

COSMOLOGICAL STASIS

LUCIEN HEURTIER

In collaboration with

K.R. Dienes, F. Huang, D. Kim, B. Thomas, and T.M.P. Tait

Based on Phys.Rev.D 105 (2022) 2, 023530 [[arXiv:2111.04753](https://arxiv.org/abs/2111.04753)]

arXiv:2207.XXXX

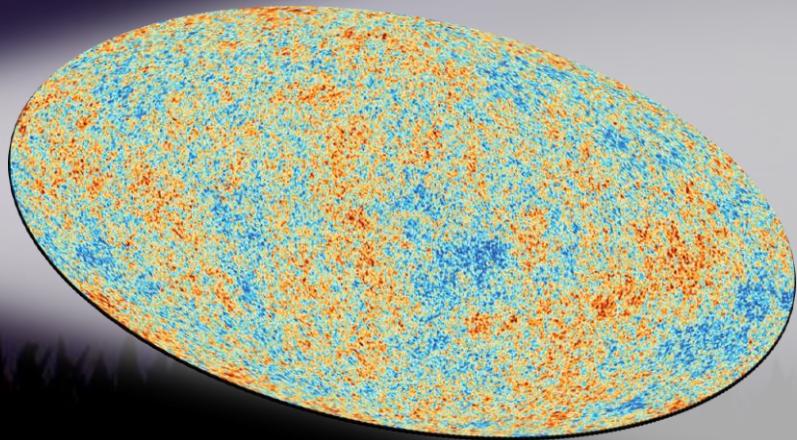
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SUSY 2022,

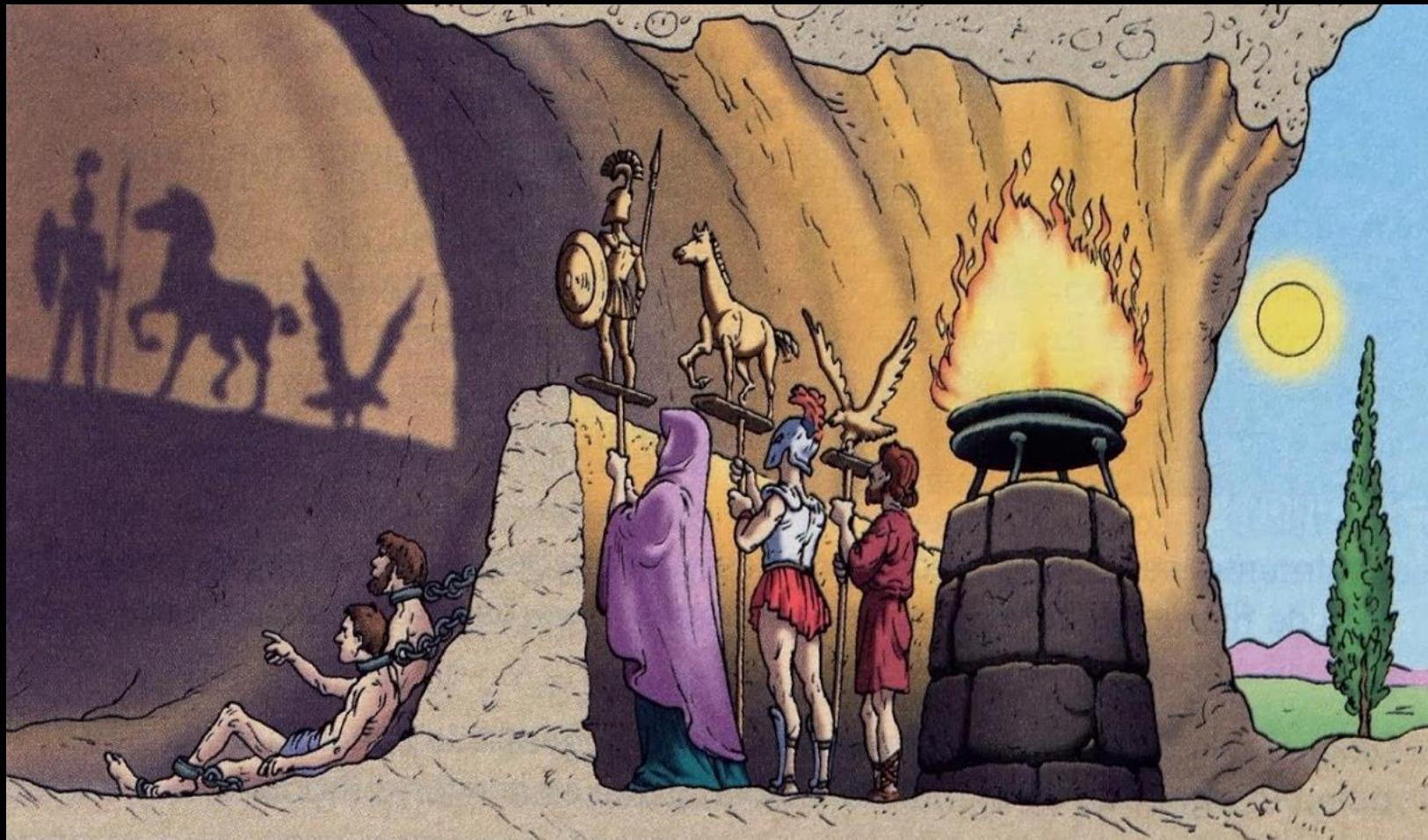
July 1st , Ioannina

Looking Back

Cosmic Microwave Background

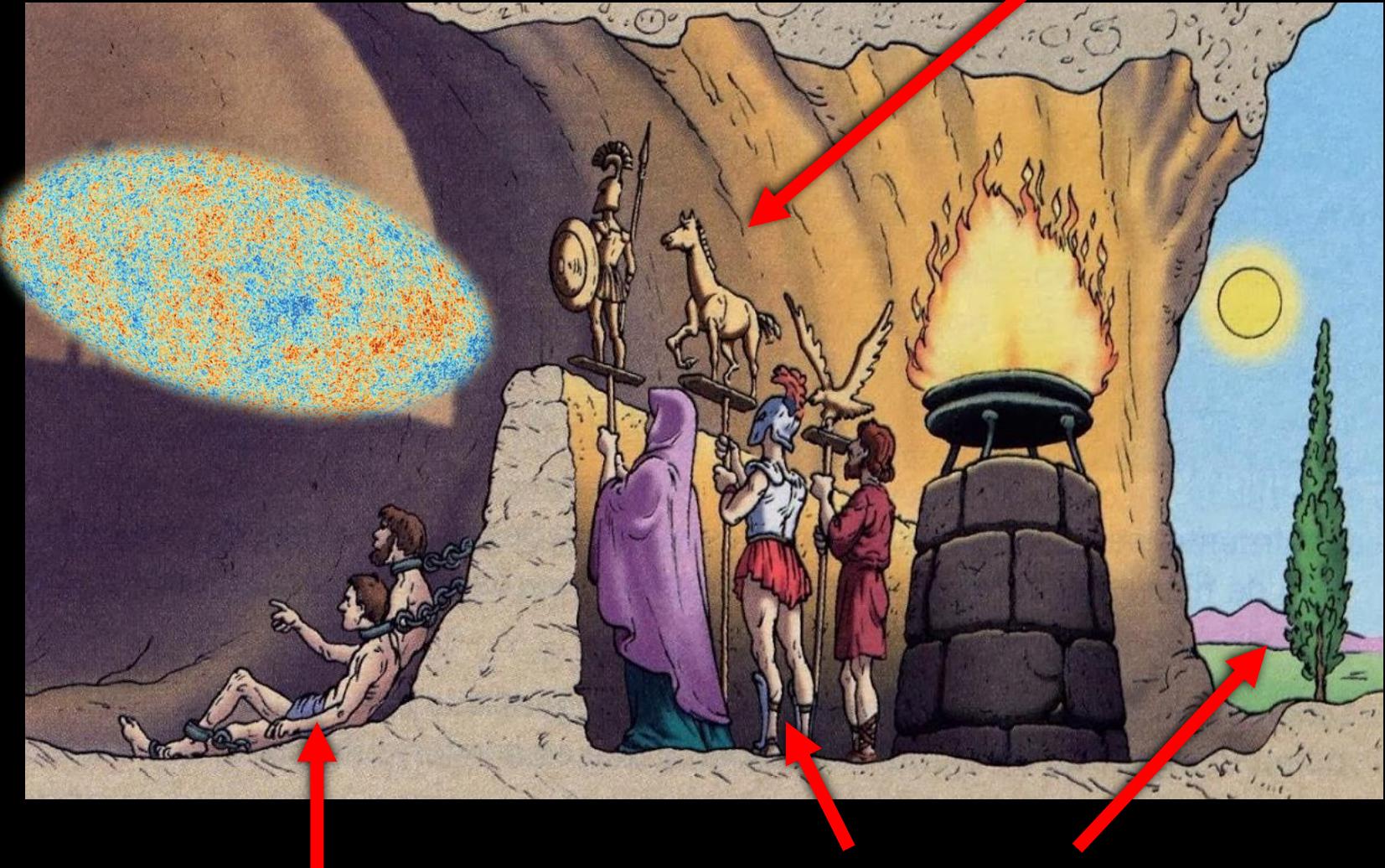


Allegory of the Cave...



Allegory of the Cave...

Λ CDM



Us

Nature

THE Λ CDM IDEOLOGY

$\ln \rho$



Radiation

Matter

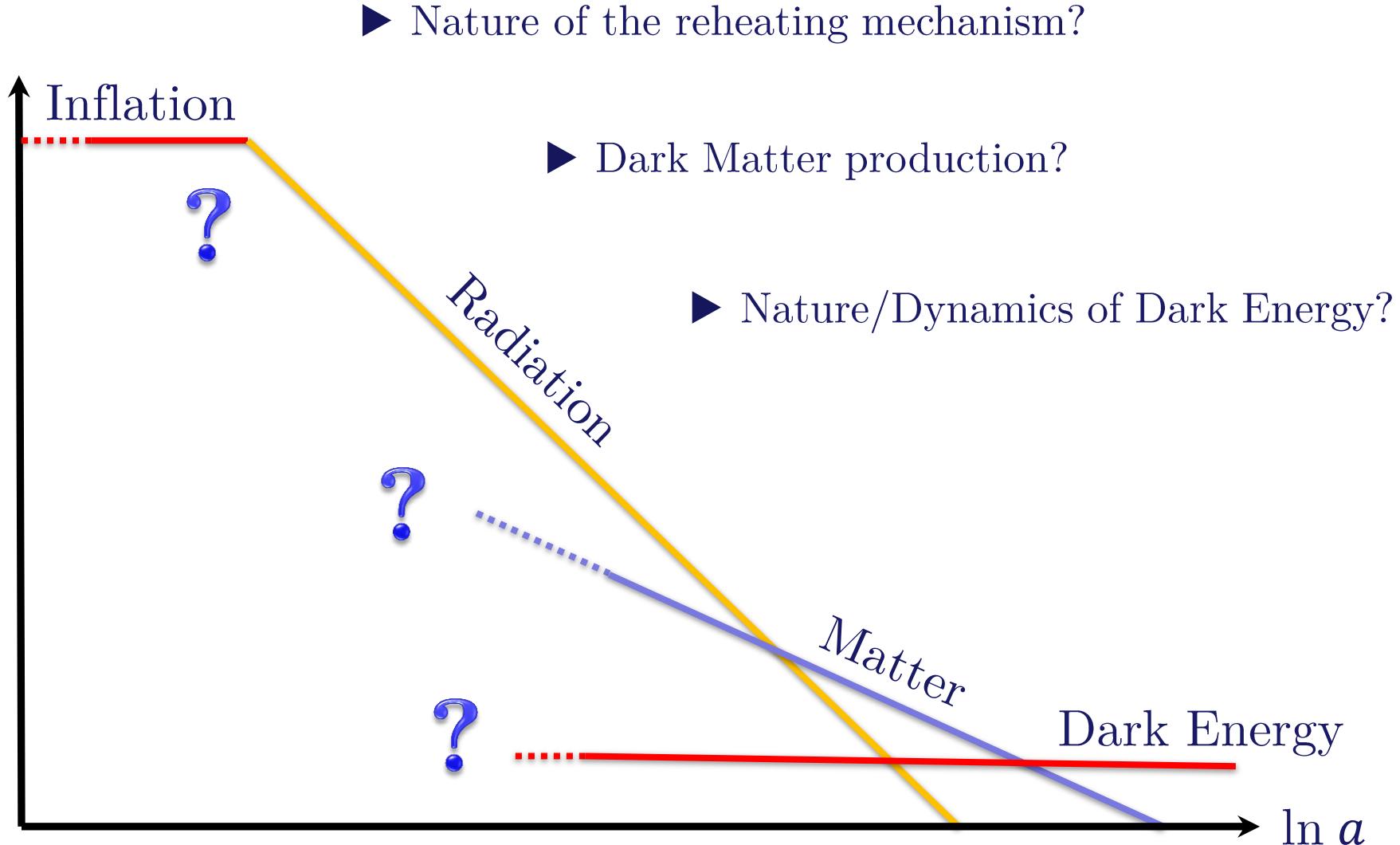
Dark Energy

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

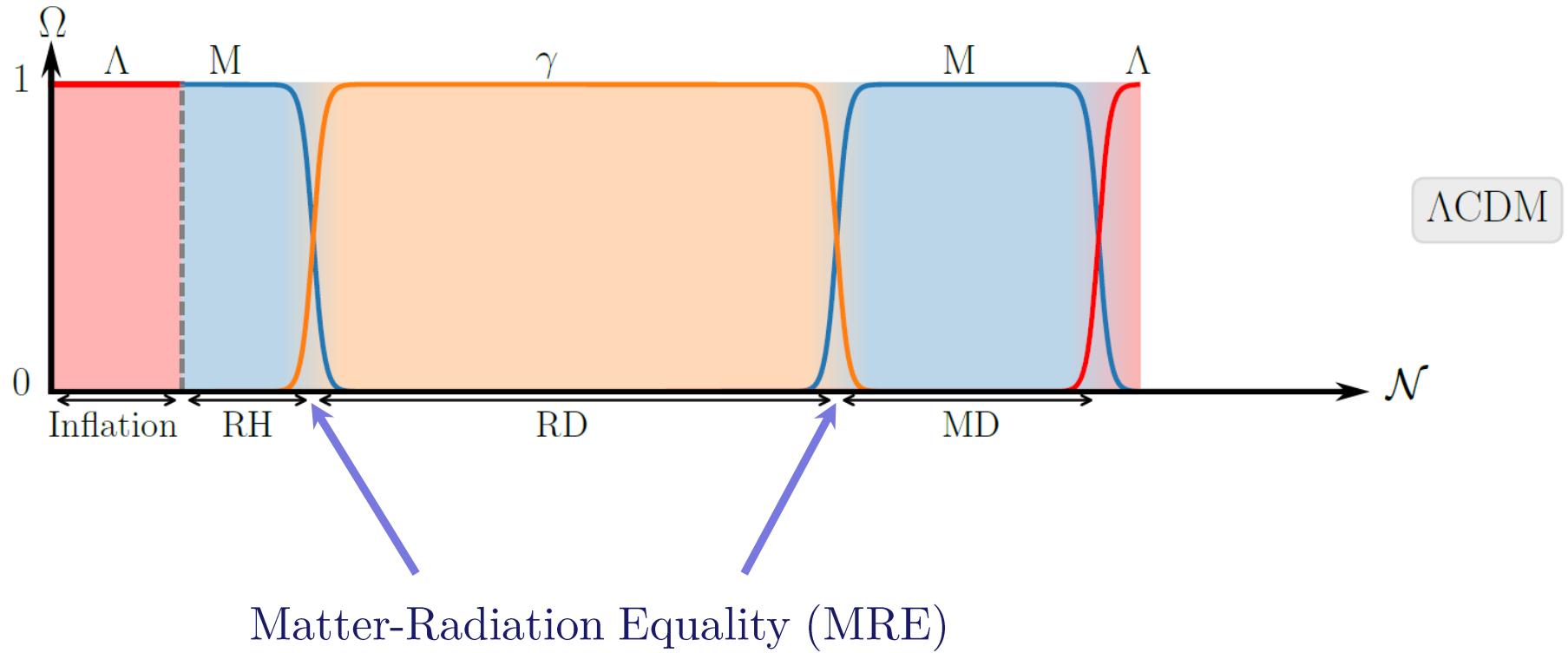
Inflation

THE Λ CDM IDEOLOGY

$\ln \rho$



THE Λ CDM IDEOLOGY

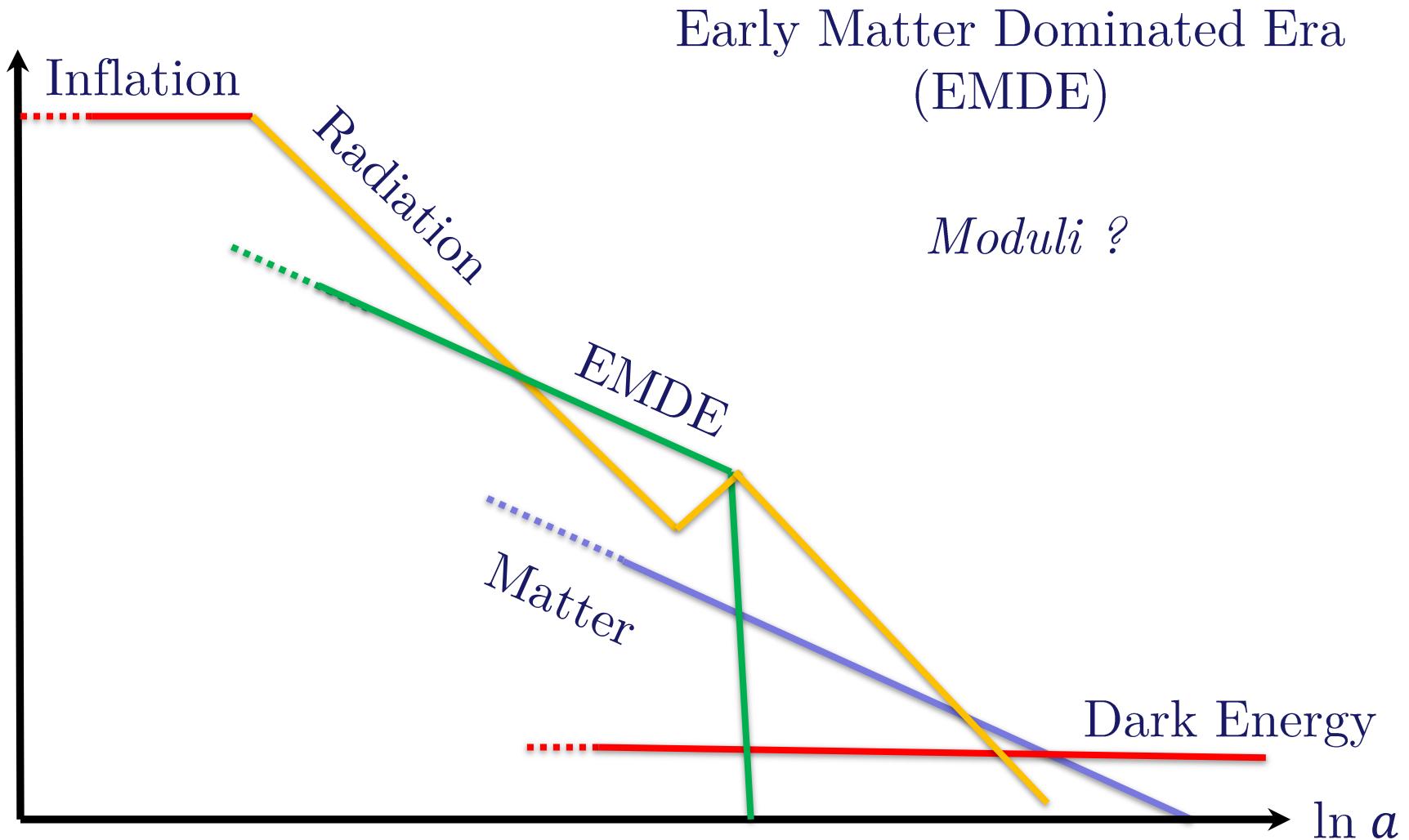


In the Λ CDM model, **MRE is localized in time**. The Universe HAS to *choose* between Matter Domination (MD) and Radiation Domination (RD).

Nature may be
Complex ...

GOING BEYOND Λ CDM

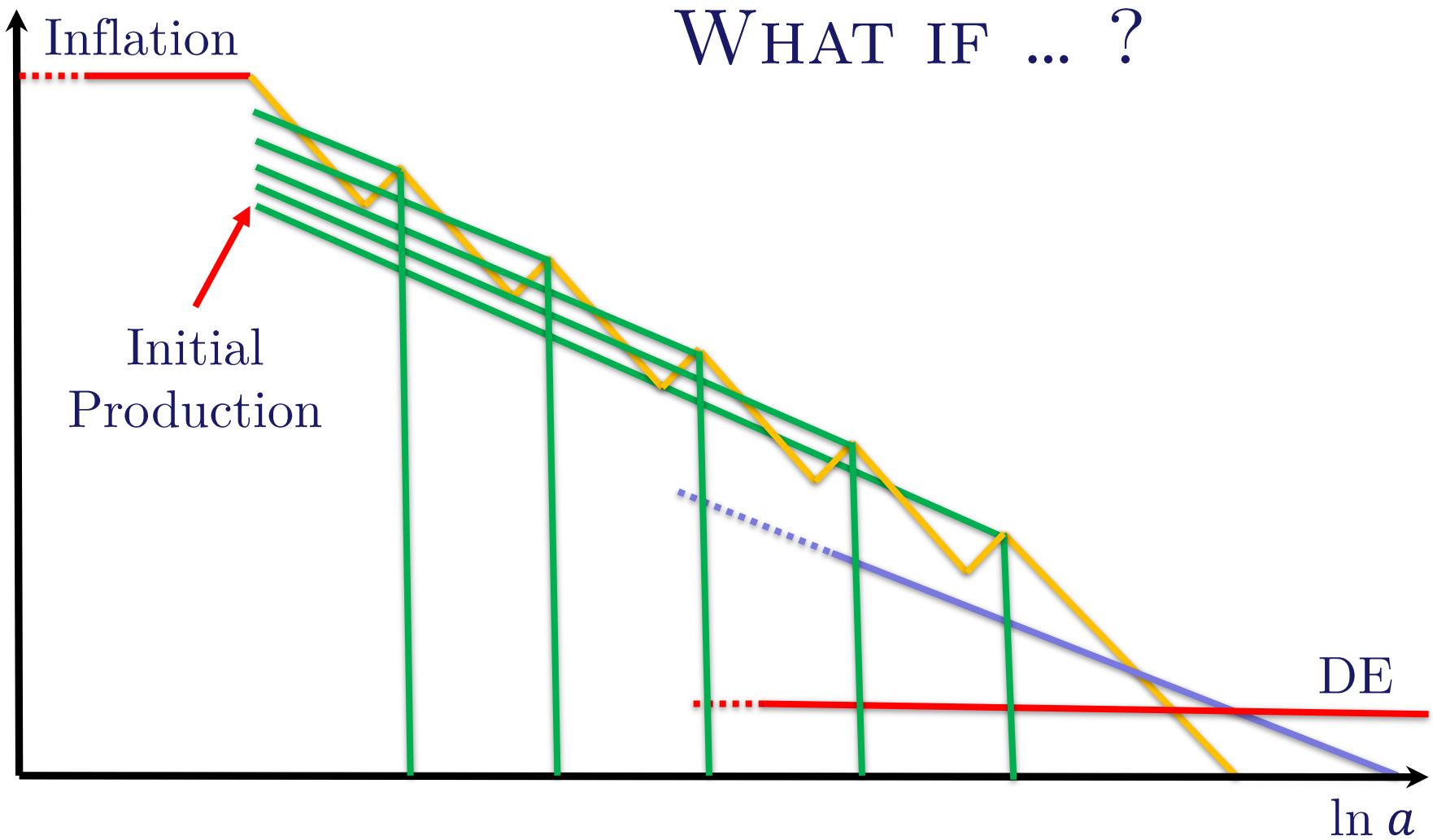
$\ln \rho$



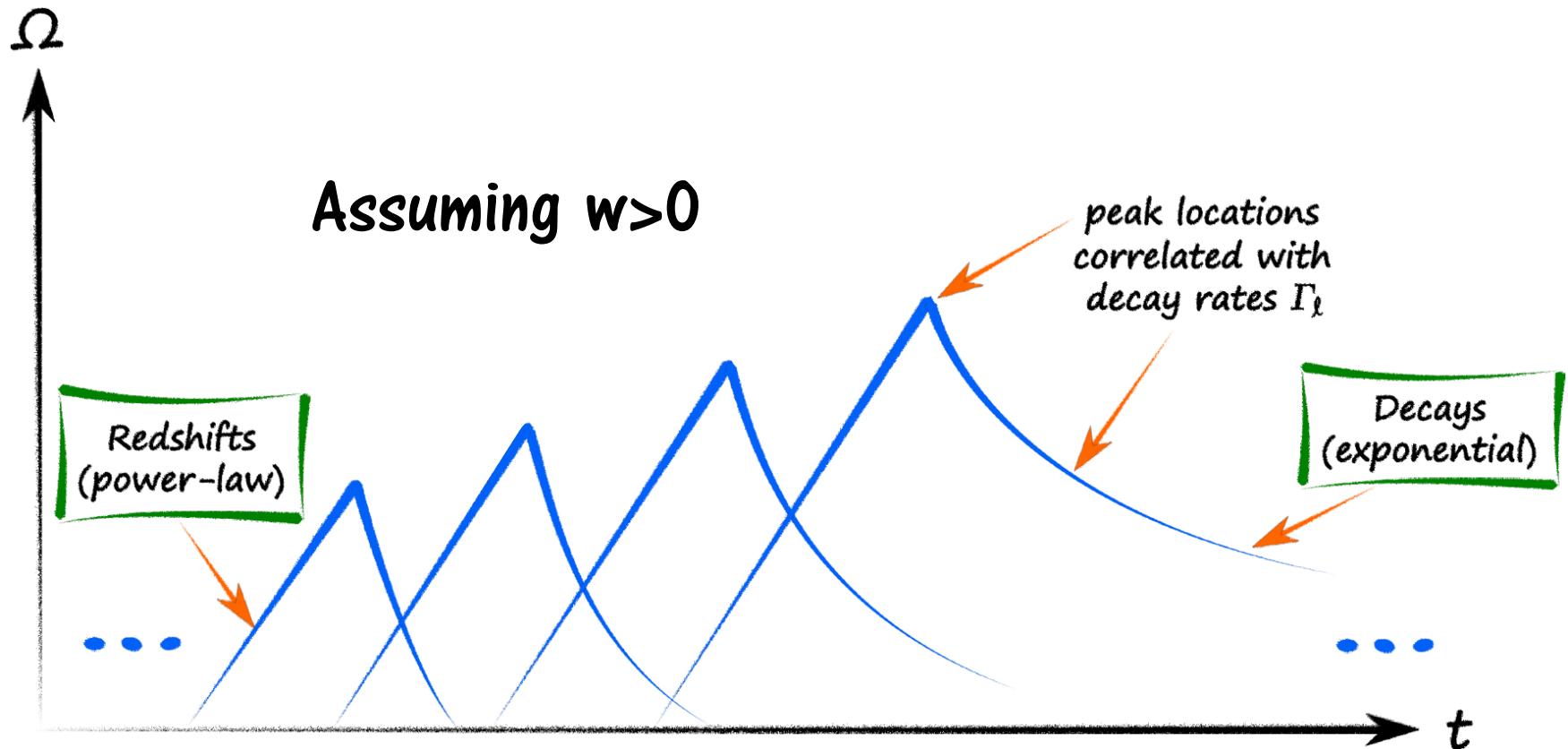
UV THEORIES MAY BE (VERY)
NON MINIMAL...

GOING (MUCH) BEYOND Λ CDM

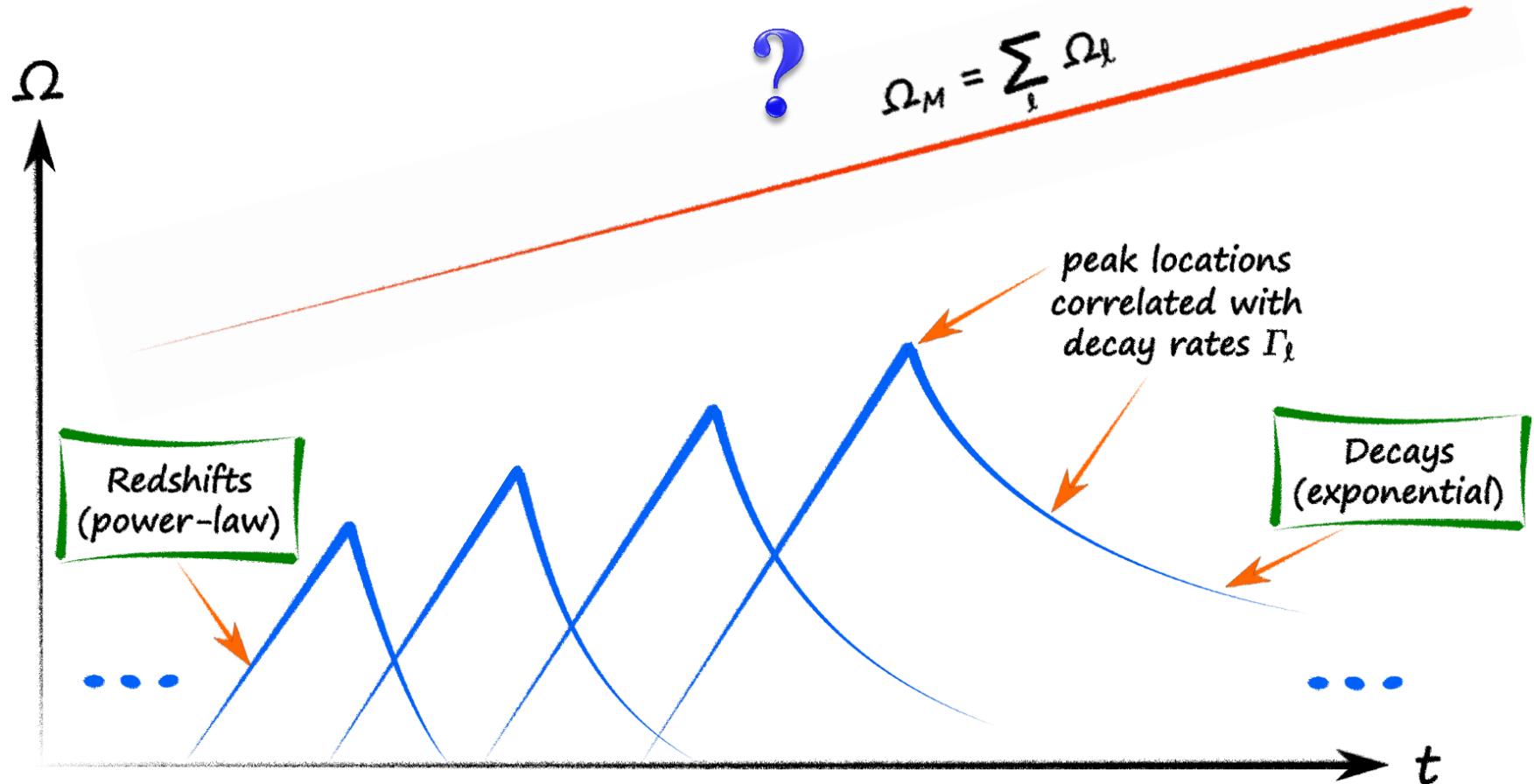
$\ln \rho$



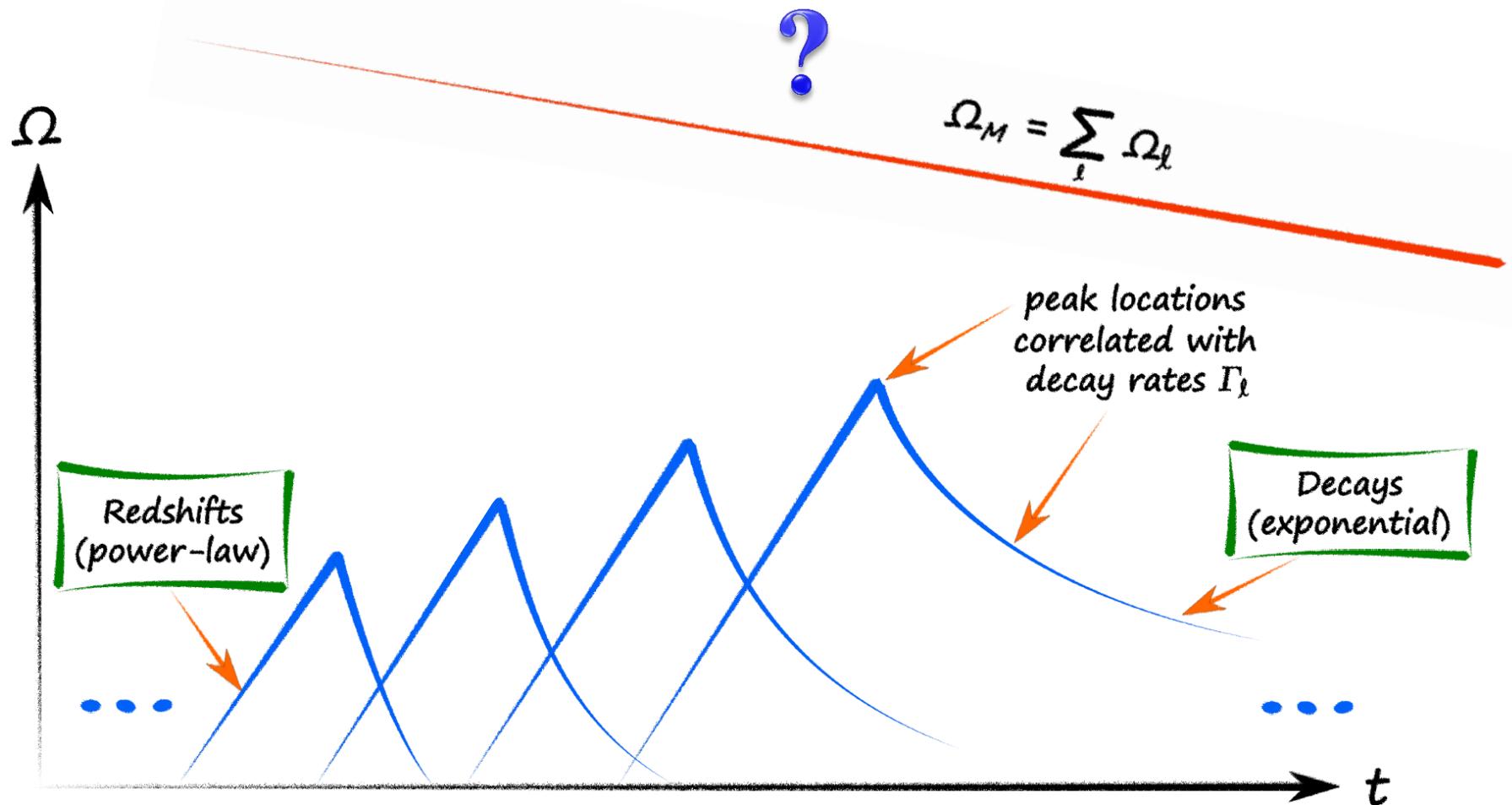
Many states decaying



Many states decaying

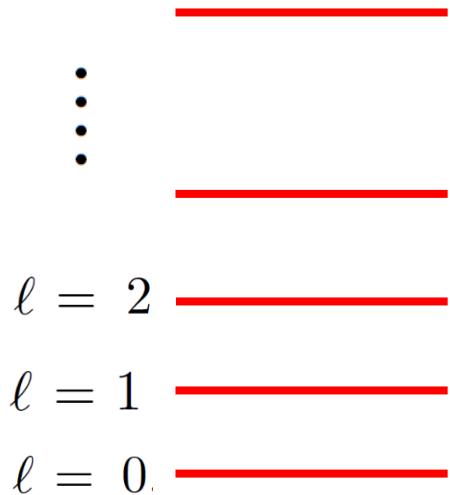


Many states decaying

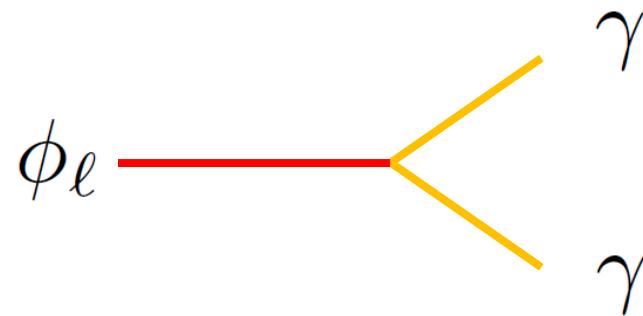


A NON-MINIMAL SET UP

Mass
Spectrum



Decay
Processes



$$\Omega_i \equiv \frac{8\pi G}{3H^2} \rho_i$$

$$\Omega_M \equiv \sum_\ell \Omega_\ell$$

$$\Omega_M + \Omega_\gamma = 1$$

MULTI-COMPONENTS DYNAMICS

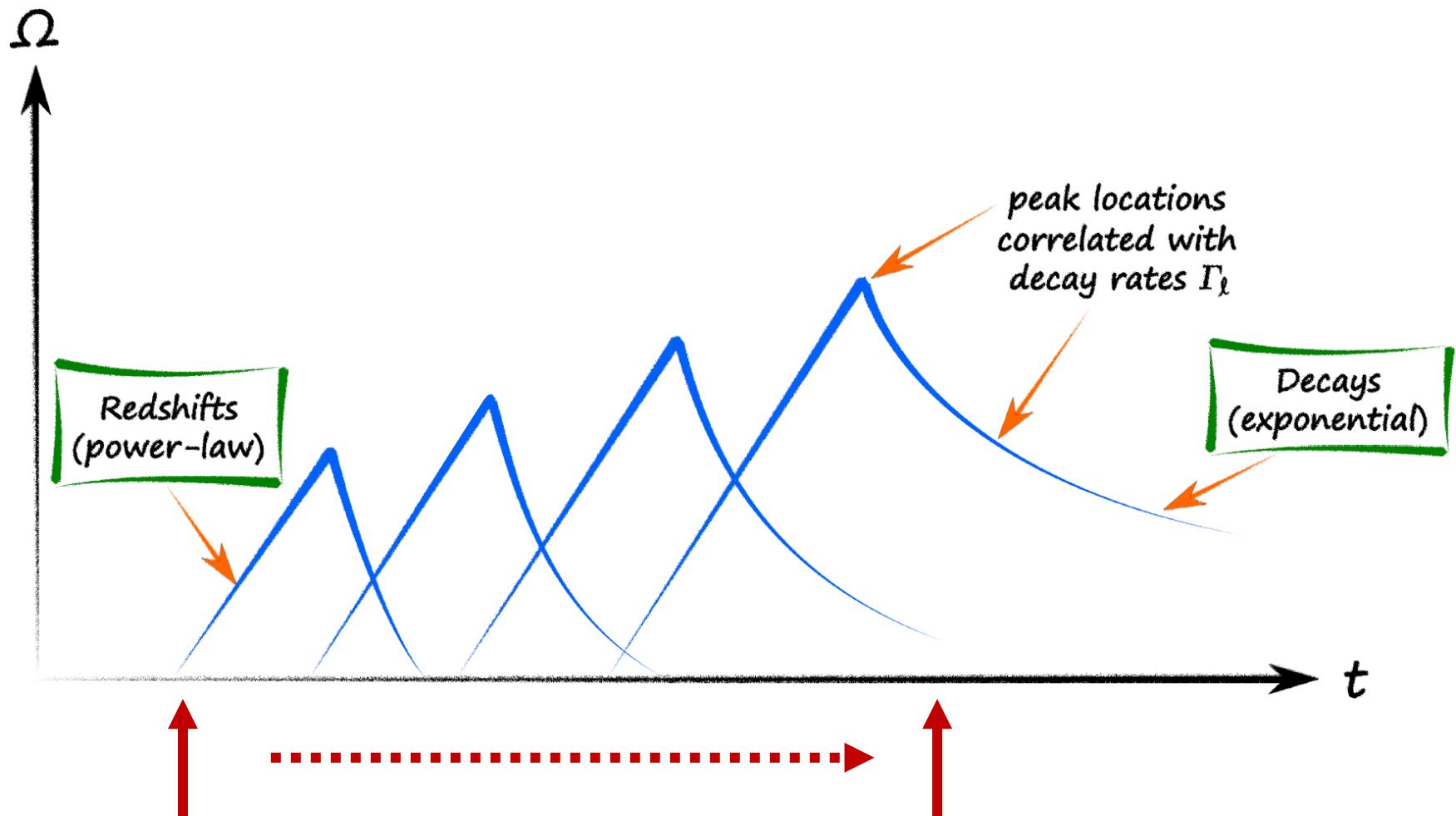
$$\begin{aligned}\frac{d\rho_\ell}{dt} &= -3H\rho_\ell - \Gamma_\ell\rho_\ell \\ \frac{d\rho_\gamma}{dt} &= -4H\rho_\gamma + \sum_\ell \Gamma_\ell\rho_\ell\end{aligned}$$

Boltzmann
Equations

+ Friedmann Equations

$$\frac{d\Omega_M}{dt} = -\sum_\ell \Gamma_\ell\Omega_\ell + H(\Omega_M - \Omega_M^2)$$

A MODEL OF STASIS



Production time
of the states ϕ_ℓ

Decay of the
lightest state

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

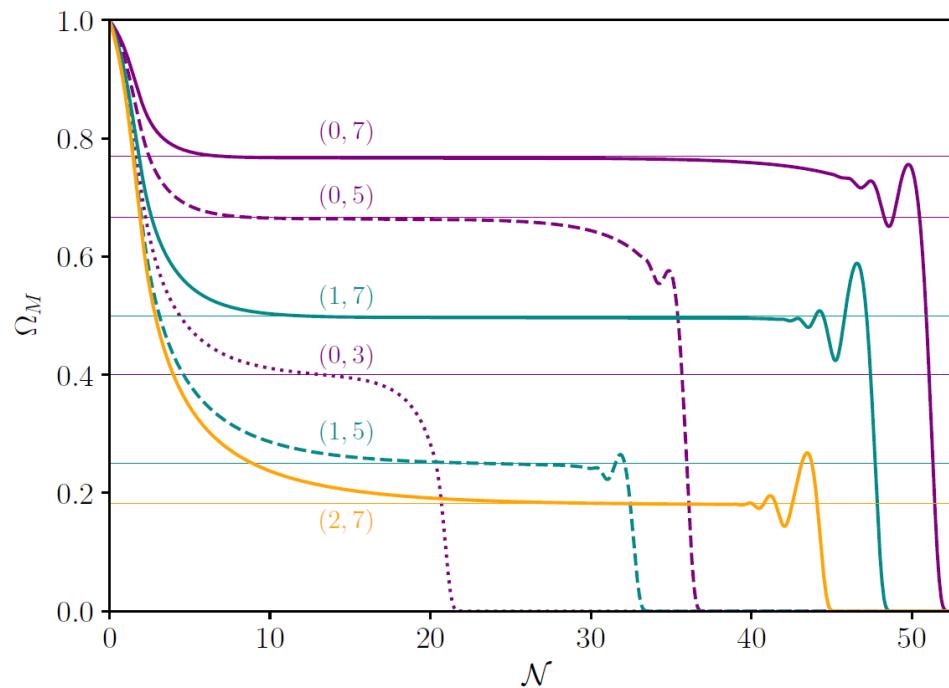
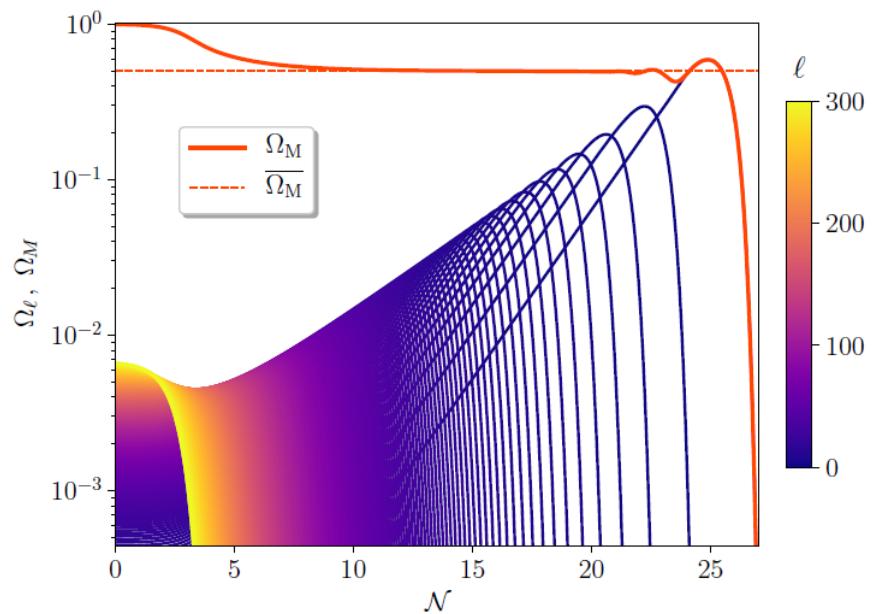
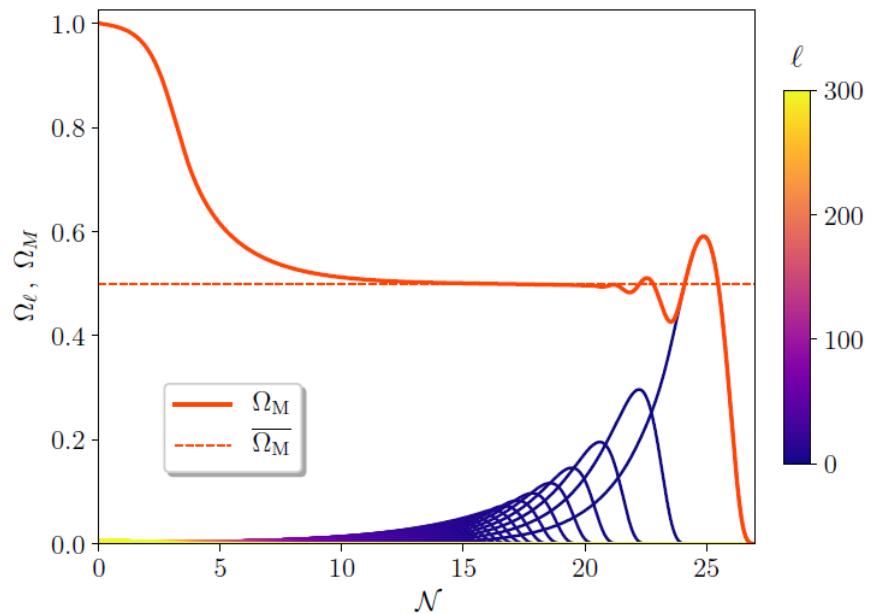
$$\Omega_\ell^{(0)} = \Omega_0^{(0)} \left(\frac{m_\ell}{m_0} \right)^\alpha$$

Free Parameters

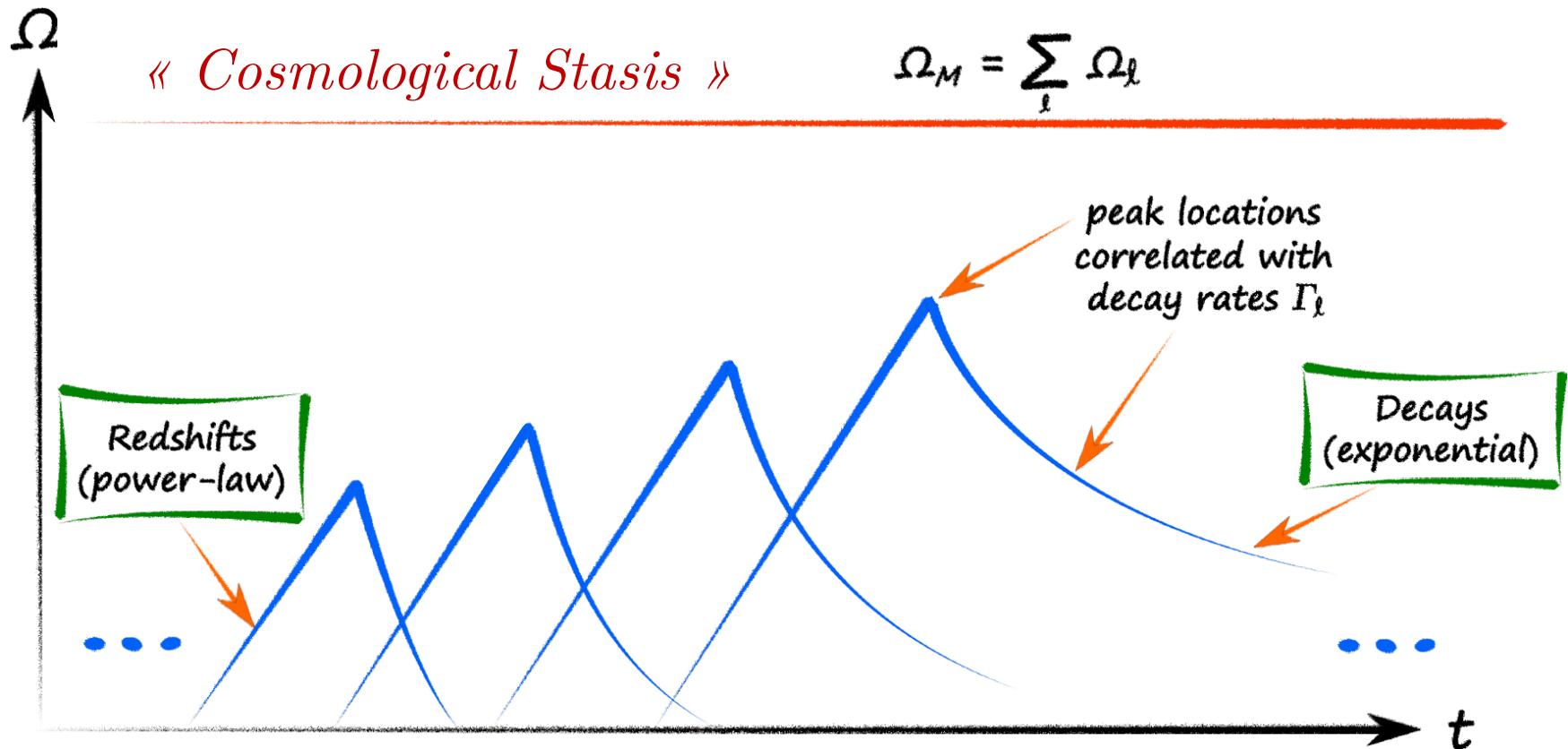
$$\{\alpha, \gamma, \delta, m_0, \Delta m, \Gamma_0, \Omega_0^{(0)}, t^{(0)}\}$$

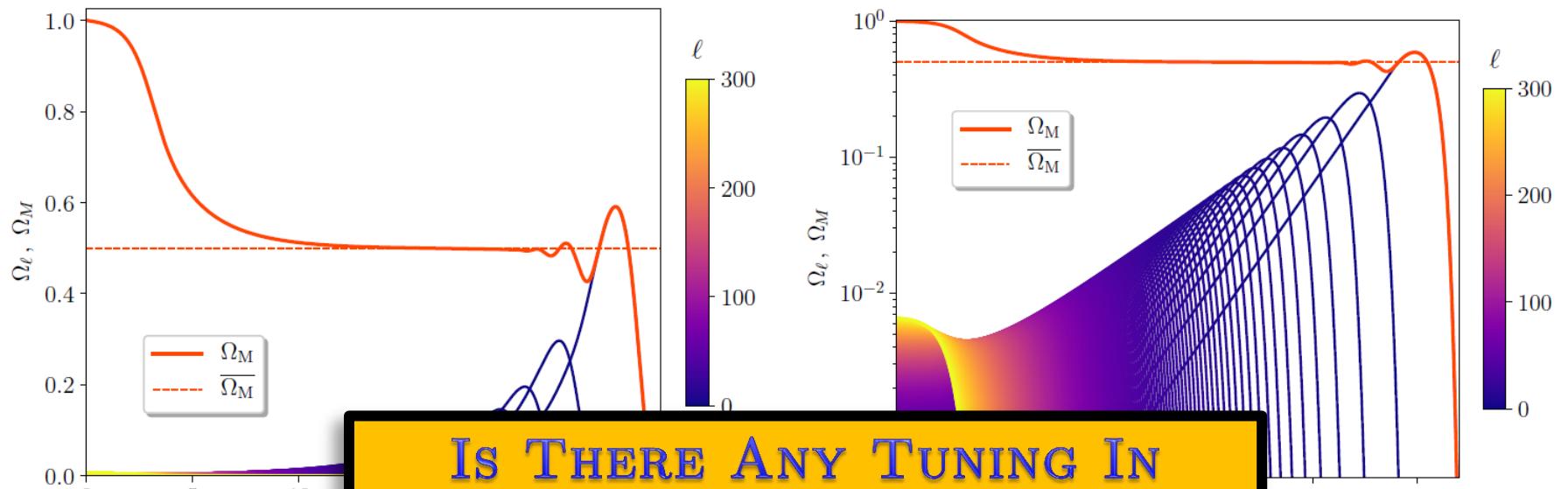
Production time of the states ϕ_ℓ



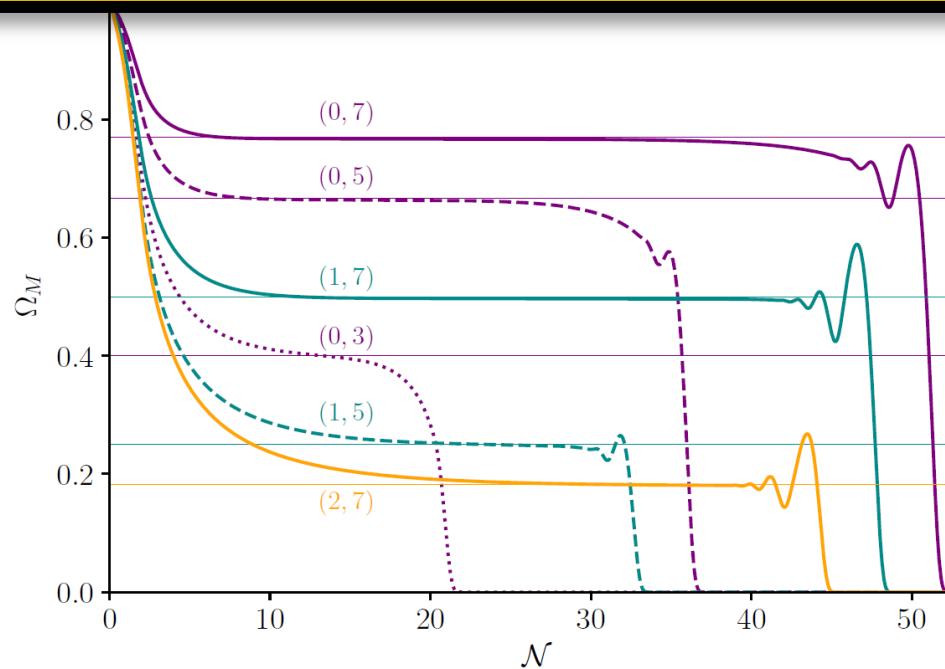

 (α, γ)

Cosmological Stasis !





IS THERE ANY TUNING IN
THERE???



CONDITIONS FOR STASIS

$$\begin{aligned}\frac{d\rho_\ell}{dt} &= -3H\rho_\ell - \Gamma_\ell\rho_\ell \\ \frac{d\rho_\gamma}{dt} &= -4H\rho_\gamma + \sum_\ell \Gamma_\ell\rho_\ell\end{aligned}$$

Boltzmann
Equations

+ Friedmann Equations

$$\frac{d\Omega_M}{dt} = -\sum_\ell \Gamma_\ell\Omega_\ell + H(\Omega_M - \Omega_M^2)$$

CONDITIONS FOR STASIS

$$\frac{d\Omega_M}{dt} = - \sum_{\ell} \Gamma_{\ell} \Omega_{\ell} + H (\Omega_M - \Omega_M^2)$$

« *Cosmological Stasis* »

$$\sum_{\ell} \Gamma_{\ell} \Omega_{\ell} = H(\Omega_M - \Omega_M^2) .$$

CONDITIONS FOR STASIS

During Stasis, $\Omega_M = \bar{\Omega}_M$

$$H(t) = \left(\frac{2}{4 - \bar{\Omega}_M} \right) \frac{1}{t}$$

$$\Omega_\ell(t) = \Omega_\ell^* \left(\frac{t}{t_*} \right)^{2-6/(4-\bar{\Omega}_M)} e^{-\Gamma_\ell(t-t_*)}$$

« Cosmological Stasis »

$$\sum_\ell \Omega_\ell(t) = \bar{\Omega}_M$$

$$\sum_\ell \Gamma_\ell \Omega_\ell(t) = \frac{2\bar{\Omega}_M(1 - \bar{\Omega}_M)}{4 - \bar{\Omega}_M} \frac{1}{t}$$

$$\frac{\sum_\ell \Gamma_\ell \Omega_\ell}{\sum_\ell \Omega_\ell} =$$

$$\frac{2(1 - \bar{\Omega}_M)}{4 - \bar{\Omega}_M} \frac{1}{t}$$

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

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

Production time of the states ϕ_ℓ



« Cosmological Stasis »

$$\sum_{\ell} \Omega_{\ell}(t) = \bar{\Omega}_M$$

$$\sum_{\ell} \Gamma_{\ell} \Omega_{\ell}(t) = \frac{2\bar{\Omega}_M(1 - \bar{\Omega}_M)}{4 - \bar{\Omega}_M} \frac{1}{t}$$

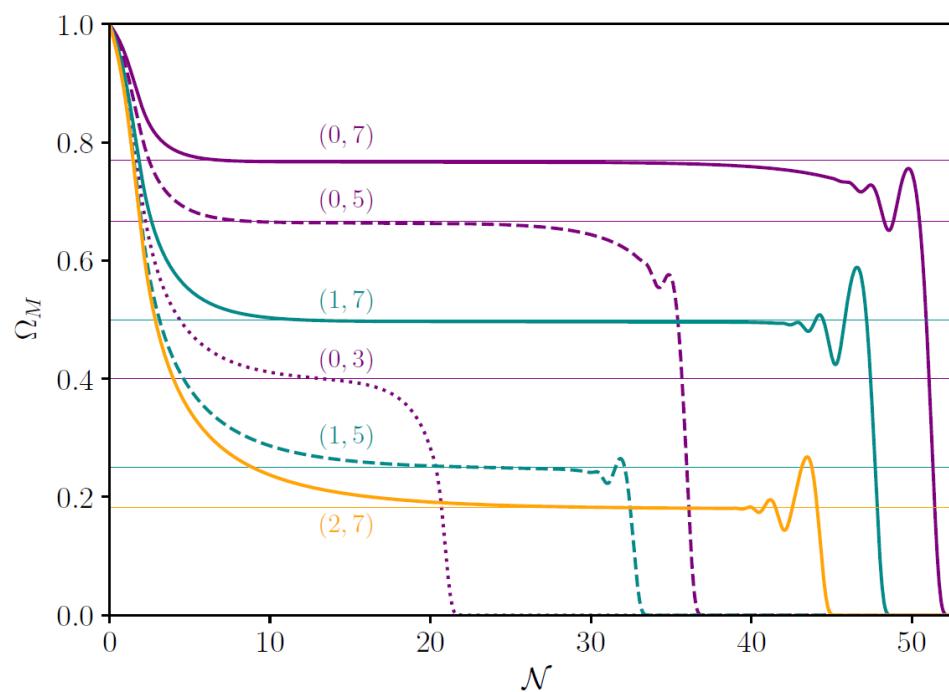
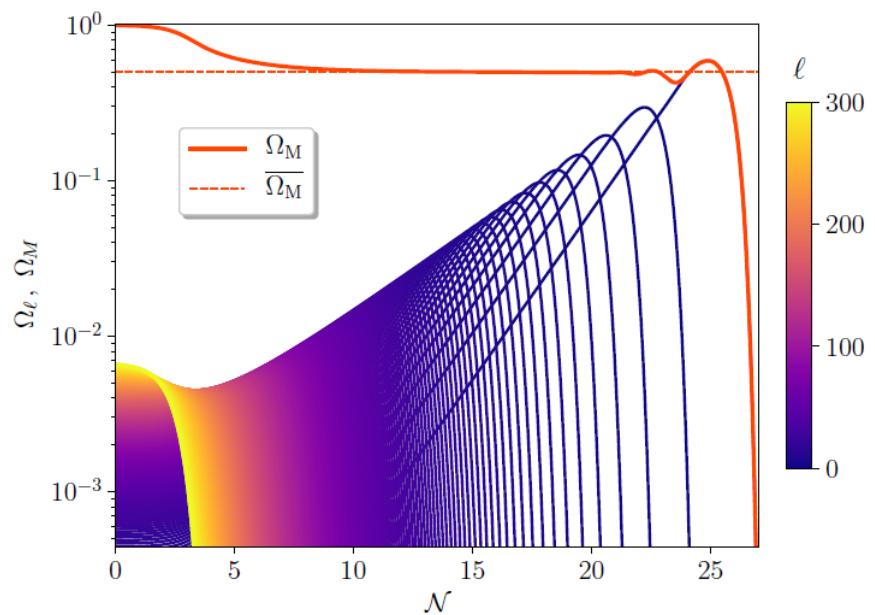
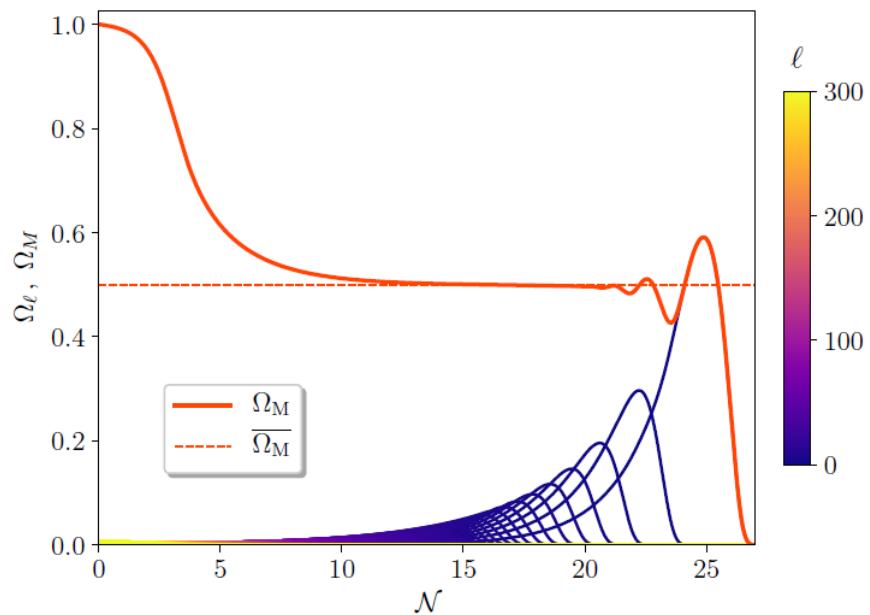
$$\frac{\sum_{\ell} \Gamma_{\ell} \Omega_{\ell}}{\sum_{\ell} \Omega_{\ell}} = \frac{2(1 - \bar{\Omega}_M)}{4 - \bar{\Omega}_M} \frac{1}{t}$$



$$\frac{\sum_{\ell} \Gamma_{\ell} \Omega_{\ell}(t)}{\sum_{\ell} \Omega_{\ell}(t)} = \frac{\alpha + 1/\delta}{\gamma} \frac{1}{t - t^{(0)}}$$

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

Is that right?



STASIS AS A GLOBAL ATTRACTOR

Friedmann Equation

$$\frac{dH}{dt} = -\frac{1}{2}H^2(4 - \Omega_M)$$

$$\frac{1}{H} - \frac{1}{H^{(0)}} = (t - t^{(0)}) \left[\frac{4 - \langle \Omega_M \rangle}{2} \right]$$

$$\langle \Omega_M \rangle \equiv \frac{1}{t - t^{(0)}} \int_{t^{(0)}}^t dt' \Omega_M(t') .$$

$$\frac{d\Omega_M}{dt} = \frac{\Omega_M}{t - t^{(0)}} \left[\frac{2(1 - \Omega_M)}{4 - \langle \Omega_M \rangle} - \left(\frac{\alpha + 1/\delta}{\gamma} \right) \right]$$

$$\frac{d\langle \Omega_M \rangle}{dt} = \frac{1}{t - t^{(0)}} [\Omega_M - \langle \Omega_M \rangle]$$

Equilibrium: $\Omega_M = \langle \Omega_M \rangle =$

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

STASIS AS A GLOBAL ATTRACTOR

$$\begin{cases} \frac{d\Omega_M}{dt} = \frac{1}{t - t^{(0)}} f(\Omega_M, \langle \Omega_M \rangle) \\ \frac{d\langle \Omega_M \rangle}{dt} = \frac{1}{t - t^{(0)}} g(\Omega_M, \langle \Omega_M \rangle), \end{cases}$$

where

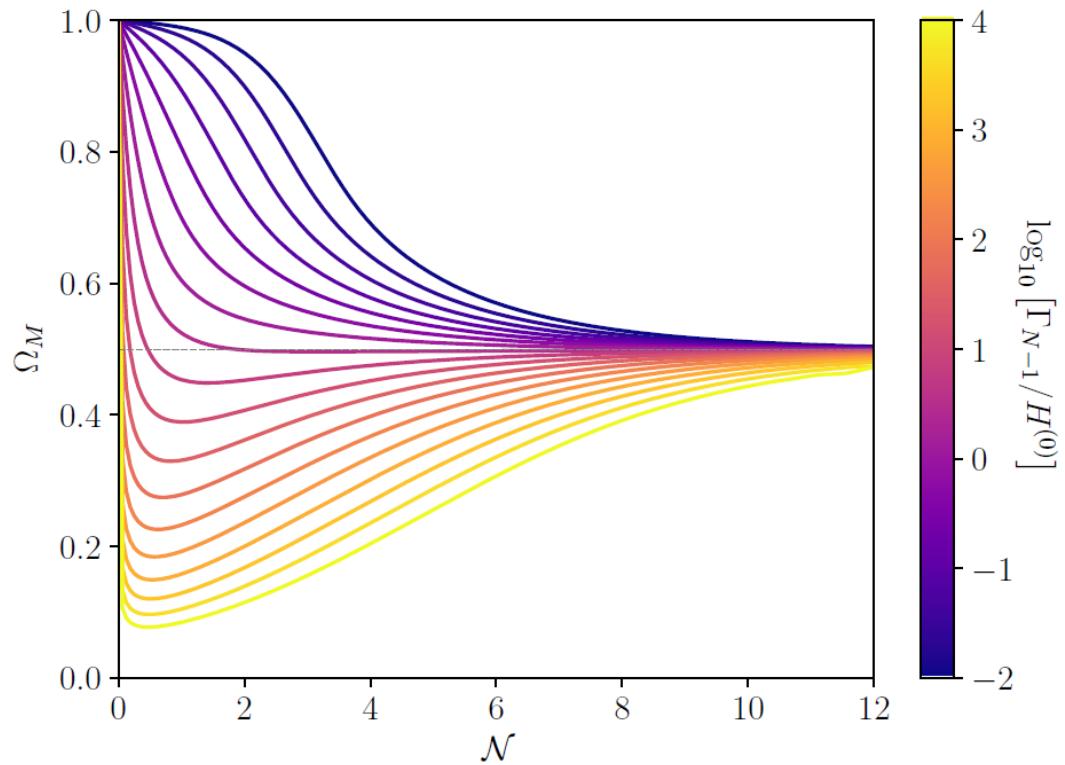
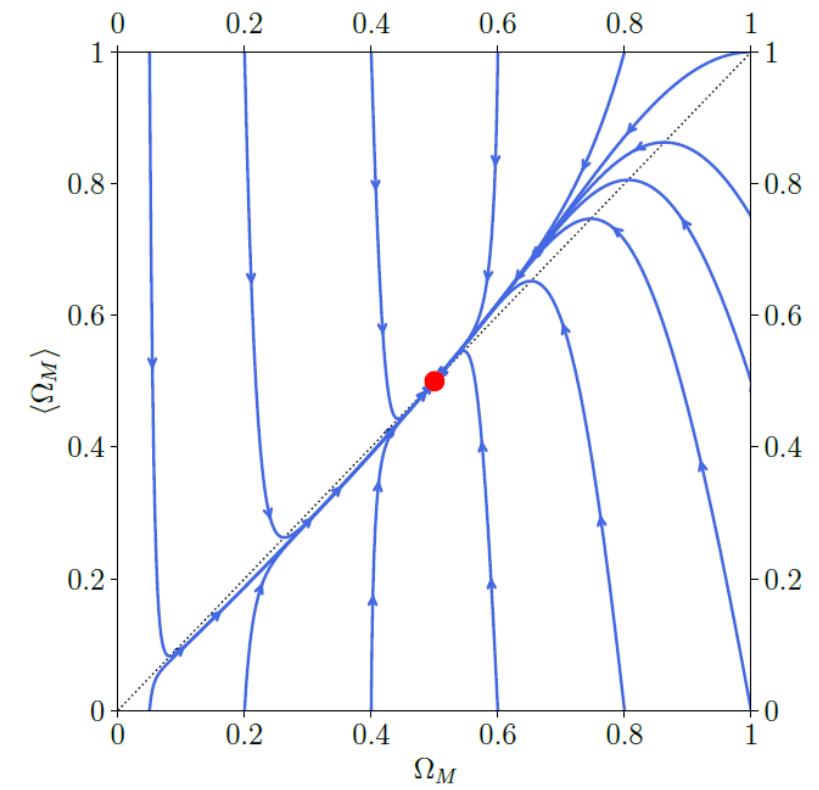
$$f(\Omega_M, \langle \Omega_M \rangle) \equiv \Omega_M \left[\frac{2(1 - \Omega_M)}{4 - \langle \Omega_M \rangle} - \frac{2(1 - \bar{\Omega}_M)}{4 - \bar{\Omega}_M} \right]$$

$$g(\Omega_M, \langle \Omega_M \rangle) \equiv \Omega_M - \langle \Omega_M \rangle.$$

$$\hat{J} = \begin{pmatrix} \partial_{\Omega_M} f & \partial_{\langle \Omega_M \rangle} f \\ \partial_{\Omega_M} g & \partial_{\langle \Omega_M \rangle} g \end{pmatrix} \quad \lambda_{\pm} = \frac{-(4 + \bar{\Omega}_M) \pm \sqrt{\bar{\Omega}_M^2 - 16\bar{\Omega}_M + 16}}{2(4 - \bar{\Omega}_M)}$$

$$\lambda_{\pm} < 0 \quad \text{for all } 0 \leq \bar{\Omega}_M \leq 1$$

STASIS AS A GLOBAL ATTRACTOR



The attractor is GLOBAL!!!

IMPLICATION FOR COSMOLOGY

STASIS:

Matter Domination (MD) → Radiation Domination (RD)

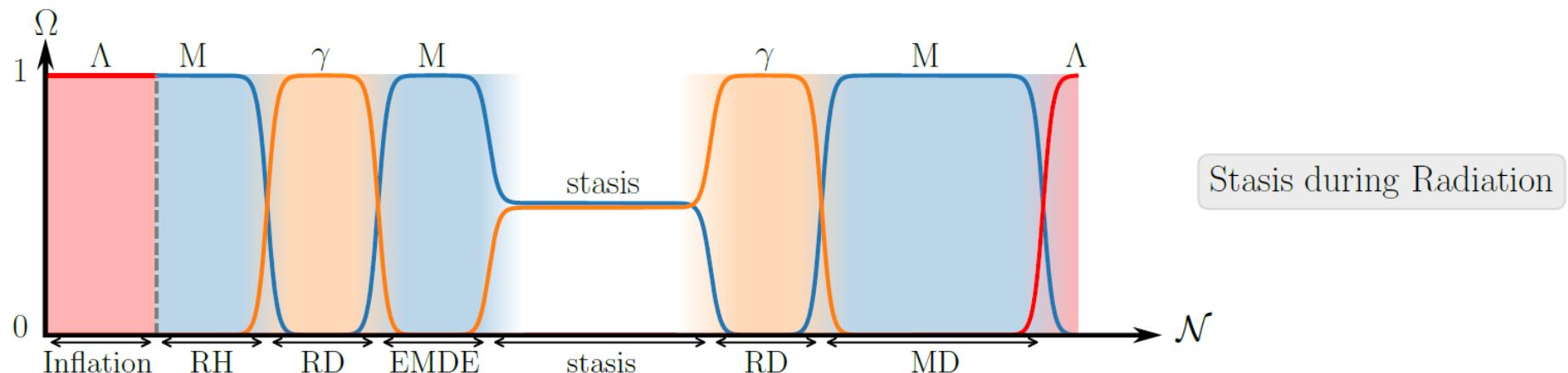
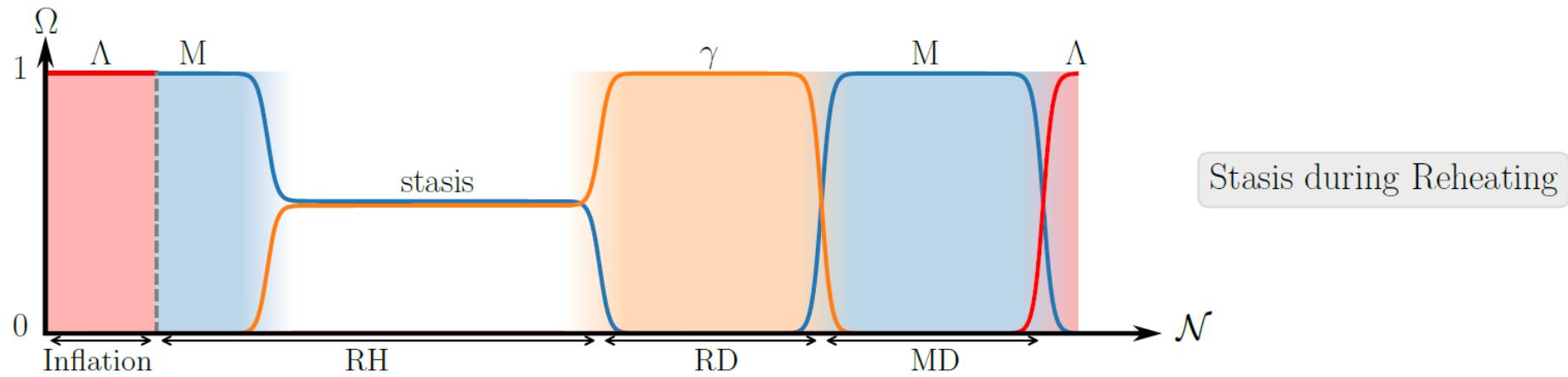


Let's splice it in the
cosmological timeline!

IMPLICATION FOR COSMOLOGY

STASIS:

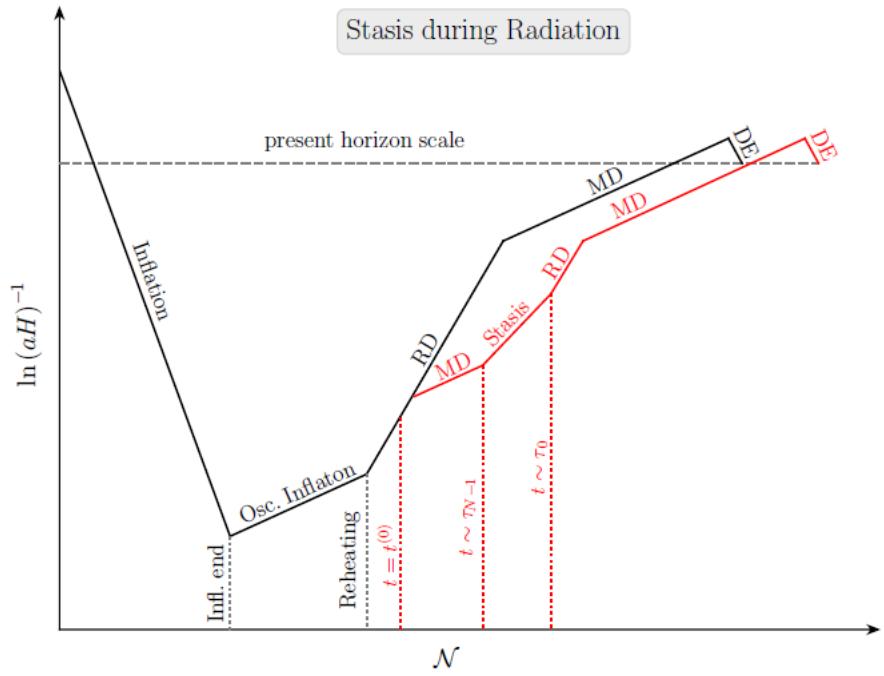
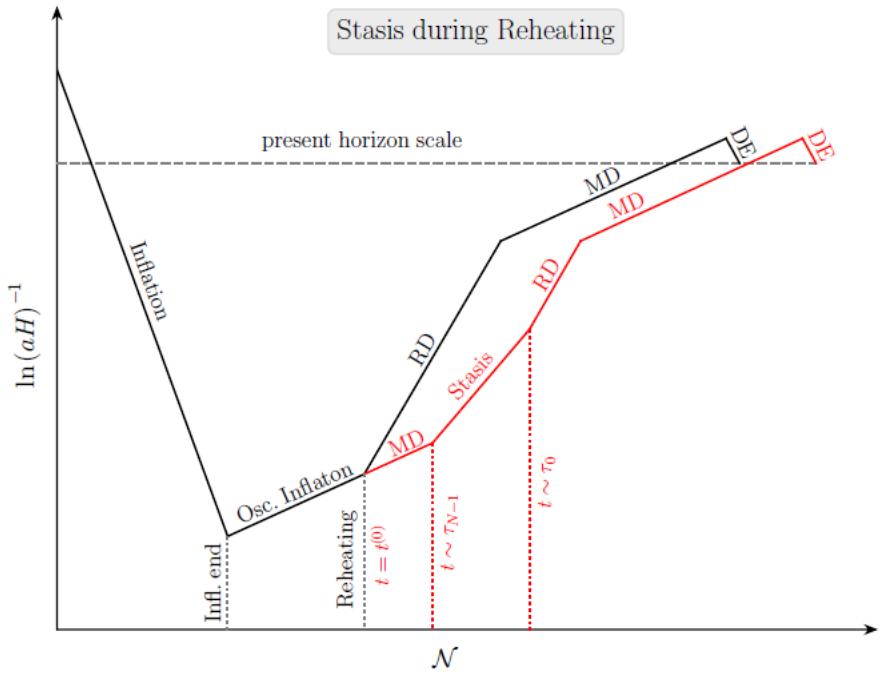
Matter Domination (MD) \rightarrow Radiation Domination (RD)



IMPLICATION FOR COSMOLOGY

STASIS:

Matter Domination (MD) → Radiation Domination (RD)



IMPLICATION FOR COSMOLOGY

- Stasis **modifies the cosmological timeline**
- It **increases the number of e -folds** since horizon exit
- It introduces an **era of non-standard cosmology** different from an EMDE
 - Dark Matter Production
 - Axion Cosmology
 - Baryo/Leptogenesis
 - Growth of Primordial Perturbations

Not a fan of
KK towers?



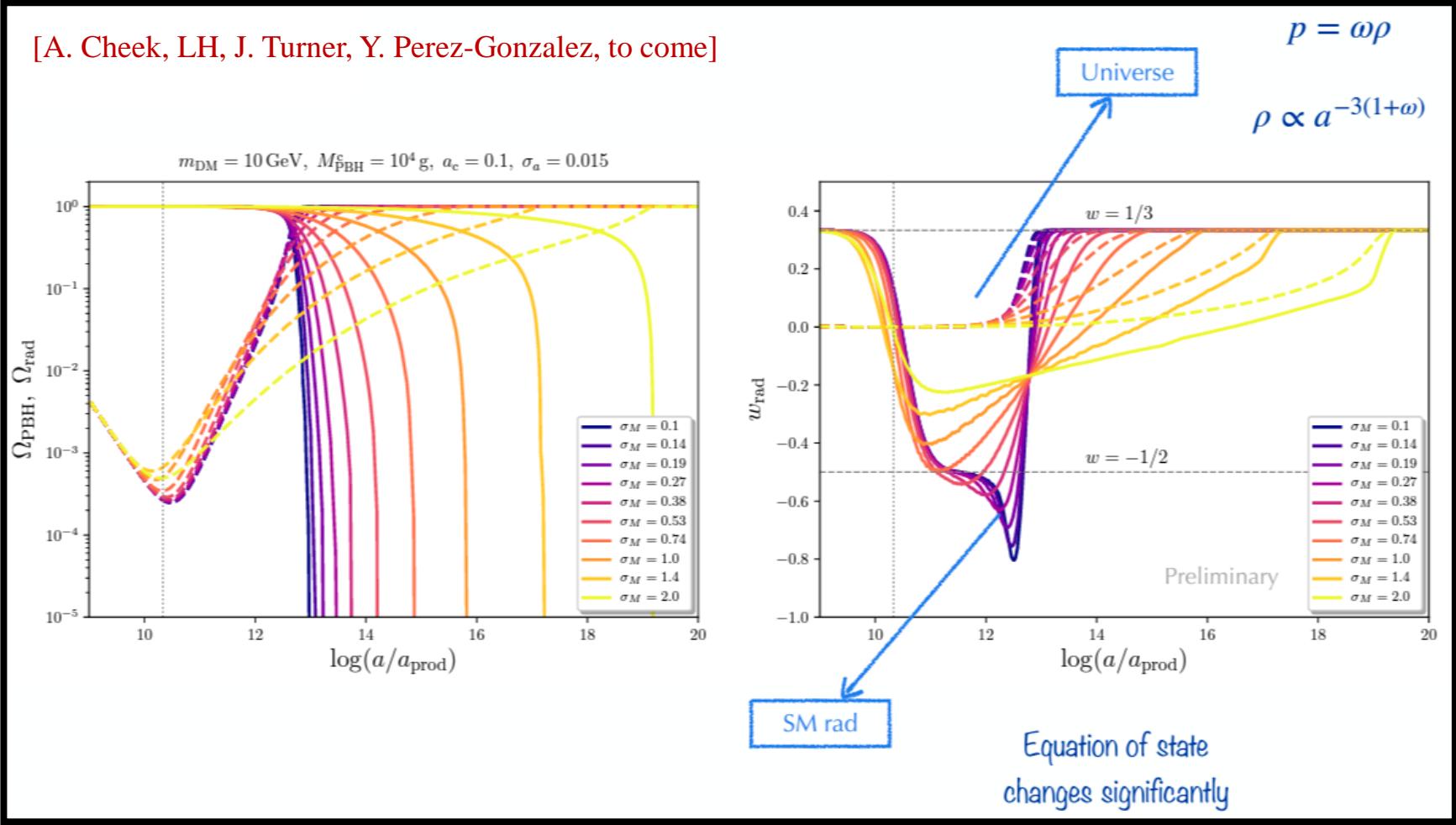
NEW
spring / summer
COLLECTION
COMING SOON

Cosmological Stasis
may arise
in various situations...

→ Stasis could arise in various frameworks

Extended Primordial Black Hole distributions...

[A. Cheek, LH, J. Turner, Y. Perez-Gonzalez, to come]



CONCLUSION

- Decaying towers of dark states can lead to (very) long periods of stasis;
- The stasis regime is **insensitive to initial conditions**, it is a **global attractor**;
- **Numerous implications**: reheating mechanism, constraints on inflation, thermal particle production in the early universe, etc.
- **Many possible extensions**: production of massive states instead of photons, **PBH evaporation**, interaction with **dark energy**, etc.

Much more to come ...

BACK UP

CONDITIONS FOR STASIS

Assume that stasis is established at time t

$$\Omega_\ell(t) = \Omega_\ell^{(0)} h(t^{(0)}, t) e^{-\Gamma_\ell(t-t^{(0)})}$$

Non-trivial redshift



$$\begin{aligned} \sum_\ell \Omega_\ell(t) &= \Omega_0^{(0)} h(t^{(0)}, t) \sum_\ell \left(\frac{m_\ell}{m_0}\right)^\alpha e^{-\Gamma_0\left(\frac{m_\ell}{m_0}\right)^\gamma(t-t^{(0)})} \\ &= \frac{\Omega_0^{(0)}}{\delta(\Delta m)^{1/\delta}} h(t^{(0)}, t) \int_0^\infty dm m^{1/\delta-1} \left(\frac{m}{m_0}\right)^\alpha e^{-\Gamma_0\left(\frac{m}{m_0}\right)^\gamma(t-t^{(0)})} \\ &= \frac{\Omega_0^{(0)}}{\gamma\delta} \left(\frac{m_0}{\Delta m}\right)^{1/\delta} \Gamma\left(\frac{\alpha+1/\delta}{\gamma}\right) h(t^{(0)}, t) \left[\Gamma_0(t-t^{(0)})\right]^{-(\alpha+1/\delta)/\gamma} \end{aligned}$$



Continuous Limit

A MODEL OF STASIS

Mass Spectrum

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

→ Inspired from a Kaluza-Klein spectrum

scalar field compactified on a circle of radius R

[Dienes & Thomas, Phys.Rev.D 85, 083523 / 85, 083524 / 86, 055013]

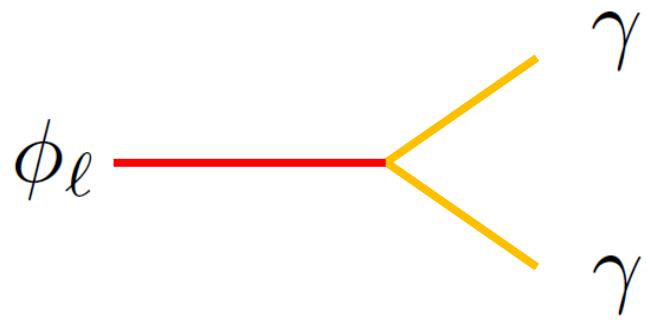
$$mR \ll 1 \text{ or } mR \gg 1 \longrightarrow \begin{aligned} \text{or } \{m_0, \Delta m, \delta\} &= \{m, 1/R, 1\} \\ \{m_0, \Delta m, \delta\} &= \{m, 1/(2mR^2), 2\} \end{aligned}$$

Bound states of some
strongly coupled theory $\longrightarrow \delta = 1/2$ [Dienes, Huang, Su, and Thomas,
PRD 95, 043526 (2017)]

A MODEL OF STASIS

Decay Widths

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



Depends on the
microscopic theory

$$\mathcal{O}_\ell \sim c_n \phi_\ell \mathcal{F} / \Lambda^{d-4}$$



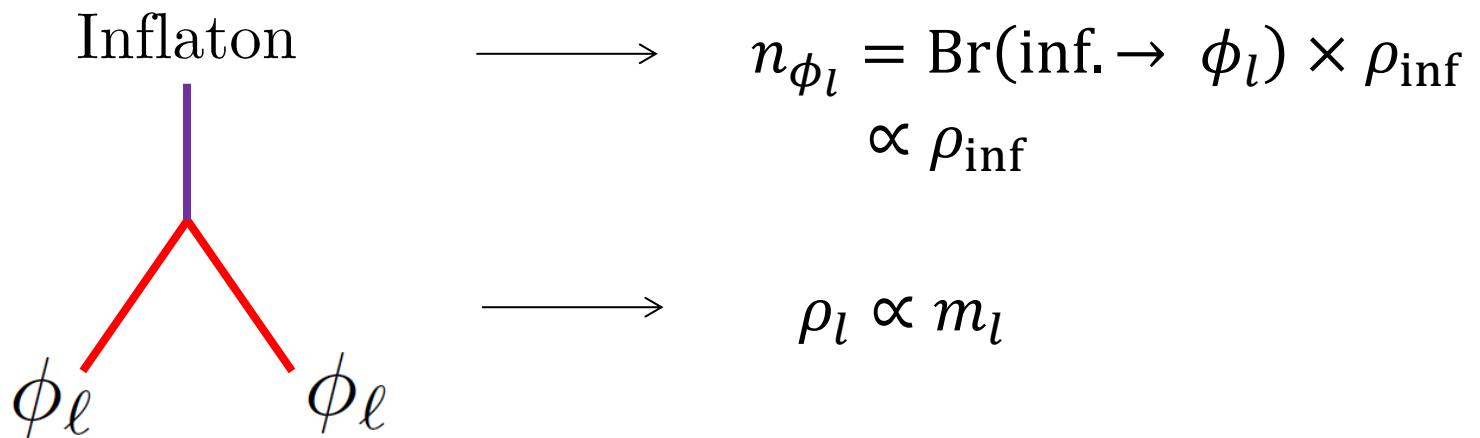
$$\begin{aligned}\gamma &= 2d - 7 \\ \gamma &= \{3, 5, 7\}\end{aligned}$$

A MODEL OF STASIS

Initial Abundances

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

Depends on the production mechanism...



Universal Inflaton Decay $\longrightarrow \alpha = 1$

STASIS WITH AN EXTRA COMPONENT

Ω_X in addition to Ω_M and Ω_γ

$$p_X = w_X \rho_X$$

Stasis requires $d\Omega_X/dt = 0$

$$\begin{cases} \bar{\Omega}_M &= (1 - 3w_X)(1 - \bar{\Omega}_X) \\ \bar{\Omega}_\gamma &= 3w_X(1 - \bar{\Omega}_X) . \end{cases}$$

$$w_X = \frac{\bar{\Omega}_\gamma}{3(\bar{\Omega}_M + \bar{\Omega}_\gamma)} .$$

Line of
Attractors...