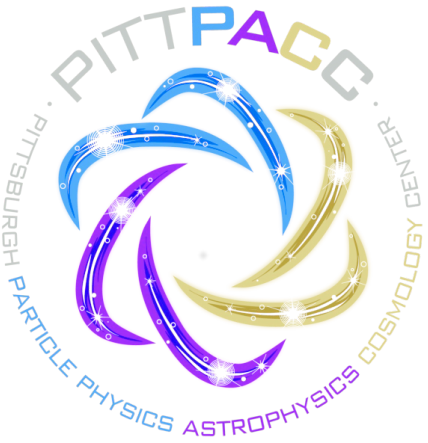


Block VIII: Cosmological Stasis

Fei Huang

PITT PACC Workshop:
Non-Standard Cosmological Epochs and Expansion Histories

Sep 07, 2024

So far, we have examined many non-standard types of cosmological epochs.

However, there is yet another kind that might be relevant for this workshop.

“COSMOLOGICAL STASIS”

First, we'll review the main ideas of cosmological stasis so that we can all be on the same page

Then we can springboard to a discussion about how it differs from other kinds of epochs and what signatures this might have

The Standard Lore: ΛCDM

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

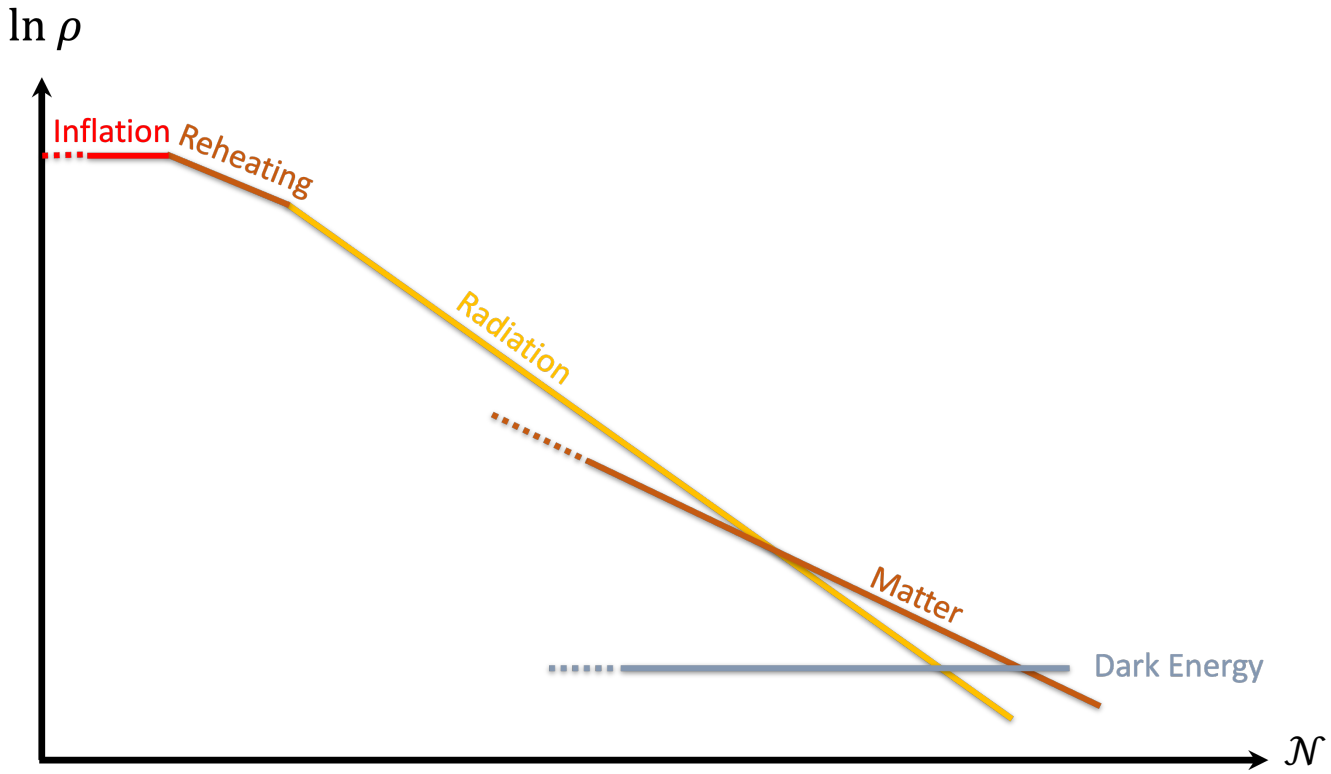
Vacuum Energy $w_\Lambda = -1$ → $\rho_\Lambda \sim a^0$

Matter $w_M = 0$ → $\rho_M \sim a^{-3}$

Radiation $w_\gamma = \frac{1}{3}$ → $\rho_\gamma \sim a^{-4}$

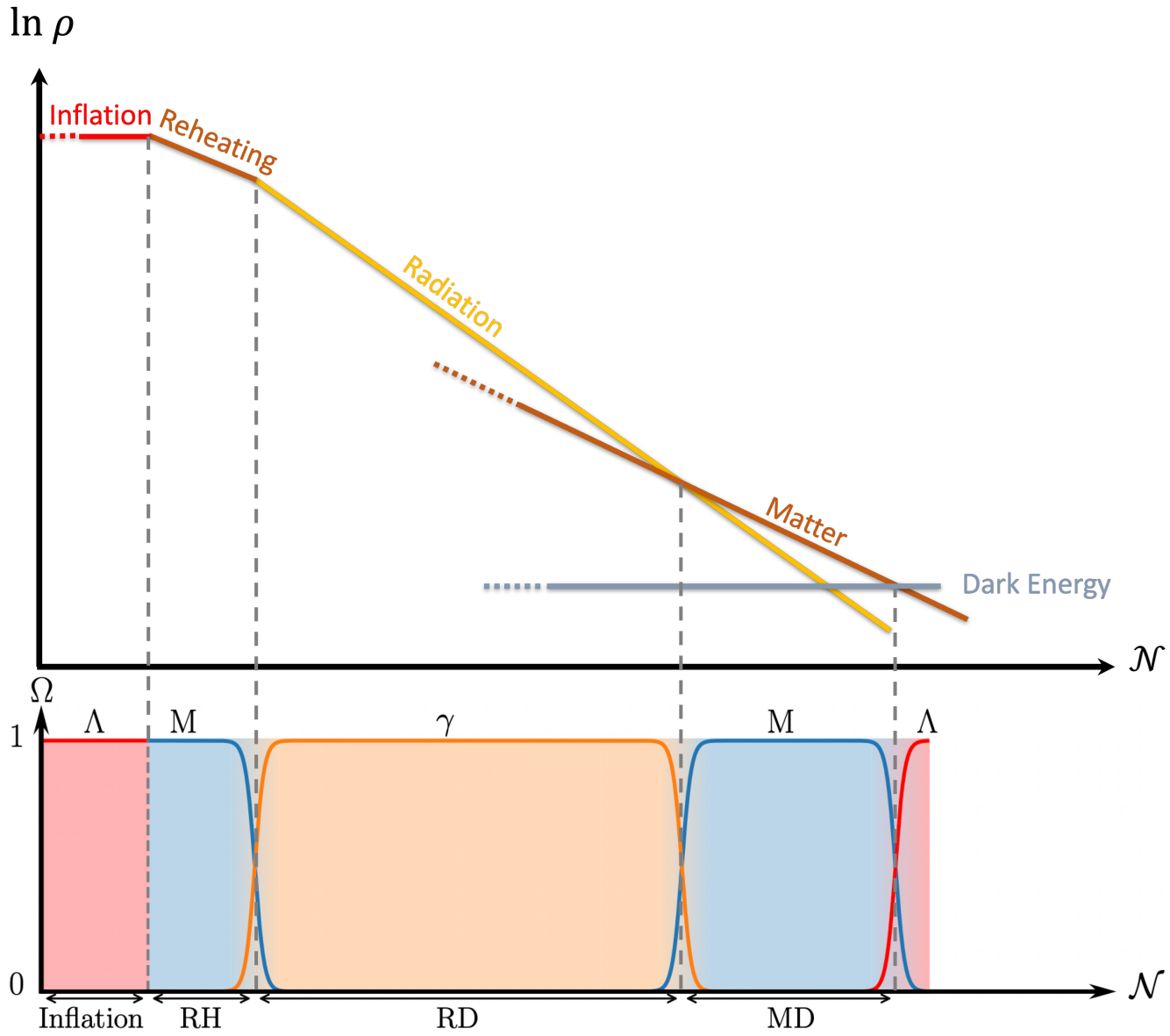
The Standard Lore: ΛCDM

$$\rho_\Lambda \sim a^0$$
$$\rho_M \sim a^{-3}$$
$$\rho_\gamma \sim a^{-4}$$



The Standard Lore: ΛCDM

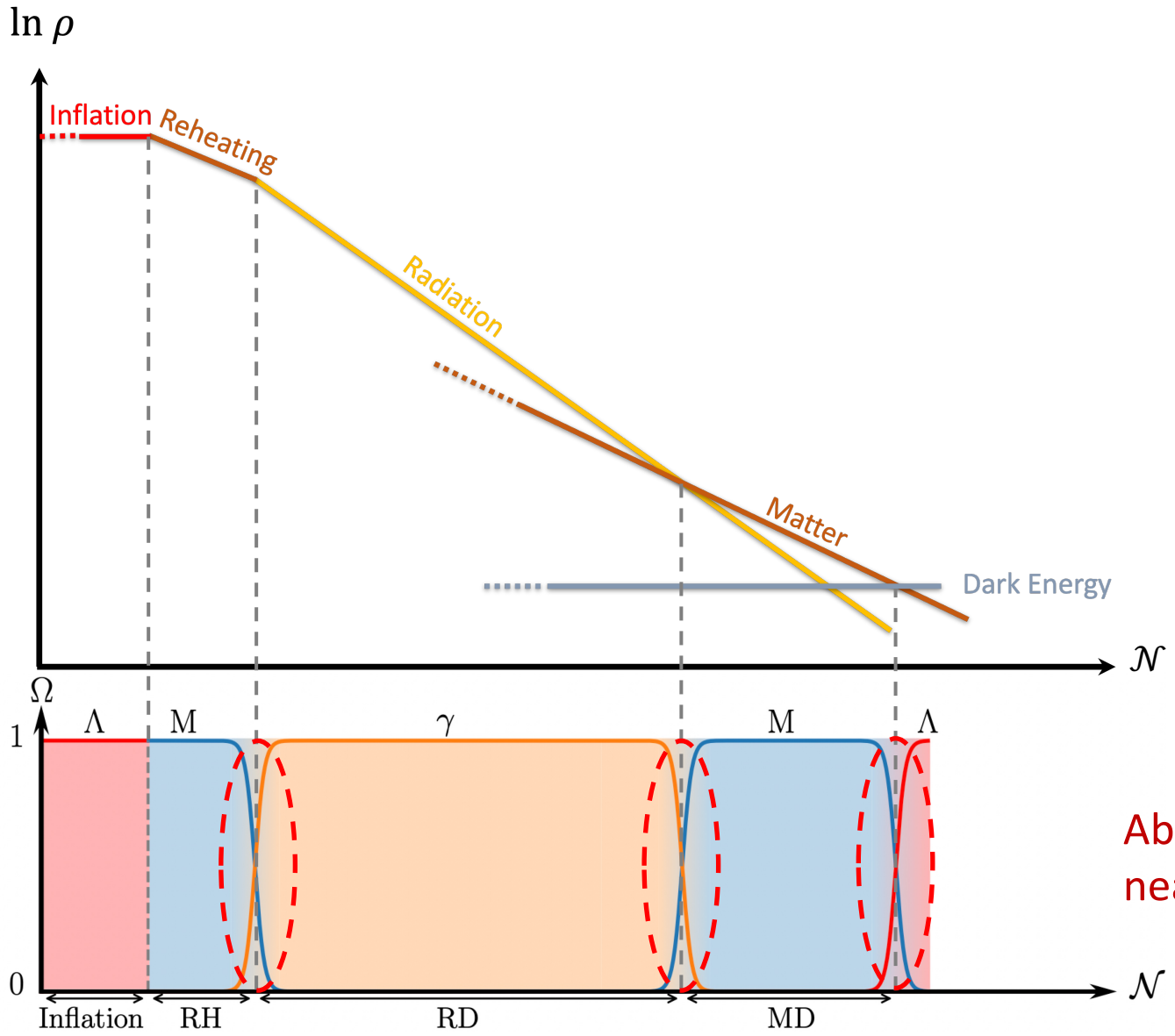
$$\rho_\Lambda \sim a^0$$
$$\rho_M \sim a^{-3}$$
$$\rho_\gamma \sim a^{-4}$$



Most parts are dominated by a single energy component.

The Standard Lore: ΛCDM

$$\rho_\Lambda \sim a^0$$
$$\rho_M \sim a^{-3}$$
$$\rho_\gamma \sim a^{-4}$$



Most parts are dominated by a single energy component.

Abundances only similar near transition points!

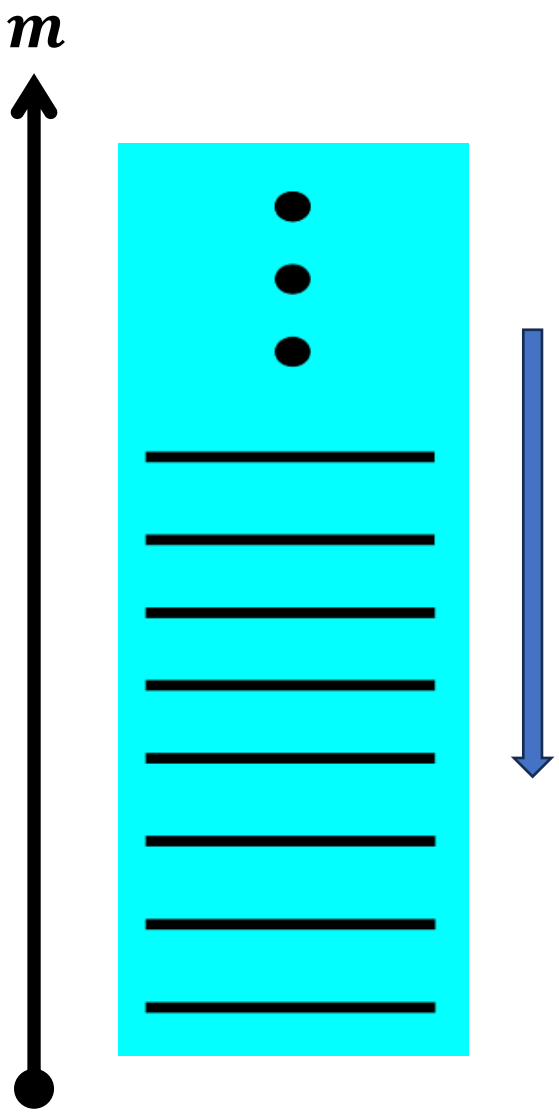
However, this picture is likely to be ***incorrect*** in the presence of many kinds of BSM physics…

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.

- Towers of 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.



A sequential process down the tower which continually converts matter into radiation.

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

Cosmological expansion $\Omega_\gamma \rightarrow \Omega_M$

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

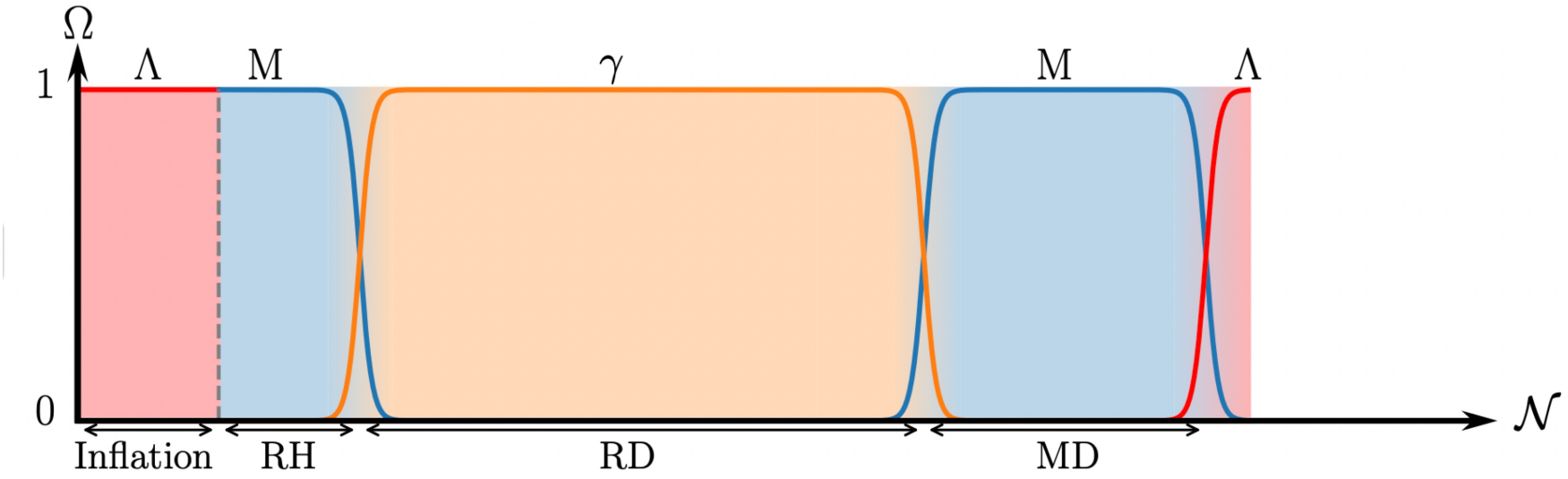
But, they CAN balance. In fact, they DO balance.

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

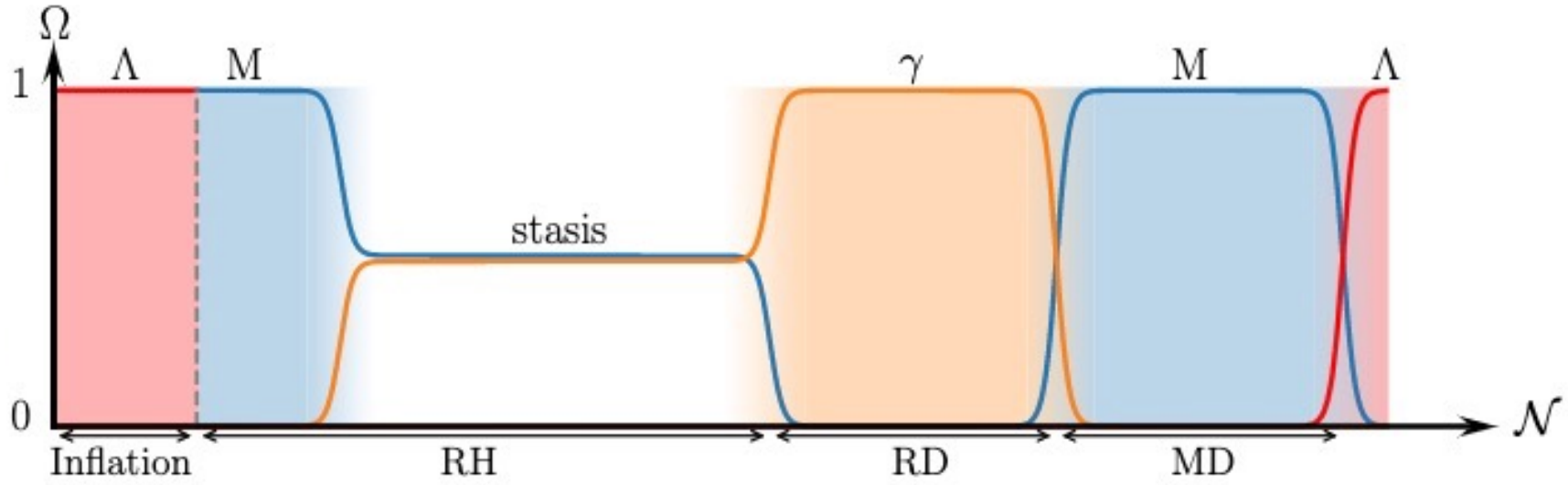
The balanced solution is an ***attractor!***

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 …

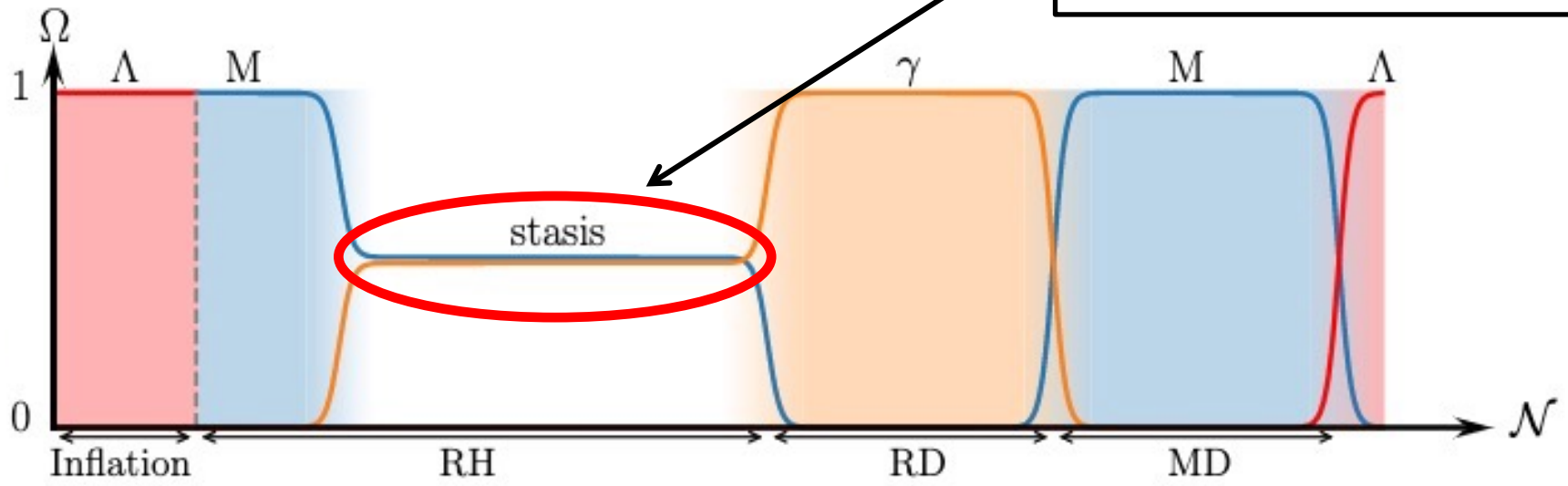


The universe may more likely evolve like this



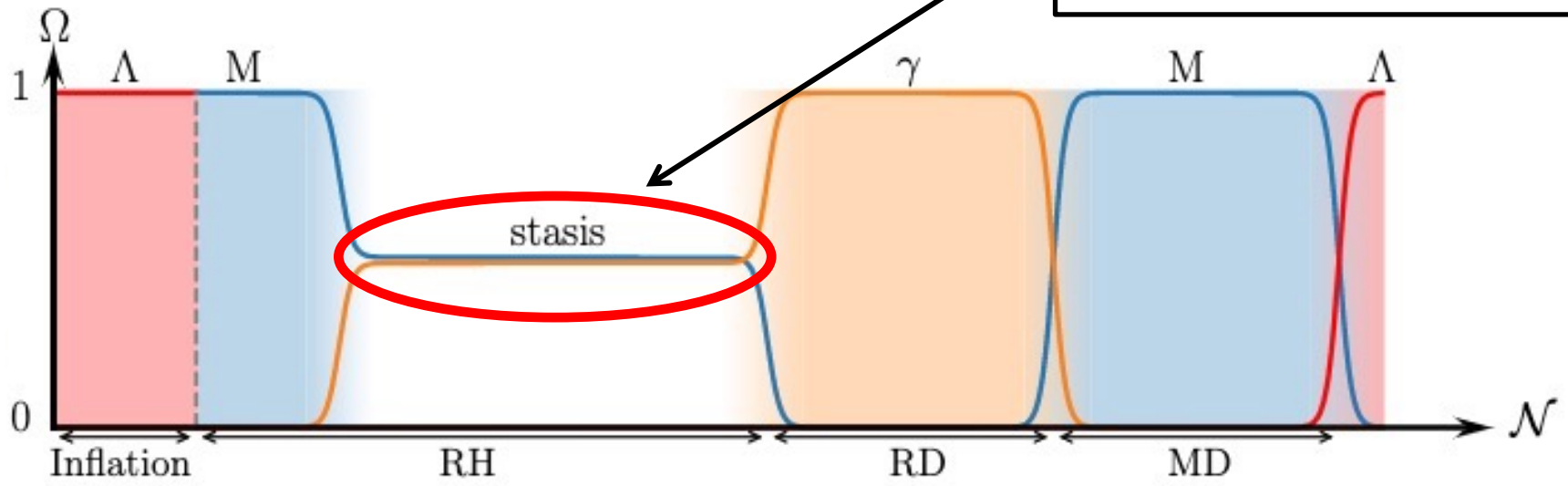
The universe may more likely evolve like this

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



The universe may more likely evolve like this

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



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 parameterize

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

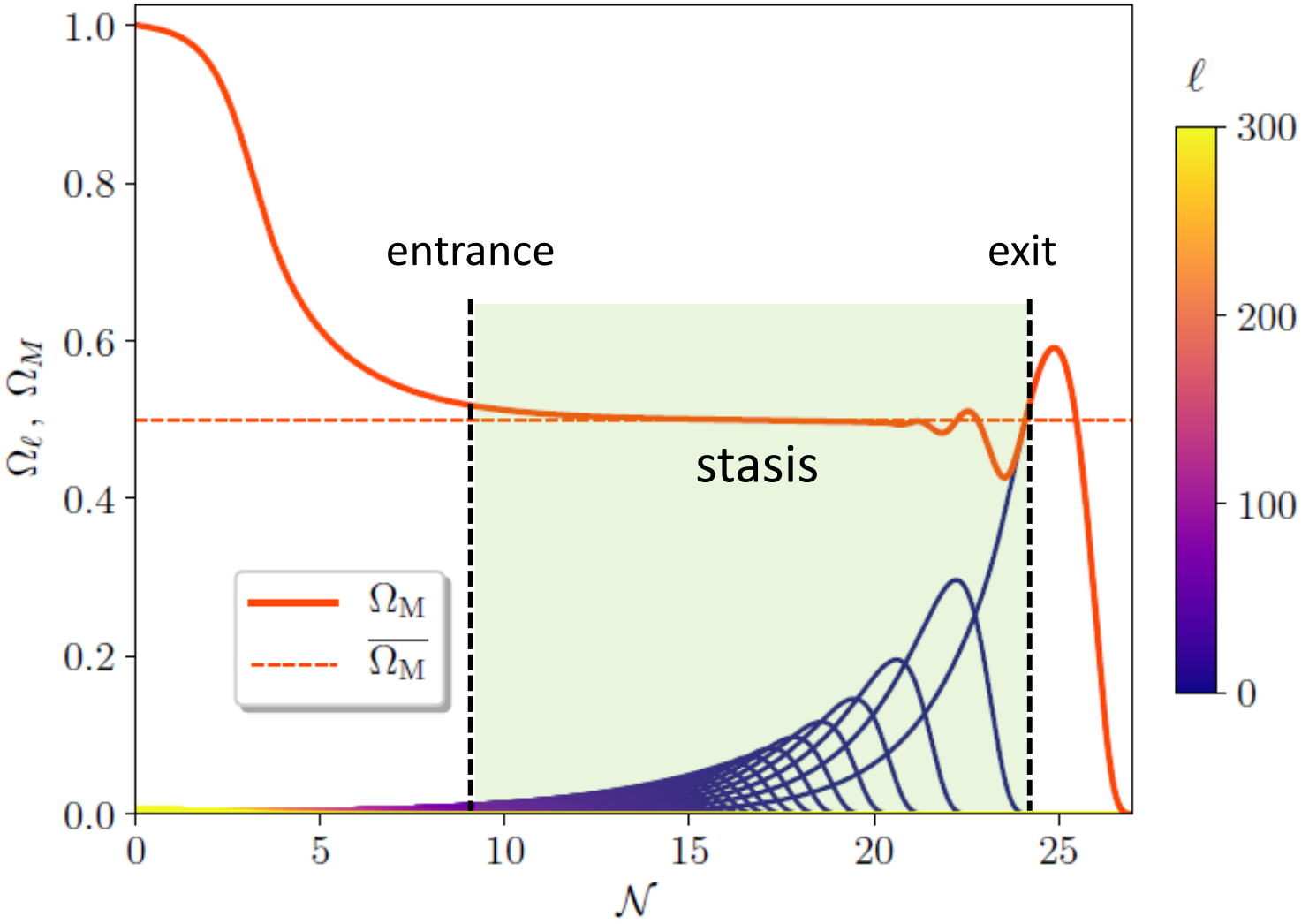
Stasis arises for all values of these parameters within the range

$$\mathbf{0 < \alpha + 1/\delta \leq \gamma/2}$$

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

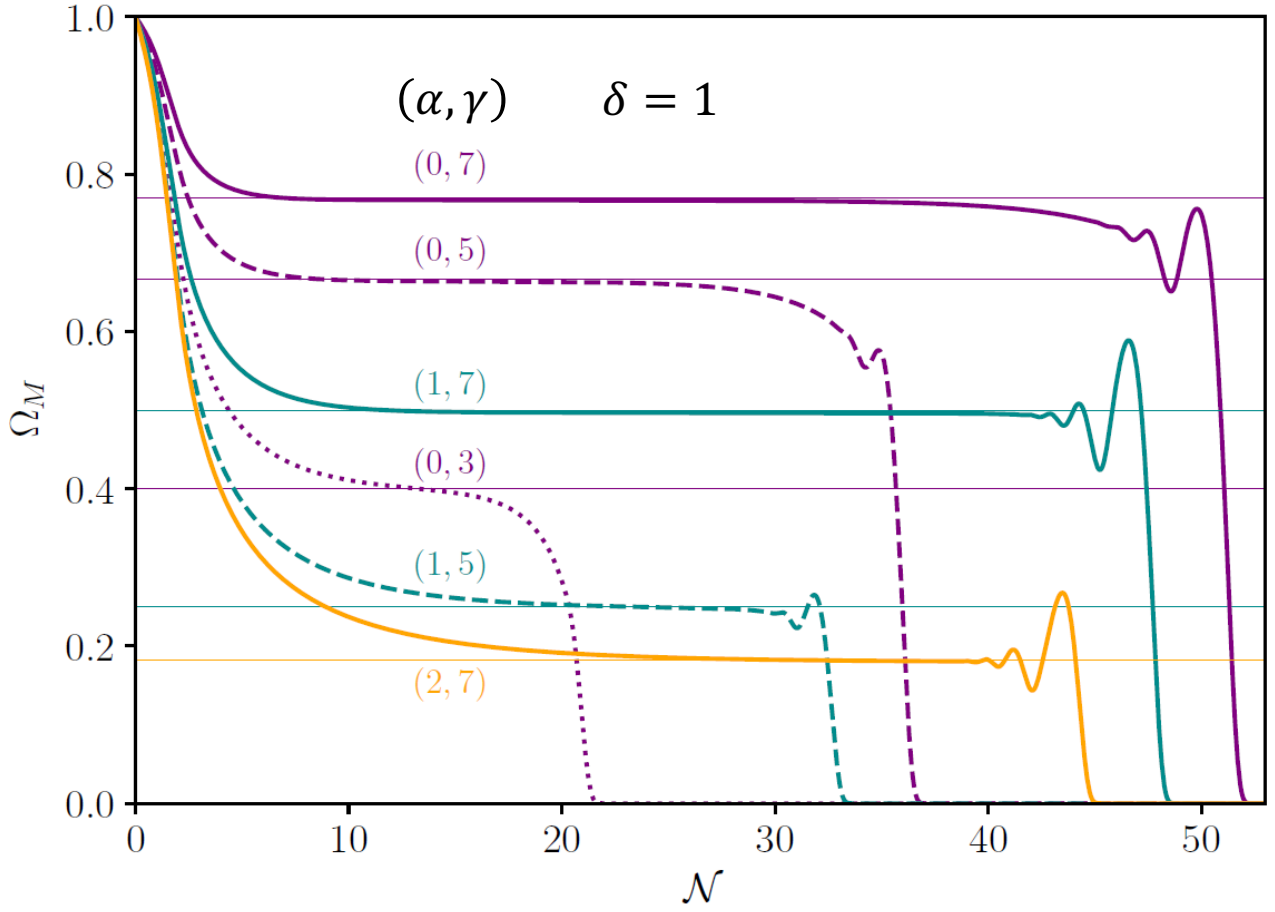
$$\overline{\Omega}_M = \frac{2\gamma\delta - 4(1+\alpha\delta)}{2\gamma\delta - (1+\alpha\delta)}$$

K. Dienes, L. Heurtier, FH, D. Kim T. Tait, B. Thomas
arXiv:2111.04753



K. Dienes, L. Heurtier, FH, D. Kim T. Tait, B. Thomas
arXiv:2111.04753

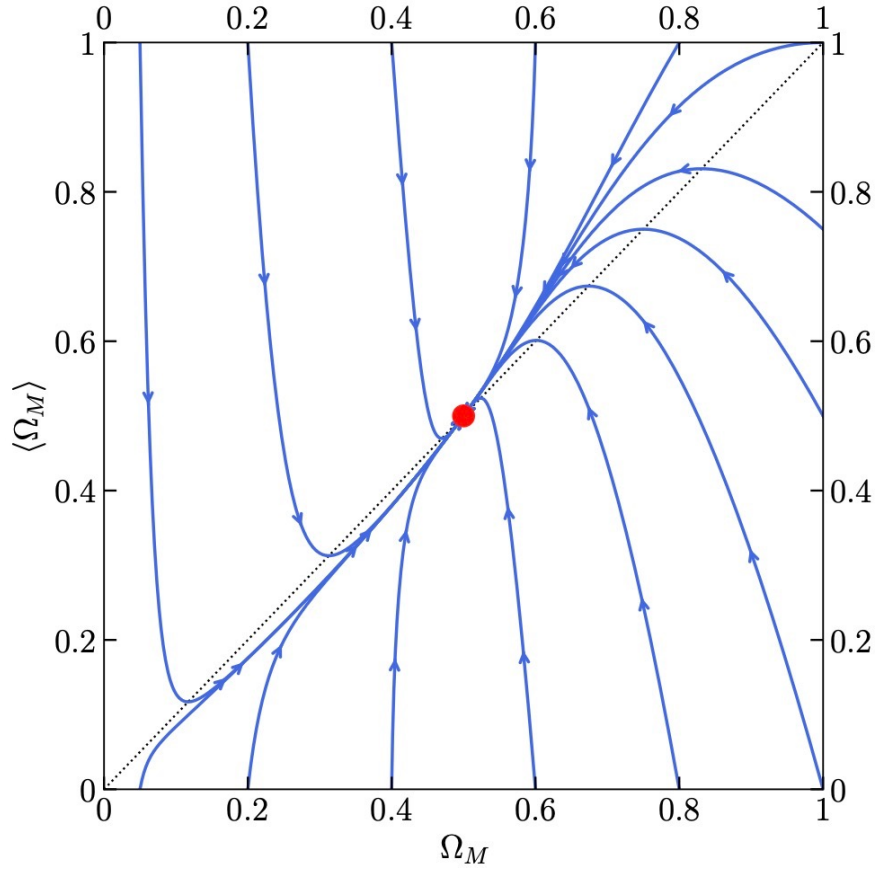
Similar behavior for other parameter choices



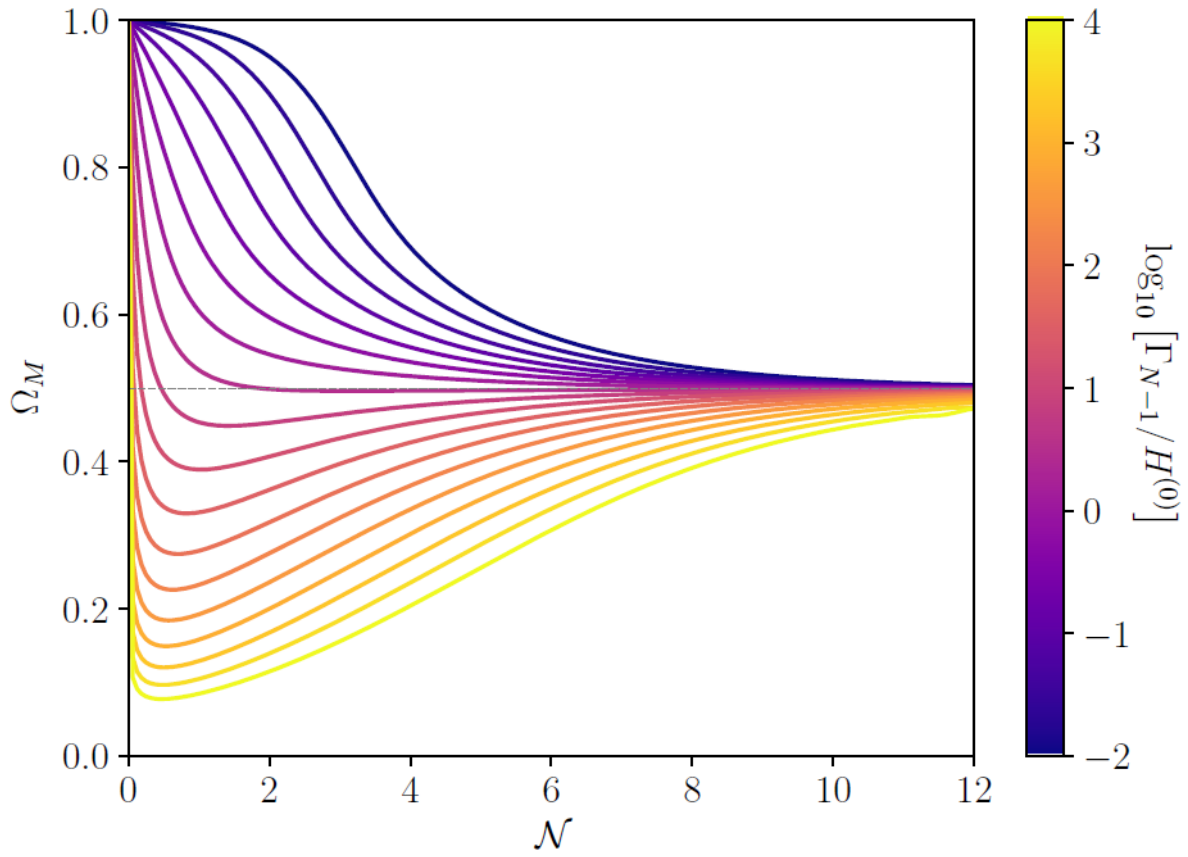
Stasis always emerges, only the stasis abundance changes

Moreover, stasis is a Global Attractor

K. Dienes, L. Heurtier, FH, D. Kim T. Tait, B. Thomas
arXiv:2111.04753



$(\alpha, \gamma, \delta) = (1,7,1) \rightarrow \bar{\Omega}_M = 1/2$

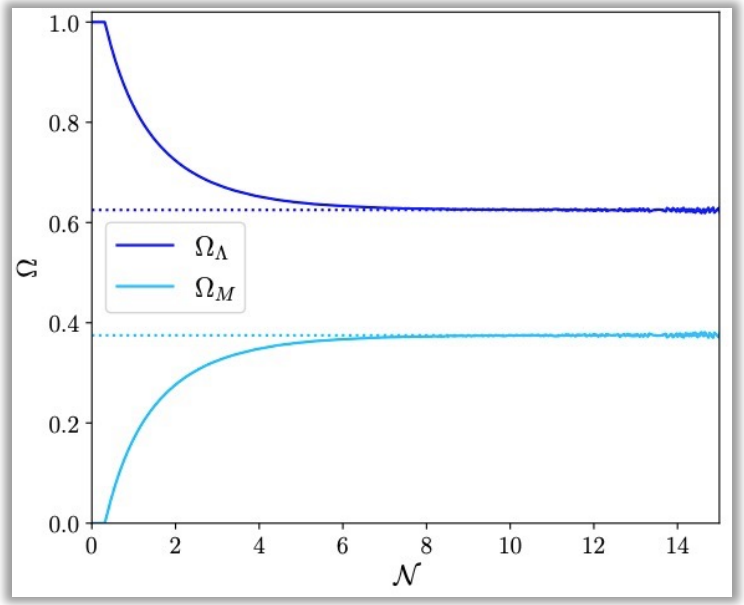


This has been a stasis between matter and radiation. But there are also other kinds of stasis:

K. Dienes, L. Heurtier, FH, T. Tait, B. Thomas
arXiv: 2309.10345

This has been a stasis between matter and radiation. But there are also other kinds of stasis:

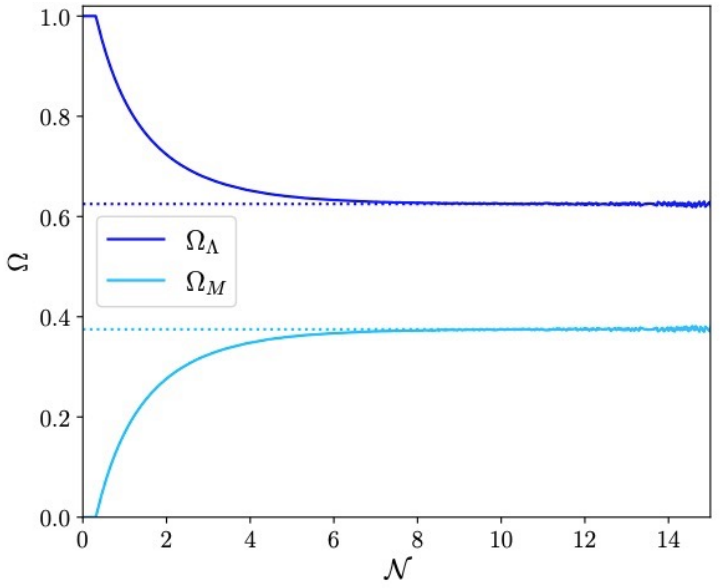
- Vacuum energy/Matter stasis

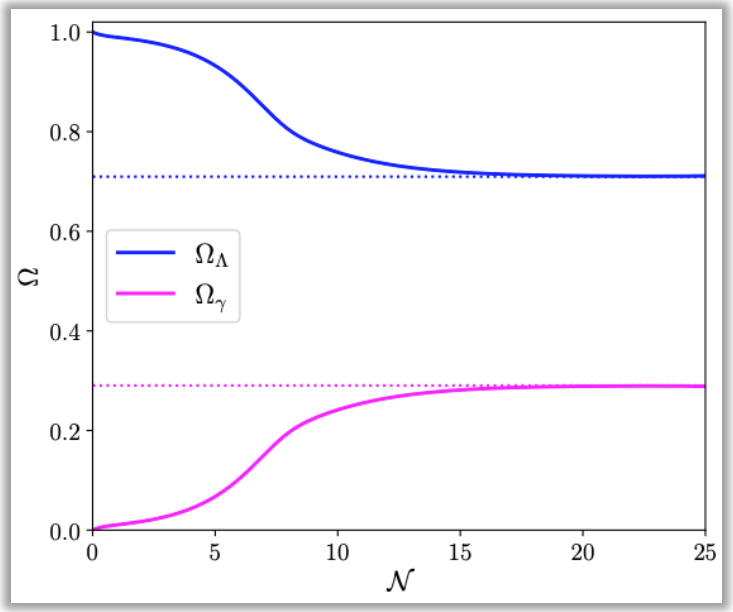


K. Dienes, L. Heurtier, FH, T. Tait, B. Thomas
arXiv: 2309.10345

This has been a stasis between matter and radiation. But there are also other kinds of stasis:

- Vacuum energy/Matter stasis
- Vacuum energy/Radiation stasis

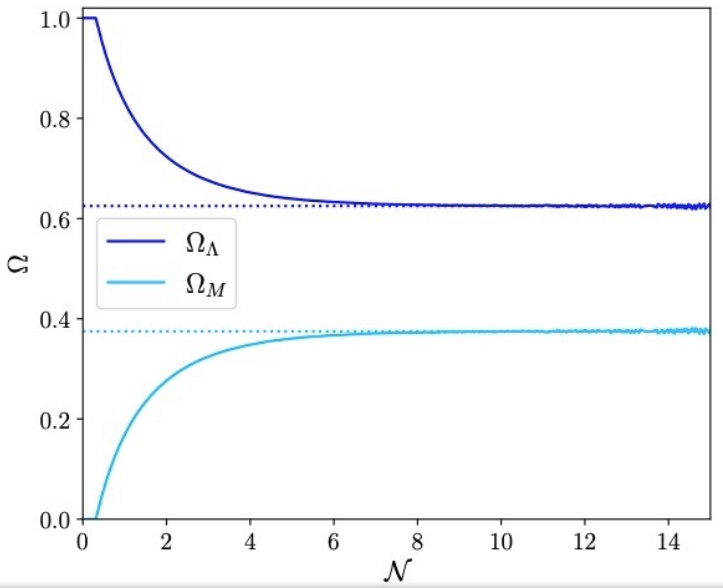


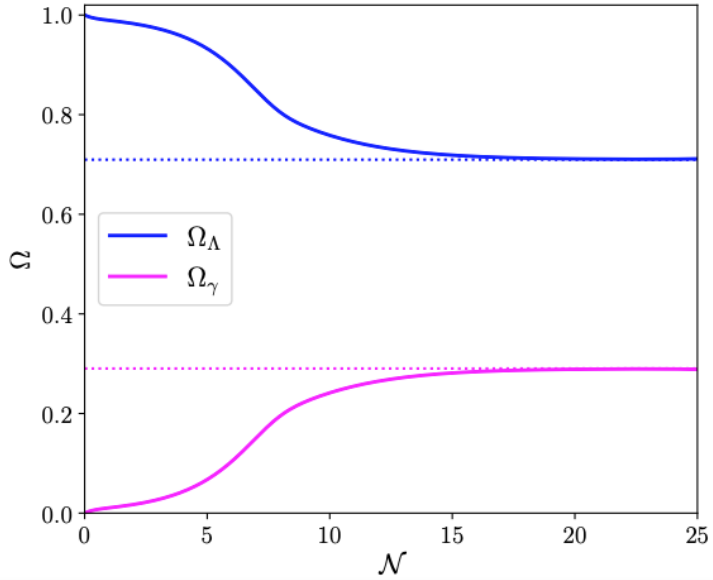


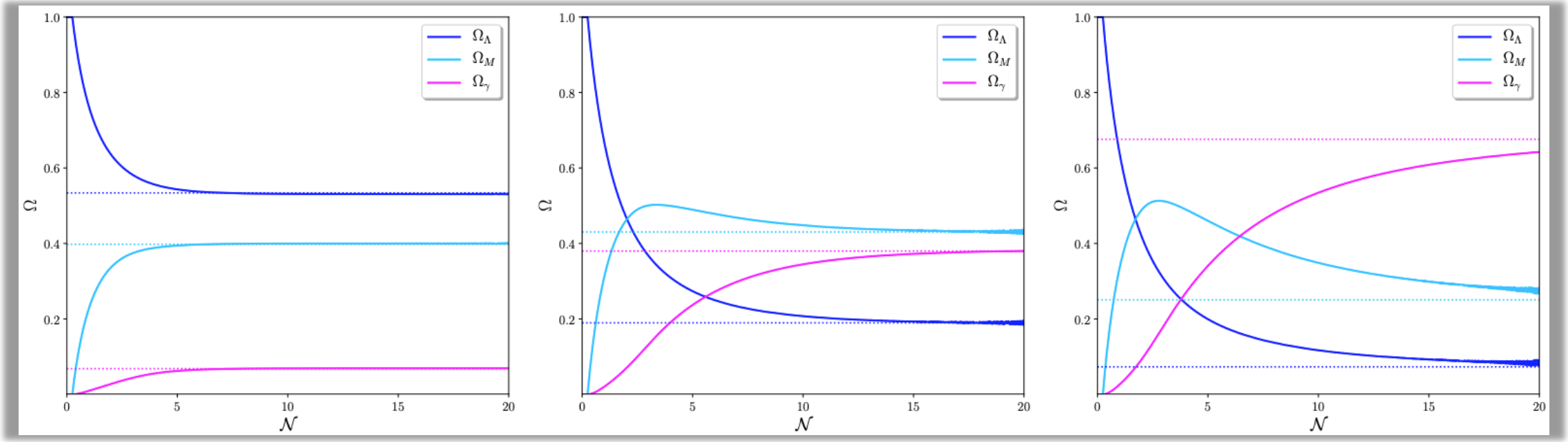
K. Dienes, L. Heurtier, FH, T. Tait, B. Thomas
arXiv: 2309.10345

This has been a stasis between matter and radiation. But there are also other kinds of stasis:

- Vacuum energy/Matter stasis
- Vacuum energy/Radiation stasis
- Triple stasis between vacuum energy, matter and radiation simultaneously







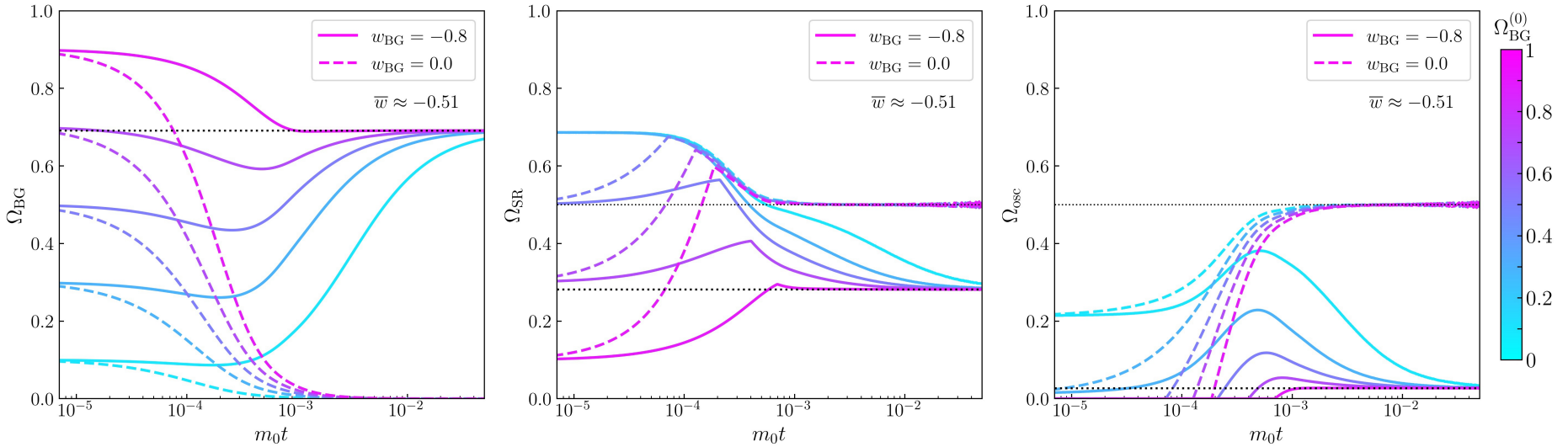
Can even have tracking behavior in vacuum energy/matter stasis

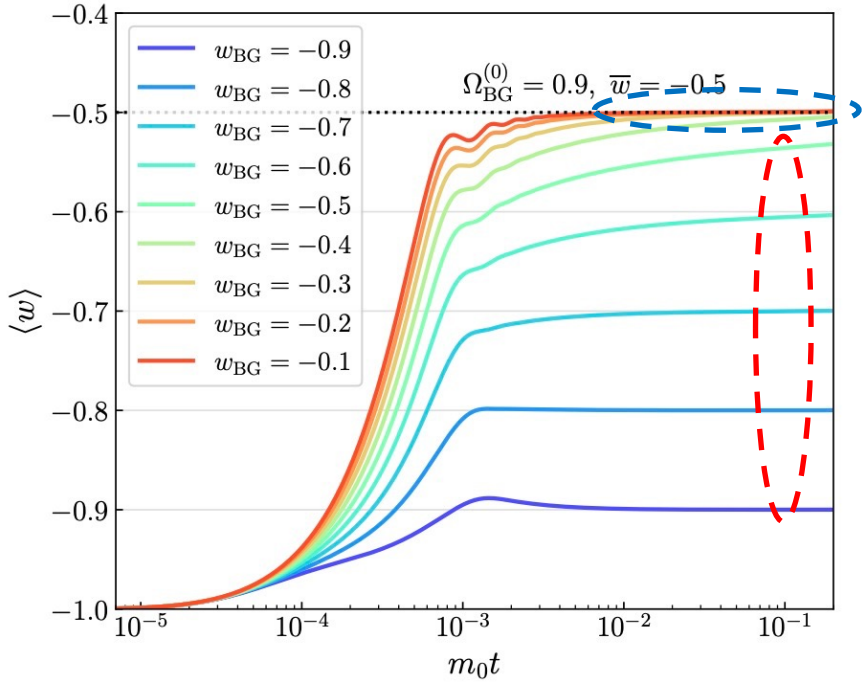
K. Dienes, L. Heurtier, FH, T. Tait, B. Thomas
arXiv: 2406.06830

Tower which leads to stasis with $\overline{w}$ if it dominates

+

Non-interacting background fluid with w_{BG}

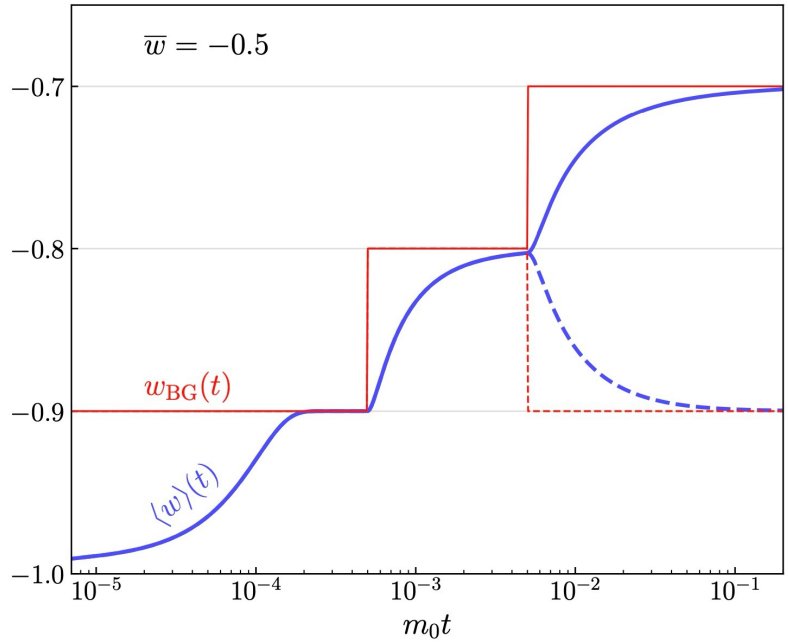




If $w_{BG} > \overline{w}$, background inflates away, EoS stays at $\overline{w}$

If $w_{BG} < \overline{w}$,
$\overline{w} \to \overline{w}' = w_{BG}$

Tracking is dynamical!



An intriguing possibility

If stasis involves ***vacuum energy***

An intriguing possibility

If stasis involves ***vacuum energy***

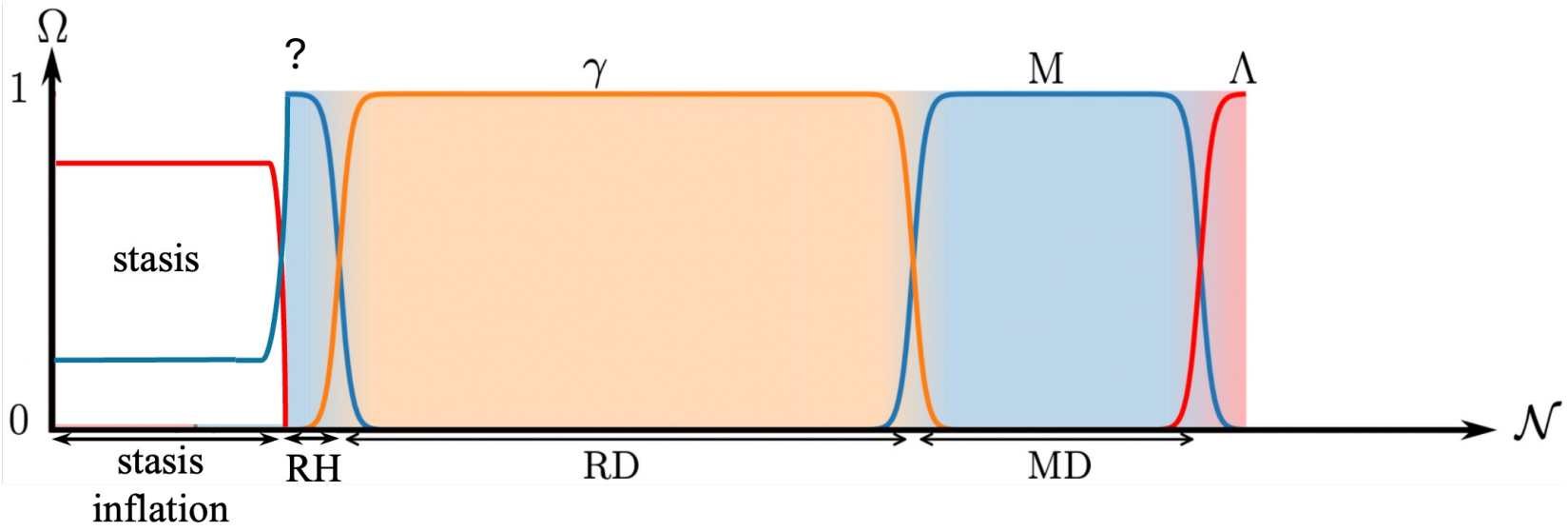
- EoS extends to $-1 < \overline{w} < 1/3$
- Accelerated expansion if $\overline{w} < -1/3$

An intriguing possibility

K. Dienes, L. Heurtier, FH, T. Tait, B. Thomas
arXiv: 2406.06830

If stasis involves ***vacuum energy***

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



Stasis inflation!

Stasis inflation

K. Dienes, L. Heurtier, FH, T. Tait, B. Thomas
arXiv: 2406.06830

- Stasis inflation does *NOT* require a complicated potential. Dynamics reflects the structure of the underlying theory, not the shape of the inflaton potential.
- Any $\overline{w} < -1/3$ is possible, and not restricted to $\overline{w} \approx -1$
- Number of e-folds (cosmology) $\longleftrightarrow$ hierarchies between *particle-physics* scales, e.g., in KK models, the start and end of stasis is related to the UV cutoff and the compactification radius
- Graceful exit: naturally occurs when transitions reach the bottom of the tower
- A non-zero matter (and potentially even radiation) abundance can be carried throughout inflation (abundances do not inflate away), thus may significantly change conditions needed for reheating.

Other types of stasis: Recent Developments

Extension of stasis into the thermal domain, no tower needed and utilizes annihilation of a single particle species instead of decay

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

Other stasis related research

Applying machine learning to stasis, developing methods to maximize the number of stasis e-folds and to analyze other mass spectra.

J. Halverson and S. Pandya
arXiv: 2408.00835

In all cases, the universe continues to expand, but the abundances stay fixed.
Time passes as measured in e-folds, but not as measured by abundances!
The two clocks have decoupled.

Discussion topics

- Model building:
  - What are the other types of stasis that can be realized?
  - Where in the cosmological timeline can it arise?
  - How does it end (“graceful exit”)?

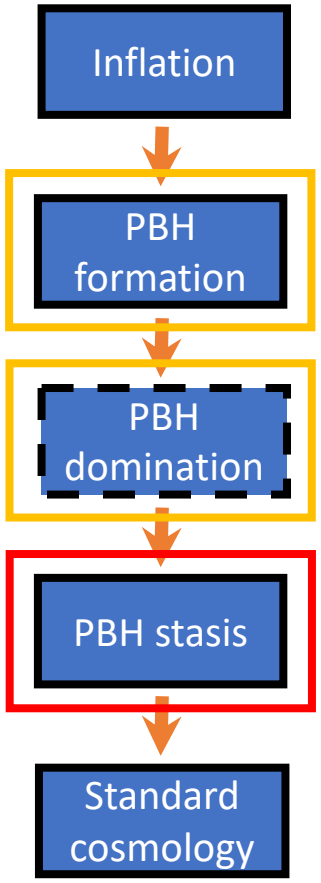
- Top-down picture:
  - What are the motivations from fundamental theory?
  - Relationship between properties of stasis and fundamental scales/parameters?

- Phenomenological/observational implications:
  - Gravitational waves
  - Inflationary observables
  - Density perturbations
  - Effects on other early-universe processes (e.g., dark-matter production, baryogenesis, …)

Cosmological implications: Cosmological timeline

K. Dienes, L. Heurtier, FH, D. Kim, T. Tait, B. Thomas
arXiv: 2212.01369

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



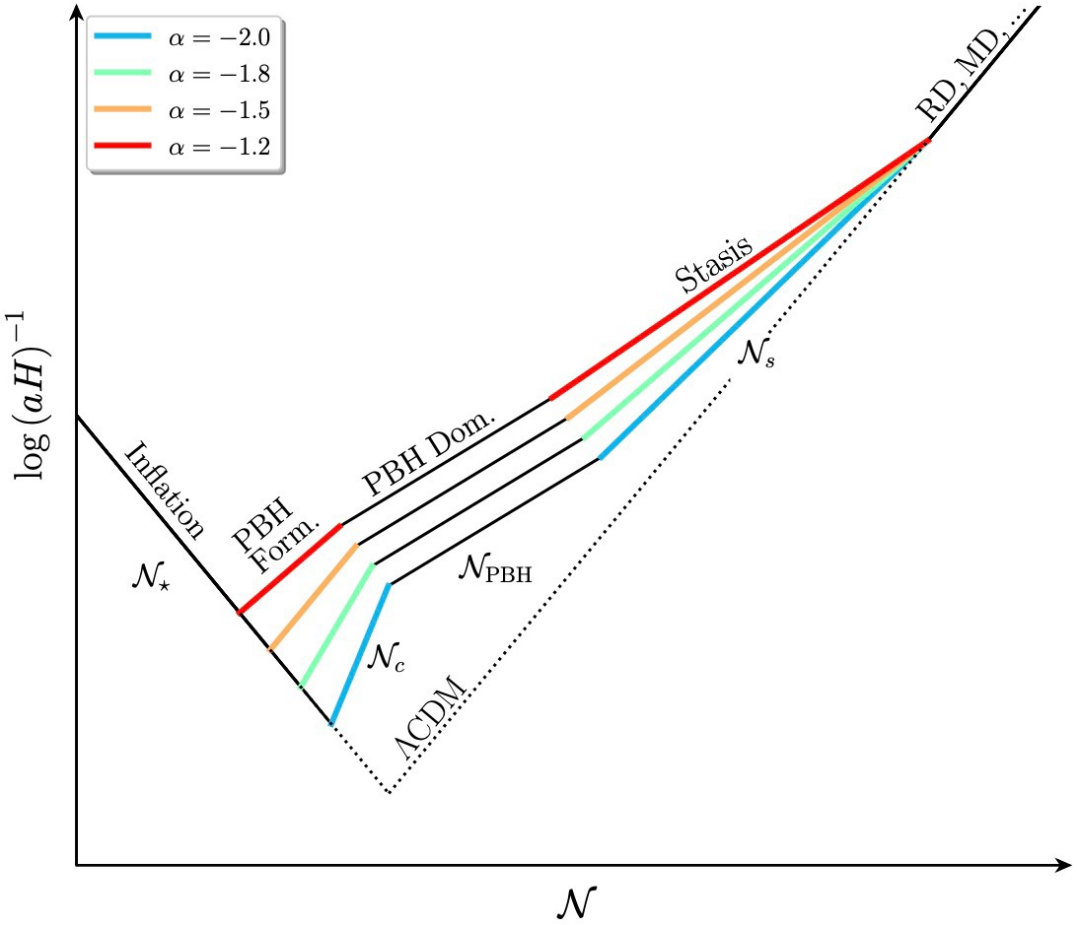
$H_* < 2.5\times10^{-5} M_P$

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

$\Omega_{\rm BH} = 1$

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

after evaporation of M_{max} …



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

backup

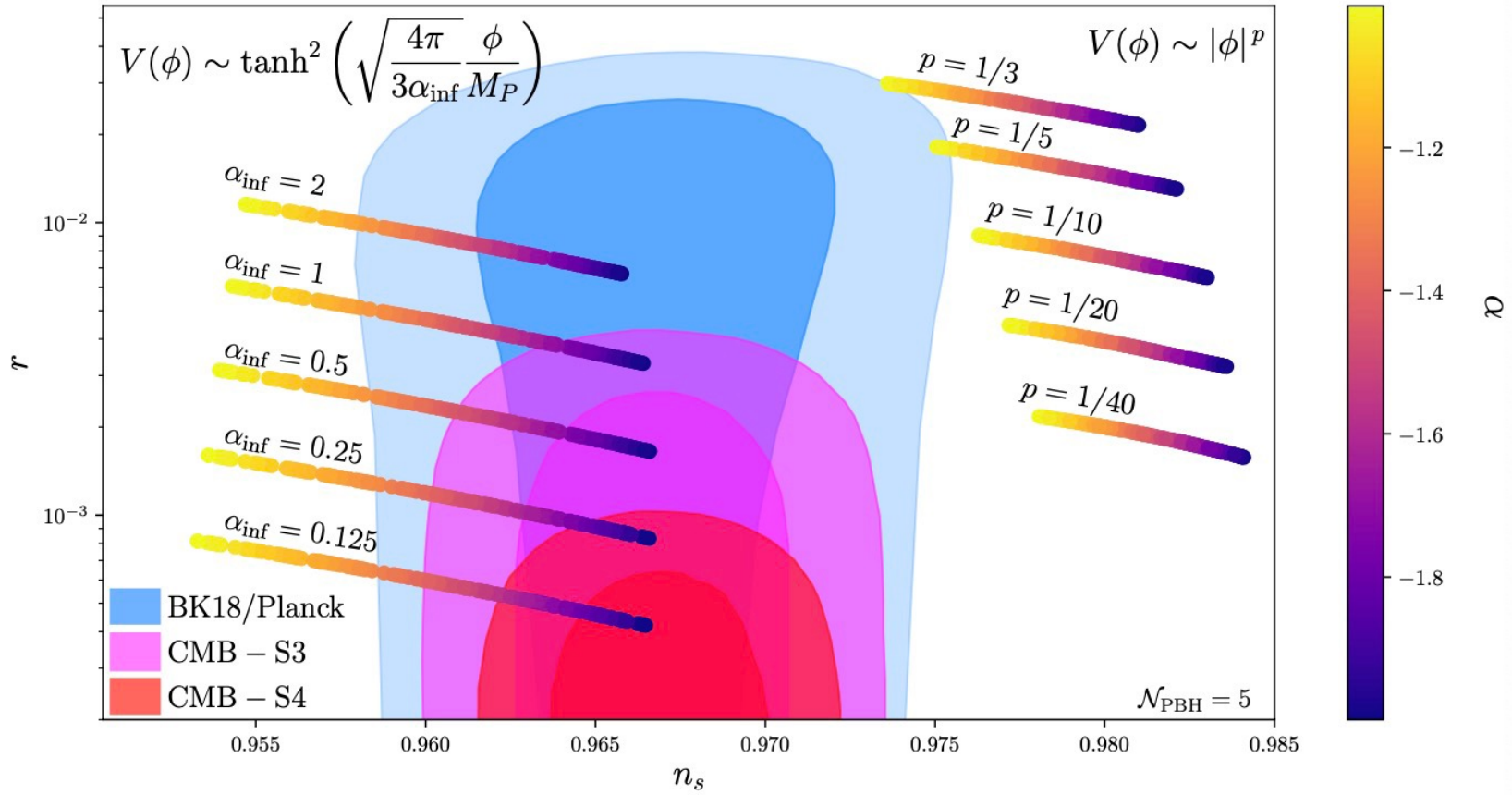
Cosmological implications: Inflationary observables

K. Dienes, L. Heurtier, FH, D. Kim, T. Tait, B. Thomas
arXiv: 2212.01369

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



backup

Cosmological implications: Gravitational waves

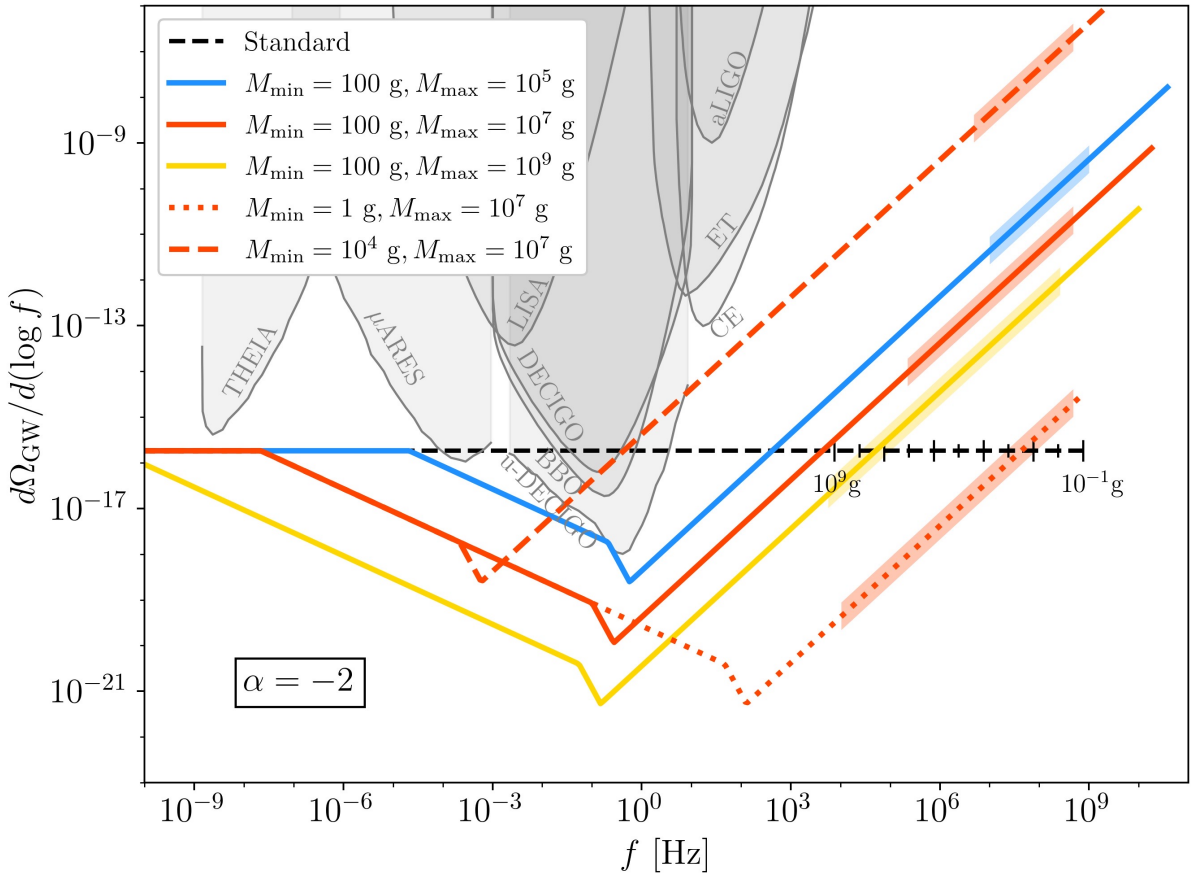
K. Dienes, L. Heurtier, FH, D. Kim, T. Tait, B. Thomas
arXiv: 2212.01369

The sequence of non-standard epochs also modifies the spectrum of ***SGWB*** from *inflation* by modifying a_k at horizon reentry $k = (aH)_k$

- ***flat*** if $w = 1/3$
- ***increasing function of*** k if $w > 1/3$
- ***decreasing function of*** k if $w < 1/3$

A GW spectrum that would be scale-invariant if produced in RD will be modified if PBH-induced stasis occurs

- Evade detection at frequencies relevant for space- or ground-based interferometer
- opportunity for GW experiment at ultra-high frequencies



$$\frac{d\Omega_{\rm GW}}{d\log f} \equiv \frac{1}{\rho_{\rm crit}(a_{\rm now})}\frac{d\rho_{\rm GW}(a_{\rm now})}{d\log f}$$

backup

A Model of Stasis

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

Free parameters

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

initial conditions

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
  - $\delta \sim 1/2$

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

- $\alpha < 0$ for misalignment production
- both $\alpha > 0$ or $\alpha < 0$ for thermal freeze-out
- $\alpha = 1$ for universal inflaton decay

backup

A Model of Stasis

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

Free parameters

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

initial conditions

Depends on particle physics model

see, e.g.,

arXiv: 1106.4546
1107.0721
1203.1923
1609.09104
1712.09919
.....

for specific models and production scenarios

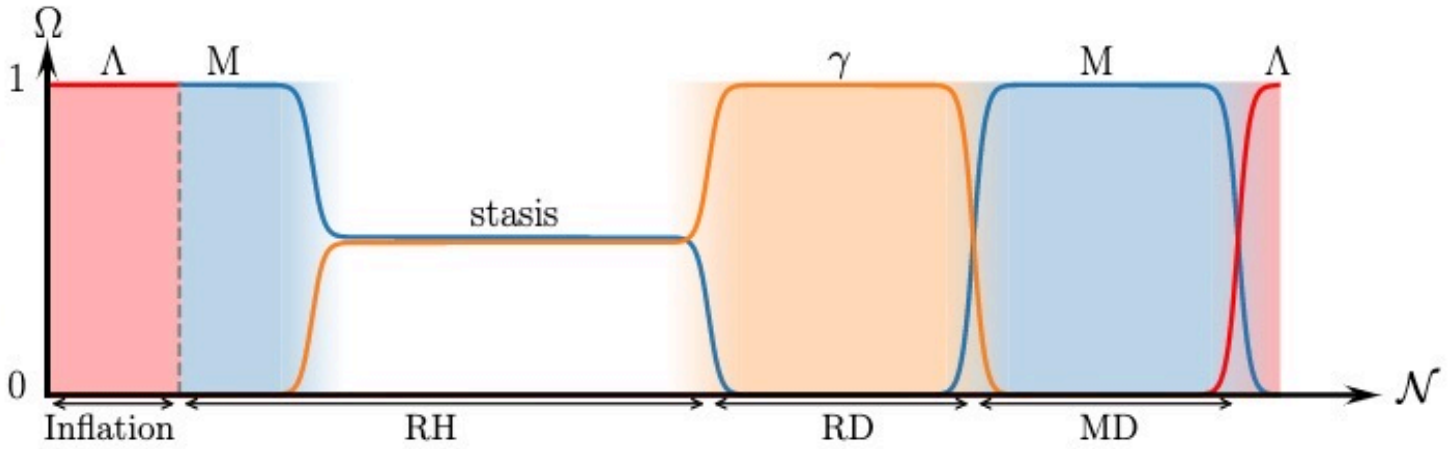
Depends on production mechanism

- $\alpha < 0$ for misalignment production
- both $\alpha > 0$ or $\alpha < 0$ for thermal freeze-out
- $\alpha = 1$ for universal inflaton decay

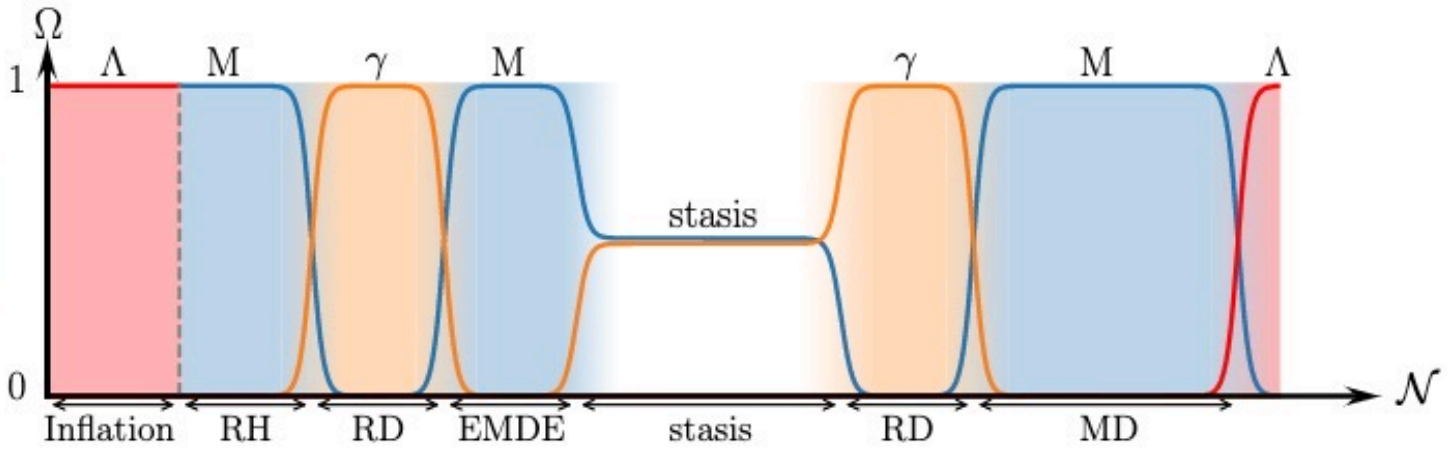
backup

Where does stasis arise?

Reheating occurs during the stasis epoch and results from the decays of ϕ_ℓ

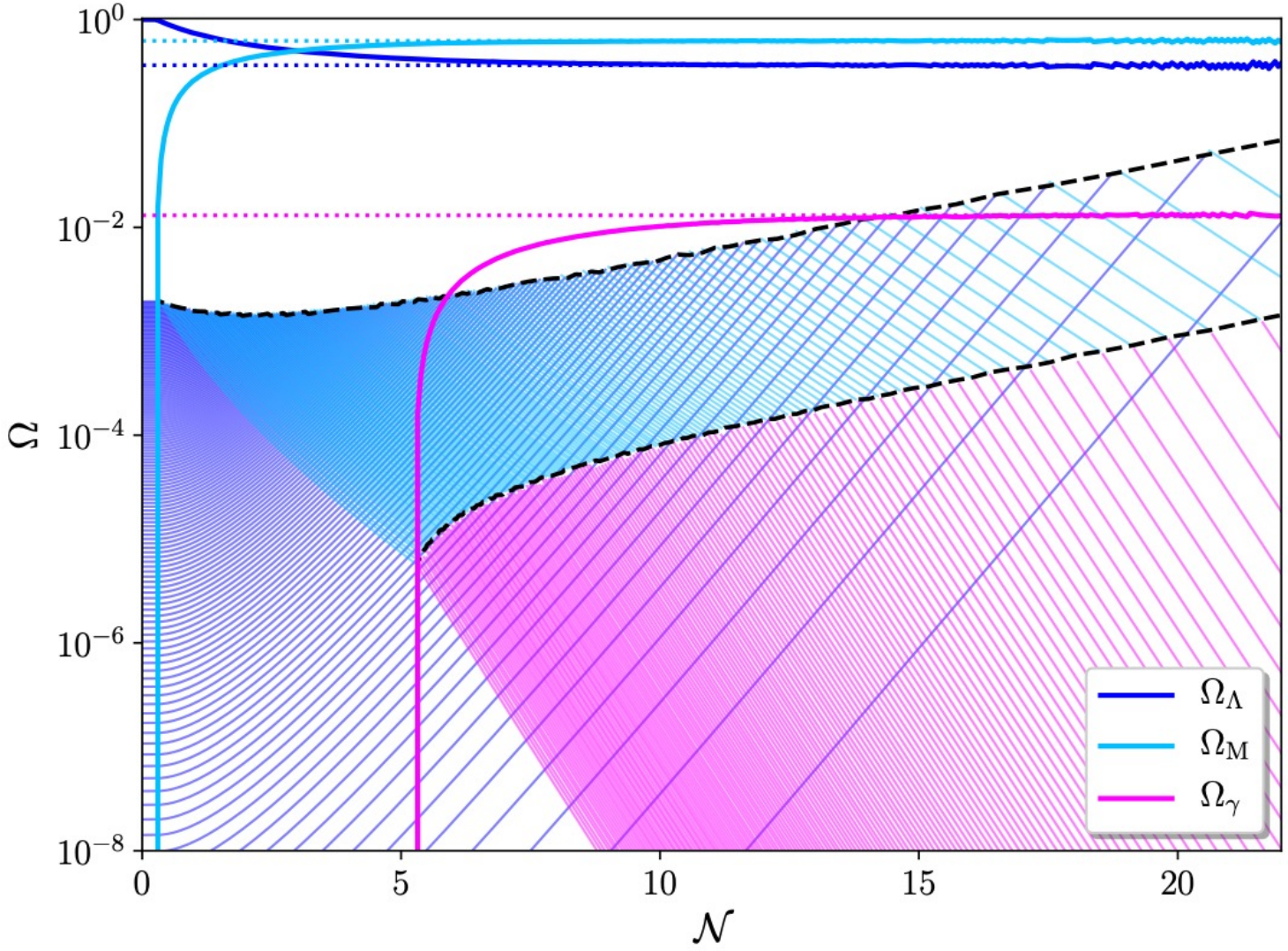


The presence of multiple matter fields first leads to an early matter-dominated era (EMDE), then stasis occurs when decays start



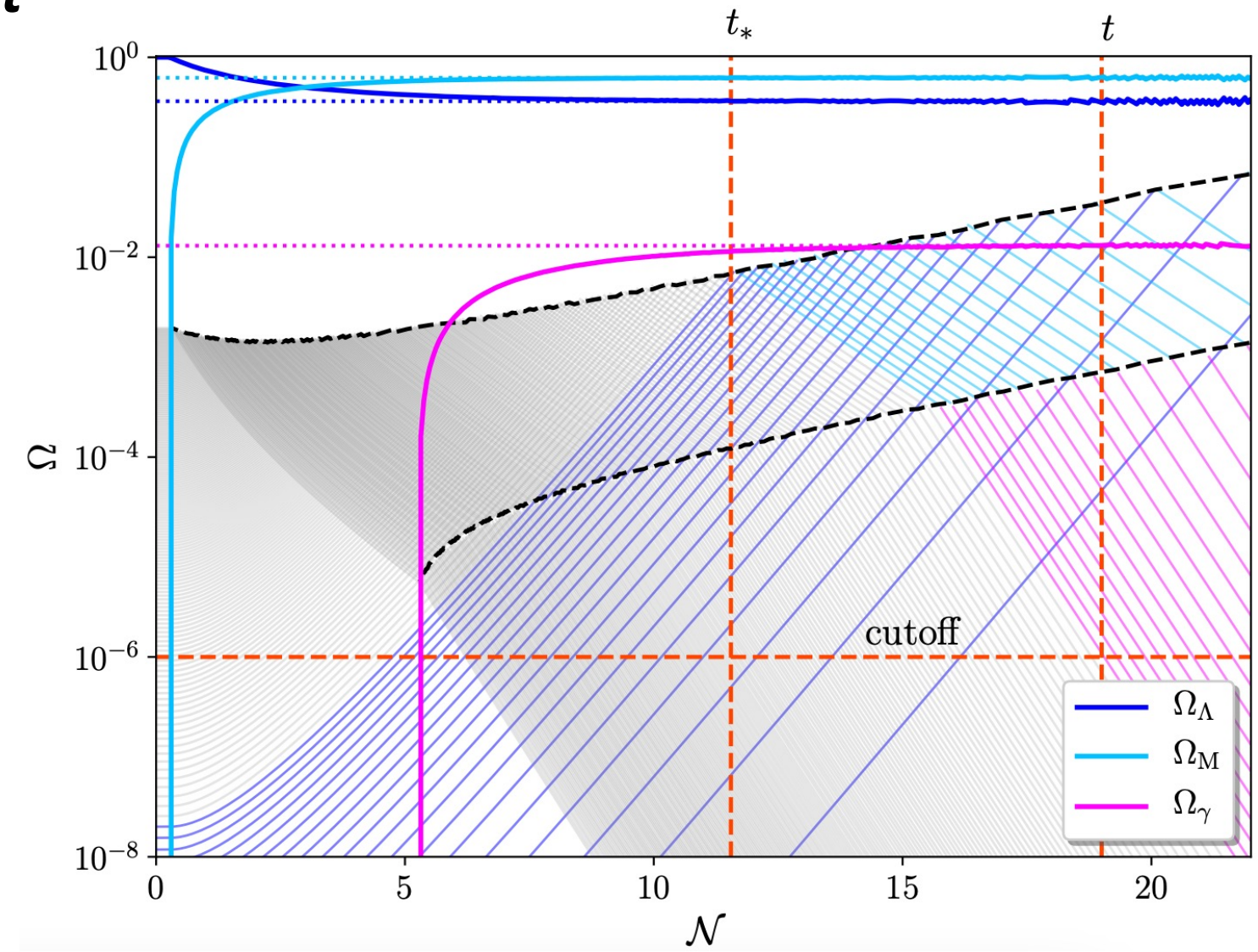
backup

Fields drop-out



backup

Fields drop-out



backup