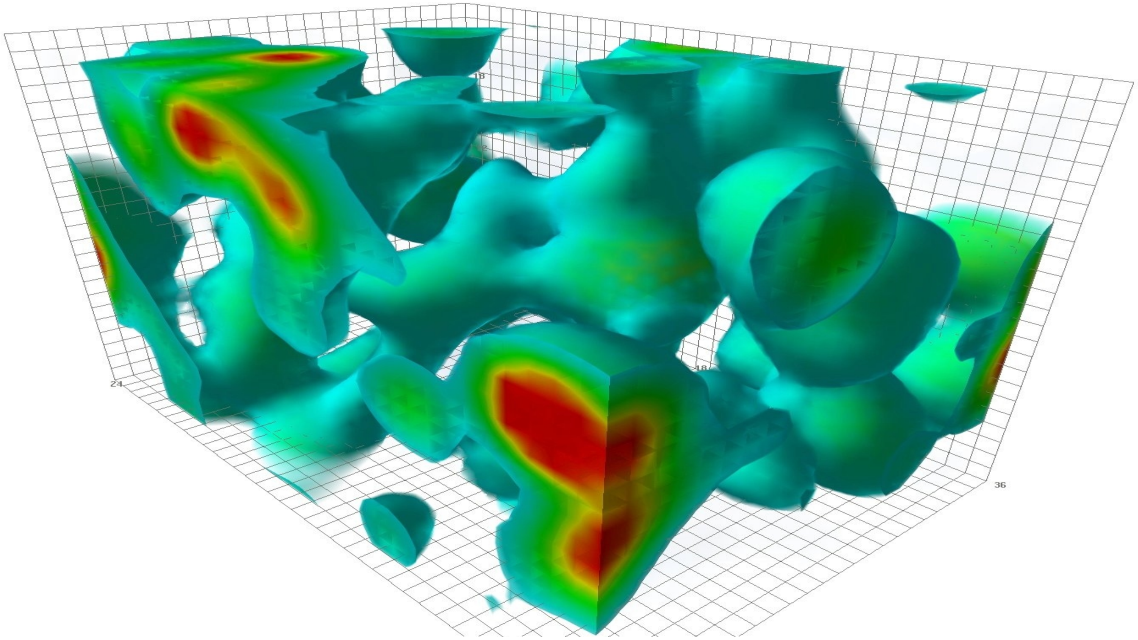

From actions to answers

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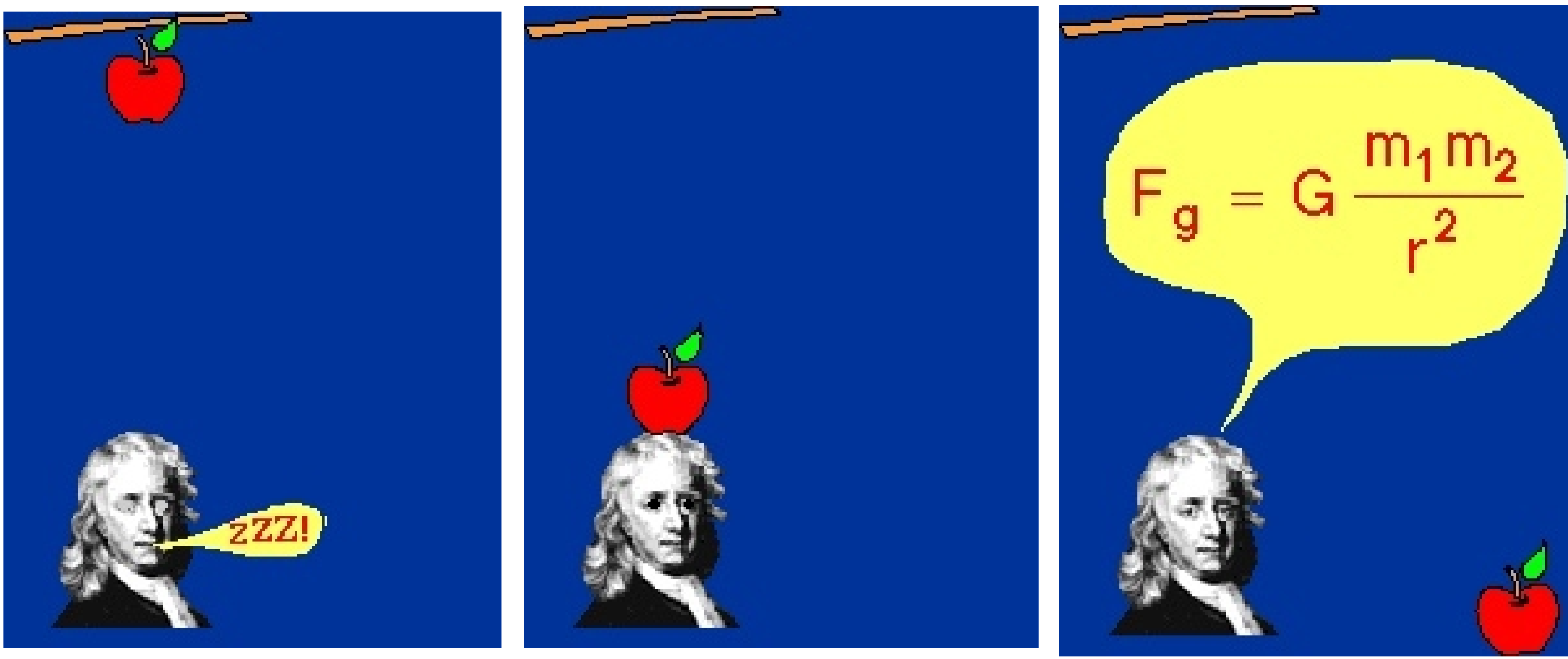
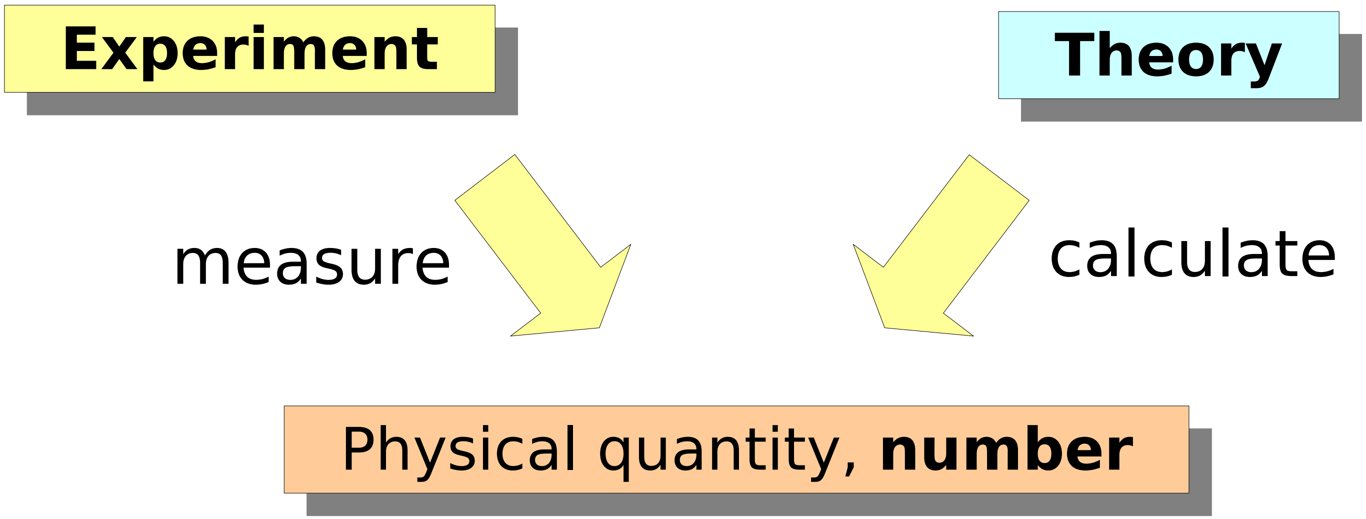
OULUN YLIOPISTO
UNIVERSITY of OULU

Physics vs. reality

Explain experiment or observation with ... a theory



Physics is about numbers!



Main duty for theoretical physicists:

Shut up and calculate!

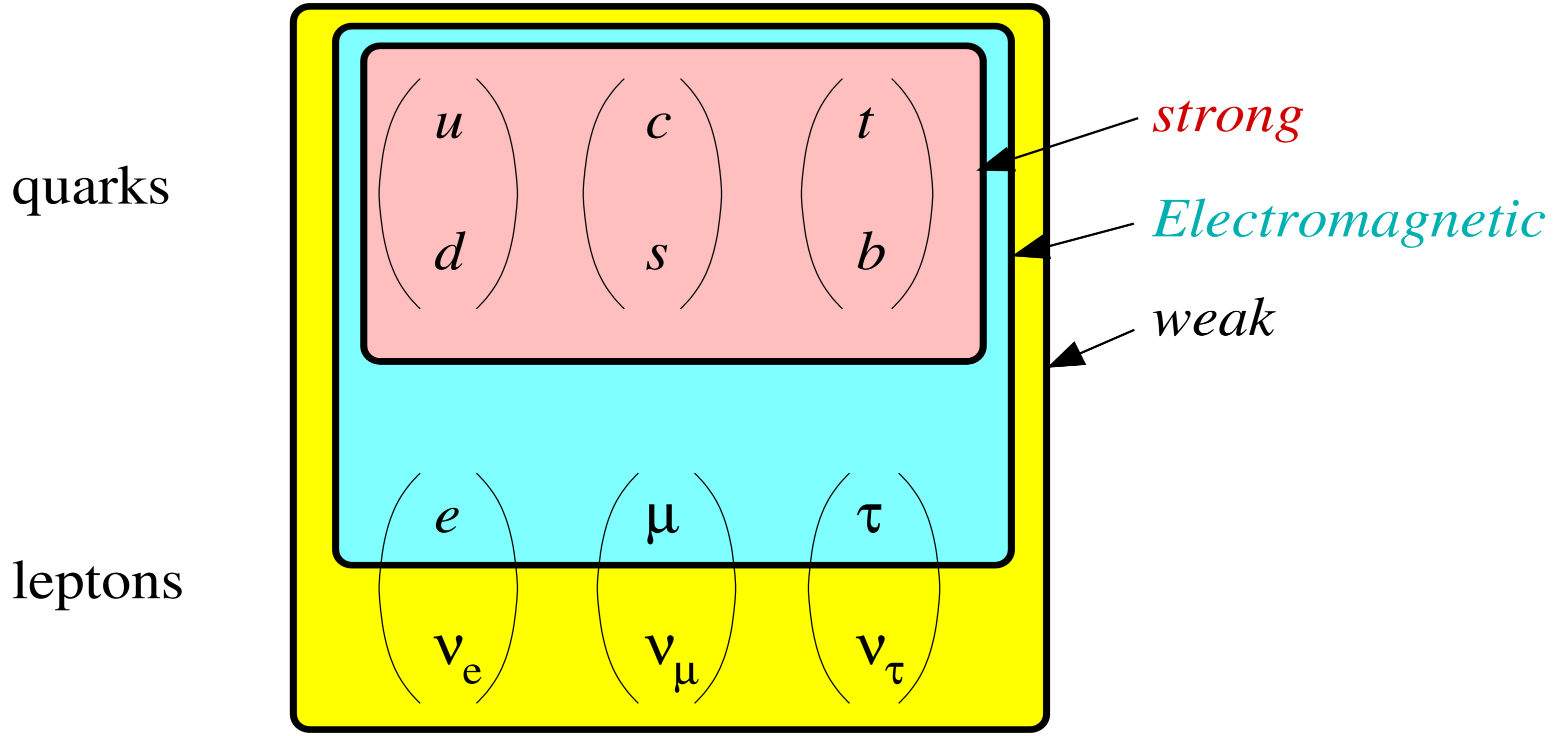
The Standard Model (of particle physics)

Plethora of particles; 3 interactions:

Electromagnetic (QED)

Strong (QCD)

Weak

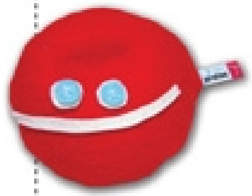


The PARTICLE ZOO

Subatomic Particle Plush Toys FROM THE STANDARD MODEL OF PHYSICS

PHOTON
The massless wavicle we know and love.

NEUTRINO
These teeny-tiny l'il "shy" guys are traveling through you right now.



PROTON
We would not be here without her positivity.

WEAK GAUGE BOSON
As the carrier particle of the weak nuclear force, he's down-right obese.

GLUON
The "glue" of the strong nuclear force.

ELECTRON
A negatively charged diminutive, busy i'il guy. And popular, too!

NEUTRON
He insists on remaining neutral.

HIGGS BOSON
A bit of a snob because he's some-times referred to as "the God paricle."

DARK MATTER
The mysterious missing mass

UP QUARK
A tiny little point inside the proton and neutron, she is friends forever with the Down Quark.

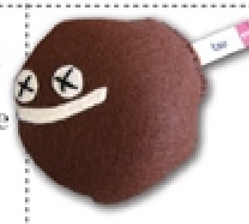
MUON
A "heavy electron" who lives fast and dies young.

coming soon!

MESONS
A slew of family cousins with names like pion, kaon, rho, and eta.

GRAVITON
Still unob-served, yet theoretically *everywhere.*

DOWN QUARK
A tiny little point inside the proton and neutron, he is friends forever with the Up Quark.



TAU
A "heavy muon" who could stand to lose a little weight.

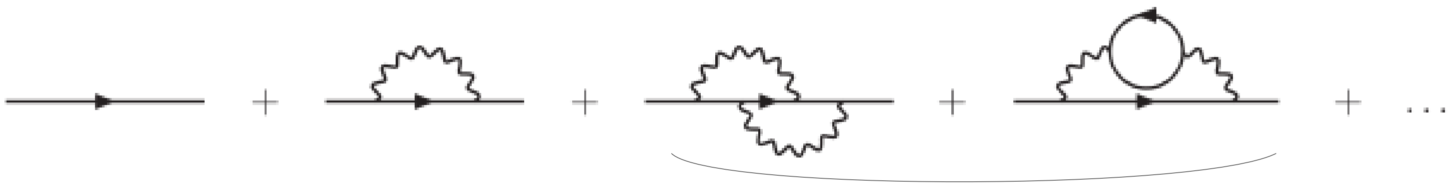
coming soon!

ANTIPARTICLES
Due to explode on the scene sometime soon.

TACHYON
Can this particle really travel faster than light?

How to compute stuff? 1. Perturbation theory

- (Semi)analytic, diagrammatic expansion
- Taylor expansion in "coupling constant"
- Works very well in QED:



α^0 α^1 α^2

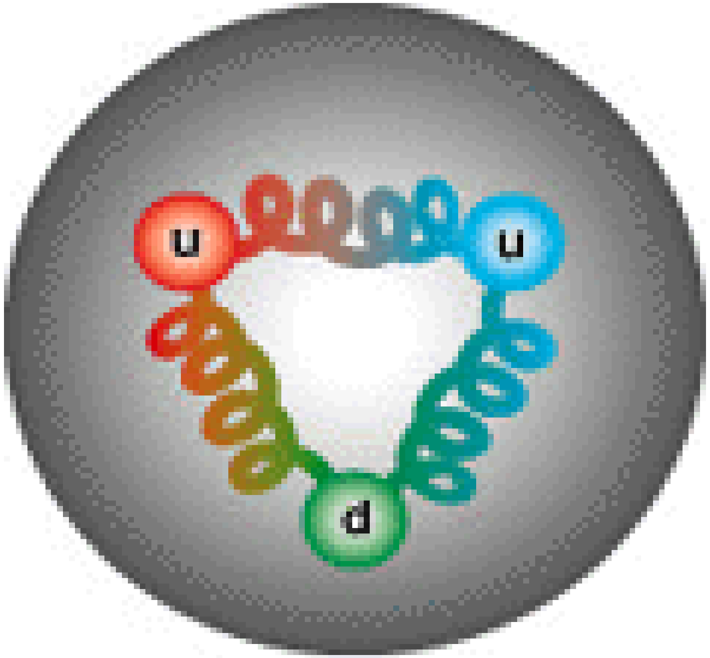
Fine structure constant

$$\alpha = \frac{e^2}{4\pi\hbar c\epsilon_0} = \frac{1}{137.036}$$

- Expansion parameter small – rapid convergence!
- Theory/experiment works to precision of ~ 10^{-10} (best theory ever!)
- Nevertheless, it does not really converge... only asymptotic

How about strong interactions, QCD:

- Electrons, photons -> **quarks, gluons**
- Quarks & gluons: building blocks of **hadrons** (protons, pions...)
- **Baryon** (proton, neutron,..): 3 quarks
- **Meson** (pion,...) quark-antiquark



What has been observed:

- *There are no free quarks; quarks are always bound within hadrons (confinement)*
- *Mass of proton ~ 938 MeV*
  Mass of u,u,d -quarks ~ 10 MeV
  Gluons massless

--> 99% of proton mass is "binding energy" due to QCD (hence, 99% of the mass of matter)

Why? Perturbation theory cannot answer

QCD "running coupling"

The QCD expansion parameter

$$\alpha_s = \frac{g_s^2}{4\pi}$$

depends on energy of the process:

- At large energy μ α_s is small

  at LHC, $\alpha_s \sim 0.12$

-> perturbation theory ~ OK

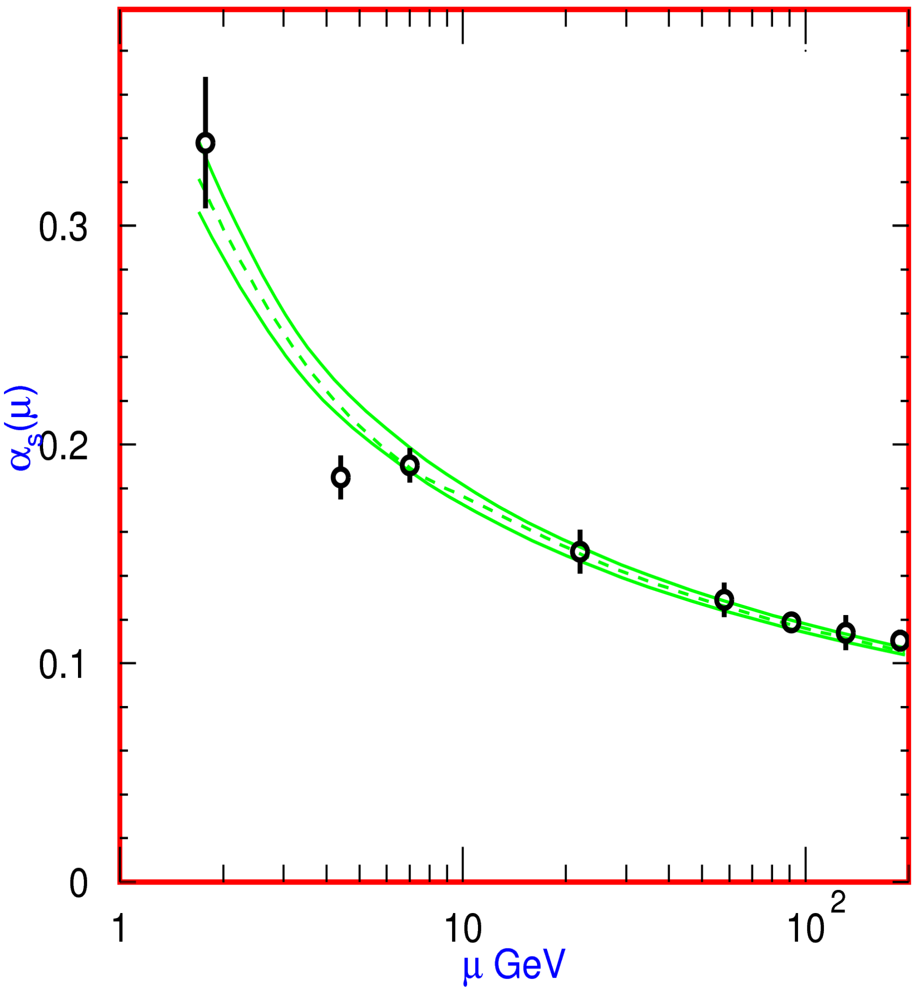
- As $\mu < 1$ GeV (proton mass),

  α_s *diverges* (apparently)

  "Strong coupling", **perturbation theory does not work.**

(Gross, Politzer, Wilczek 1974, Nobel 2004)

PDG 2008



QCD on the lattice:

QCD defined by Feynman path integral

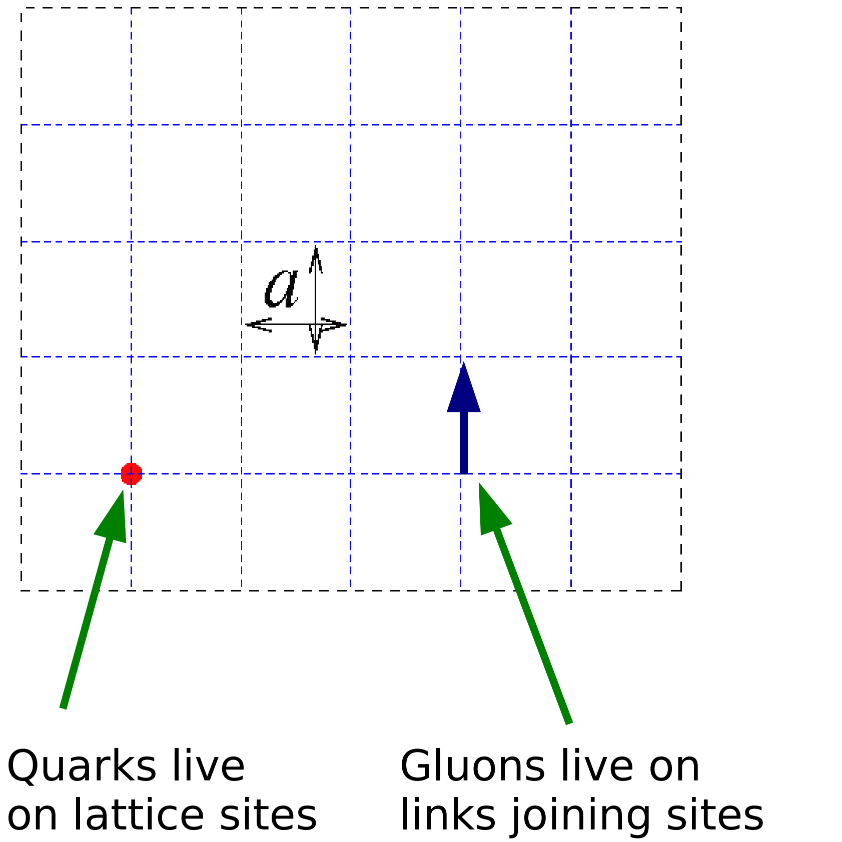
$$Z = \int dA\, d\psi\, e^{iS(A,\psi)}$$

Mid-70's Ken Wilson showed how to put quantum field theories (including QCD) on a discrete lattice

→ path integral becomes well-defined and finite, suitable for numerical evaluation

→ Computer simulations start at end of 70's

→ Lattice provides the best *definition* of the theory!

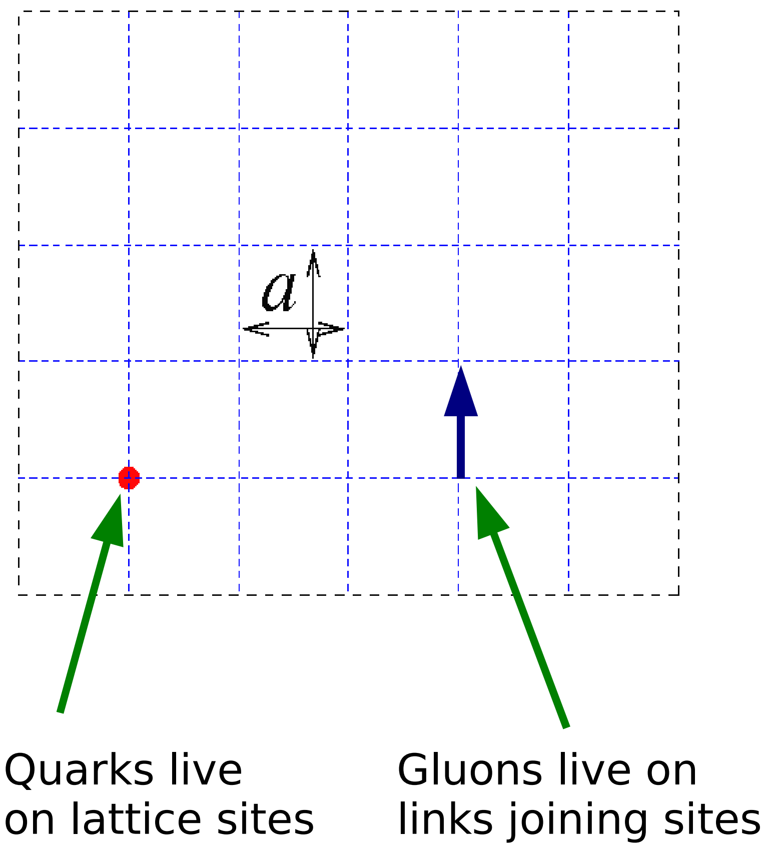


Physics in femto-universe:

Features:

- 4-dim. discrete spacetime lattice
- Lattice spacing ***a***; need continuum limit a→0
- Calculate at several different a, extrapolate a→0

⇒ full quantum theory, no approximations



- Full QCD simulations very expensive! Only recently accuracy comparable to experiments has been reached.
- Active field, with many subfields: ~500 participants at the annual “Lattice” conferences

Why lattice QCD is expensive?

– 4-dimensions

– quantum

– fermions (quarks)

Fermions can be integrated out, but that makes the action *non-local: fermion determinant*

$$Z=\int dU\, d\psi\, e^{-S_G(U)-\overline{\psi}M(U)\psi}=\int dU\, det[M(U)]e^{-S_G(U)}$$

Quenched simulation: just ignore the fermion determinant (not used any more)

Currently largest volumes in use: 60^4 - 100^4

Large-scale computing

Lattice simulations are large-scale supercomputing projects.

To get most bang for the buck, some groups design their own computers, down to the chip level

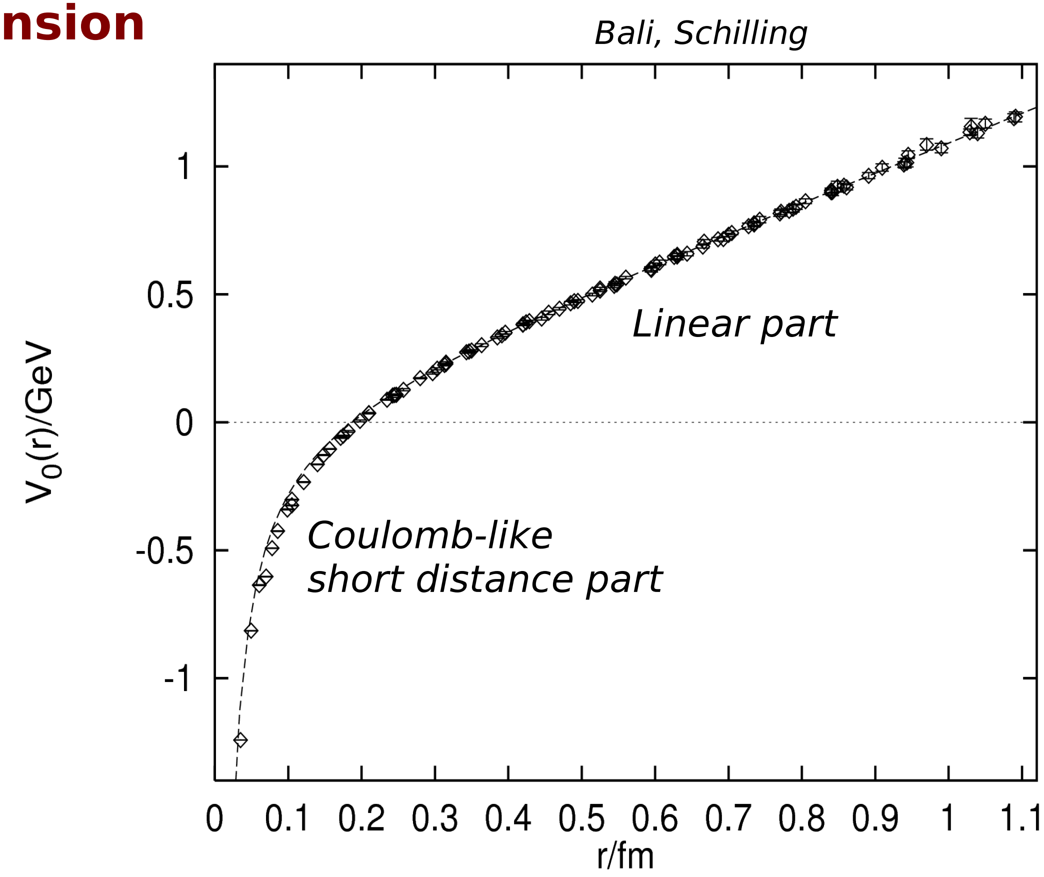
QCDOC, Brookhaven

It works!

Measure quark-antiquark potential in a meson:
at large distances: linear increase
$\Rightarrow$ constant force, **string tension**

$\Rightarrow$ it takes infinite energy to move quarks infinite distance from each other

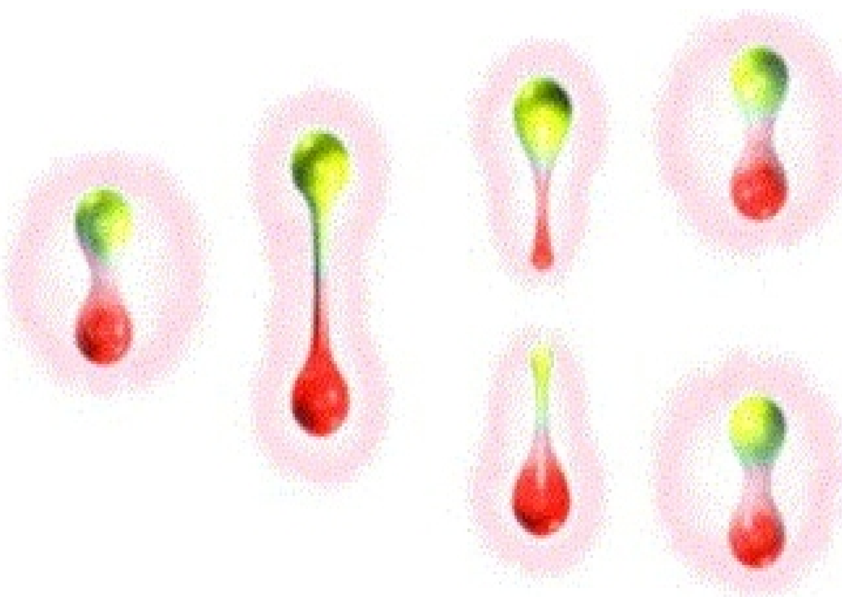
$\Rightarrow$ **quark confinement**

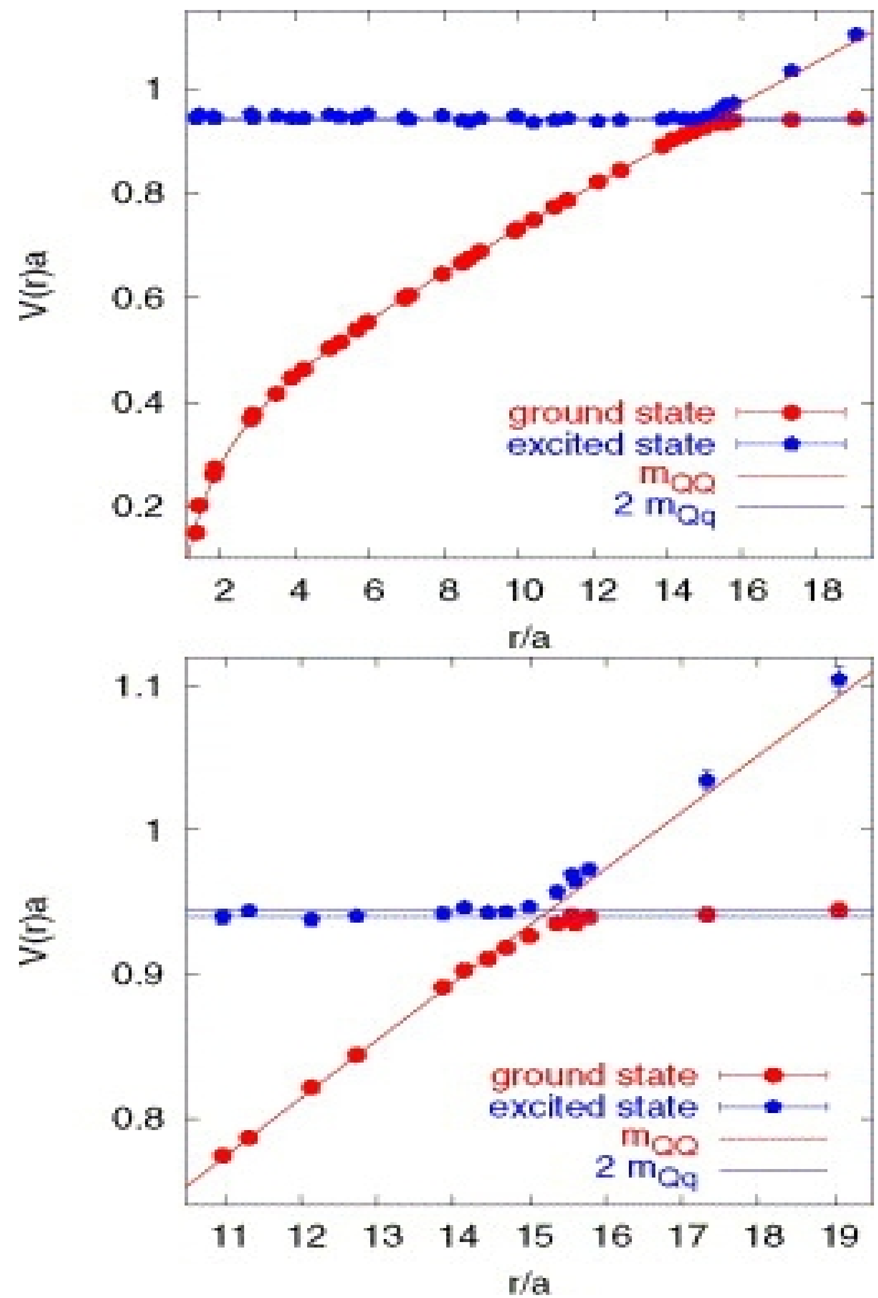


String breaking

In reality, the string breaks forming a new pair of mesons.

Recently observed in simulations (Attig etal, 2005)

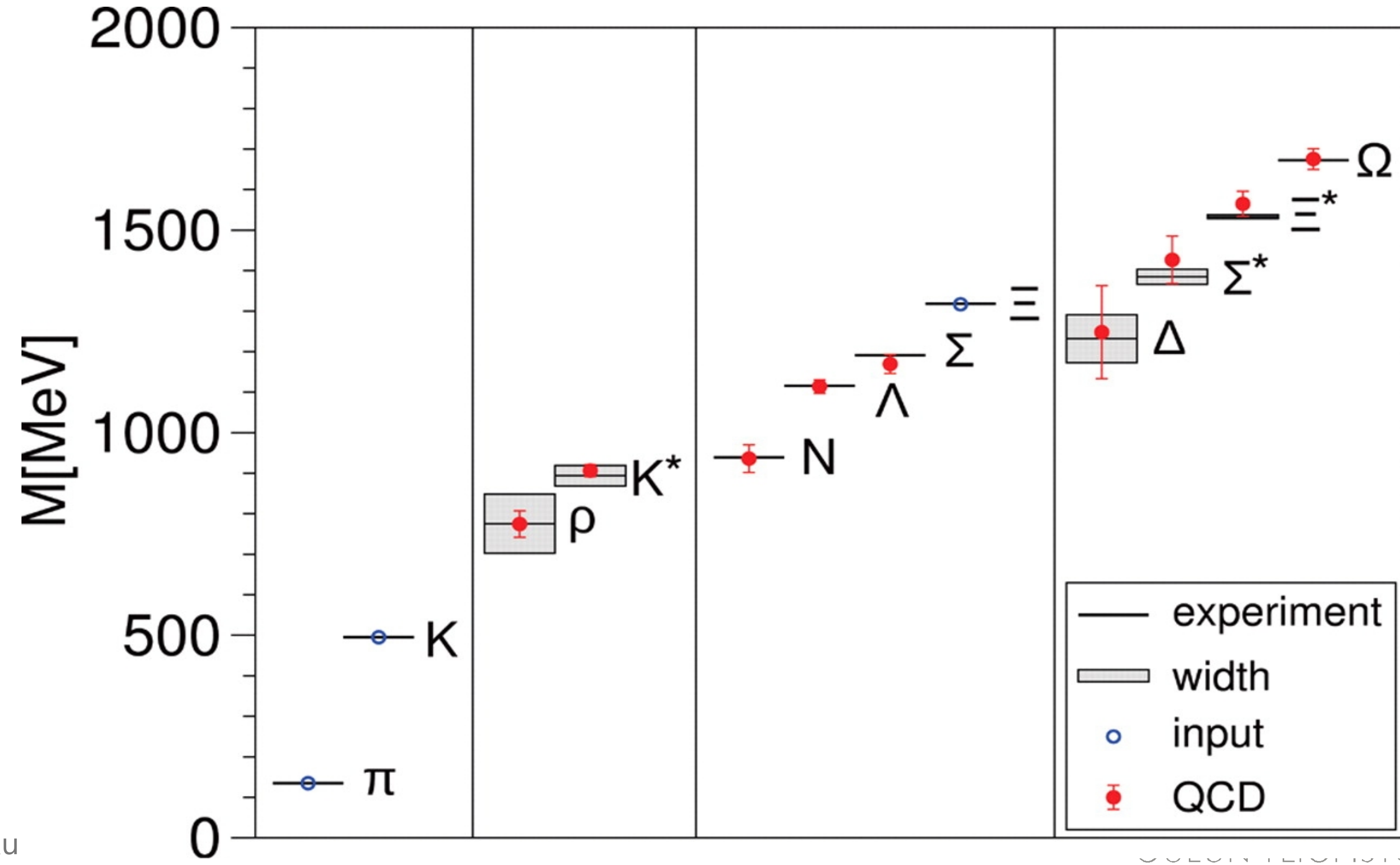




Hadron masses?

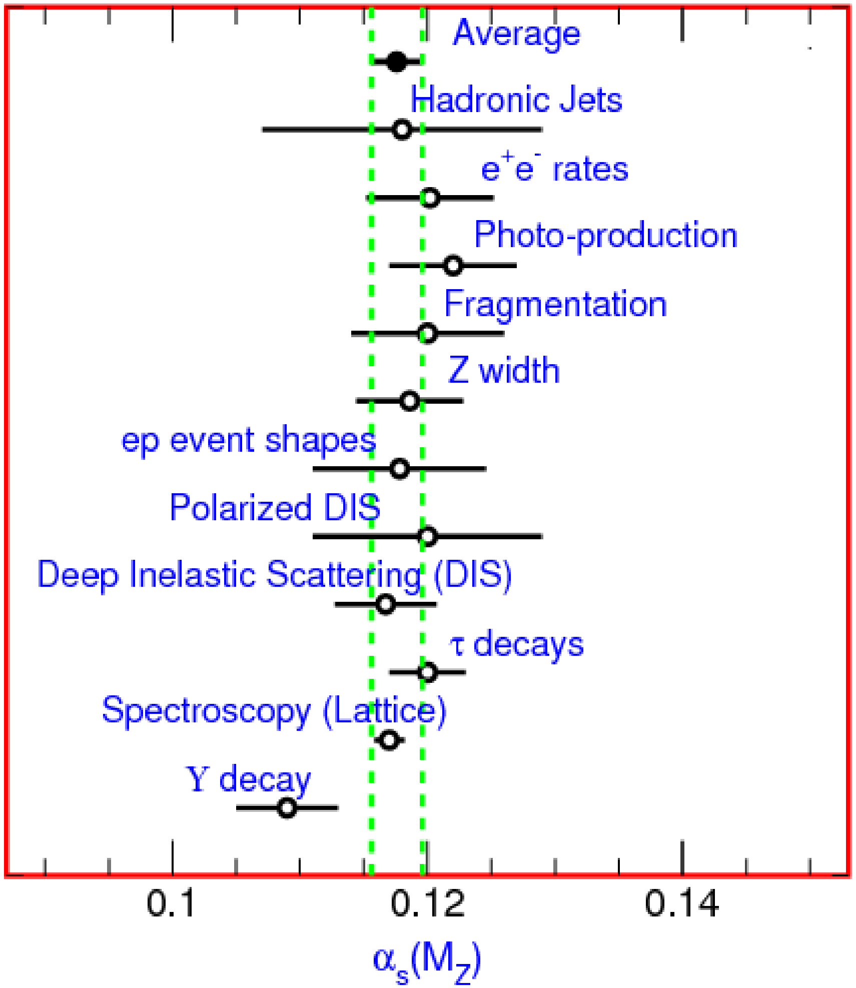
Works very well!

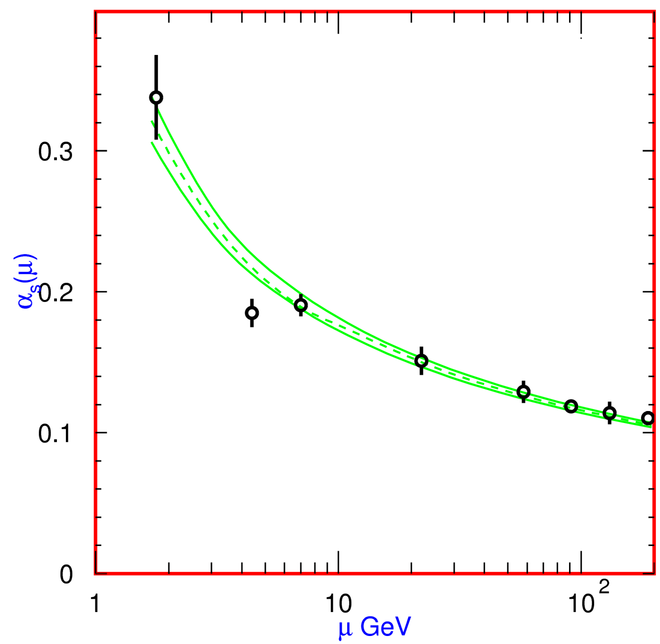
BMW collaboration, Science 2008



Results are competitive with experiments

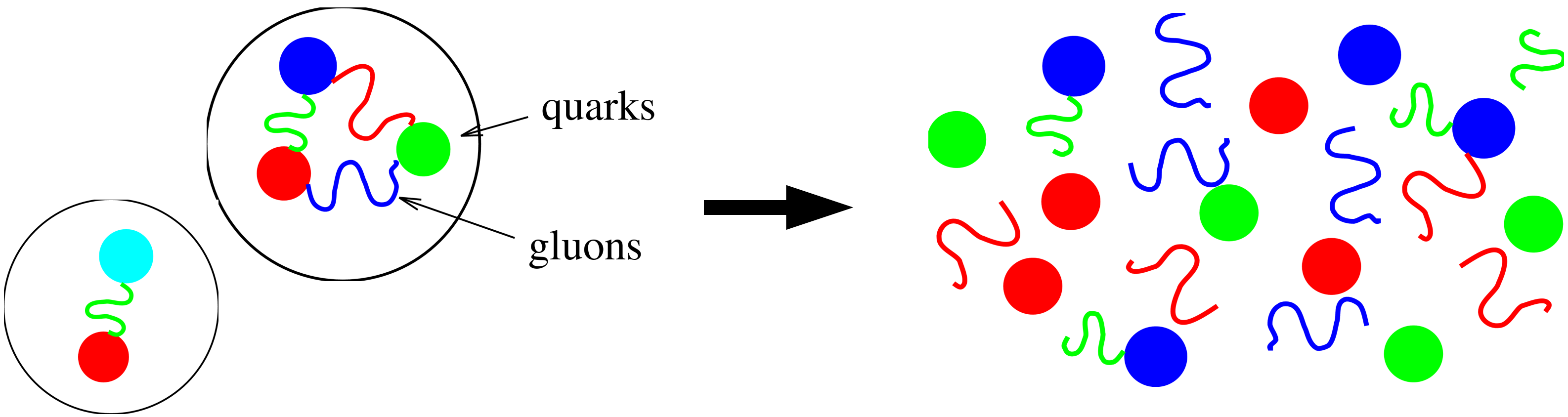
α_s at M_Z





At high T: quark-gluon plasma

At high temperature or density, hadrons (protons, neutrons etc.) “melt” and form ***quark-gluon plasma****:* dense gas of quarks and gluons



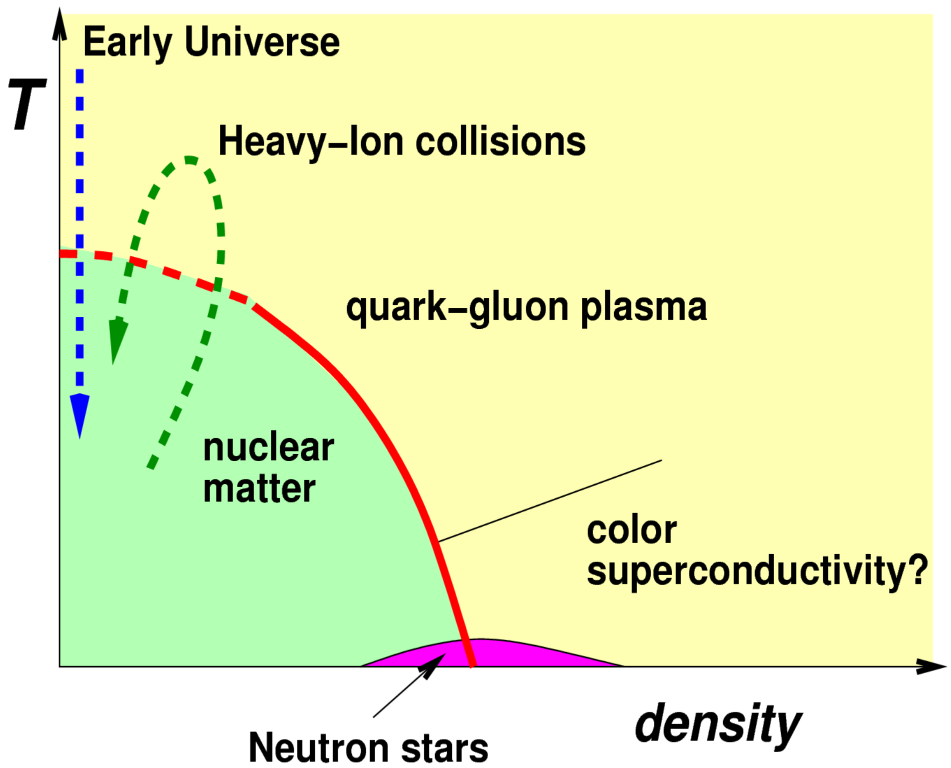
Hadrons

Quark-gluon plasma

Lattice simulations; experimentally verified (RHIC, Brookhaven)

Transition temperature $T_c \sim 170$ MeV

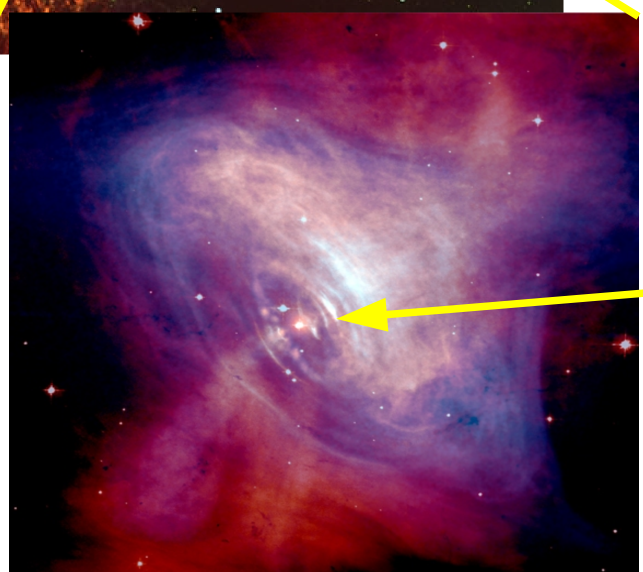
QCD phase diagram



- Quark-gluon plasma (should be) found at high temperature and density
- To study the transition lattice simulations are needed
- Nature of the transition? 1^{st} order/continuous?
- Location of the “triple point”?
- Only the low-density region is currently under numerical control: “sign problem”!

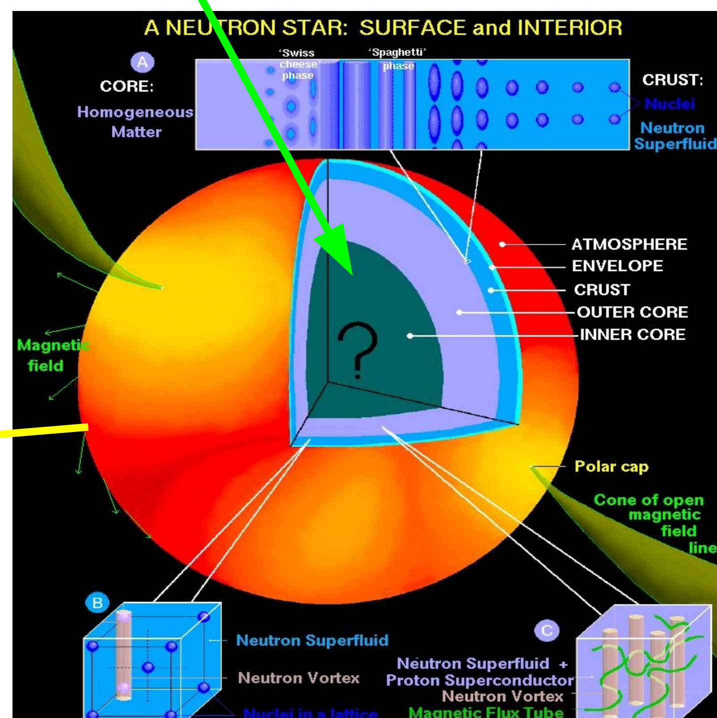
Neutron Stars

Crab nebula



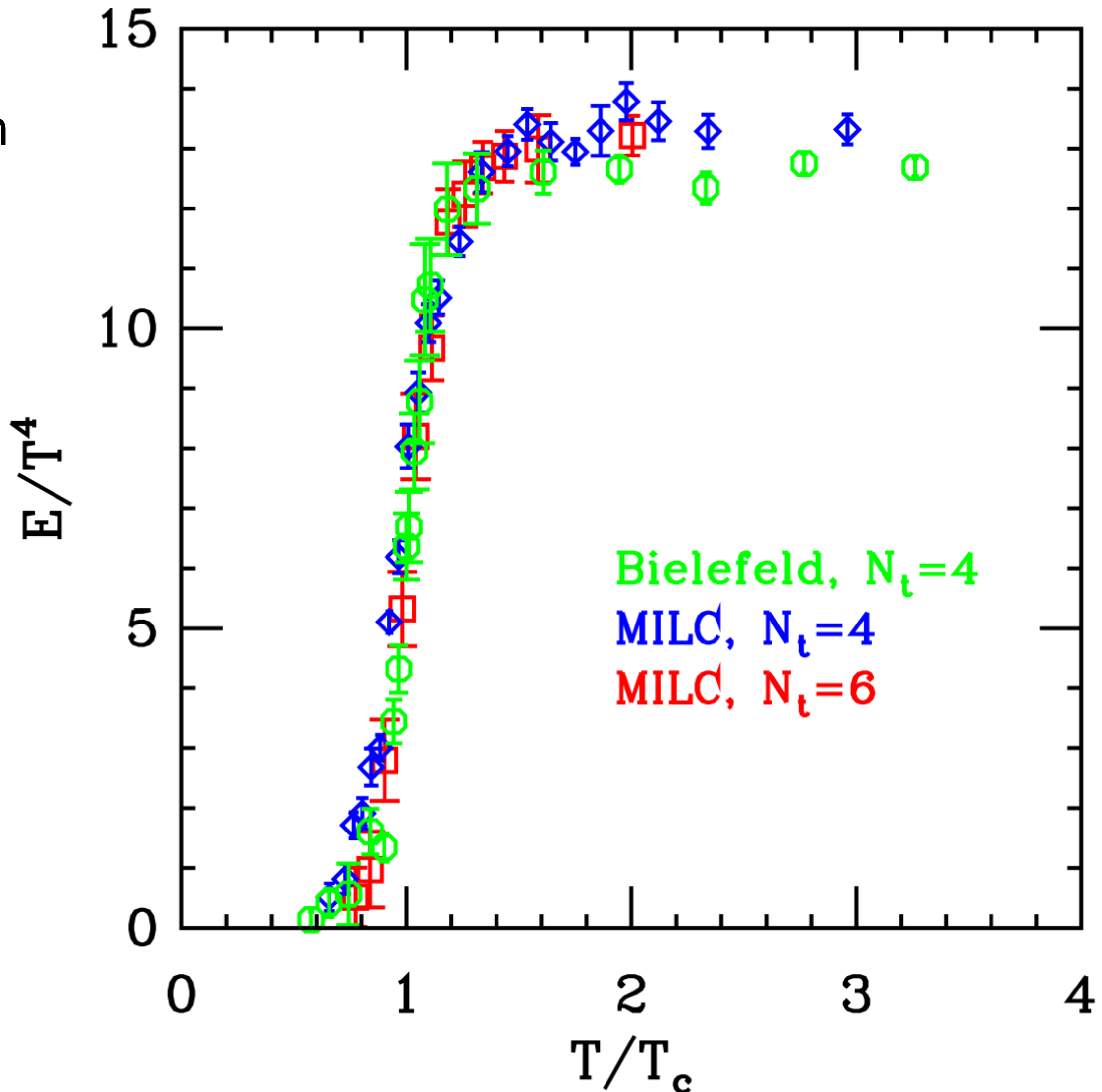
Quark matter core
inside neutron stars?

Equation of state determines
stability & maximum size



Transition to quark-gluon plasma

- Phase transition clearly observed in simulations; e.g. energy density:



Is QCD perturbative at extremely high T?

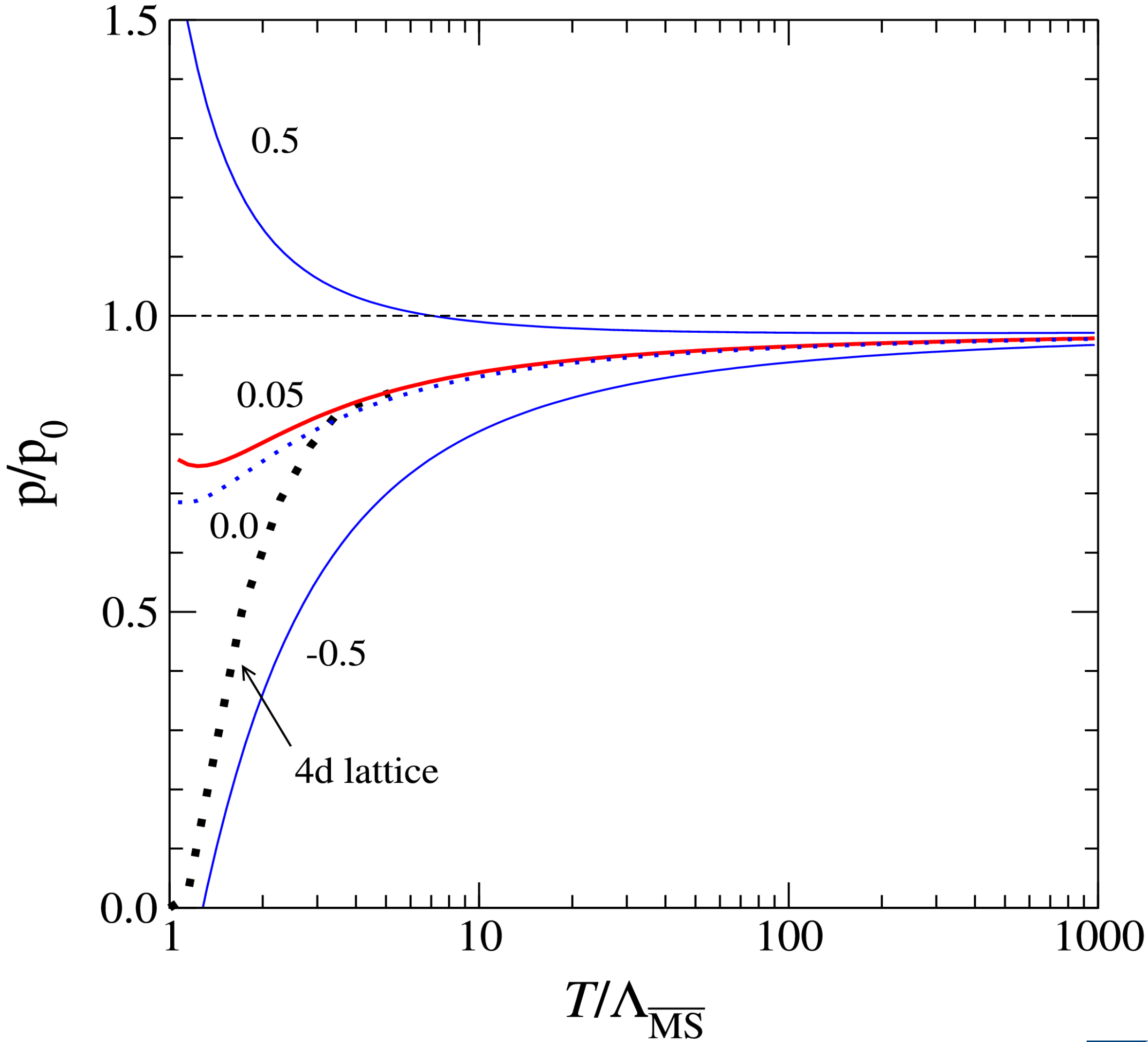
High T -> small α_s
pert. theory should work?

Can be studied using *effective theory* simulations
[Hietanen, Kajantie, Laine, Rummukainen, Schroeder]

P.T. works well only at extremely high

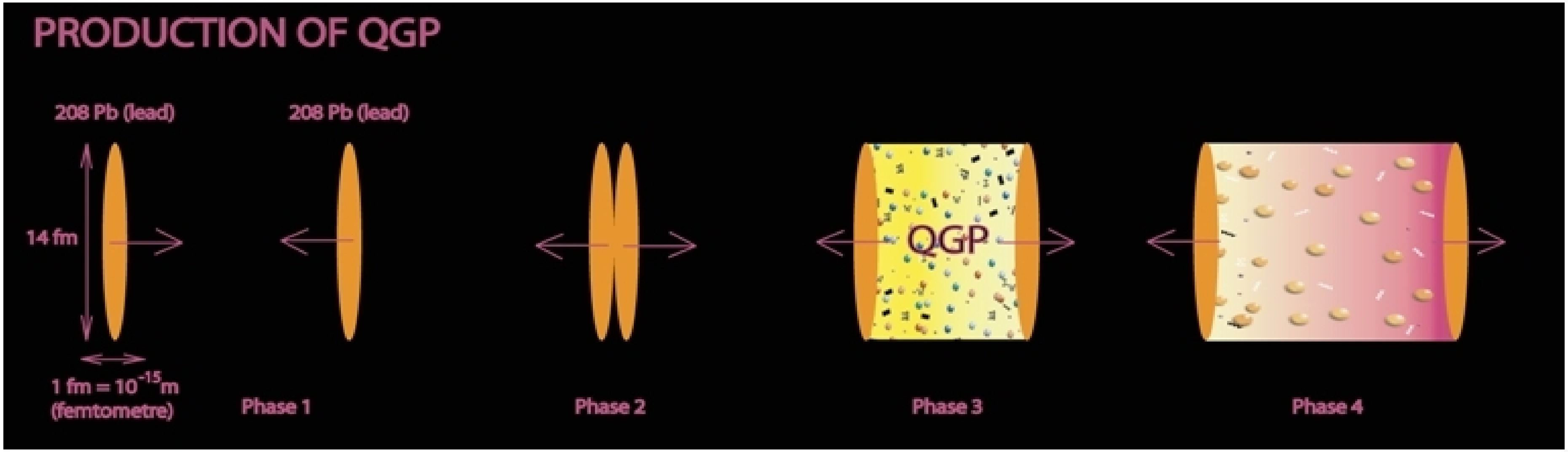
T > 100-1000 T_c

Figure: pressure, normalized to ideal gas



Heavy Ion collision experiments

Collide two heavy nuclei together at high energy: “little bang”



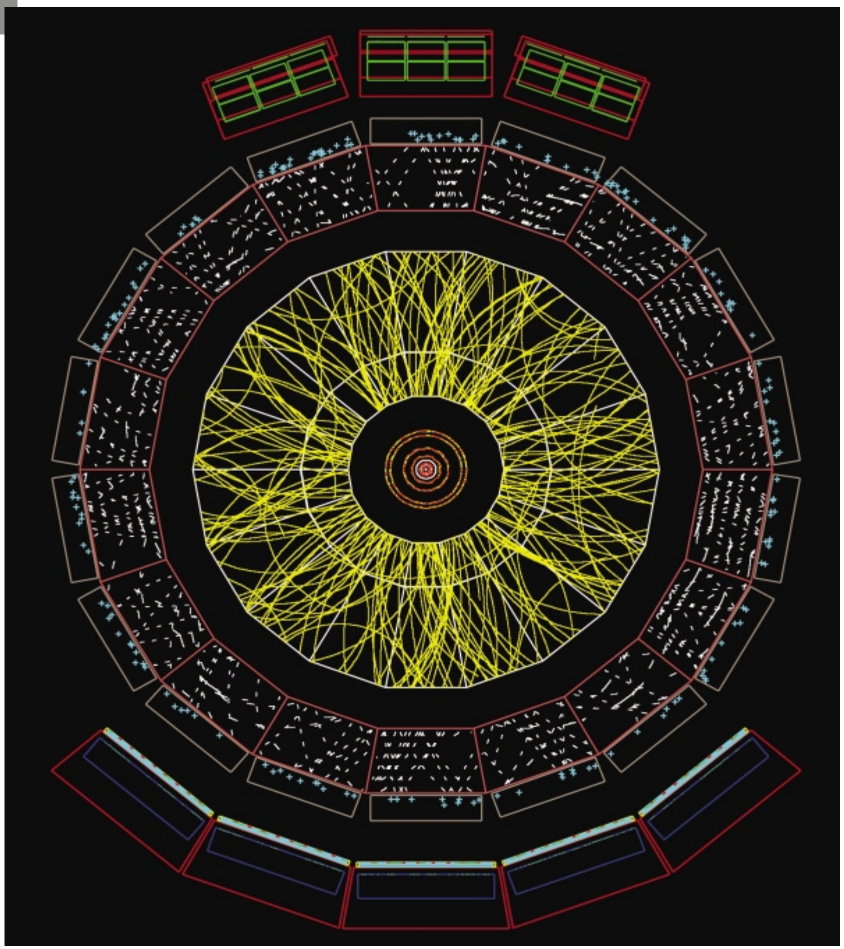
RHIC, Brookhaven; LHC (Alice experiment), CERN; GSI (planned)

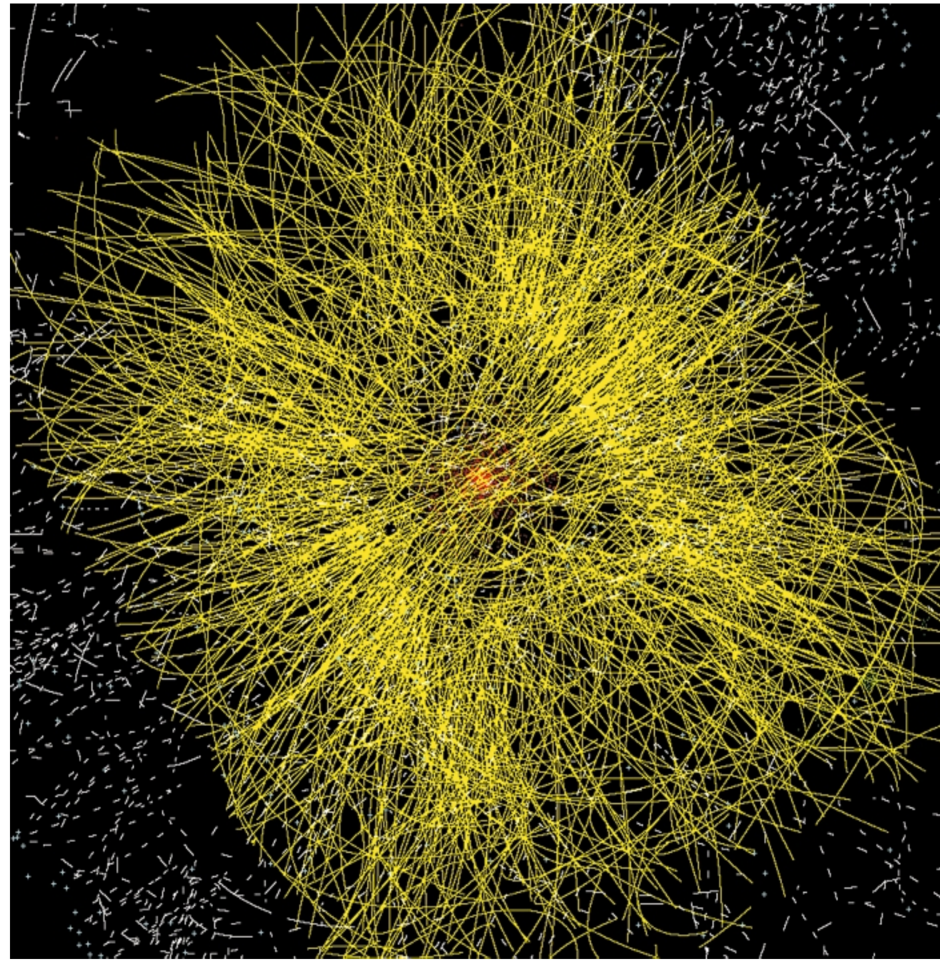
Transient and complicated system!

Time dependent, off-equilibrium system: simulations require special methods (non-standard lattice simulations)

- Thermalisation? Equation of state? Particle production?

Alice, Pb-Pb -collision (simulated)





QCD plasma instability

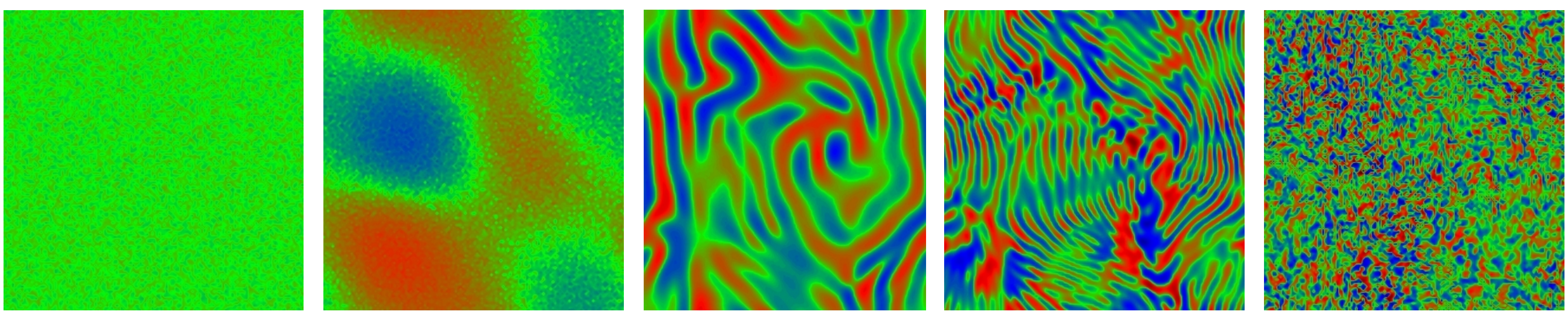
The initial state of Heavy-Ion collision is far from thermal.

Observation (RHIC, 2004-6): plasma is “thermalised” very rapidly, much faster than most estimates suggest. Why?

Non-equilibrium real-time process: requires special methods; HTL effective theory

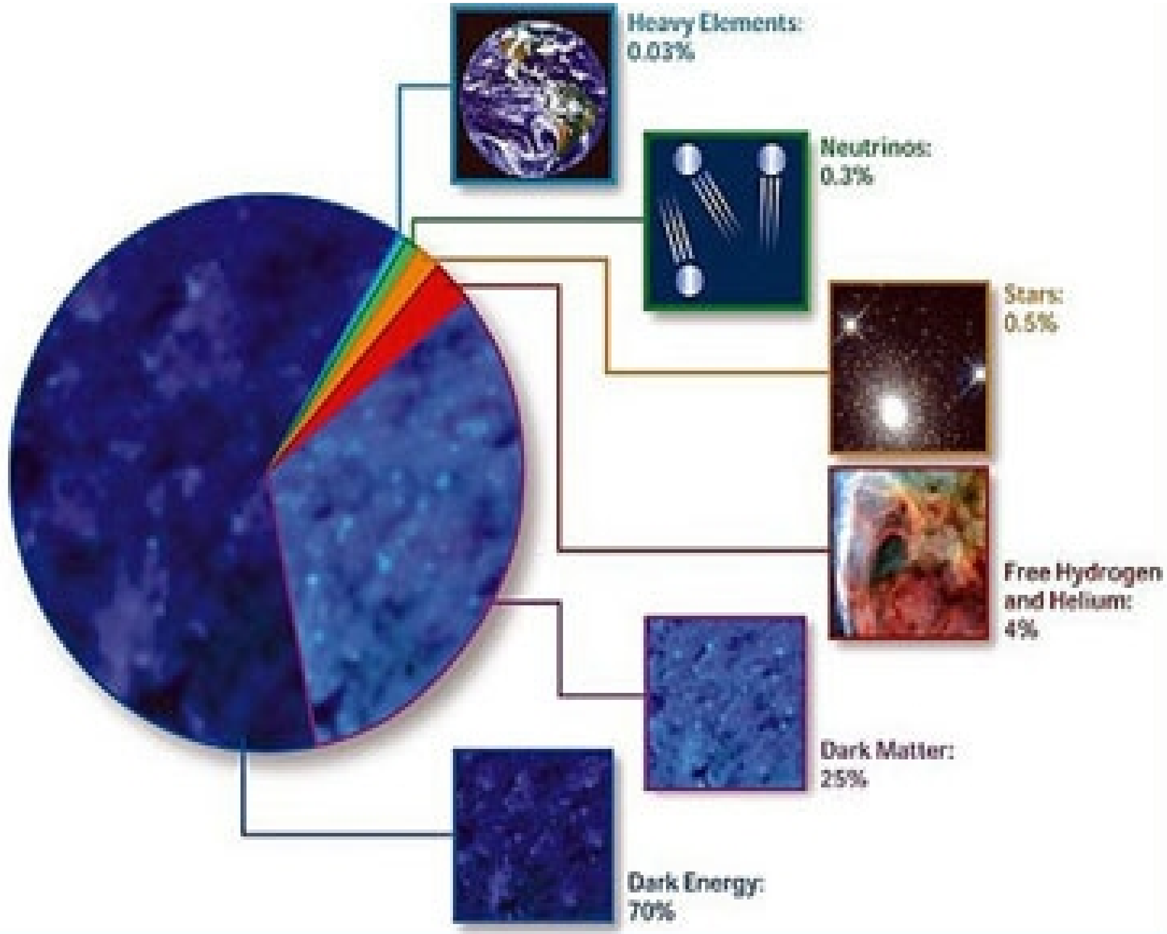
Results: with suitable initial conditioins, there is (Weibel) **plasma instability** -> exponential growth in some gluon modes -> rapid thermalisation

[Bödeker, Rummukainen JHEP 0707:022 (2007)]



Beyond QCD: Electroweak theory at high T

Universe contains matter (baryons), not antimatter! **Why?**



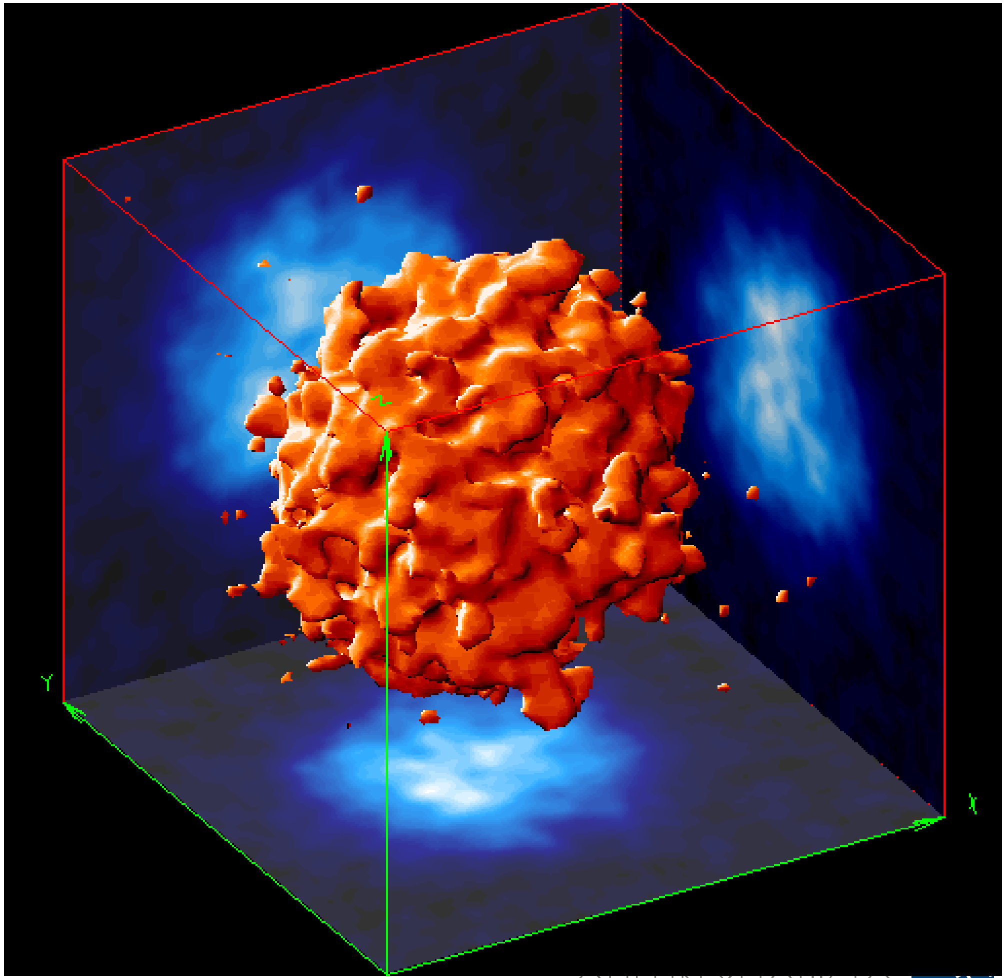
Normal stuff: 4-5% (known elementary particles)

“Dark”, exotic (unknown) matter 24%

Missing 71%: vacuum energy, “dark energy”.

Electroweak baryogenesis

- Electroweak phase transition happened in ~ 10^{-10} s old Universe
- Last possible moment to generate matter-antimatter asymmetry: **baryogenesis**



- If 1^{st} order phase transition, it proceeds through *bubble nucleation*
- Matter could be generated on the surface of the growing bubbles
- Does it work? → Lattice simulations

Moore, Rummukainen, Tranberg

Electroweak baryogenesis

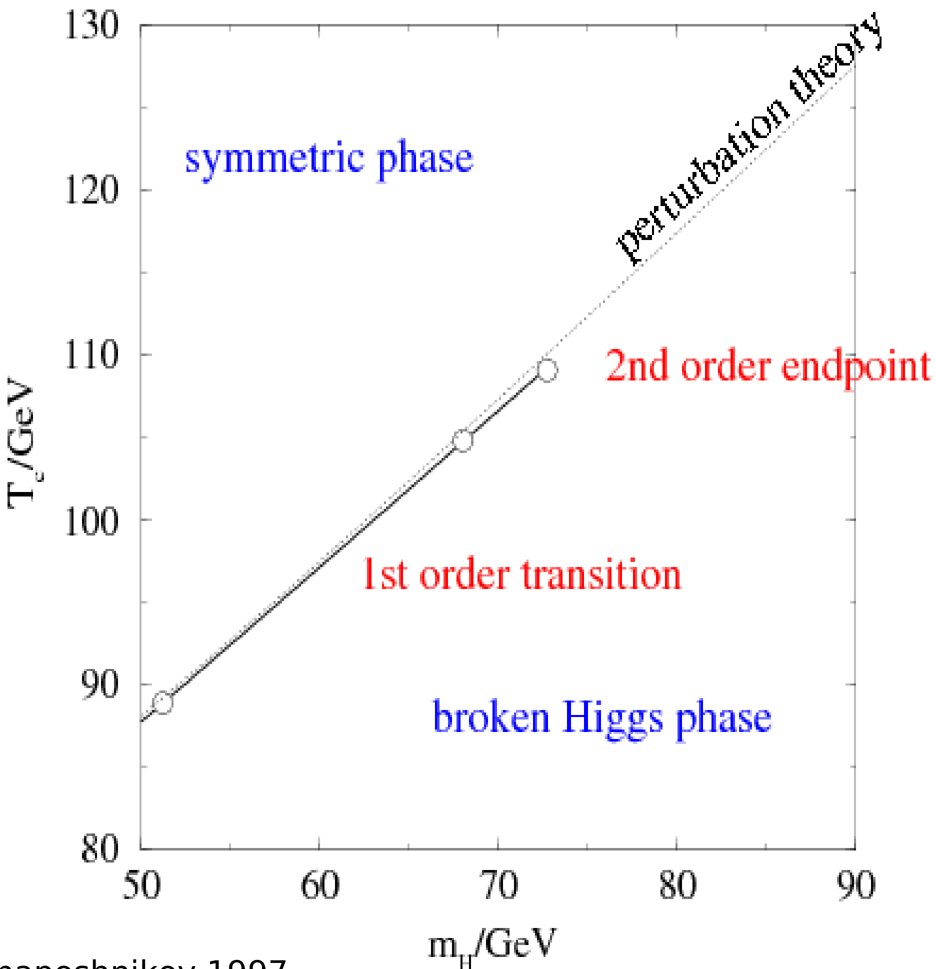
- Simulations showed that the transition is of 1st order only if Higgs mass

  m_H < 72 GeV

- Present experimental limit
  m_H > 115 GeV

⇒ EW baryogenesis not possible in the Standard Model

⇒ ***"New physics" required for succesful baryogenesis***
(extended electroweak sector, supersymmetry, leptogenesis ...)



Kajantie,Laine,Rummukainen,Shaposhnikov 1997

Finally:

- From the very beginning, lattice simulations have been an important *qualitative* tool for studying QCD
- Now also quantitative precision competes with experiments!
- In addition to bread-and-butter QCD calculations, lattice methods can be applied to a wide range of novel problems
- In Finland, we have studied:
  - Electroweak theory
  - Supersymmetry
  - Non-equilibrium physics
  - Extra dimensions
  - Technicolor (with Jyväskylä)
- *Growing research program; lots of interesting problems to be studied!*