Cosmic Phase Transitions and Material Transformations

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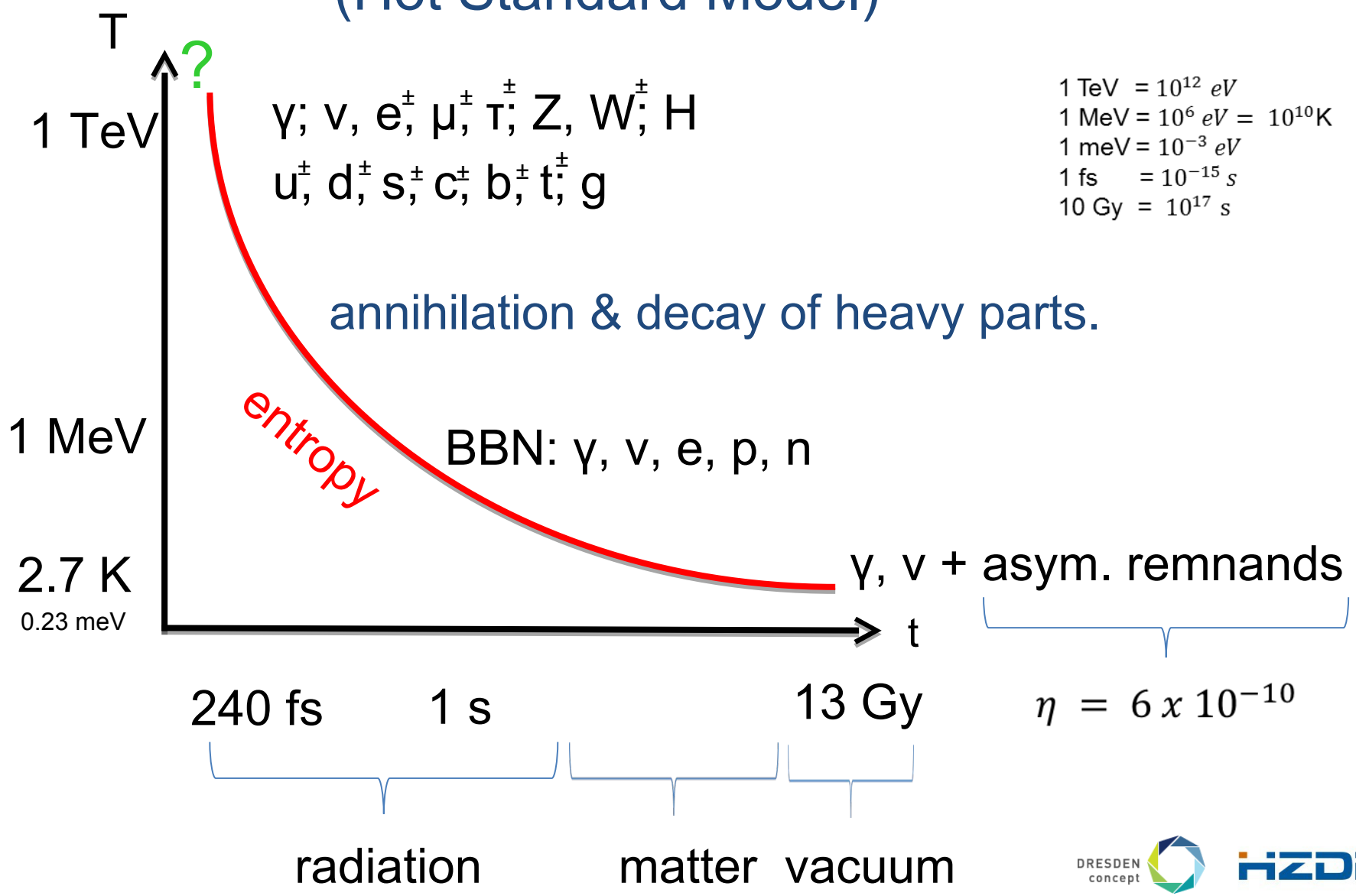
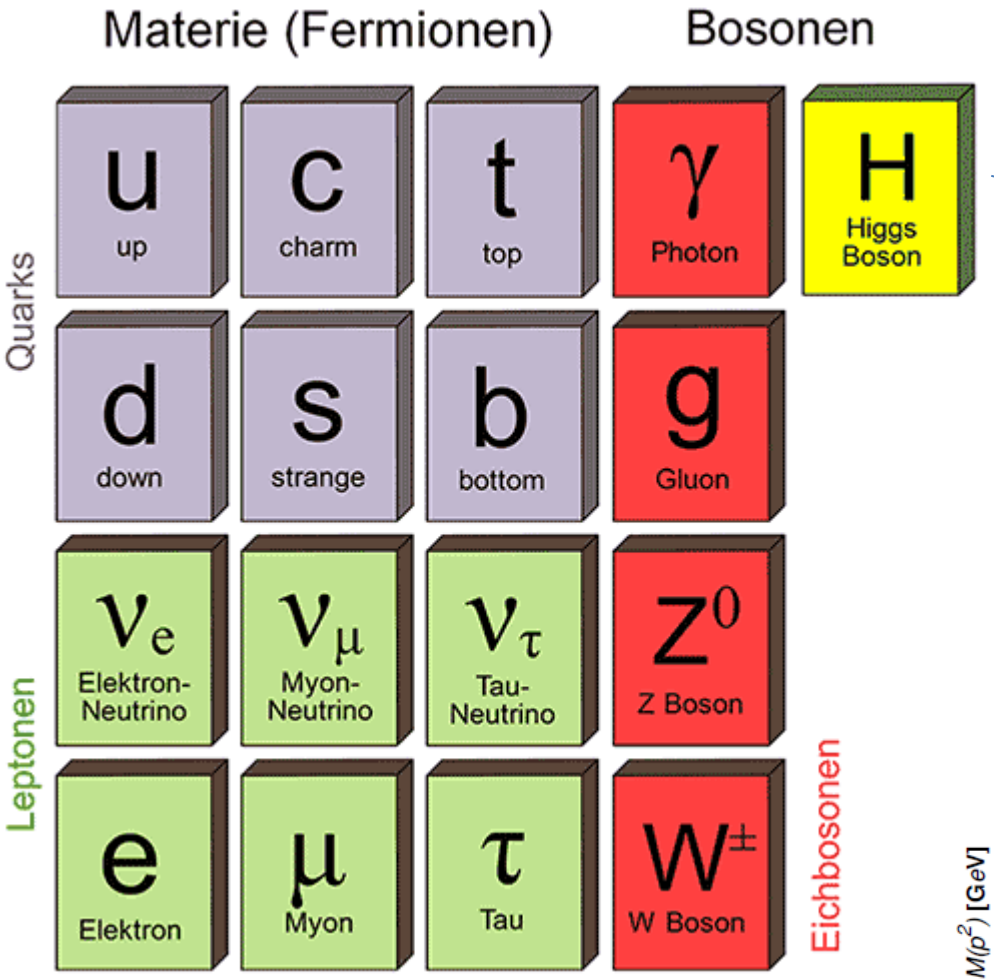
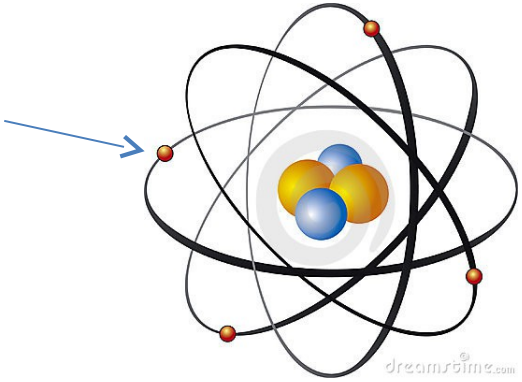
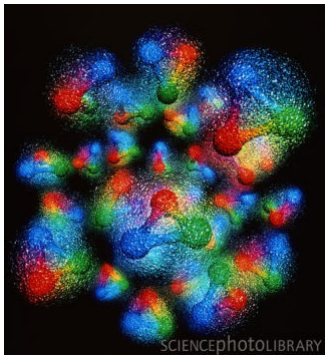
Particle Destruction in the Universe (Hot Standard Model)



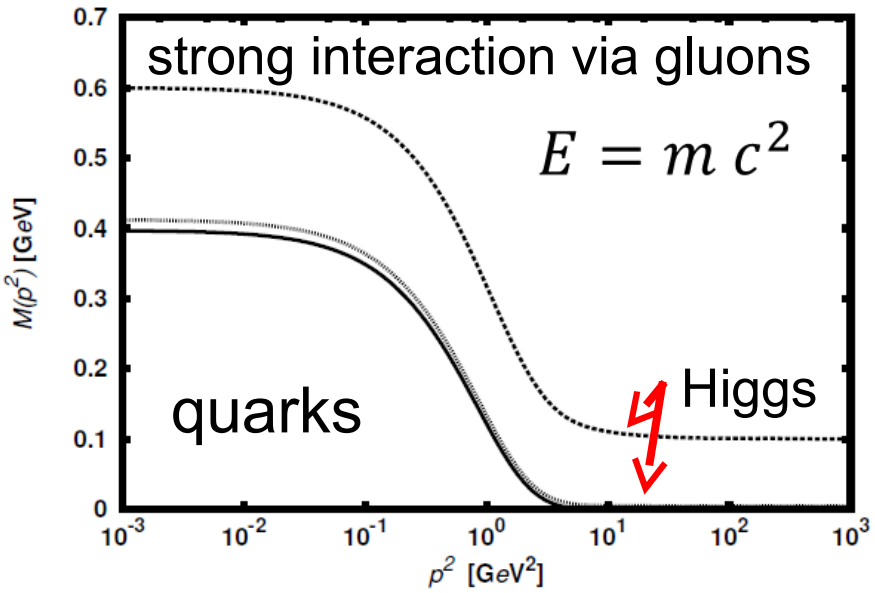
That is all we know: SM …





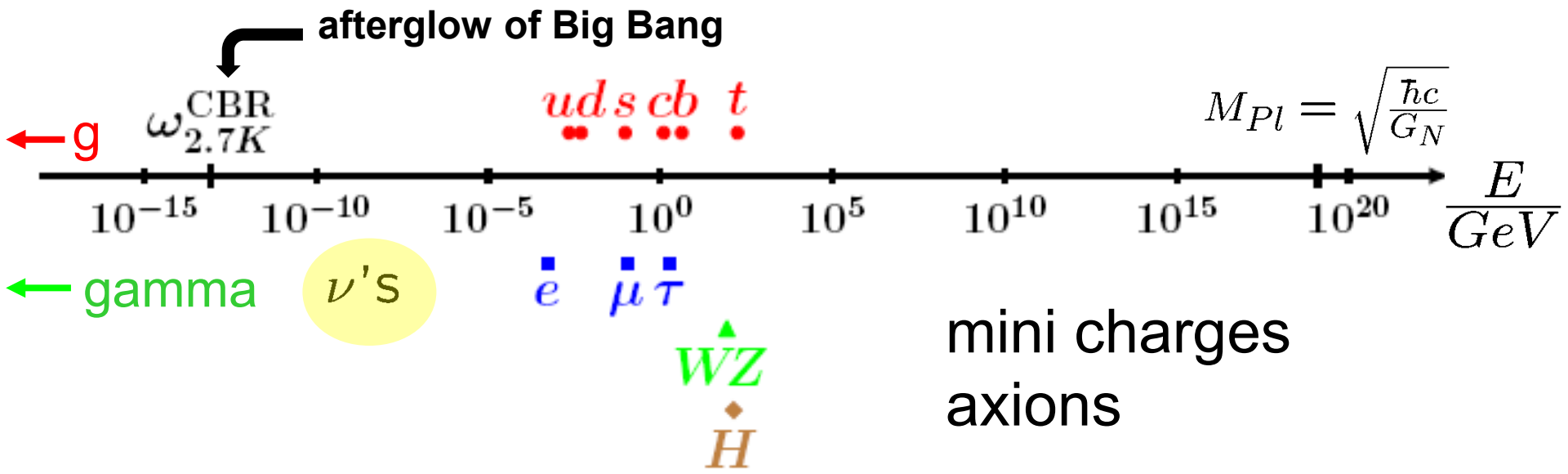


M. Viebach (2013), TU Dresden & HZDR



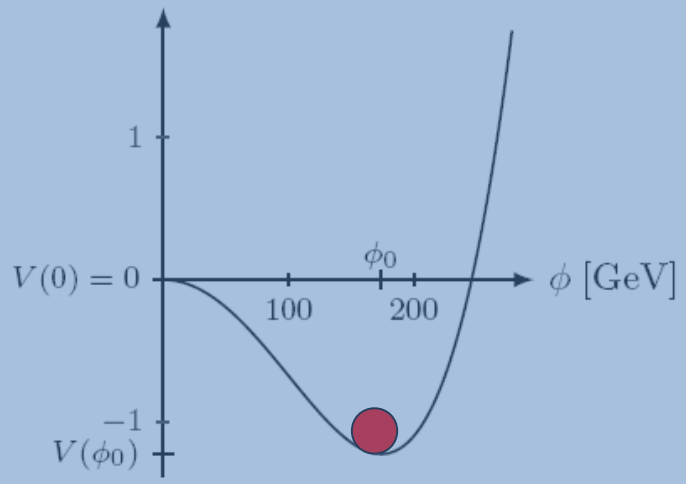
…& Gravity
& principles

SM Higgs: Mass Matters (Die Masse macht‘s)



mini charges
axions
....

$V_{Higgs}[10^8 \mathrm{GeV}^4]$

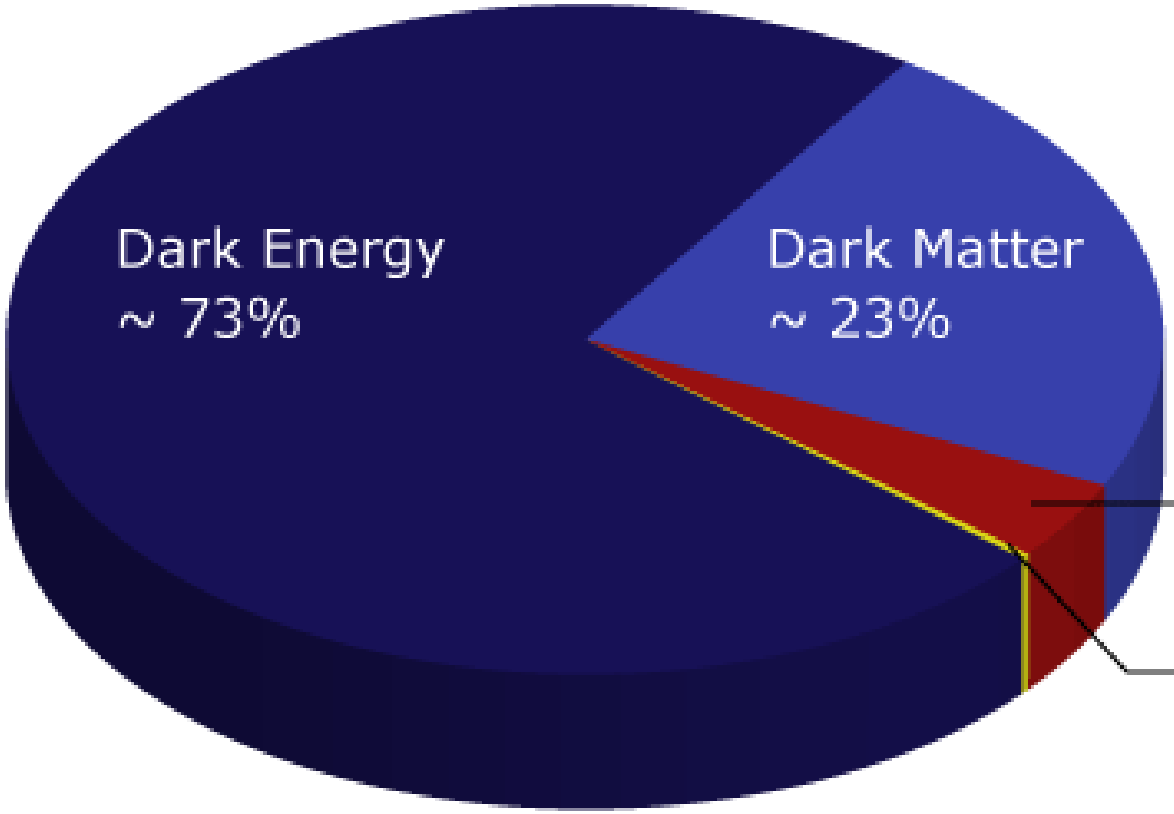


vacuum parameters:

$$e = V(\phi_0) = -1.22 \times 10^8\,\mathrm{GeV}^4$$
$$\phi_0 = 174\ \mathrm{GeV}$$
$$m_\phi = 126\ \mathrm{GeV}$$

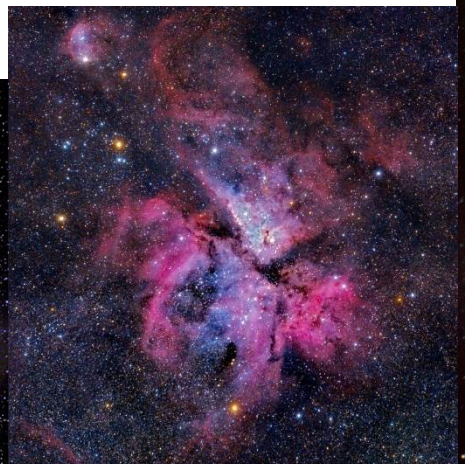
the new ether?

The Universe‘s Content: essentially unknown



Other nonluminous components
intergalactic gas 3.6%
neutrinos 0.1%
supermassive BHs 0.04%

Luminous matter
stars and luminous gas 0.4%
radiation 0.005%



Symmetry of Matter – Antimatter in the Universe?

10^{-9}

only that excess remained

(A) Dark Energy = Lambda = vacuum ?
Solving the Cosmological Lambda Problem

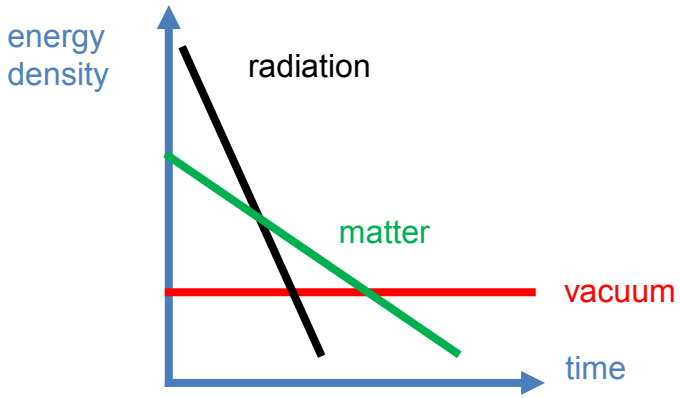
Quantum Vacuum

Pauli (1950): e0(F) + e0(B) = 0

Zel'dovich (1968): e0(F) + e0(B) = Lambda ?=? Dark Energy

only correct if #(F) = #(B) (as in super symmetry; not in SM)
→new particles are needed

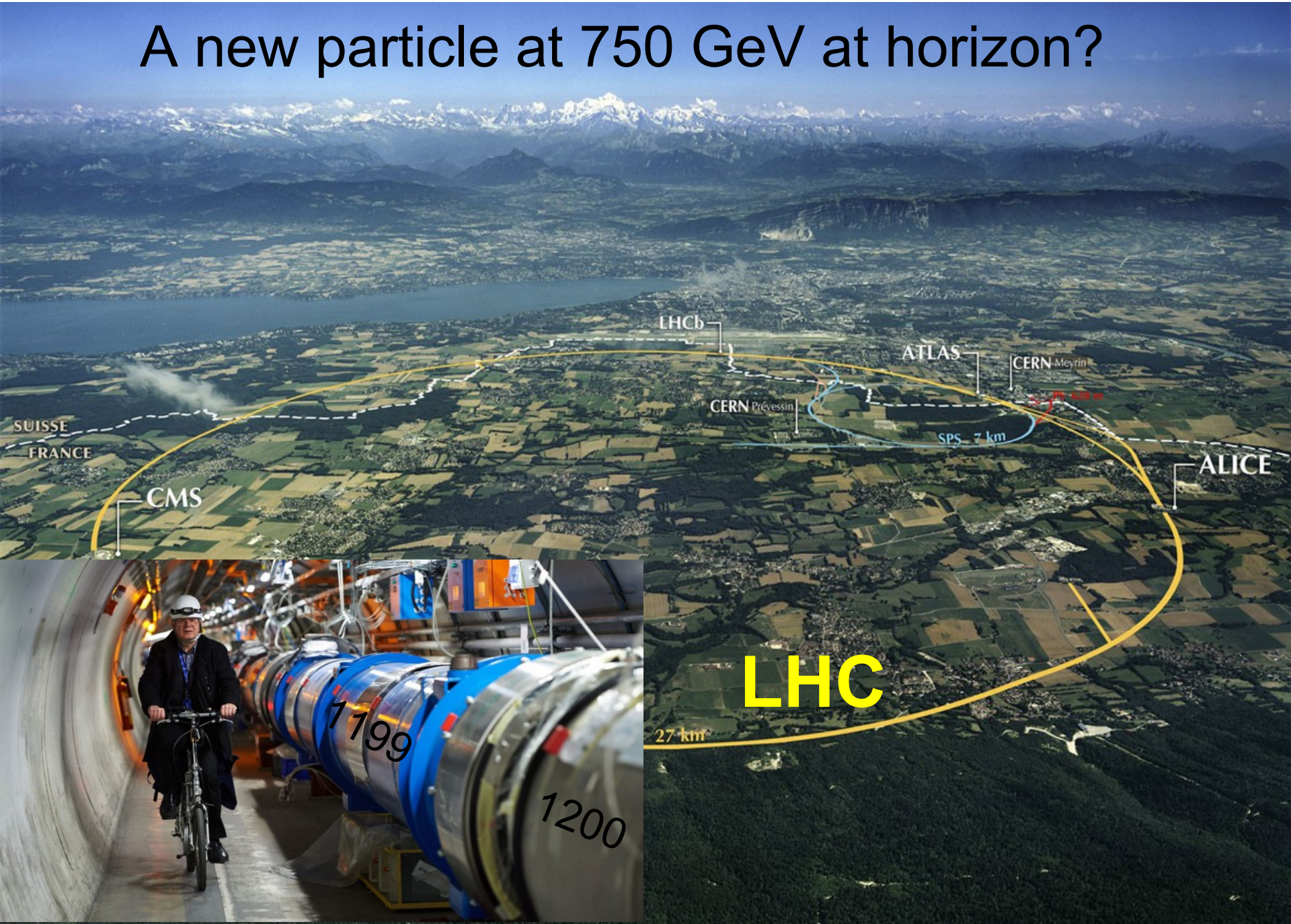
naively: e0 = 10^123 Lambda



Why just now?

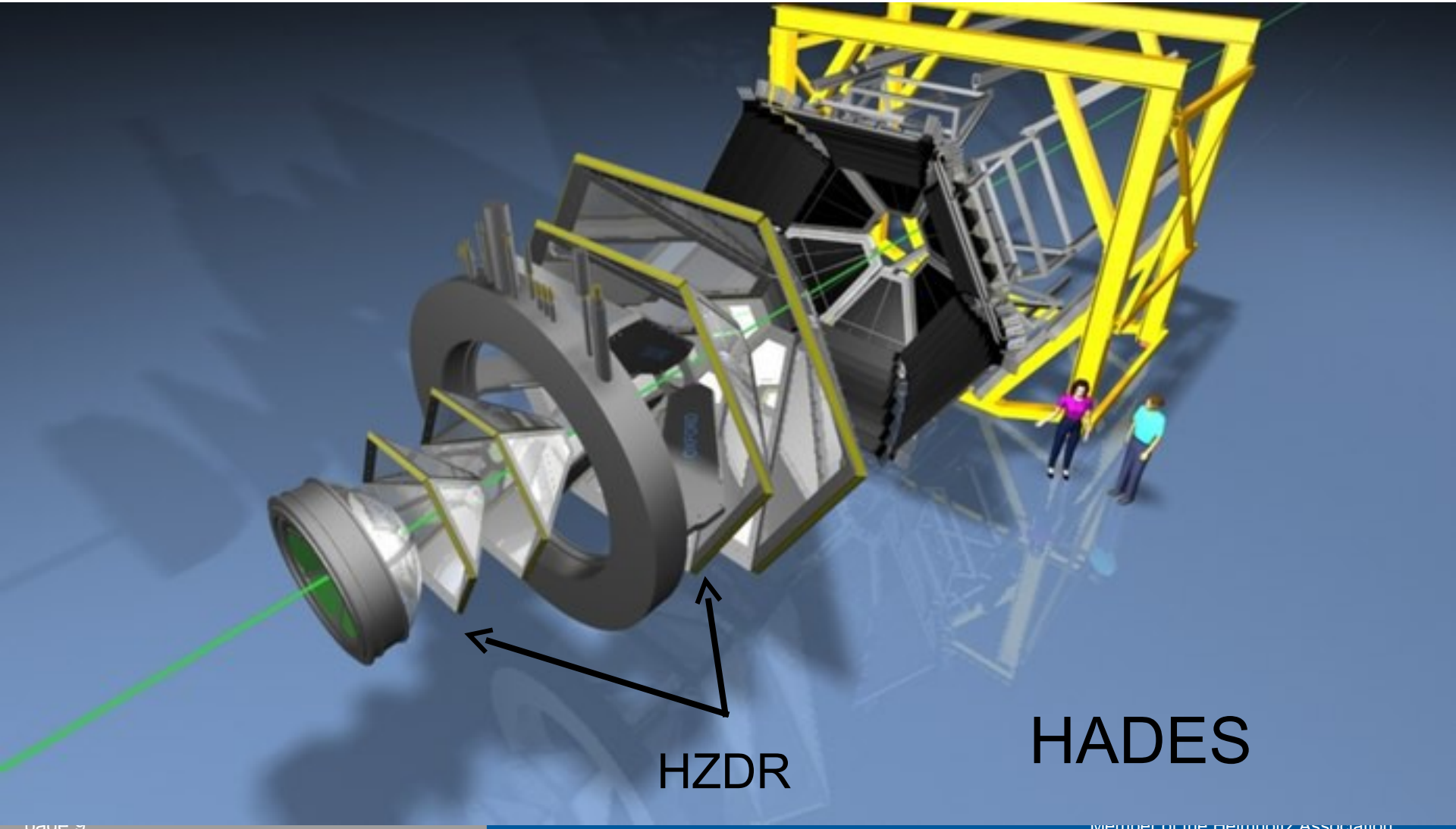
after 13 Gy

A new particle at 750 GeV at horizon?

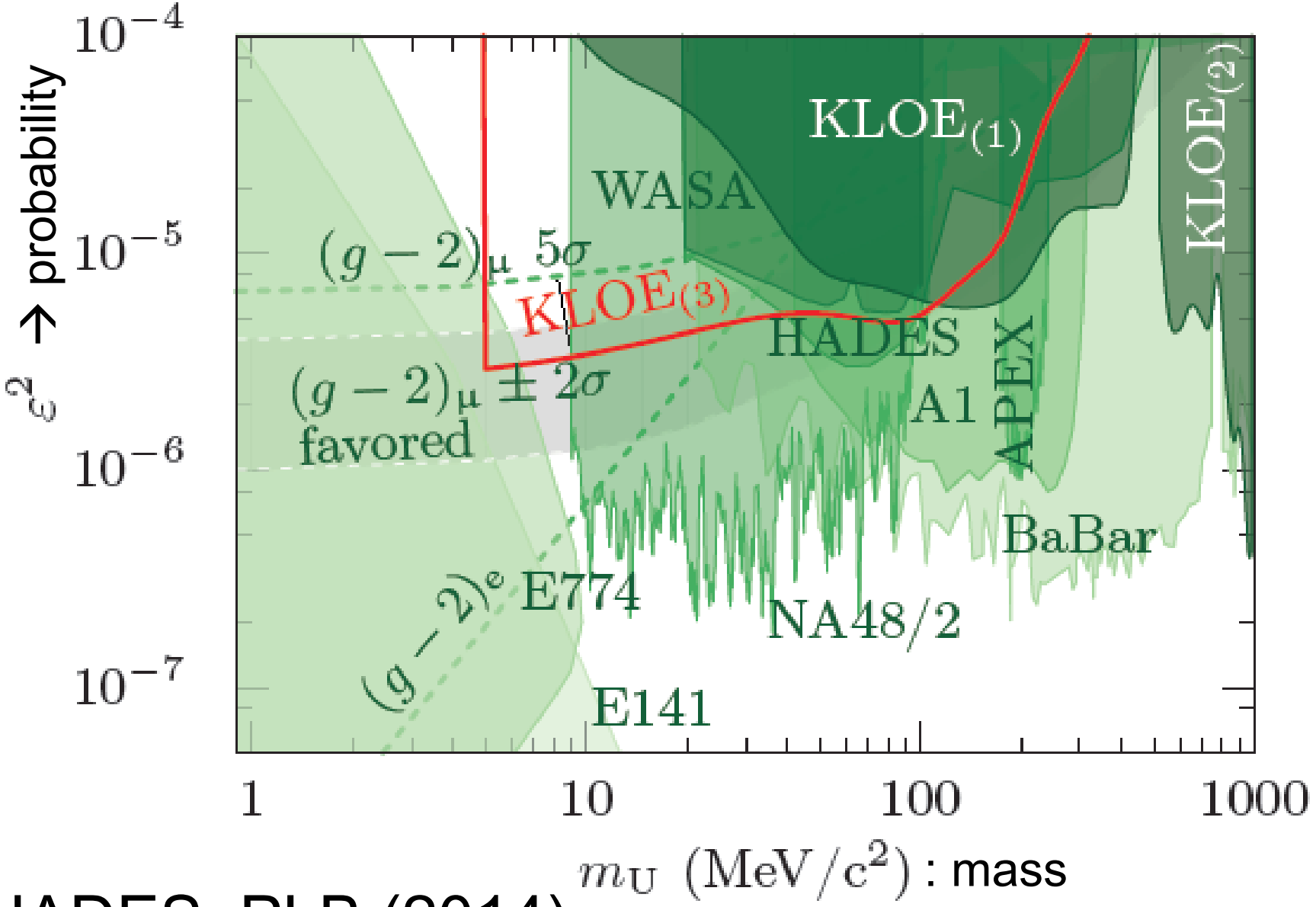


(B) Dark Matter = unknown → where to look for what???

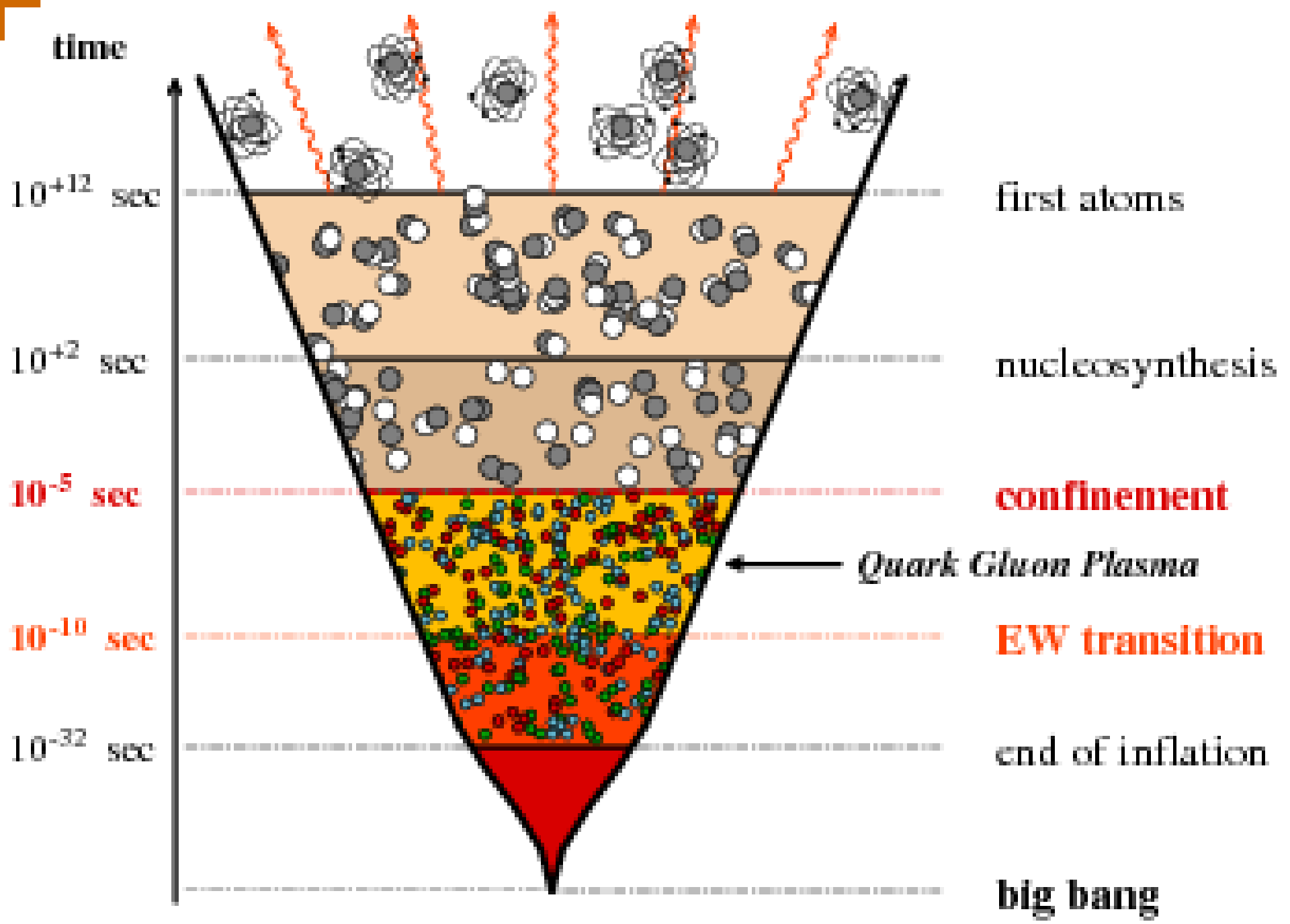
→ testing hypotheses



A dark boson as candidate for Dark Matter



HADES, PLB (2014)


time
10^{+12} sec
10^{+2} sec
10^{-5} sec
10^{-10} sec
10^{-32} sec
first atoms
nucleosynthesis
confinement
Quark Gluon Plasma
EW transition
end of inflation
big bang

Previous Dreams:
History of Universe = Sequence of Phase Transitions

going backward in time:	T
- e+ e- annihilation, BBN:	1 MeV
- QCD deconfinement:	150 MeV
- electroweak symmetry restoration:	150 GeV
- supercooled inflation:	10^15 GeV

Tools (1): Thermodynamics

EoS: $p(T, \mu_{(i)})$

Gibbs-Duham:

$$e + p - Ts - \sum_i \mu_{(i)} n_{(i)} = 0$$

Euler

$$s = \frac{\partial p}{\partial T},\ n_{(i)} = \frac{\partial p}{\partial \mu_{(i)}}$$

susceptibilities:

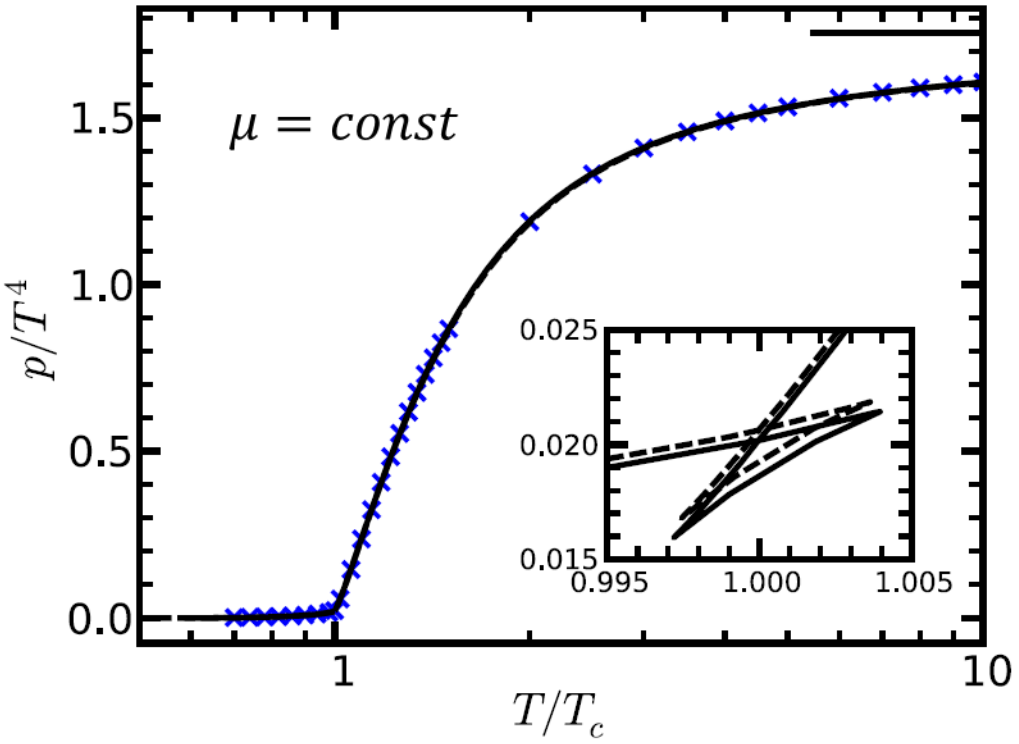
$$\frac{\partial^2 p}{\partial \mu_{(i)} \partial \mu_{(j)}}$$

Taylor expansion (Bielefeld):

$$p = T^4 \sum_n c_n(T) \left(\frac{\mu}{T}\right)^n \qquad c_n(T) = \frac{1}{n!} \frac{\partial^n (p/T^4)}{\partial (\mu/T)^n}$$

First-Order Phase Transition

pressure loop

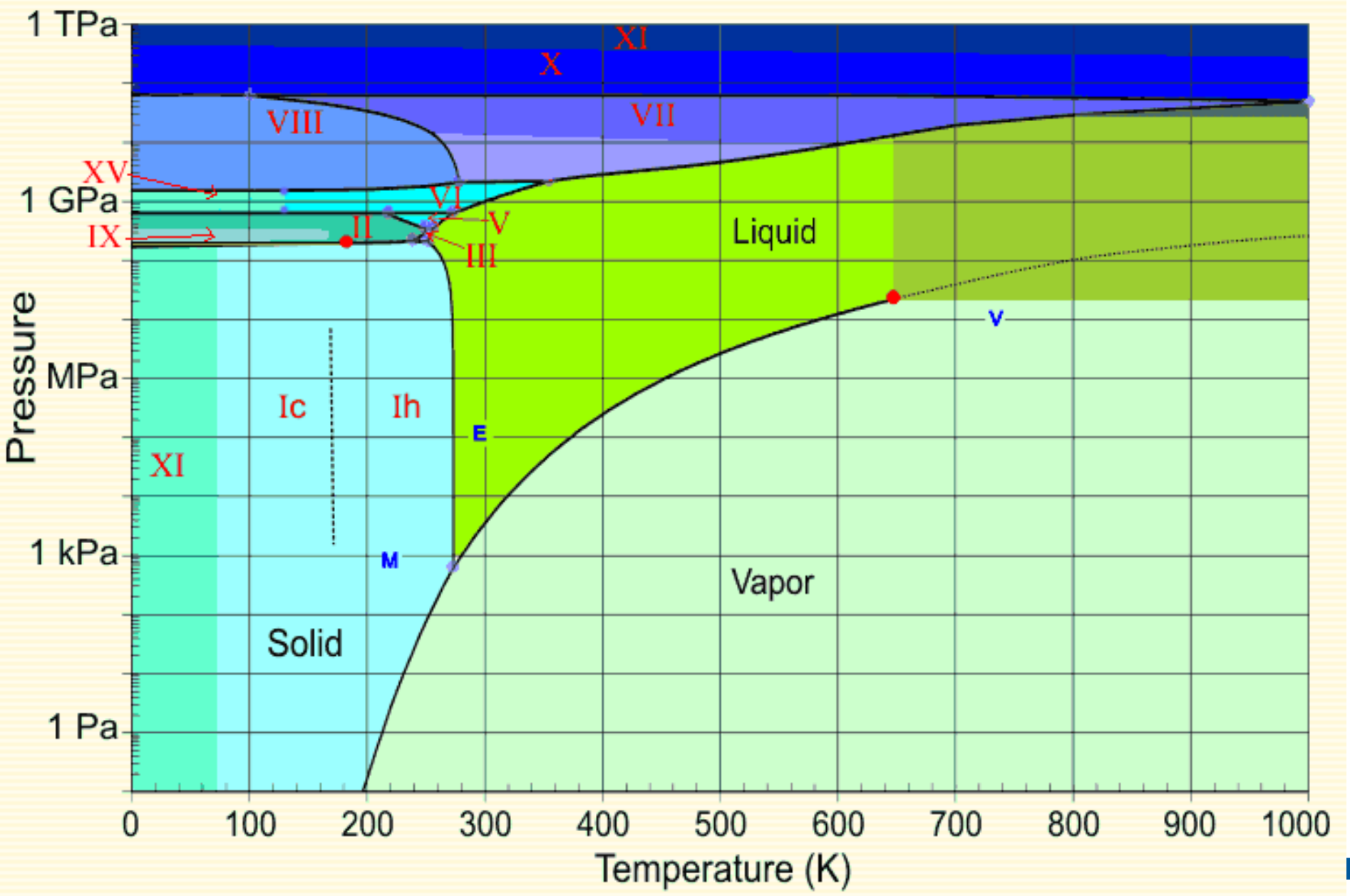


entropy and particle densities from Euler: jumps at Tc
→2-phase mixture, s = x s1 + (1- x) s2, x = volume fraction of phase 1,
n = x n1 + (1-x) n2

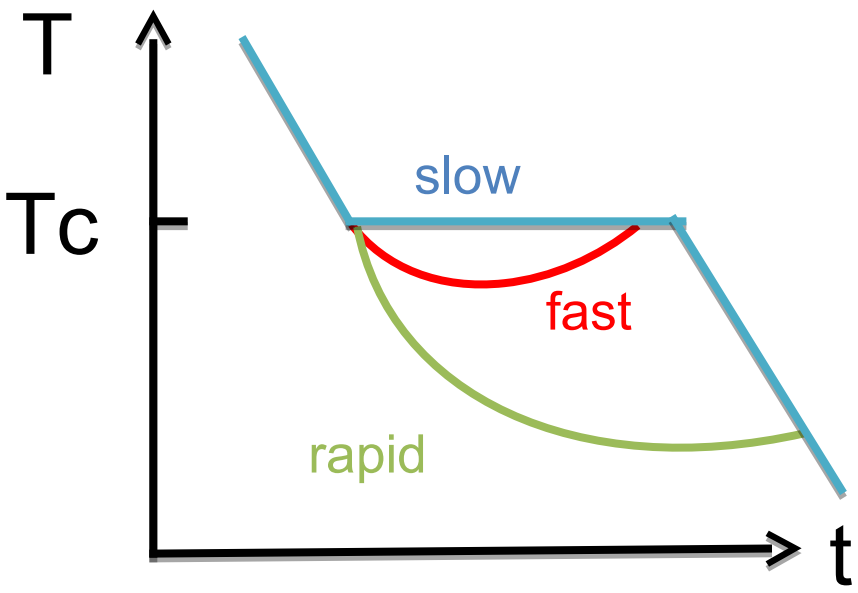
Gibbs criteria: max. entropy → T1 = T2 (thermal equ.)
mu1 = mu2 (chem. equ.)
p1 = p2 (mech. equ.)

1 2

phase diagram of water



Expanding Systems



release of latent heat

slow: near equilibrium
fast: super cooling + reheating
rapid: hyper cooling,
super cooling only

expansion dynamics → Einstein eqs.
vs. bubble creation (nucleation) and growth and coalescence

25. November 1915

Einstein gibt seine Allgemeine Relativitätstheorie (V4) bekannt

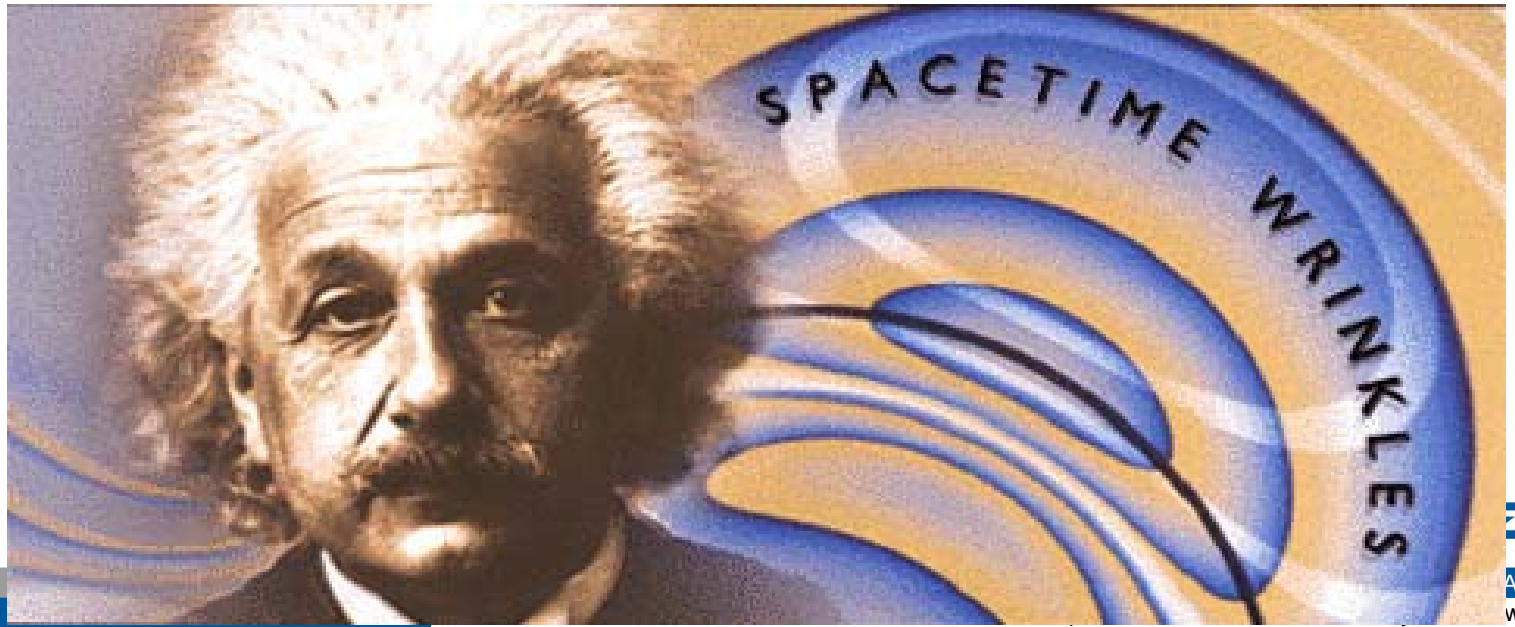
Schwerkraft = Verbiegung von Raum und Zeit

$$4 = 1 + 3$$

nach vielen Irrungen & Verwirrungen

Die Serie meiner Gravitationsarbeiten
Ist eine Kette von Irrwegen

Einstein-Krimi und Duell mit Hilbert



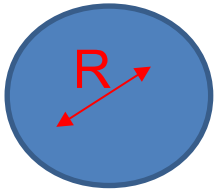
Tools (2): Friedmann Eqs.

Einstein & cosmological principle → Friedmann eqs.

EoS

$$\dot{e} = -3\mathcal{C}(e+p)\sqrt{e}$$

$$\dot{R} = \mathcal{C}R\sqrt{e}$$



$$\mu_B <<< T$$

or n R^3 = const.

included in e, p

flat U. → $\epsilon,\ \Lambda = 0$

$$M_{Pl} = \sqrt{\frac{\hbar c}{G_N}}$$

$$\mathcal{C} = \frac{1}{M_{Pl}}\sqrt{\frac{8\pi}{3}}$$

$$p(e) = p_{e.w.} + p_{QCD} + p_?$$

$$p = d_{eff}\frac{\pi^2}{90}T^4$$

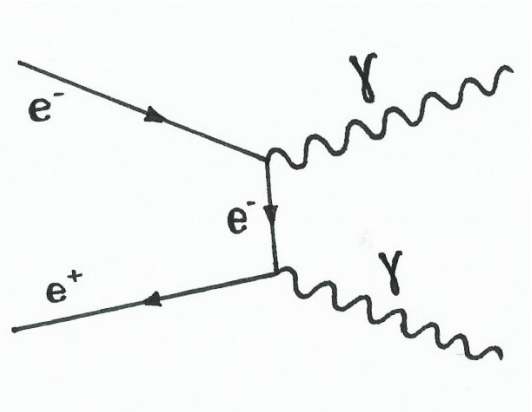
d_γ	d_ν	$d_{e^\pm}$	$d_{\mu^\pm}$	d_{eff}
2	$\frac{7}{8}6$	$\frac{7}{8}4$	$\frac{7}{8}4$	14

$$e = d_{eff}\frac{\pi^2}{30}T^4$$

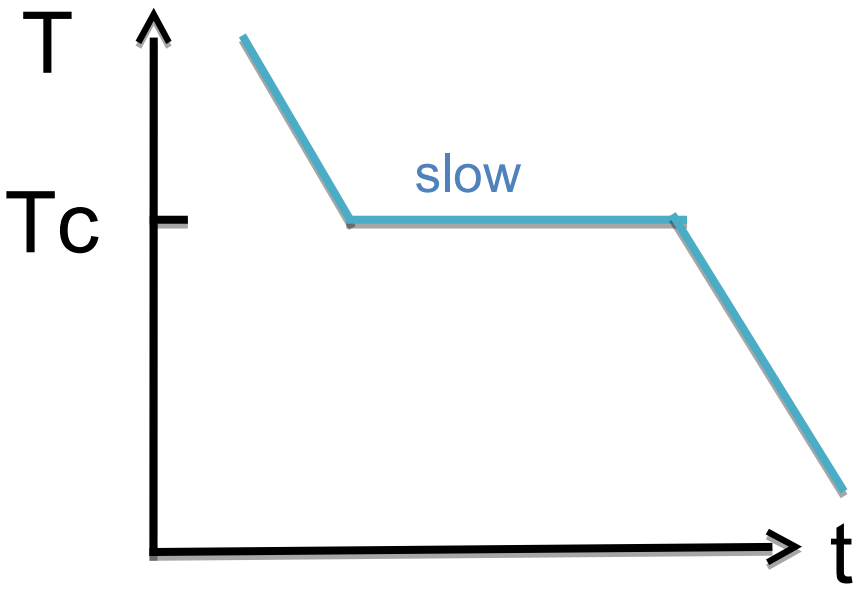
d_g	d_q	d_{eff}
16	$\frac{7}{8}3_c3_f2_s2_c$	47

1. e+ e- annihilation: not a PT

QED = theory of e+ e- photons



?



latent heat from e+ e- subsystem

Big Bang e+ e- Annihilation

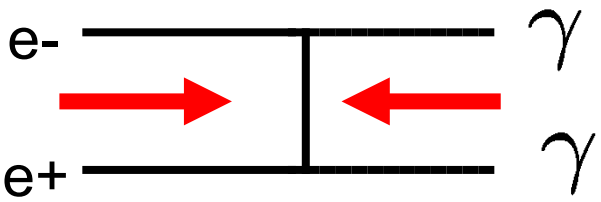
t ~ 0.3 s: neutrino decoupling

$$\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{1/3}$$

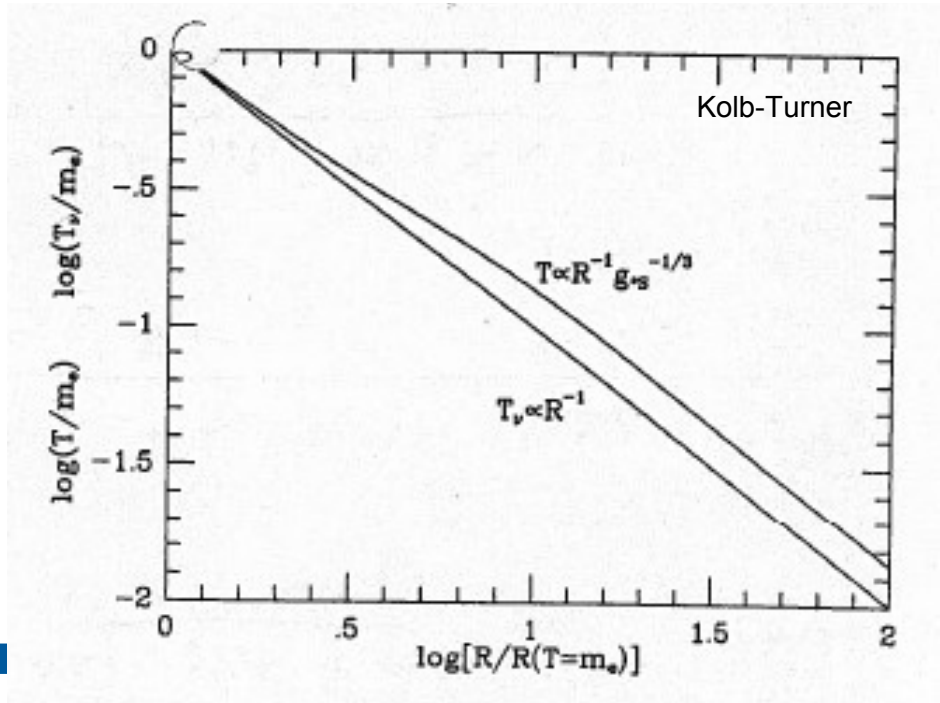
$$n_{e-} = n_{e+} + \Delta$$

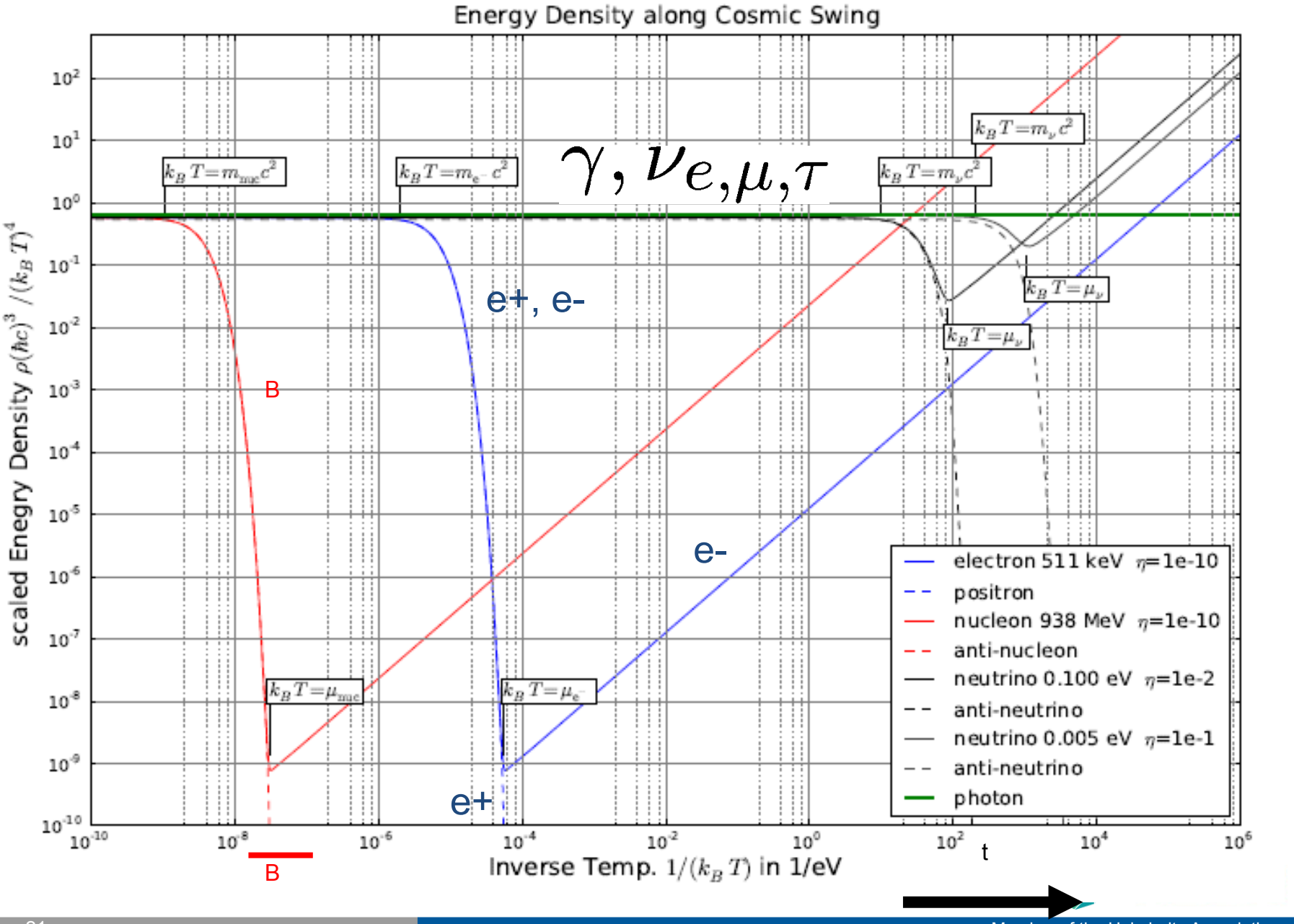
$$\frac{\Delta}{n_{e+}} = \mathcal{O}(10^{-9})$$

t ~ 15 s, T ~ 3 x 10^9 K: e+ e- annhilation

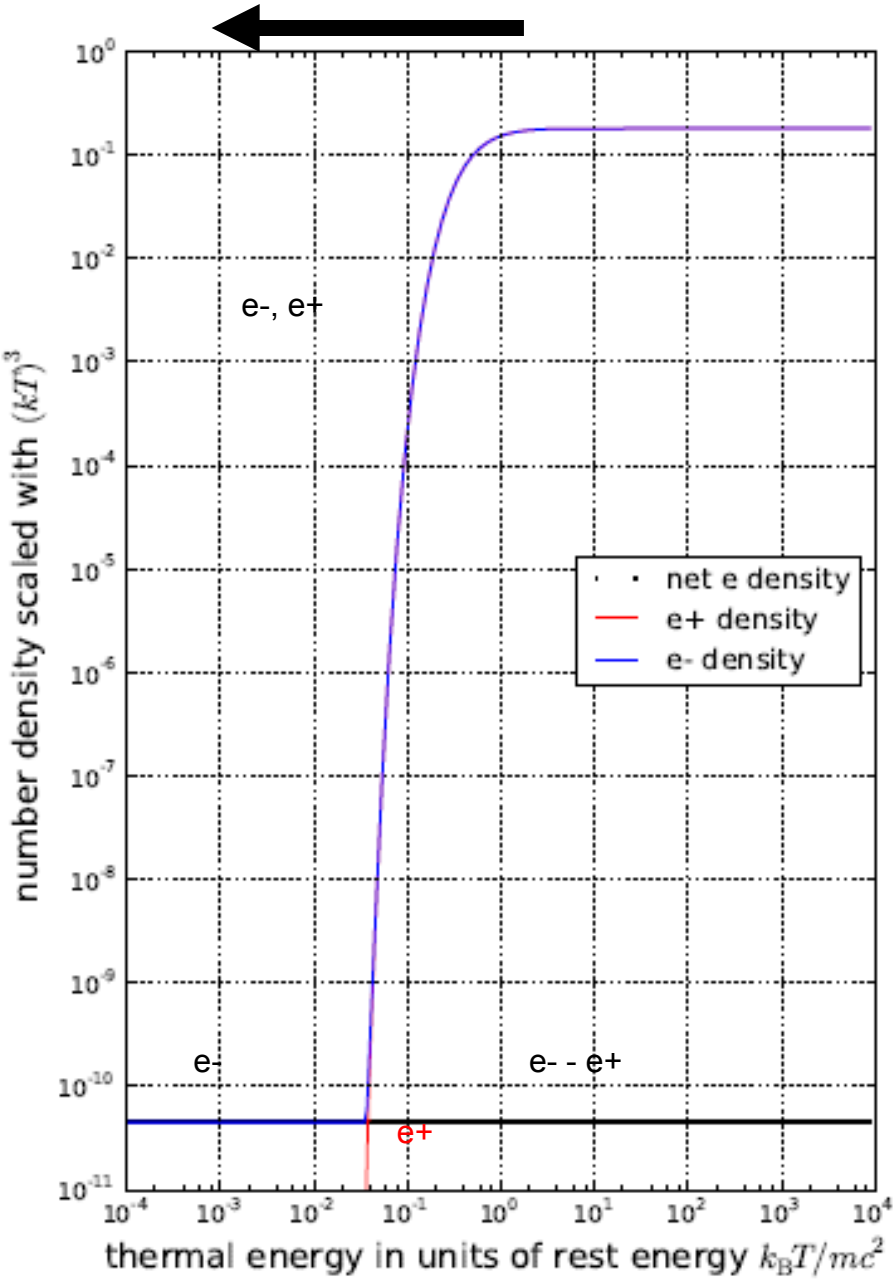


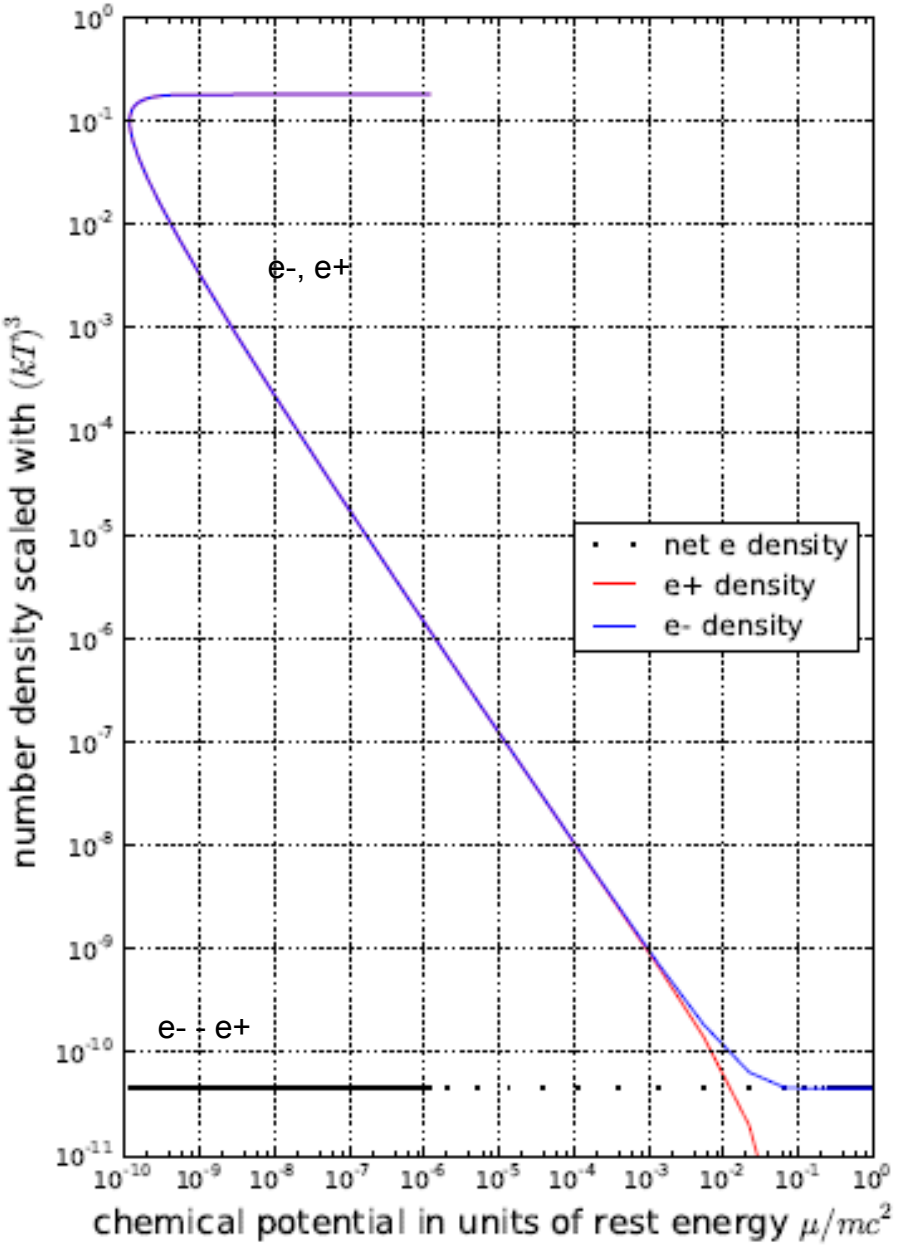
disappearance of last antimatter in universe
only excess electrons survive
„reheating“ of photons, nucleons




Energy Density along Cosmic Swing
$\gamma, \nu e, \mu, \tau$
$k_B T = m_{mc} c^2$
$k_B T = m_{e^-} c^2$
$k_B T = m_\nu c^2$
$k_B T = m_\nu c^2$
$k_B T = \mu_\nu$
$k_B T = \mu_\nu$
$k_B T = \mu_{mc}$
$k_B T = \mu_{e^-}$
e+, e-
e-
e+
B
B
electron 511 keV η=1e-10
positron
nucleon 938 MeV η=1e-10
anti-nucleon
neutrino 0.100 eV η=1e-2
anti-neutrino
neutrino 0.005 eV η=1e-1
anti-neutrino
photon
scaled Enegry Density $\rho(\hbar c)^3/(k_B T)^4$
Inverse Temp. $1/(k_B T)$ in 1/eV
t

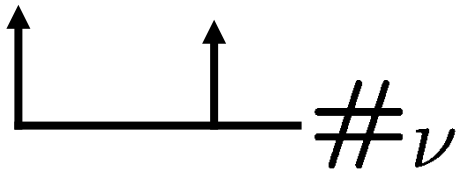
Disapparence of Anti-Matter (2)

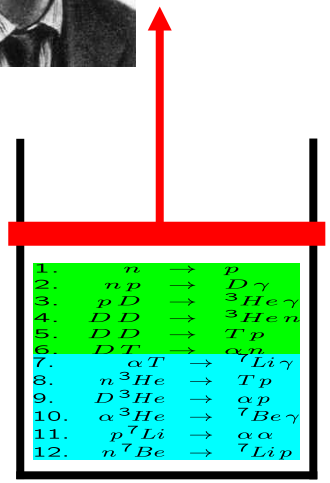




The Universe as Reactor

Friedmann: T(t) from e_{tot}, p_{tot}





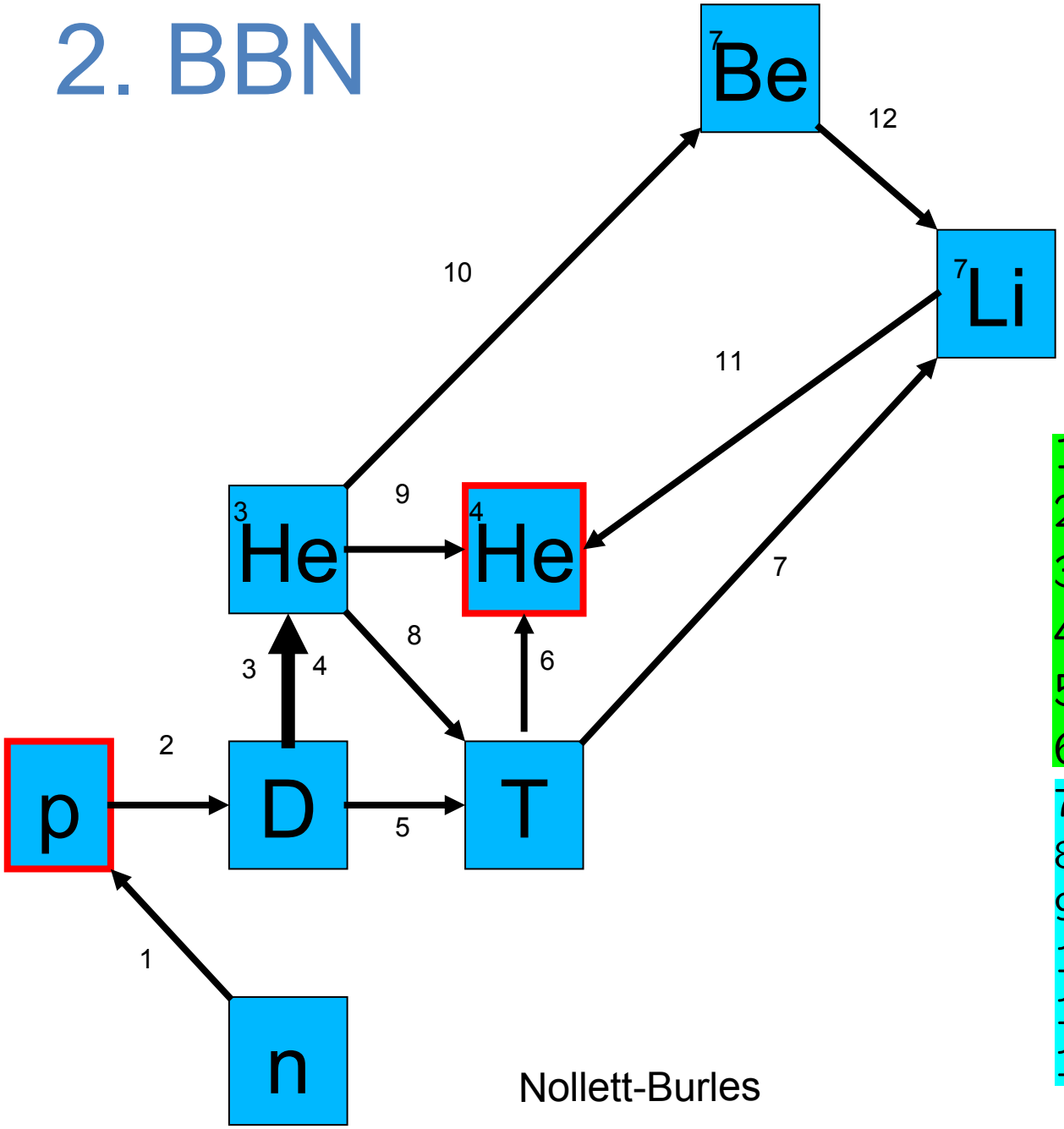
$$p^+ + e^- \rightarrow n + \nu_e$$

only destruction after BNN

D: baryometer

4He: chronometer

2. BBN



Nollett-Burles

1. $n \rightarrow p$
2. $n\,p \rightarrow D\,\gamma$
3. $p\,D \rightarrow {}^3He\,\gamma$
4. $D\,D \rightarrow {}^3He\,n$
5. $D\,D \rightarrow T\,p$
6. $D\,T \rightarrow \alpha\,n$

7. $\alpha\,T \rightarrow {}^7Li\,\gamma$
8. $n\,{}^3He \rightarrow T\,p$
9. $D\,{}^3He \rightarrow \alpha\,p$
10. $\alpha\,{}^3He \rightarrow {}^7Be\,\gamma$
11. $p\,{}^7Li \rightarrow \alpha\,\alpha$
12. $n\,{}^7Be \rightarrow {}^7Li\,p$

Rate Equations for 2 → 2 Processes

$$\dot{Y}_i = \sum_{kl,x} Y_k Y_l < \sigma v >_{kl \to ix} - \sum_{k,jx} Y_i Y_k < \sigma v >_{ik \to jx}$$

rates (T)

Init. Conds.: earlier equilibrium values

integrate up to freeze-out

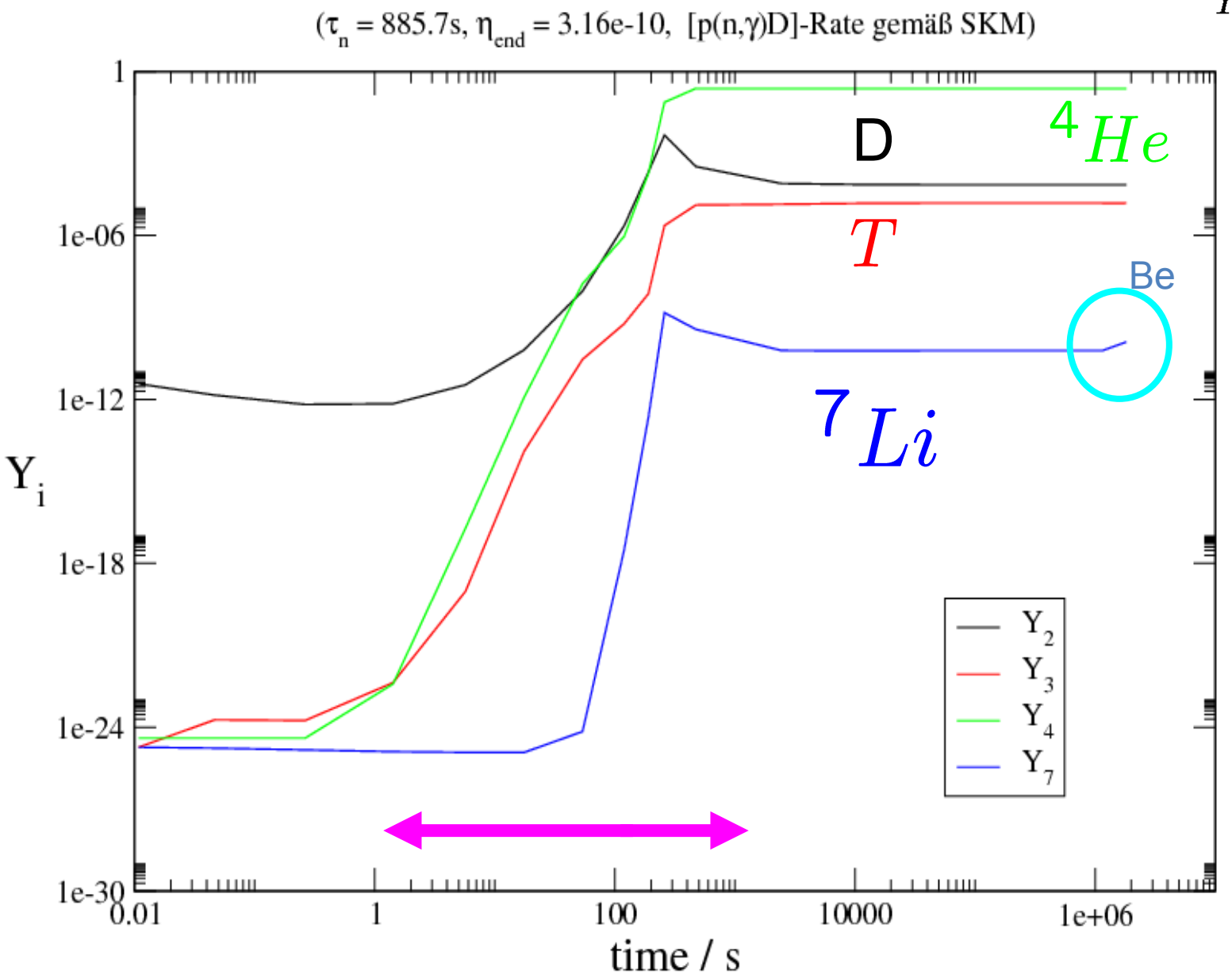
add decays

T(t)

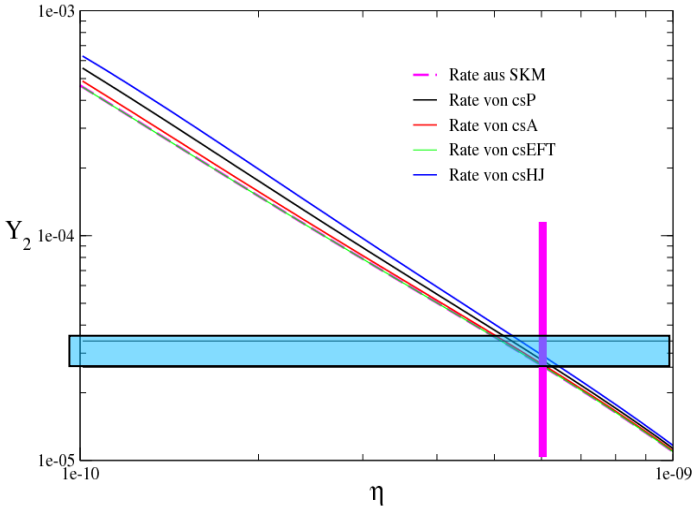
Evolution of Abundances

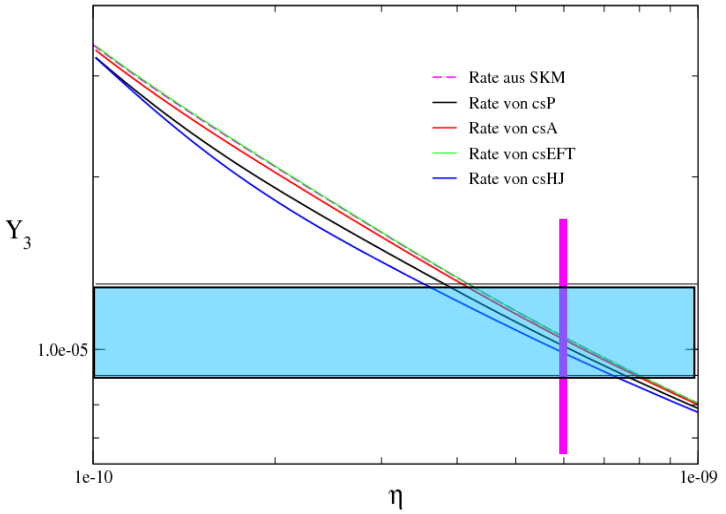
$Y_i = X_i / A_i$

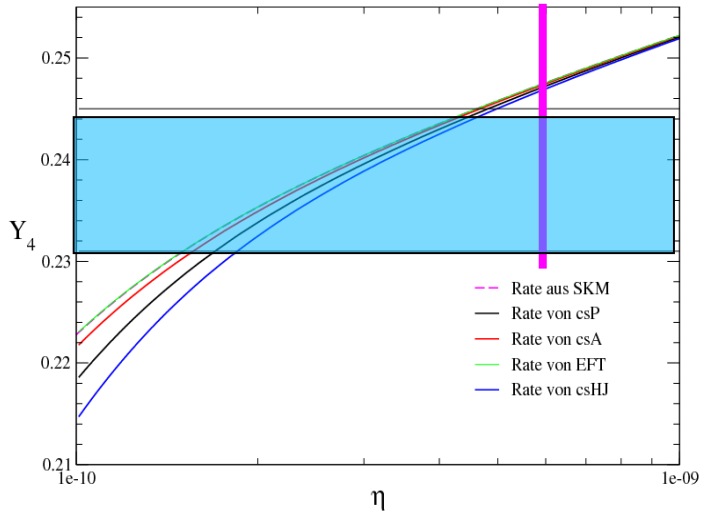
mass fraction

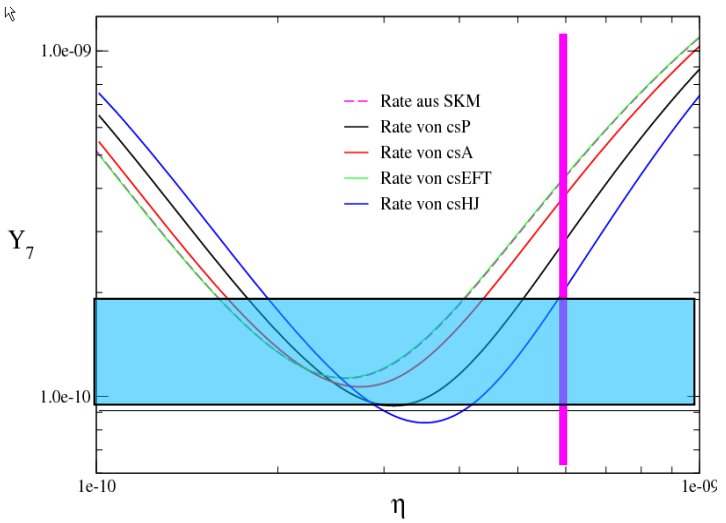


Cosmic Concordance?





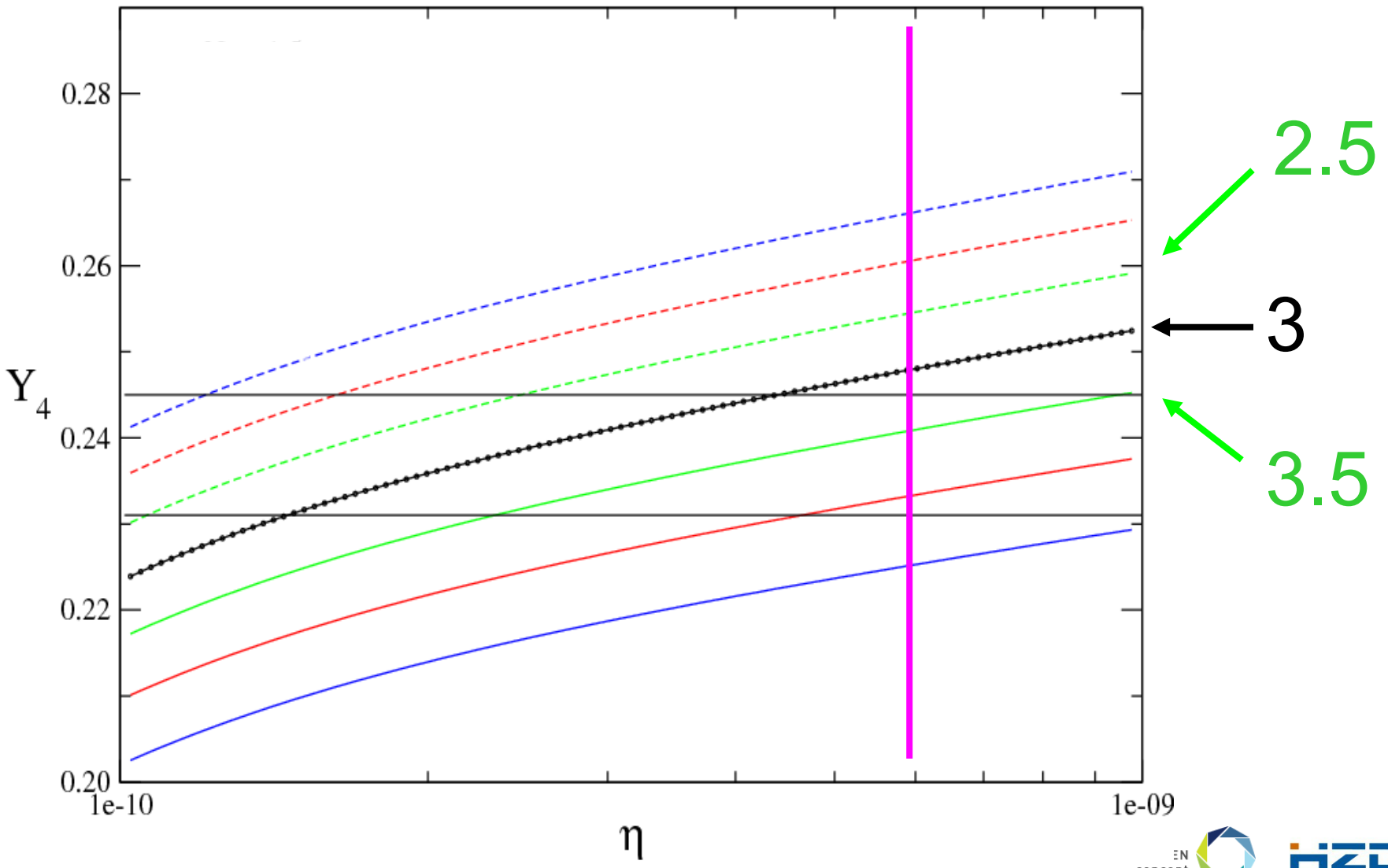




→new physics beyond Standard Model?

Xdimensions, more neutrinos, axions, SUSY particles, G(t), ...

Number of Light Neutrinos

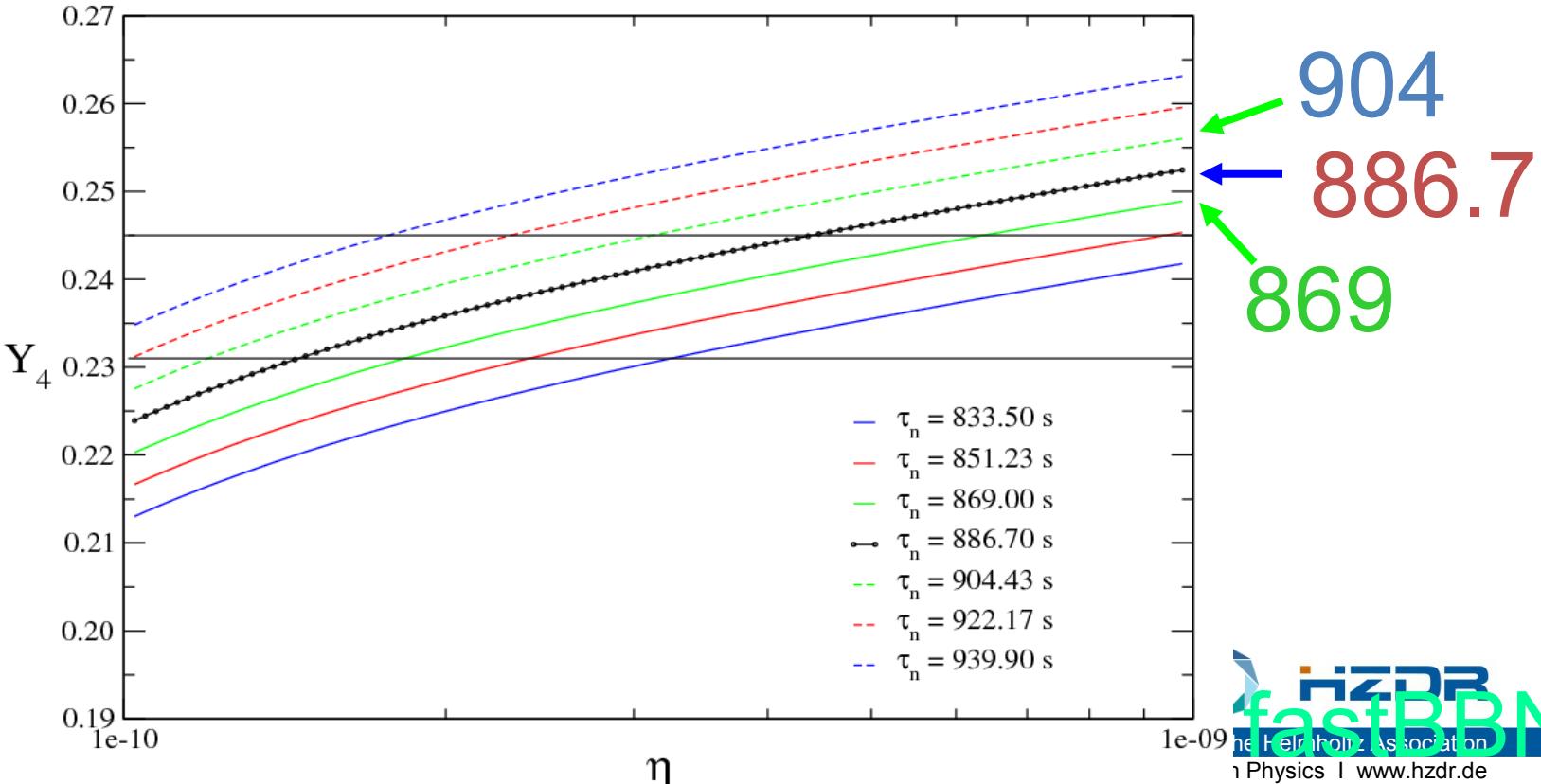


Neutron Life Time

$$n \rightarrow p^{+} e^{-} \nu_e$$

nearly all n are in 4He: Y(4He) depends τ_n and also on $\#_\nu$

(other abundances are robust)



fasfBBN

Helmholtz Association

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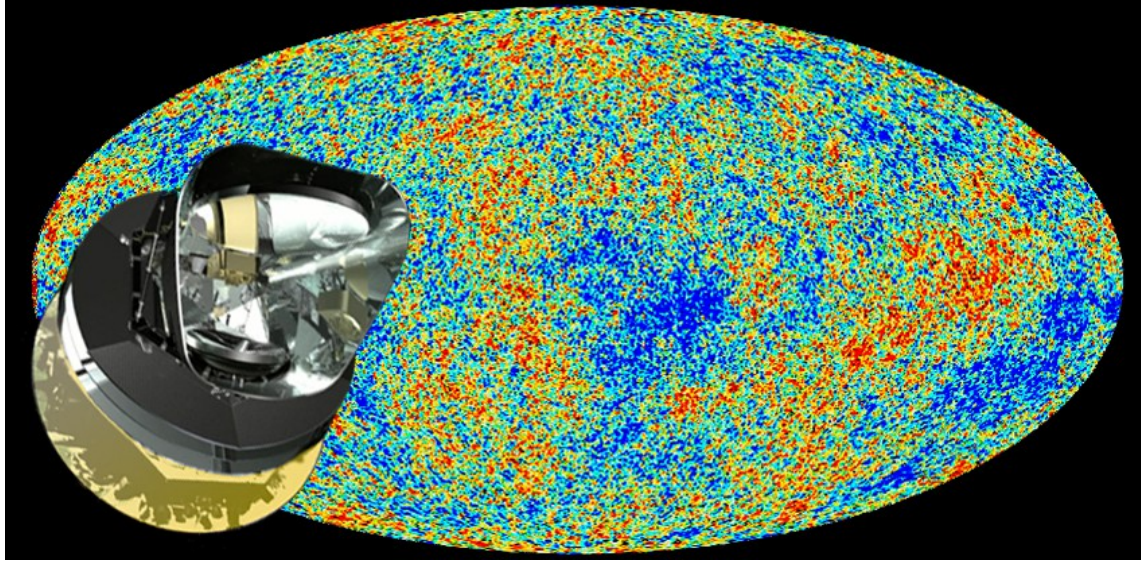
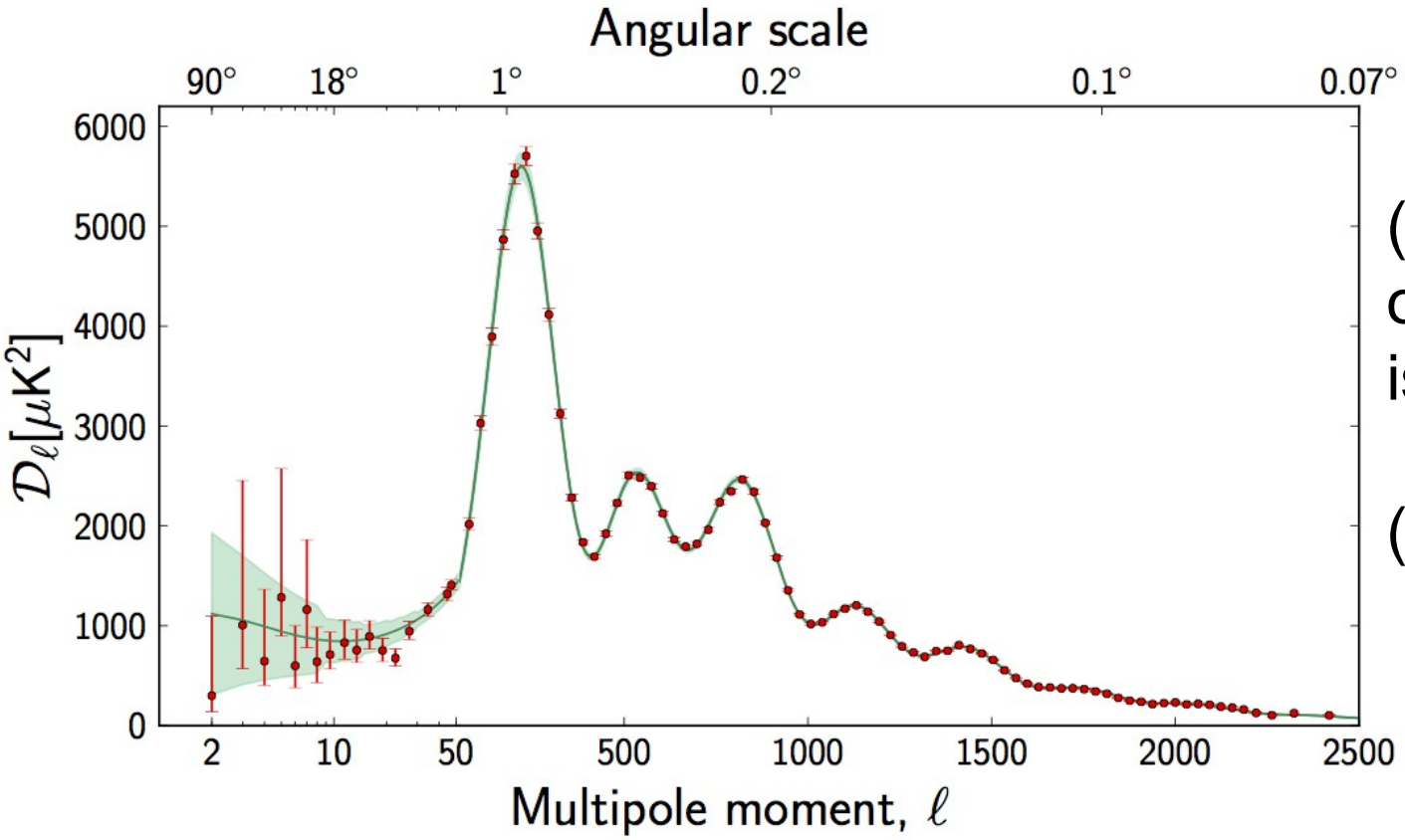
Planck era

sub-% fluctuations of 2.7 K CMB



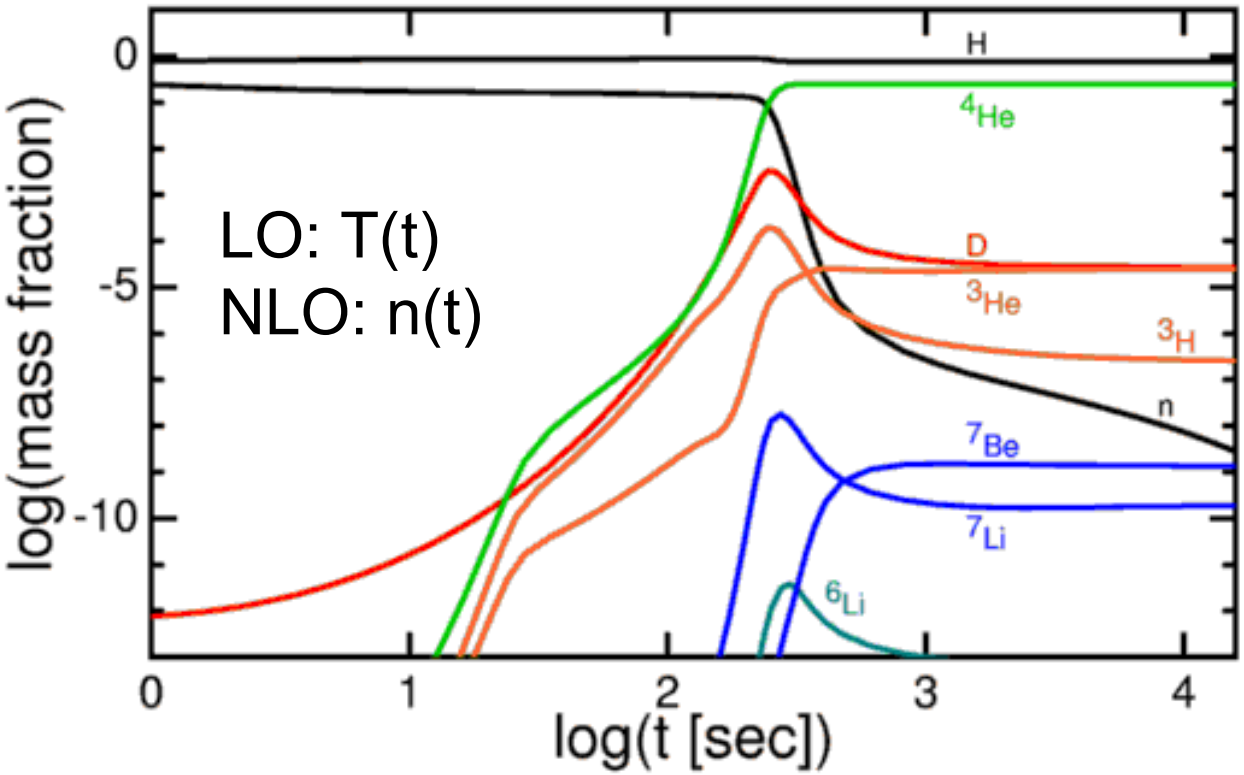


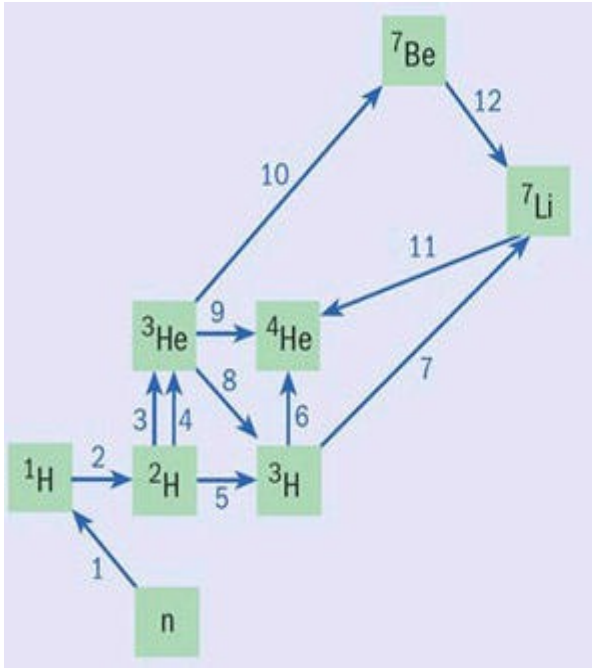
(i) expansion of Universe is accelerated

(ii) $\Omega_b\, h^2 = 0.02205$

= baryon density

Too many details in Big Bang Nucleosynthesis?

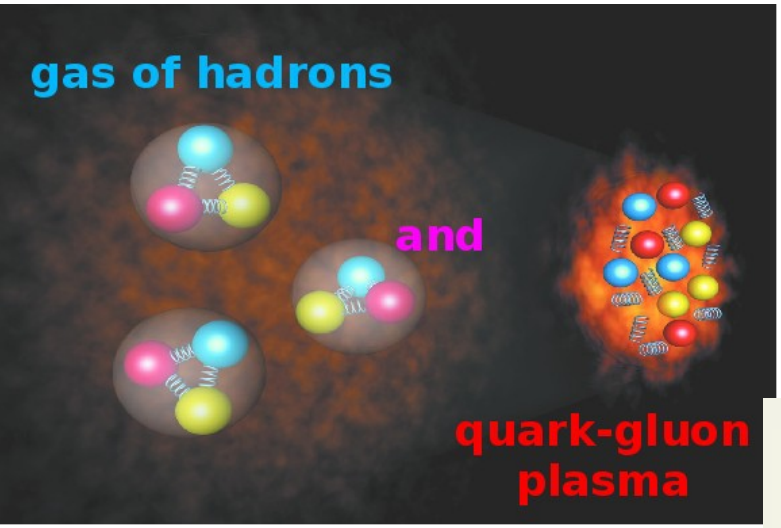


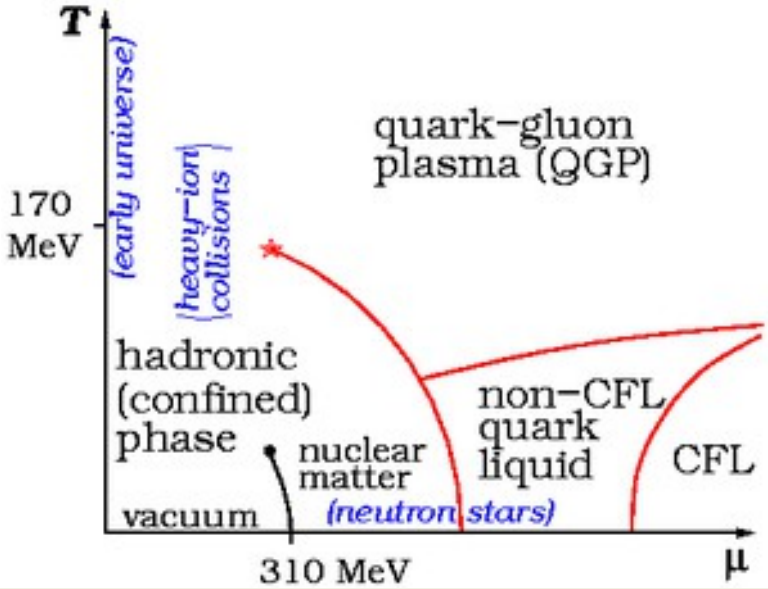


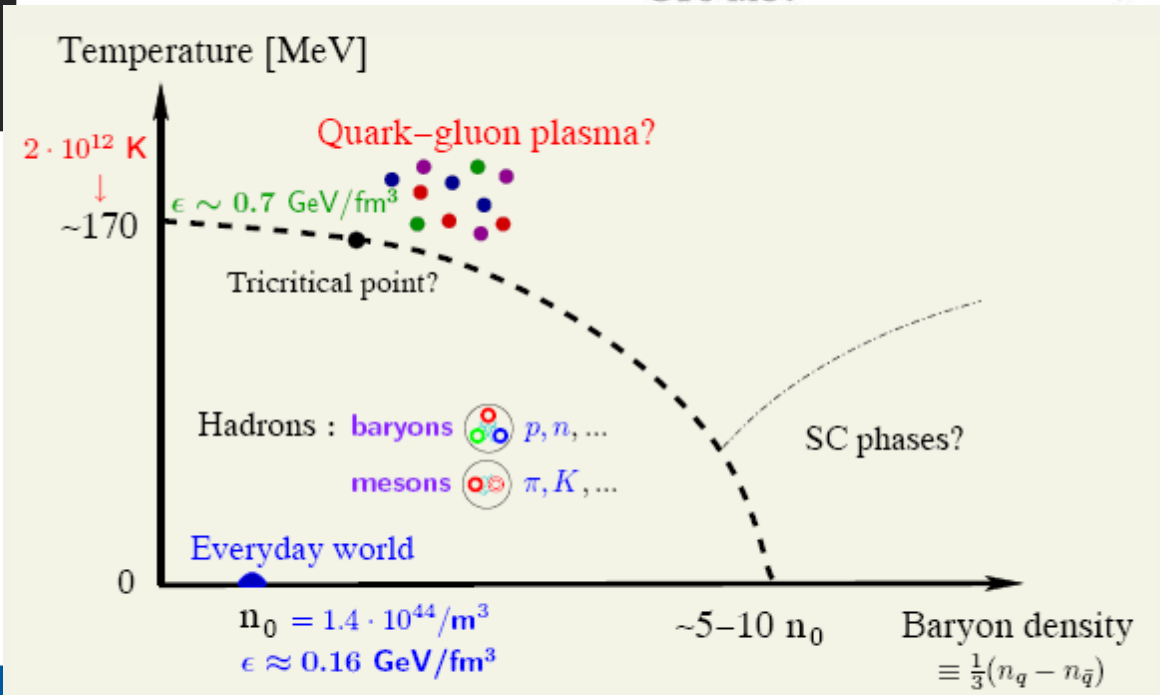
tension of primordial deuterium fraction and Planck data (ii)
→ LUNA/Felsenkeller: precision data of $d(p,\gamma)$ 3He

3. Confinement Transition

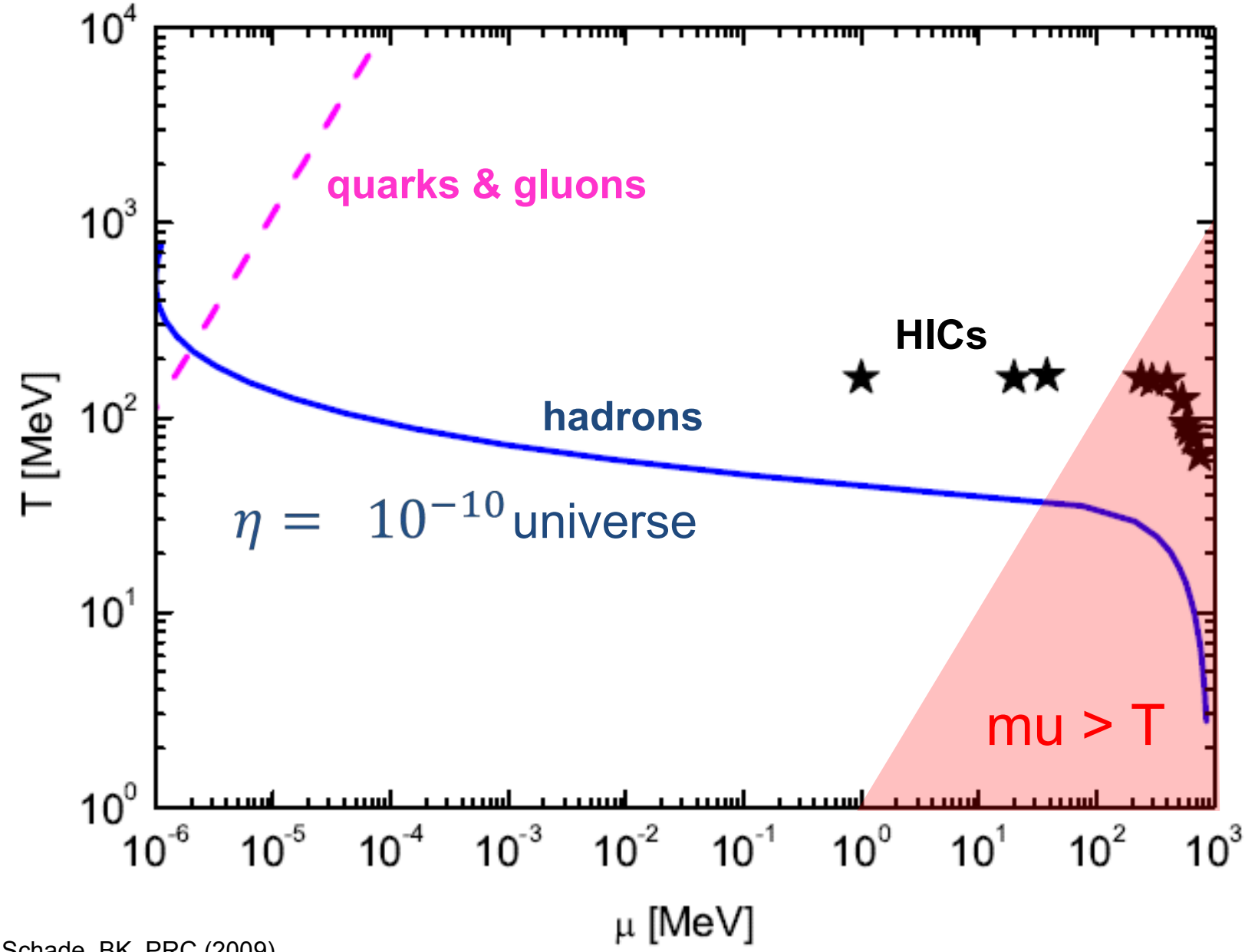
QCD = theory of hadrons







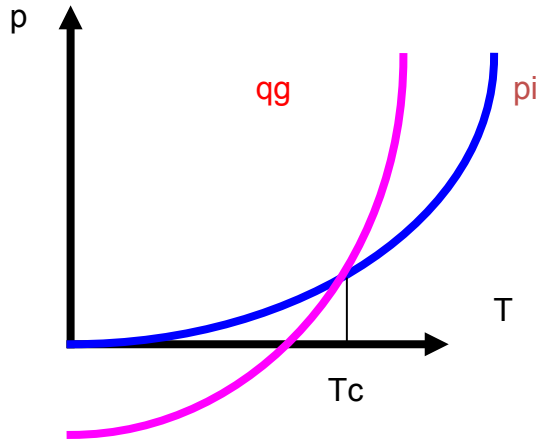
Cosmic Swing: from estimates to precision



stars: chem. freeze-out ABC
(Andronic, Braun-Munzinger, Cleymans et al.)

Schade, BK, PRC (2009)

Bag Model EoS: too simple



Gibbs criteria for phase equilibrium
(maximum entropy)

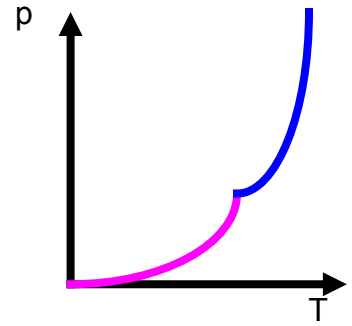
p_qg = p_pi
T_qg = T_pi
mu_qg=mu_pi

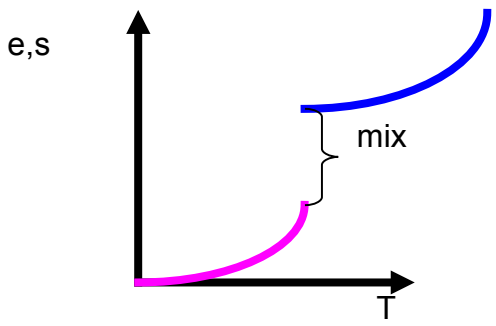
-p = free energy

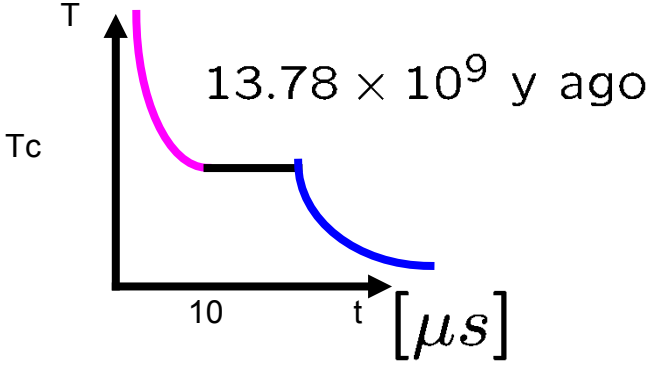
1st order pt
(nucleation,
bubbles etc.)

$$p_\pi = 3\frac{\pi^2}{90}T^4$$

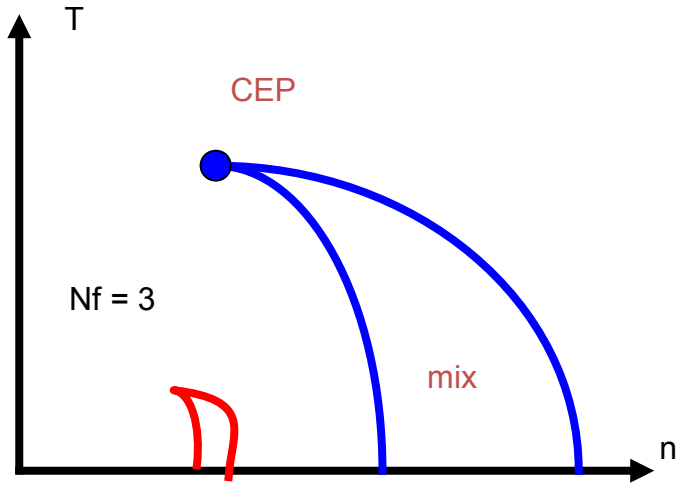
$$p_{gq} = 30\frac{\pi^2}{90}T^4 - B,\ B = (235\mathrm{MeV})^4$$

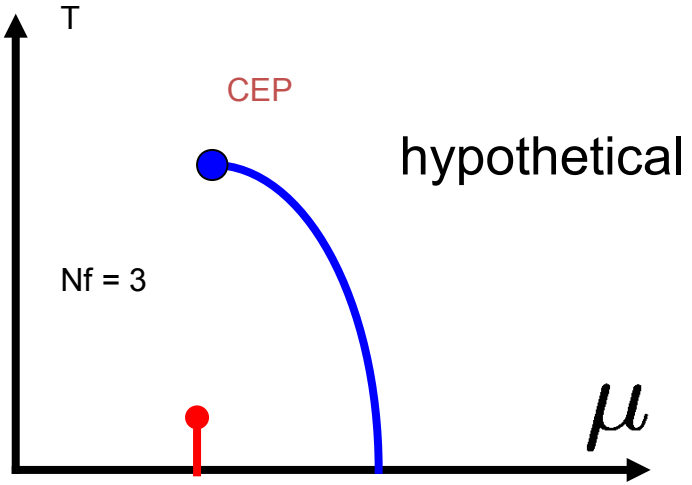


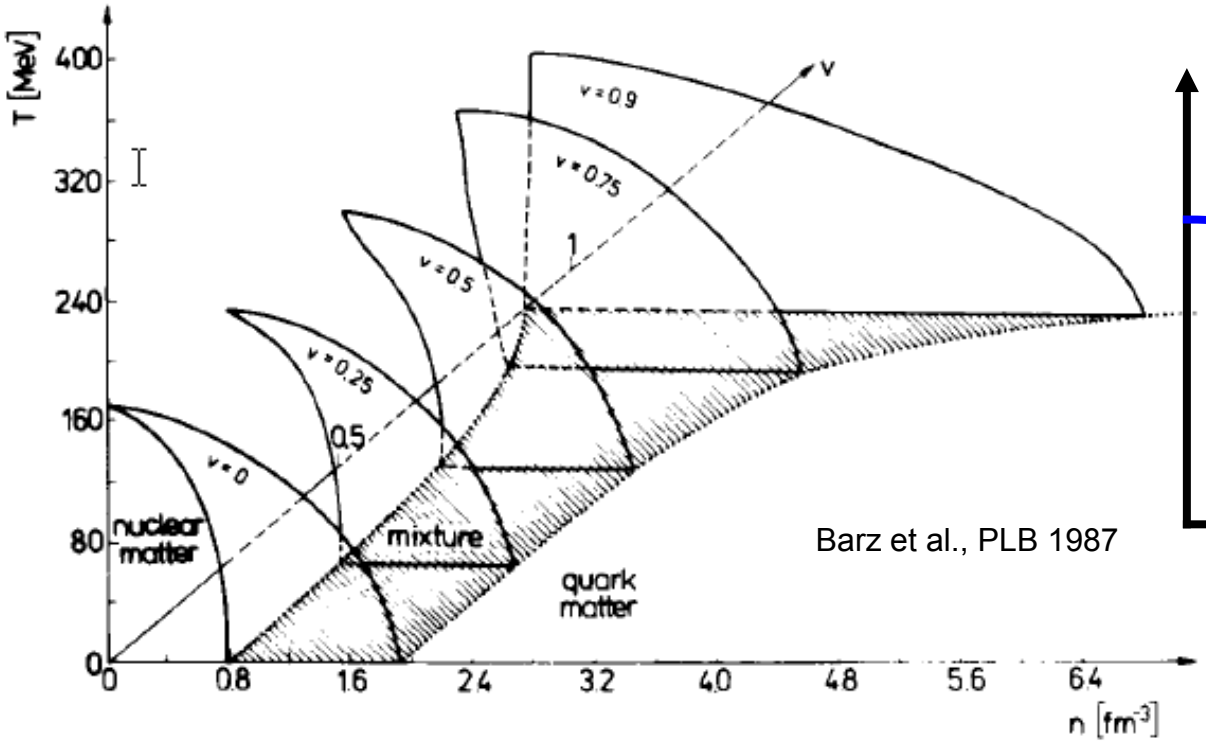




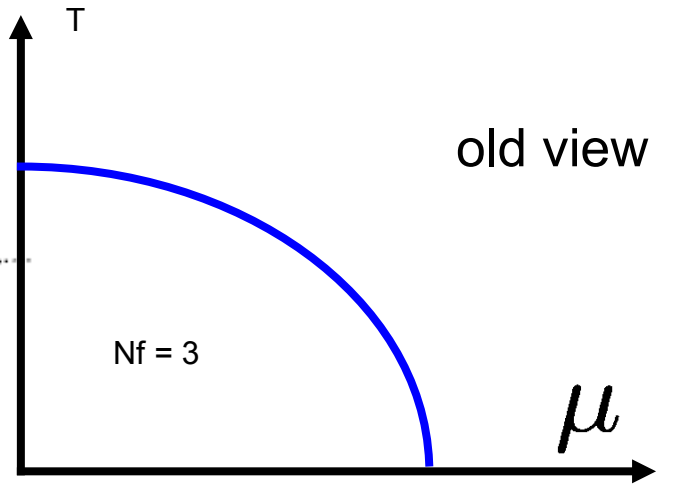
Phase Diagram of SIM



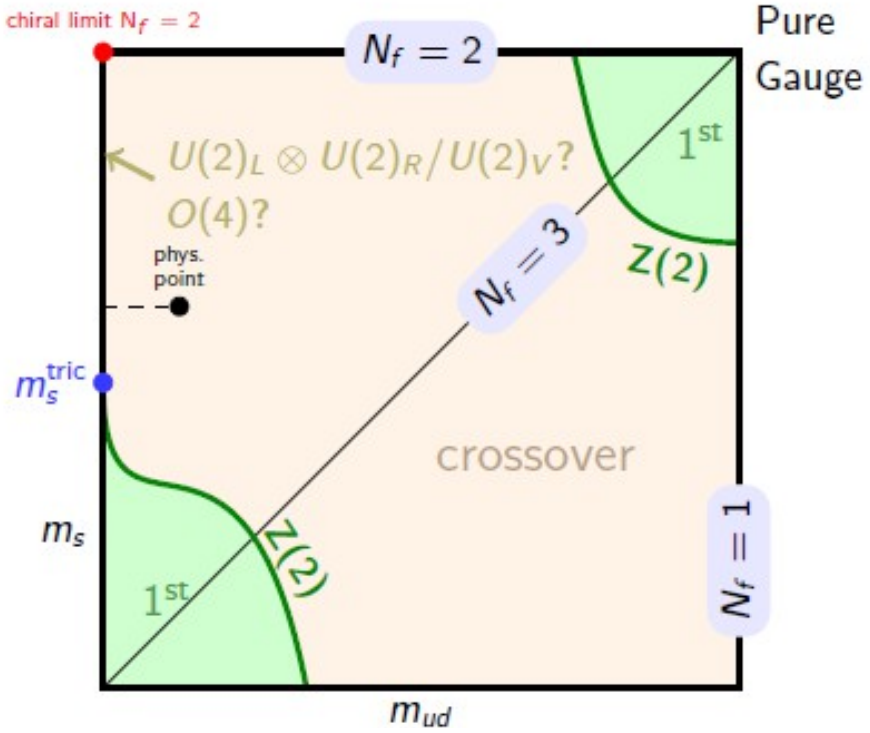


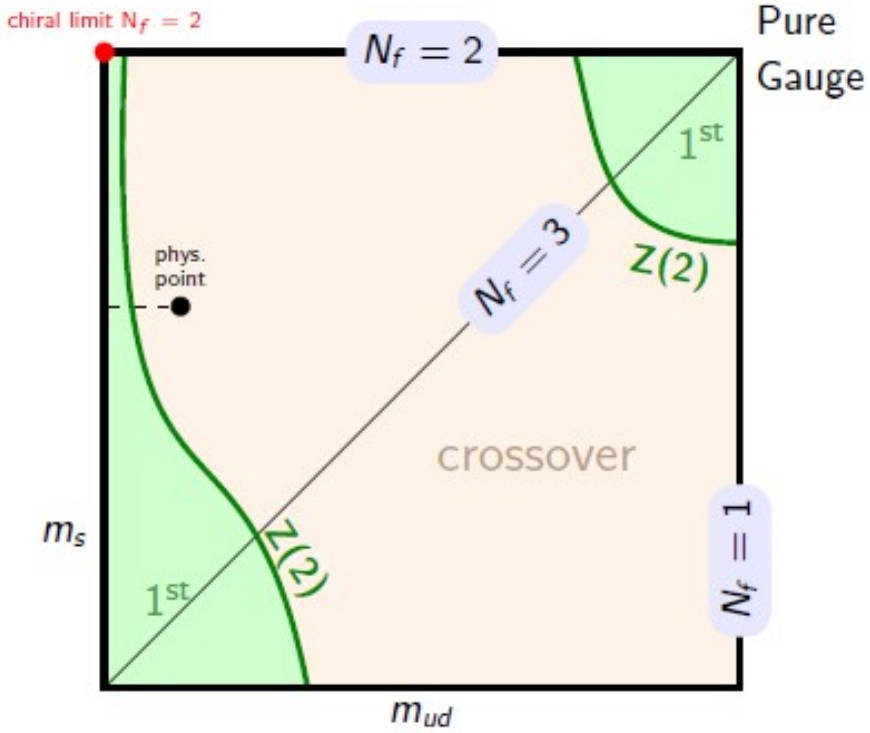


Barz et al., PLB 1987

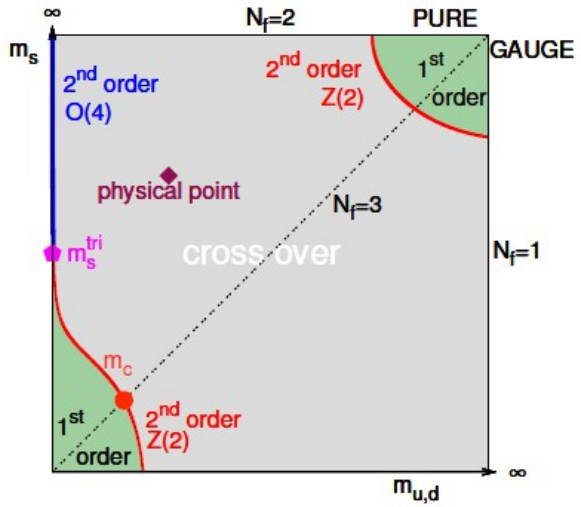


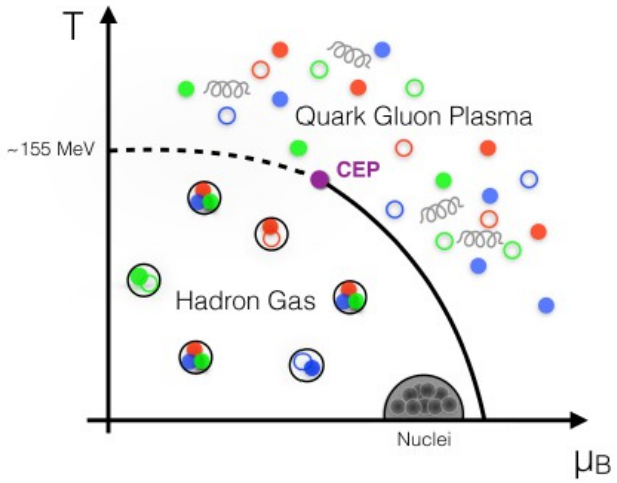
Columbia Plots (mu = 0)





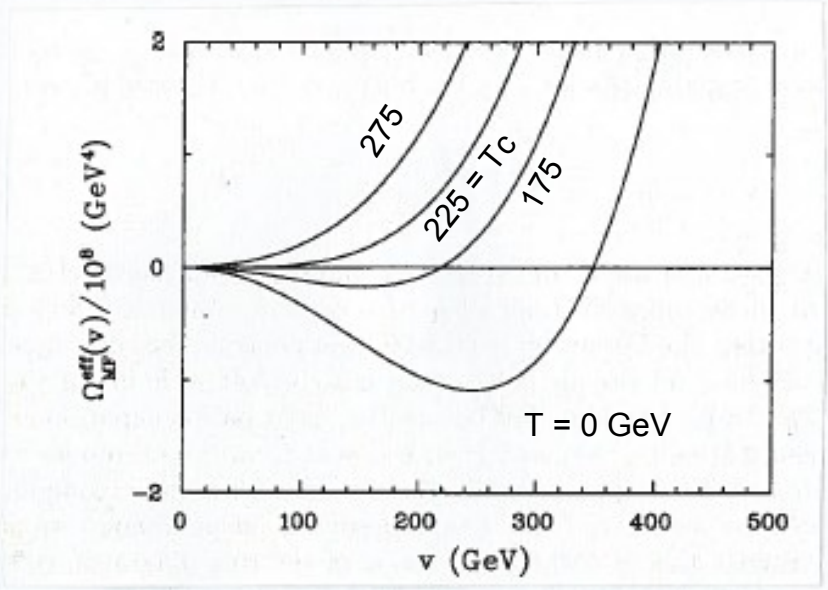
from Pinke, Philipsen





from Ding, Karsch, Mukherjee

4. Electroweak Sector

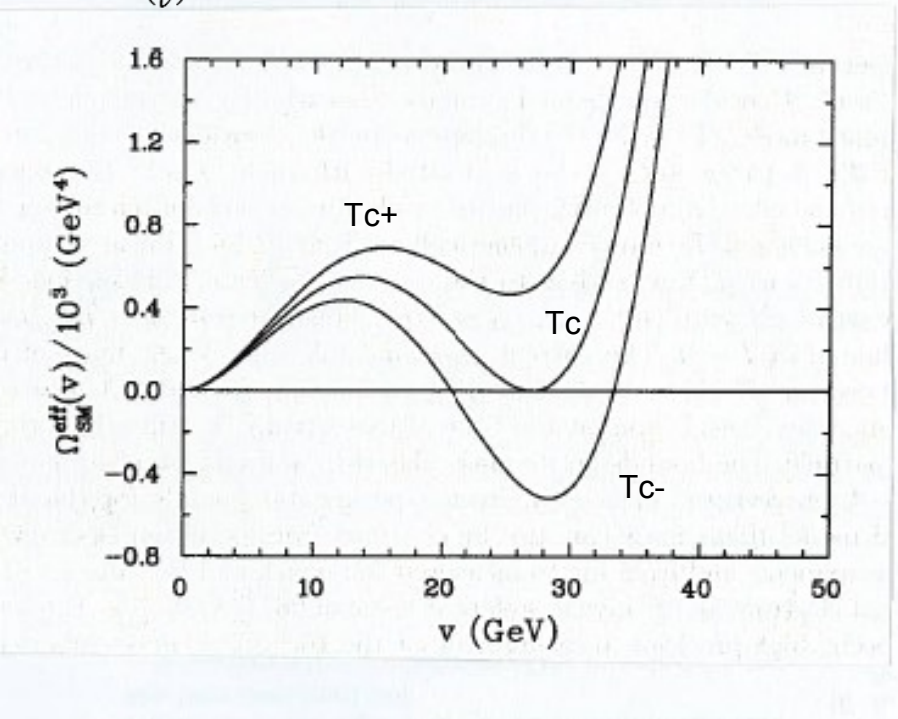


effective potential ~ pressure

(i) mean field approximation

2nd order PT: p, p‘ = cont., p‘‘ jumps

$< \Phi > = \begin{pmatrix} 0 \\ v \end{pmatrix} / \sqrt{2}, \quad M_W = g\, v/2, \; M_Z = v\sqrt{g^2 + g'^2}/\, 2$



(ii) improved pert. approach by ring diagrams

Tc = 140 GeV: very weak 1st order PT

(iii) improved approach (lattice)

no PT in SM

5. The quest for 1st order PTs

1. generate net numbers of B and L at electroweak scale

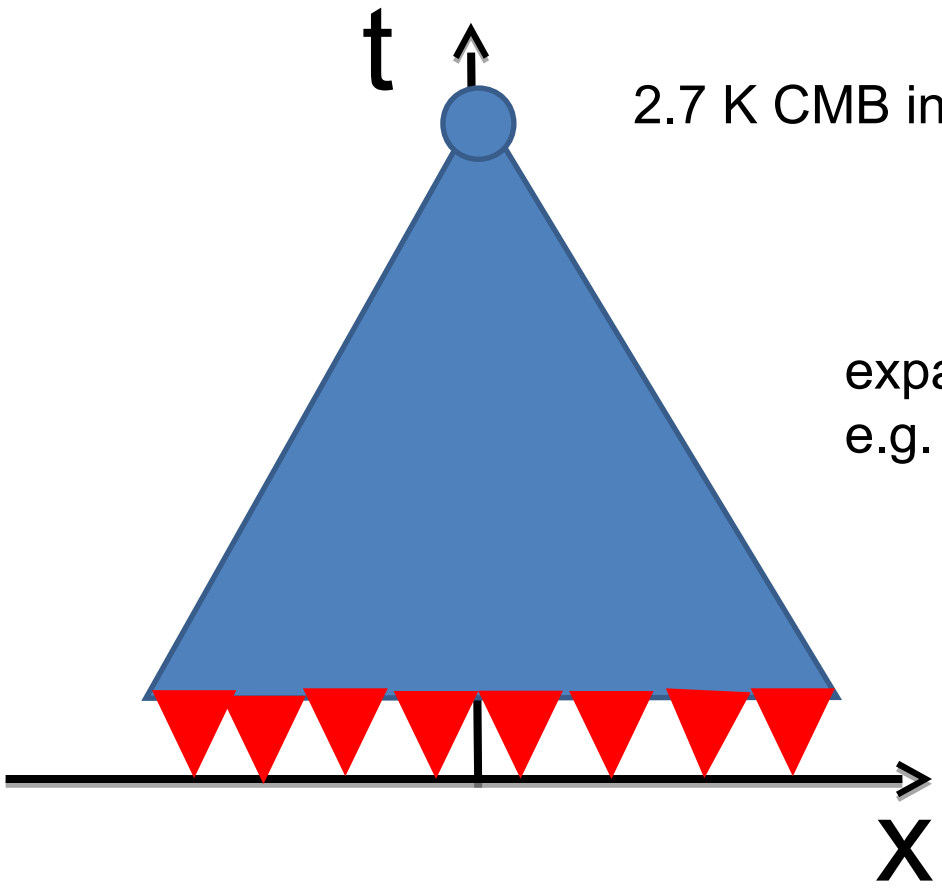
Sakharov criteria: (1967)
- B and L changing processes
- C, CP violations
- off-equilibrium

} SM

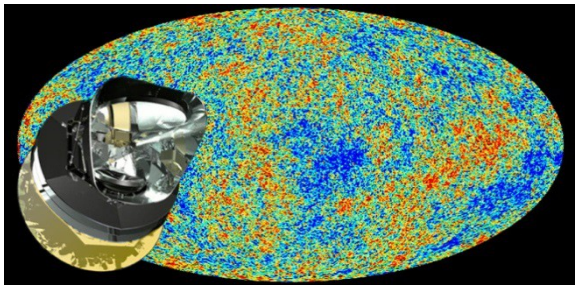
MSM with 1 add. Higgs

2. make inflation to solve standard problems in cosmological SM

flatness, age, causality, entropy, monopole, ….



2.7 K CMB in any direction

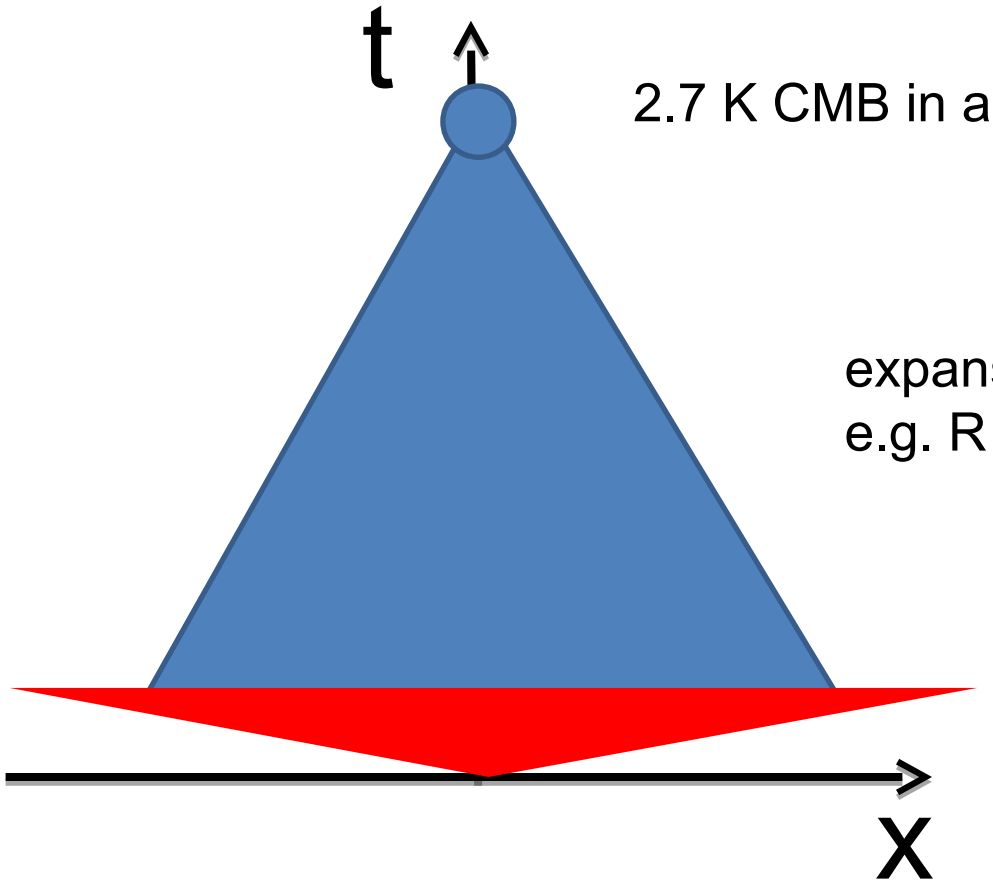


expansion is decelerated at all times,
e.g. R ~ t^k, k < 1

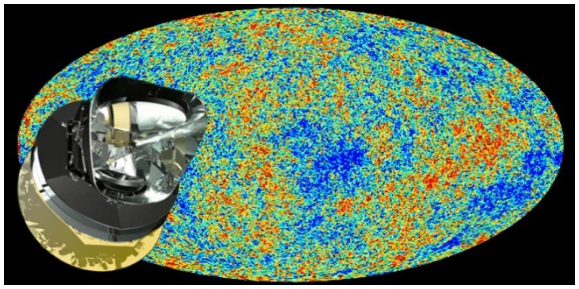
10,000 causally disconnected regions

analog: flatness scales with $/\,\Omega(t) - 1\,/ = /\,\Omega(t0) - 1\,/\,(T0/T)^n$

→ early fine tuning needed,
e.g. by 50 digits



2.7 K CMB in any direction

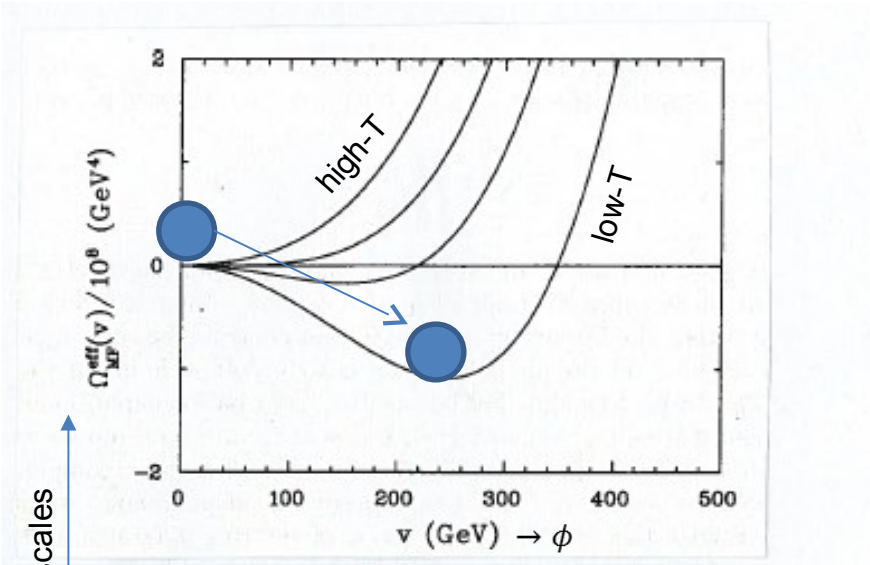


expansion is decelerated at later times,
e.g. R ~ t^k, k < 1

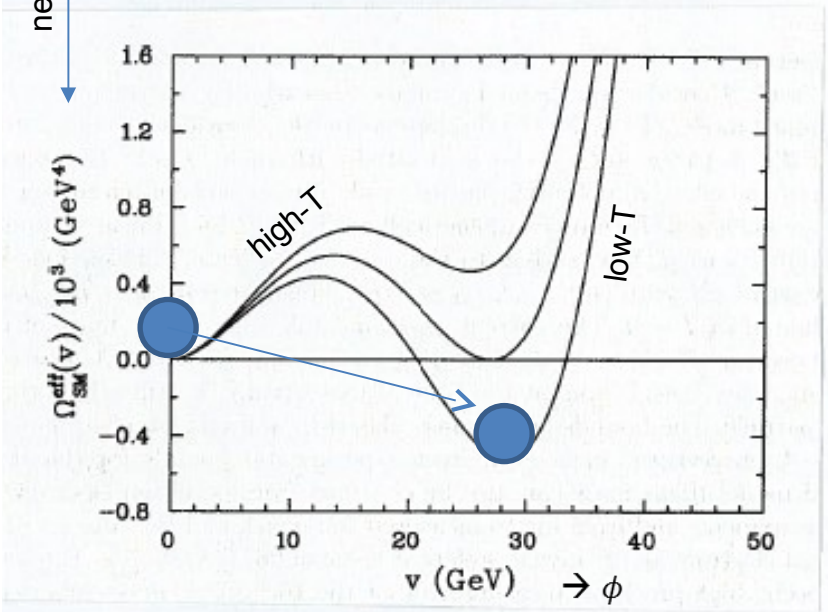
1 causally connected region,
accelerated expansion,
60 e-foldings in R

CMB fluctuations = thermal fluctuations within a tiny region at early times,
red-shifted to super-horizon scales by inflation

(i) Inflation driven by a new scalar field



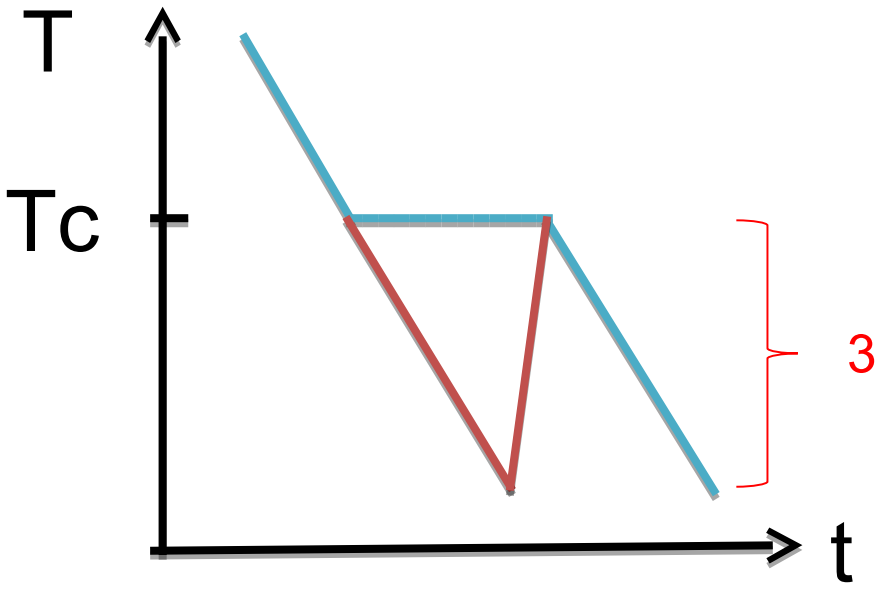
new scales



either slow roll down …

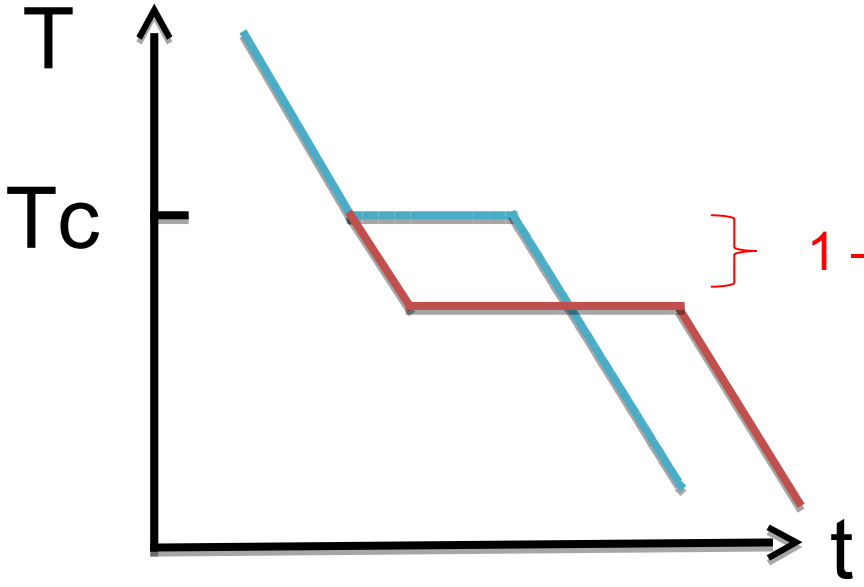
… or tunneling
(as 1st order PT)

(ii) Inflation by hyper/super cooling



old inflation scenario
(Guth, 1980 for GUT, Tc ~ 10^15 GeV)

30 orders of magnitude



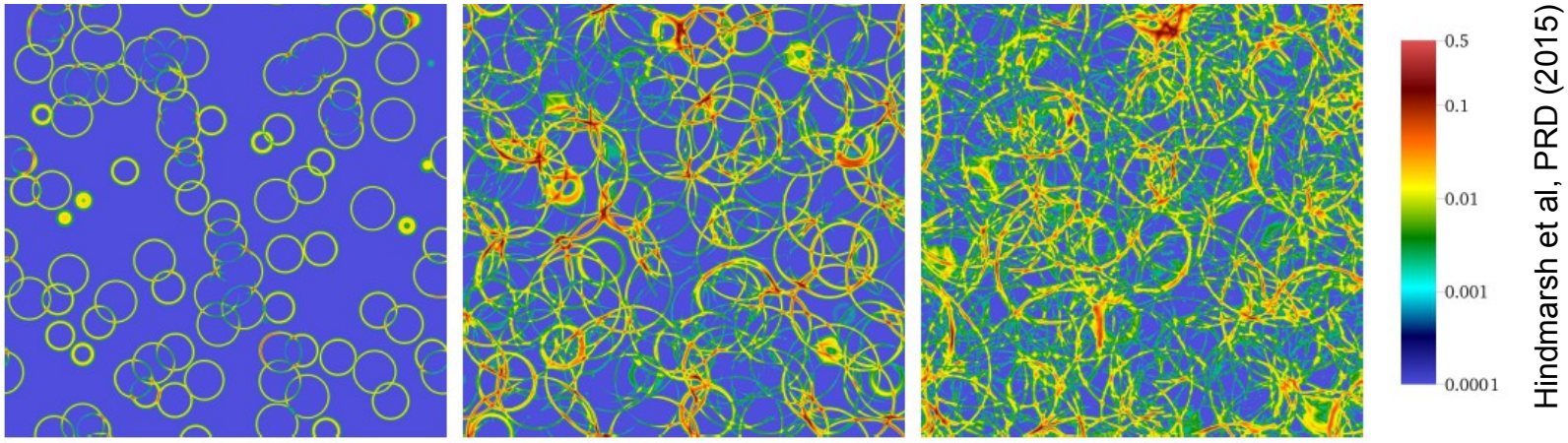
1 – 2 orders of magnitude

Tepid Inflation
(BK, Lucacs, Paal, PLB 1987)

Sound of 1st order PTs

boiling water: noise of bubble dynamics
early universe: gravitational waves

only in extensions of the SM (anyhow needed for DE & DM)



Hindmarsh et al, PRD (2015)

FIG. 4. Slices of fluid kinetic energy density E/T_c^4 at $t = 500\,T_c^{-1}$, $t = 1000\,T_c^{-1}$ and $t = 1500\,T_c^{-1}$ respectively, for the $\eta/T_c = 0.15$, $N_b = 988$ simulation.

gravitational waves = long-distance travellers in universe
→ probes of the material therein
e.g. viscosities (sound attenuation)

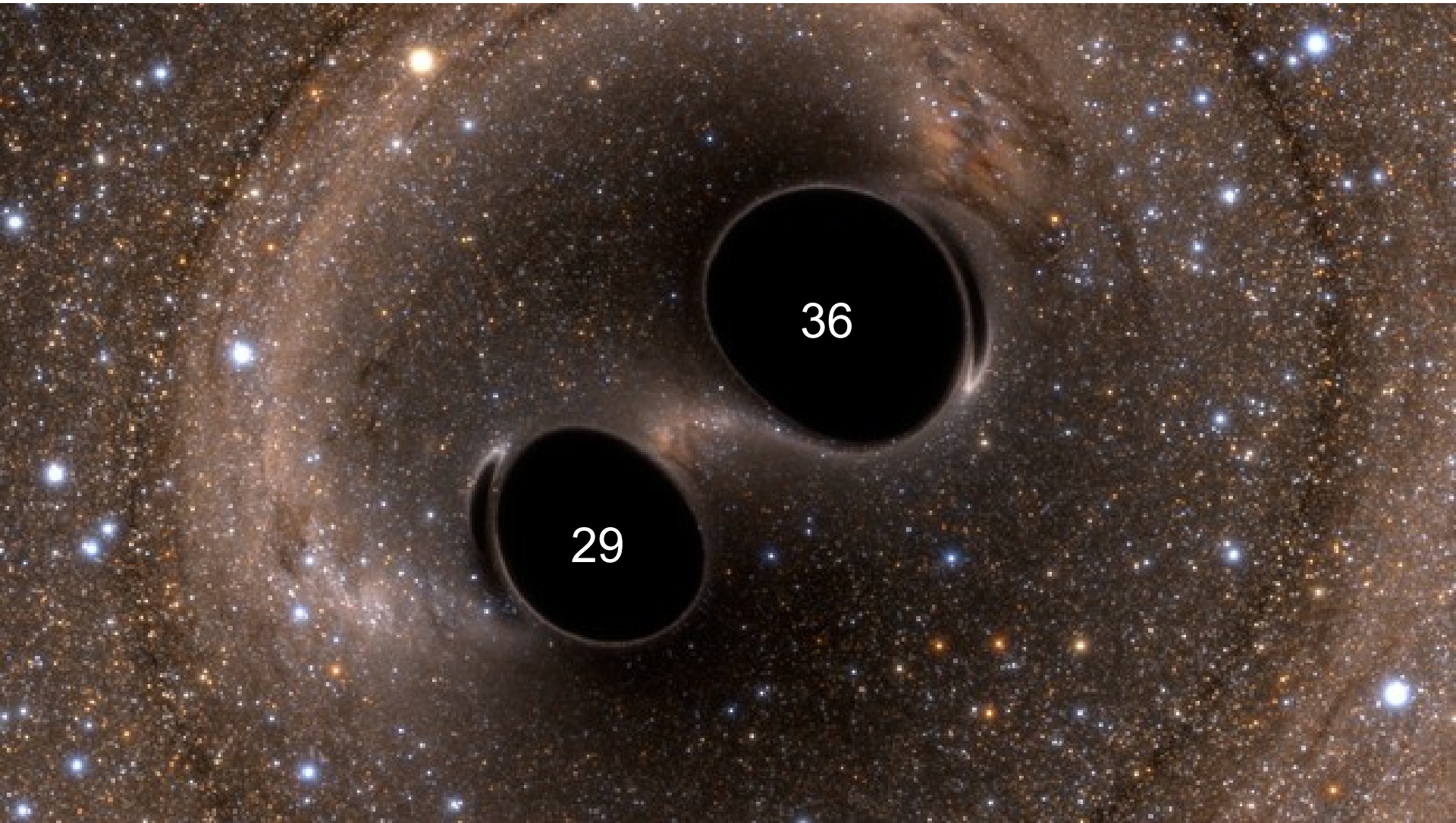
(Aug. 2016: 2 + 1 events)

Zwei Schwarze Löcher verschmelzen zu Einem

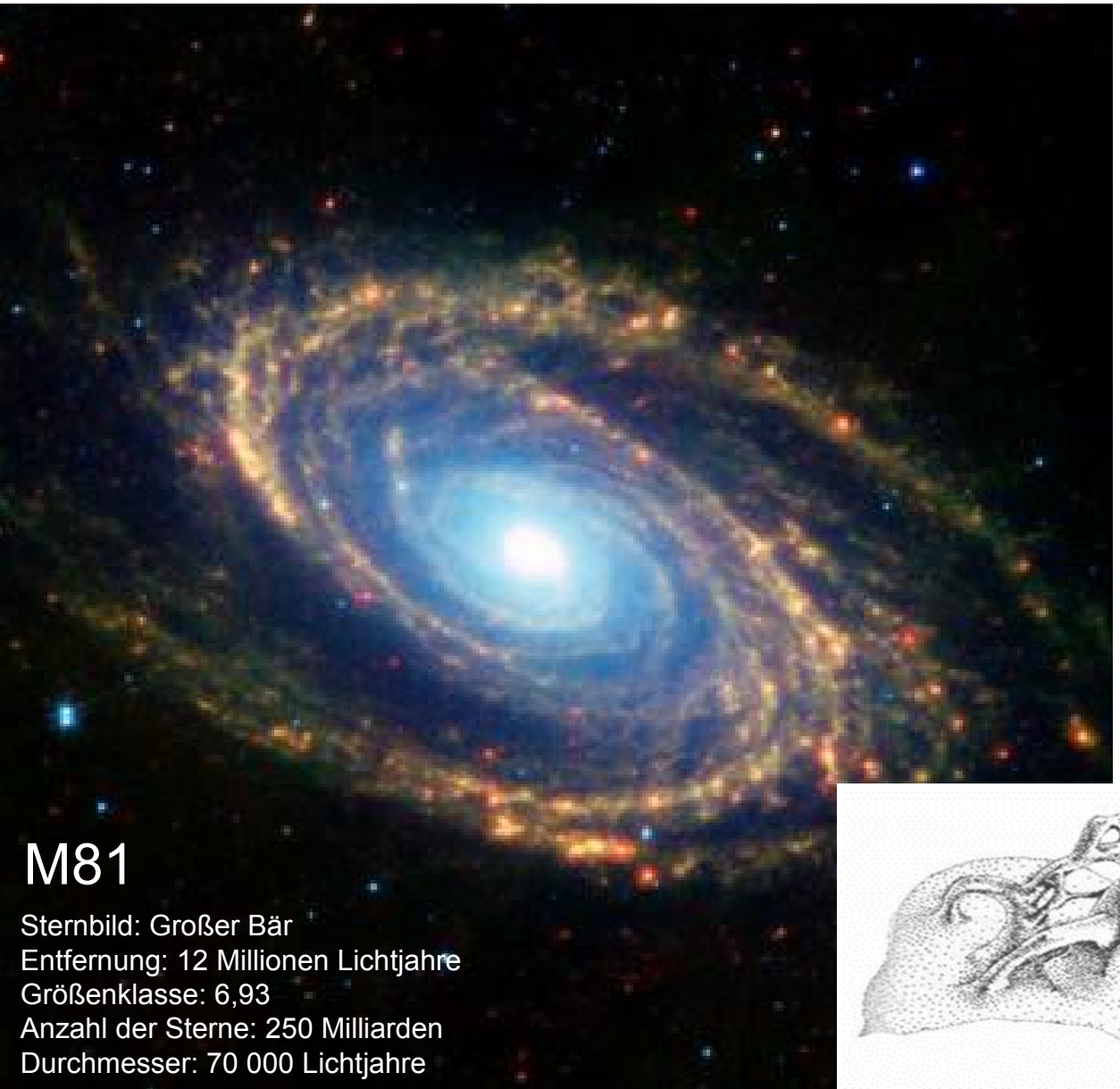
36 + 29 > 62: Thermodynamik Schwarzer Löcher

Hawking 1972

E = m c ^2 → Gravitationswellen



Überall Schwarze Löcher?

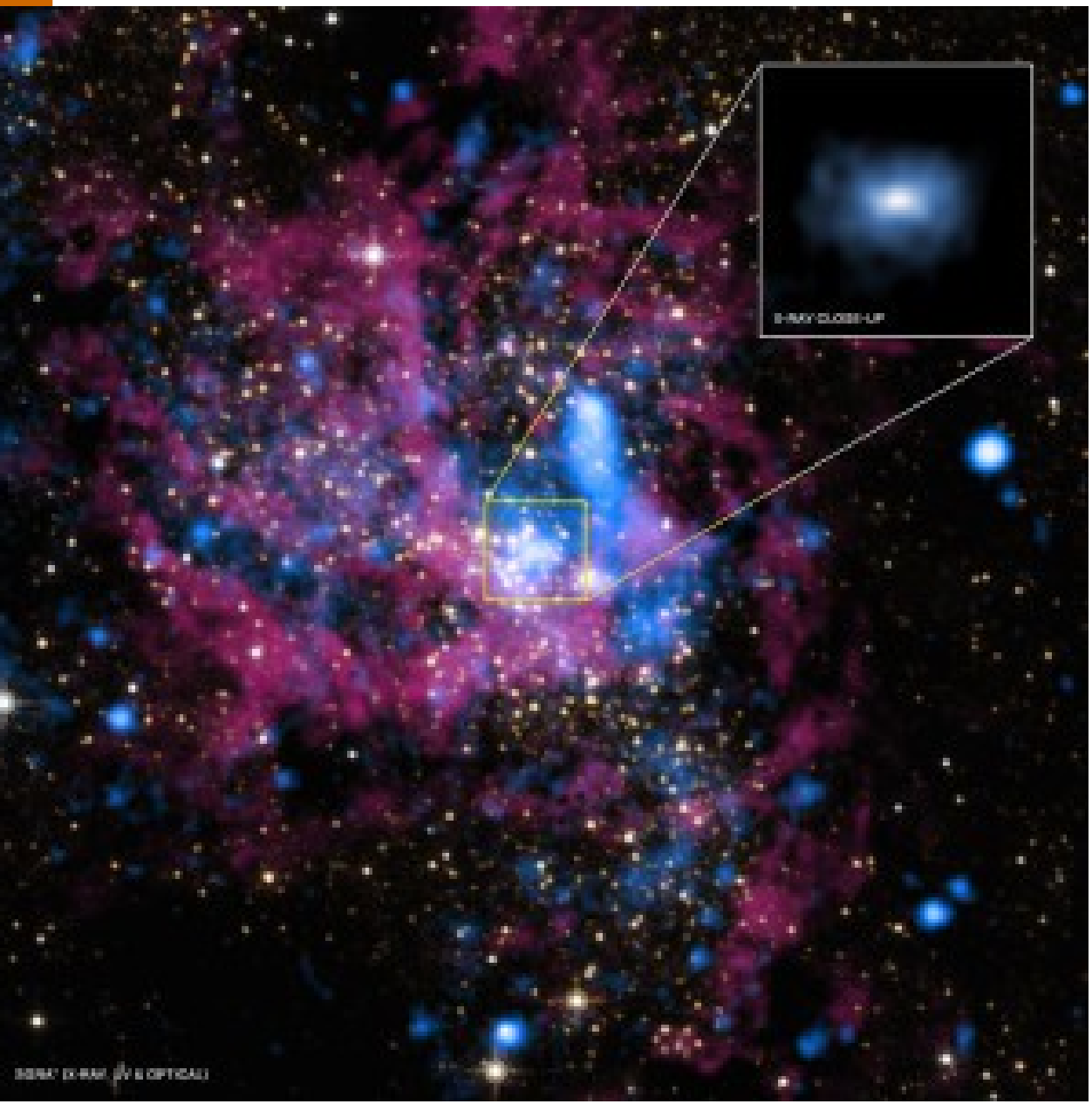


M81

Sternbild: Großer Bär
Entfernung: 12 Millionen Lichtjahre
Größenklasse: 6,93
Anzahl der Sterne: 250 Milliarden
Durchmesser: 70 000 Lichtjahre

Haushalt

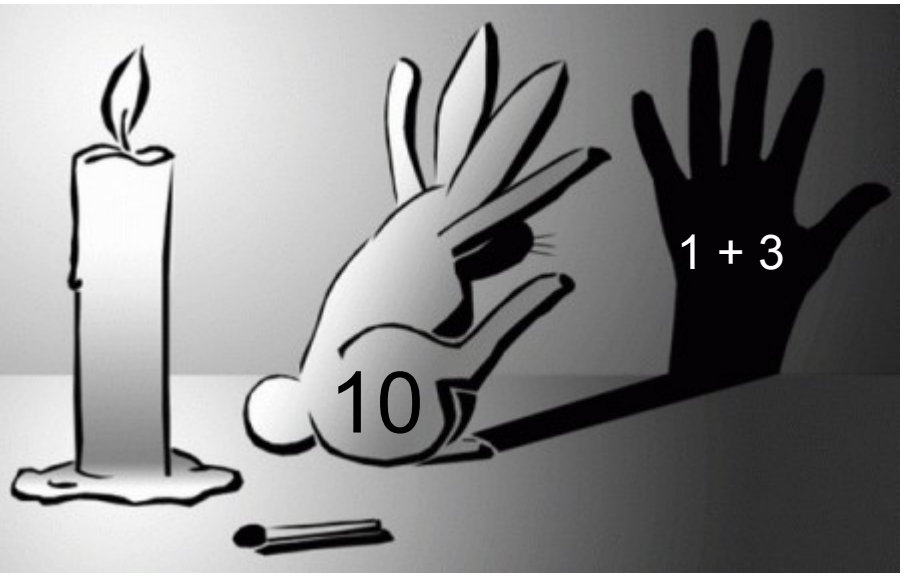
galaktische Zentren
galaktische Kollisionen
direkter Sternkollaps
Akkretion von
Neutronensternen
primordiale Reste



Sagittarius A*: ein super-massives Schwarzes Loch im Zentrum unserer Milchstraße

Our world as shadowgraph in a 10-dimensional Universe

Plato's allegory of the cave



- critical fermionic
  SUSY String-Theory: D = 10
- critical bosonic
  String-Theory: D = 26
- M-Theory: D = 11

Gott schuf das Volumen, der Teufel die Oberfläche

Where are the Extra-Dimensions?

→ Holography of strongly coupled systems
(QGP, LHC at CERN, holographic superconductors, …):
5 dimensions are enough

Summary

cosmic evolution due to expansion
→ sequence of material transformations

despite of previous expectations:
annihilations (e.g. e+ e-)
QCD confinement
electroweak symmetry breaking
} not PTs

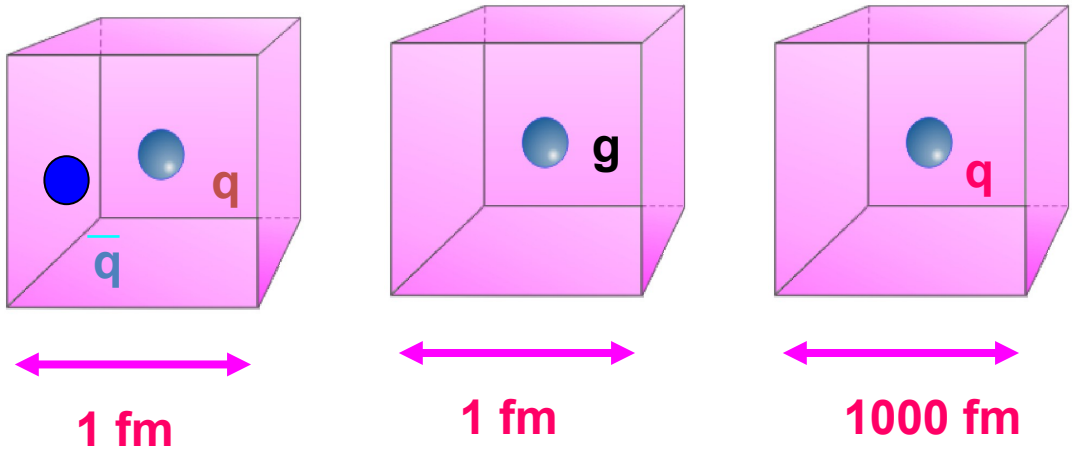
precision cosmology → BBN: near-perfect
DE, DM problems

inflation paradigm: solution of standard problems

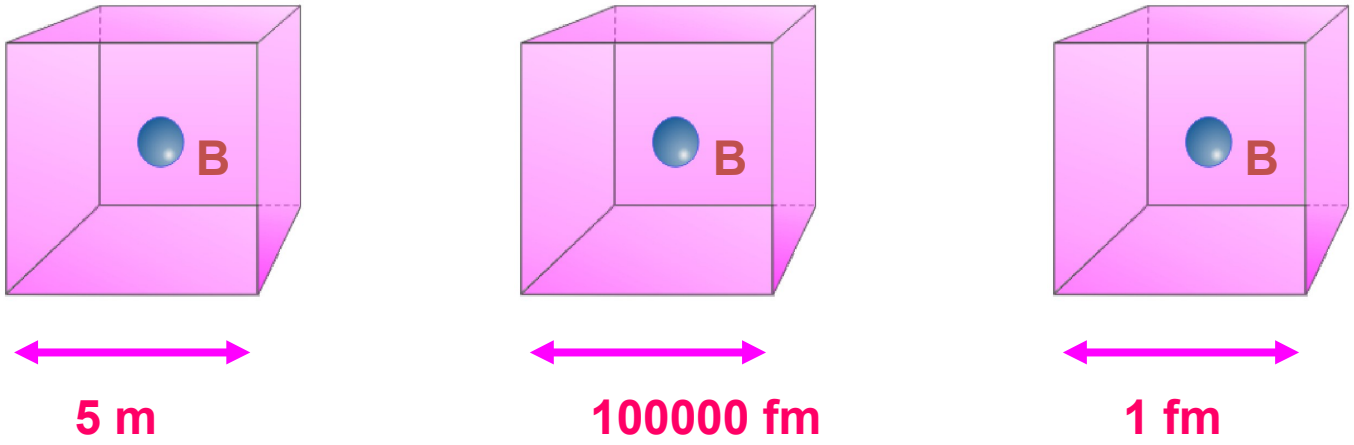
lepto-baryon genesis: when/how?

Stretching of Distances

T = 170 MeV



T = 2.3 x 10^{-10} MeV expansion by factor 10^{11}



Dark Matter

On average

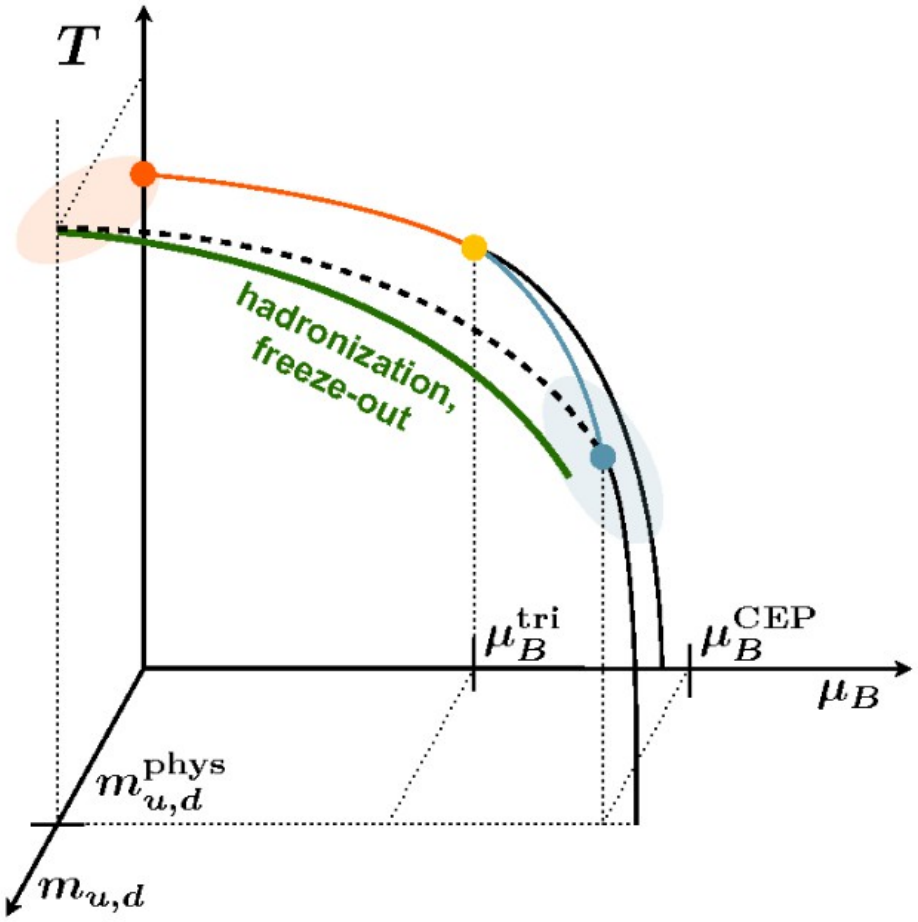
0.3×10^{-30} g/cm^3

On Earth

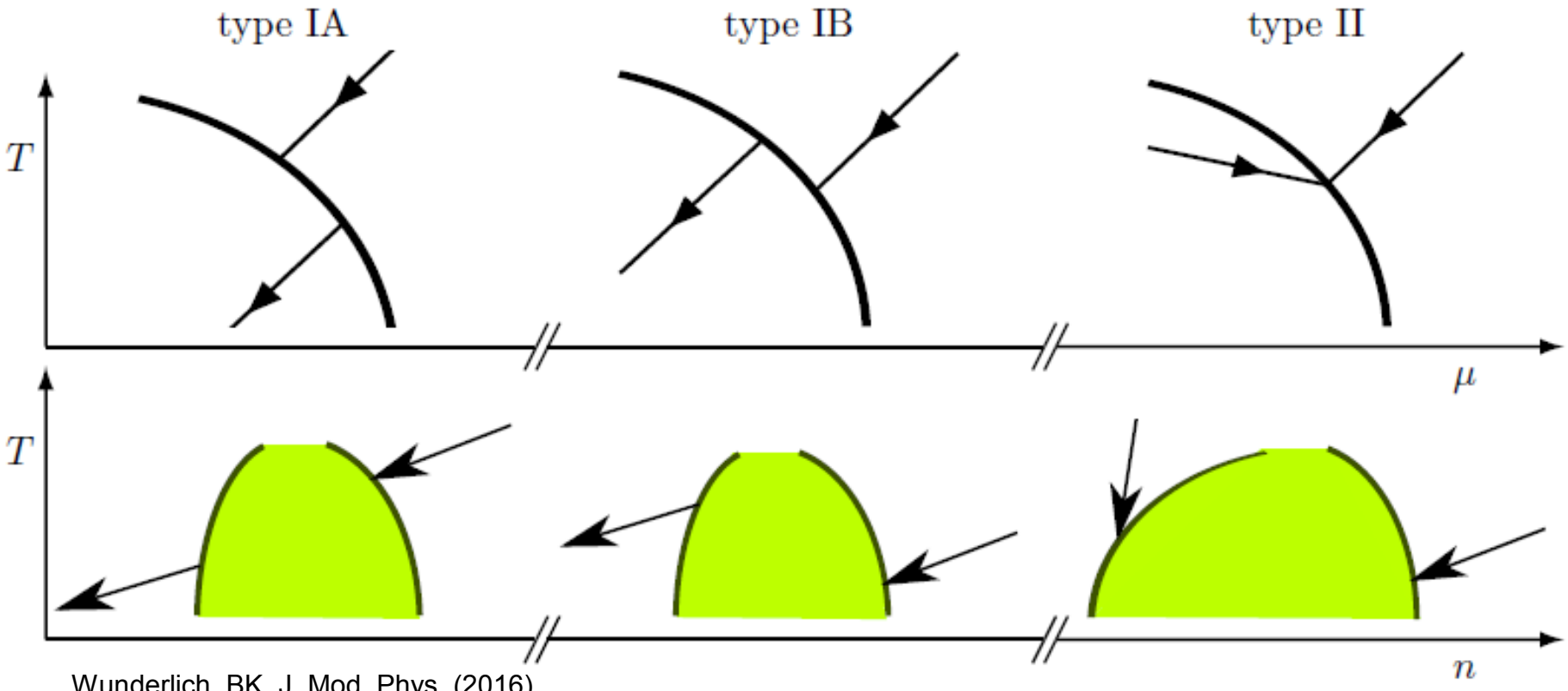
1 g/cm^3

In nuclei & neutron stars

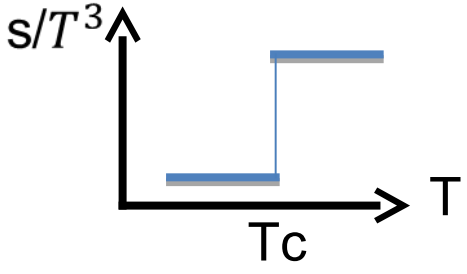
10^{15} g/cm^3

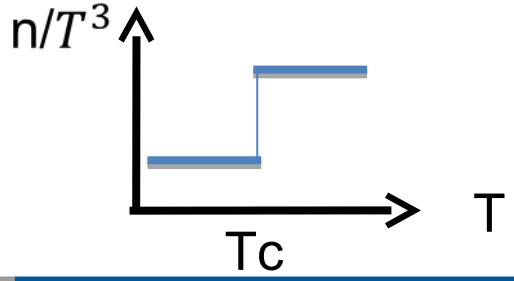

T
hadronization,
freeze-out
$\mu_B^{\rm tri}$
$\mu_B^{\rm CEP}$
μ_B
$m_{u,d}^{\rm phys}$
$m_{u,d}$

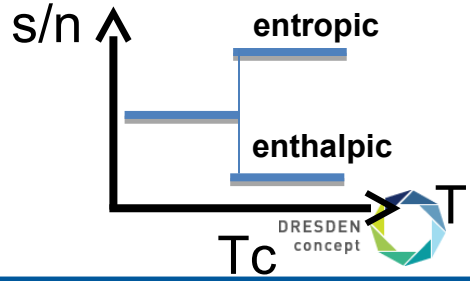
Crossing the phase border line



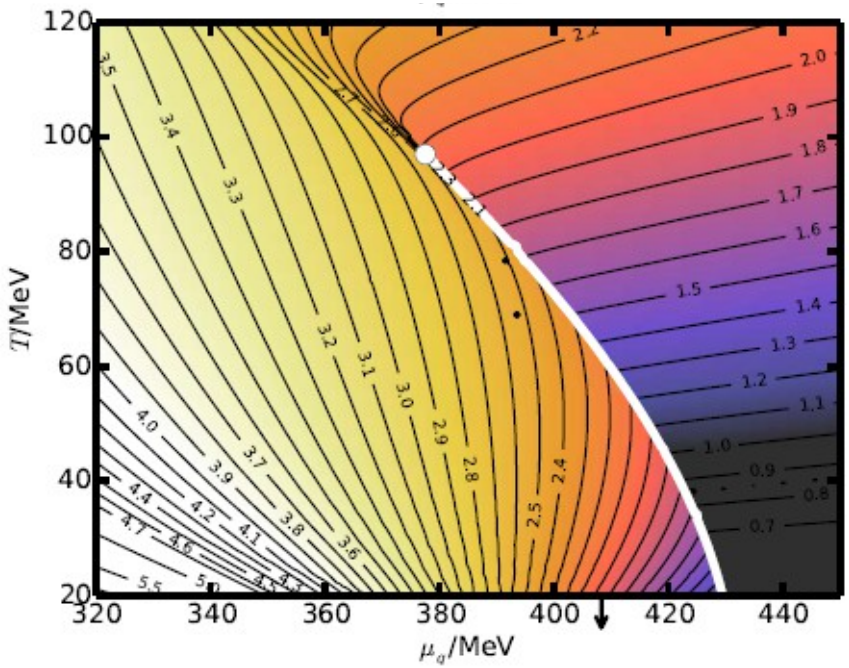
Wunderlich, BK, J. Mod. Phys. (2016)

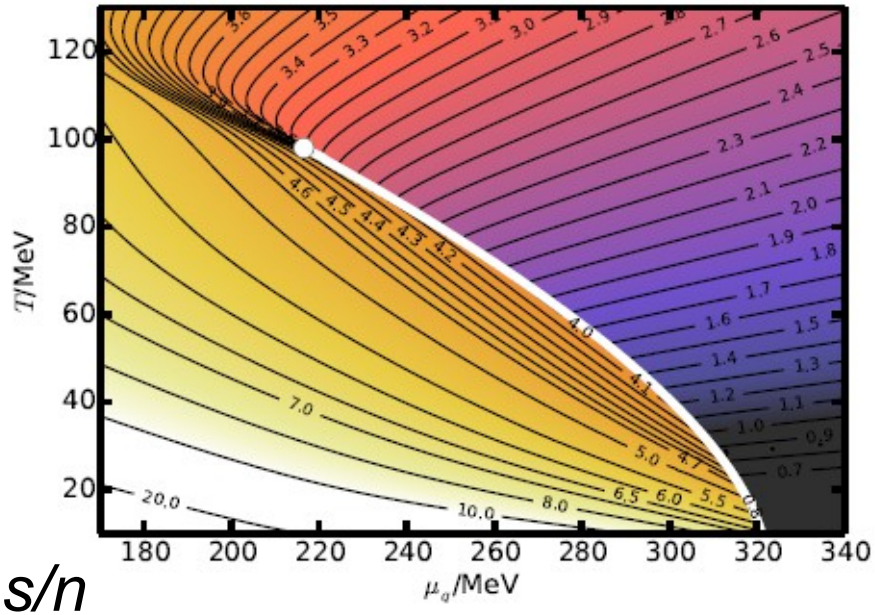






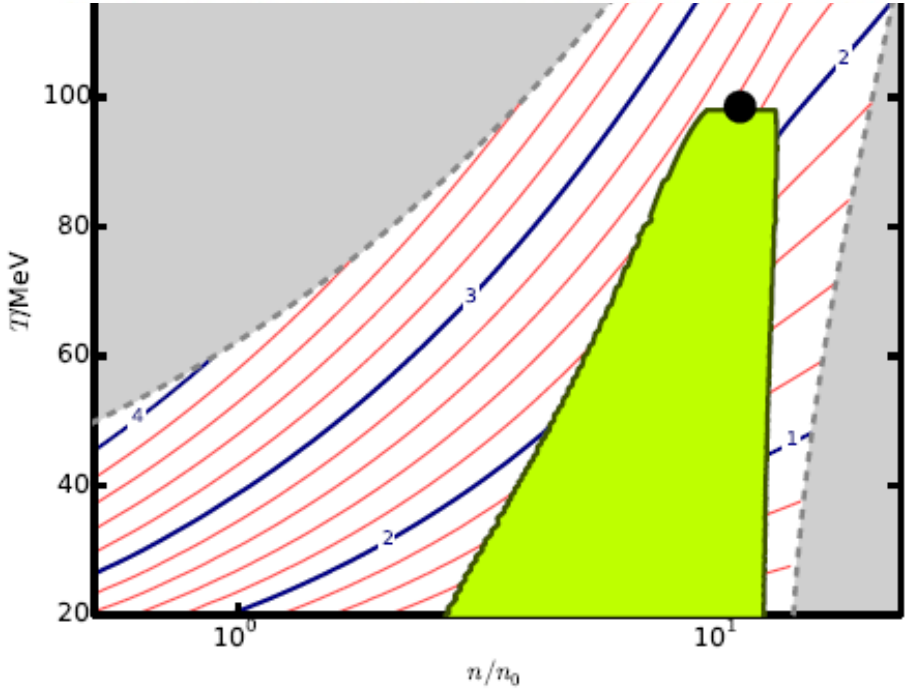
mu = const

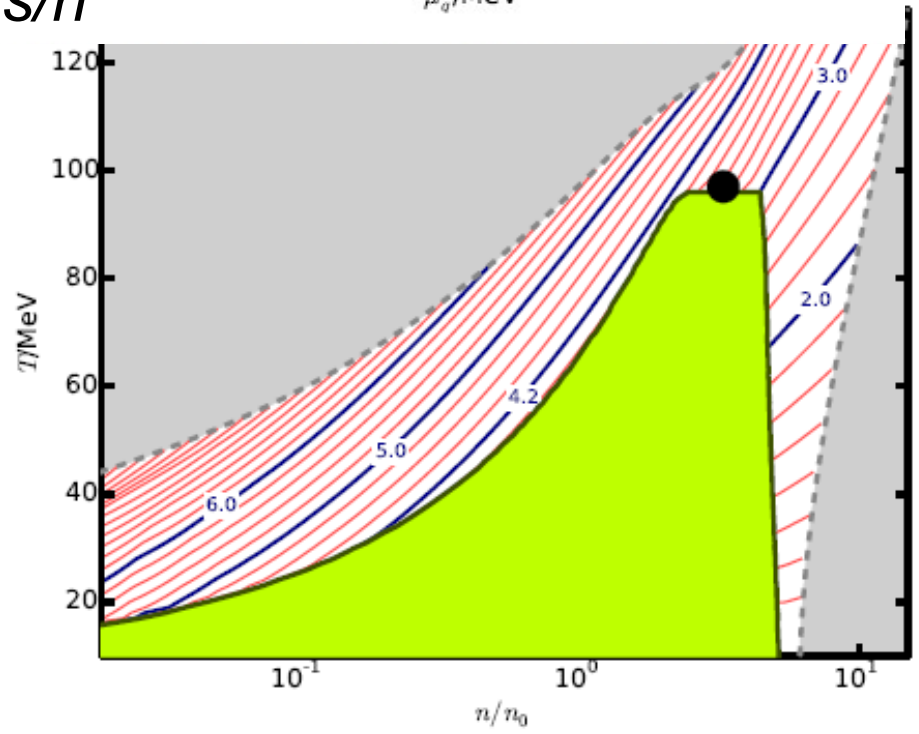


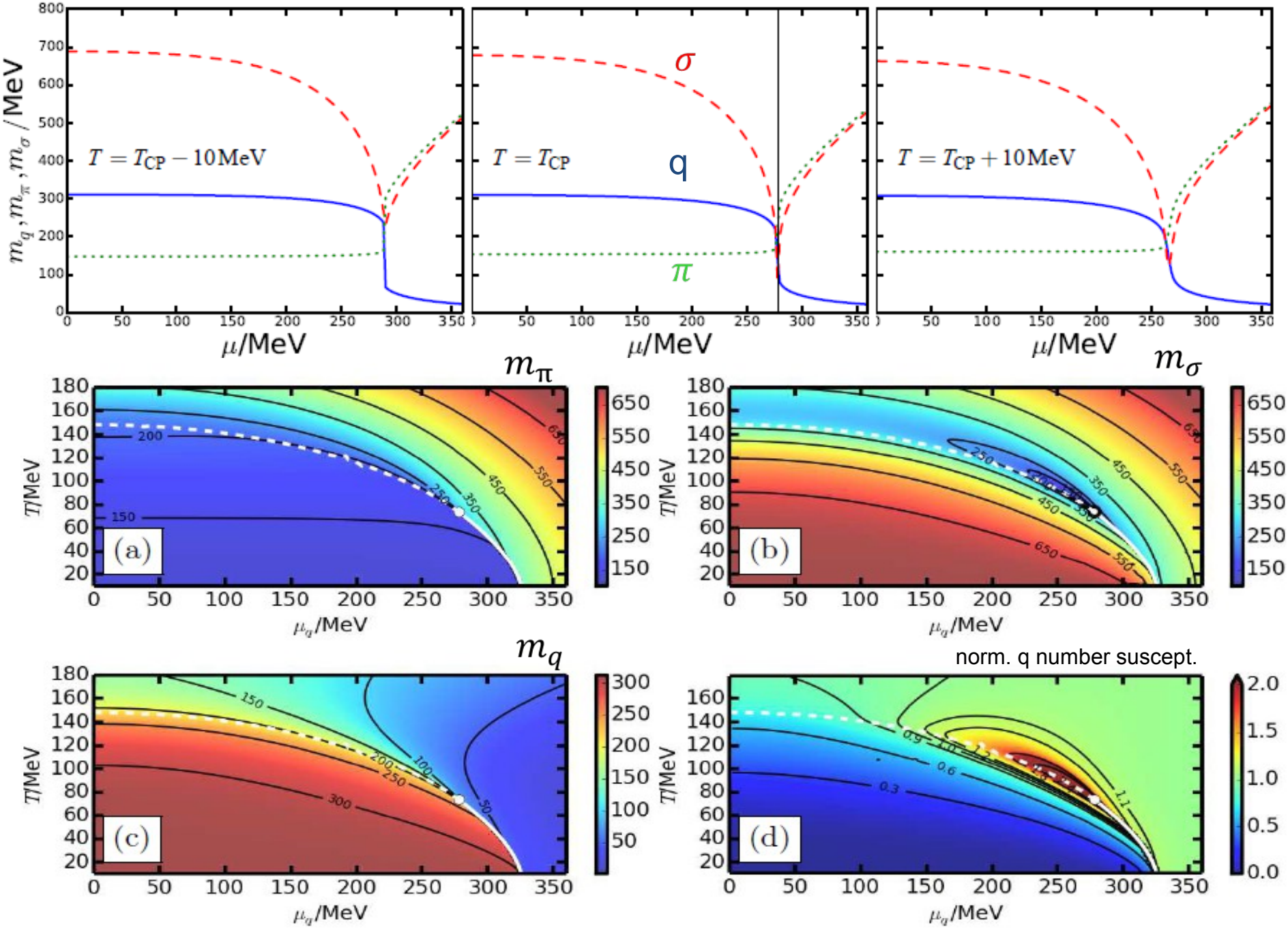


1

s/n






m_q, m_π, m_σ /MeV
$T = T_{CP} - 10\text{MeV}$
$T = T_{CP}$
$T = T_{CP} + 10\text{MeV}$
σ
q
π
μ/MeV
m_π
m_σ
m_q
T/MeV
μ_q/MeV
(a)
(b)
(c)
(d)
norm. q number suscept.

w = 1000 MeV, q + pi → q + gam