

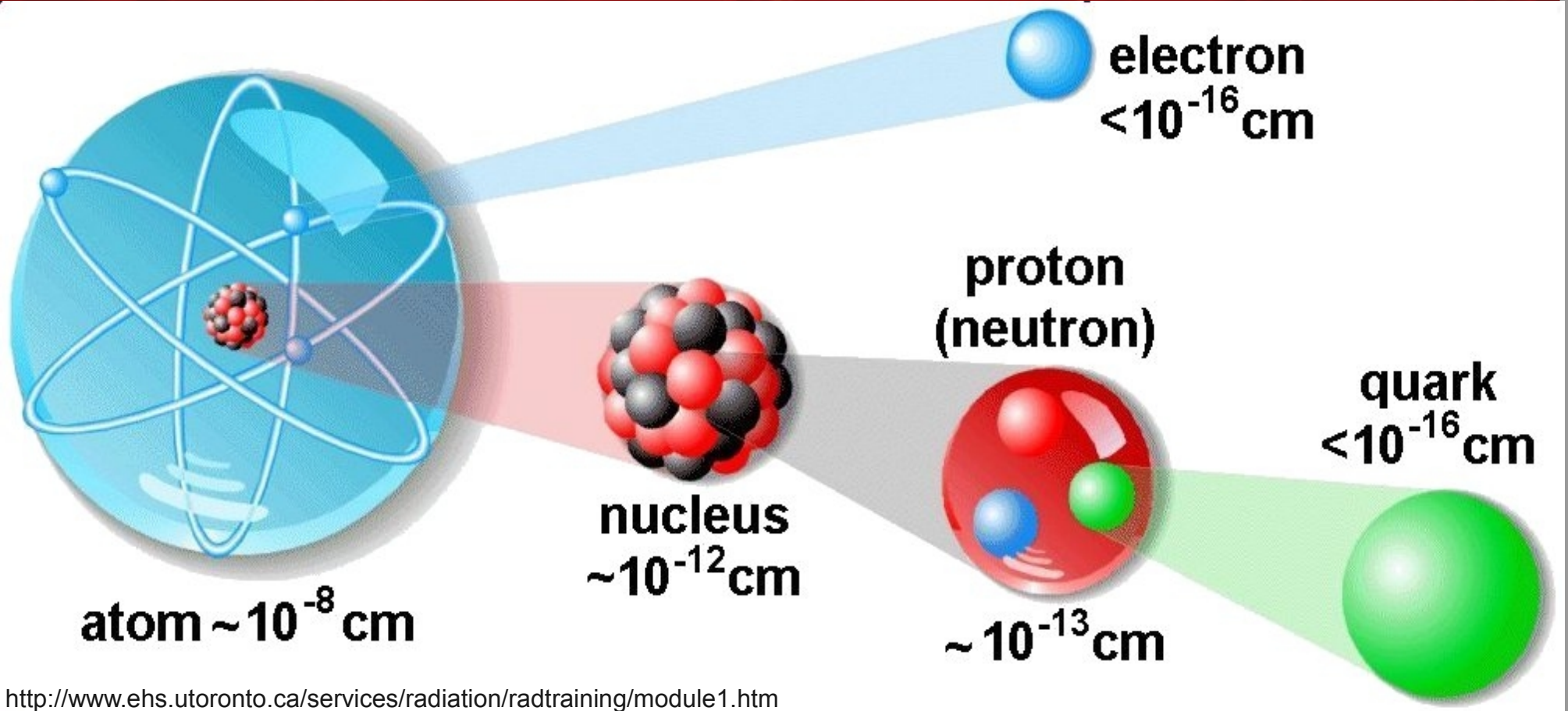
Jets as a probe of the Quark Gluon Plasma

Christine Nattrass
Yale University
Goldhaber Lecture 2008

Outline

- What is a quark gluon plasma?
- Why do we want to study it?
- How do we study it?
- What have we learned?
- Conclusions

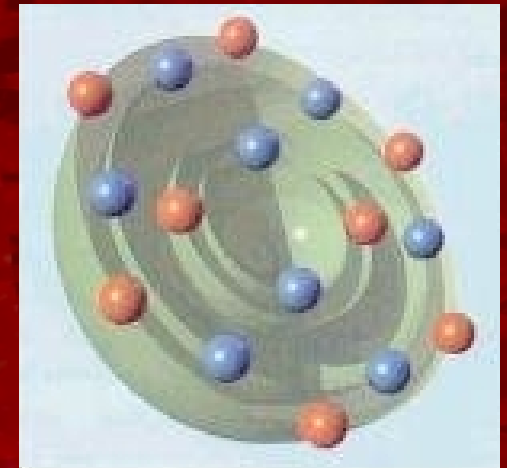
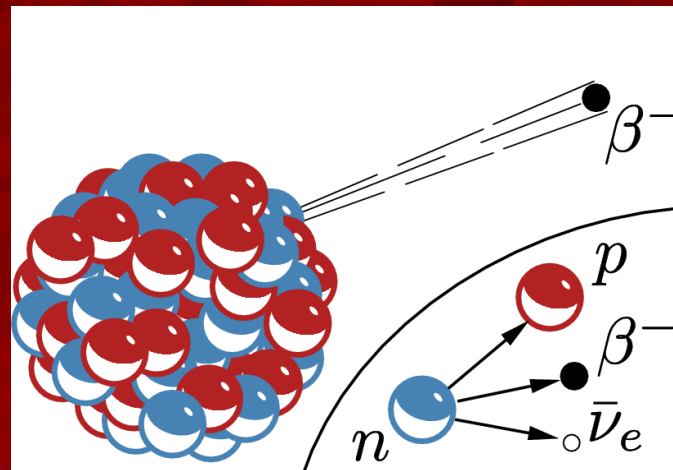
The structure of matter



Who was Gertrude Goldhaber?



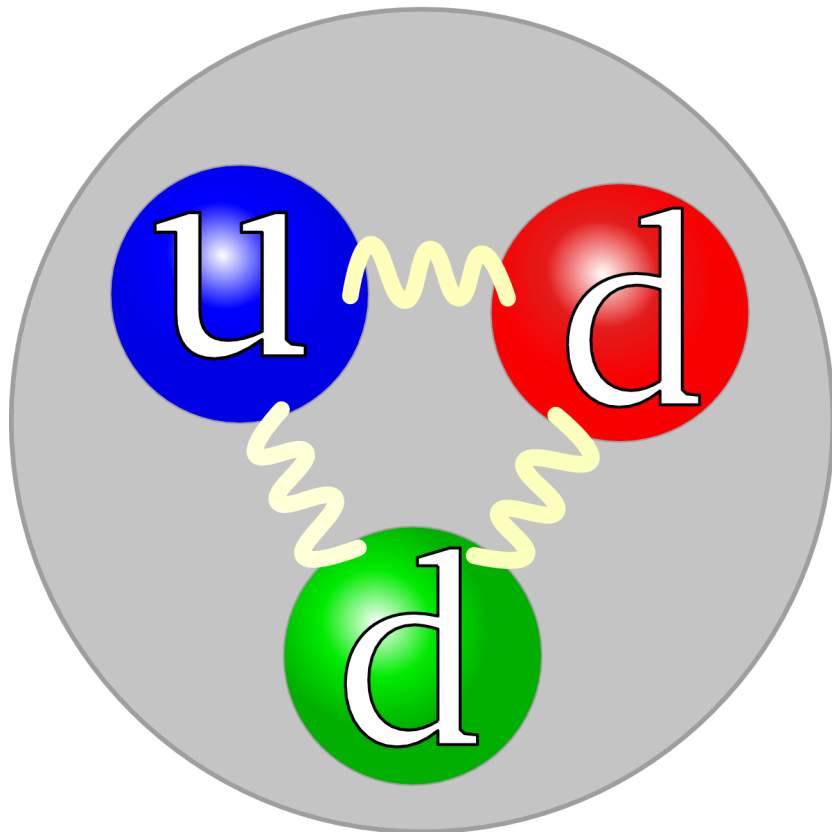
Gertrude Scharff Goldhaber
July 14, 1911 — February 2, 1998
http://cwp.library.ucla.edu/Phase2/Goldhaber_Gertrude_Scharff@812345678.html



- Beta decay – demonstrated that the beta particle was an electron
- Shell model – provided experimental evidence for closed shells in heavy nuclei
- Created first 3-D plot

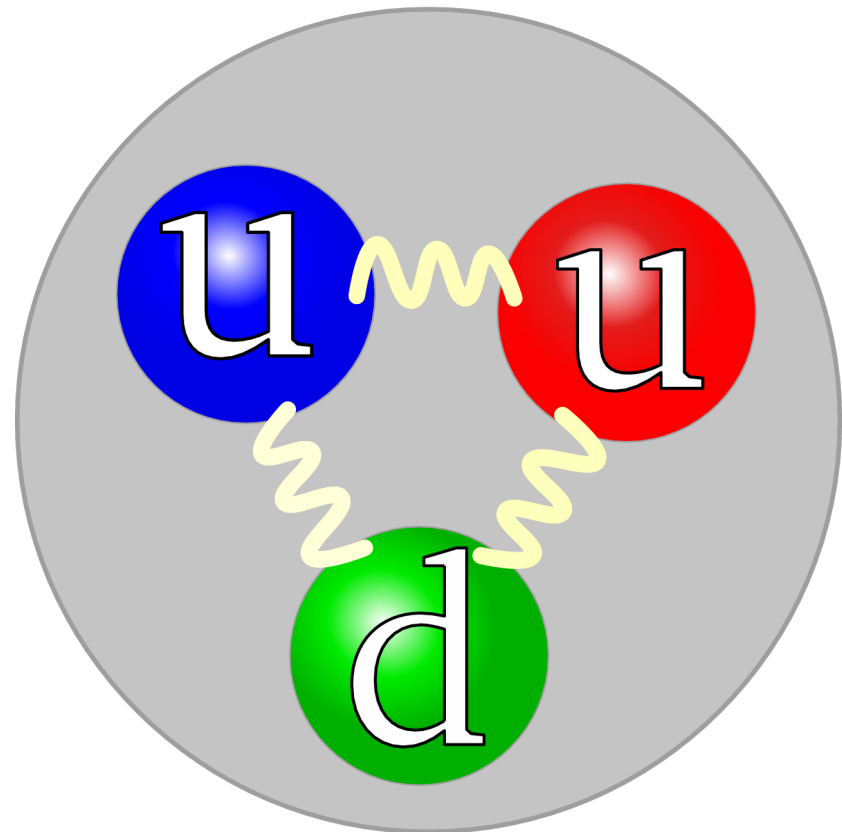
http://upload.wikimedia.org/wikipedia/commons/a/aa/Beta-minus_Decay.svg
<http://universe-review.ca/114-05-nuclearenergy.jpg>
<http://www.nap.edu/html/biomems/ggoldhaber.html>

Nucleons – the proton and neutron



Neutron

http://en.wikipedia.org/wiki/Image:Quark_structure_neutron.svg

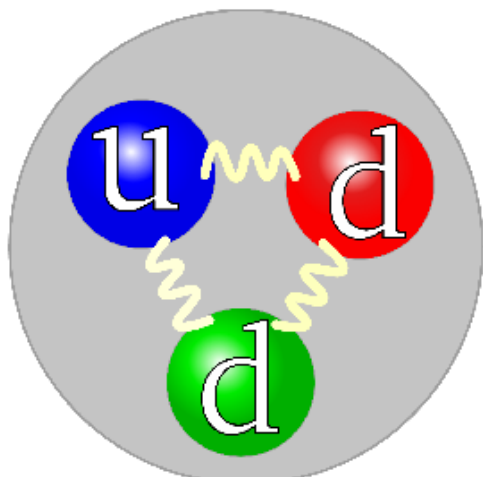


Proton

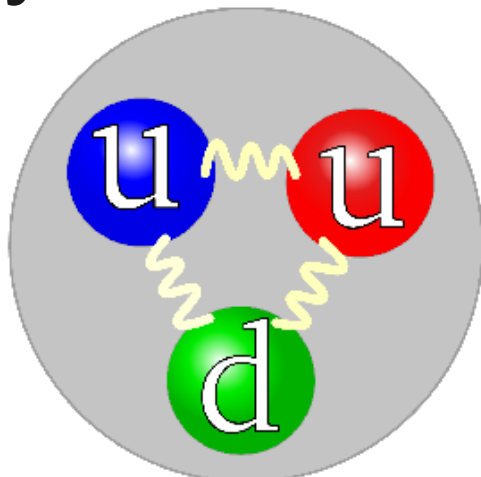
http://en.wikipedia.org/wiki/Image:Quark_structure_proton.svg

Other particles - hadrons

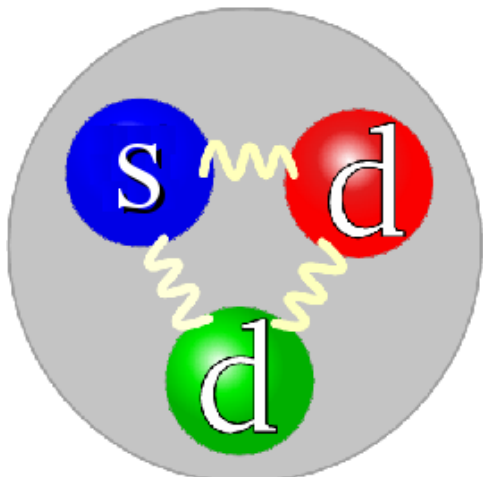
Baryons



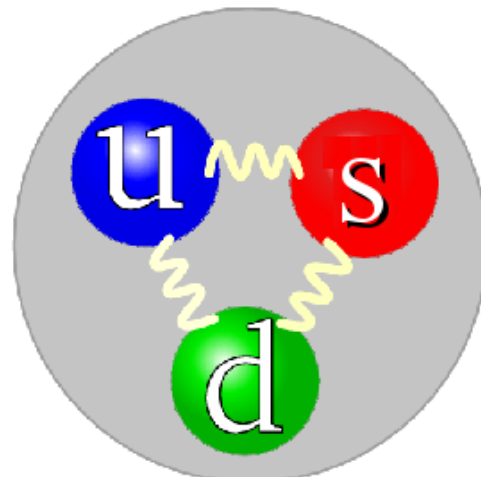
Neutron



Proton

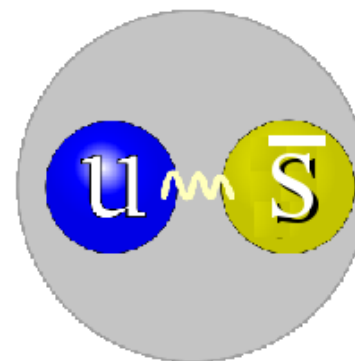


Sigma

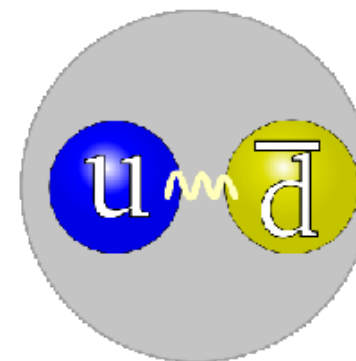


Lambda

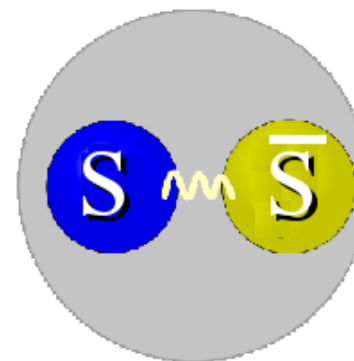
Mesons



Kaon



Pion



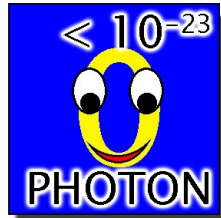
Phi

The Standard Model

QUARKS



LEPTONS



FORCE CARRIERS: BOSONS

Weak force

Electromagnetic force

Strong force

The Standard Model fundamental particle zoo

http://e4.physik.uni-dortmund.de/bin/view/ATLAS/SmBilder?PhotoarchivePlugin_page=1&PhotoarchivePlugin_view=detailed

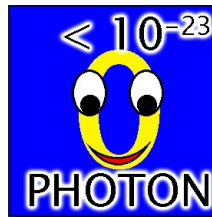
The Standard Model

QUARKS

 2.75 UP	 1300 CHARM	 178000 TOP
 6 DOWN	 1:10 STRANGE	 4500 BOTTOM

LEPTONS

 0.511 ELECTRON
--



FORCE CARRIERS: BOSONS

Weak force

Electromagnetic force

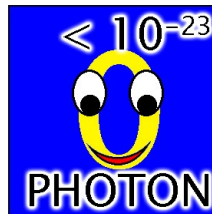
Strong force

The Standard Model fundamental particle zoo

http://e4.physik.uni-dortmund.de/bin/view/ATLAS/SmBilder?PhotoarchivePlugin_page=1&PhotoarchivePlugin_view=detailed

The Standard Model

QUARKS	 2.75 UP	 1300 CHARM	 178000 TOP
	 6 DOWN	 110 STRANGE	 4500 BOTTOM
	 0.511 ELECTRON	 105.7 MUON	 1777 TAU



FORCE CARRIERS: BOSONS

Weak force

Electromagnetic force

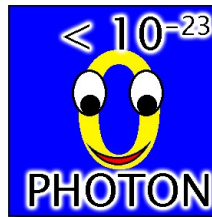
Strong force

The Standard Model fundamental particle zoo

http://e4.physik.uni-dortmund.de/bin/view/ATLAS/SmBilder?PhotoarchivePlugin_page=1&PhotoarchivePlugin_view=detailed

The Standard Model

QUARKS	 2.75 UP	 1300 CHARM	 178000 TOP
	 6 DOWN	 1.10 STRANGE	 4500 BOTTOM
	 0.511 ELECTRON	 105.7 MUON	 1777 TAU
	 $< 3 \cdot 10^{-6}$ NEUTRINO e	 < 0.19 NEUTRINO μ	 < 18.2 NEUTRINO τ



FORCE CARRIERS: BOSONS

Weak force

Electromagnetic force

Strong force

The Standard Model
fundamental particle zoo

The Standard Model

QUARKS	 2.75 UP	 1300 CHARM	 178000 TOP	 91188 Z^0
	 6 DOWN	 1.10 STRANGE	 4500 BOTTOM	 80430 W^+/W^-
	 0.511 ELECTRON	 105.7 MUON	 1777 TAU	 $< 10^{-23}$ PHOTON
LEPTONS	 $< 3 \cdot 10^{-6}$ NEUTRINO e	 < 0.19 NEUTRINO μ	 < 18.2 NEUTRINO τ	 theory: 0 GLUON

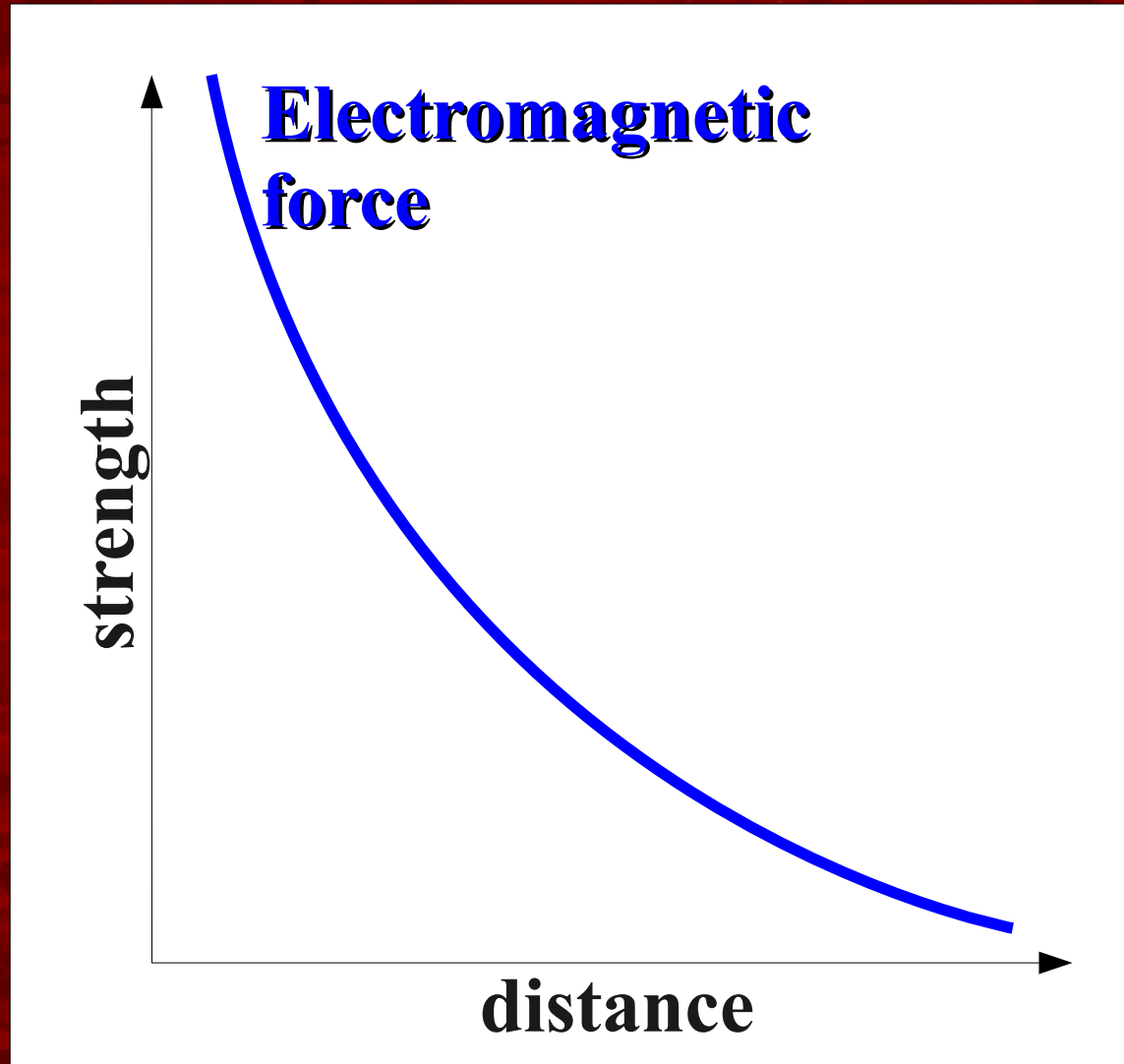
FORCE CARRIERS: BOSONS



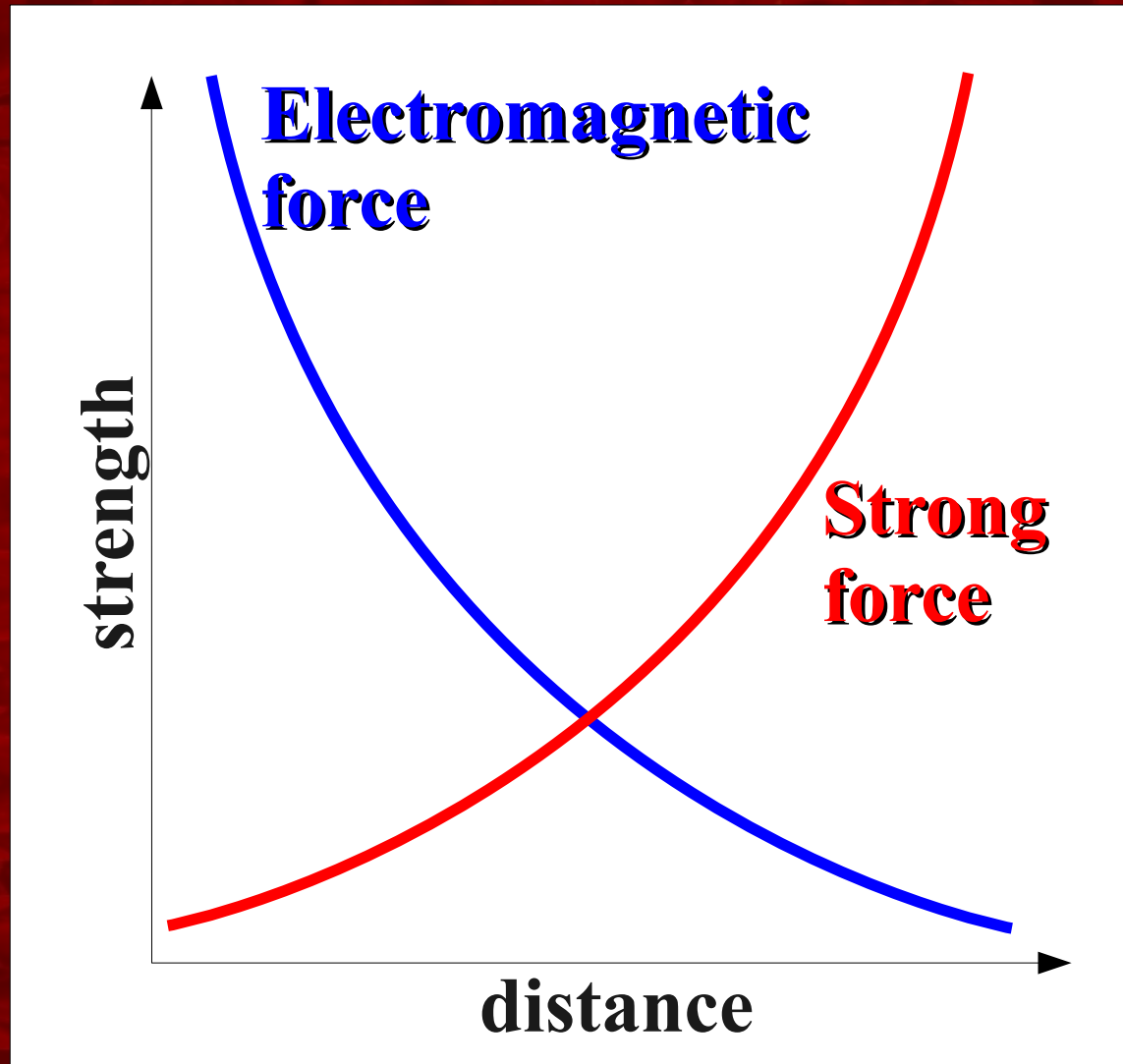
The Standard Model
fundamental particle zoo

http://e4.physik.uni-dortmund.de/bin/view/ATLAS/SmBilder?PhotoarchivePlugin_page=1&PhotoarchivePlugin_view=detailed

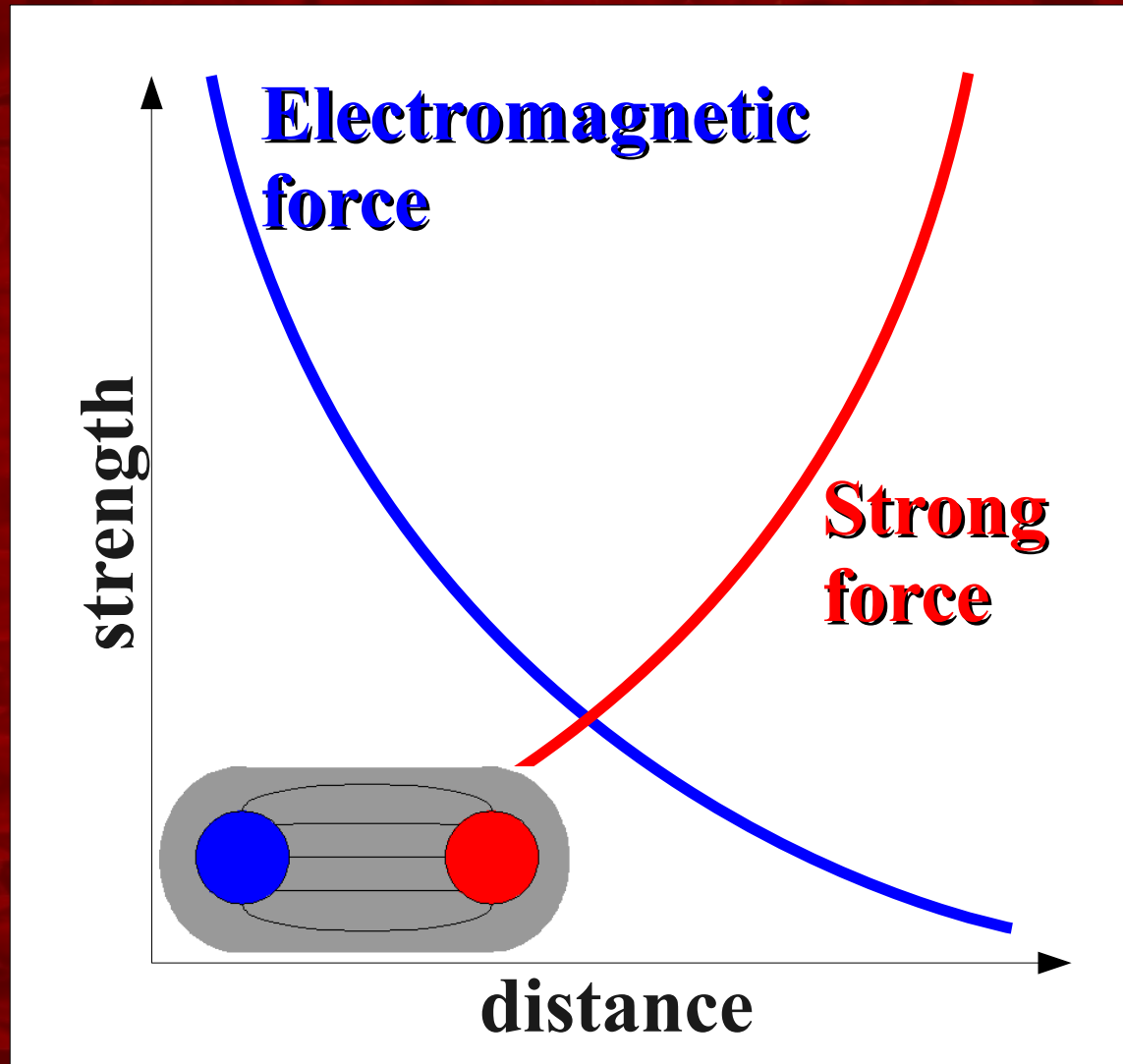
What keeps the nucleus together?



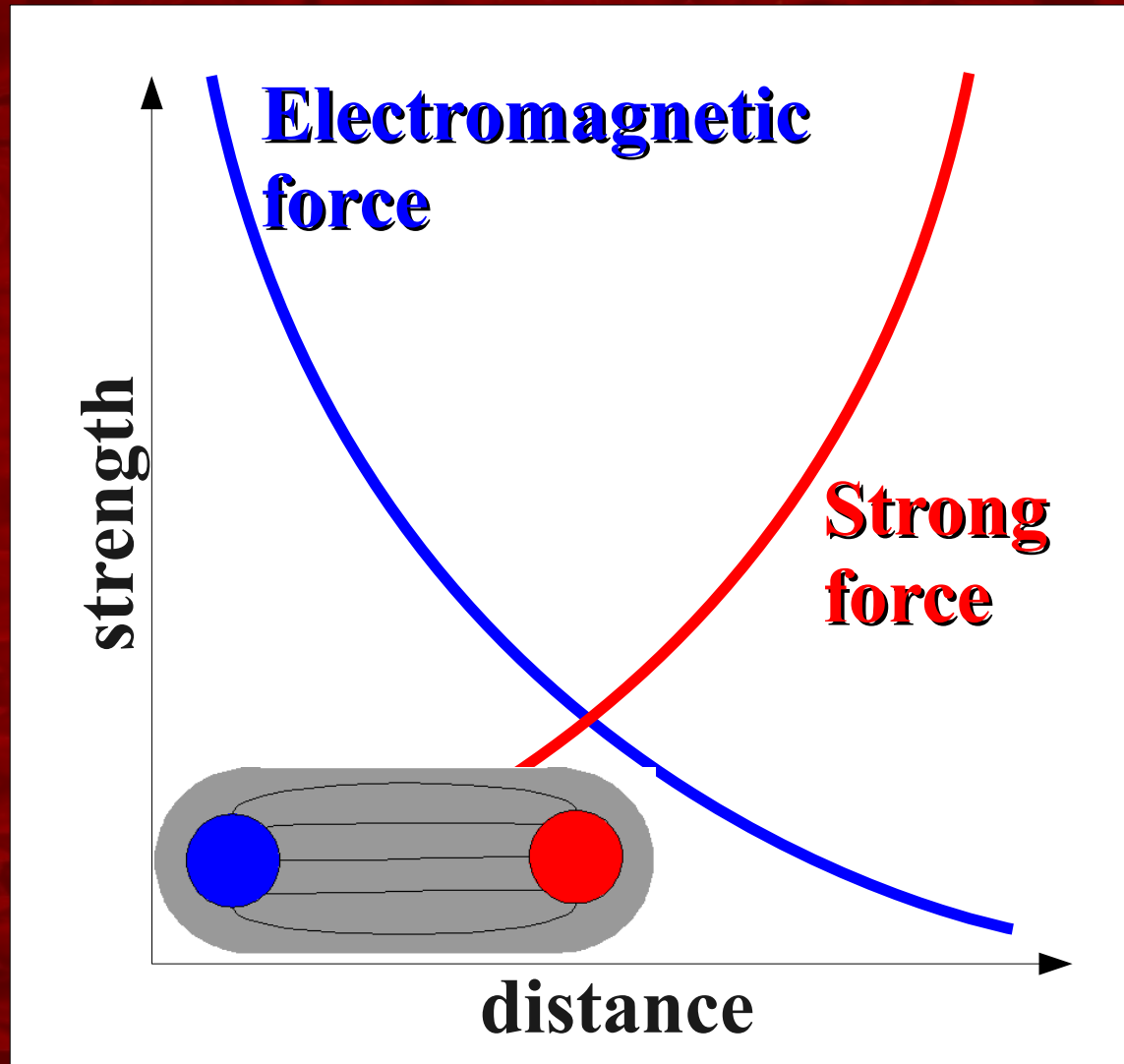
What keeps the nucleus together?



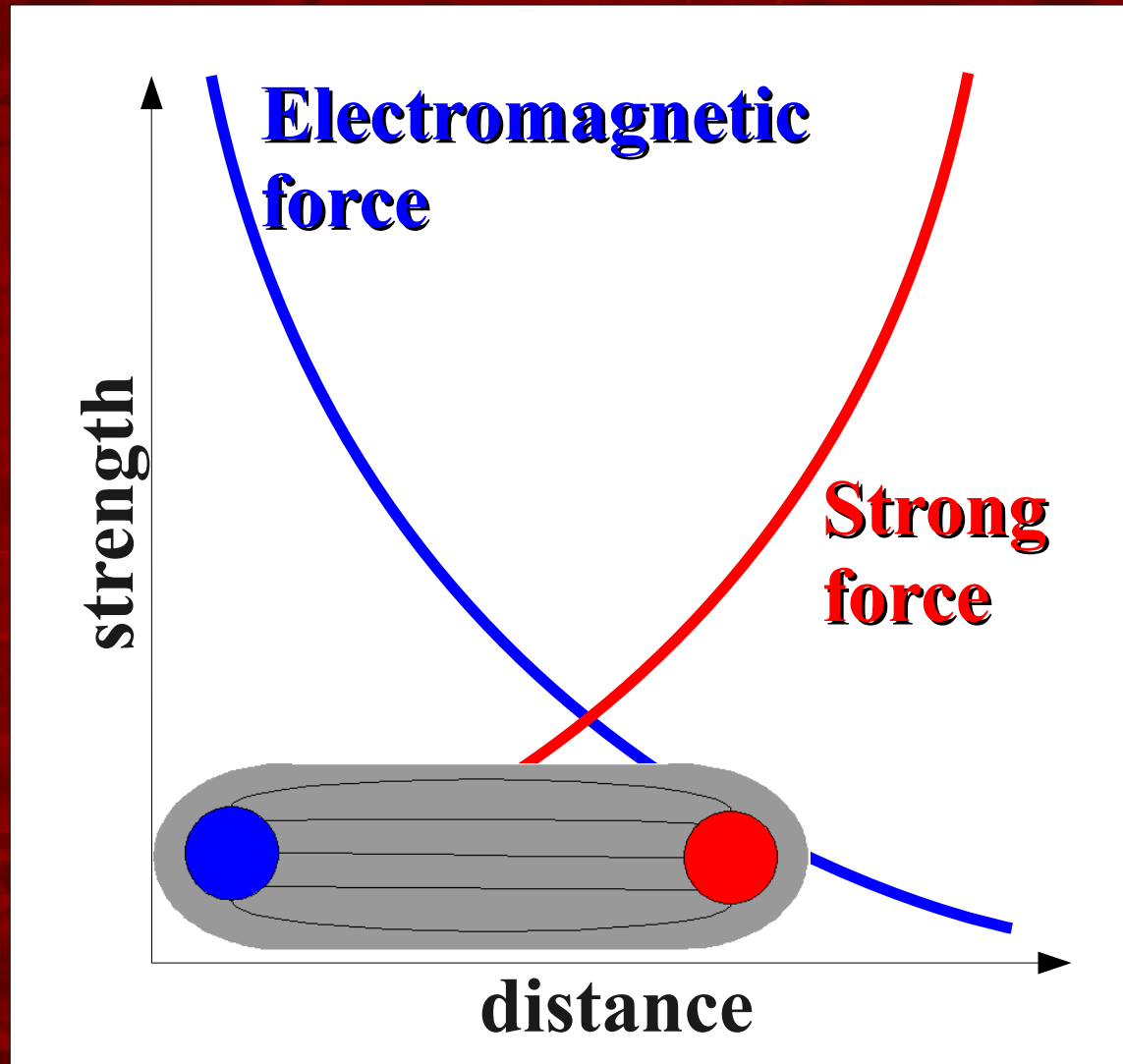
What keeps the nucleus together?



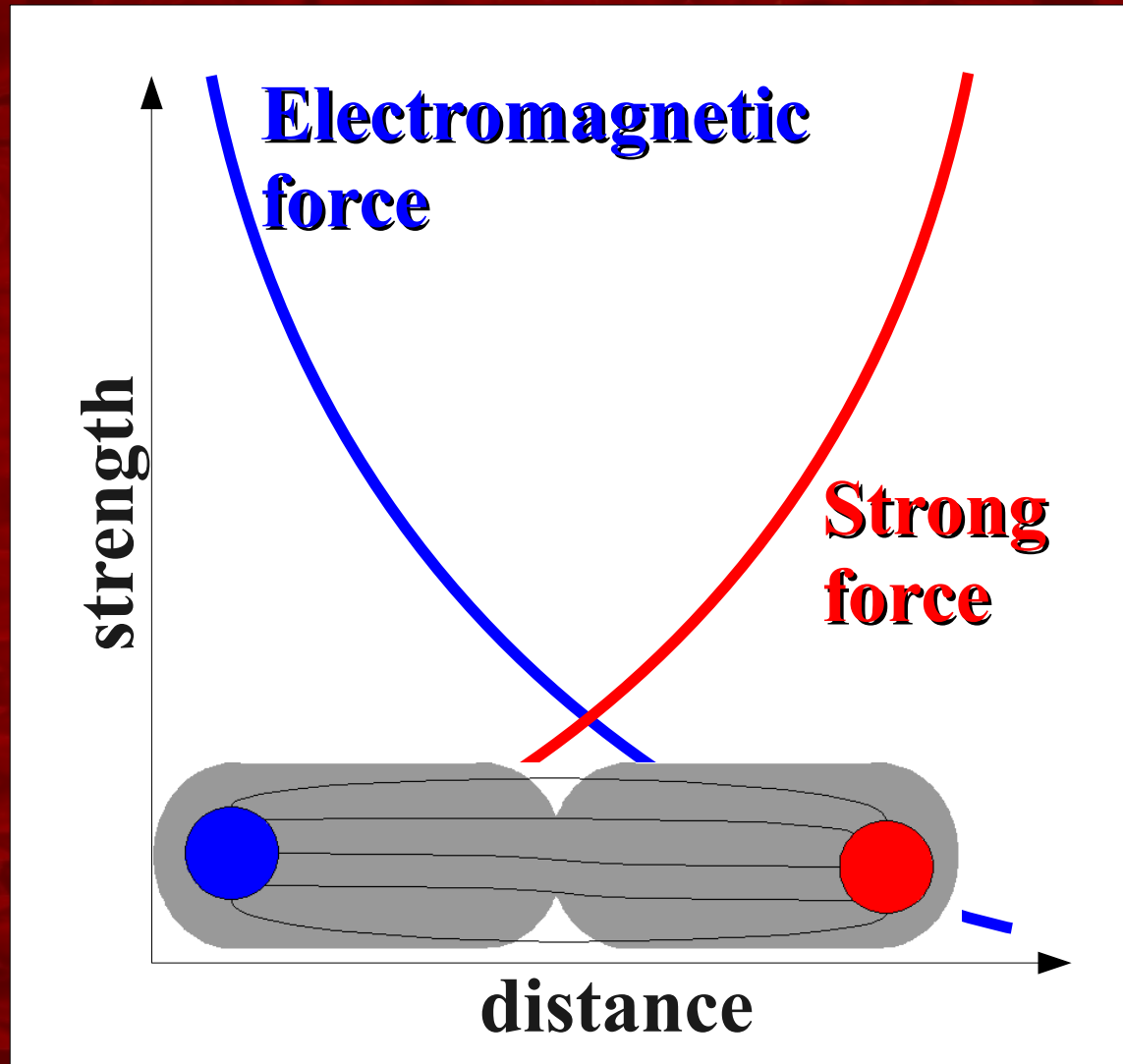
What keeps the nucleus together?



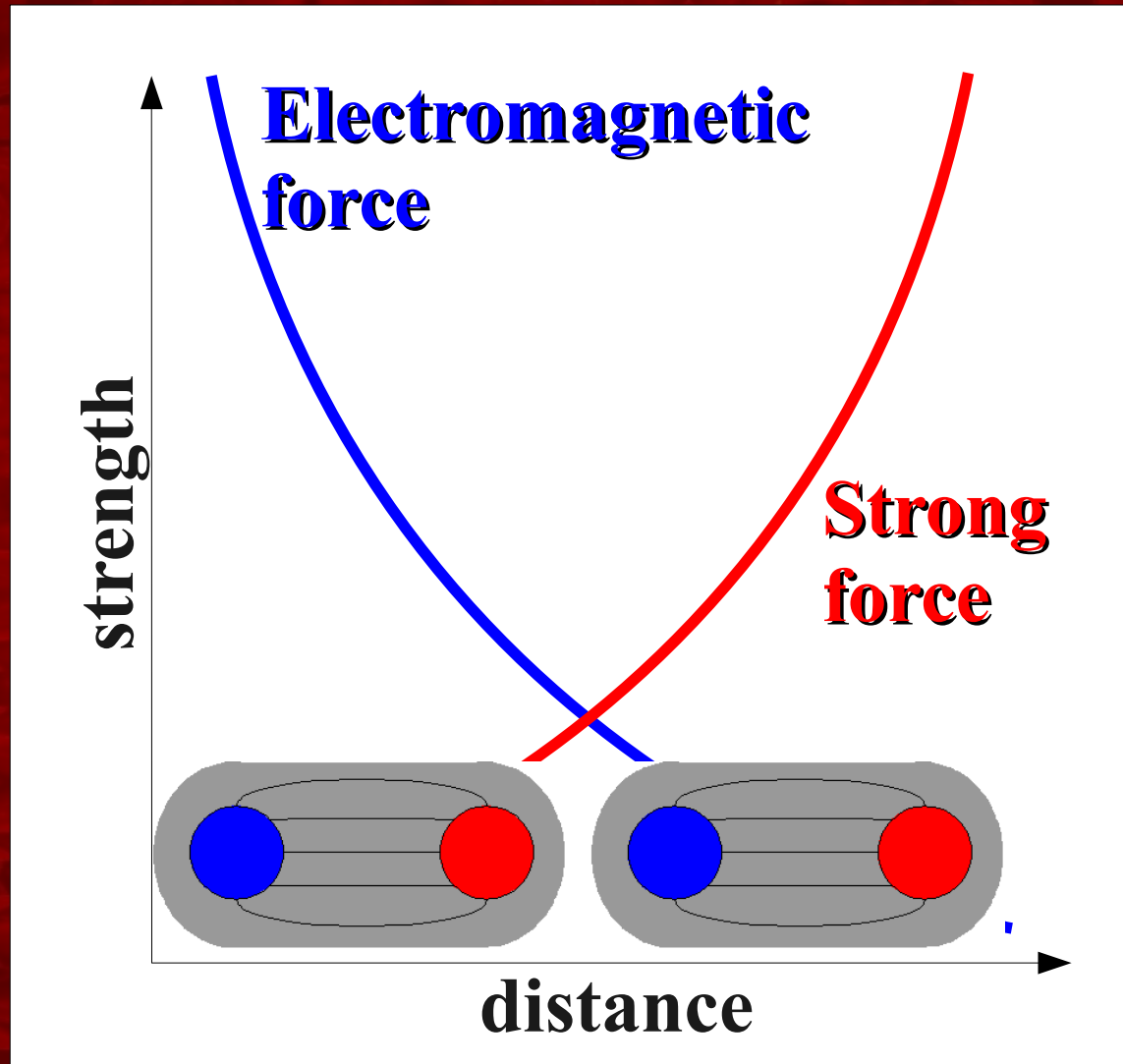
What keeps the nucleus together?



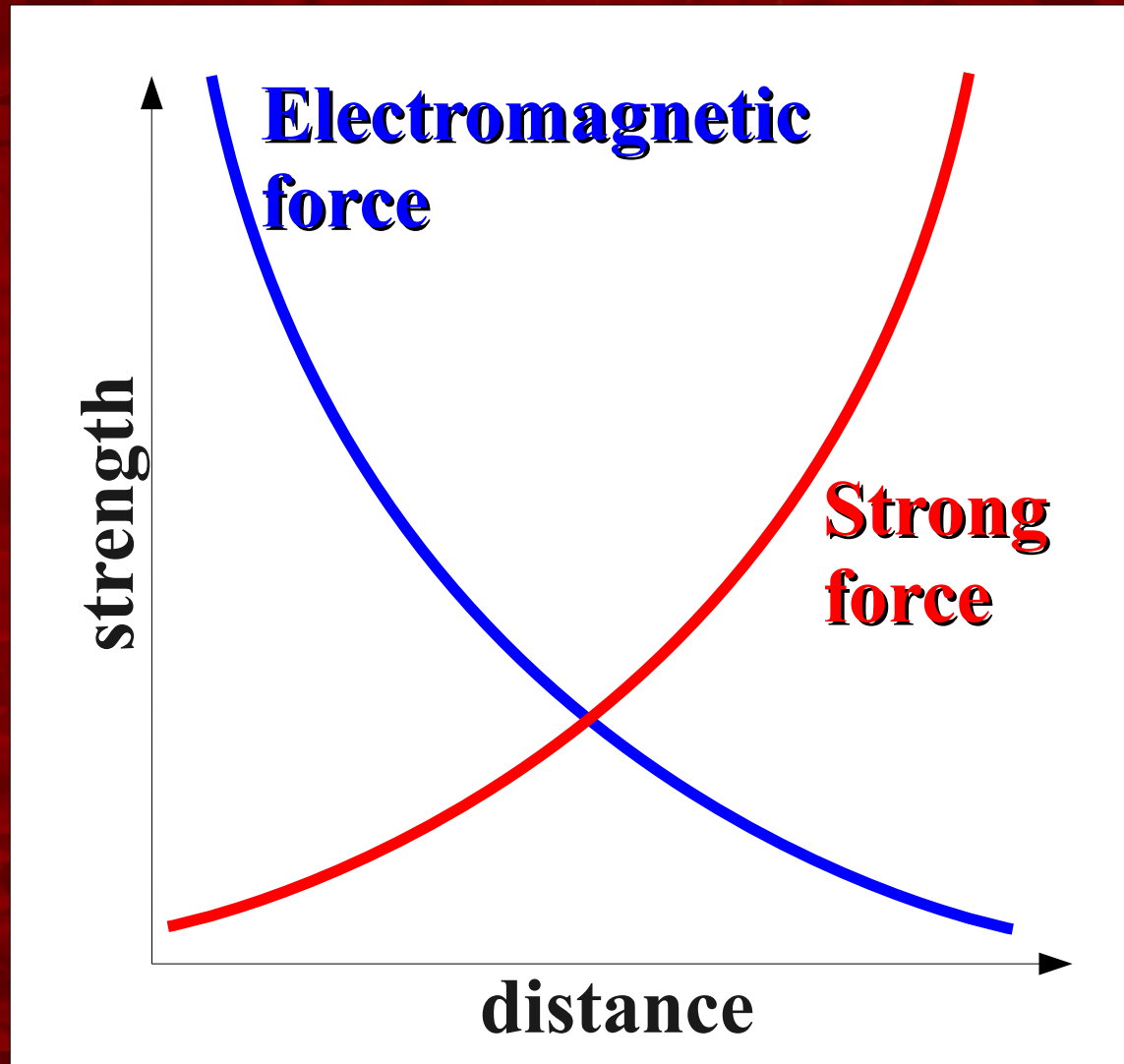
What keeps the nucleus together?



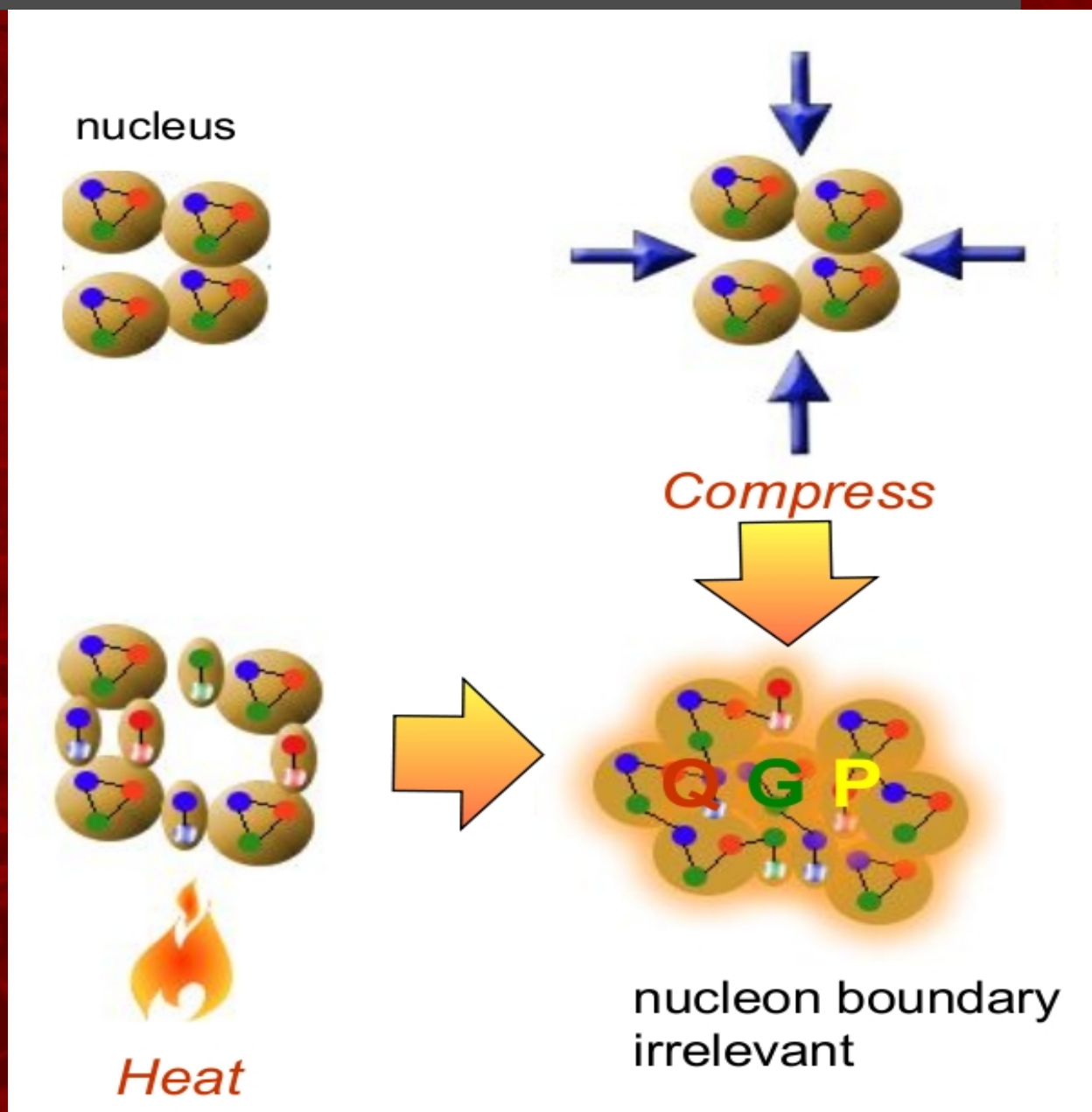
What keeps the nucleus together?



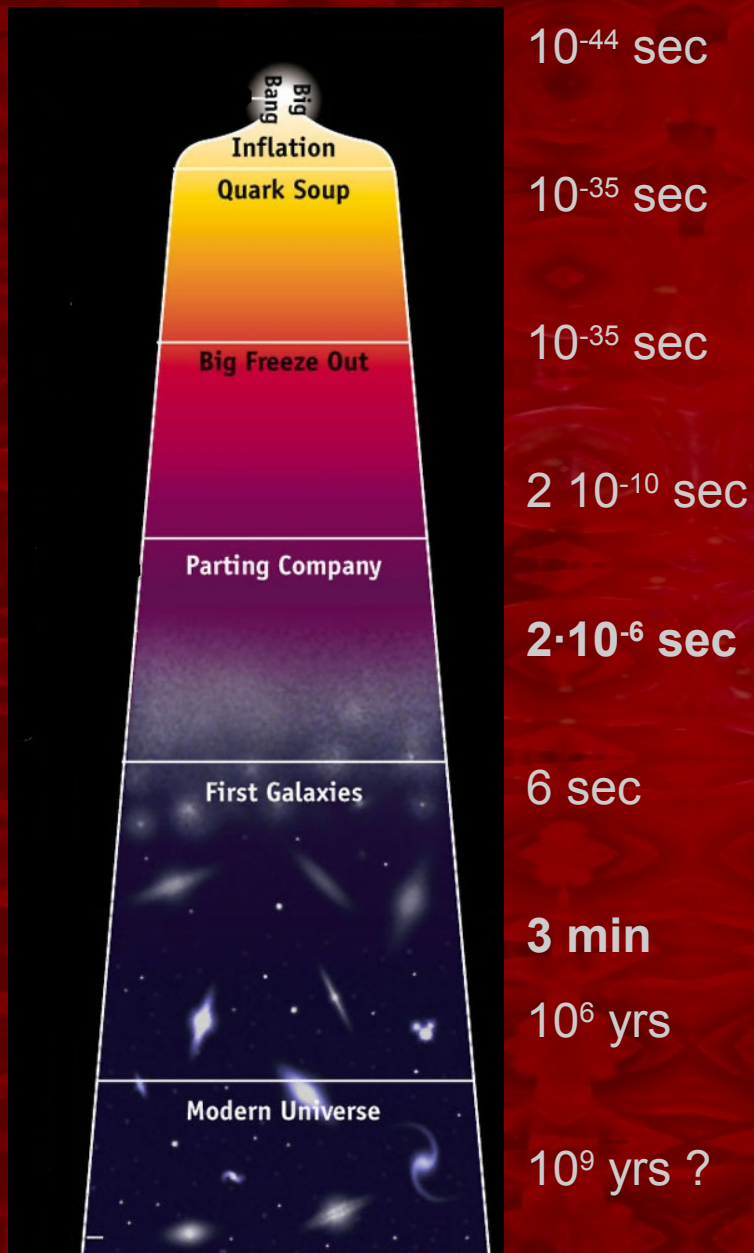
What keeps the nucleus together?



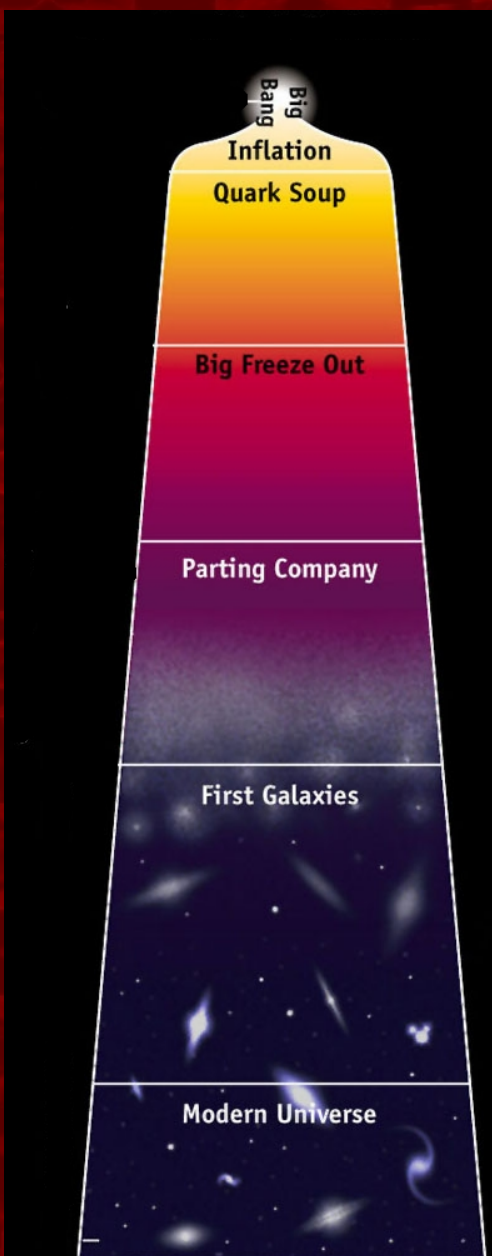
How to make a Quark Gluon Plasma



Evolution of the Universe

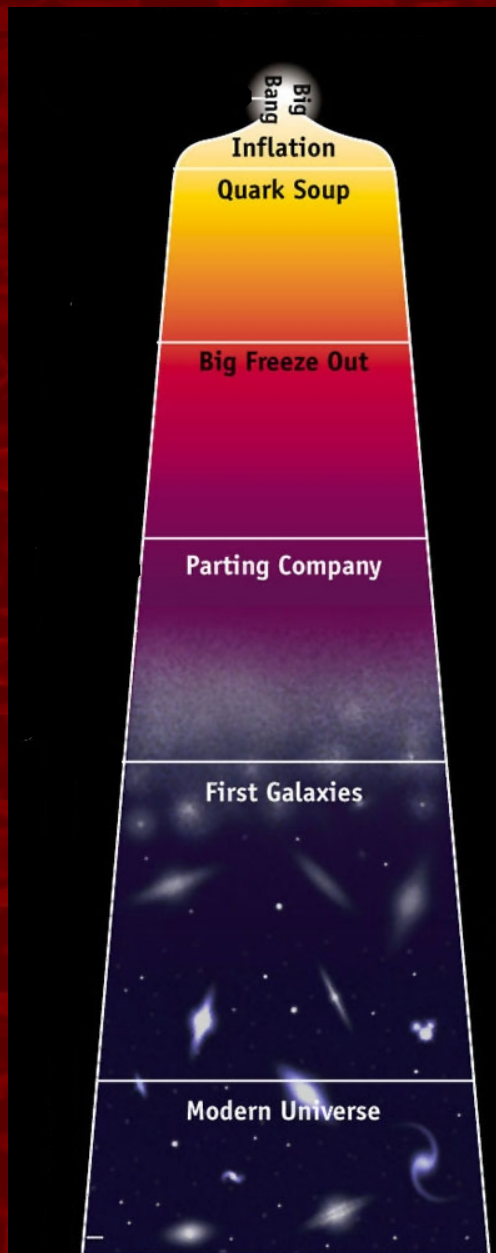


Evolution of the Universe



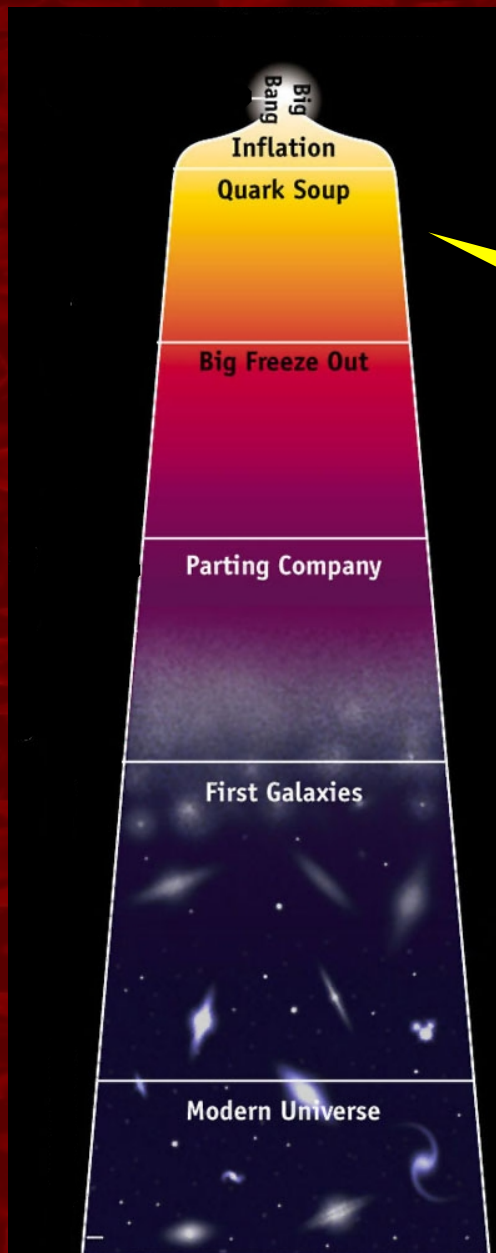
The universe gets cooler !

Evolution of the Universe



Reheating Matter ?

Evolution of the Universe



Reheating Matter ?

?

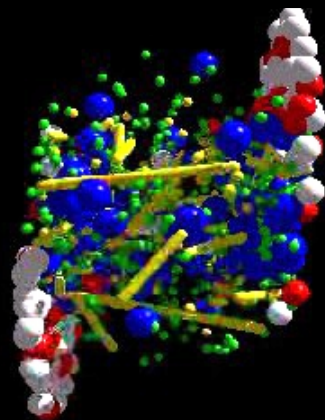
Need temperatures
around
 $1.5 \cdot 10^{12}$ K
 $\sim 10^6$ times hotter than the
core of the sun

A heavy ion collision

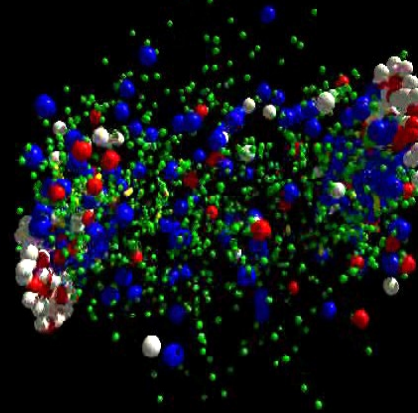
Relativistic pancakes



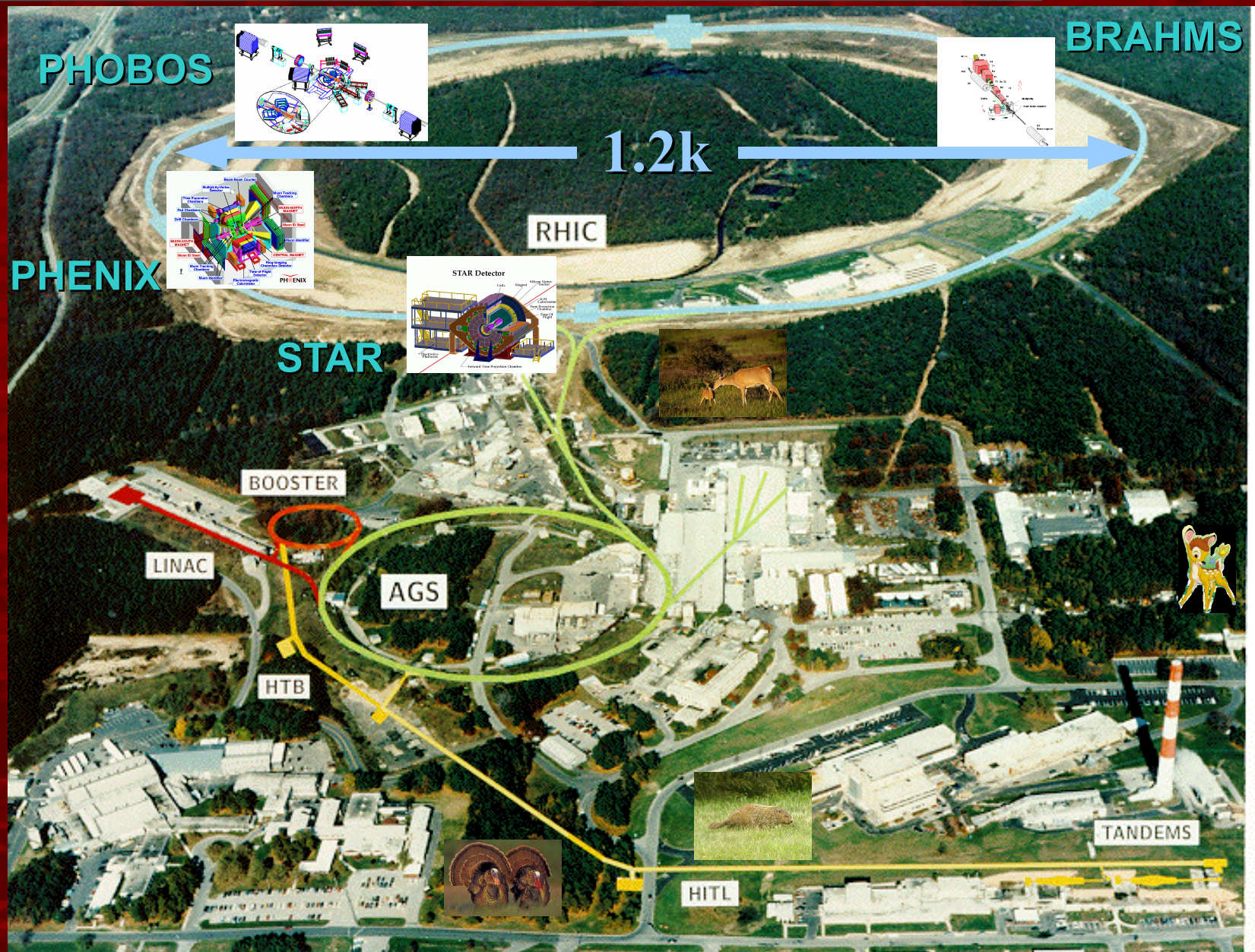
Quark soup



Explosive hadron soda

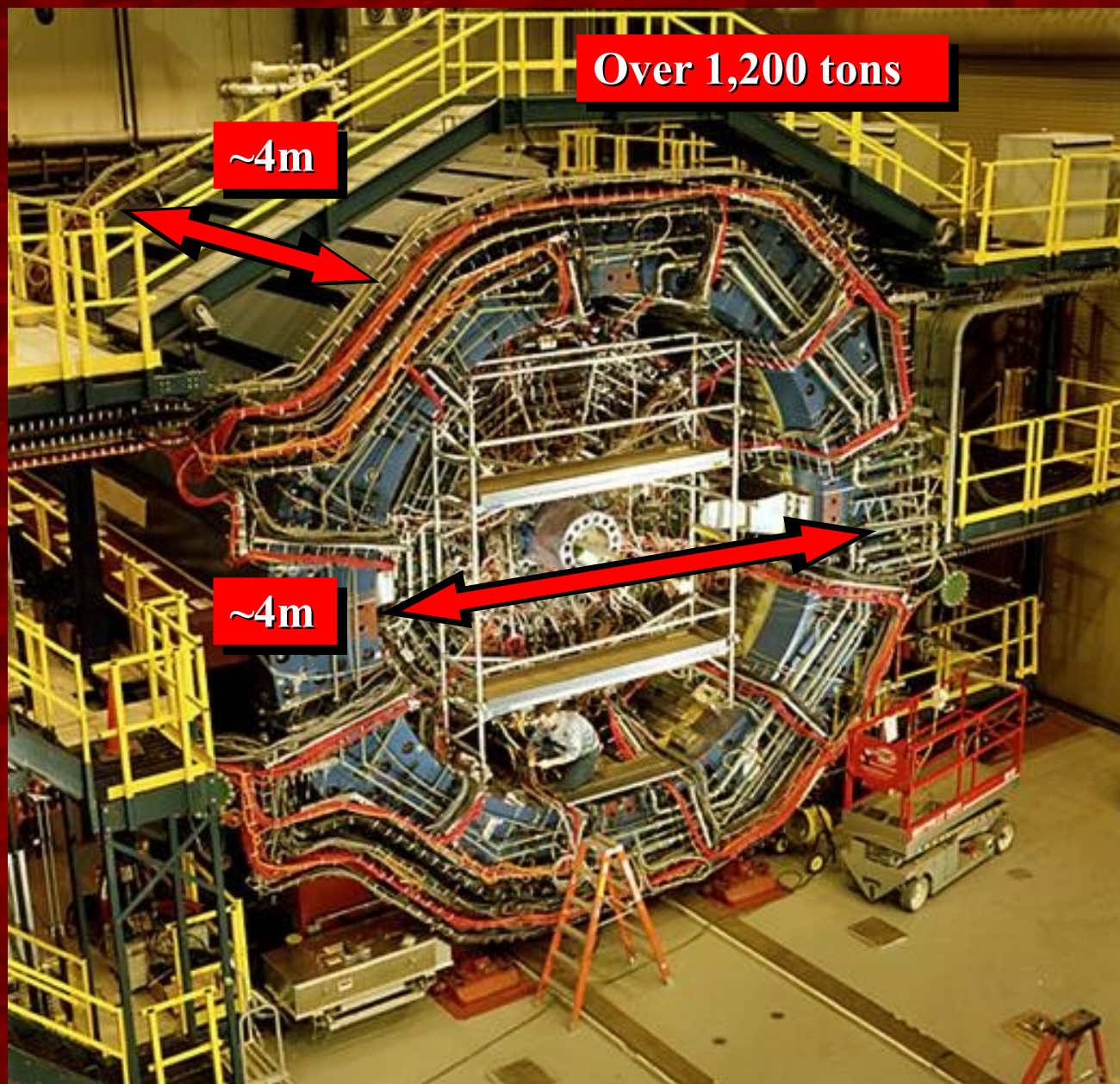


Relativistic Heavy Ion Collider



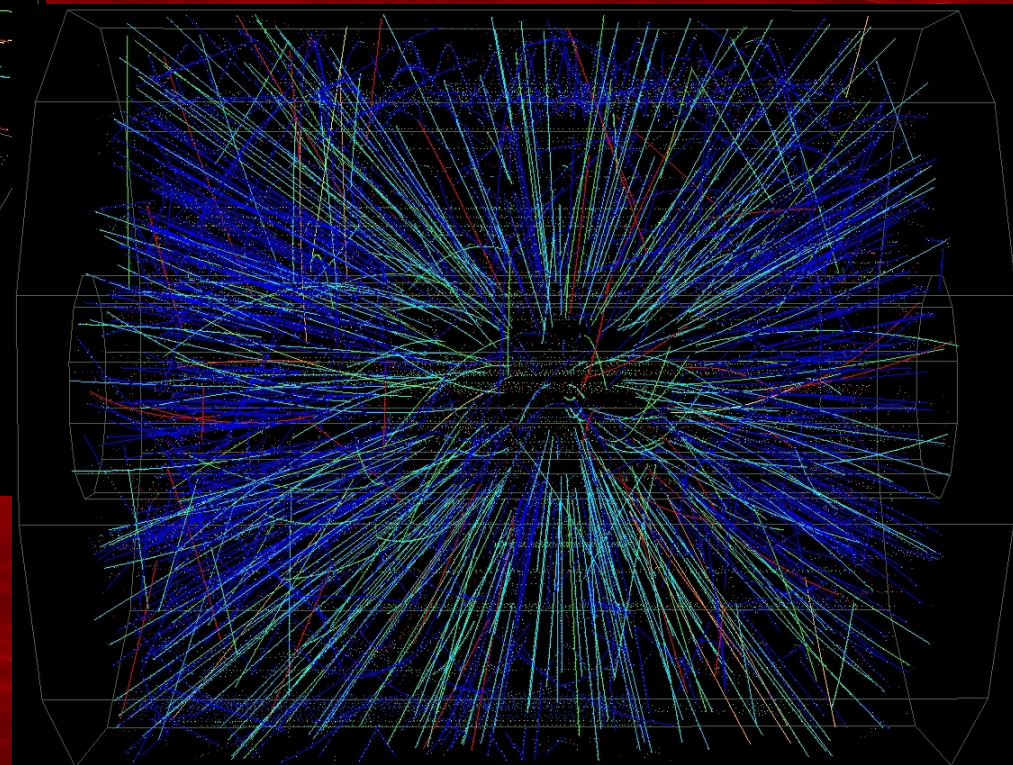
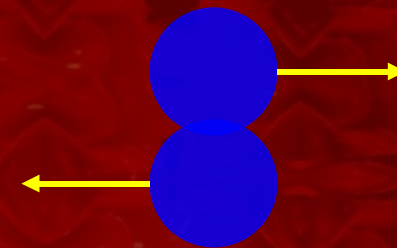
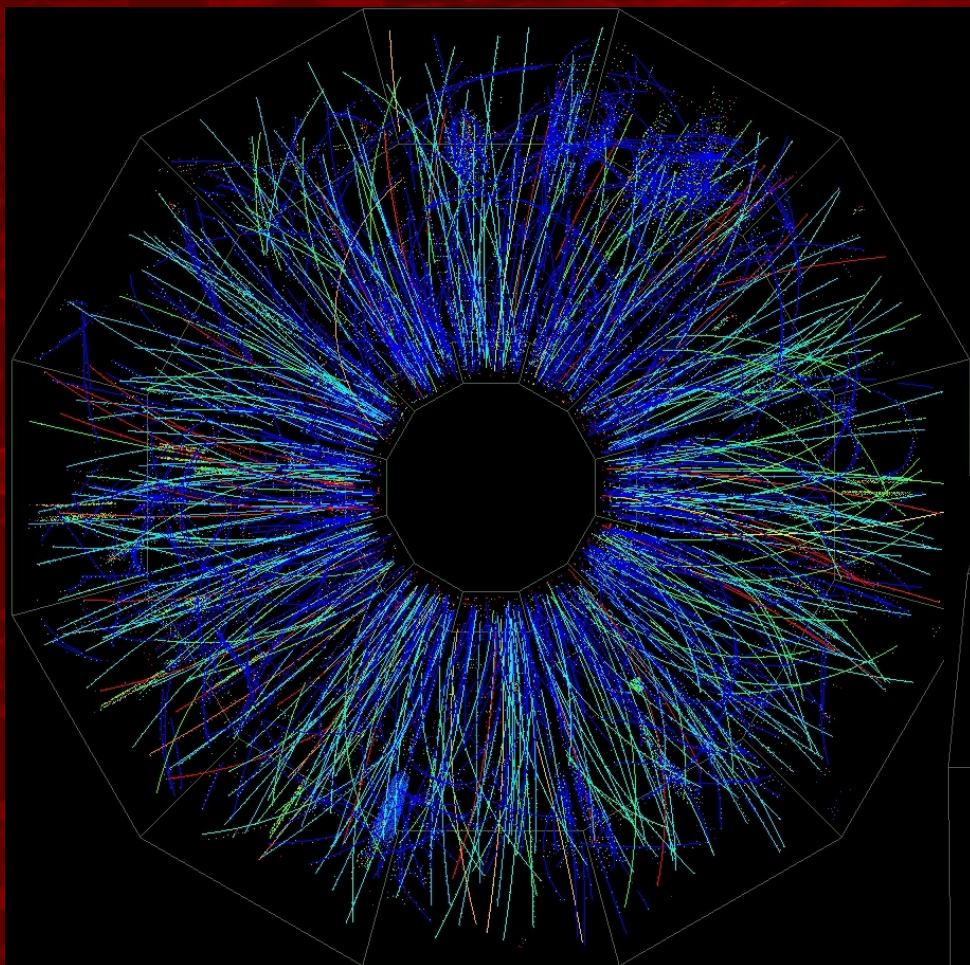
Christine Nattrass (Yale), Goldhaber Seminar, BNL, May 23, 2008

The STAR detector

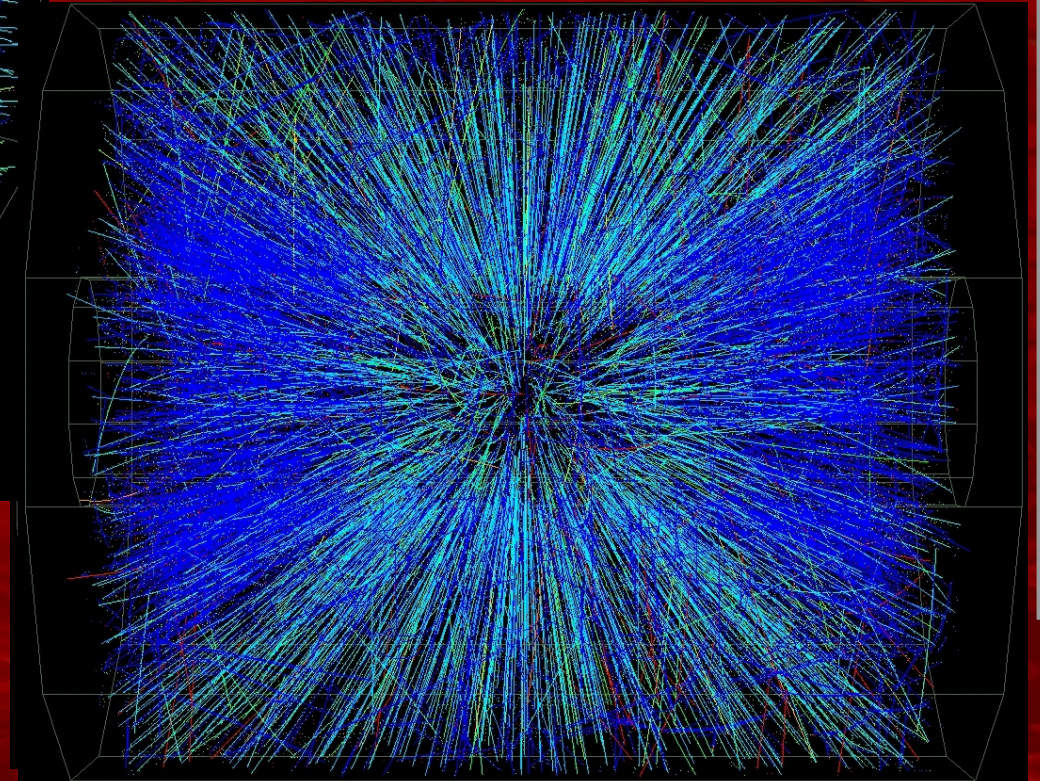
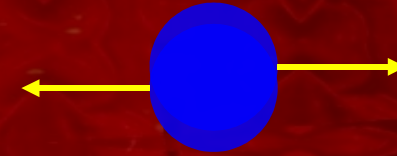
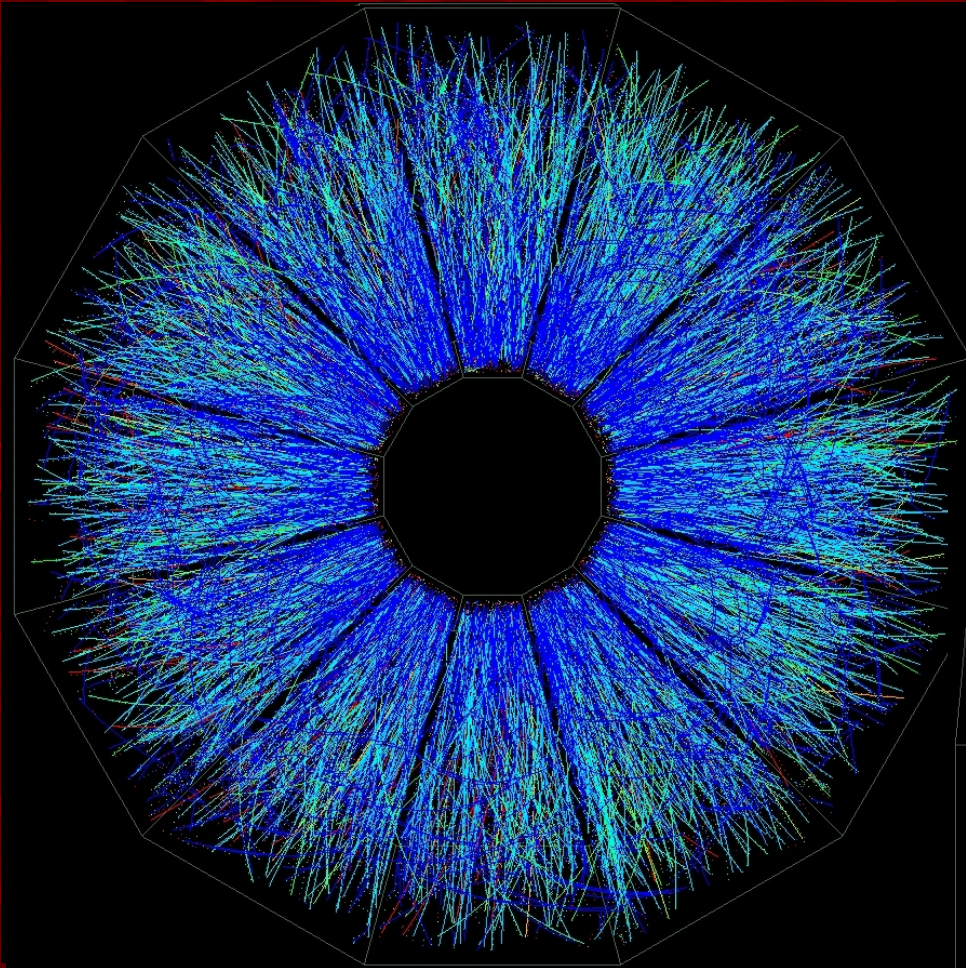


Christine Nattrass (Yale), Goldhaber Seminar, BNL, May 23, 2008

Peripheral collision



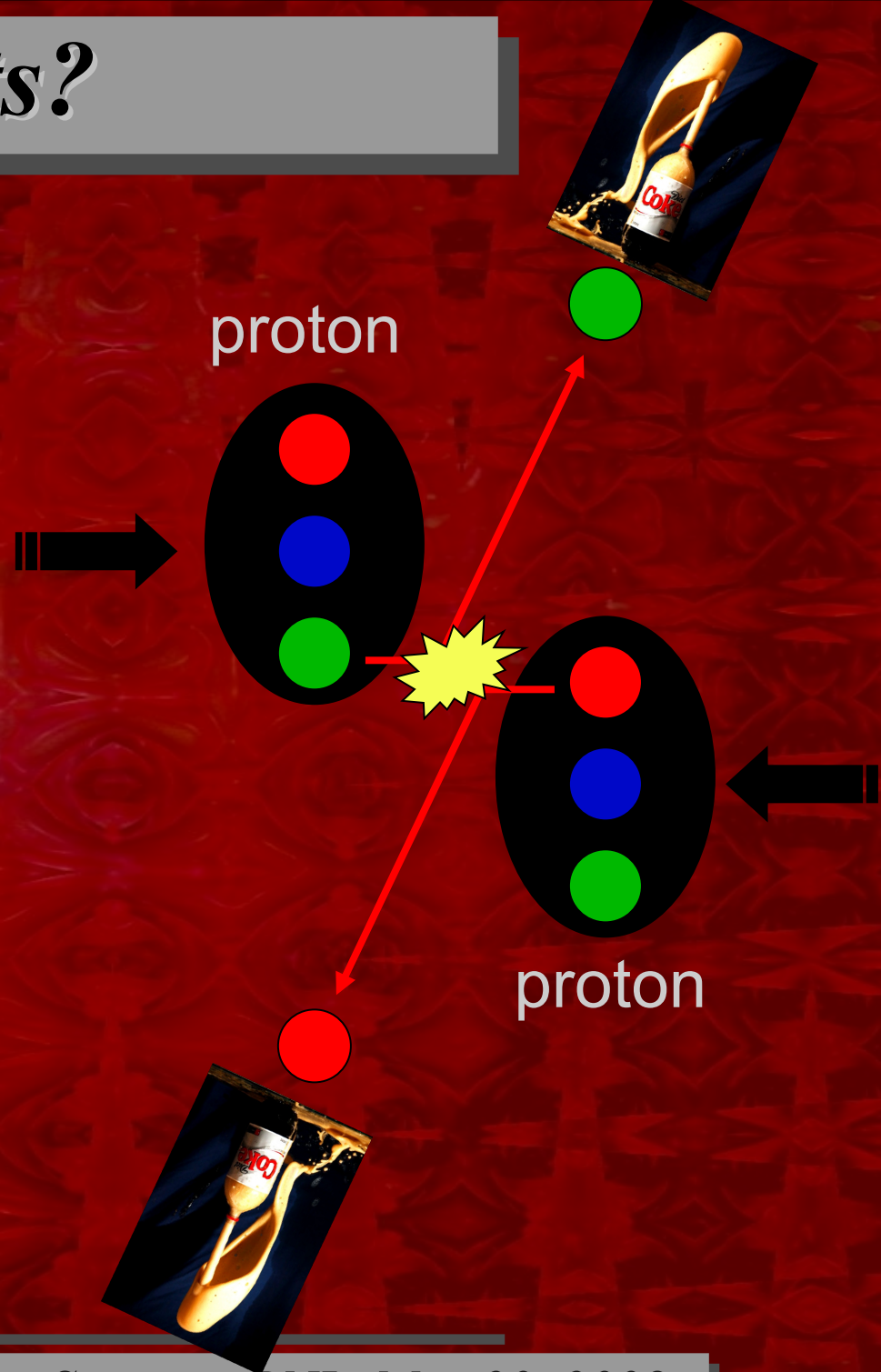
Central collision



~2000 tracks

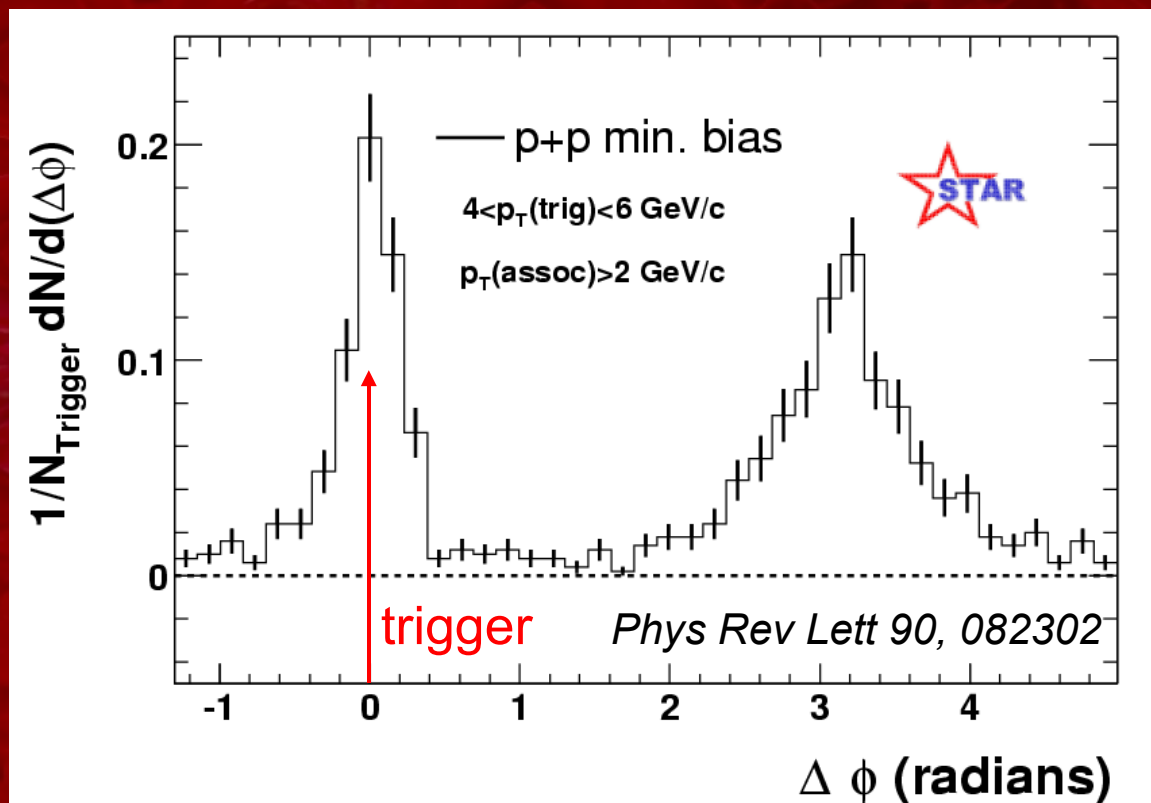
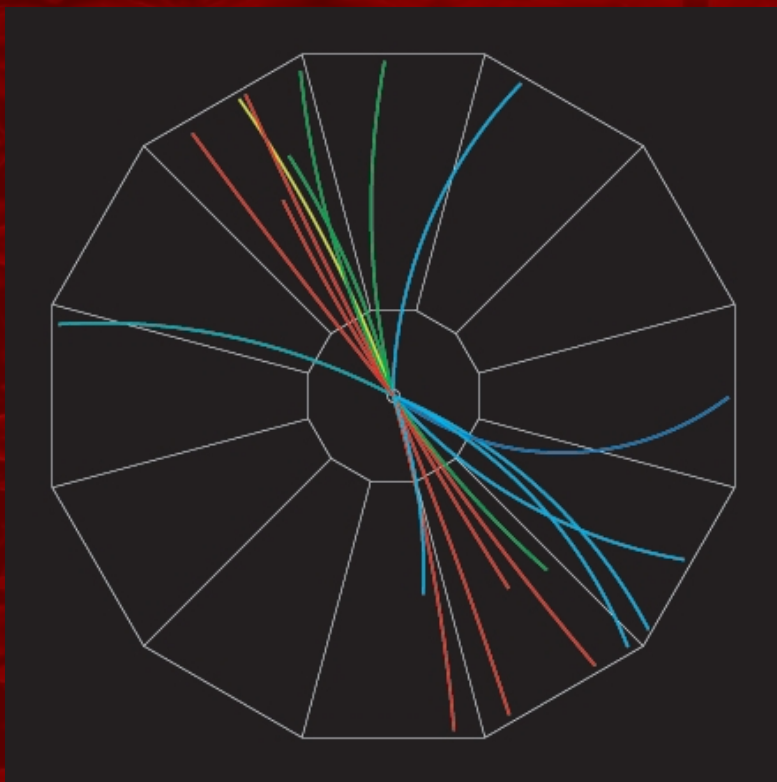
What are jets?

- Jets –hard scattering of partons (quarks and gluons)
- Studied in dozens of experiments

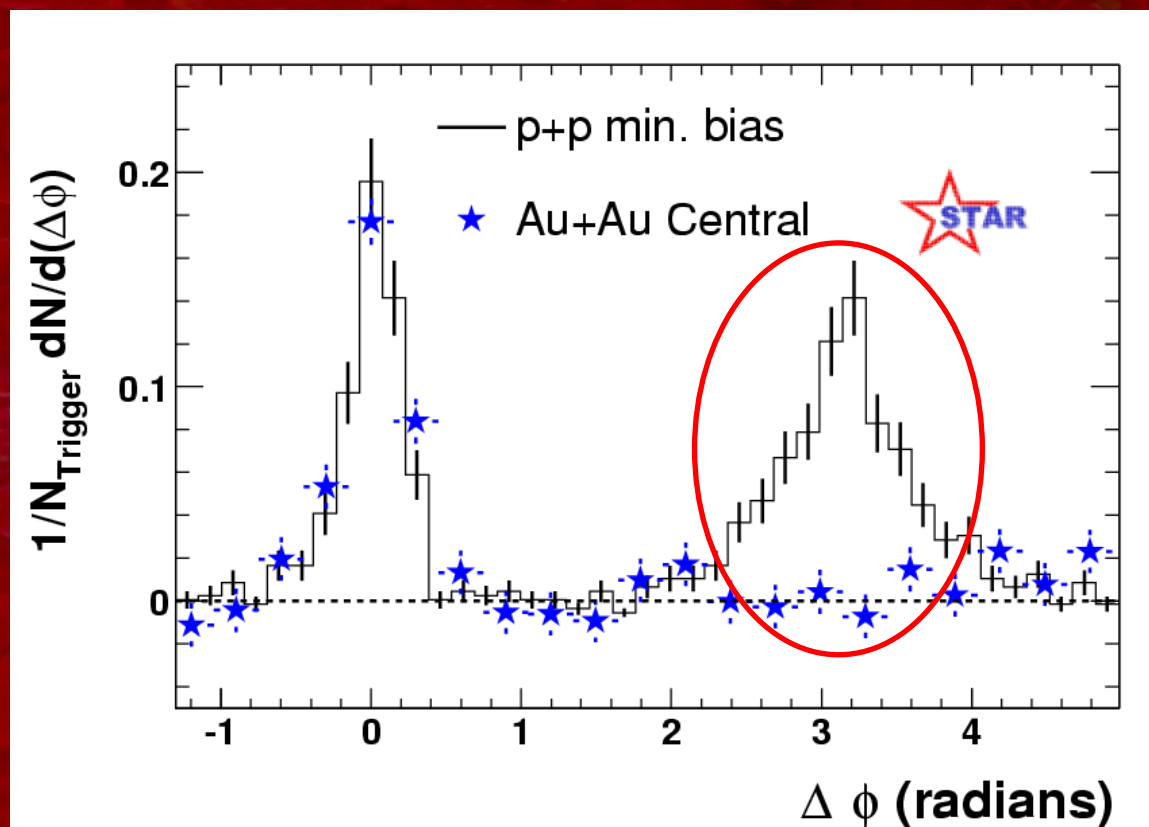
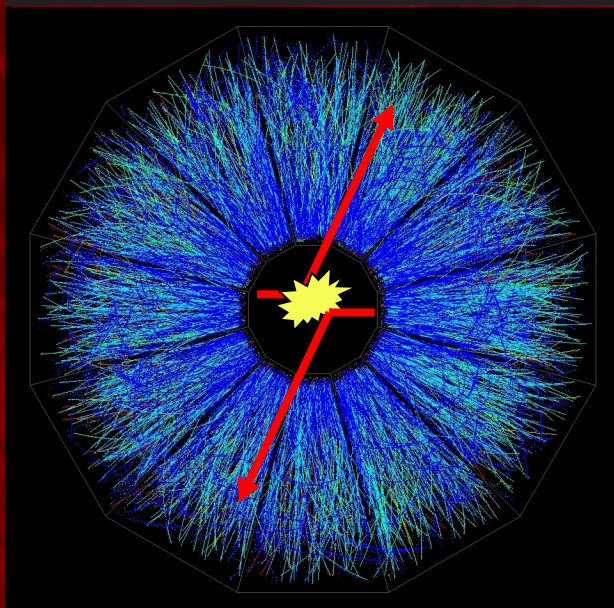
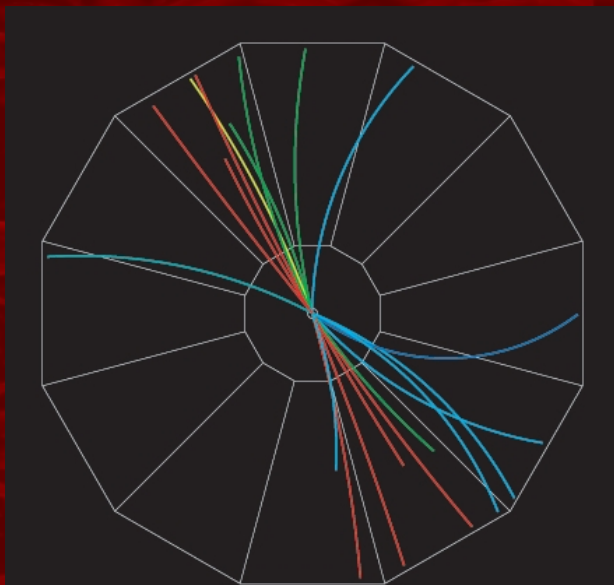


Jets – azimuthal correlations

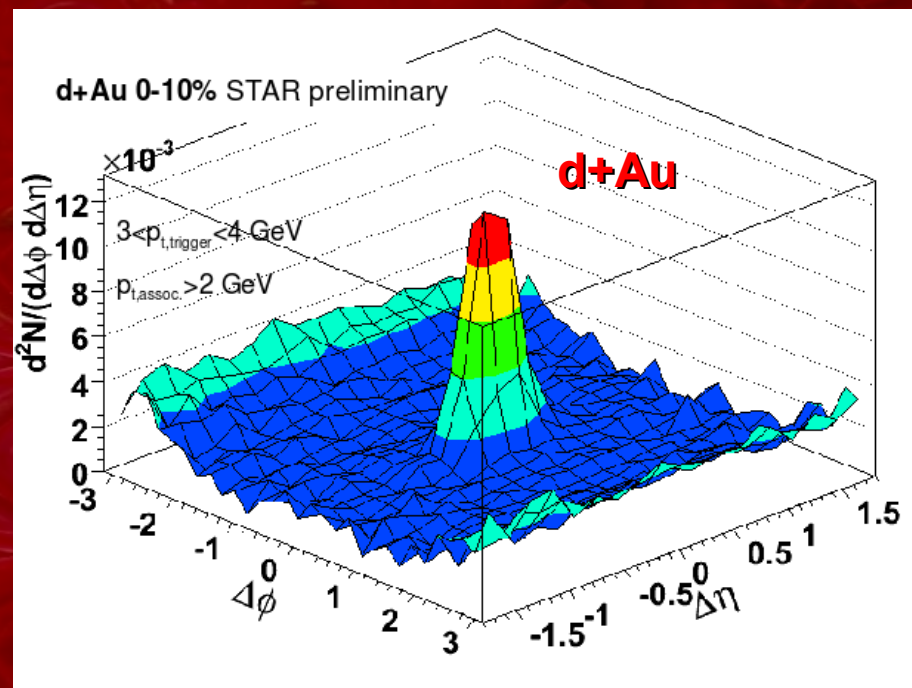
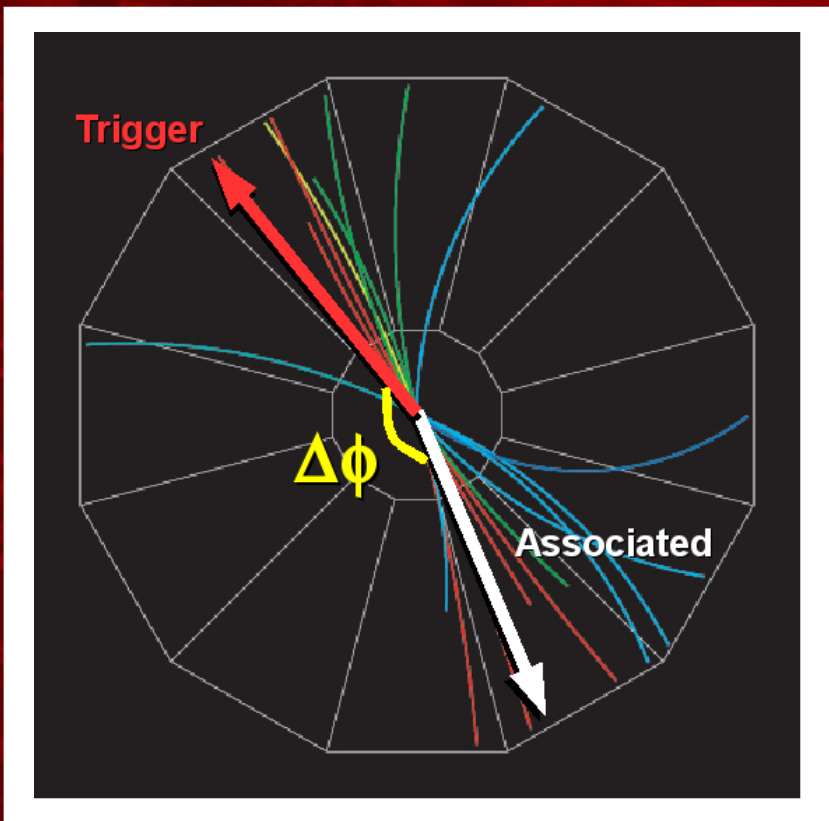
$p+p \rightarrow \text{dijet}$



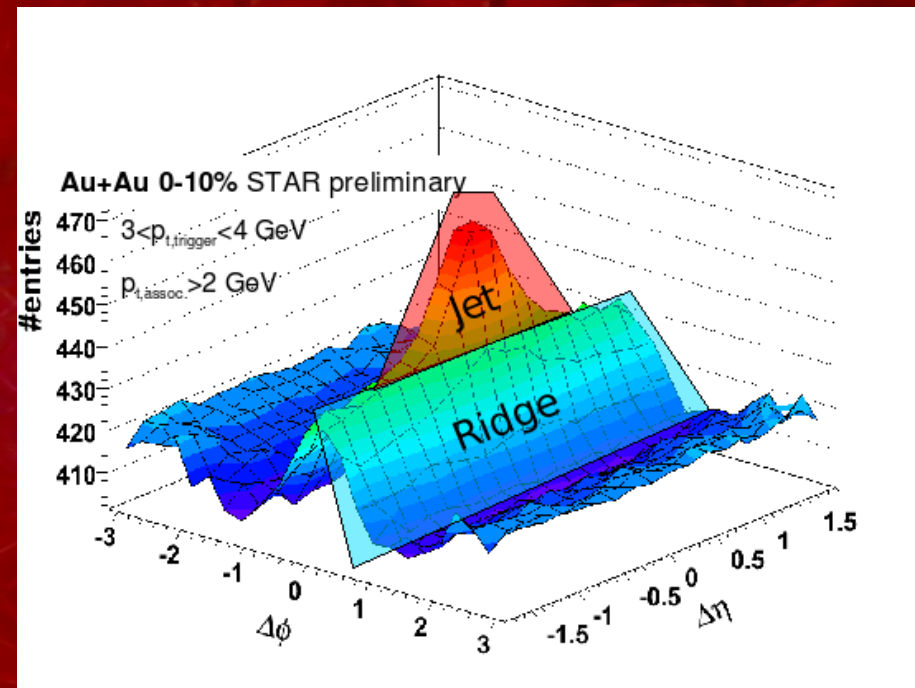
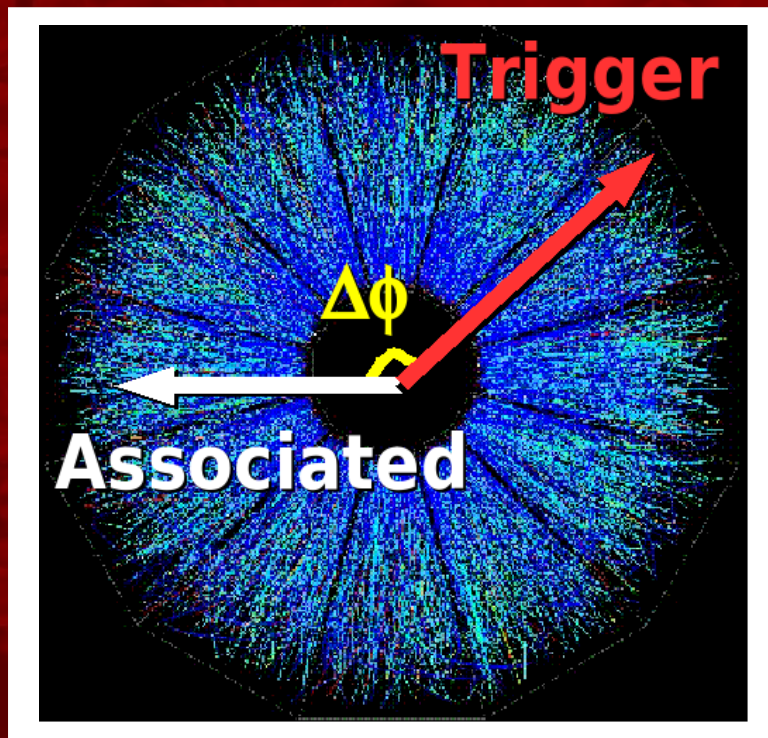
Jets – azimuthal correlations



Looking in two dimensions



In two dimensions in Au+Au



What I've studied

Different systems and energies

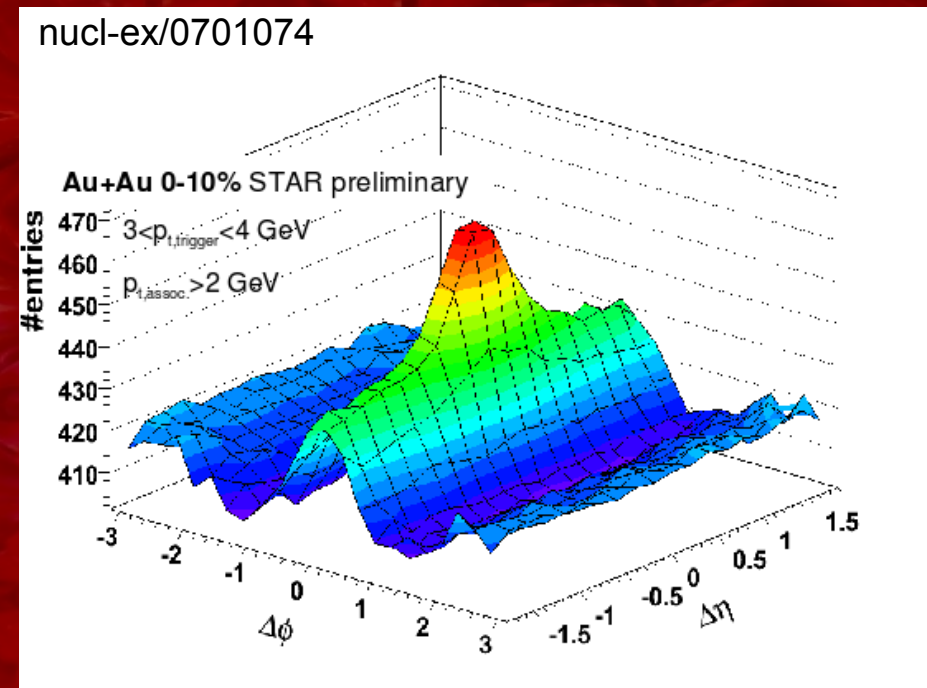
- Cu+Cu $\sqrt{s_{NN}} = 200$ GeV
- Cu+Cu $\sqrt{s_{NN}} = 62$ GeV
- Au+Au $\sqrt{s_{NN}} = 62$ GeV

Different particles

- K_s^0, Λ, Ξ

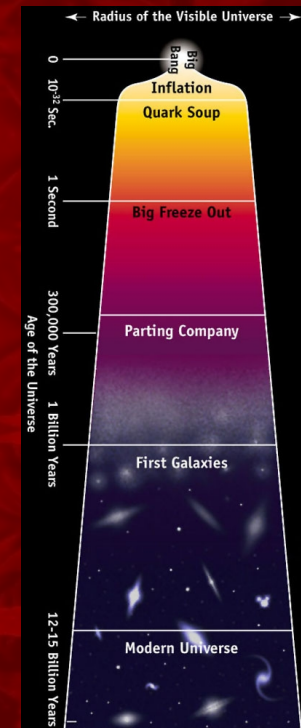
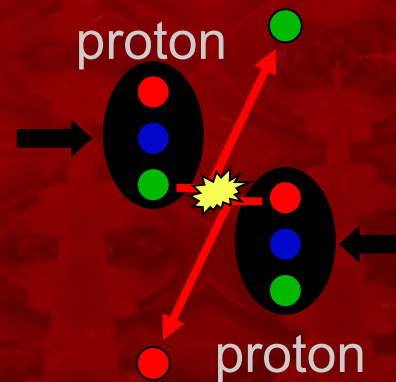
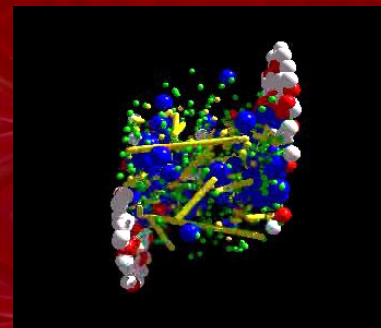
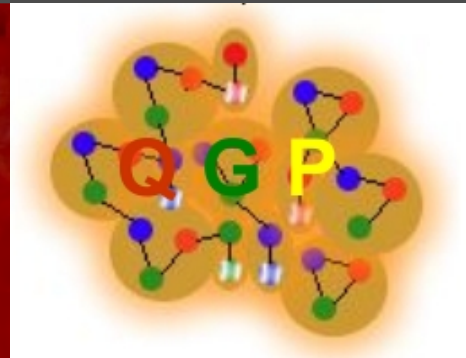
Results:

- Jet looks like p+p, *Ridge* looks like the rest of the A+A collision
- *Ridge* grows with energy
- The fewer nucleons in the collision, the smaller the *Ridge*



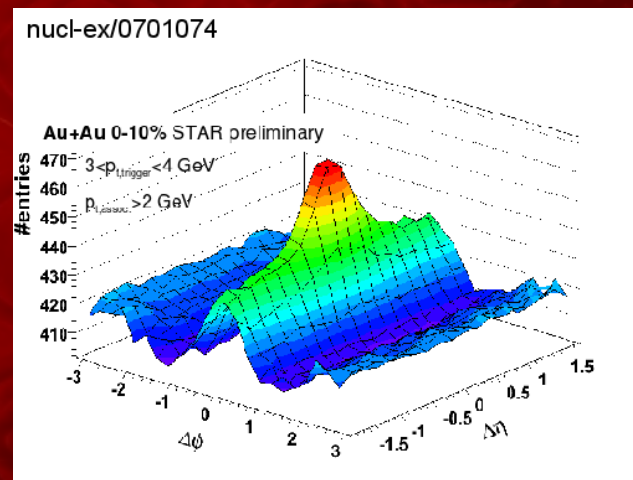
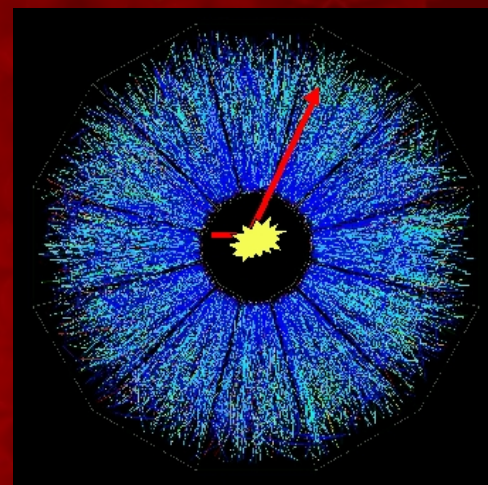
Conclusions

- If we get nuclear matter dense enough, we make a new phase of matter
- This quark gluon plasma is similar to what was present in the early universe
- We can produce a QGP in heavy ion collisions
- We can study it using probes such as jets



Conclusions

- We see evidence of a hot, dense medium from studying jets at RHIC
 - One of the jets almost disappears
 - The other jet is modified dramatically



Many, many thanks to

- John Harris
- Helen Caines
- Jana Bielcikova
- The entire Yale group,
past and present
- STAR