

Gravitational waves from cosmological phase transitions

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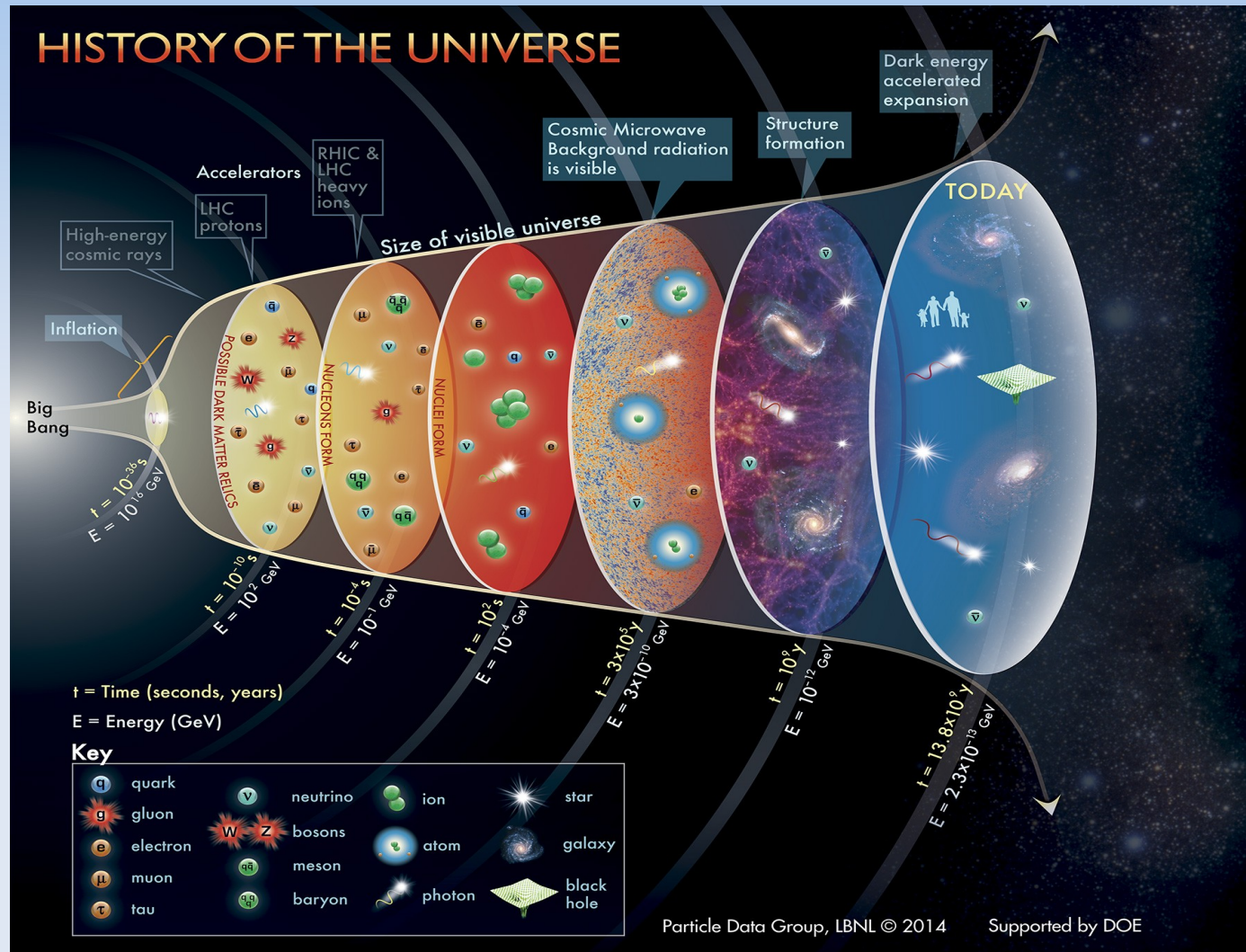


MU days 2026
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Outline



Standard Cosmology



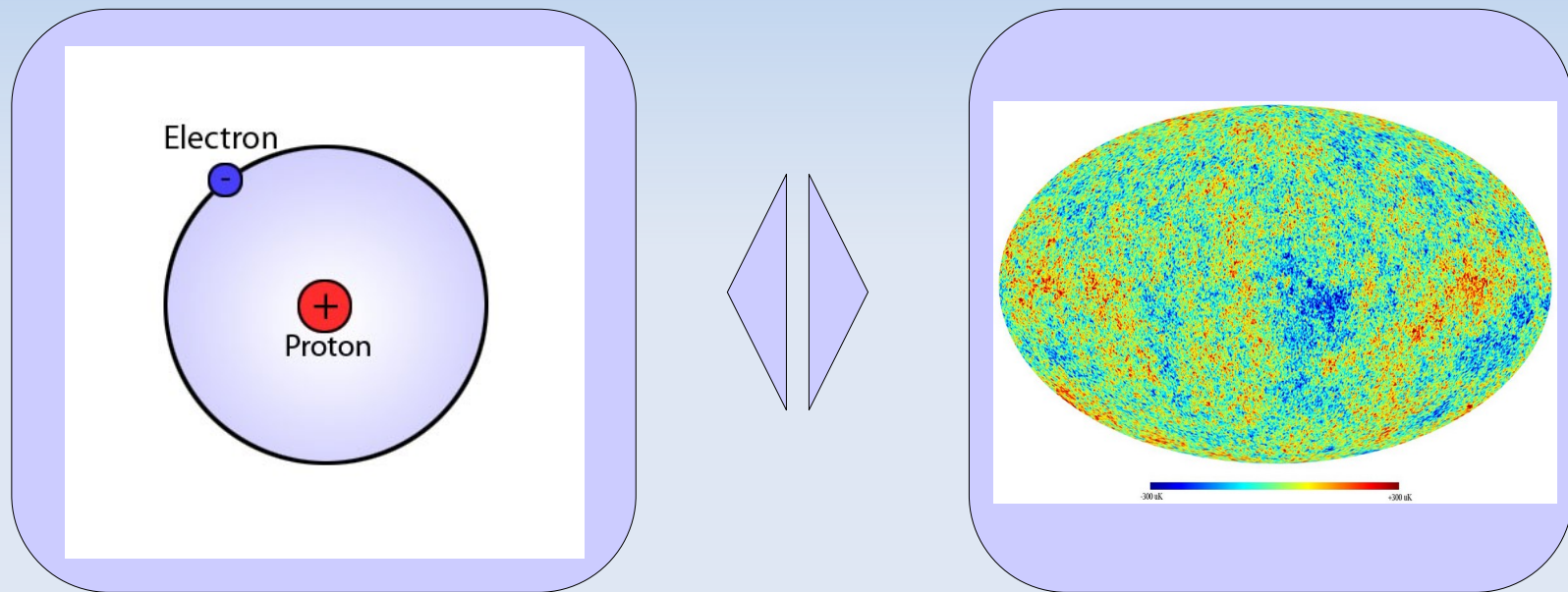
time



temperature

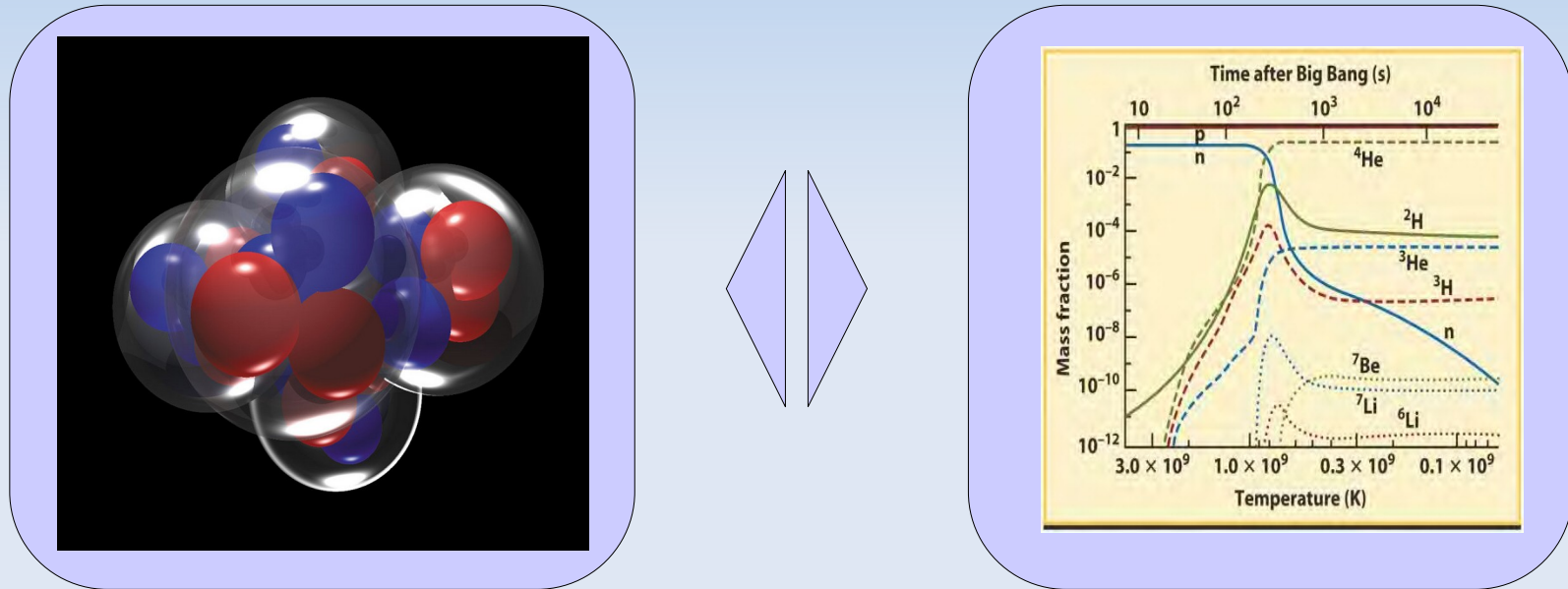


Atomic physics at $T \sim \text{eV}$



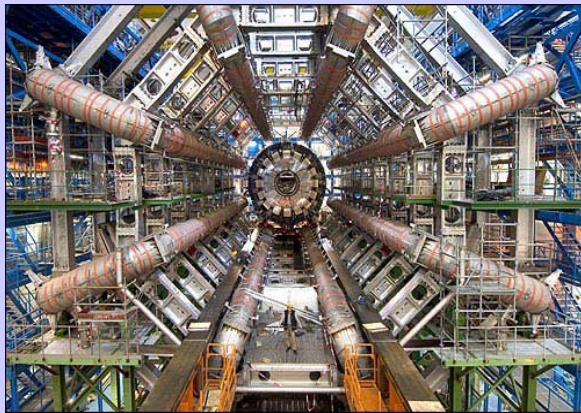
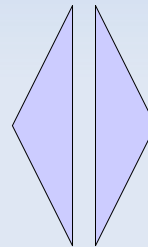
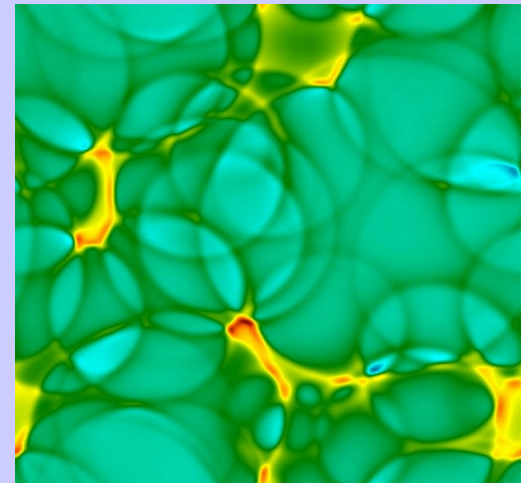
The Cosmic Microwave Background **links** atomic physics to cosmology at temperature $T \sim \text{eV}$

Nuclear physics at $T \sim \text{MeV}$



Big bang nucleosynthesis **links** nuclear physics to cosmology at temperature $T \sim \text{MeV}$

Phase transition at $T \sim 100 \text{ GeV}$?

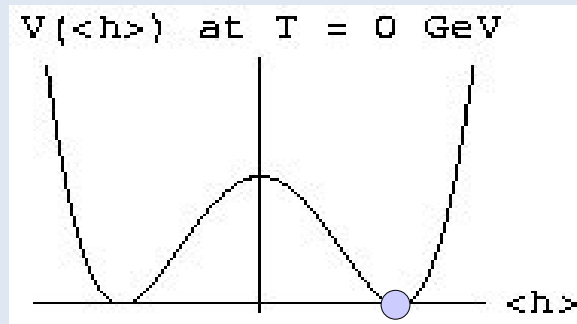


Possibly, the electroweak phase transition drove the Universe **out-of-equilibrium**. This would provide a link to current particle physics experiments.

Electroweak symmetry breaking

The **Mexican hat** potential is designed to lead to a finite Higgs vacuum expectation value (VEV) and break the electroweak symmetry

$$V(h) = \frac{\lambda}{4} (h^2 - v^2)^2$$

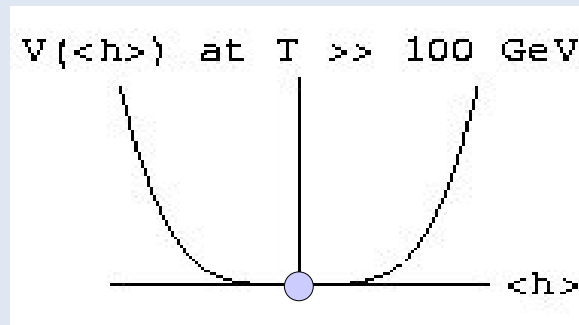
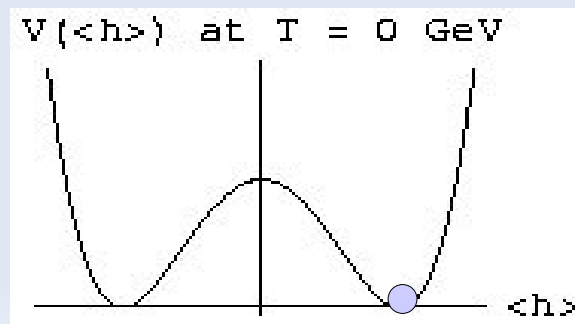


Electroweak symmetry breaking

[Weinberg '74]

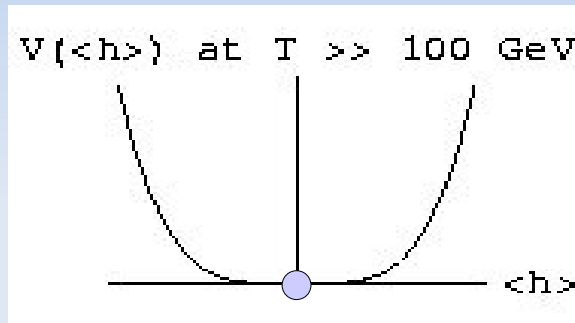
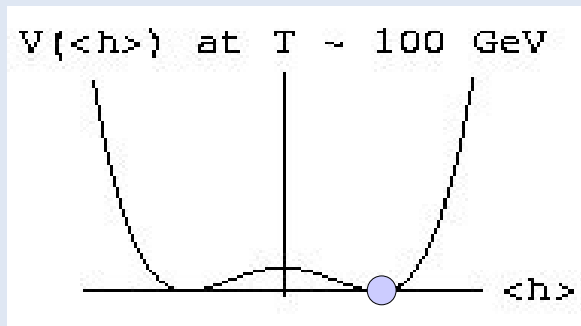
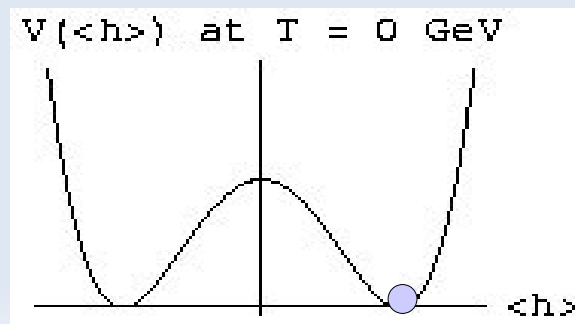
At large temperatures the symmetry is restored

$$V(h, T) = \frac{\lambda}{4} (h^2 - v^2)^2 + \text{const} \times h^2 T^2 + \text{details}$$



Electroweak symmetry breaking

Depending on the details, the phase transition can be very weak or even a cross over

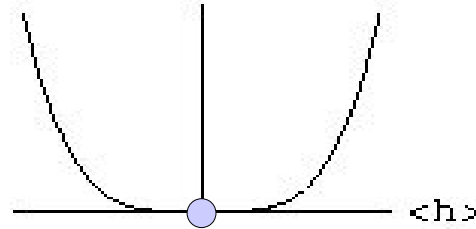


second-order
crossover

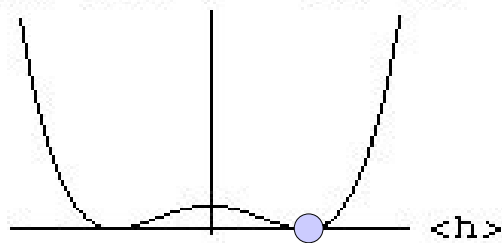
Electroweak symmetry breaking

It can also be a strong phase transition if a **potential barrier** separates the new phase from the old phase

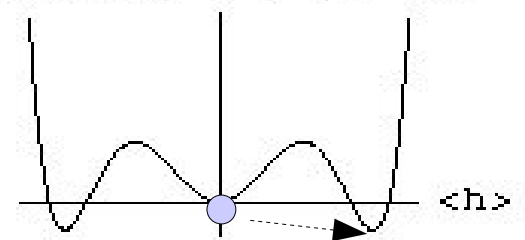
$V(\langle h \rangle)$ at $T \gg 100 \text{ GeV}$



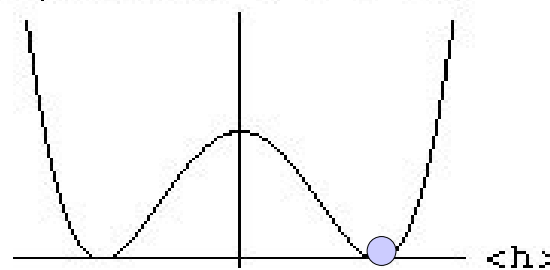
$V(\langle h \rangle)$ at $T \sim 100 \text{ GeV}$



$V(\langle h \rangle)$ at $T \sim 100 \text{ GeV}$



$V(\langle h \rangle)$ at $T = 0 \text{ GeV}$



second-order
crossover

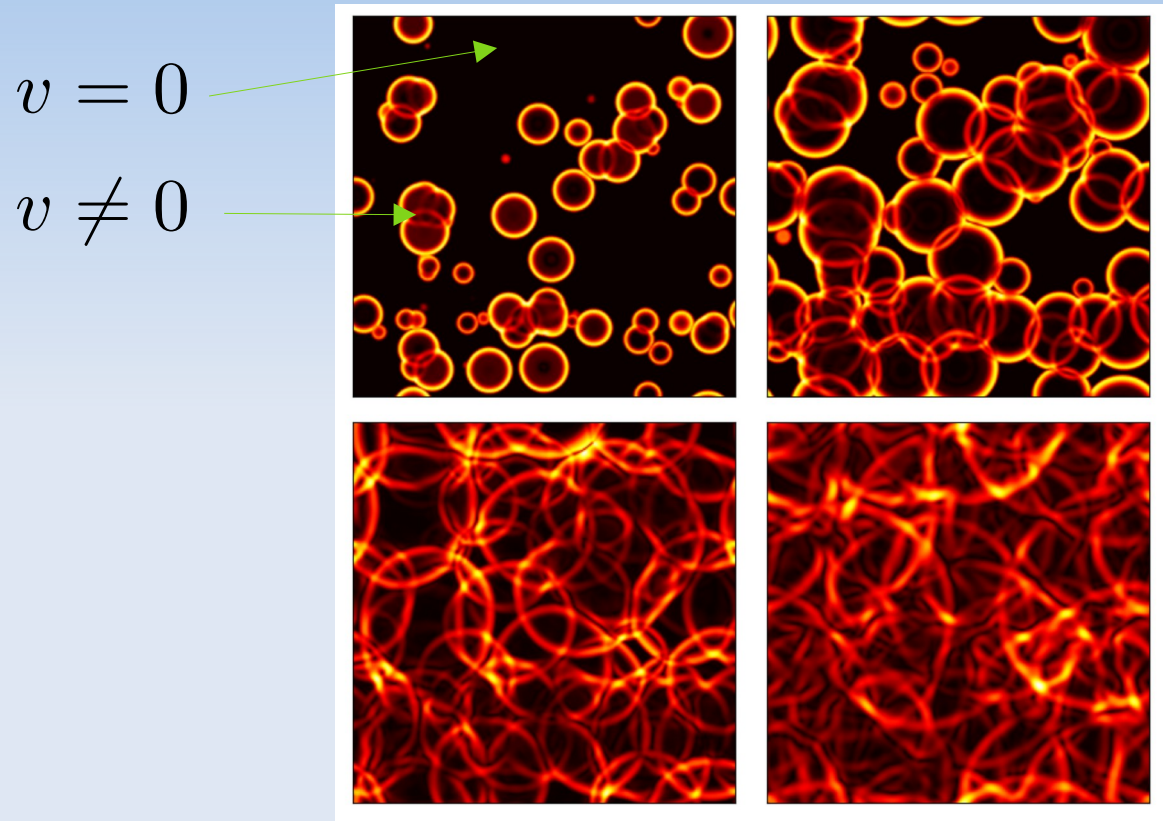
first-order

First-order phase transitions



- first-order phase transitions proceed by bubble nucleations
- in case of the electroweak phase transition, the "Higgs bubble wall" separates the symmetric from the broken phase
- this is a violent process ($v_{wall} \simeq O(c)$) that drives the plasma out-of-equilibrium and sets the fluid into motion

Gravitational waves



During the first-order phase transitions, the nucleated bubbles expand and set the fluid into motion. Finally, the colliding bubbles break spherical symmetry and generate **stochastic gravitational waves**.

Outline



Back of the envelope

The wavelength of the produced gravitational waves scales as

$$\lambda_{now} \simeq \text{few \% of } \frac{1}{H_*} \times \frac{T_*}{T_{now}}$$

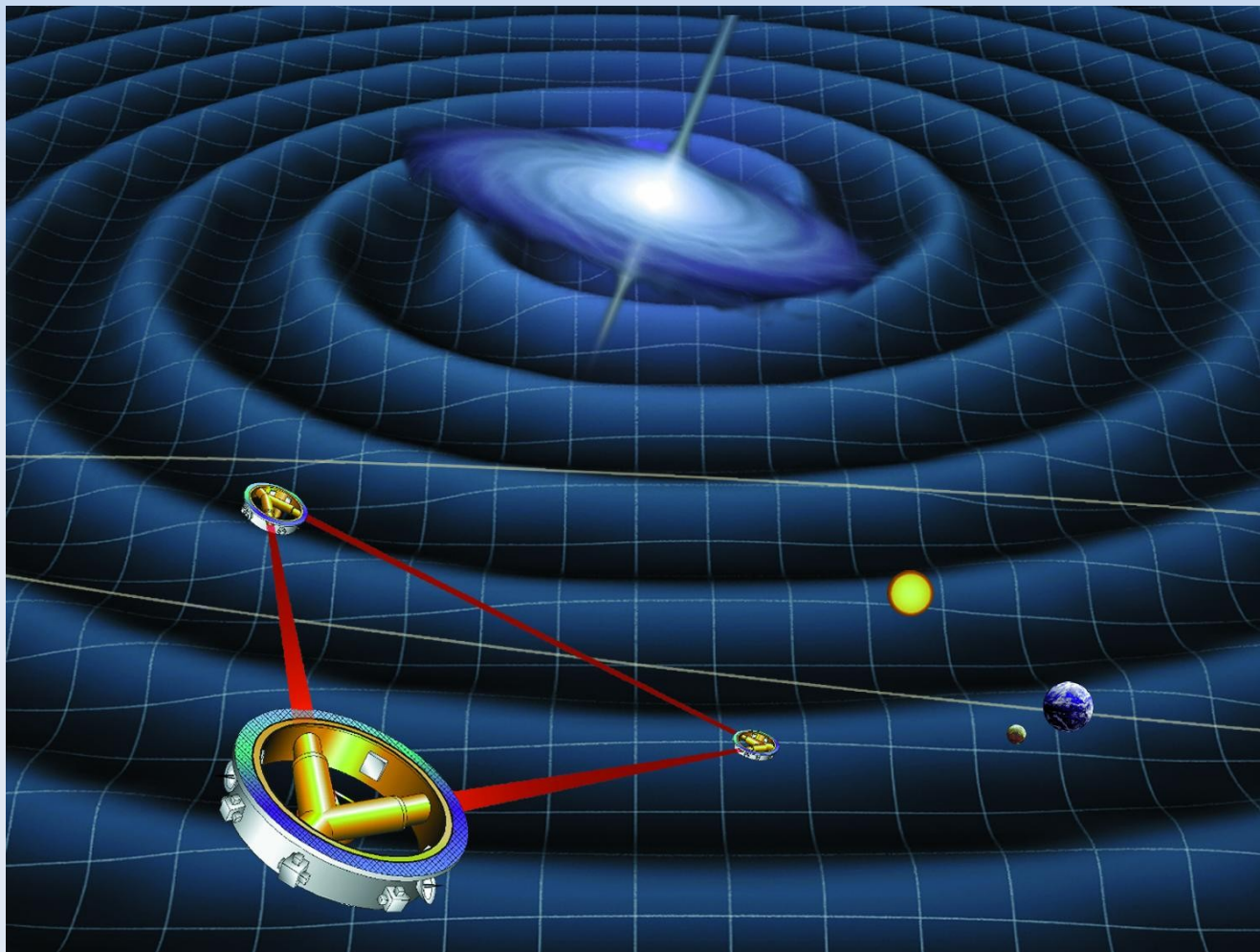
size of the
observable universe

$$H_* \simeq \frac{T_*^2}{M_{Planck}}$$

redshifting

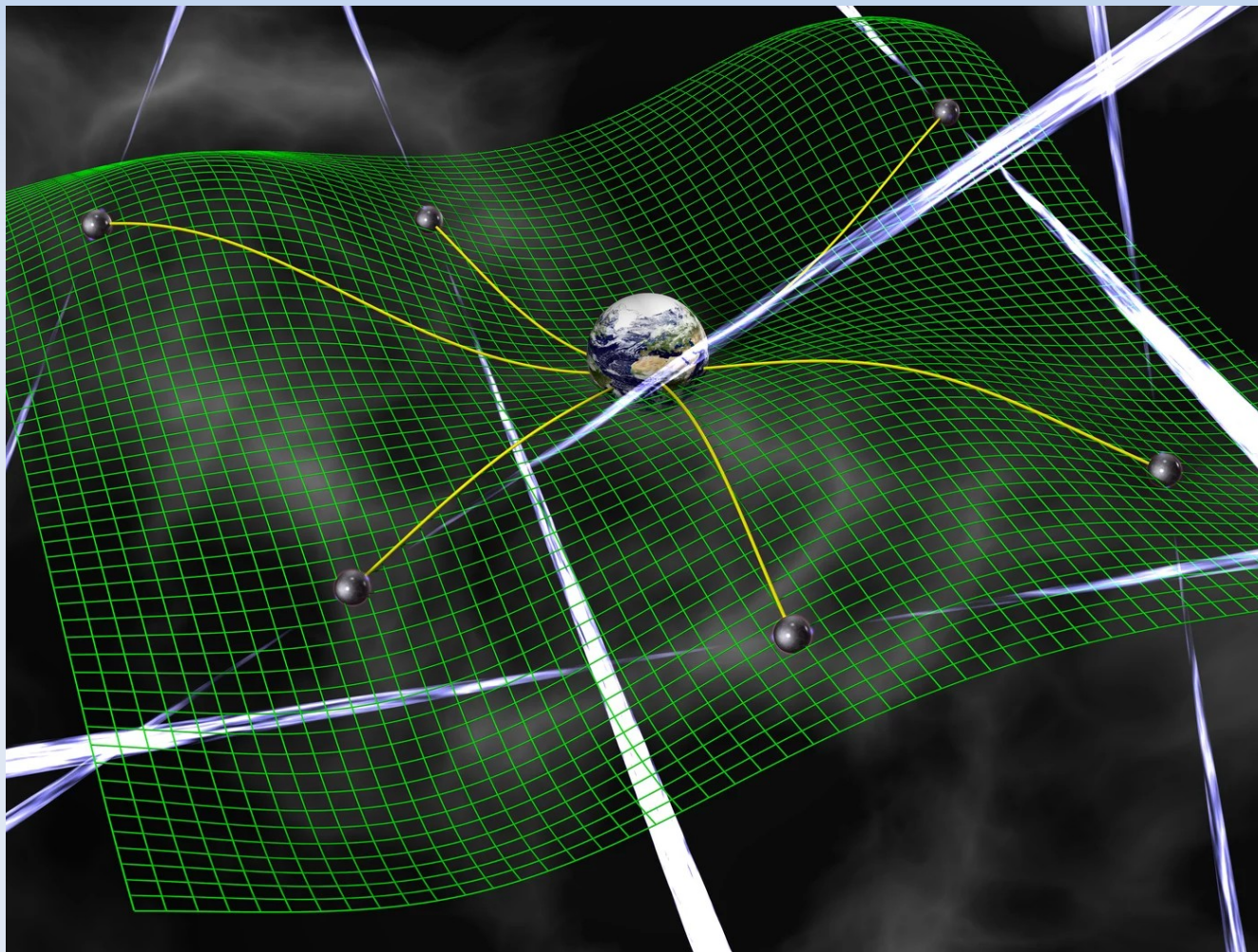
LISA

$$T_* \simeq 100 \text{ GeV} \rightarrow \lambda_{now} \simeq 10^{10} m$$



Pulsar timing arrays

$$T_* \simeq 100 \text{ MeV} \rightarrow f_{\text{now}} \simeq \text{nHz}$$



Outline



Phase transitions have a rich phenomenology

Considering only a single expanding bubble during the phase transitions, there are different expansion modes depending on the velocity of the bubble wall

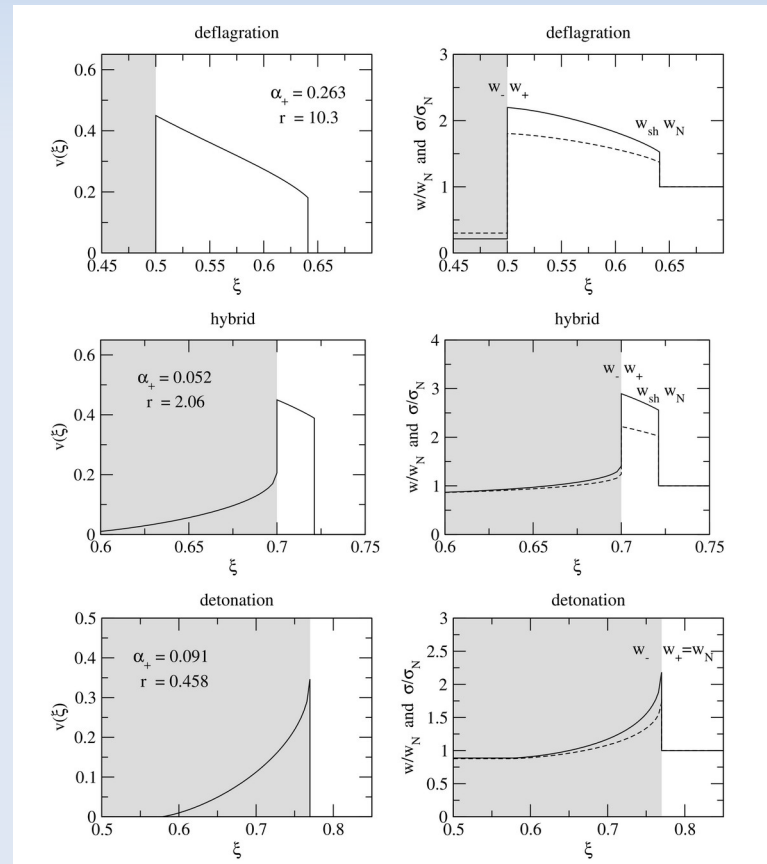
Phase transitions have a rich phenomenology

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deflagrations

hybrids

detonations

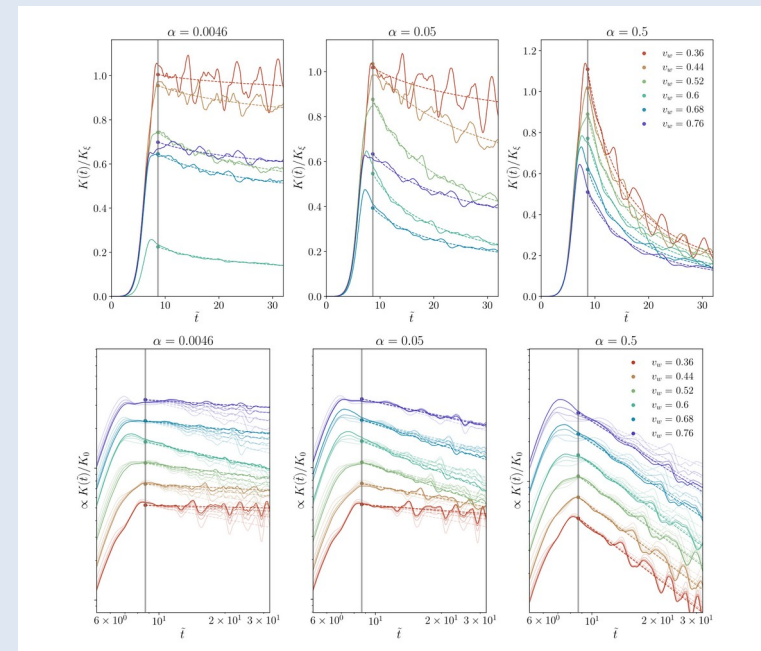


Phase transitions have a rich phenomenology

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The GWs are produced by sound waves that reside for a long time in the plasma. Sound waves decay only due to expansion and non-linearities

Acoustic turbulence is an important feature of the dynamics



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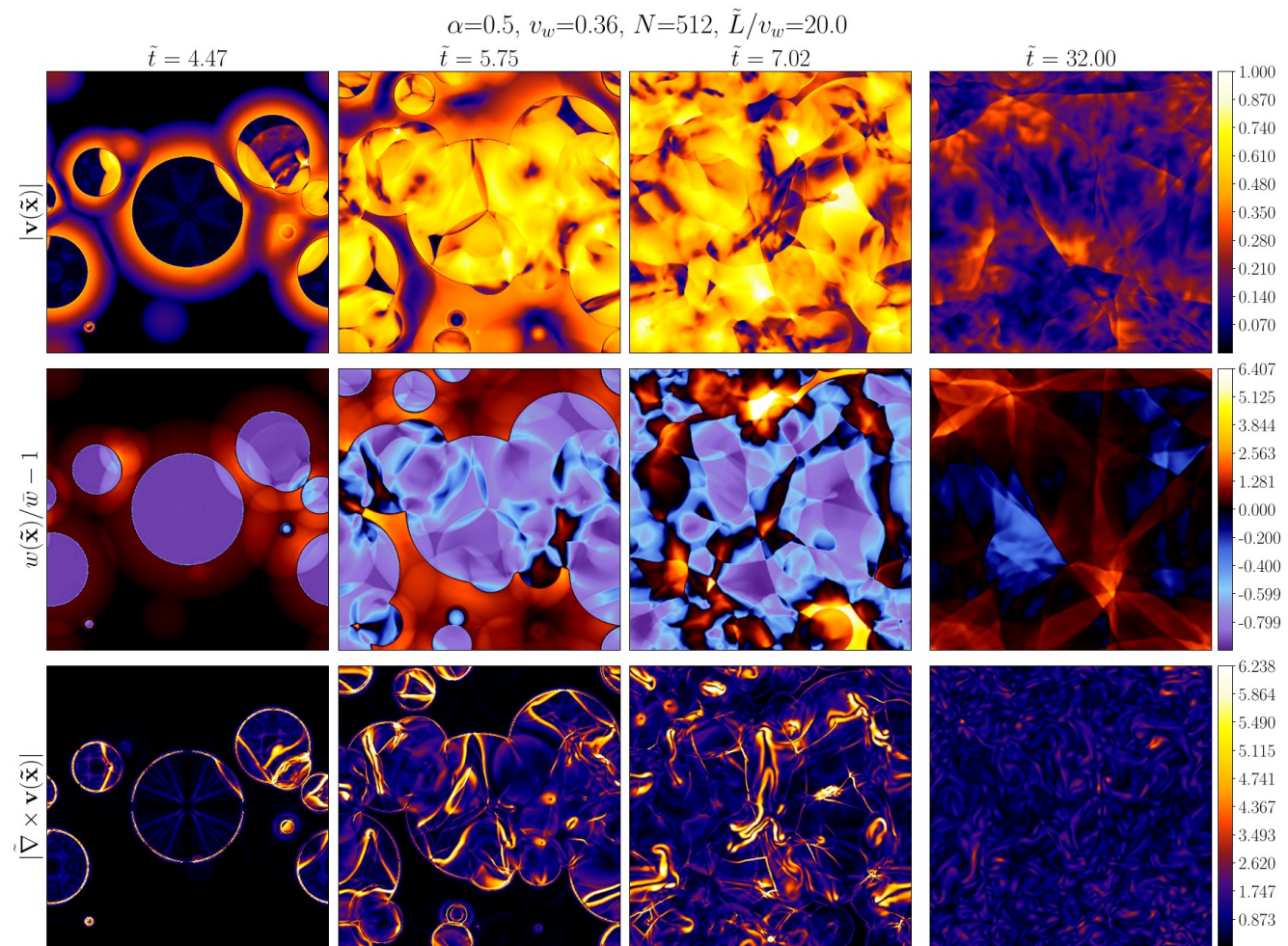
→ reliable GW predictions are based on hydrodynamic simulations of the phase transition

Hydro simulations

kinetic
energy

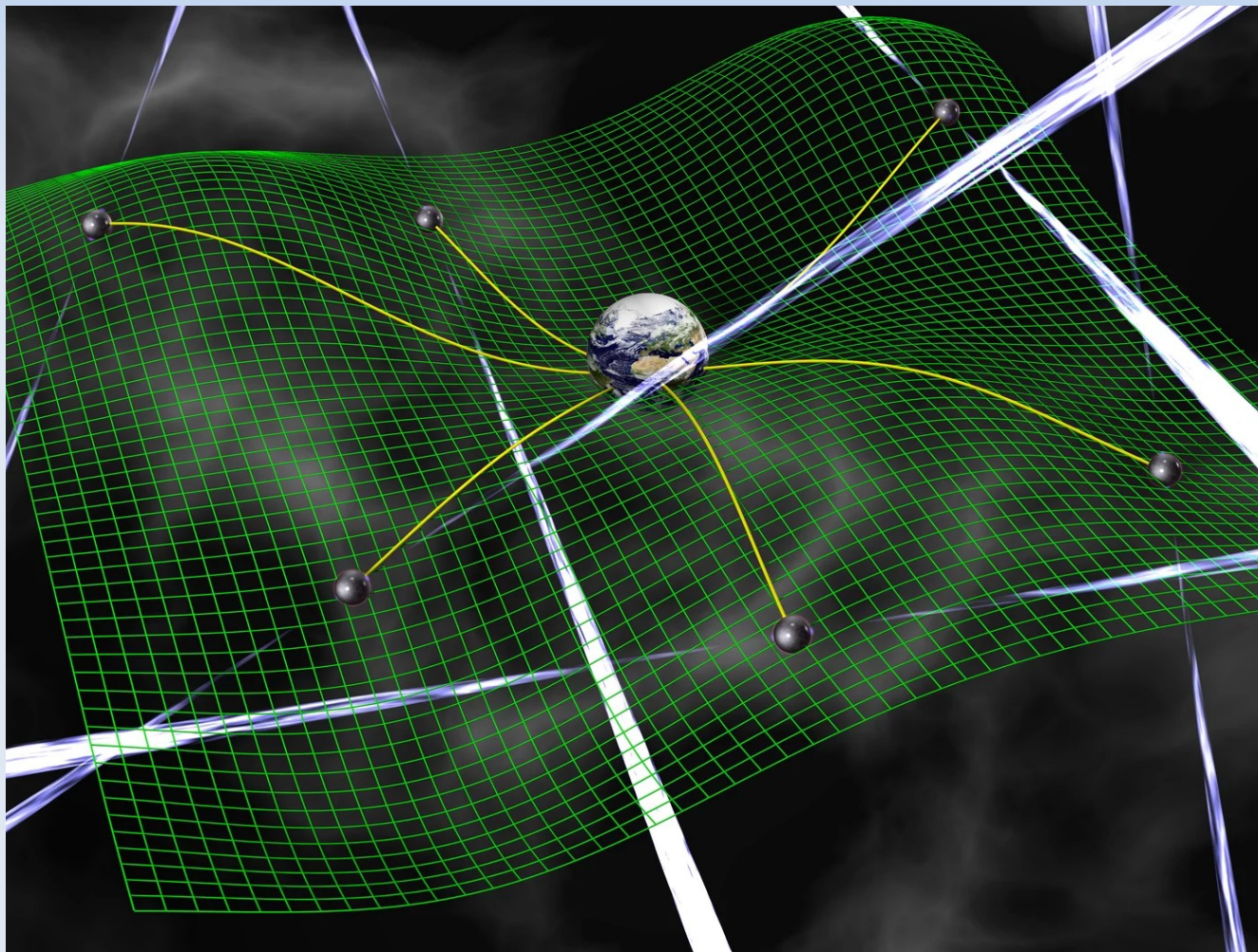
thermal
energy

vorticity

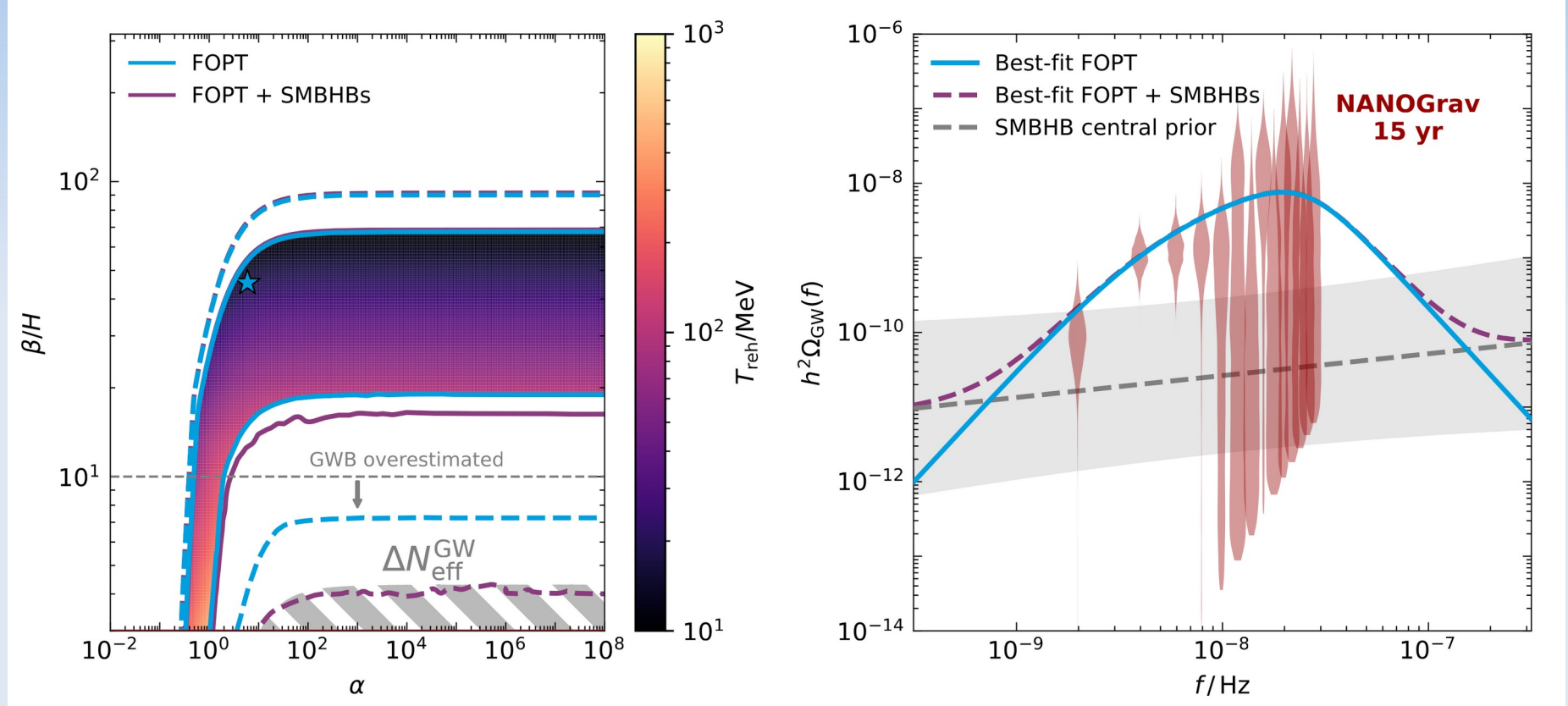


Pulsar timing arrays

$$T_* \simeq 100 \text{ MeV} \rightarrow f_{\text{now}} \simeq \text{nHz}$$



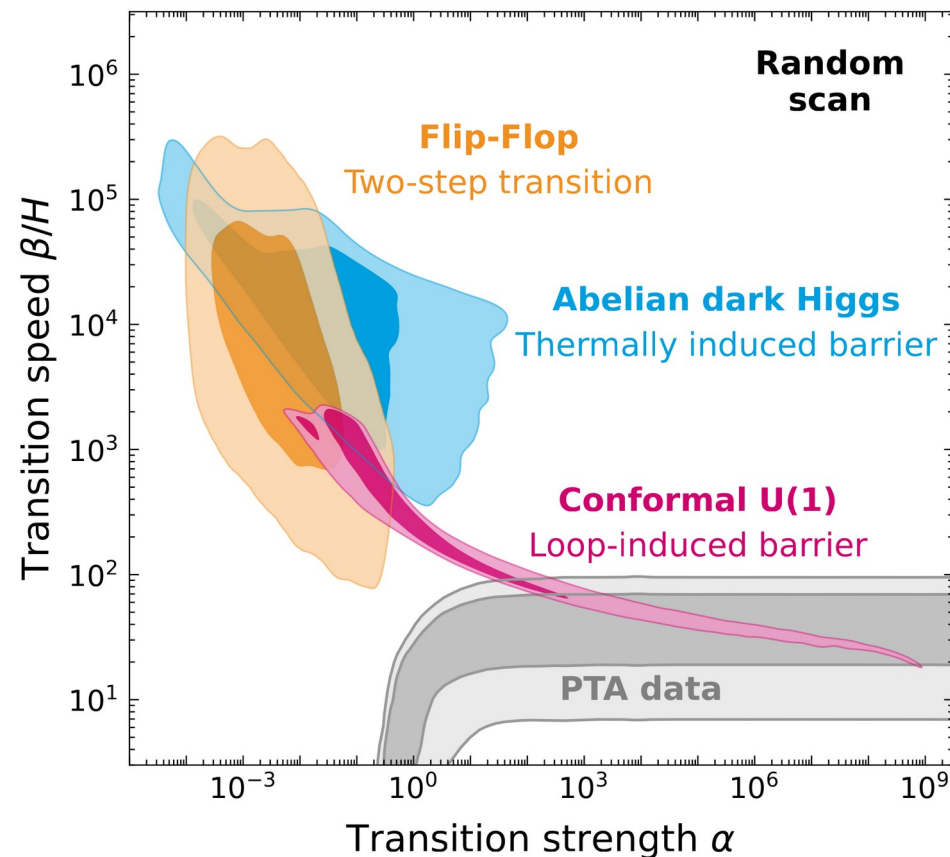
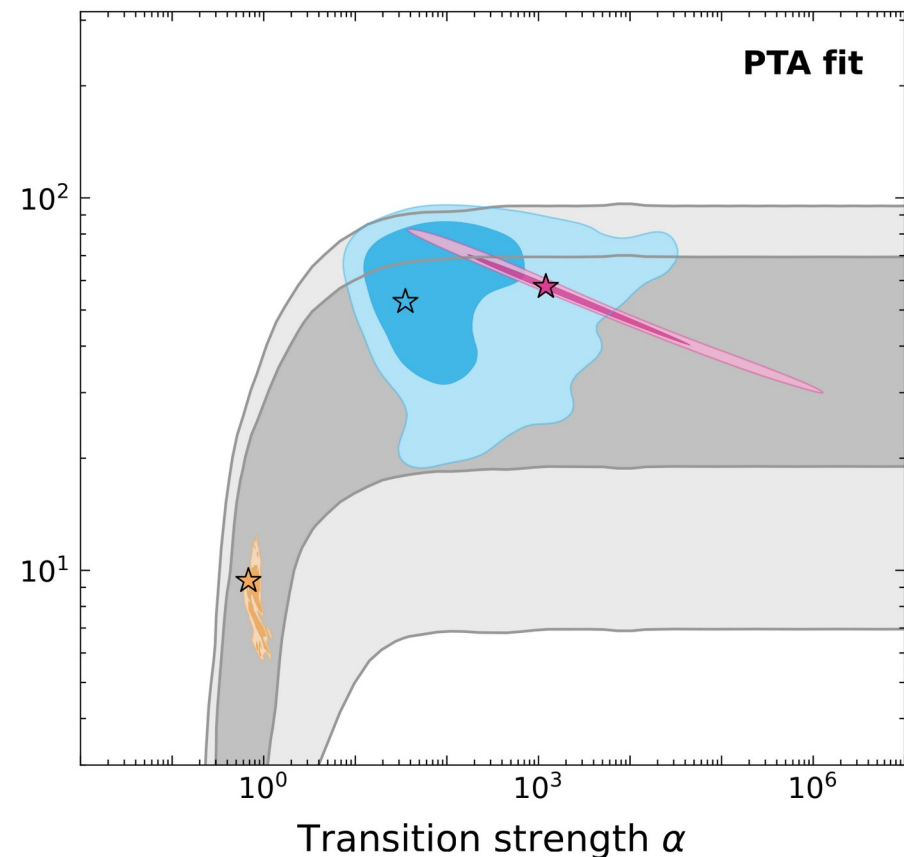
The PTA signal serves as a testbed for GW spectra



A model-agnostic fit of the GW to spectra from 1st order phase transitions reproduces the signal very well.

[Bringmann, TK, Matuszak, Schmidt-Hoberg, Tasillo '26]

Some model building



The data tends to favor very strong and slow phase transitions. The ideal model class are models with **near-conformal** behavior. (phase transition induced by the running of couplings).

[Bringmann, TK, Matuszak, Schmidt-Hoberg, Tasillo '26]

Summary

Cosmological phase transitions are an intriguing source of primordial gravitational waves

LISA (~2035) will provide a complementary probe of the electroweak symmetry breaking via GWs from PTs

Current PTA experiments hint at a GW signal and serve as a testbed driving the field forward

