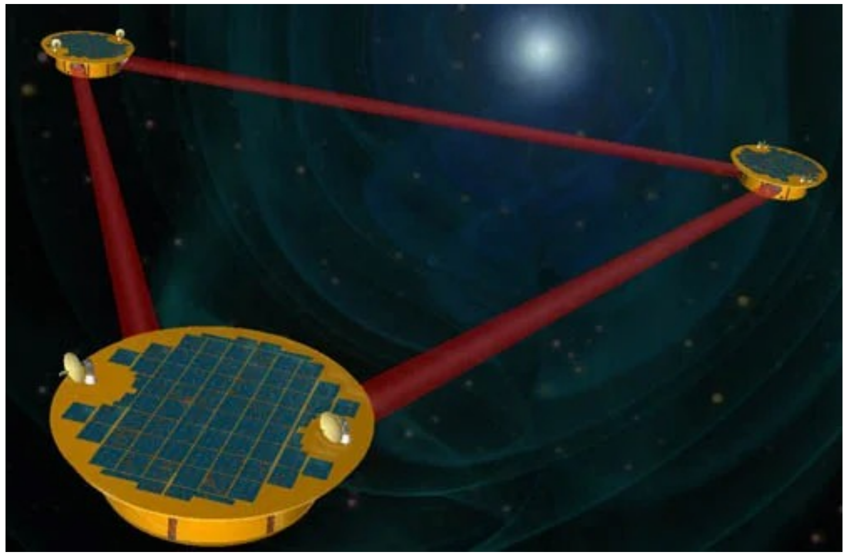
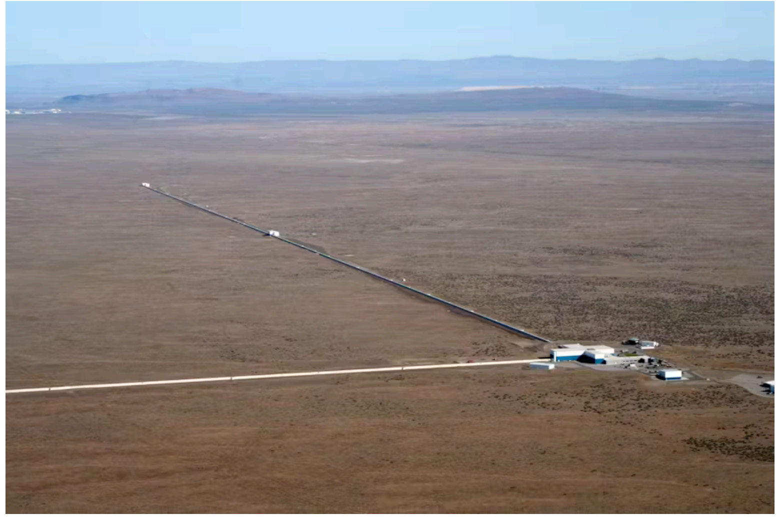
Gravitational wave as a new window to the early universe

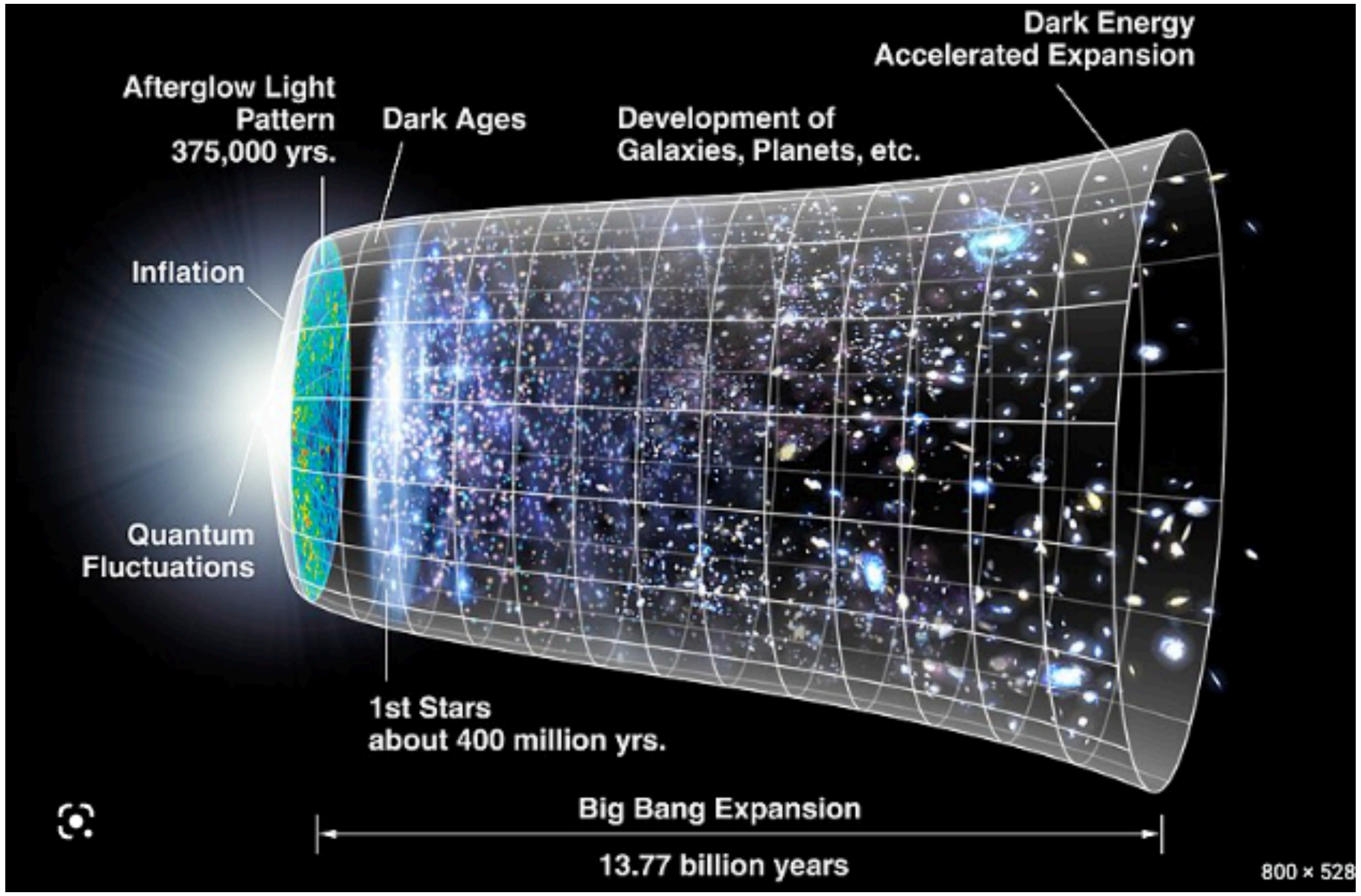
LianTao Wang
Univ. of Chicago

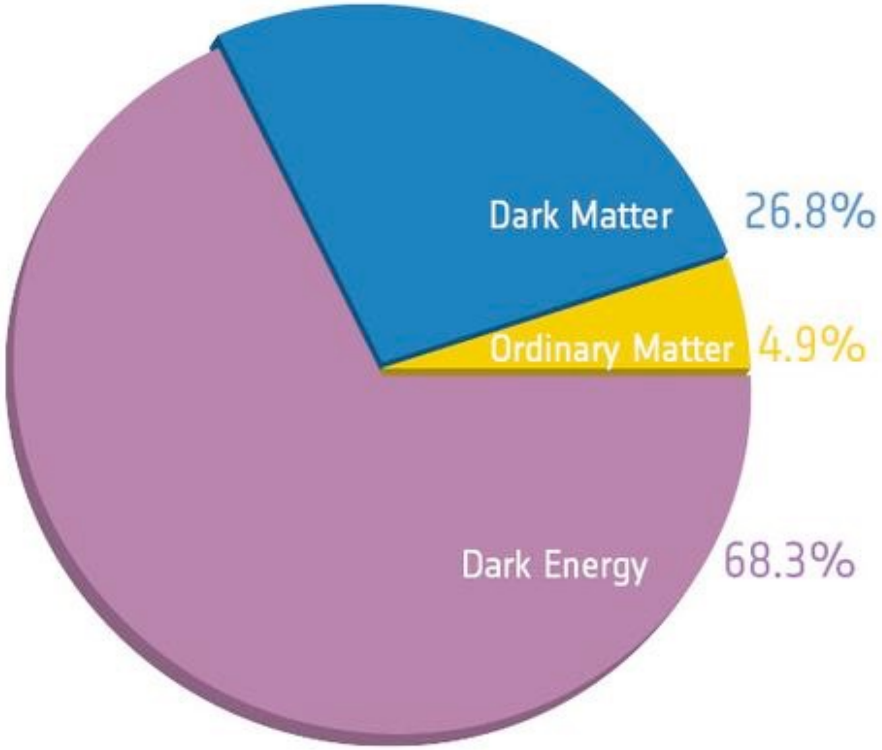




University of Illinois at Chicago, Nov 13, 2024

Cosmos

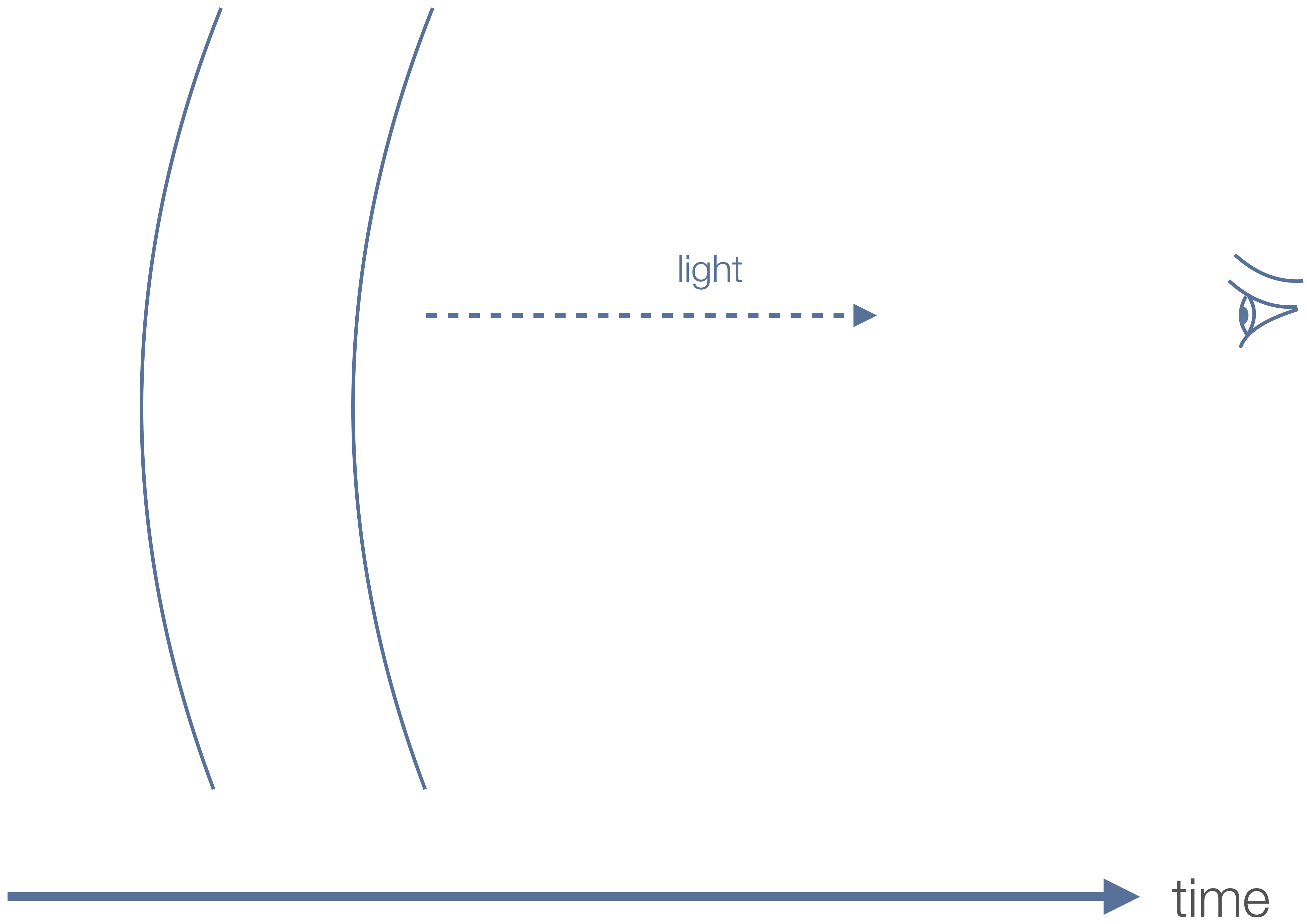




A standard model of cosmology.

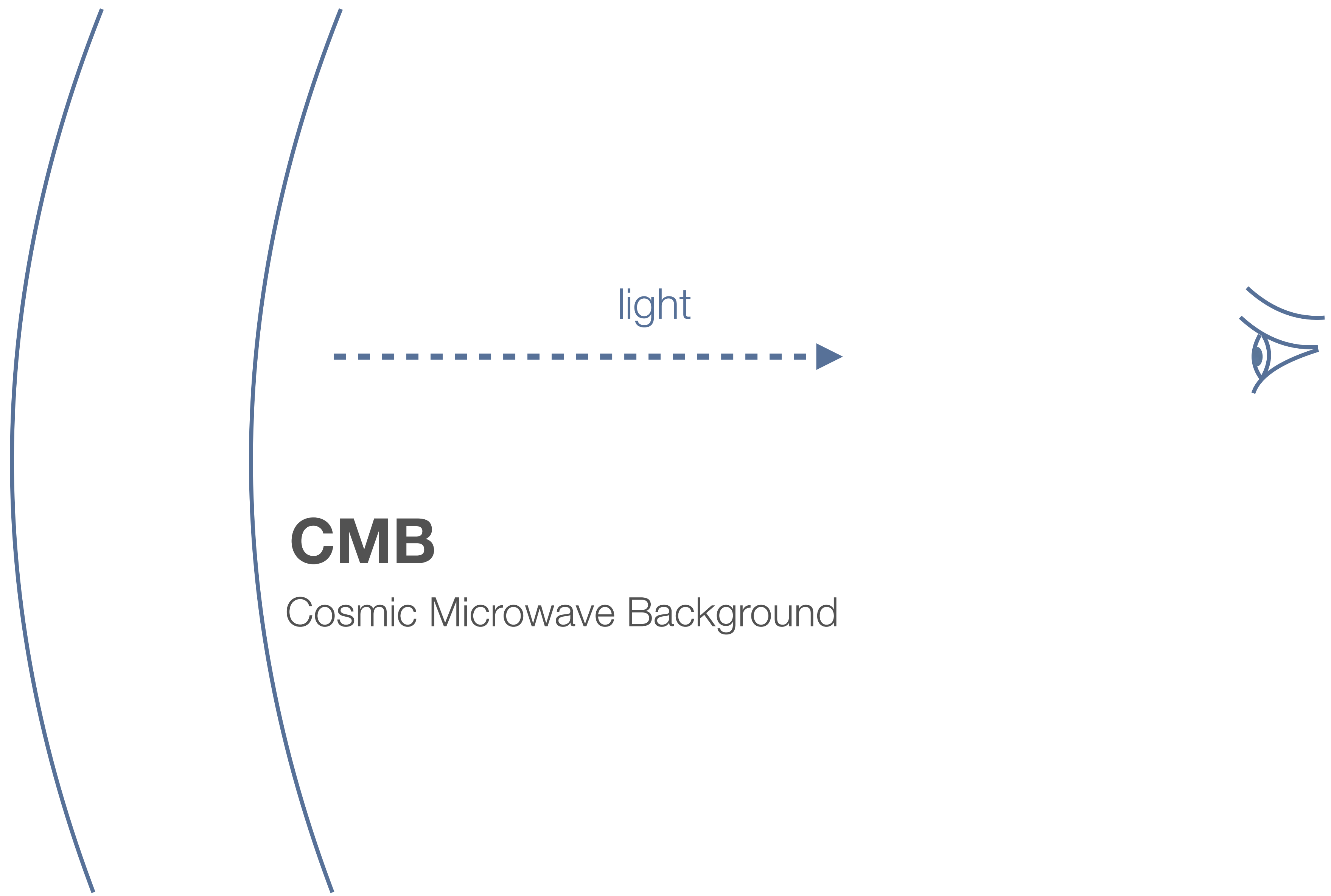
What do we know

Observing universe with light

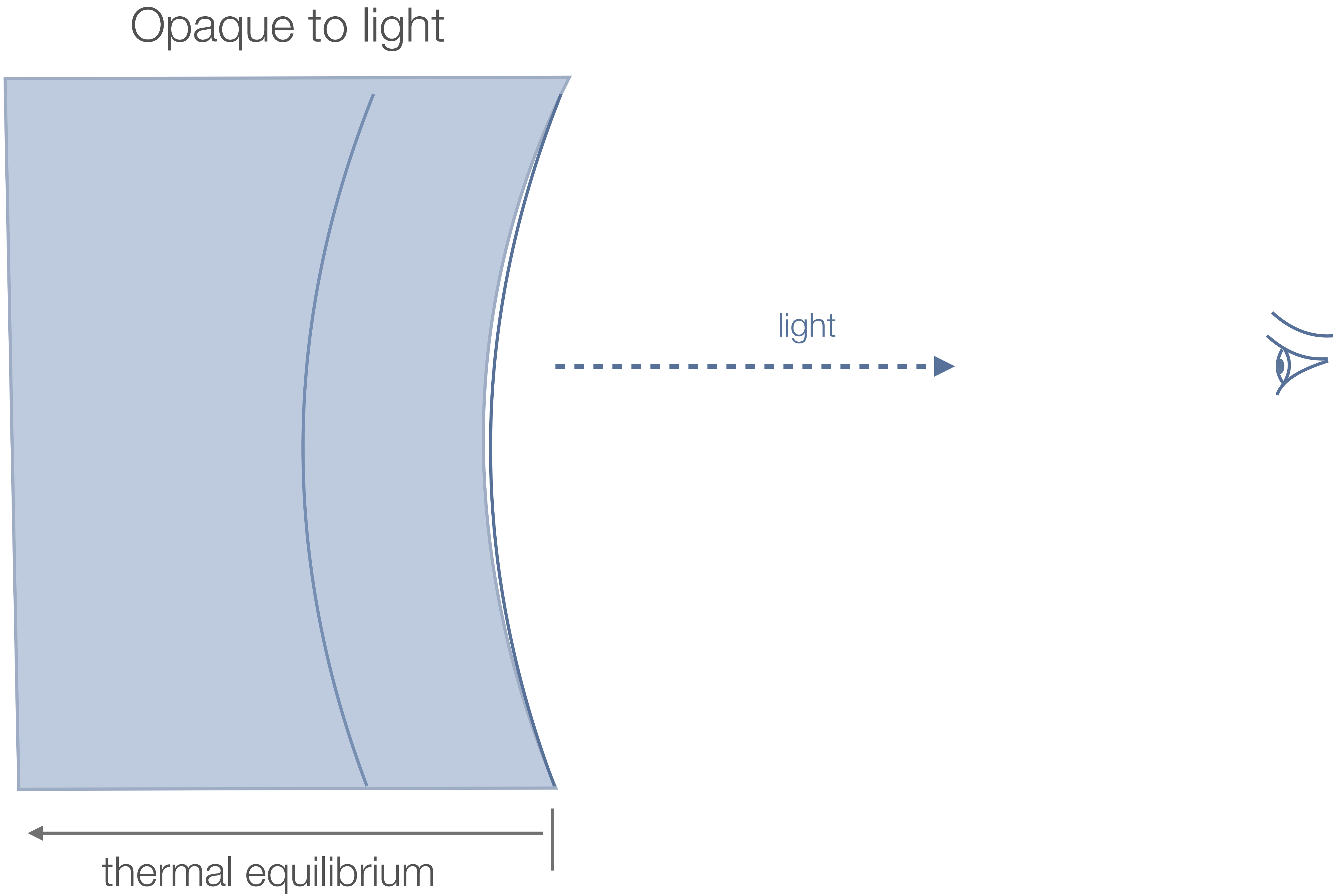


What do we know

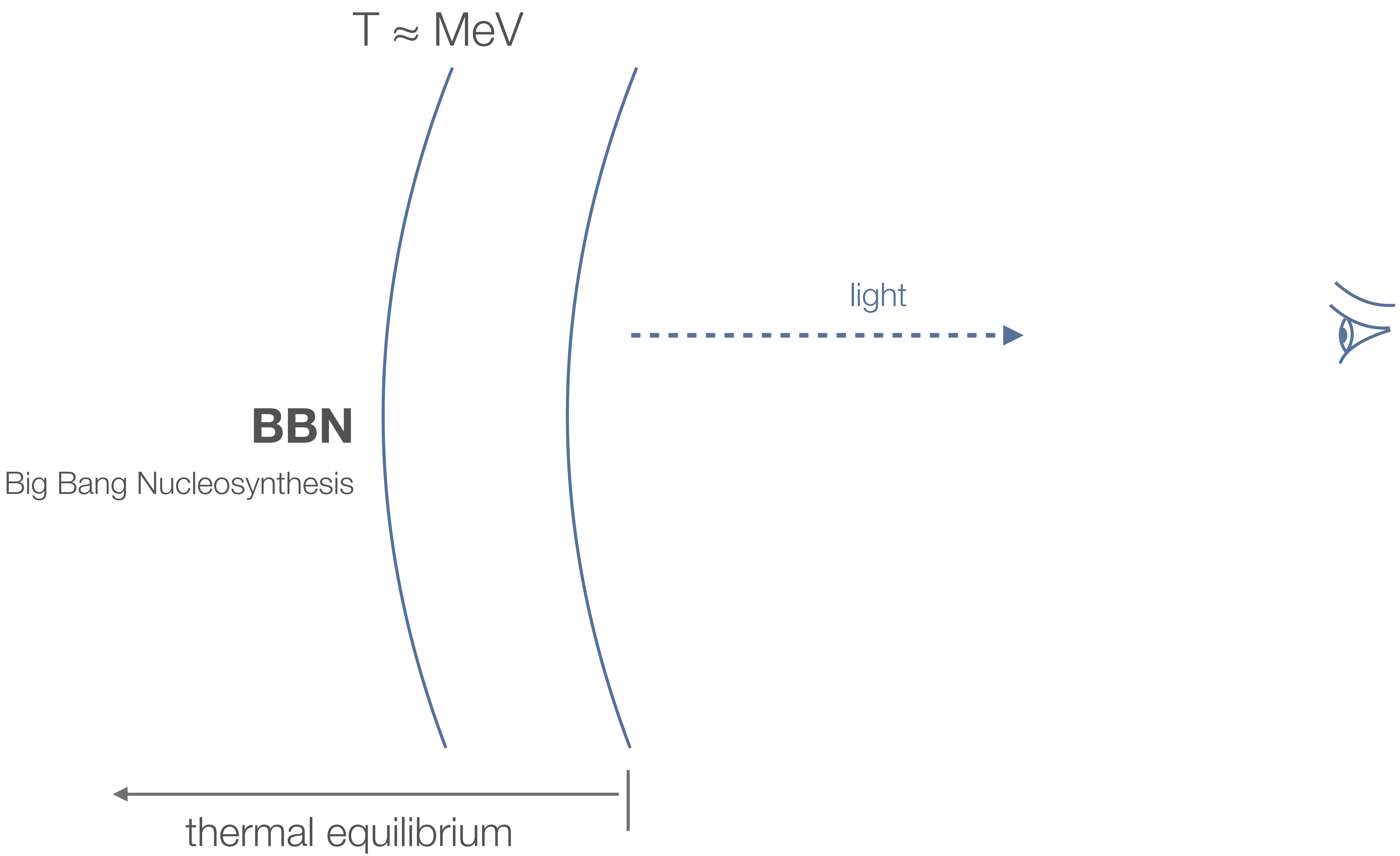
Recombination:
$T \approx \mathrm{eV}$



What do we know

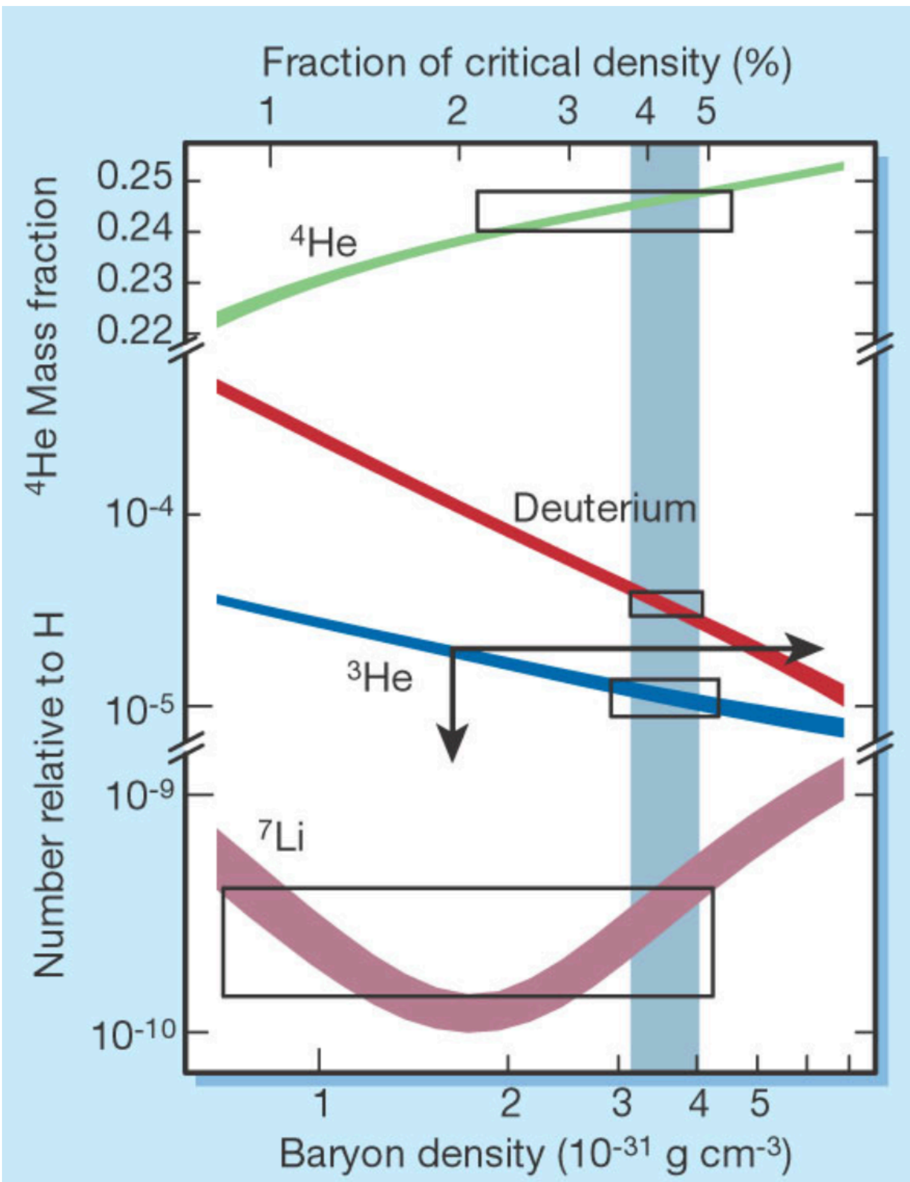


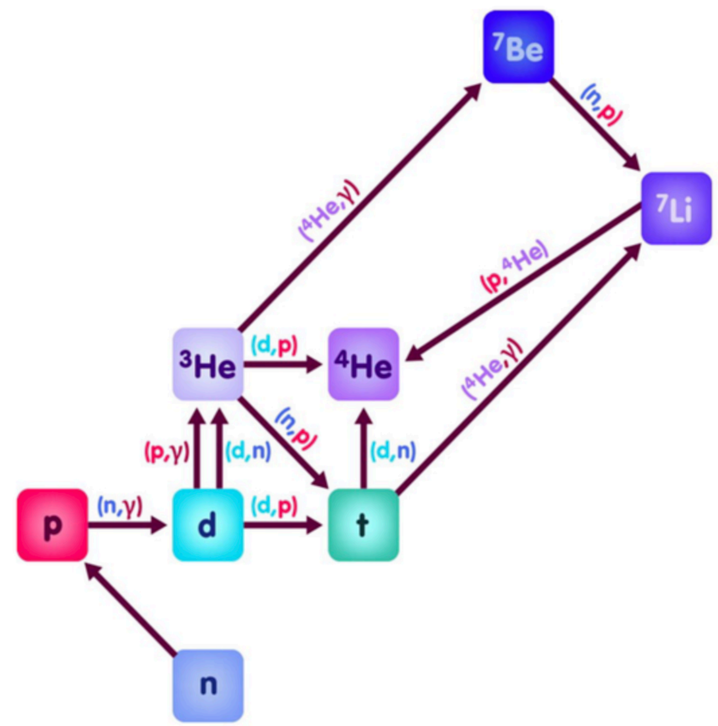
What do we know



Big bang nucleosynthesis

G. Steigman





1) $n \rightarrow {}^1H + e^- + \upsilon^-$
2) ${}^1H + n \rightarrow {}^2H + \gamma$
3) ${}^2H + {}^1H \rightarrow {}^3He + \gamma$
4) ${}^2H + {}^2H \rightarrow {}^3He + n$
5) ${}^2H + {}^2H \rightarrow {}^3H + {}^1H$
6) ${}^2H + {}^3H \rightarrow {}^4He + n$
7) ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8) ${}^3He + n \rightarrow {}^3H + {}^1H$
9) ${}^3He + {}^2H \rightarrow {}^4He + {}^1H$
10) ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11) ${}^7Li + {}^1H \rightarrow {}^4He + {}^4He$
12) ${}^7Be + n \rightarrow {}^7Li + {}^1H$
13) ${}^4He + {}^2H \rightarrow {}^6Li + \gamma$
14) ${}^6Li + {}^1H \rightarrow {}^3He + {}^3He$

Thermal eq. In early universe

+

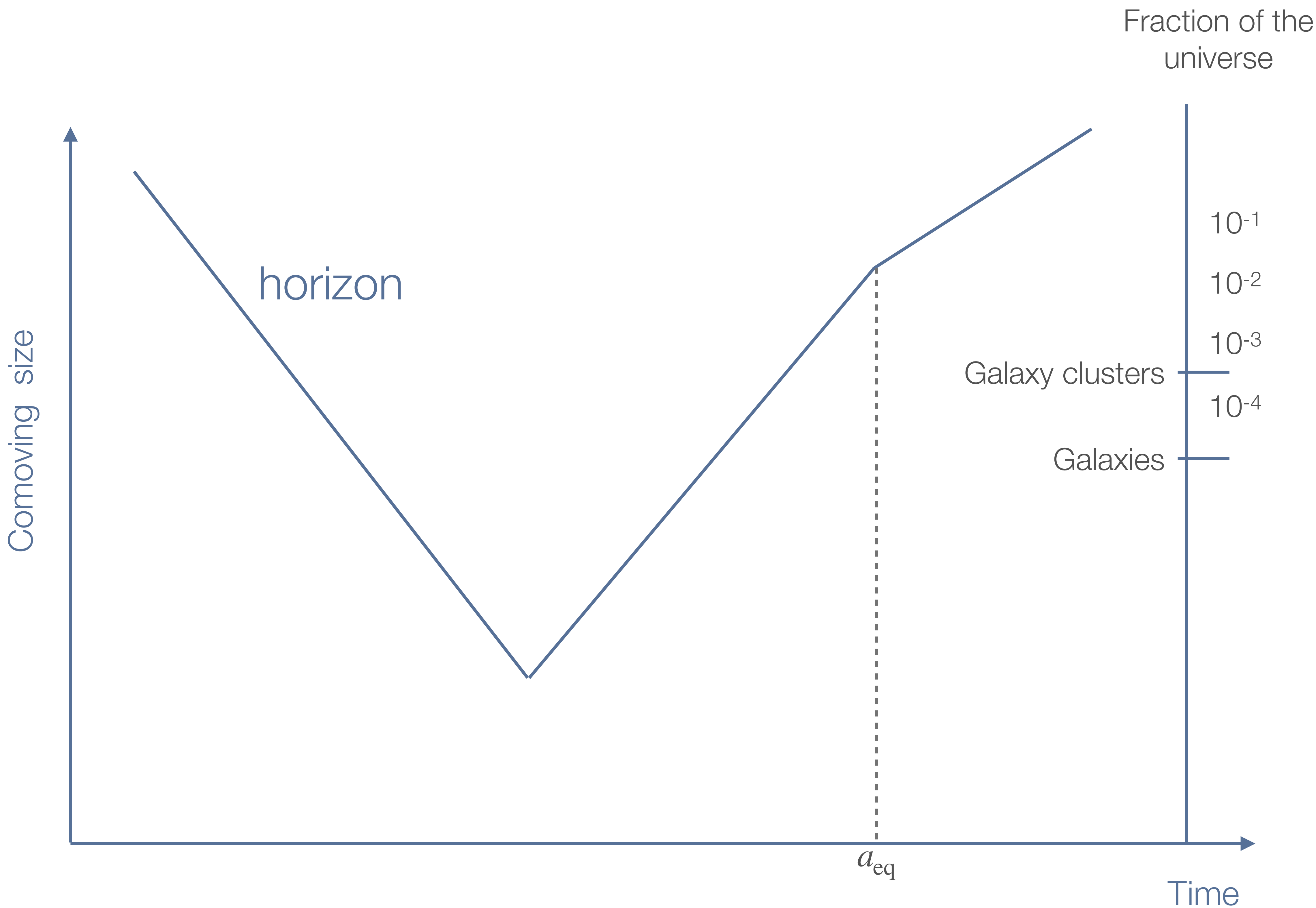
Nuclear reaction properties

+

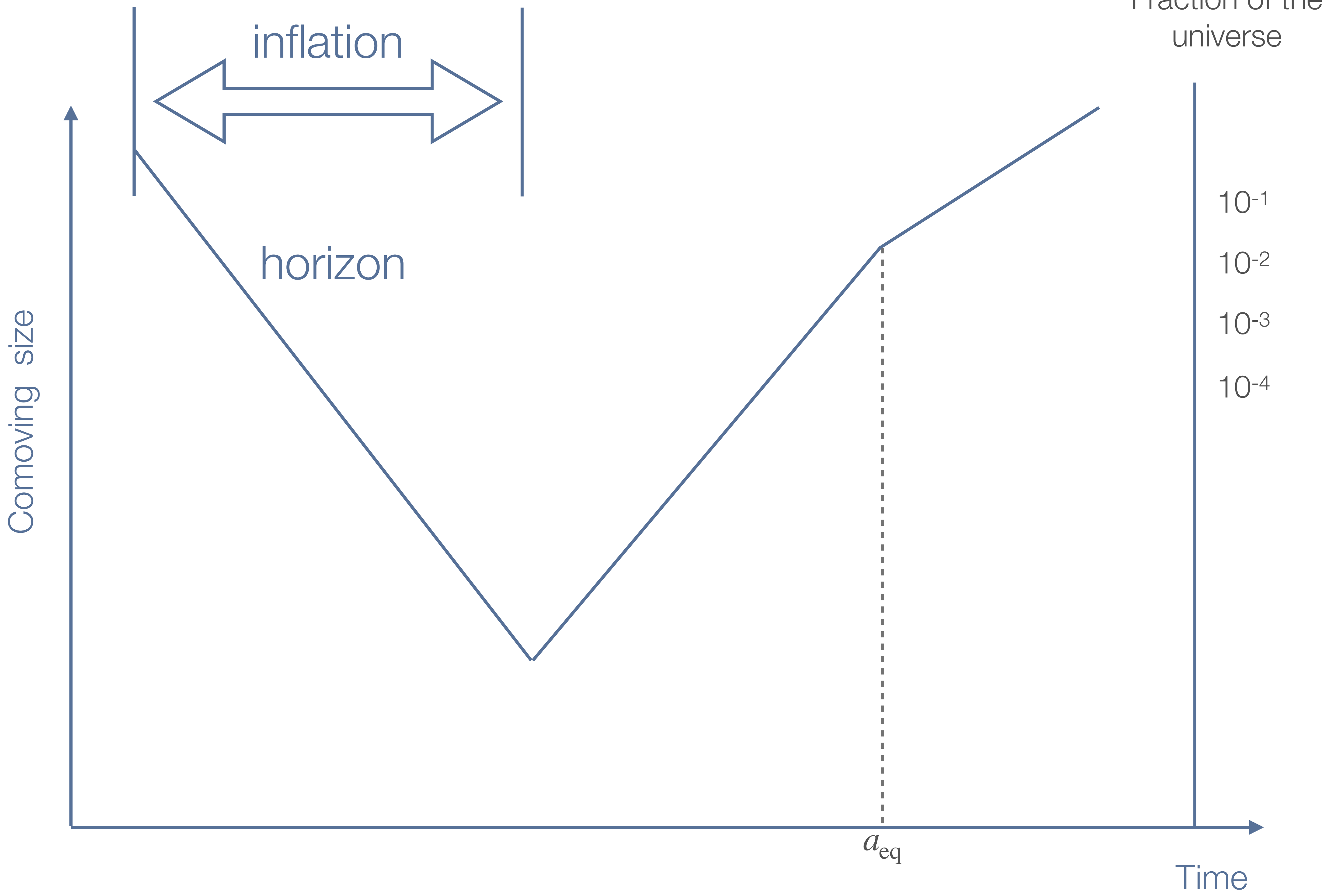
Tests by observation

What we think we know

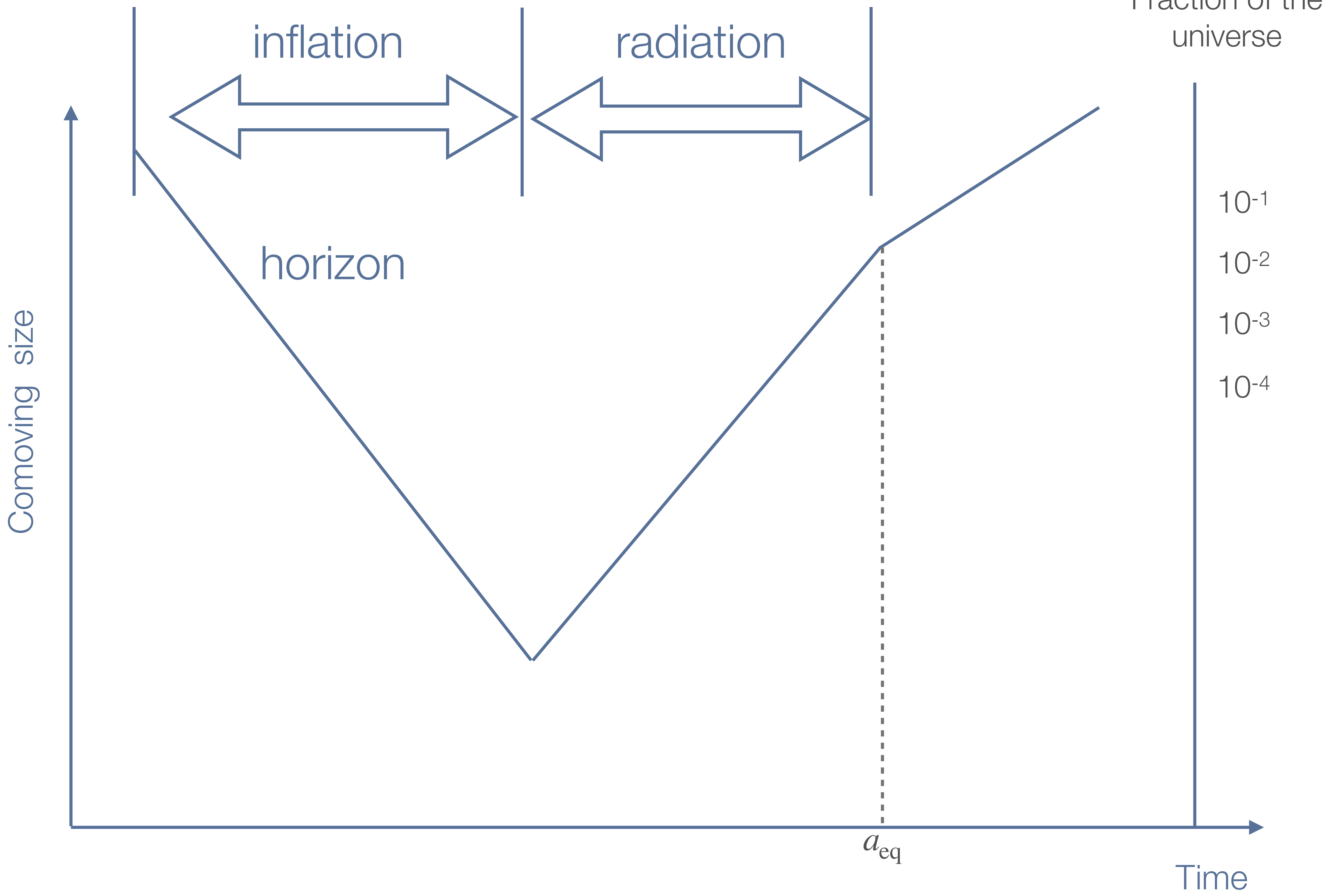
Changing cosmic horizons



Epochs

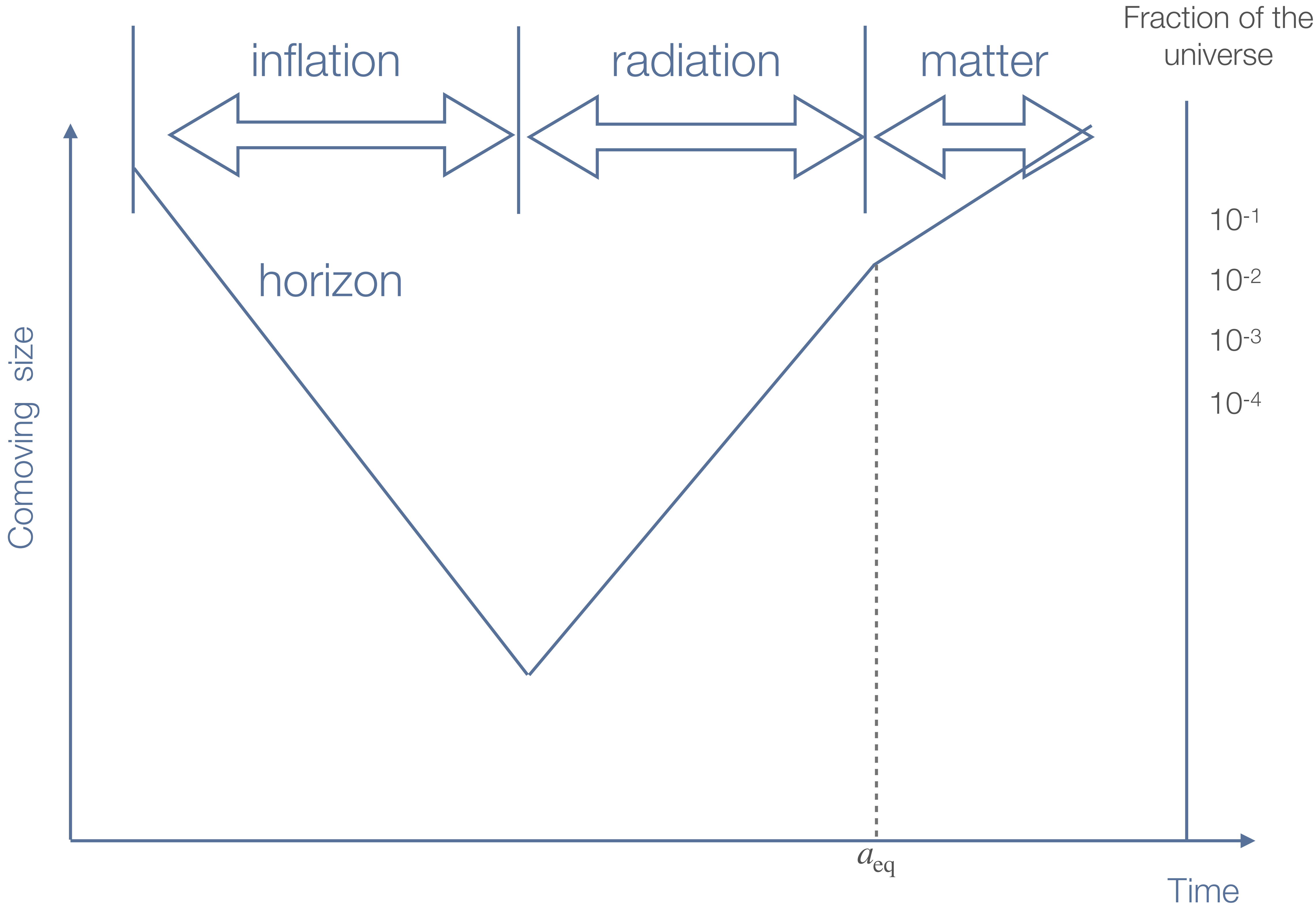

inflation
horizon
Fraction of the universe
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Comoving size
$a_{\rm eq}$
Time

Epochs



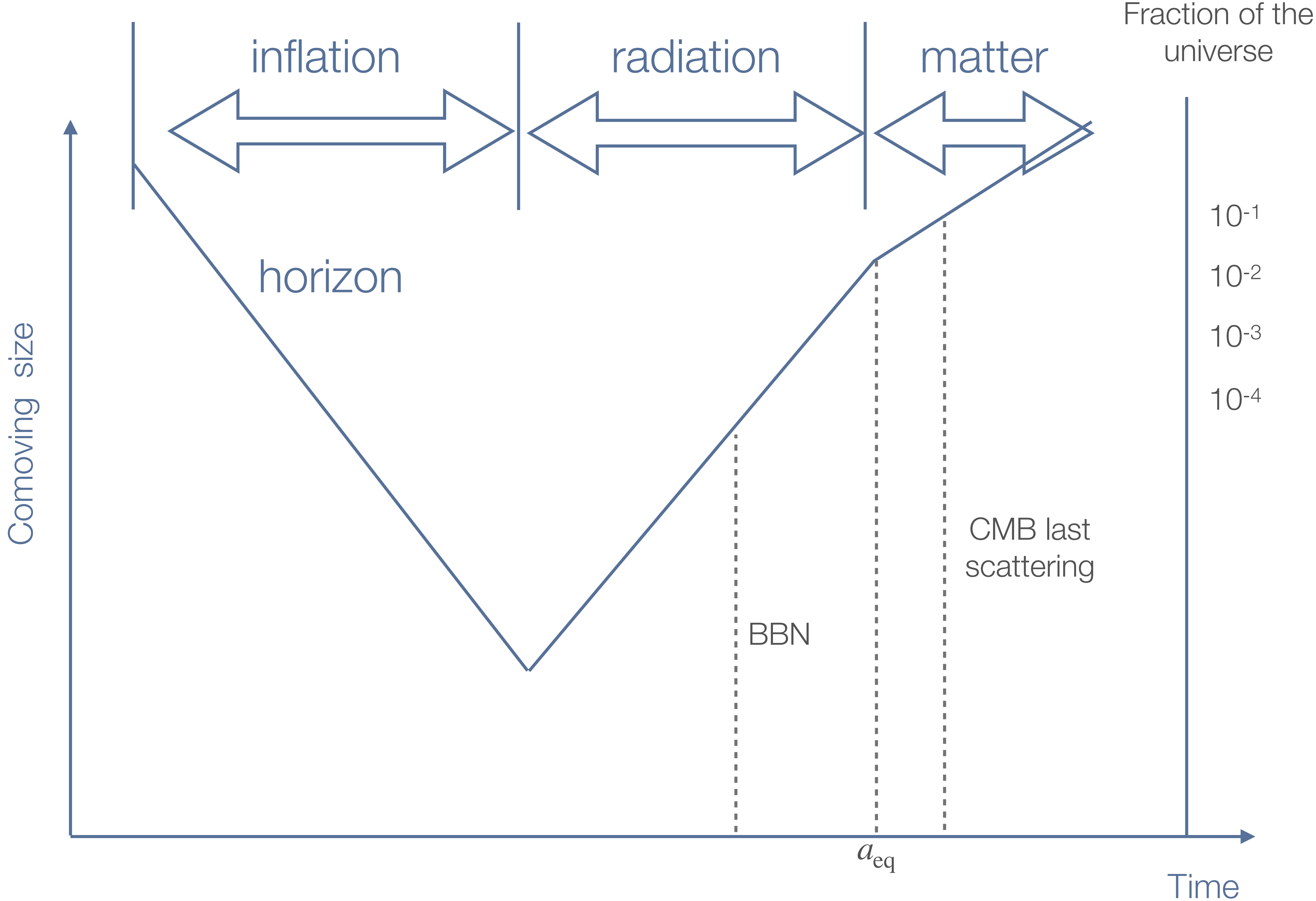
inflation
radiation
Fraction of the universe
horizon
Comoving size
10^{-1}
10^{-2}
10^{-3}
10^{-4}
a_{eq}
Time

Epochs

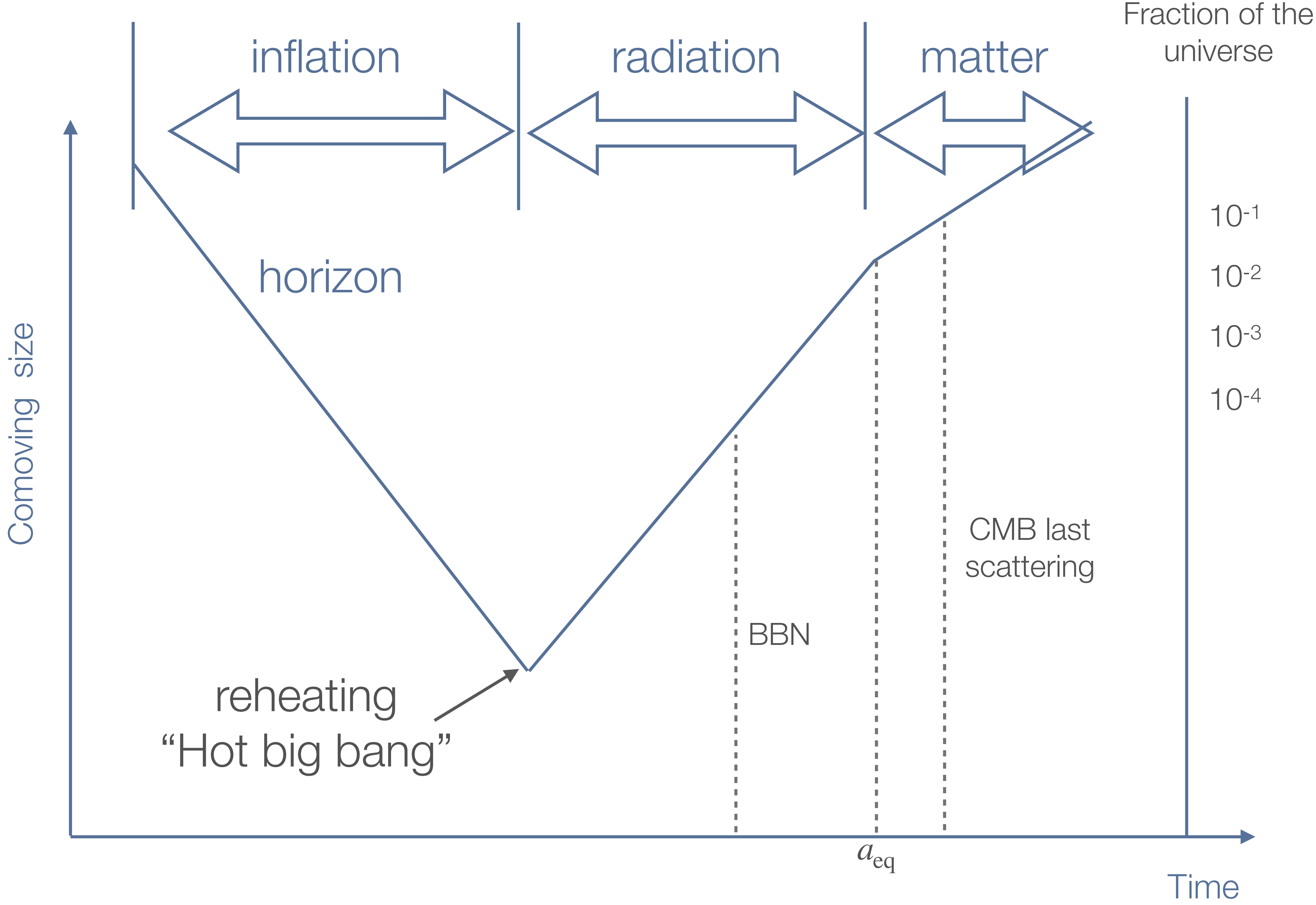


inflation
radiation
matter
Fraction of the universe
horizon
Comoving size
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$a_{\rm eq}$
Time

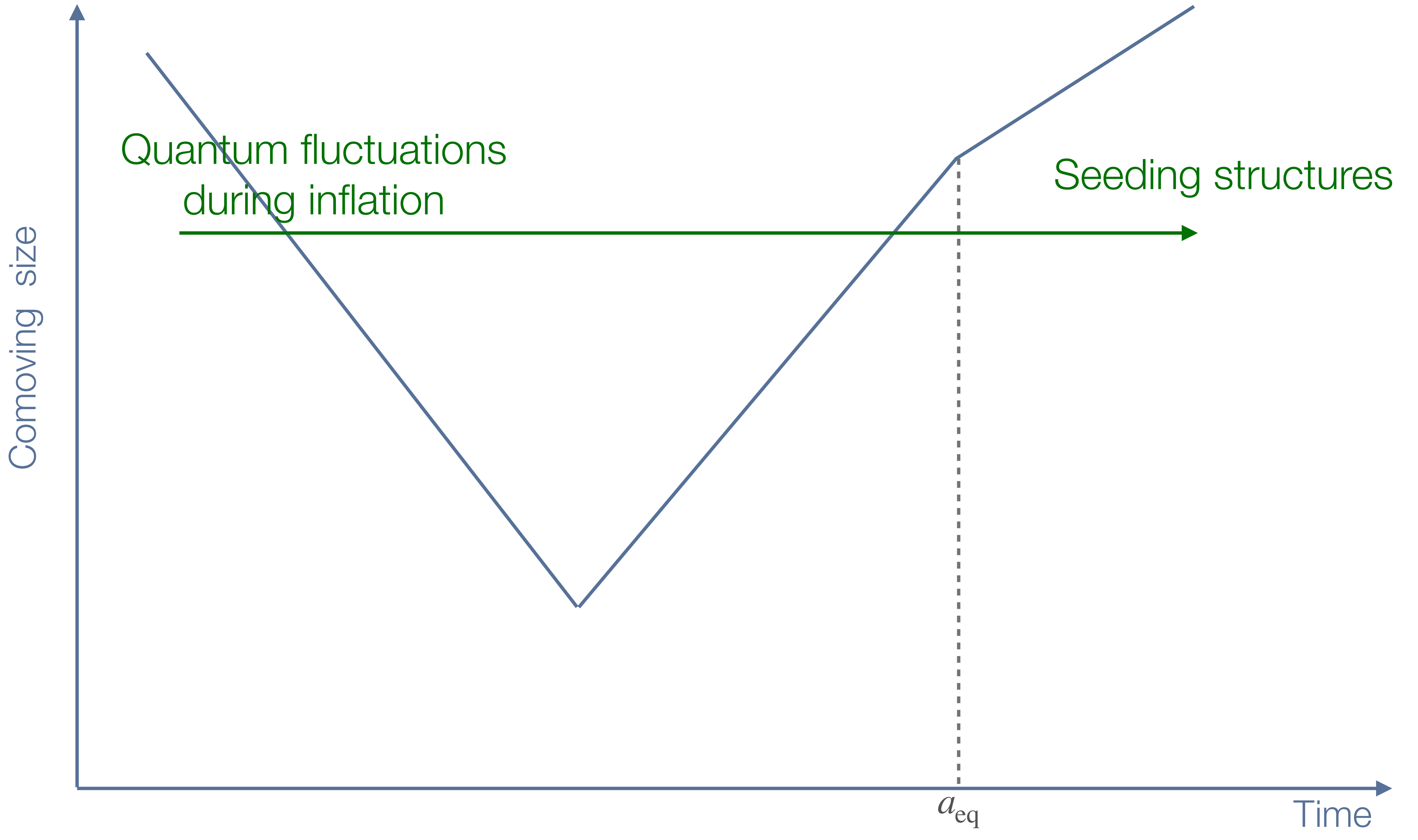
Changing horizons



Changing horizons



Perturbations



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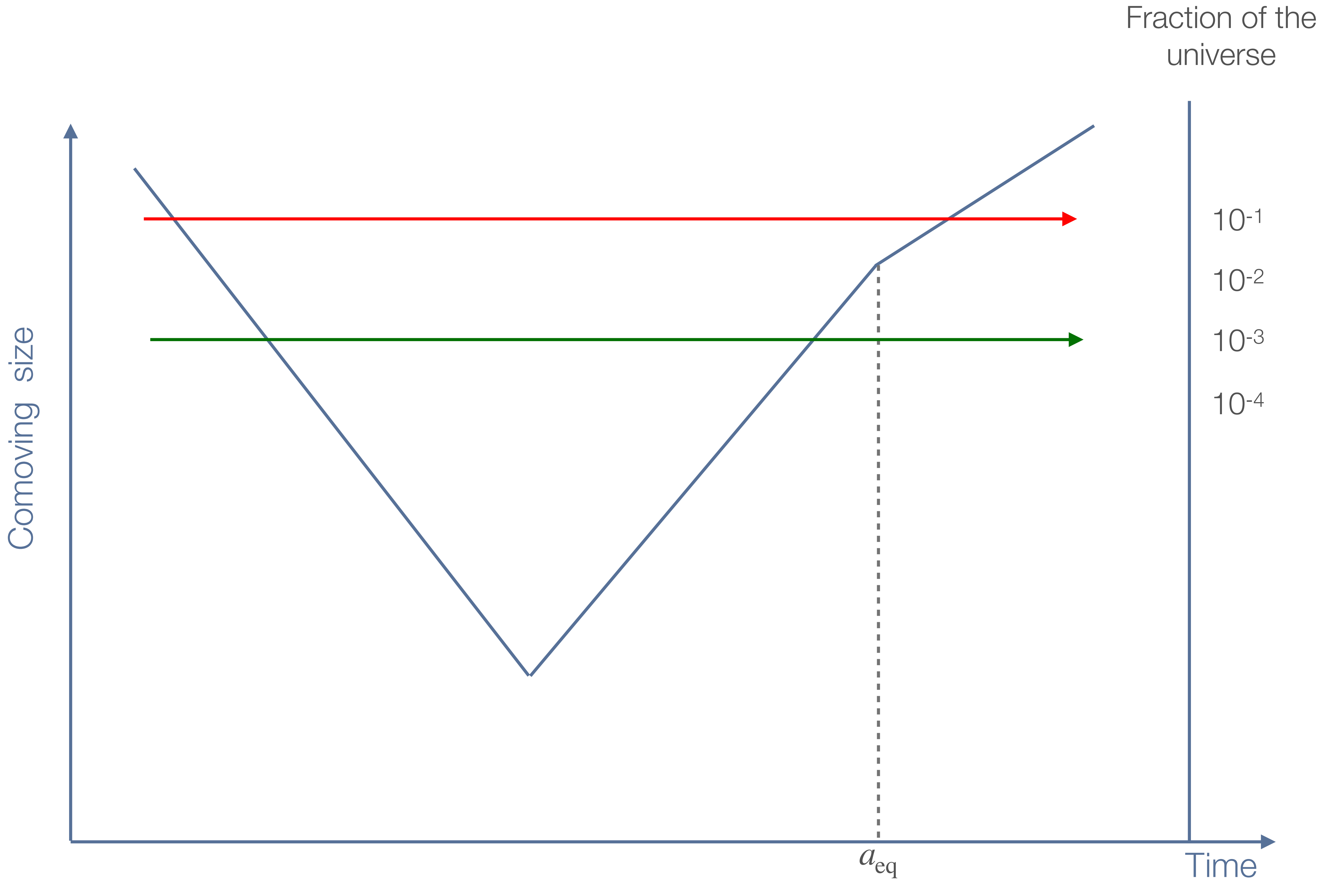
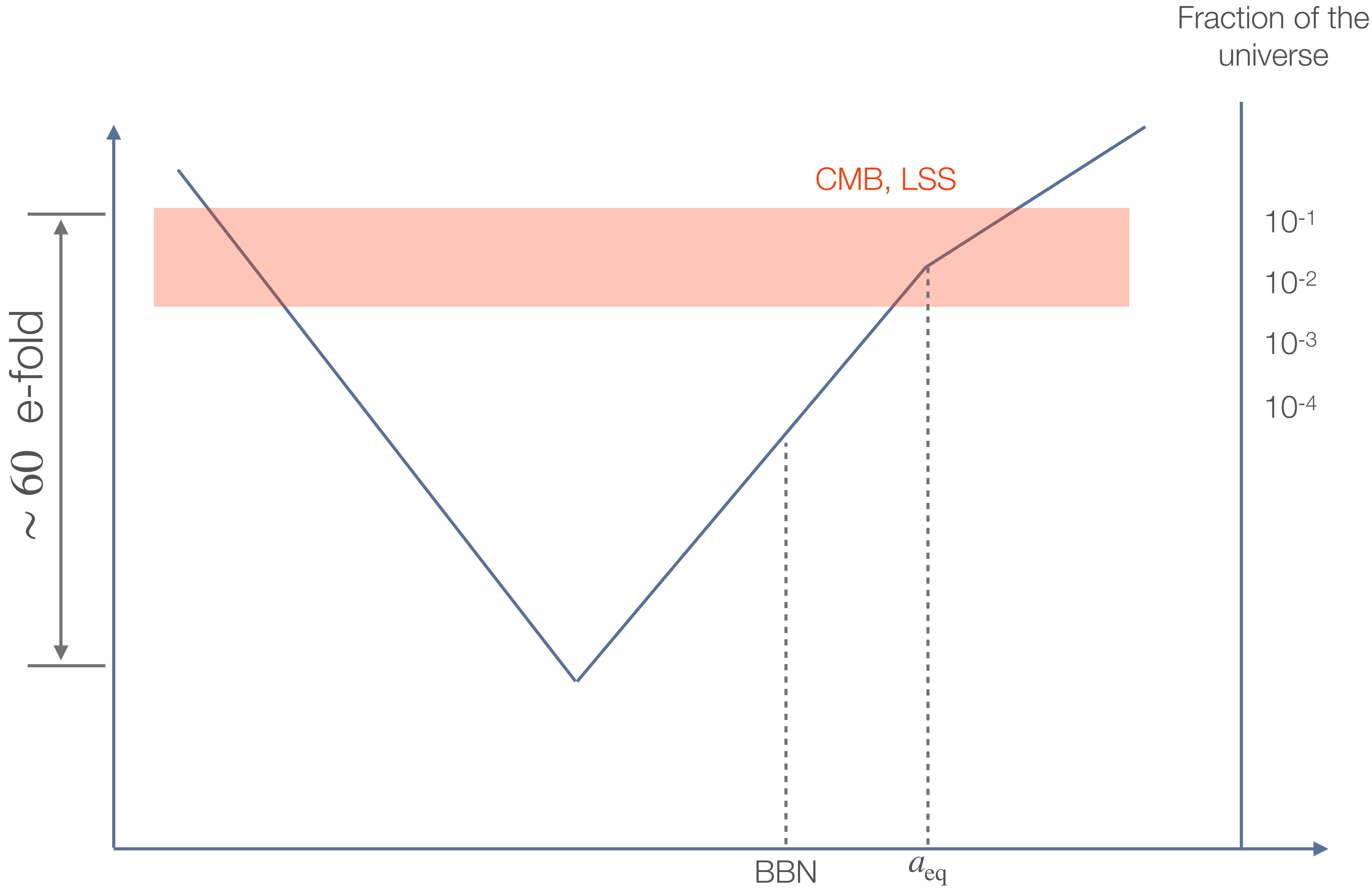
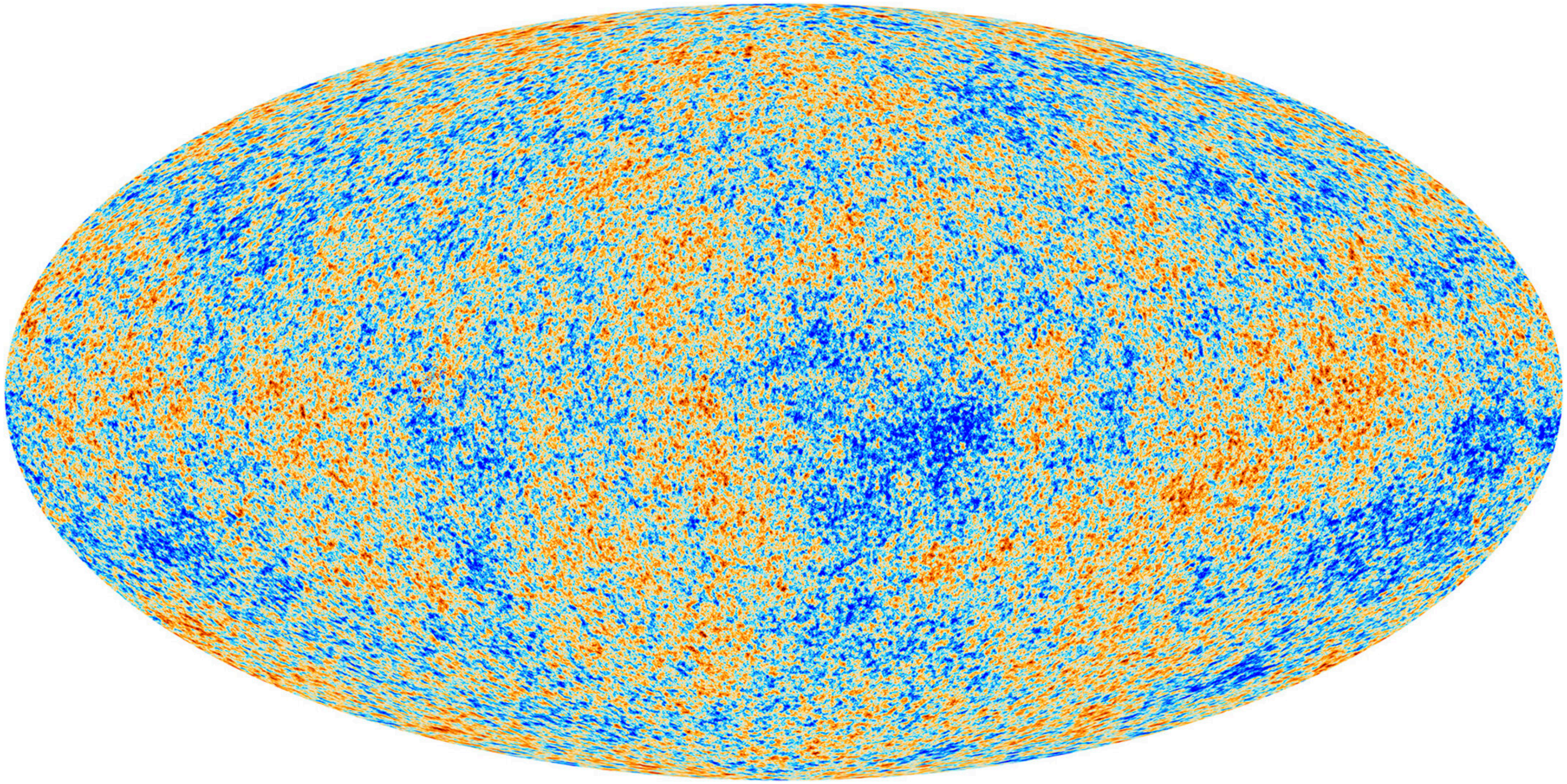


Large scale structure

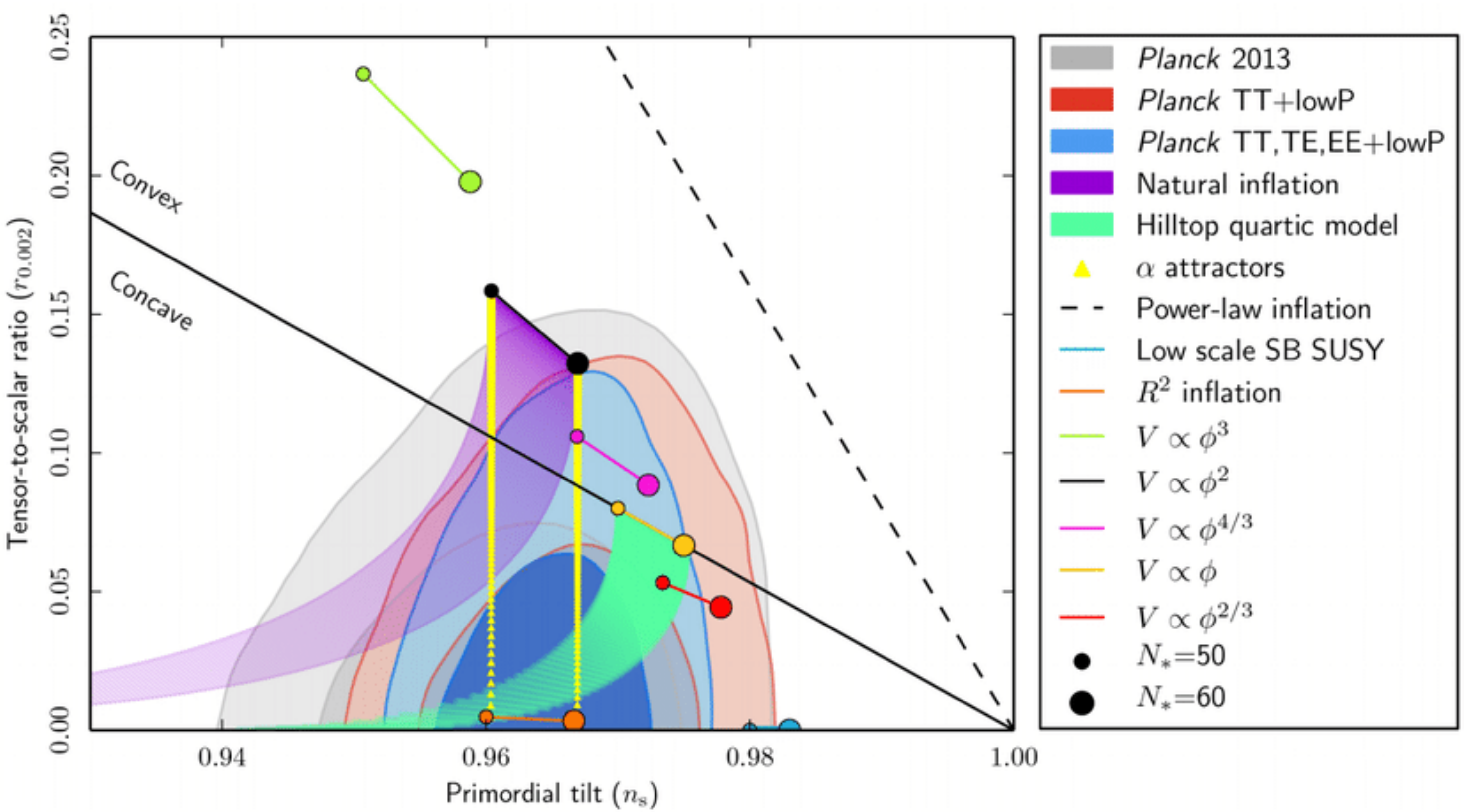


CMB



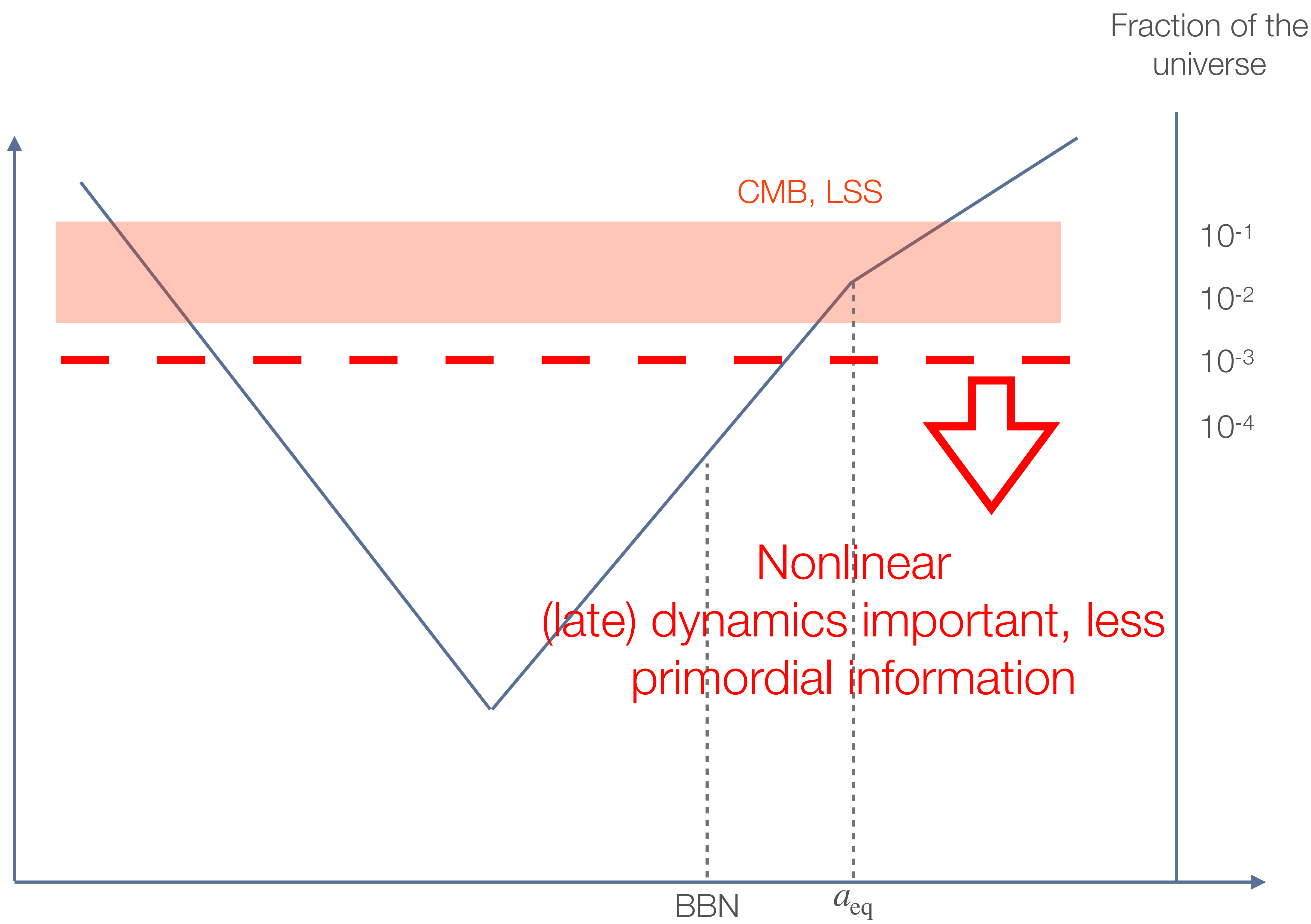
Teaches us a lot of about primordial large scale fluctuations

CMB

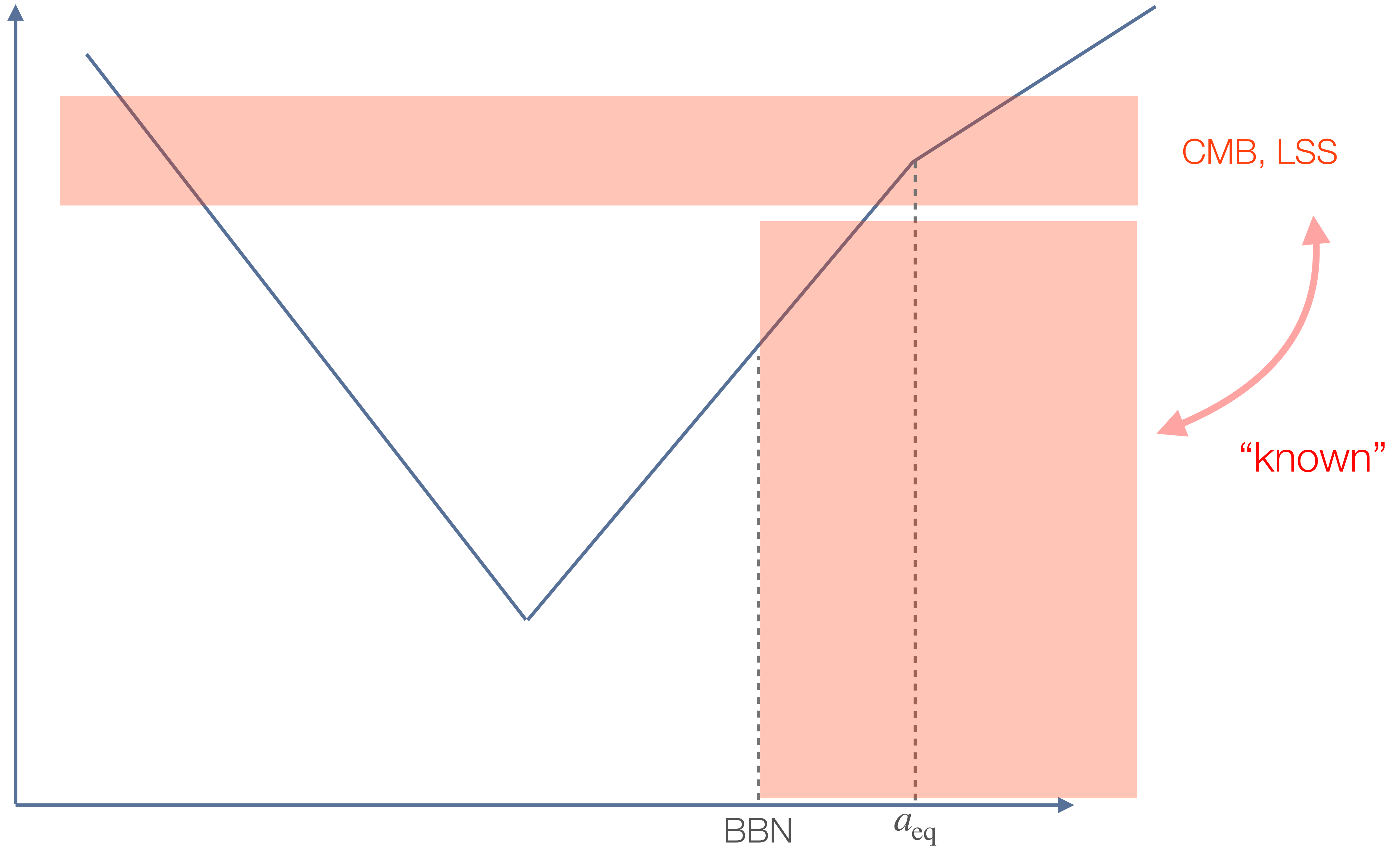


Teaches us a lot of about primordial large scale fluctuations

Large scale structure

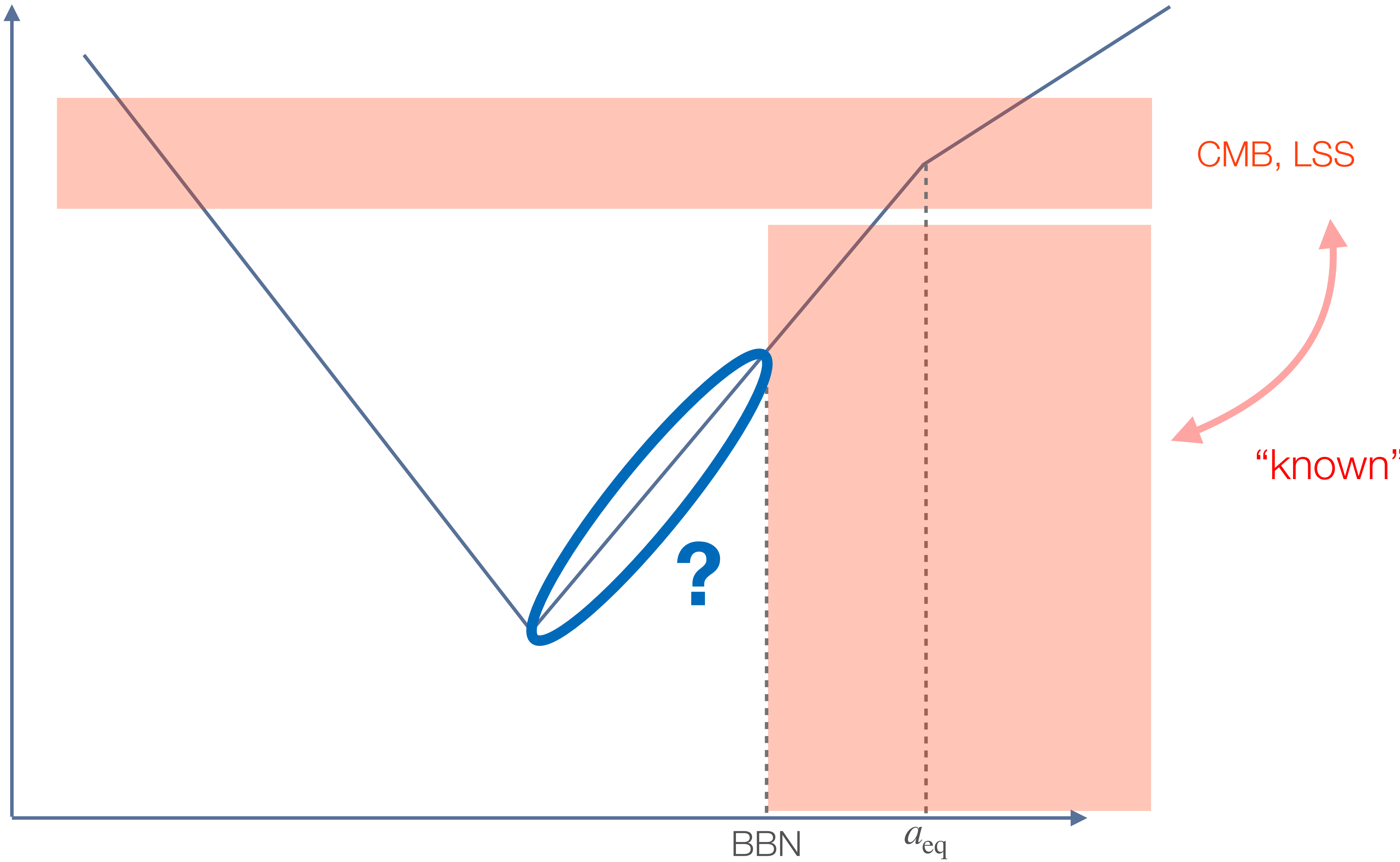


What we know



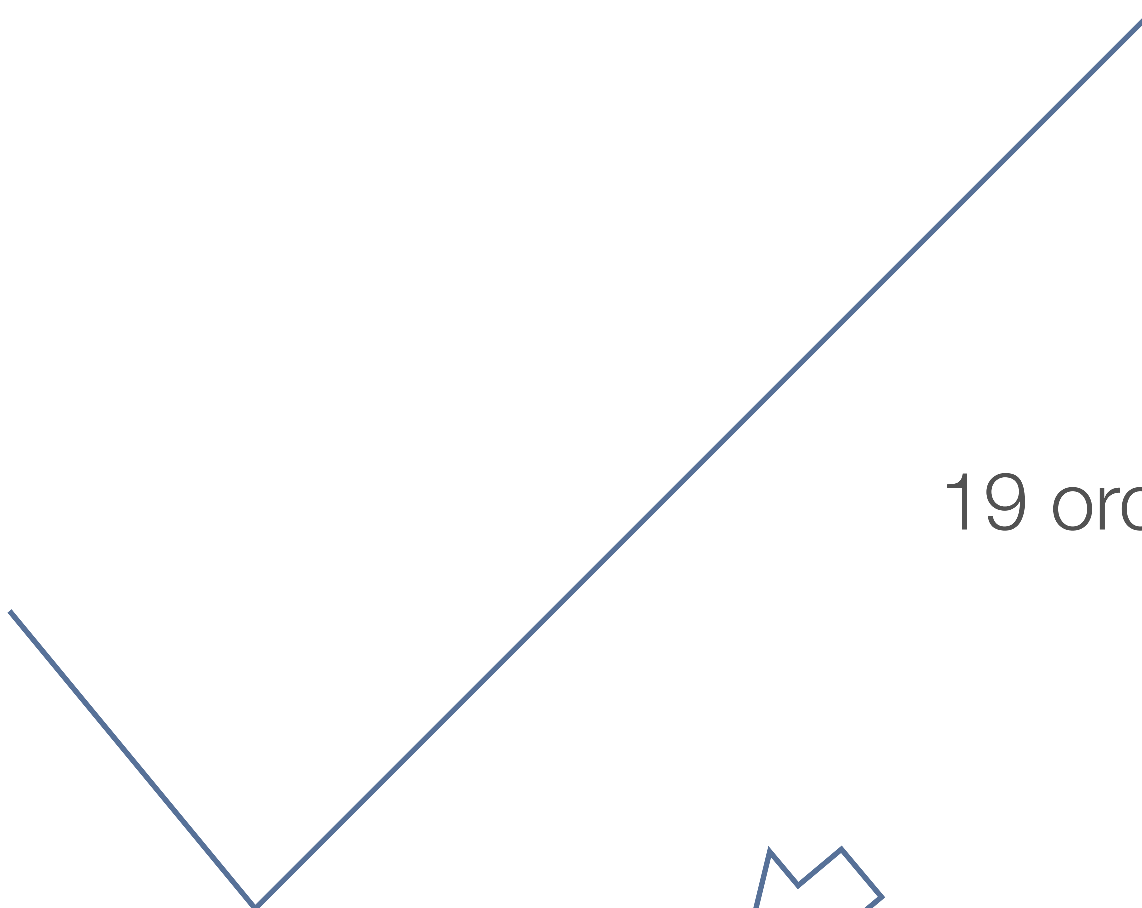
Large gaps in our knowledge

Reheating and after



Reheating and after

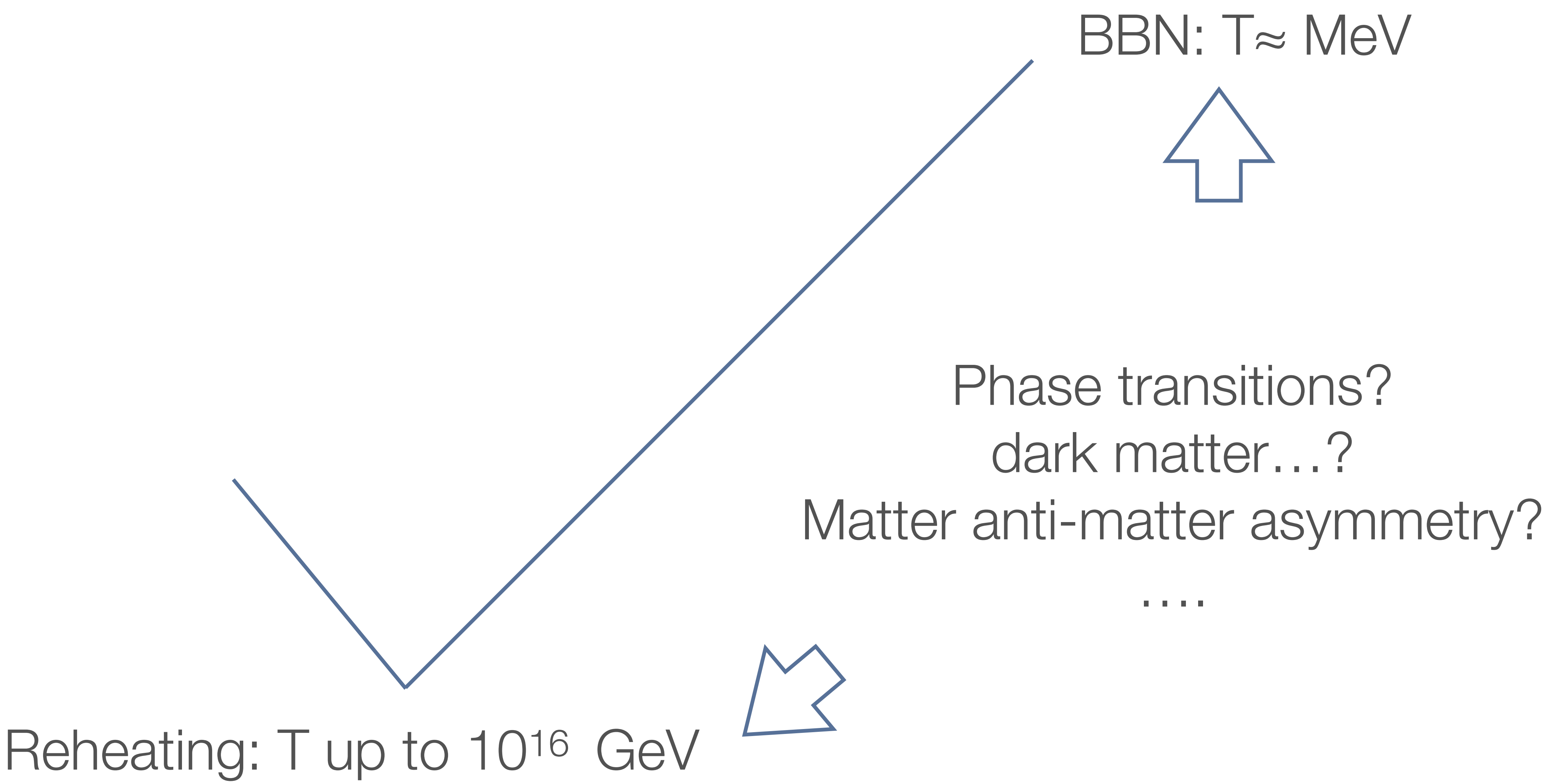
BBN: T≈ MeV



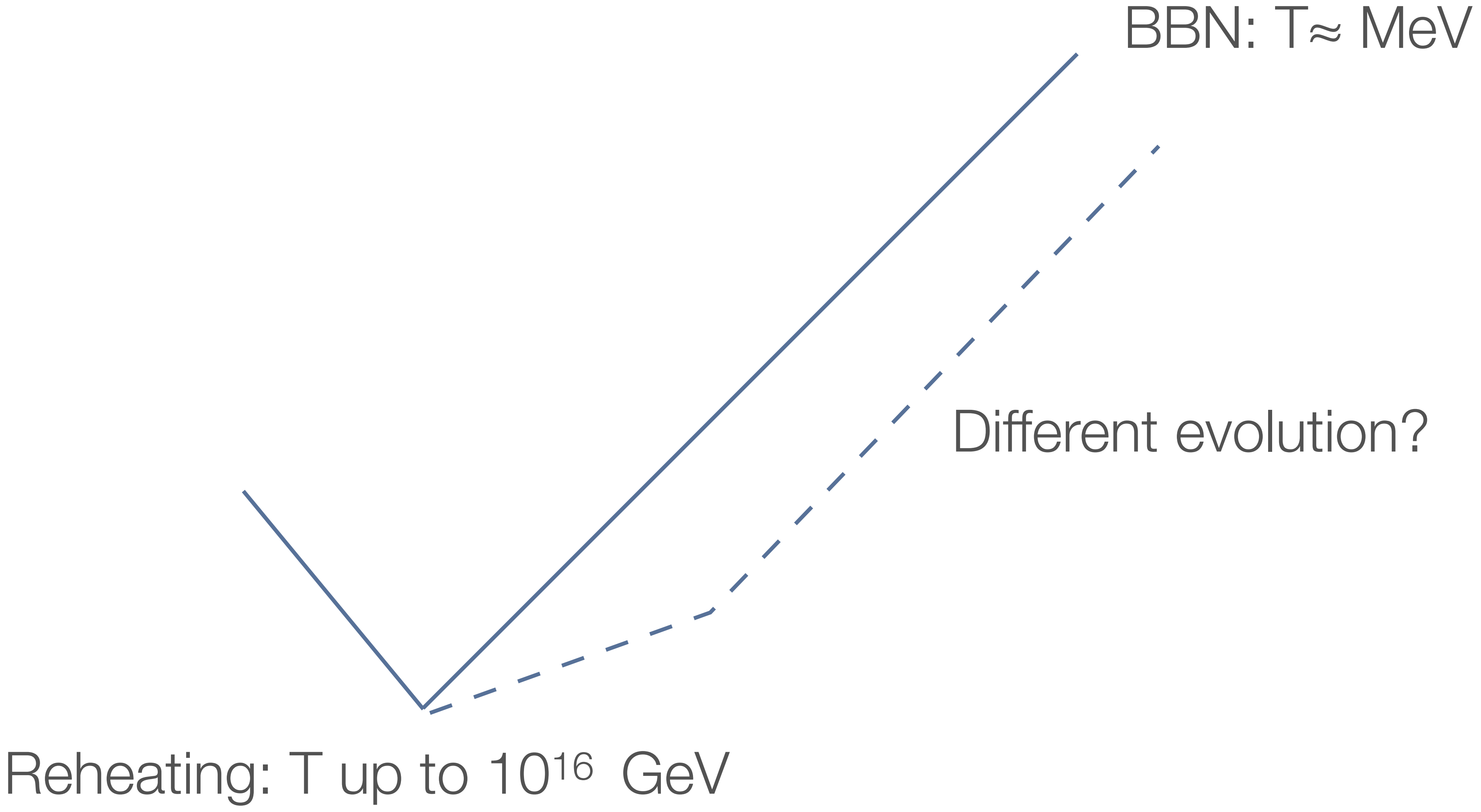
19 order of magnitude in temperature

Reheating: T up to 10^{16} GeV

Reheating and after



Reheating and after



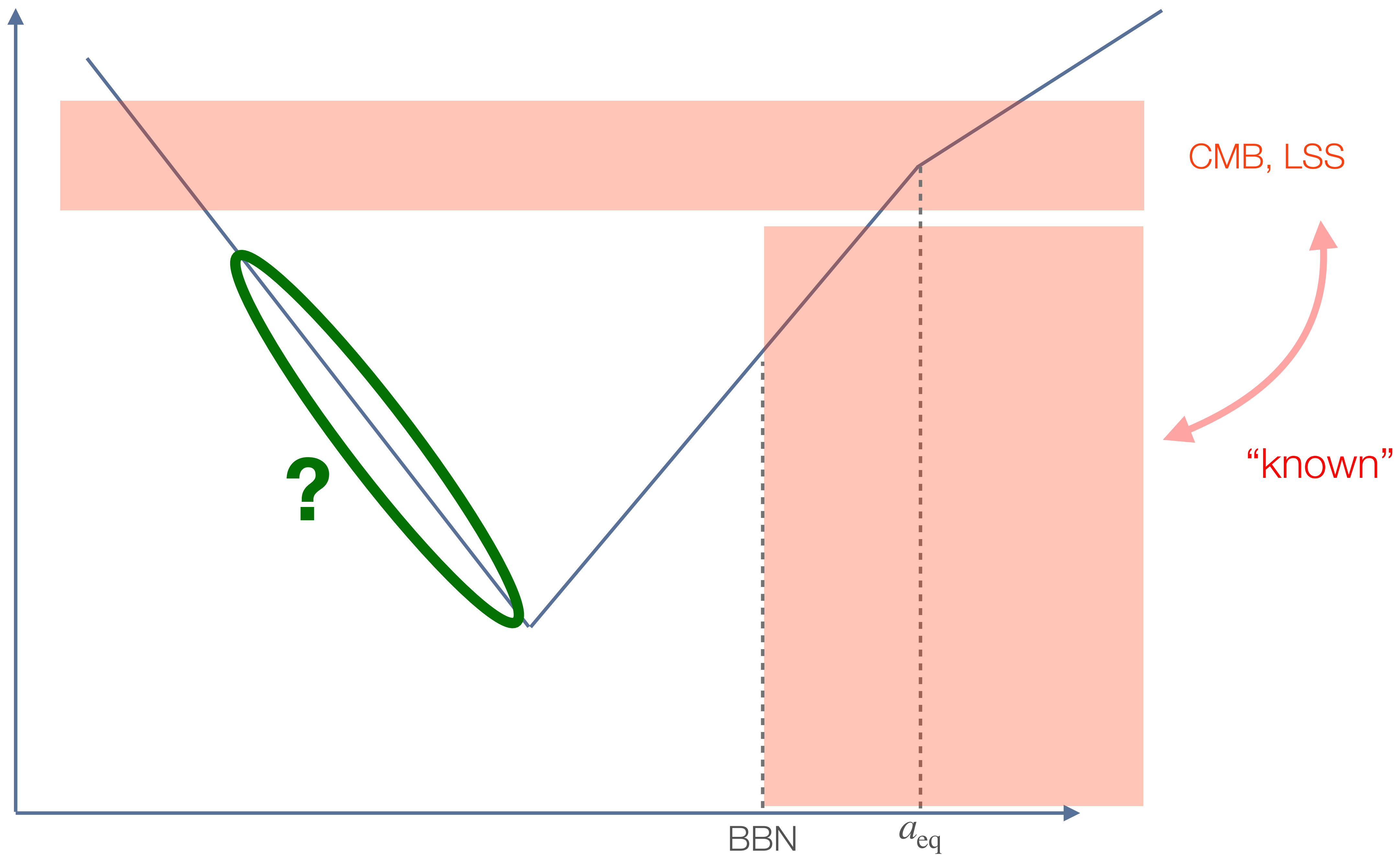
Reheating and after

BBN: T≈ MeV

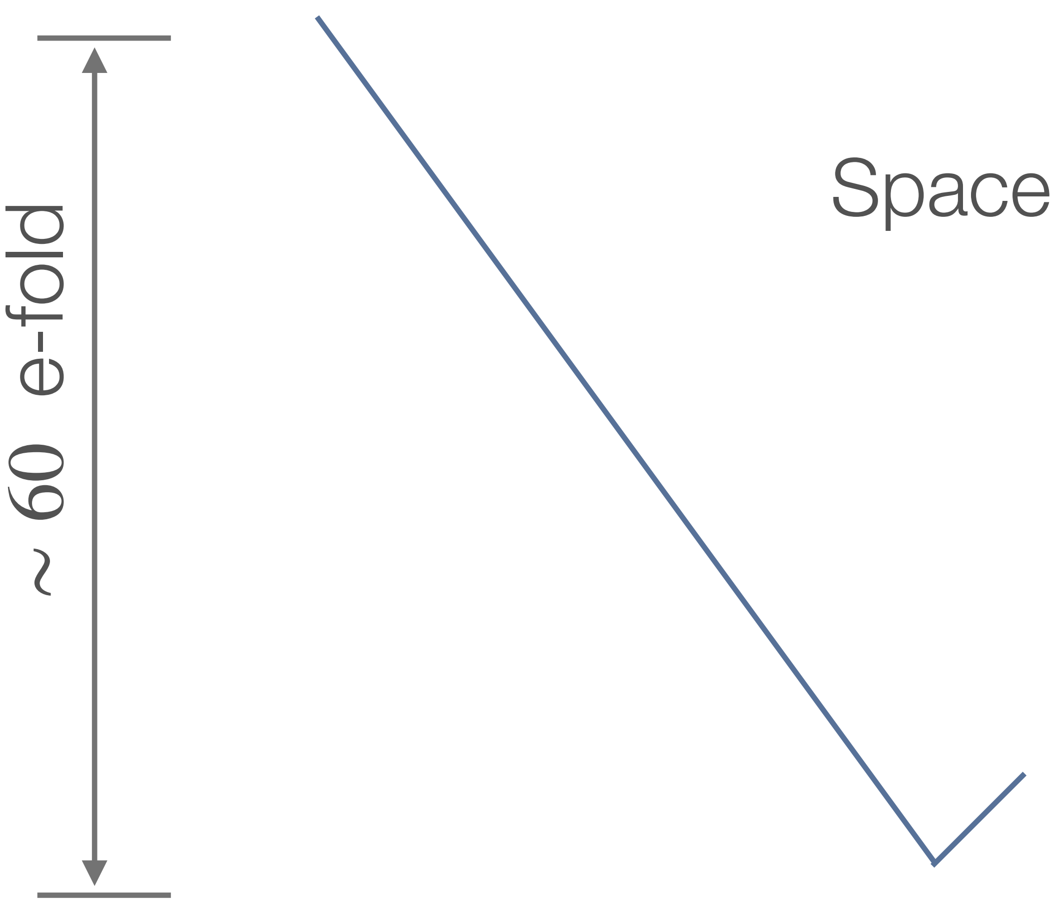
Probably something still beyond our imagination!

Reheating: T up to 10^{16} GeV

Inflation

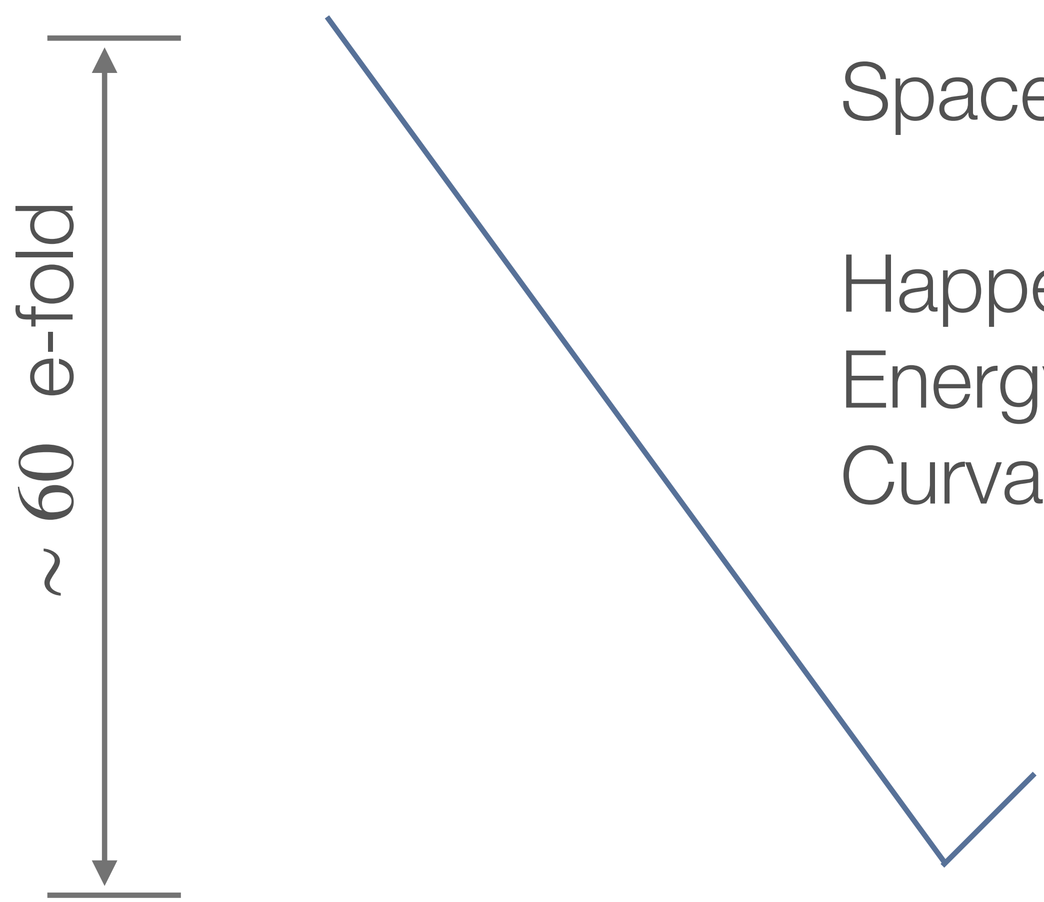


Inflationary era



Space grow by a factor of e^{60}

Inflationary era

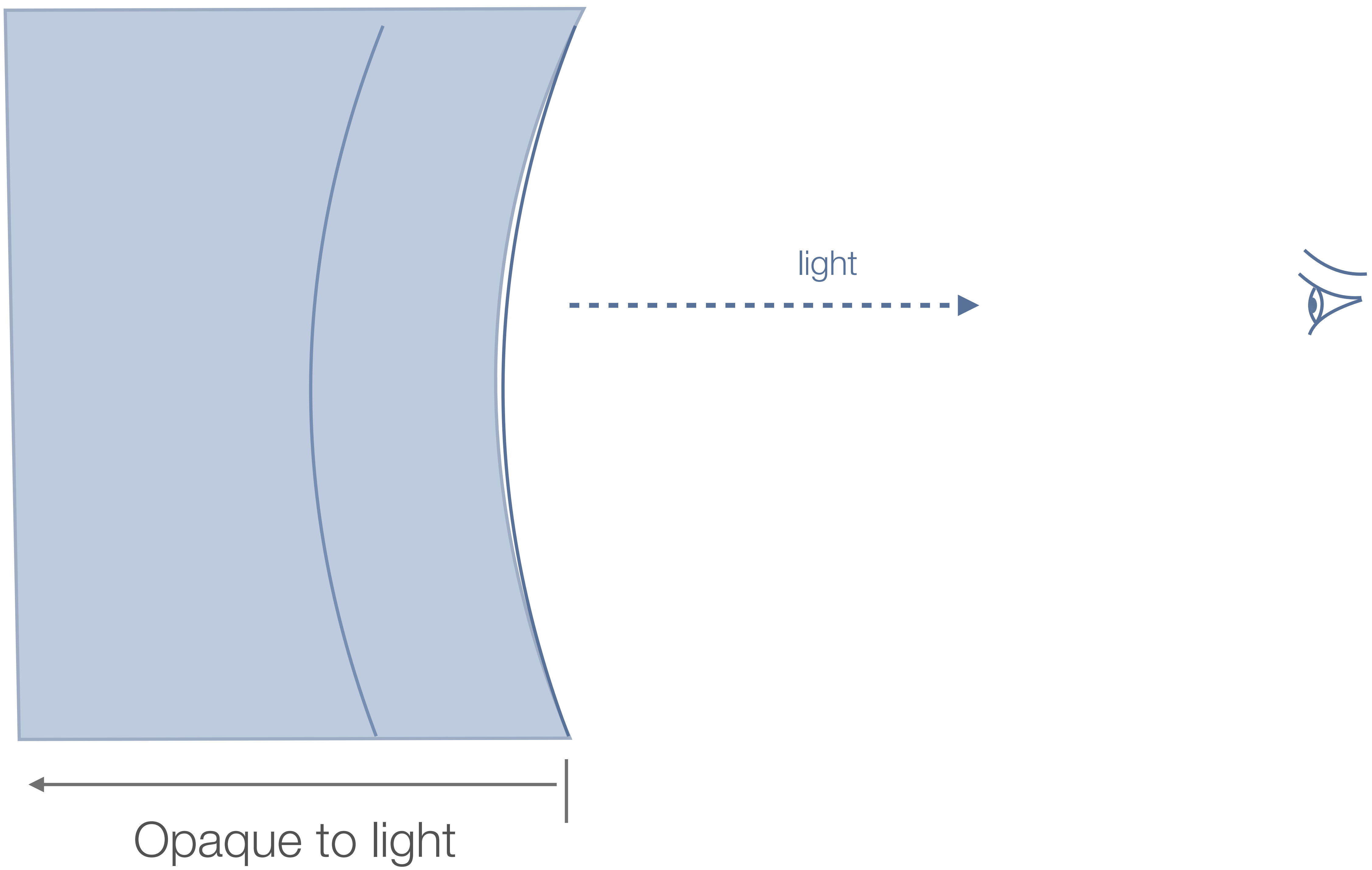


Space grow by a factor of e^{60}

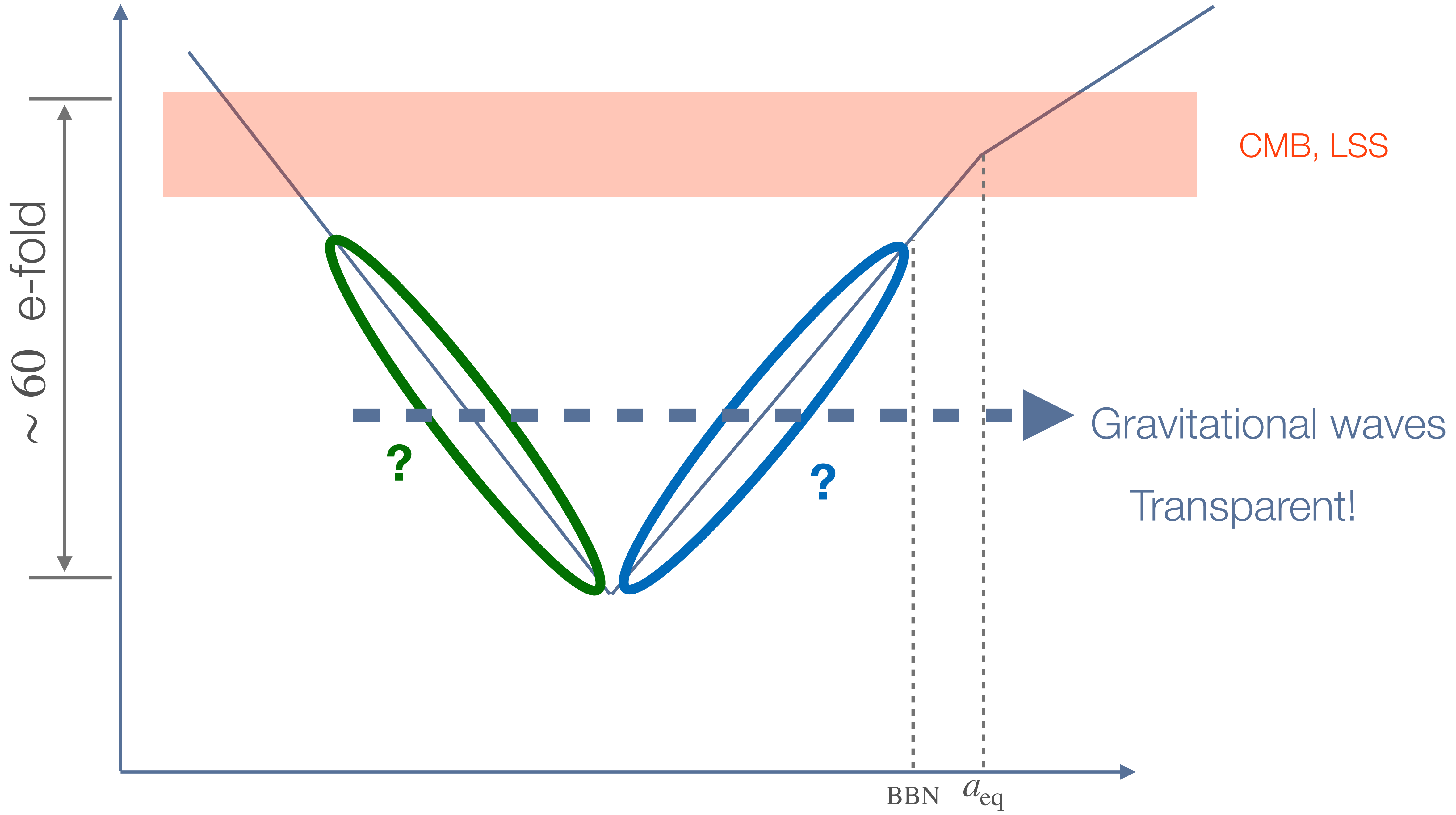
Happening under extreme conditions:
Energy scale up to 10^{16} GeV
Curvature up to 10^{13} GeV

Exactly what happened?

How to see through the thermal fog?



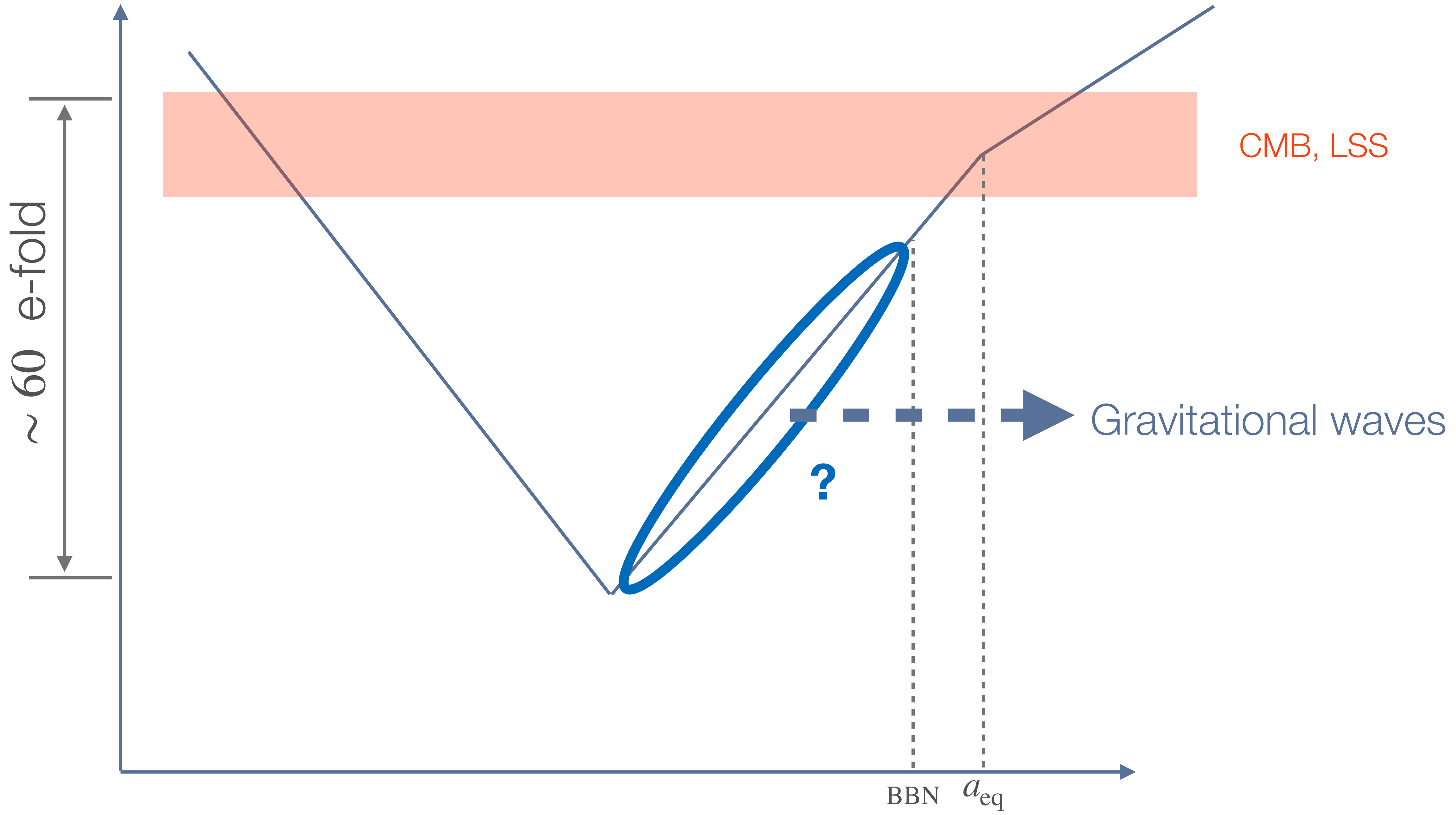
A new window



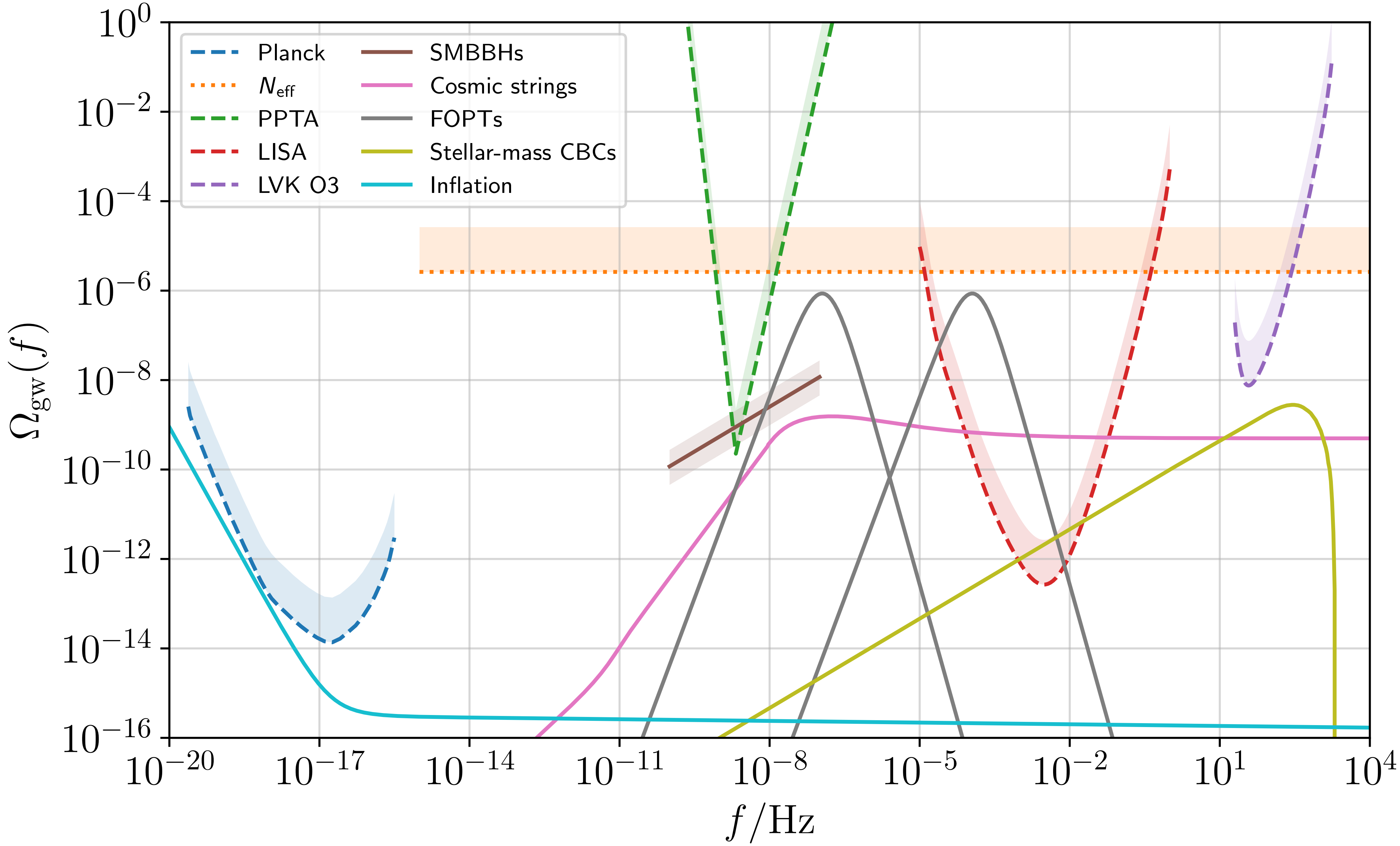
~ 60 e-fold
CMB, LSS
?
?
Gravitational waves
Transparent!
BBN
$a_{\rm eq}$

A few stories

Post inflationary

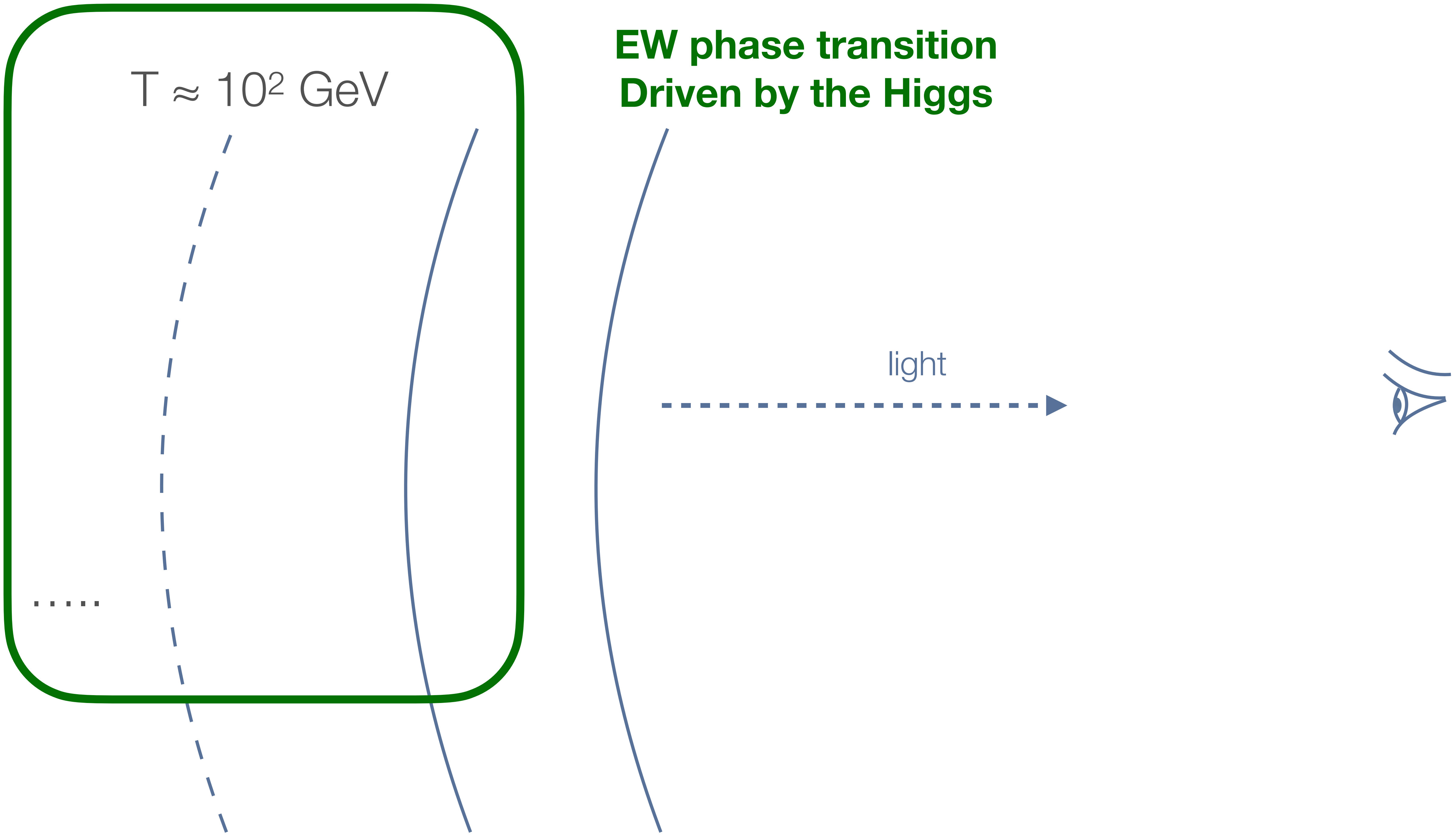


Review by Renzini et al, 2202.00178



Typically, need something quite dramatic.

A benchmark

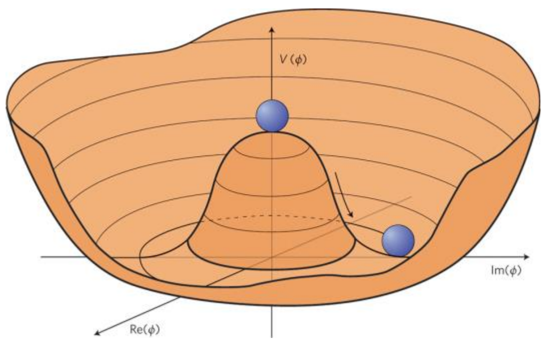


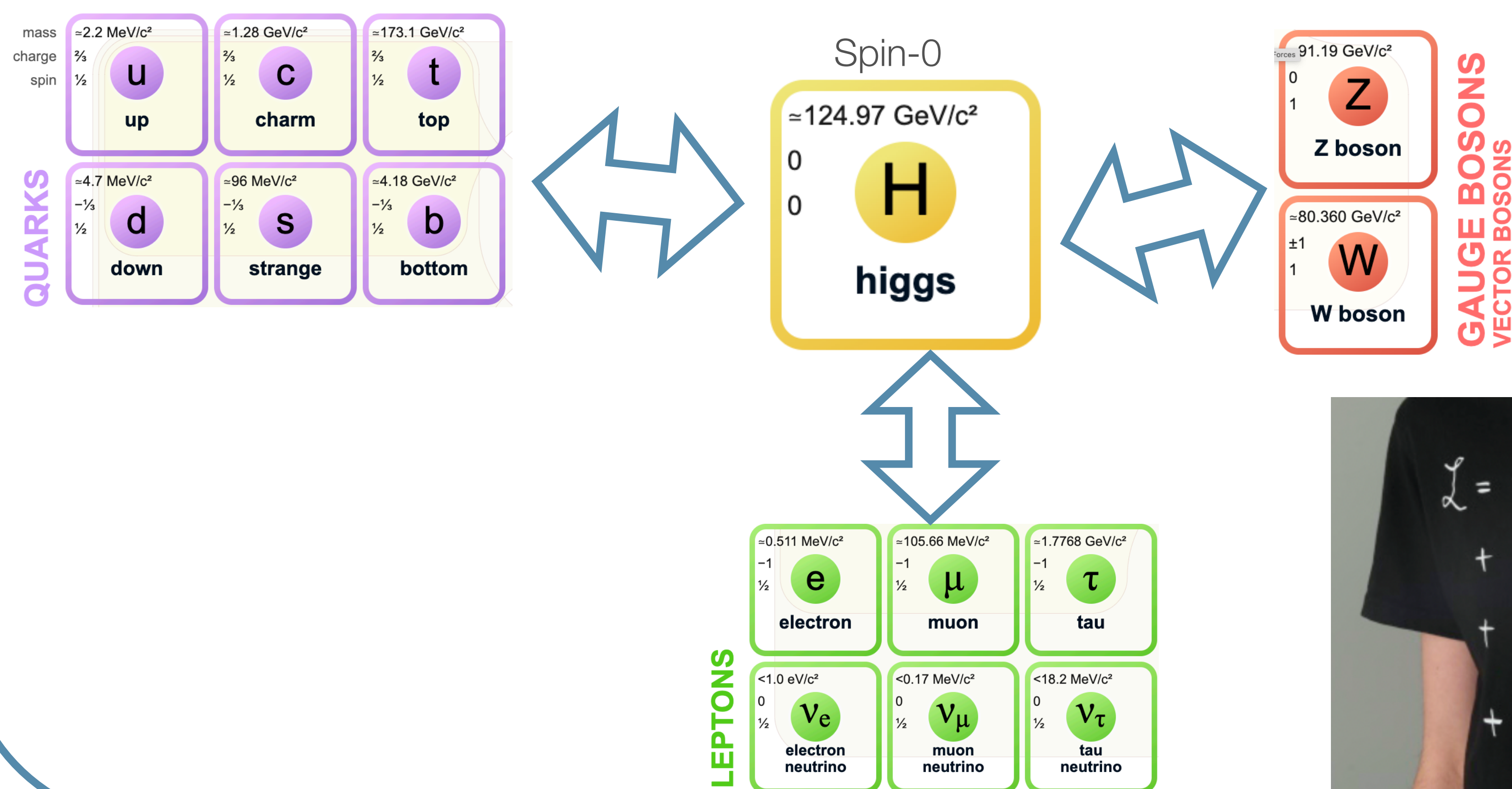
Electroweak phase transition in the Standard Model

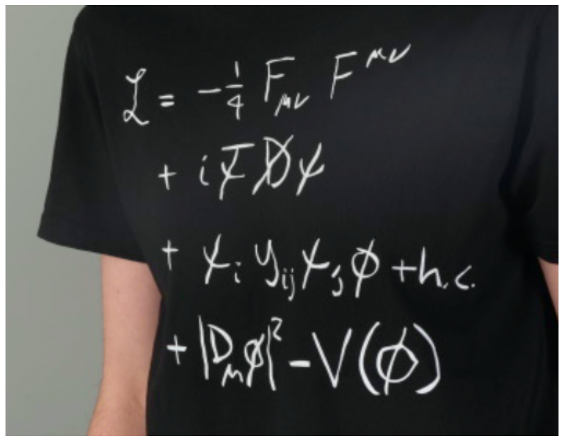
A simple "Mexican hat" potential.

⇒ Electroweak symmetry breaking

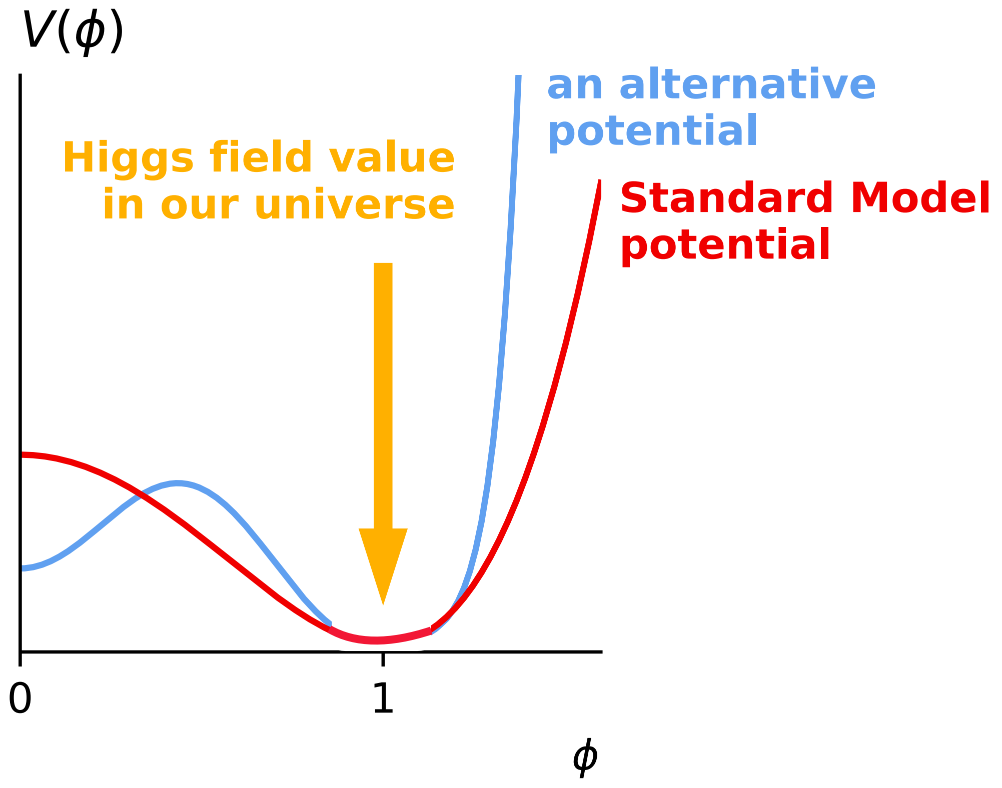
⇒ gives masses of SM particles







What do we know about the Higgs potential?



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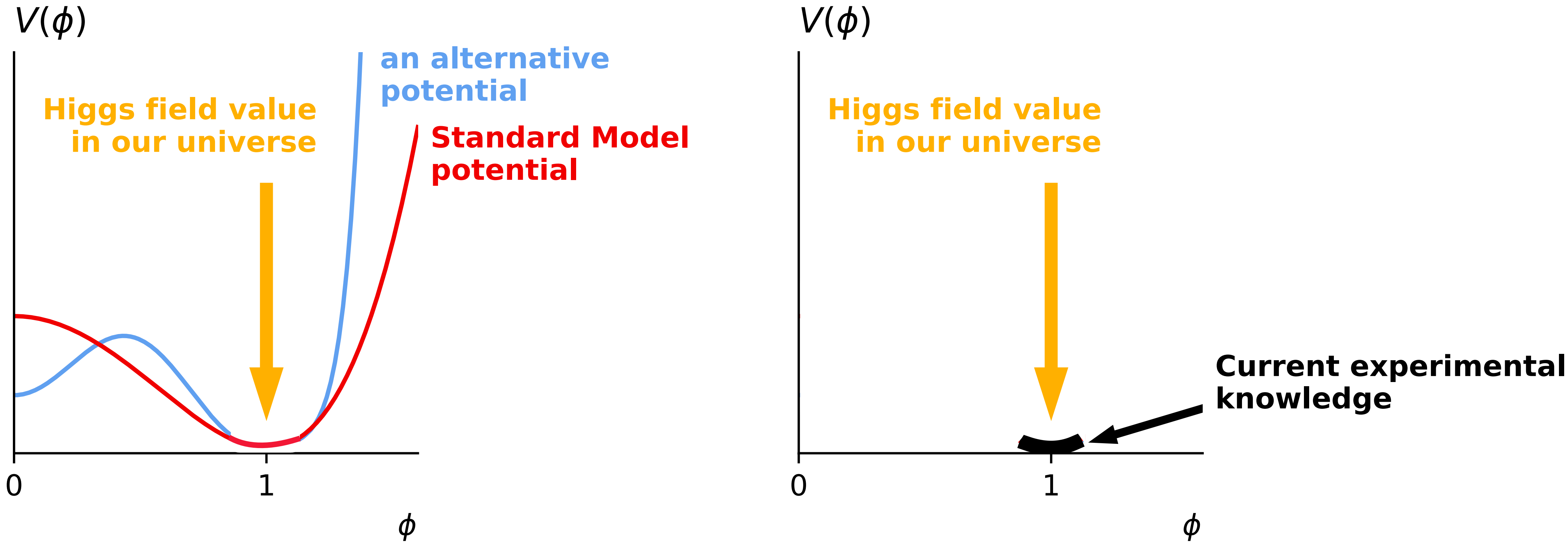
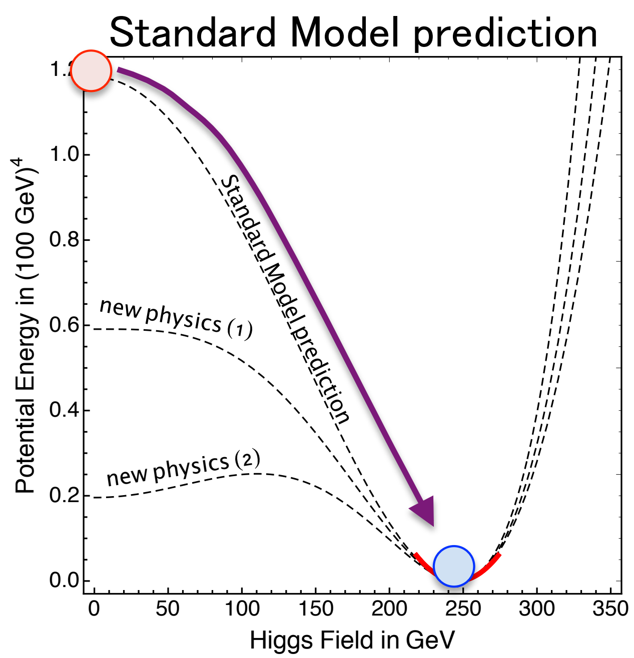
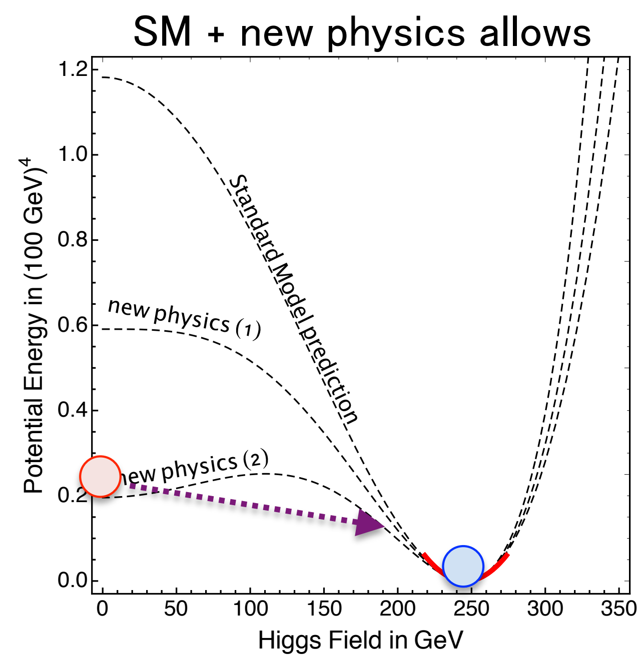
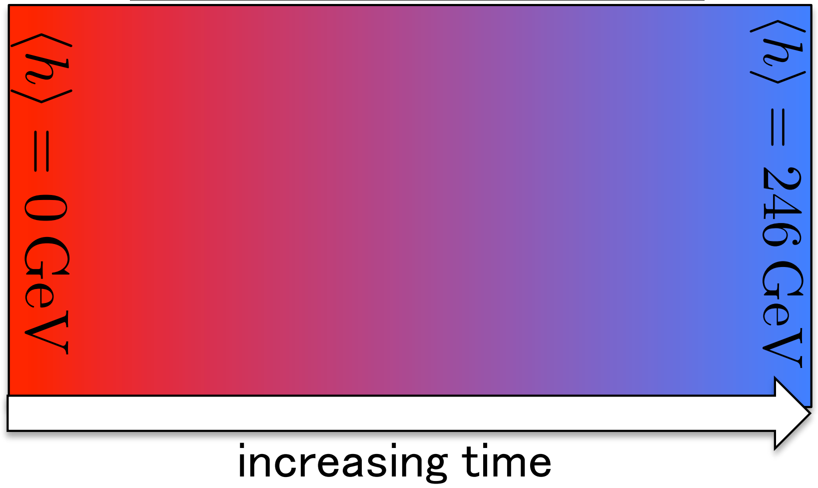


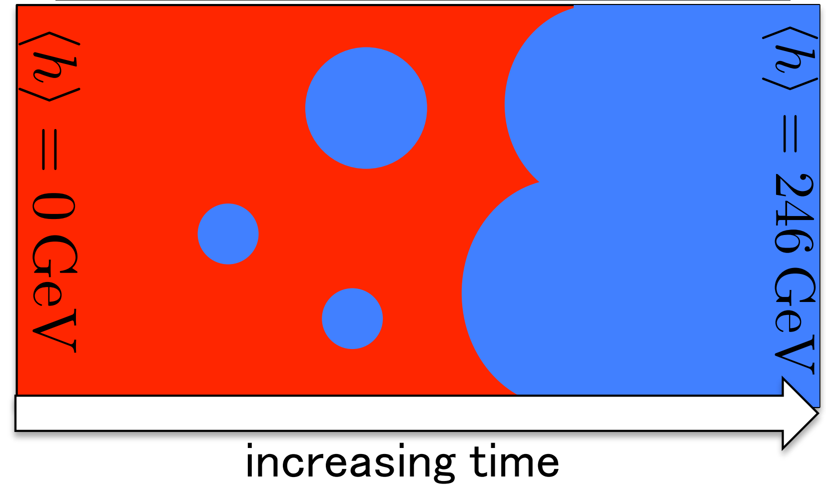




Continuous Crossover



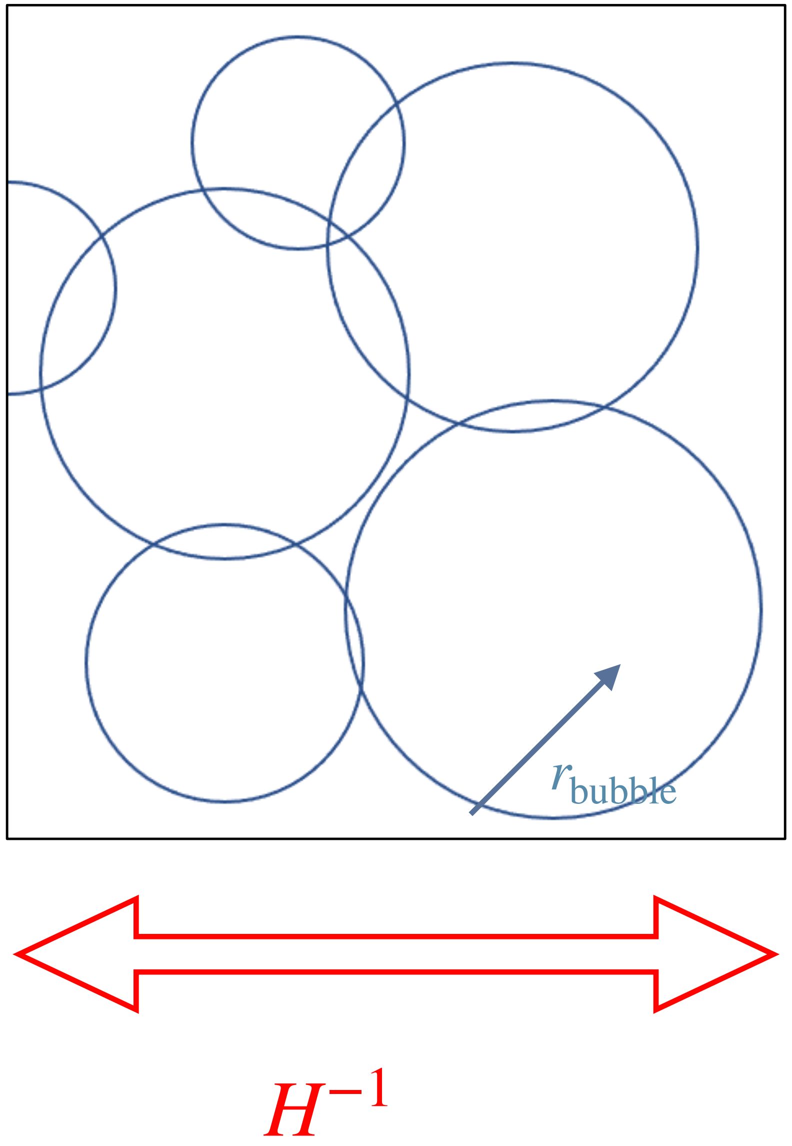
First Order Phase Transition



How does Higgs evolve in the early universe?

1st order phase transition

Proceed through bubble nucleation.

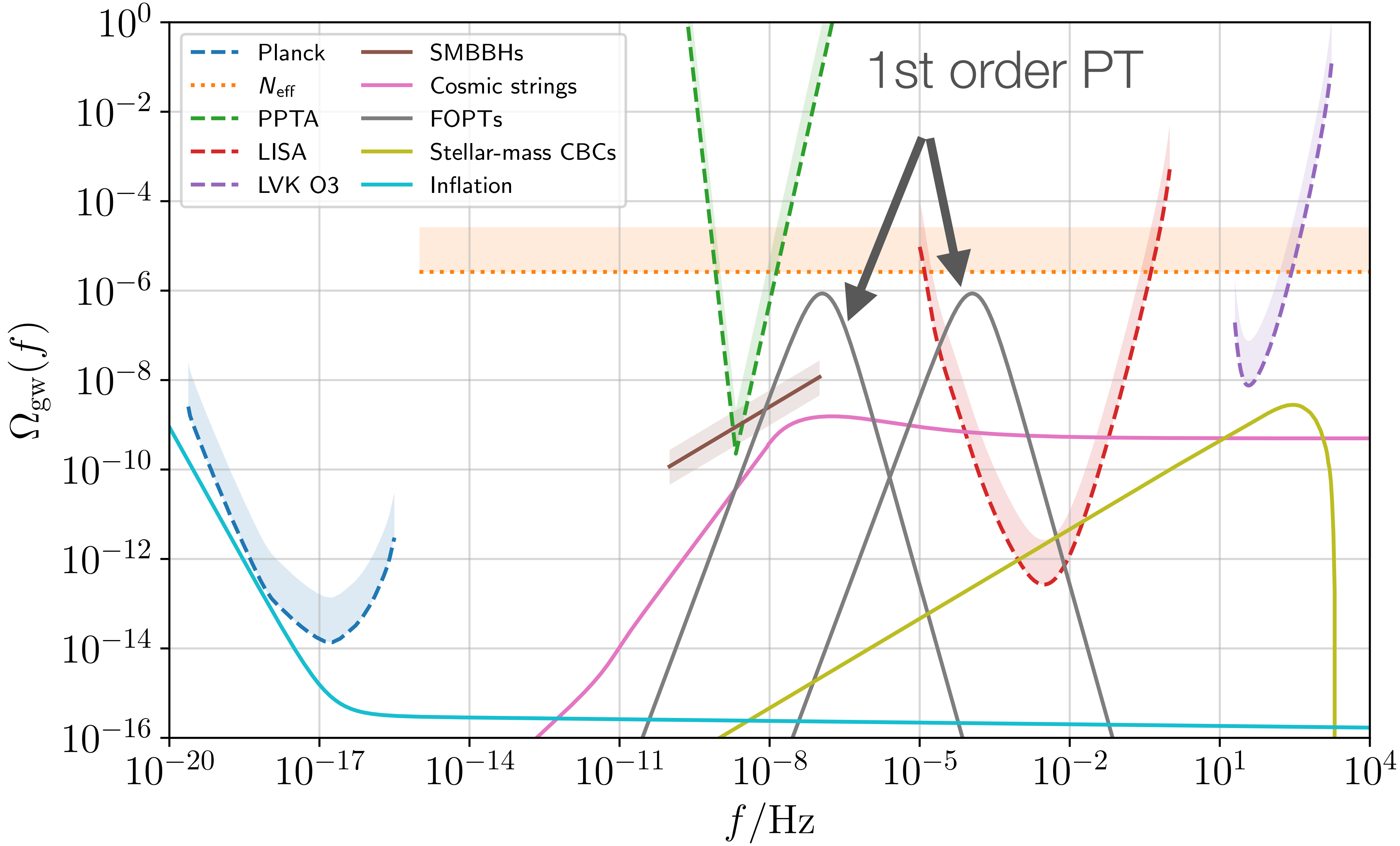


Bubble collision
Violent process involving bubble wall, plasma …

⇒ Gravitational wave

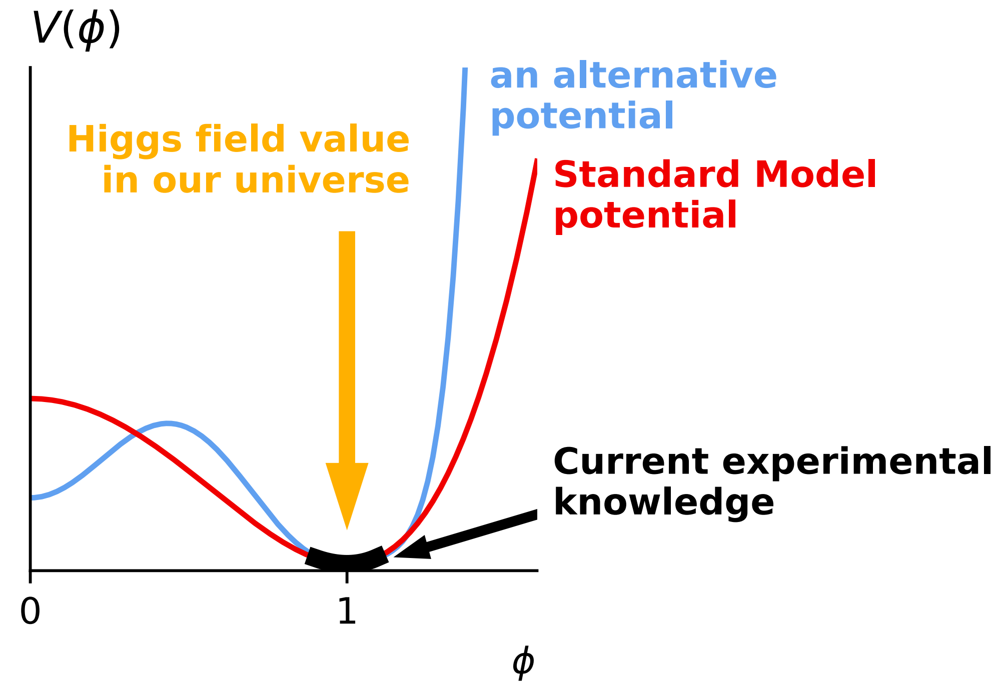
⇒ wave-length ≈ bubble size ≈ H^{-1}

Review by Renzini et al, 2202.00178

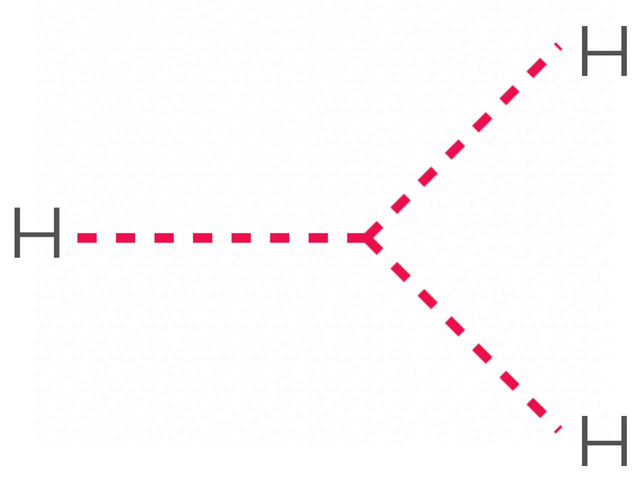


Typically, need something quite dramatic.

Better measurement of the Higgs

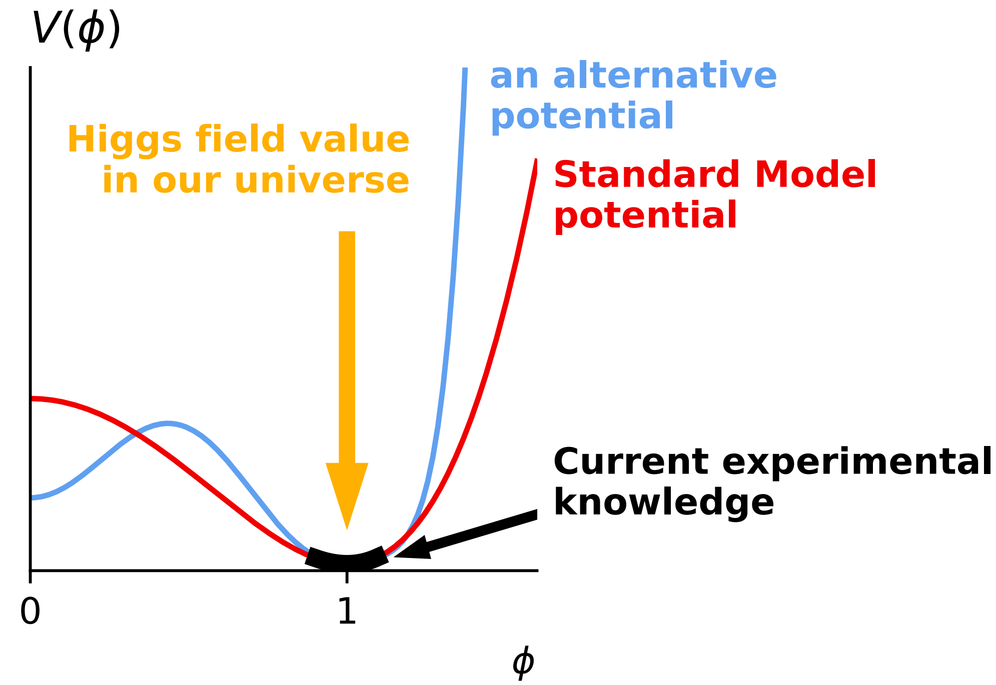


1. Self-coupling

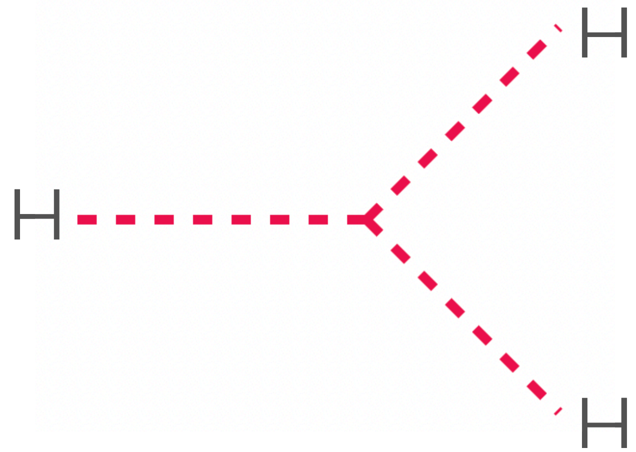


Unique kind of coupling.
Important to observe it!

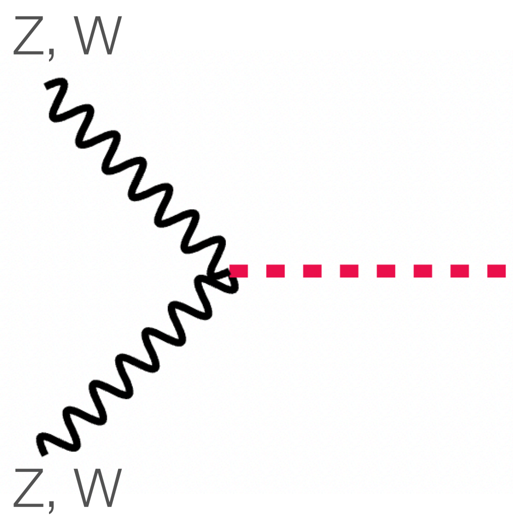
Better measurement of the Higgs



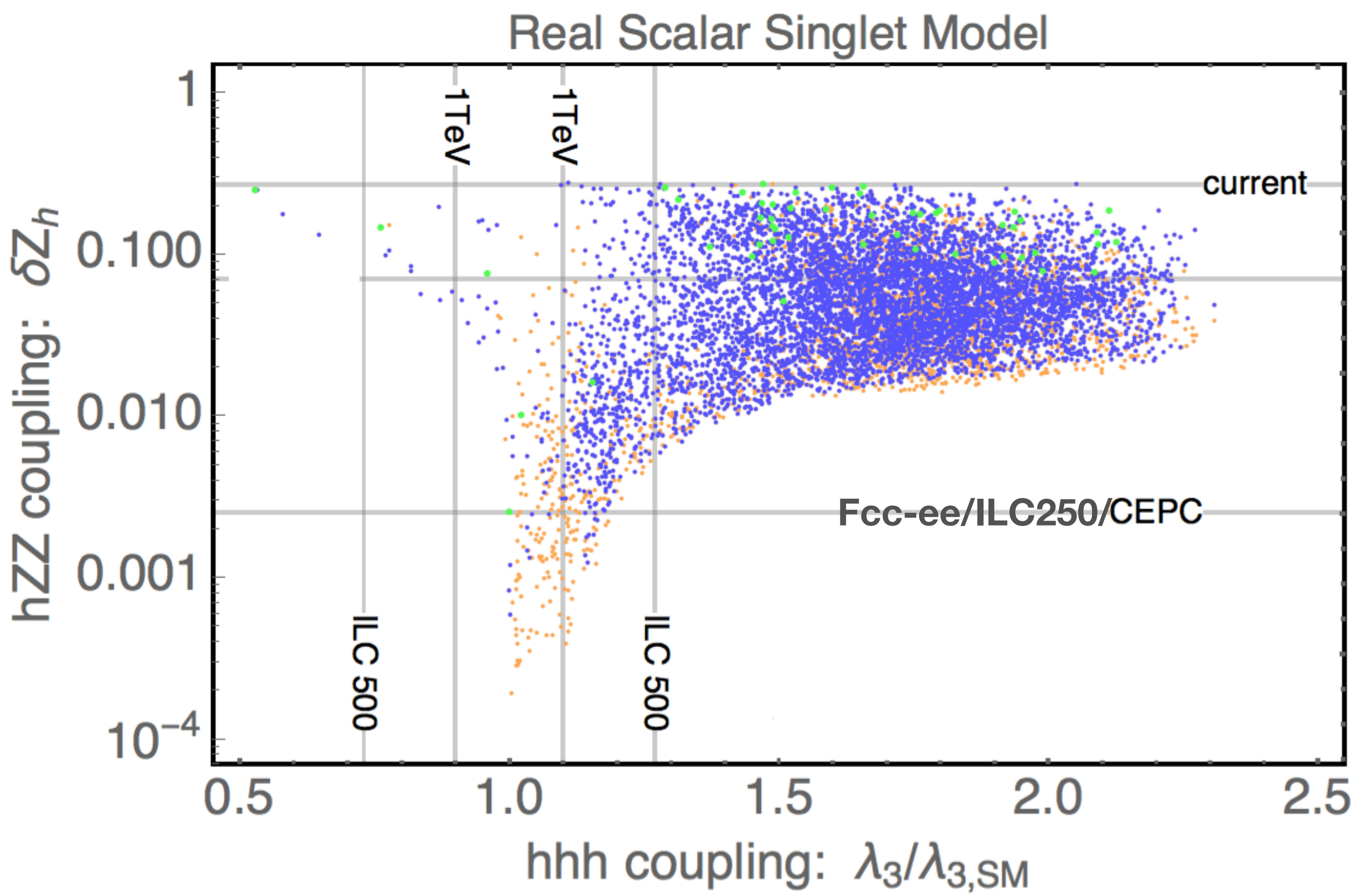
1. Self-coupling



2. New physics in the alternative scenario often induce changes in other Higgs coupling, such as hZ

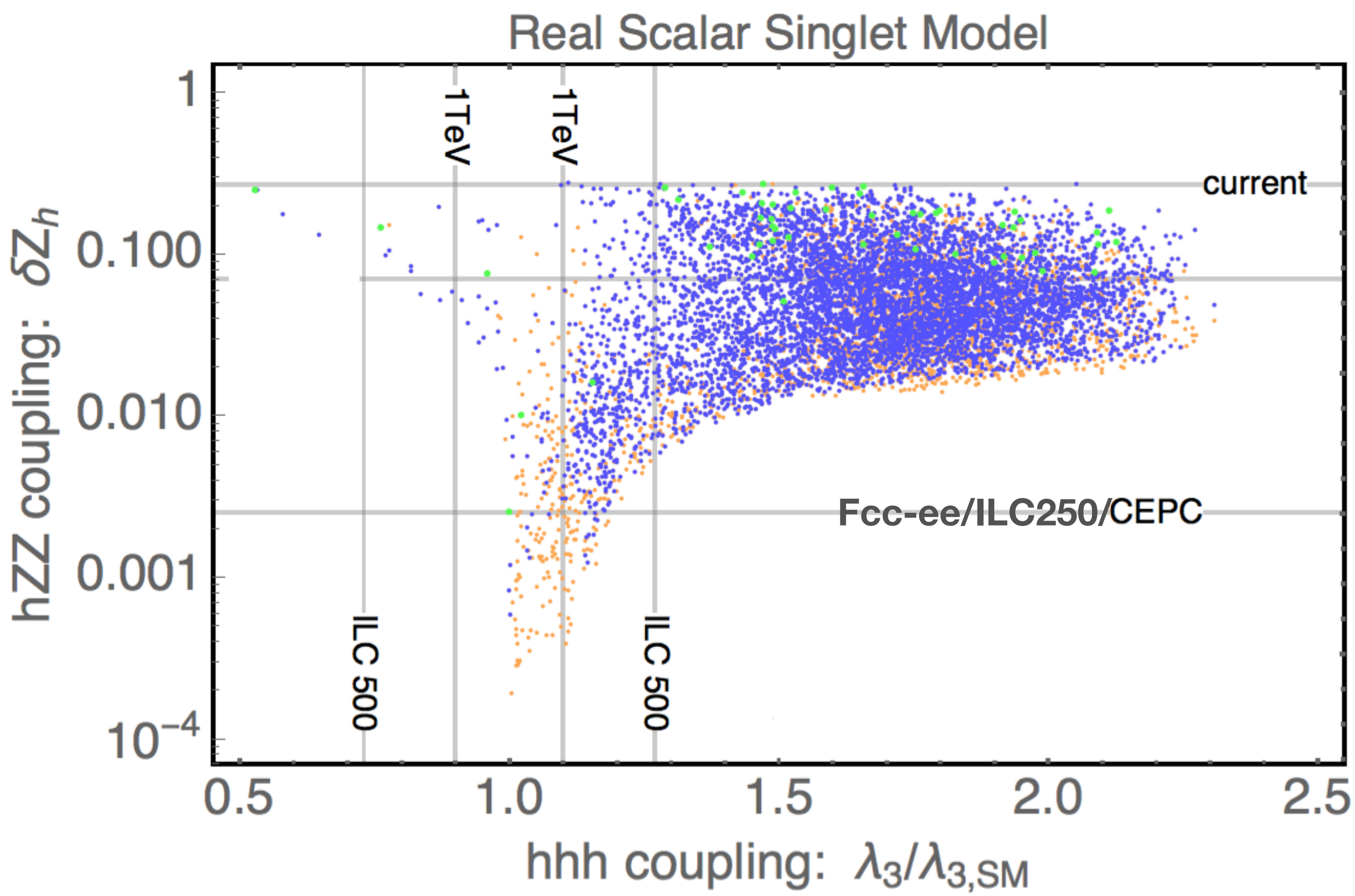


EW phase transition



Models with 1st order EWSB, large gravitational wave signal.

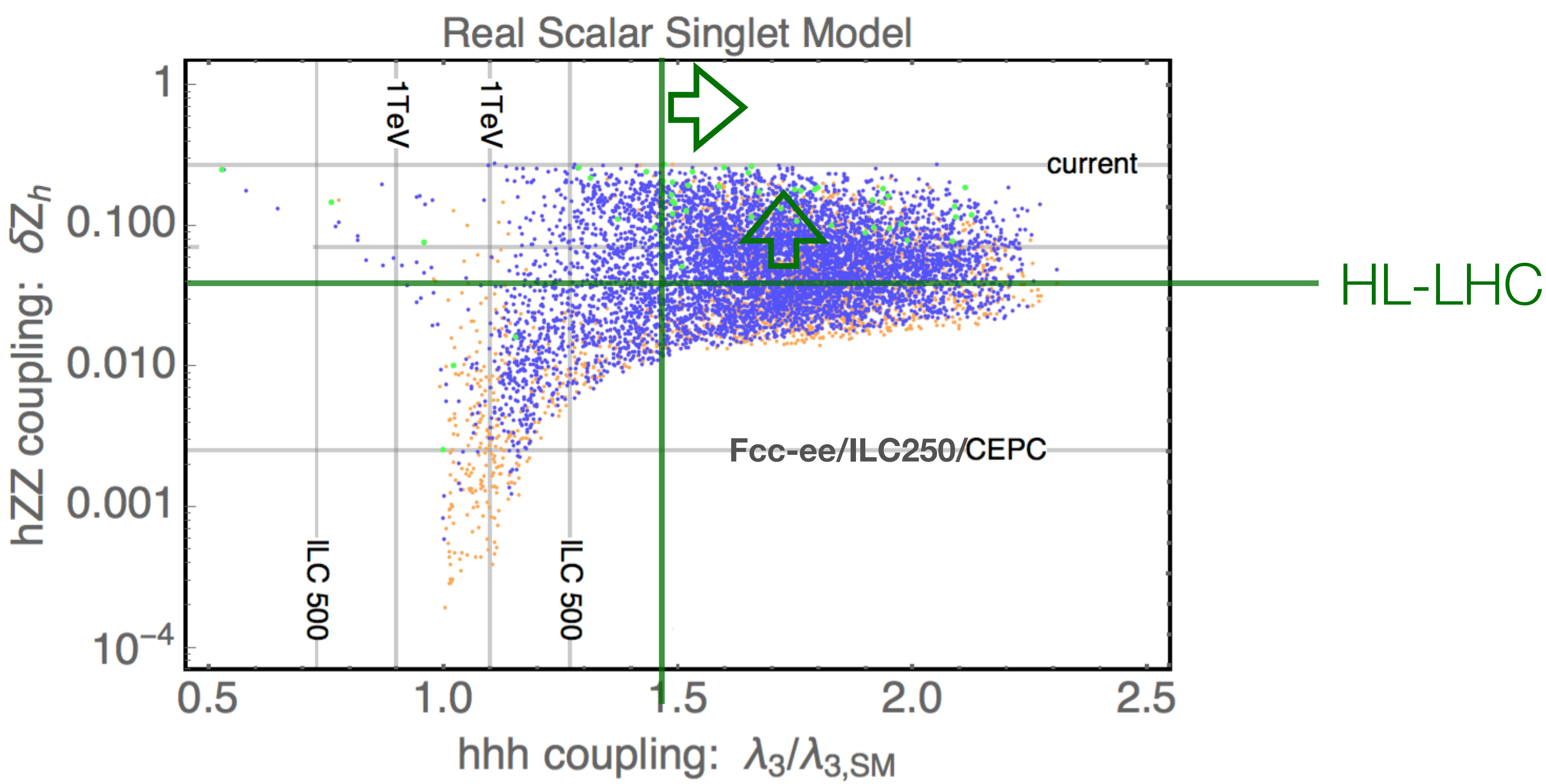
EW phase transition



Combine cosmic (gravitational wave) and terrestrial (Higgs coupling)

Nail the electroweak phase transition

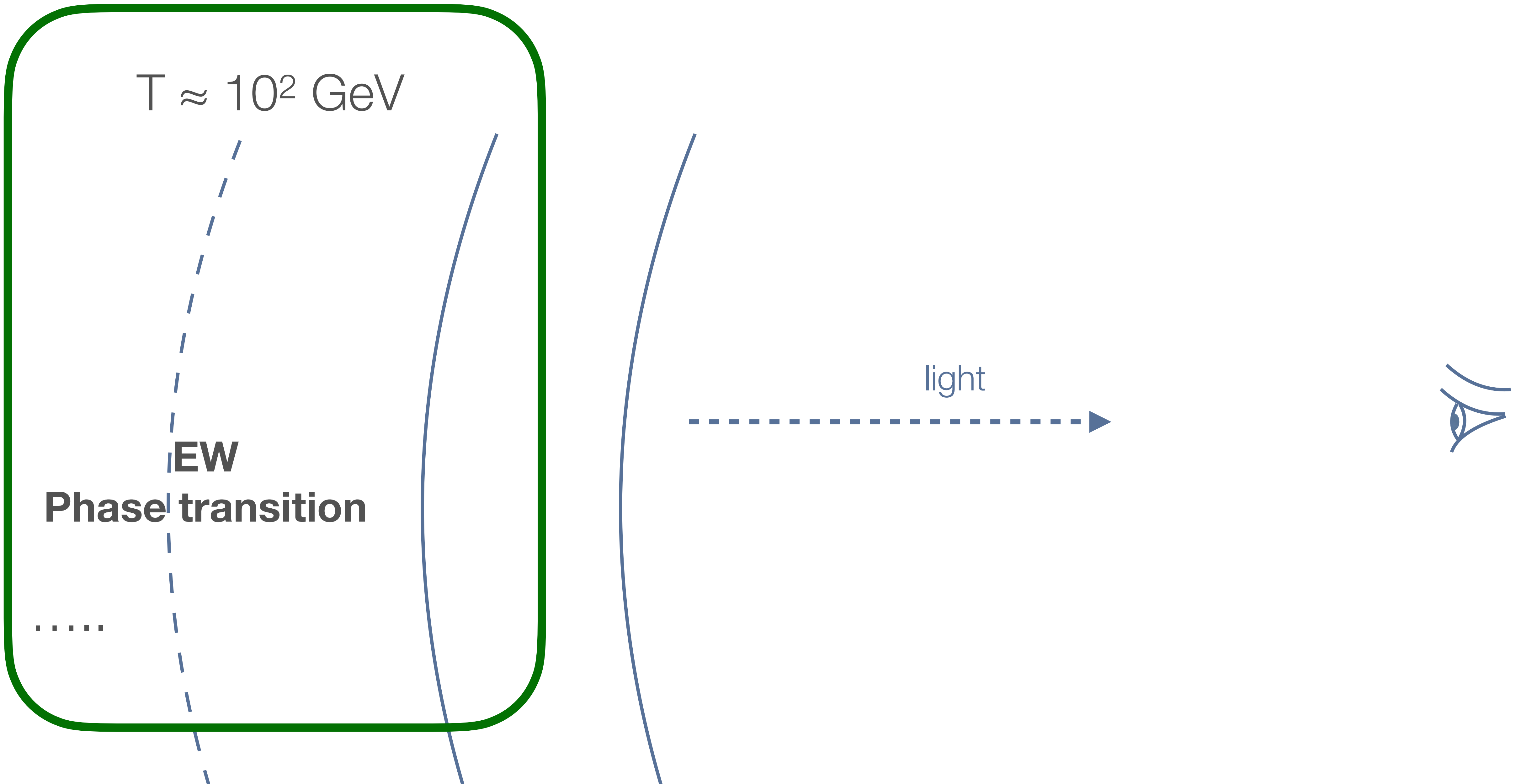
EW phase transition



Combine cosmic (gravitational wave) and terrestrial (Higgs coupling)

Nail the electroweak phase transition

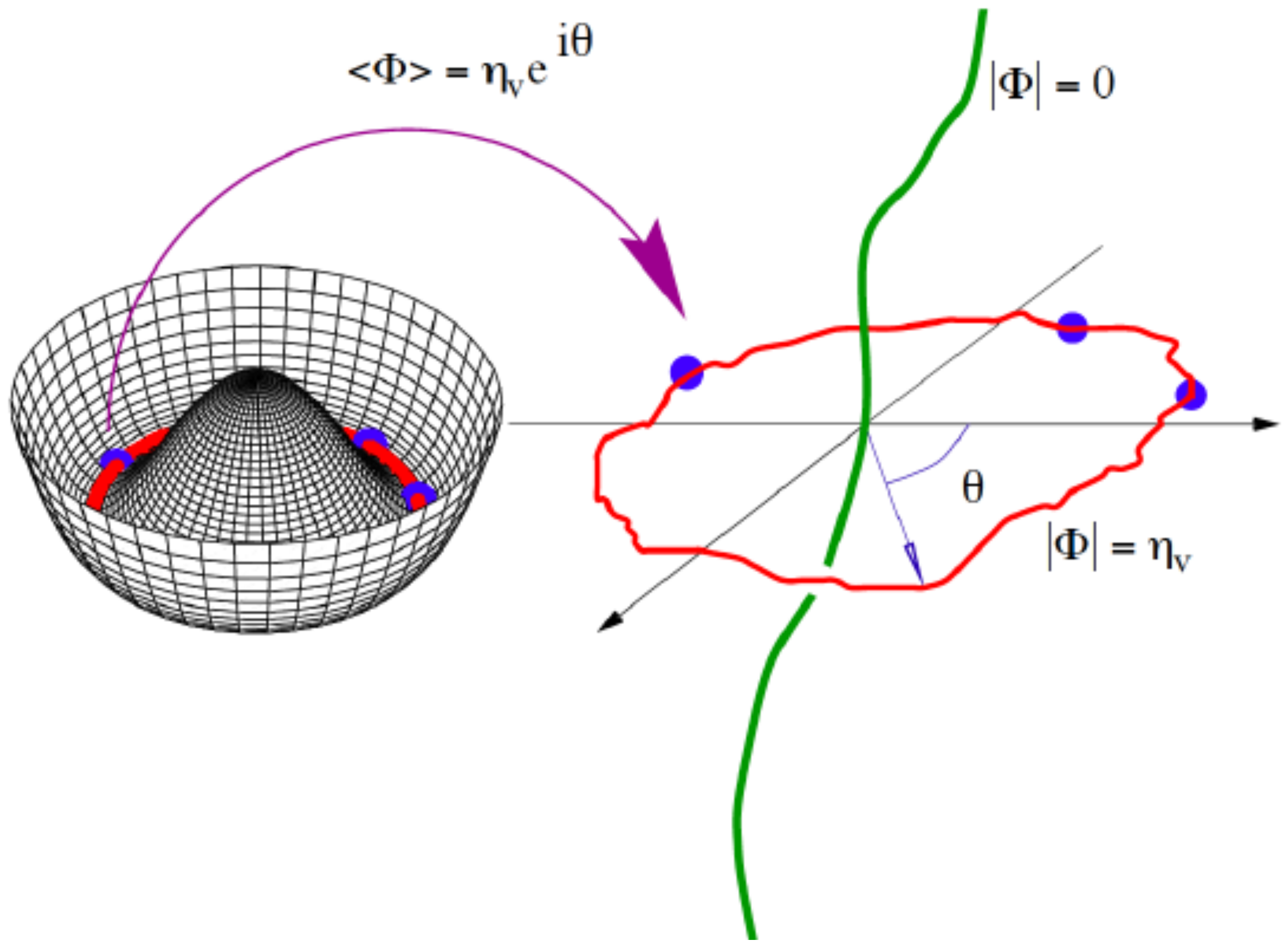
Would be a new milestone



Combine cosmic (gravitational wave) and terrestrial (Higgs coupling)

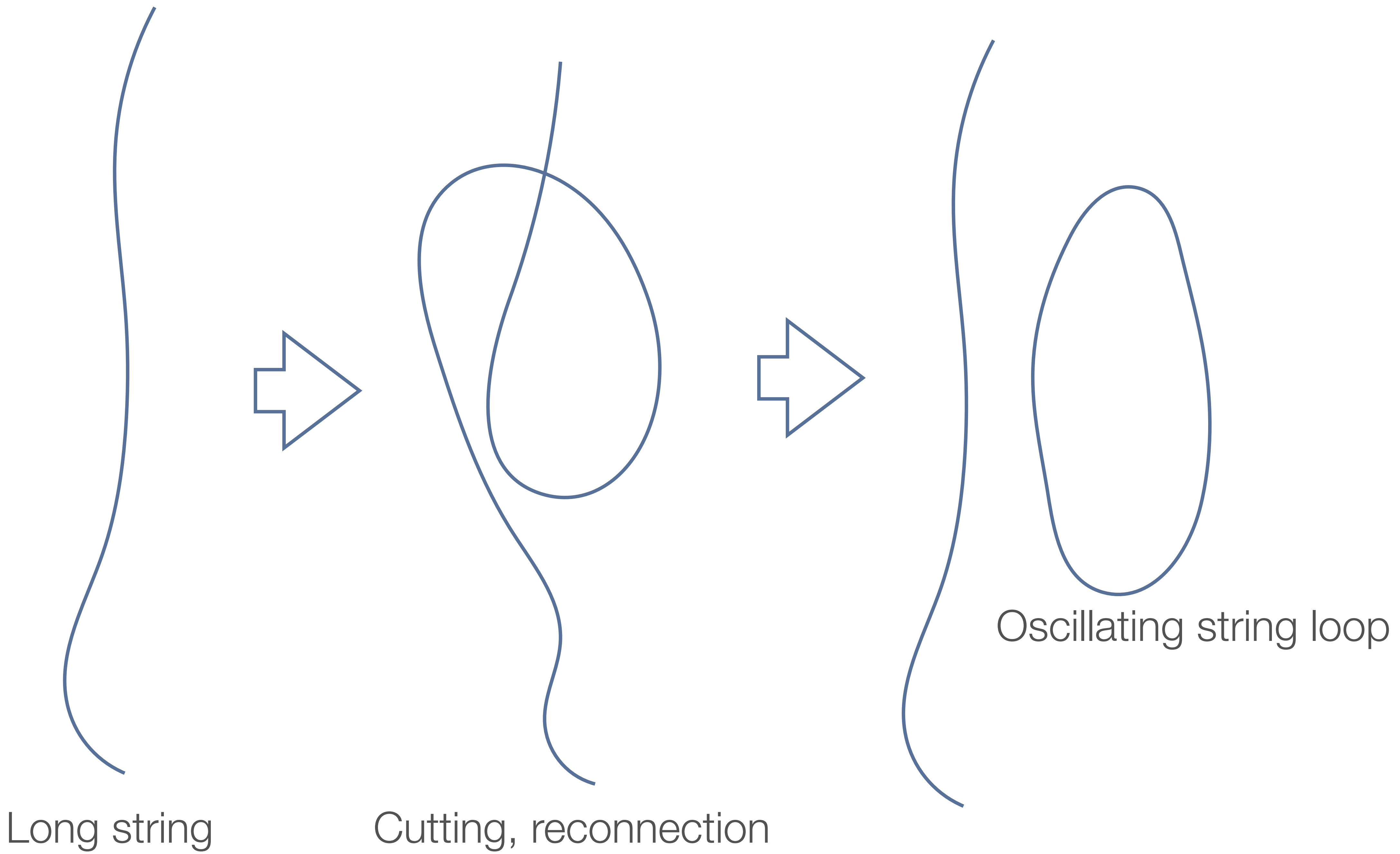
Nail the electroweak phase transition

2nd order phase transition

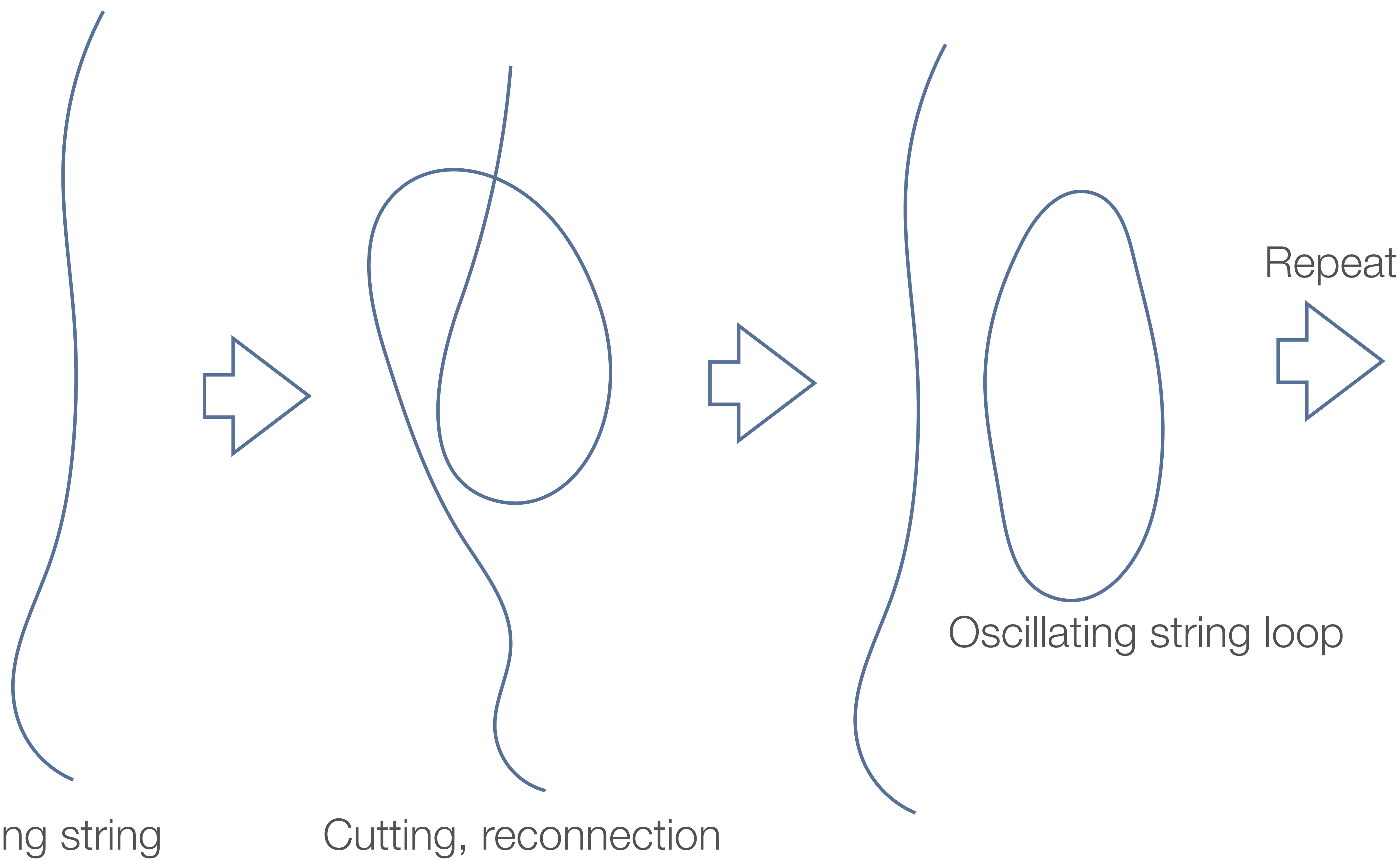


Cosmic strings

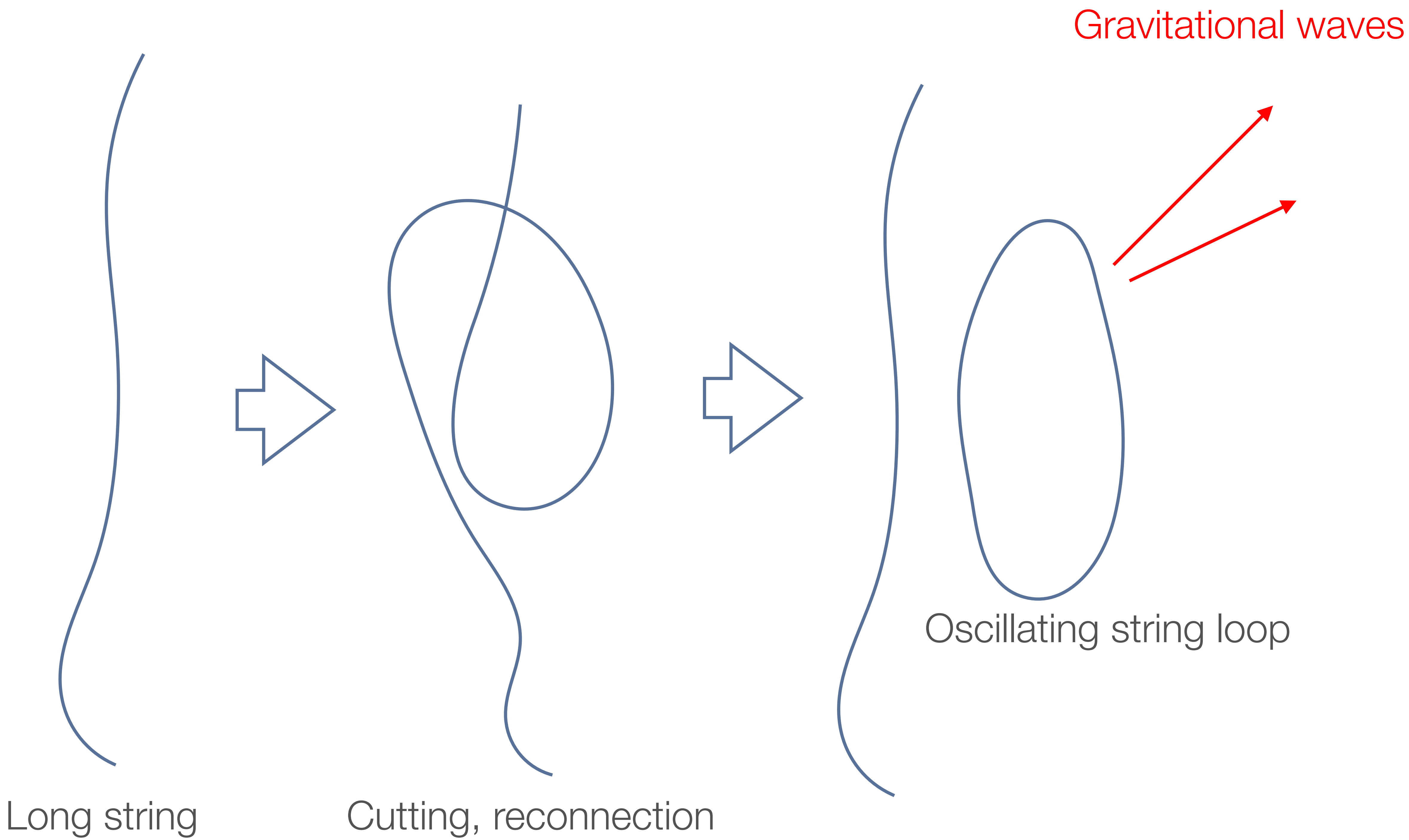
Cosmic string and gravitational wave

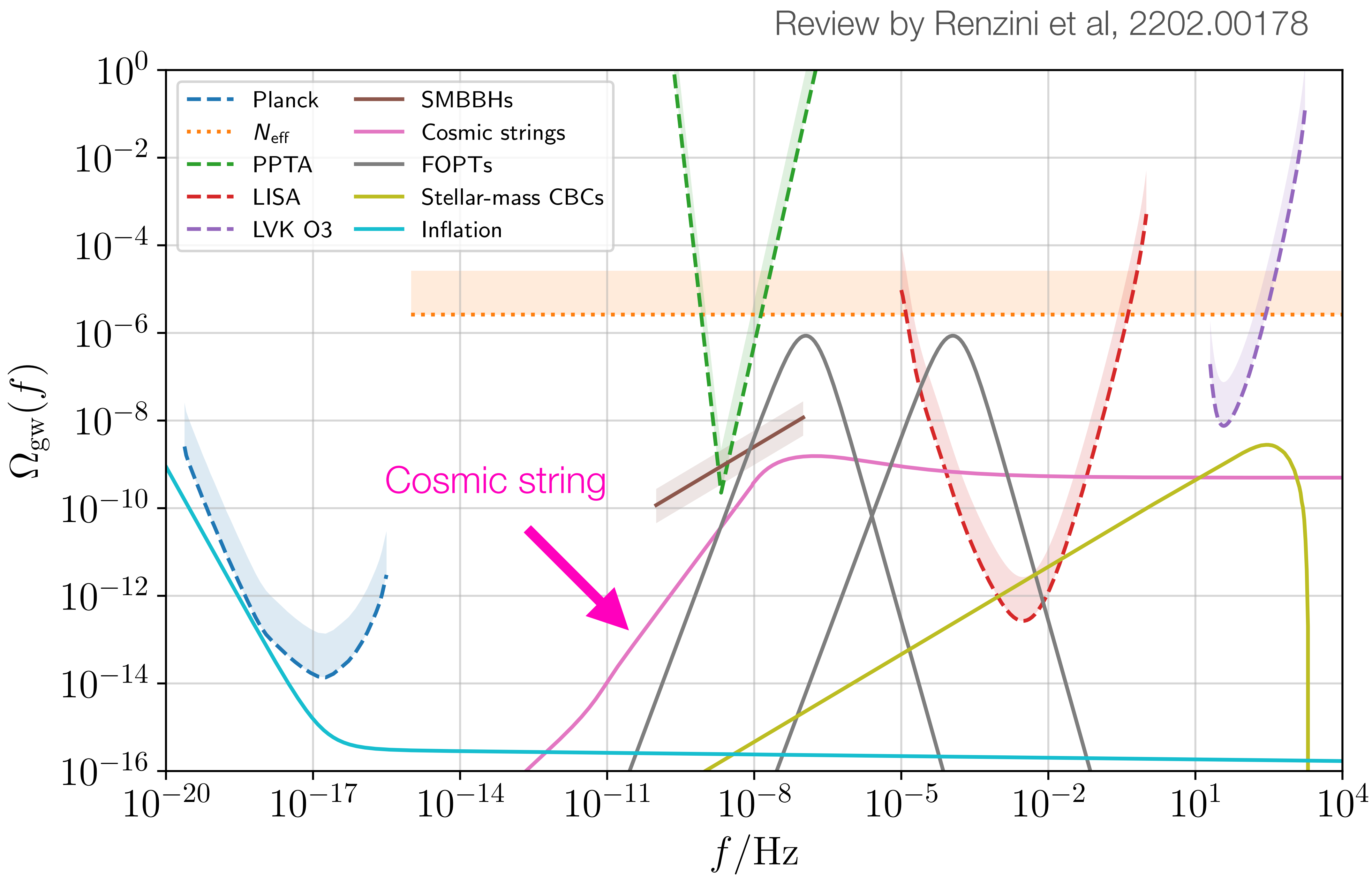


Cosmic string and gravitational wave



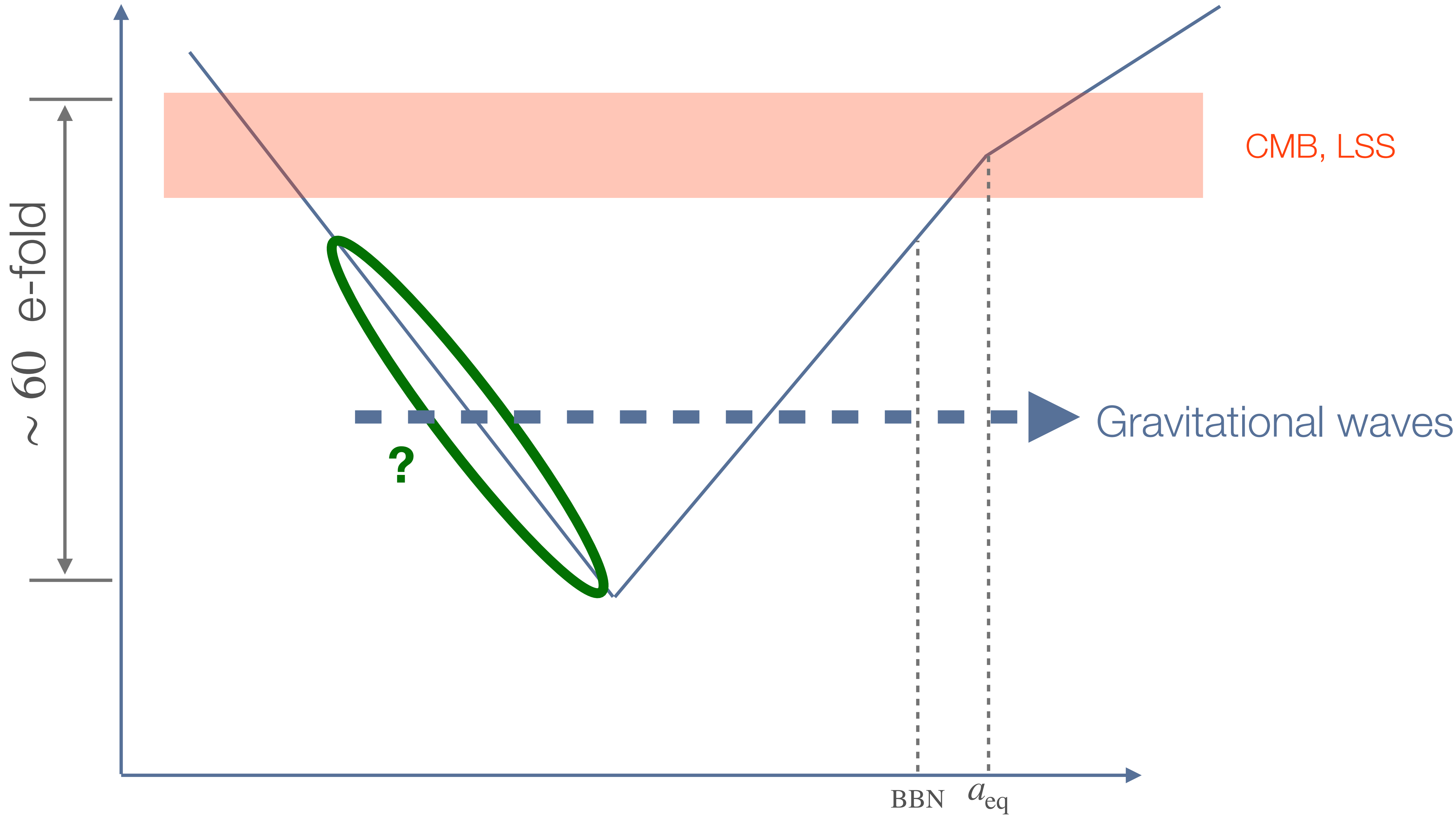
Cosmic string and gravitational wave



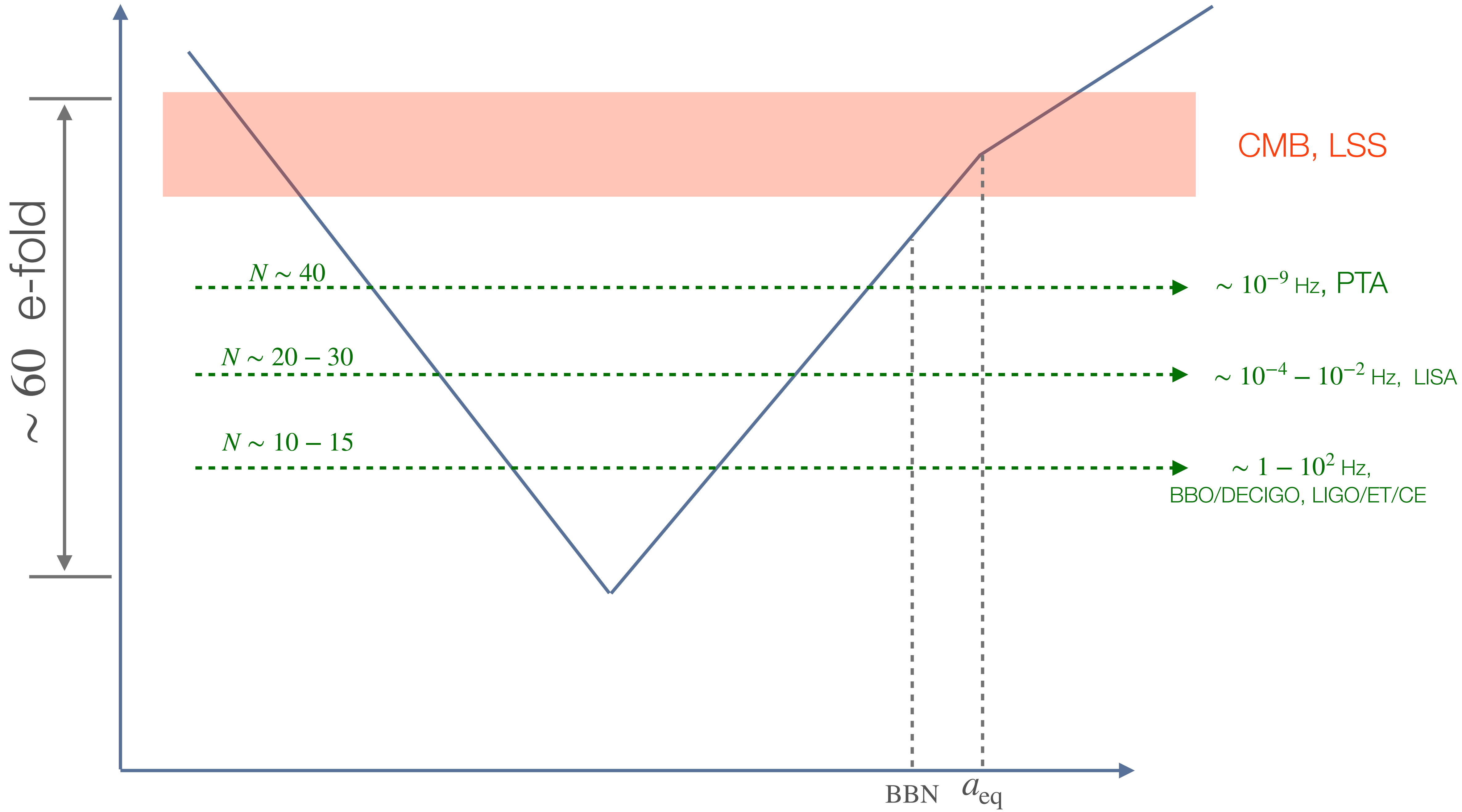


Typically, need something quite dramatic.

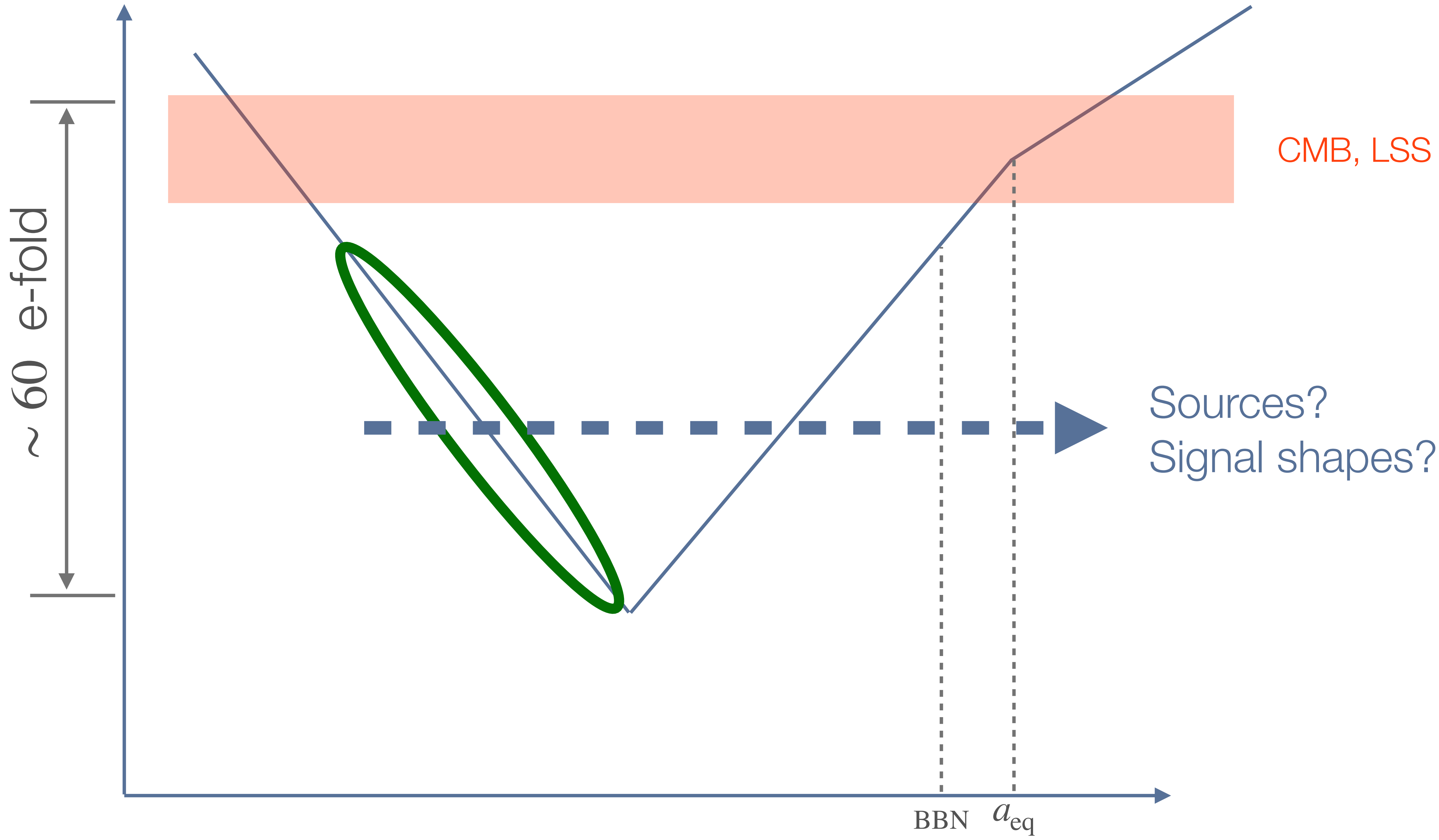
Inflationary era



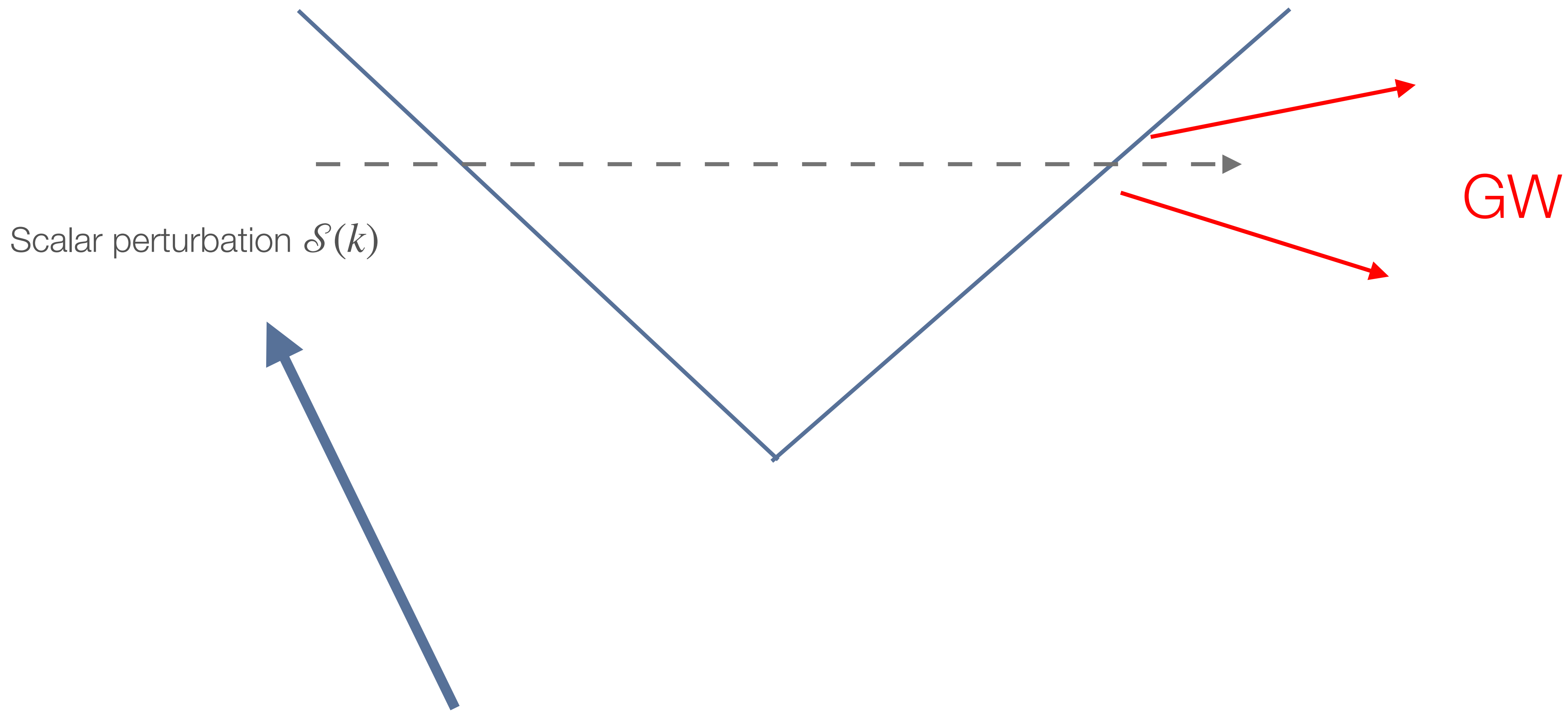
Early universe



Inflationary era

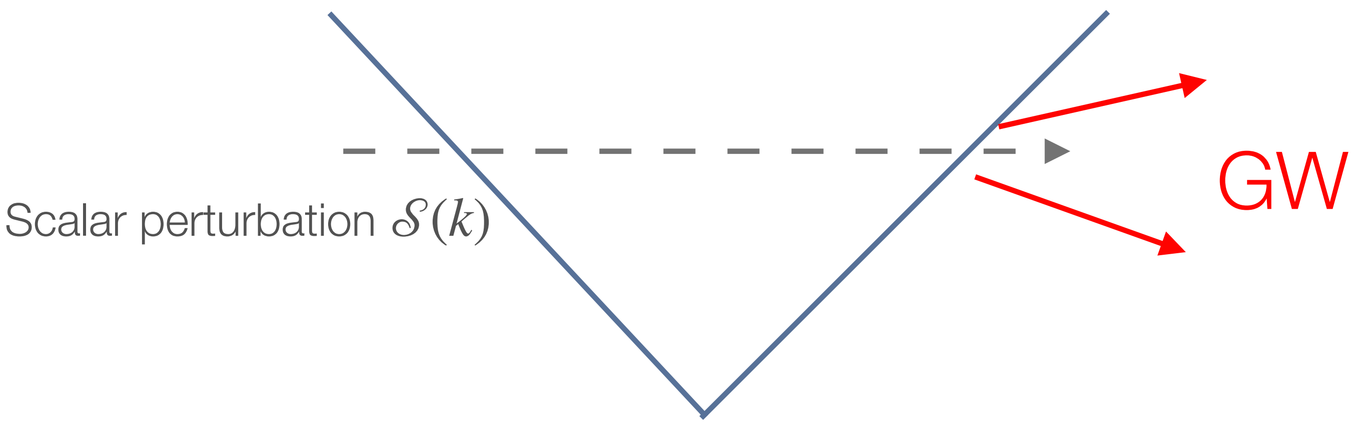


Example: secondary GW

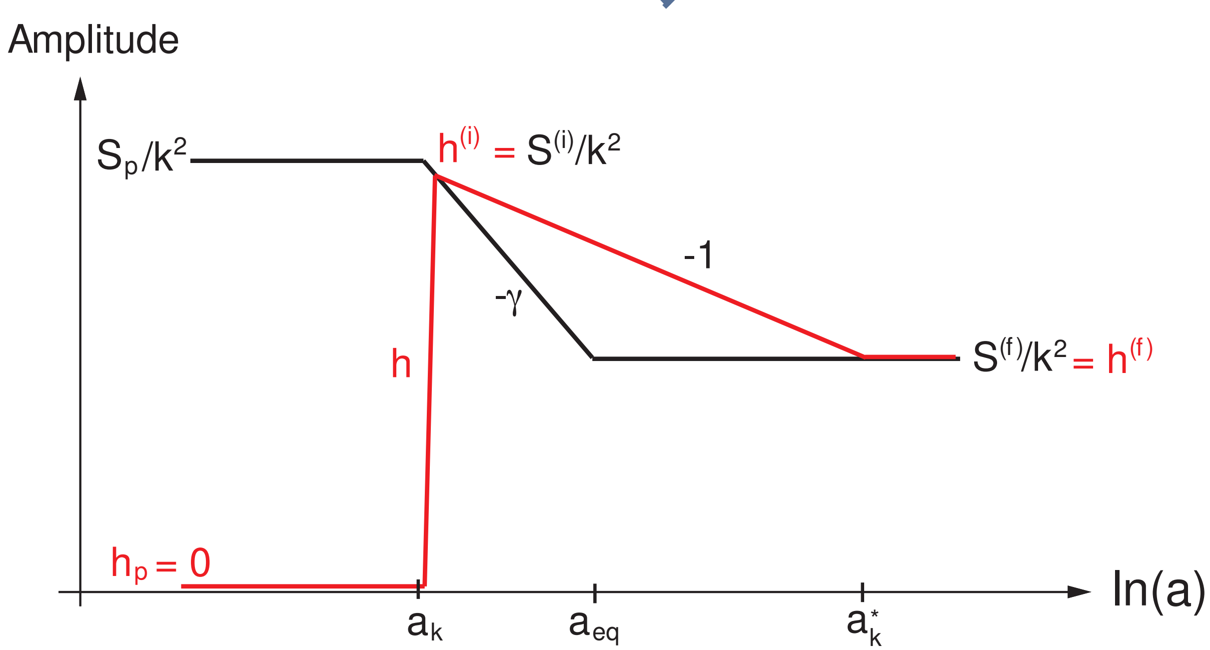


In addition to the inflaton, many other fields have quantum fluctuations

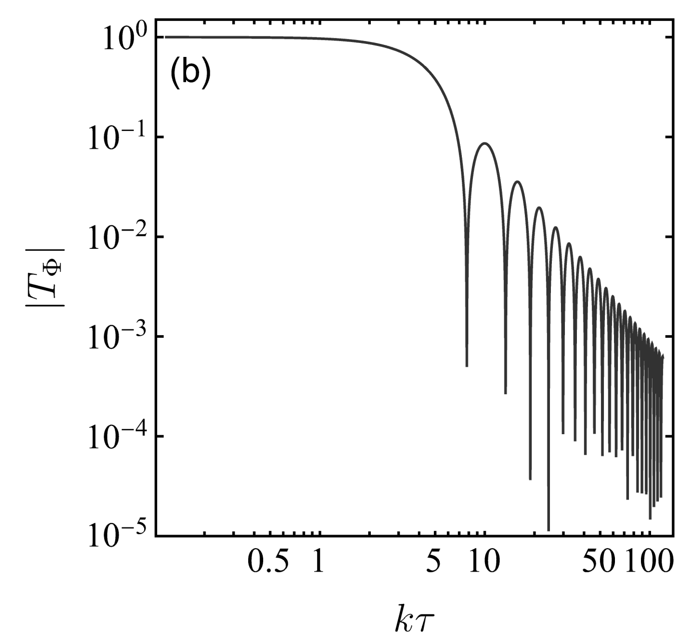
Example: secondary GW



$$h''_{\mathbf{k}} + 2\mathcal{H}h'_{\mathbf{k}} + k^2 h_{\mathbf{k}} = \mathcal{S}(\mathbf{k}, \eta)$$



Baumann, Steinhardt, Takahashi, hep-th/0703290



Modes enter horizon during RD, starts oscillate, and generates GW

A spectator light scalar

R. Ebadi, S. Kumar, A. McCune, H. Tai, LTW 2023

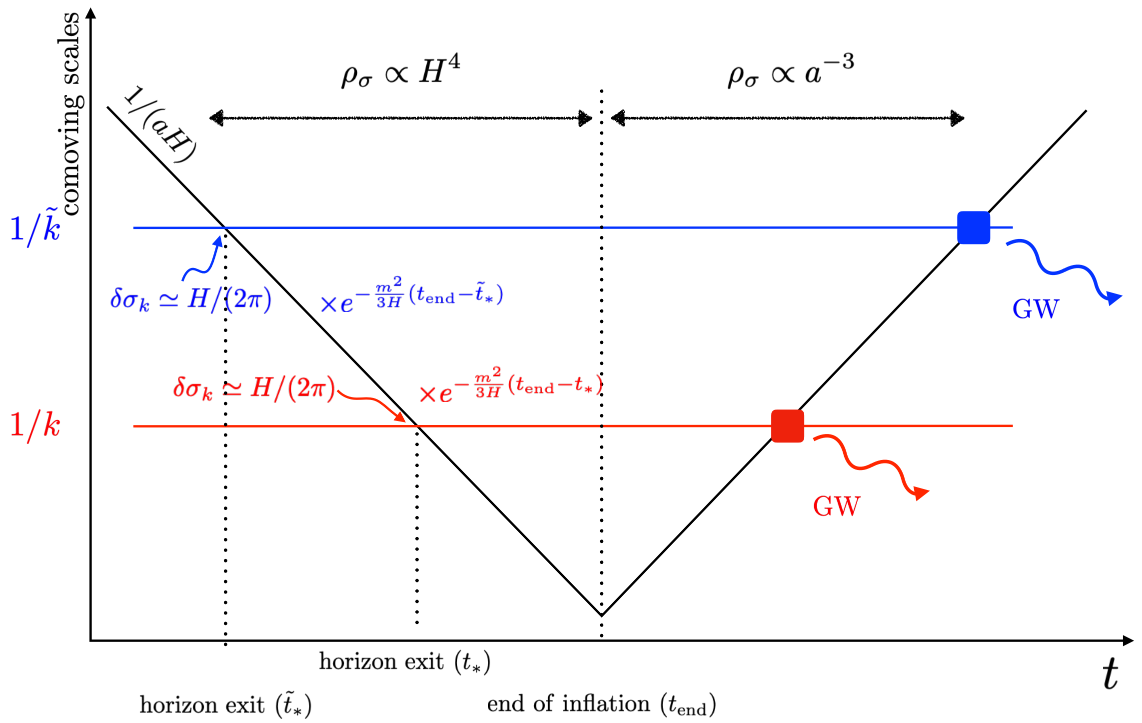
$$\mathcal{L} = \frac{1}{2}(\partial\sigma)^2 - \frac{1}{2}m^2\sigma^2 - \frac{\lambda}{4}\sigma^4$$ with $m < H$

The spectrum of its fluctuation can be studied by stochastic method

Starobinsky and Yokoyama, 1994; Markkanen, Rajantie, Stopyra, Tenkanen, 1904.11917

$$\mathcal{P}_f(k) = \sum_n \frac{2}{\pi} f_n^2 \Gamma\left(2 - 2\frac{\Lambda_n}{H}\right) \sin\left(\frac{\Lambda_n \pi}{H}\right) \left(\frac{k}{H}\right)^{2\Lambda_n/H} \quad \to \mathscr{A}\left(\frac{k}{H}\right)^{\frac{2\Lambda_{\text{lowest}}}{H}}$$ for $k \ll H$

Blue tilt



At horizon exit:
Amplitude ≈ H

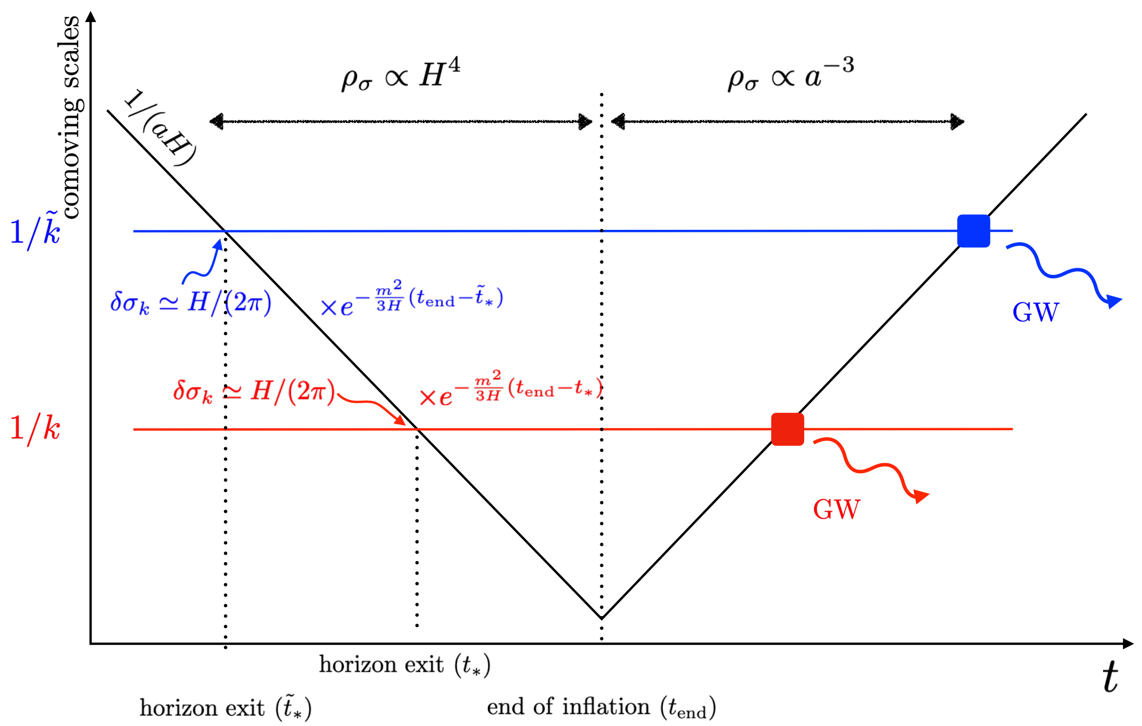
After exit, damping

$$\dot{\sigma} = -\frac{m_\sigma^2 \sigma}{3H}$$

$$\sigma_k(t) = \sigma(t_*) \exp\left(-\frac{m_\sigma^2}{3H}(t-t_*)\right) = \sigma(t_*)\left[\exp\left(-H(t-t_*)\right)\right]^{\frac{m_\sigma^2}{3H^2}} = \sigma(t_*)\left[\frac{k(t)}{H}\right]^{\frac{m_\sigma^2}{3H^2}}$$

More damping for longer wave-length (earlier exit)

Blue tilt



At horizon exit:
Amplitude ≈ H

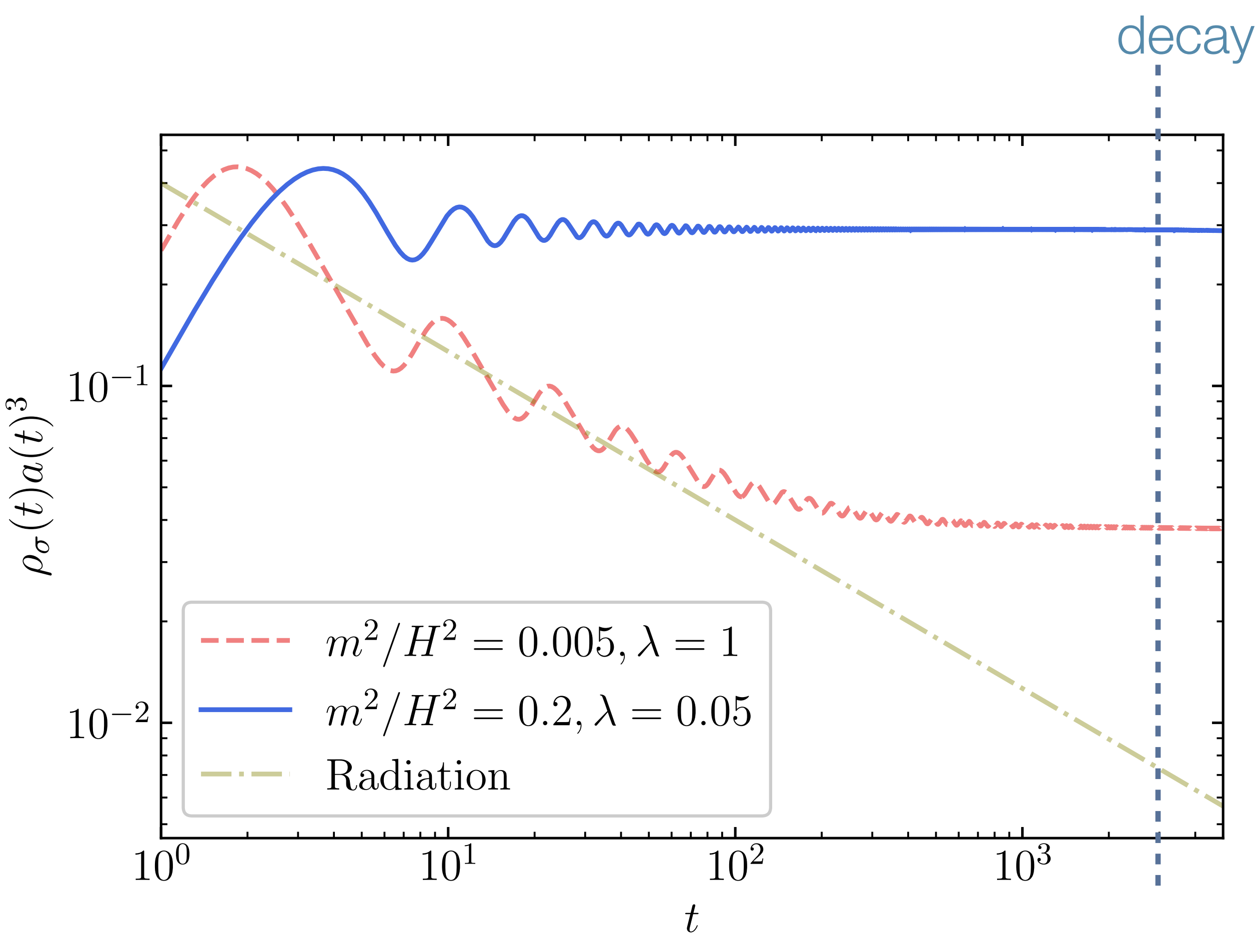
After exit, damping

$$\dot{\sigma} = -\frac{m_\sigma^2 \sigma}{3H}$$

For more general scalar theory

$$\mathcal{P}_f(k) = \sum_n \frac{2}{\pi} f_n^2 \Gamma\left(2 - 2\frac{\Lambda_n}{H}\right) \sin\left(\frac{\Lambda_n \pi}{H}\right) \left(\frac{k}{H}\right)^{2\Lambda_n/H} \quad \to \mathscr{A}\left(\frac{k}{H}\right)^{\frac{2\Lambda_{\rm lowest}}{H}} \quad \text{for } k \ll H$$

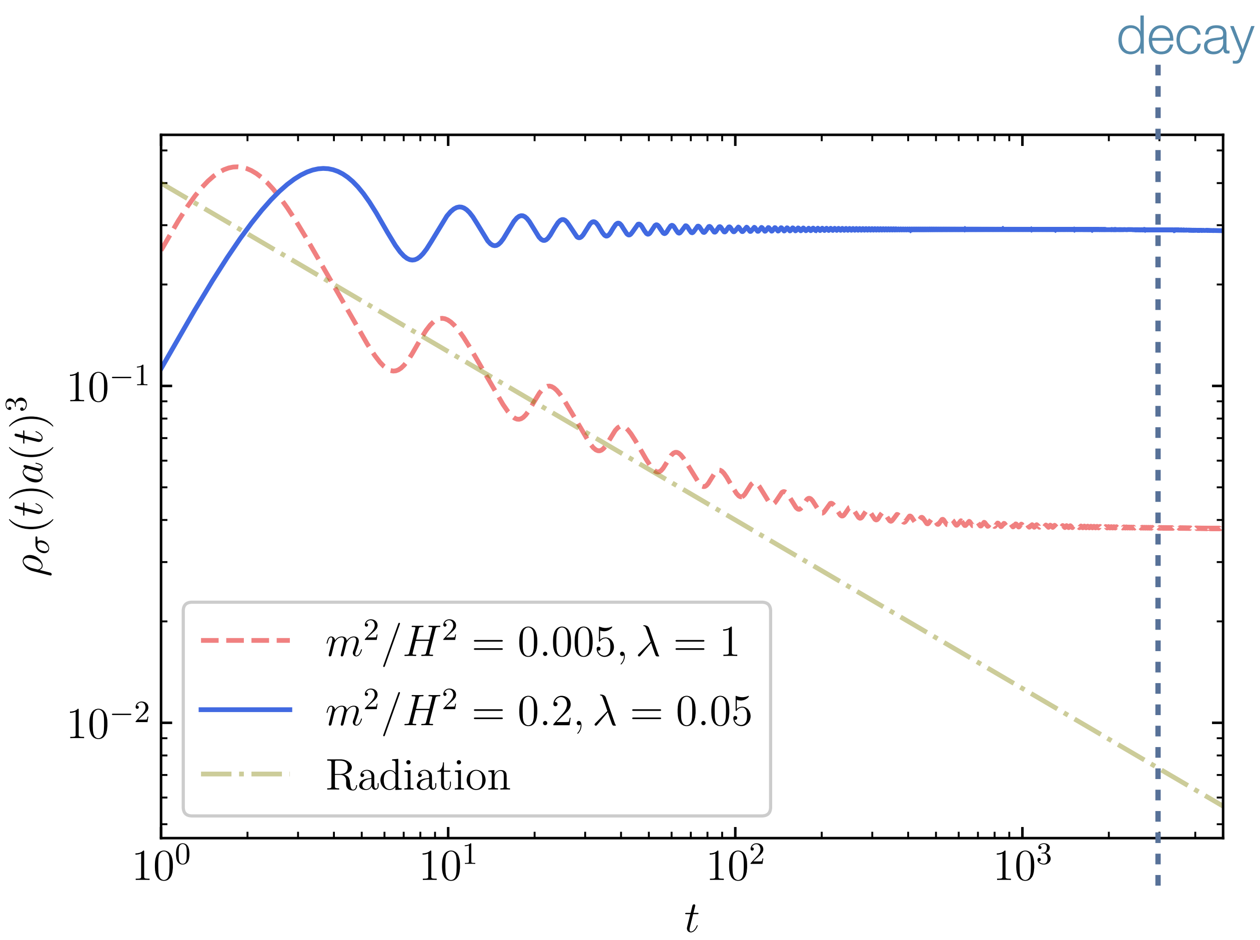
After inflation



Eventually,
evolve like matter

Can become important

After inflation

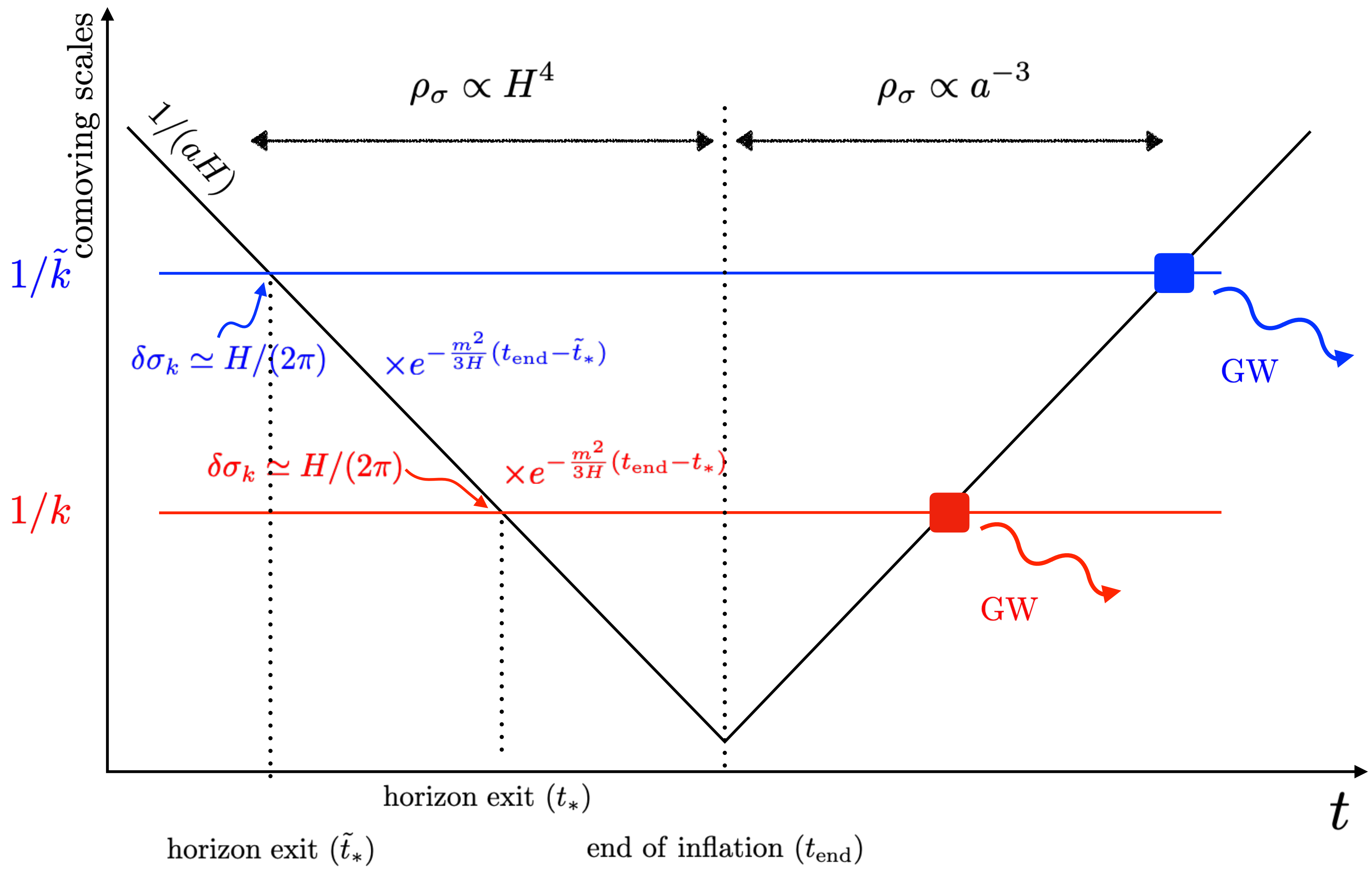


Eventually,
evolve like matter

Can become important

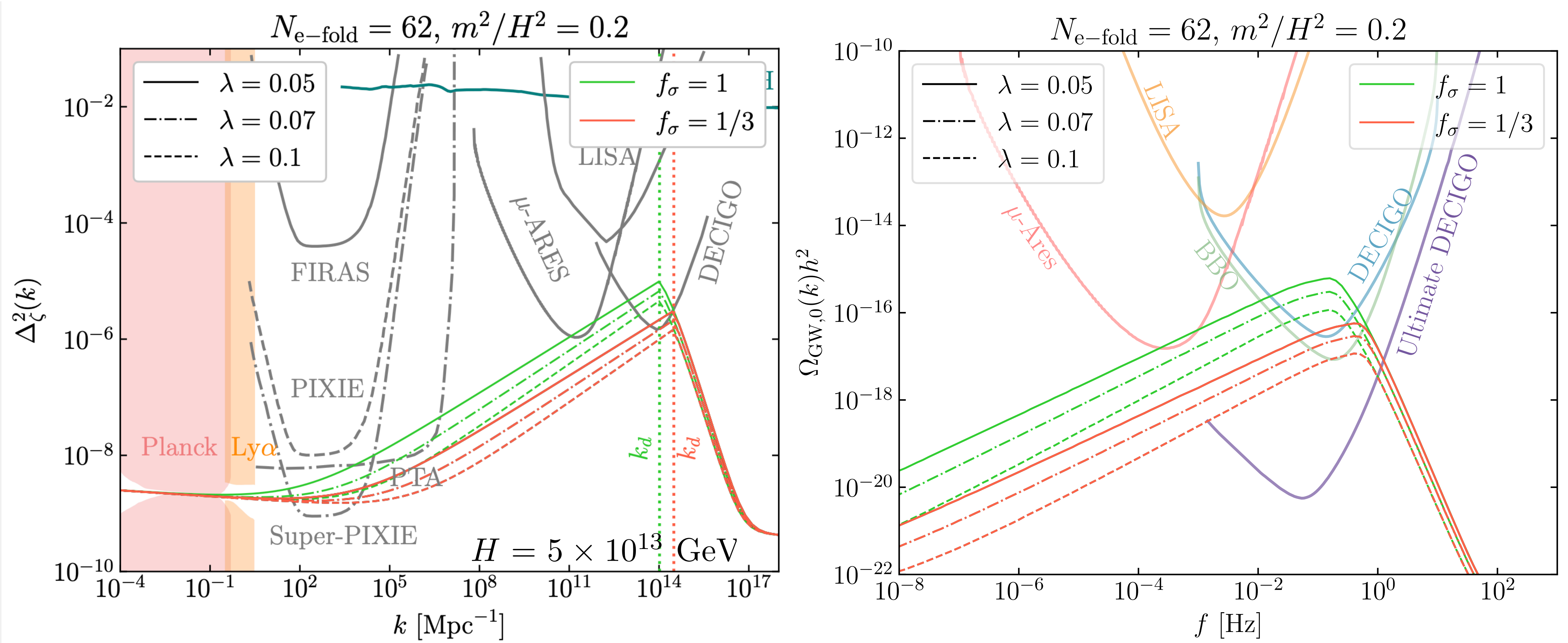
$$\Delta^2_\zeta(k) = \begin{cases} \Delta^2_{\zeta_r}(k) + \left(\frac{f_\sigma(t_d)}{4+3f_\sigma(t_d)}\right)^2 \Delta^2_{S_\sigma}(k), \;\; k < k_d, \\ \Delta^2_{\zeta_r}(k) + \left(\frac{f_\sigma(t_d)(k_d/k)}{4+3f_\sigma(t_d)(k_d/k)}\right)^2 \Delta^2_{S_\sigma}(k), \;\; k > k_d \end{cases}$$

2nd GW


comoving scales
$1/(aH)$
$\rho_\sigma \propto H^4$
$\rho_\sigma \propto a^{-3}$
$1/\tilde{k}$
$1/k$
$\delta\sigma_k \simeq H/(2\pi)$
$\times e^{-\frac{m^2}{3H}(t_{\rm end}-\tilde{t}_*)}$
$\delta\sigma_k \simeq H/(2\pi)$
$\times e^{-\frac{m^2}{3H}(t_{\rm end}-t_*)}$
GW
GW
t
horizon exit (t_*)
horizon exit $(\tilde{t}_*)$
end of inflation $(t_{\rm end})$

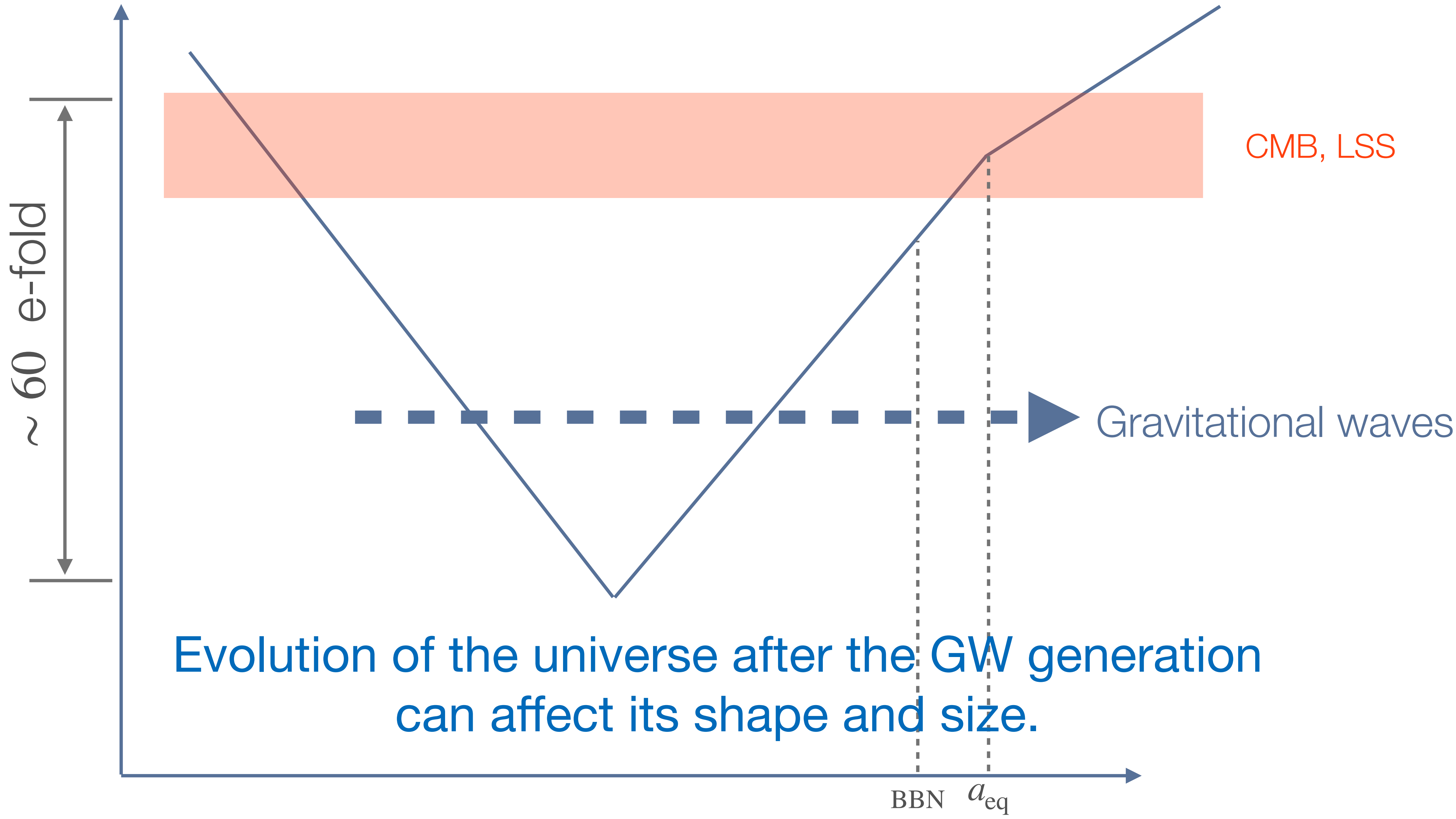
Power spectrum, GW

Reza Ebadi, Soubhik Kumar, Amara McCune, Hanwen Tai, LTW, 2307.12048



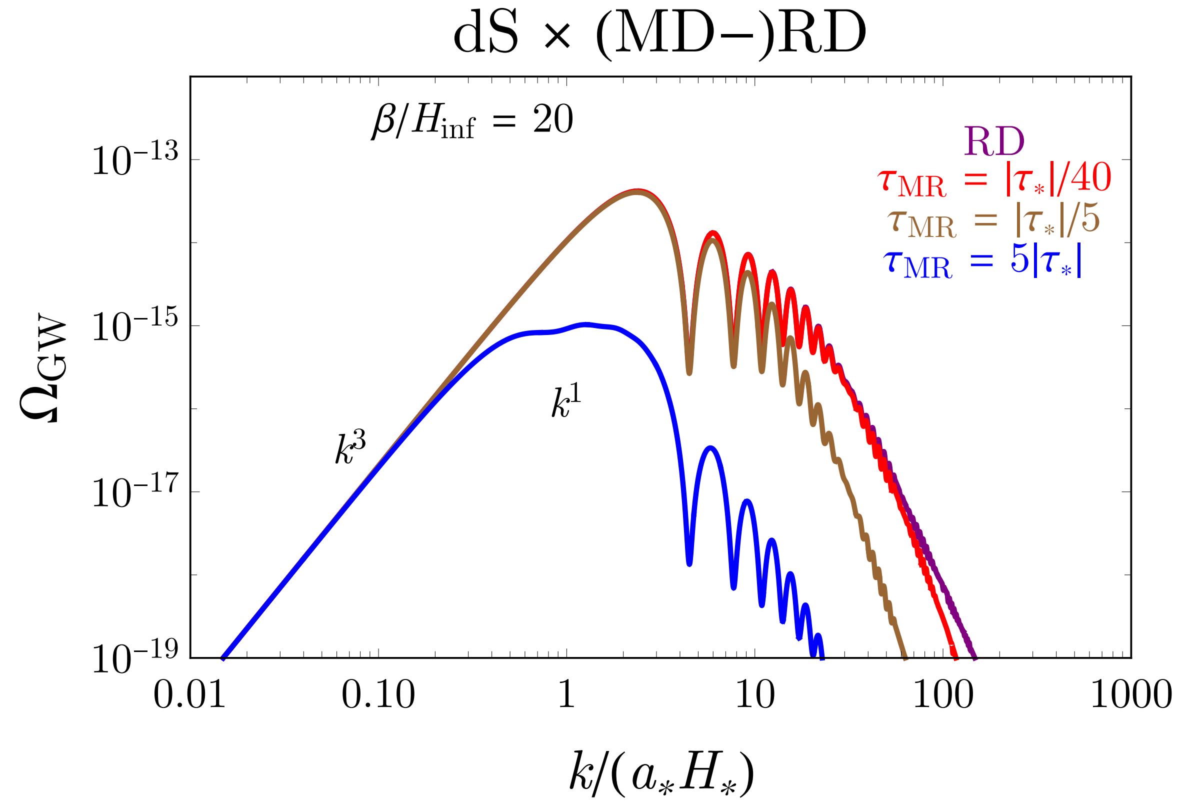
Assuming the scalar behave similar to curvaton.
Becoming important before decay.

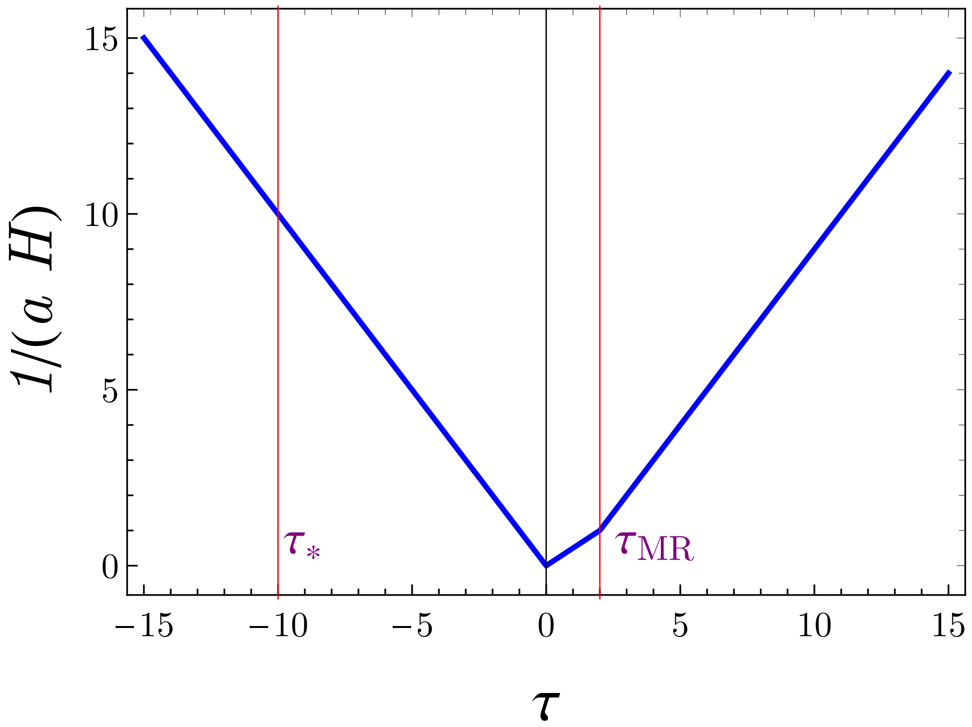
Information on later evolution



Evolution of the universe after the GW generation
can affect its shape and size.

Comparing scenarios





Scenarios after reheating.

$\tau_{\rm MR}$ = MD-RD transition

Conclusions

- GW will be a great tool in probing early universe, especially for epochs “invisible” through other means.
  - Long term prospect. Probably the only way to get these information.
- Discovery and study its shape very informative.