What is the maximum temperature ever reached in the universe?

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in collaboration with

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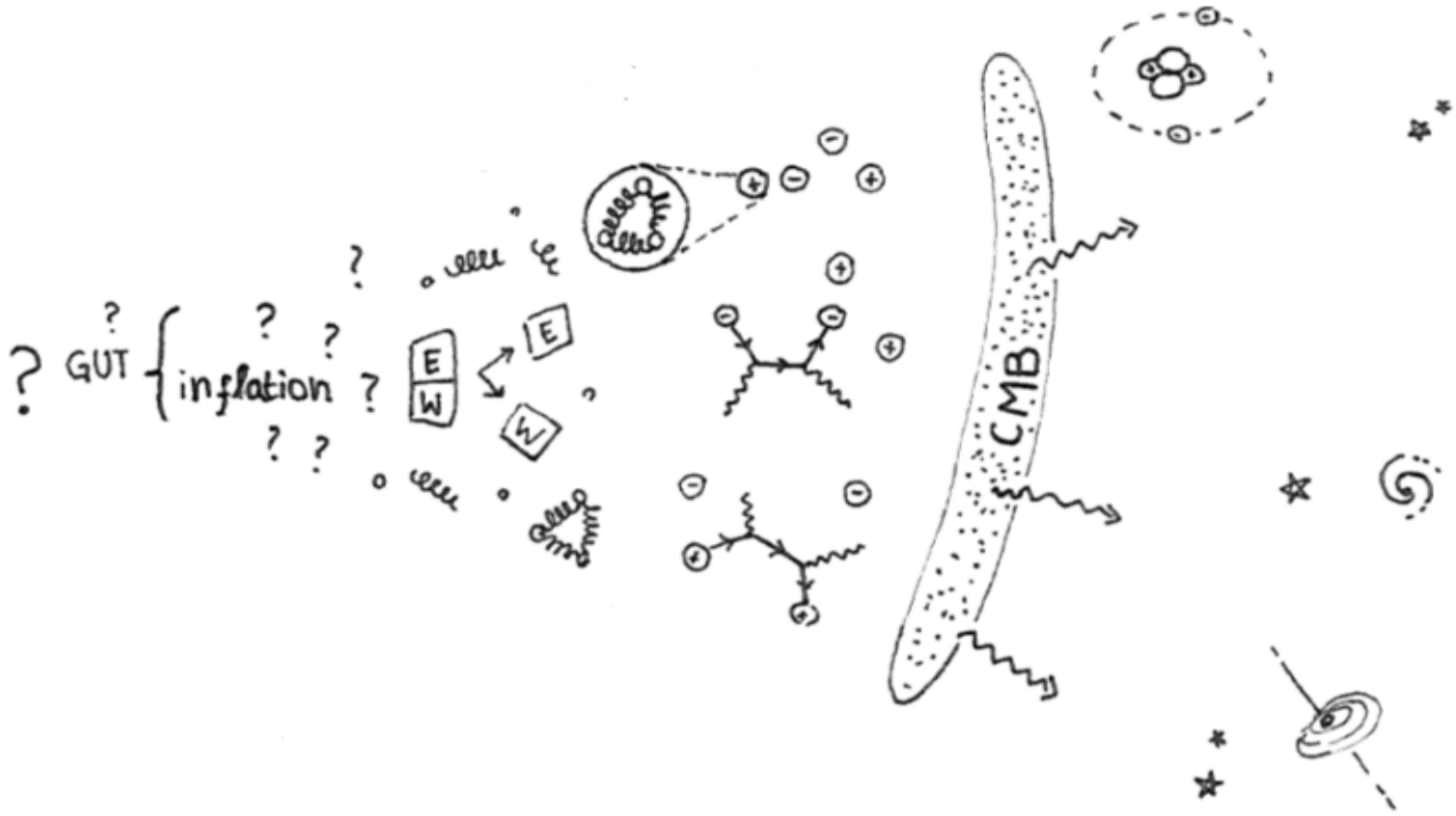
Swiss Cosmology Days 2025 - ETH Zurich

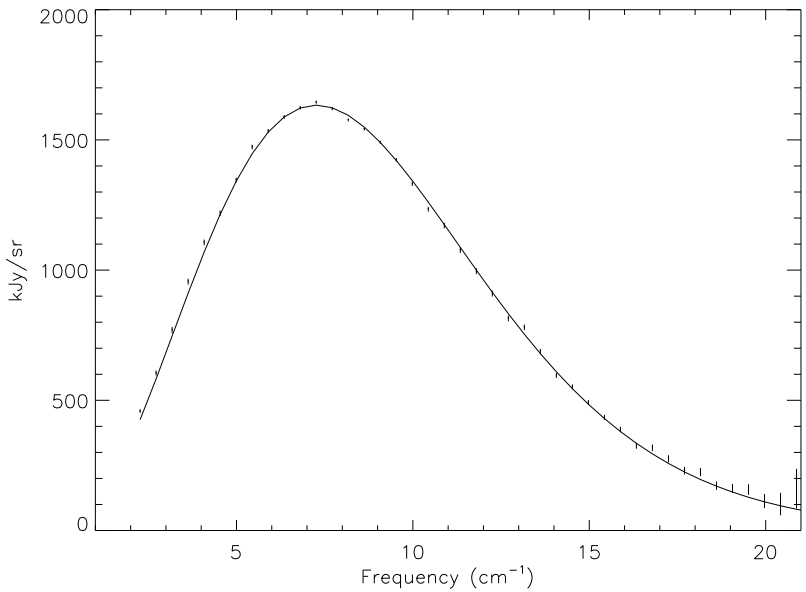
GWs could probe the early universe... but so many models!



is there something we are already sure about? yes!

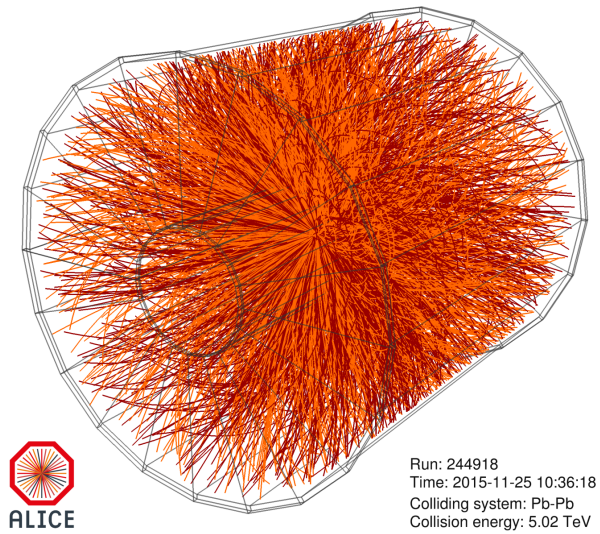
Cosmic Microwave Background originates from a thermal system

the CMB temperature spectrum as a perfect blackbody



D.J. Fixsen *et al.*, Astrophys.J. 473 (1996) 576

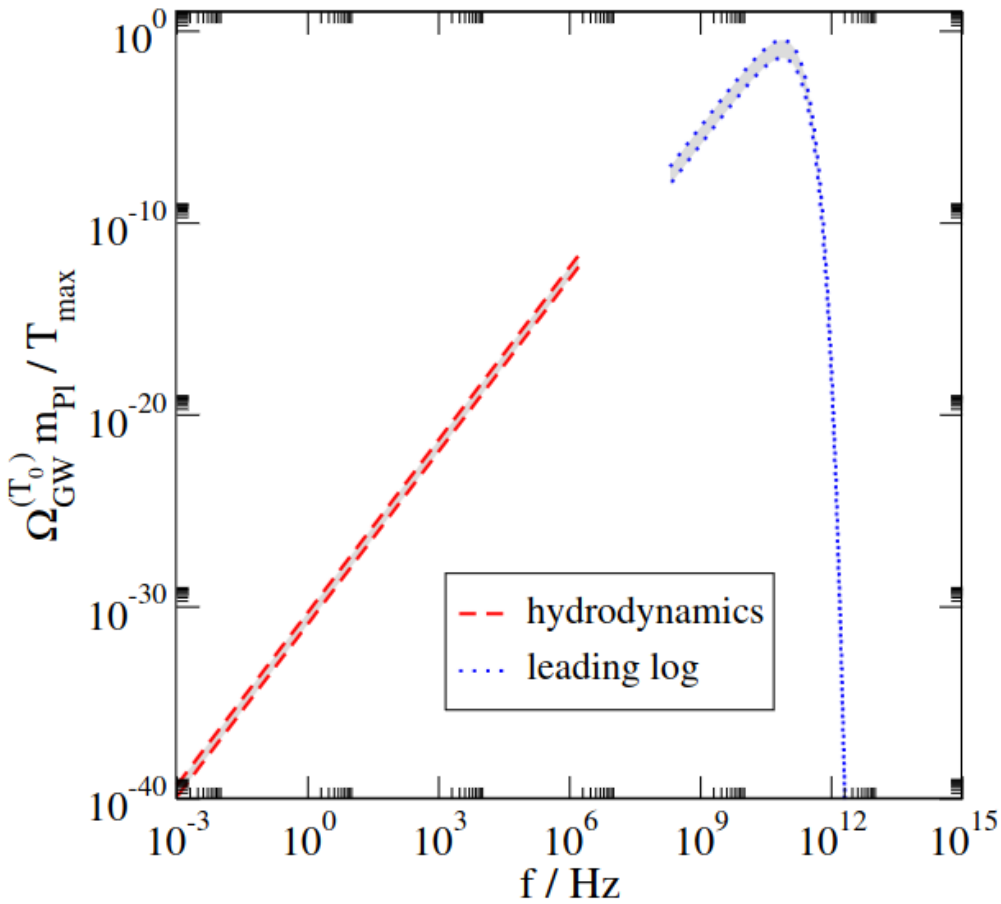
collider searches test the primordial plasma



tracks from a lead-lead collision recorded by the ALICE TPC at CERN

and anisotropies in a thermal plasma can source GWs![1]

from J. Ghiglieri and M. Laine, JCAP 07 (2015) 022



hydrodynamic fluctuations

$\Omega_{\rm gw} \sim \underbrace{\hat{\eta}}_{\text{viscosity}} T_{\rm max} \times f^3$

particle scatterings

$\Omega_{\rm gw} \sim T_{\rm max} \times f^4 \underbrace{n_{\rm B}(f/T_{\rm max})}_{\text{Boltzmann distr.}}$

[1] J. Ghiglieri, G. Jackson, M. Laine and Y. Zhu, JHEP 07 (2020) 092,
J. Ghiglieri, M. Laine, J. Schütte-Engel and E. Speranza, JCAP 04 (2024) 062.

what do we know about the maximal temperature?[2]

Big Bang Nucleosynthesis

$\Gamma(T)$

efficient interactions

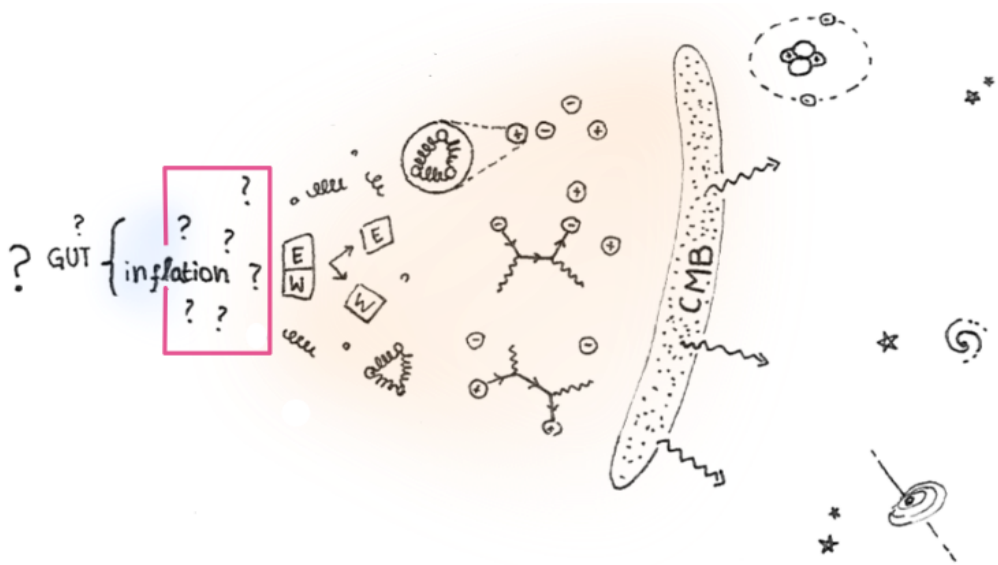
$H^2 \sim 2e_\gamma + N_{\text{eff}}\, e_\nu + \ldots$

universe's expansion

$$T_{\text{max}} \in [10^{-2}, 10^{18}]\,\text{GeV}$$

[2] J. Ghiglieri, G. Jackson, M. Laine and Y. Zhu, JHEP 07 (2020) 092, J. Ghiglieri, M. Laine, J. Schütte-Engel and E. Speranza, JCAP 04 (2024) 062.

can we predict the maximal temperature?

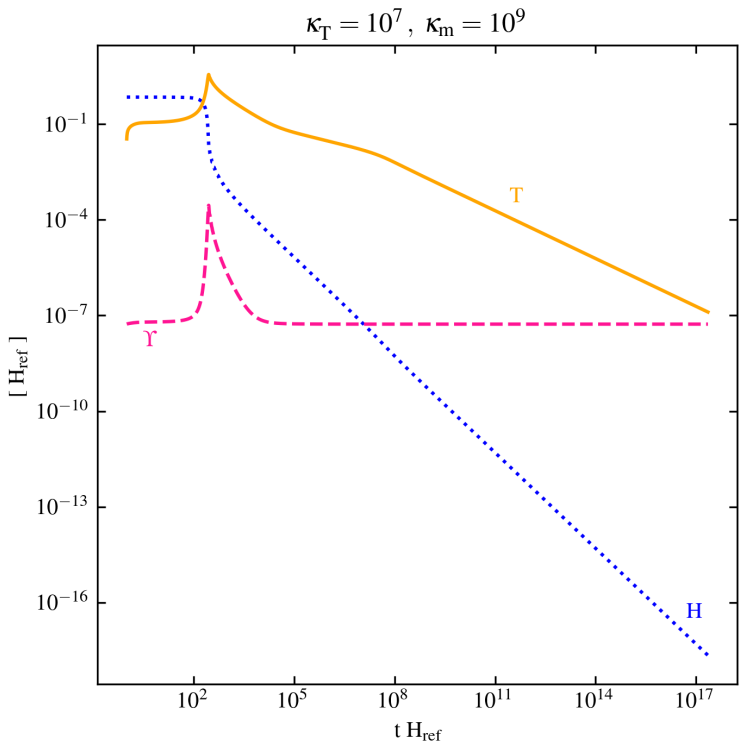


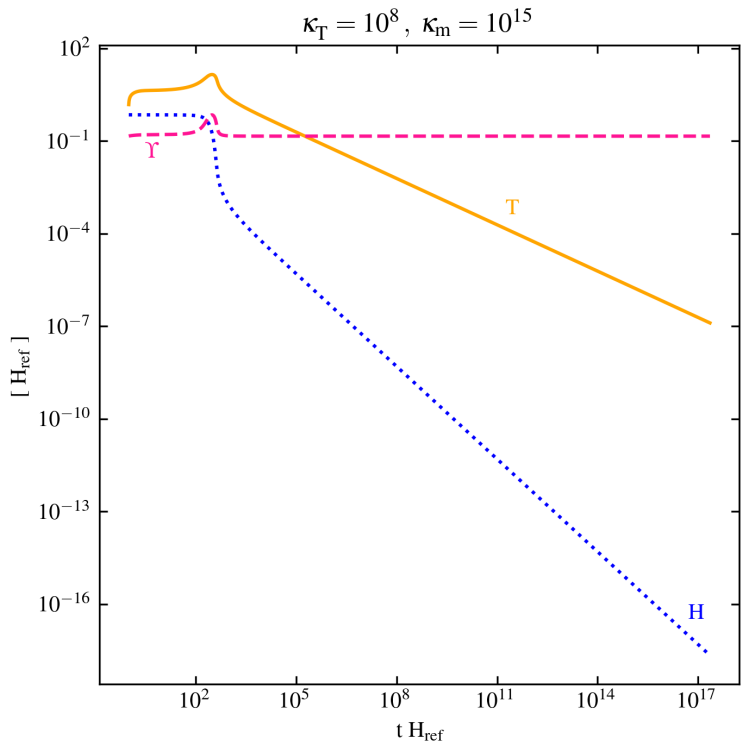
* thermal state required down to $t_{\text{BBN}} \sim 10\,\text{s}$
* early vacuum state predicted at $t \sim 10^{-32}\,\text{s}$
* T_{max} reached in transition period [3]

[3] H. Kolesova, M. Laine and S. Procacci, JHEP 05 (2023) 239

$T_{\rm max}$ depends on initial conditions of thermal epoch[5]

* the universe expands at rate H
* $\Upsilon \sim \frac{\kappa_{\rm T} T^3 + \kappa_{\rm m} m^3}{f_a^2}$ transfers energy to the plasma[4]
* plasma at T dominates at some point after inflation

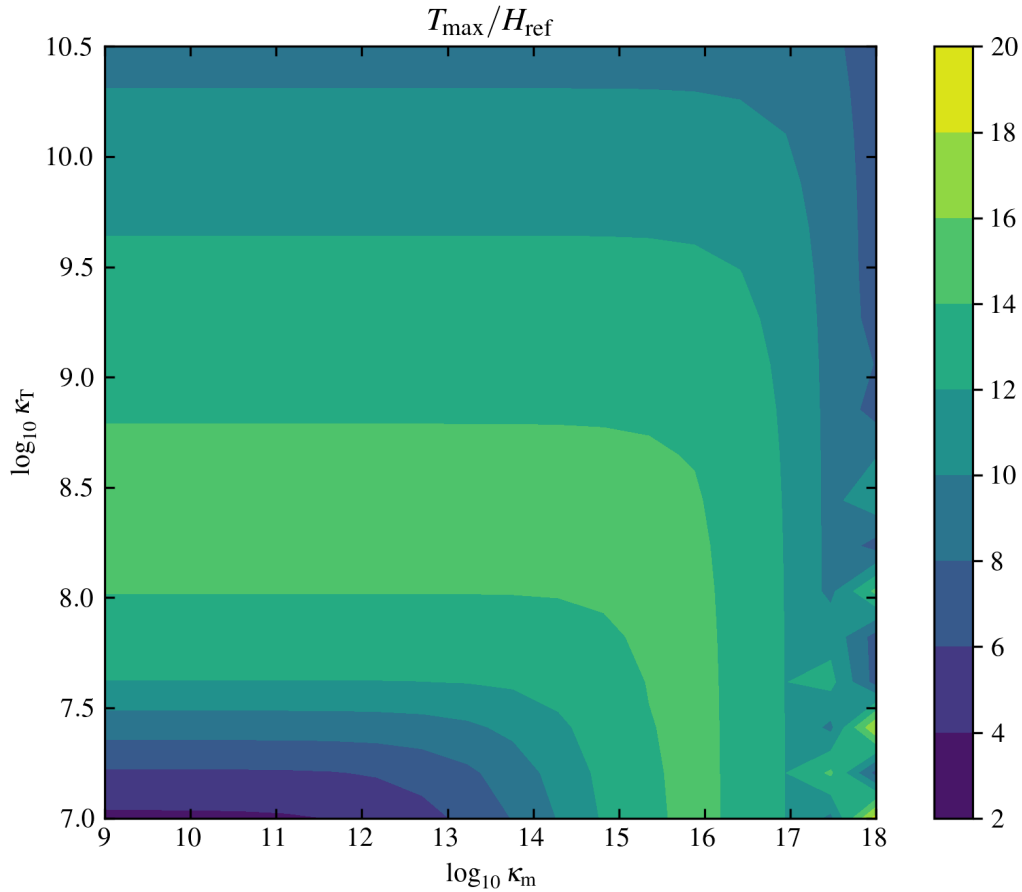




[4] M. Laine, L. Niemi, S. Procacci and K. Rummukainen, JHEP 11 (2022) 126, M. Laine, S. Procacci, A. Rogelj, JCAP 10 (2024) 040.

[5] H. Kolesova, M. Laine and S. Procacci, JHEP 05 (2023) 239.

a model-dependent upper bound for T_{max}

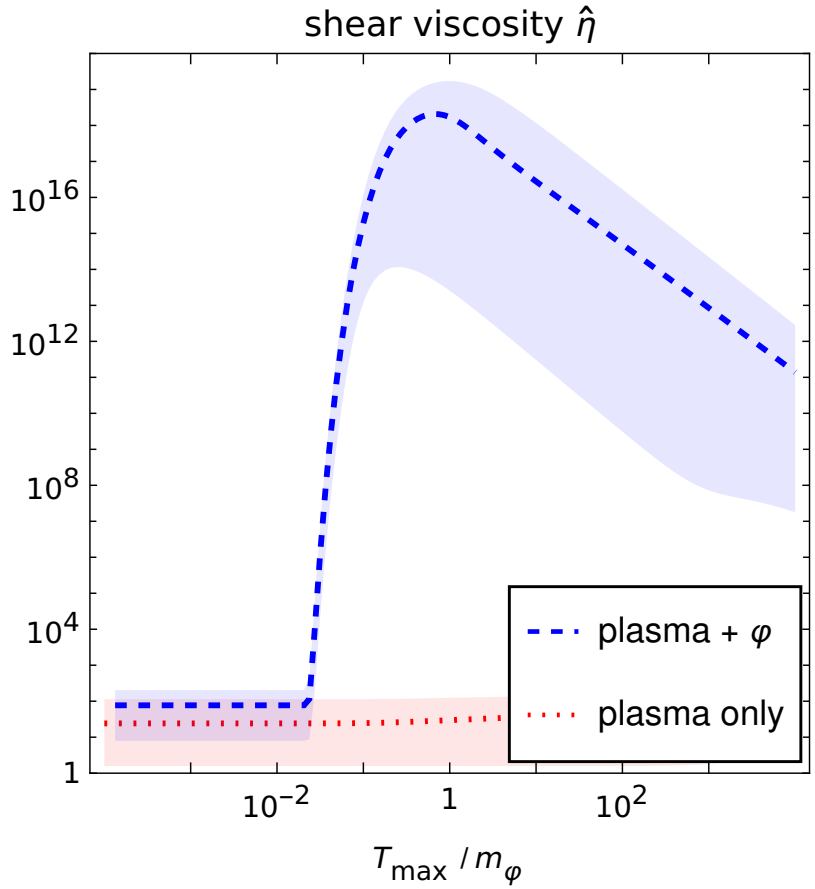


* κ_{m} and κ_{T} determine the reheating mechanism[6]

* $\sim H_{\mathrm{ref}}$ sets the energy scale of inflation

[6] M. Laine, S. Procacci and A. Rogelj, JCAP 10 (2024) 040.

viscosity $\hat{\eta}$ enhanced by weakly-interacting extensions[7]



* more degrees of freedom at high energies?

* weaker interactions $\Rightarrow$ higher viscosity

[7] P. Klose, M. Laine and S. Procacci, JCAP 05 (2022) 021.

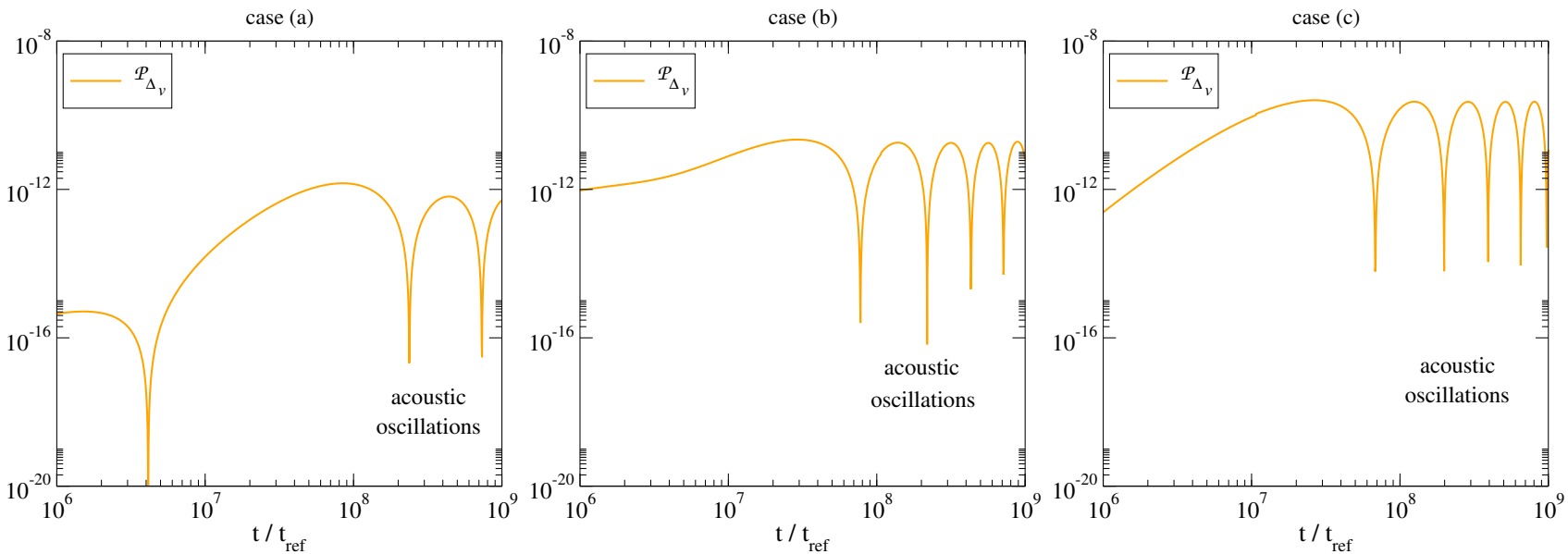
is $T_{\rm max}$ observable?

$$\Omega_{\rm gw}\, h^2 \approx \underbrace{10^{-29} \times \left(\frac{f}{\rm kHz}\right)^3}_{\rm model-independent} \times \underbrace{\frac{\overbrace{\hat{\eta}}^{\rm known\ in\ SM}\, T_{\rm max}}{m_{\rm pl}}}_{\rm model-dependent}$$

* SM extensions could make the signal visible at high f
* but then $T_{\rm max}$ degenerates with $\hat{\eta}$...
* what are other observational inputs?

scalar perturbations affected by high $T_{\rm max}$ as well[8]

$\Delta_v \equiv$ energy density perturbations



$\longrightarrow \longrightarrow$ faster reheating $\longrightarrow \longrightarrow$

[8] see Alica Rogelj's talk yesterday!

M. Laine, S. Procacci and A. Rogelj, JCAP 10 (2024) 040.

What is the maximum temperature ever reached in the universe?

let's keep asking this question!

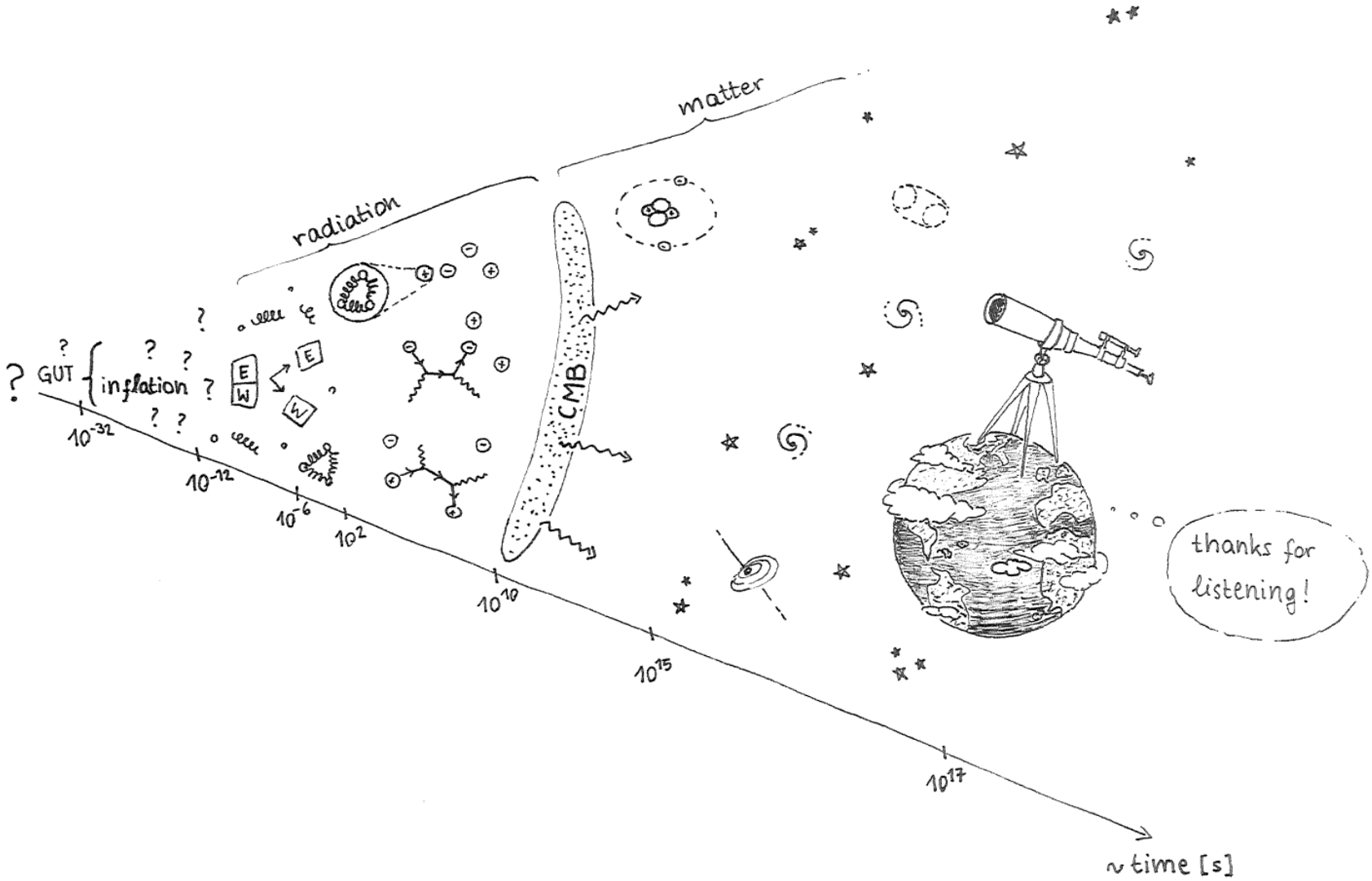
it's of great interest for

stochastic gravitational wave background

large (and less large)-scale structures

thermalization models

fundamental physics at high energies


matter
radiation
GUT
inflation
E
W
CMB
10^{-32}
10^{-12}
10^{-6}
10^{2}
10^{10}
10^{15}
10^{17}
~ time [s]
thanks for listening!