Workshop on

Cosmological Implications

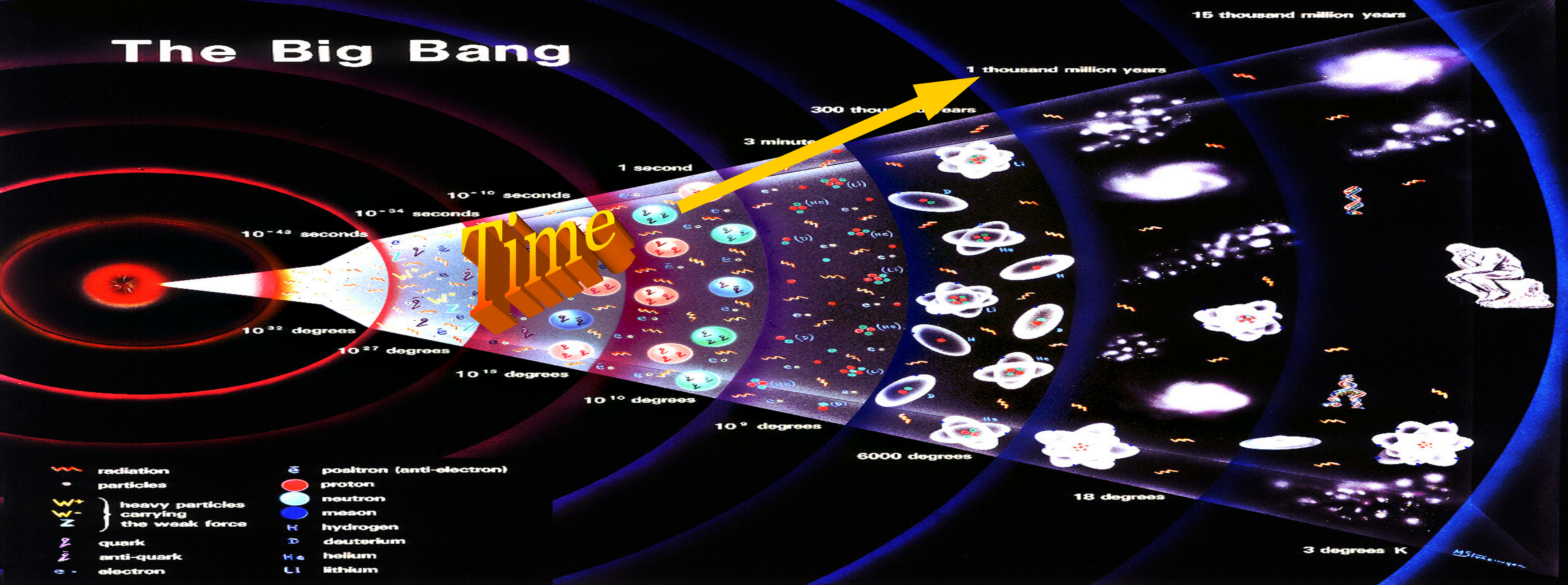
or

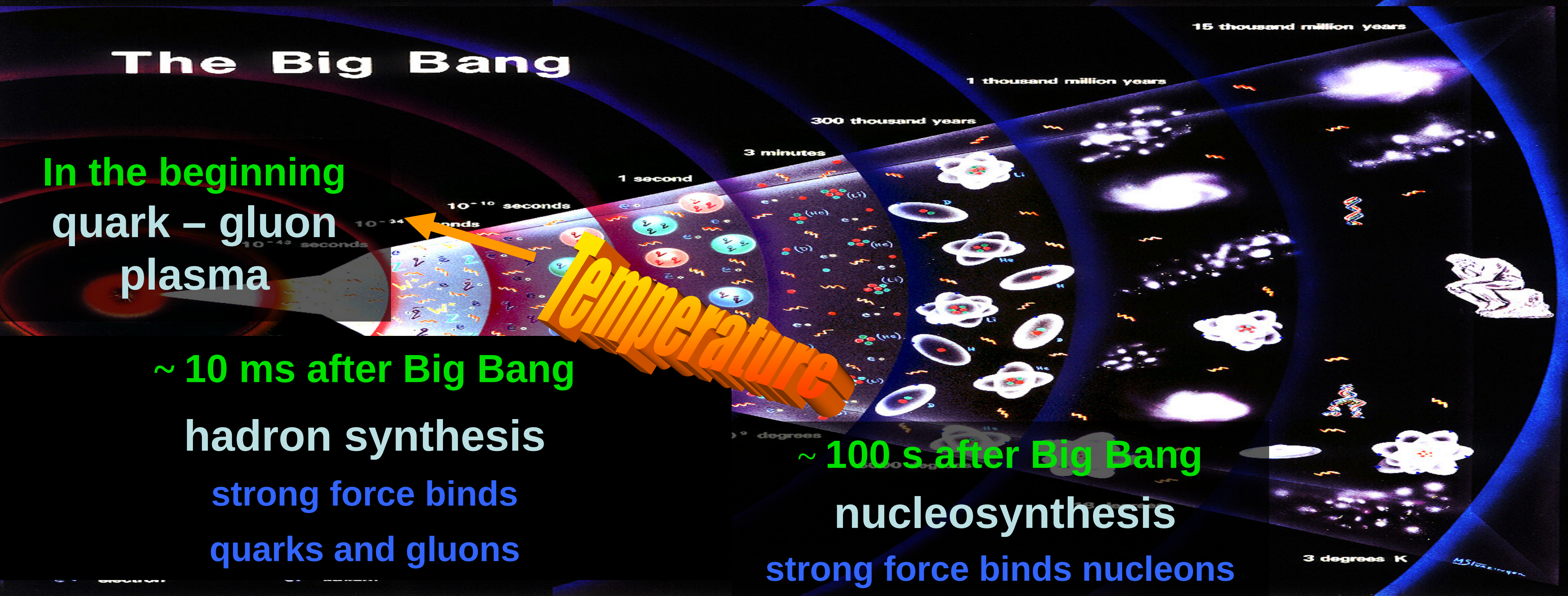
Observable Implications of a Cosmological Phase Transition

2005 RHIC & AGS Users' Meeting

Organized by Vicki Greene,

Vanderbilt University


The Big Bang
15 thousand million years
1 thousand million years
1 second
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium
Time


The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10⁻¹⁰ seconds
3 degrees K
In the beginning
quark – gluon
plasma
Temperature
~ 10 ms after Big Bang
hadron synthesis
strong force binds
quarks and gluons
~ 100 s after Big Bang
nucleosynthesis
strong force binds nucleons

Magic, Metaphor or Measurement?

- We are crossing into a new frontier of scientific inquiry. Scientists from around the world will use this facility (RHIC) to answer some of the most basic questions about the properties of matter and the evolution of our universe.
  - Energy Secretary Bill Richardson ,June 12, 2000

- Nuclear physicists have now demonstrated that the material essence of the universe at a time mere microseconds after the big bang consists of a ubiquitous quark-gluon liquid... RHIC is of course not a telescope pointed at the sky but an underground accelerator on Long Island; it is, nevertheless, in effect, a precision cosmology instrument for viewing a very early portion of the universe...
  - Ben Stein, PHYSICS NEWS UPDATE The American Institute of Physics Bulletin of Physics News Number 728 April 20, 2005

Workshop Agenda

1:30 Introduction - Vicki Greene

1:40 Hitchhiker's Guide to the Early Universe - Paul Stankus

2:15 Quarks and Cosmology - Robert Scherrer

2:45 The QCD Equation of State - Frithjof Karsch

3:15 From quantum black holes to relativistic heavy ions - Dmitri Kharzeev

3:45 Experimental results from RHIC - Mike Tannenbaum

4:30 Further questions and discussion

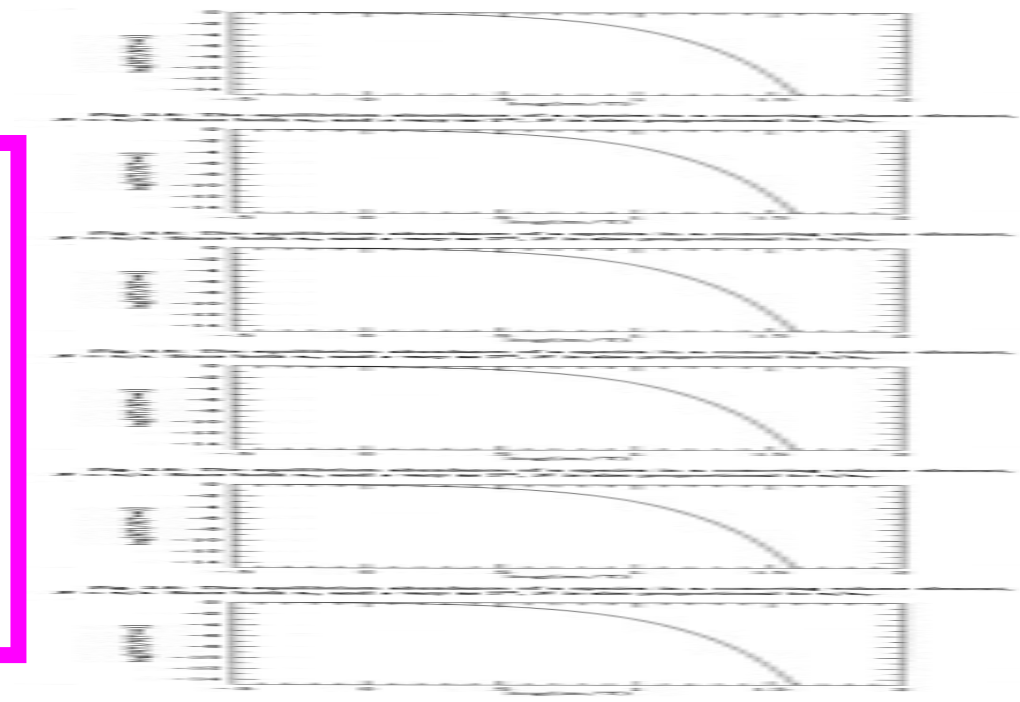
4:45 finish

Golden Rule 1: Entropy per co-moving volume is conserved

Golden Rule 2: All chemical potentials are negligible

Golden Rule 3: All entropy is in relativistic species

Expansion covers many decades in T, so typically either T>>m (relativistic) or T<<m (frozen out)



Kolb & Turner, *The Early Universe*, Westview 1990

P.Stankus

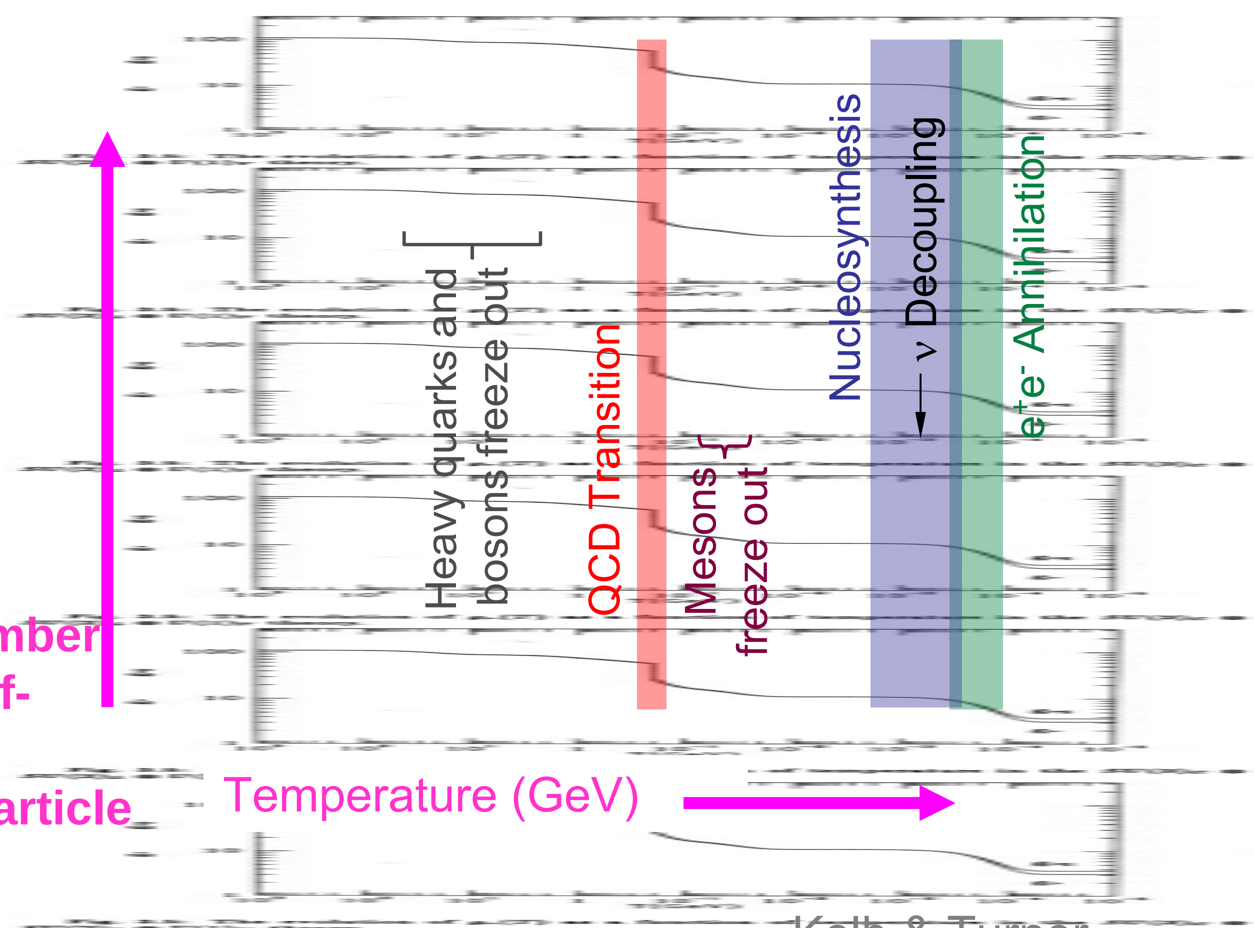
Entropy S in co-moving volume $(\Delta\chi)^3$ preserved; entropy density $s = \frac{S}{V} = \frac{S}{(\Delta\chi)^3 a^3}$

For relativistic gas $s = \frac{2\pi^2}{45} g_{*S} T^3 \quad g_{*S} \equiv \sum_{\text{Bosons } i} g_i + \frac{7}{8} \sum_{\text{Fermions } j} g_j$ degrees of freedom

$$\frac{S}{(\Delta\chi)^3} \frac{1}{a^3} = \frac{2\pi^2}{45} g_{*S} T^3$$

Golden Rule 4:

$$T \propto \left(g_{*S}\right)^{-1/3} \frac{1}{a}$$



P.Stankus

P.Stankus

Golden Rule 5: Equilibrium is boring!

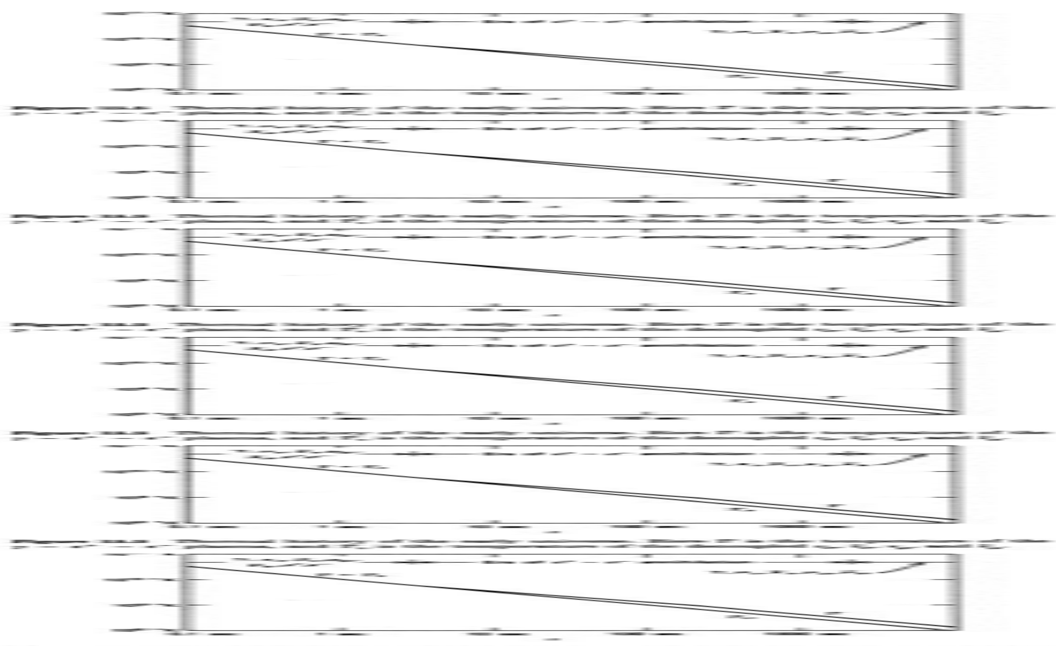
Would you like to live in thermal equilibrium at 2.75^{o}K?

That which survives:

(1) Relics $T>m$ but $\Gamma>H$
(CMB photons, neutrinos, gravitons, dark matter? free quarks, magnetic monopoles…)

(2) Remnants $T<m$ but $\mu\neq 0$
(baryons $\gamma/B \sim 10^{10}$, electrons, dark matter?)

Example of e^+e^- annihilation transferring entropy to photons, after neutrinos have already decoupled (relics).



Weinberg, *Gravitation and Cosmology*, Wiley 1972

The QCD quark-hadron transition is typically ignored by cosmologists as uninteresting

Weinberg (1972): Considers Hagedorn-style limiting-temperature model, leads to $a(t) \propto t^{2/3}|\ln t|^{1/2}$; but concludes "…the present contents…depends only on the entropy per baryon…. In order to learn something about the behavior of the universe before the temperature dropped below $10^{12\,o}$K we need to look for fossils [relics]…."

Kolb & Turner (1990): "While we will not discuss the quark/hadron transition, the details and the nature (1st order, 2nd order, etc.) of this transition are of some cosmological interest, as local inhomogeneities in the baryon number density could possibly affect…primordial nucleosythesis…"

R. Scherrer

A Brief History of the Universe

T > 100 GeV	Inflation? Baryogenesis?
T ~ 100 GeV	Electroweak phase transition
T ~ 100 MeV	Quark-gluon phase transition
T > 1 MeV	Dark matter freezes out?
T = 0.1 – 1 MeV	Primordial Nucleosynthesis
T = 3000 K	Recombination – CMB
20 K < T < 3000 K	The "dark ages"
T < 20 K	Observational Astronomy

$$1 \text{ MeV} = 10^{10} \text{ K}$$

We have precision measurements that constrain the nature of the universe at T = 3000 K (= 1 eV) and T = 0.1 – 1 MeV.

What about the quark era?

At T > 100 MeV:

- Universe is radiation-dominated (i.e., dominated by relativistic particles)
- Most particles are in thermal equilibrium and relativistic
- Cosmological constant is irrelevant

Quark-Hadron Phase Transition

In the 1980's, several groups investigated the effect of the QCD phase transition on primordial nucleosynthesis

(Witten; Applegate, Hogan, RJS; Alcock, Fuller, Matthews)

Assumed: A first order phase transition, leading to inhomogeneities in the initial densities of hadrons.

Quark-Hadron Phase Transition

Interest in this scenario was intense for a while, but died out:

1. QCD Phase transition not first order, so no large inhomogenities?
2. Initial motivation was to make baryon density much higher and allow for a “pure baryon” universe. This is ruled out by other observations.

R. Scherrer

What happens in the quark era?

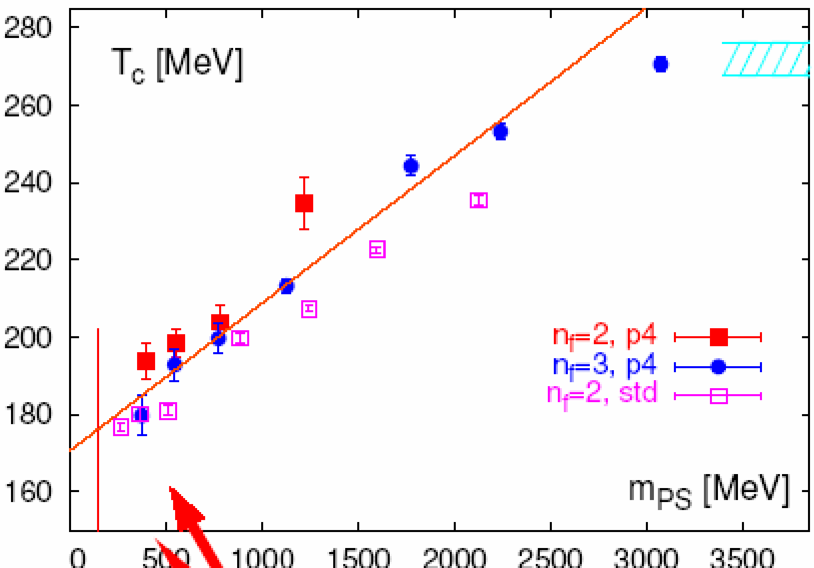
Suppose the universe behaves differently than we expected at T > 100 MeV? (Currently taken to be a perfect gas with zero viscosity, and pressure = density/3). Any effects? (unfortunately, currently part of the "dark ages")

1. Relic impact on nucleosynthesis? Hard to do unless it produces inhomogeneities. But small effects can be detectable here.

2. What else happens at T > 100 MeV?
   Freeze-out of relic dark matter particle?
   Effects on baryogenesis?

3. What are the cosmological effects of the observed RHIC quark-gluon phase?

LGT: Critical temperature, equation of state



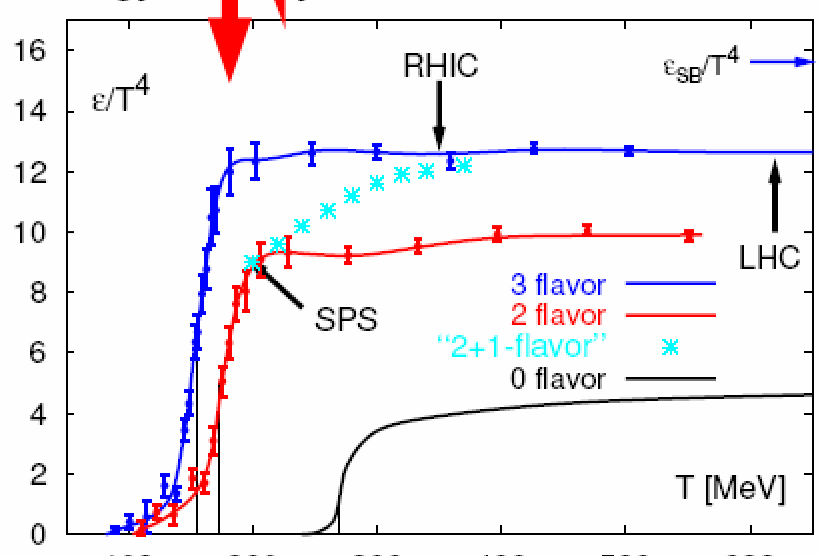
T_c

- $m_{PS} \gtrsim 300\ MeV$ (chiral limit??)
- $a \simeq 0.2\ fm$ (continuum limit??)
- improved staggered fermions,
  $\Rightarrow$ flavor symmetry breaking
  (need even better fermion actions)

ϵ_c

- $m_{PS} \simeq 770\ MeV$ (!!!)
- $V \simeq (4\ \mathrm{fm})^3$ (thermodynamic limit)

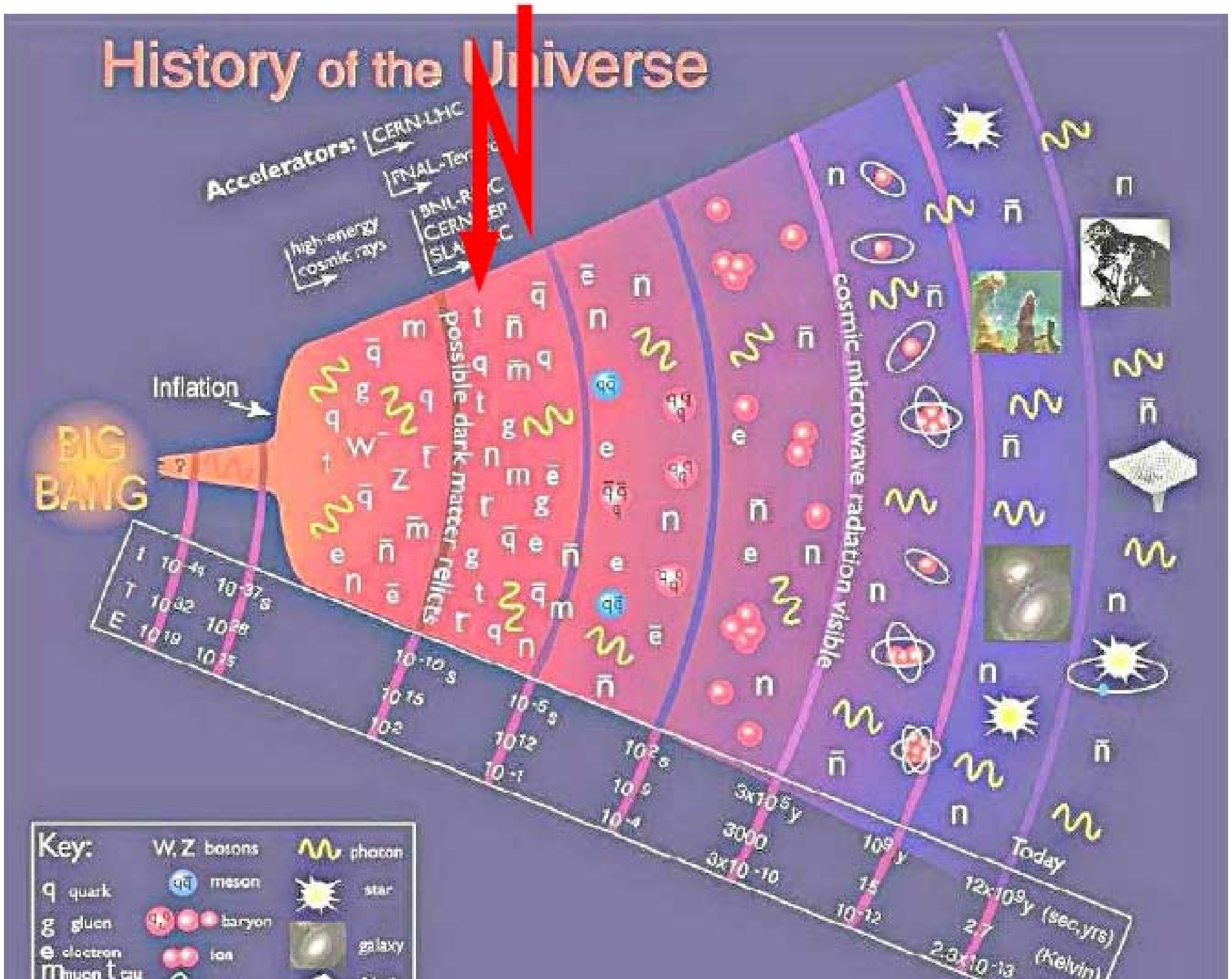
energy density for 0, 2 and 3-flavor QCD



Dark matter and the QCD equation of state

F. Karsch

- weakly interacting massive particles (WIMP) freeze out in the QGP at time $t_{freeze} \sim m_{WIMP}/25$ GeV $\sim (0.4 - 40)$GeV



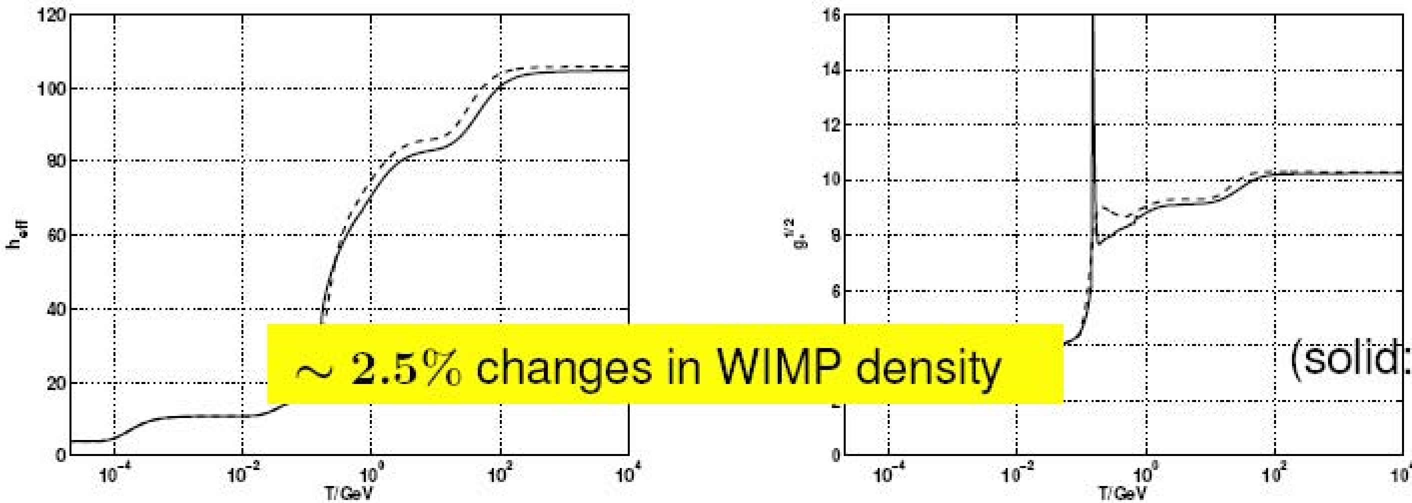
Dark matter and the QCD equation of state

M.Hindmarsh and O. Philipsen, PR D71 (2005) 087302.

- abundancy of weakly interacting massive particles (WIMP) sensitive to the evolution of the early universe ⇔ sensitive to the QCD EoS

energy density: $\frac{\epsilon}{T^4} = \frac{\pi^2}{30} g_{eff}(T)$; entropy density: $\frac{s}{T^4} = \frac{2\pi^2}{45} h_{eff}(T)$

$$\frac{n_{WIMP}}{s} \sim g_*^{-1/2}(T) = \frac{g_{eff}^{1/2}}{h_{eff}} \left(1 + \frac{T}{3} \frac{d \ln h_{eff}}{dT} \right)^{-1}$$



$\sim 2.5\%$ changes in WIMP density

(solid:QGP)

Primordial black holes formation during the QCD phase transition in the Early Universe ?

D. Kharzeev

QCD phase transition in the Early Universe:

sQGP: small pressure, high energy density =>

gravitational collapse into a black hole is likely(?)

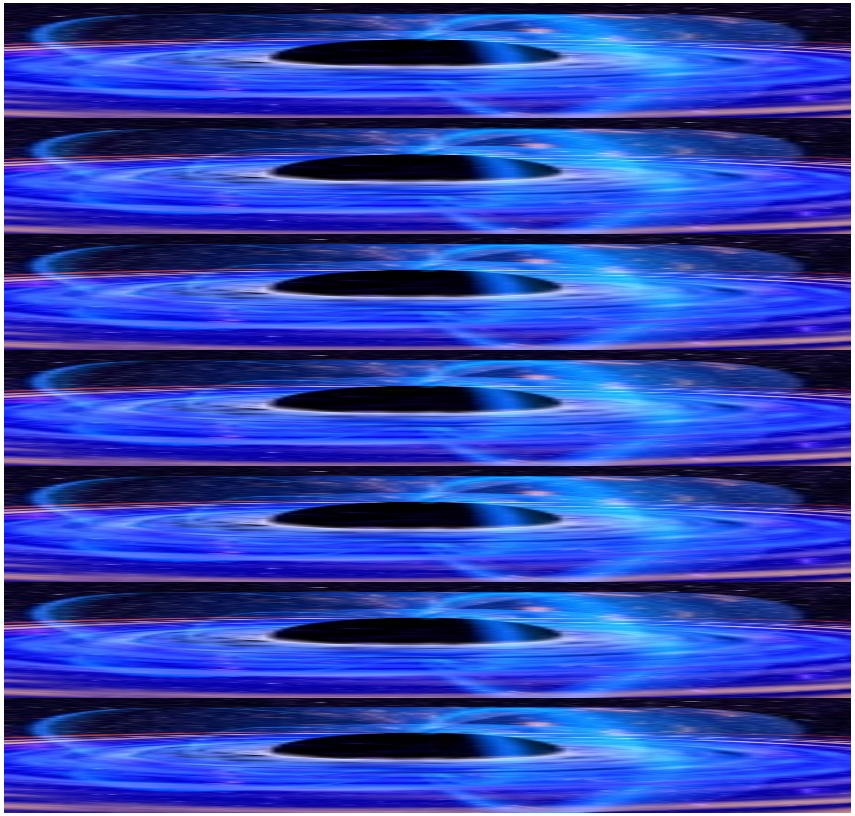
K. Jedamzik, PRD55(97) 5871

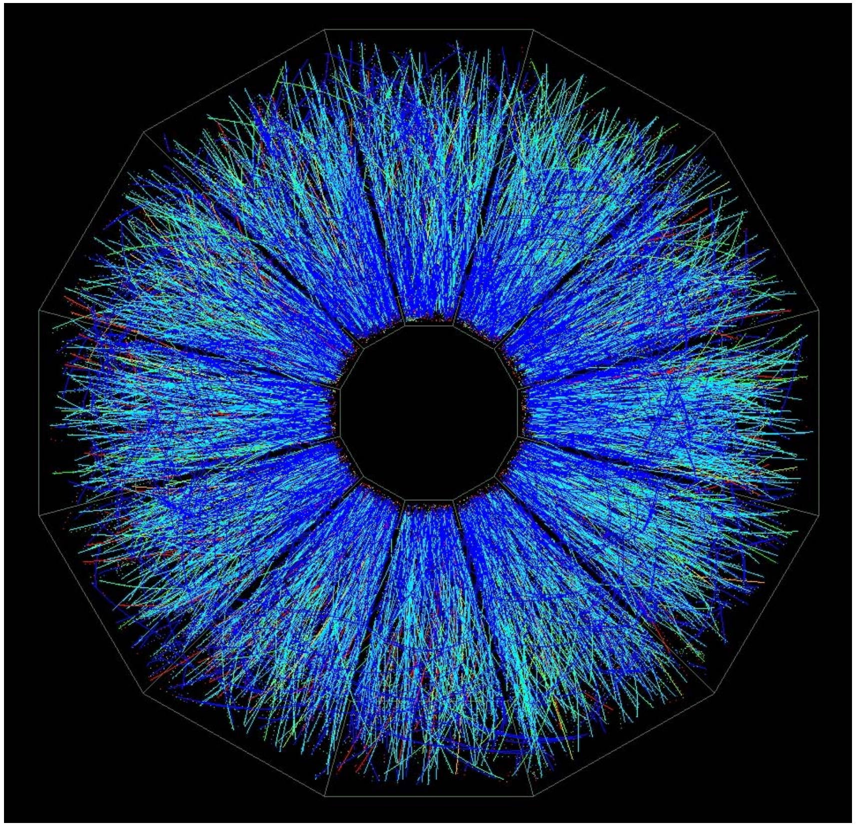
The primordial black holes, with a peak in the mass distribution at the QCD horizon mass scale (~ 1 M_{sun}):

dark matter? MACHO's? (MAssive Compact Halo Objects)

A link between General Relativity and QCD?
solution to some of the RHIC puzzles?

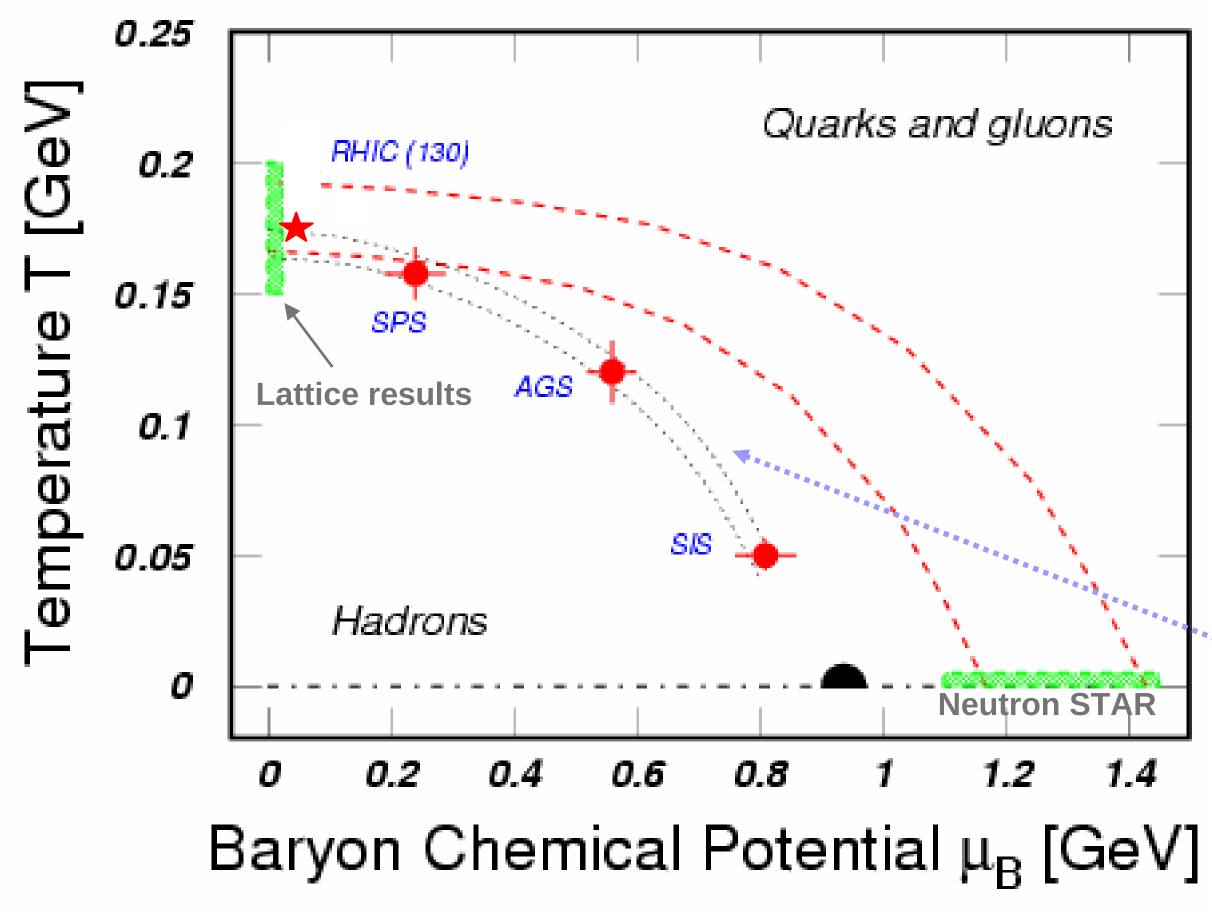
Black holes ⟷ RHIC collisions





JHT1

Phase Diagram from Thermal Fit of particle ratios---``chemical”



- **Final-state analysis suggests RHIC reaches the phase boundary**
- **Hadron resonance ideal gas** (M. Kaneta and N. Xu, nucl-ex/0104021 & QM02)
  - **T_{CH} = 175 ± 10 MeV**
  - **μ_B = 40 ± 10 MeV**
- **<E>/N ~ 1 GeV**

(J. Cleymans and K. Redlich, Phys.Rev.C, 60, 054908, 1999)

- Where is the QGP critical point?

M. Tannenbaum

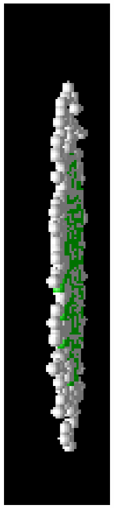
JHT1 add masashis comments about lattice results on left and neutron star on the right
Jim Thomas, 7/17/2002

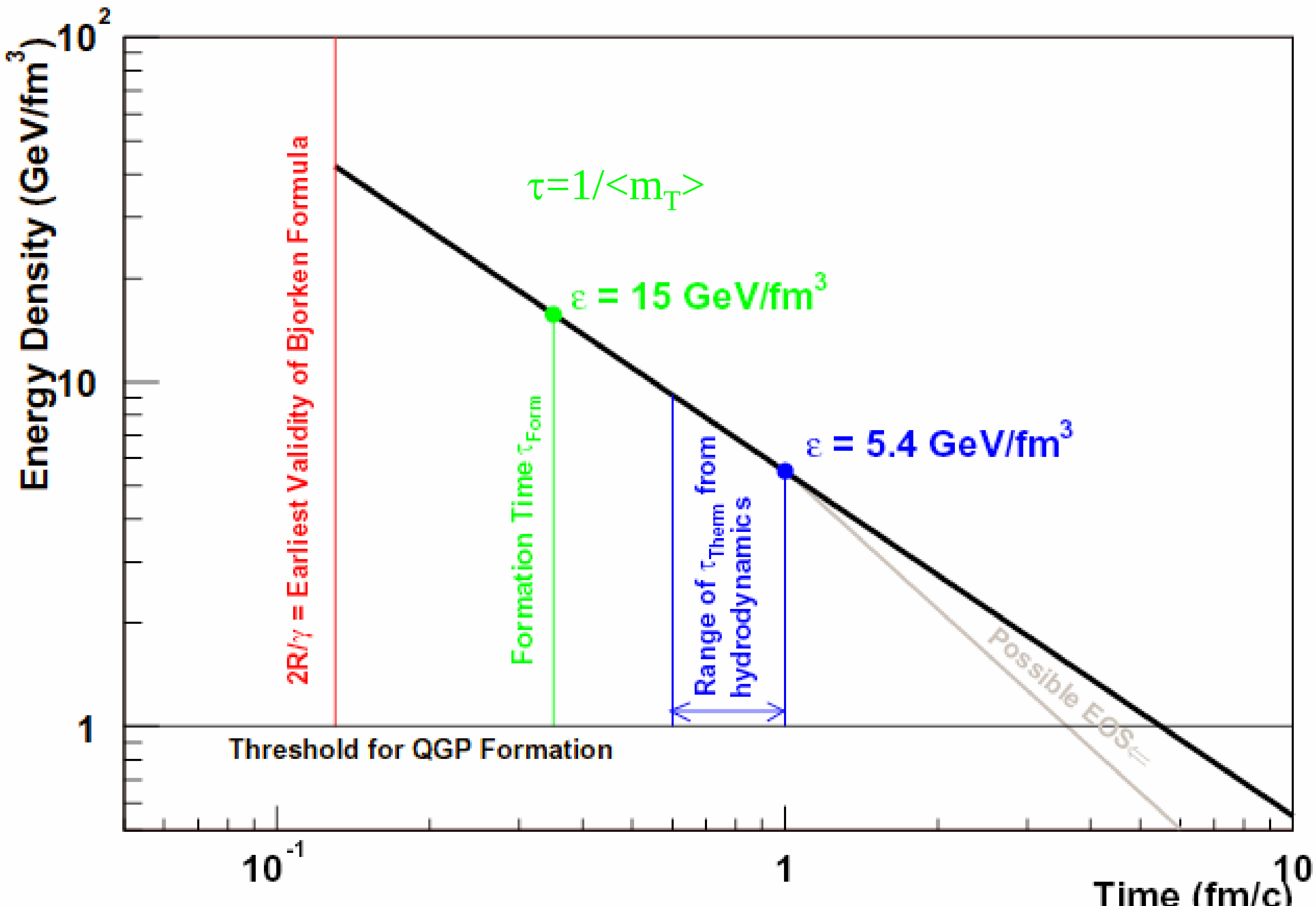
Conclusions

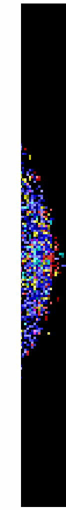
- Cosmological implications of observations at RHIC is a thorny problem, but it is reasonable (essential?) to revisit – and an interesting cosmological problem in its own right.
- Places to look:
  - Effects on nucleosynthesis resulting from fluctuations
  - WIMPS
  - Primoridal black holes
  - Effects on baryogenesis
  - Dark matter?, Machos?
- Metaphor or measurements – we will have to answer the question.

My thanks to Paul, Bob, Frithof, Dima, and Mike!

Spacetime evolution is important







P.Stankus

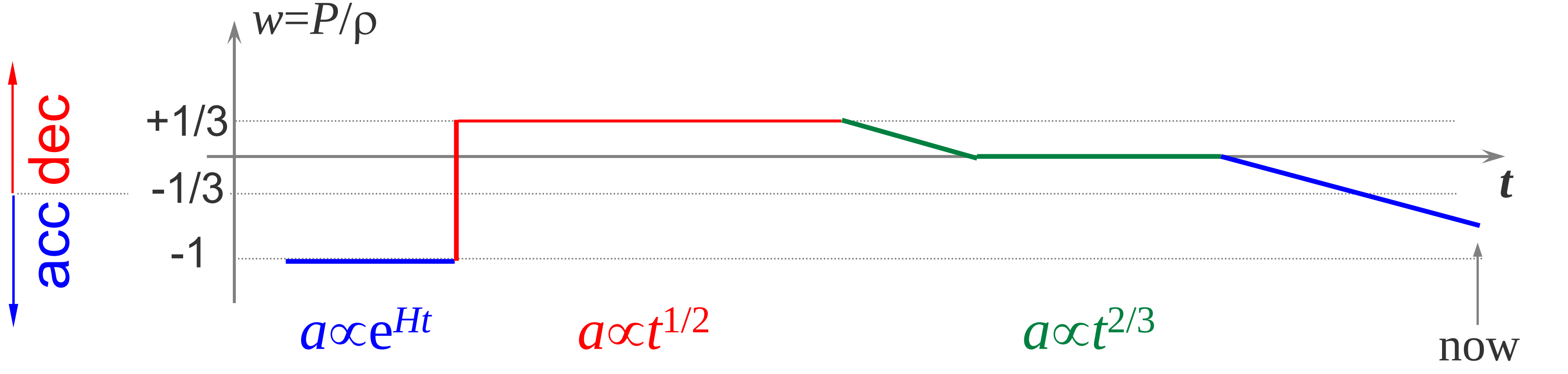
The New Standard Cosmology in Four Easy Steps

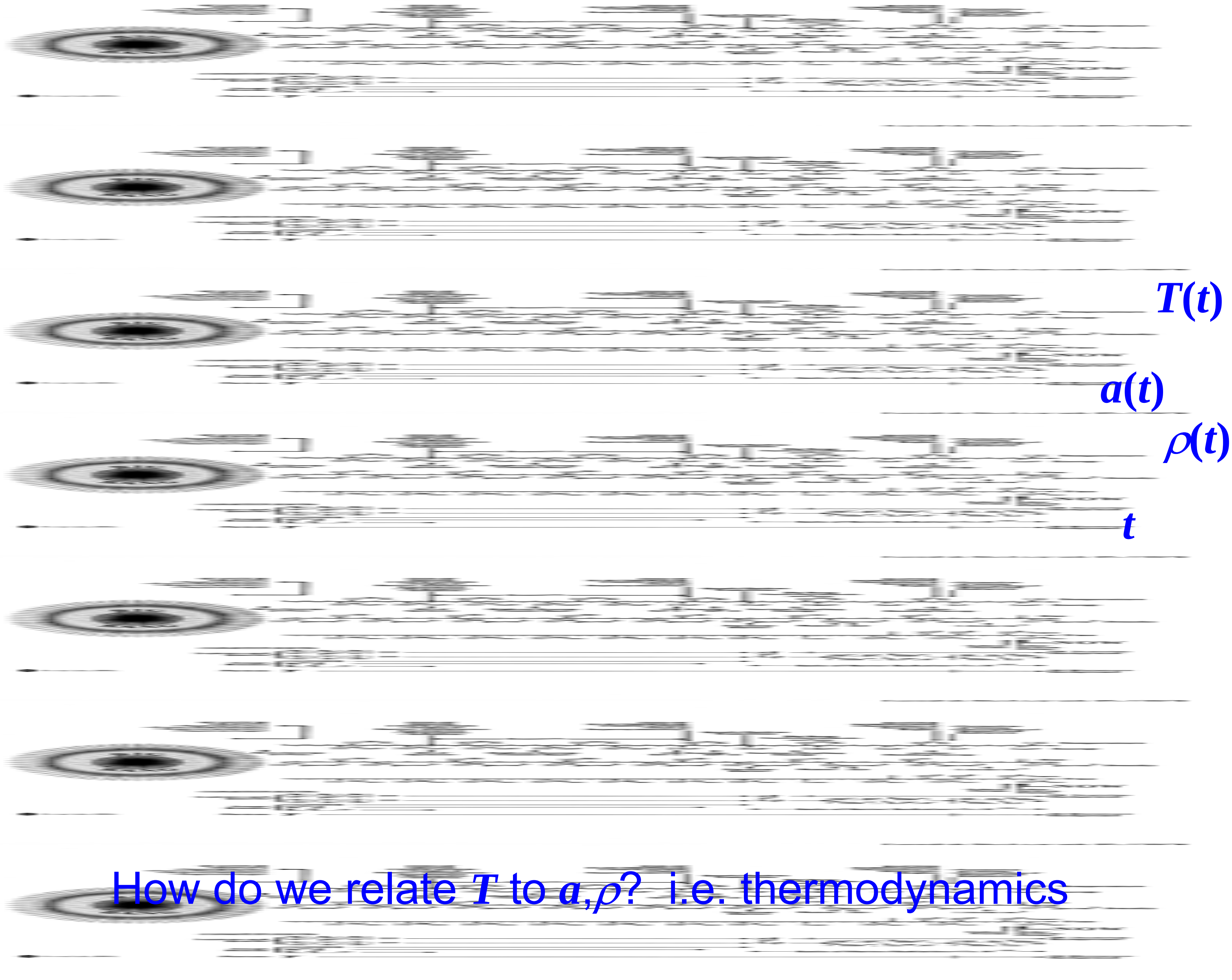
Inflation, dominated by "inflaton field" vacuum energy

Radiation-dominated thermal equilibrium

Matter-dominated, non-uniformities grow (structure)

Start of acceleration in $a(t)$, return to domination by cosmological constant and/or vacuum energy.





How do we relate T to a,ρ? i.e. thermodynamics

Conclusions

- lattice calculations (at $\mu = 0$) produced a lot of evidence for substantial deviations from ideal gas behavior for $T \lesssim (2-3)T_c$, *i.e.* in the temperature regime accessible to RHIC
- HTL-resummed perturbation theory and quasi-particle models descripe lattice results above $\sim 3\ T_c$ quite well
- heavy quark free energies and the running coupling change smoothly across T_c
- evidence for remnants of confinement
- no evidence for an unusually large Coulombic coupling at short distances

Outline

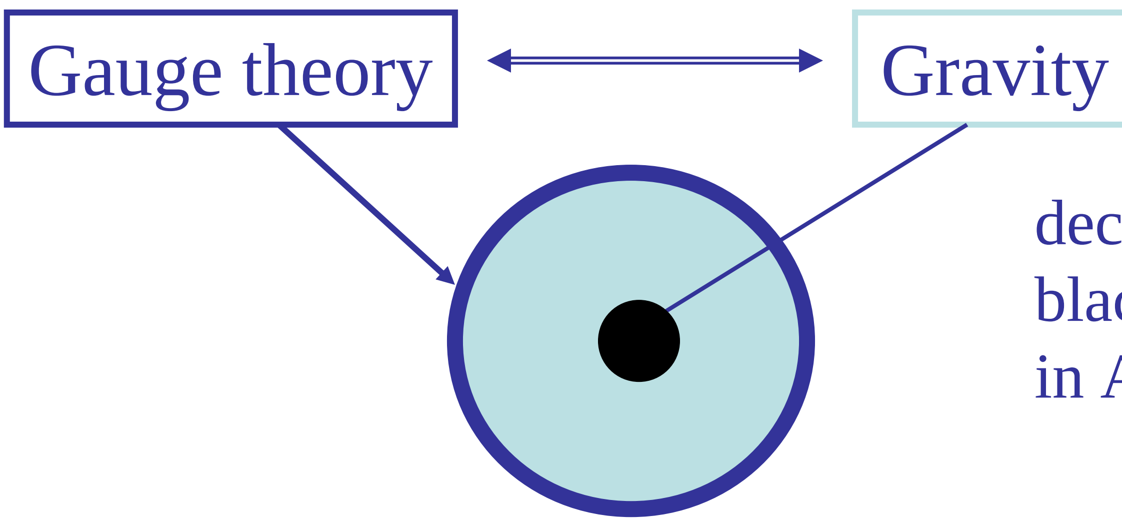
- Why black holes cannot be produced at RHIC

- Why black holes may anyway teach us about
  the properties of QCD matter produced at RHIC
  and in the Early Universe

Can black holes anyway help us to understand the physics at RHIC?

One new idea: use a mathematical correspondence between a gauge theory and gravity in AdS space

Maldacena



deconfinement - black hole formation in $AdS_5 x S_3 x T$ space

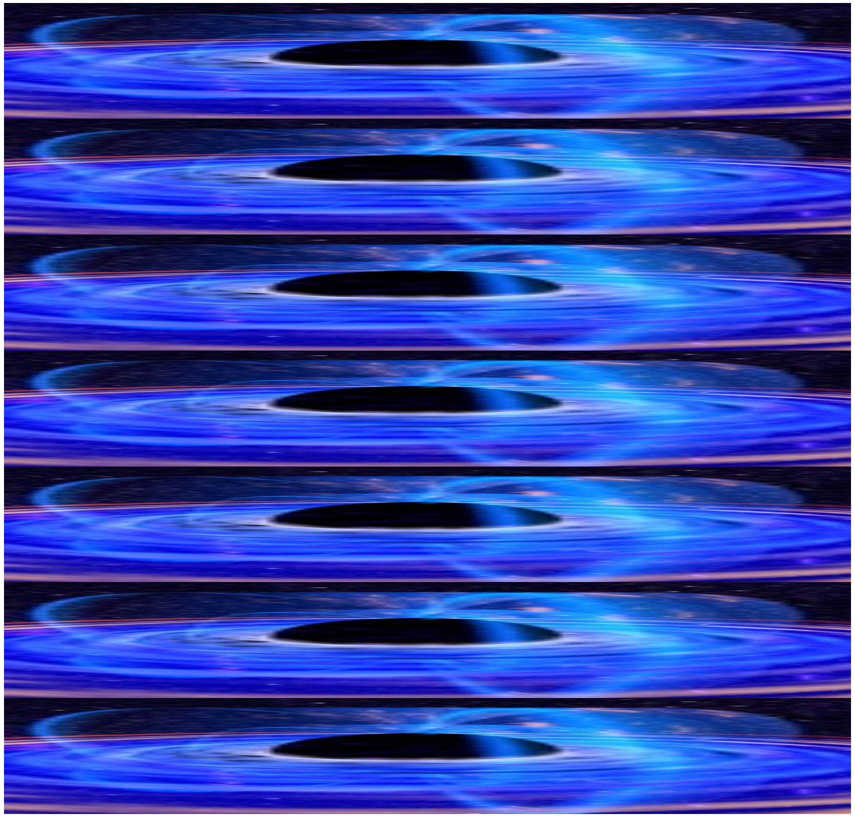
boundary

Witten; Polyakov; Gubser, Klebanov; Son, Starinets, Kovtun; Nastase; …

Anti de Sitter space - solution of Einstein's equations with a negative cosmological constant Λ
(de Sitter space - solution with a positive Λ (inflation))

Black holes radiate

S.Hawking '74



Black holes emit thermal radiation with temperature

$$T = \frac{\kappa}{2\pi}$$

acceleration of gravity at the surface, $(4GM)^{-1}$

Similar things happen in non-inertial frames

Einstein's Equivalence Principle:

Gravity ⟷ Acceleration in a non-inertial frame

↓

An observer moving with an acceleration a detects a thermal radiation with temperature

$$T = \frac{a}{2\pi}$$

W.Unruh '76

In both cases the radiation is due to the presence of event horizon

Black hole: the interior is hidden from
an outside observer;
Schwarzschild metric

Accelerated frame: part of space-time is hidden
(causally disconnected) from
an accelerating observer;
Rindler metric

$$\rho^2 = x^2 - t^2, \quad \eta = \frac{1}{2}\ln\left|\frac{t+x}{t-x}\right|$$

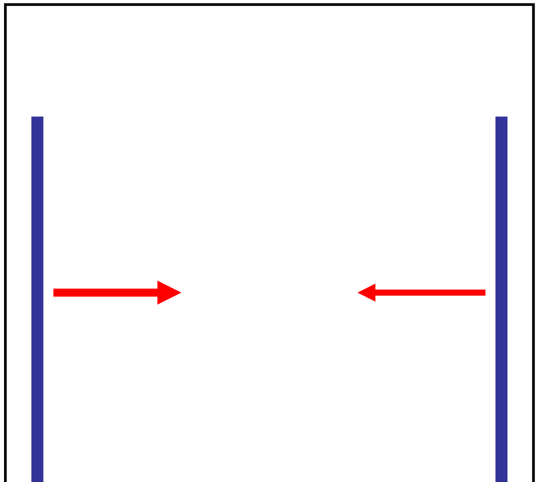
$$ds^2 = \rho^2 d\eta^2 - d\rho^2 - dx_\perp{}^2$$

Where on Earth can one achieve the largest acceleration (deceleration) ?

Relativistic heavy ion collisions! -
stronger color fields: $E \sim \sigma \quad \rightarrow \quad E \sim \frac{Q_s^2}{g}$

$$v_{initial} \simeq c; \quad v_{final} \simeq 0; \quad \Delta t \simeq 1/Q_s$$

$$a \simeq Q_s \sim 1 \text{ GeV}; \quad T = \frac{a}{2\pi} \sim 160 \text{ MeV}$$



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