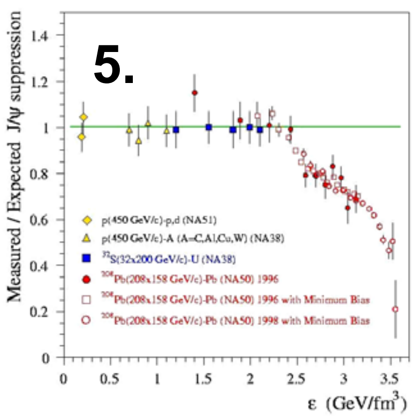
1. has an energy density > than ε_c
2. has a freeze-out temperature ~ T_c
3. over-produces strange hadrons
4. modifies properties of light hadrons
5. dissolves heavy-quark mesons
6. over-produces photons
7. exhibits quark & gluon degrees of freedom
8. absorbs jets

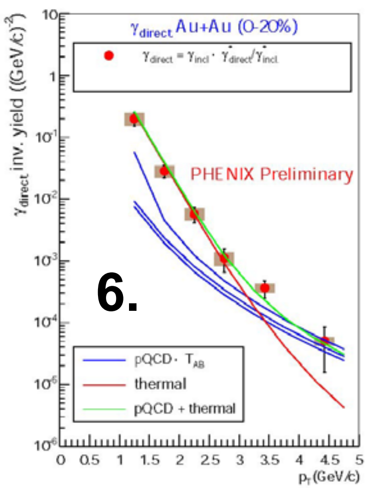


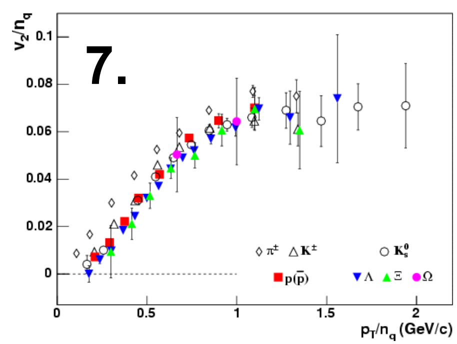


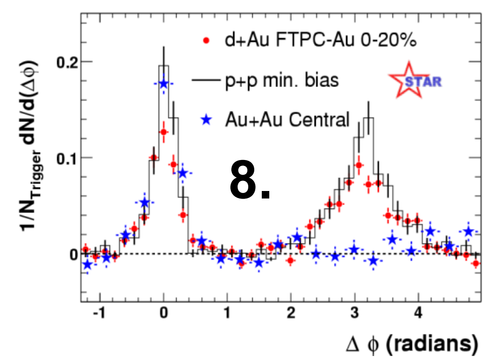






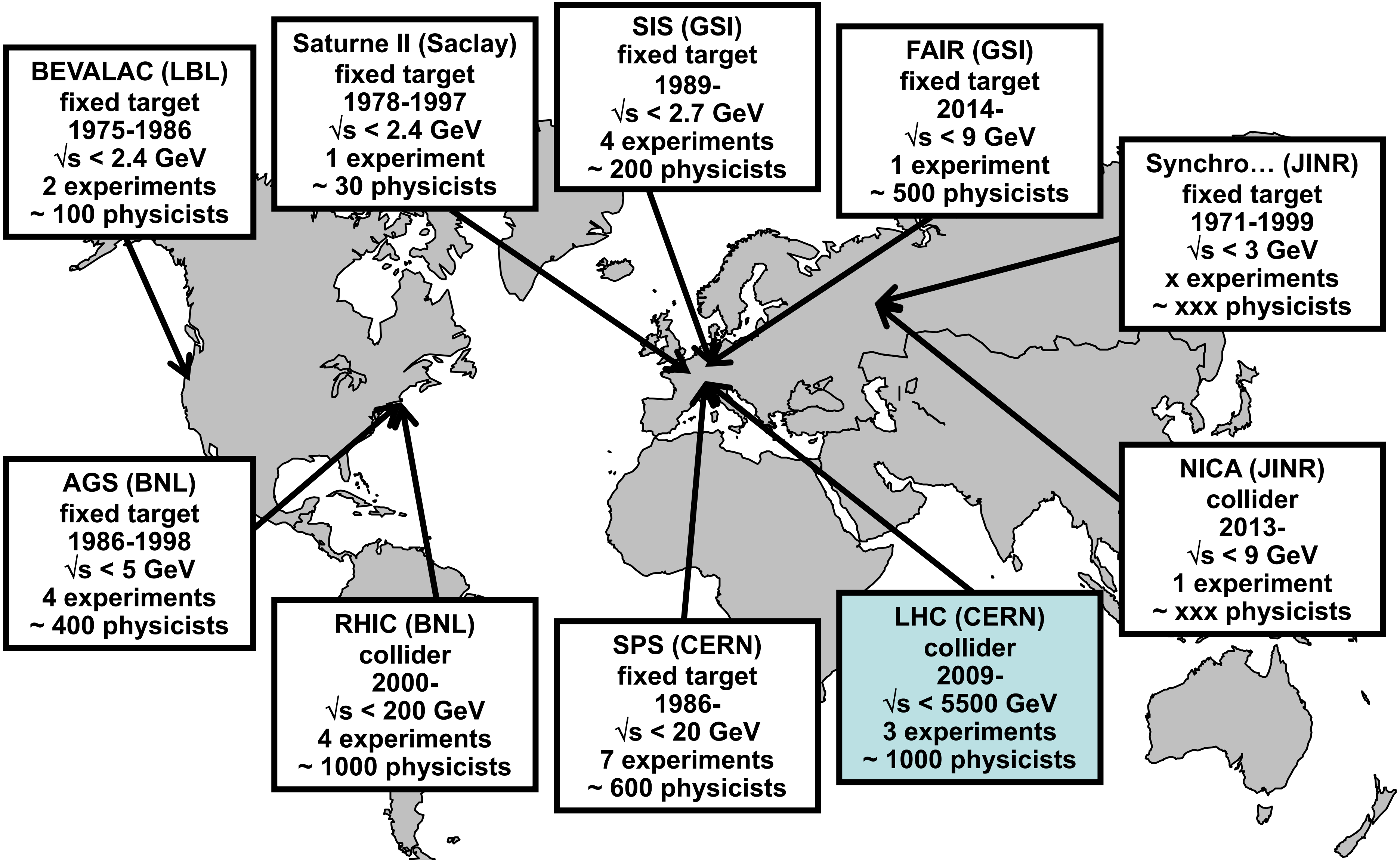






the medium behaves like a quark-gluon plasma

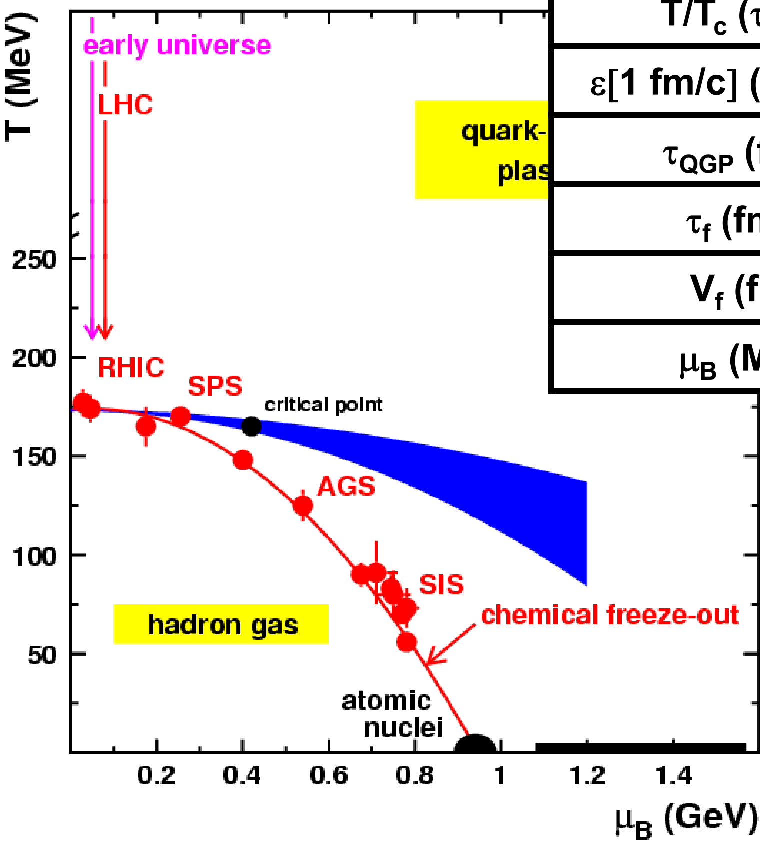
1975-2009: 34 years of heavy-ion collisions



Heavy ion collisions & QGP @ LHC

the biggest step in energy in the history of heavy-ion collisions

machine	SPS	RHIC	LHC	
$\sqrt{s}$ (GeV)	17	200	5500	= 0.18 mJ
N_{ch}	1000	4000	50 000	
τ^0_{QGP} (fm/c)	1	0.2	0.1	⇒ faster
T/T_c (τ^0_{QGP})	1.1	1.9	3.0-4.2	⇒ hotter
ε[1 fm/c] (GeV/fm^3)	3	5	15-60	⇒ denser
τ_{QGP} (fm/c)	$\leq$ 2	2-4	$\geq$ 10	⇒ longer
τ_f (fm/c)	~ 10	20-30	30-40	
V_f (fm^3)	~ 1100	~ 2200	~ 6200	⇒ bigger
μ_B (MeV)	250	20	1	

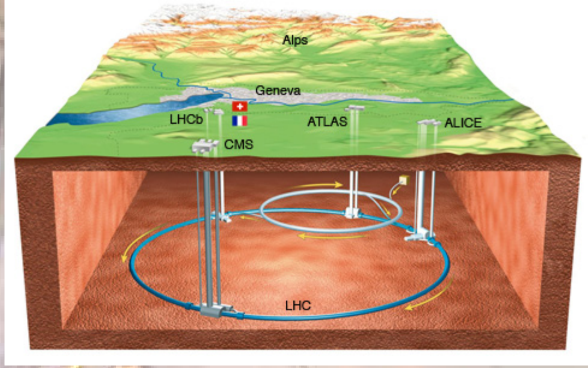


- new environment
- better conditions for studying the QGP
- each collision is a "Little Bang"

J. Schukraft, Nucl. Phys. A 698 (2002) 287

The LHC (Large Hadron Collider) @ CERN (European Organization for Nuclear Research)

The LHC in numbers



mean depth : 100 meters, circumference : 27 km, 9593 magnets

beam energy : 2.75 TeV Pb, 7 TeV proton (= 99.9999991 % of speed of light)

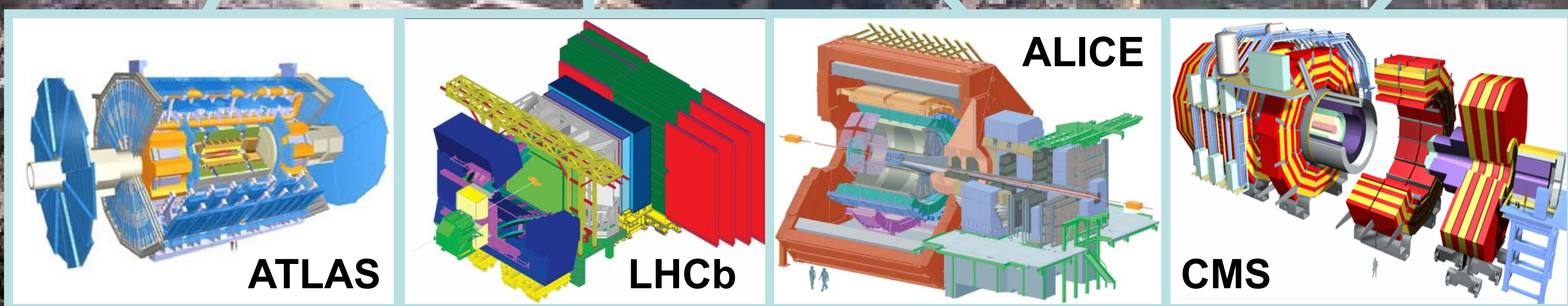
1 TeV = motion energy of a flying mosquito, size mosquito / size nucleus = 10^{12}

2808 bunches, 10^{11} protons/bunch, 11245 turn/s, 600 millions collisions/s

4 detectors

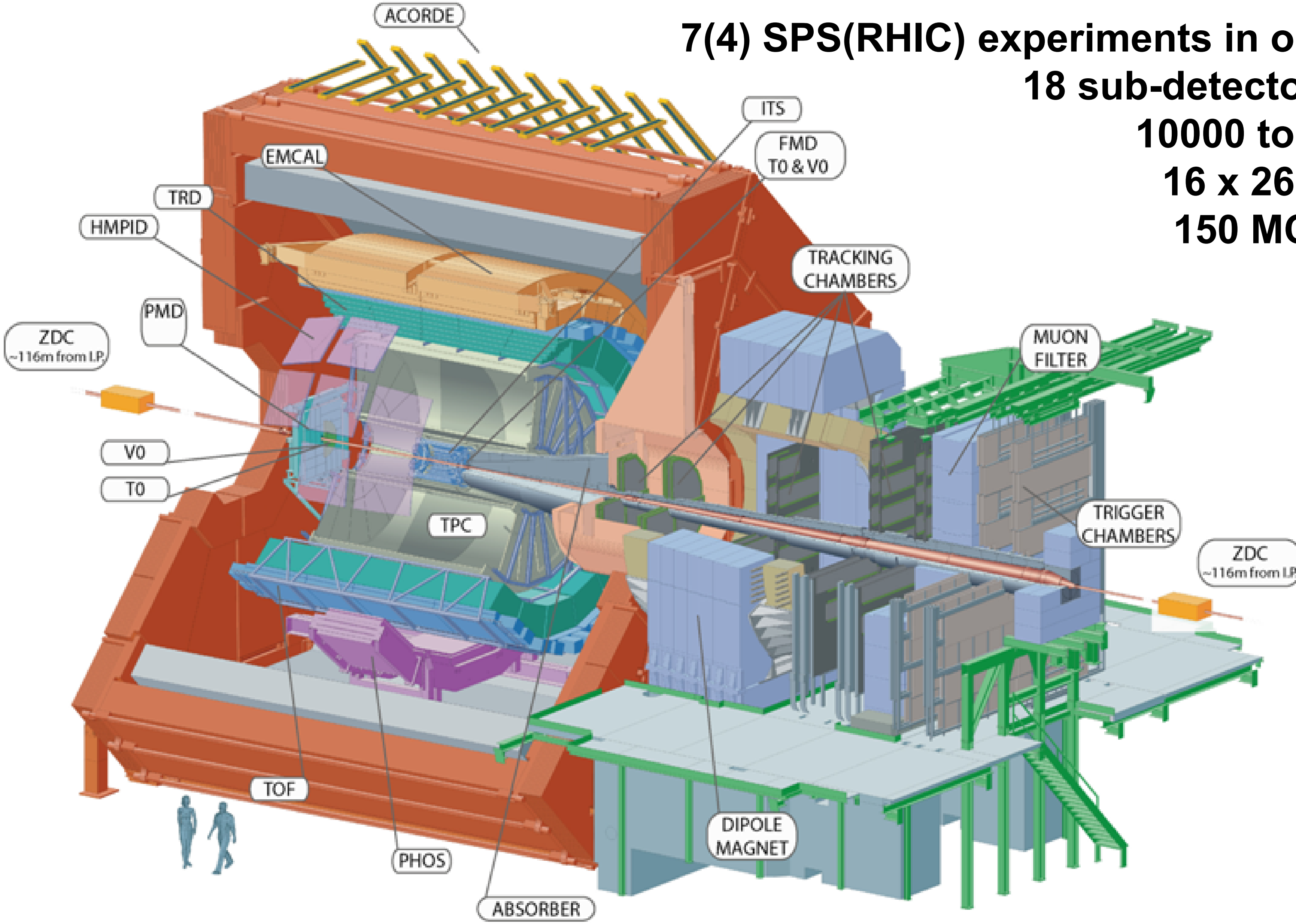
LHC detectors

1990-1996 : design
1992-2002 : R&D
2000-2010 : construction
2002-2007 : installation
2002-2009 : commissioning
Sept. 2009→ data taking



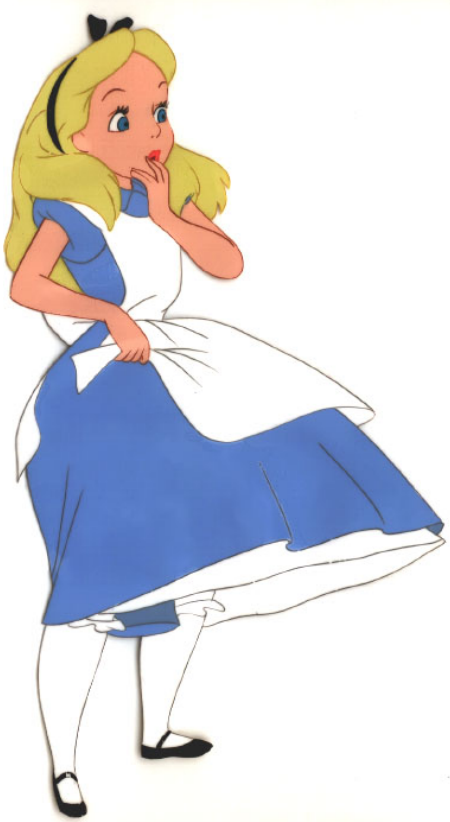
LHC research program (key words): Higgs, supersymmetry, dark matter, dark energy, matter-antimatter imbalance, quark-gluon plasma, extra-dimensions…

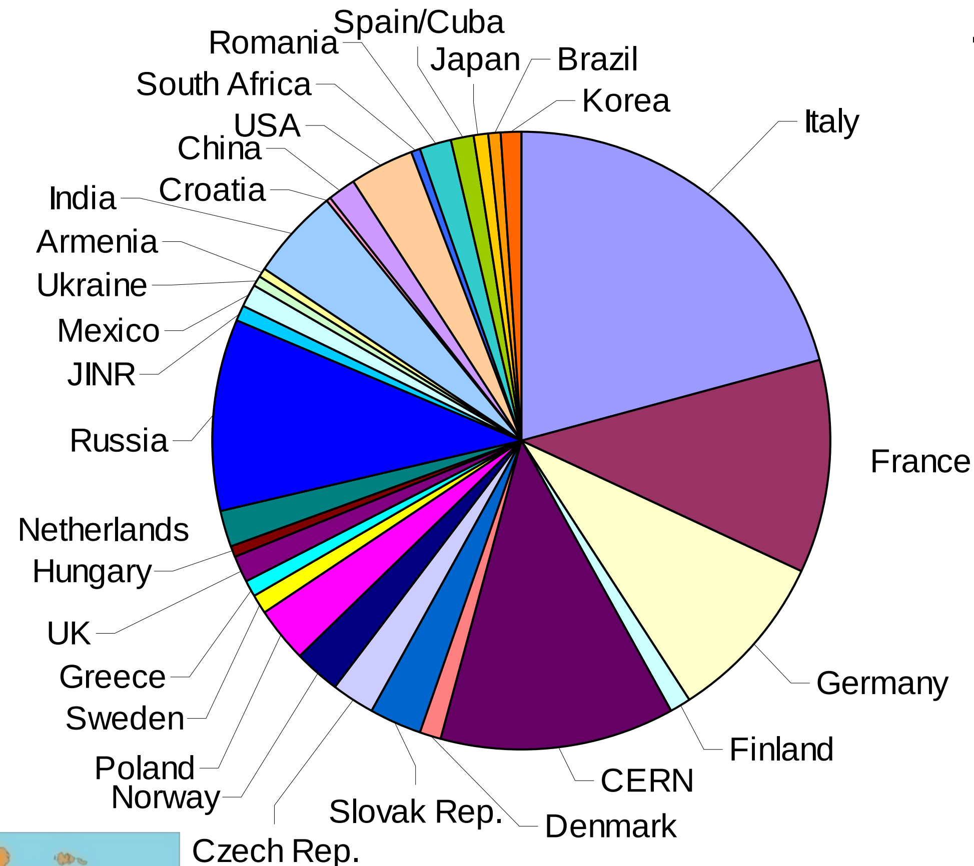
ALICE (A Large Ion Collider Experiment)



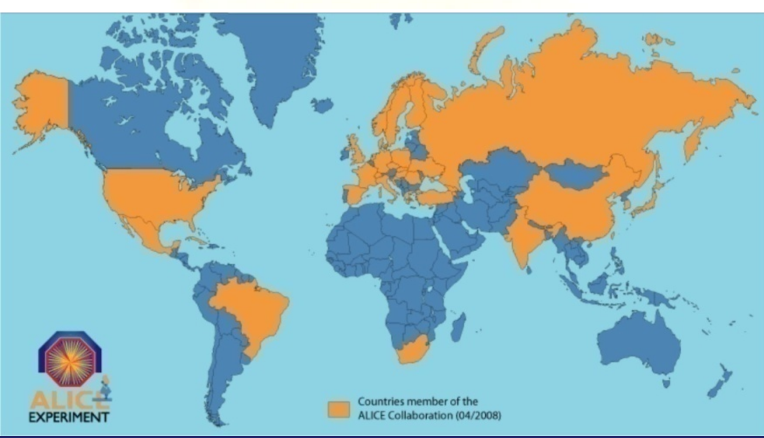
7(4) SPS(RHIC) experiments in one
18 sub-detectors
10000 tons
16 x 26 m
150 MCH

ALICE collaboration





1000 members
109 institutes
31 countries



ALICE shopping list

time →

hard scattering

- hard photons
  ⇨ pQCD
- heavy flavors
  ⇨ pQCD
- jets
  ⇨ pQCD

QGP

- thermal photons
  ⇨ QGP temperature
- heavy flavors
  ⇨ QGP properties
- jet quenching
  ⇨ QGP density

hadronization

- EbyE fluctuations
  ⇨ critical behavior
- l.m. dilepton, DCC
  ⇨ chiral symmetry
- exotica
  ⇨ QGP condens.

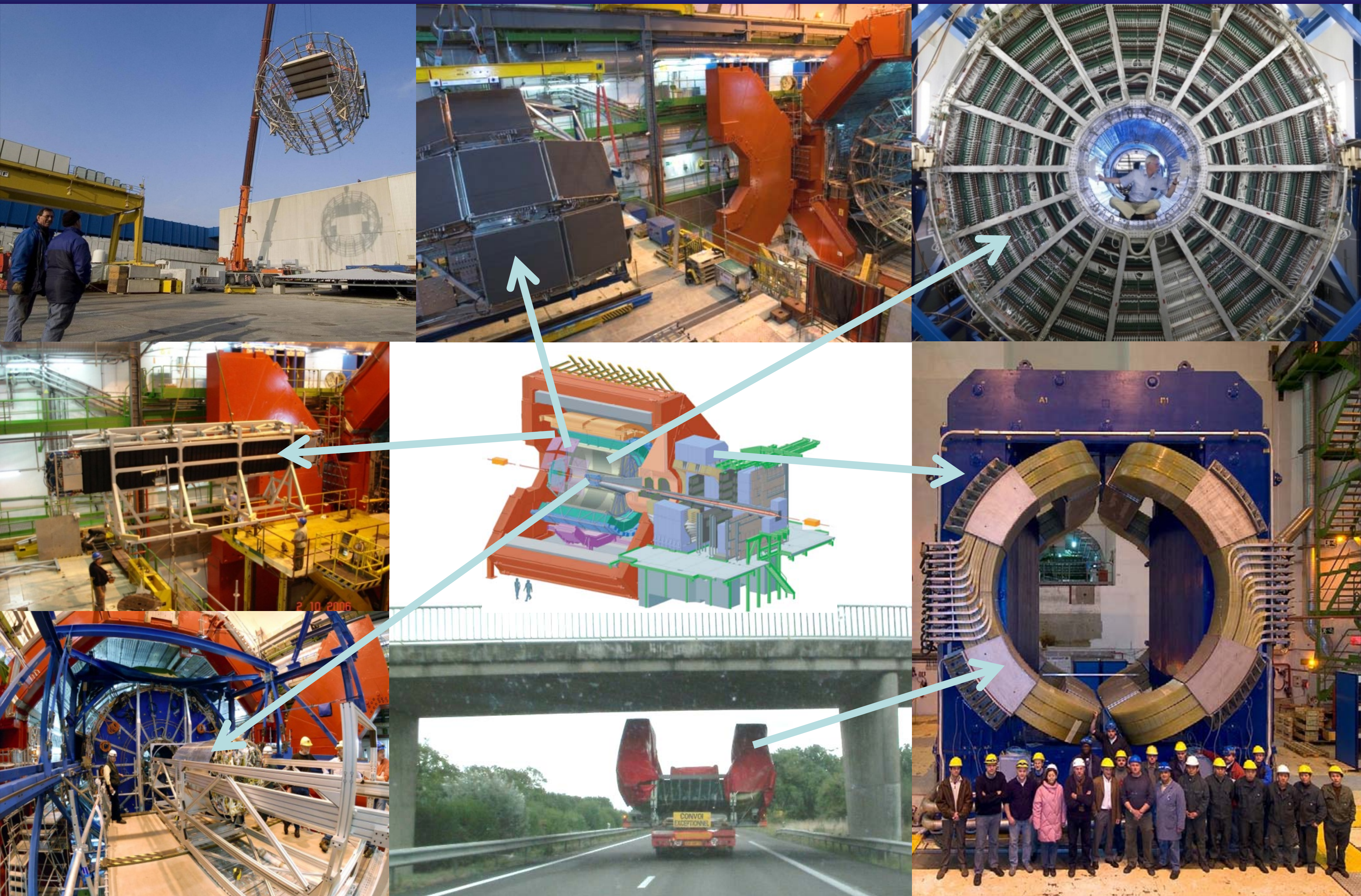
freeze-out

- particle yields, spectra, flow & HBT
  ⇨ thermal & chemical conditions
  ⇨ dynamical evol.
  ⇨ indirect info from the early stage

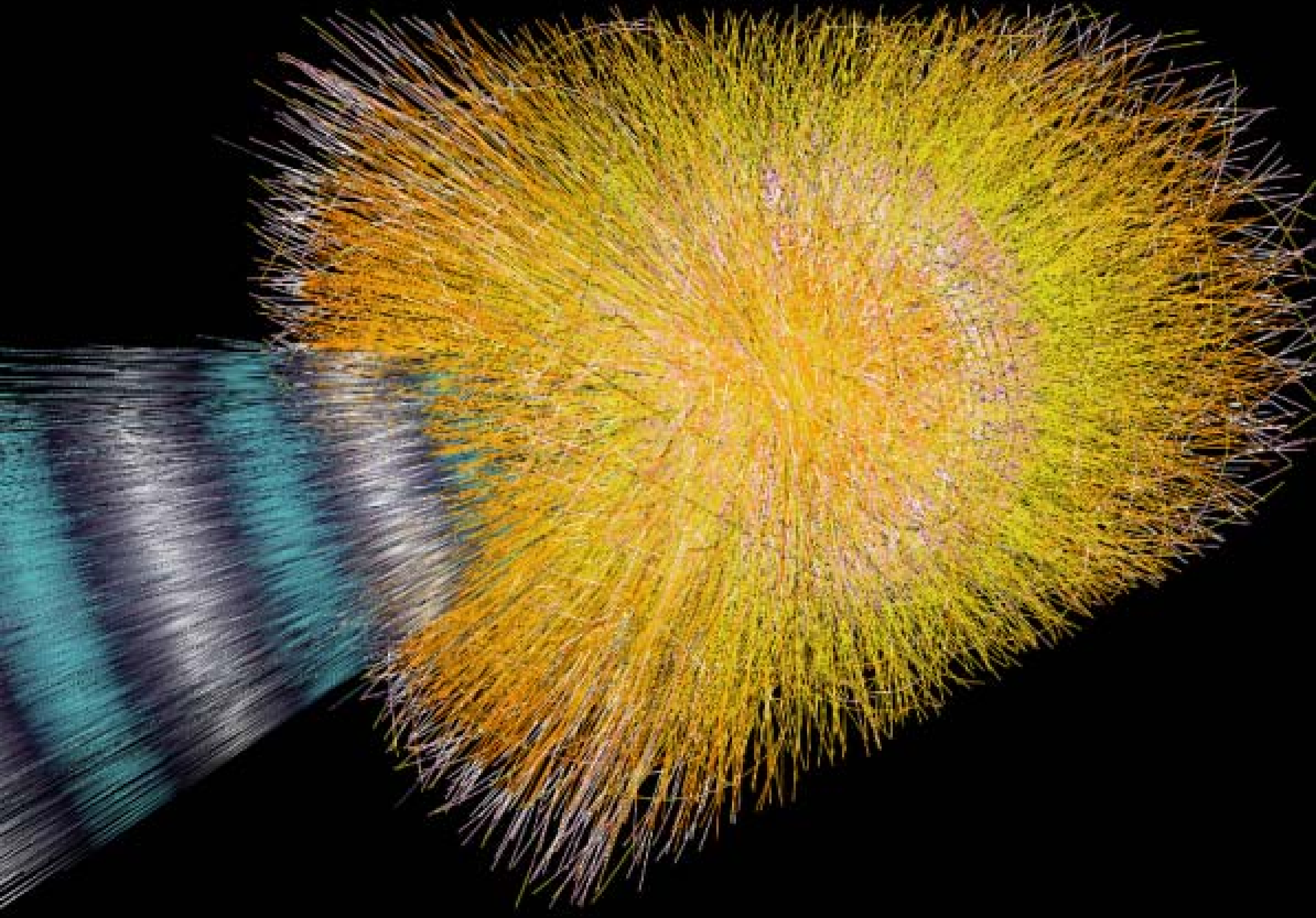
← p_t

ALICE is designed to explore a broad p_t range and to correlate most of the signals

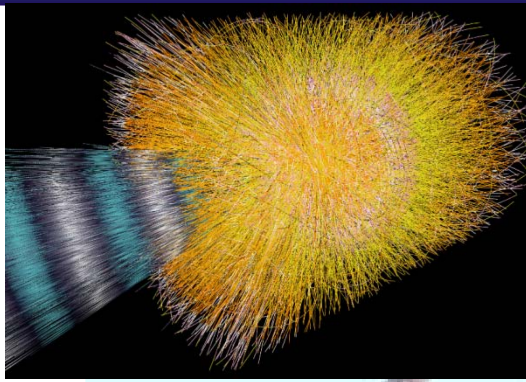
ALICE in a few pictures



How a PbPb collision will look like in ALICE

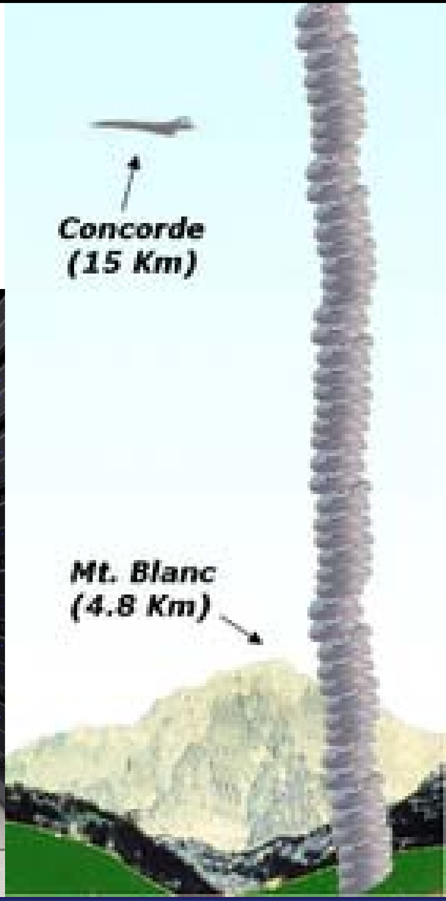


ALICE computing

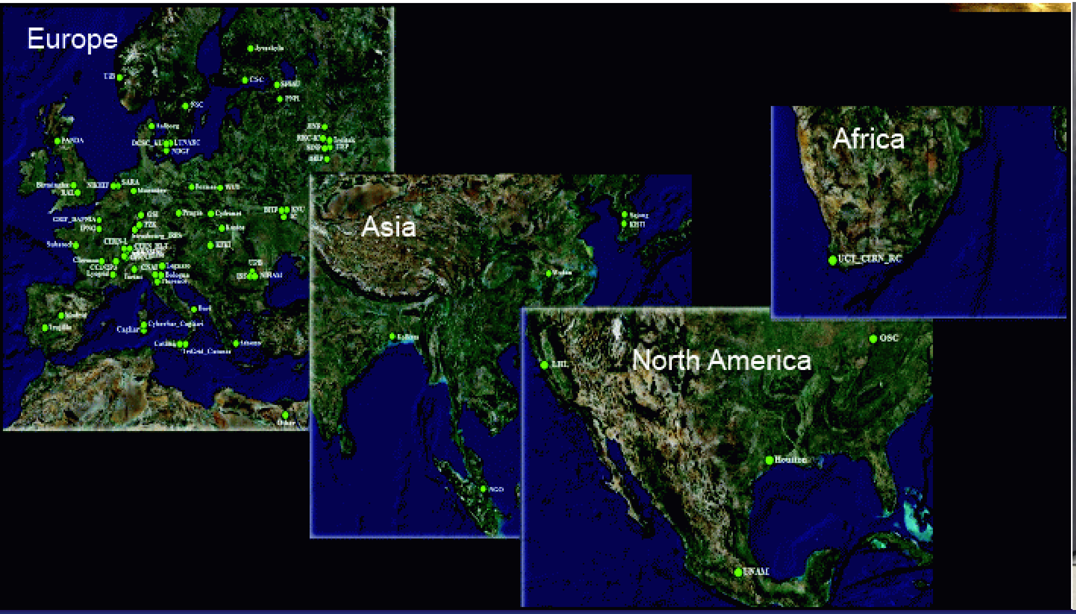


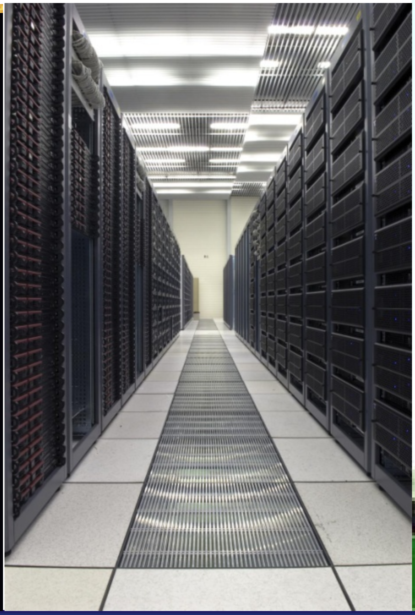
- one central PbPb collision produces ~ 80 MB of data
- ALICE data taking rate = 1.2 GB/s
- in a year (~ 10 months) = $12 \cdot 10^6$ GB = 12 PB = $12 \cdot 10^9$ MB
- 1 CD, storage = 700 MB, thickness ~ 2 mm

$\rightarrow$ data volume in one year : 10 million CDs i.e. a stack of 20 km!



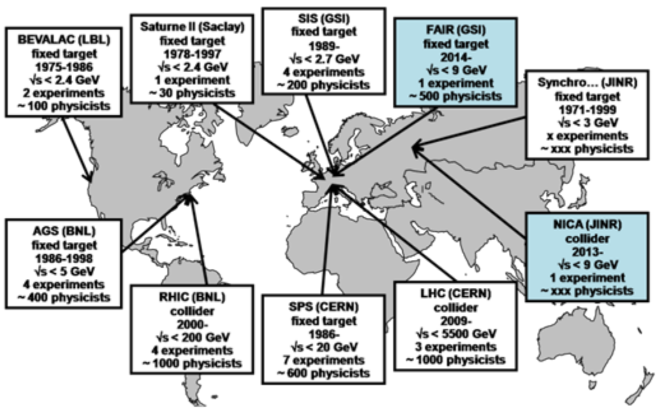
LHC data storage & analysis distributed on the world computing grid

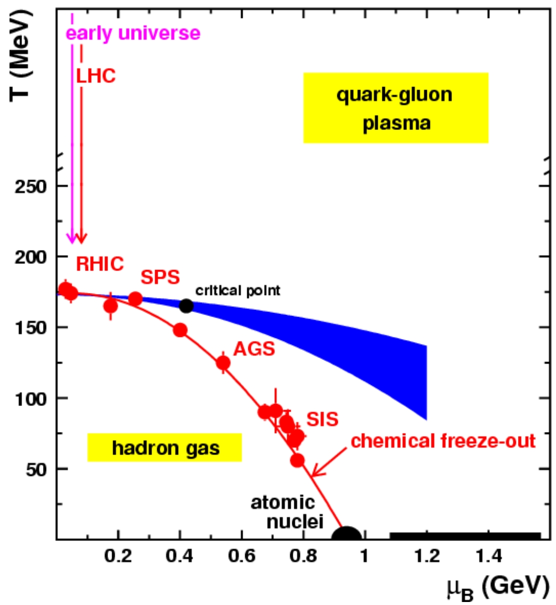




Summary

- The Quark-Gluon Plasma is a new phase of matter predicted by Quantum ChromoDynamics
- A QGP could have been produced a few microseconds after the Big Bang and might exist in the core of neutron stars
- Heavy ion collisions are the only tool to produce and study the QGP in the lab
- Experimental results collected at SPS and RHIC show evidence for the formation of the QGP in heavy ion collisions
- The LHC opens a new era with better conditions for the study of the QGP
- 2 other machines/experiments will explore from ~2015 on the low T – high μ_B region of the QCD phase diagram and search the critical point






First LHC beams by mid September. Stay tuned...