Gravitational wave signals from the early universe

LianTao Wang
Univ. of Chicago

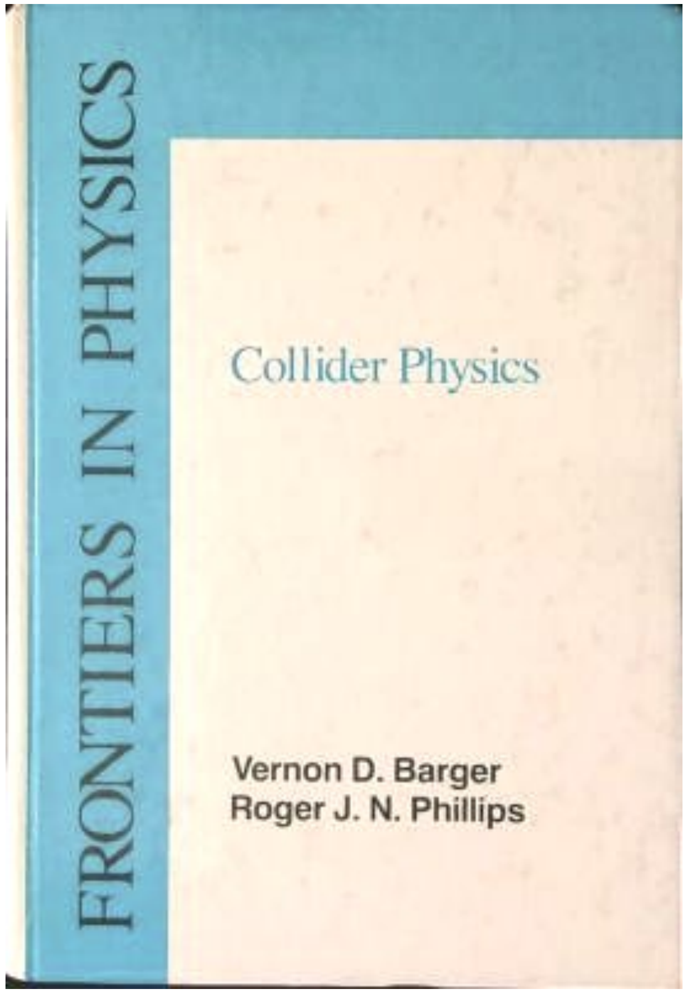
Phenomenology before and after the Standard Model. Madison, June 5 2025

Pheno in my memory

Remarkably time translation invariant!

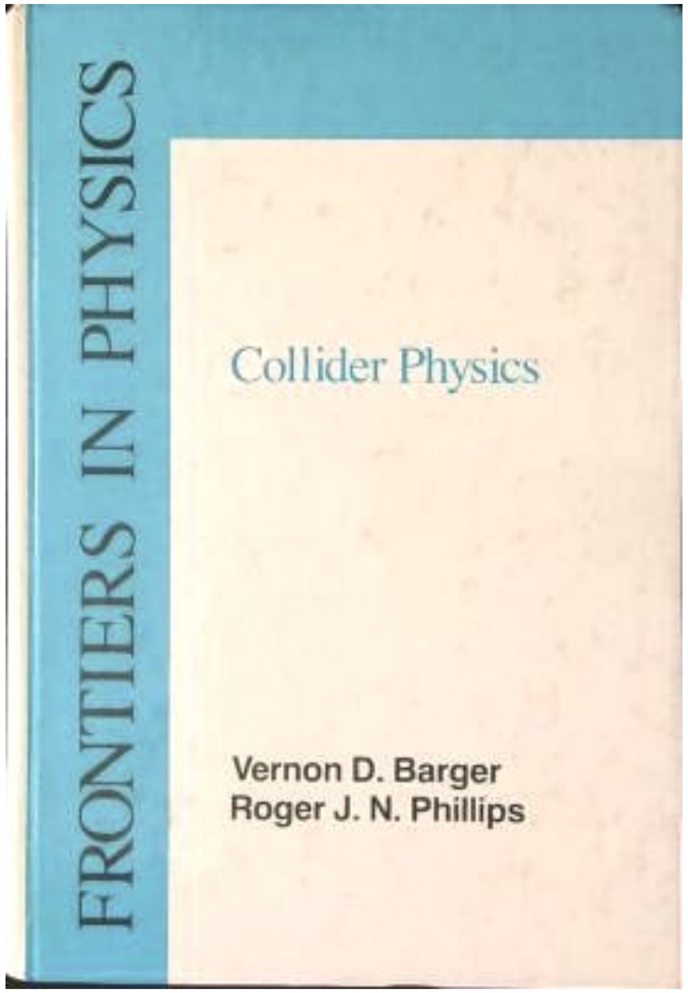
Pheno at UW, where my career was launched
My time here: 2002-2004

Colliders at the energy frontier



Mad(ison)graph

Colliders at the energy frontier



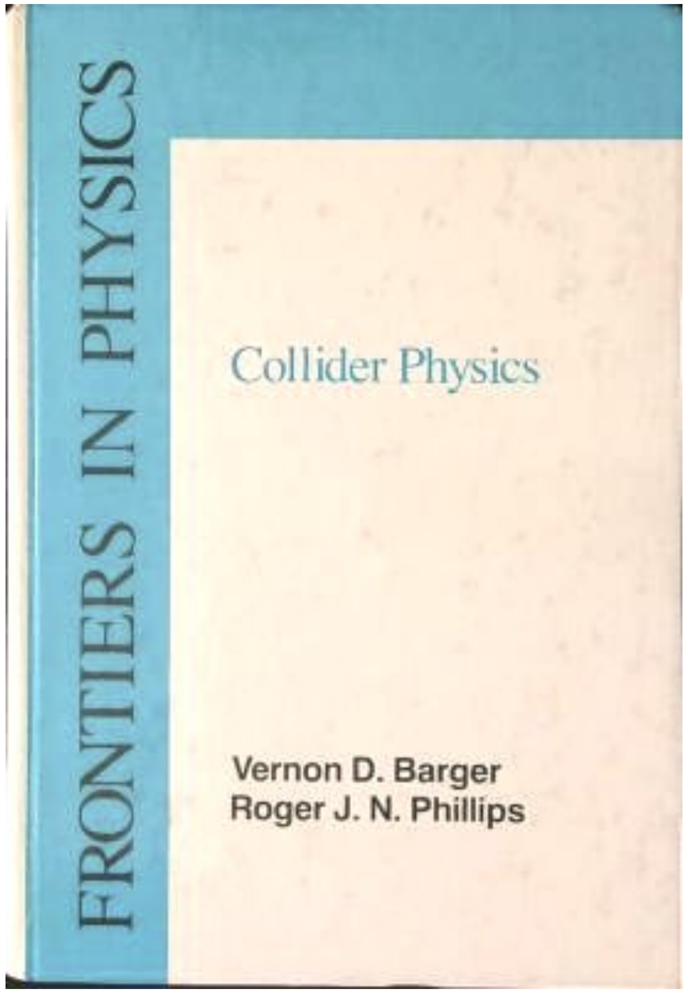
…SppS ⇒ LEP ⇒ Tevatron ⇒ LHC…

Discoveries:
W/Z, top, Higgs

Hoping to address:
UV completion of SM
Dark matter
…

Mad(ison)graph

Colliders at the energy frontier



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Discoveries:
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…

Mad(ison)graph

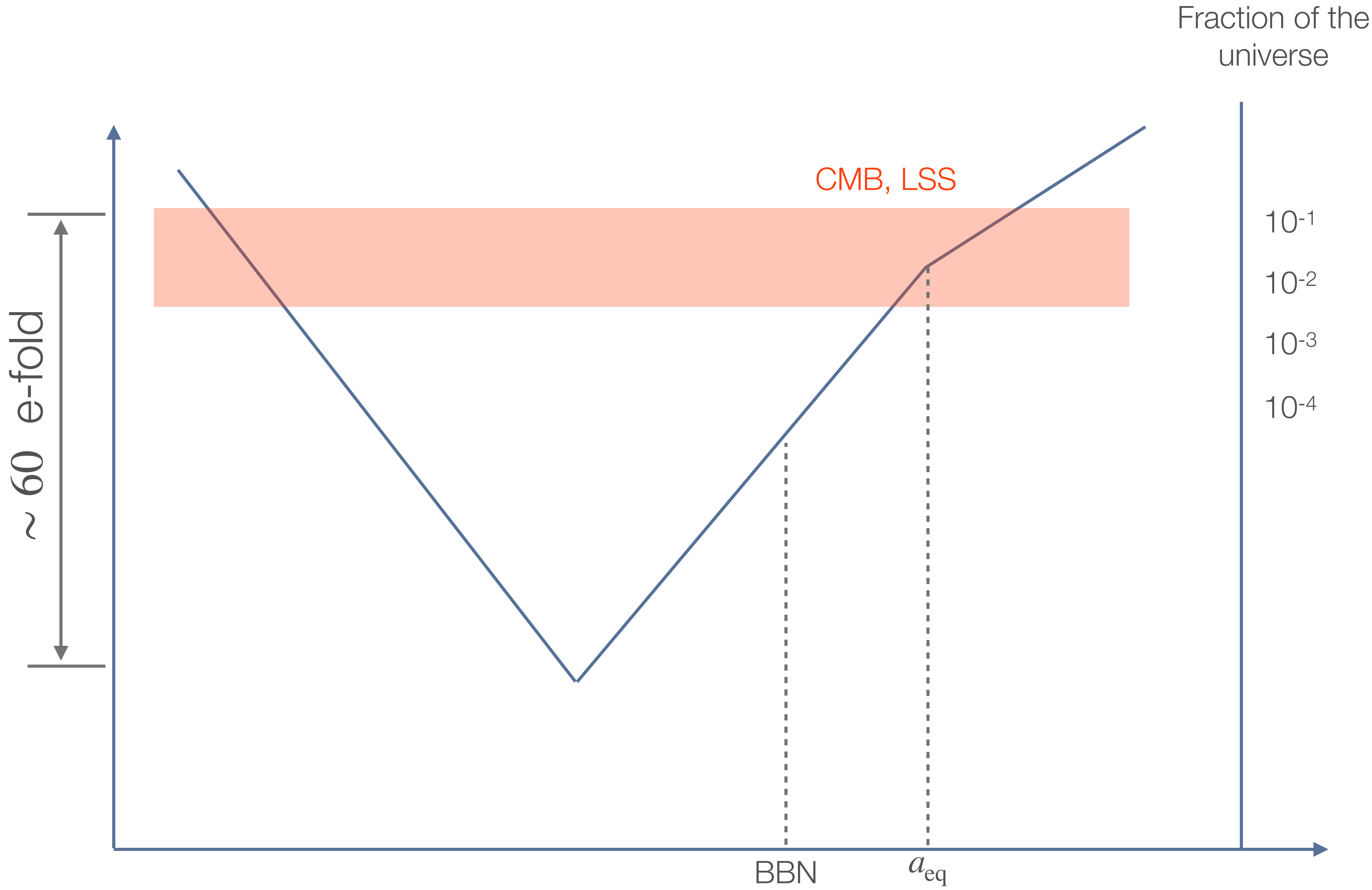
I have been lucky to be part
of these excitements

This talk

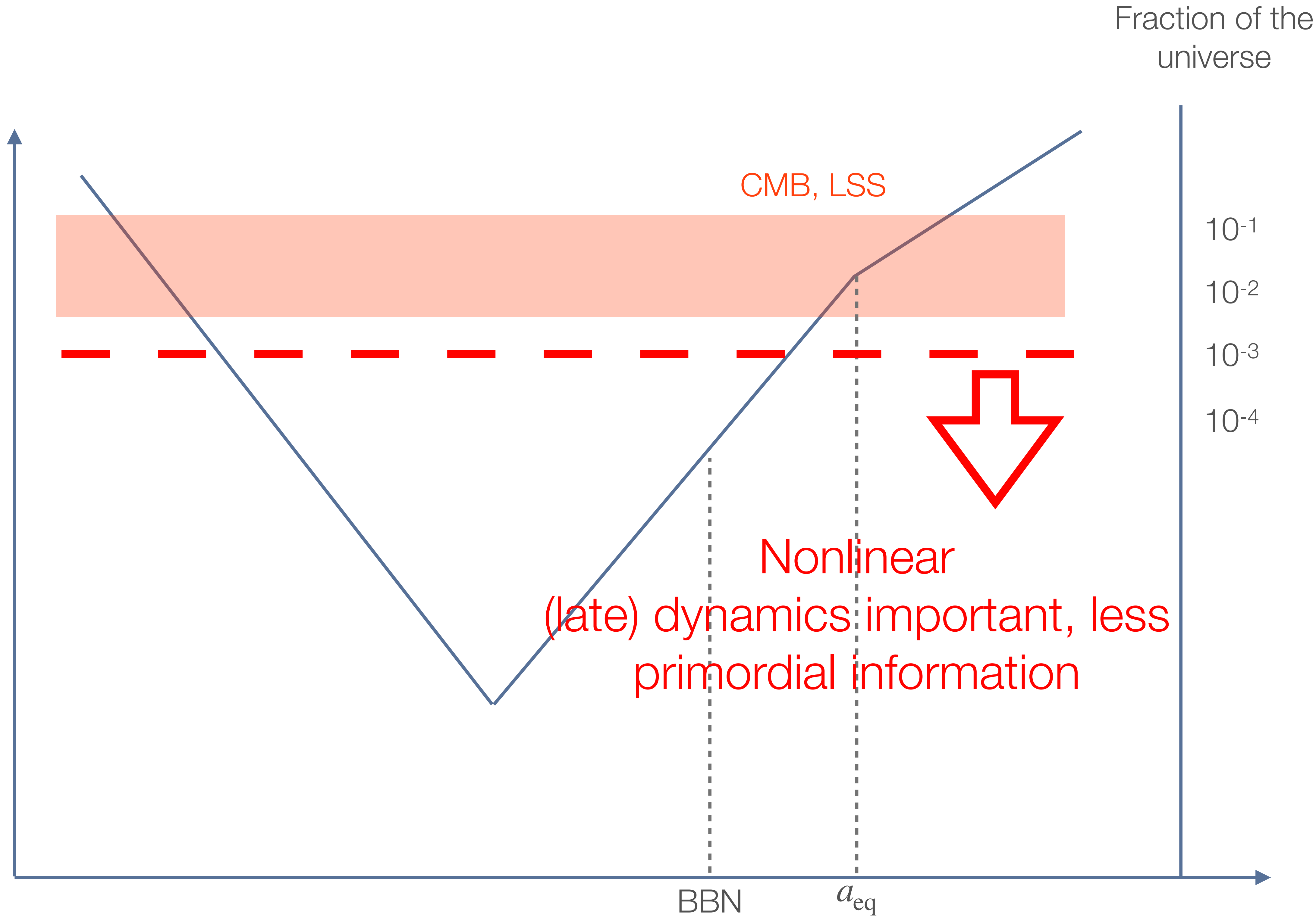
- Gravitational wave and early universe
  - Motivation
  - A coupling simple stories

A field which will have a lot data, will see tremendous advances in the coming decades.

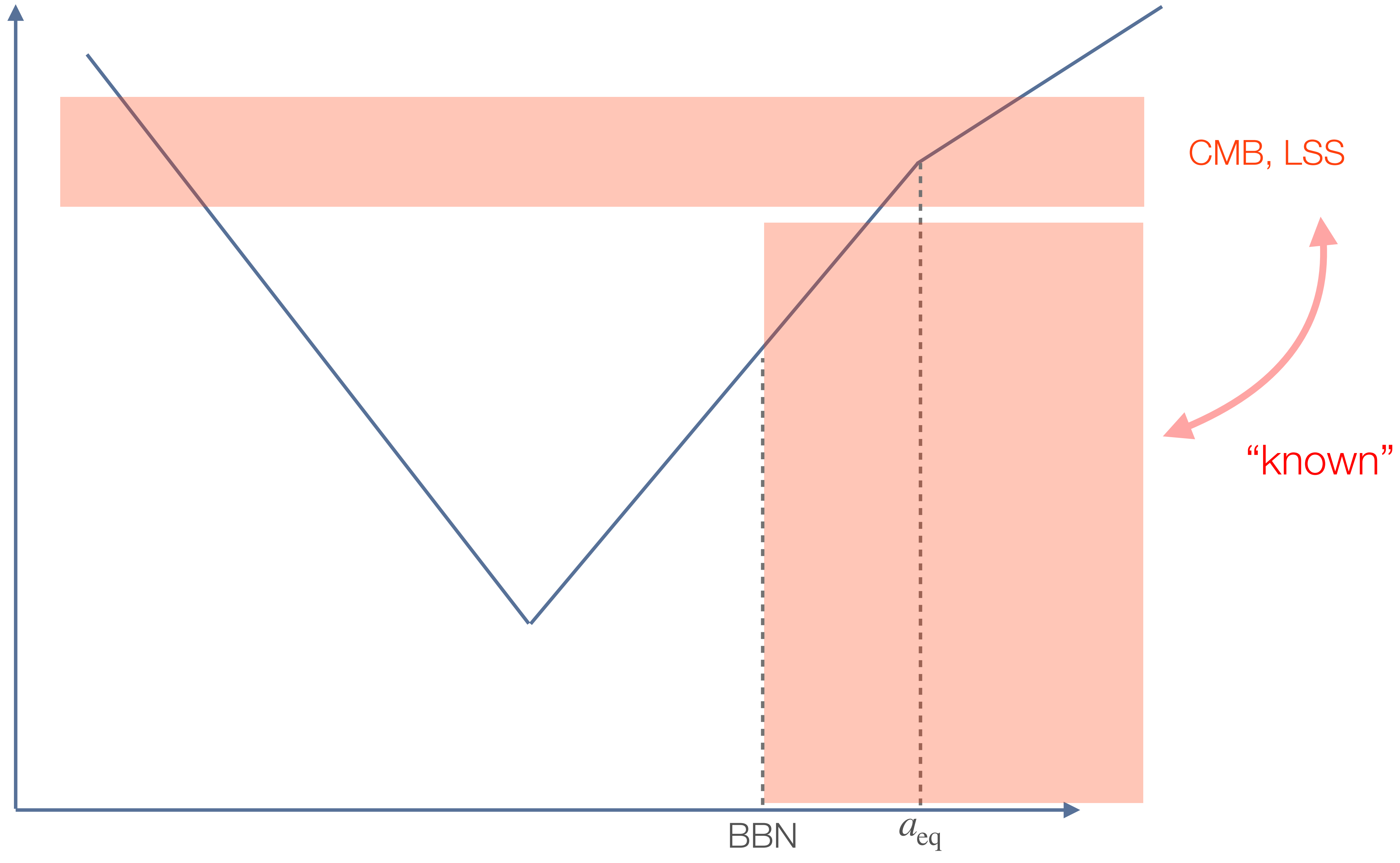
Large scale structure



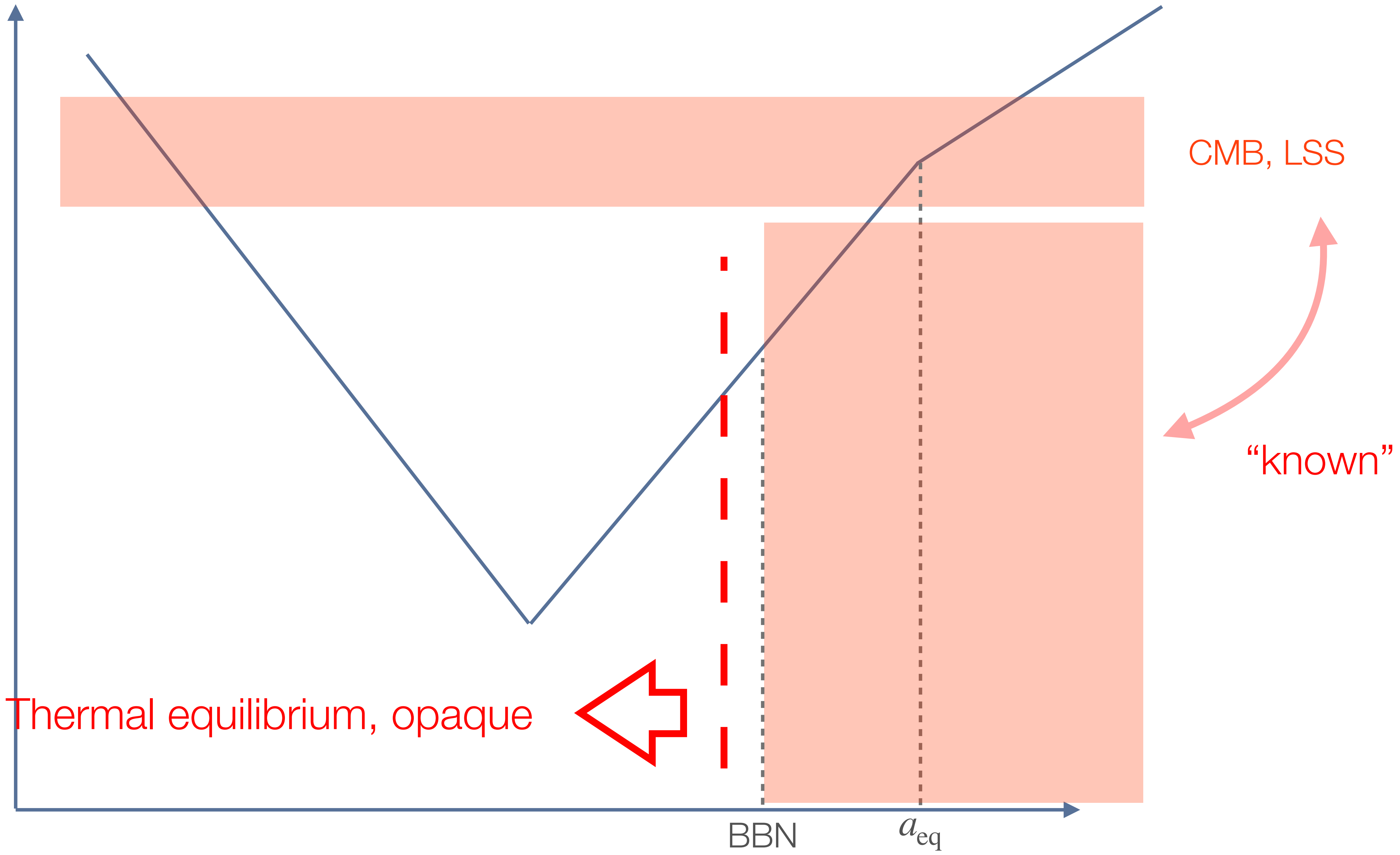
Large scale structure



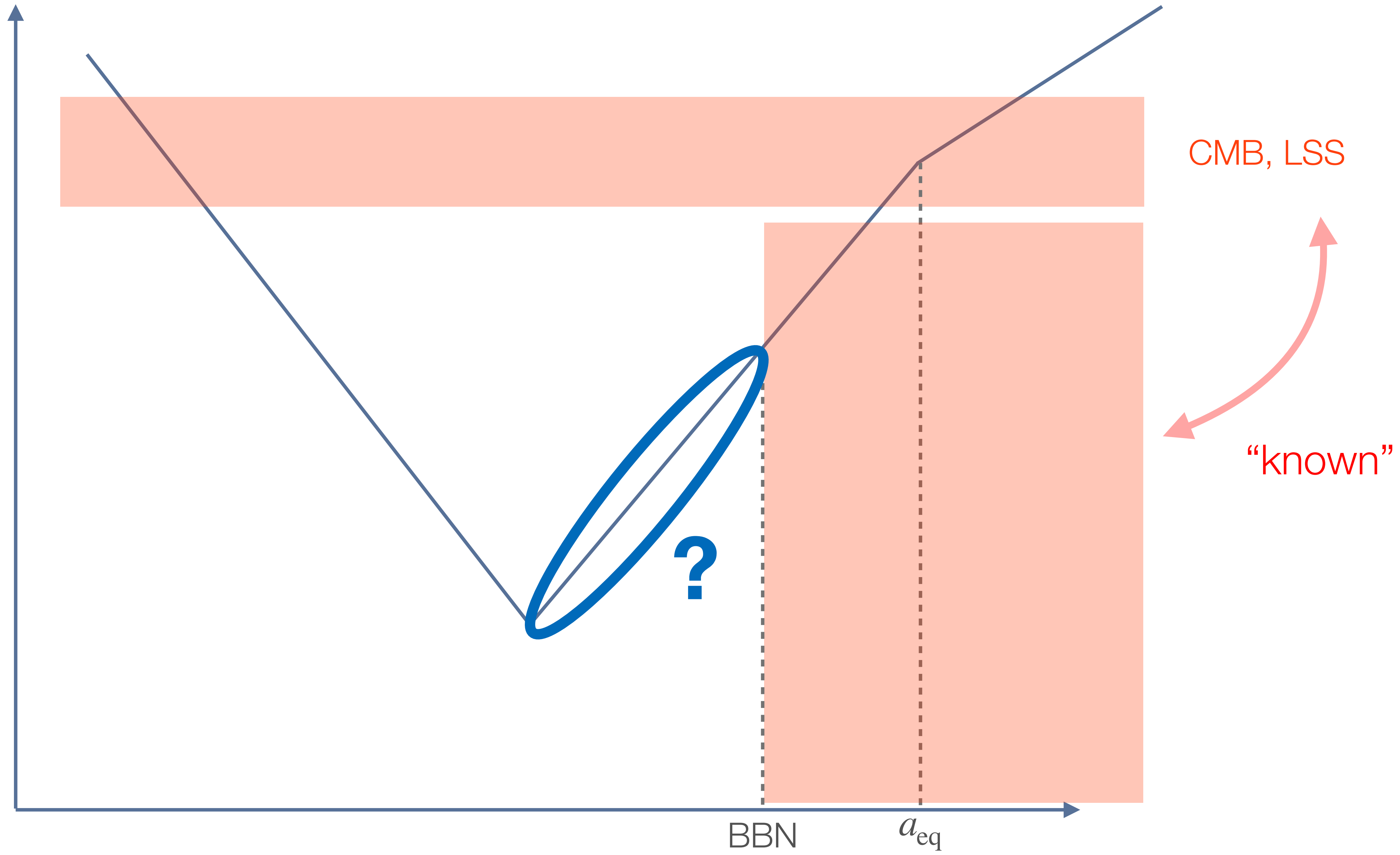
What we know



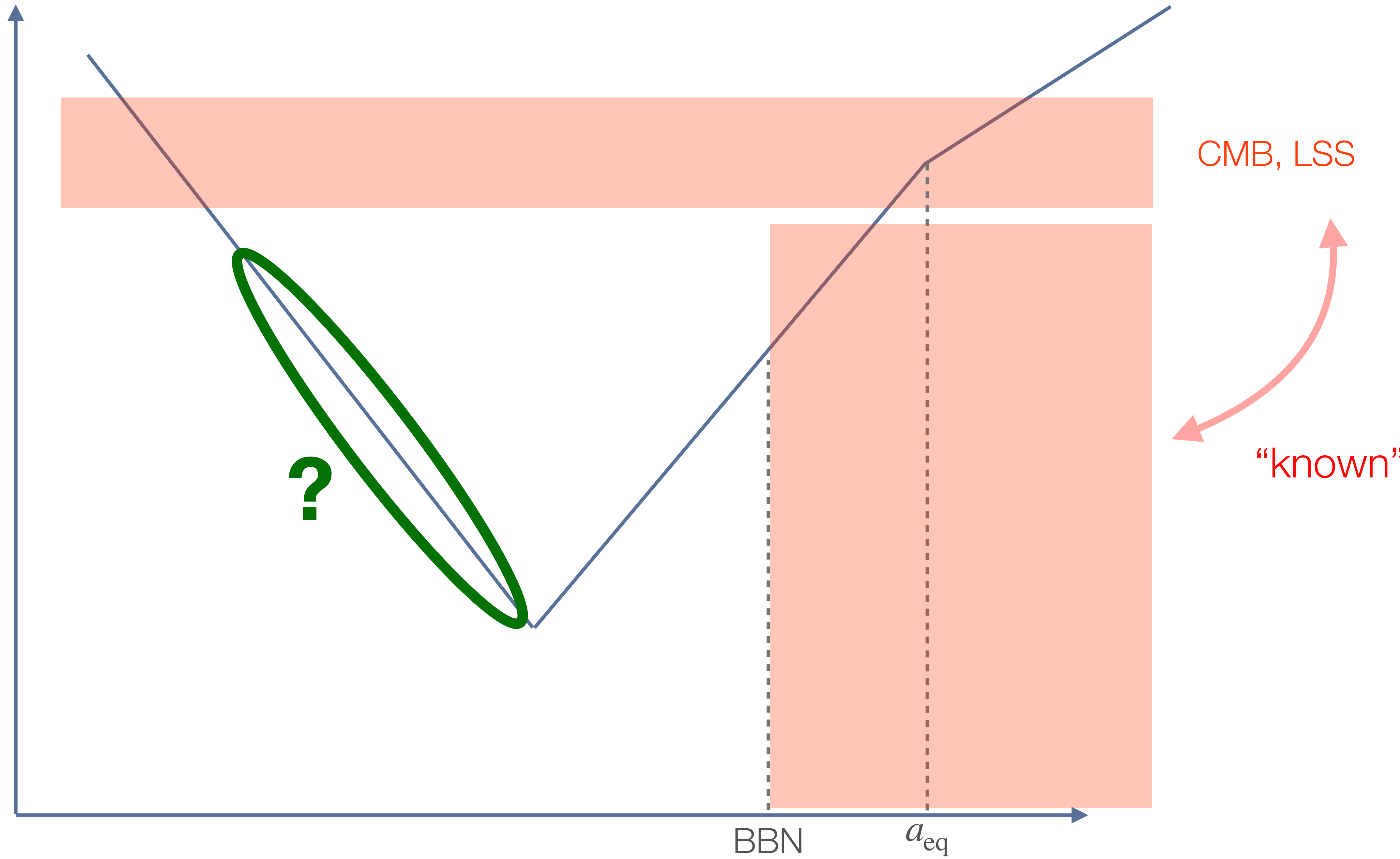
What we know



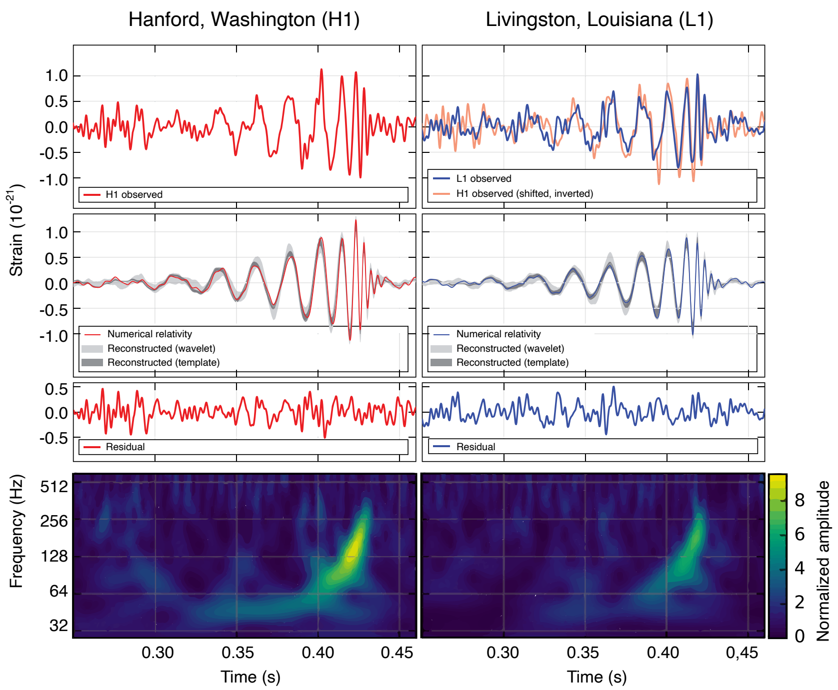
Reheating and after?

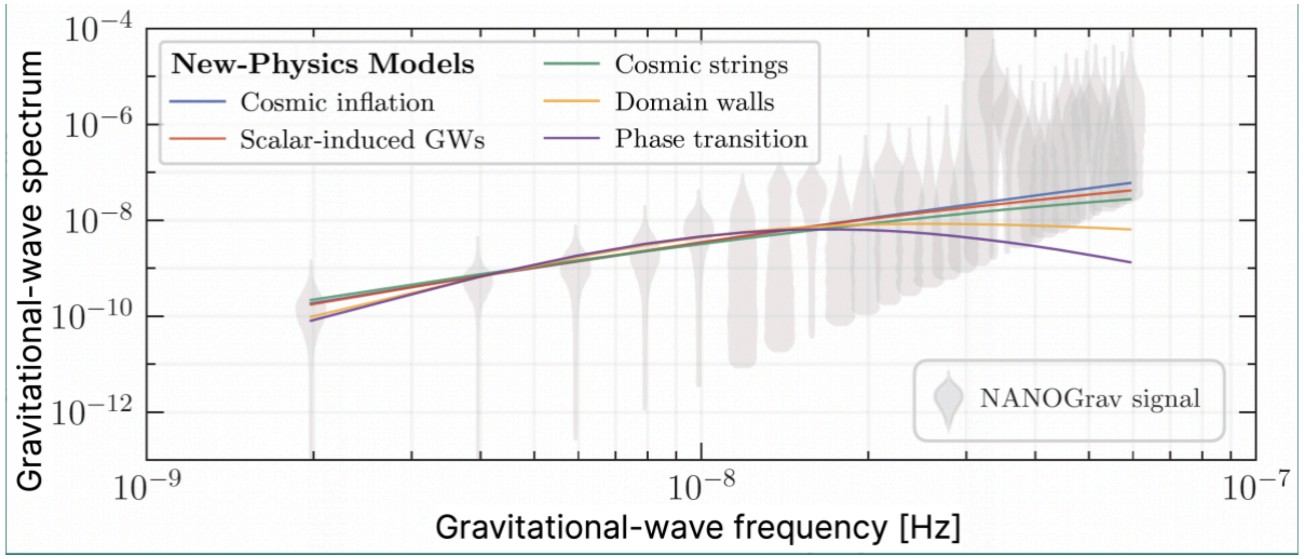


Inflation?



GW Discoveries

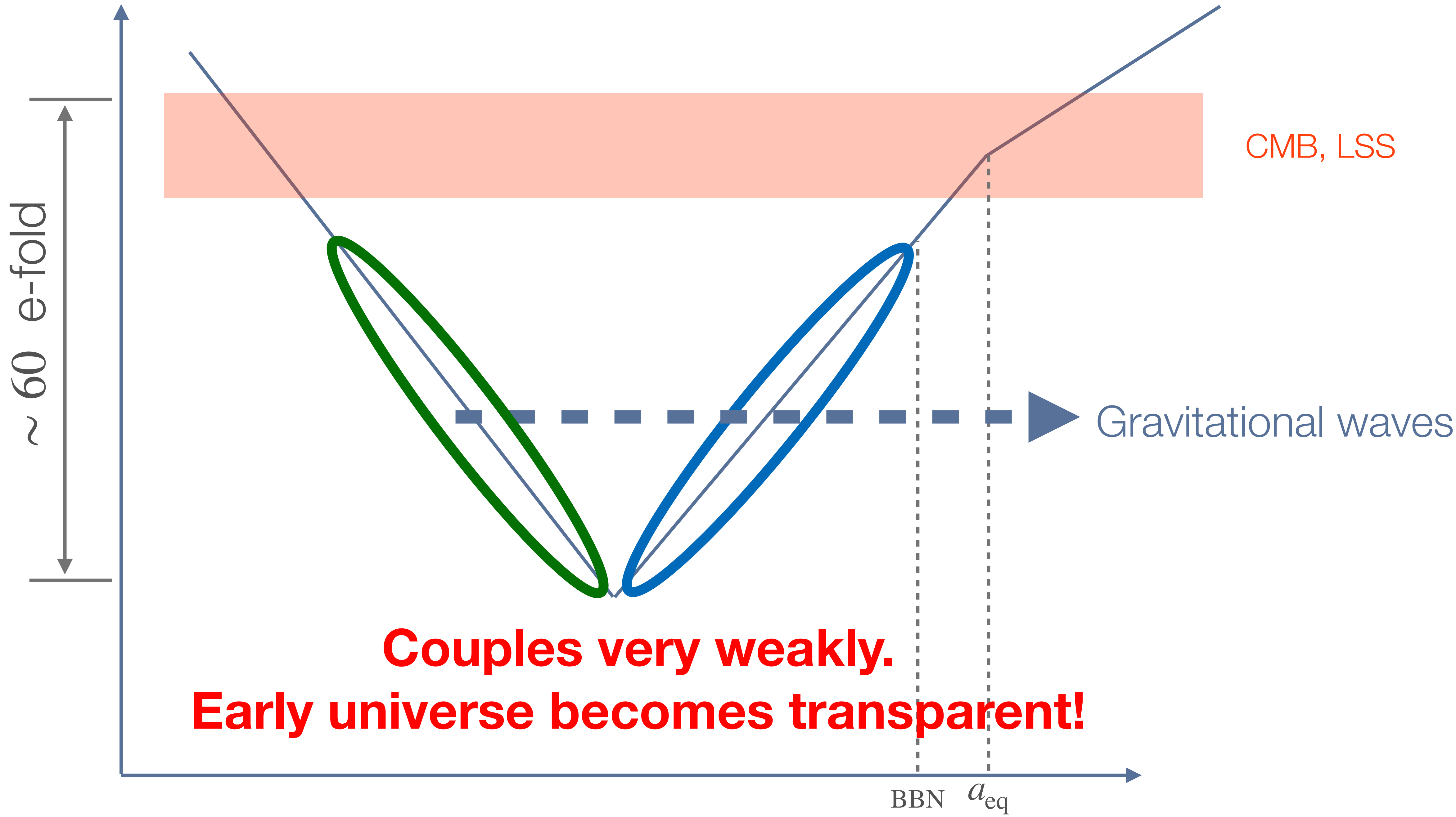




LIGO

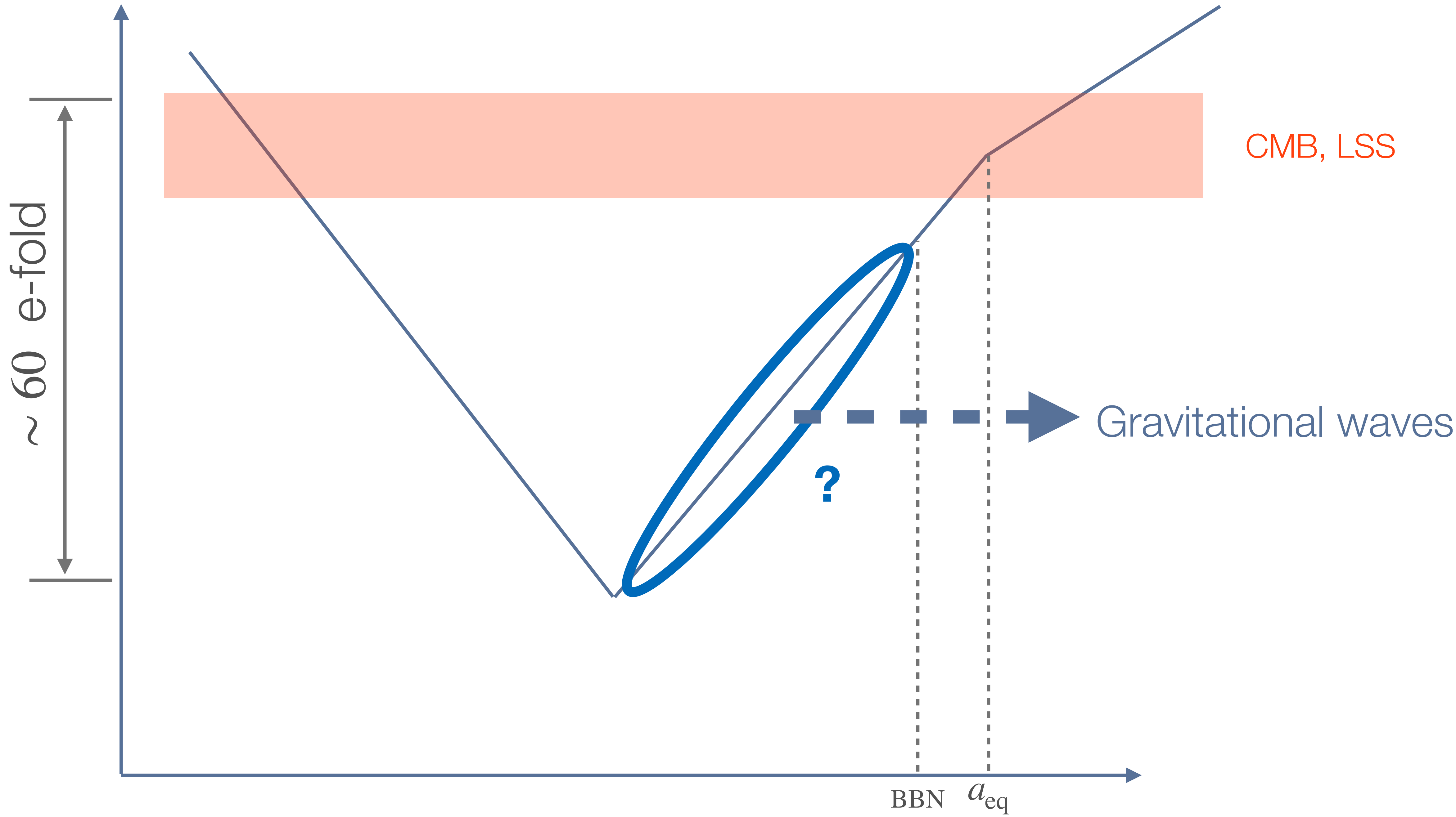
NanoGrav

A new window: gravitational waves

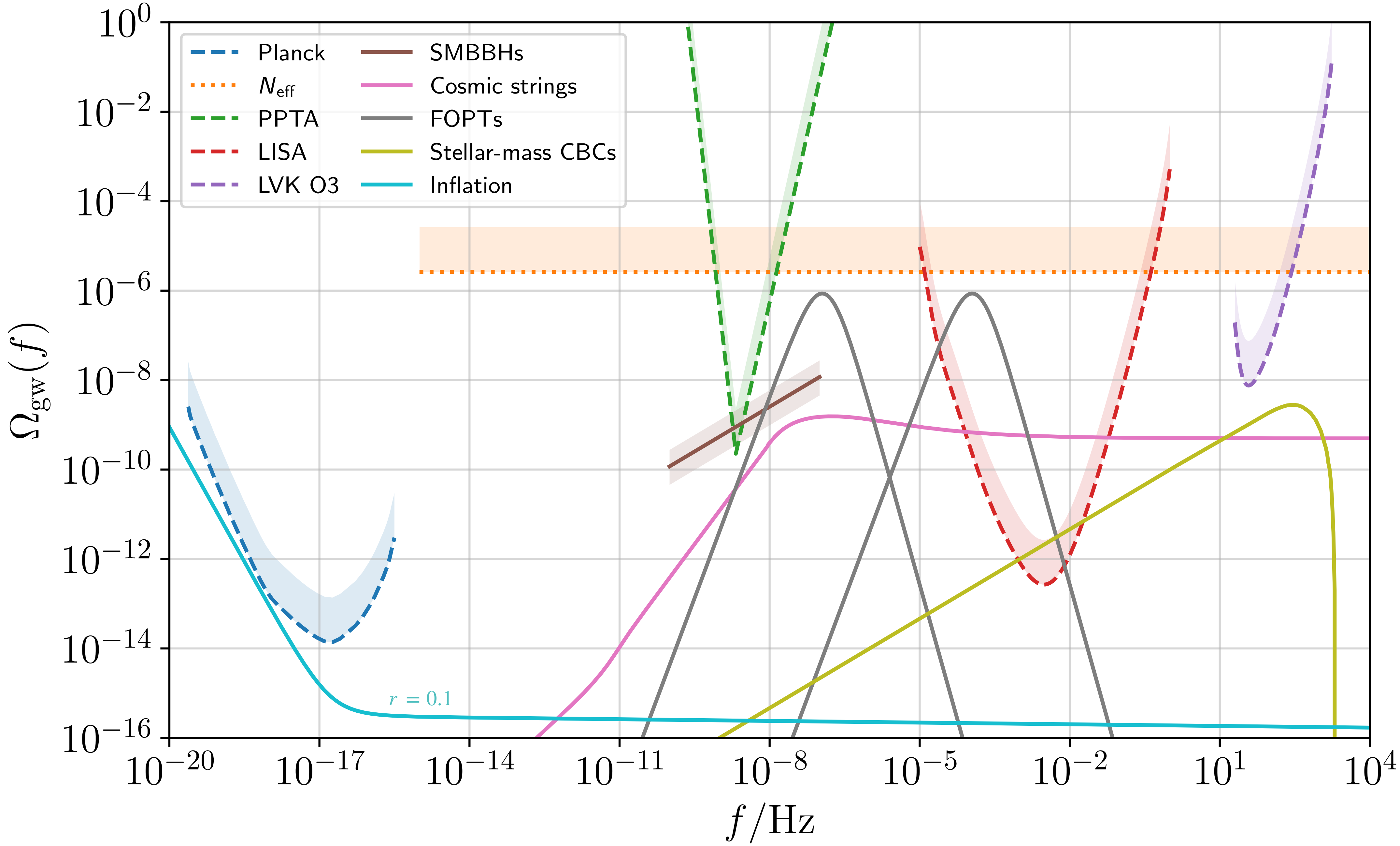


Couples very weakly.
Early universe becomes transparent!

Post inflationary

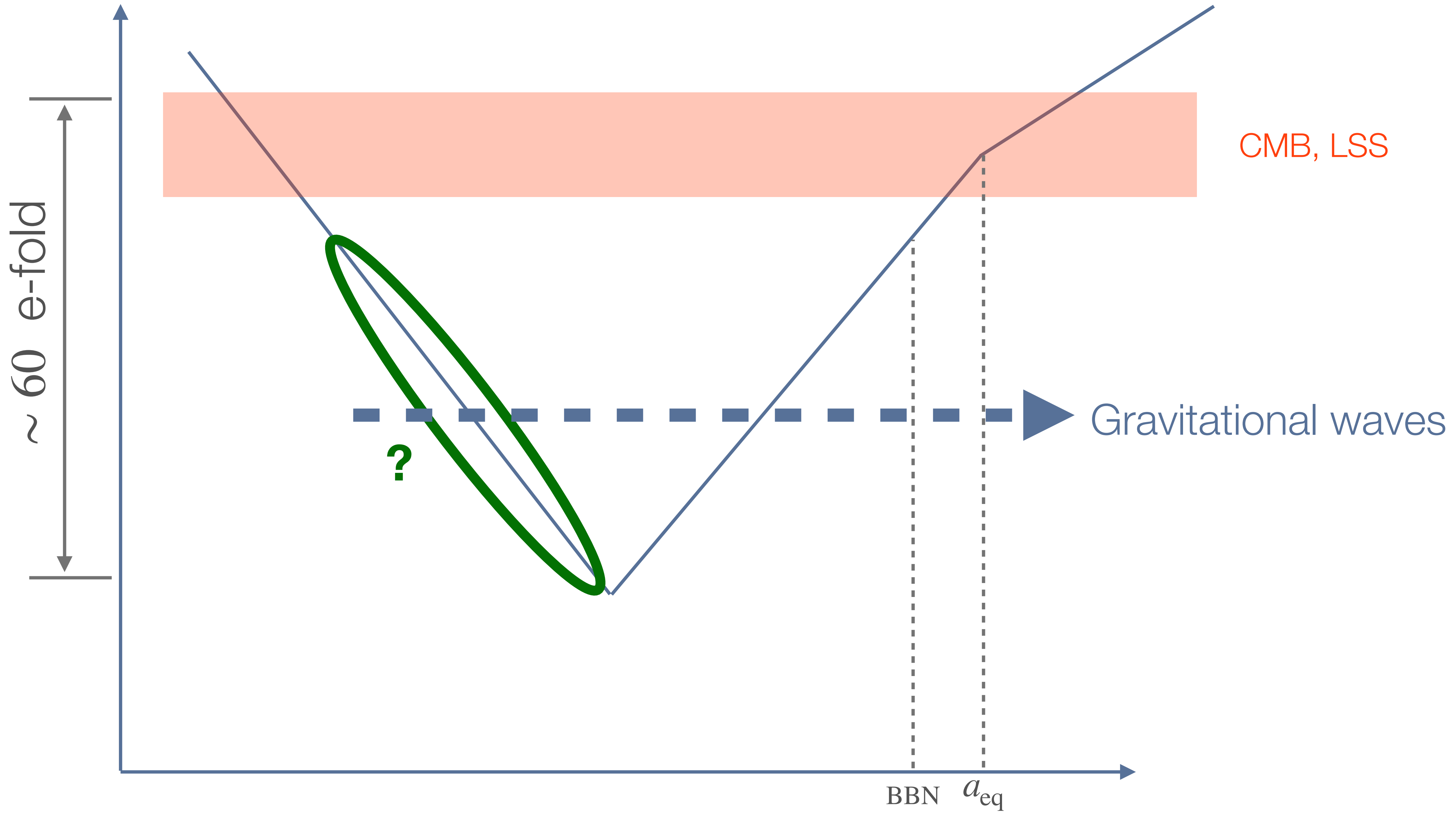


Review by Renzini et al, 2202.00178



Typically, need something quite dramatic.

Inflationary era



A few stories

(Primary) GW from phase transition

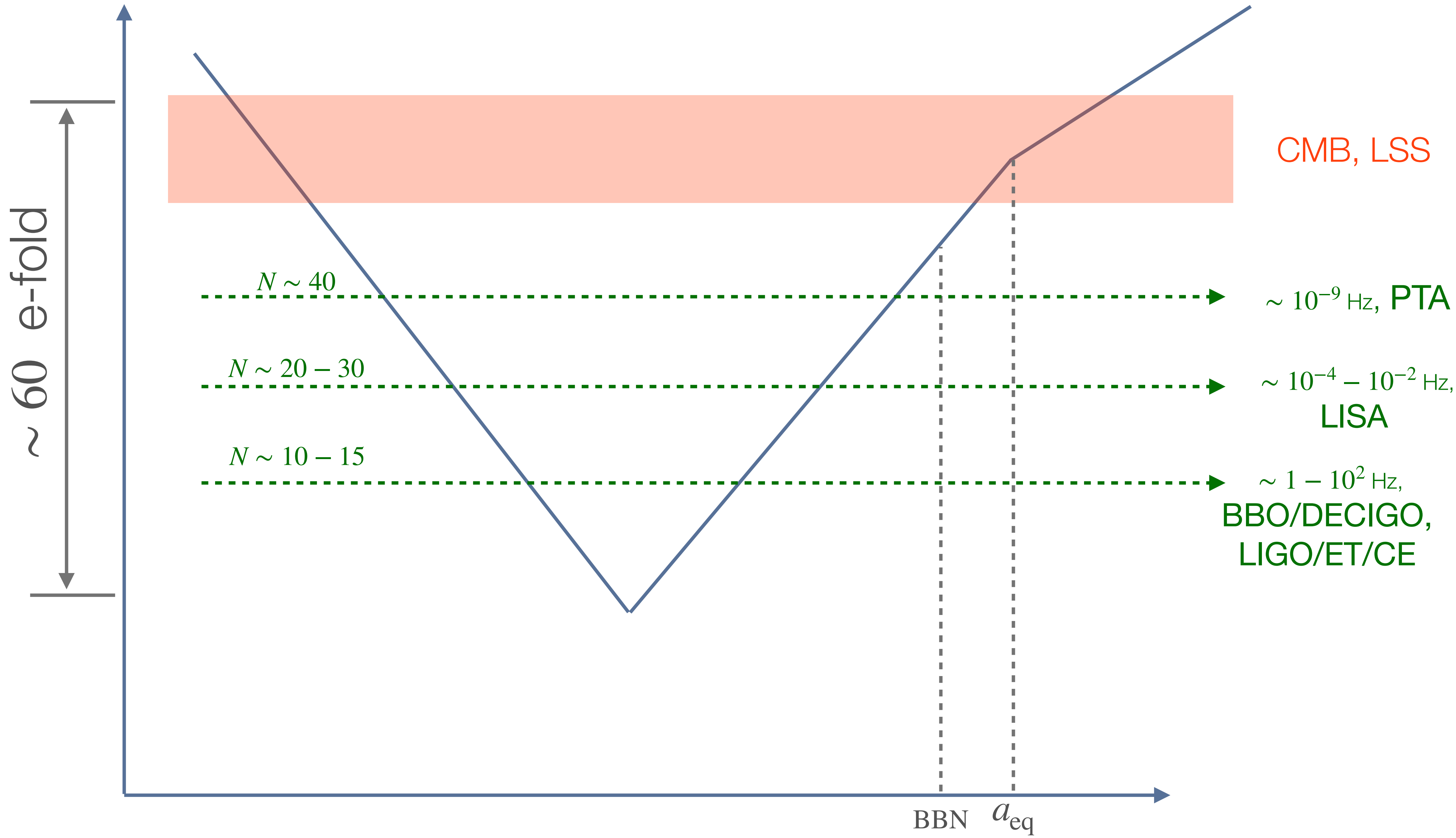
Secondary GW from spectator scalar

A few stories

$\boxed{\text{(Primary) GW from phase transition}}$

Secondary GW from spectator scalar

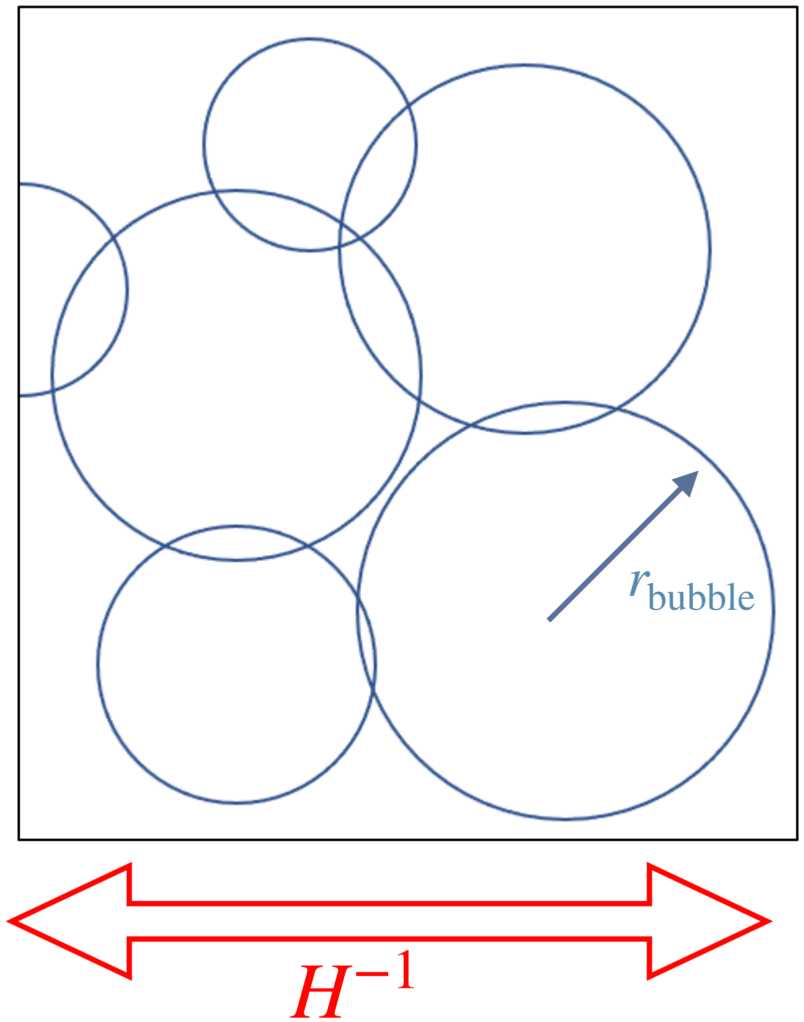
GW generated during inflation



1st order phase transition

Phase transition is 1st order, and spectator sector does not dominate energy density:

$$S_4(t) \simeq S(t_*) + \beta(t_* - t) + \ldots \qquad \beta^4 \ll m_\sigma^4 \ll 3M_{\rm Pl}^2 H^2$$

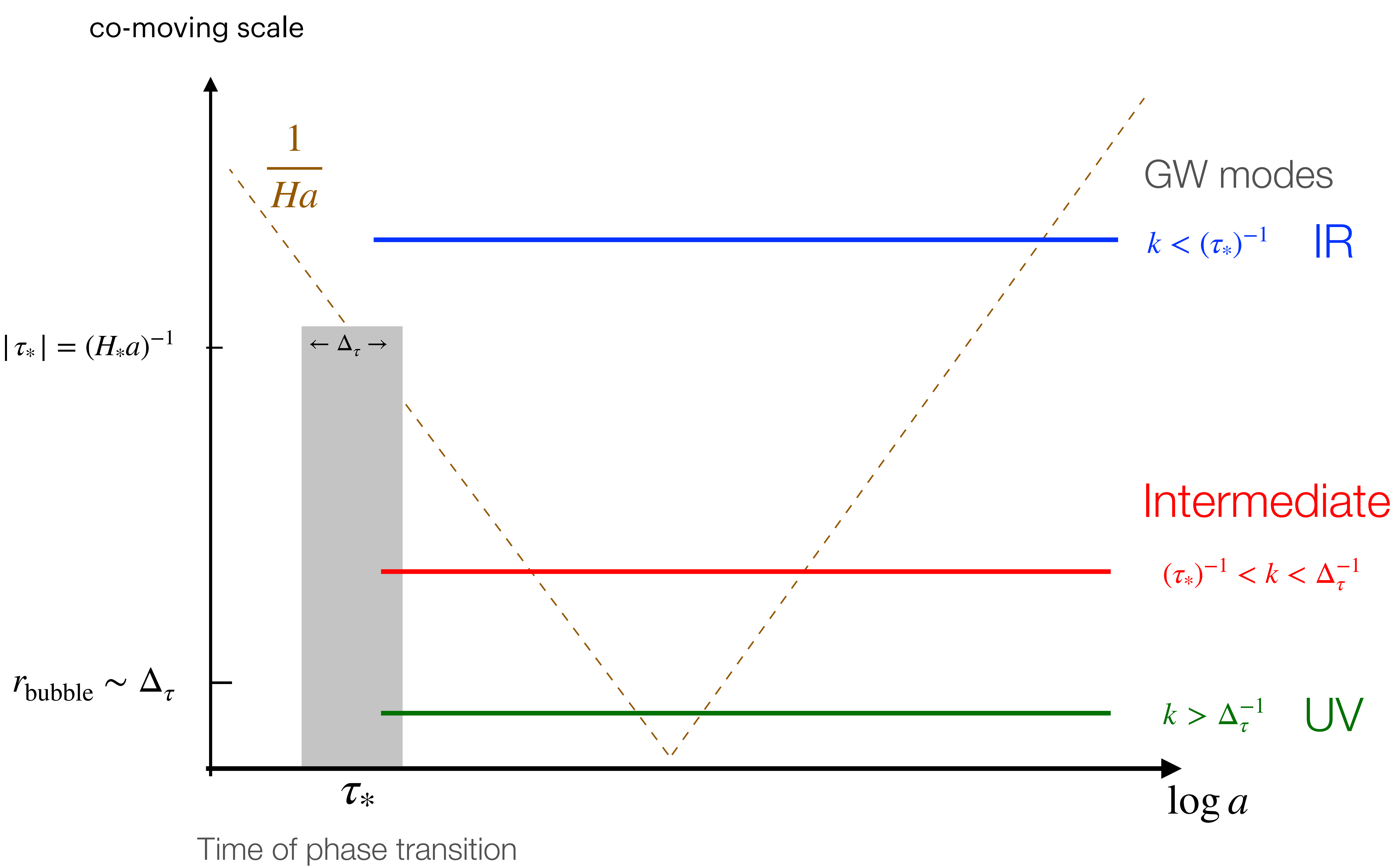


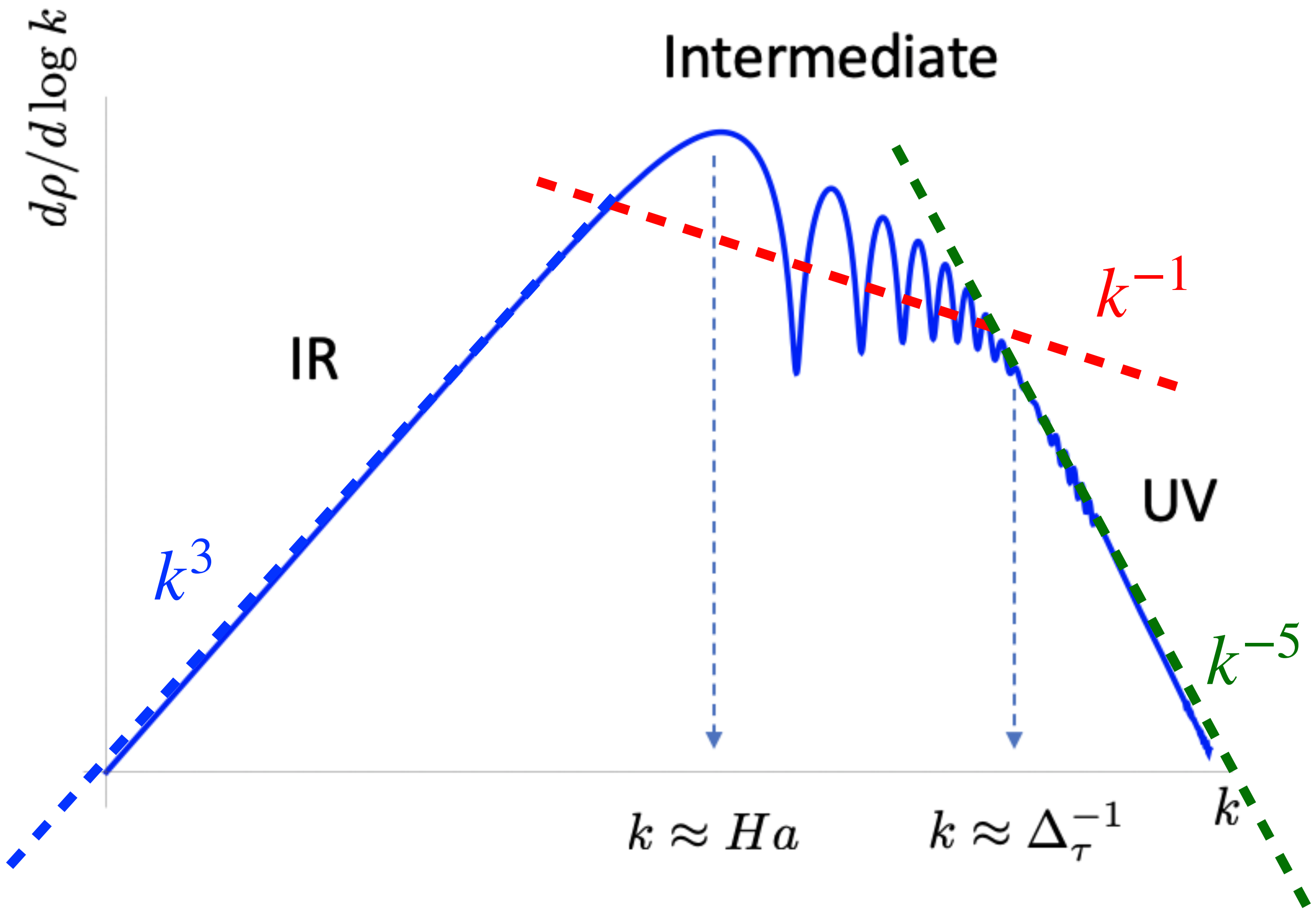
$$\beta^{-1} \sim r_{\rm bubble} \ll H^{-1}$$

$$t_{\rm bubble\ collision} \sim r_{\rm bubble} \ll H^{-1}$$

An instantaneous source of GW.

GW in three regimes





$$\frac{d\rho_{\rm GW}}{d\log k} \propto k^3 \langle (h')^2 \rangle$$

IR: $h = \text{constant} \times \dfrac{\sin k\tau}{k\tau}$

Intermediate: $h \propto \dfrac{\cos(k\tau_*)}{k^2}\dfrac{\sin k\tau}{k\tau}$

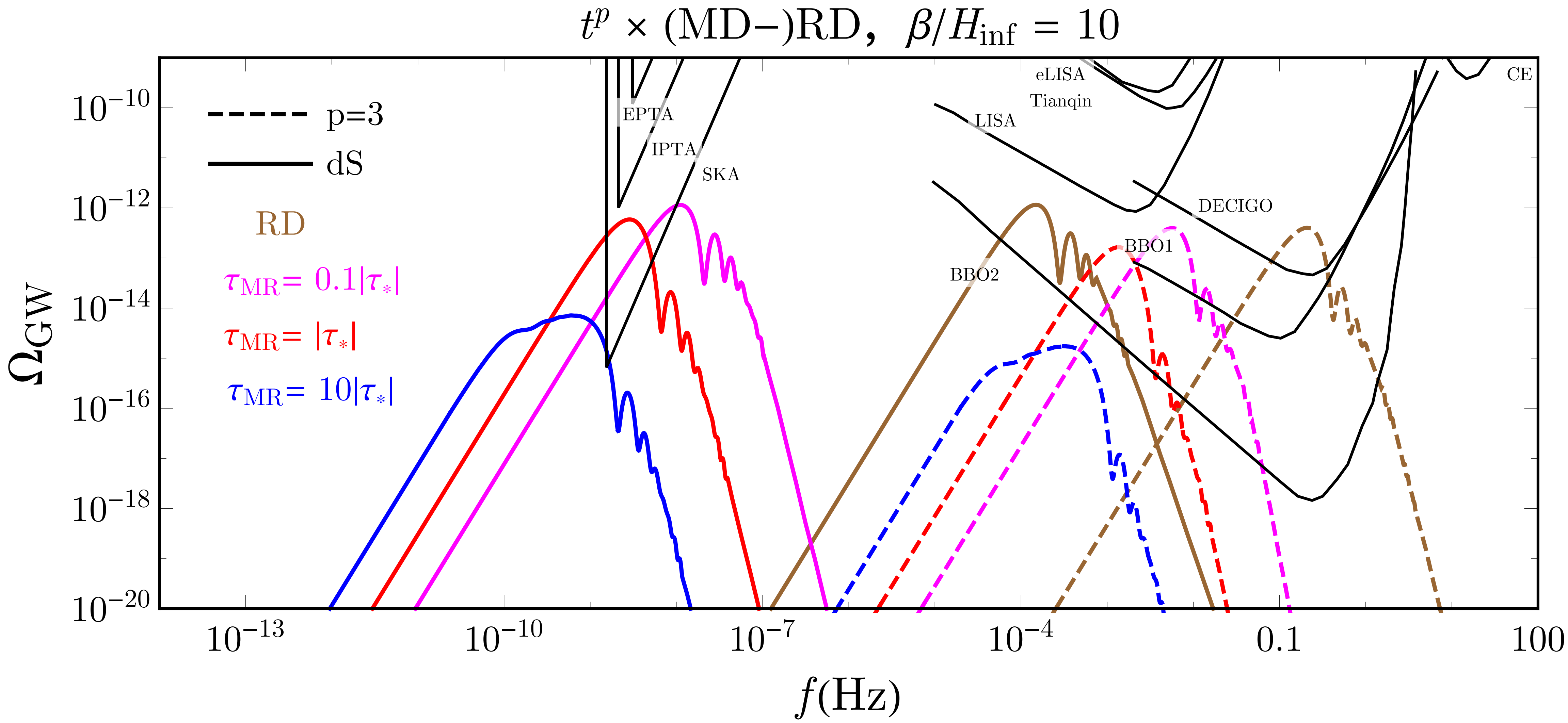
UV: $\dfrac{d\rho_{\rm GW}}{d\log k} \propto k^{-5}$

Details of source matters, determined by numerical simulation

Huber, Konstantin, 0806.1828

Cutting, Hindmarsh, Wier, 1802.05712

Haipeng An, KunFeng Lyu, Siyi Zhou, and LTW 2009.12381, 2201.05171



$$\Omega_{\rm GW}^{\rm max} \sim \Omega_R \times \left(\frac{\Delta\rho_{\rm vac}}{\rho_{\rm inf\star}}\right)^2 \times \left(\frac{H_\star}{\beta}\right)^5 \tilde{\Delta} \times F(H_\star/H_r, a_\star/a_r, \cdots)$$

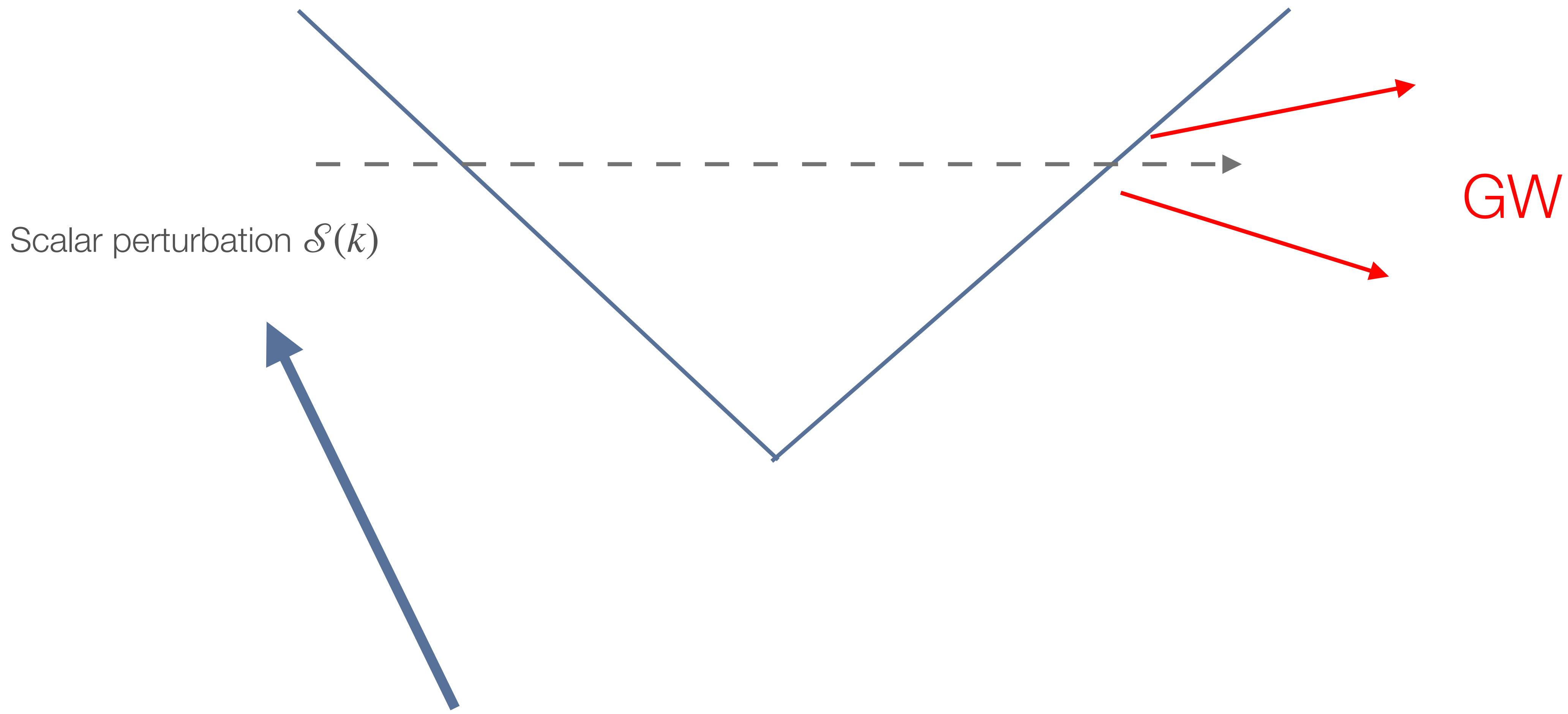
$$\approx 10^{-13} \times \left(\frac{\Delta\rho_{\rm vac}/\rho_{\rm inf\star}}{0.1}\right)^2 \times \left(\frac{H_\star/\beta}{0.1}\right)^5$$

A few stories

(Primary) GW from phase transition

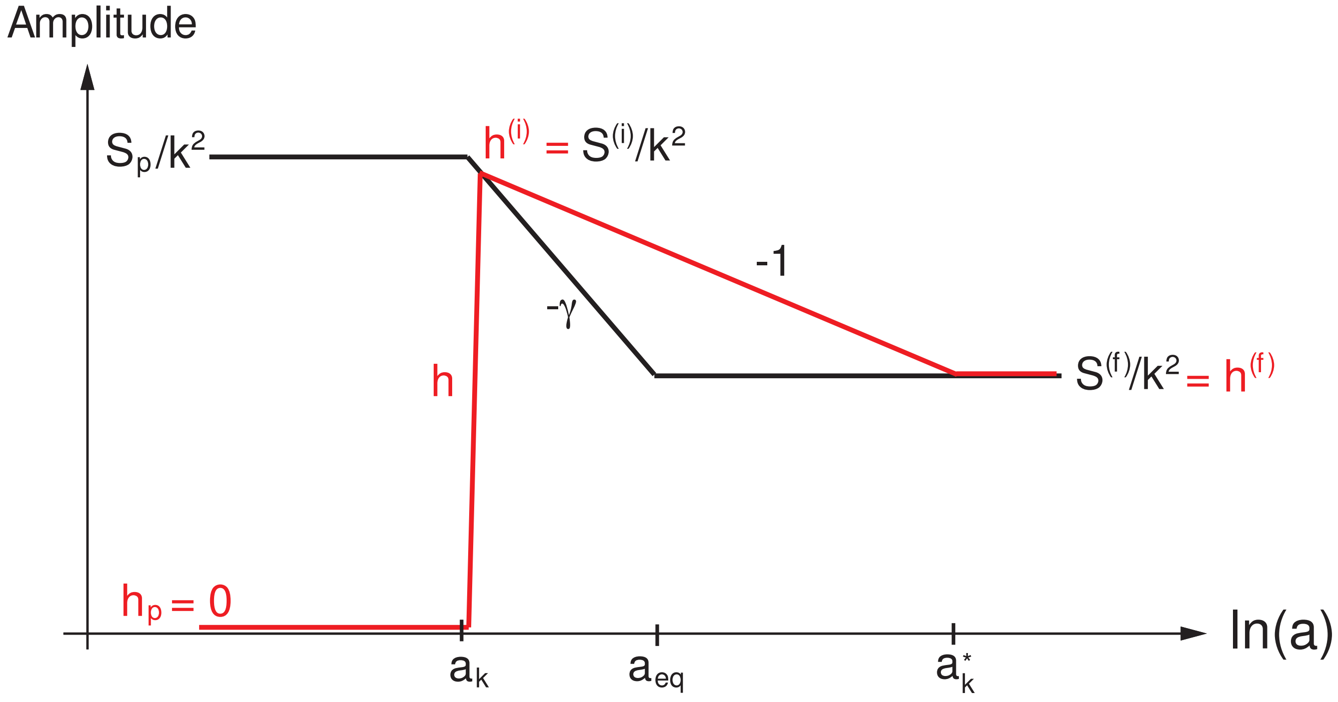
Secondary GW from spectator scalar

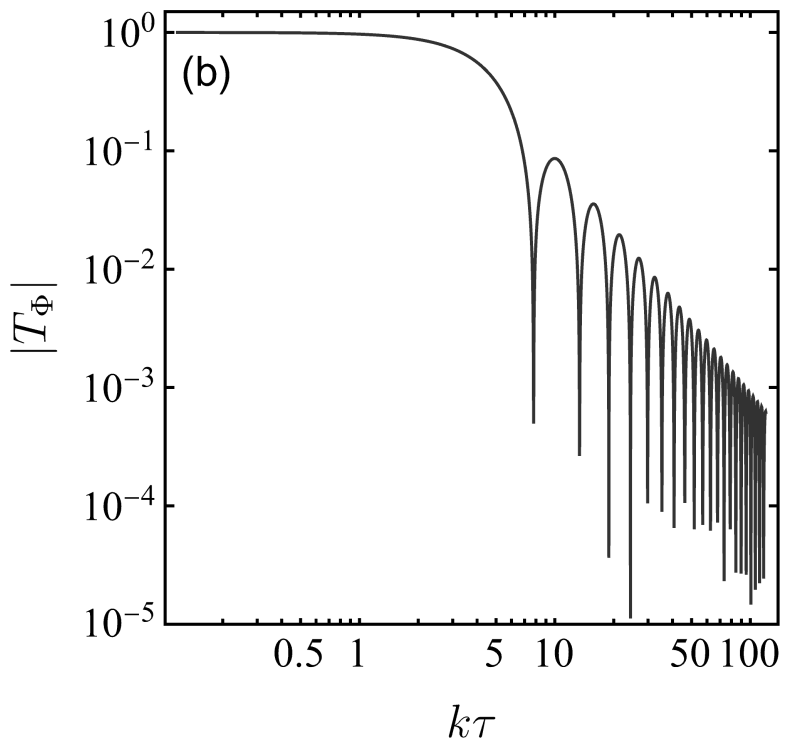
Secondary GW



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

Example: secondary GW

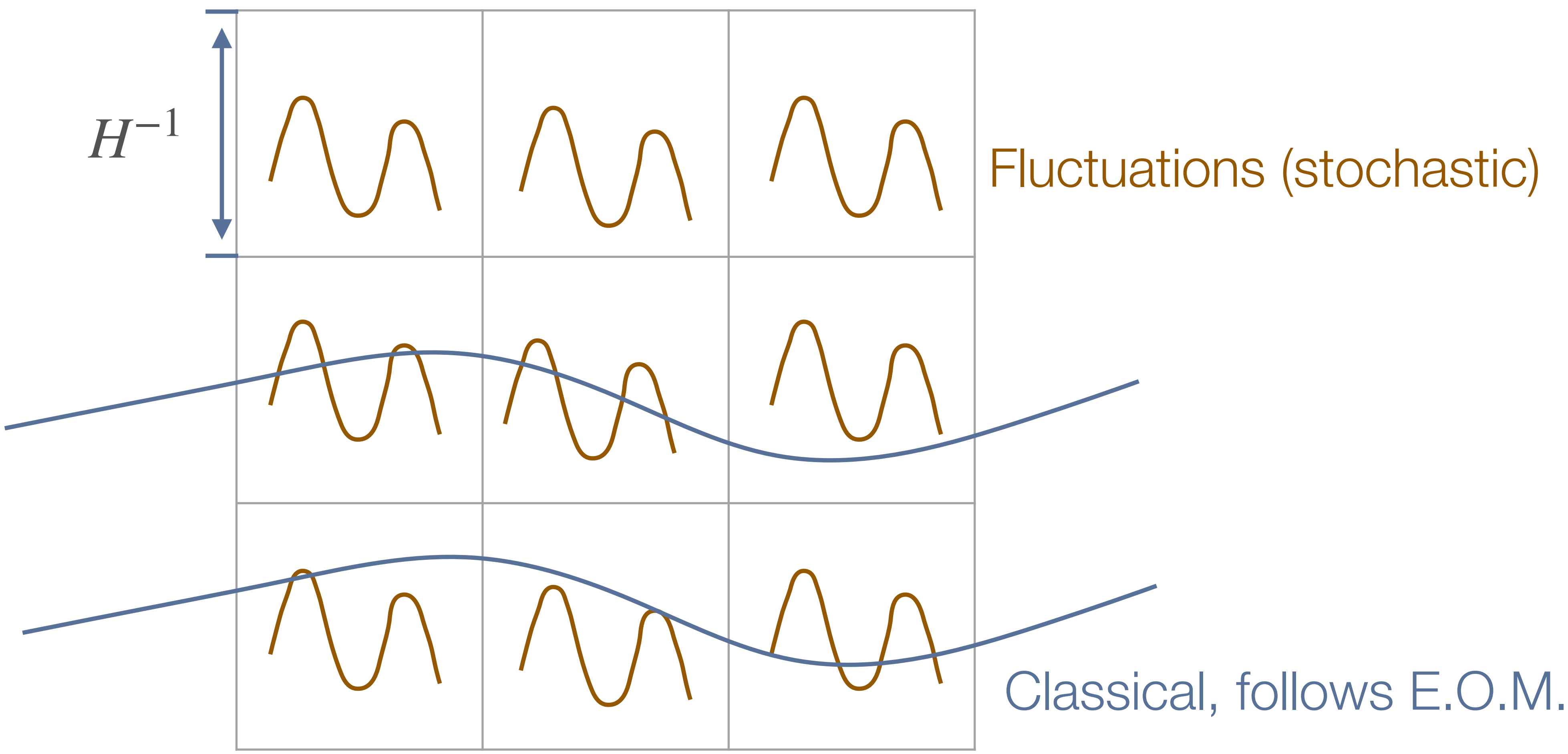




Baumann, Steinhardt, Takahashi, hep-th/0703290

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

Evolution of fluctuations: small vs large scales



A spectator light scalar

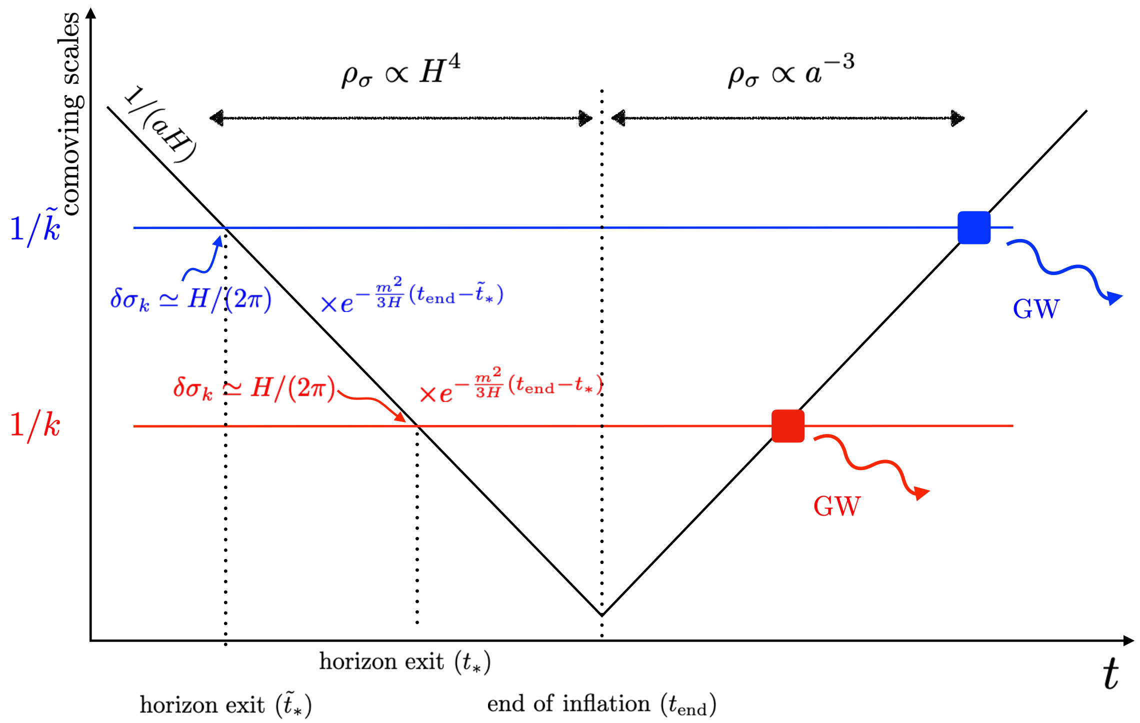
R. Ebadi, S. Kumar, A. McCune, H. Tai, LTW 2023

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

Fluctuation in $\boldsymbol{\sigma}$ will generate curvature perturbation

$\Rightarrow$ GW

Blue tilt

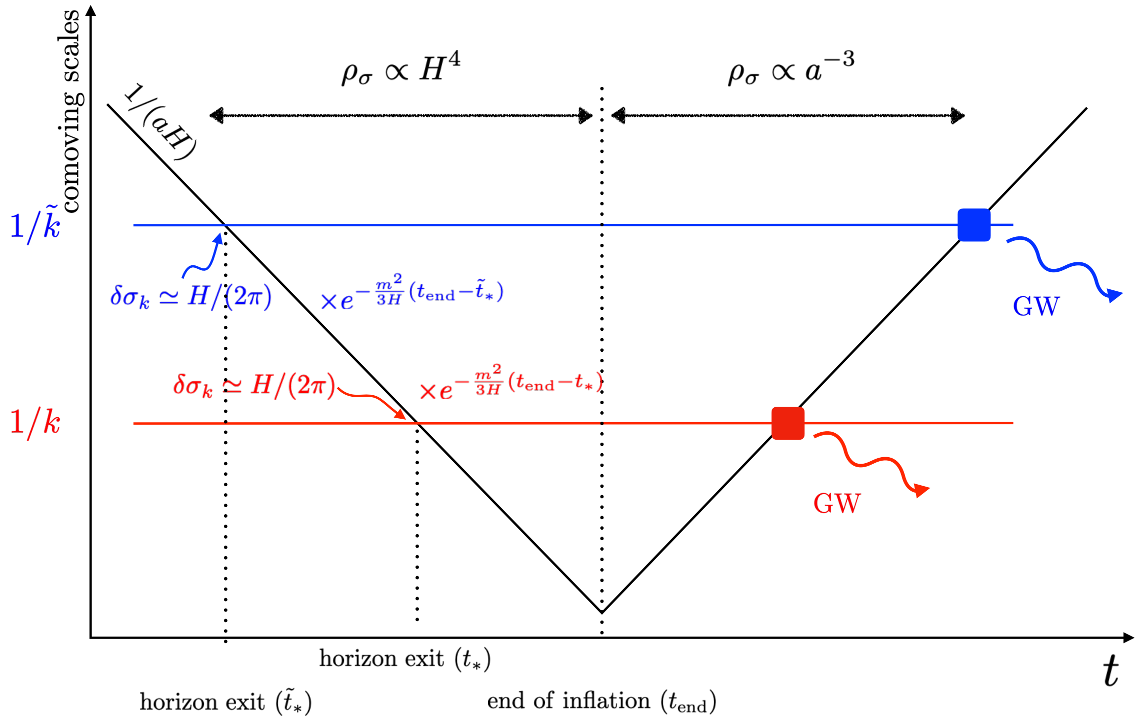


At horizon exit:
Amplitude ≈ H

After exit, damping

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

Blue tilt



At horizon exit:
Amplitude ≈ H

After exit, damping

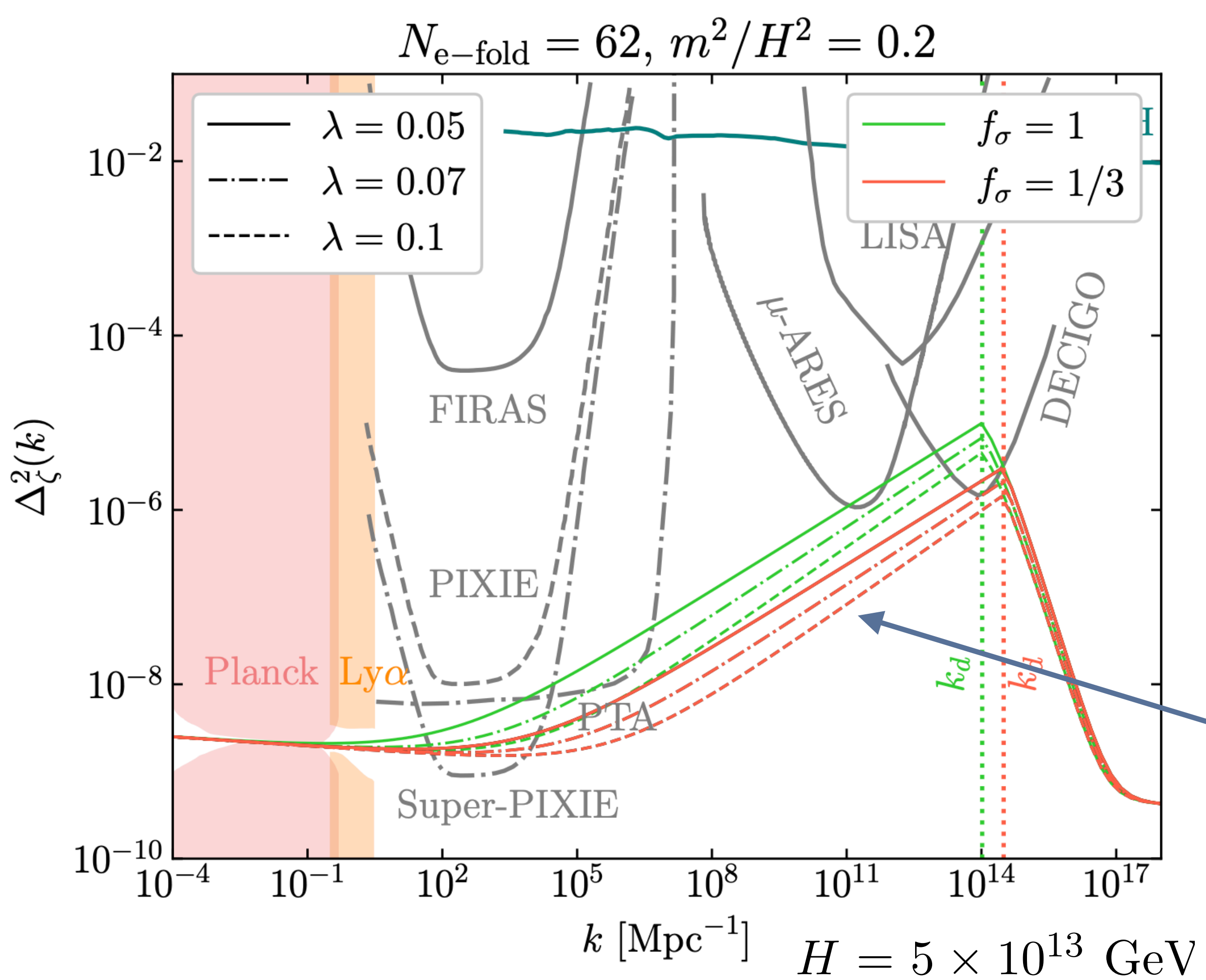
$$\dot{\sigma} = -\frac{m_\sigma^2 \sigma}{3H}$$

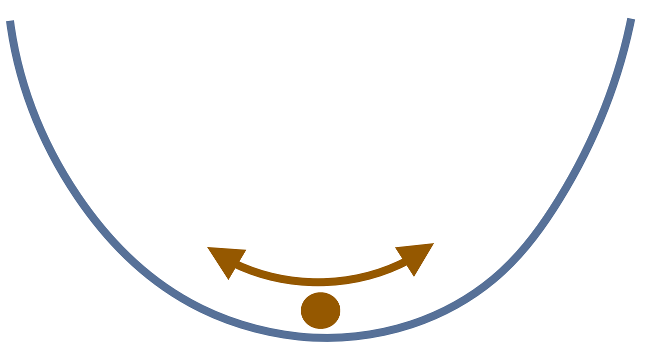
$$\sigma_k(t) = \sigma(t_*) \exp\left(-\frac{m_\sigma^2}{3H}(t - t_*)\right) = \sigma(t_*) \left[\exp\left(-H(t-t_*)\right)\right]^{\frac{m_\sigma^2}{3H^2}} = \sigma(t_*) \left[\frac{k(t)}{H}\right]^{\frac{m_\sigma^2}{3H^2}}$$

More damping for longer wave-length (earlier exit)

Power spectrum

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

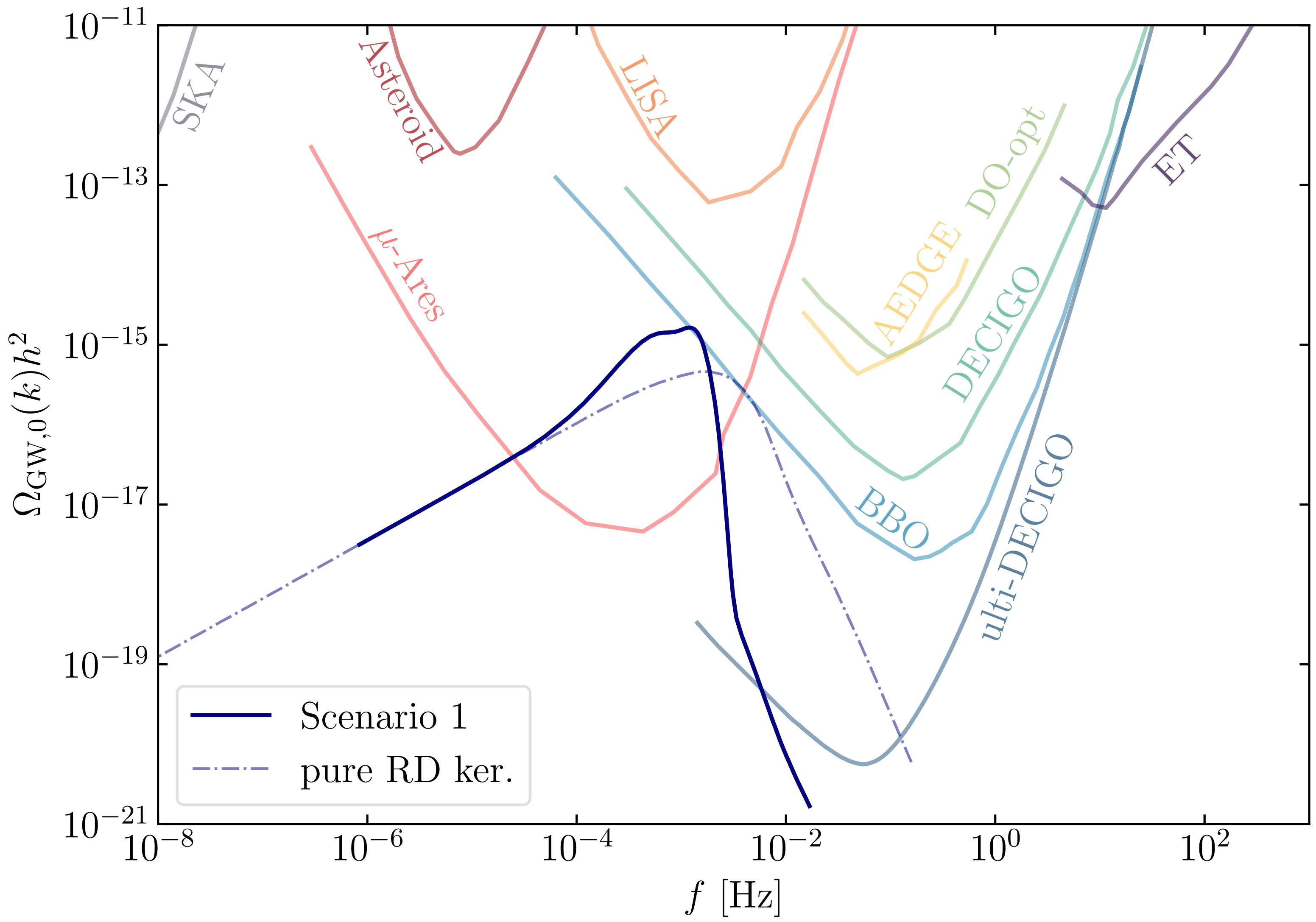




blue tilt

Assuming the scalar behave similar to curvaton.
Becoming important before decay.
Assumption: scalar field does not dominate (more later)

Secondary GW

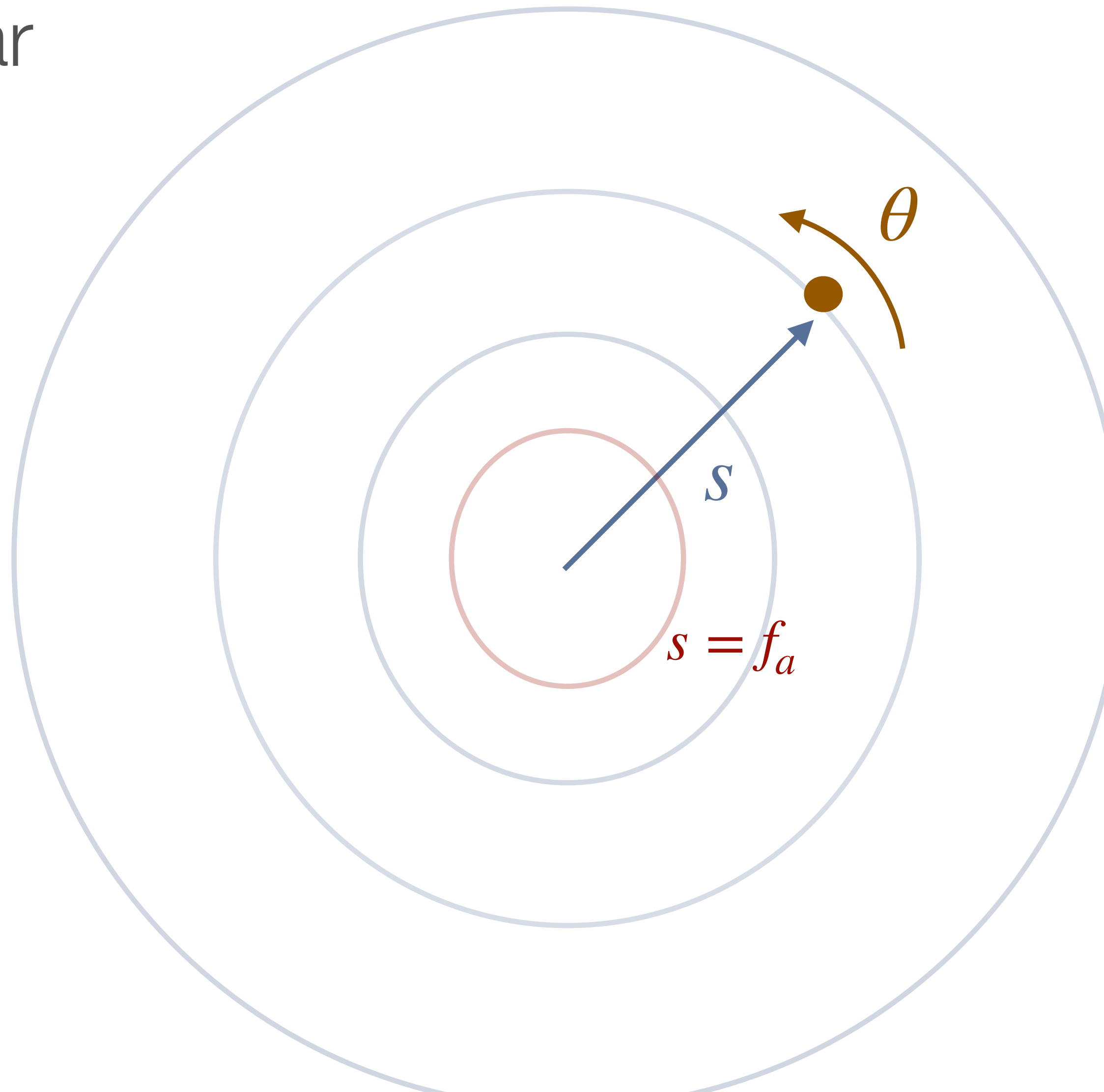


Just an example to show the spectrum, other frequency/signal strength possible

Complex scalar

Soubhik Kumar, Hanwen Tai, LTW, 2410.17291

Complex scalar

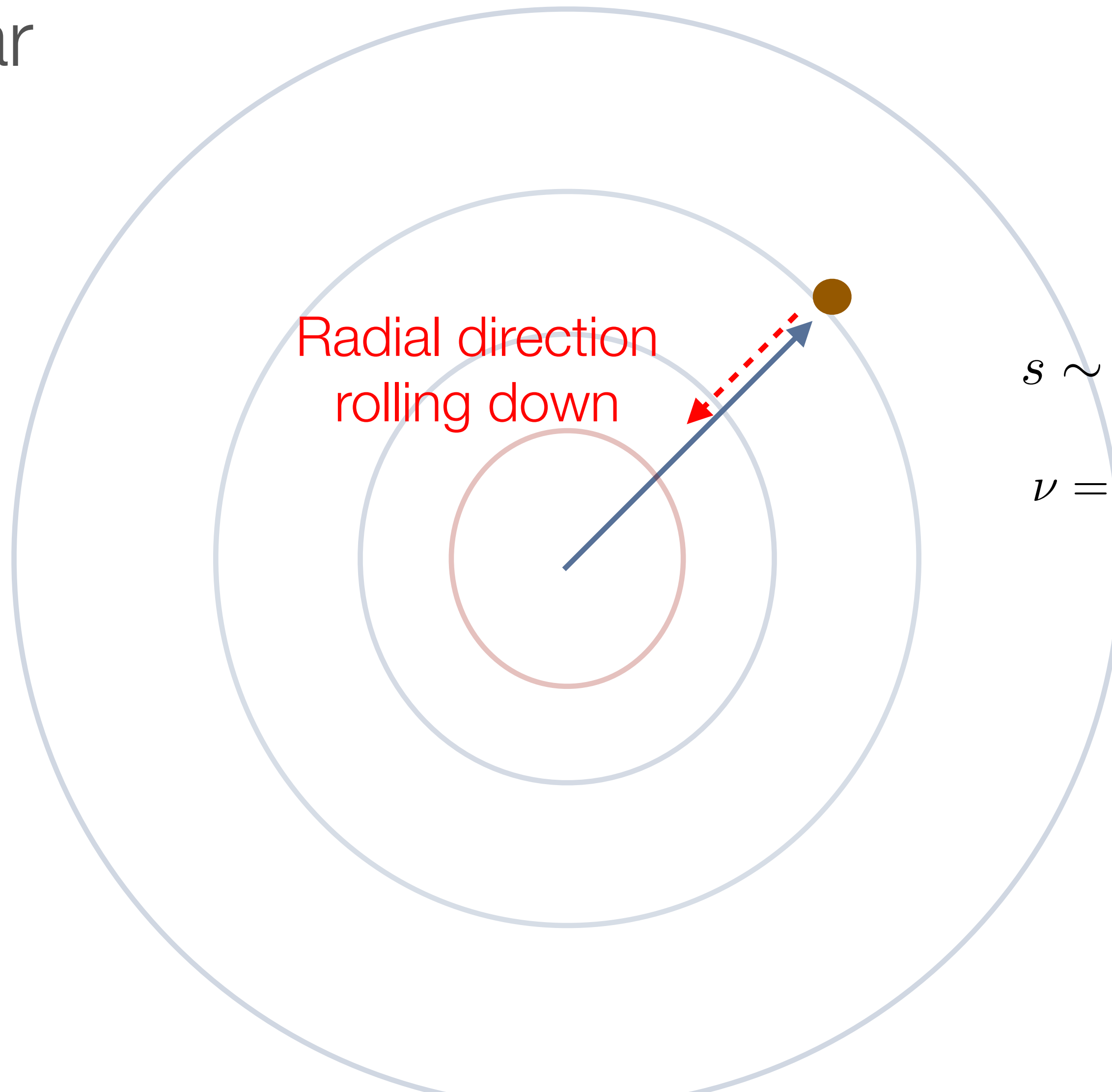


$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu s)^2 + \frac{1}{2}s^2(\partial_\mu \theta)^2 - \lambda_\Phi (s^2 - f_a^2)^2/4 + \frac{1}{2}m^2 s^2 \theta^2.$$

Rolling radial mode

Soubhik Kumar, Hanwen Tai, LTW, 2410.17291

Complex scalar



$$s \sim \exp(-(3/2-\nu)Ht)$$

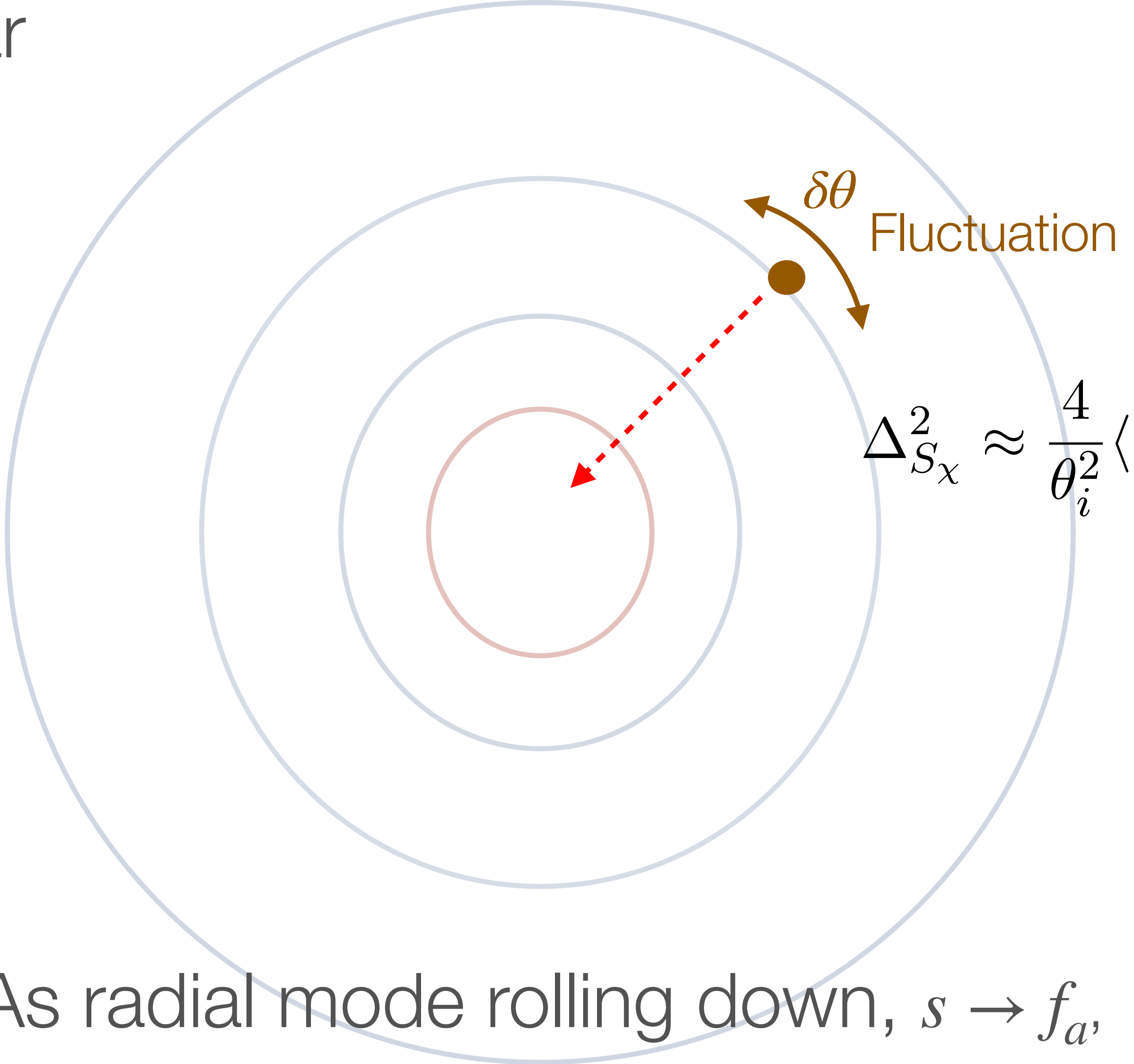
$$\nu = \sqrt{9/4 - m_s^2/H^2}$$

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu s)^2 + \frac{1}{2}s^2(\partial_\mu \theta)^2 - \lambda_\Phi (s^2 - f_a^2)^2/4 + \frac{1}{2}m^2 s^2 \theta^2.$$

Fluctuations

Soubhik Kumar, Hanwen Tai, LTW, 2410.17291

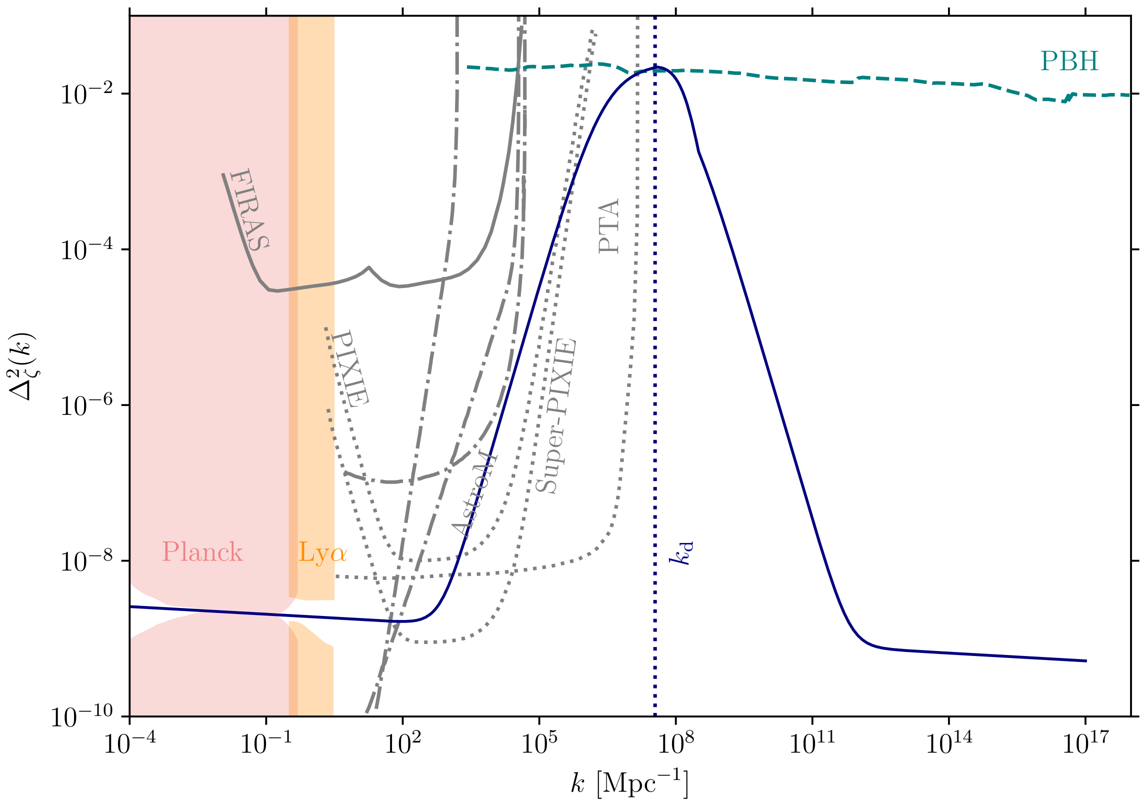
Complex scalar

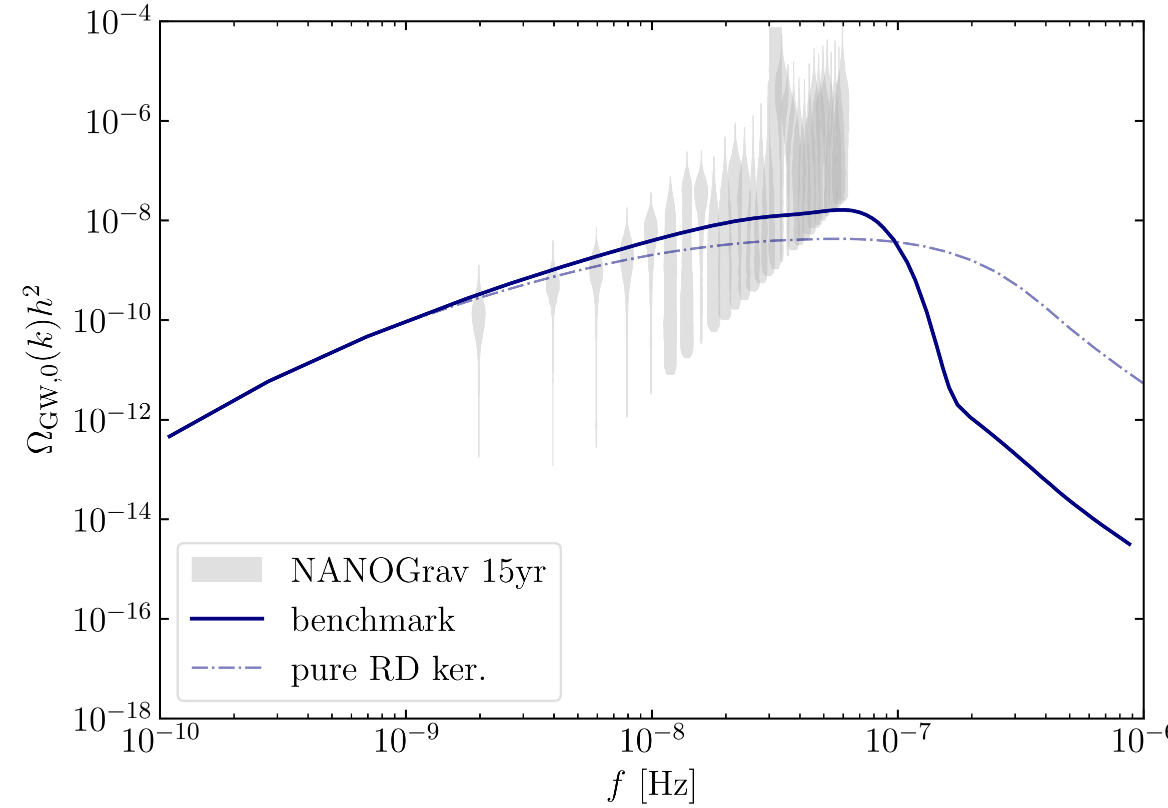


$$\Delta^2_{S_\chi} \approx \frac{4}{\theta_i^2}\langle(\delta\theta)^2\rangle = \left(\frac{H}{\pi\theta_i\langle s\rangle}\right)^2$$

As radial mode rolling down, $s \to f_a$,
Fluctuation becomes larger.

A benchmark





$$\chi_{0,\mathrm{end}} = f_a = 0.6H,\ H = 1.9 \times 10^{12}\ \text{GeV},\ m = 0.05H,\ \lambda_\Phi = 0.75$$

N	k_{end} [Mpc^{-1}]	k_{EMD} [Mpc^{-1}]	k_{d} [Mpc^{-1}]
59.2	1.18×10^{22}	3.14×10^{8}	4.0×10^{7}

More stories

Topological defects:

Y. Bao, K. Harigaya, LTW, 2407.17525

Axion rotation and kination:

K. Harigaya, K. Inomata, 2309.00228

Features of inflaton potential

J. Fumagalli, G. Palma, S. Renaux-Petel, S. Sypsas, L. T. Witkowski, and C. Zenteno 2111.14664

Y.-F. Cai, J. Jiang, M. Sasaki, V. Vardanyan, and Z. Zhou 2105.12554

….

Conclusions

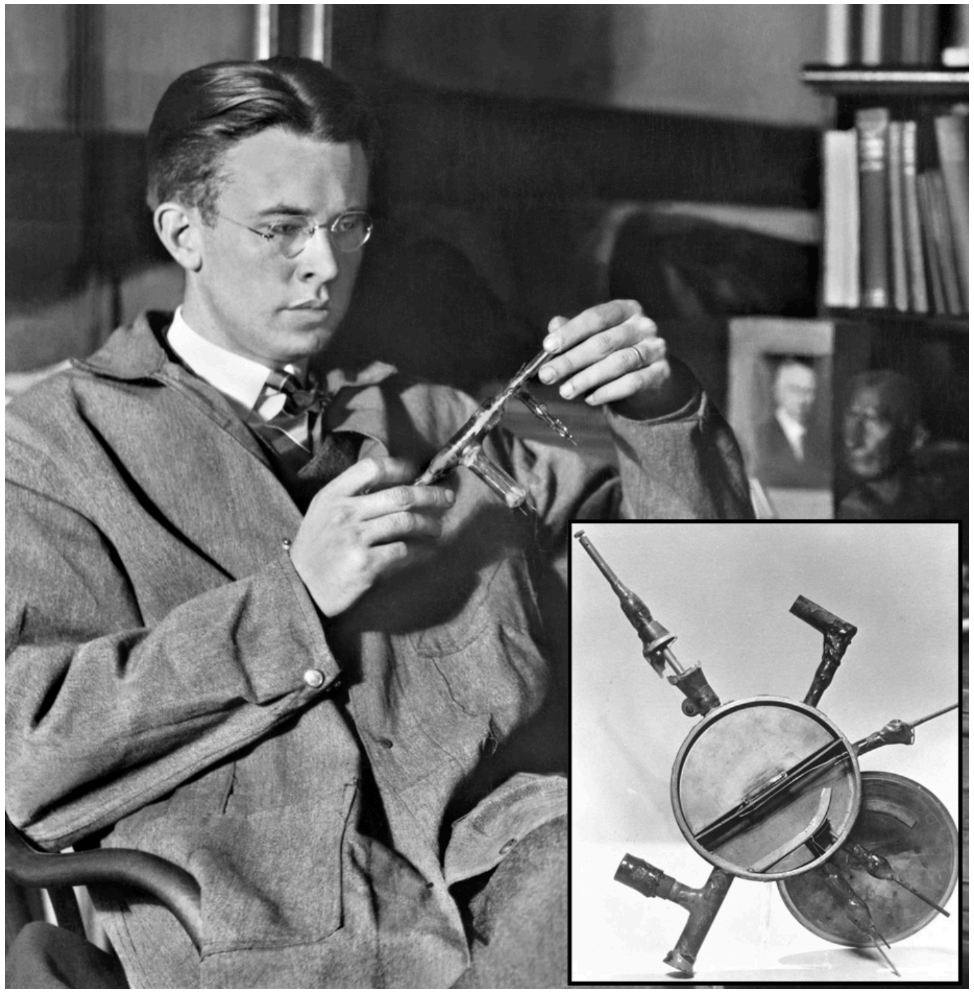
- SM is complete. But new physics is clearly needed. We are in the “after the SM” era.
- One place where new physics happens is early universe: inflation, dark matter, baryon asymmetry.

Conclusions

- Gravitational wave offers a new and unique window into early universe.
    - Inflationary dynamics, phase transitions, defects, …
- Beginning of a new era. More exciting work ahead.

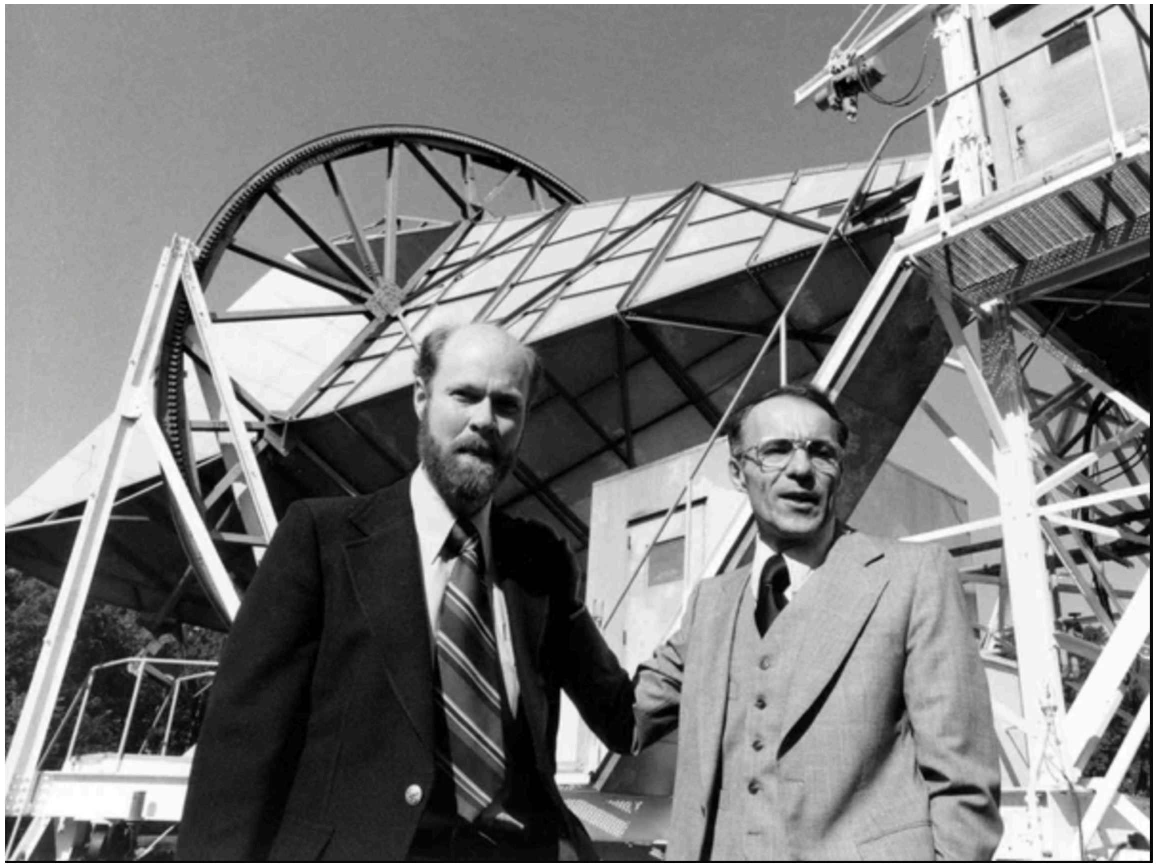
Beginnings of exciting times

E. Lawrence



LBNL

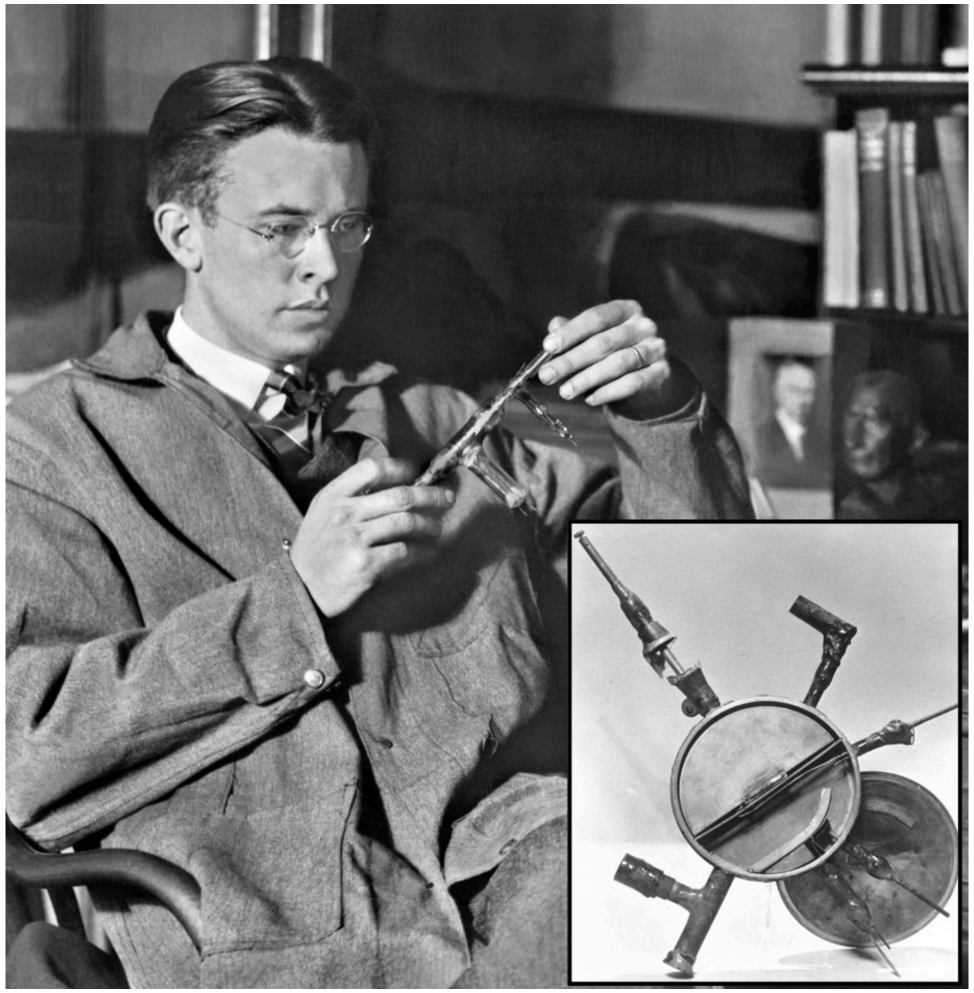
A. Penzias and R. Wilson



AP

Beginnings of exciting times

E. Lawrence



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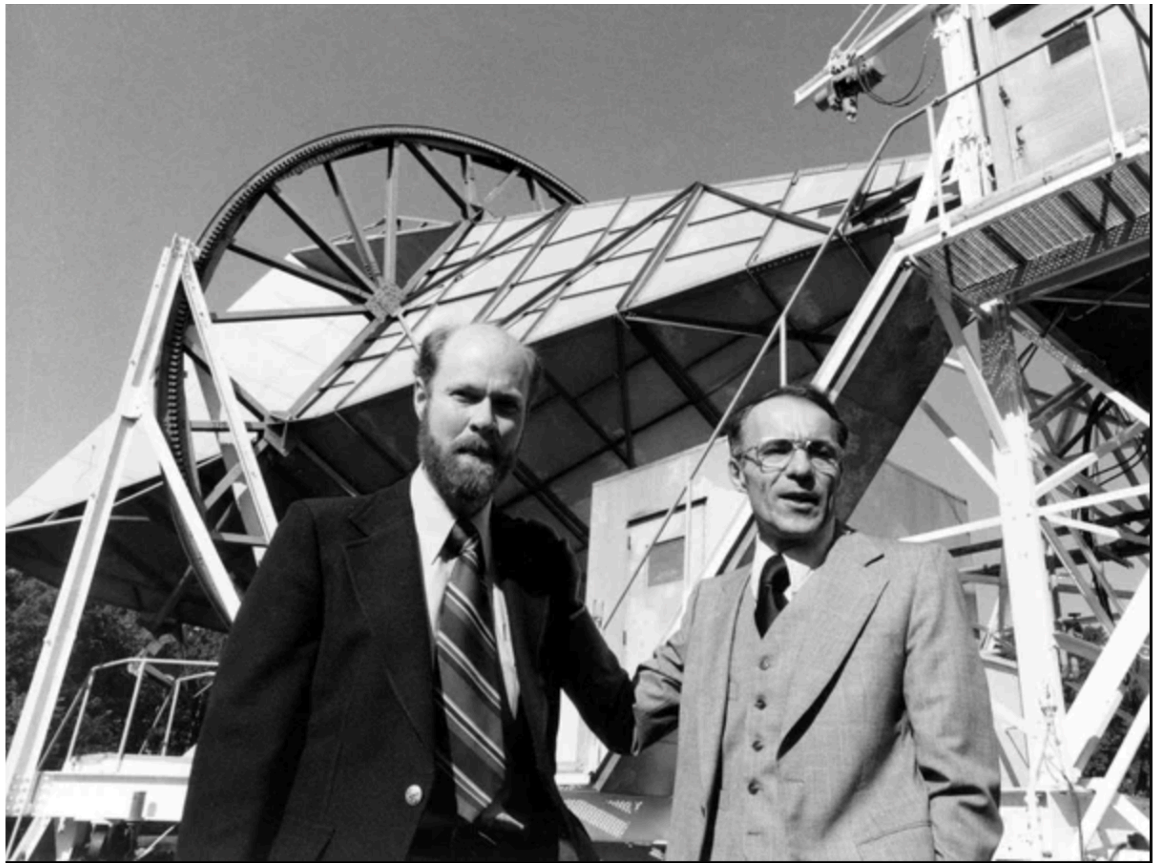


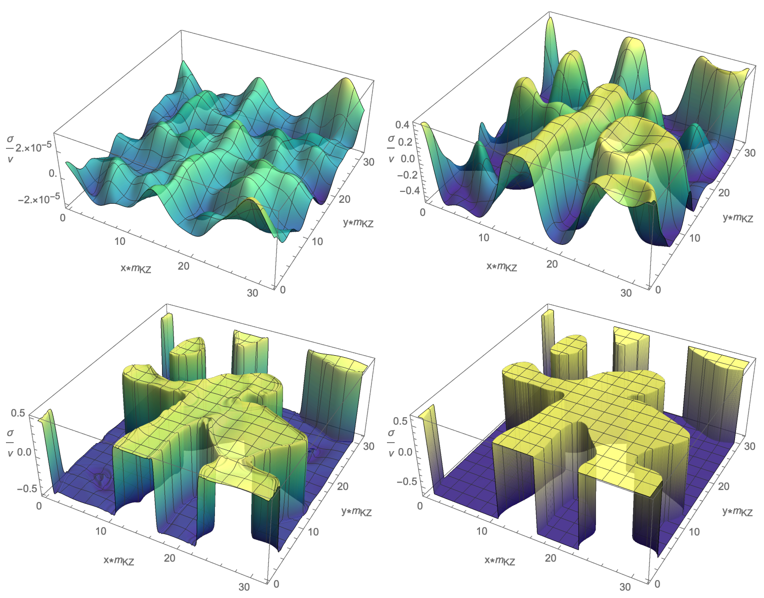
AP

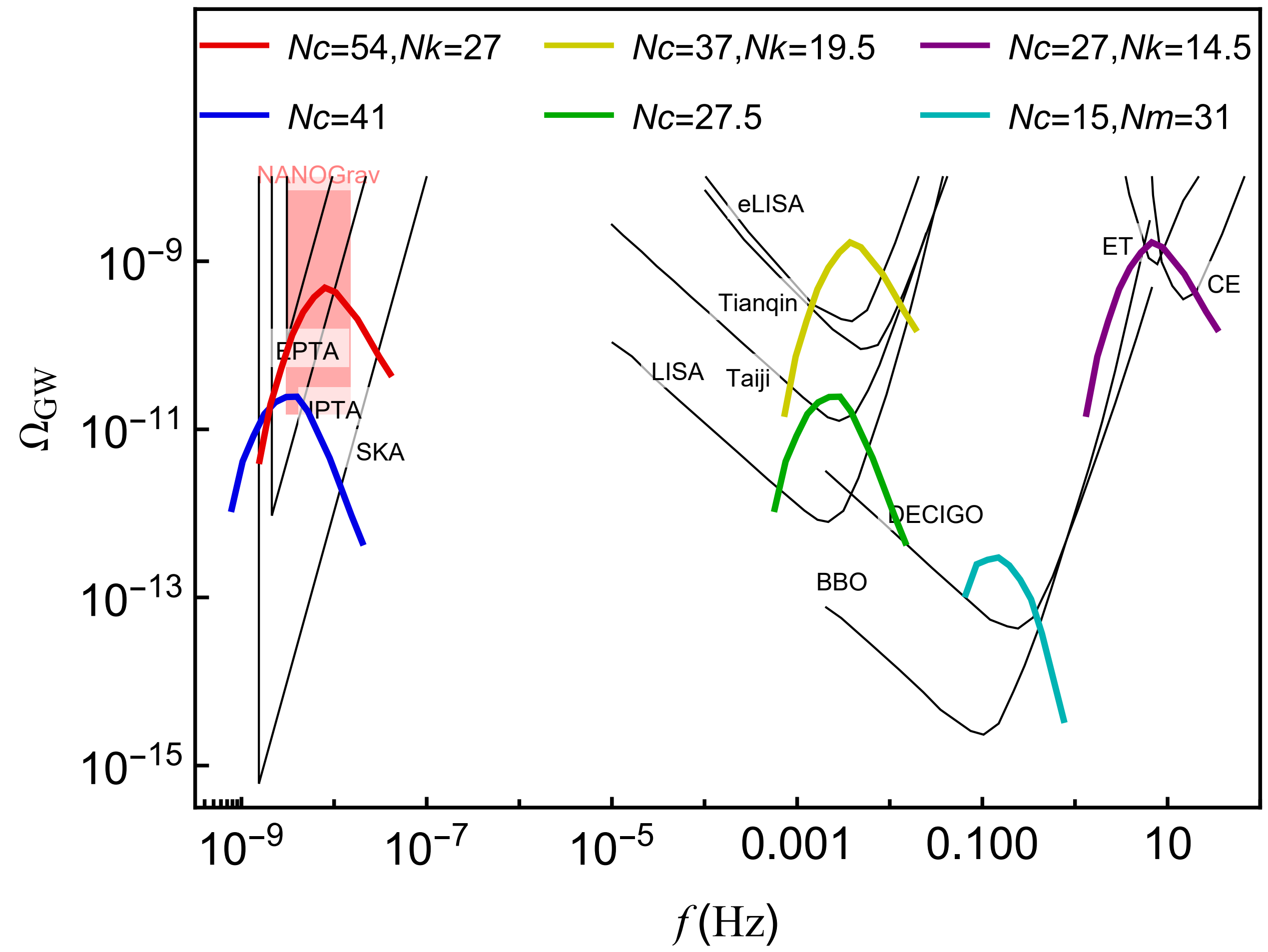
We are at a similar historical juncture for gravitational waves

Extra

From topological defects

H. An and C. Yang, 2304.02361





Domain wall from a 2nd order phase transition as source for GW.

Stochastic method

The spectrum of its fluctuation on large scales
can be studied by stochastic method

Starobinsky and Yokoyama, 1994

Fokker-Planck
$$\frac{\partial P_{\rm FP}(t,\sigma)}{\partial t} = \left(\frac{V''(\sigma)}{3H} + \frac{V'(\sigma)}{3H}\frac{\partial}{\partial\sigma} + \frac{H^3}{8\pi^2}\frac{\partial^2}{\partial^2\sigma} \right) P_{\rm FP}(t,\sigma)$$

$P_{\rm FP}(t,\sigma)$: 1-pt PDF for field σ

Stochastic method

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Starobinsky and Yokoyama, 1994

Fokker-Planck $$\frac{\partial P_{\mathrm{FP}}(t,\sigma)}{\partial t} = \left(\boxed{\frac{V''(\sigma)}{3H} + \frac{V'(\sigma)}{3H}\frac{\partial}{\partial\sigma}} + \frac{H^3}{8\pi^2}\frac{\partial^2}{\partial^2\sigma} \right) P_{\mathrm{FP}}(t,\sigma)$$

Classical evolution, drift

$P_{\mathrm{FP}}(t,\sigma)$: 1-pt PDF

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Classical evolution, drift Stochastic, diffusion

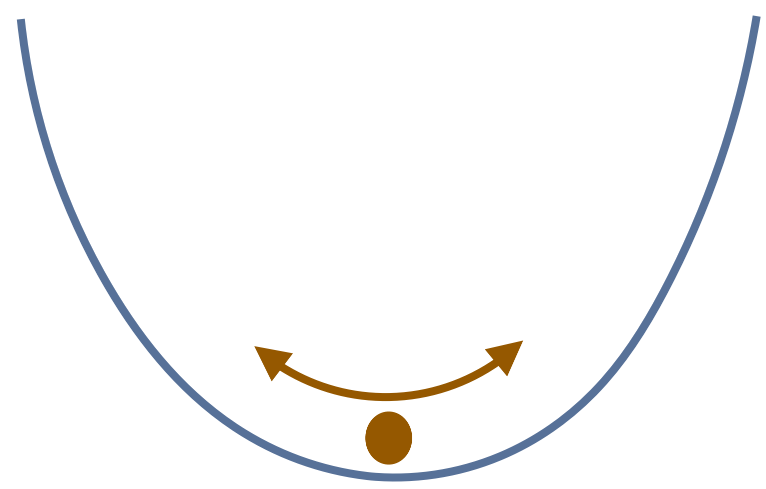
$P_{\rm FP}(t,\sigma)$: 1-pt PDF

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 $m < H$

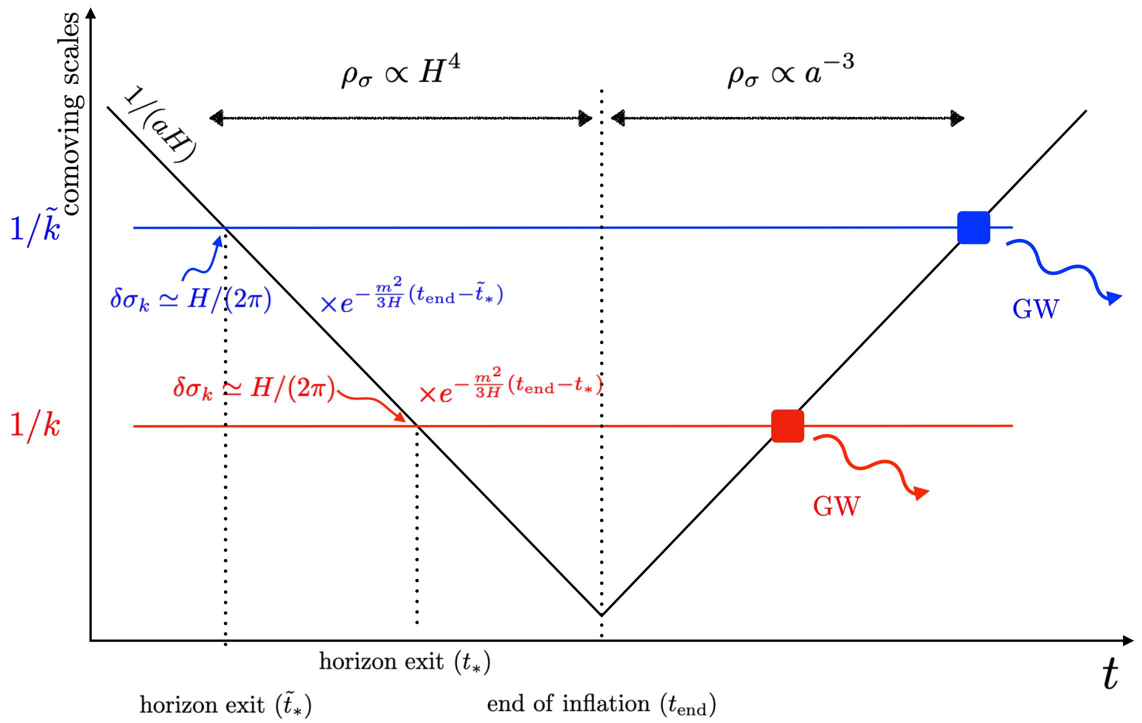


$$\mathcal{P}_f(k) = \sum_n \frac{2}{\pi} f_n^2 \Gamma\left(2 - 2\frac{\Lambda_n}{H}\right)\sin\left(\frac{\Lambda_n \pi}{H}\right)\left(\frac{k}{H}\right)^{2\Lambda_n/H} \quad \to \mathscr{A}\left(\frac{k}{H}\right)^{\frac{2\Lambda_{\rm lowest}}{H}}$$

for $k \ll H$

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

Blue tilt



At horizon exit:
Amplitude ≈ H

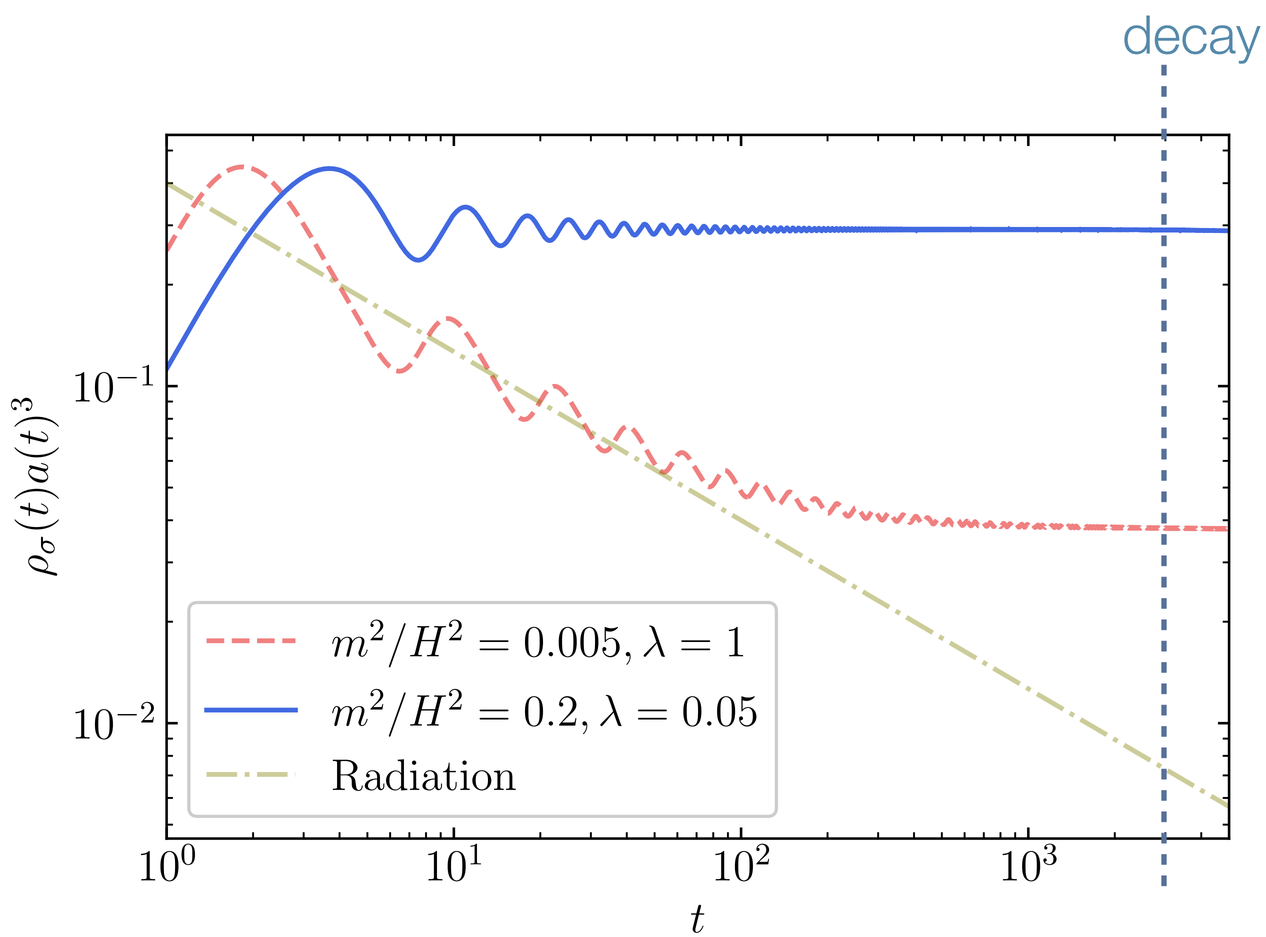
After exit, damping

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

For more general scalar theory

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

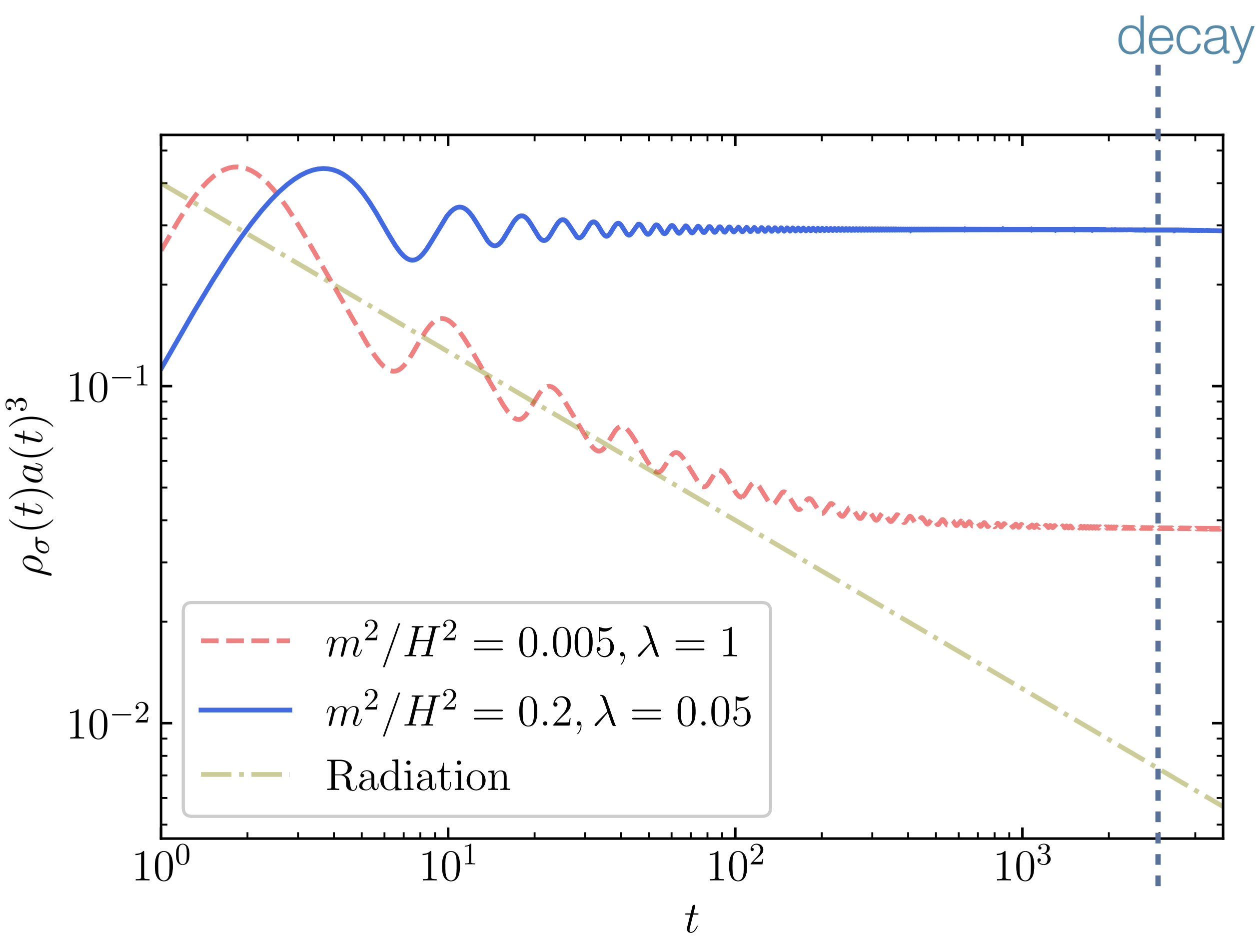
After inflation



Eventually,
evolve like matter

Can become important

After inflation



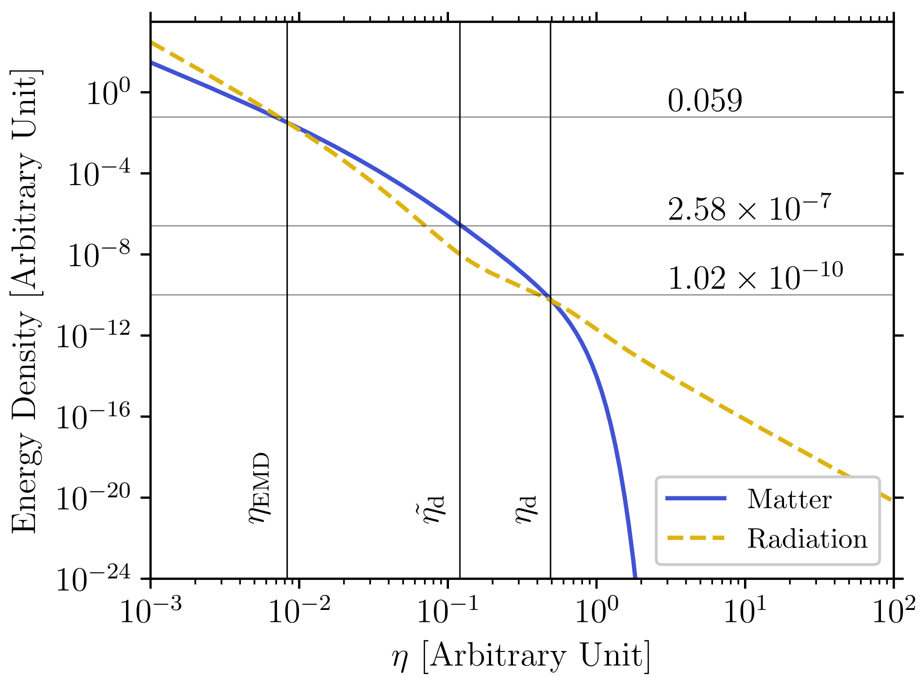
Eventually,
evolve like matter

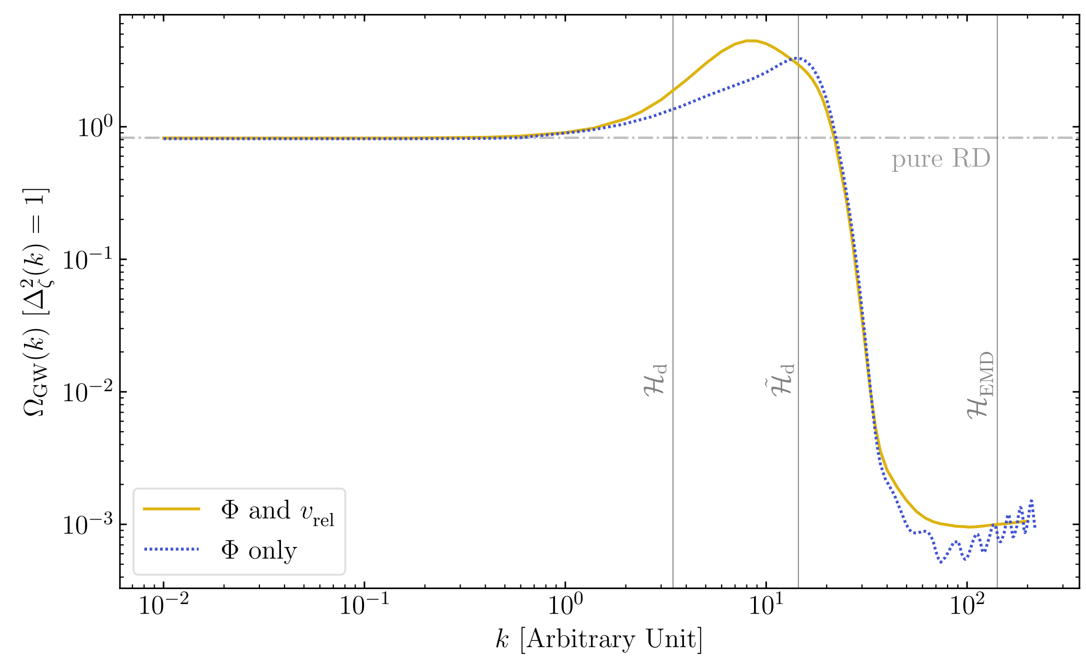
Can become important

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

More general scenario

Soubhik Kumar, Hanwen Tai, LTW, 2410.17291





More generally, can consider the case scalar perturbation dominates (curvaton-like).
Larger signal, interesting spectral shape.
To treat this properly, much care is needed, numerically challenging.

More general scenario

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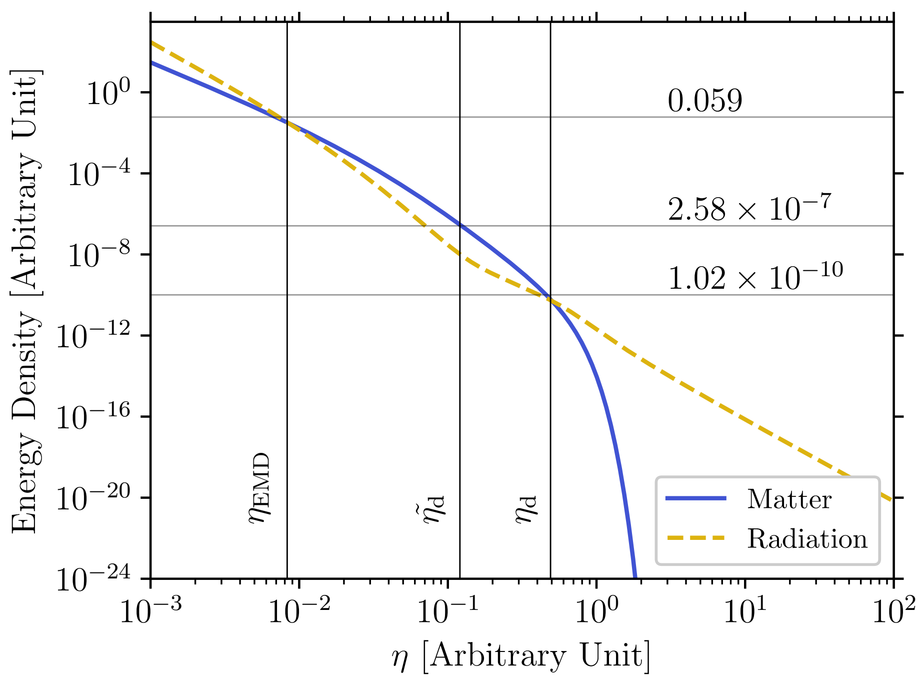

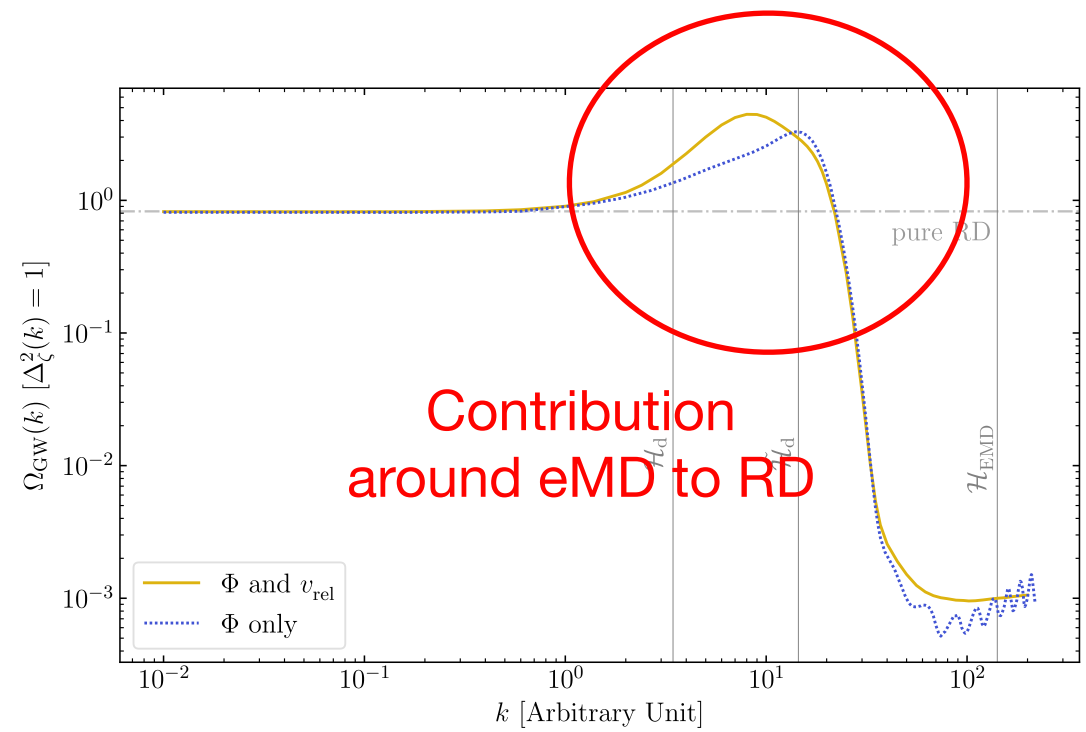

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