WEIZMANN INSTITUTE OF SCIENCE

The 2025 Beijing Particle Physics and Cosmology Symposium

Cosmological Stasis and Its Observational Signatures

Fei Huang

Based on work done in collaboration with

K. Dienes, L. Heurtier, D. Kim, T. Tait, B. Thomas [arXiv:2111.04753]
K. Dienes, L. Heurtier, D. Kim, T. Tait, B. Thomas [arXiv:2212.01369]
K. Dienes, L. Heurtier, T. Tait, B. Thomas [arXiv:2309.10345]
K. Dienes, L. Heurtier, T. Tait, B. Thomas [arXiv:2406.06830]
V. Knapp-Perez [arXiv:2502.20449]
K. Dienes, L. Heurtier, B. Thomas, D. Hoover, A. Paulsen [arXiv:2503.19959]

Sep 26, 2025

The Standard Lore: ΛCDM

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

Vacuum Energy $w_\Lambda = -1$

Matter $w_M = 0$

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

The Standard Lore: ΛCDM

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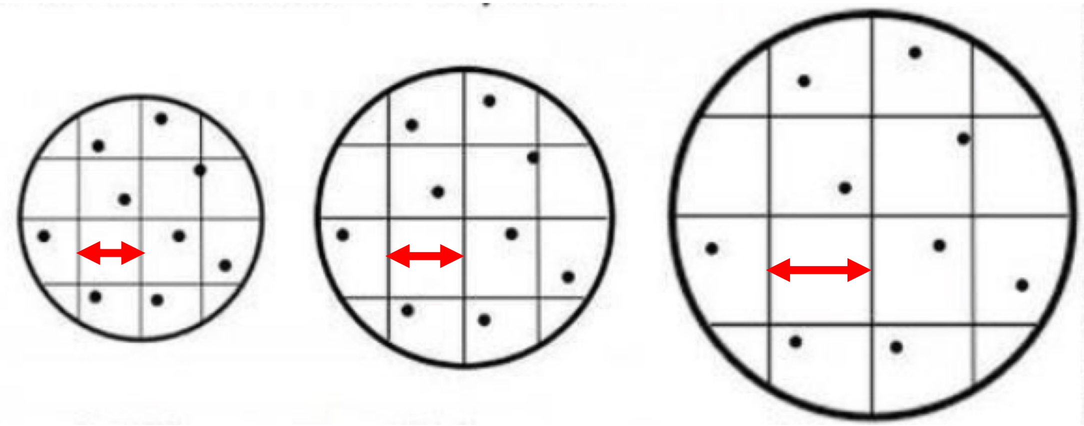

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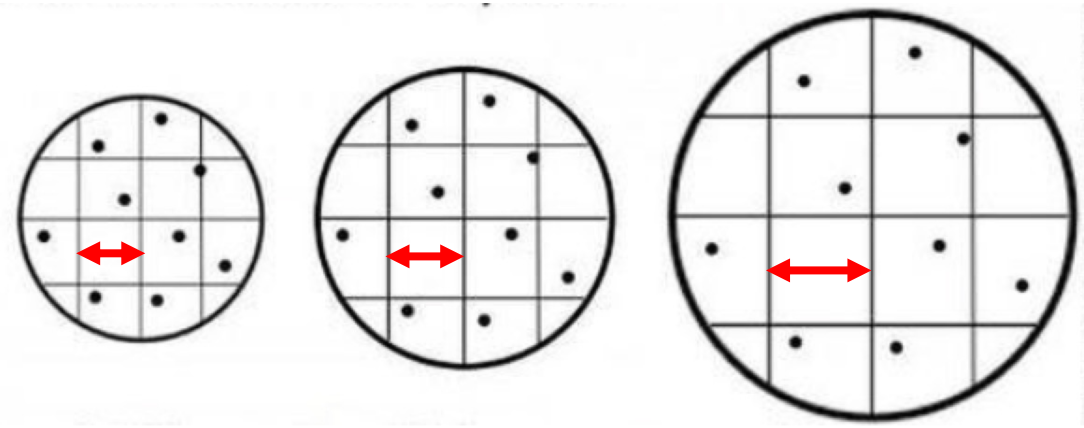

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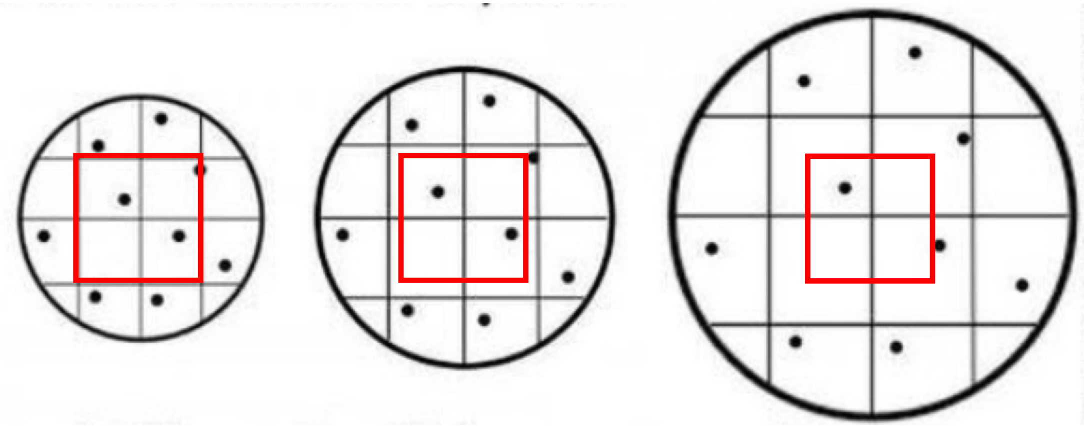

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$$E \approx m$$

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

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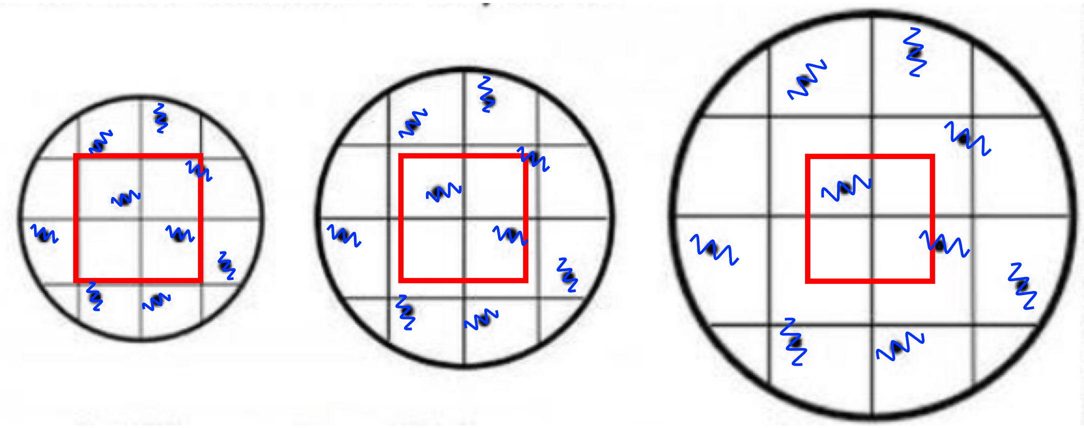

$$\ell_{phys}(t) = a(t)\ell$$

$$E \approx p \sim 1/\lambda$$

$$\rho_\gamma(t) = n_\gamma(t) \times p$$

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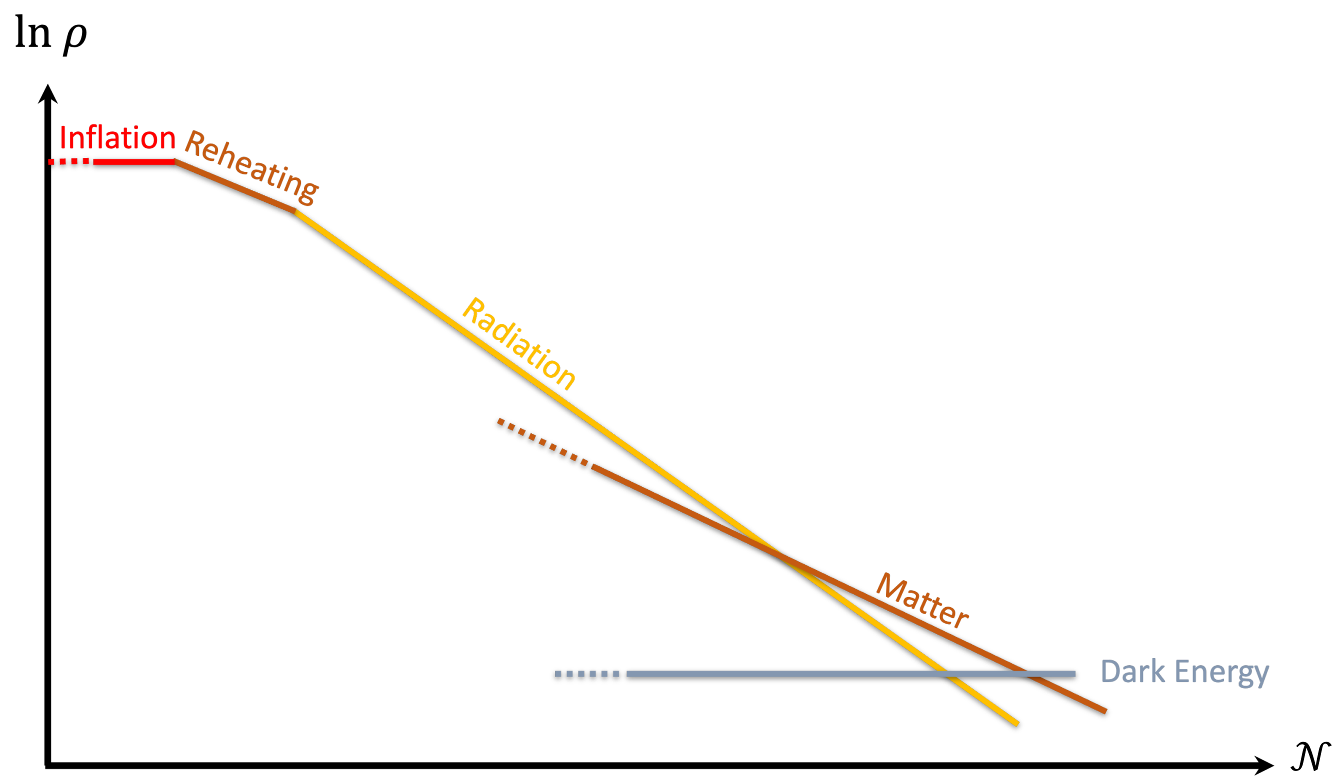

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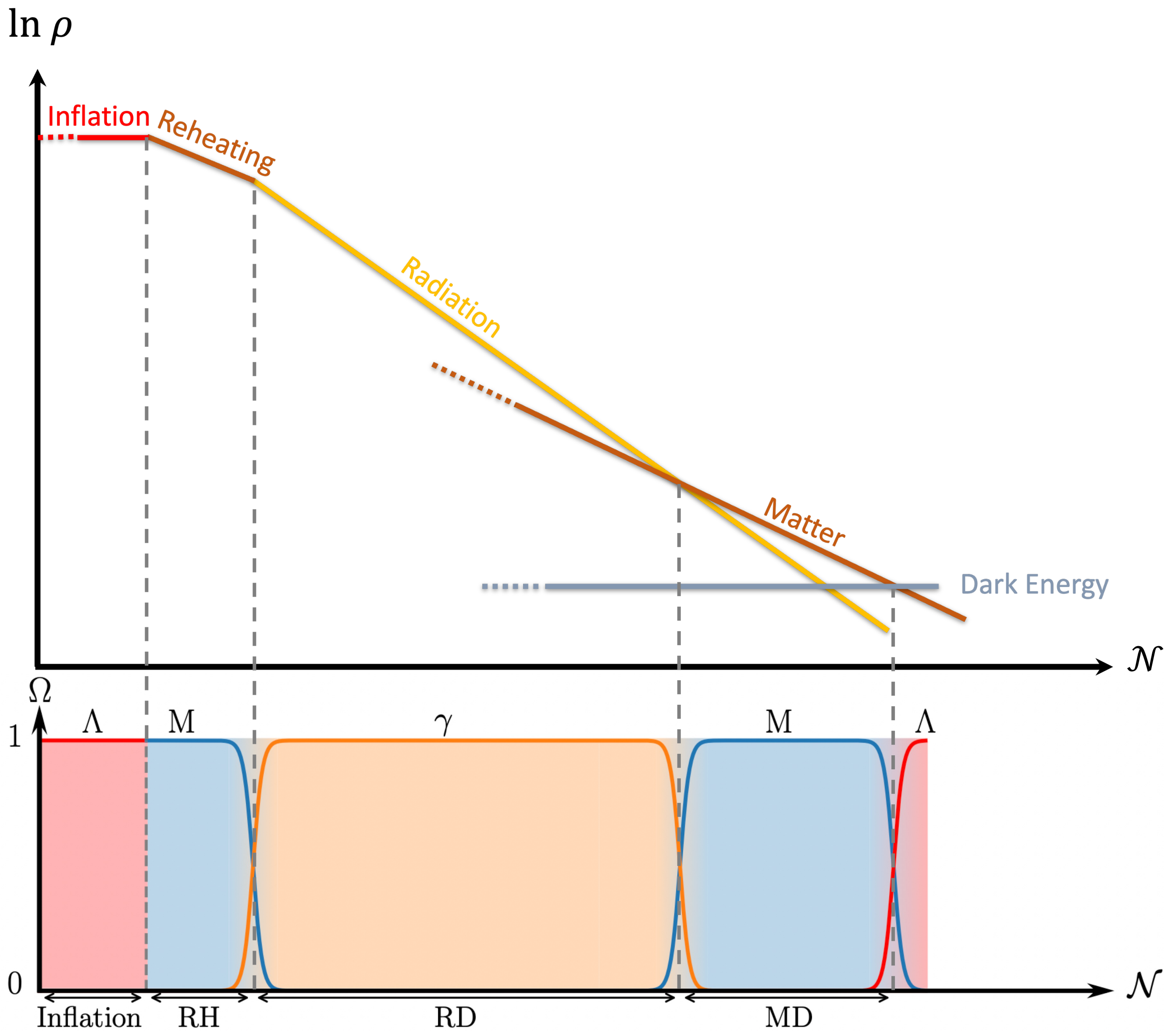

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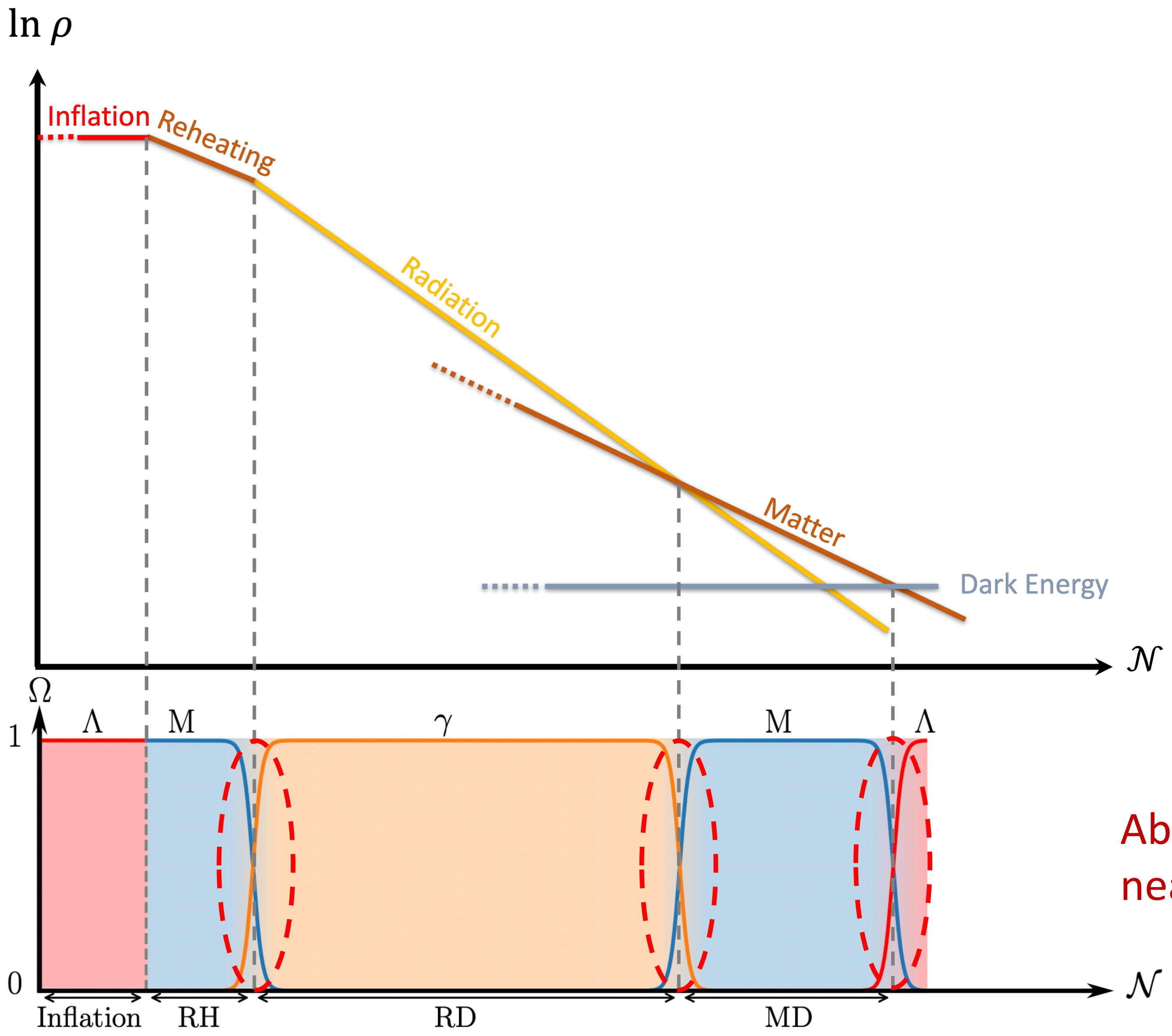

$$\rho_\Lambda \sim a^0$$
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Most parts are dominated by a single energy component.

Abundances only similar near transition points!

However, this picture is likely to be ***<u>incorrect</u>*** in the presence of many kinds of BSM physics…

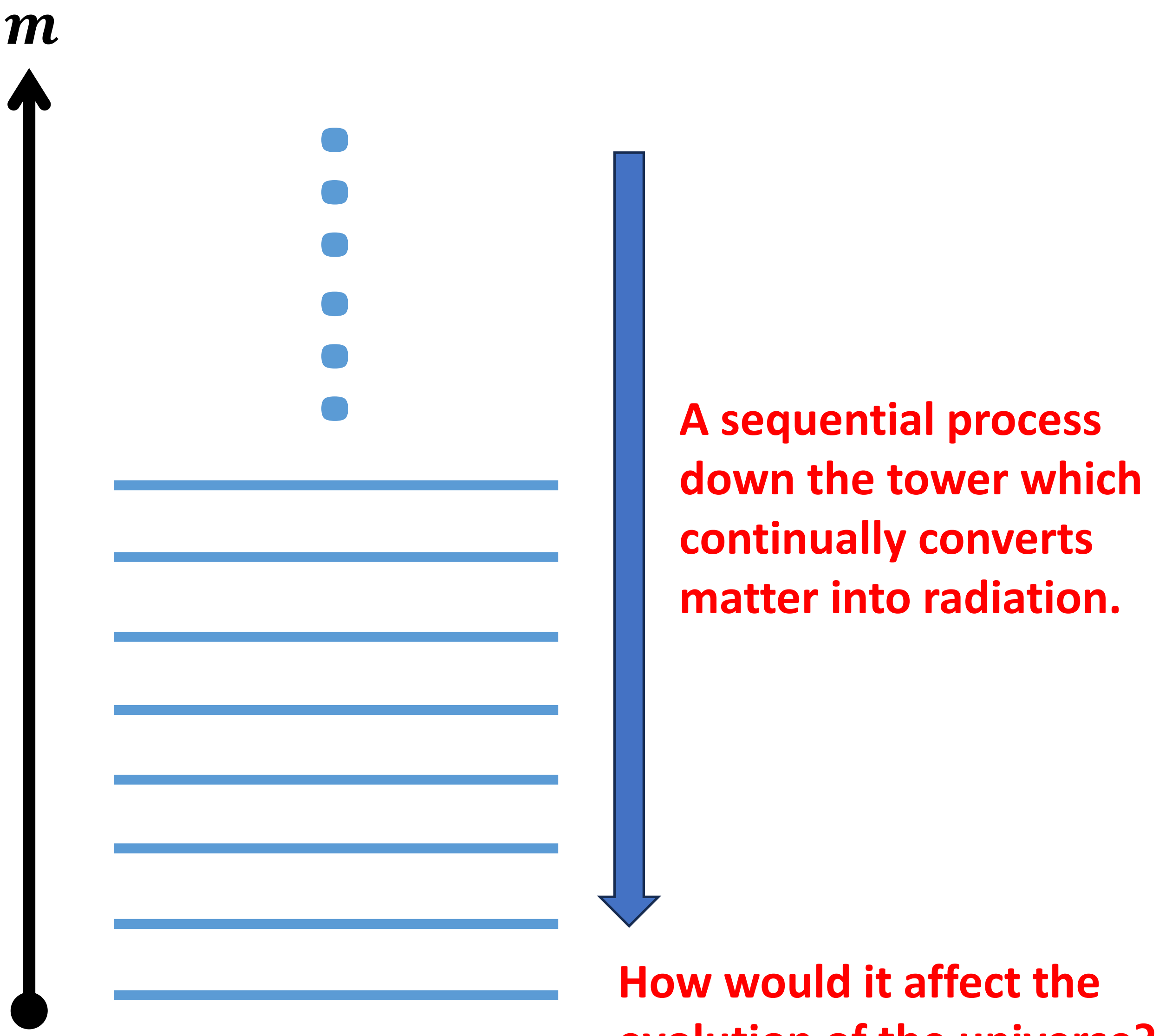
A wide variety of scenarios for BSM physics predict towers of unstable states with a broad spectrum of masses, lifetimes and cosmological abundances, for example

- 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, potentially infinite (or bounded by a relevant cutoff) – generally stretch across many orders of magnitude in mass.
- Such states are generally unstable and can decay.
- Heavy states at top of tower tend to have largest decay widths and decay first, then lighter ones. Decays thus proceed "down the tower".
- For any state, the dominant decay mode is to the lightest states available. Such decay products are therefore produced with huge amounts of kinetic energy (relativistic) and are effectively radiation.
- Let us assume the decay products are particles outside of the tower, e.g., photons or other light particles in a thermal bath.



How would it affect the evolution of the universe?

Example: A Decaying Tower

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

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

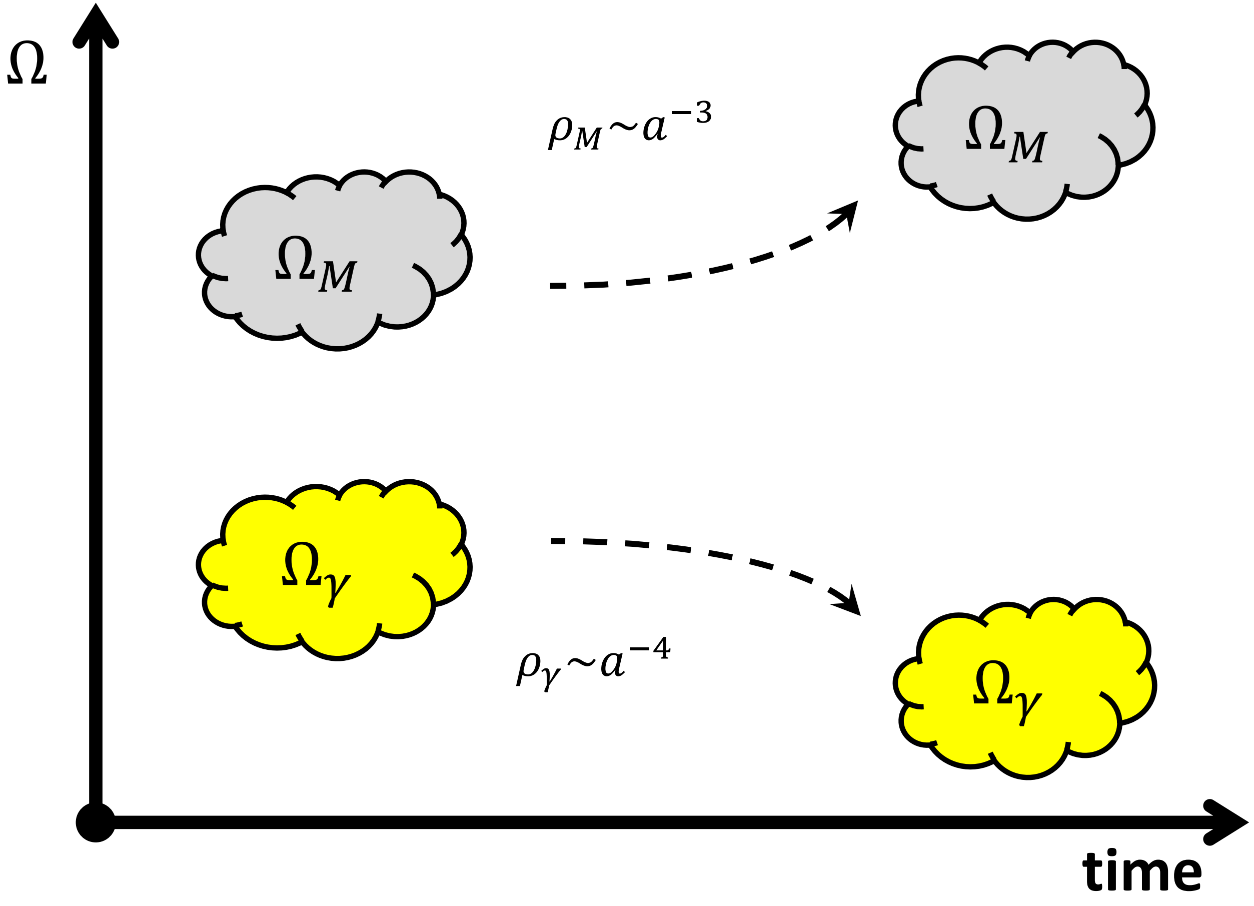
$$H^2 = \frac{8\pi G}{3}(\rho_M + \rho_\gamma)$$

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

$$\Omega_M = \sum_\ell \Omega_\ell$$

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

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



Example: A Decaying Tower

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

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

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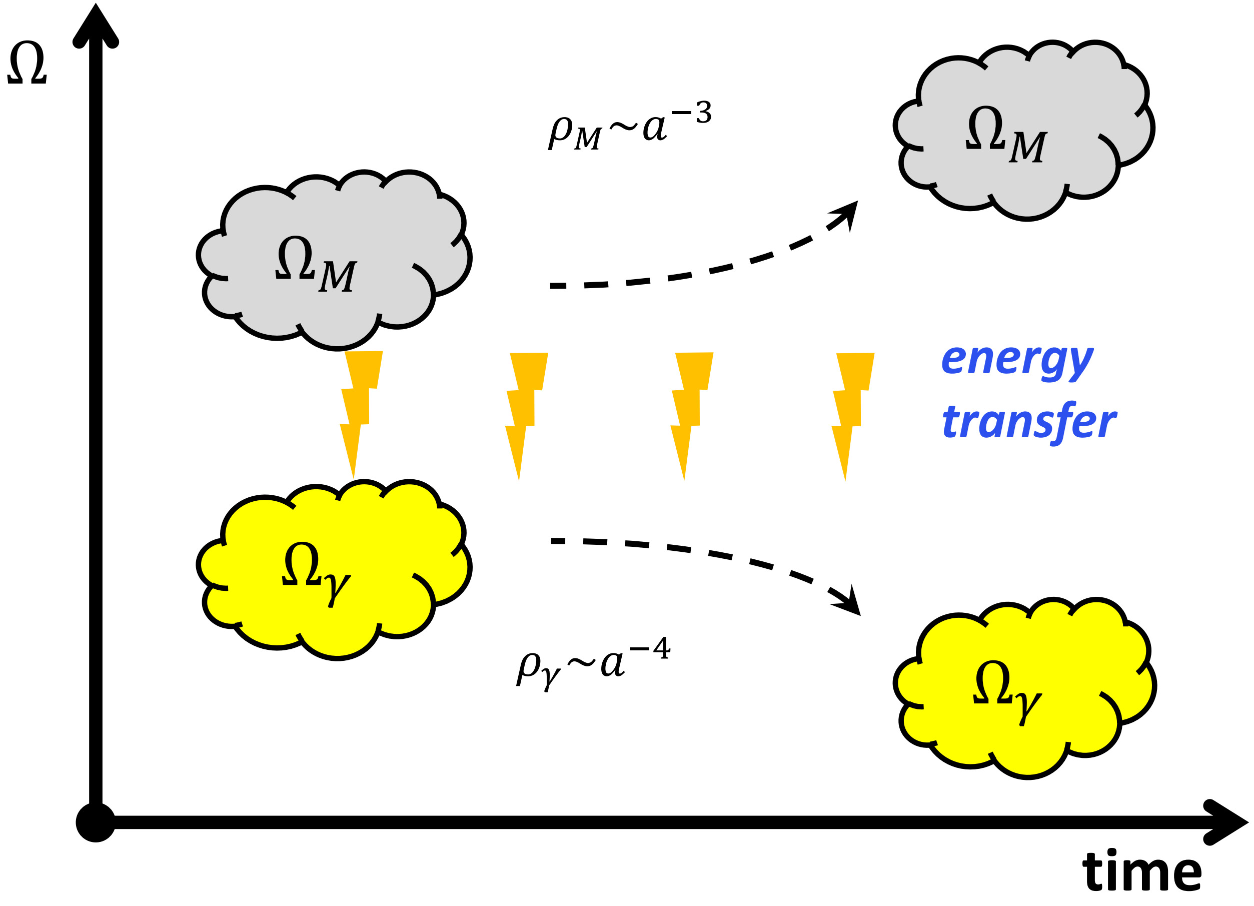

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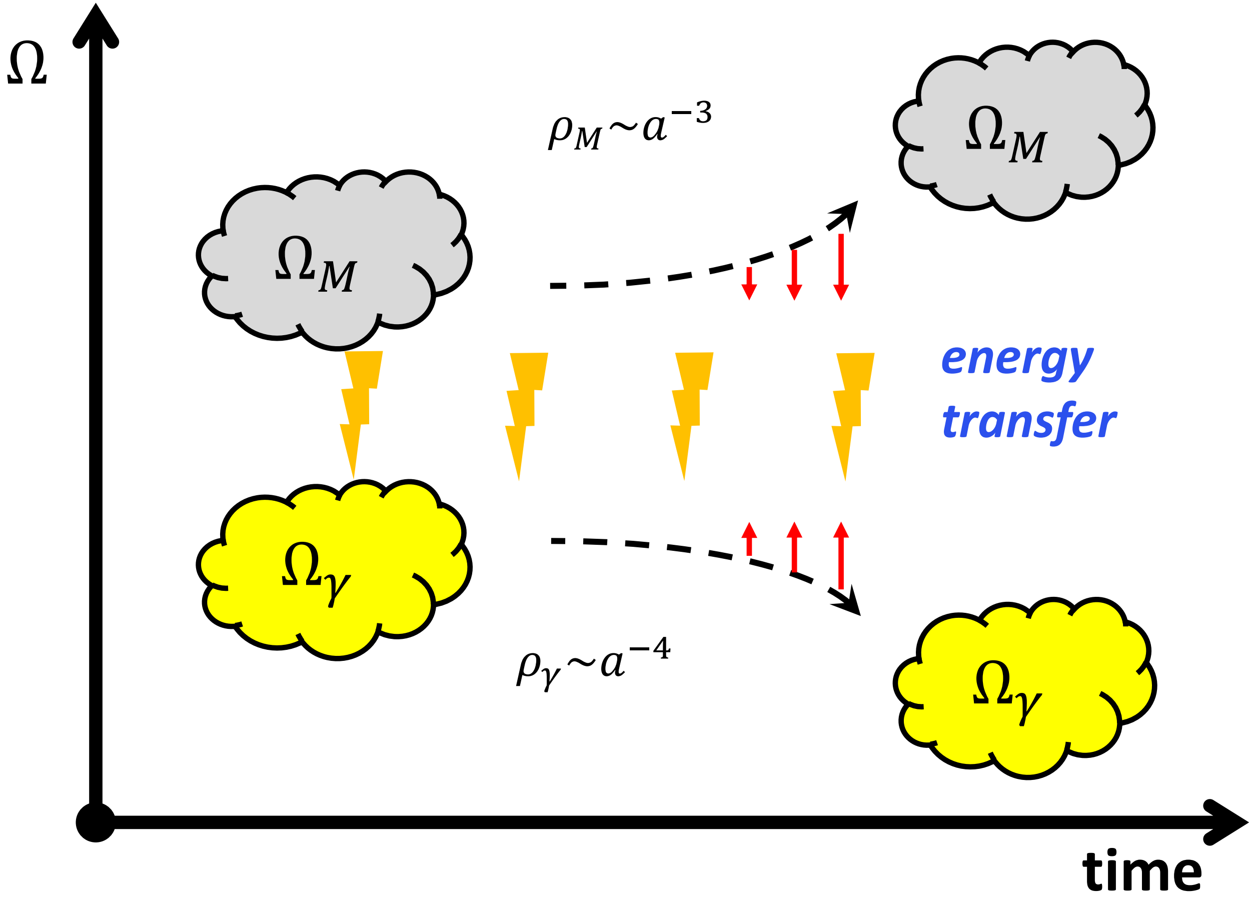


Cosmological expansion $\Omega_\gamma \to \Omega_M$

Sequential decays of tower states $\Omega_M \to \Omega_\gamma$

Can these two effects balance? Seems like too much to ask for!

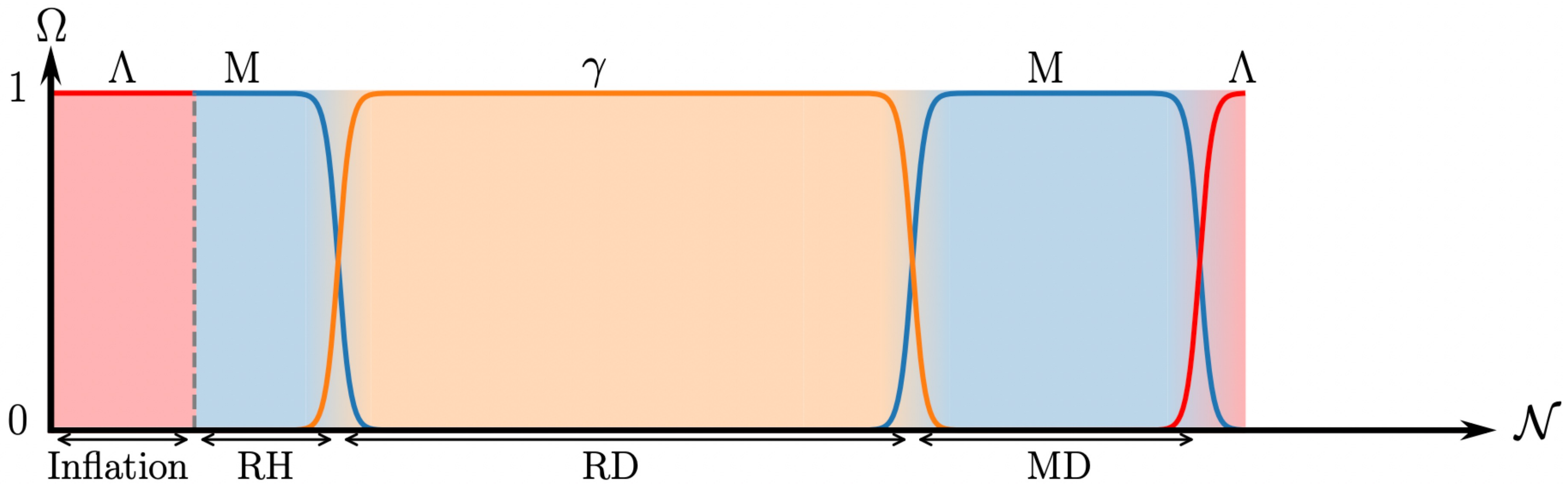
But, they CAN balance. In fact, they DO balance.

Even if they don't start out by balancing, the system will quickly come into balance all by itself!

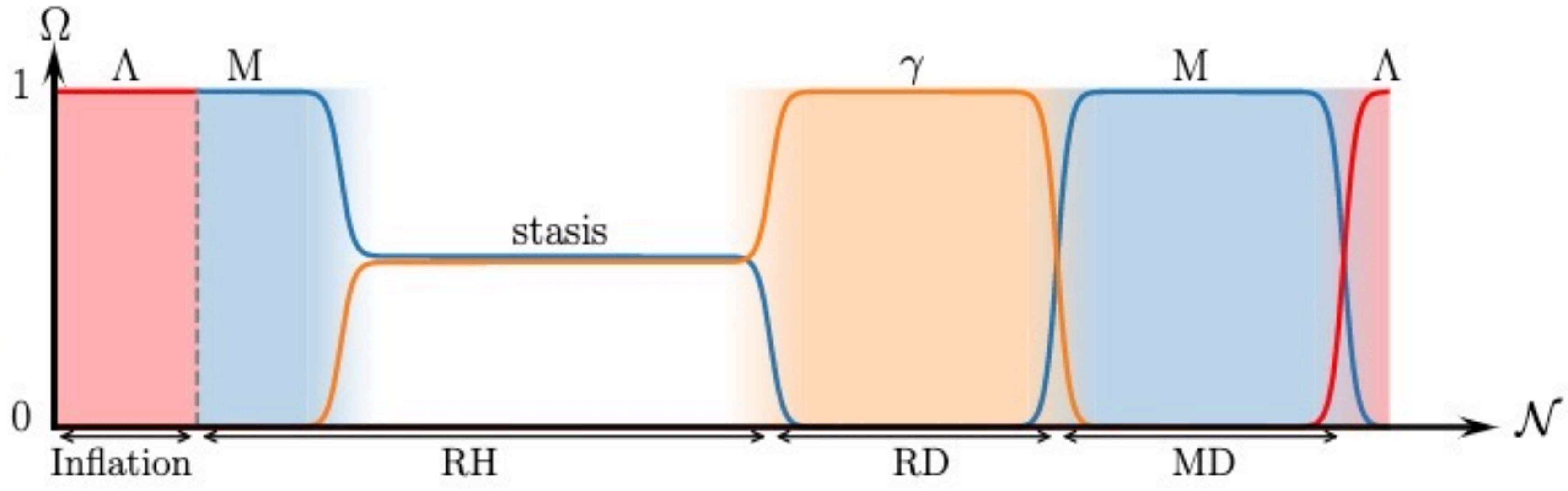
The balanced solution is an ***attractor!***

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

Therefore, Instead of a picture like this …

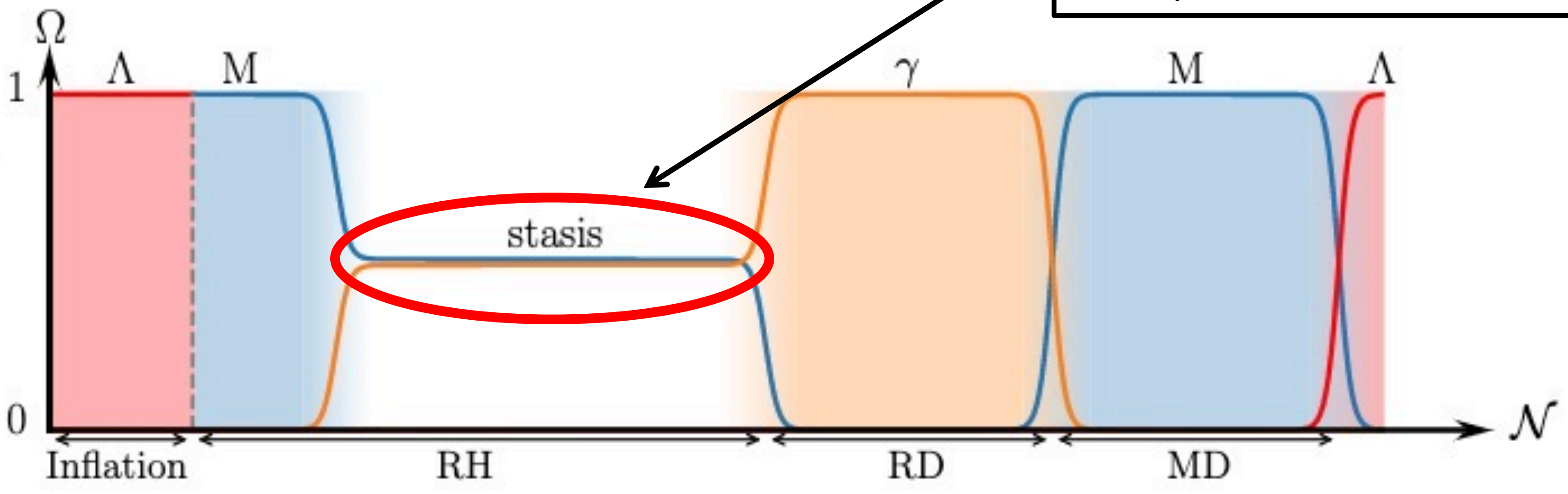


The universe may more likely evolve like this



The universe may more likely evolve like this

- constant abundances
- nothing dominates
- any constant abundances are possible



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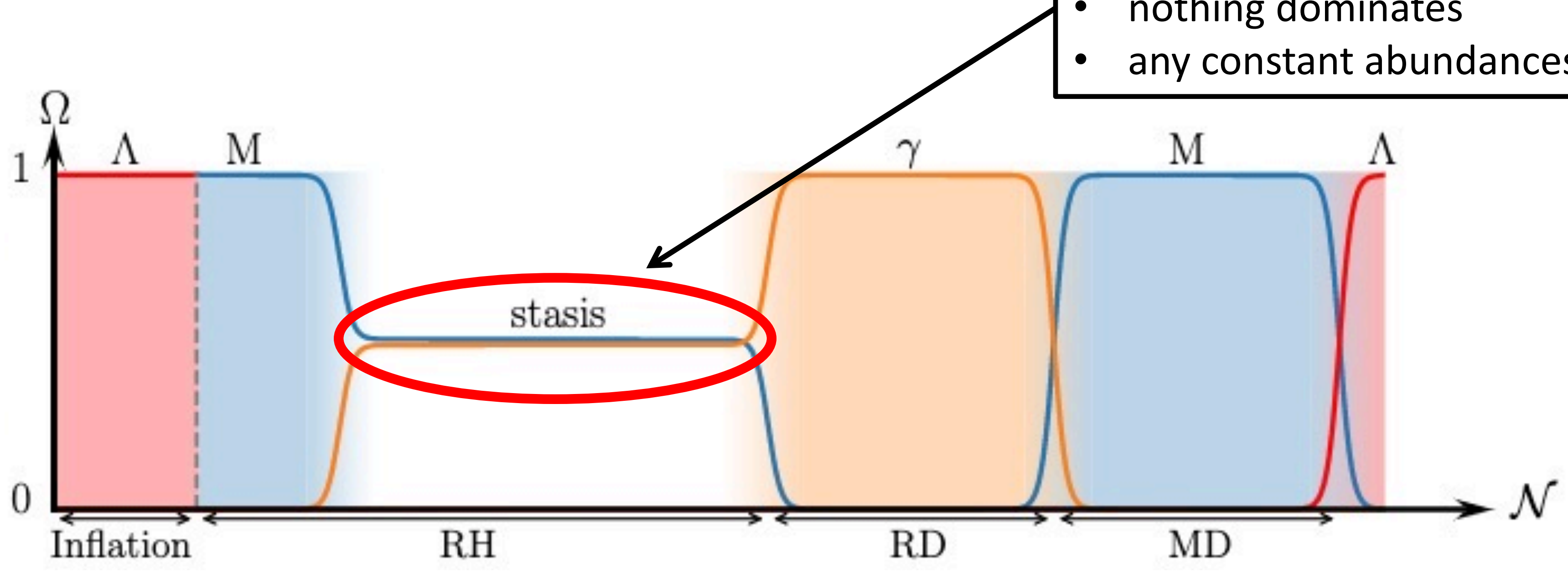

This may seem surprising, but …

- ➢ Naturally occurs for a variety of models and for a wide range of parameters
- ➢ No finetuning required
- ➢ Global Attractor – Even ***unavoidable***!!!

For example, we can parametrize

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

Stasis arises for all values of these parameters within the range

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

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

$$\overline{\Omega}_M = \frac{2\gamma\delta - 4(1+\alpha\delta)}{2\gamma\delta - (1+\alpha\delta)}$$

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

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

initial conditions

Free parameters

$$\left\{\alpha, \gamma, \delta, m_0, \Delta m, \Gamma_0, \Omega_0^{(0)}, t^{(0)}, N\right\}$$

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
  - $\delta \sim 1/2$
- String axiverse
  - $m_\ell \sim m_0 \exp(\mu\ell)$

Halverson and Pandya
arXiv:2408.00835

Depends on decay mode

- if ϕ_ℓ decays to photons through contact operator $\mathcal{O}_\ell \sim c_\ell \phi_\ell \mathcal{F}/\Lambda^{d-4}$, $\gamma = 2d - 7$, e.g., $\gamma \sim \{3, 5, 7\}$

Depends on the production mechanism

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

Long, Sham Es Haghi, Venegas
arXiv:2506.04502

For example, we can parametrize

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

Evaporation rate ~~Decay Widths~~ $\Gamma_\ell = \Gamma_0 \left(\frac{m_\ell}{m_0}\right)^\gamma$

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

A naturally continuous mass distribution

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

with $\delta = 1$

Hawking evaporation indicates

$$\gamma = -3$$

lighter PBHs evaporate faster

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

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

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

all evaporation products are ***relativistic!***

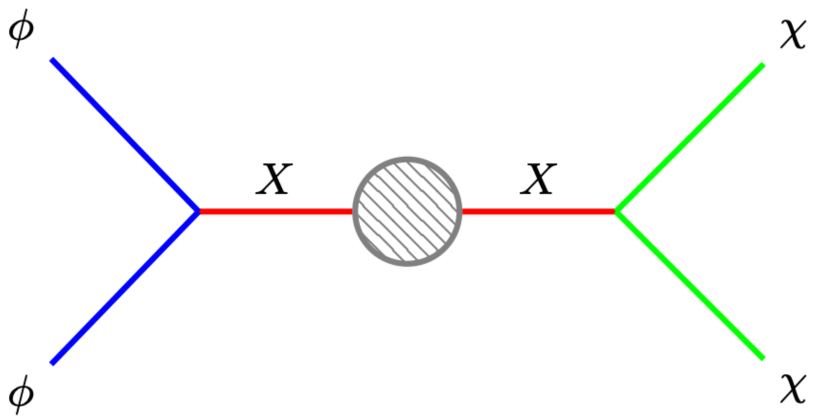
Does it have to be a tower?

J. Barber, K. Dienes, B. Thomas
arXiv: 2408.16255

- Annihilation of a single particle species

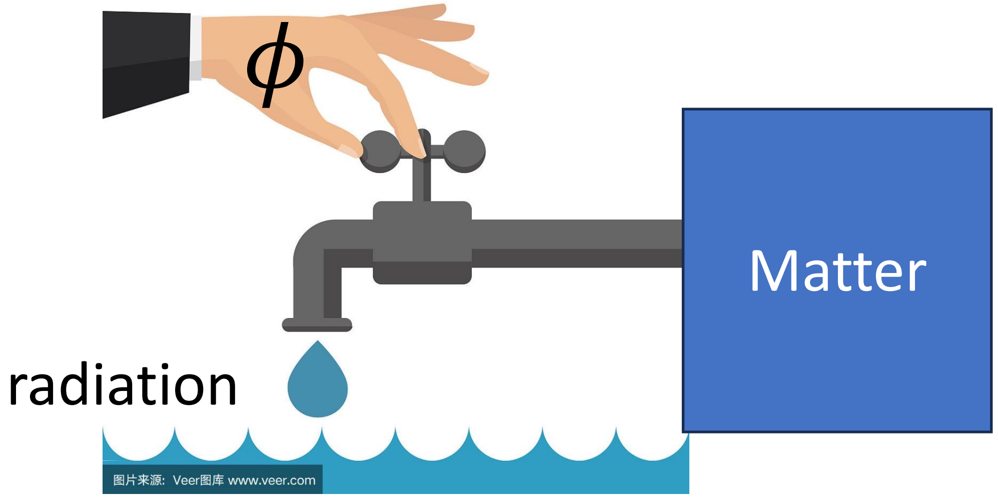
Matter field ϕ in thermal equilibrium with itself, characterized by a temperature T

<u>*Not*</u> in equilibrium with radiation χ



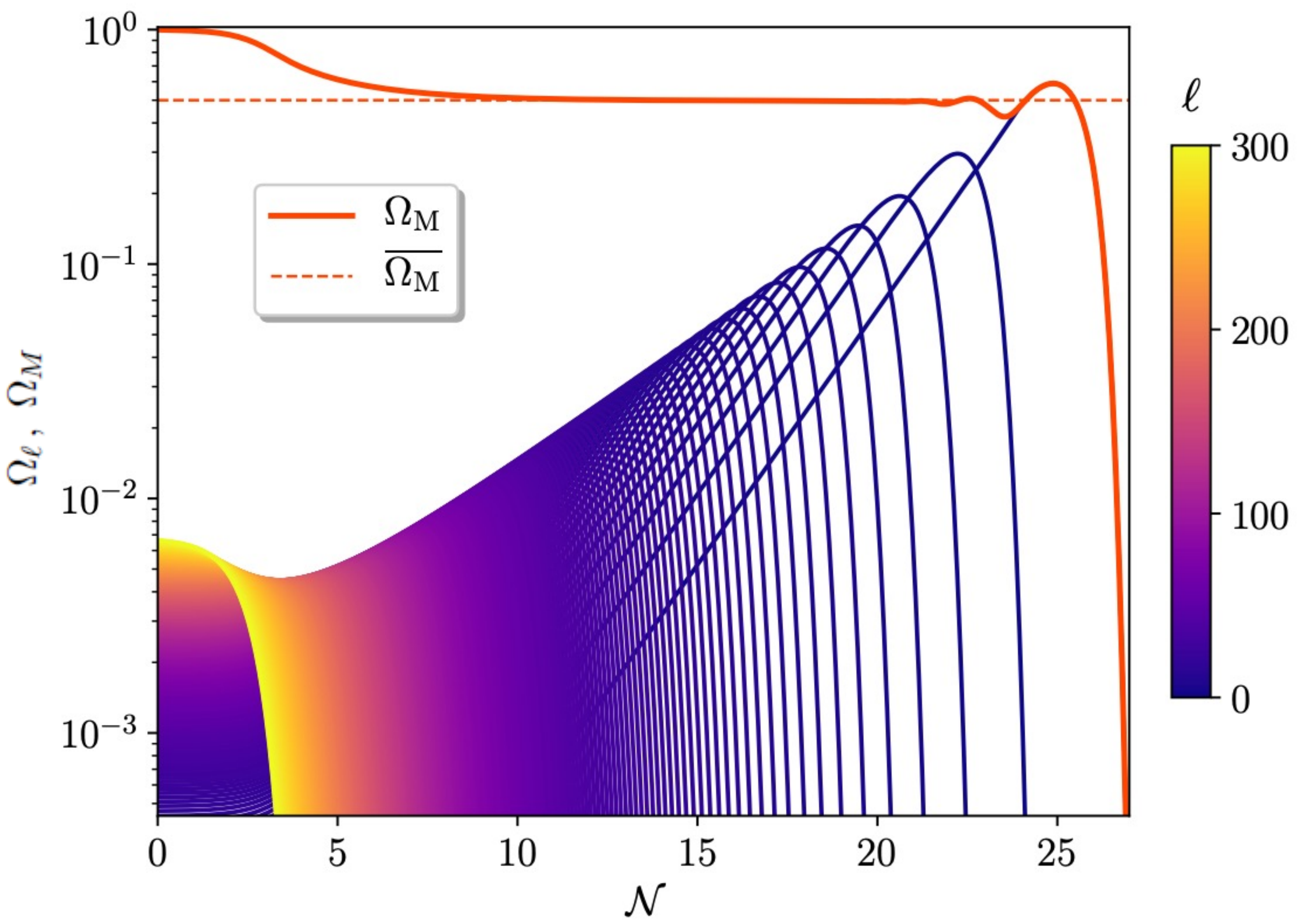
FH, V. Knapp-Perez
arXiv: 2502.20449

- Field-dependent decay
  - When the decay rate of matter is regulated by the dynamics of a scalar field ϕ under a Hubble mass potential, the decay rate can match the expansion rate and results in a matter/radiation stasis



Numerical Examples

Dienes, Heurtier, FH, Kim Tait, Thomas
arXiv:2111.04753



$$(\alpha, \gamma, \delta) = (1,7,1) \rightarrow \overline{\Omega}_M = 1/2,\ N = 300,\ \mathcal{N}_s \sim \frac{2\gamma\delta}{4-\overline{\Omega}_M} \log N$$

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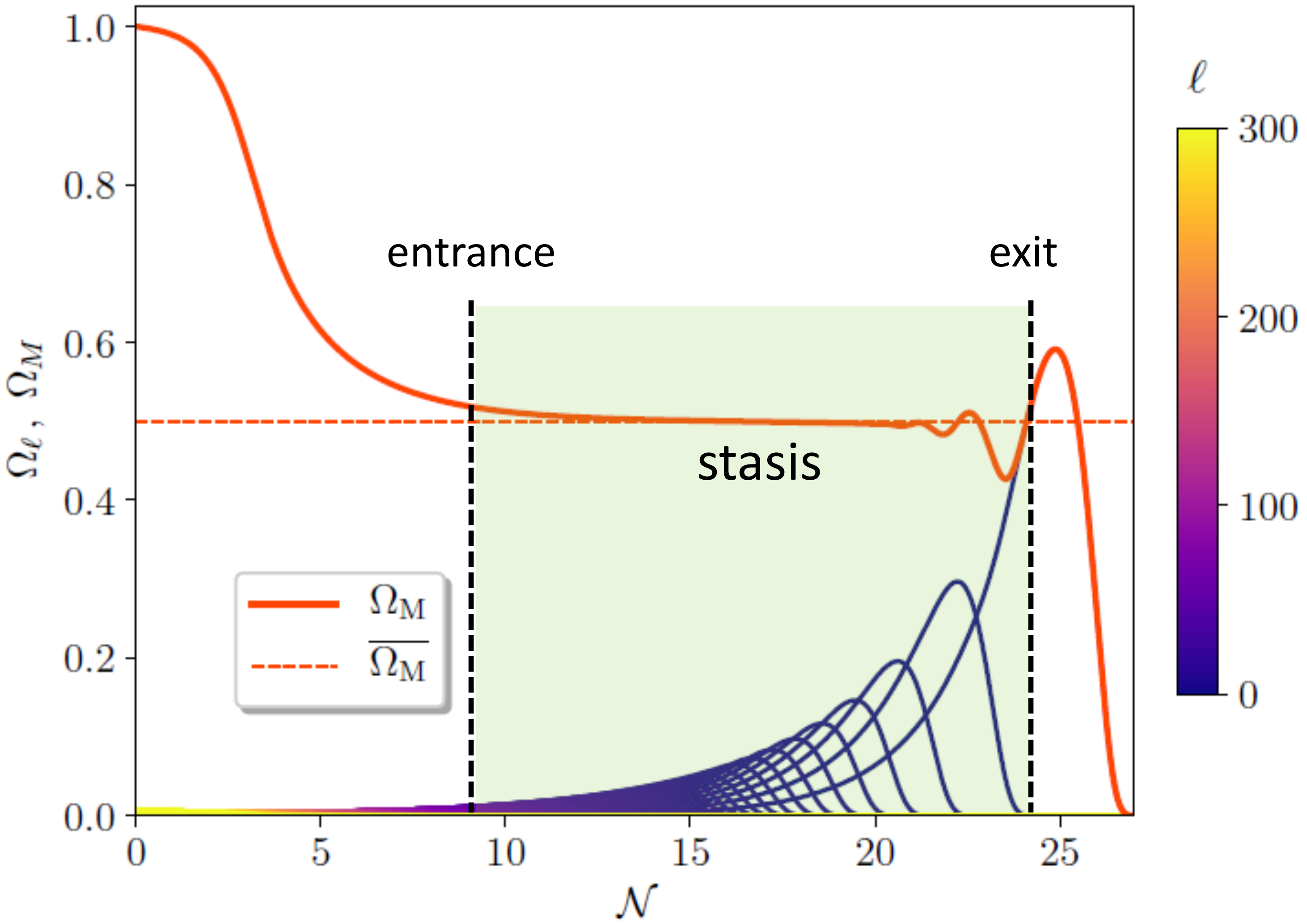

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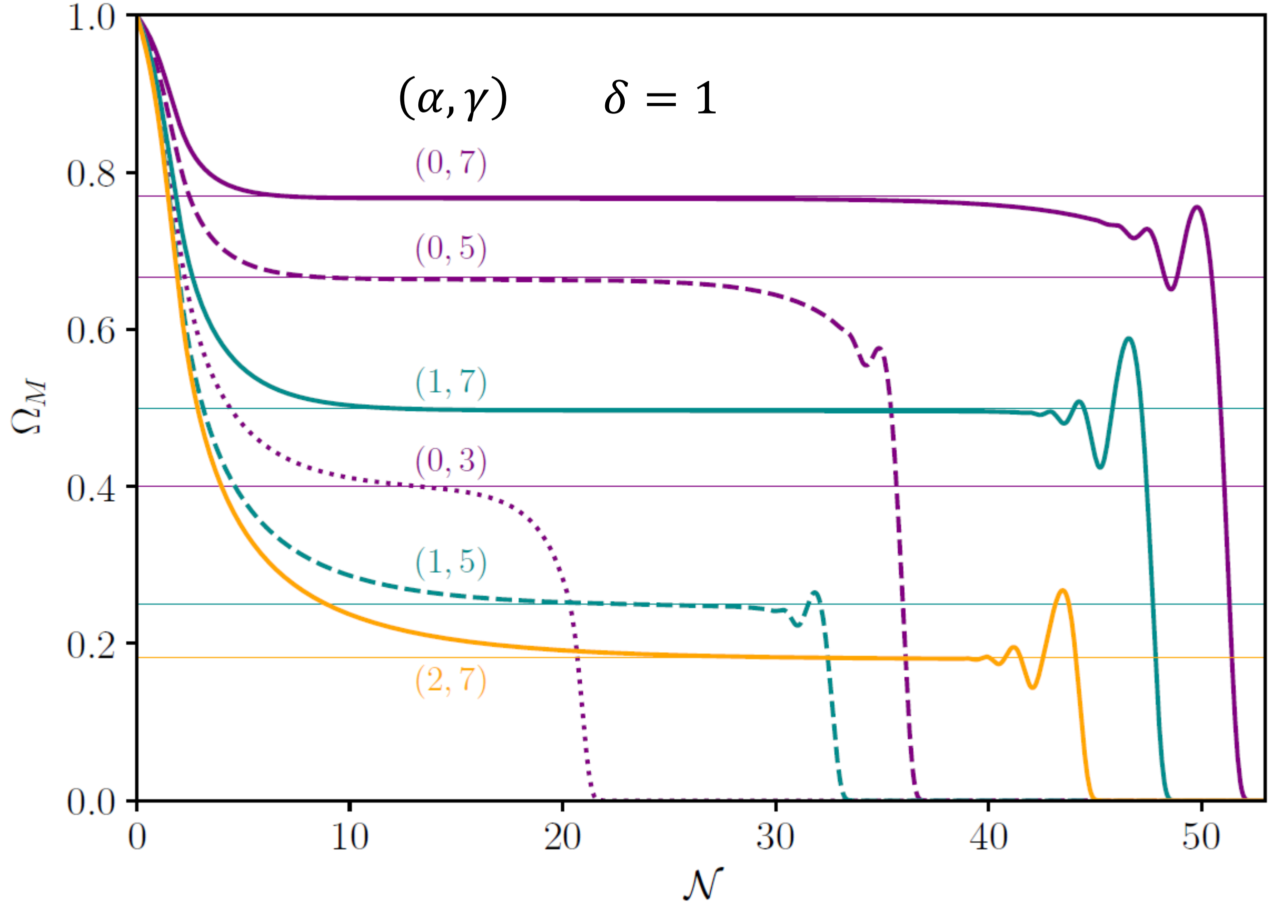
arXiv:2111.04753

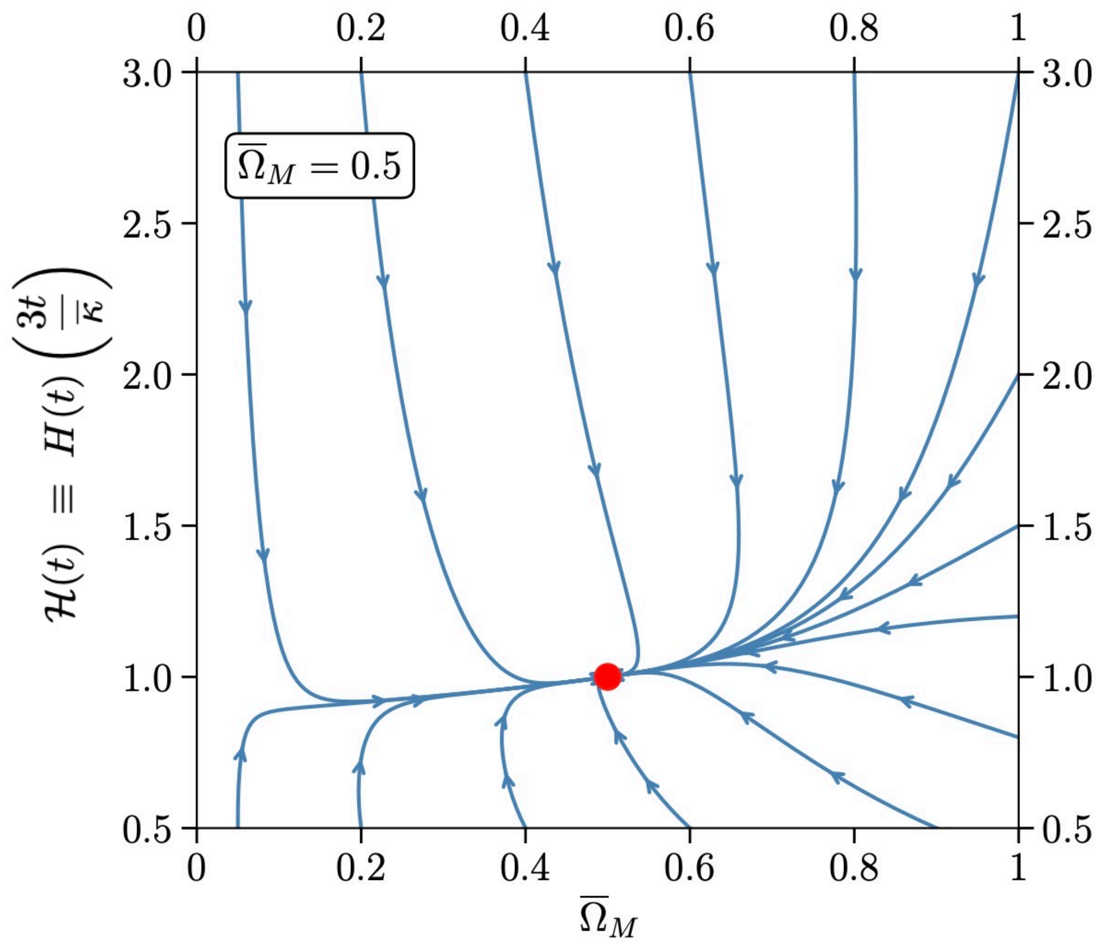
Similar behavior for other parameter choices



Stasis always emerges, only the stasis abundance changes

Moreover, stasis is a Global Attractor

Dienes, Heurtier, FH, Kim Tait, Thomas
arXiv:2111.04753



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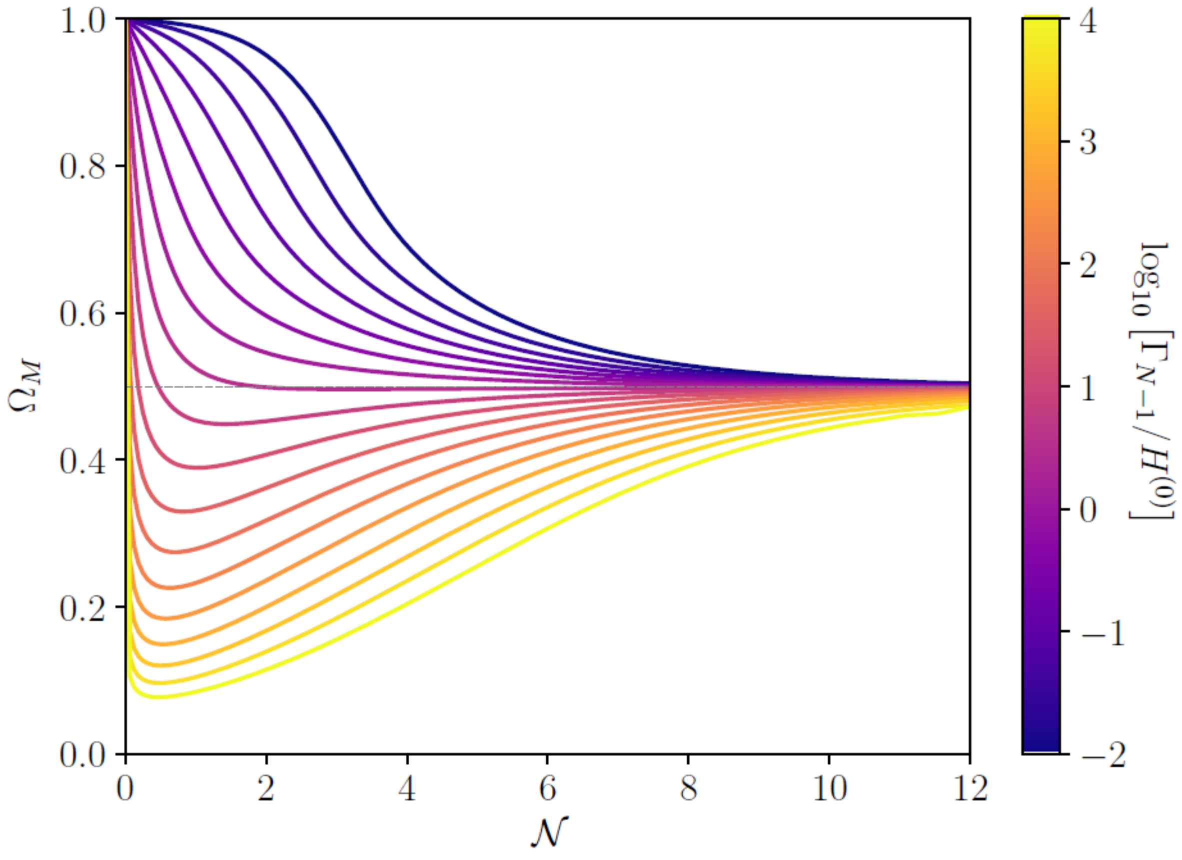
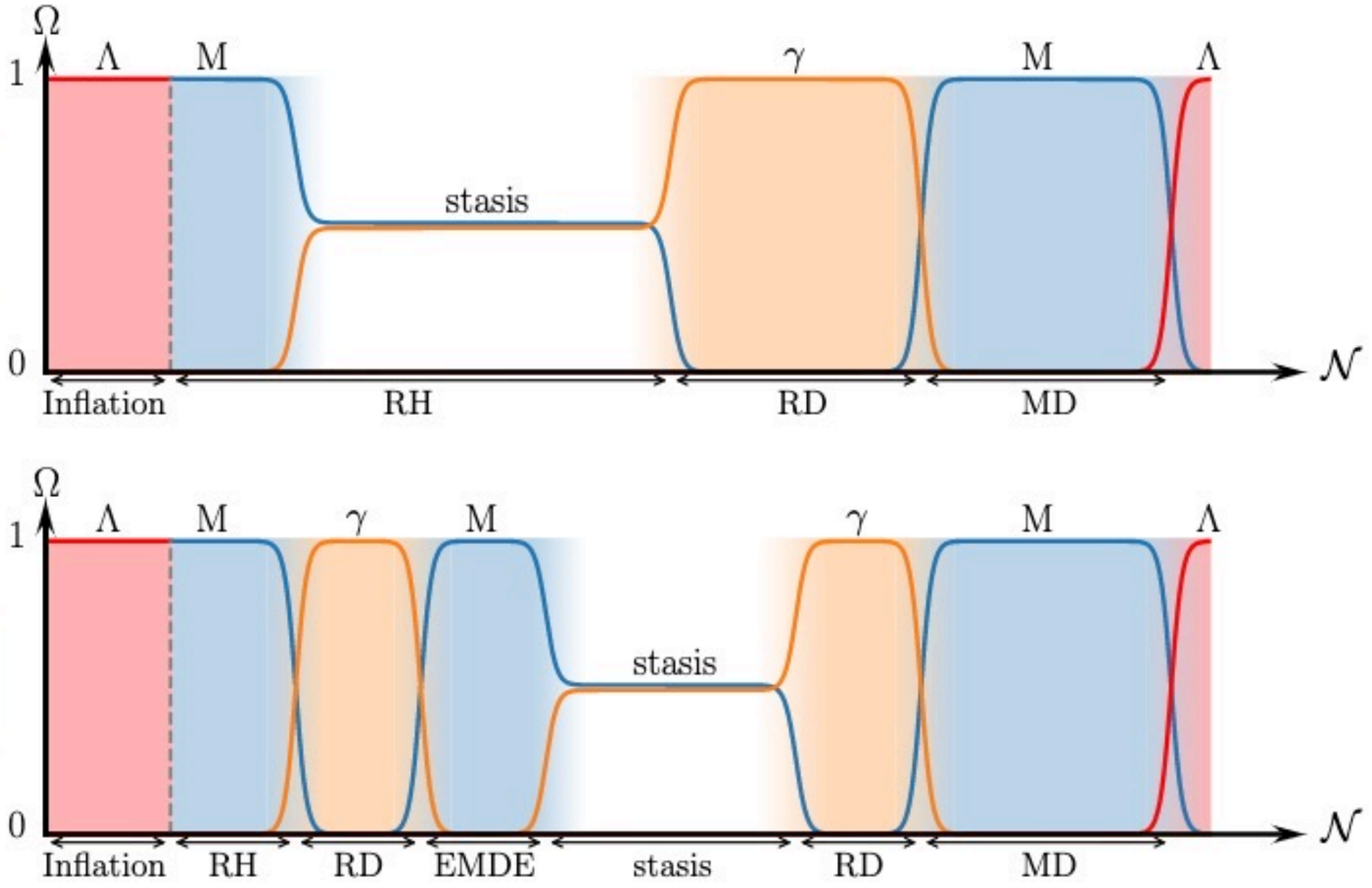


Where does stasis arise?

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



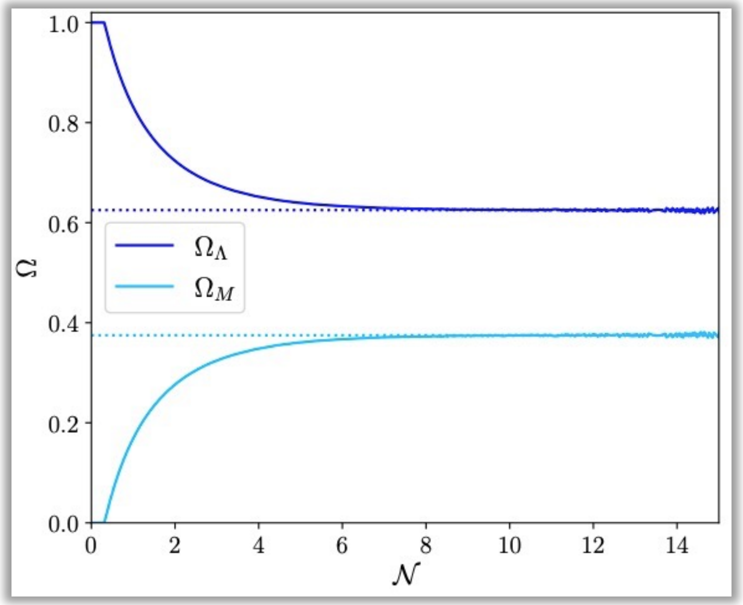
Thus far, we have seen stasis arises between matter and radiation.

Are there other types of stasis?

Other types of stasis

Dienes, Heurtier, FH, Tait, Thomas
arXiv: 2309.10345

- Vacuum energy/Matter stasis



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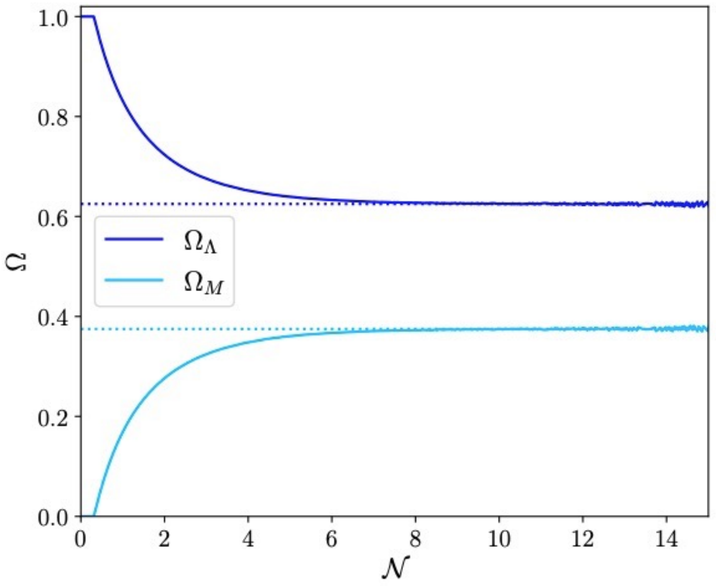

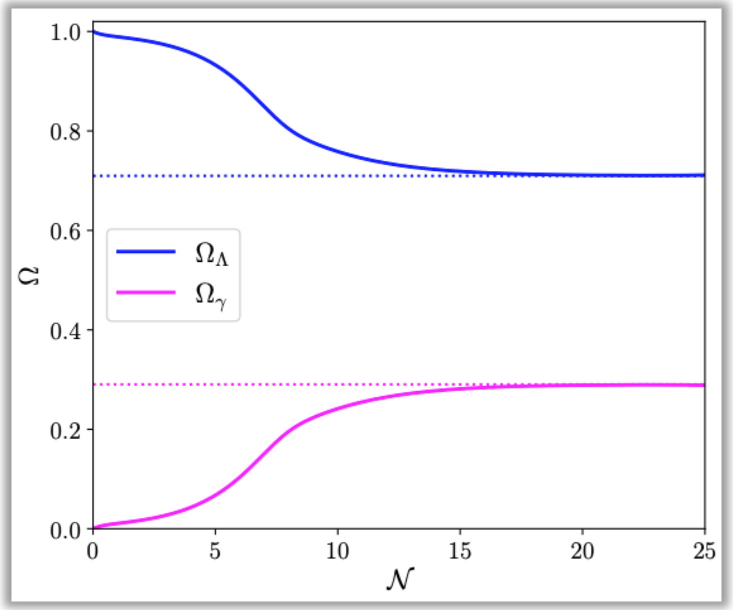

Other types of stasis

Dienes, Heurtier, FH, Tait, Thomas
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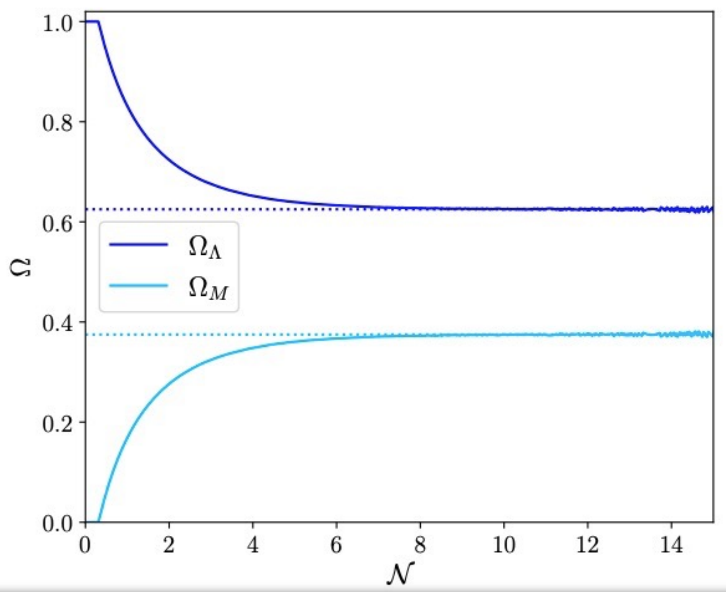
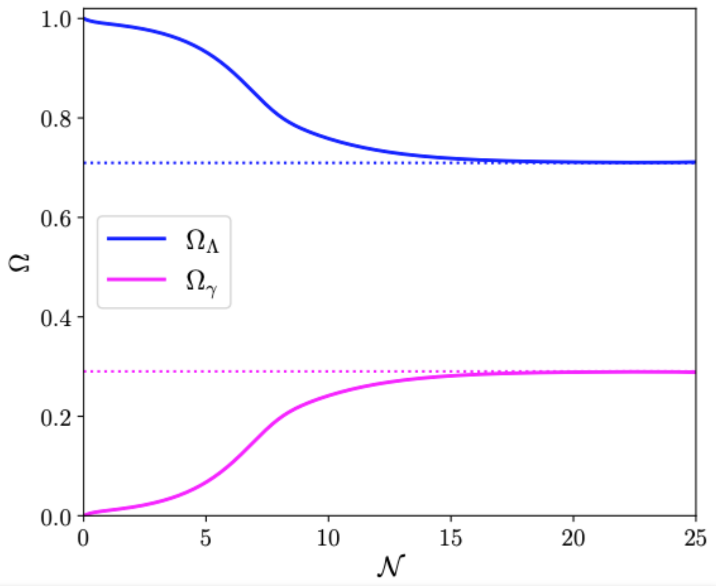
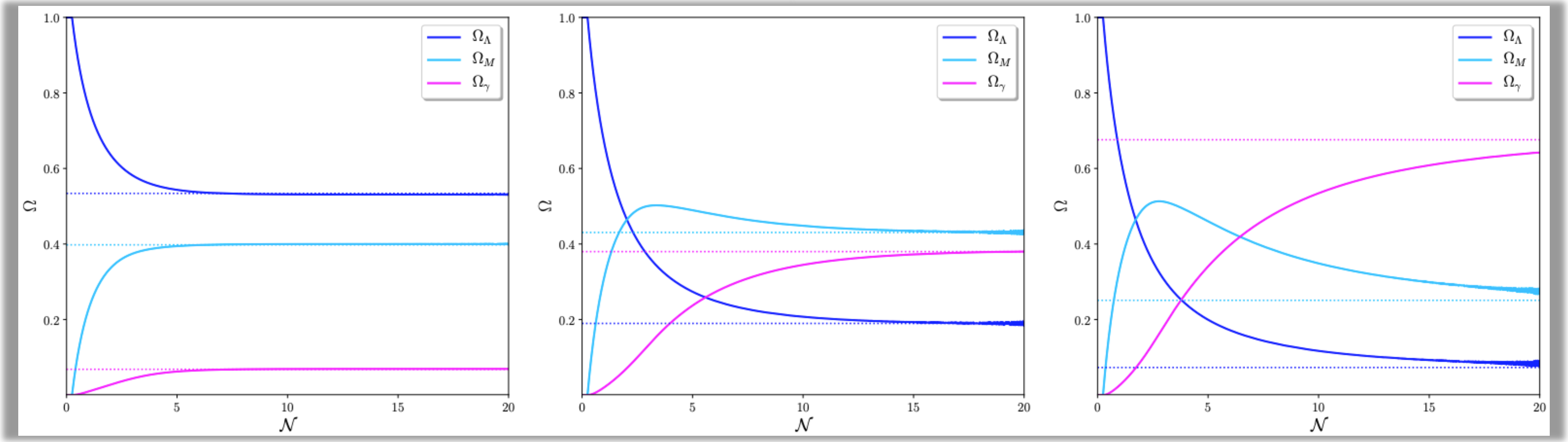
- Vacuum energy/Matter stasis
- Vacuum energy/Radiation stasis
- Triple stasis between vacuum energy, matter, and radiation simultaneously







Stasis-induced inflation?

Among these possibilities, we observe that if stasis involves ***vacuum energy*** …

- EoS extends to the region $-1 < \overline{w} < 0$
- Accelerated expansion if $\overline{w} < -1/3$
- Stasis can potentially *be* the **inflation** epoch!

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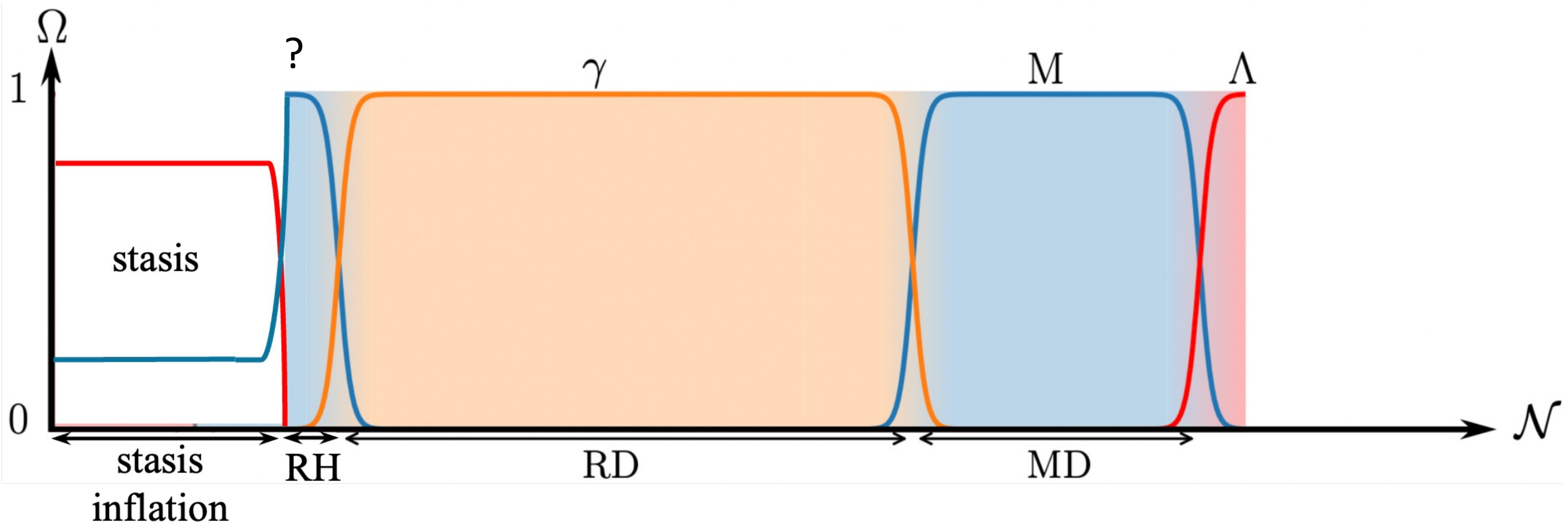

Stasis inflation!

Dienes, Heurtier, FH, Tait, Thomas
arXiv: 2406. 06830

Stasis inflation is an intriguing possibility …

- If such a stasis epoch can endure for $\mathcal{N}_e \sim 60$ e-folds of expansion, it can in principle solve the ***horizon and flatness problems***.

- The number of e-folds of inflation (***cosmology***) is often related in a deep way to ***hierarchies among fundamental particle-physics scales*** – e.g., in KK theories

$$\mathcal{N}_e \sim \log N \,, \qquad \text{where} \qquad N \sim (R M_{\mathrm{UV}})^n$$

compactification radius

# of compactified dimensions

UV cutoff: $M_P^{(D)}$ or M_{string}

- Complicated potentials are in principle ***not required***. Dynamics reflects the structure of the underlying theory, not the shape of the inflaton potential.

Stasis inflation is an intriguing possibility …

- As we have seen, during stasis inflation, any $\overline{w} < -1/3$ is possible, and not restricted to $\overline{w} \approx -1$
- A "***graceful exit***" is built into this scenario. Stasis inflation naturally ends when underdamping transitions reach the bottom of the tower
- A ***non-zero constant matter abundance*** (and potentially even radiation abundance) can be carried throughout inflation (abundances ***do not*** inflate away), thus may significantly change conditions needed for reheating.

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Of course, any model of inflation along these lines would also need to …

- produce a (nearly scale-invariant) density perturbation spectrum consistent with CMB data, etc;
- satisfy applicable constraints on non-Gaussianities and isocurvature;
- eventually reheat the universe (presumably from the decays of the tower states after stasis ends)

Stasis inflation is a scenario that warrants further exploration!

Observational signatures

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

Observational signatures

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

- Before we ask this question, perhaps we should first ask, what type of stasis?
  - vacuum energy/matter stasis?
  - matter/radiation stasis?
  - vacuum energy/radiation stasis
  - triple stasis?
  - What is the model?

Observational signatures

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

- Before we ask this question, perhaps we should first ask, what type of stasis?
  - vacuum energy/matter stasis?
  - matter/radiation stasis? ← we shall focus on this for the rest of the talk.
  - vacuum energy/radiation stasis
  - triple stasis?
  - What is the model?

Observational signatures: PBH stasis

Dienes, Heurtier, FH, Kim, Tait, Thomas
arXiv: 2212.01369

PBH-induced stasis implies a sequence of epochs that modifies the standard cosmological timeline

Inflation — $H_* < 2.5\times10^{-5} M_P$

↓

?

$$\alpha \equiv -\frac{3w_c+1}{w_c+1}$$

$$\Omega_{\rm BH} = 1$$

↓

PBH stasis — $$\overline{\Omega}_{\rm BH} = \frac{4\alpha+10}{\alpha+7}$$

↓

Standard cosmology — after evaporation of $\mathrm{M_{max}}$ …

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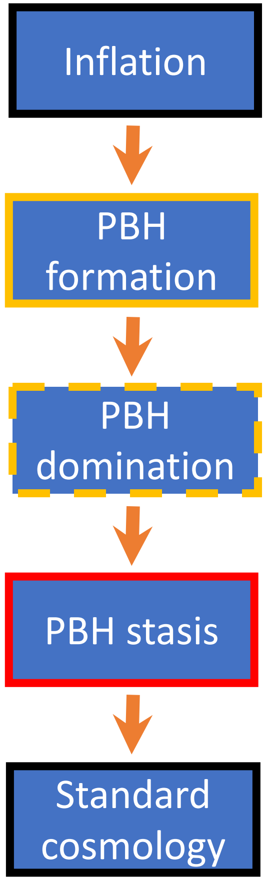

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- **Inflation** — $H_* < 2.5\times10^{-5} M_P$
- ↓ **PBH formation** — $\alpha \equiv -\dfrac{3w_c+1}{w_c+1}$
- ↓ **PBH domination** — $\Omega_{\rm BH} = 1$
- ↓ **PBH stasis** — $\overline{\Omega}_{\rm BH} = \dfrac{4\alpha+10}{\alpha+7}$
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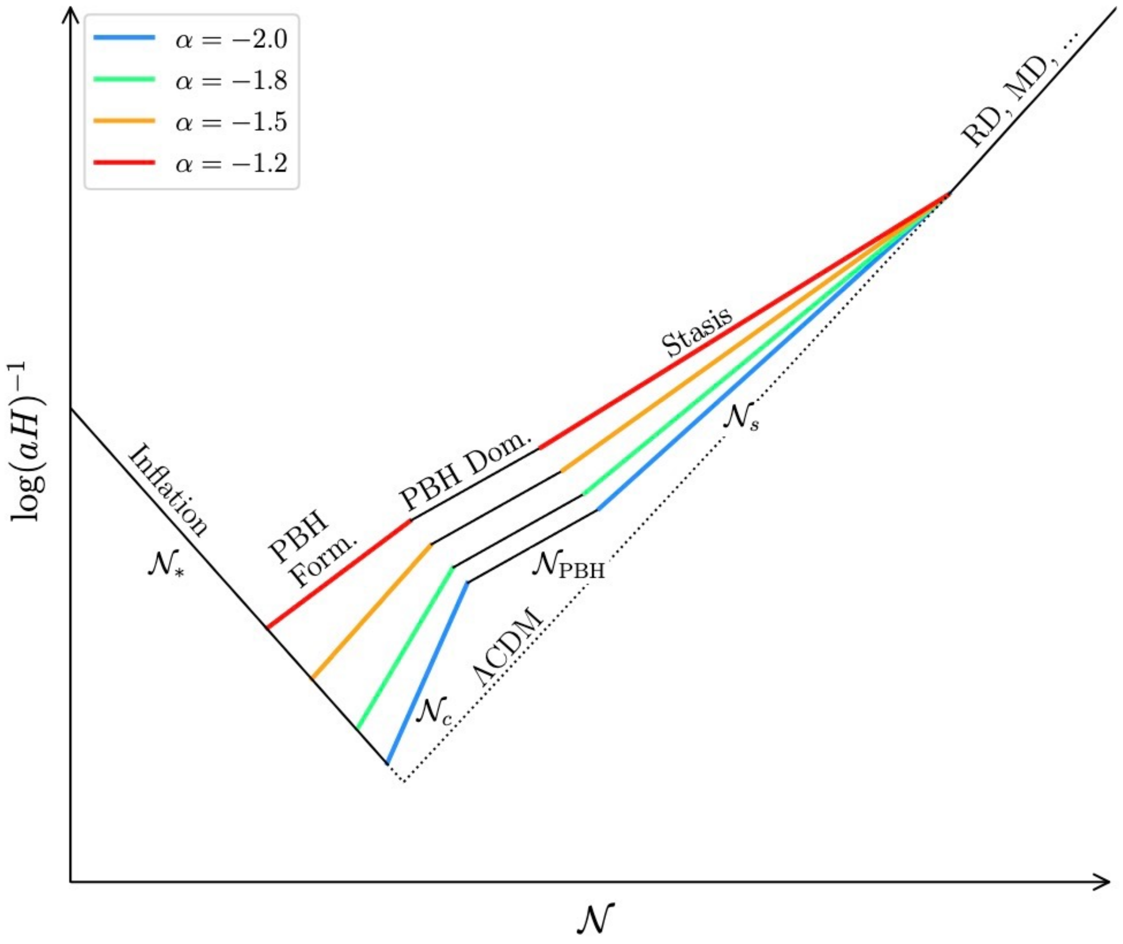

Slopes of each epoch depend on EoS parameter of each epoch, can be fully determined by α

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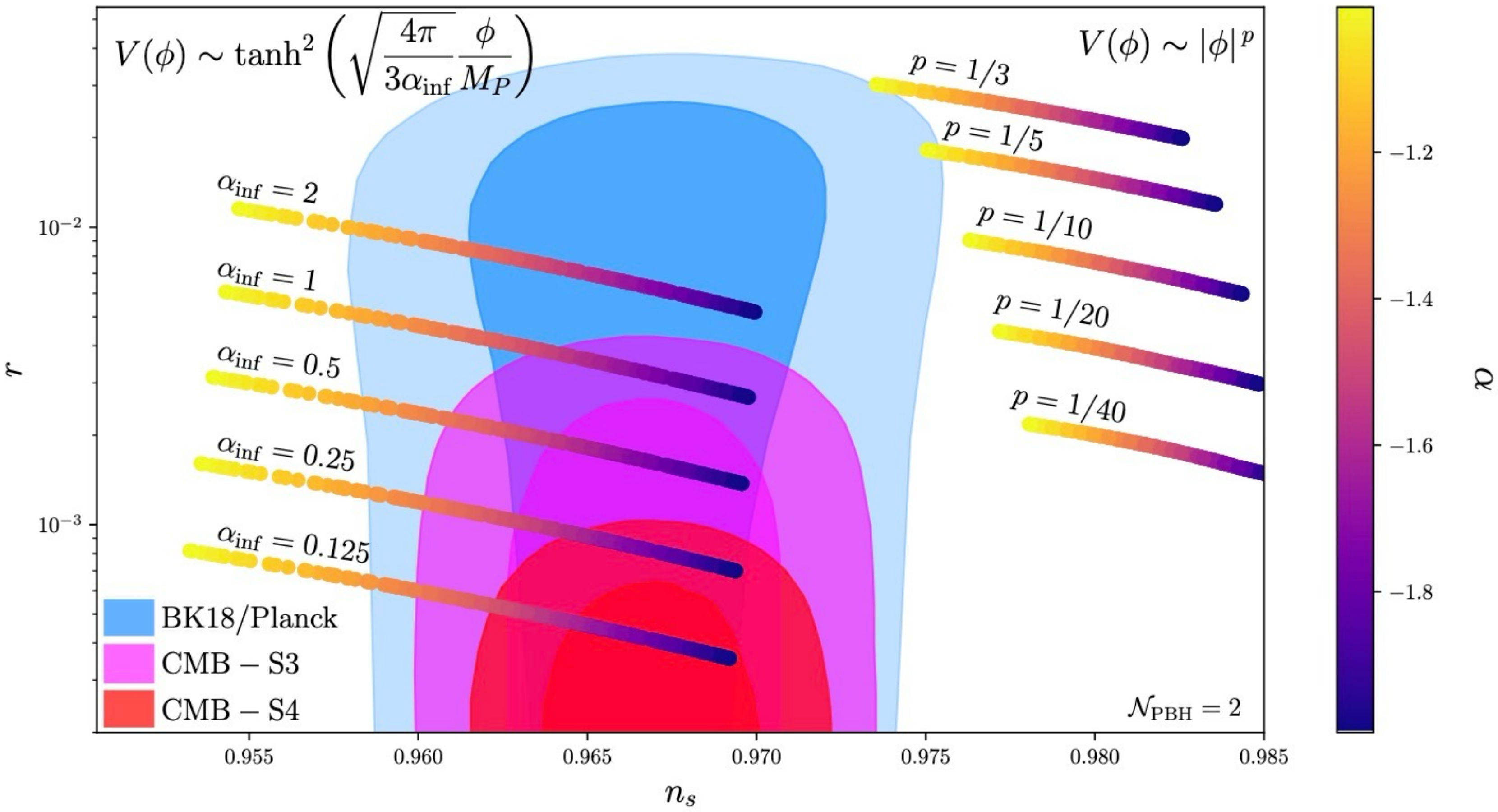
The modification to the cosmological timeline is tightly constrained by the CMB measurements through ***Spectral index*** n_s and ***tensor-to-scalar ratio*** r

With increasing α

- n_s tends to decrease
- r tends to increase
- increases the tension for α-attractor potentials
- reduces the tension for polynomial potentials

$M_{\rm min} = 1\ {\rm g}\,, M_{\rm max} = 10^9\ {\rm g}$



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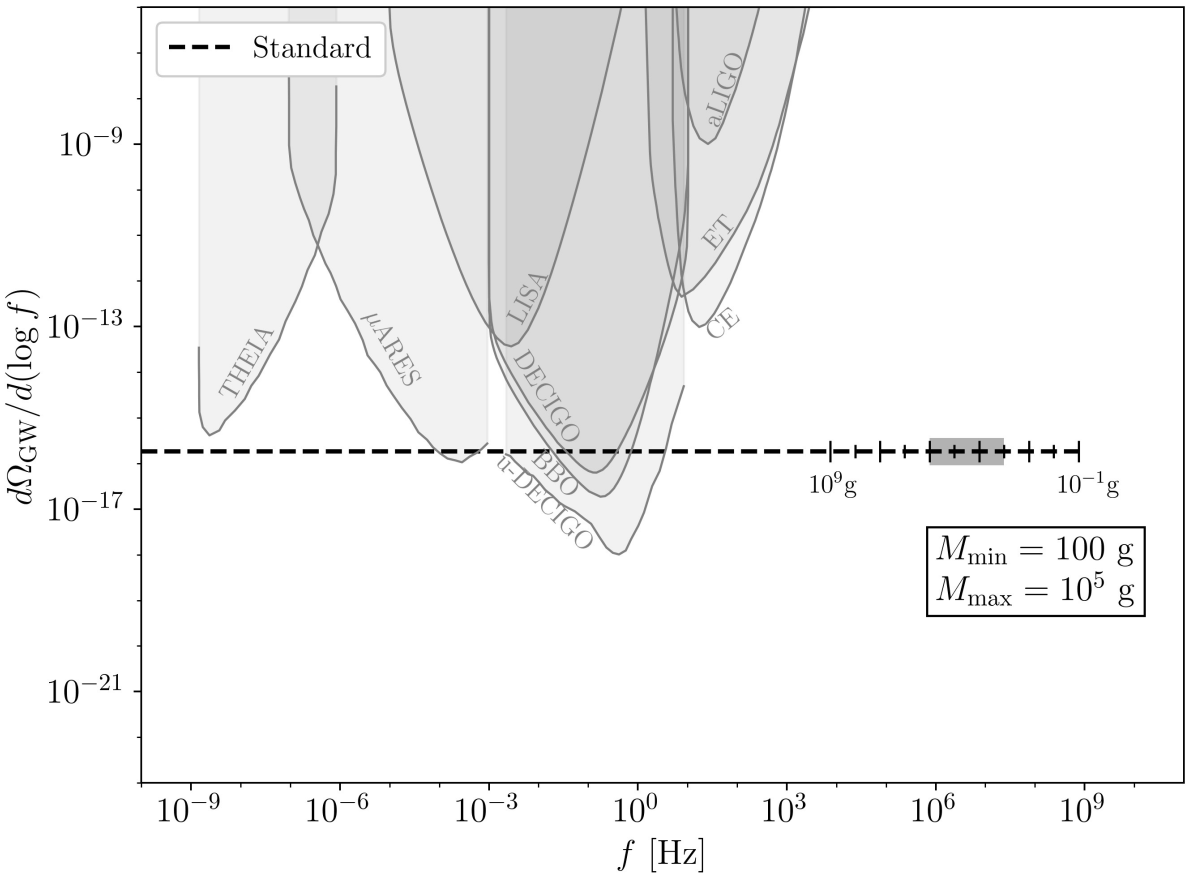

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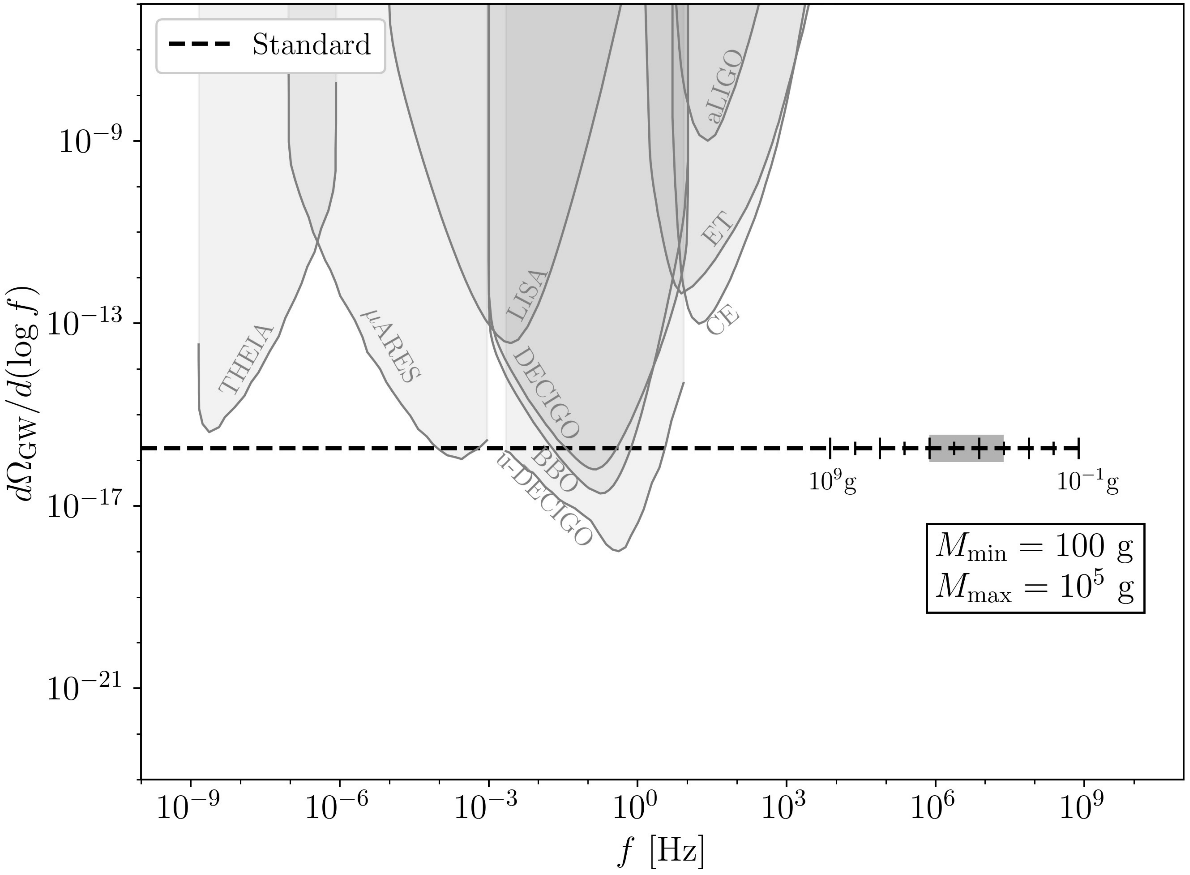

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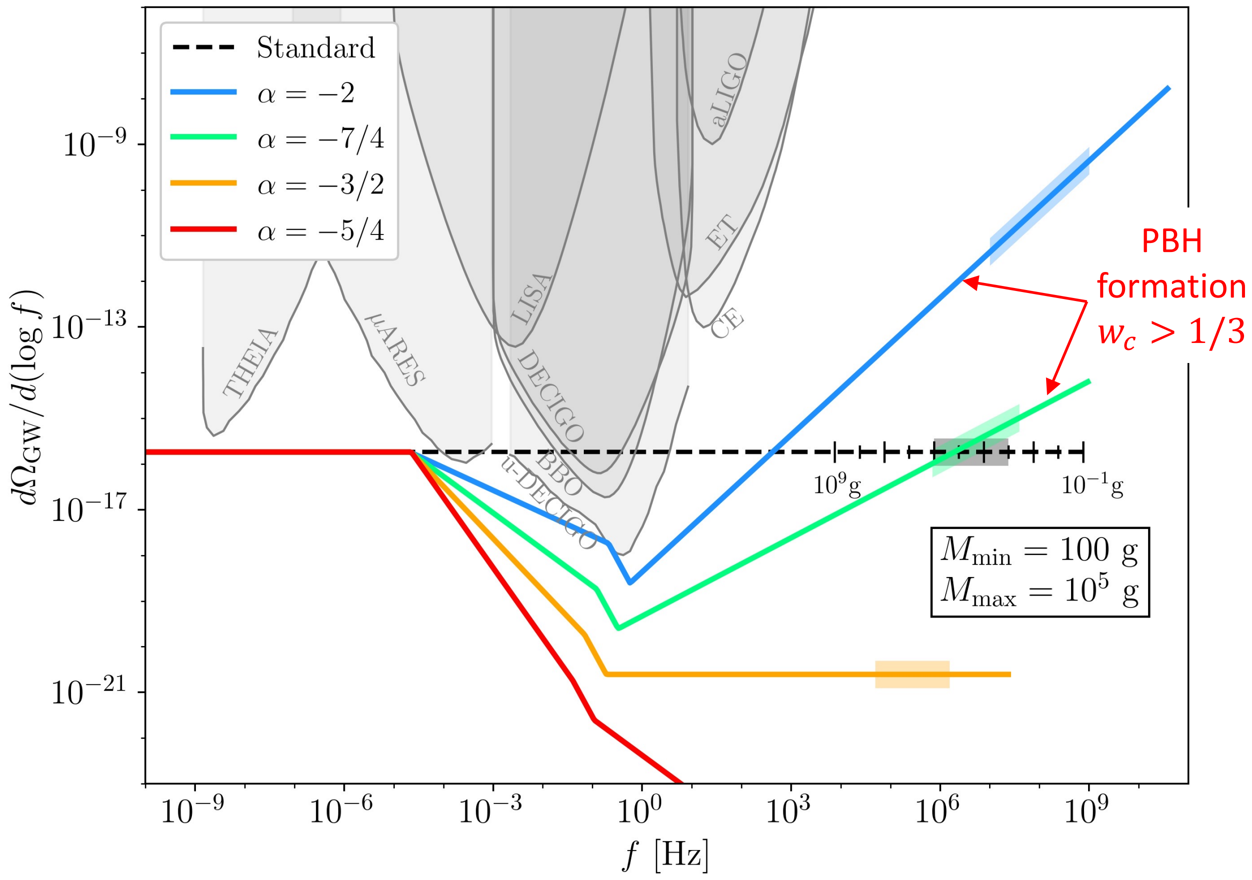

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From 0th order to 1st order

- The observational implications presented thus far are essentially due to modified background expansion histories.

- At background level, a stasis epoch mimics an epoch of perfect fluid domination (PFD) wherein $w_{PF} = \overline{w}$.

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Is a stasis epoch equivalent to a PFD epoch with the same EoS?

Need to look at the perturbation level!

Observational signatures at the perturbation level

More specifically, let's consider

- A matter/radiation stasis caused by a tower of decaying particles (and a PFD with the same EoS)

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- A "**spectator**" component χ which
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  - interacts with other components ***only through gravity***.

In other words, let χ be a population of decoupled **dark-matter** particles.

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 $0 < \overline{w} < 1/3$.

As we'll see, the results differ significantly from the corresponding results for PFD!

Observational signatures at the perturbation level

Since χ is decoupled (no source/sink terms):

$$\nabla_\mu \left(T_\chi\right)^\mu{}_\nu = 0$$

This relation yields an equation of motion for $\delta_{k\chi}$

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

On the other hand, the evolution of Φ_k follows from the Einstein equation:

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

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Background energy density of X

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Effective EoS parameter $\langle w \rangle \equiv \sum_X \Omega_X\, w_X$

sum over all cosmological components X

Effective sound speed of X

Observational signatures at the perturbation level

First, let's consider a PFD epoch, in this case, $\langle w \rangle = w_{PF} = c_{sPF}^2$, and therefore

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Vanishes!

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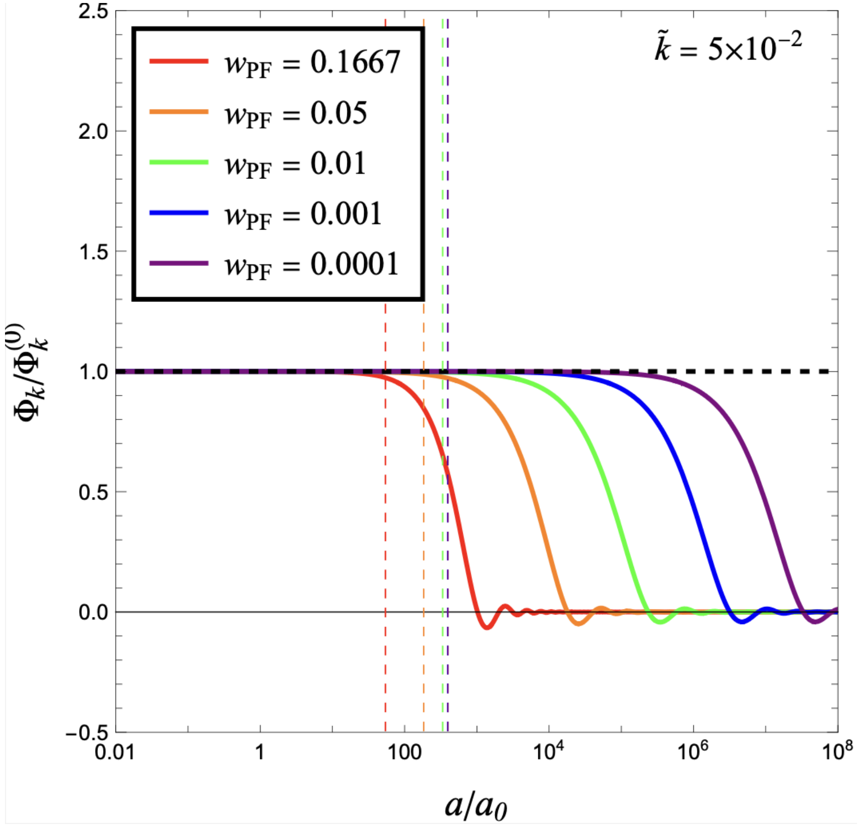

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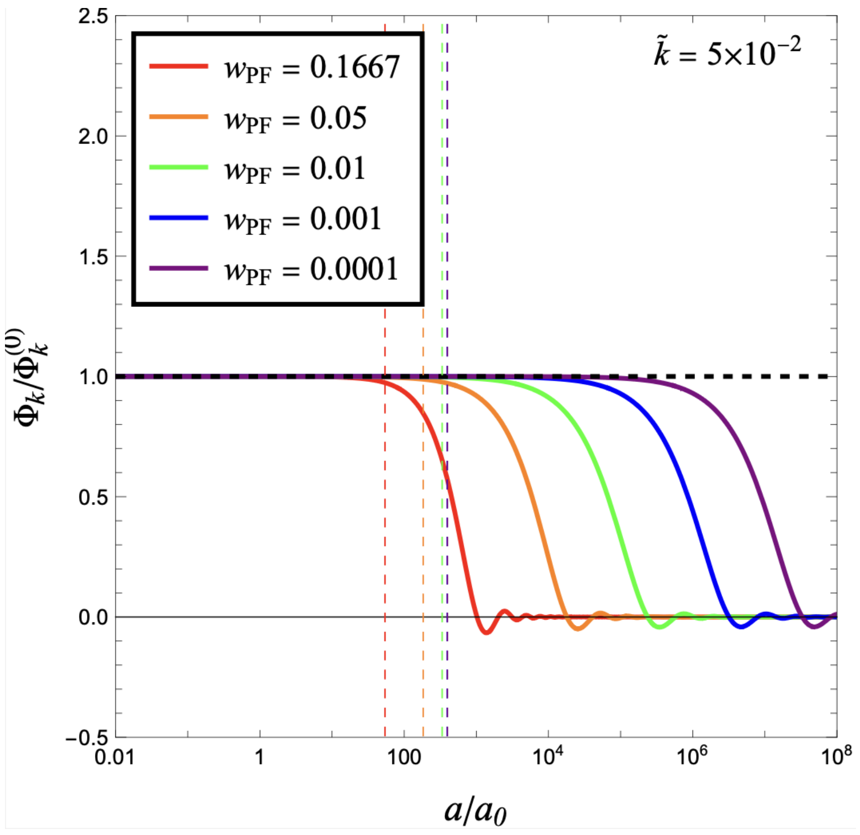

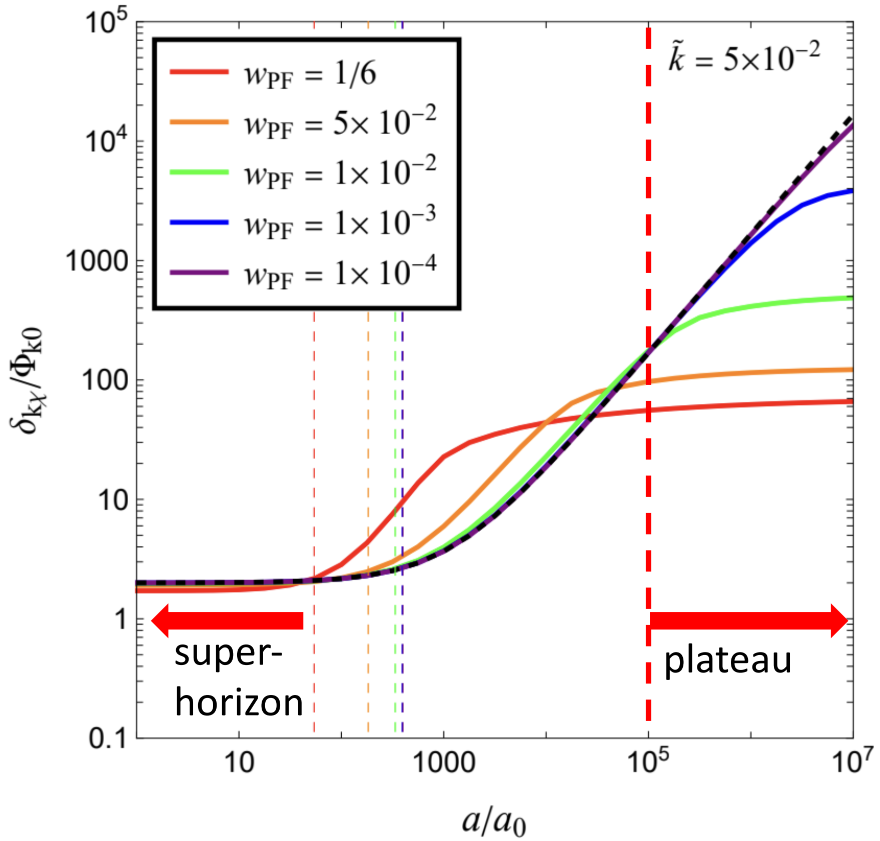

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Now, let's consider a matter/radiation stasis, where $c_{s\ell}^2 = w_\ell = 0$, $c_{s\gamma}^2 = w_\gamma = 1/3$, and $\langle w \rangle = w_\gamma \Omega_\gamma + \sum_\ell \mathrm{w}_\ell \Omega_\ell$, and thus,

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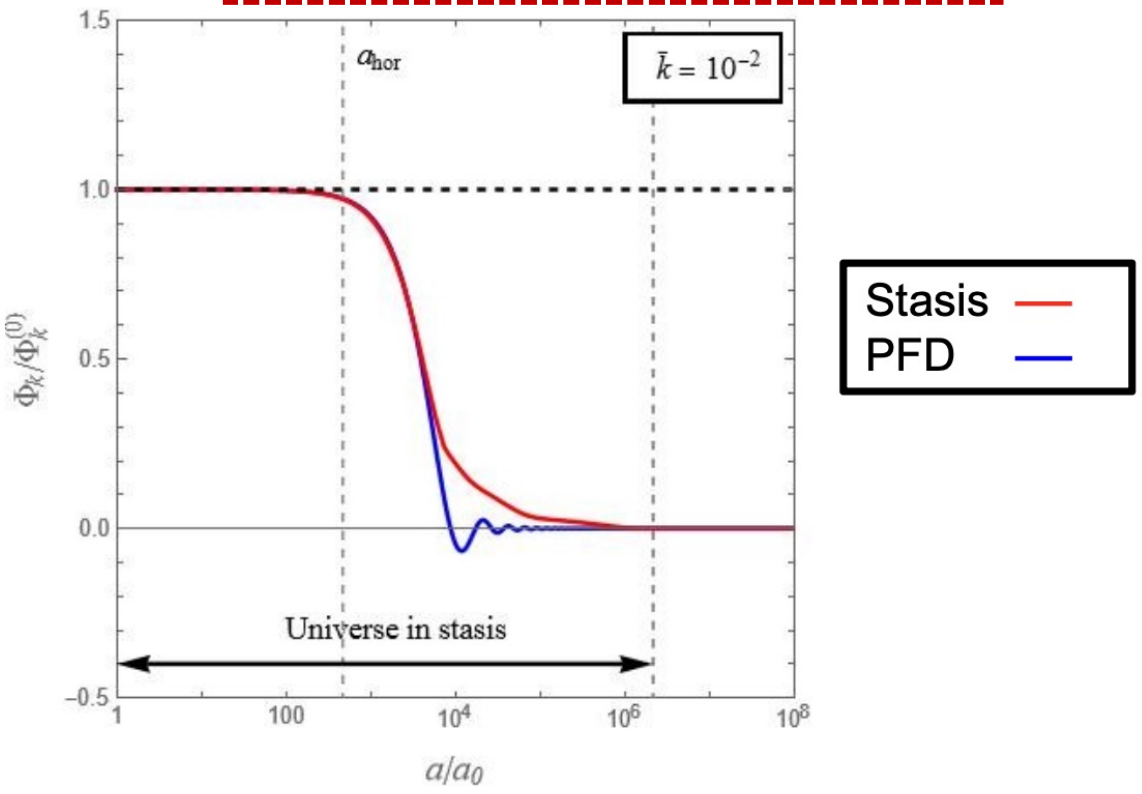
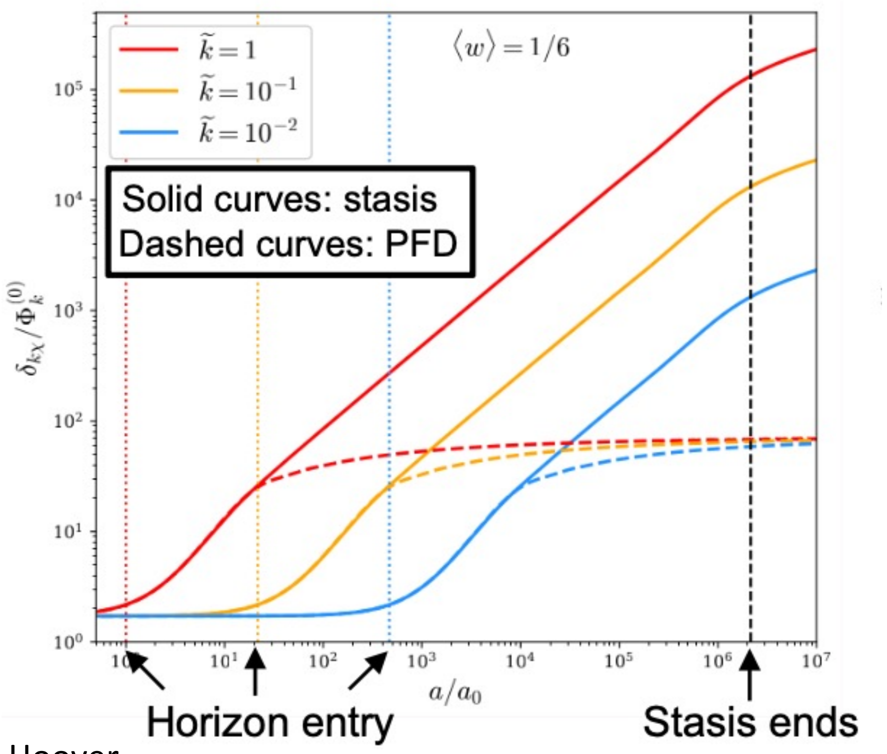
These effects can dramatically impact how $\delta_{k\chi}$ evolves!



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:

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



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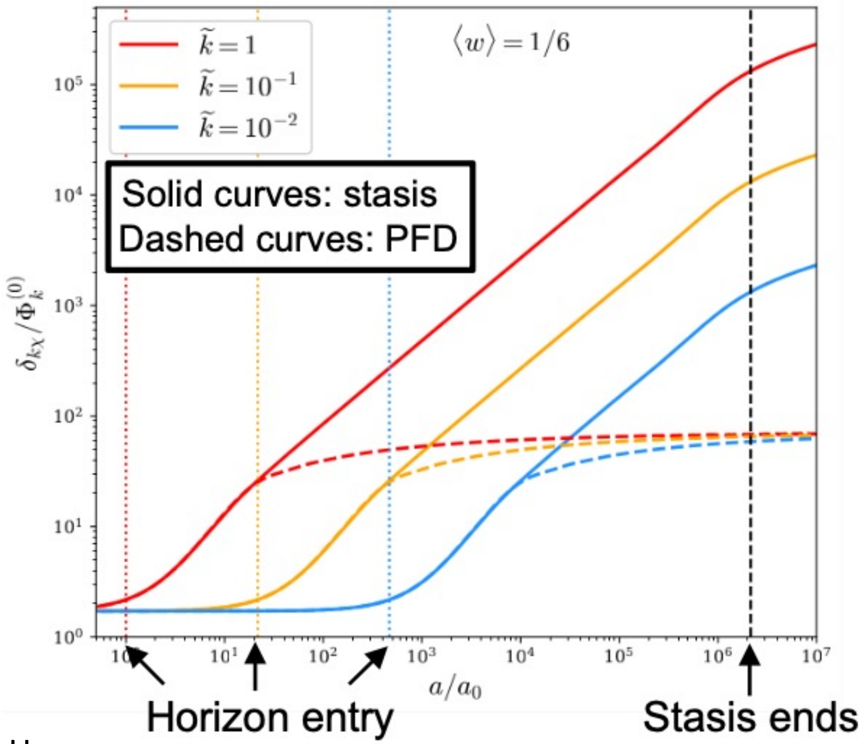

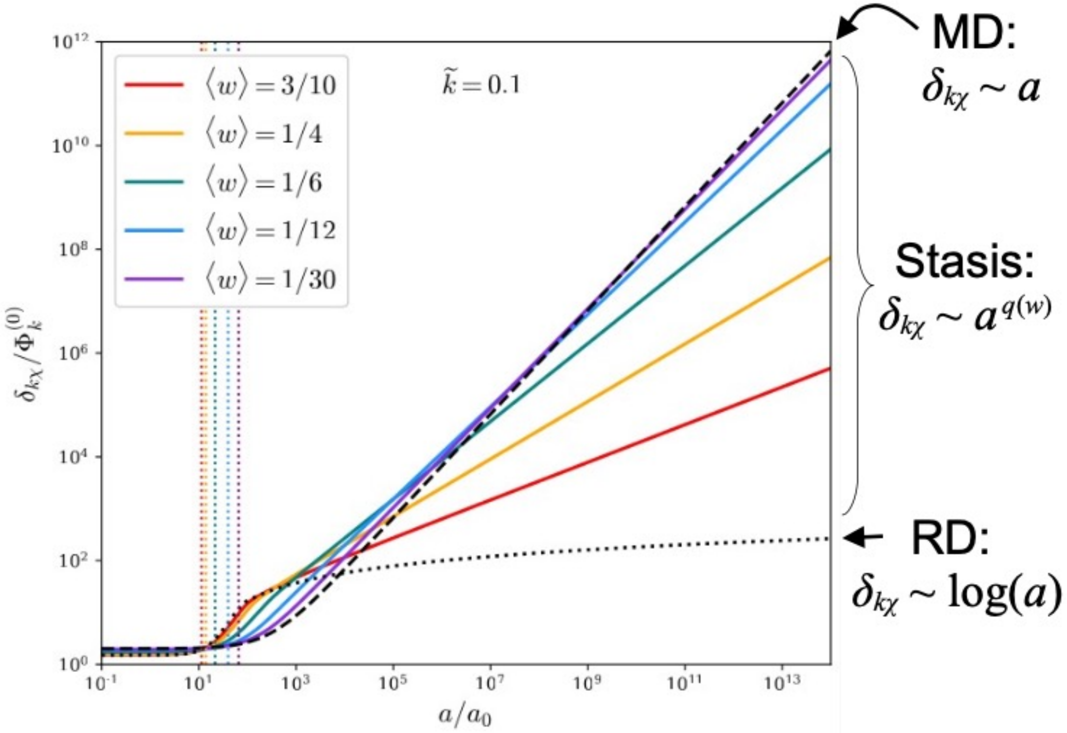

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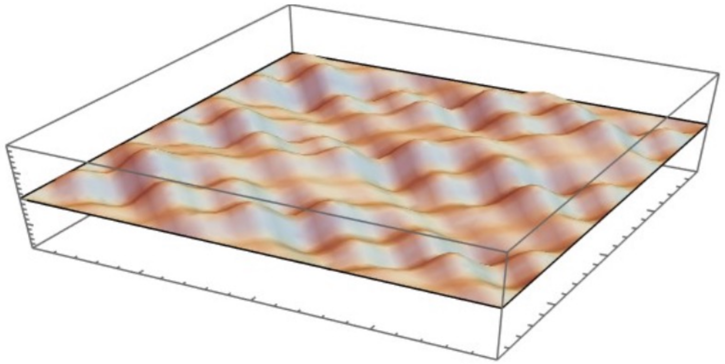
This power-law growth interpolates between the logarithmic growth during radiation domination and the linear growth during matter domination!

Observational signatures at the perturbation level

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



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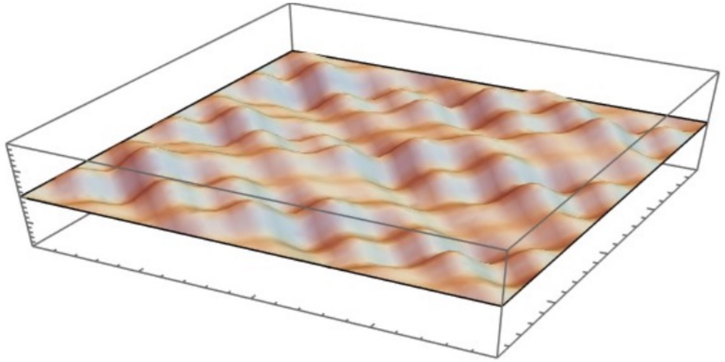
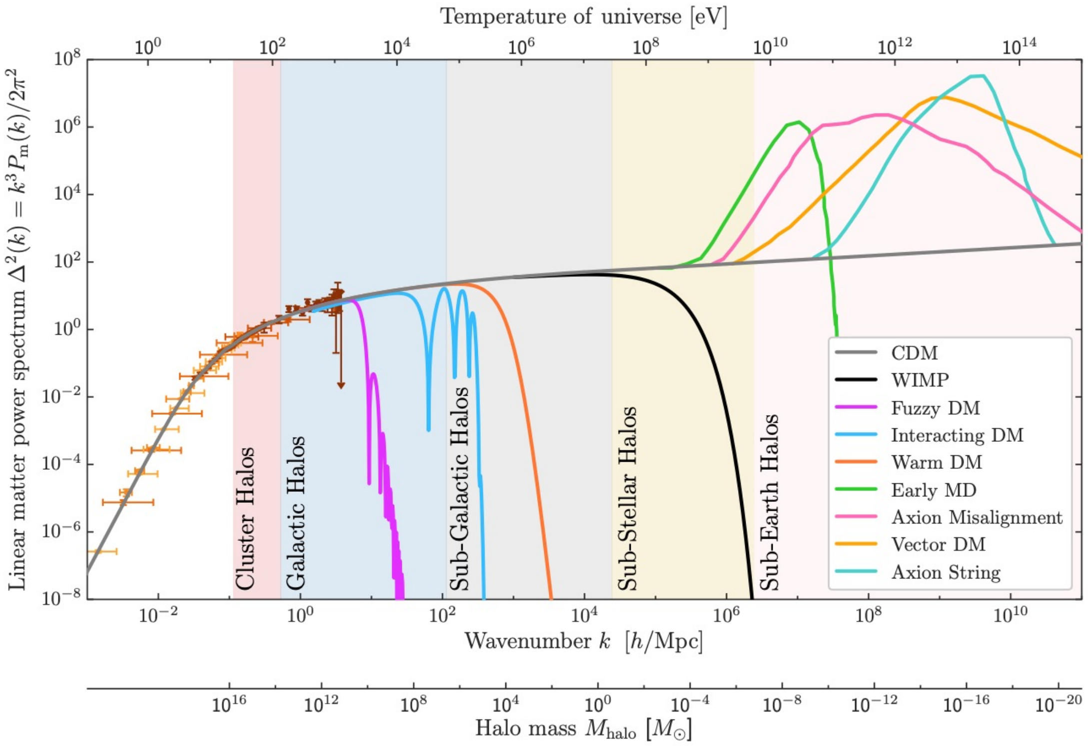


Enhancements or suppressions in the **linear matter power spectrum** relative to the standard cosmology across different ranges of k can have observational consequences for **cosmic structure**.

In the stasis case, they could lead to the formation of small, dense clumps of matter – **microhalos**.



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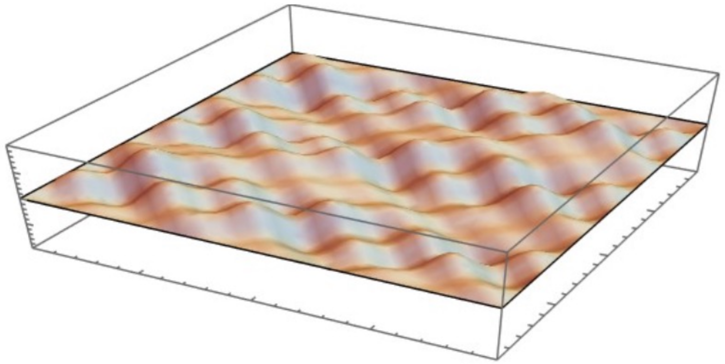

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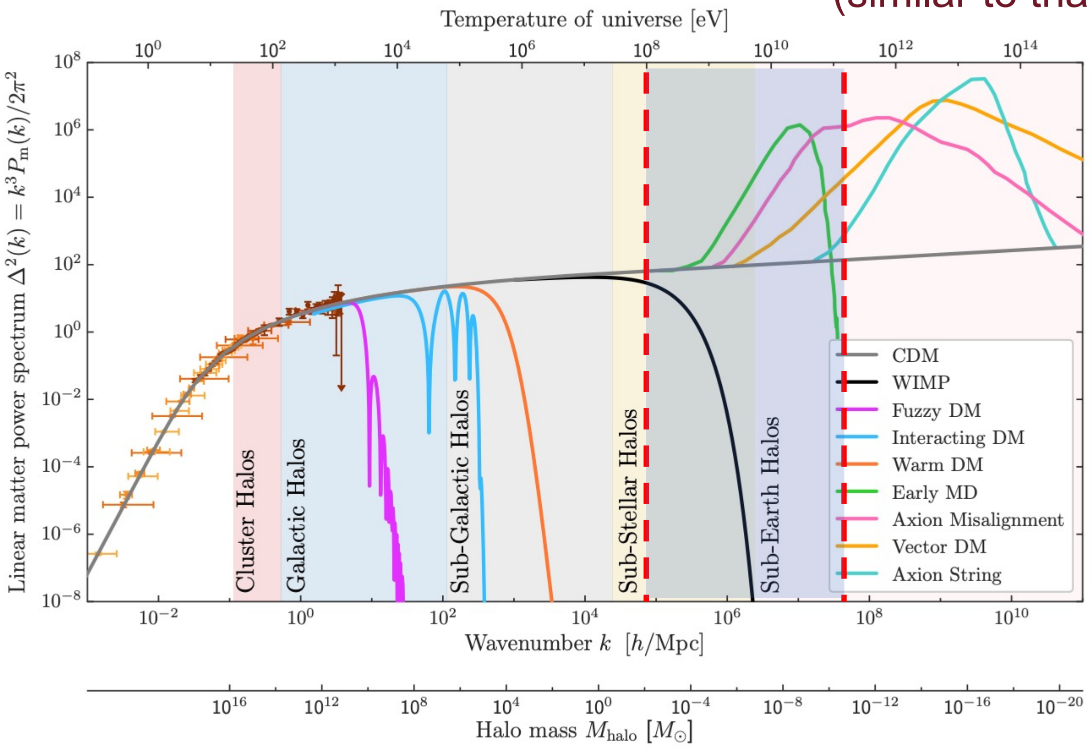
Regime of interest
(similar to that for EMDEs)



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.

- Stasis can be generated via different ways, such as a ***tower of decaying matter states***, and a population of ***evaporating PBHs*** with an extended mass spectrum, and has different forms, such as matter/radiation stasis, and vacuum energy/matter stasis, etc.

- The existence of a stasis epoch can lead to a number of phenomenological implications, ranging from the effects on inflationary observables, primordial gravitational wave background, to the enhanced formation of small scale structures.

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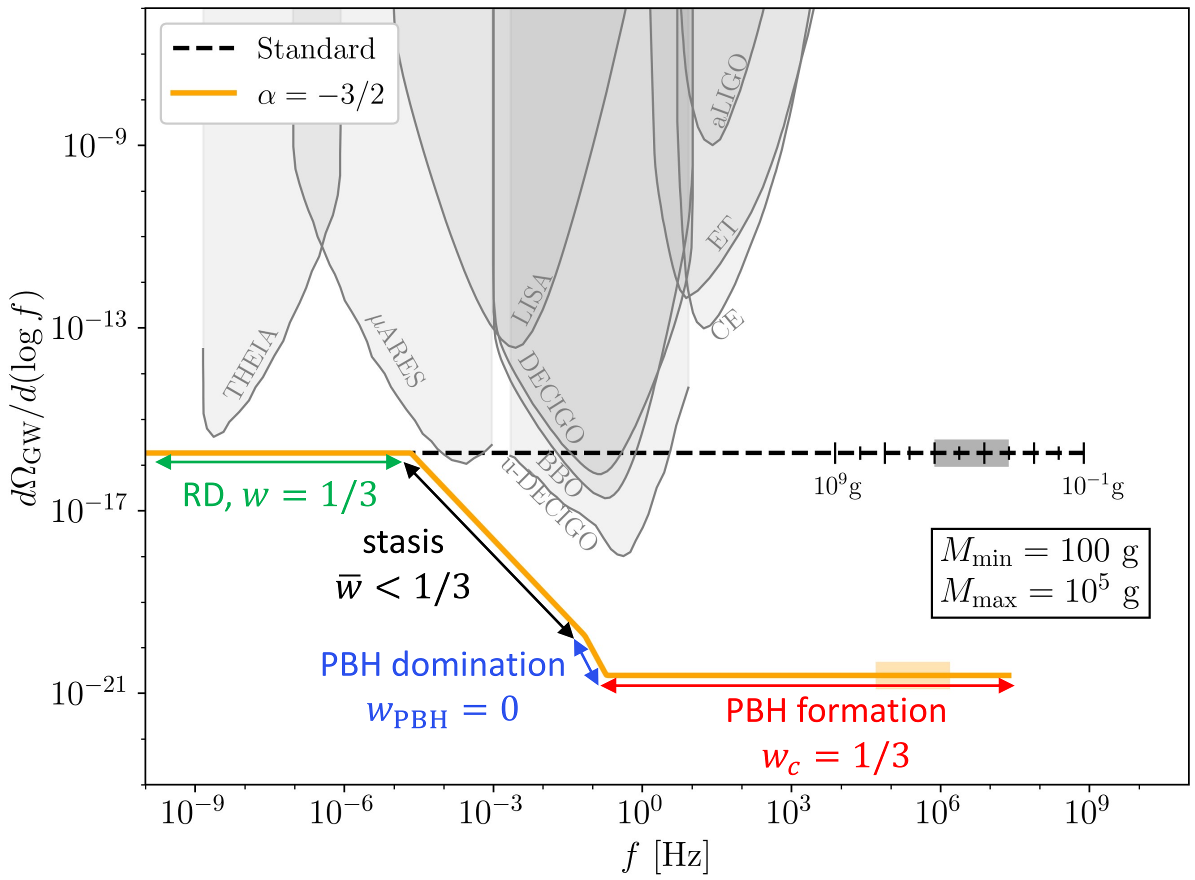

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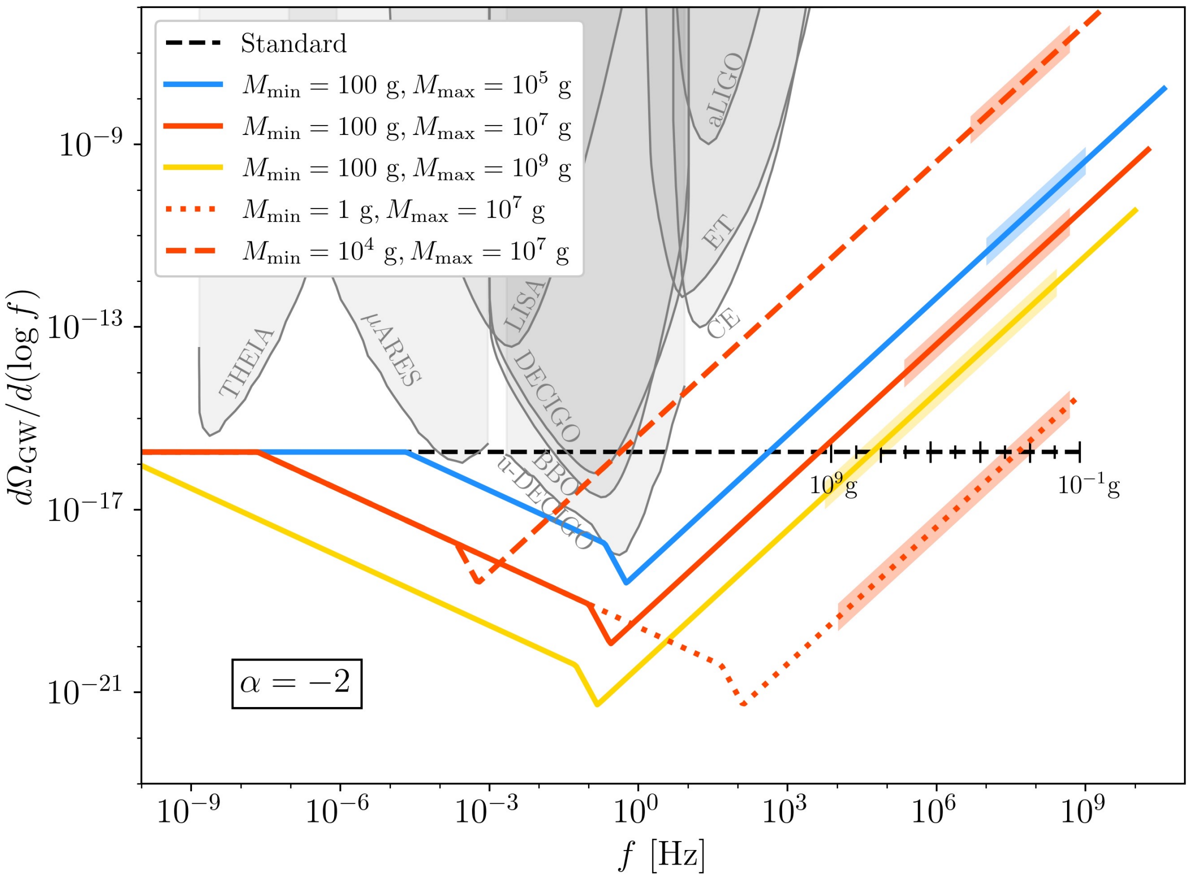

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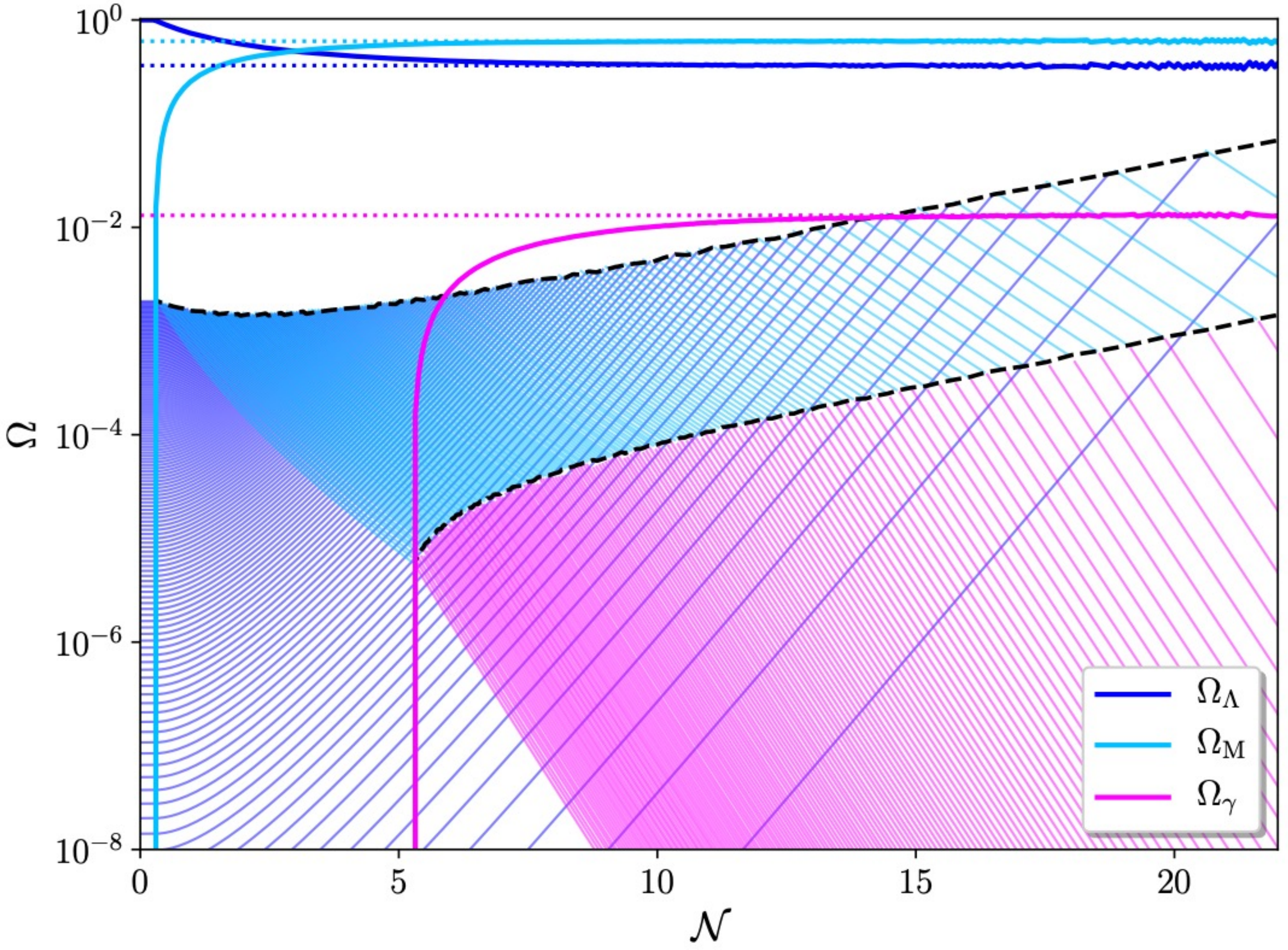

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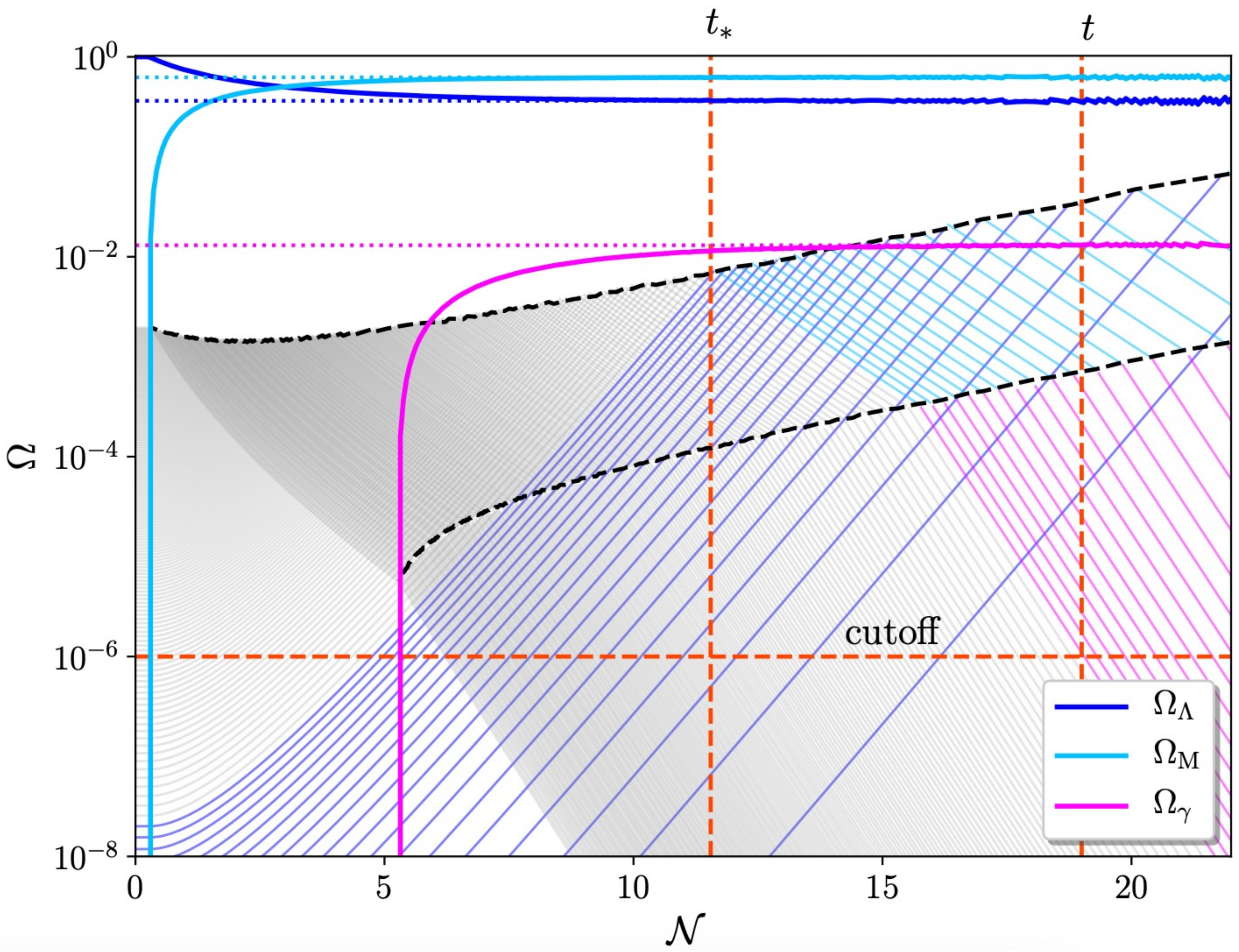

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