

Cosmological Stasis and Its Phenomenological Implications

Fei Huang

based on arXiv:2111.04753
arXiv:2212.01369
arXiv:2309.10345
arXiv:2406.06830
arXiv:2502.20449
arXiv:2503.19959
arXiv:2610.23808

with Dienes, Heurtier, Kim, Tait, Thomas
Dienes, Heurtier, Kim, Tait, Thomas
Dienes, Heurtier, Tait, Thomas
Dienes, Heurtier, Tait, Thomas
Knapp-Perez
Dienes, Heurtier, Hoover, Paulsen, Thomas
Dienes, Hajkarim, Heurtier, Sinha, Thomas, Xu

Oct 24, 2026

The Standard Lore: Λ CDM

Equation of State $w_i = \frac{P_i}{\rho_i}$

Vacuum Energy $w_\Lambda = -1$

Matter $w_M = 0$

Radiation $w_\gamma = \frac{1}{3}$

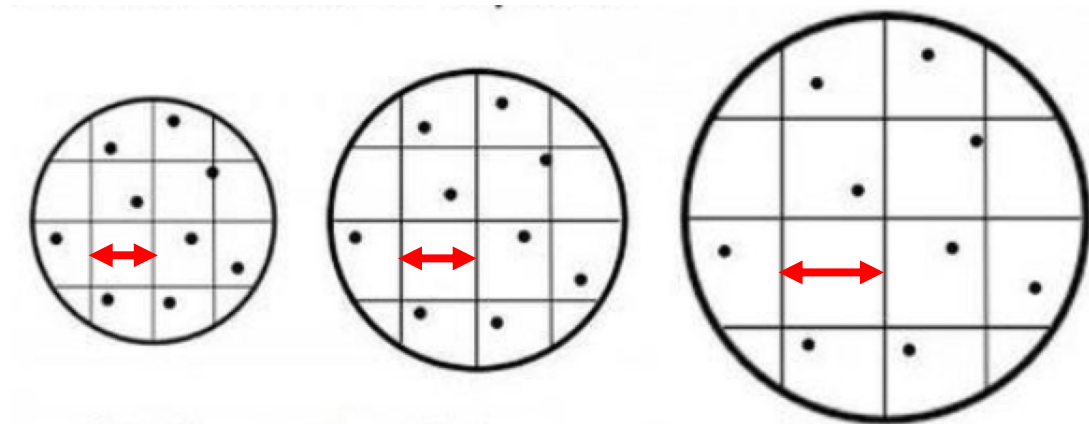
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Equation of State $w_i = \frac{P_i}{\rho_i} \rightarrow \frac{d\rho_i}{dt} = -3(1 + w_i)H\rho_i$
 $\rho_i \sim a^{-3(1+w_i)}$

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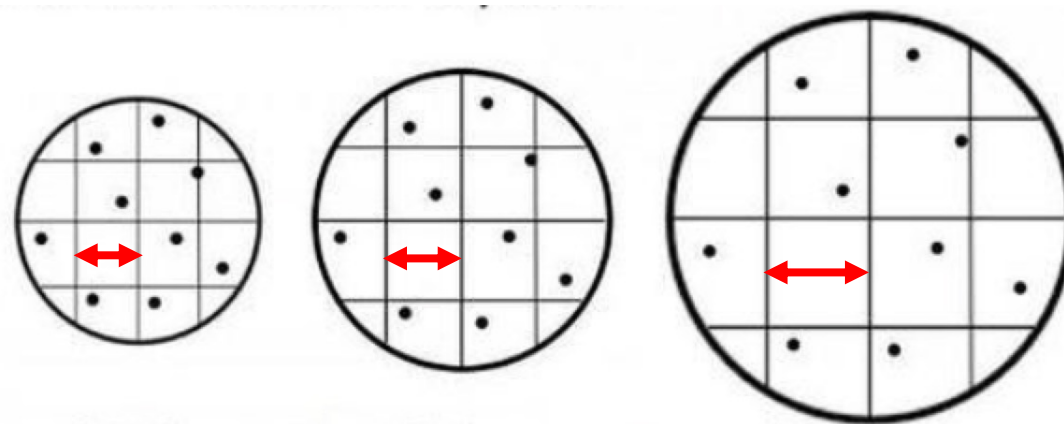
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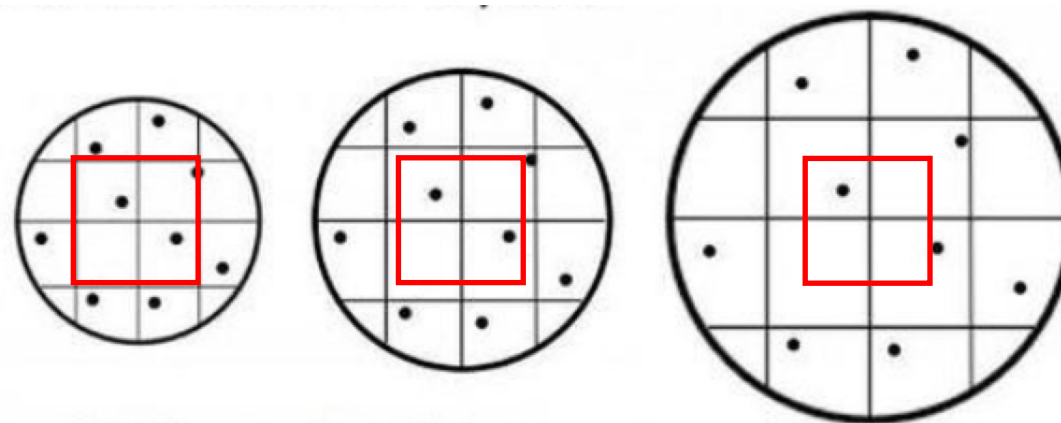
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$$\rho_M(t) = n_M(t) \times m$$

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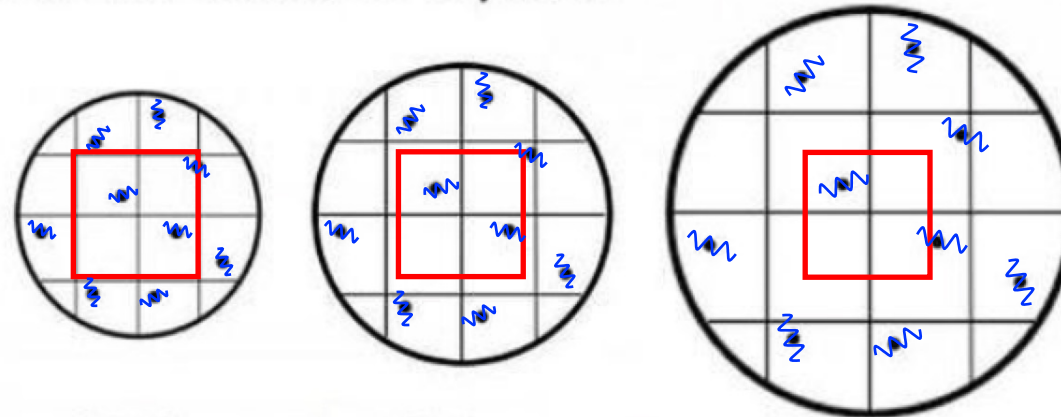
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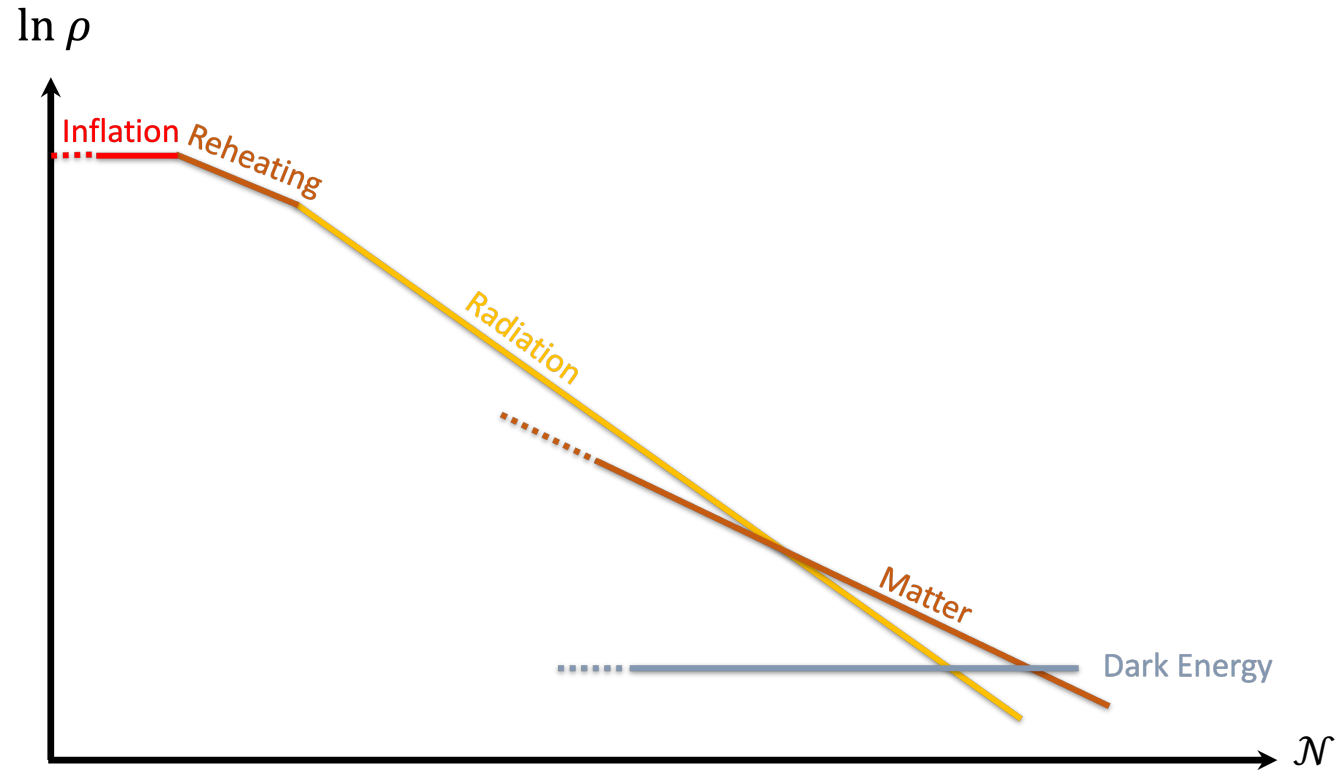
Radiation $w_\gamma = \frac{1}{3} \Rightarrow$

$$\begin{aligned} \rho_\Lambda &\sim a^0 \\ \rho_M &\sim a^{-3} \\ \rho_\gamma &\sim a^{-4} \end{aligned}$$



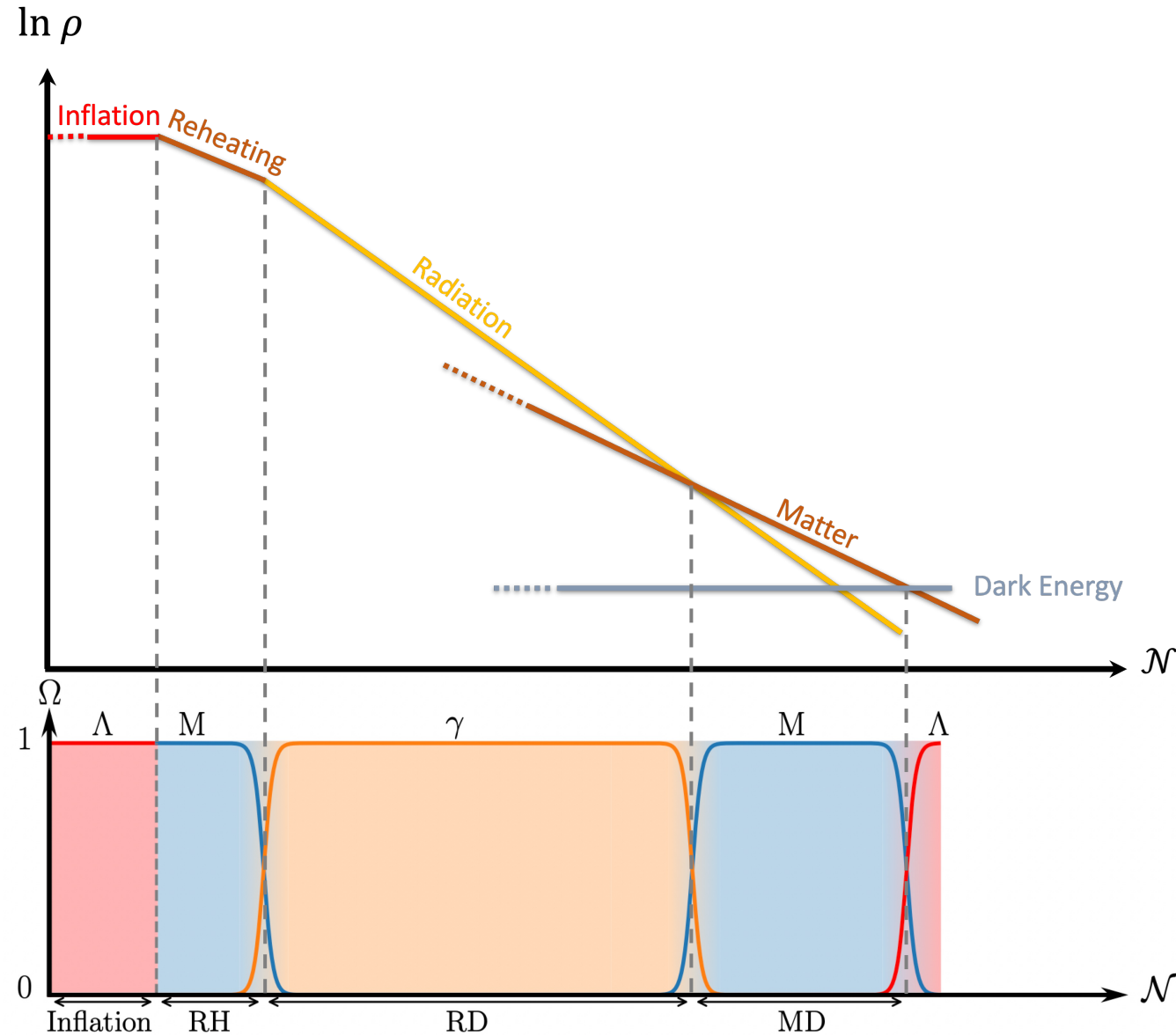
$$\begin{aligned} \ell_{phys}(t) &= a(t)\ell \\ E &\approx p \sim 1/\lambda \\ \rho_\gamma(t) &= n_\gamma(t) \times p \end{aligned}$$

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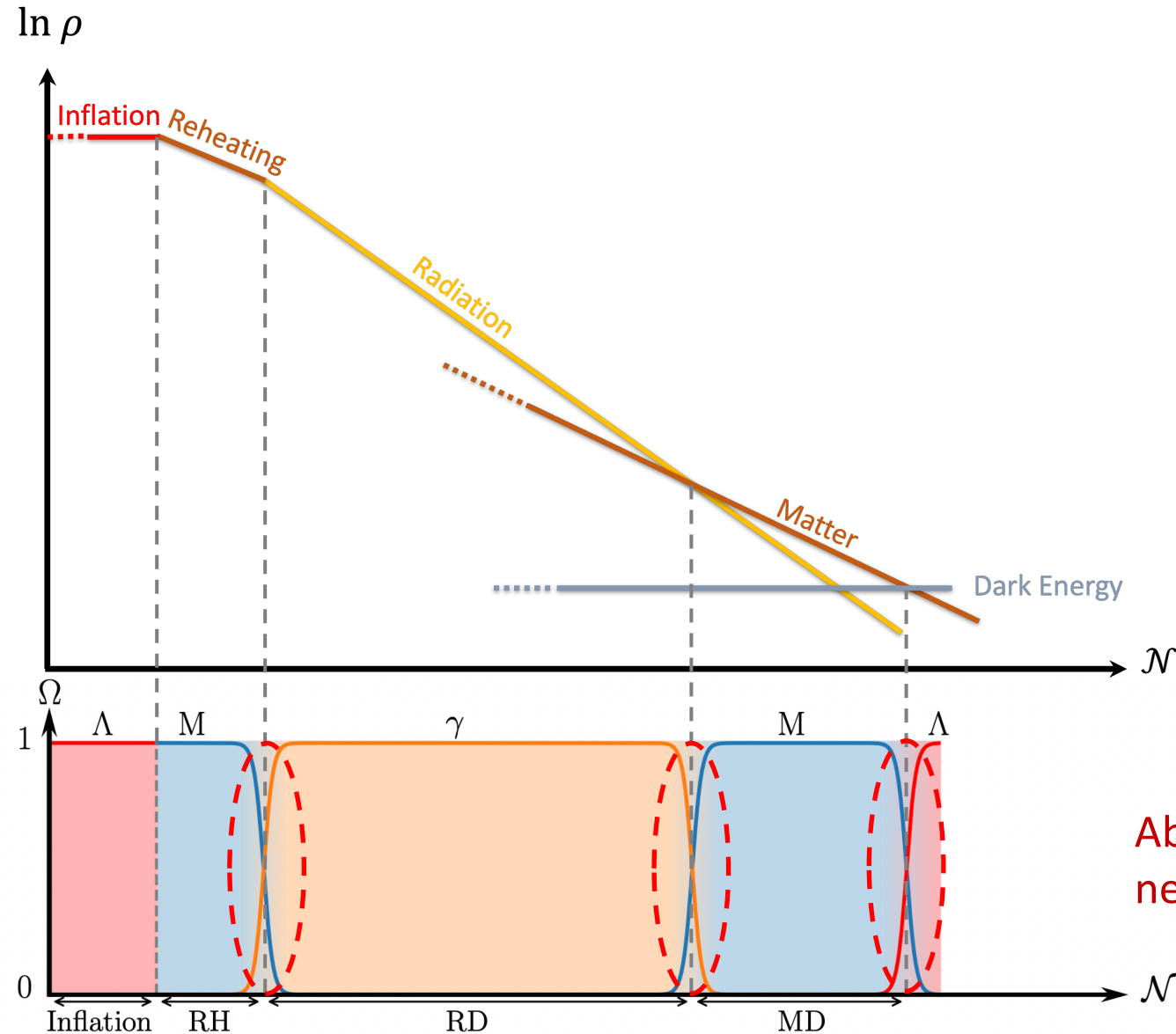
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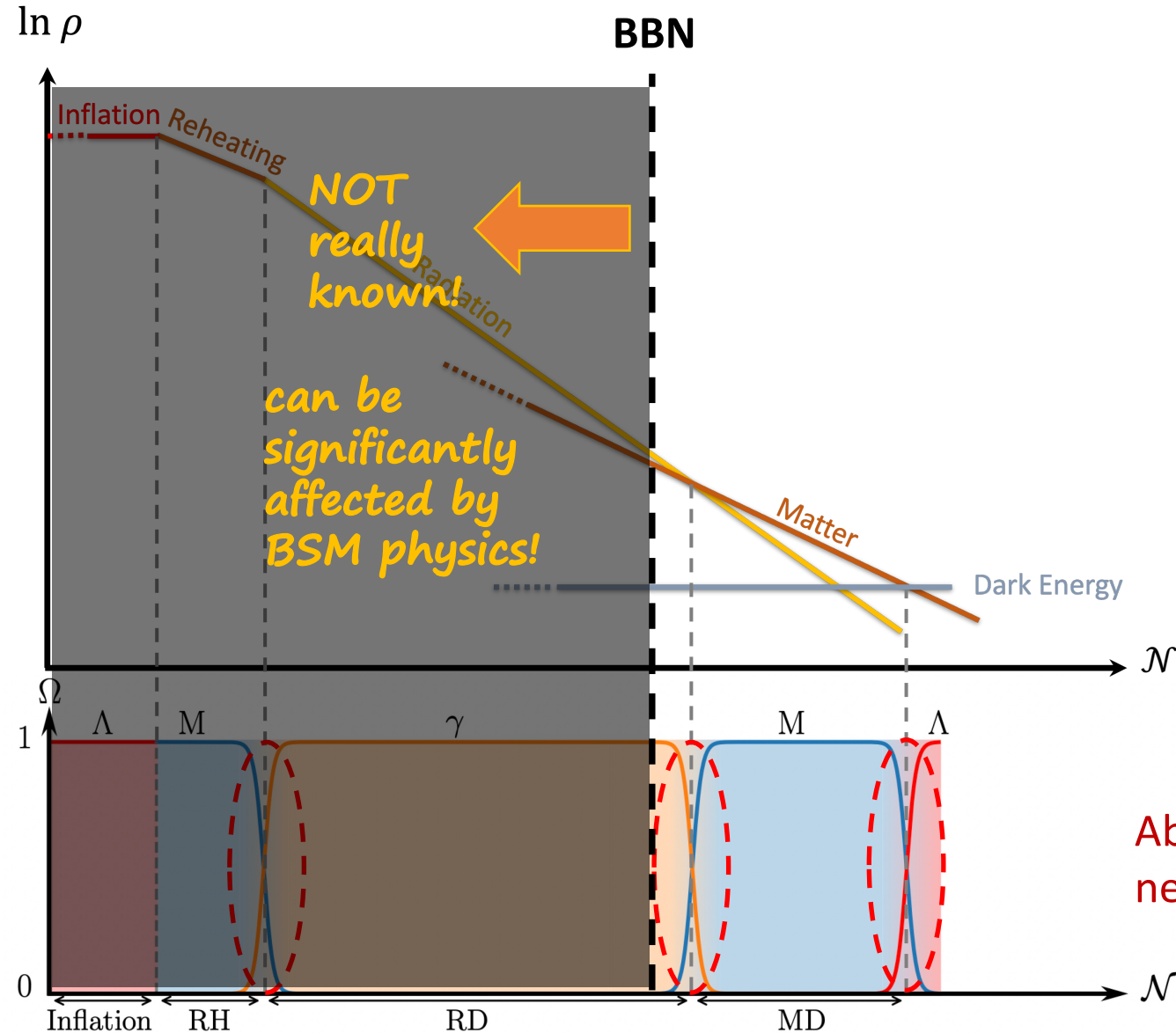


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Indeed, the Λ CDM picture can be potentially **incorrect** in the presence of many kinds of BSM physics...

A wide variety of scenarios for BSM physics predict towers of unstable states with a broad spectrum of masses, lifetimes and cosmological abundances, for example

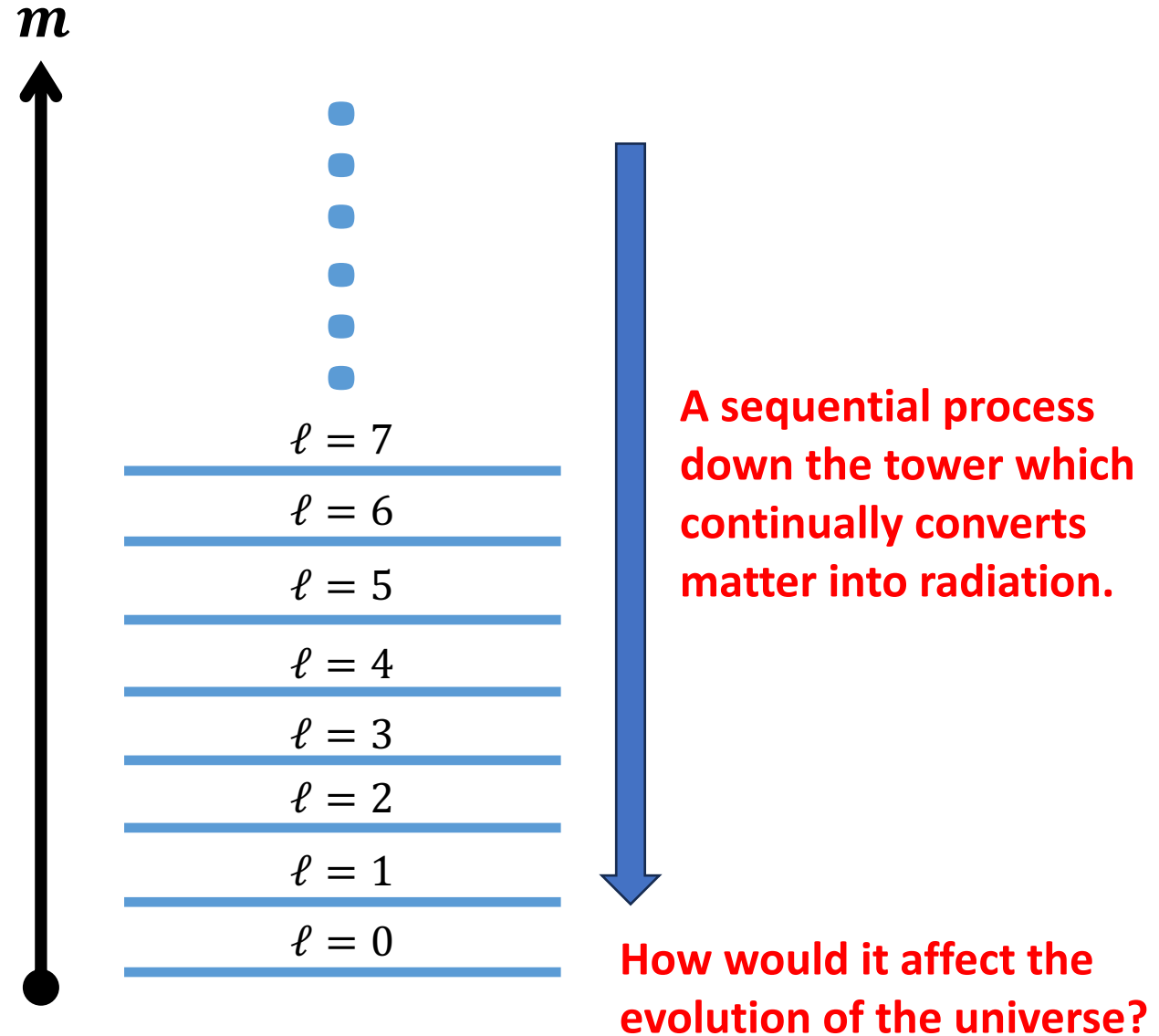
- Theories with extra spacetime dimensions (KK towers)
- String theory (string moduli, axions, KK towers, oscillator states)
- Scenarios with confining dark/hidden-sector gauge groups (bound-state resonances)
- PBHs with extended mass spectrum



If any of these towers exists in the early universe, dynamics across the entire tower can affect the evolution of the universe significantly.

Example: A Decaying Tower

- A Tower of (matter) states, mass spectrum generally stretches across many orders of magnitude.
- Such states are generally unstable and can decay.
- Heavier states at top of tower tend to decay first, then lighter ones. Decays thus proceed “down the tower”.
- Let us assume the decay products are light particles outside of the tower, e.g., photons or other light particles in a thermal bath.



Example: A Decaying Tower

$$\frac{d\rho_\ell}{dt} = -3H\rho_\ell$$

$$\frac{d\rho_\gamma}{dt} = -4H\rho_\gamma$$

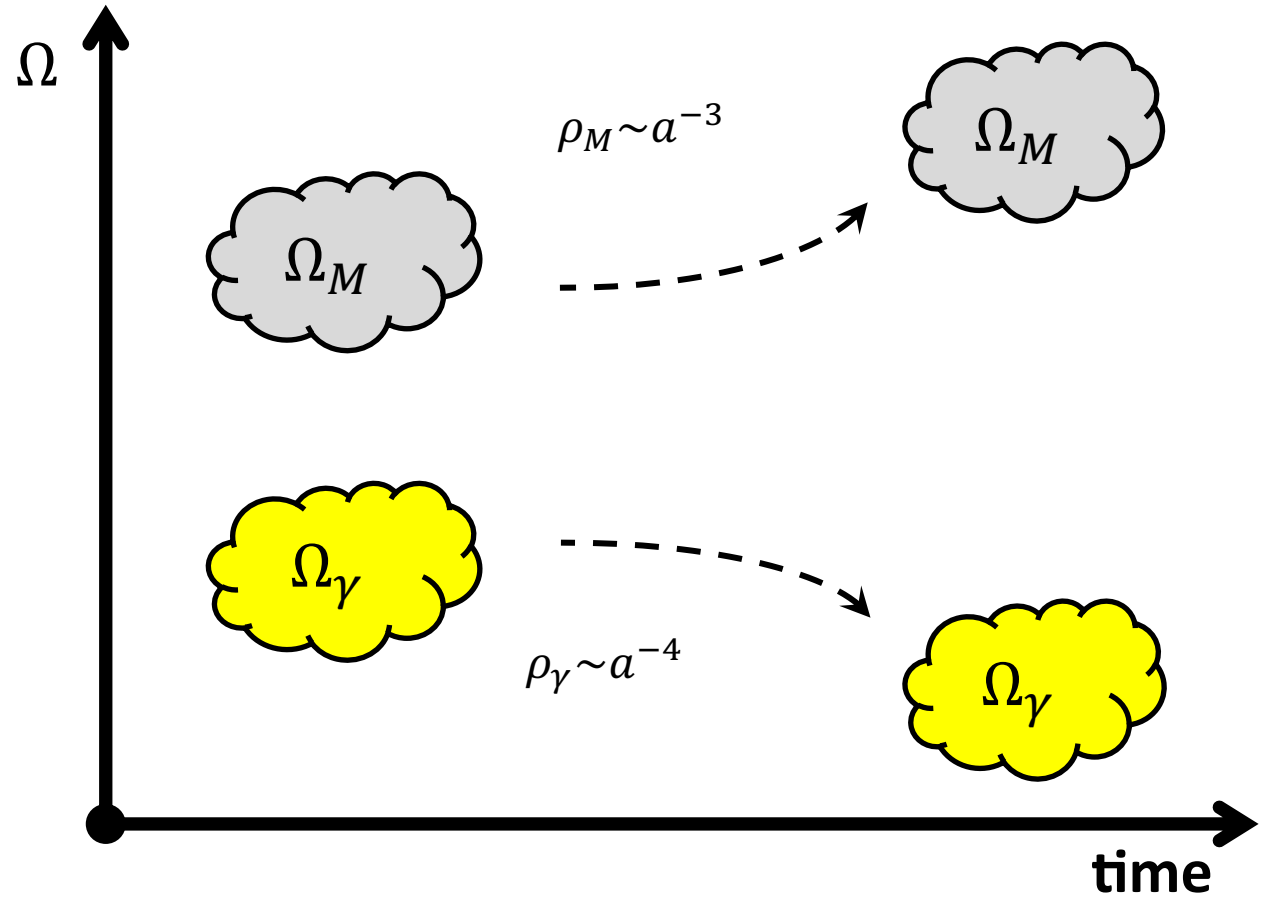
$$H^2 = \frac{8\pi G}{3}(\rho_M + \rho_\gamma)$$

↓

$$\Omega_\ell = \frac{8\pi G}{3H^2}\rho_\ell$$
$$\Omega_M = \sum_\ell \Omega_\ell$$

$$\frac{d\Omega_M}{dt} = H\Omega_M\Omega_\gamma$$

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$$\frac{d\rho_\ell}{dt} = -3H\rho_\ell - \Gamma_\ell\rho_\ell$$

$$\frac{d\rho_\gamma}{dt} = -4H\rho_\gamma + \sum_\ell \Gamma_\ell\rho_\ell$$

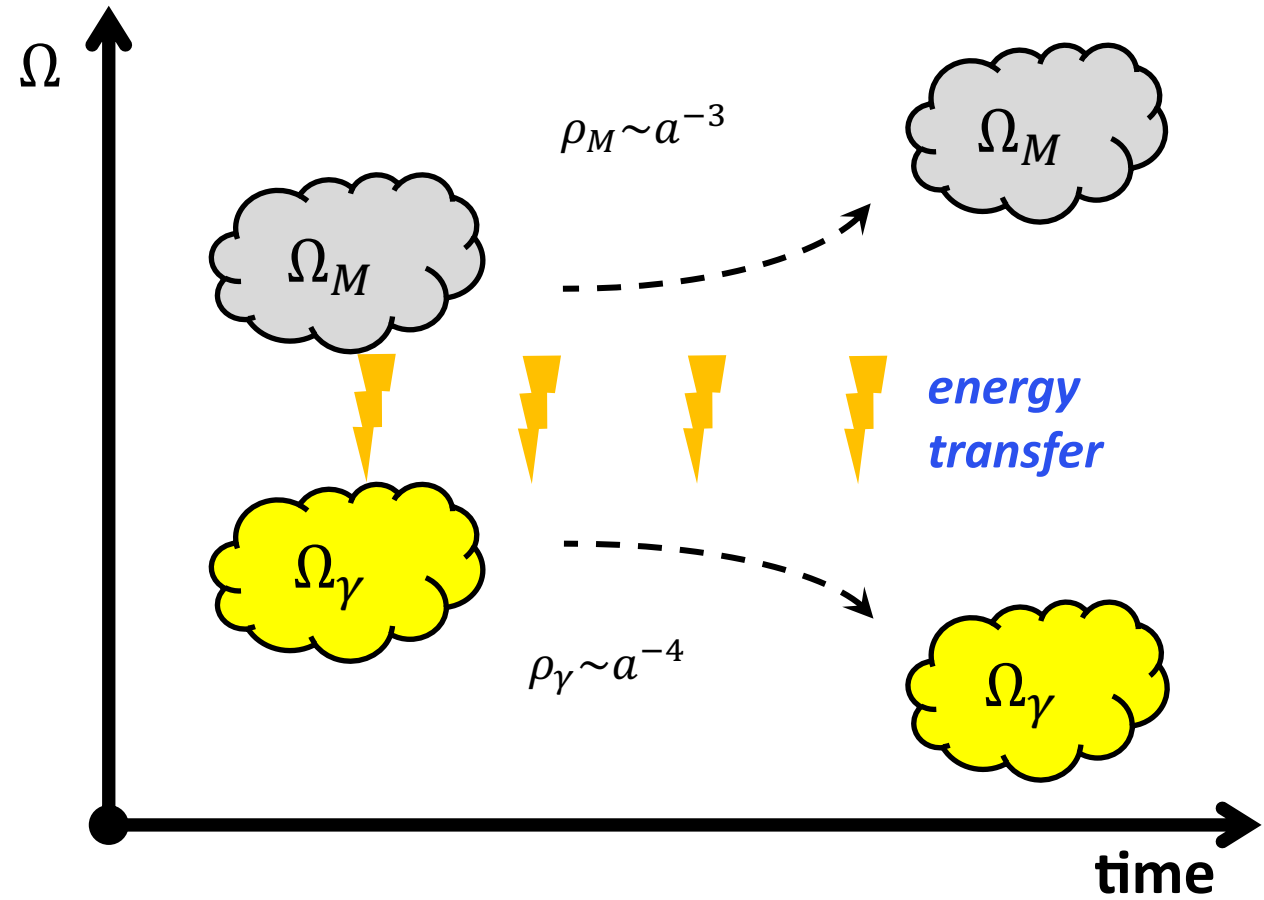
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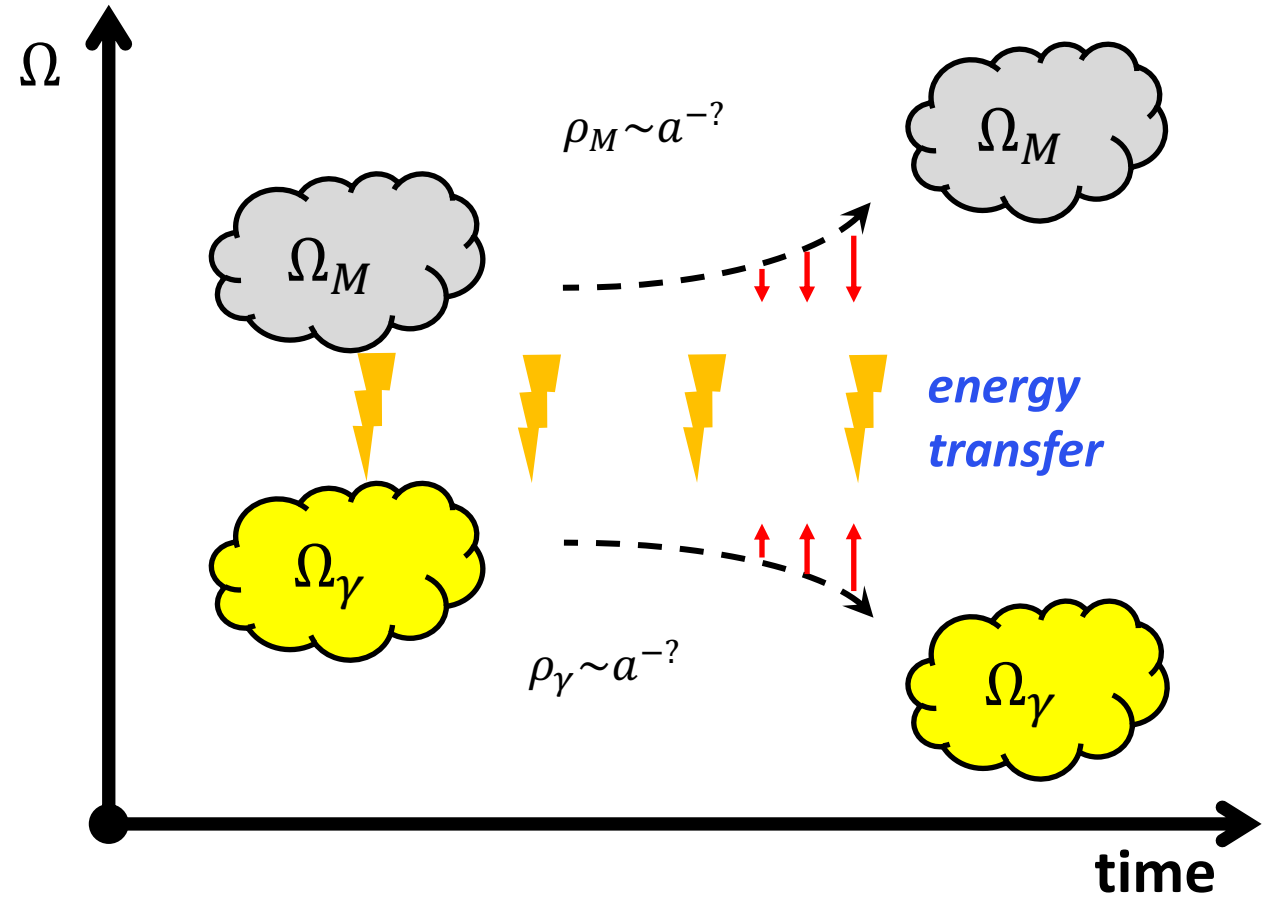
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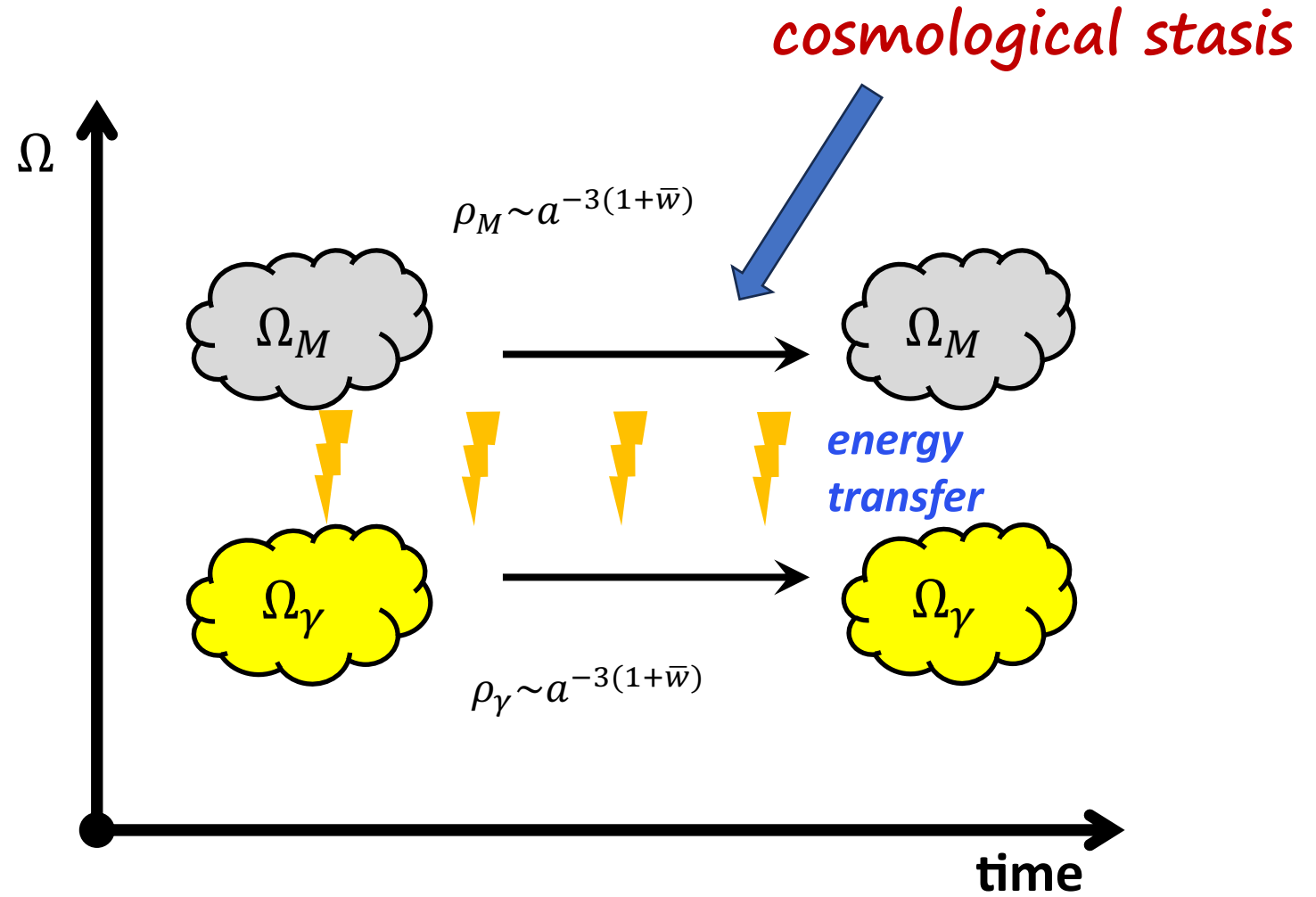
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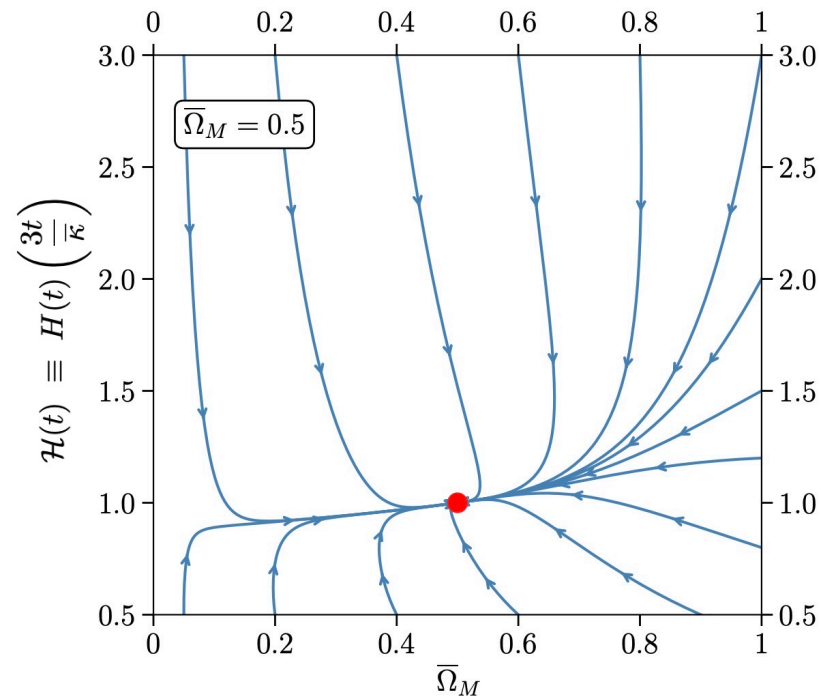


Why do we care about cosmological stasis?

- Naturally occurs in a variety of BSM scenarios
 - **tower dynamics** in theories of extra dimension, string axiverse, PBHs
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- **Global attractor** for a wide range of parameters, no finetuning, even **unavoidable**!!!



Especially remarkable because particle decay and cosmological expansion are very different things --- one is particle physics, the other cosmology!

For example, we can parametrize

A tower of states

Mass Spectrum

$$m_\ell = m_0 + (\Delta m)\ell^\delta$$

Decay Widths

$$\Gamma_\ell = \Gamma_0 \left(\frac{m_\ell}{m_0} \right)^\gamma$$

Initial Abundances

$$\Omega_\ell^{(0)} = \Omega_0^{(0)} \left(\frac{m_\ell}{m_0} \right)^\alpha$$

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Mass spectrum depends on particle physics model

- KK excitations of a 5-d scalar field compactified on a circle of radius R
 - $\delta \sim 1$ for $mR \ll 1$
 - $\delta \sim 2$ for $mR \gg 1$
- Bound states of strongly-coupled gauge theory
 - $\delta \sim 1/2$
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 - $m_\ell \sim m_0 \exp(\mu\ell)$

Halverson and Pandya
arXiv:2408.00835

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Depends on the production mechanism

- misalignment production $\longrightarrow \alpha < 0$
- thermal freeze-out $\longrightarrow \alpha > 0$ or $\alpha < 0$
- universal inflaton decay $\longrightarrow \alpha \sim 1$
- PBH evaporation $\longrightarrow \alpha \sim \pm 1$
- Gravitational production $\longrightarrow \alpha \sim 1, 1/2, 2$

Long, Sham Es Haghi, Venegas
arXiv:2506.04502



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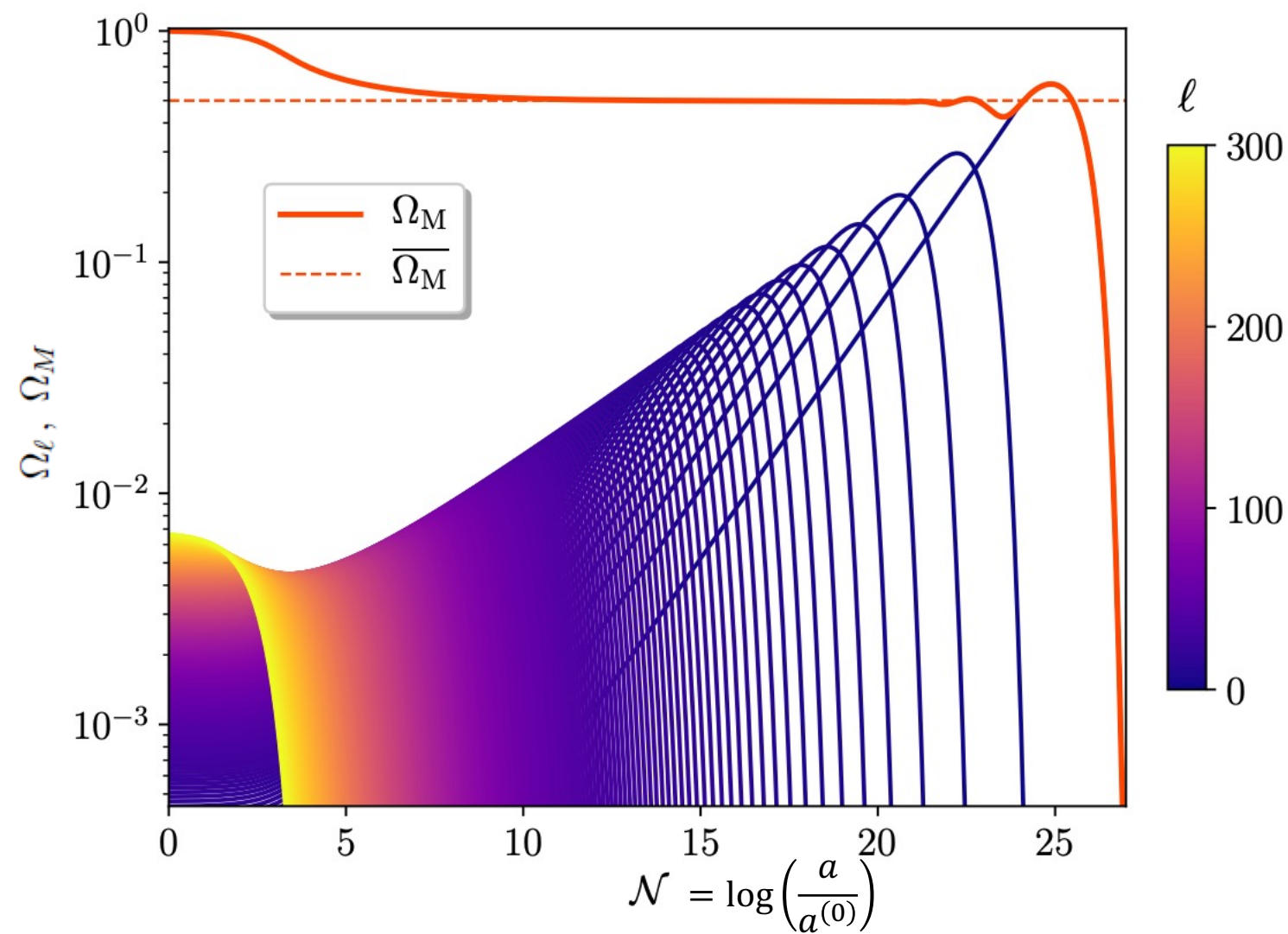
Stasis arises for all values of these parameters within the range

$$\alpha + 1/\delta \in (0, \gamma/2)$$

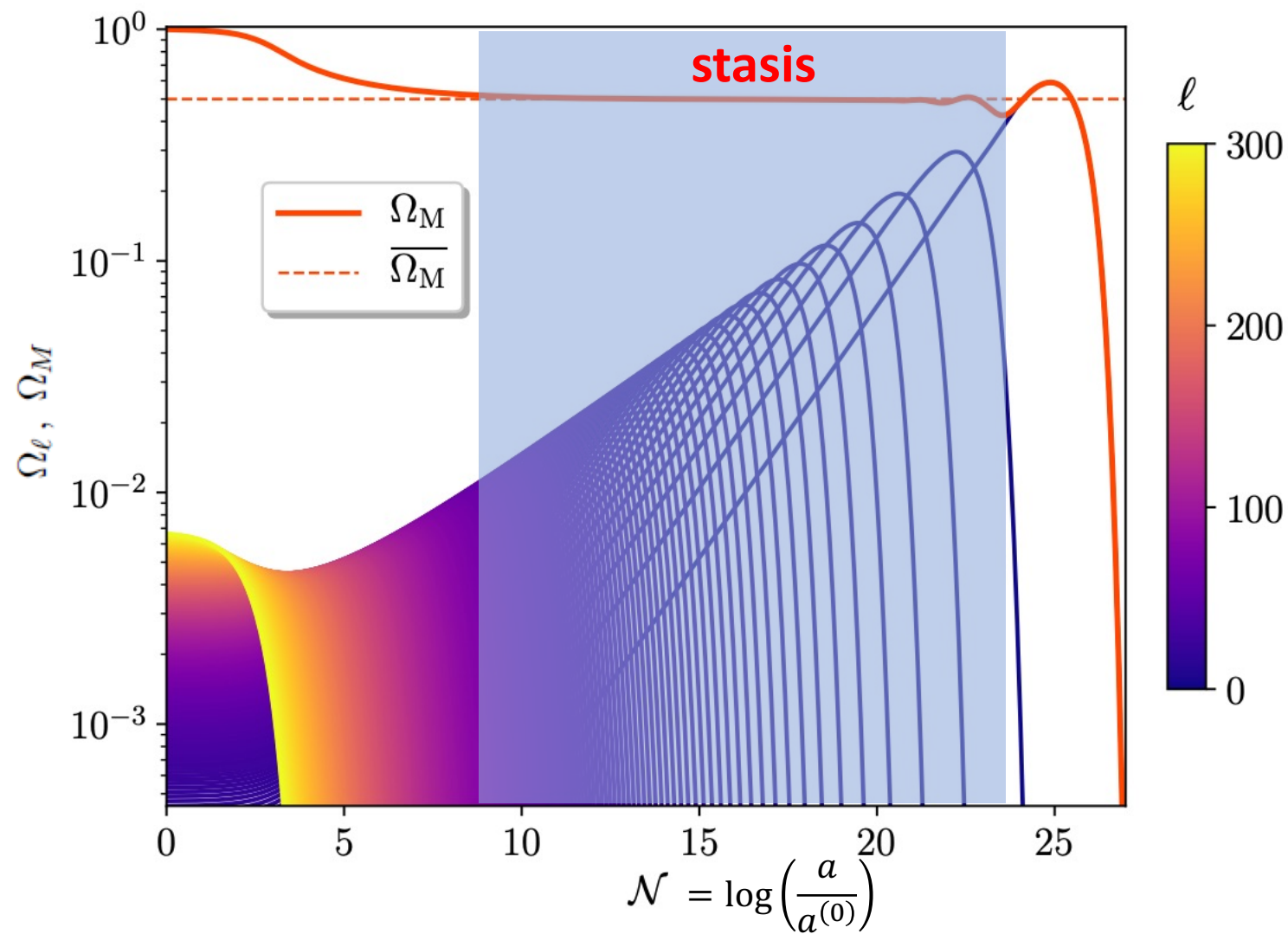
regardless of $m_0, \Delta m, \Gamma_0, \Omega_0^{(0)}$.

$$\bar{\Omega}_M = \frac{2\gamma\delta - 4(1 + \alpha\delta)}{2\gamma\delta - (1 + \alpha\delta)}, \quad \bar{\Omega}_\gamma = 1 - \bar{\Omega}_M$$

$$\bar{w} = w_M \bar{\Omega}_M + w_\gamma \bar{\Omega}_\gamma = \frac{1 - \bar{\Omega}_M}{3}$$



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How do we know if the universe had gone through a period of stasis?

In other words, what are the observational consequences?

At the background level

Matter $w_M = 0$

Radiation $w_\gamma = \frac{1}{3}$



effective EoS parameter

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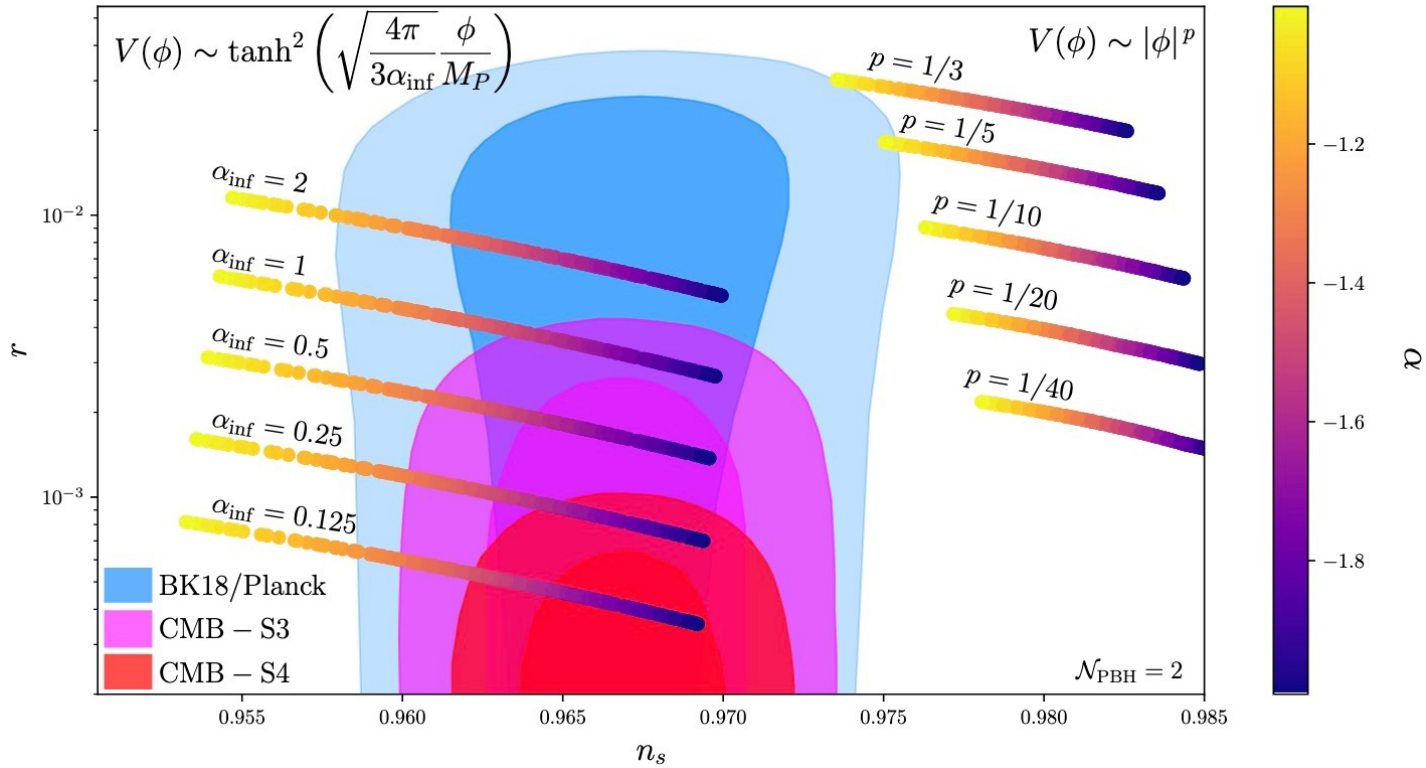
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- Such modified background expansion histories can lead to observational implications.

Effects from modified background expansion history

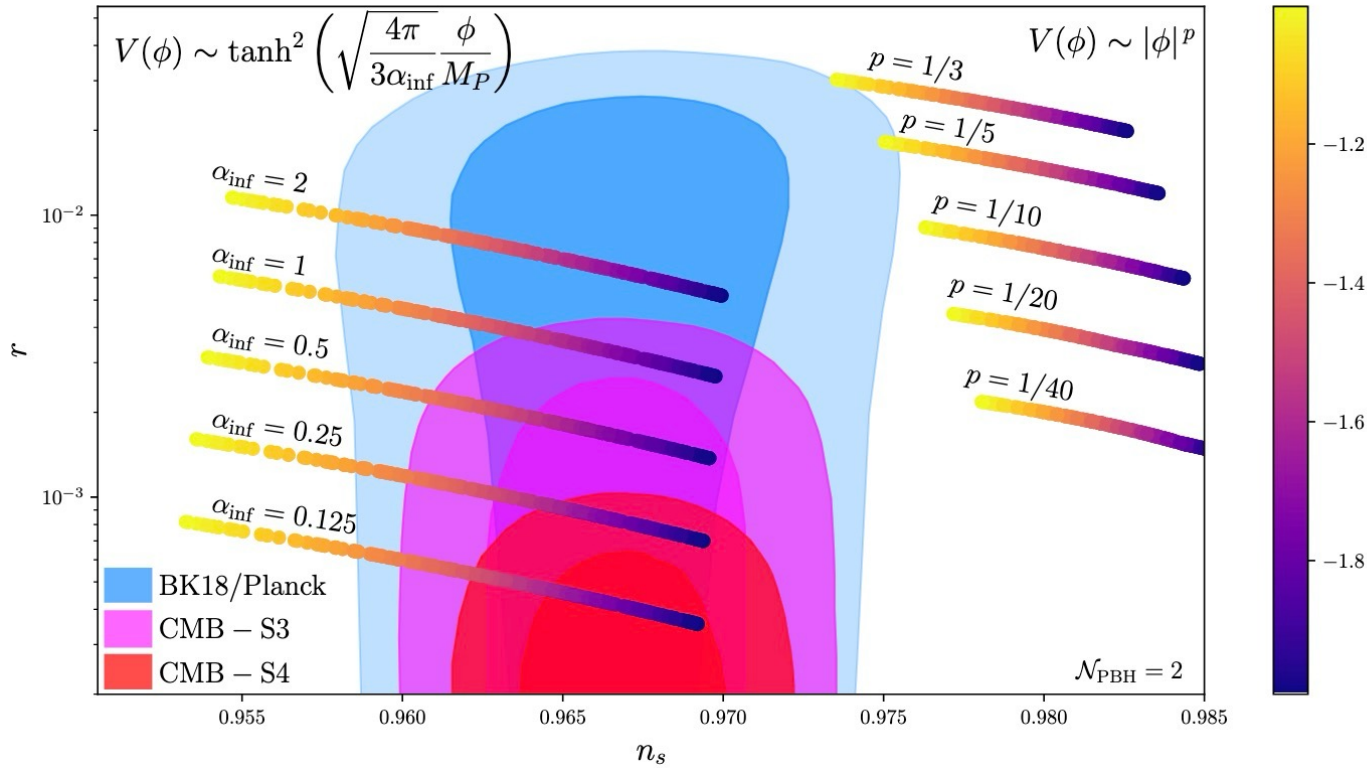
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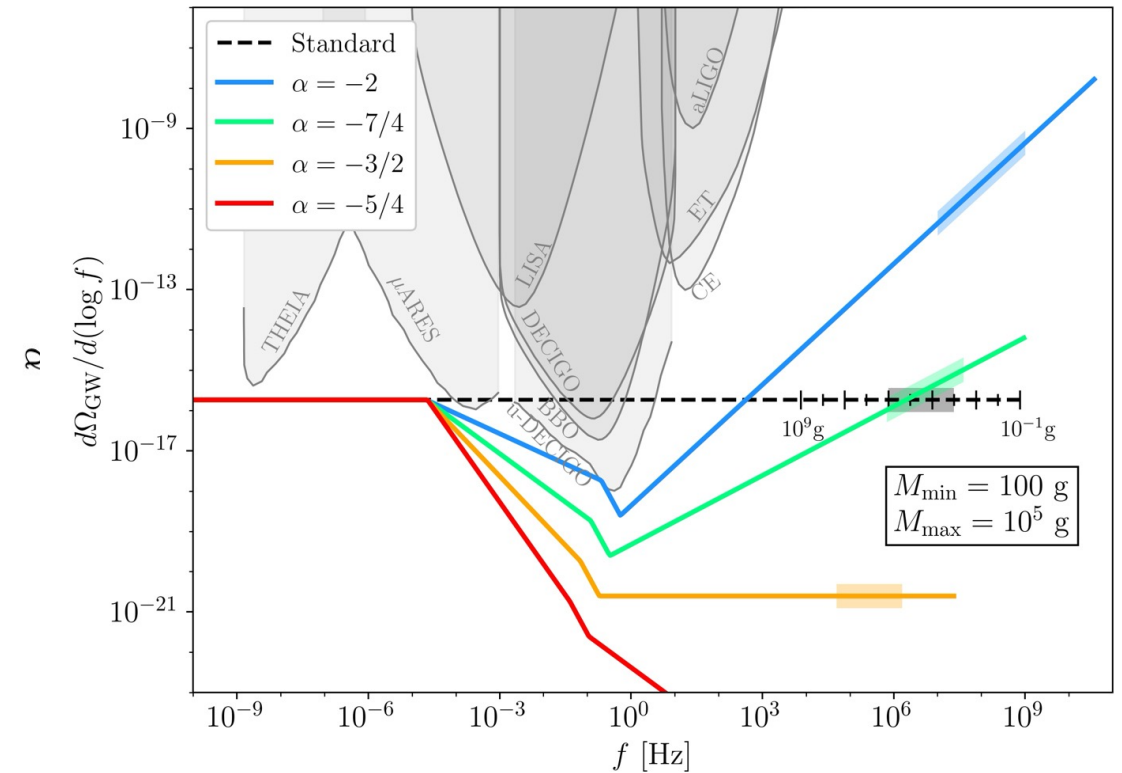
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distorts the GW spectrum from inflation,
 which would be scale-invariant in ΛCDM

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Need to look at the perturbation level!

Observational signatures at the perturbation level

More specifically, let's consider

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We'll now examine how density perturbations $\delta_\chi \equiv \Delta\rho_\chi/\rho_\chi$ evolves during a **matter/radiation stasis** (and the corresponding PFD epoch) with $0 < \bar{w} < 1/3$.

As we'll see, the results differ significantly in these two scenarios!

Observational signatures at the perturbation level

Equation of motion for $\delta_{k\chi}$

$$\delta''_{k\chi} + \frac{3}{2a} (1 - \langle w \rangle) \delta'_{k\chi} = -3\Phi''_k - \frac{9}{2a} (1 - \langle w \rangle) \Phi'_k + \tilde{k}^2 a^{3\langle w \rangle - 1} \Phi_k$$

Evolution of Φ_k

$$\Phi''_k + \frac{(7 + 3\langle w \rangle)}{2a} \Phi'_k + \frac{\langle w \rangle k^2}{a^4 H^2} \Phi_k = \frac{4\pi G}{a^2 H^2} \sum_X \bar{\rho}_X \delta_{kX} (\langle w \rangle - c_{sX}^2)$$

Effective sound
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Vanishes!

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Effective sound speed of X

stasis:

$$\begin{aligned} w_\ell &= c_{s\ell}^2 = 0 \\ w_\gamma &= c_{s\gamma}^2 = 1/3 \\ \langle w \rangle &= w_\gamma \Omega_\gamma + \sum_\ell w_\ell \Omega_\ell \end{aligned}$$

Doesn't generally vanish!

Φ_k and δ_{kX} non-trivially **coupled** during stasis.

Vanishes!

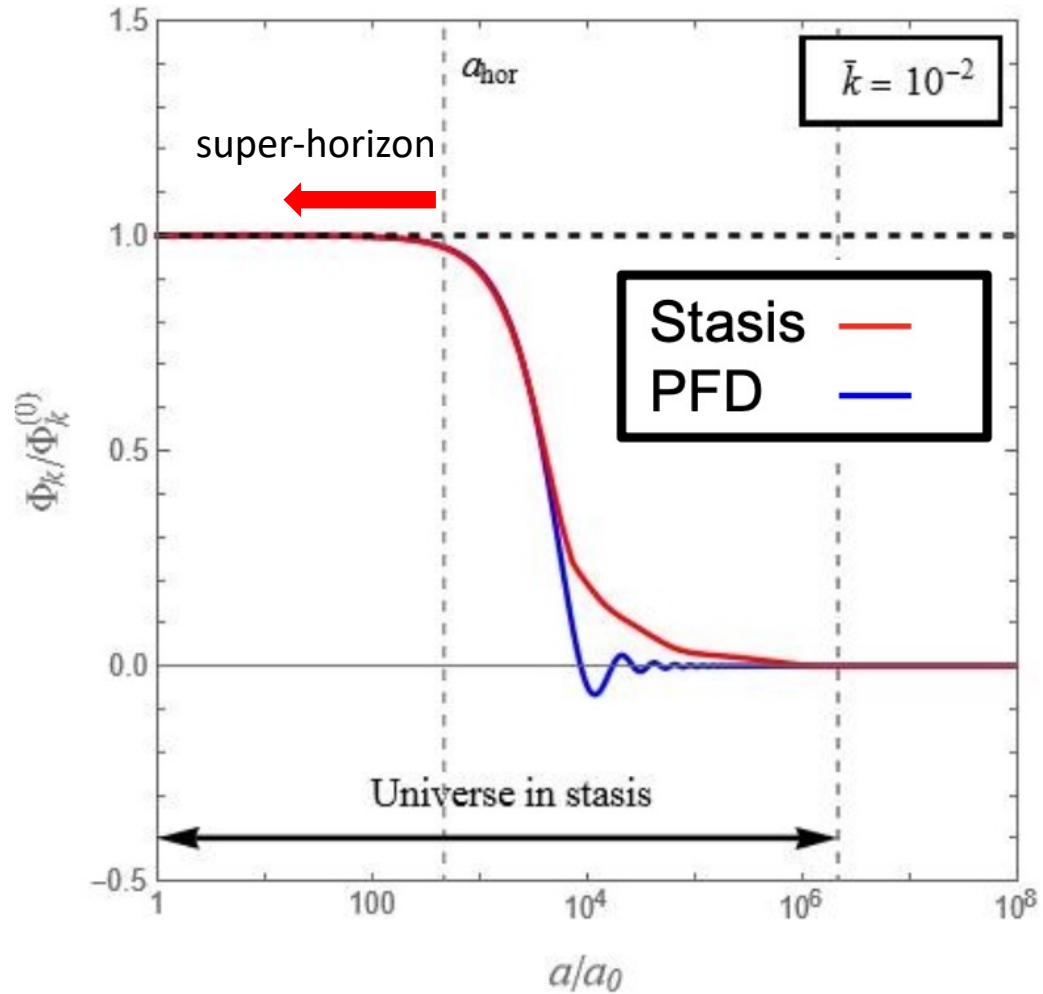
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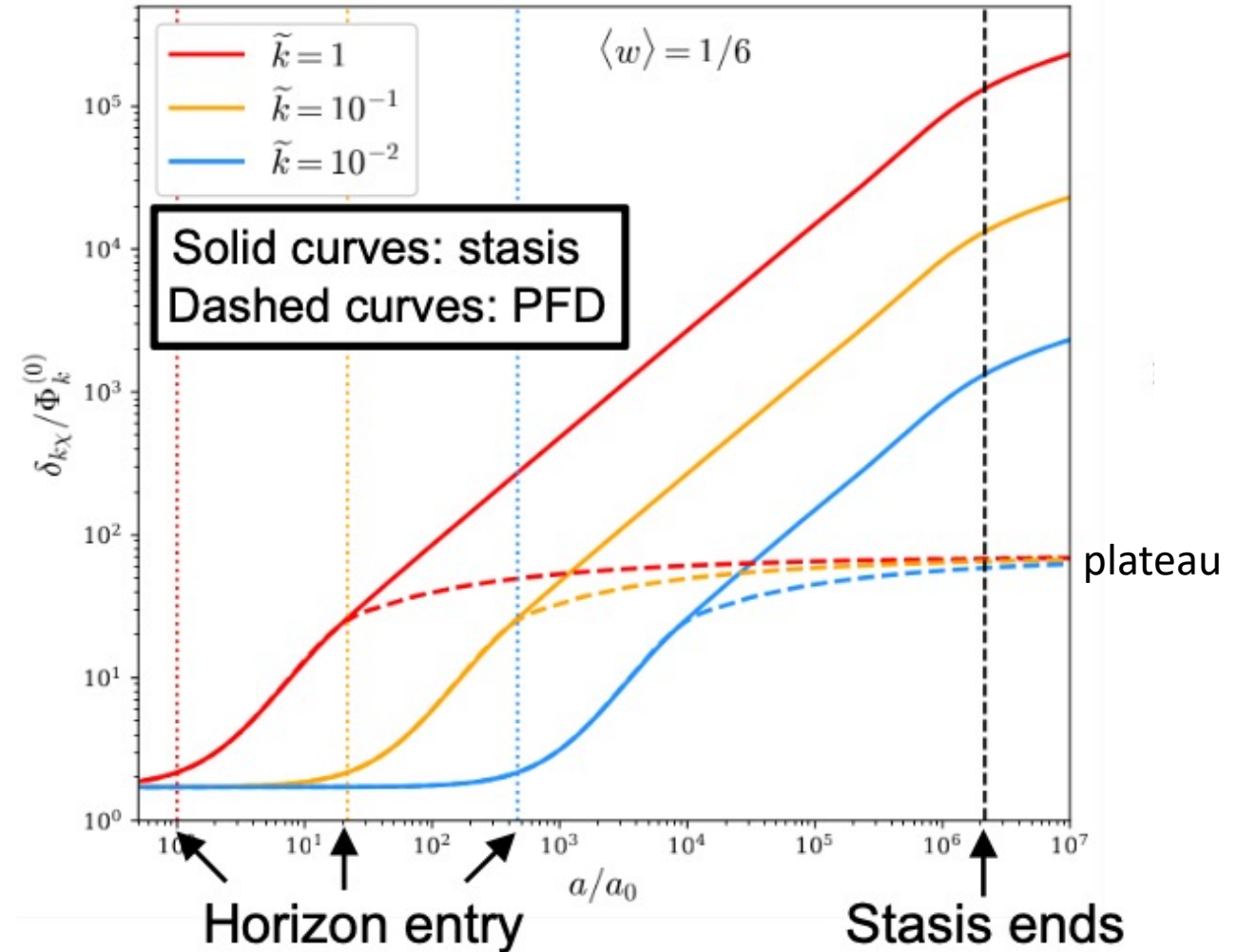
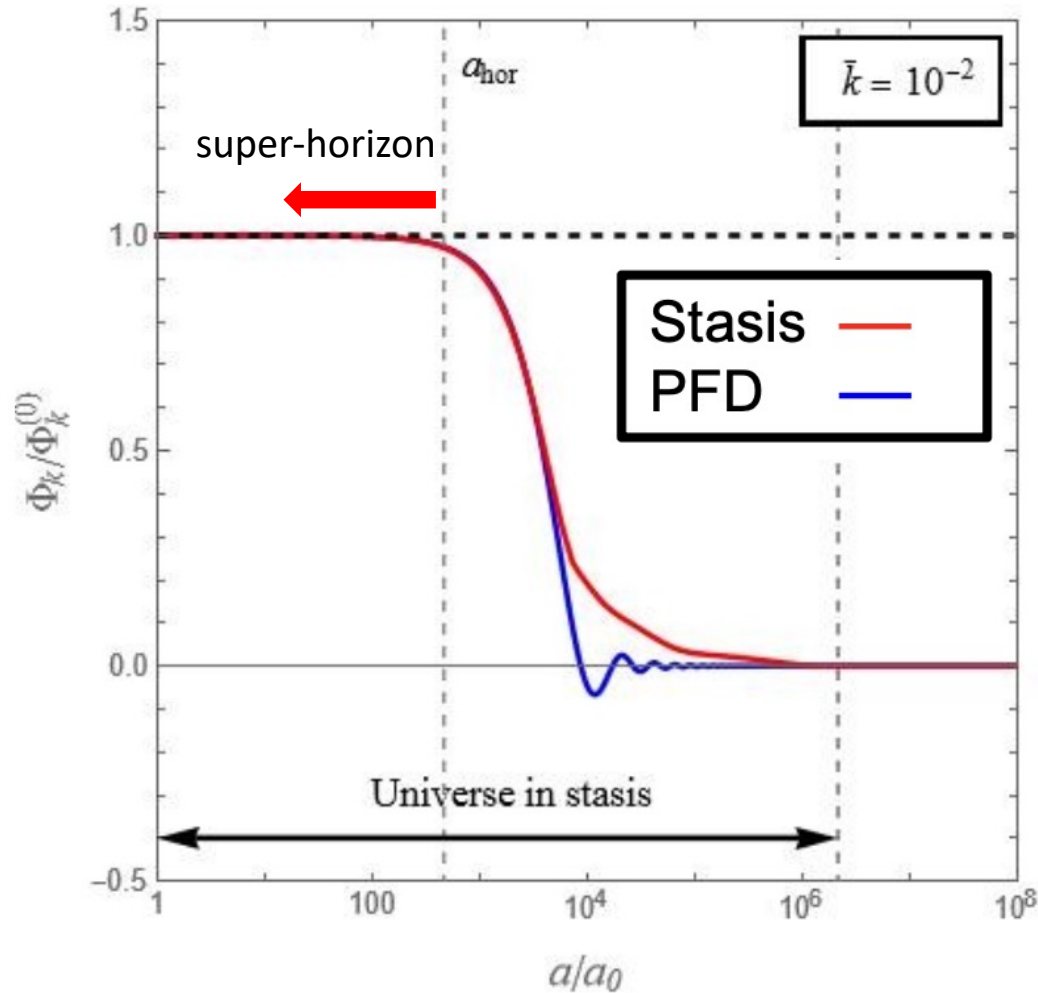
Observational signatures at the perturbation level

Dienes, Heurtier, Hoover,
FH, Paulsen, Thomas
arXiv: 2503.19959



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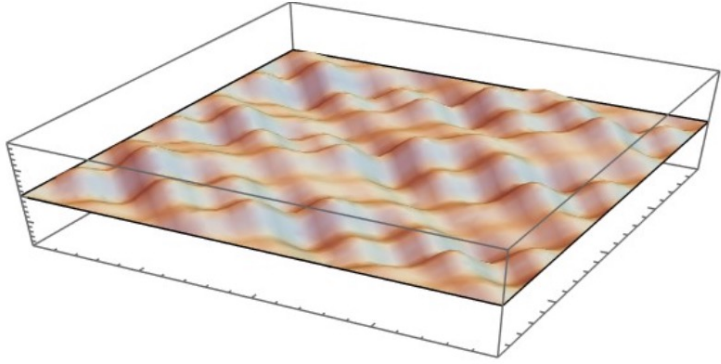


PFD: $\delta_{k\chi}$ reaches plateau

stasis: $\delta_{k\chi} \sim a^{q(\langle w \rangle)}$, enhanced, power-law growth

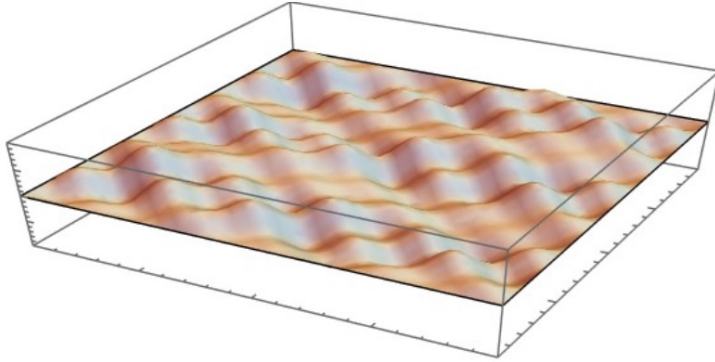
Observational signatures at the perturbation level

Small primordial inhomogeneities in the matter density provide the seeds for the formation of structure at later times.



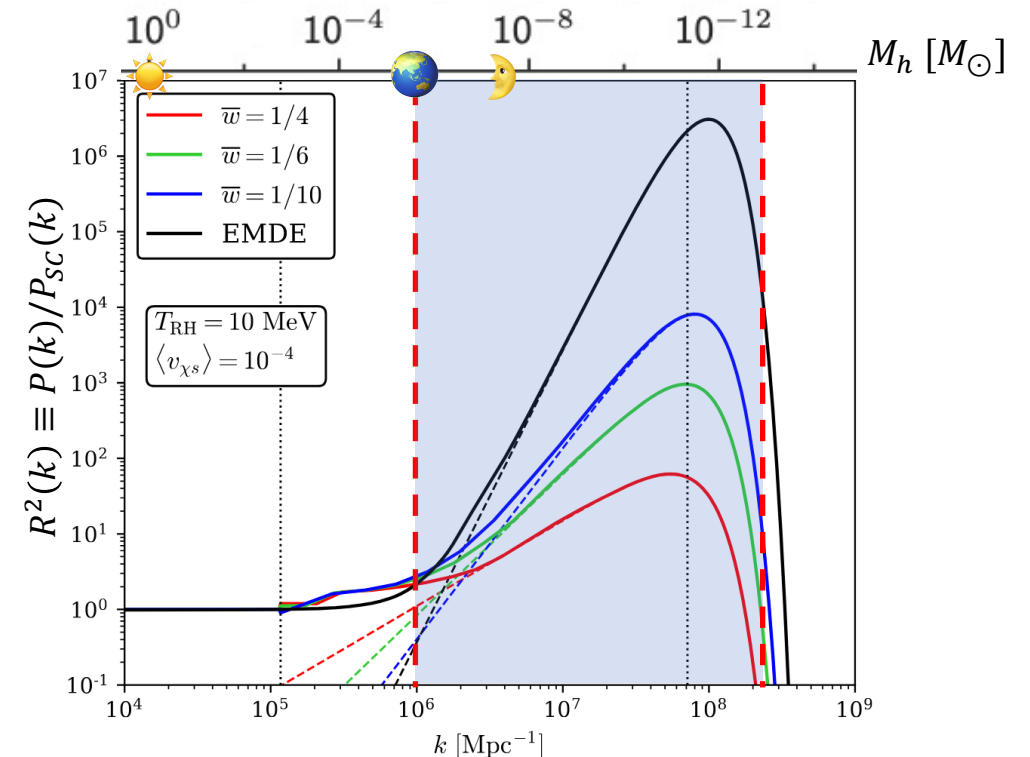
Observational signatures at the perturbation level

Small primordial inhomogeneities in the matter density provide the seeds for the formation of structure at later times.



Enhancements or suppressions in the **linear matter power spectrum** relative to the standard cosmology across different ranges of k can have observational consequences for **cosmic structure**.

In the stasis case, they could lead to the formation of small, dense clumps of matter – **microhalos** at earth and sub-earth masses.



Observational signatures at the perturbation level - SIGW

- Scalar perturbations can induce GWs at the 2nd order.
- SIGWs produced during stasis differ from Λ CDM due to
 - a different Φ_k
 - nontrivial velocity effects including both the **bulk motion** of the fluids and the **relative motion** between the fluids



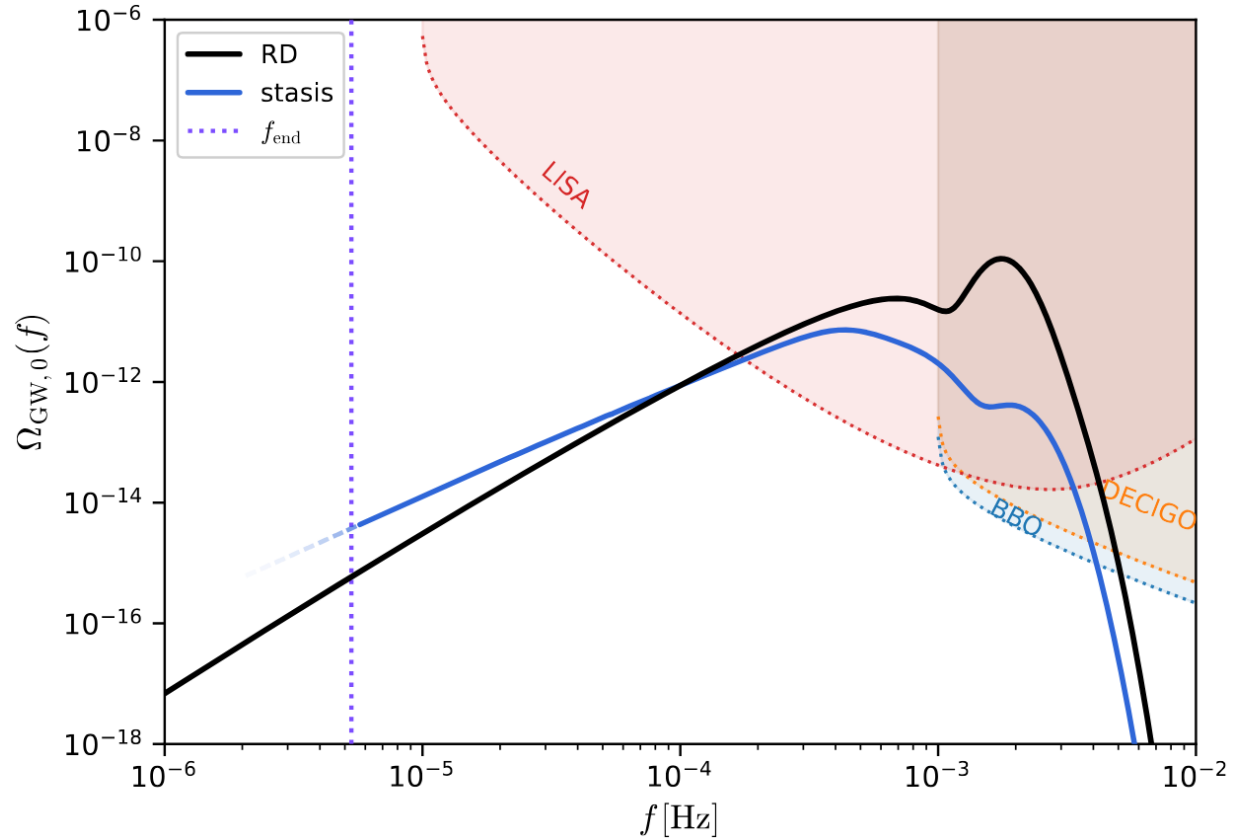
New formalism needed to accommodate the **multi-fluid** nature of stasis!

Observational signatures at the perturbation level - SIGW

Dienes, Heurtier, Hajkarim,
FH, Sinha, Thomas, Xu
arXiv: 2610.23808

- Scalar perturbations can induce GWs at the 2nd order.
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New formalism needed to accommodate the multi-fluid nature of stasis!

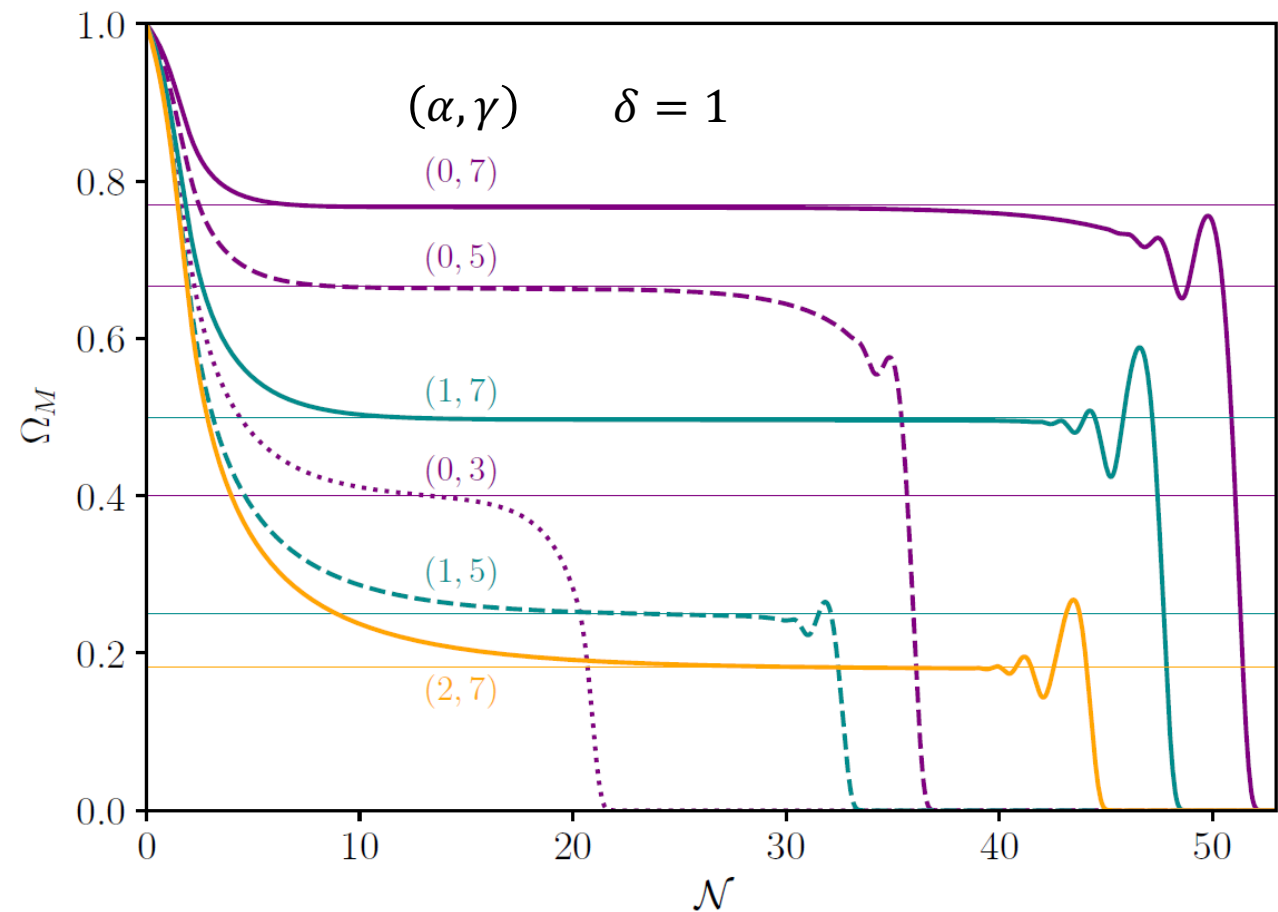


- Resulting GW spectrum has a significantly different shape compared to that in Λ CDM.

Summary

- **Stable, mixed-component cosmological eras** – i.e., **stasis eras** – are a viable cosmological possibility – and one that can arise naturally in many extensions of the Standard Model.
- The existence of a stasis epoch can lead to a number of phenomenological implications, at background level, it affects the predictions on the inflationary observables, primordial gravitational wave background,
- At the perturbation level, stasis can lead to enhanced formation of small scale structures, and a spectrum of SIGW that is distinctly different from the standard cosmology

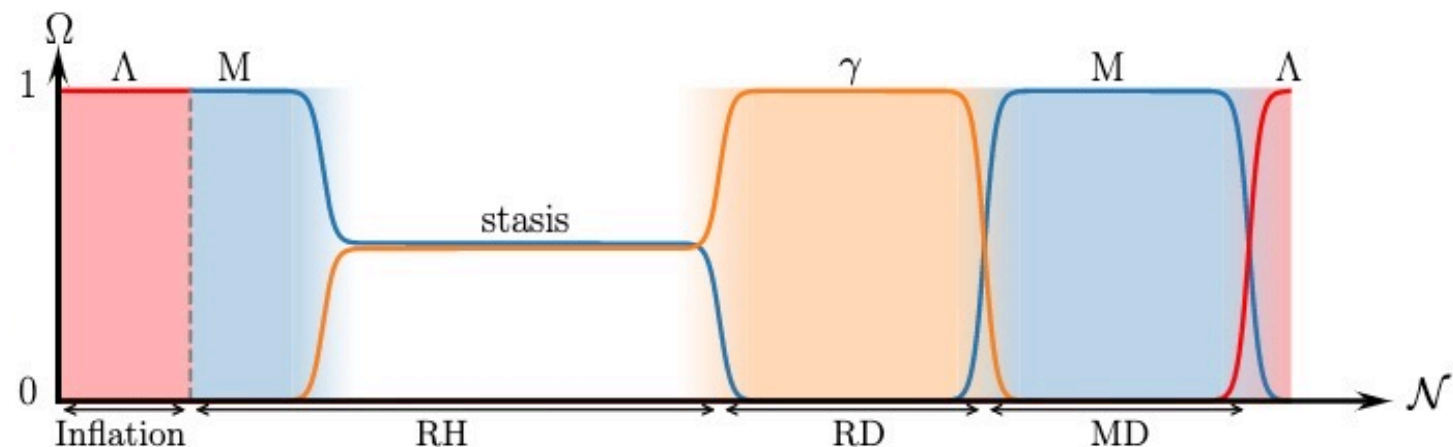
Similar behavior for other parameter choices



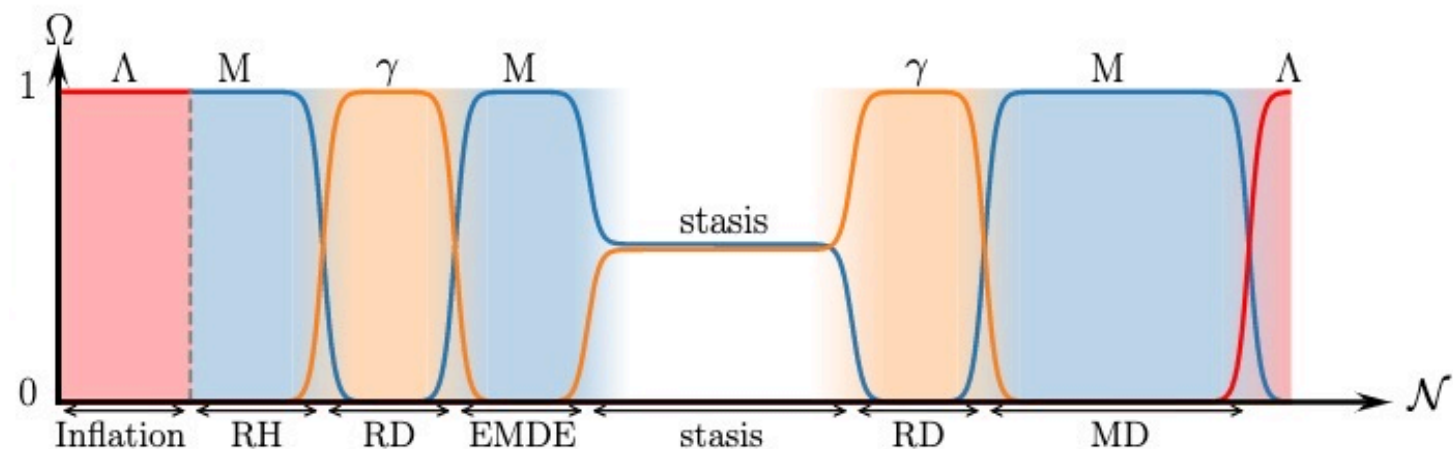
Stasis always emerges, only the stasis abundance changes

Where does stasis arise?

Reheating occurs during the stasis epoch and results from decays of states in the tower

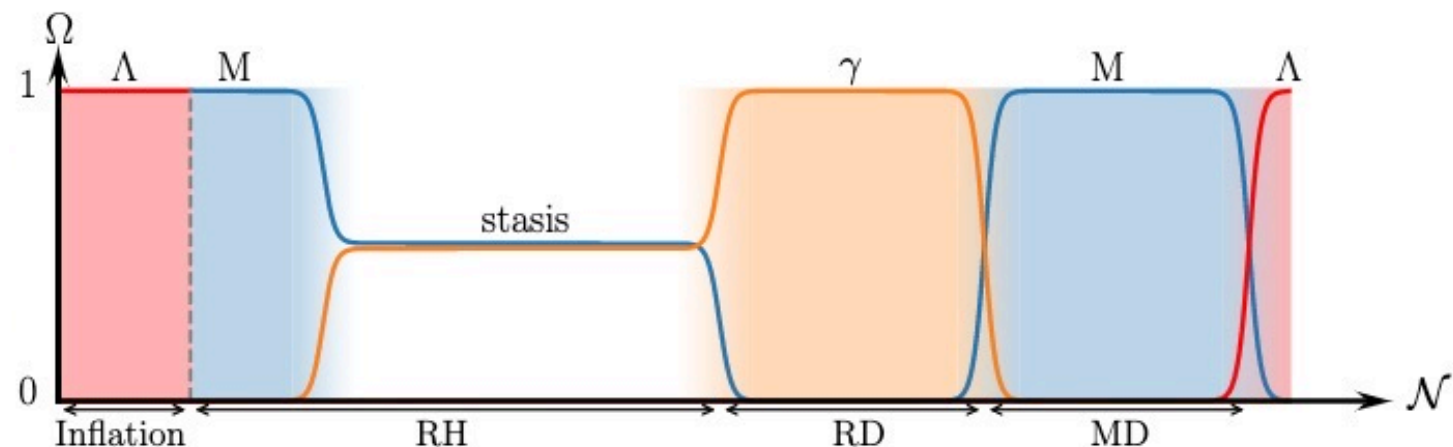


The presence of multiple matter fields first leads to an early matter-dominated era (EMDE), then stasis occurs when decays start

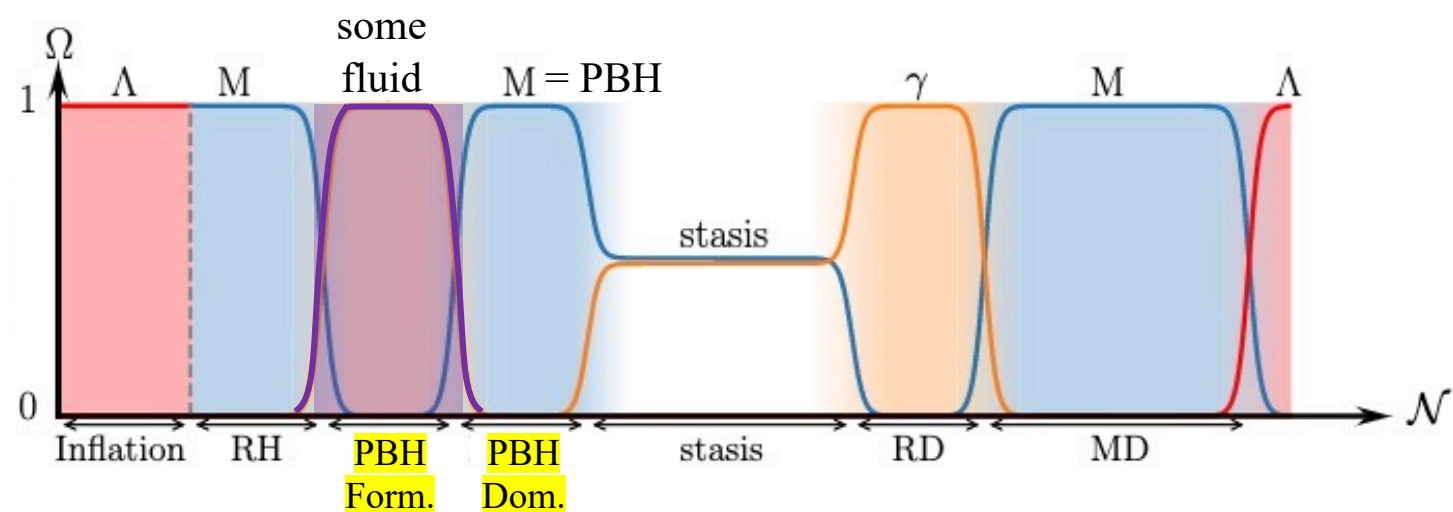


Where does stasis arise?

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For PBH-induced stasis, its existence implies the PBH formation and PBH domination epochs.



①

②

③

For example, we can parametrize

PBHs with a wide mass spectrum

~~A tower of states~~

Mass Spectrum

$$m_\ell = m_0 + (\Delta m)\ell^\delta$$

Decay Widths

$$\Gamma_\ell = \Gamma_0 \left(\frac{m_\ell}{m_0} \right)^\gamma$$

Initial Abundances

$$\Omega_\ell^{(0)} = \Omega_0^{(0)} \left(\frac{m_\ell}{m_0} \right)^\alpha$$

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A naturally continuous mass distribution

$$n_{BH}(t) = \int_0^\infty dM f_{BH}(M, t)$$

amounts to $\delta = 1, \Delta m \rightarrow 0$

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particle decay:

$$\frac{d\rho}{dt} + 3H\rho = -\Gamma\rho$$

BH evaporation:

$$\frac{d\rho}{dt} + 3H\rho = -\frac{\varepsilon M_P^4}{M^3} \rho$$

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Hawking evaporation indicates

$$\gamma = -3$$

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mass range $0.1 \text{ g} \lesssim M_{\min} < M_{\max} \lesssim 10^9 \text{ g}$

$H_\star < 2.5 \times 10^{-5} M_P$
from CMB

evaporate before BBN

$$T_{BH} \sim 1.06 \text{ TeV} \left(\frac{10^{10} \text{ g}}{M} \right)$$

all evaporation products are **relativistic!**

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To have $\Omega^{(0)}(M_i) \sim M_i^\alpha$, need

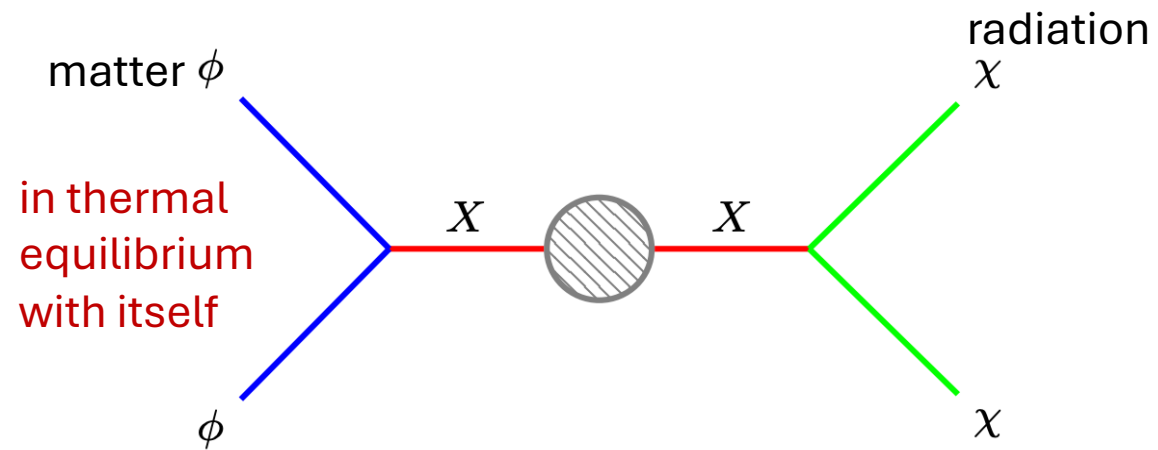
$$f_{BH}(M_i, t_i) = \begin{cases} C M_i^{\alpha-1}, & M_{\min} < M_i < M_{\max} \\ 0, & \text{otherwise} \end{cases}$$

with $\alpha < 0$ to achieve stasis. Arises naturally if PBHs form via the collapse of a scale-invariant power spectrum, and α depending on w_c of the PBH formation epoch.

backup

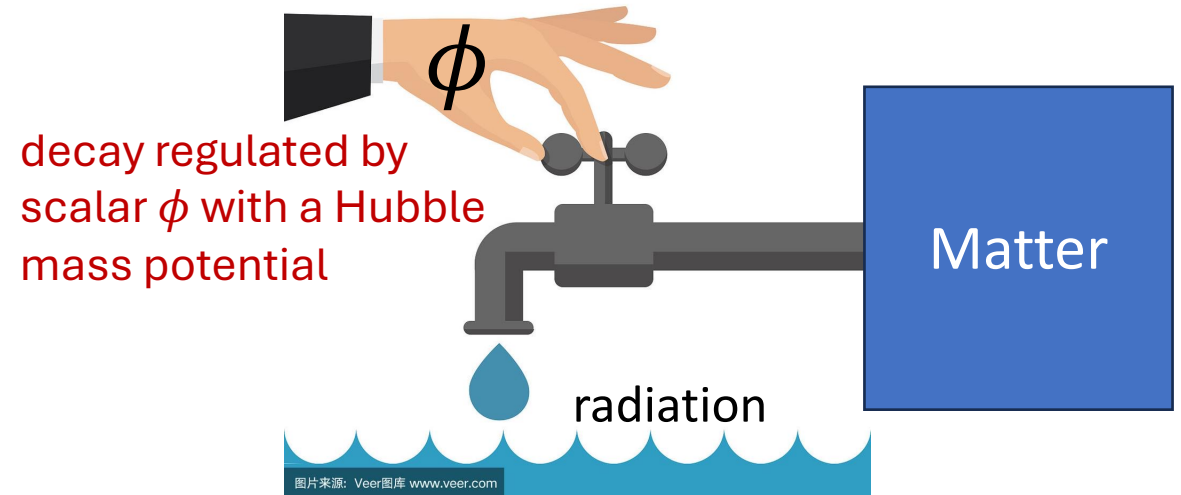
Other Models

Annihilation of a single particle species



Barber, Dienes, Thomas, arXiv: 2408.16255

Field-dependent decay

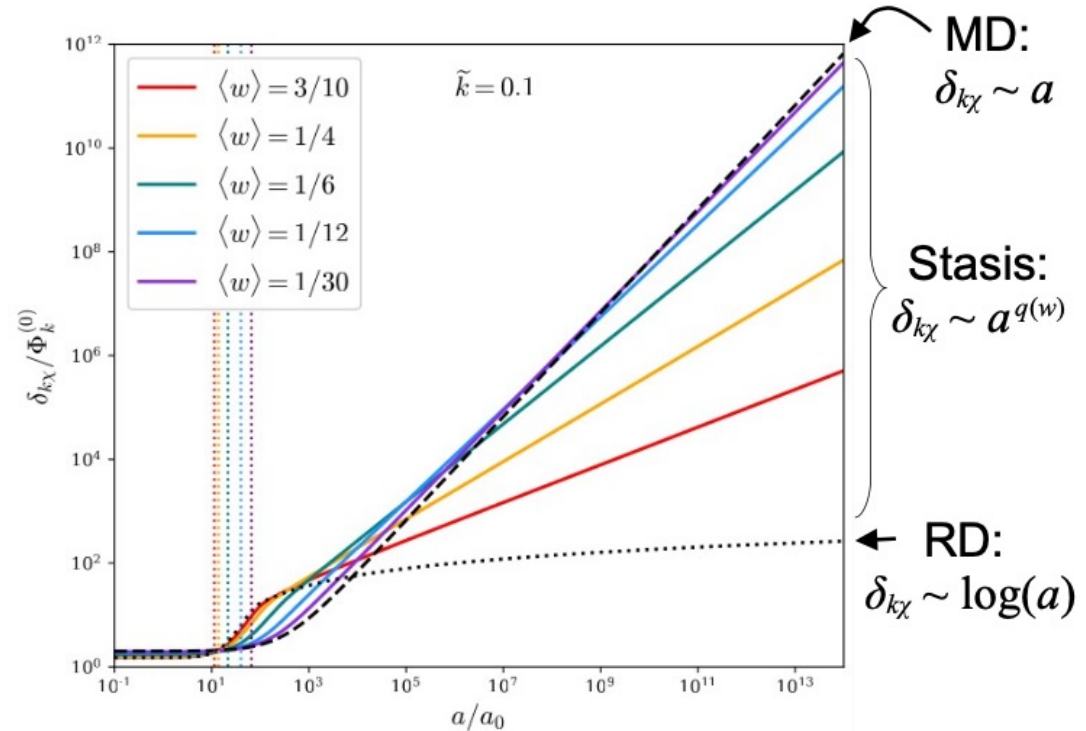
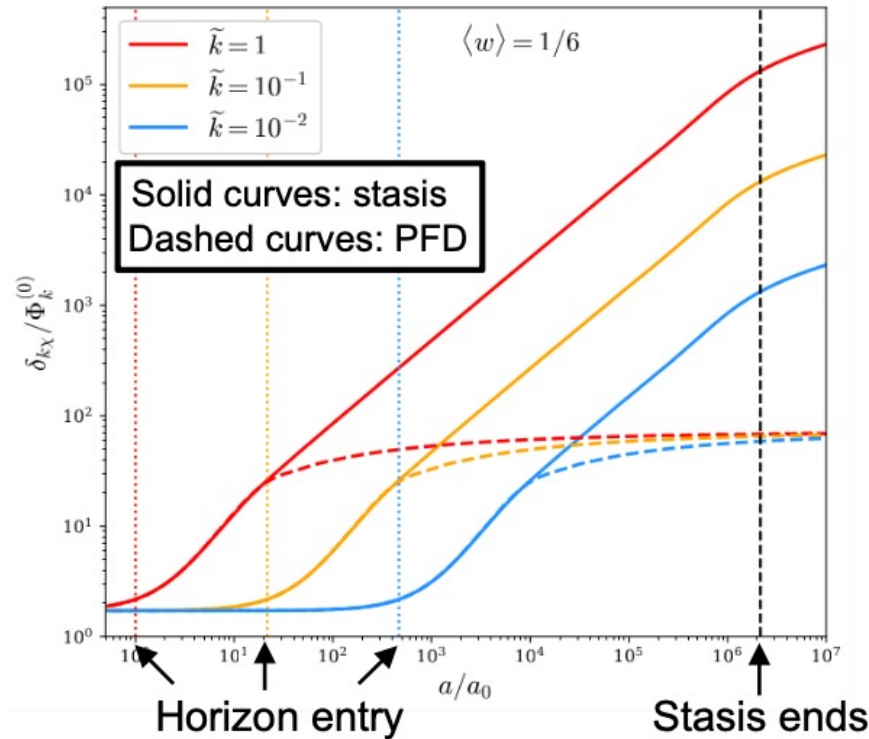


FH, Knapp-Perez, arXiv: 2502.20449

Observational signatures at the perturbation level

We find that after entering the horizon (when $k \sim aH$), modes experience **enhanced, power-law growth** until stasis ends:

$$\delta_{k\chi} \sim a^{q(\langle w \rangle)} \quad , \quad \text{where} \quad q(\langle w \rangle) \equiv \frac{1}{4} \left[3\langle w \rangle - 1 \pm (9\langle w \rangle - 78\langle w \rangle + 25)^{\frac{1}{2}} \right]$$



This power-law growth interpolates between the logarithmic growth during radiation domination and the linear growth during matter domination!