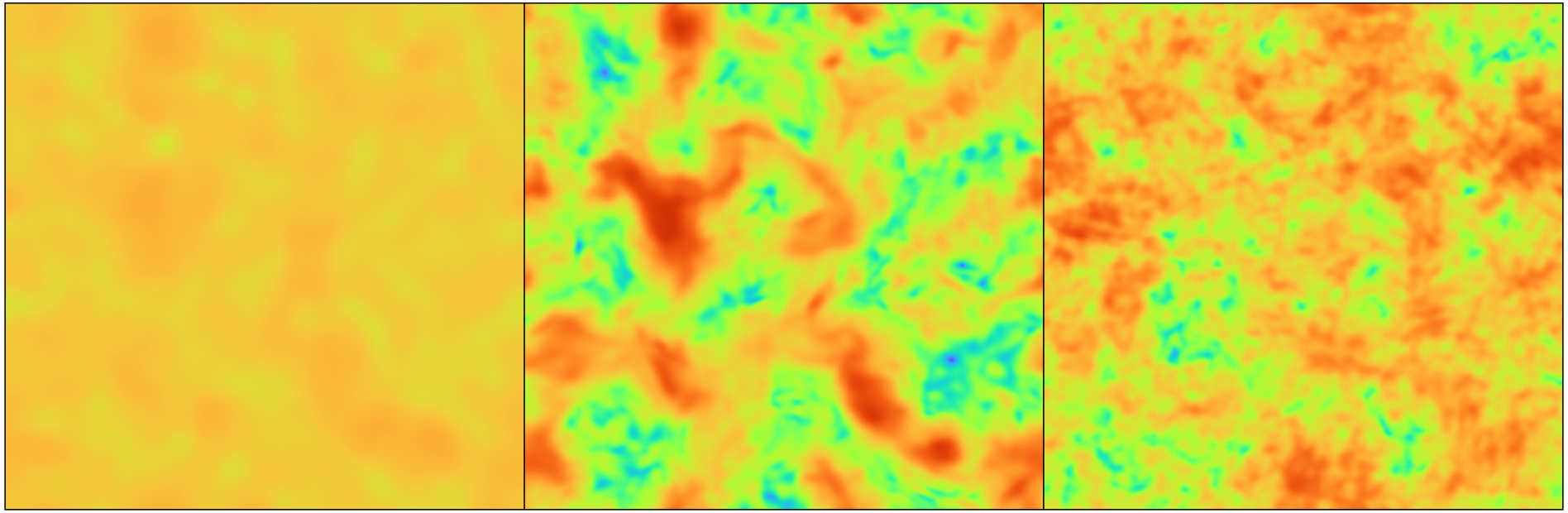
Gravitational waves probes of reheating after inflation



Zach Weiner

University of Illinois at Urbana-Champaign --> U Washington Seattle

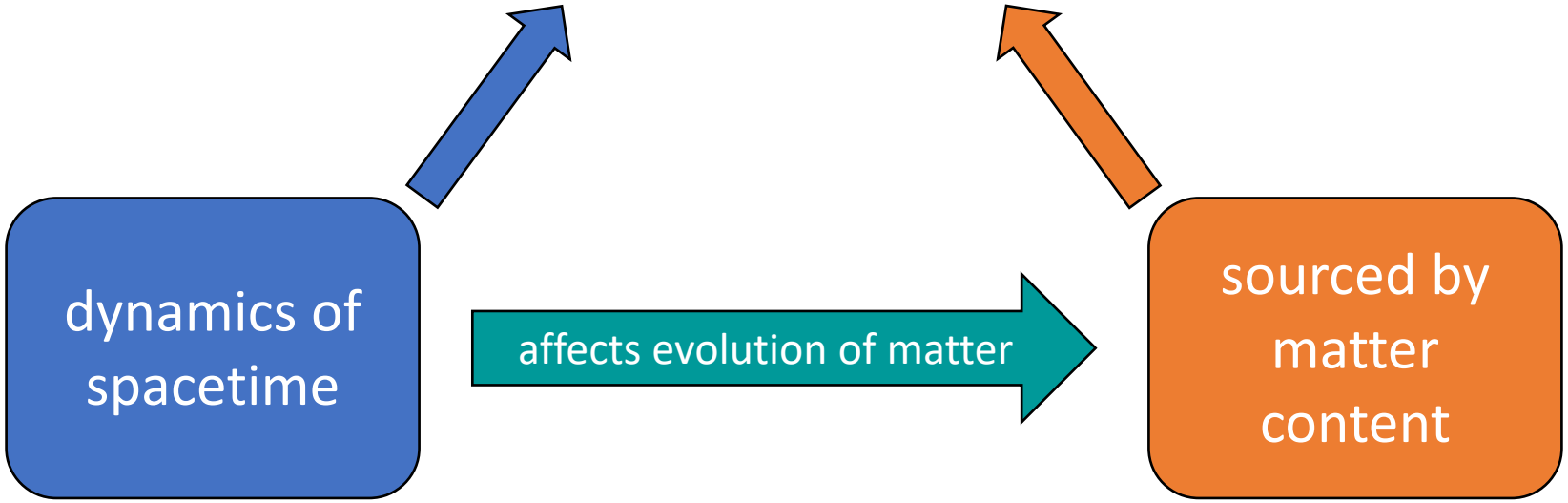
CSGF Program Review 2021

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

DOE CSGF

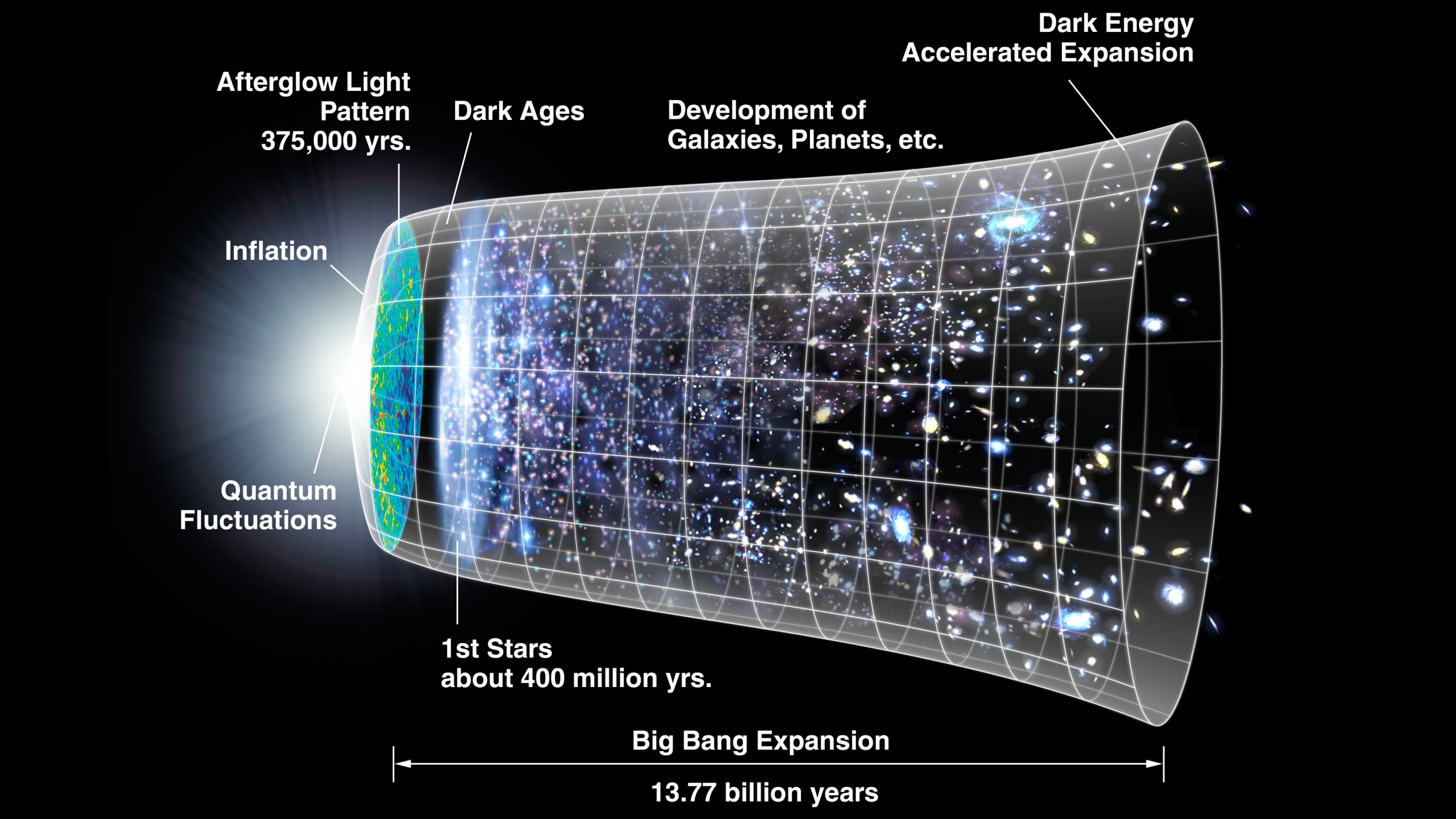
Einstein's general relativity

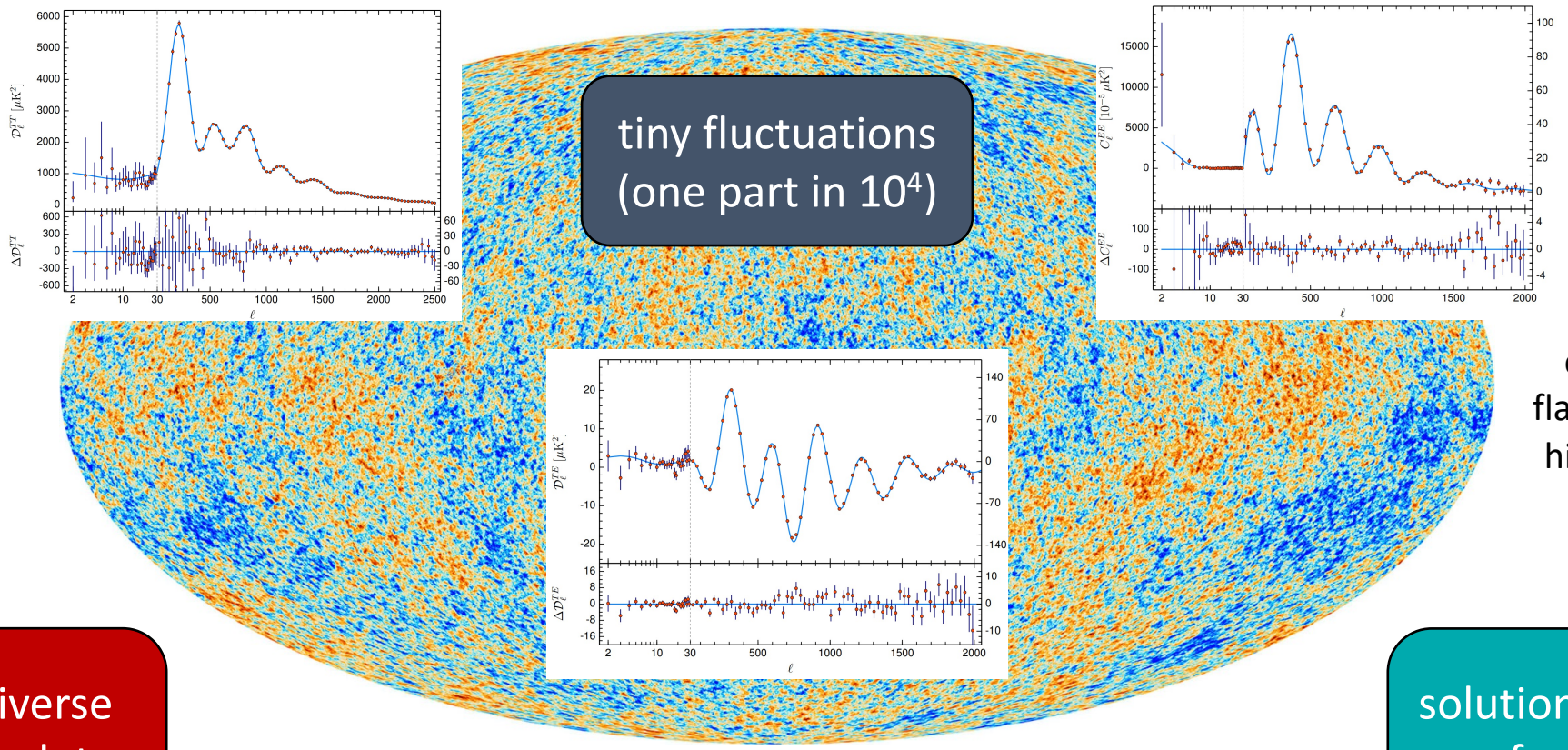
$$G_{\mu\nu} \sim T_{\mu\nu}$$



two (of many) confirmed predictions:

- the Universe **expands**
- anisotropic stress sources **gravitational waves**

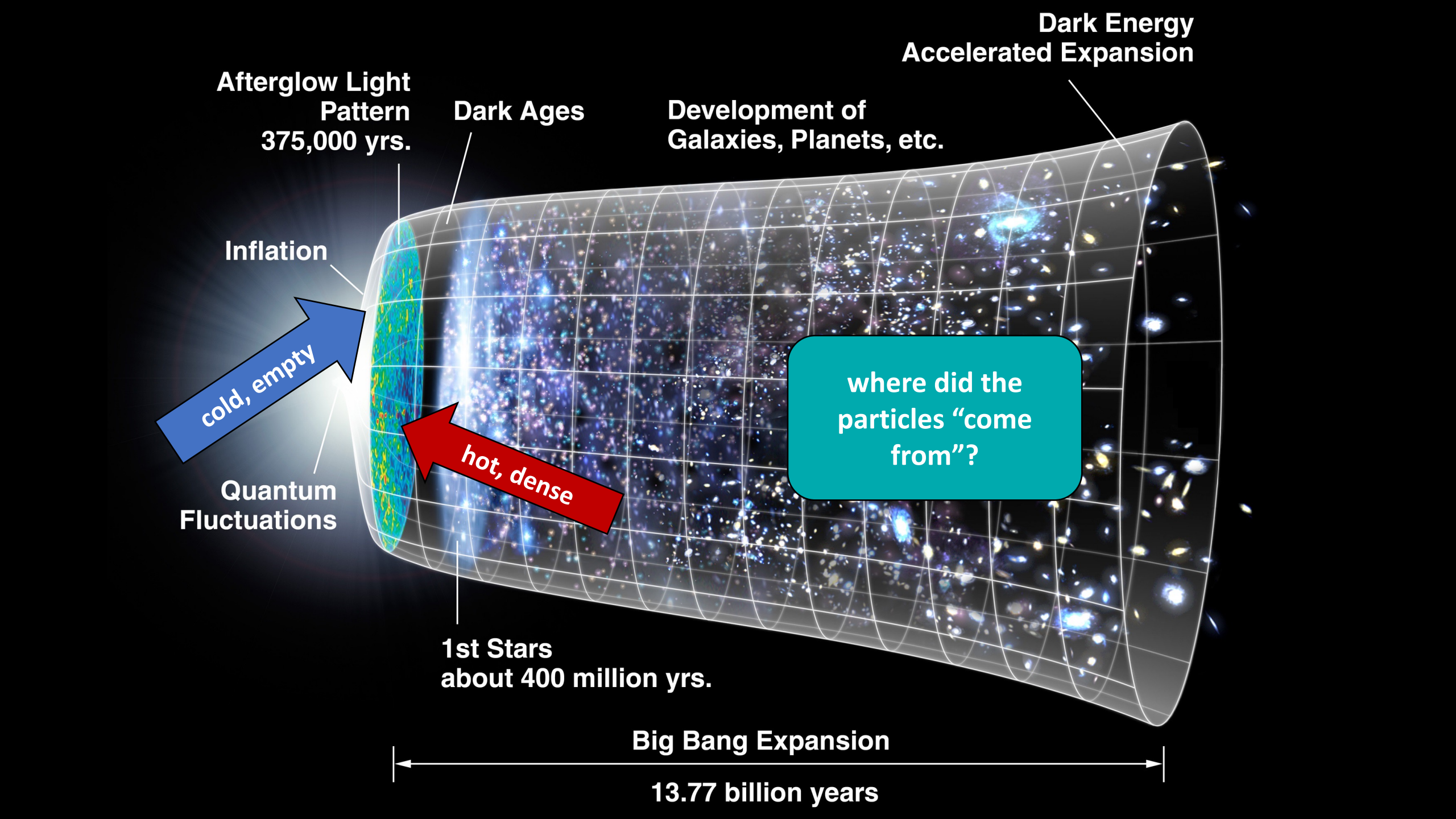

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years



also a causal explanation for flatness and lack of high-energy relics

problem: Universe isn't old enough to agree so precisely!

solution: early phase of accelerated expansion


Dark Energy
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375,000 yrs.
Dark Ages
Development of
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Inflation
cold, empty
hot, dense
where did the
particles “come
from”?
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
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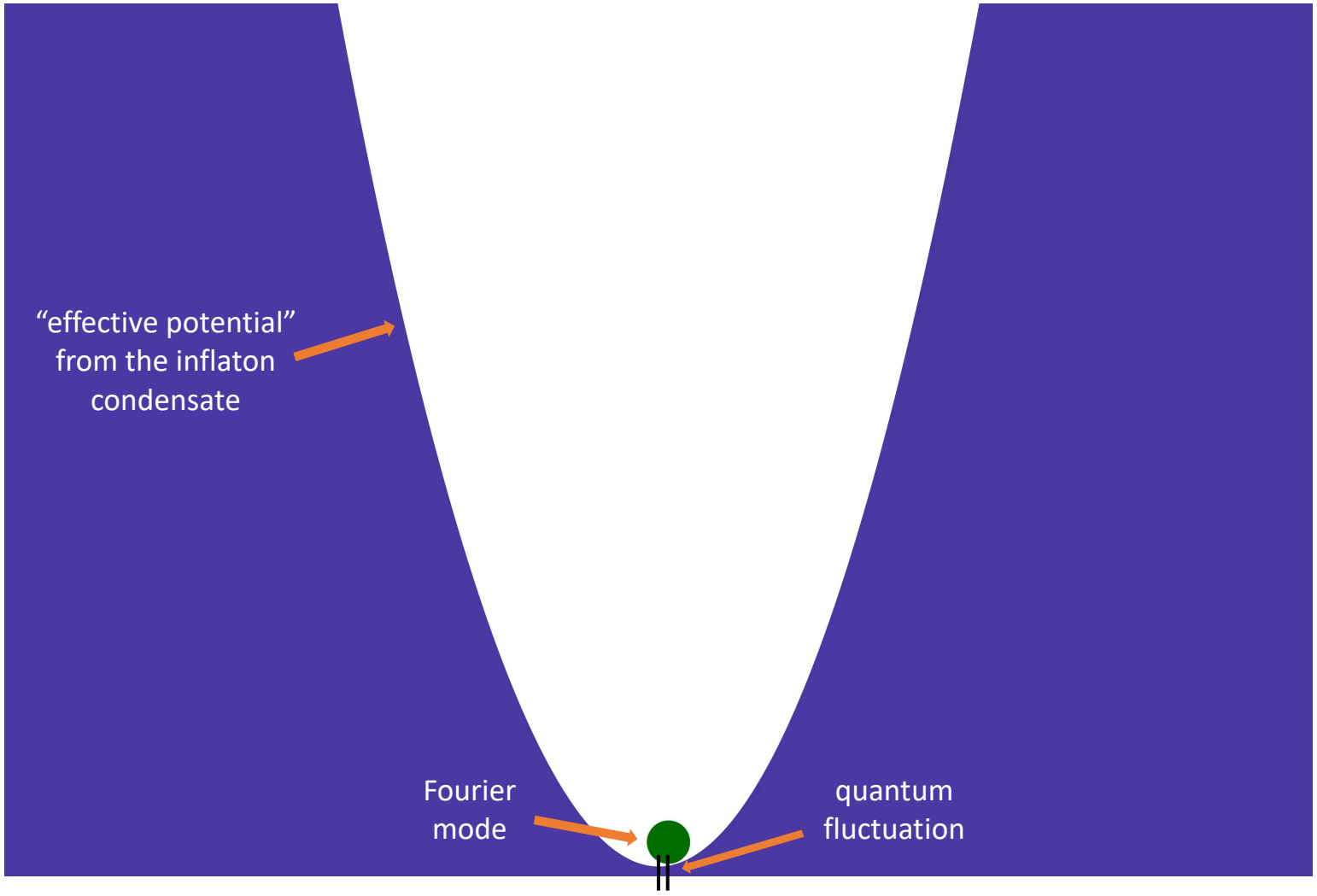
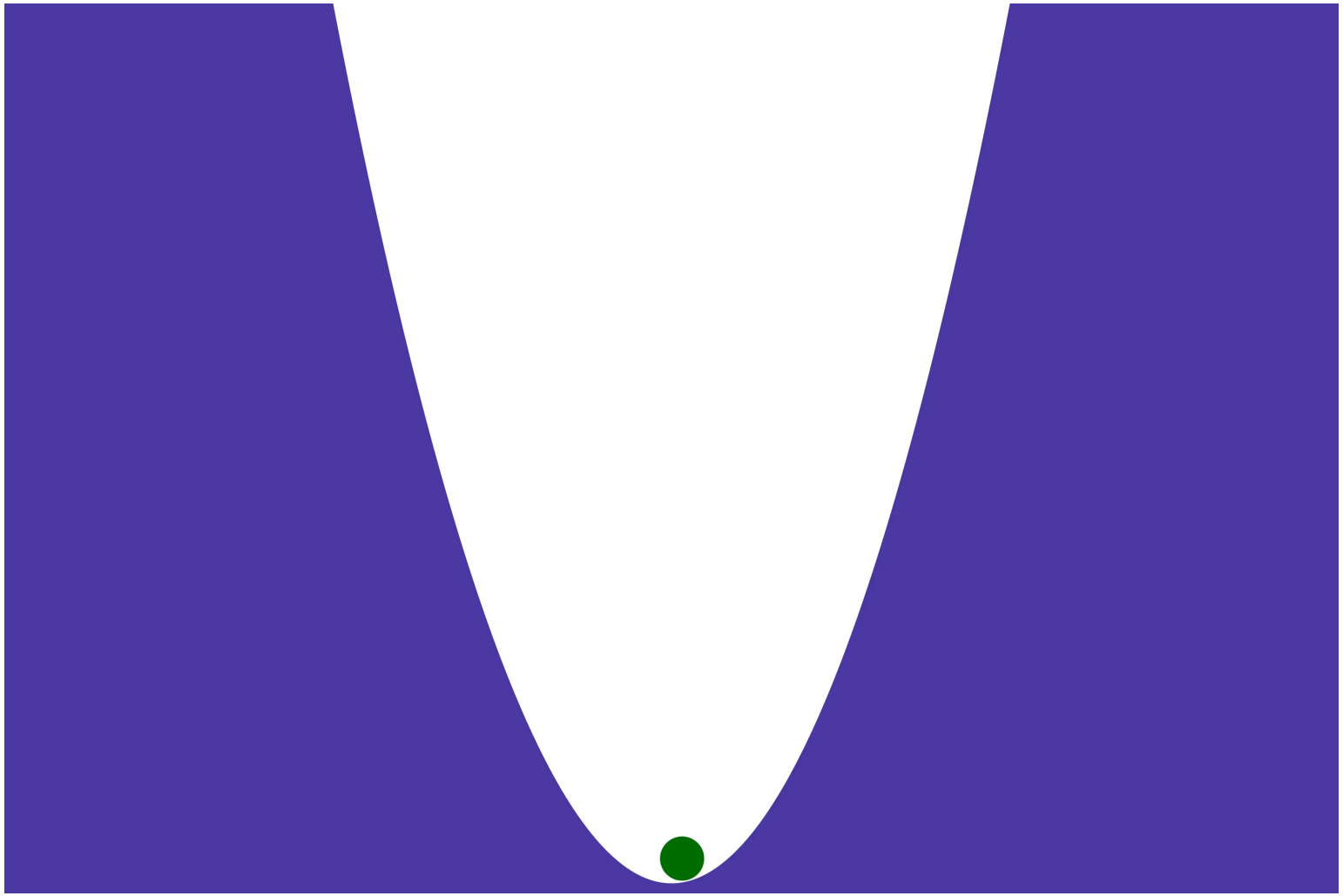
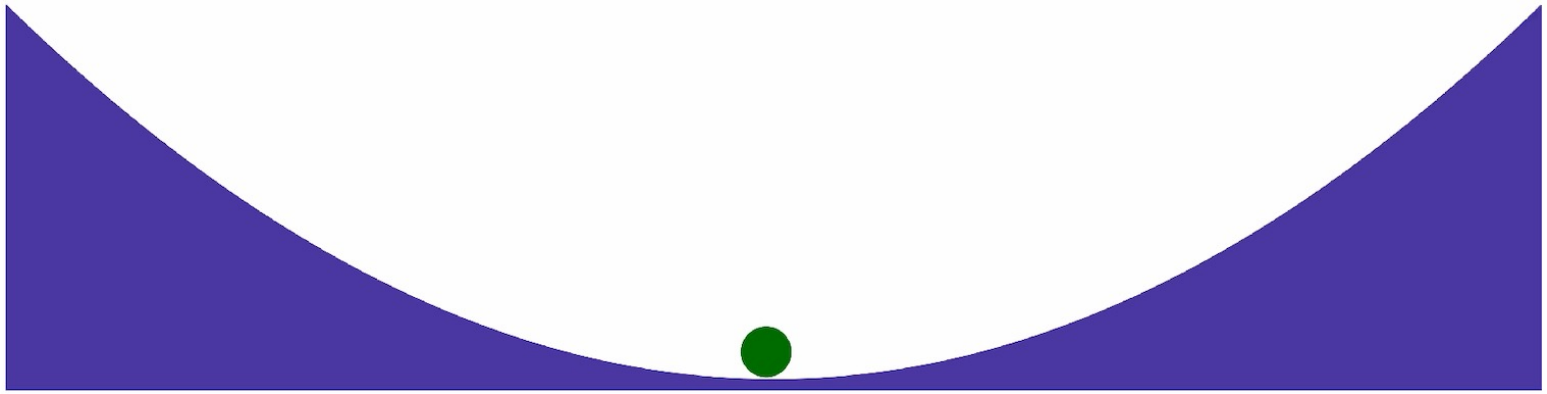
Off resonance



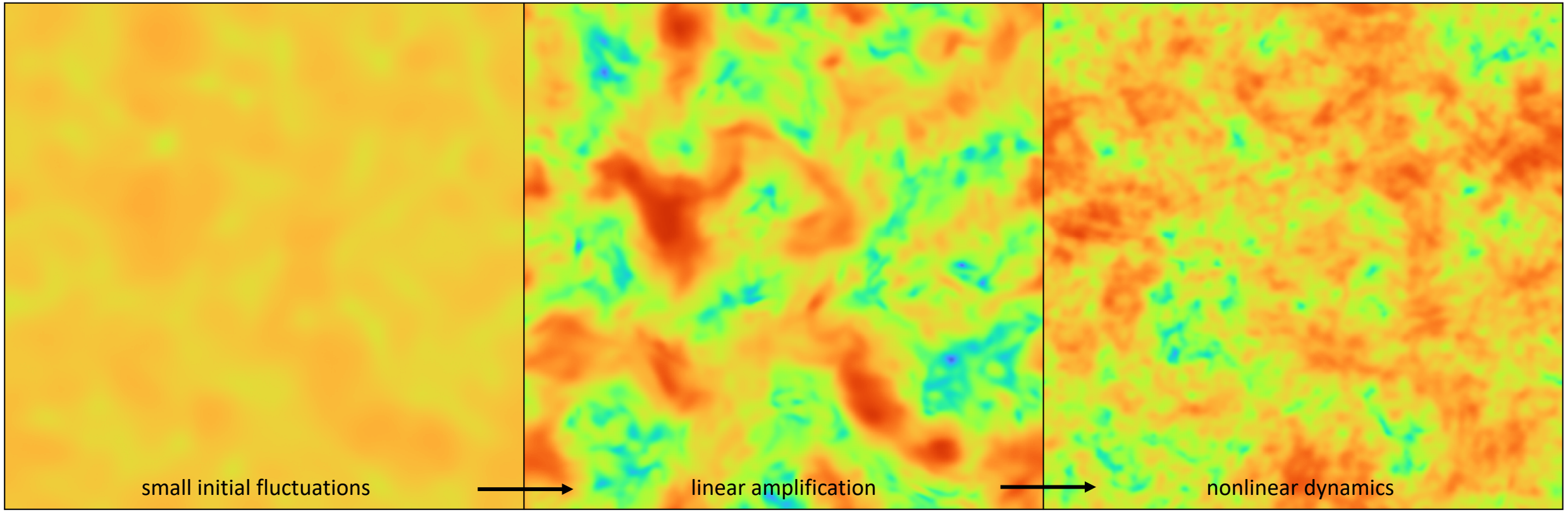
On resonance



On resonance



Tachyonic production of gauge bosons



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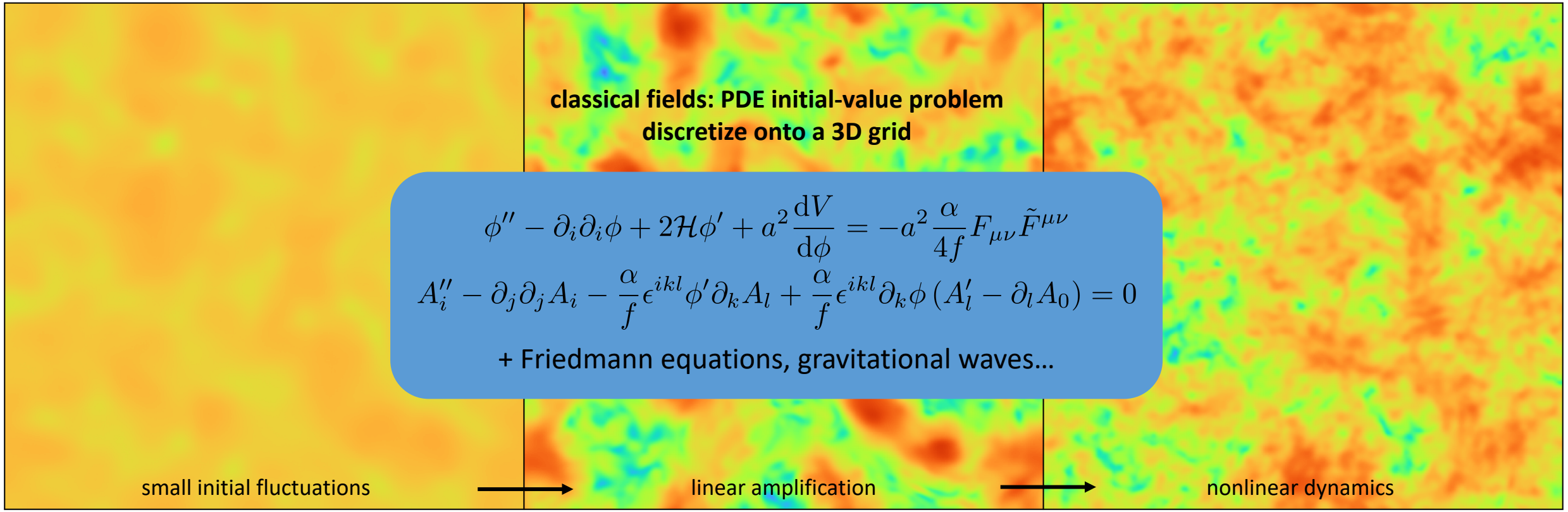
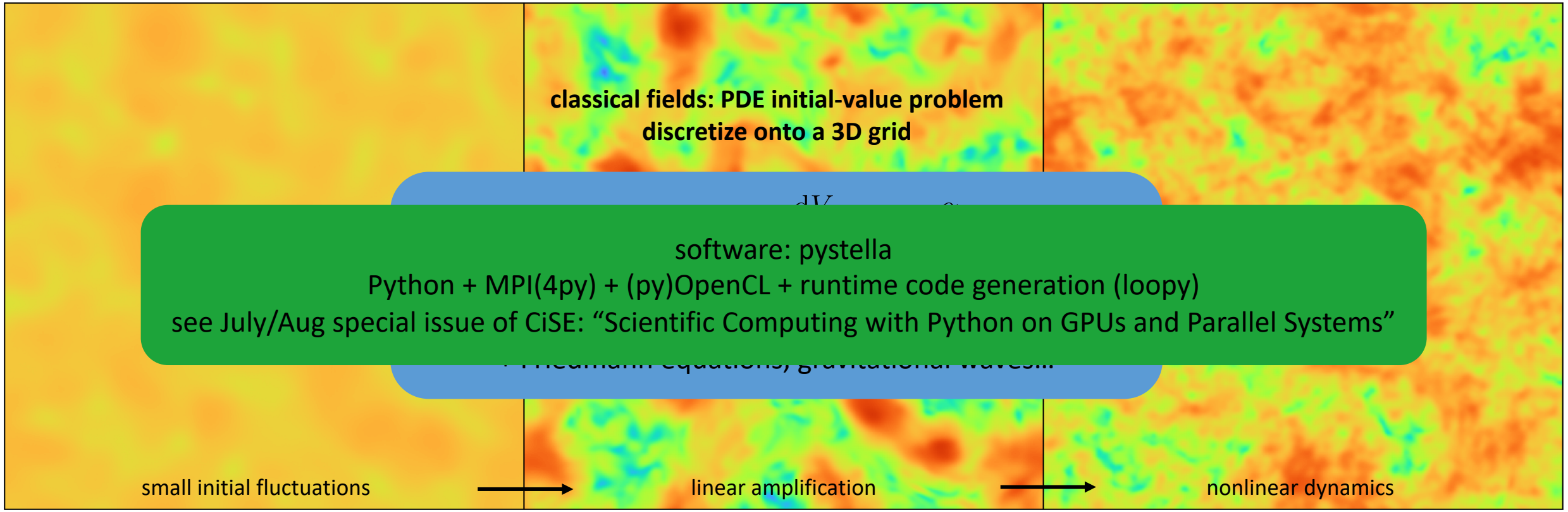


Tachyonic production of gauge bosons



Generation of gravitational waves

Preheating generates anisotropic stress

$$T_{ij}^{A} = -\frac{1}{a^2}\left[E_i E_j + B_i B_j + \frac{\delta_{ij}}{2}\left(\mathbf{E}^2 + \mathbf{B}^2\right)\right]$$

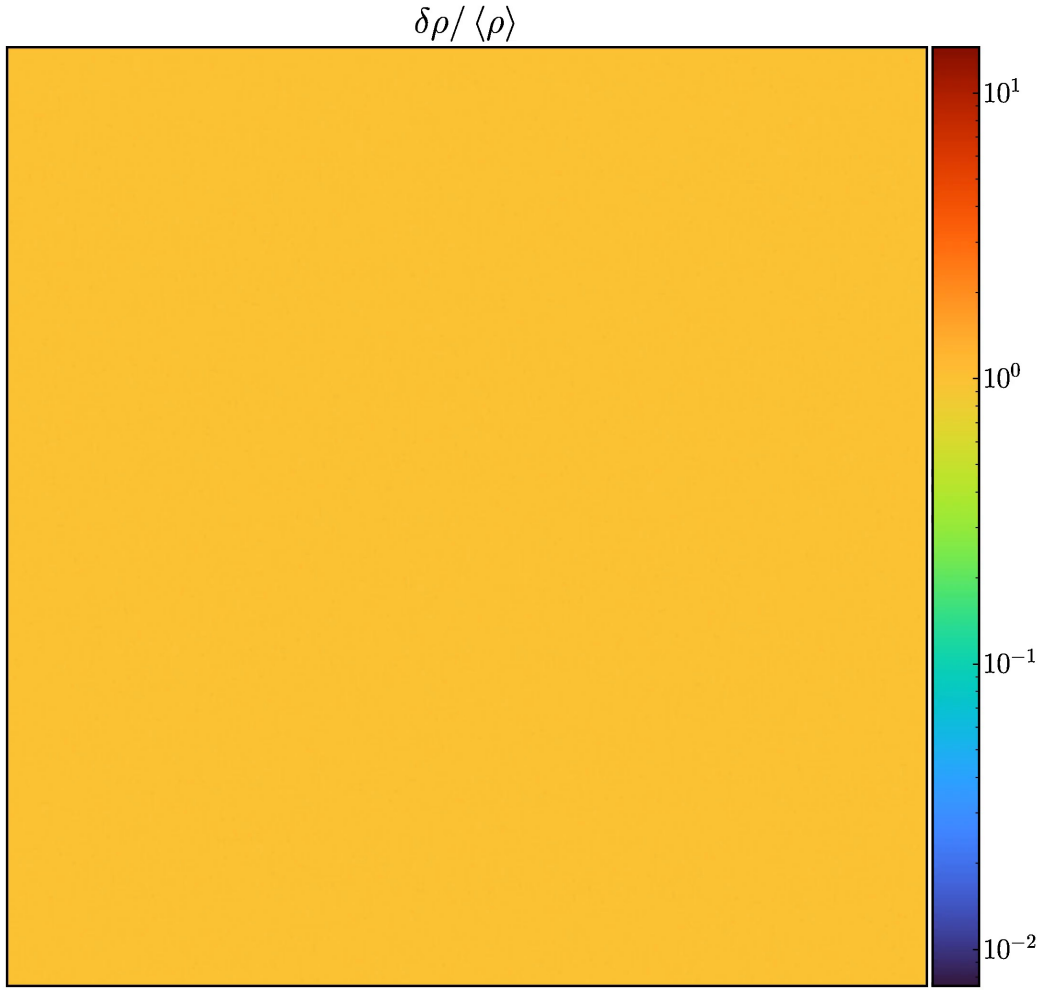
$$T_{ij}^{\phi} = \partial_i\phi\partial_j\phi - a^2\delta_{ij}\left(\frac{1}{2}\partial_\mu\partial^\mu\phi + V(\phi)\right)$$

which sources gravitational waves

$$h_{ij}'' - \partial_k\partial_k h_{ij} + 2\mathcal{H}h_{ij}' = \frac{2}{M_{\rm pl}^2}T_{ij}^{\rm TT}$$

linear, inhomogeneous PDE

transverse-traceless projection of the stress tensor



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which sources gravitational waves

$$h''_{ij} - \partial_k\partial_k h_{ij} + 2\mathcal{H}h'_{ij} = \frac{2}{M^2_{\rm pl}}T^{\rm TT}_{ij}$$

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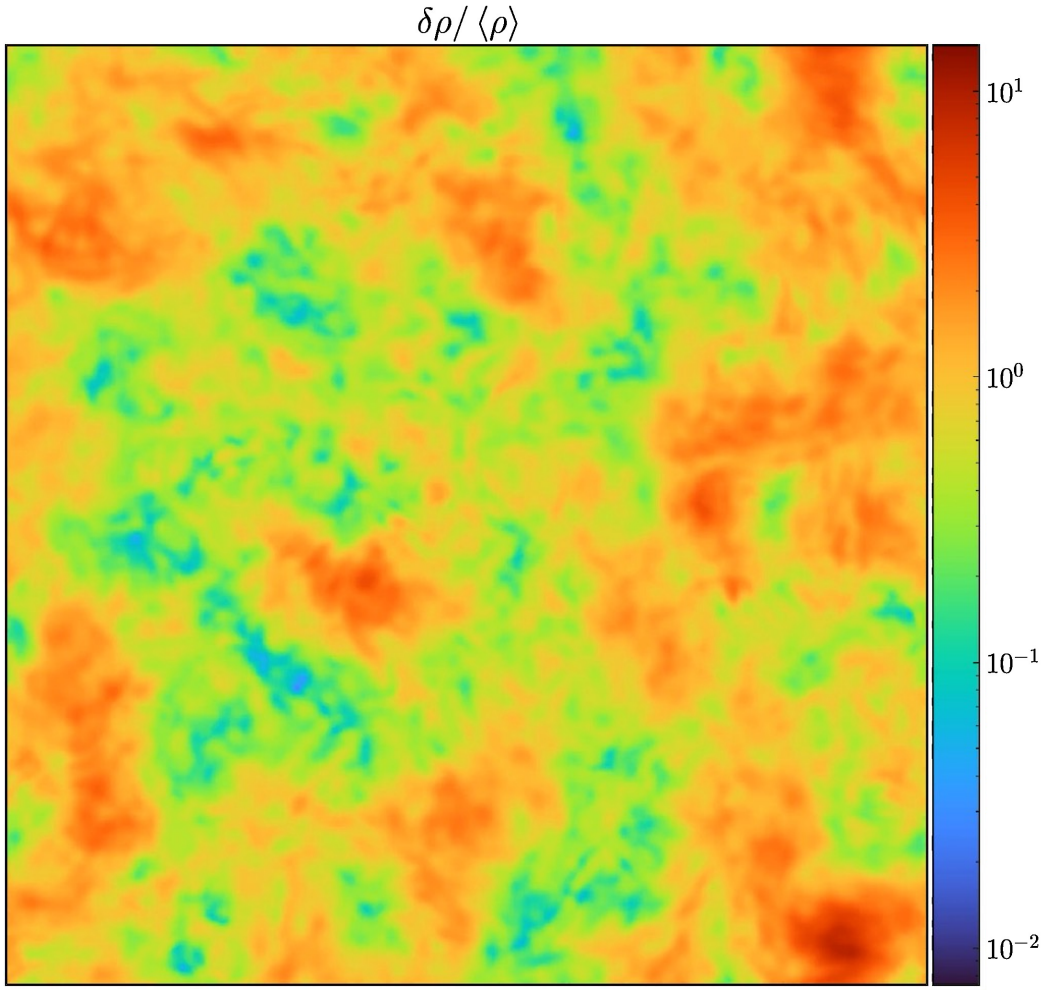
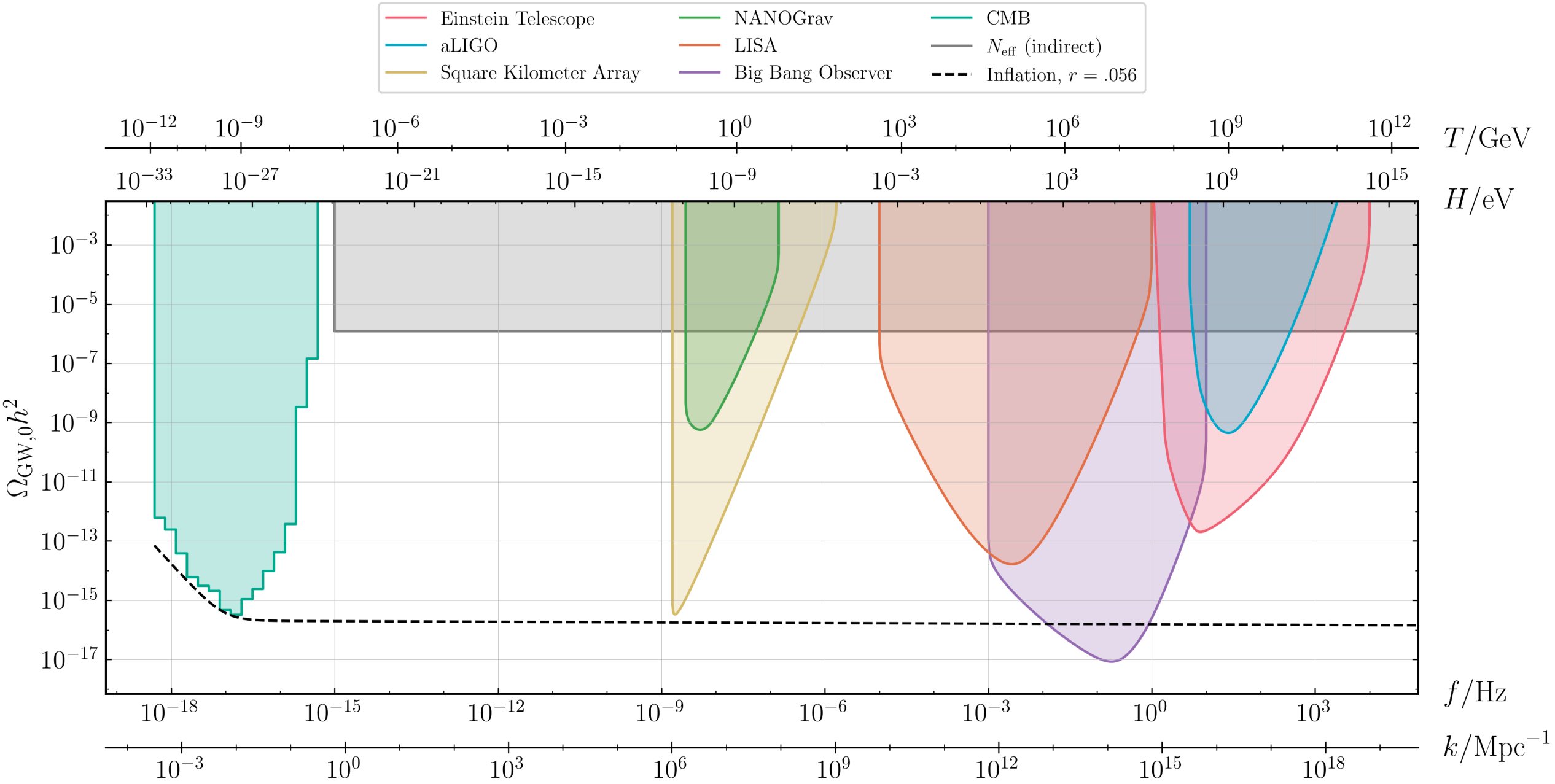
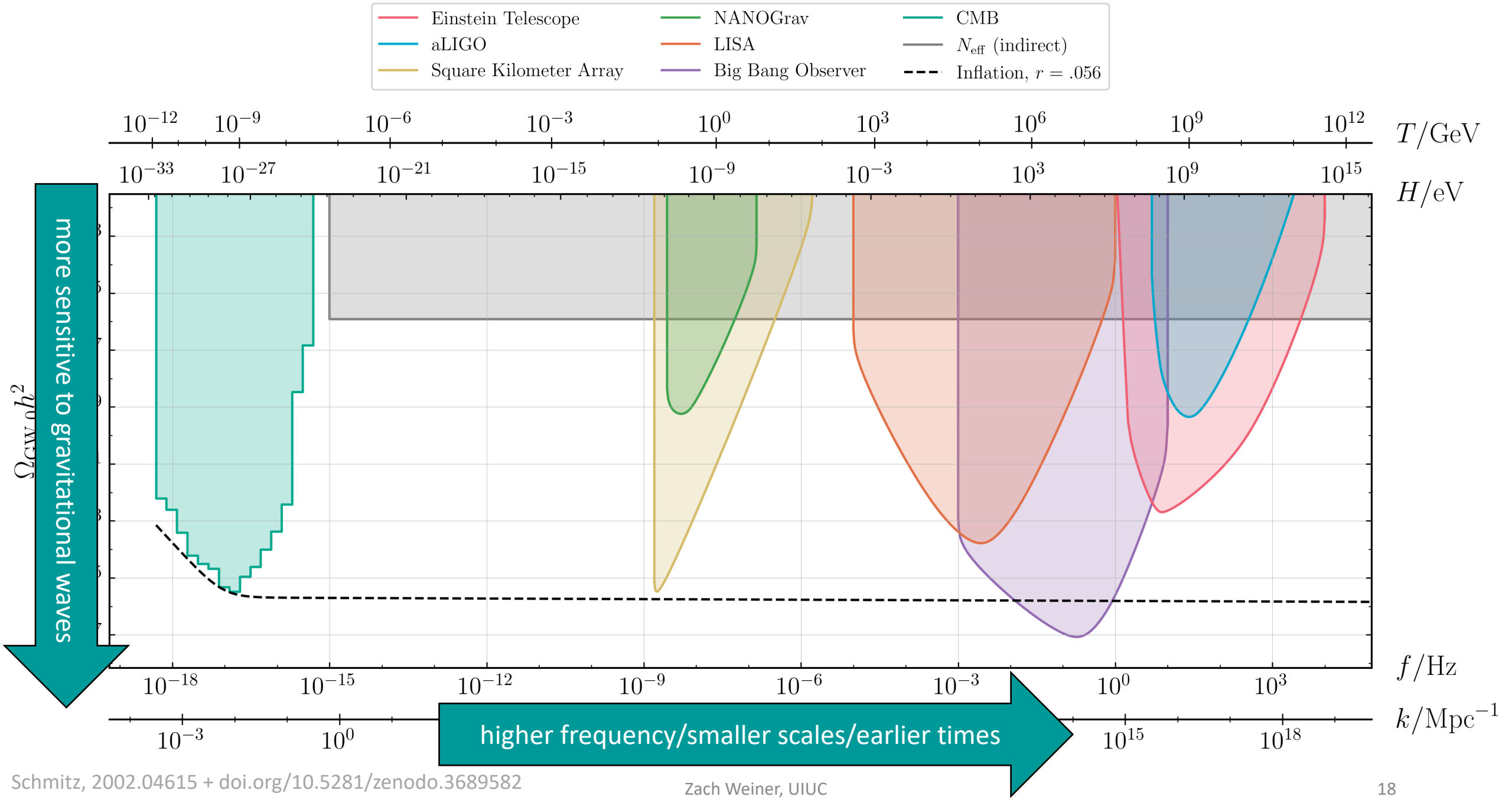




Schmitz, 2002.04615 + doi.org/10.5281/zenodo.3689582
CMB curve: Clarke, Copeland, Moss 2004.11396



Schmitz, 2002.04615 + doi.org/10.5281/zenodo.3689582
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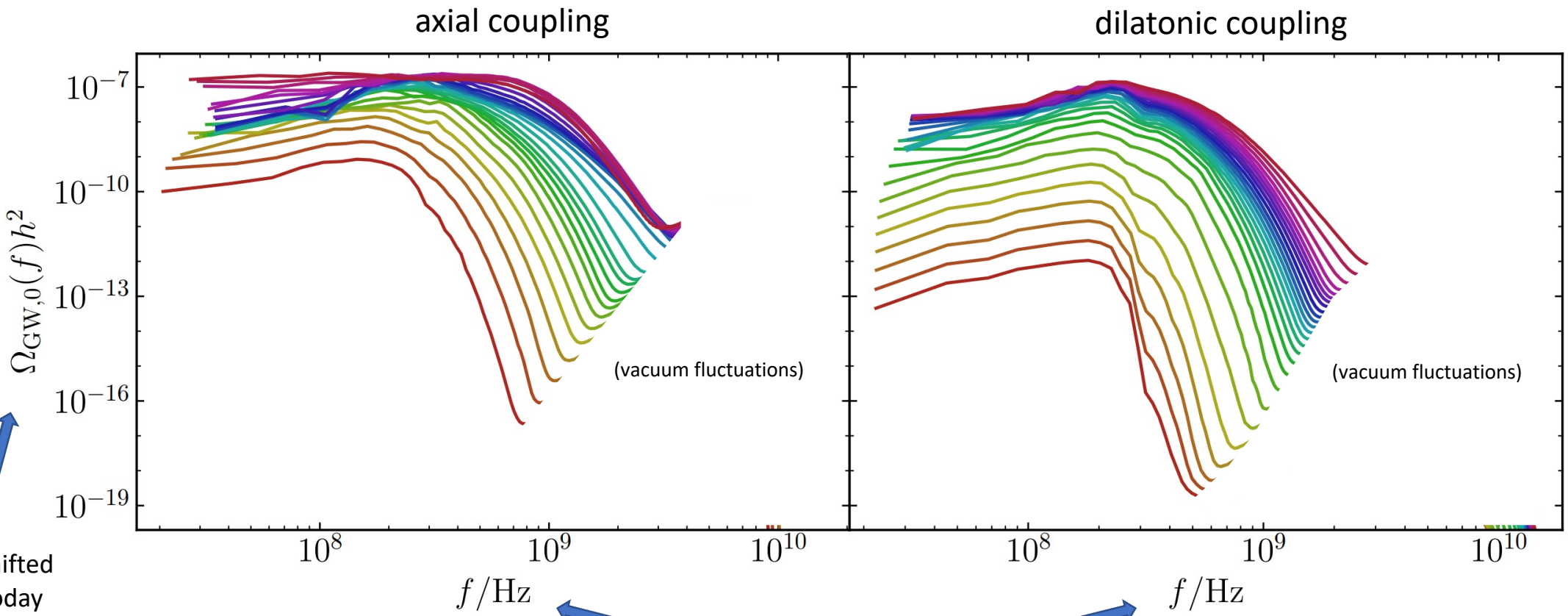
rapid development of inhomogeneities → gravitational waves!



redshifted to today

frequency observed today

$\sim \rho^{1/4}$

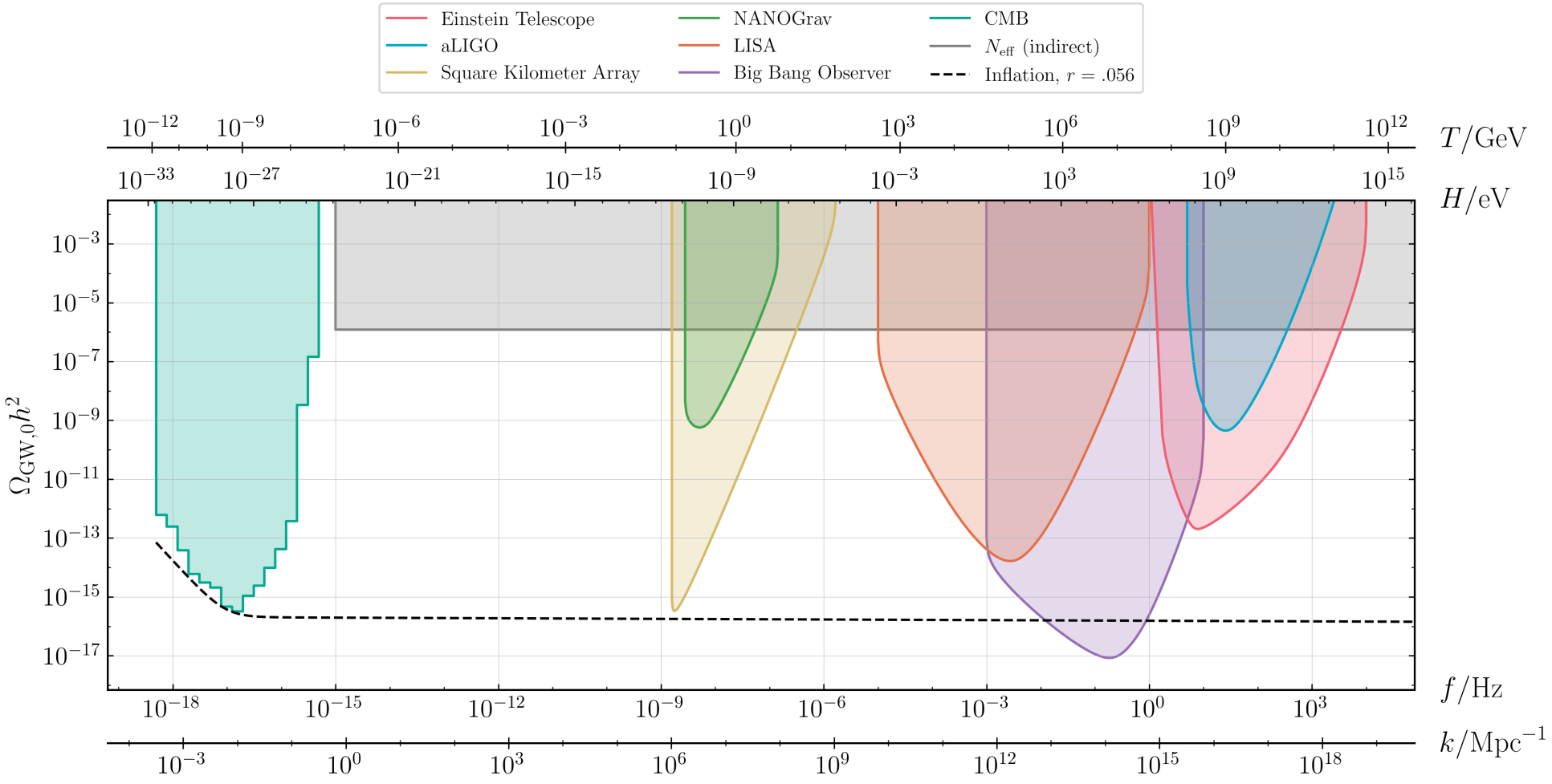
direct detection? =(

Indirect constraints

- Gravitational waves contribute to **energy in radiation**
- Experiments measure the energy budget with **percent-level precision**
  - Next-gen: improve by an order of magnitude

*arXiv:1508.02393

Indirect constraints



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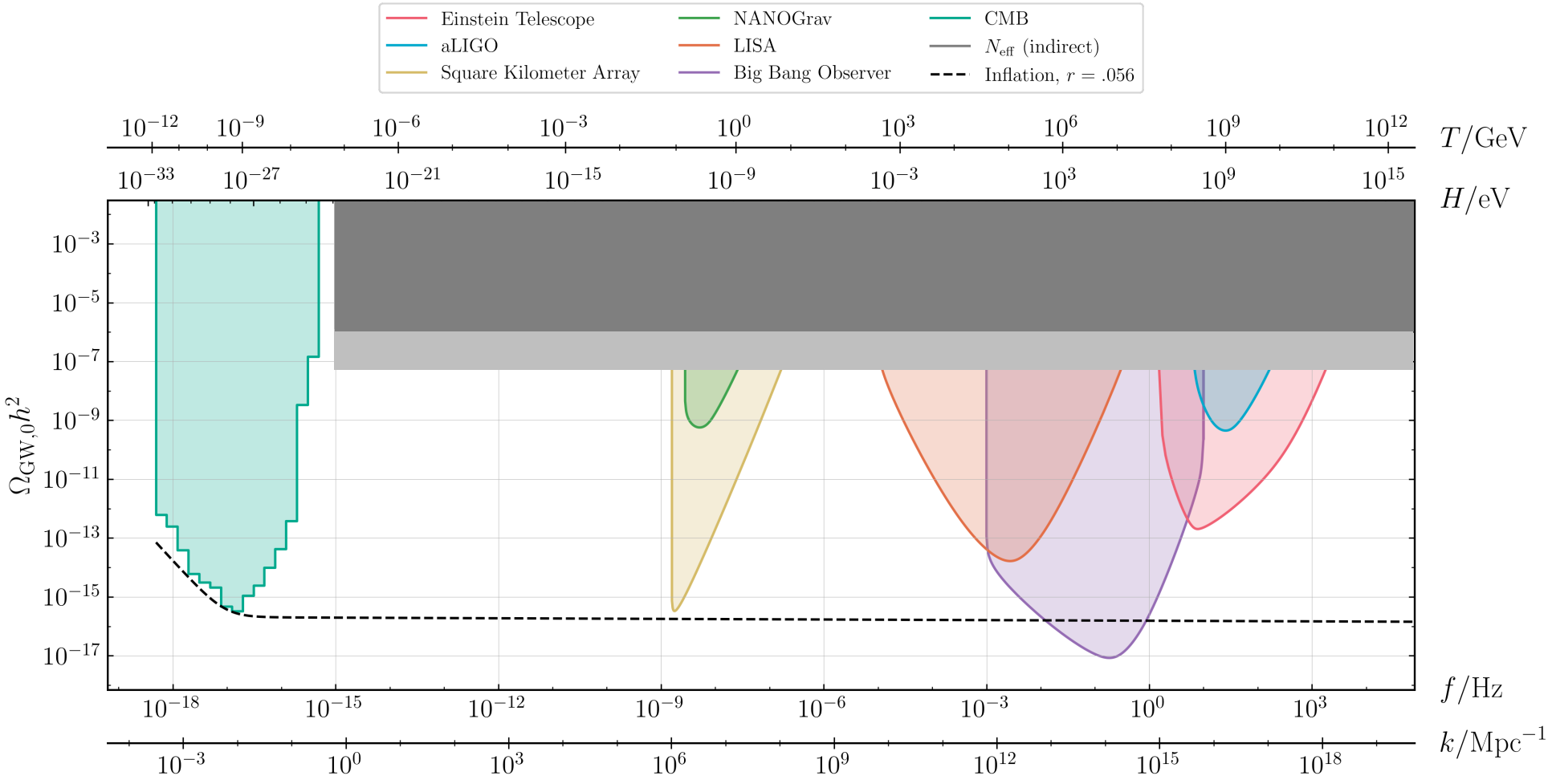
Indirect constraints



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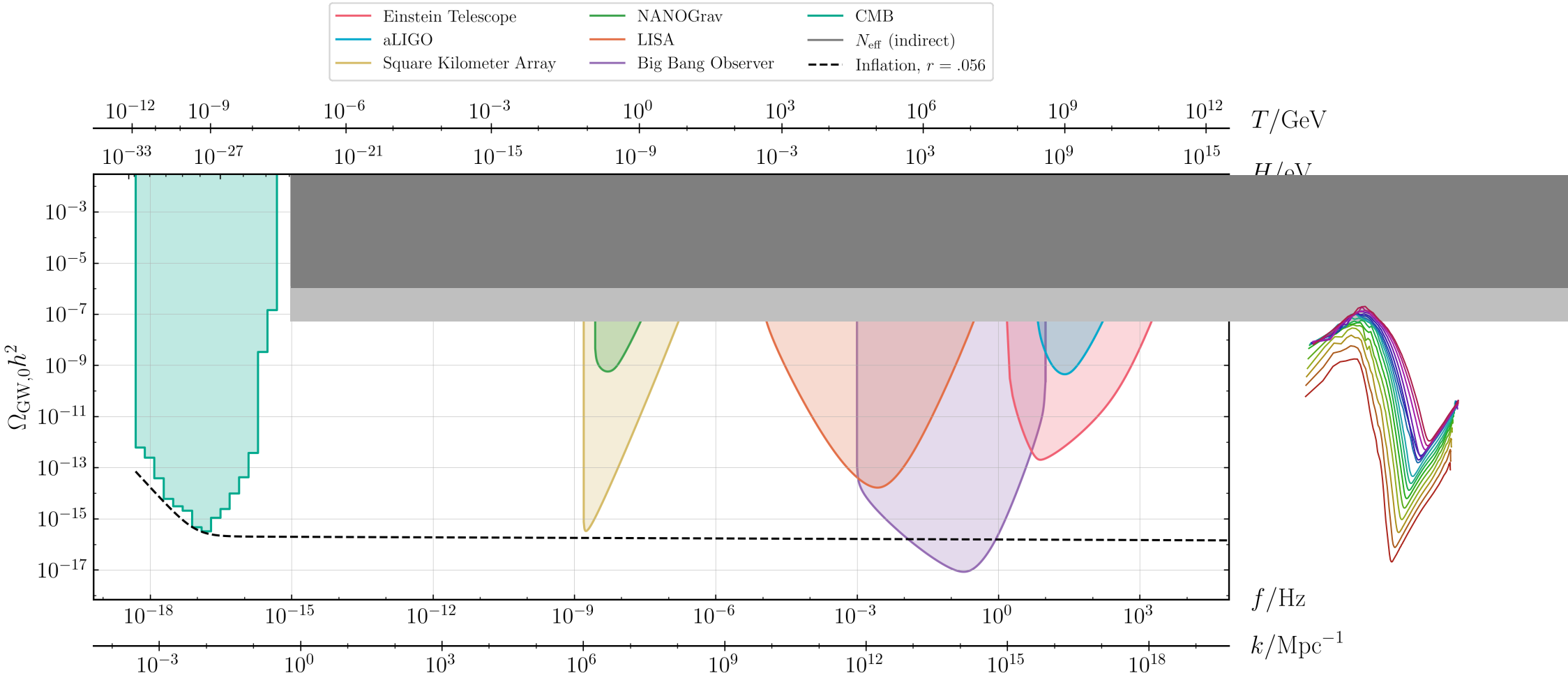
Indirect constraints



*arXiv:1508.02393

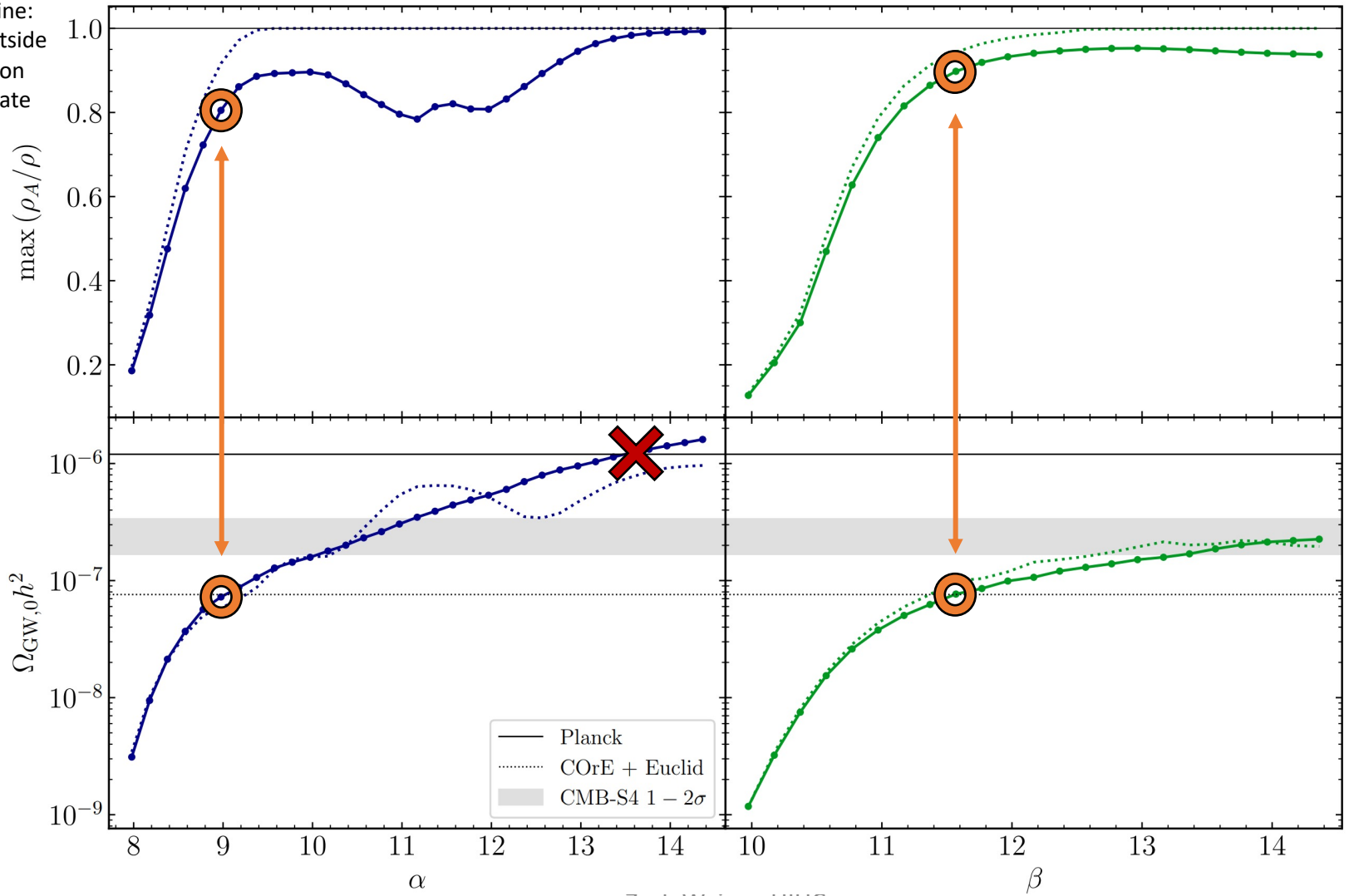
Constraints from preheating

dashed line: energy outside of inflaton condensate

efficiency of preheating

Now: constrain high couplings
-> rules out inflationary phenomenology, primordial black holes, etc.

total (integrated) energy in GWs



axial coupling

dilatonic coupling

Next-gen: probe or rule out efficient preheating!