Andrea Tesi

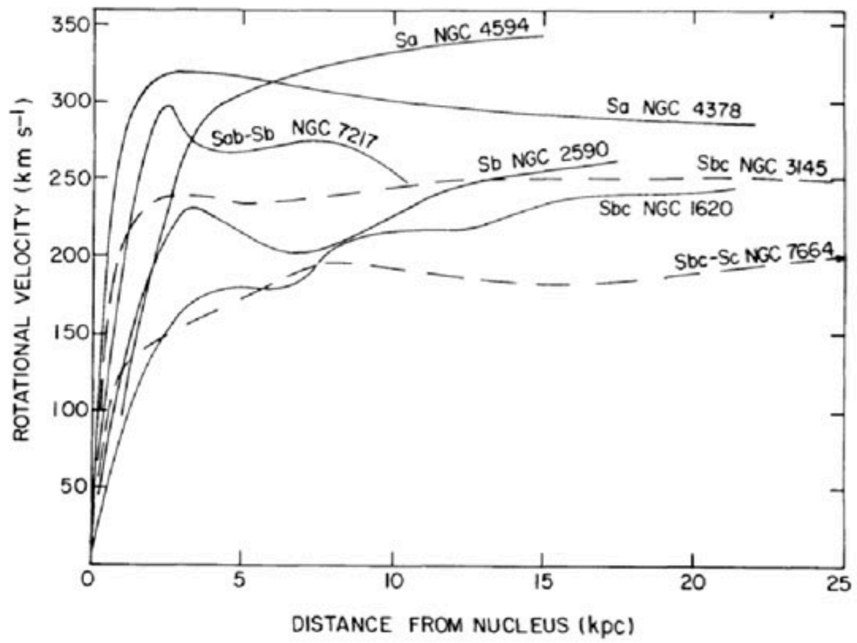
dark matter from inflationary fluctuations

work in collaboration
with Raghuveer Garani and Michele Redi
-TPPC-

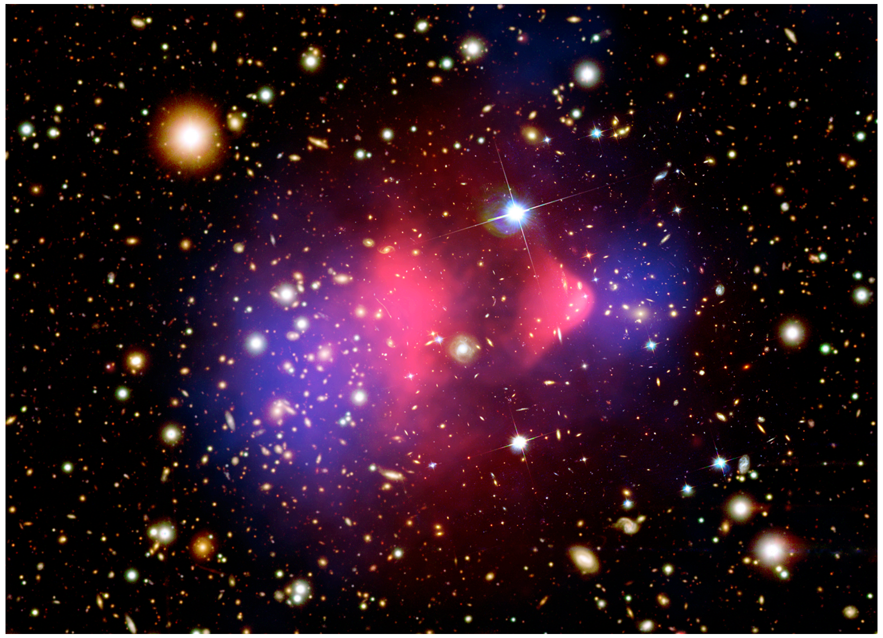
florence theory group day — 22/02/2023

Dark Matter

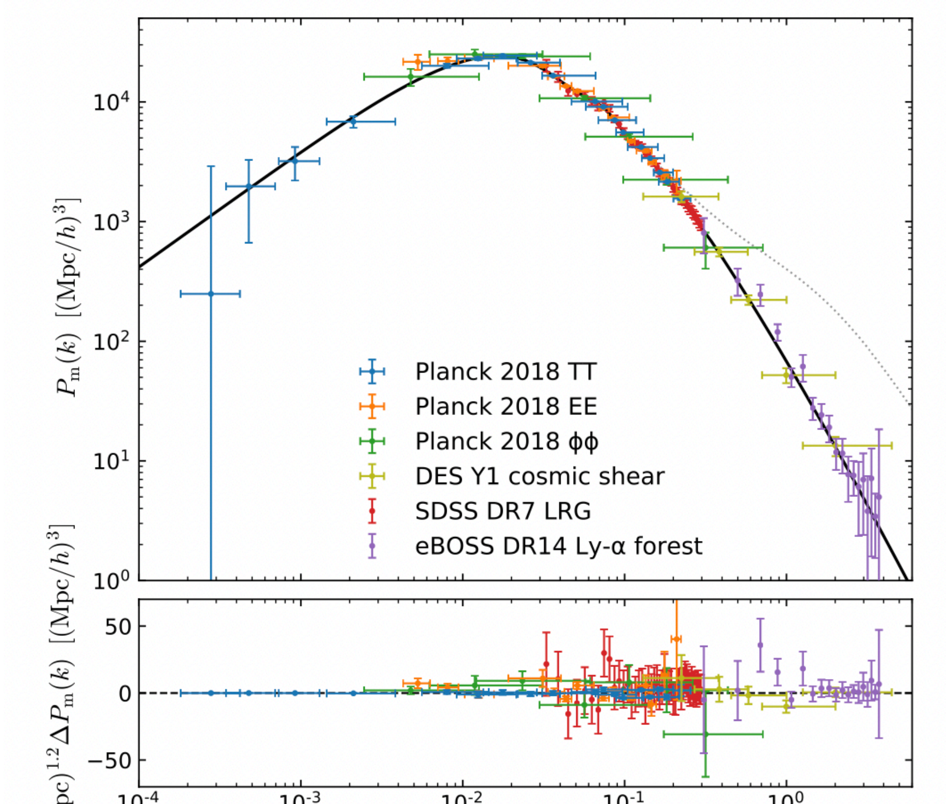
evidences are only gravitational



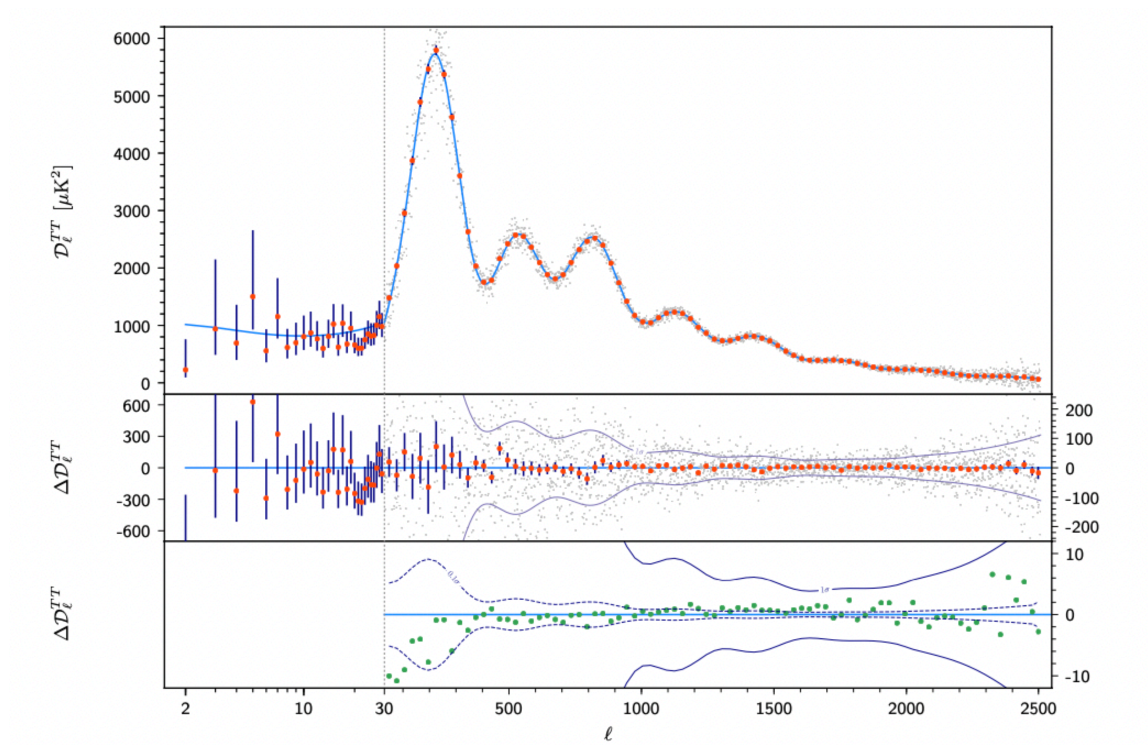
[Rubin et al]



[ESA, Bullet Cluster]



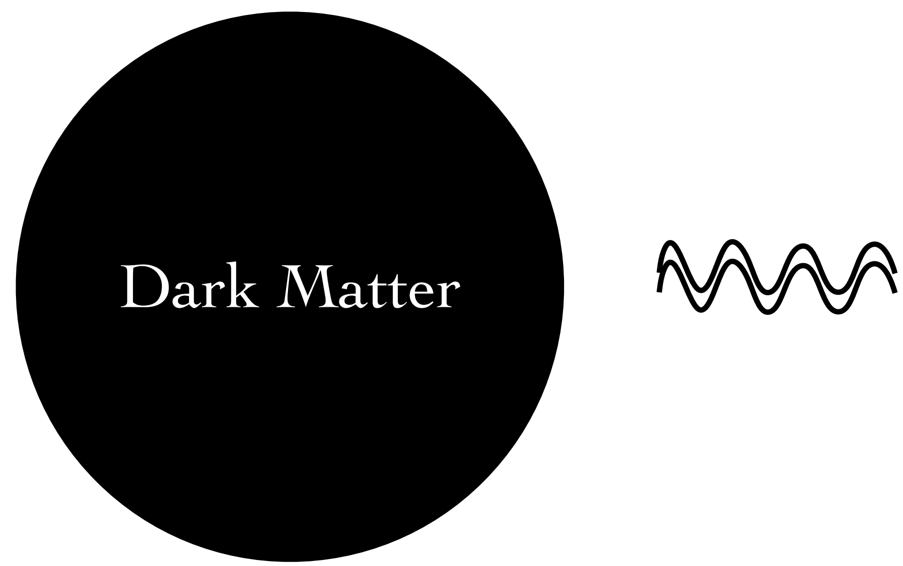
[Chabanier et al]



[PLANCK]

let's assume that

dark matter has only gravitational coupling with us
and see how far we can progress



$h_{\mu\nu}$

the main challenge is to explain **DM abundance** (25% of the budget)

if not coupled how does it get produced?

‘standard cosmology’

reconstructed by measuring 1-point and 2-point function of energy densities today

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[2011]

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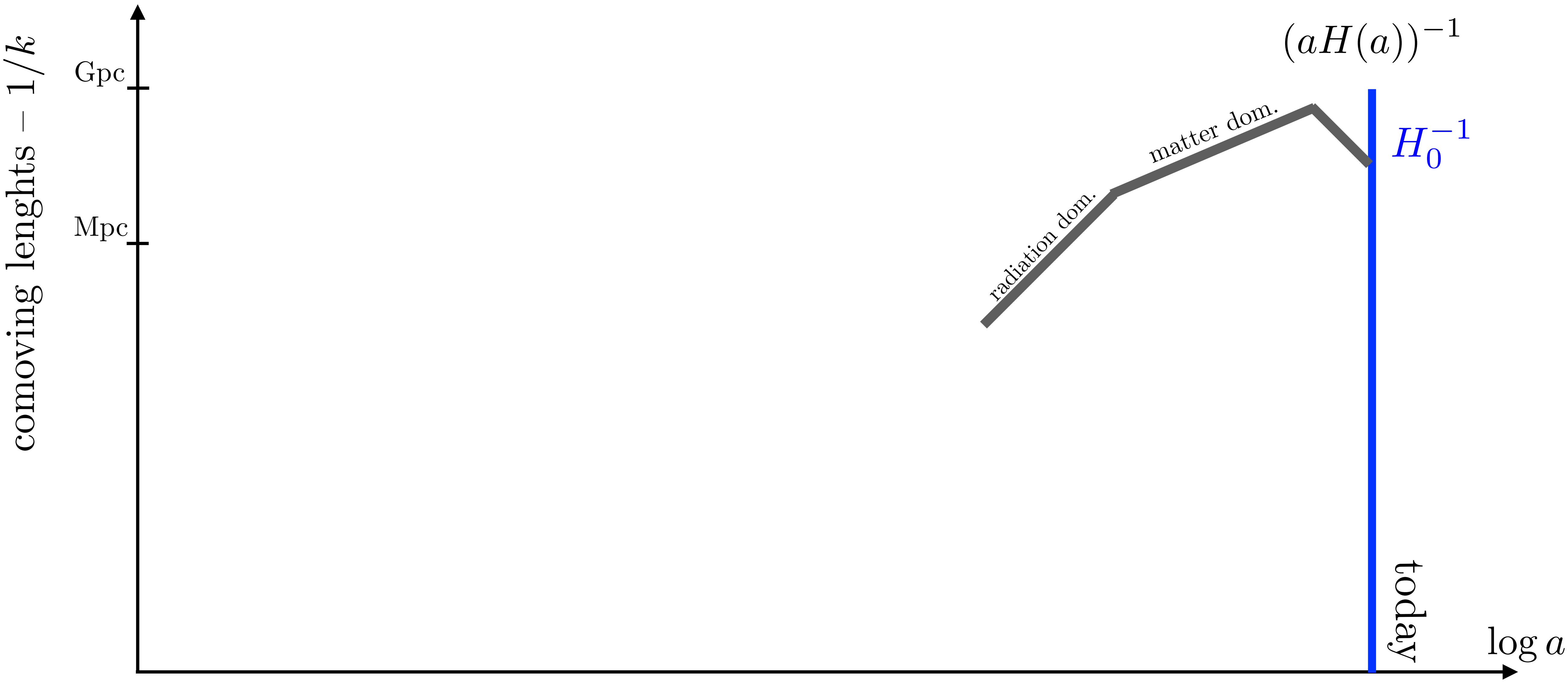

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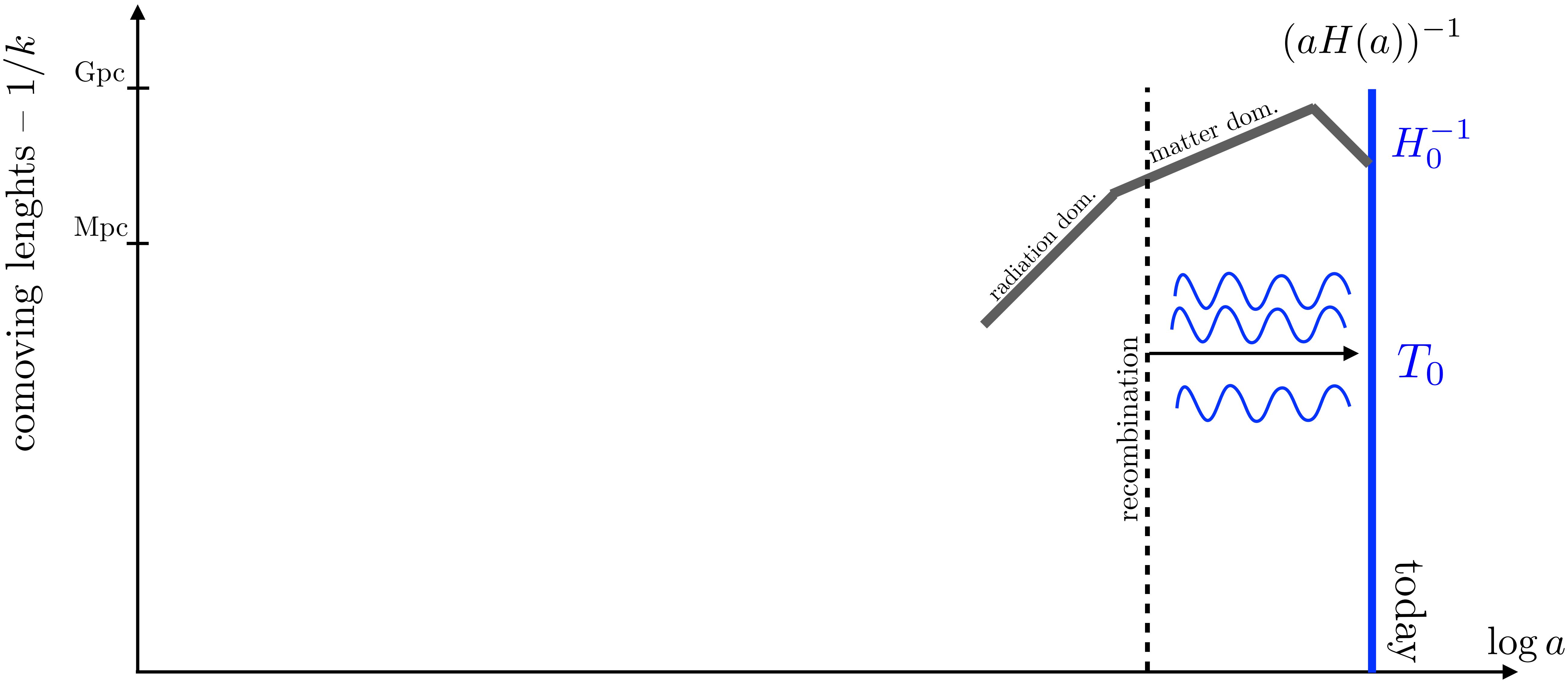

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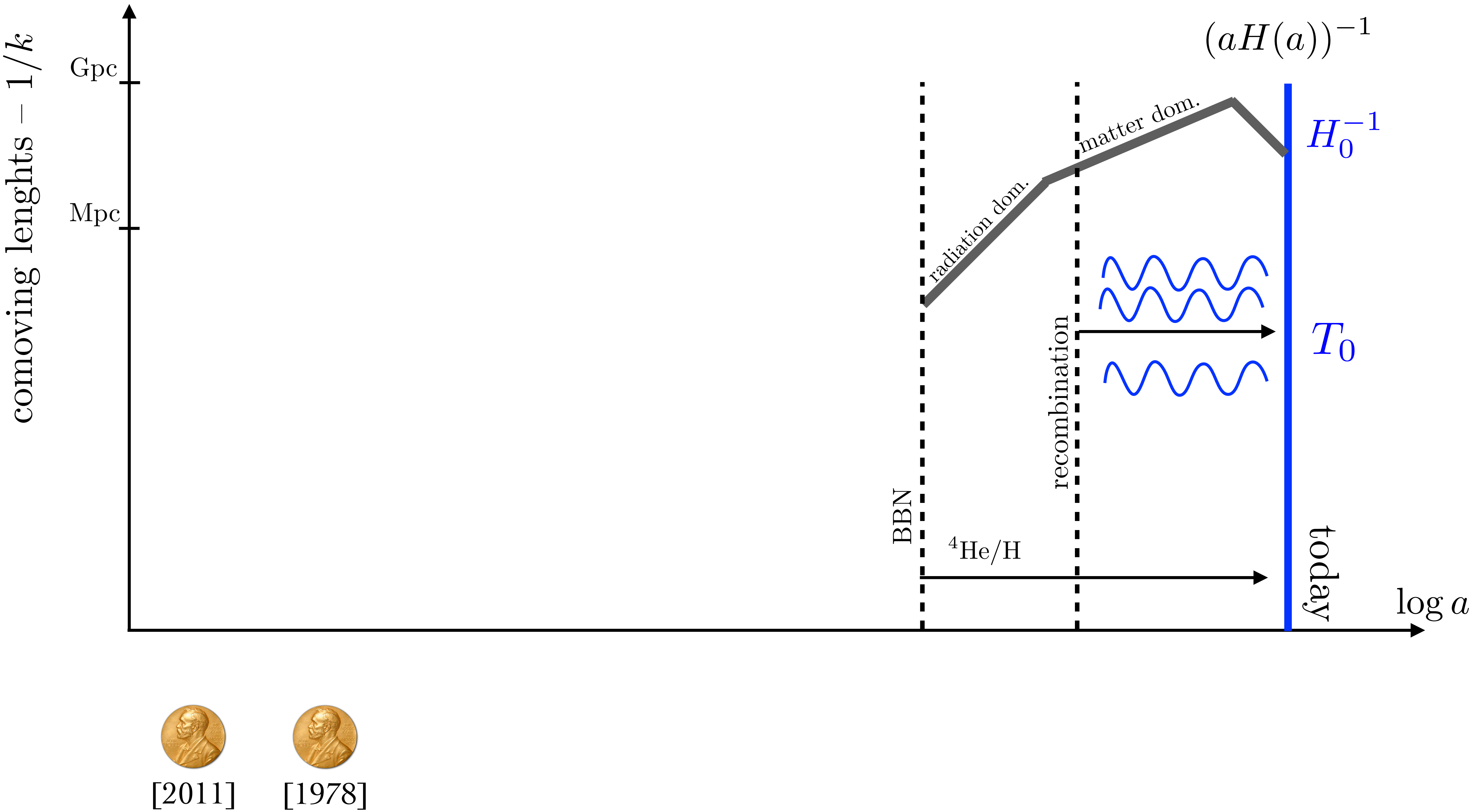

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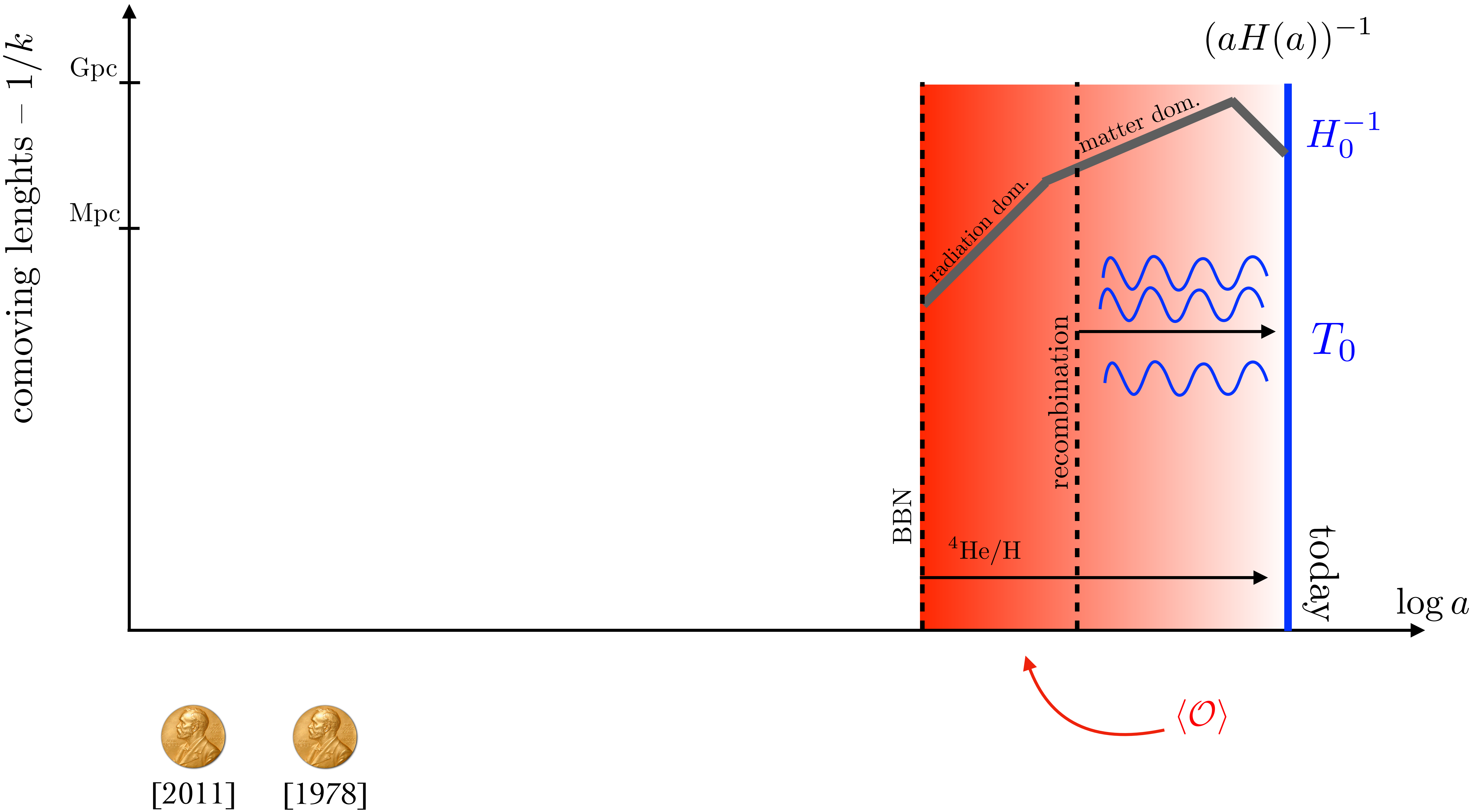

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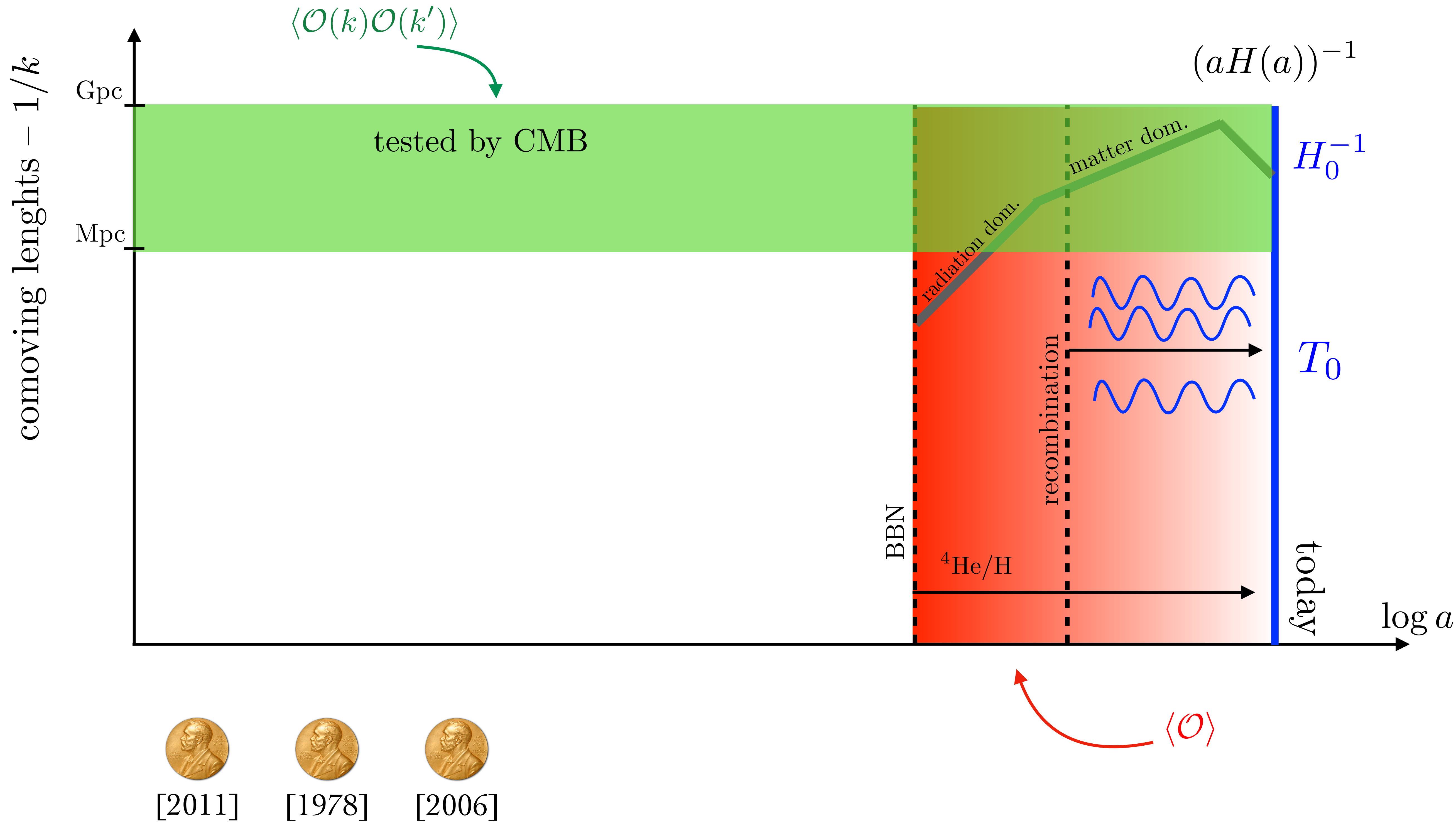

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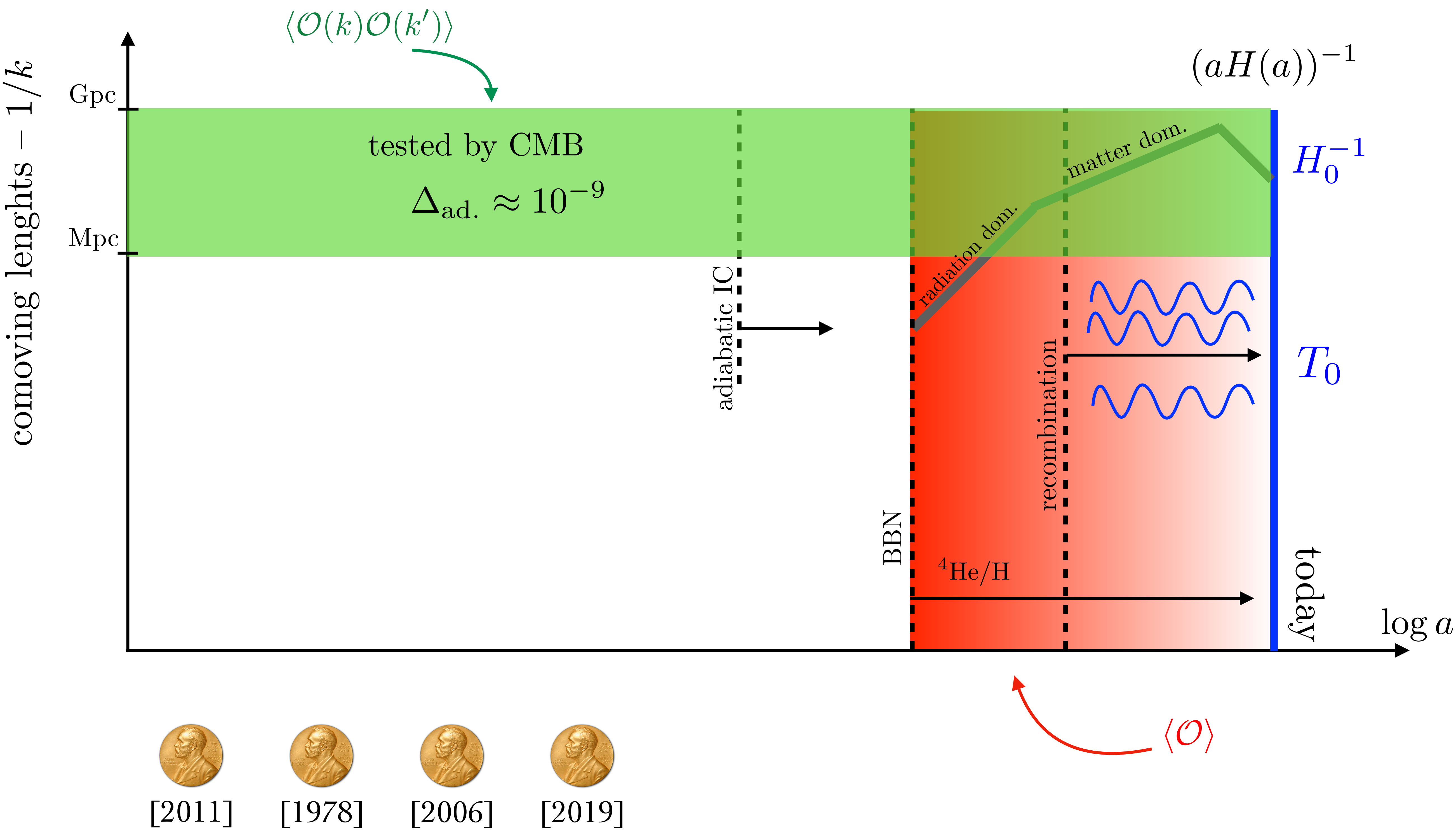

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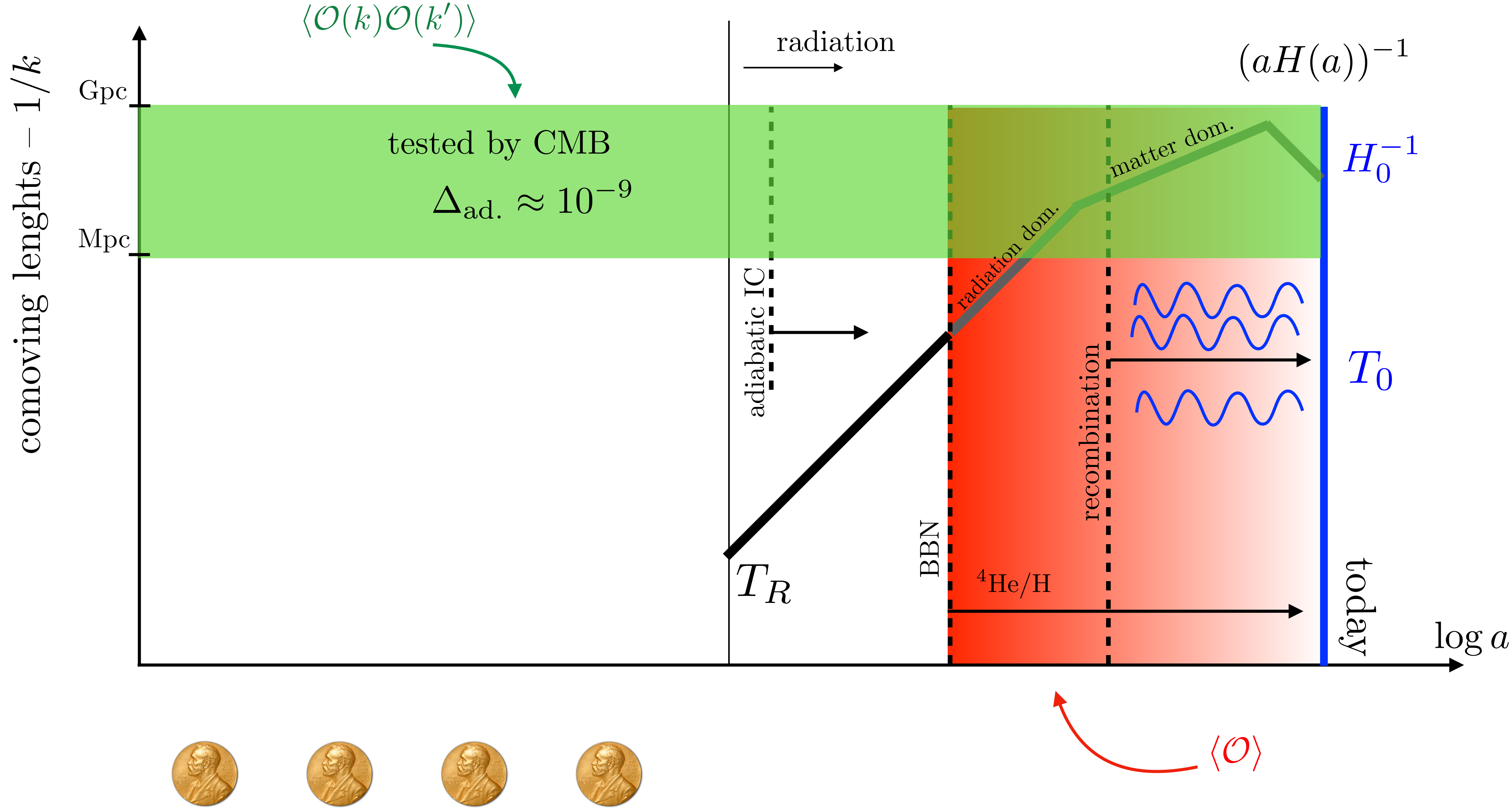

[2011] [1978] [2006] [2019]

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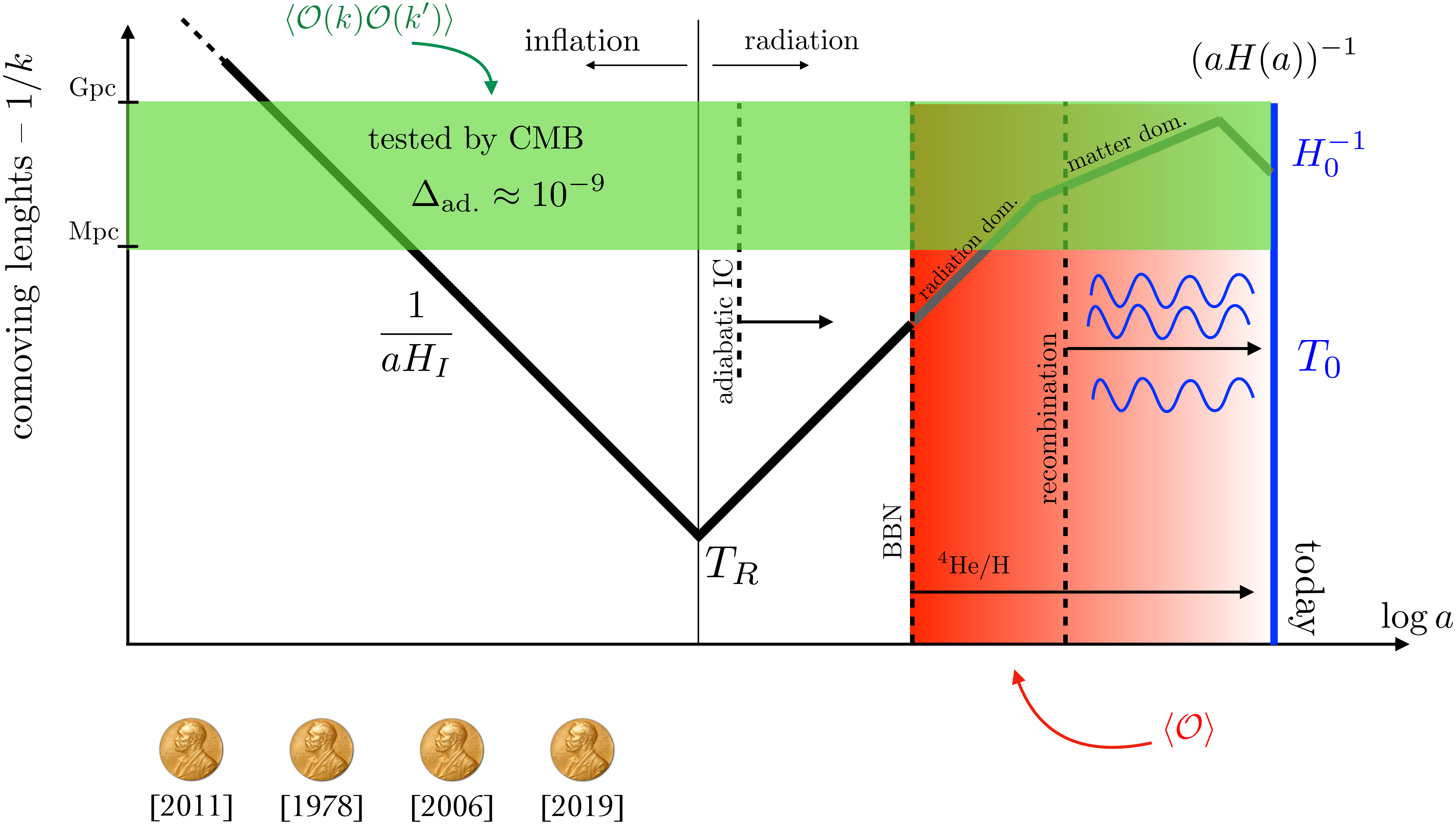
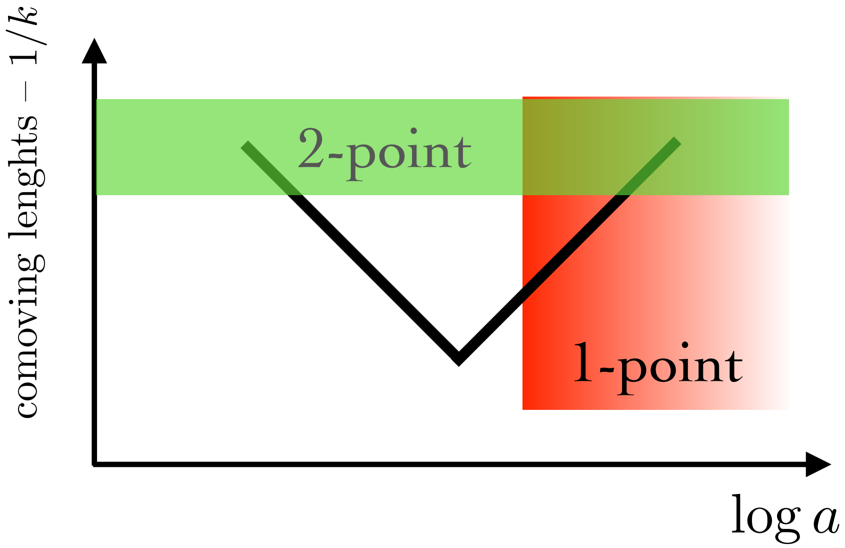
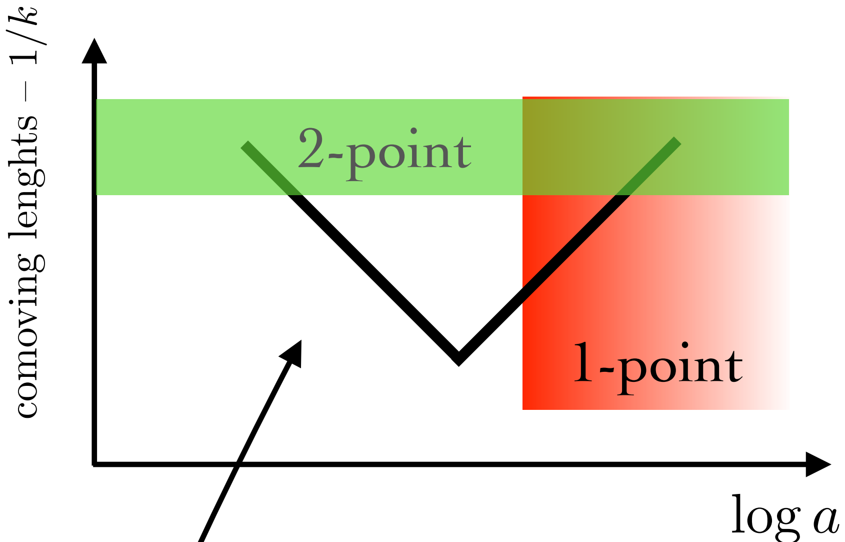




'standard cosmology'

only depends upon the reheating temperature
+ the Hubble scale during inflation
+ adiabatic initial conditions

- PLANCK mission: $H_I \lesssim 10^{14}\mathrm{GeV}$
- BBN constraints: $\sqrt{H_I M_{\mathrm{Pl}}} \gtrsim T_R \gtrsim \mathrm{MeV}$
- PLANCK mission: $\Delta_{\mathrm{non-ad.}} \lesssim 10^{-11}$ (universe has adiabatic IC)



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within this consolidated framework we can ask:

can we produce DM gravitationally respecting these values?

(in the white area space for ideas/models)

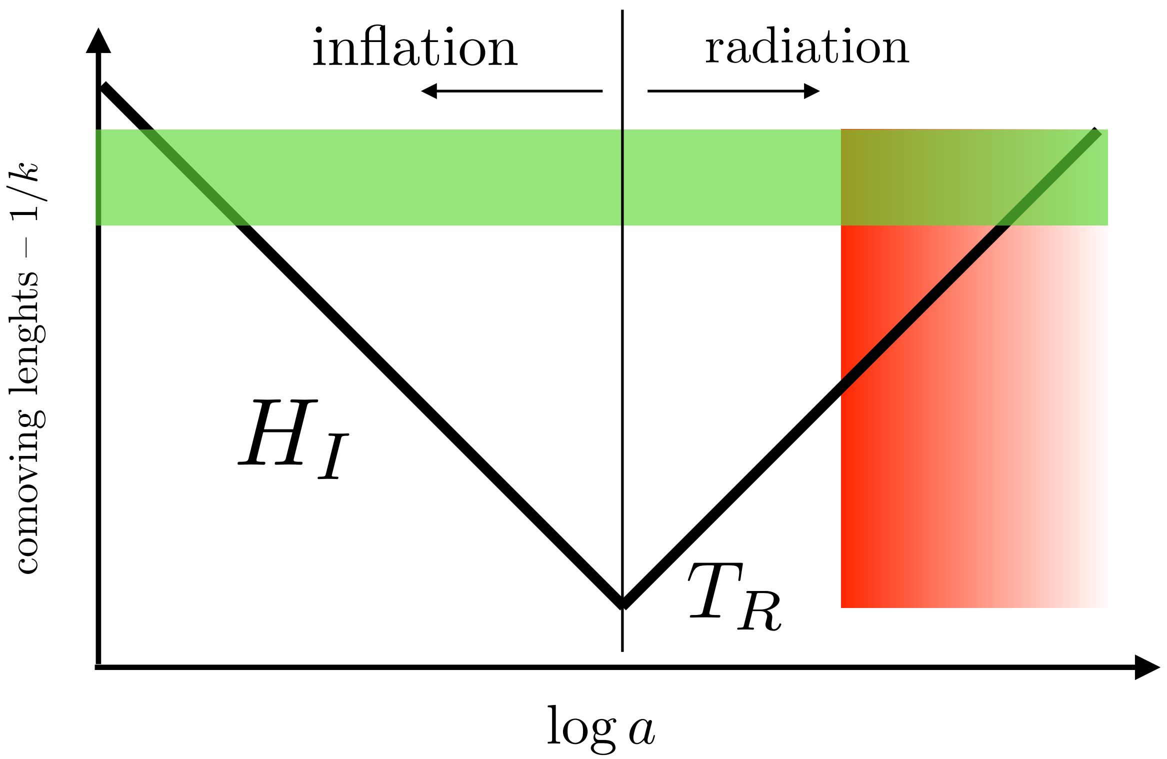
what we know about dark matter

- **energy density behaves as a cold relic** $\rho \approx mn \sim 1/a^3$
  (well before matter domination)
- **if a thermal relic** $m \gtrsim \mathrm{KeV}$
- **overdensities are adiabatic**
- **cosmologically stable** $\tau \gg 10^{10}\mathrm{year}$ (accidental stability / very light)
- **abundance**

$$\frac{\Omega_{\mathrm{DM}}}{25\%} = m\left(\frac{n}{s}\right)_{\mathrm{today}} \times \frac{\frac{86\pi^2}{1485}T_0^3}{H_0^2 M_{\mathrm{Pl}}^2} \approx \frac{m}{0.4\mathrm{eV}}\left(\frac{n}{s}\right)_{\mathrm{today}}$$

need to compute n/s

how to use gravity to create dark matter?



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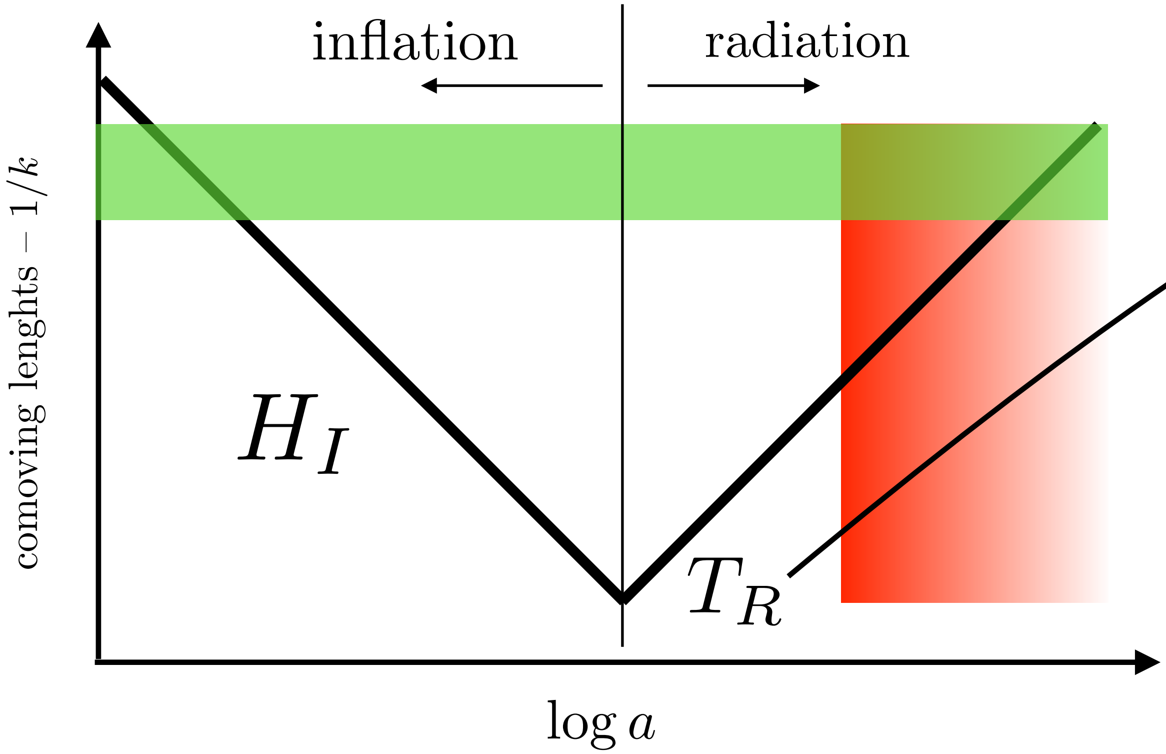

during **radiation**
we can exploit thermal SM particles
to produce DM through **graviton exchange**

[Garni et al.]

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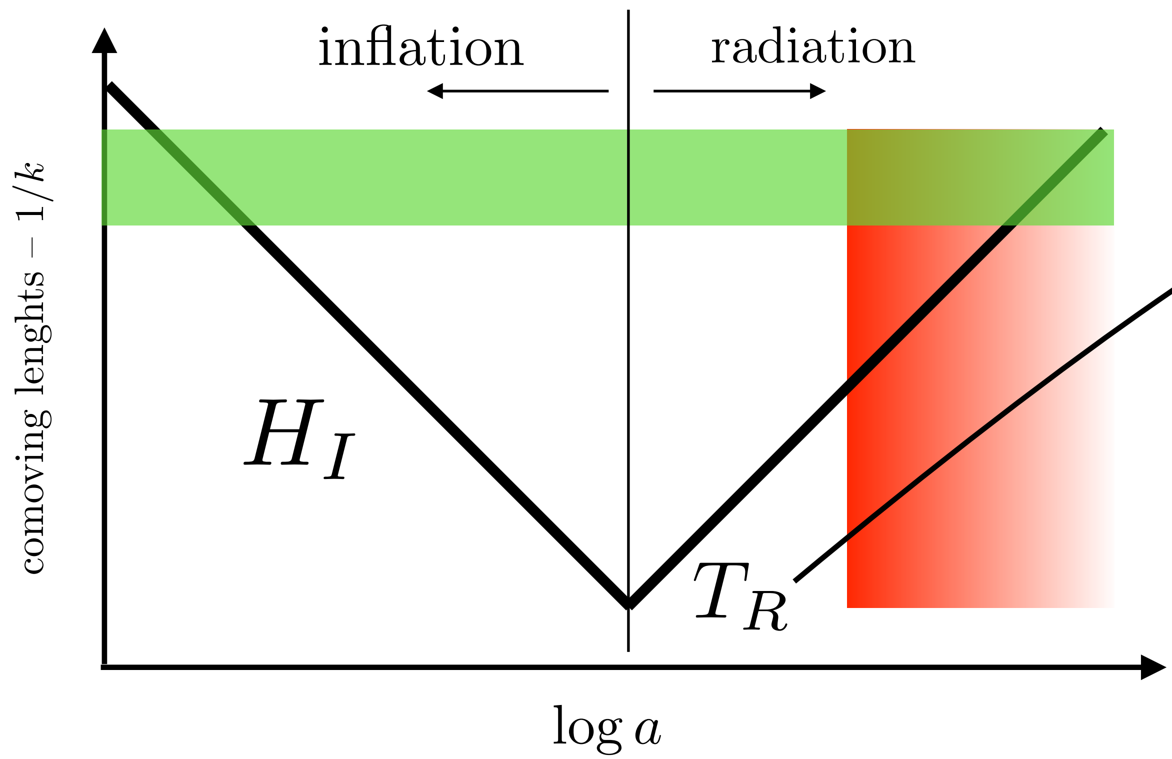

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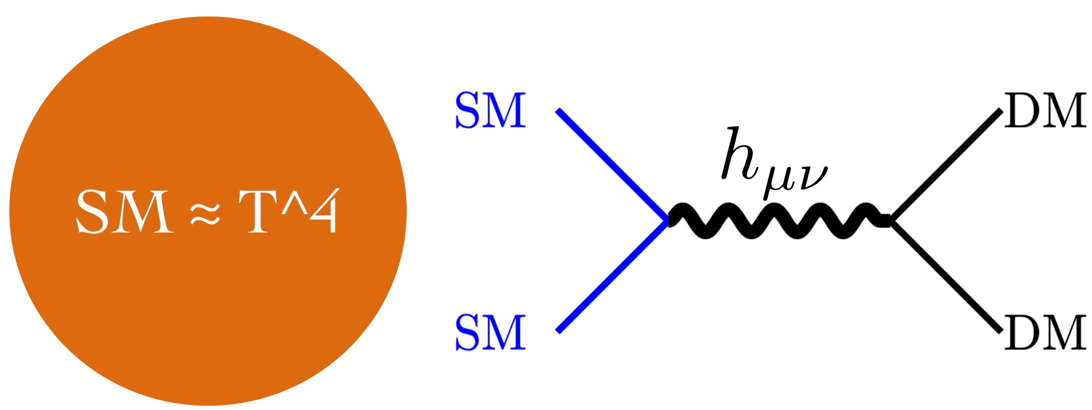

$$\left(\frac{n}{s}\right)_{\text{today}} \approx \frac{T_R^3}{M_{\text{Pl}}^3}$$

small number density, **heavy** dark matter
need extra structure for stability

[Redi, Tillim, AT+
Redi, Garani, AT]

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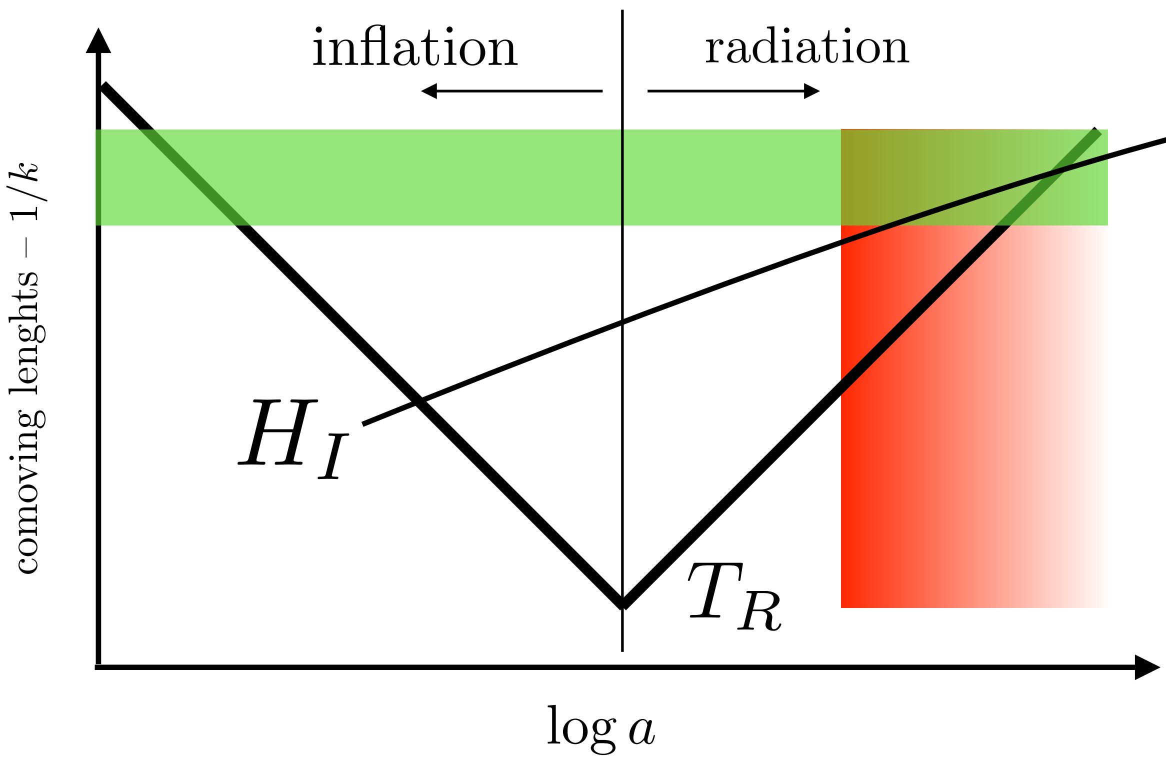

$$a(t) = e^{H_I t}$$

during **inflation**
we can exploit the de Sitter temperature
to generate power for quantum fields

[Ford '76 + Chung, Kolb, Giudice, Riotto '90s]

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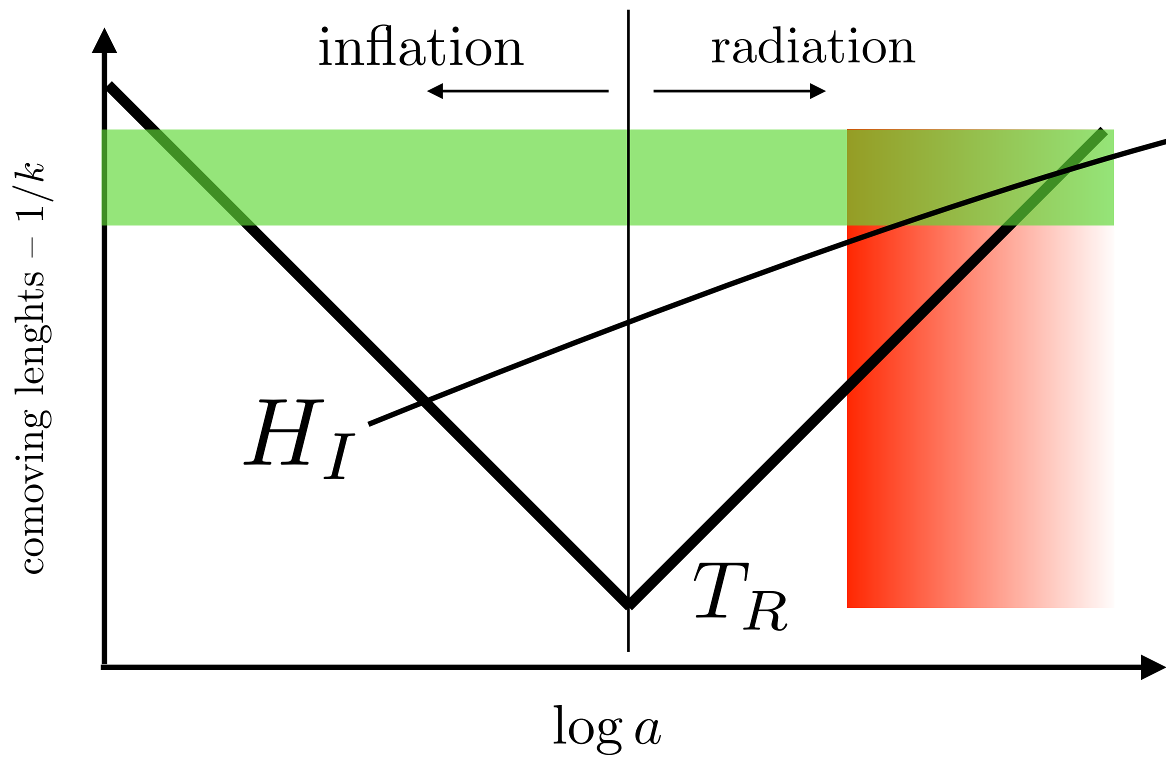

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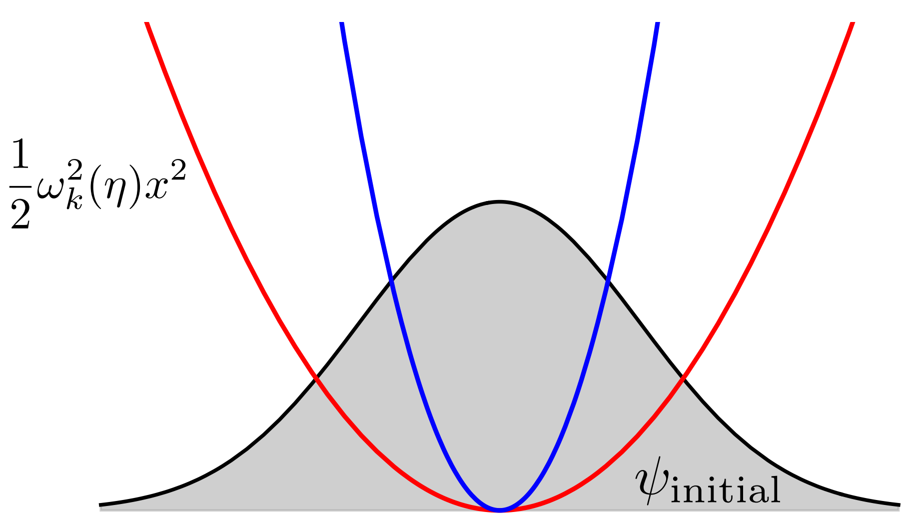

in the right variable analogy with
a quench for a harmonic oscillator
(inflation stretches non-adiabatically
the length of the pendulum)

$$N_f \approx \omega_i/\omega_f$$

gravitational particle production during inflation

a very elegant mechanism
free quantum fields in curved space

$$\frac{1}{2}\int d^4x\sqrt{-g}(\partial\phi)^2$$

the paradigm is a quantum scalar field in the FRW metric

$$\phi(\eta,\vec{x}) = \frac{1}{a}\int \frac{d^3k}{(2\pi)^3}\left(v_k(\eta)b_{\vec{k}}e^{-i\vec{x}\cdot\vec{k}} + h.c\right) \qquad dt = a d\eta$$

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mode functions have **Bunch-Davies initial conditions**

$$v_k'' + (k^2 - \frac{a''}{a})v_k = 0 \qquad v_k(\eta \to -\infty) = \frac{1}{\sqrt{2k}}e^{-ik\eta} \qquad a''/a = \frac{2}{\eta^2}$$

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de Sitter

$$\boxed{\Delta_\phi(k)|_{\mathrm{exit}} = \frac{H_I^2}{4\pi^2}}$$

power spectrum (FT of 2-point function)
energy stored in the field!

gravitational particle production during inflation

non-adiabatic evolution of mode functions generates a quantum power spectrum

$$\langle \phi^2 \rangle \approx \frac{H_I^2}{4\pi^2}$$

$$T_{\rm dS} = \frac{H_I}{2\pi}$$

symmetry **caveat**
weyl invariance must be broken

gauge fields and chiral fermions
do not see dS temperature

maximal production for **goldstone bosons!**

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- application to:
- **dark photon** (massive gauge field)
- **QCD axion** dark matter

gravitational particle production during inflation

following the evolution of **mode by mode**
the energy density of the field behaves **as non-relativistic matter**

$$\left(\frac{n}{s}\right)_{\rm today} \approx \sqrt{\frac{M_{\rm Pl}}{m}}\left(\frac{H_I}{2\pi M_{\rm Pl}}\right)^2 \gg 1$$

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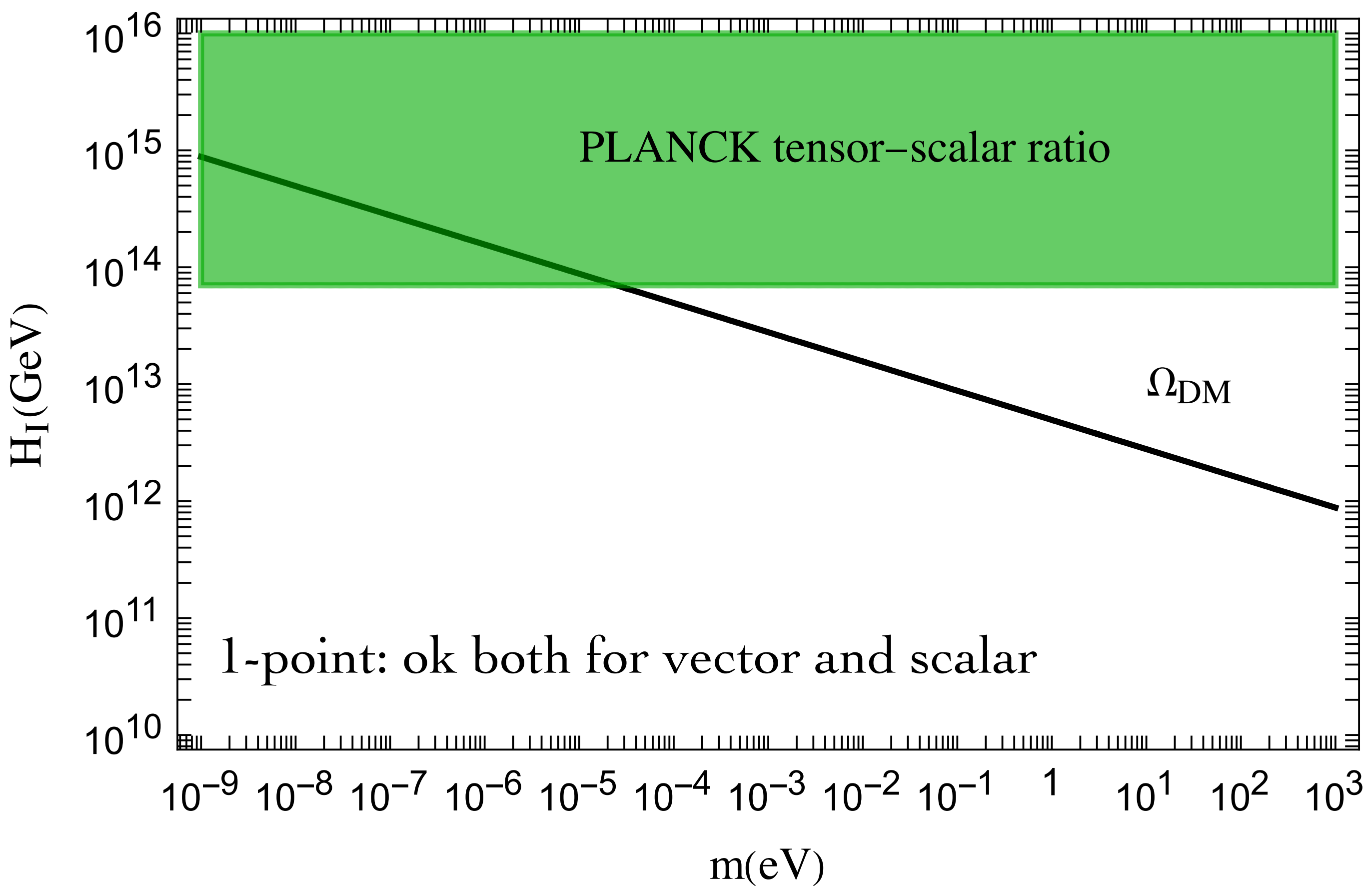
light and cold DM,
production is non-thermal

[Graham, Mardon, Rajendran]

[...]

[Michele Redi + AT]



isocurvature component: non-adiabatic initial condition

inspecting the 2-point function we discover
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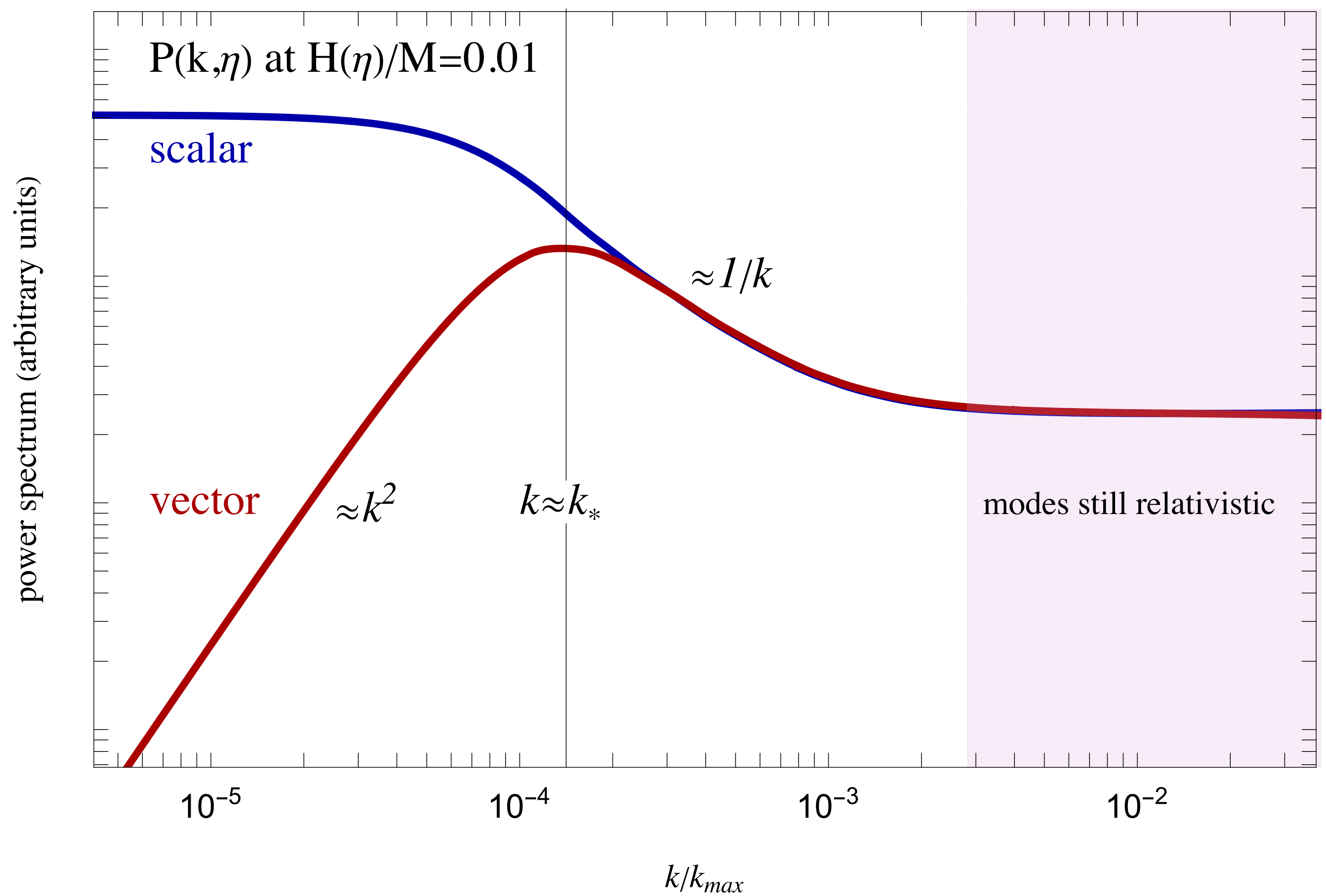

massive vector has **small power** at large distance scale: not affected by CMB
massive scalar has **large power** at large distance scale: **excluded** by CMB+LSS

isocurvature component: non-adiabatic initial condition

DM fluctuations are orthogonal to the one of the inflaton!

$$\Delta_{\rm iso} = \langle \frac{\delta\rho^2}{\rho^2} \rangle \Big|_{\rm iso}$$

PLANCK bound

$$\Delta_{\rm iso} \lesssim 10^{-11}$$

scalar DM produced via inflationary fluctuations: $\Delta_{\rm iso} \approx O(1)$

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- **Possible resolutions:**

- **Massive gauge boson,** power removed at large scale by dynamics (dark photon)

- **Phase transition during inflation:** goldstones fluctuates only on small scales

QCD axion produced during inflation

with Michele Redi [2211.06421]

+ ongoing with Chiara Cabras, Raghuveer Garani

QCD axion DM from inflationary dynamics

axion, goldstone boson of Peccei-Quinn symmetry, can be DM

$$\Phi = \frac{f+\rho}{\sqrt{2}} e^{ia/f_a}$$

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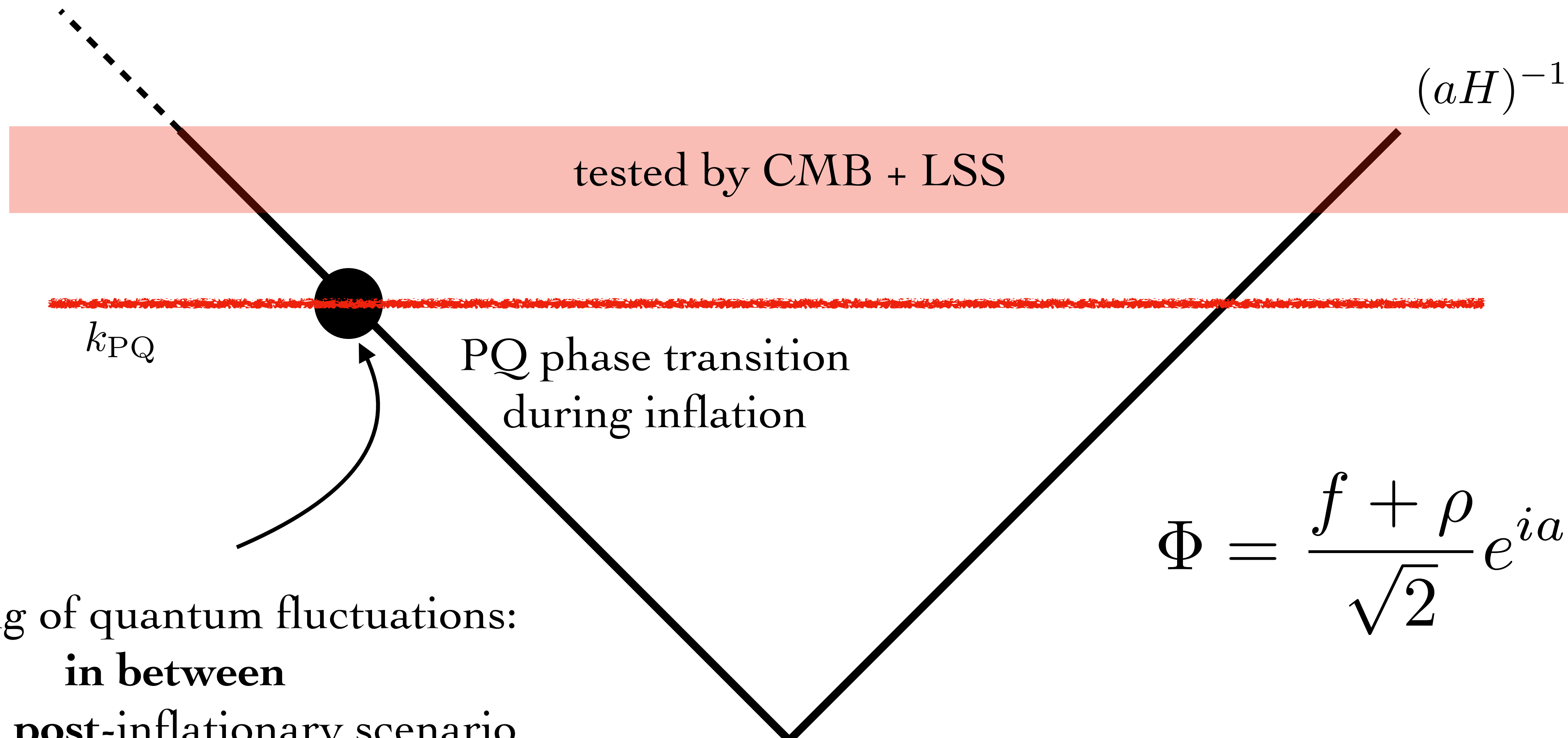

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beginning of quantum fluctuations:
in between
pre- and **post**-inflationary scenario

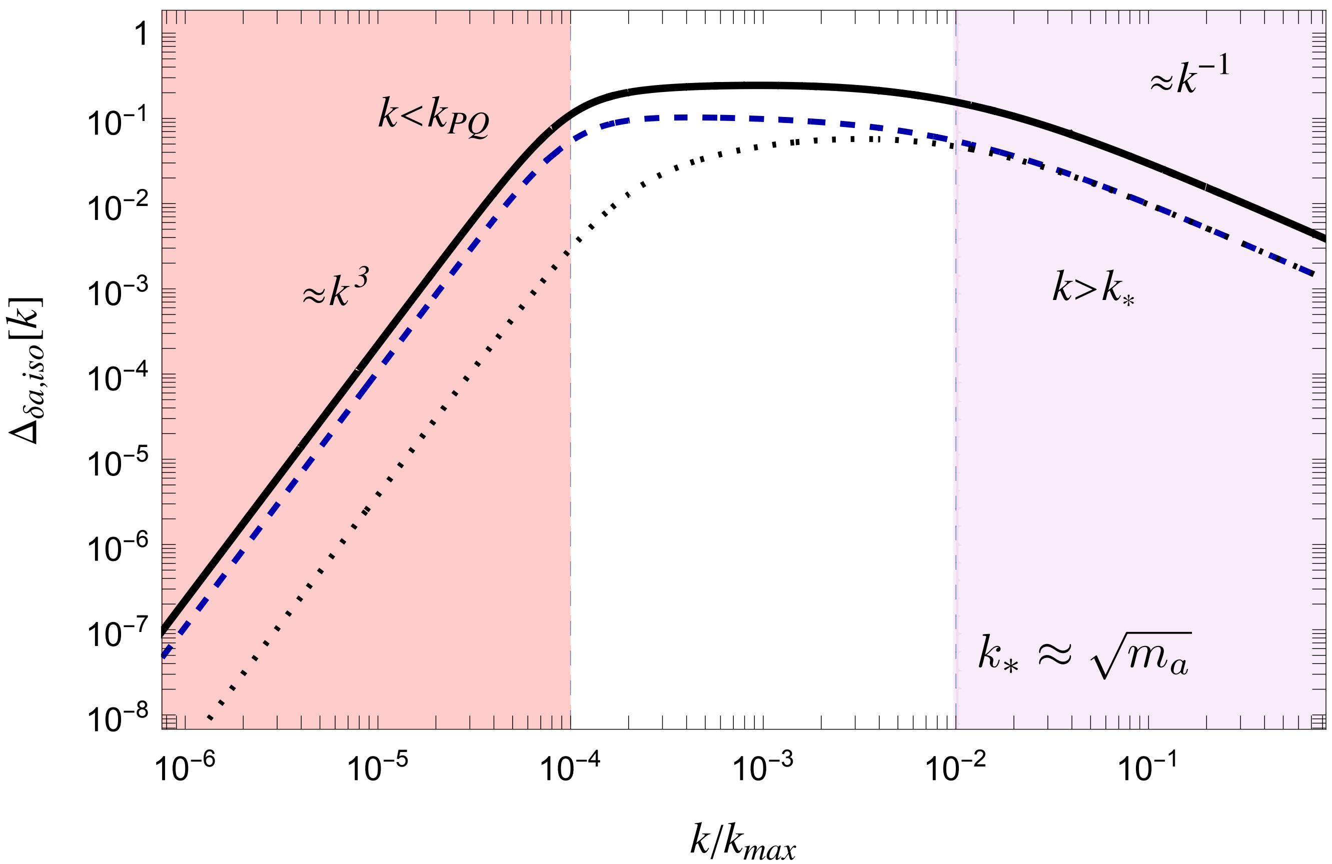
$$\Delta_\phi(k)|_{\rm exit} = \frac{H_I^2}{4\pi^2}\min[1, \frac{k^3}{k_{\rm PQ}^3}]$$

suppression at small k,
to avoid bounds

axion isocurvature power spectrum

O(1) over-density in axion isocurvature at “small scales”

$$\Delta^{\rm iso}_{\delta_a}(\eta,k) \approx \frac{\Omega^2_{a,\rm inf}}{\Omega^2_a}\frac{k^3}{3\log^2(k_*/k_{\rm PQ})k^3_{\rm PQ}}$$



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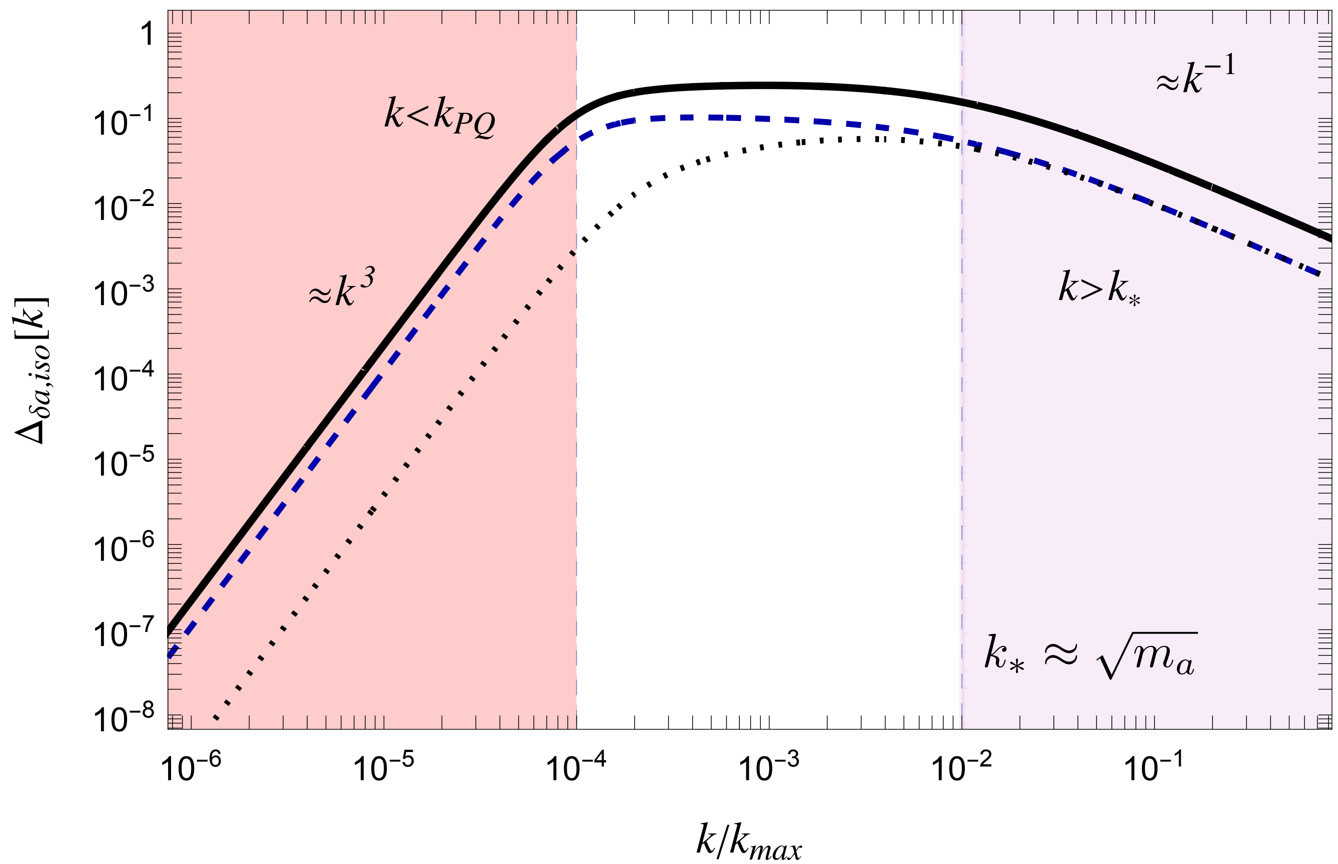


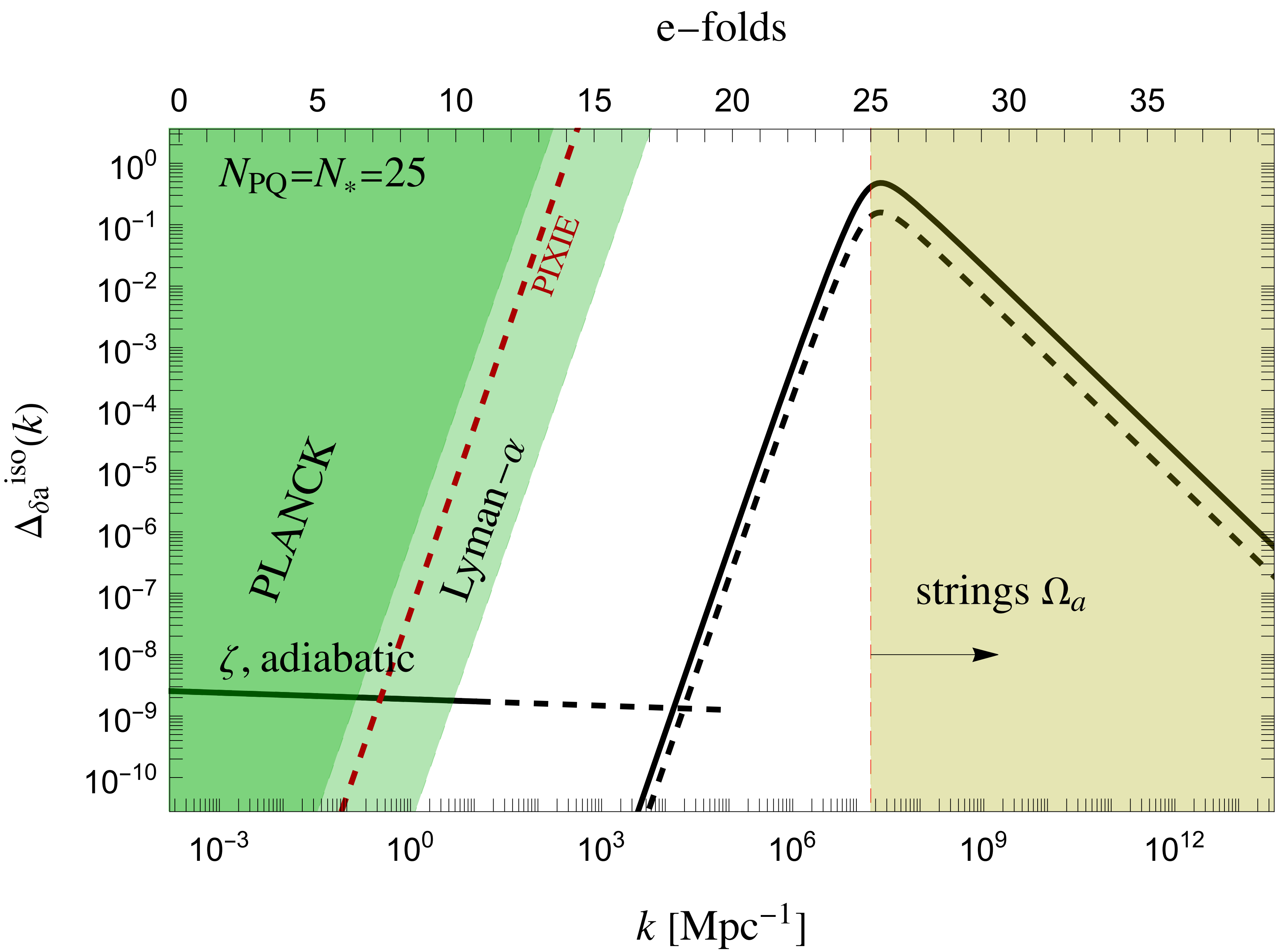
- **Cosmological probes to test this prediction:**
  - CMB power spectrum
  - Future CMB distortions
  - Matter power spectrum

$$\Delta_{\rm iso} = |f_{\rm iso}|^2 A_s (k/k_0)^3$$

$A_s = 2\times 10^{-9}$

$k_0 = 0.05/{\rm Mpc}$

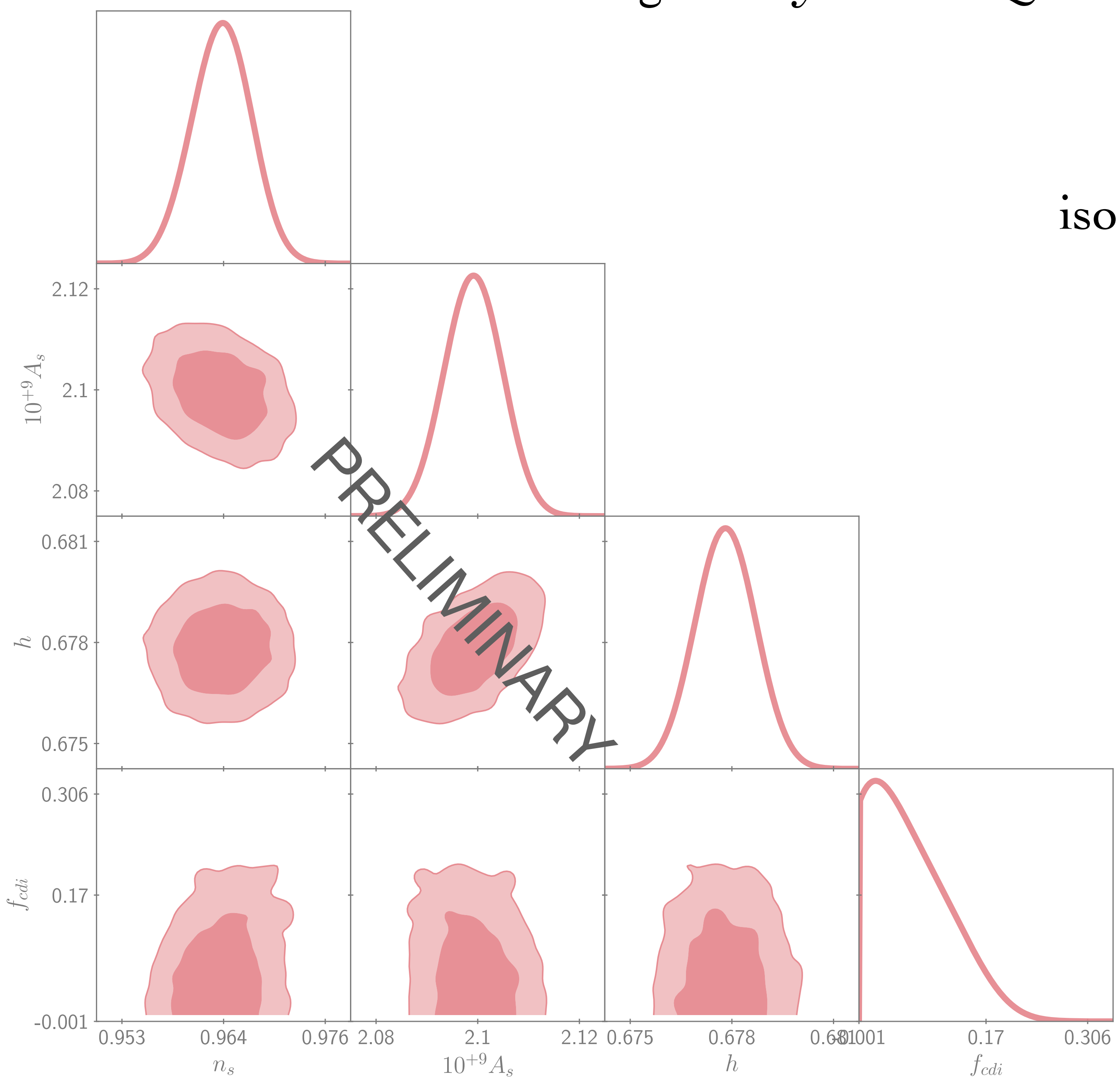
meso-inflationary qcd axion



[2211.06421]

cosmological tests of DM produced inflationary

goes beyond the QCD axion case*



iso DM affects CMB TT-power spectrum can be studied in linear theory

$$\delta C_\ell / C_\ell \propto |f_{\rm iso}|^2 (\ell/\ell_{\rm eq})$$

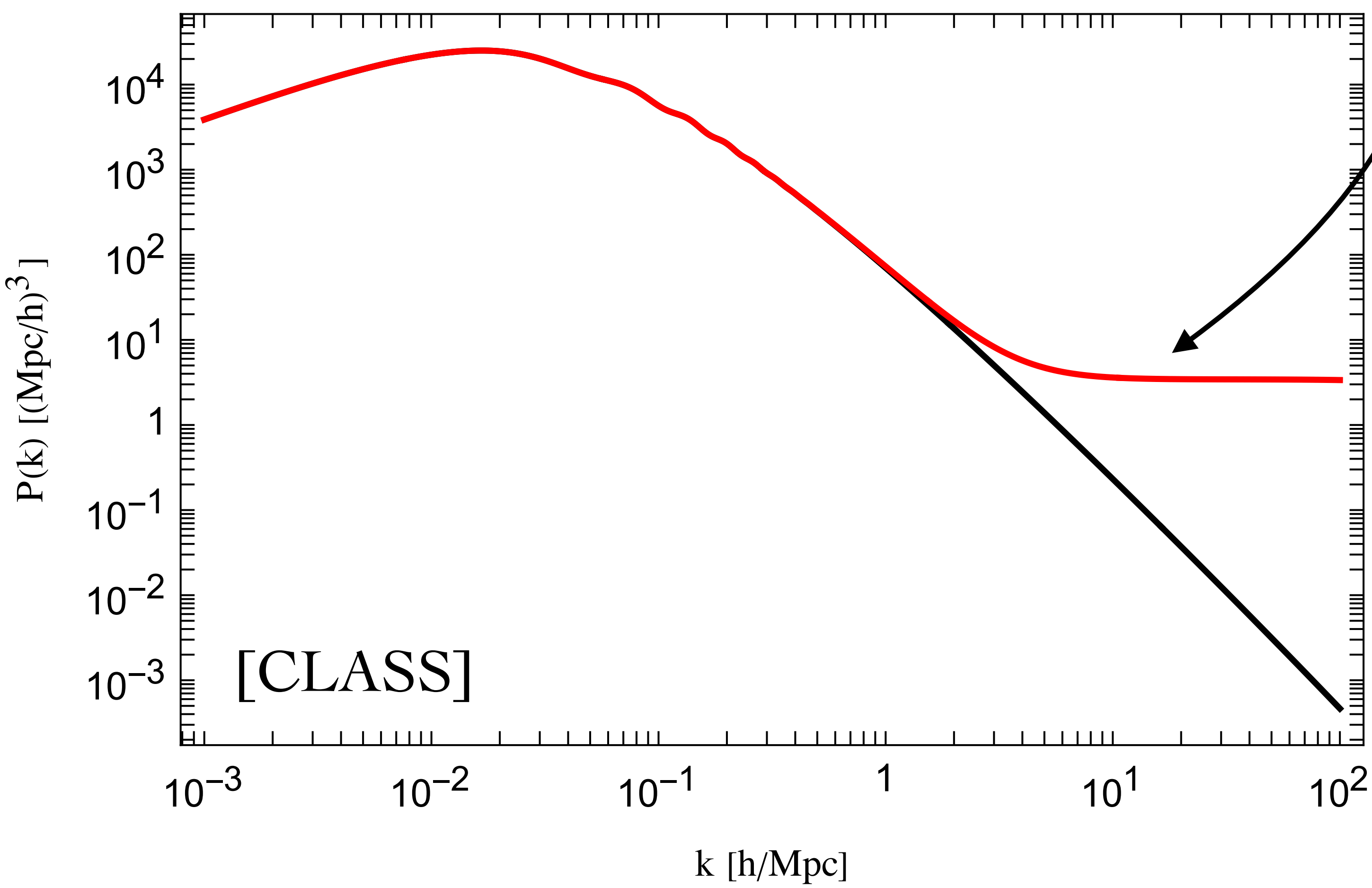
$$|f_{\rm iso}| \lesssim 0.2$$

*topological defects prevents phase transition to happen on very large scales

cosmological tests of DM produced inflationary

Matter Power Spectrum

$$P_m(k) \propto \frac{1}{k^3}\left(\Delta_\zeta(k) + \beta\Delta_{\rm iso}(k)\right) \propto \beta\frac{|f_{\rm iso}|^2}{k_0^3}$$



effects grows with k
(like SMEFT at colliders…)

$$|f_{\rm iso}| \lesssim 0.003$$

[recast of Murgia et al]

conclusions

dark matter from inflationary fluctuations

- **produced** without assuming ad hoc coupling to the SM
- leaves cosmological **imprints**
- generic population of **mini-clusters** (lensing)

- affects also well know case of **QCD axion DM**
- axion **string-wall** network modified

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for the future:

- applications to ALP dark matter
- phase-transitions of scalar fields during inflation
- primordial black holes

THANK YOU!