Non-Standard Cosmology:

From Cosmic Inflation to Dark Matter Production

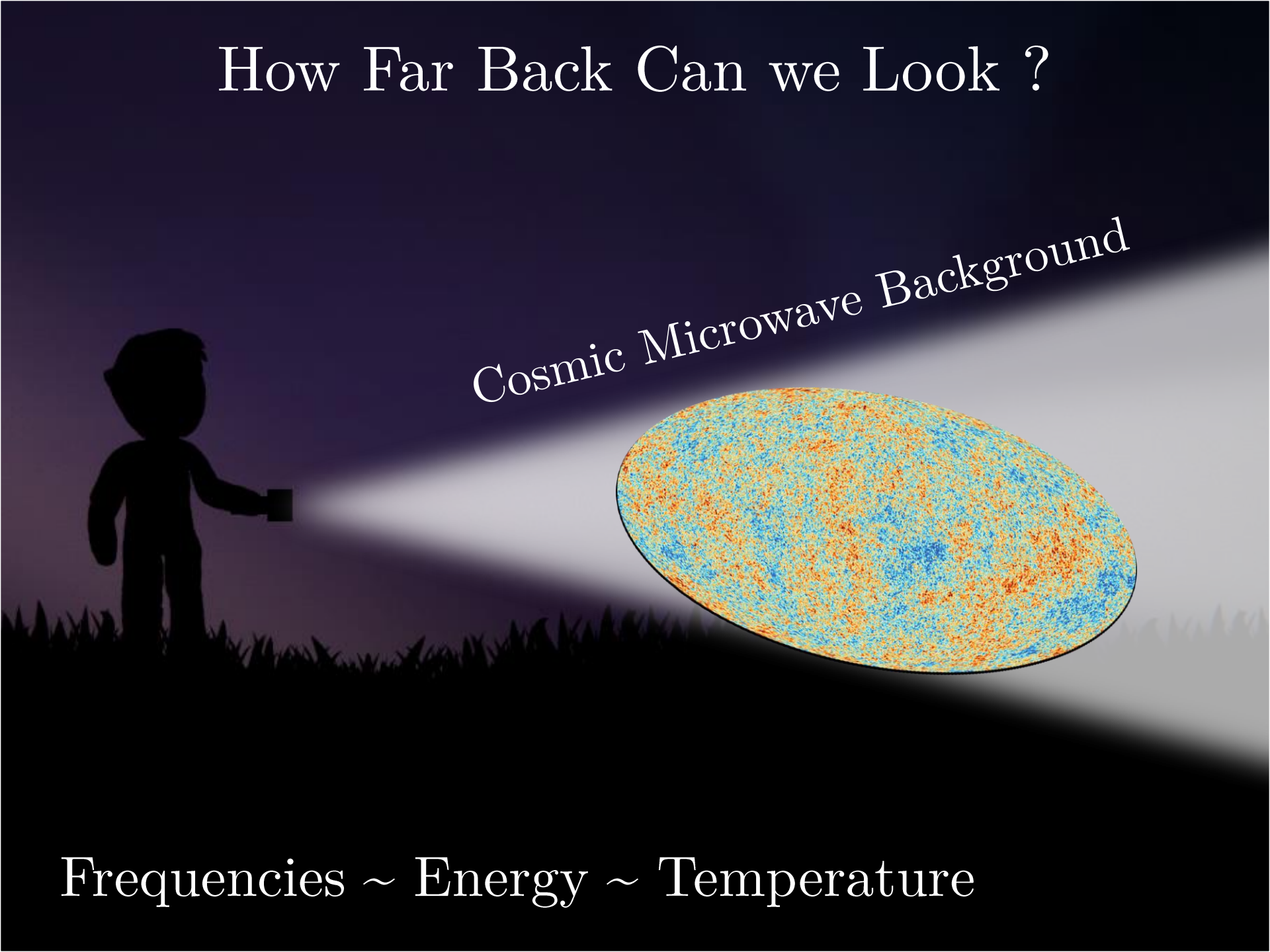
Lucien Heurtier

YETI, Durham, July 13th 2022

Durham University

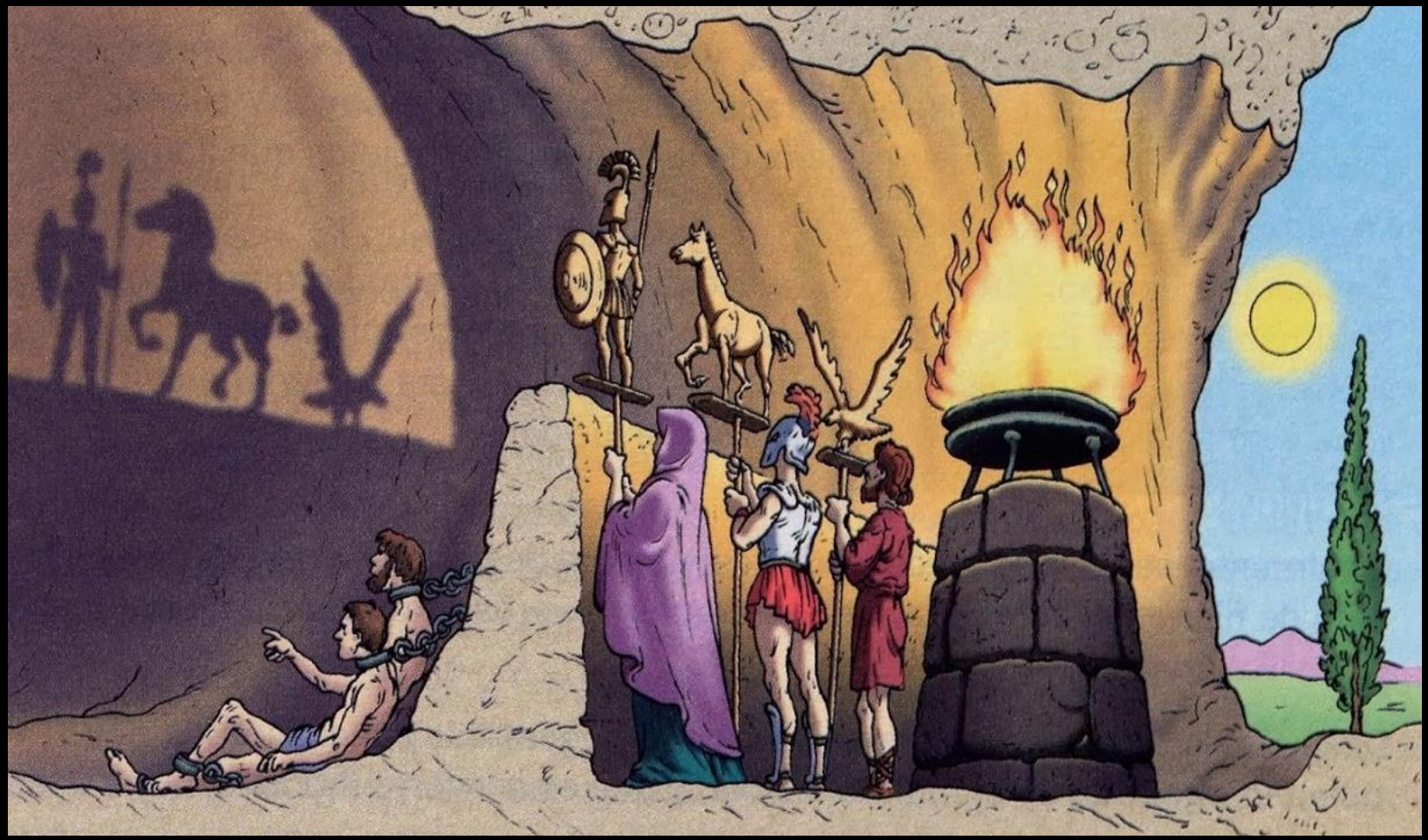
IP3

How Far Back Can we Look ?

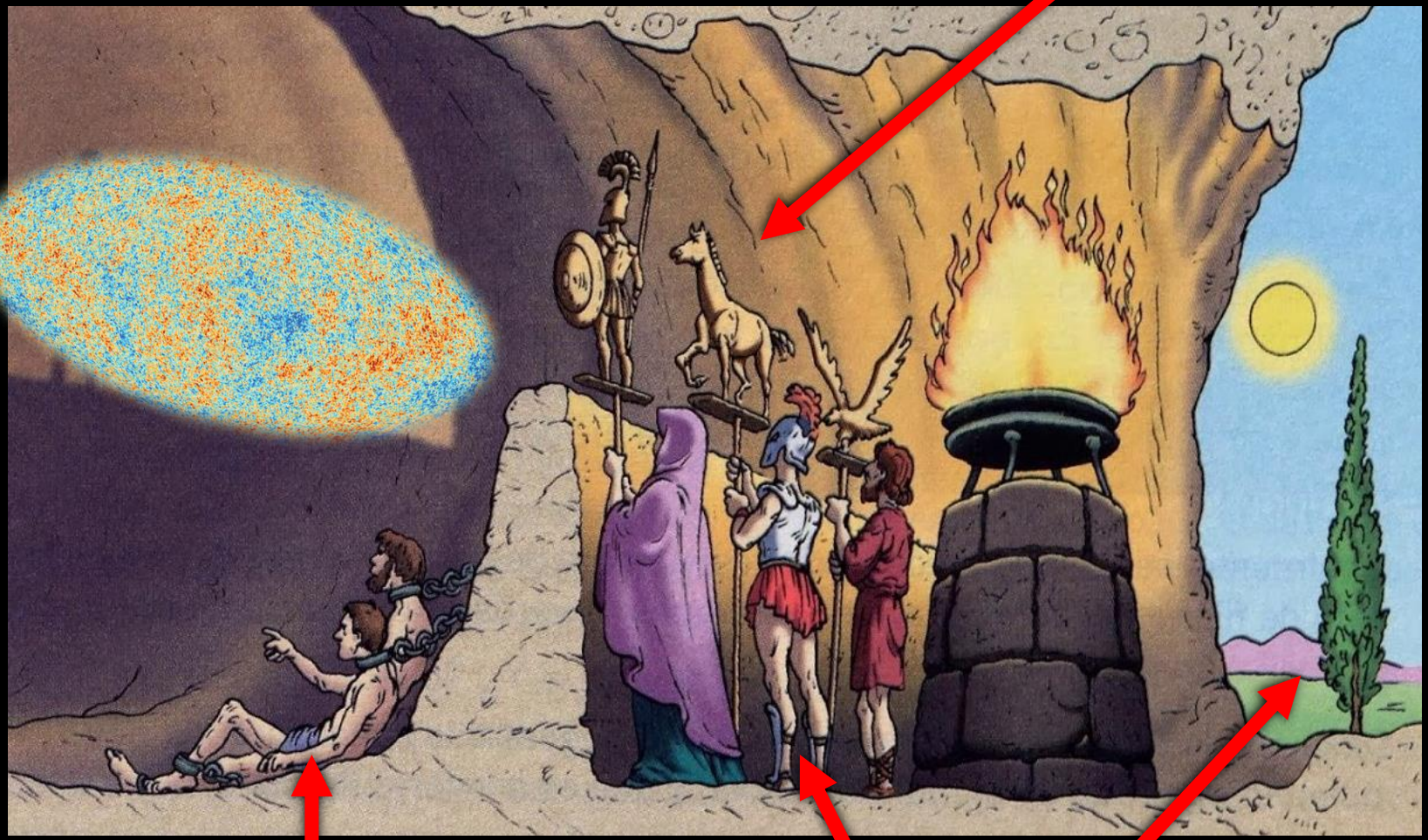


Frequencies ~ Energy ~ Temperature

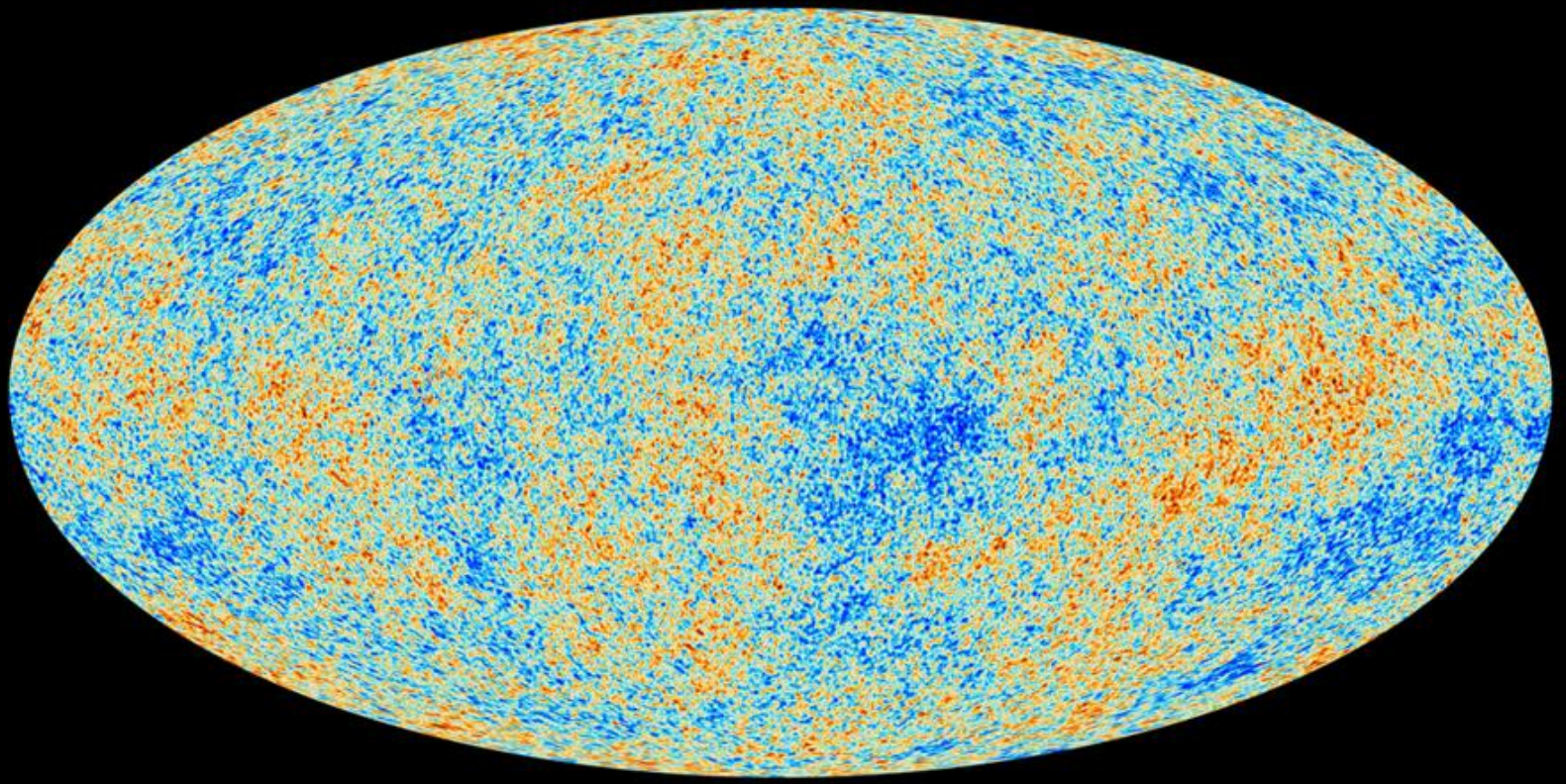
Allegory of the Cave...



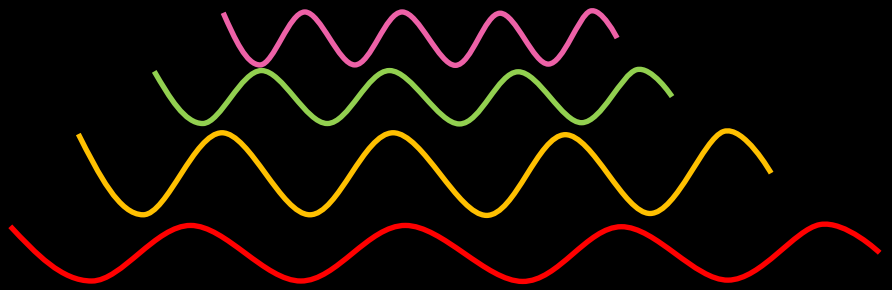
Allegory of the Cave...



What's there?

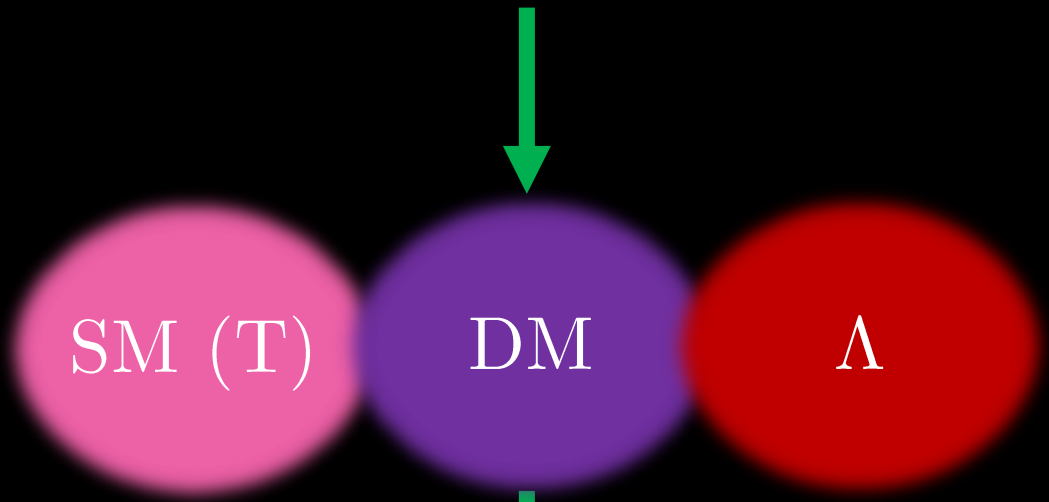


A Quasi – Homogeneous, Flat Universe



Primordial Perturbations

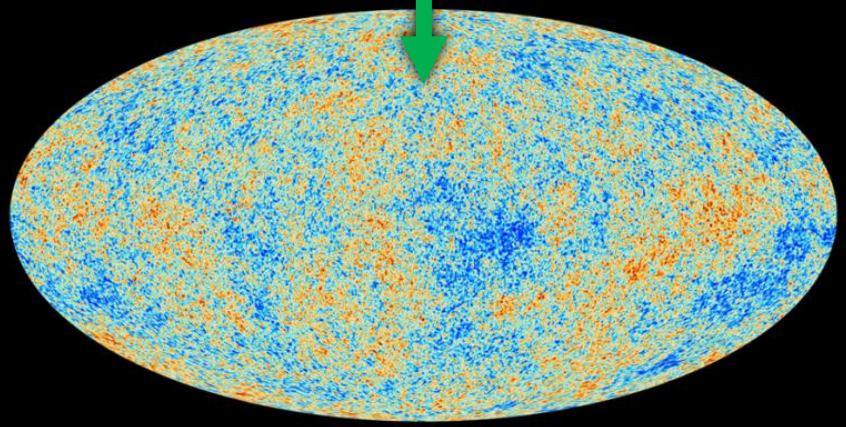
(Theory, high energy)



Propagation

ΛCDM (?)

(Theory, high energy)



Cosmological Data

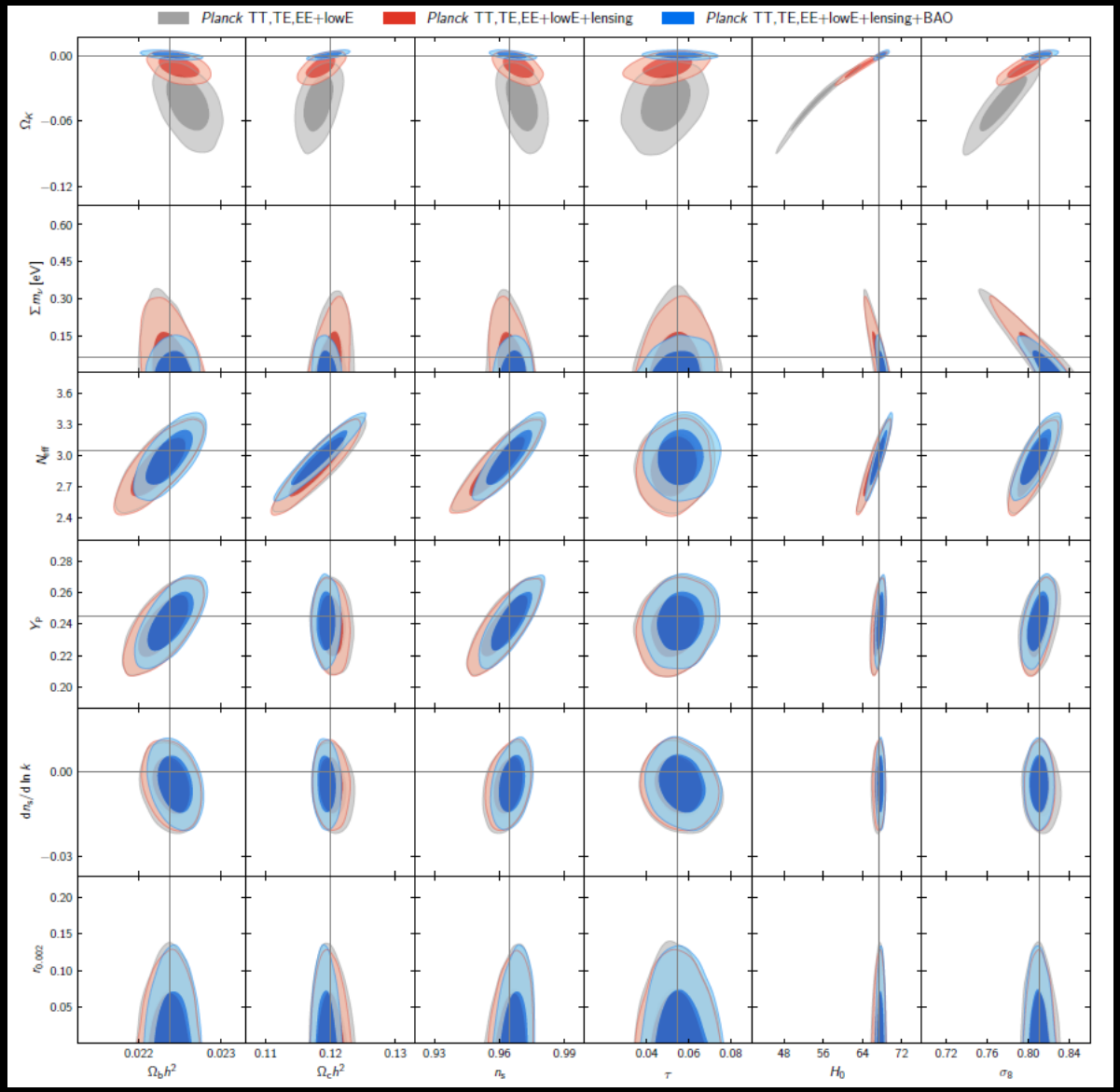
(Measurable, low energy)

Bottom-Up

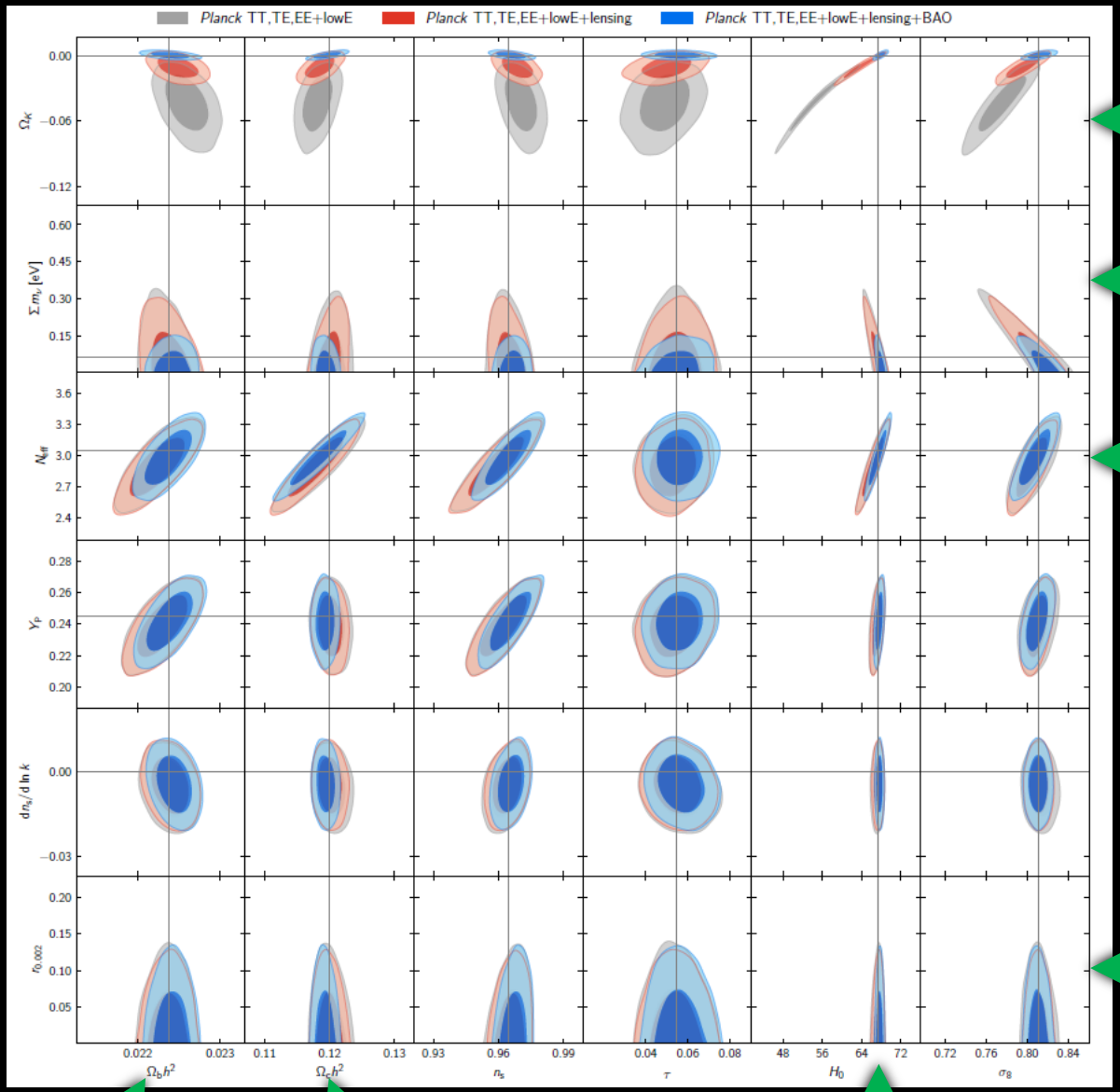
What kind of model can explain the data?

Top-Down

What does a given theory predict?



Planck 2018 results. VI. Cosmological parameters
Astron.Astrophys. 641 (2020) A6



Flat Universe

Small neutrino masses

No dark radiation

Small CMB tensor modes

Baryons

DM

Expansion Rate

The ΛCDM Ideology

1) Cosmological Principles : *The Universe is Homogeneous and Isotropic, we are no special observer*

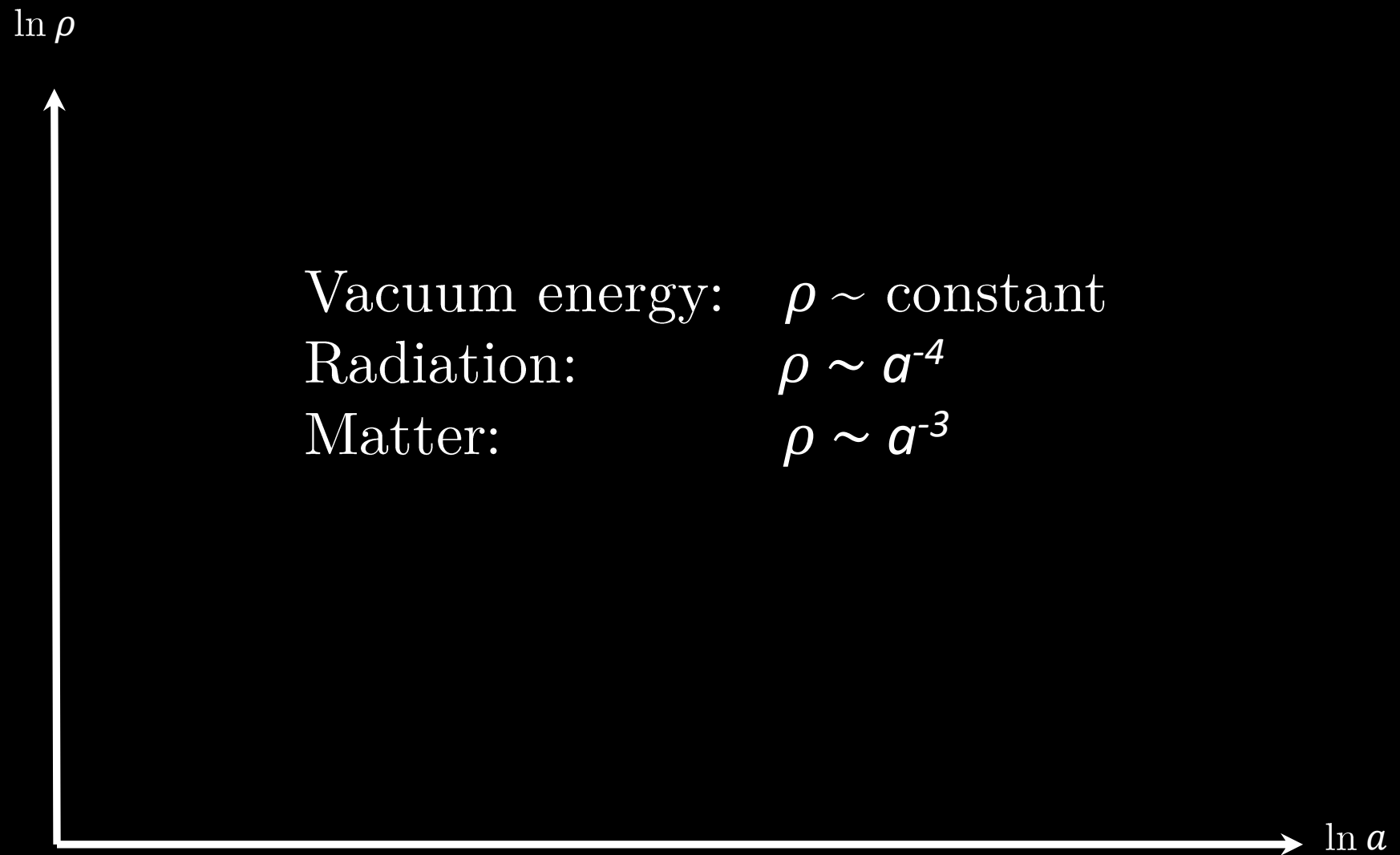
2) Use perfect fluids with equation of state:

$$P = w\,\rho$$

3) The Universe is composed only of

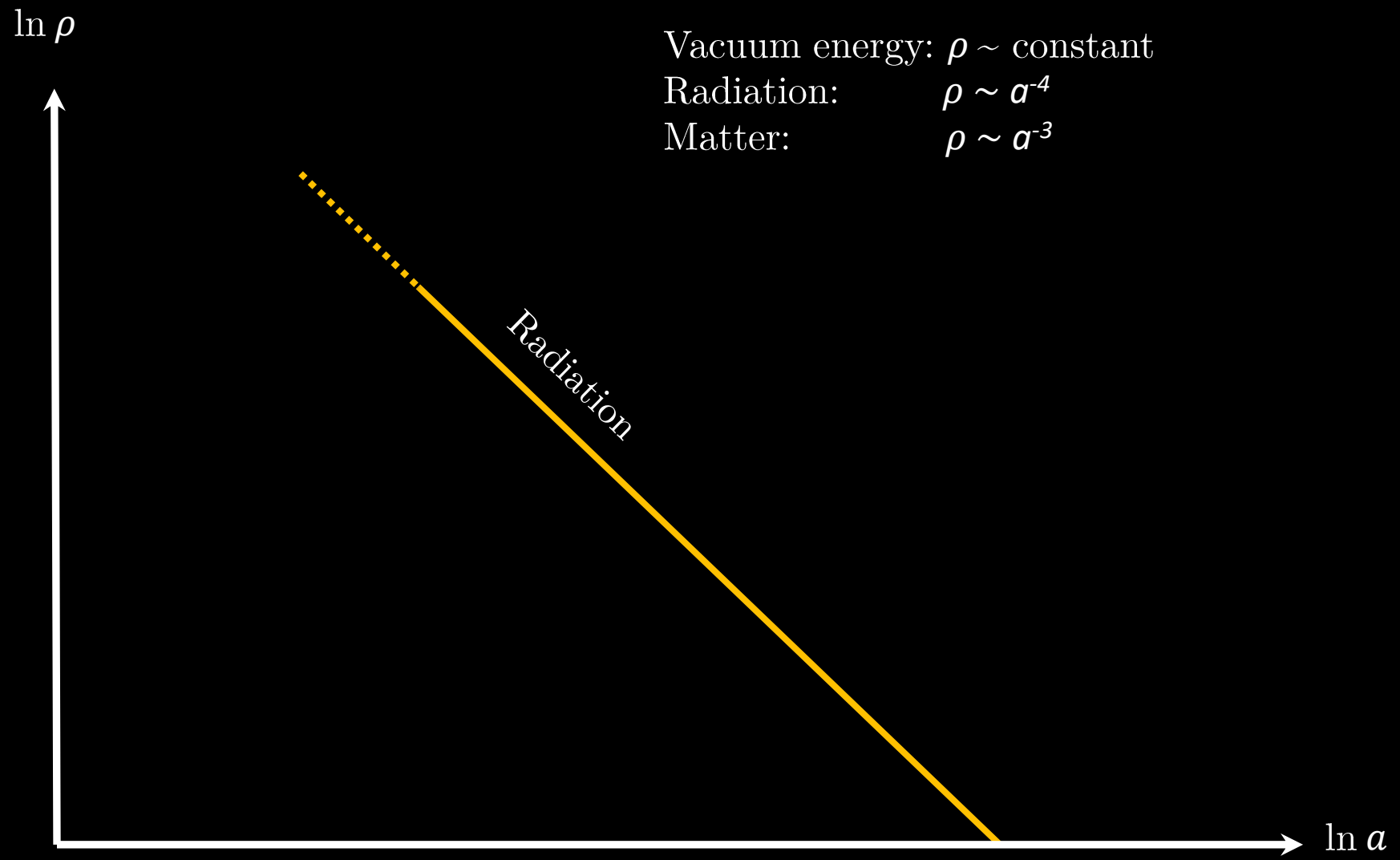
- Cold Dark Matter: $w_{\mathrm{DM}} = 0$
- Radiation: $w_{\mathrm{rad}} = 1/3$
- Dark Energy: $w_{\mathrm{DE}} = -1$

The ΛCDM Ideology



Vacuum energy: $\rho \sim$ constant
Radiation: $\rho \sim a^{-4}$
Matter: $\rho \sim a^{-3}$

The ΛCDM Ideology



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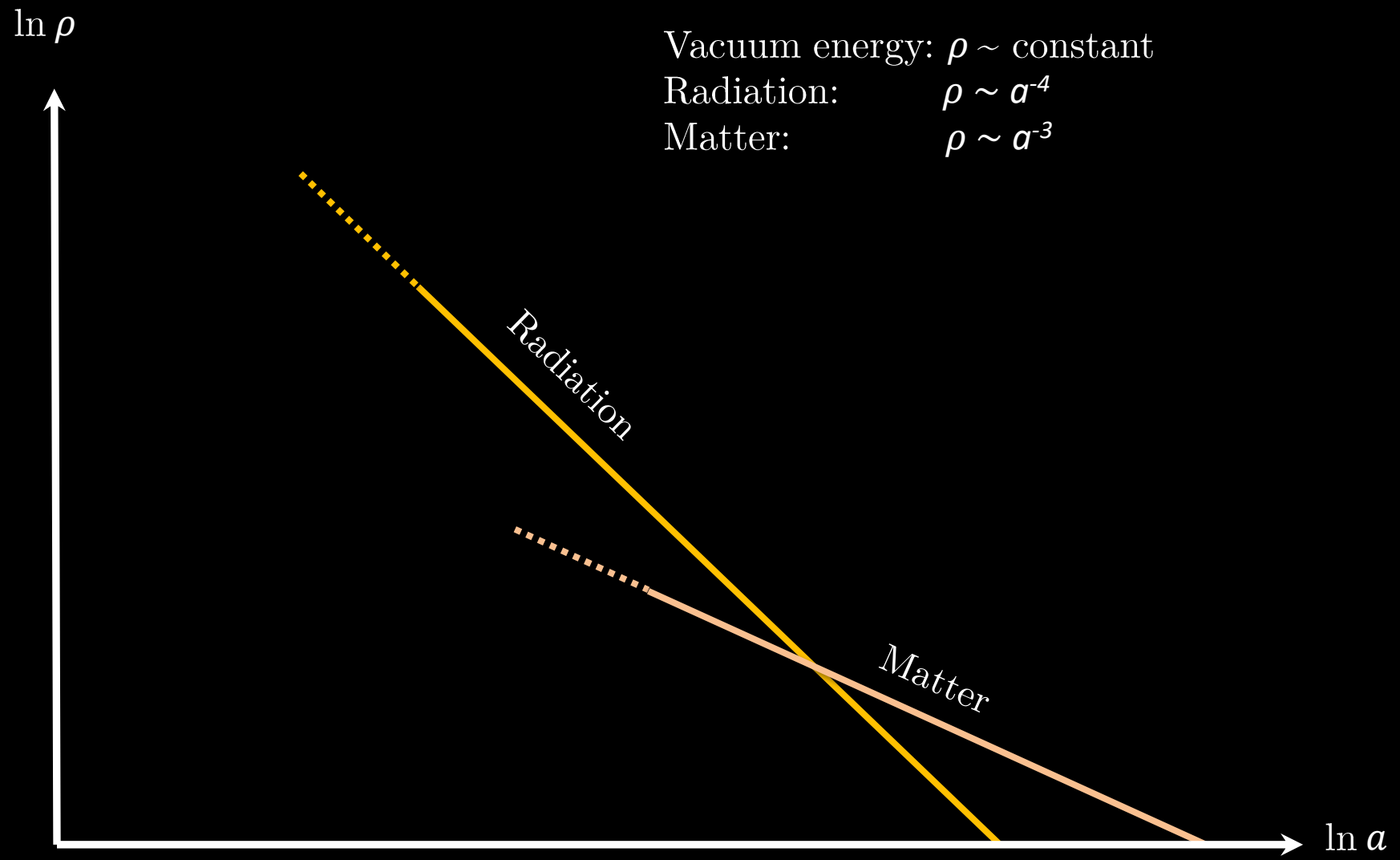

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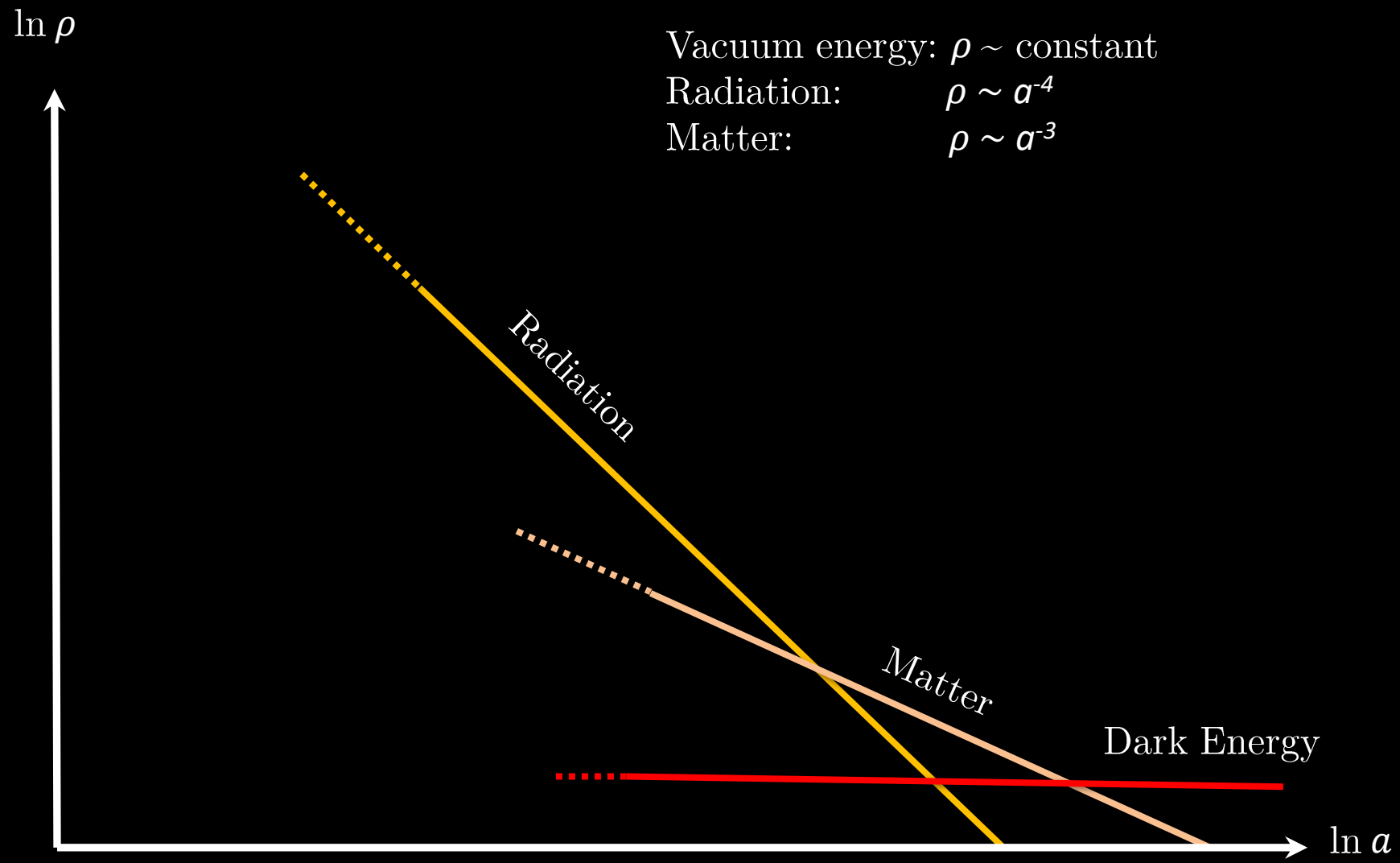

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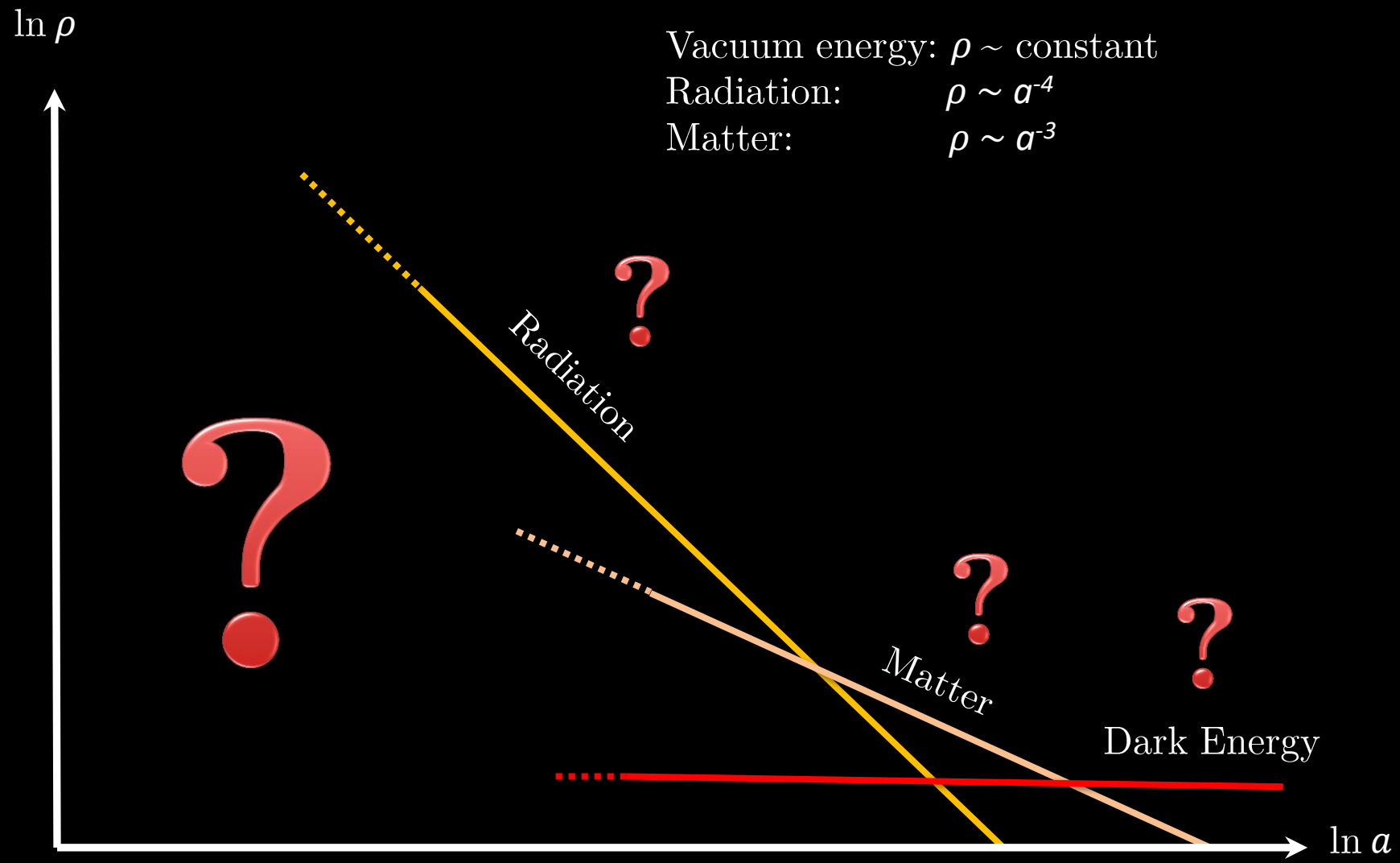

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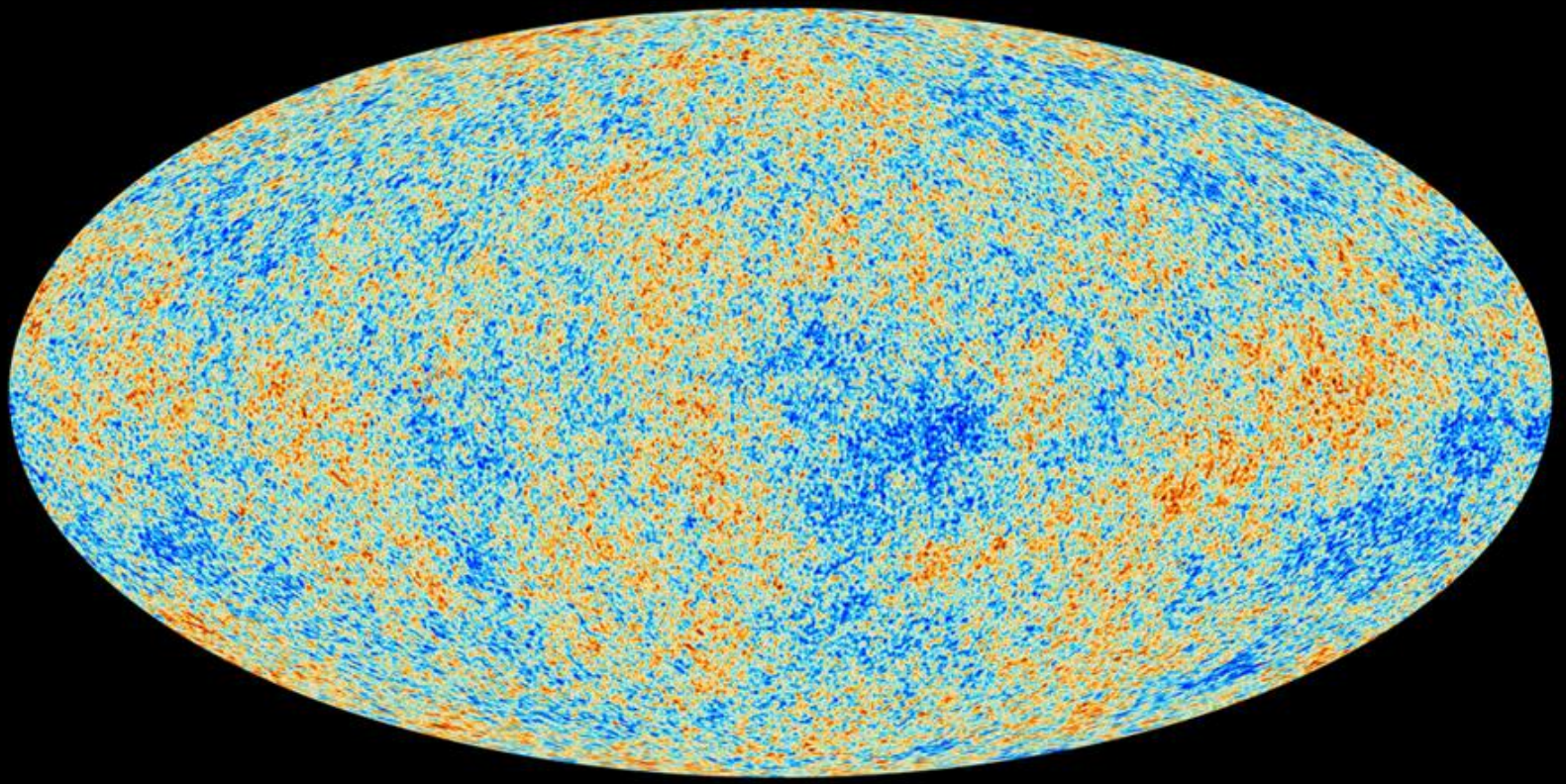


A Quasi – Homogeneous, Flat Universe

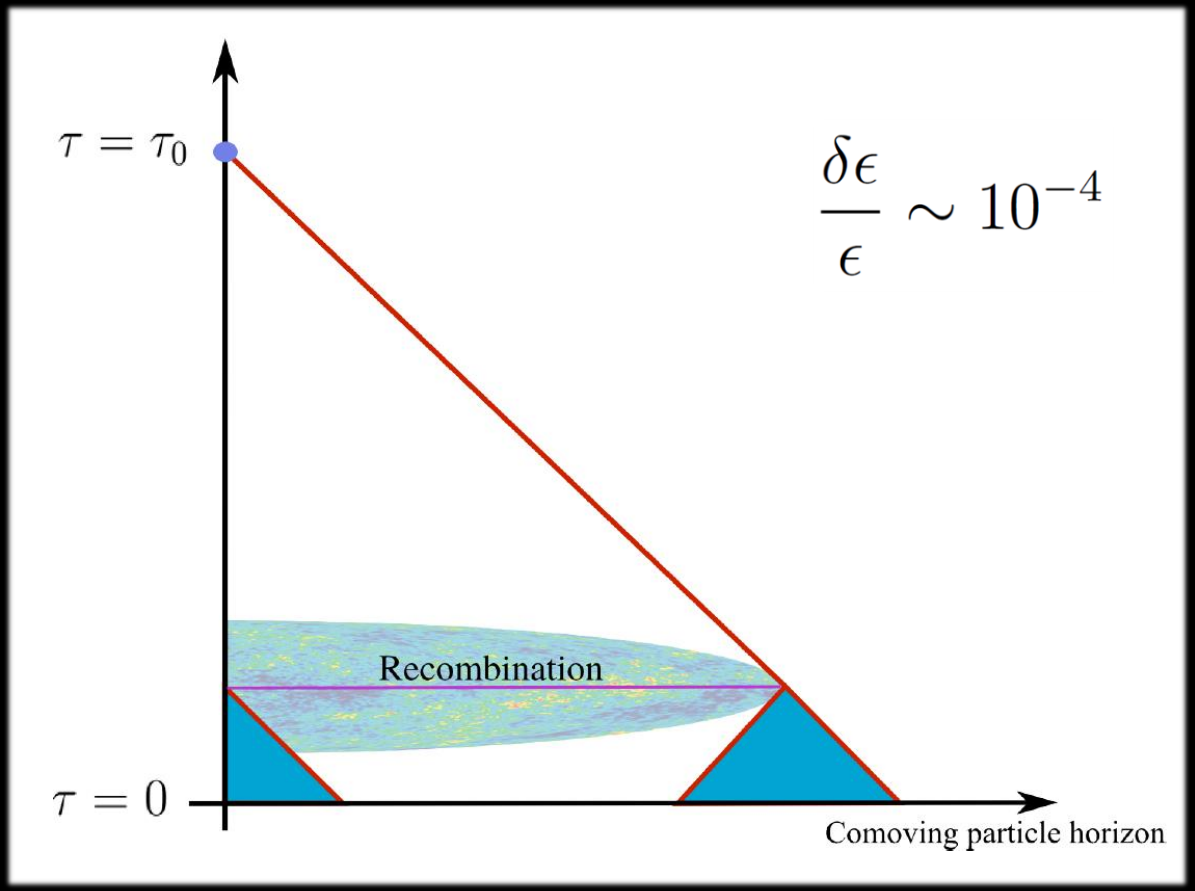
Why is our universe so flat?

$$1 - \Omega(a) = -\frac{k}{(aH)^2}$$

$$|1 - \Omega(a_0)| \lesssim 0.01$$

$$\begin{aligned} |1 - \Omega(a_{BBN})| &\lesssim \mathcal{O}\left(10^{-16}\right) \\ |1 - \Omega(a_{GUT})| &\lesssim \mathcal{O}\left(10^{-55}\right) \\ |1 - \Omega(a_P)| &\lesssim \mathcal{O}\left(10^{-61}\right) \end{aligned}$$

Why is the CMB so homogeneous?

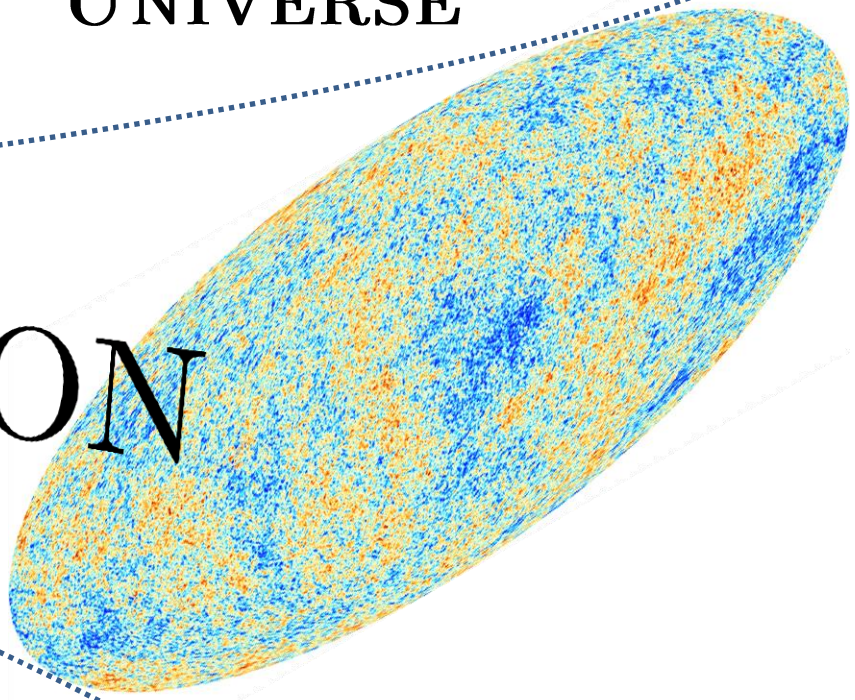


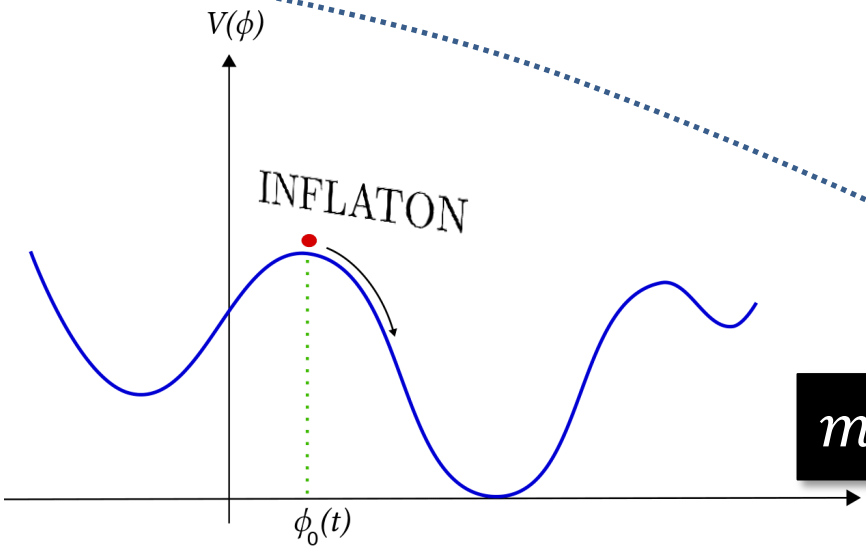
The Cosmic Inflation Paradigm

Primordial Universe

Homogeneous, flat Universe

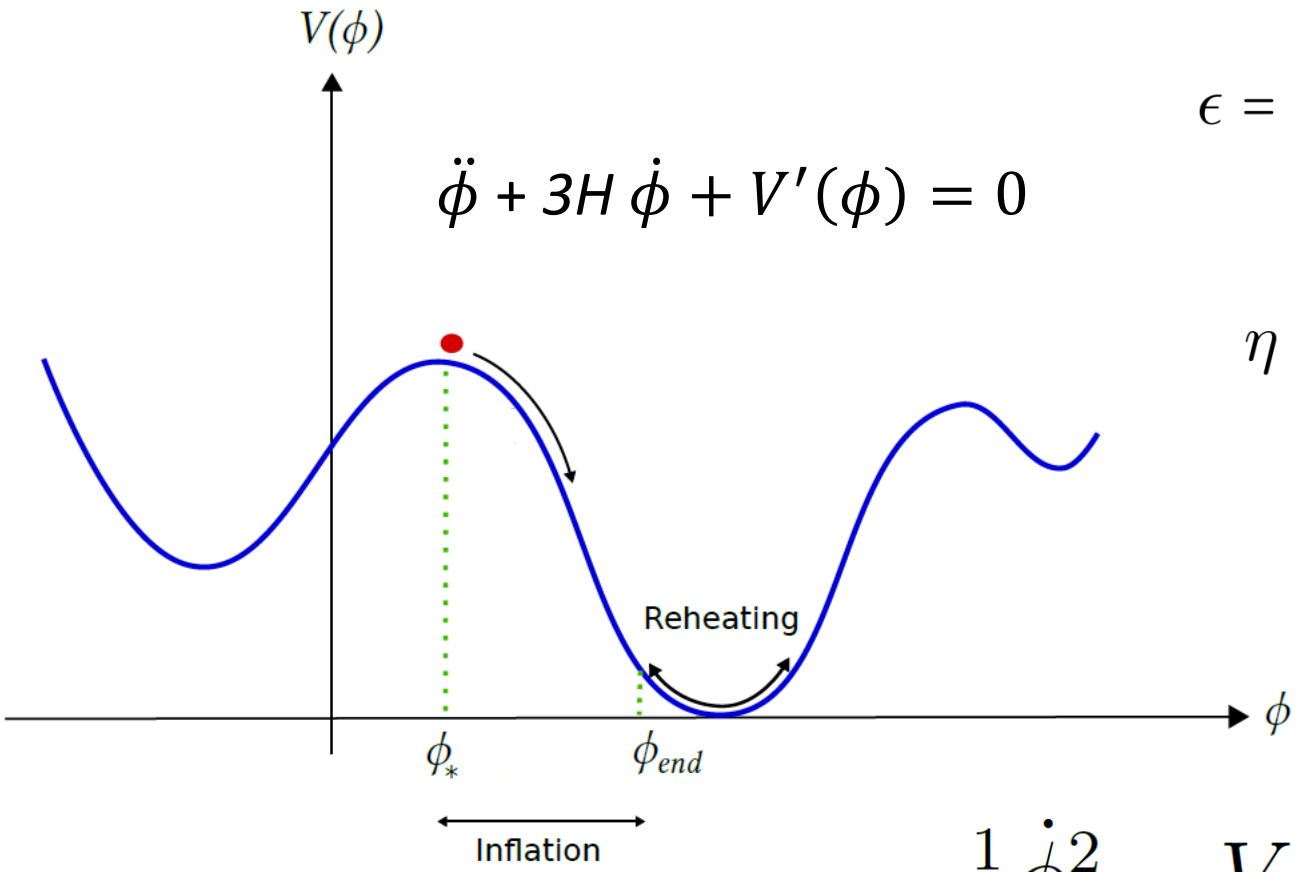
INFLATION





$m_\phi \sim 10^{13}\,\mathrm{GeV}$

Single Field Inflation



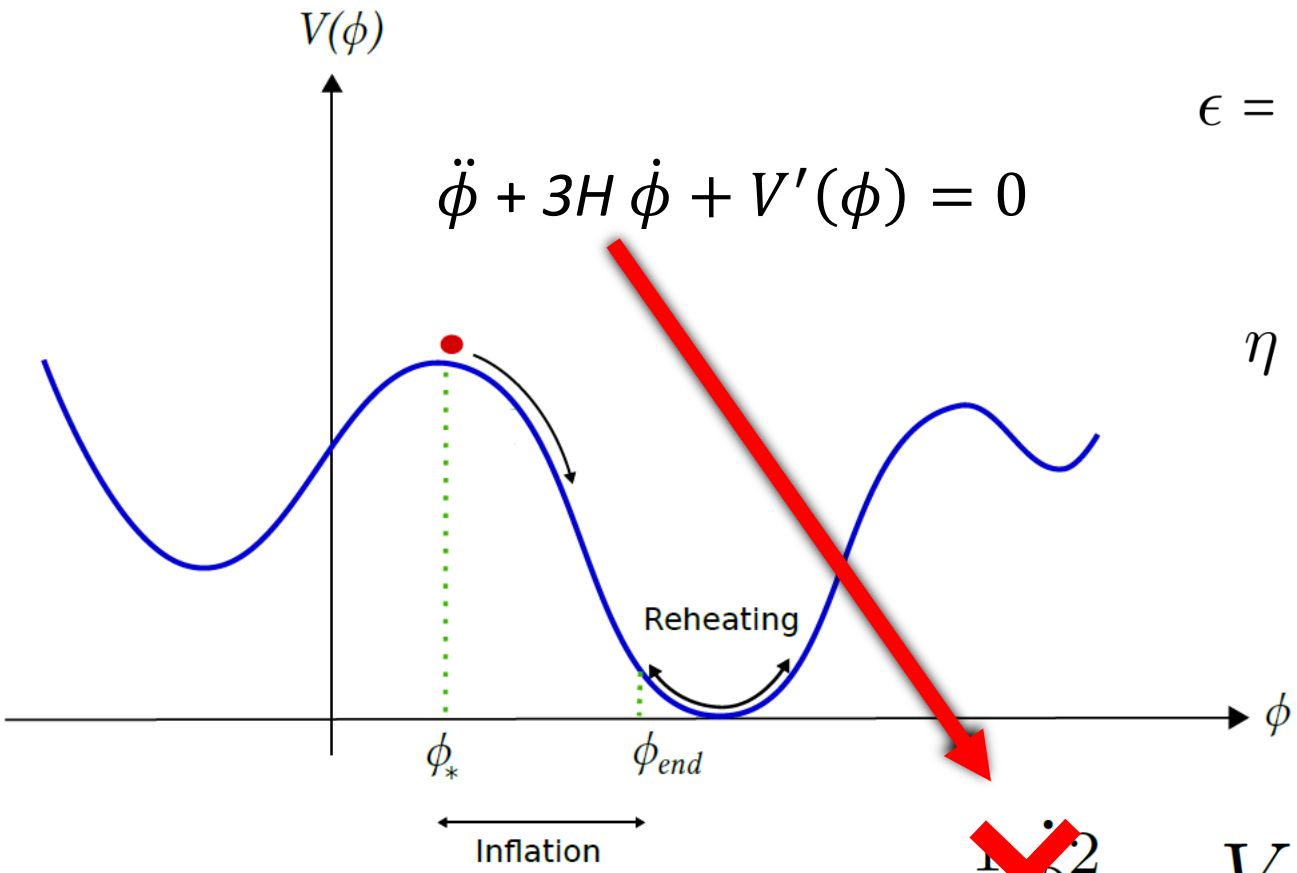
$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$\eta = \left|\frac{V''}{V}\right| \ll 1$$

$$\omega_\phi = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

Single Field Inflation



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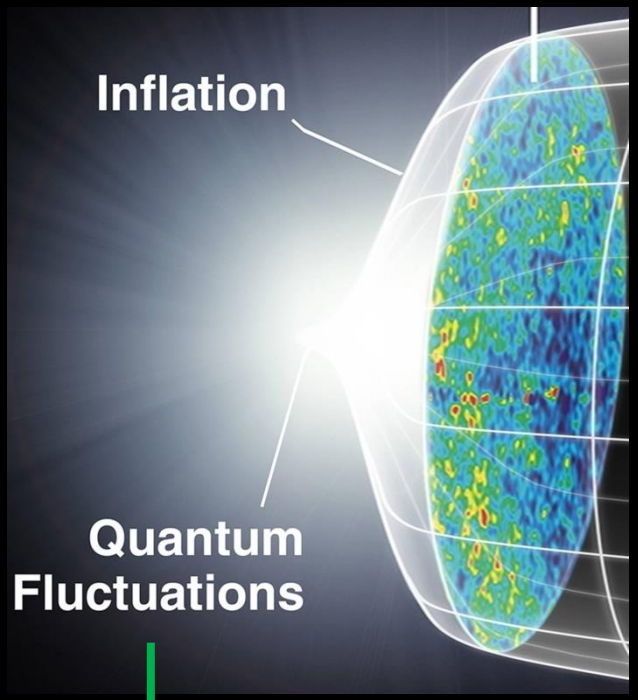
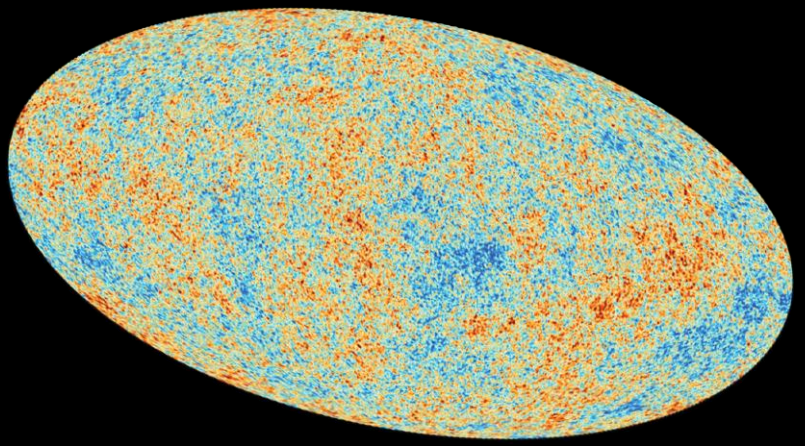
$$\omega_\phi = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \sim -1$$



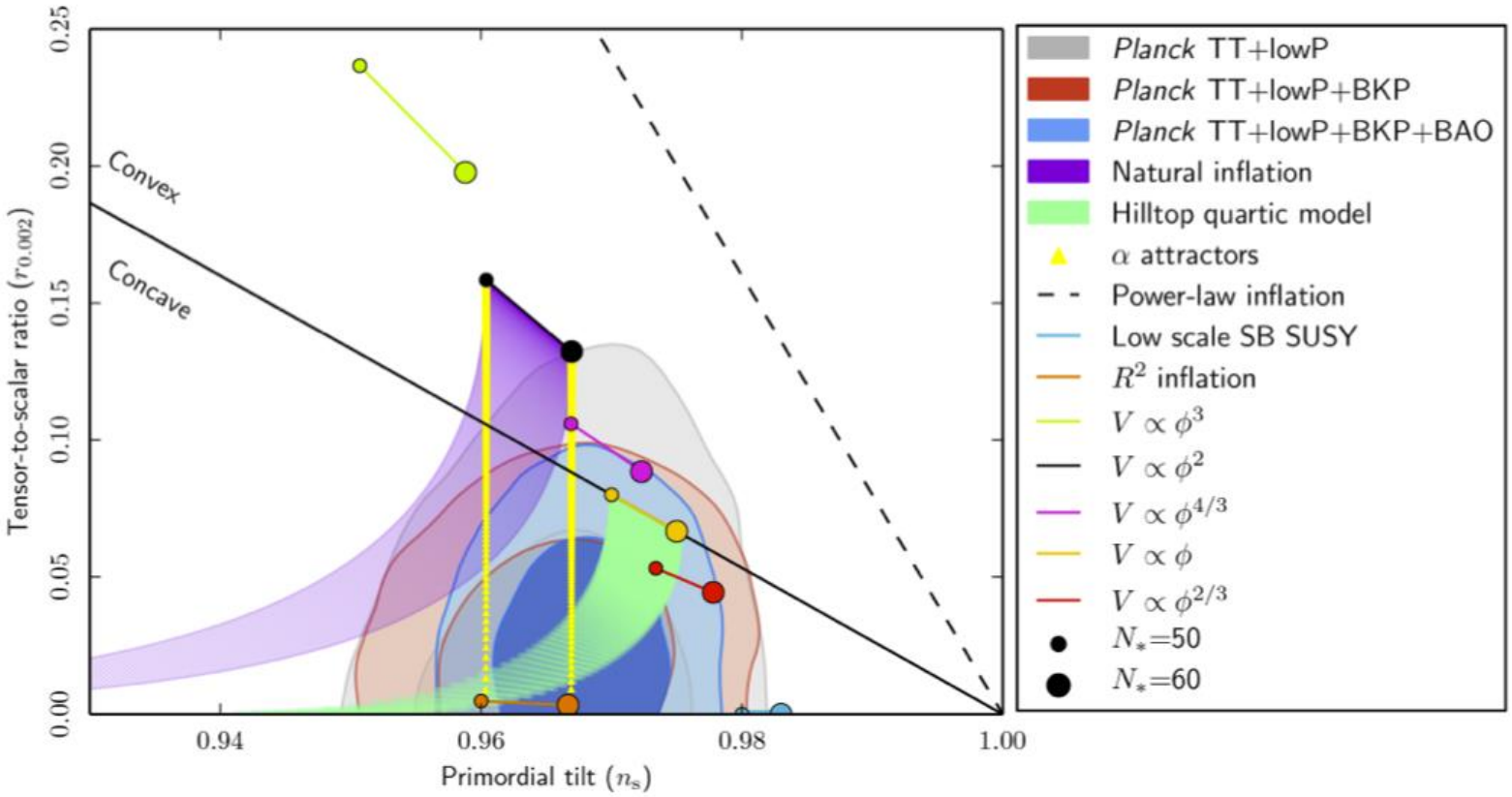
CMB
Perturbations



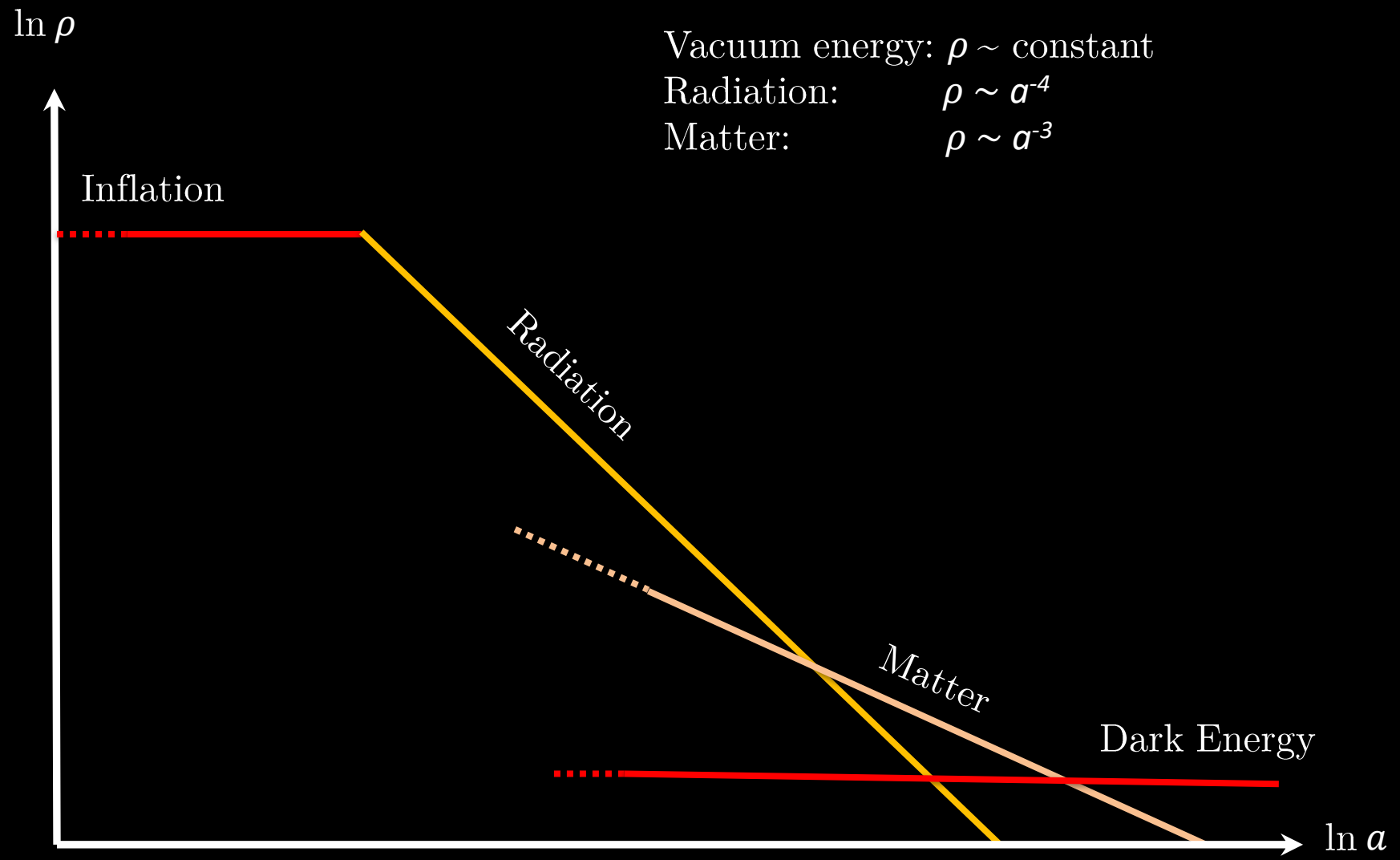
Primordial
Perturbations

Observational constraints?

- Tensor to scalar ratio : $r = 16\,\varepsilon$
- Spectral index : $n_s = 1\ - 6\,\varepsilon + 2\,\eta$



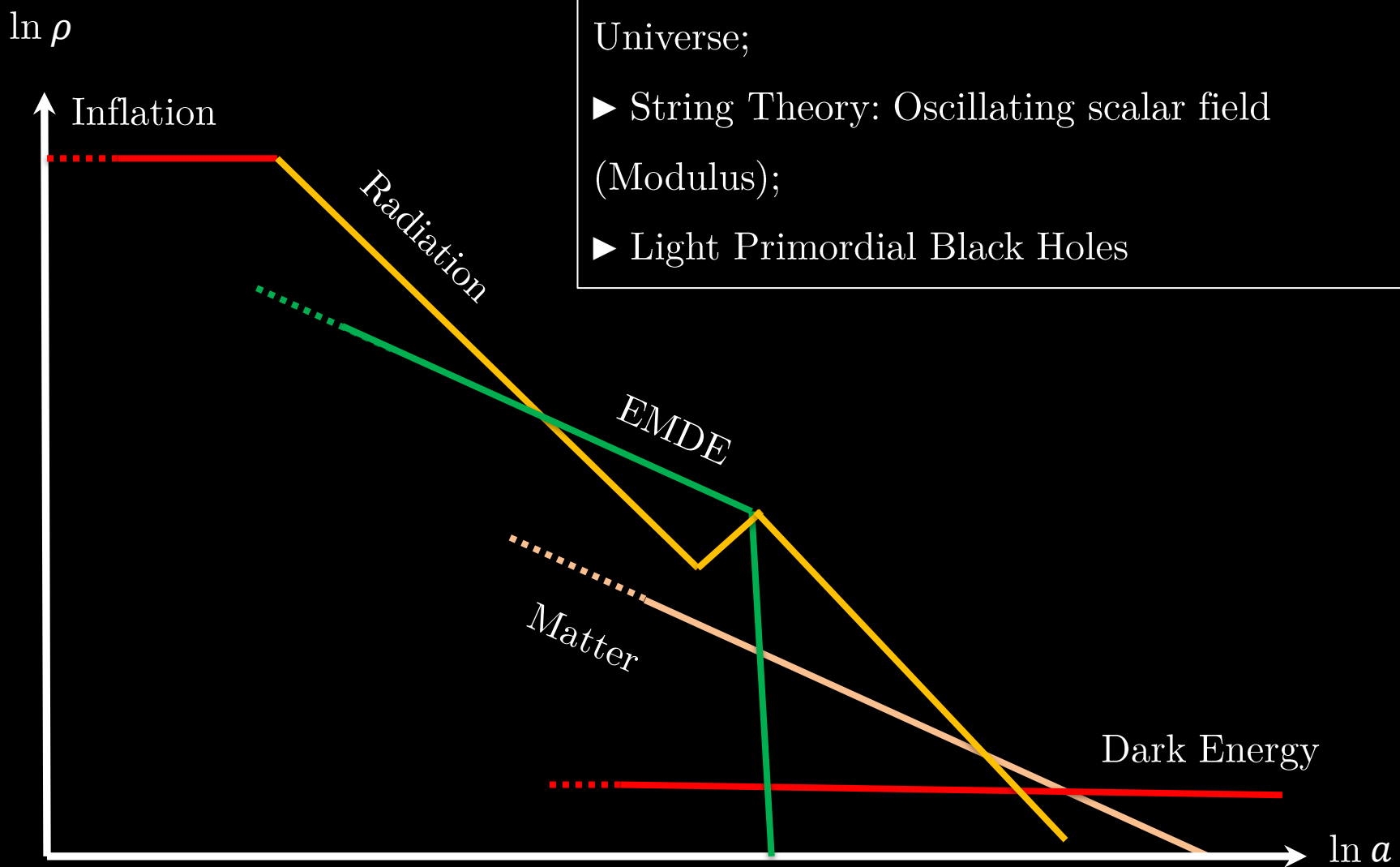
The ΛCDM Ideology



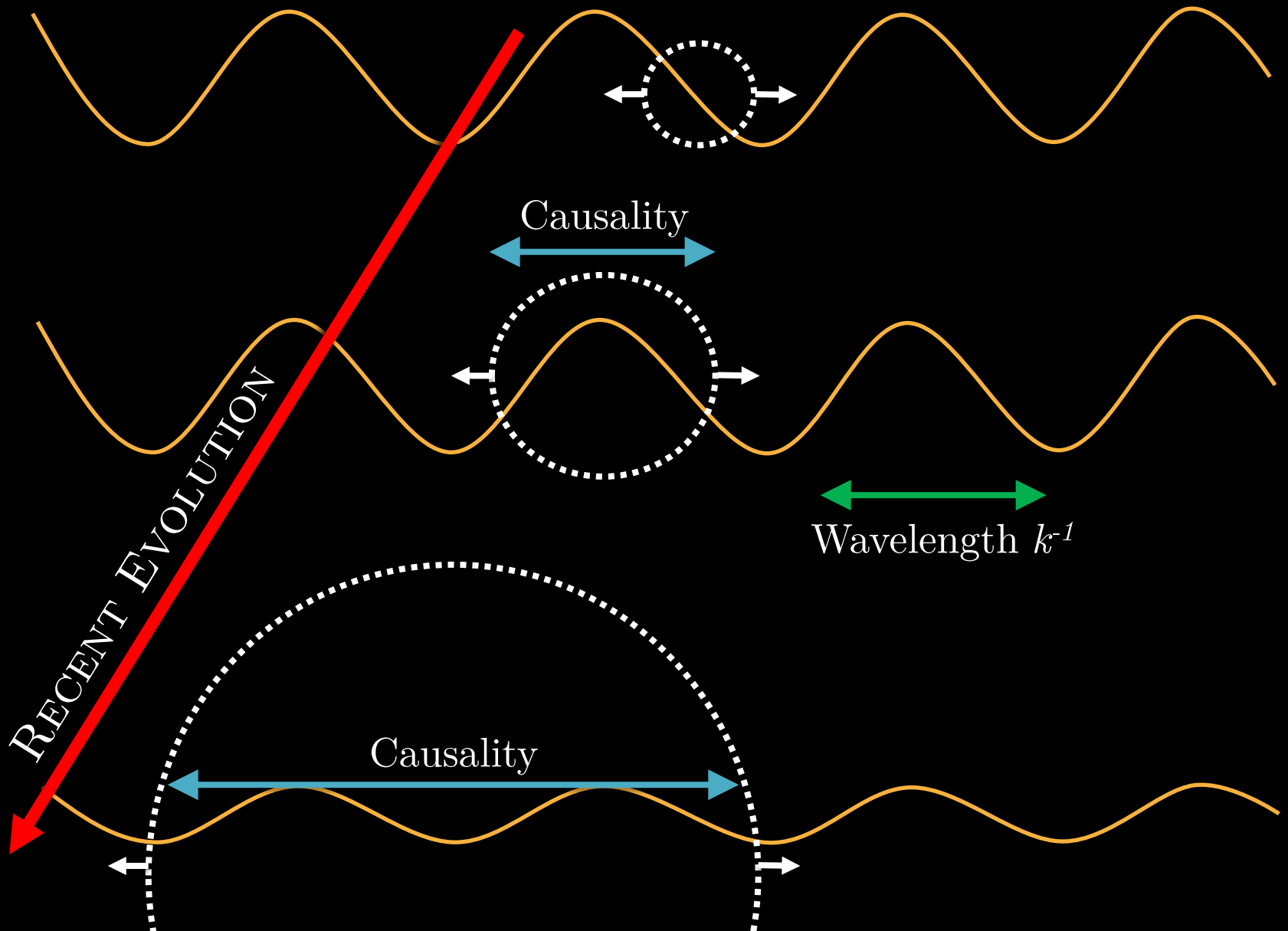
Non-Standard Cosmology *and* Inflation

Example: Early Matter Dominated Era? (EMDE)

- Long-lived particle produced in the early Universe;
- String Theory: Oscillating scalar field (Modulus);
- Light Primordial Black Holes



Primordial Perturbation Evolution



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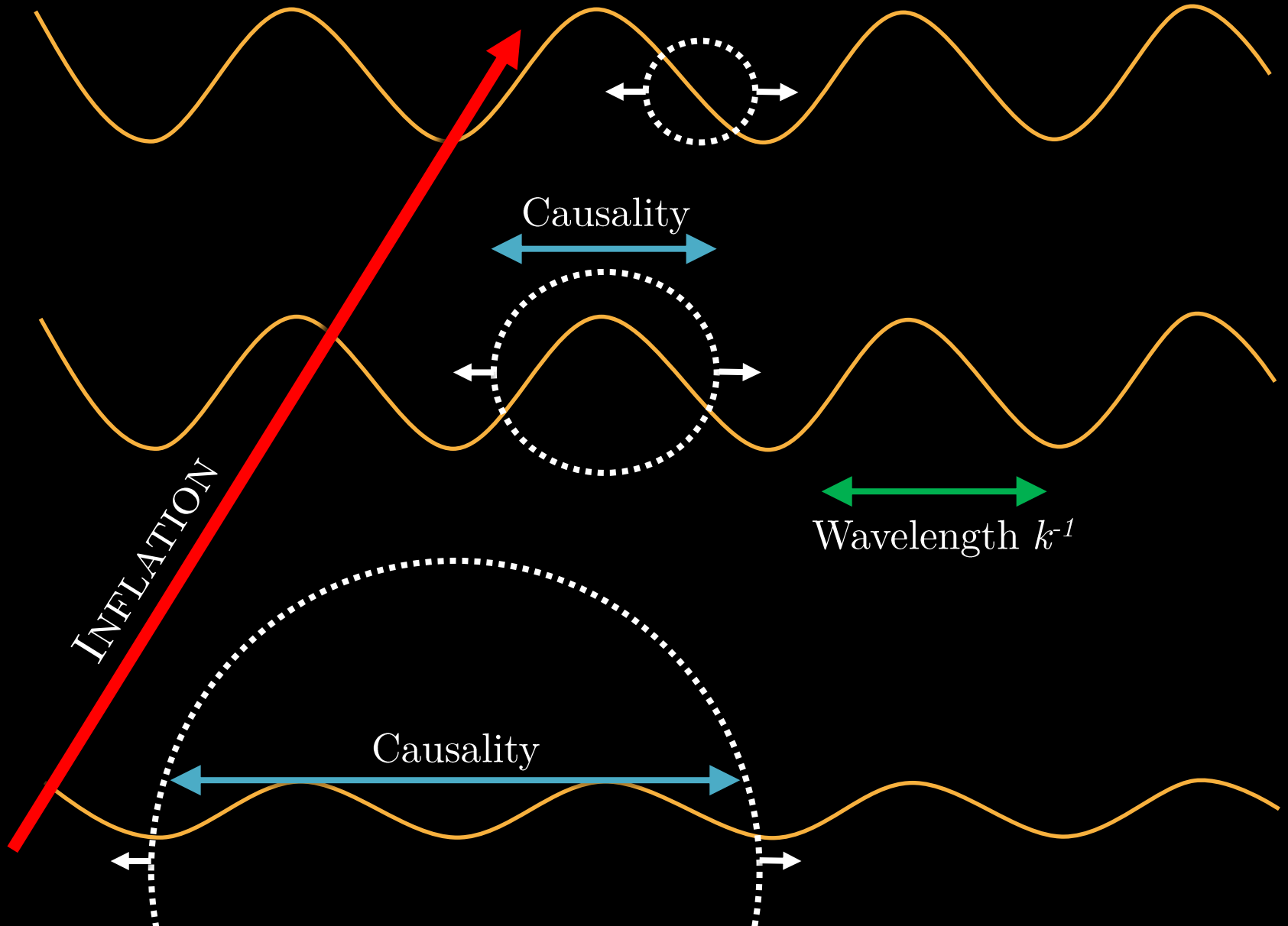
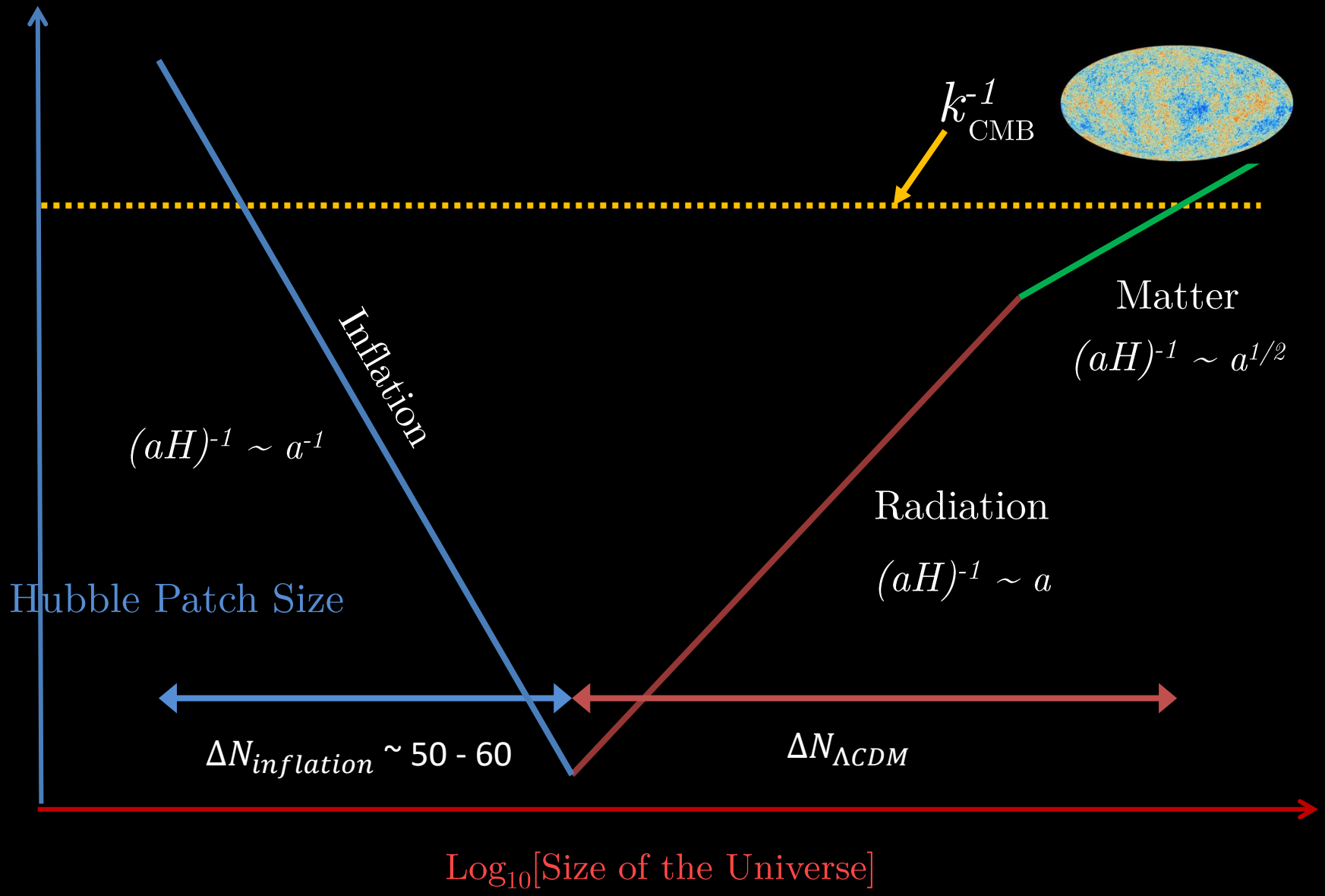


Number of e-Folds



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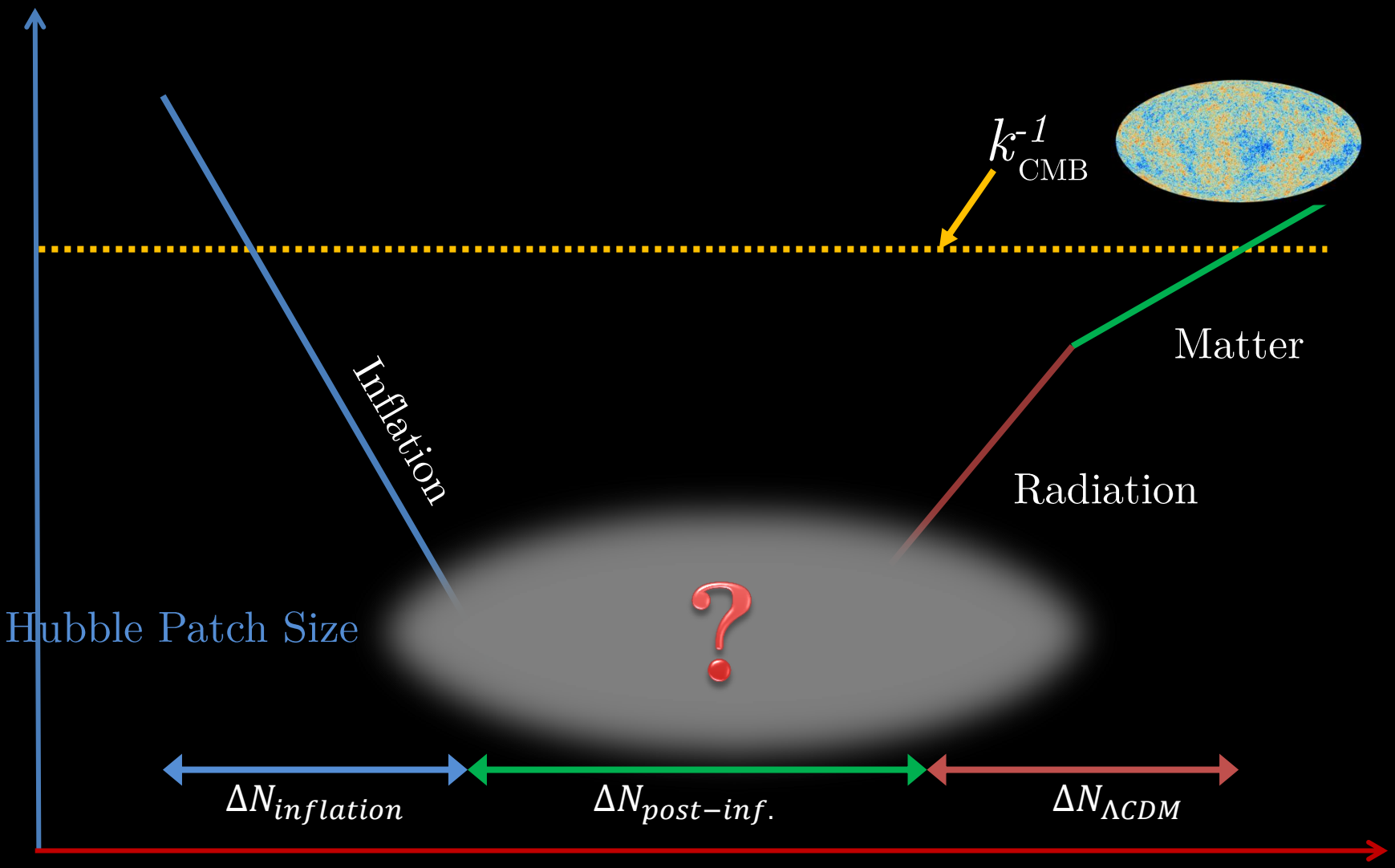

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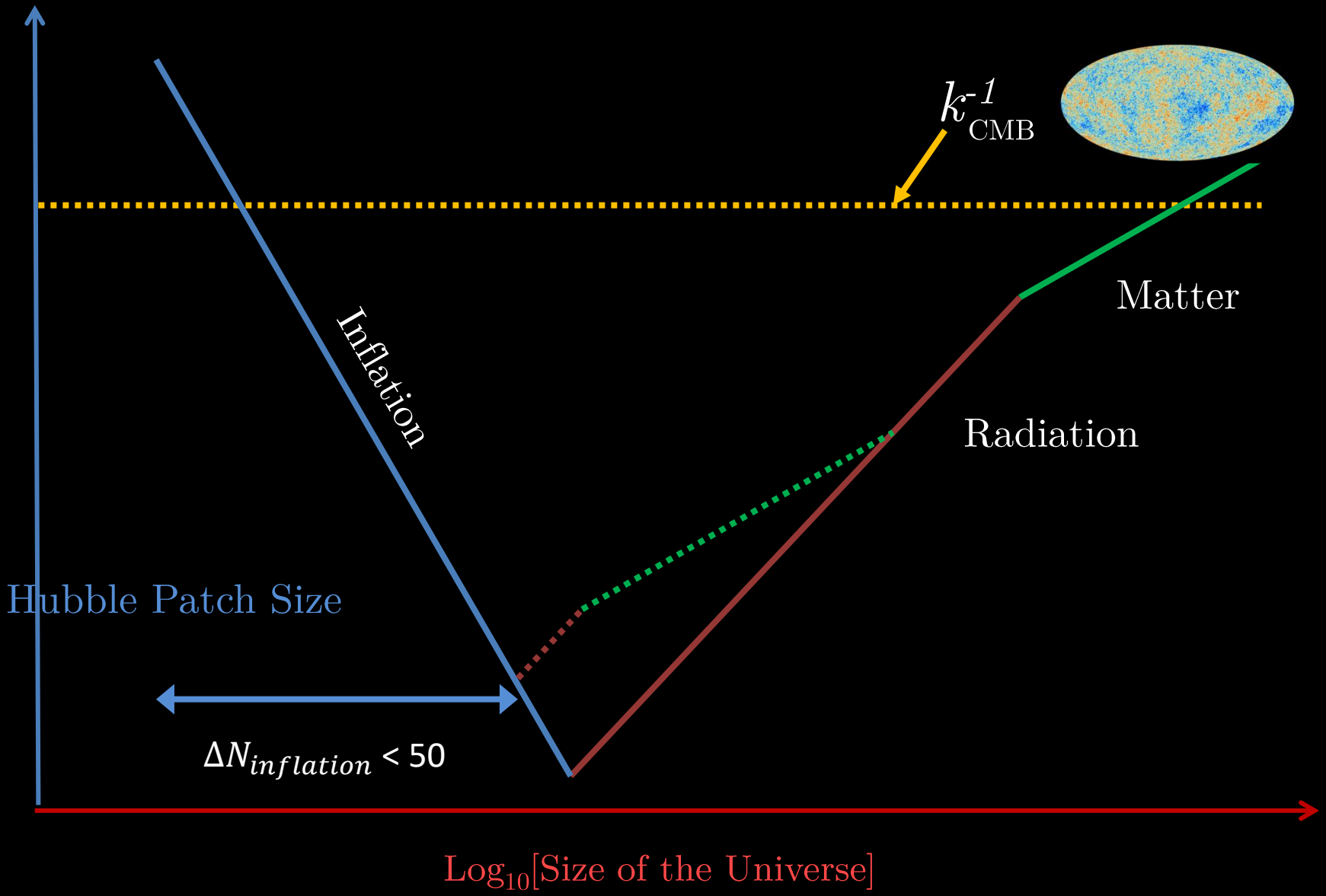

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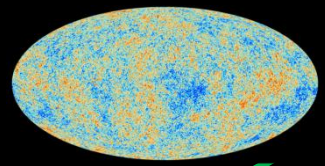


k^{-1}_{CMB}

Inflation

Matter

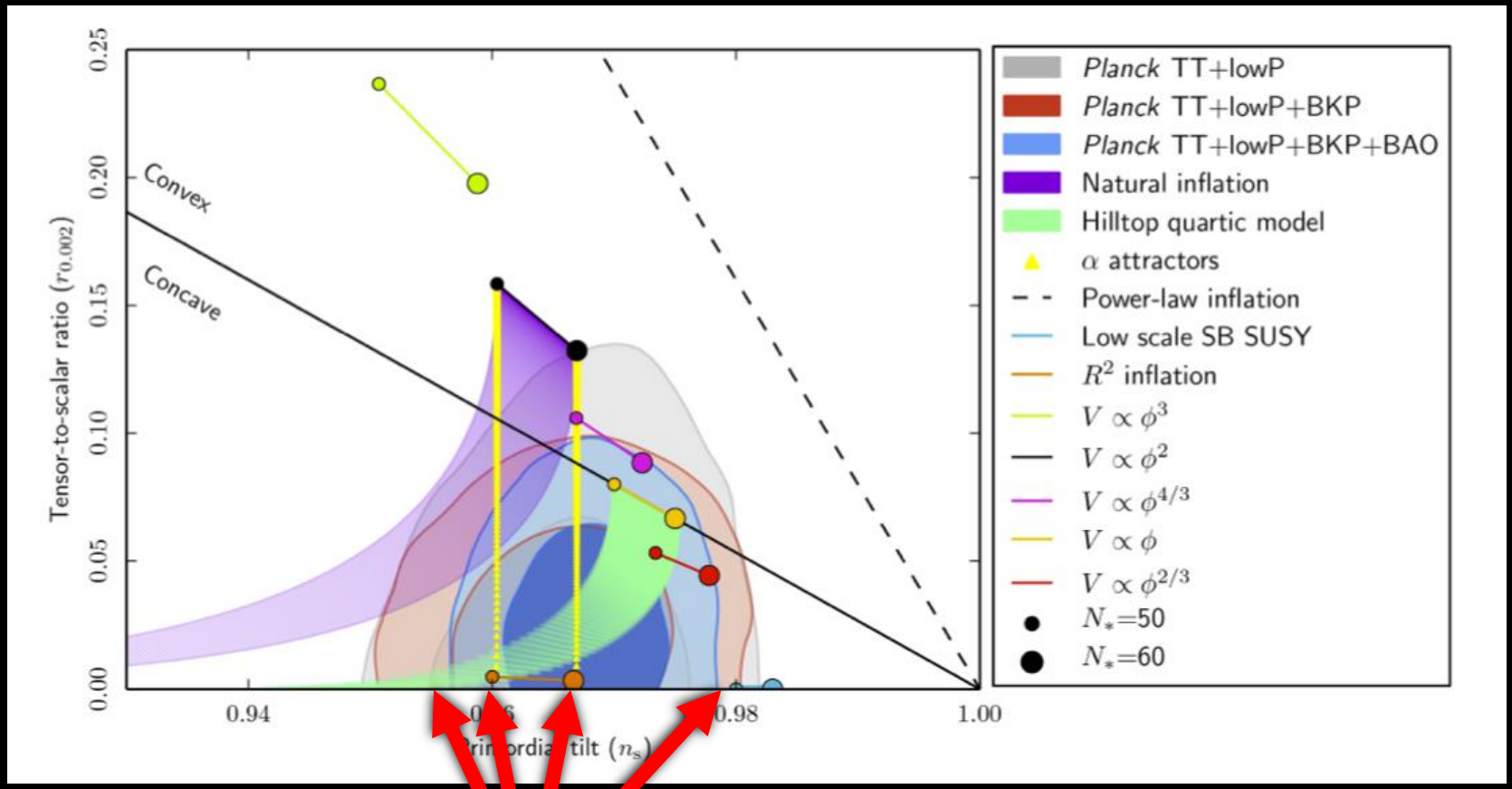
Radiation

Hubble Patch Size

$\Delta N_{inflation} > 60$

Log_{10}[Size of the Universe]

Number of e-Folds

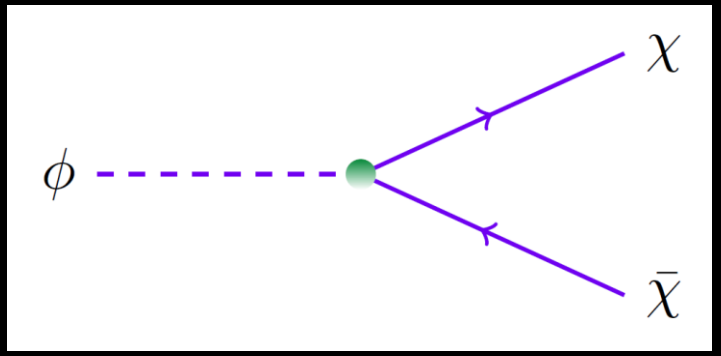


Where do we stand?

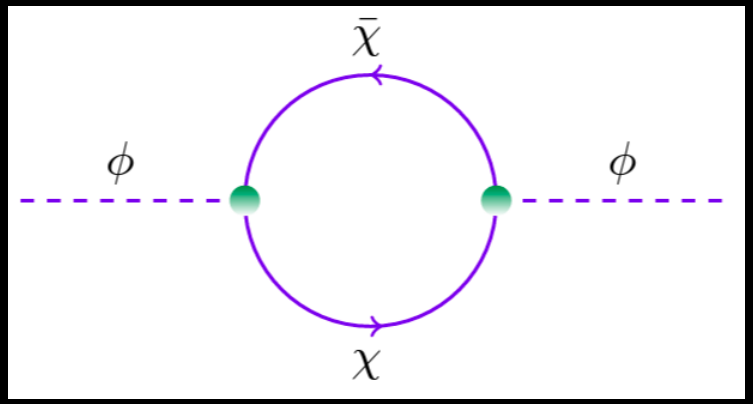
Post – Inflationary Physics
can be constrained
using Inflation Observables

Inflaton Interactions

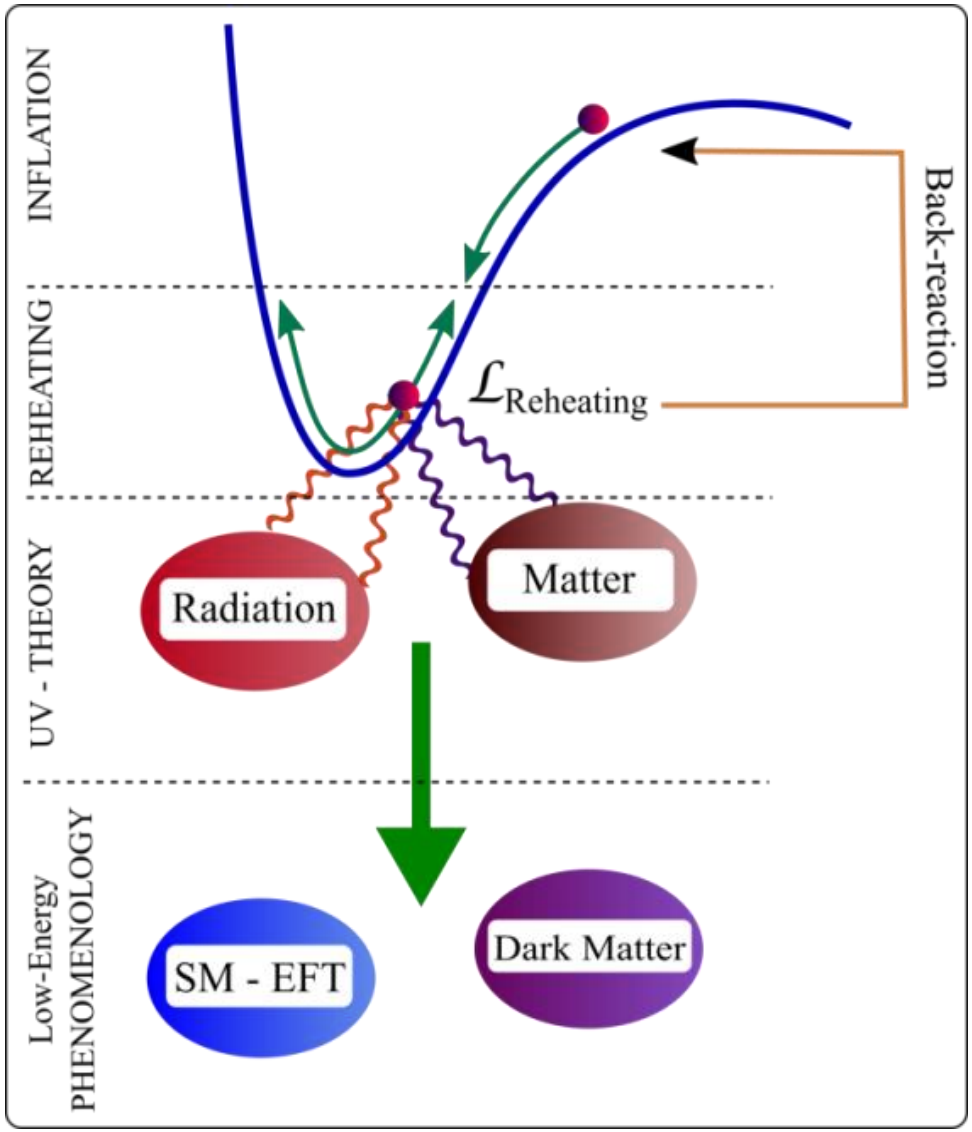
Inflaton Decay ?



$$\rho_\phi = 3H^2 M_p^2 = 3\Gamma_\phi^2 M_p^2 = \frac{\pi^2 g_*}{30} T_R^4$$



Interactions → Flatter/Steeper



Loop corrections backreact on the inflationary trajectory

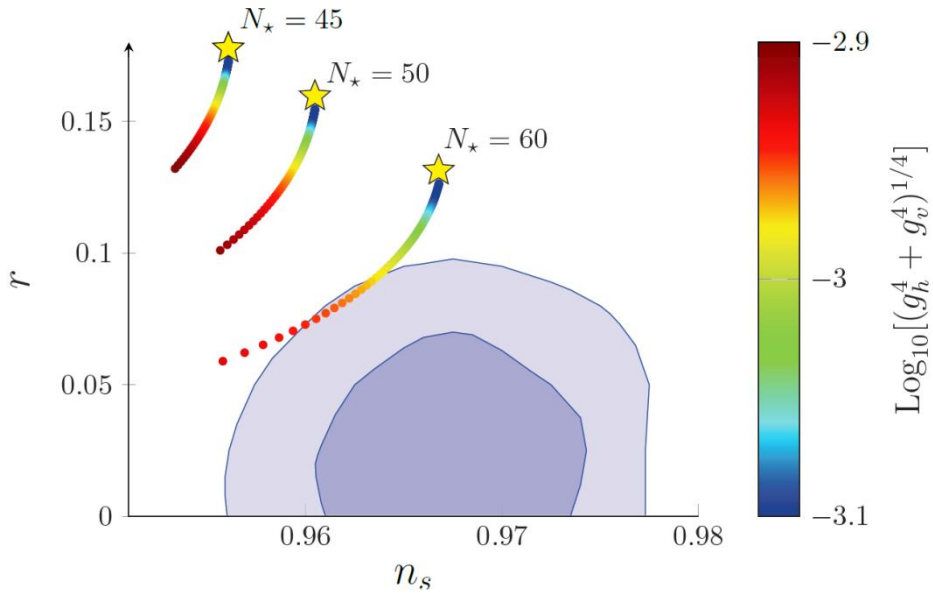
↓

Destabilizes the inflaton at large field values

↓

Modifies the predictions for inflation observables (r, n_s)

Interactions → Flatter/Steeper



Loop corrections backreact on the inflationary trajectory

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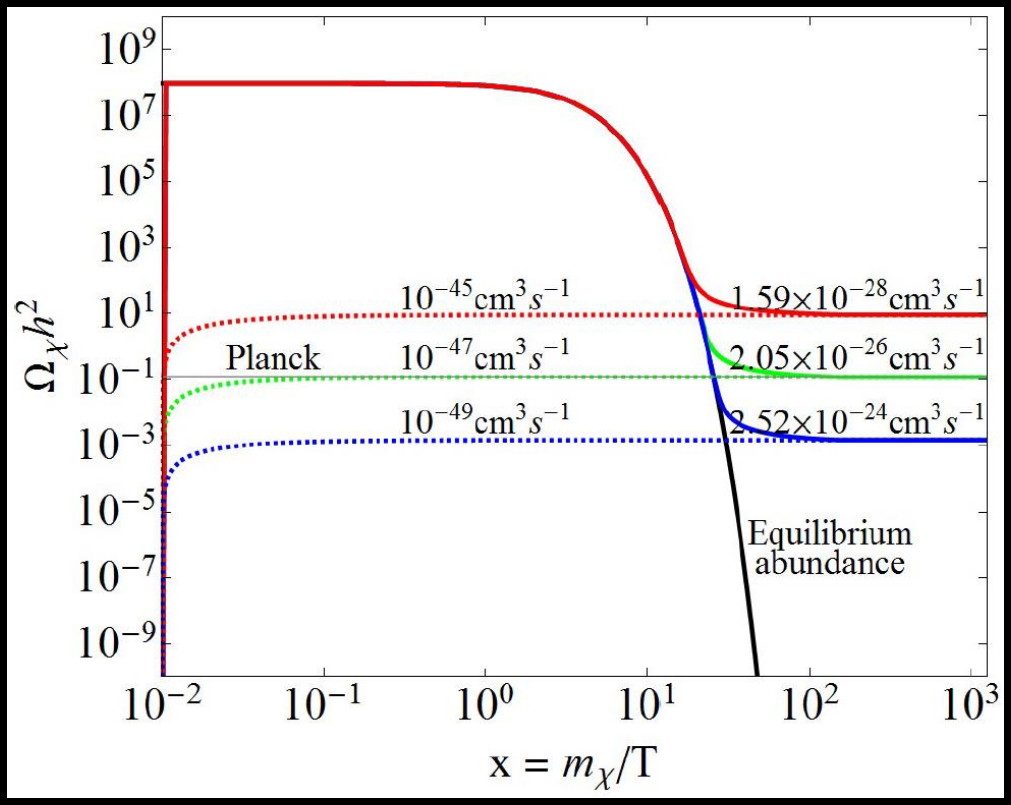
Modifies the predictions for inflation observables (r, n_s)

Non-Standard Cosmology *and* Dark Matter

Dark Matter Freeze-In/Out

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right)$$



Dark Matter Freeze-In/Out

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2 \right)$$

Observable

Dark Matter Freeze-In/Out

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2 \right)$$

Observable

Statistical Physics

Dark Matter Freeze-In/Out

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right)$$

Observable

Dark-Matter Model

Statistical Physics

Dark Matter Freeze-In/Out

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right)$$

Observable

COSMOLOGY

Dark-Matter Model

Statistical Physics

Dark Matter Freeze-In/Out

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2 \right)$$

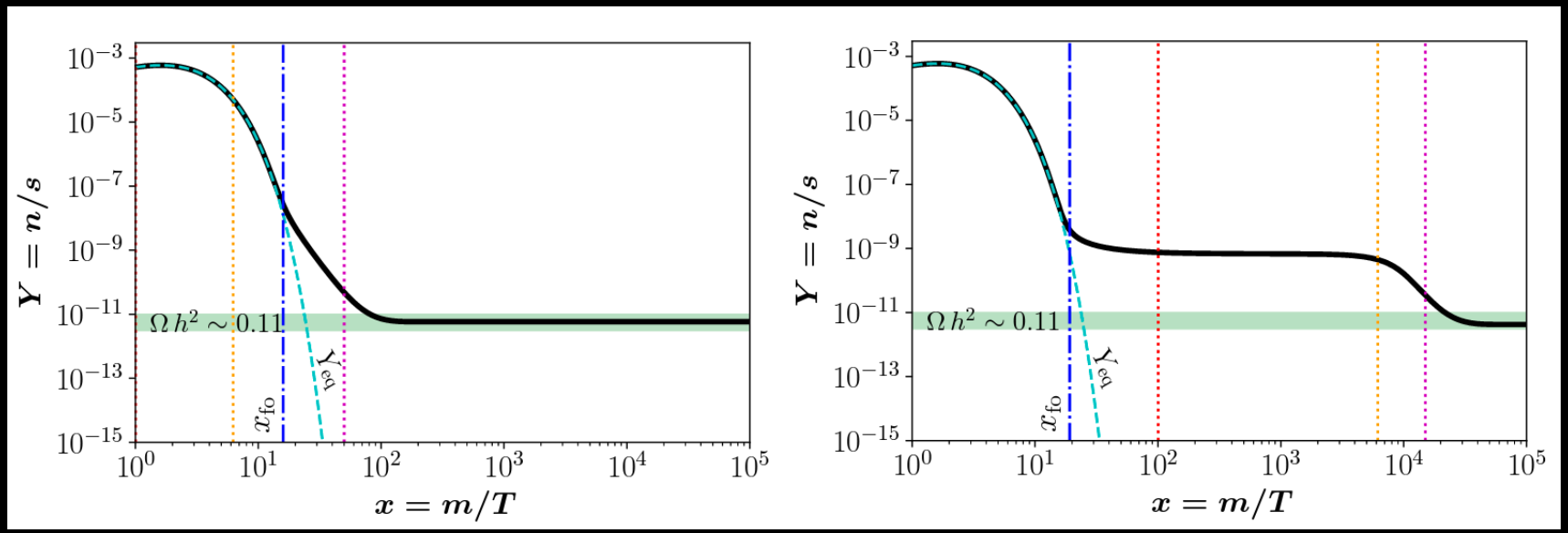
- Radiation Domination: $H \propto T^2$
- Matter Domination: $H \propto T^{3/2}$
- Arbitrary Equation of State: $H \propto T^{\frac{3}{2}(1+w)}$

+ Evolution of $T(t)$

Affects the value of Ωh^2

Dark Matter Freeze-In/Out

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right)$$



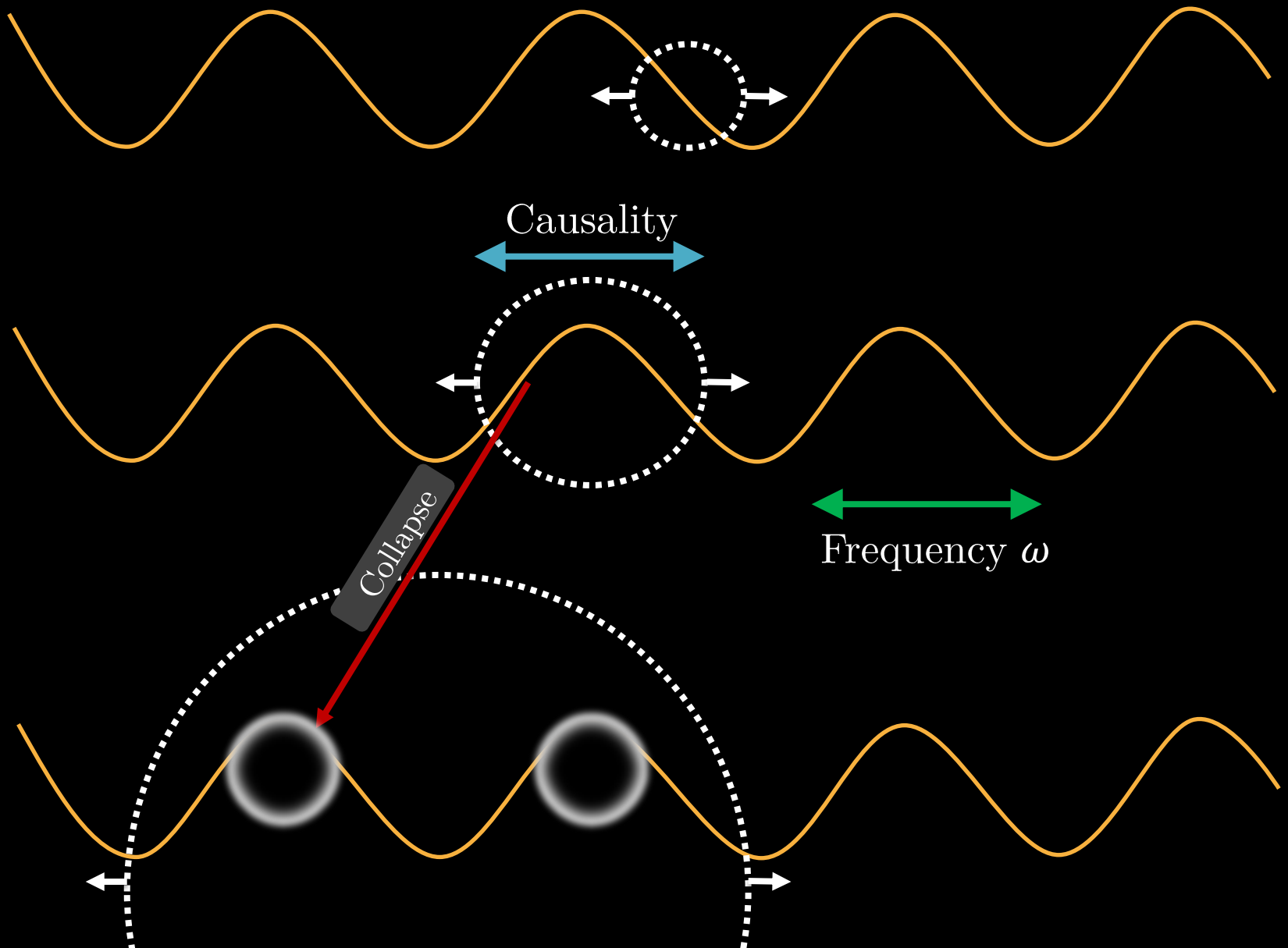
Reconstructing Non-standard Cosmologies with Dark Matter
P. Arias, N. Bernal, A. Herrera, C. Maldonado
JCAP 10 (2019) 047 [ArXiv: 1906.04183]

Different predictions for $\langle\sigma v\rangle$!!!

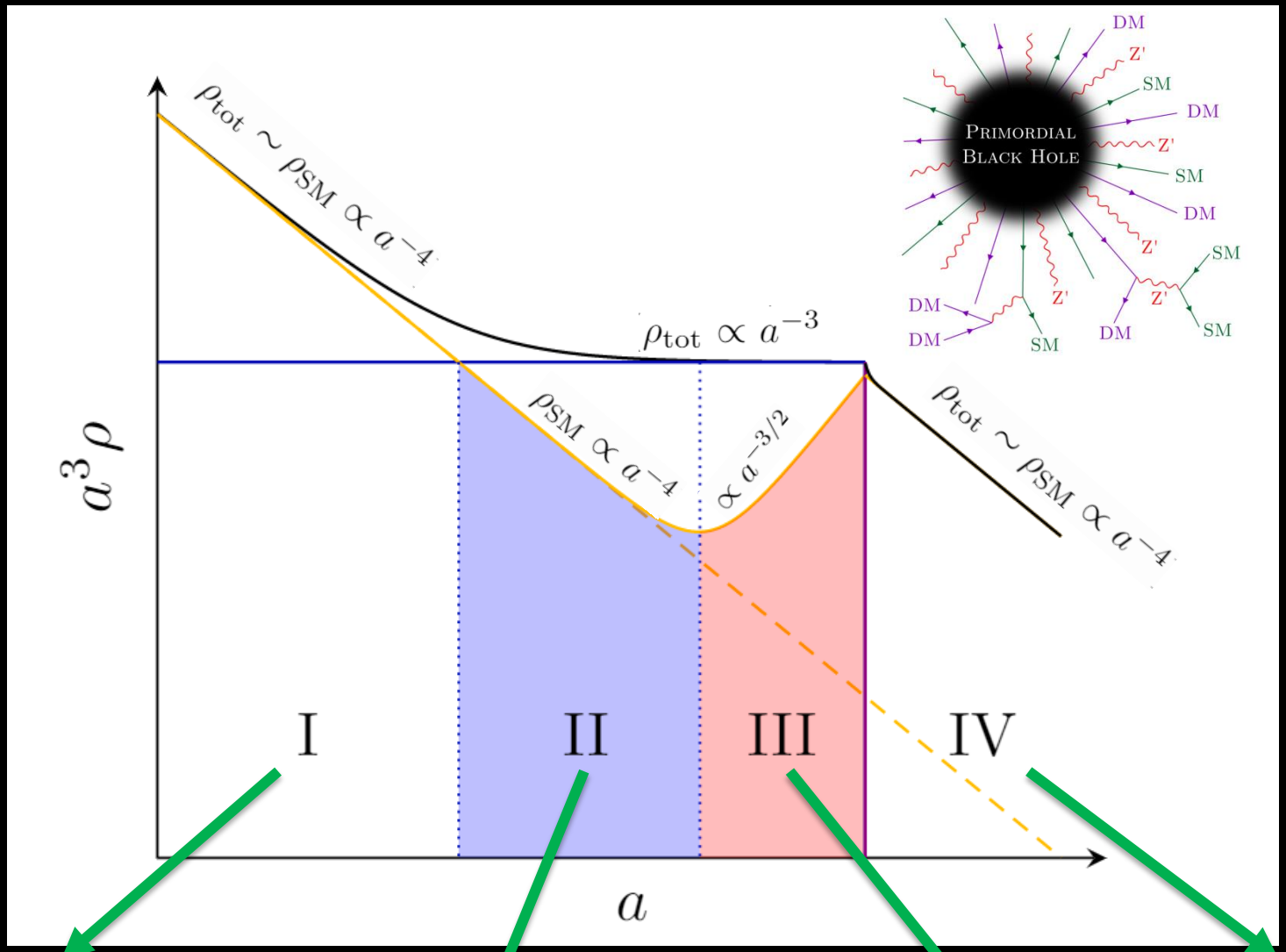
A Mixed Example:

Primordial Black Holes

Why Primordial Black Holes?



Modified Cosmology



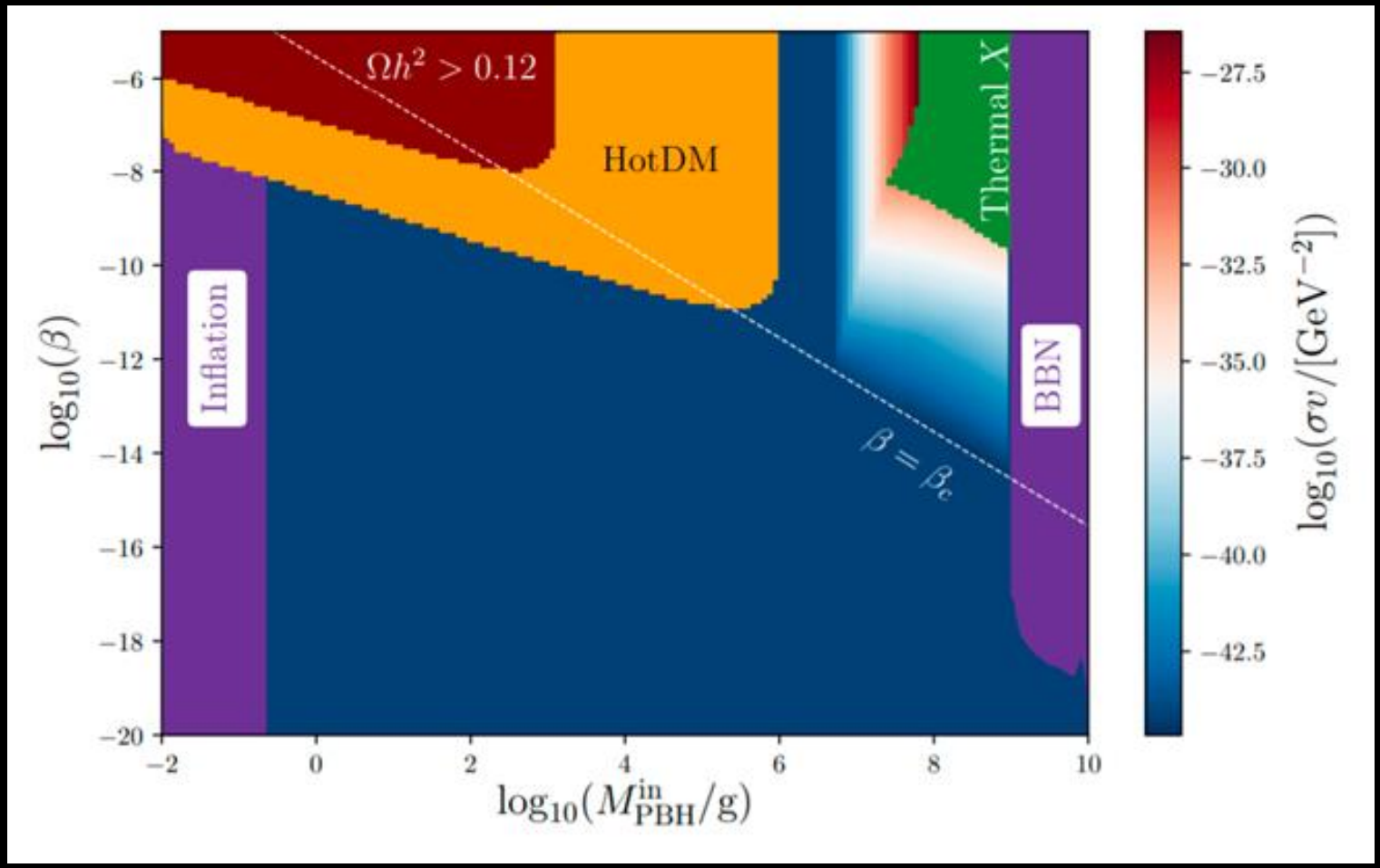
FI/FO + entropy dilution

Matter-Dominated FI/FO

FI/FO during entropy injection

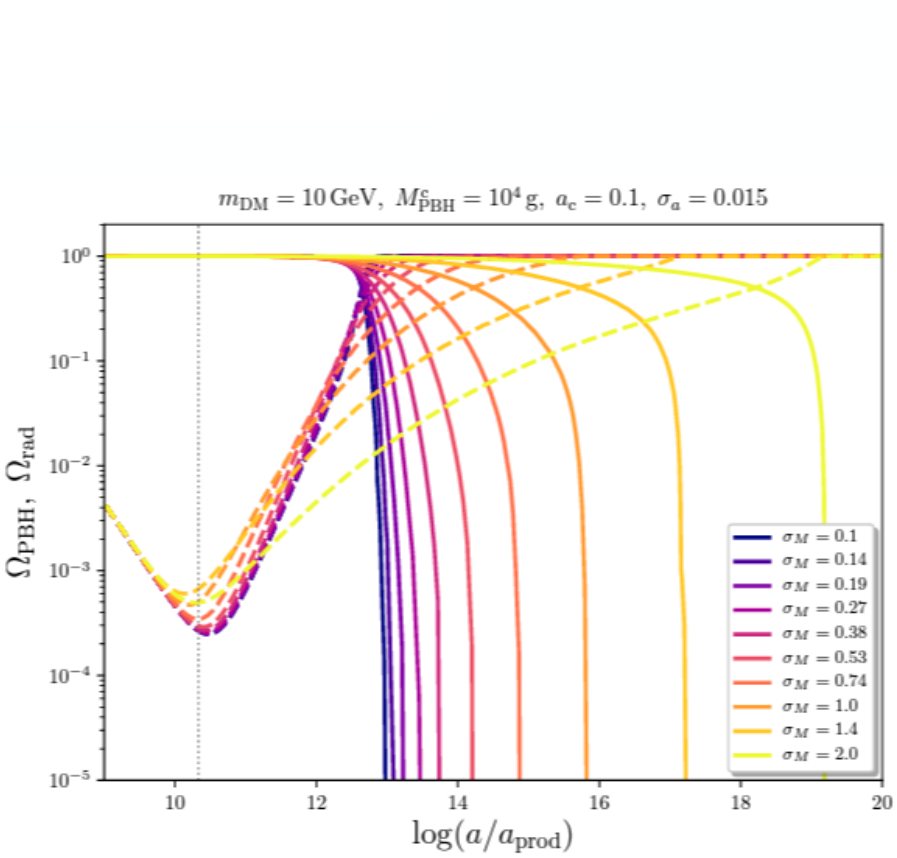
Regular FI/FO

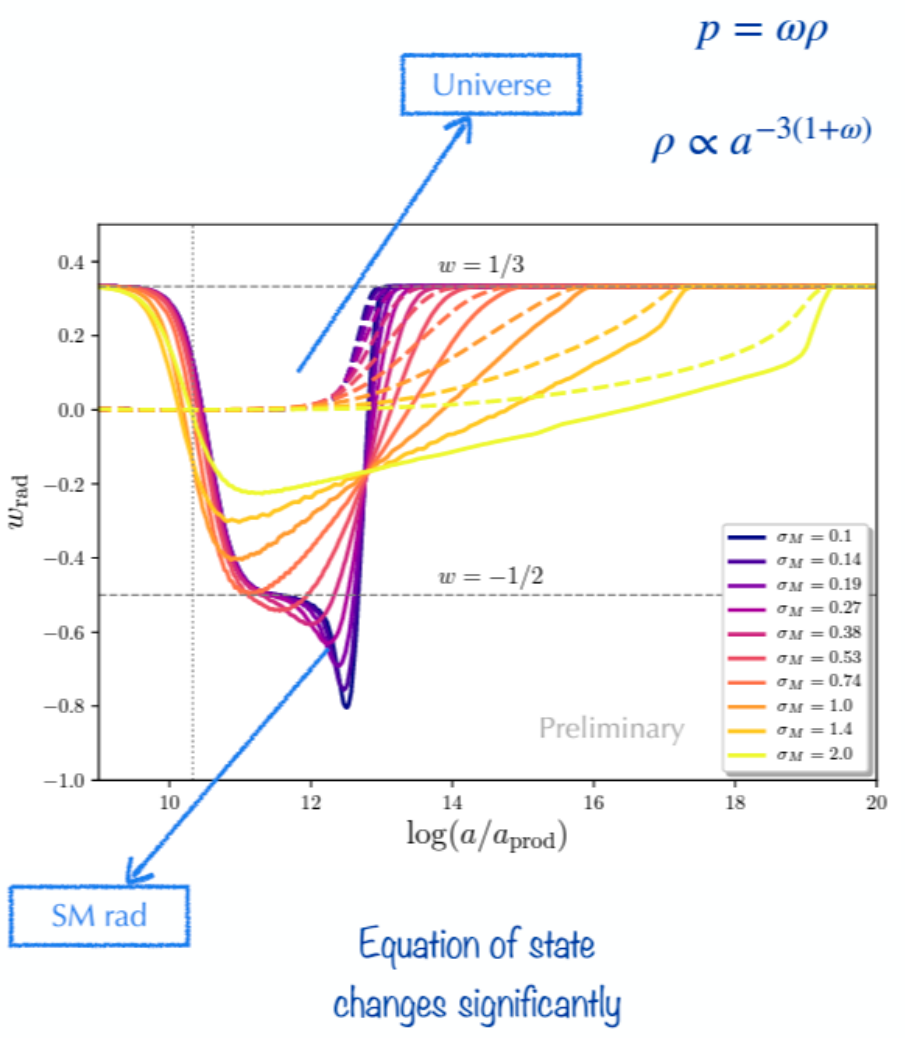
Dark Matter Production



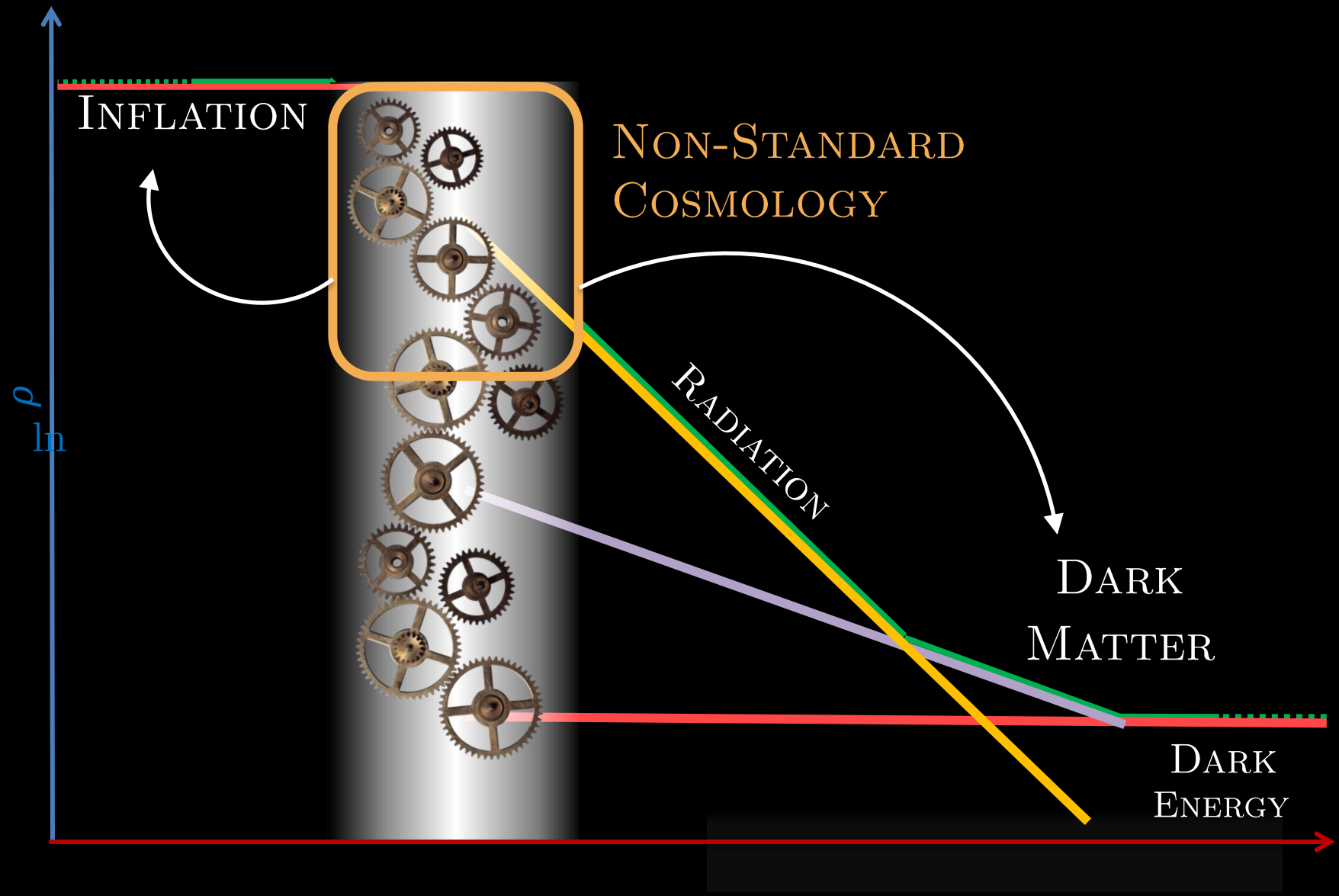
Primordial black hole evaporation and dark matter production
A. Cheek, LH, Y. Perez-Gonzalez and J. Turner,
Phys.Rev.D 105 (2022) 1, 015023 [ArXiv: 2107.00016]

Beyond the Monochromatic Approximation





The Take-Away Message



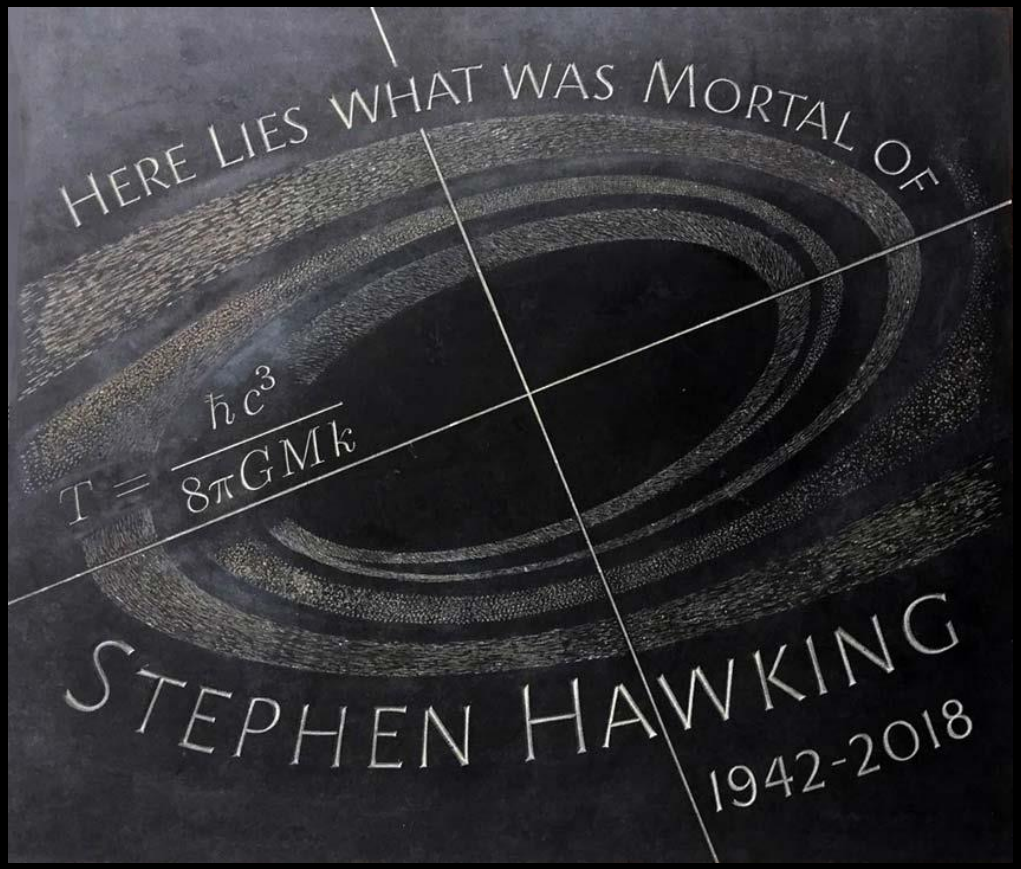
There is More...

- When was the Universe reheated? How?
- Interactions of the Inflaton field Loop induced corrections to the inflation potential...
- Formation of Primordial Black Holes during during different eras of cosmology
- The Gravitational-wave spectrum evolves in different ways, depending on the Universe's equation of state...
- ...

Thank You!

Black Holes Evaporate...

S. Hawking, 1975



Why Primordial Black Holes?

Primordial Black Hole Distribution

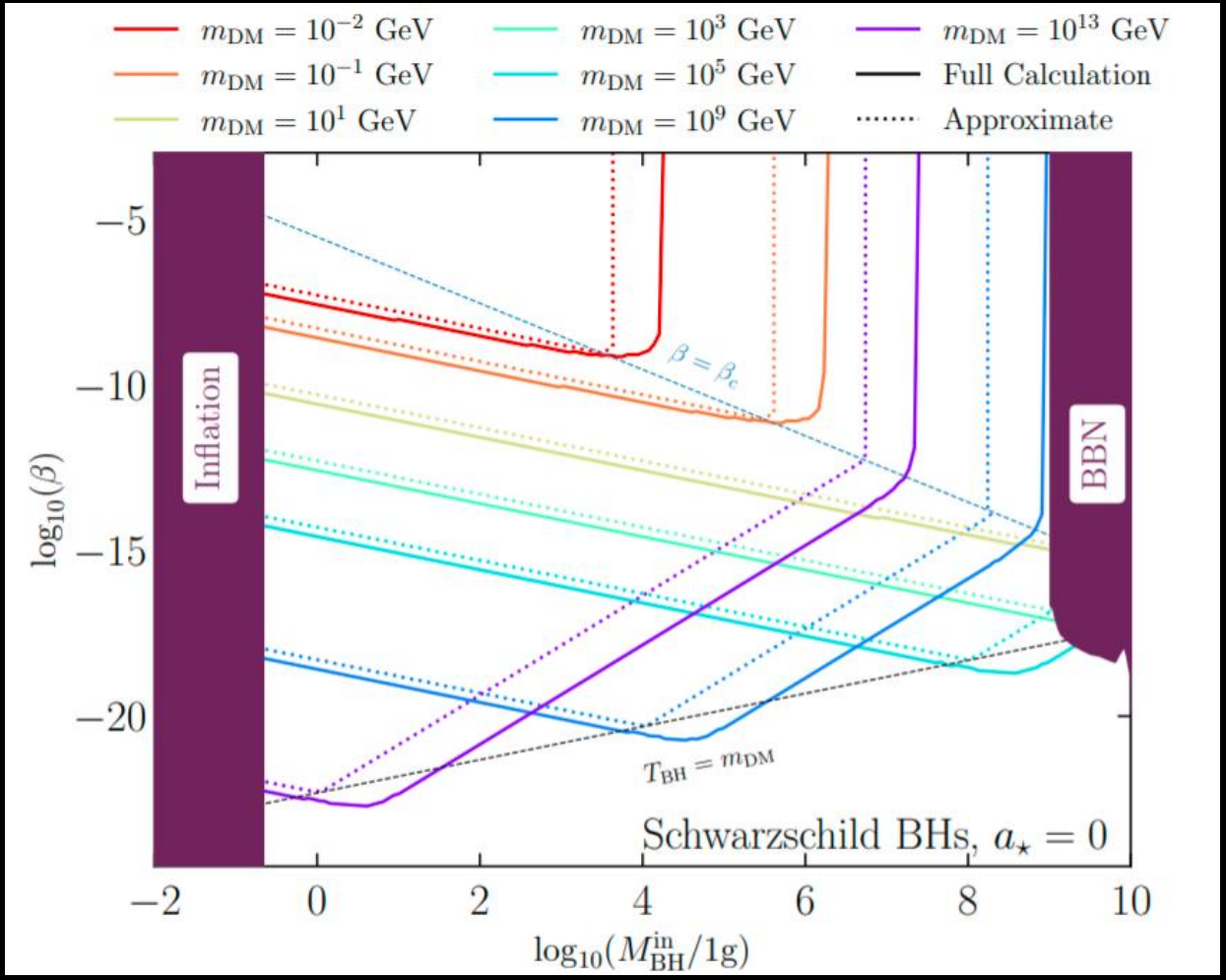
$f_{\mathrm{PBH}}(M_{\mathrm{PBH}})$

- Some may be stable and participate to the DM relic abundance ($M_{\mathrm{PBH}} \gtrsim 10^{15}\,\mathrm{g}$)
- Some may be unstable and evaporate after BBN ($10^{15}\,\mathrm{g} \lesssim M_{\mathrm{PBH}} \lesssim 10^{9}\,\mathrm{g}$)
- Some may be unstable and evaporate before BBN ($M_{\mathrm{PBH}} \lesssim 10^{9}\,\mathrm{g}$)

Can (Seriously) affect the history of the Universe ...

DM from Evaporation

$$f_{\rm PBH}(M) = \delta(M - M_{\rm PBH})$$



[Cheek, LH, Perez-Gonzalez and Turner '22]