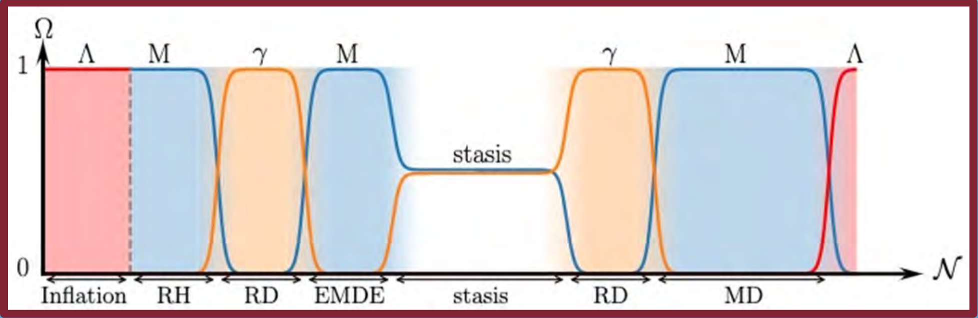
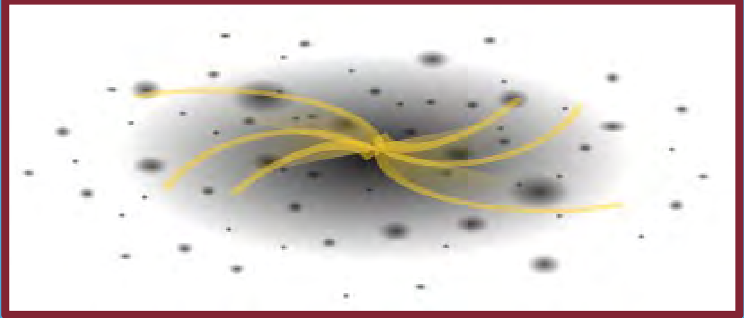
Cosmological Stasis and Its Observational Signatures





Brooks Thomas

LAFAYETTE COLLEGE

Work supported in part by NSF

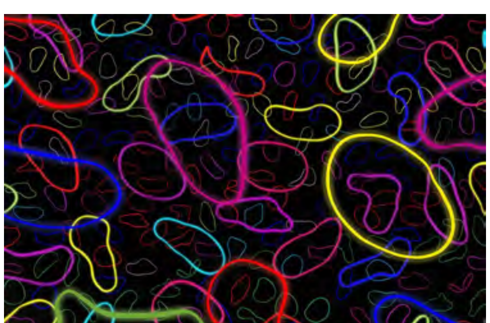
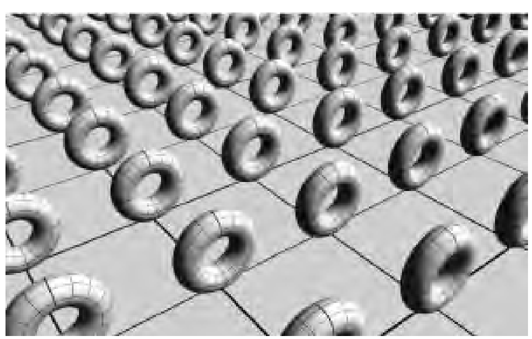
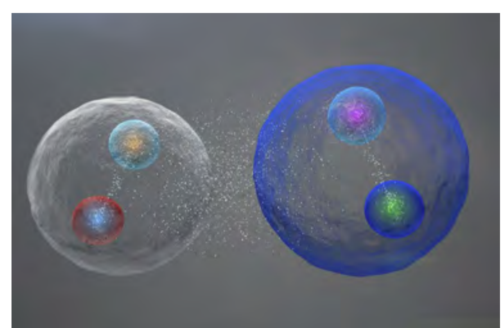
Based on work done in collaboration with:

- **K. R. Dienes, F. Huang, L. Heurtier, D. Kim, and T. M. P. Tait [2111.04753, 2212.01369]**
- **K. R. Dienes, F. Huang, L. Heurtier, and T. M. P. Tait [2309.10345, 2406.06830]**
- **K. R. Dienes, F. Huang, L. Heurtier, D. Hoover, and A. Paulsen [2503.19959]**

PASCOS 2025, Durham University, July 22nd, 2025

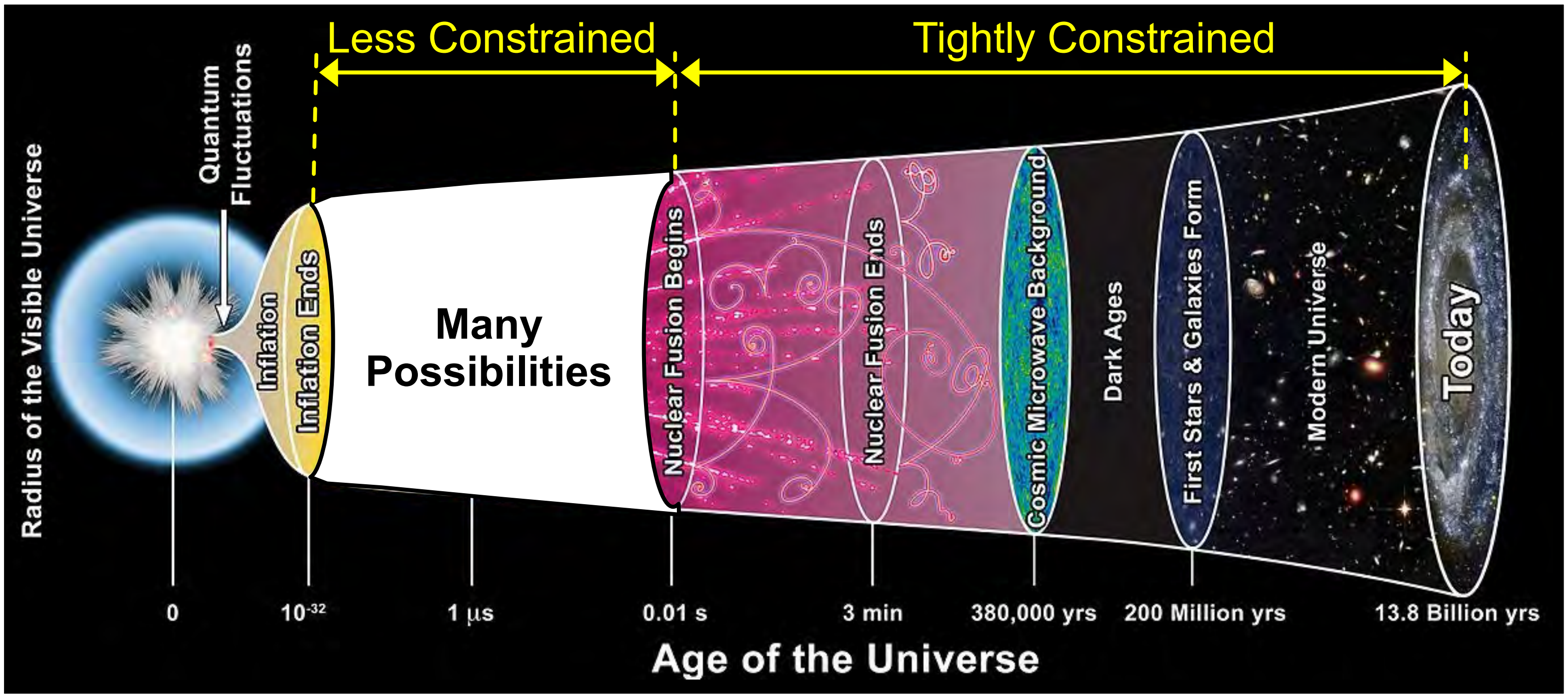
Towers of Unstable States

- A wide variety of scenarios for new-physics predict **towers of massive, unstable states** with a broad spectrum of masses, cosmological abundances, and lifetimes.
- Such towers are a generic feature of, for example,...
  - String theory (string moduli, axions, etc.)
  - Theories with extra spacetime dimensions (KK towers)
  - Scenarios with confining dark/hidden-sector gauge groups (bound-state resonances)
  - Scenarios which lead to the production of primordial black holes with an extended mass spectrum (the black holes themselves)
- In some cases, such states can give rise to astrophysical signals, signals at colliders, etc.; in others, they are too heavy/short-lived.


Cosmological Consequences

- The presence of such towers can have a significant impact on early-universe cosmology – even if the tower states are too heavy/short-lived to be accessible.



- Indeed, such towers can give rise to epochs of **cosmic stasis**: epochs wherein the abundances of multiple cosmological energy components (matter, radiation, etc.) remain effectively constant over an extended period. **[Dienes, Huang, Heurtier, Kim, Tait, BT '21]**
- These epochs are often **global attractors**: if the basic conditions under which they arise are satisfied, the universe will evolve toward them.

Cosmological Stasis

- Cosmological stasis is a phenomenon in which the abundances of multiple cosmological energy components (matter, radiation, etc.) remain **effectively constant** over an extended period.
- In order to see how this phenomenon can arise, let's consider a universe consisting only of massive matter ($w = 0$) and radiation ($w = 1/3$).

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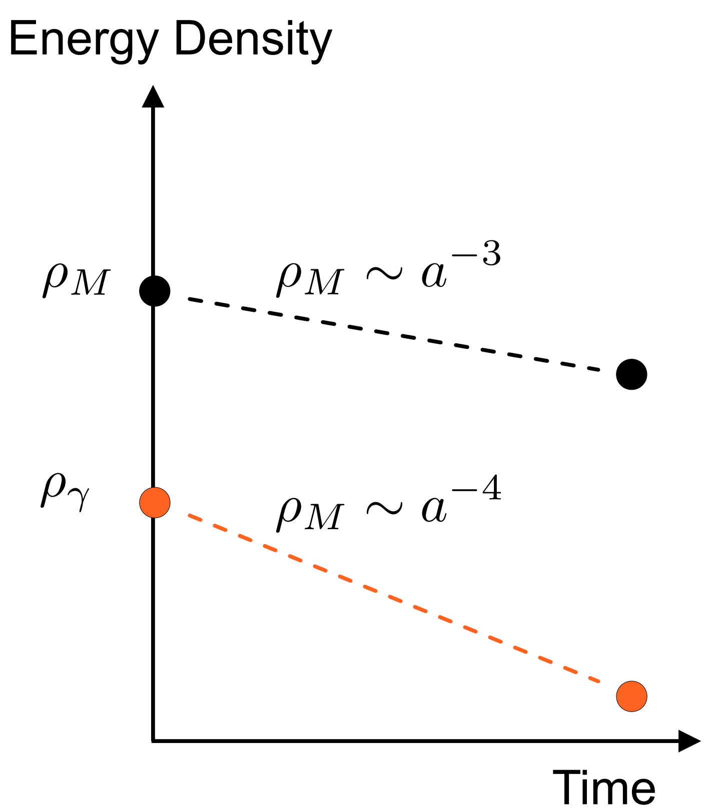

Boltzmann Equations

$$\frac{d\rho_M}{dt} = -3H\rho_M$$

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

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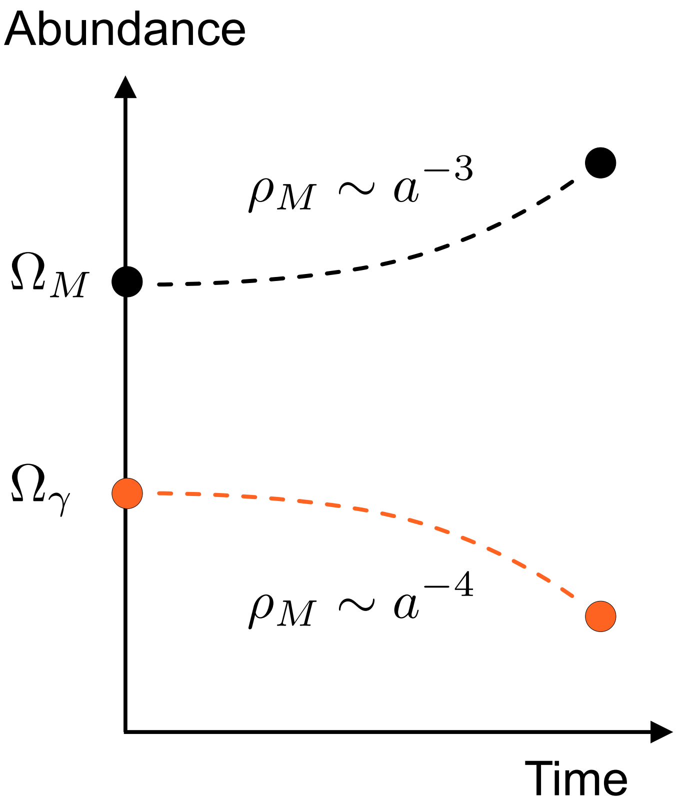

Boltzmann Equations

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

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- Expansion drives Ω_M upward, Ω_γ downward.

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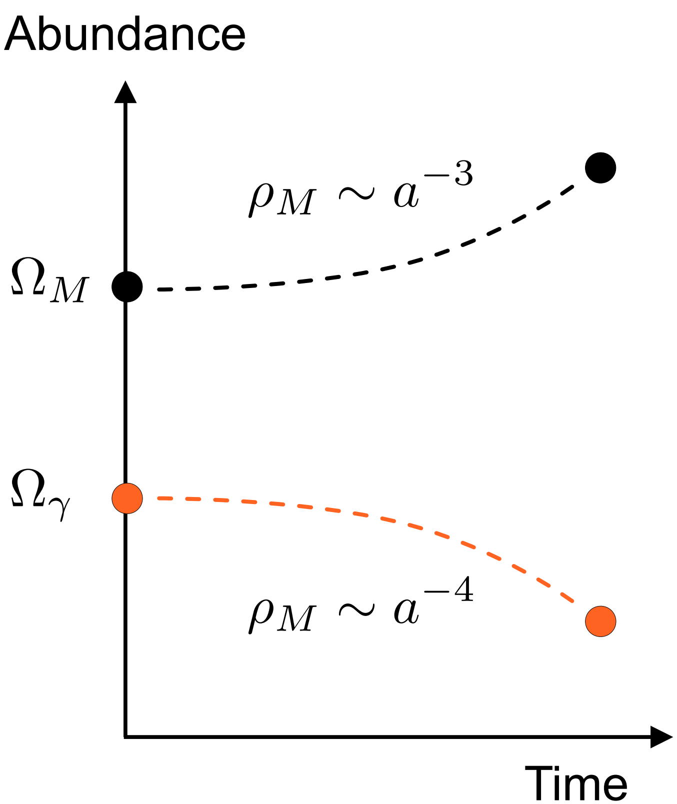

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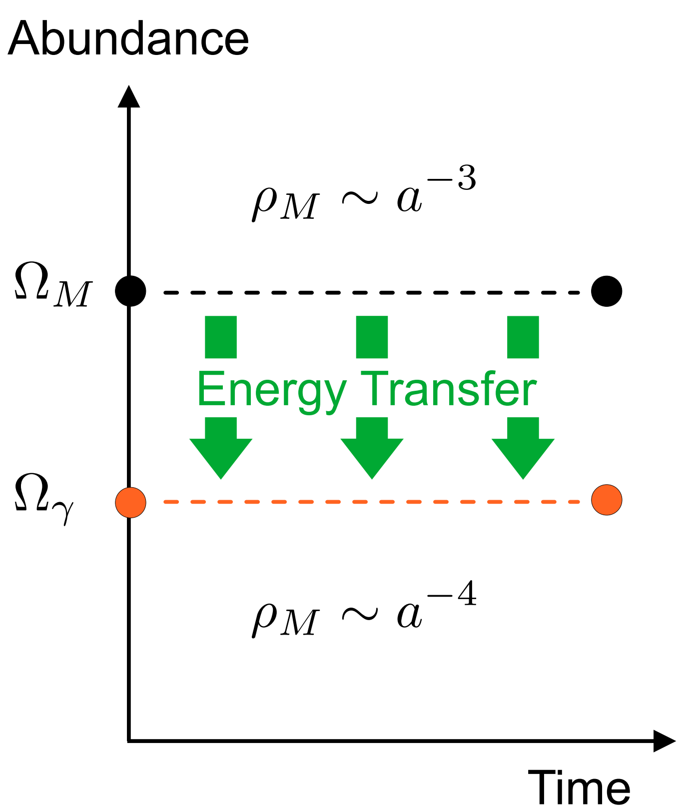

Boltzmann Equations

$$\frac{d\Omega_M}{dt} = H\Omega_M\Omega_\gamma - P(t)$$

$$\frac{d\Omega_\gamma}{dt} = -H\Omega_M\Omega_\gamma + P(t)$$

"Pump" from component with higher to lower w.

- Expansion drives Ω_M upward, Ω_γ downward.
- However, in the presence of additional dynamics, the situation changes.
- If some process "pumps" energy density from matter to radiation at a rate $P(t) \propto t^{-1}$, it can **counteract** the effect of expansion.

Cosmological Stasis

- We've seen that stasis arises when source and sink tems in the Boltzmann equations "pump" energy density from one component to another at a rate that compensates for Hubble expansion.

Q So how can such a "pump" arise in practice?

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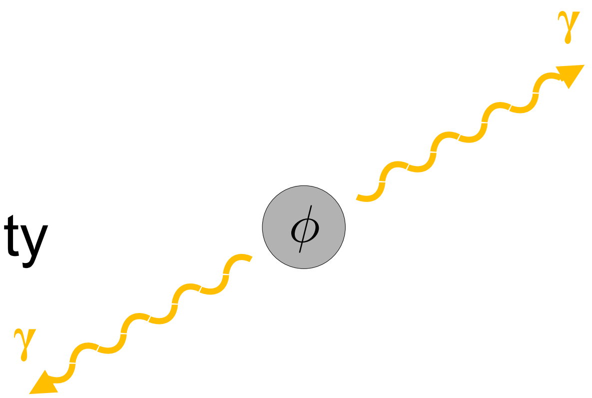
A One natural mechanism via which energy density can be transferred from matter to radiation is **particle decay**.



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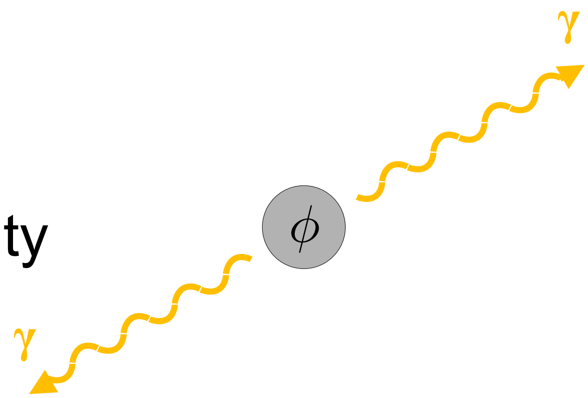

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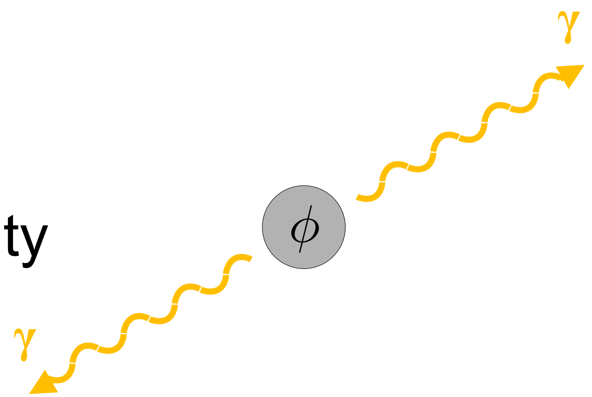

- The exponential decay of a single matter species, which occurs over a relatively short time period, is insufficient for achieving stasis.
- However, a ***tower of matter states*** ϕ_ℓ, where $\ell = 0, 1, 2, \ldots, N - 1$, whose decay widths Γ_ℓ and initial abundances $\Omega_\ell^{(0)}$ scale across the tower as a function of their mass m_ℓ can indeed give rise to a pump that compensate for the effect of cosmic expansion over a extended period.

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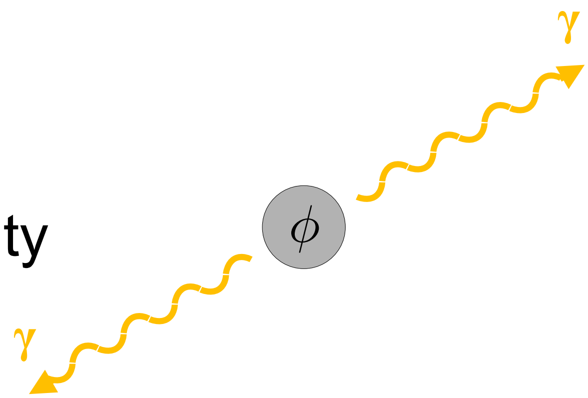

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This is why we expect stasis to be a fairly common feature in BSM cosmologies. As discussed earlier, towers of massive, unstable states are a generic feature of many well-motivated extensions of the SM!

A Concrete Realization

[Dienes, Huang, Heurtier, Kim, Tait, BT '21]

- Let's consider a tower of N such matter states ($w_M = 0$) with...

Masses	Decay Widths	Initial Abundances
$m_\ell = m_0 + (\Delta m)\ell^\delta$	$\Gamma_\ell = \Gamma_0 \left(\frac{m_\ell}{m_0}\right)^\gamma$	$\Omega_\ell^{(0)} = \Omega_0^{(0)} \left(\frac{m_\ell}{m_0}\right)^\alpha$

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- Towers of states with mass spectra of this form arise naturally in many extensions of the Standard Model.
  - KK excitations of a 5D scalar: $\begin{cases} mR \ll 1 \longrightarrow \delta \sim 1 \\ mR \gg 1 \longrightarrow \delta \sim 2 \end{cases}$
  - Bound states of a strongly-coupled gauge theory: $\delta \sim \frac{1}{2}$
- Decay to radiation ($w_\gamma = 1/3$) through ***contact operators*** of dimension d implies a scaling: $\mathcal{O}_\ell \sim \frac{c_\ell}{\Lambda^{d-4}} \phi_\ell \mathcal{F} \longrightarrow \gamma = 2d - 7$

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- Scaling of initial abundances depends on how they're generated:

Misalignment production $\longrightarrow$ $\alpha < 0$

Thermal freeze-out $\longrightarrow$ $\alpha < 0$ or $\alpha > 0$

Universal inflaton decay $\longrightarrow$ $\alpha \sim 1$

PBH evaporation $\longrightarrow$ $\alpha \sim \pm 1$

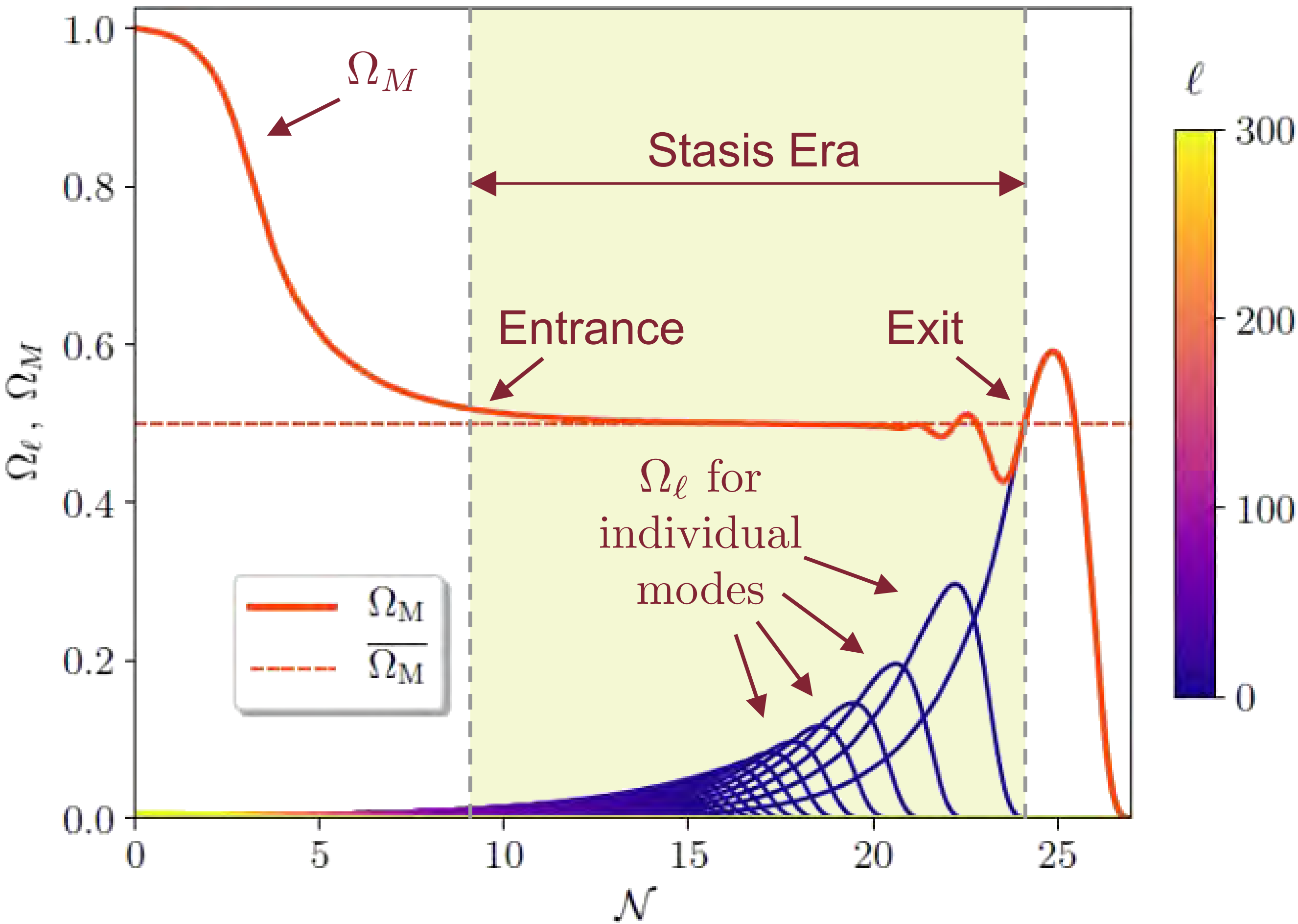
Gravitational production $\longrightarrow$ $\alpha \sim 0, 1/2,$ or 2

...

[Long, Shams Es Haghi, Venegas '25]

The Emergence of Stasis

- In BSM scenarios of this sort, stasis emerges generically, with minimal additional assumptions.



Parameter Choices

$$\alpha = 1$$
$$\gamma = 7$$
$$\delta = 1$$
$$N = 300$$
$$\frac{m_0}{\Delta m} = 1$$
$$\frac{\Gamma_{N-1}}{H^{(0)}} = 0.01$$

Stasis Abundances

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

- The matter and radiation abundances during stasis turn out to depend on the model parameters α, γ, and δ.

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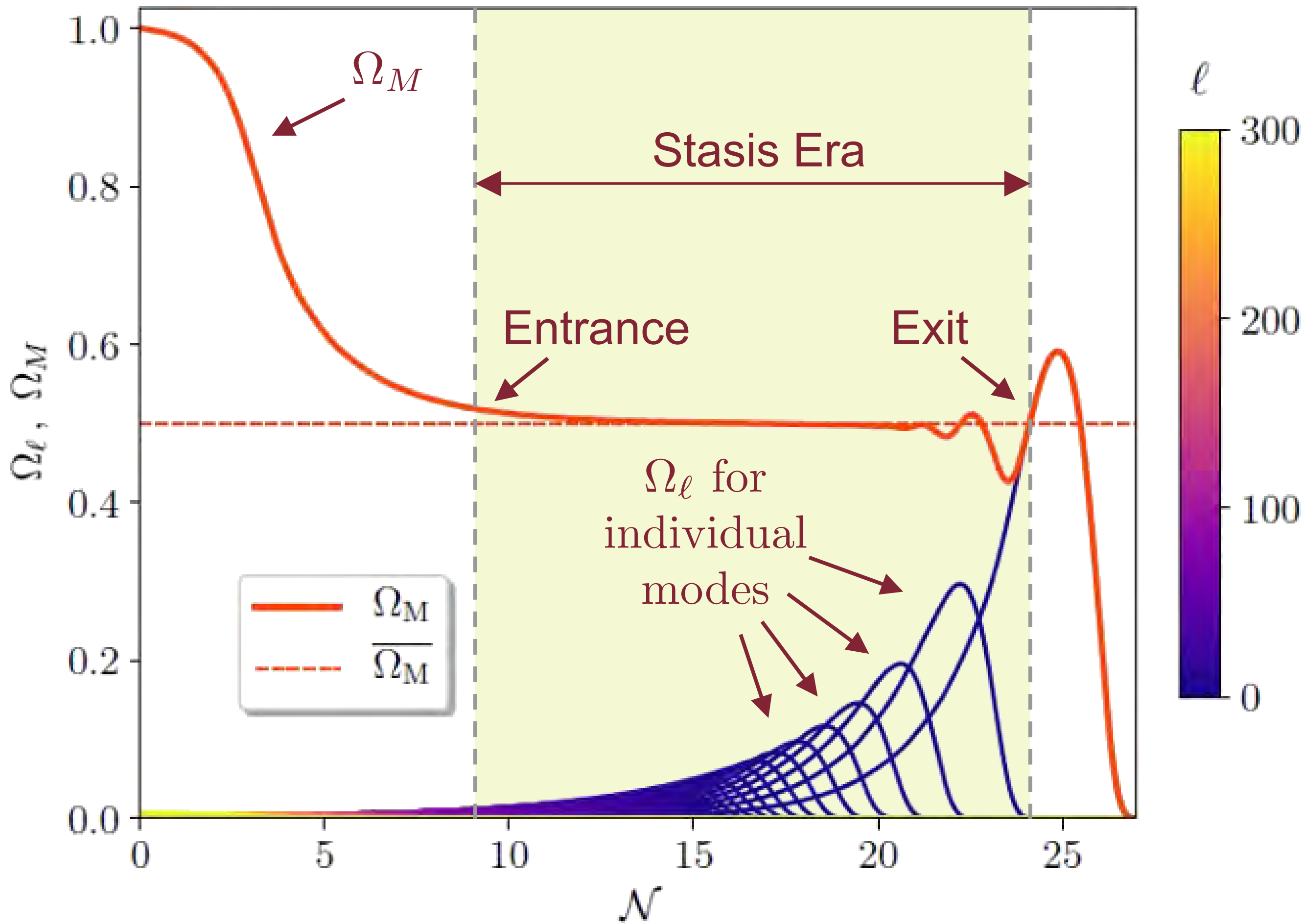

- The **effective equation-of-state parameter** $\overline{w}$ for the universe is constant during stasis – but takes a non-canonical value within the range $0 < \overline{w} < 1/3$.

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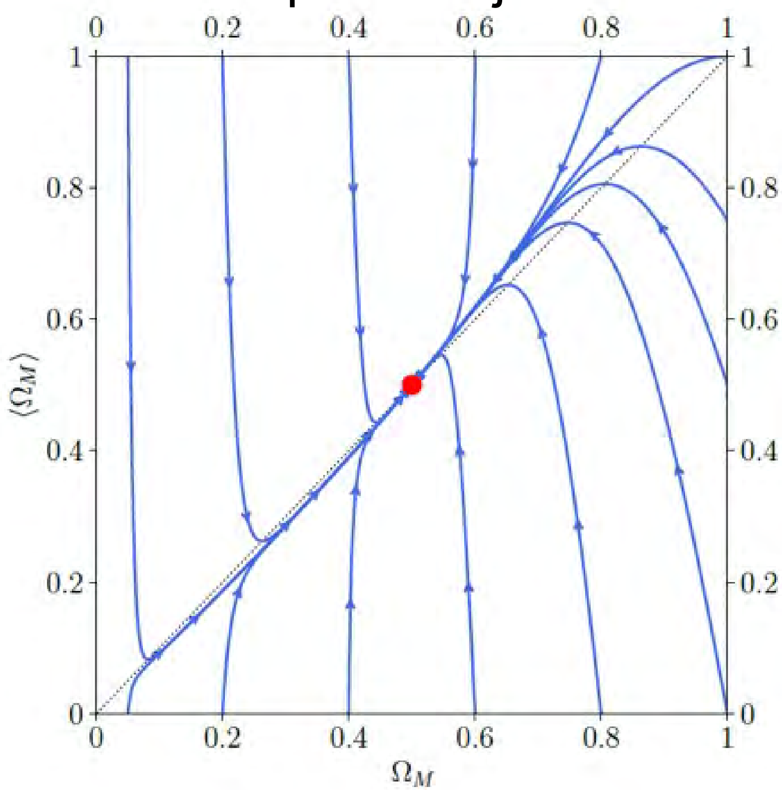
$$\overline{w} = \Omega_M w_M + \Omega_\gamma w_\gamma$$

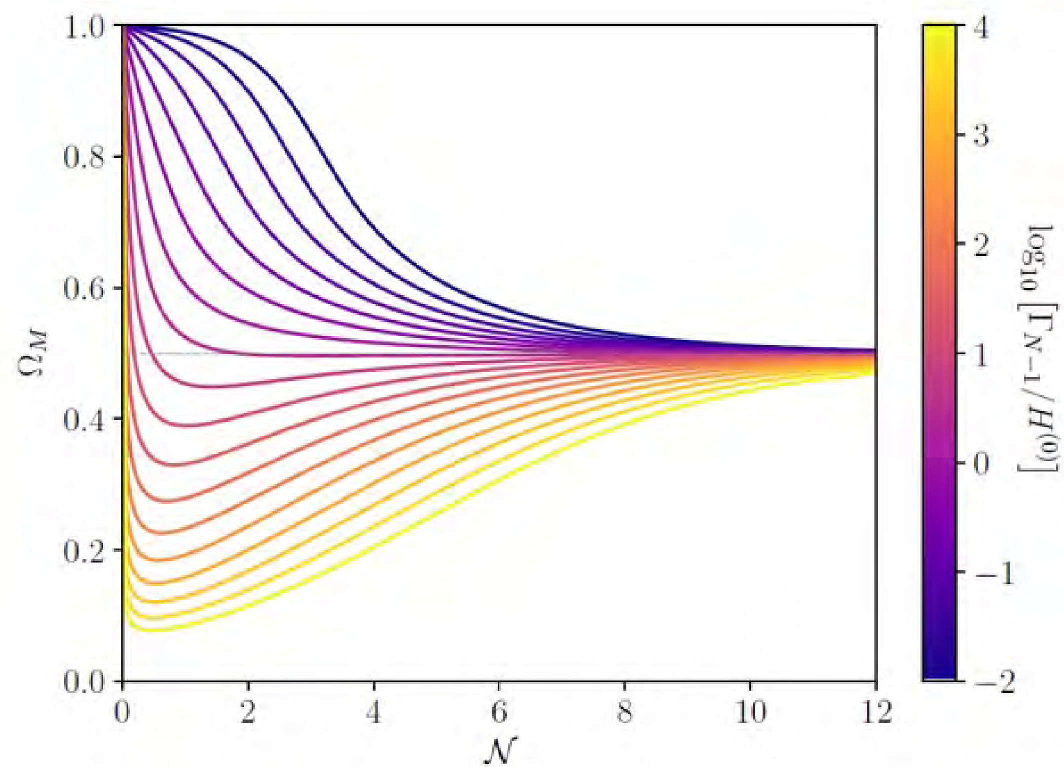
Stasis as a Global Attractor

- Perhaps even more importantly, achieving cosmological stasis does not require a fine-tuning of the initial conditions for Ω_M and H – or, alternatively, for Ω_m and its time-average $\langle\Omega_M\rangle$ – or for the ratio $\Gamma_{\text{N-1}}/H^{(0)}$.
- In fact, stasis is a ***global attractor*** in the sense that Ω_M and Ω_γ will ***evolve toward their stasis values*** regardless of what these initial conditions are.

State-Space Trajectories



Ω_M vs. t For Different $\Gamma_{\text{N-1}}/H^{(0)}$

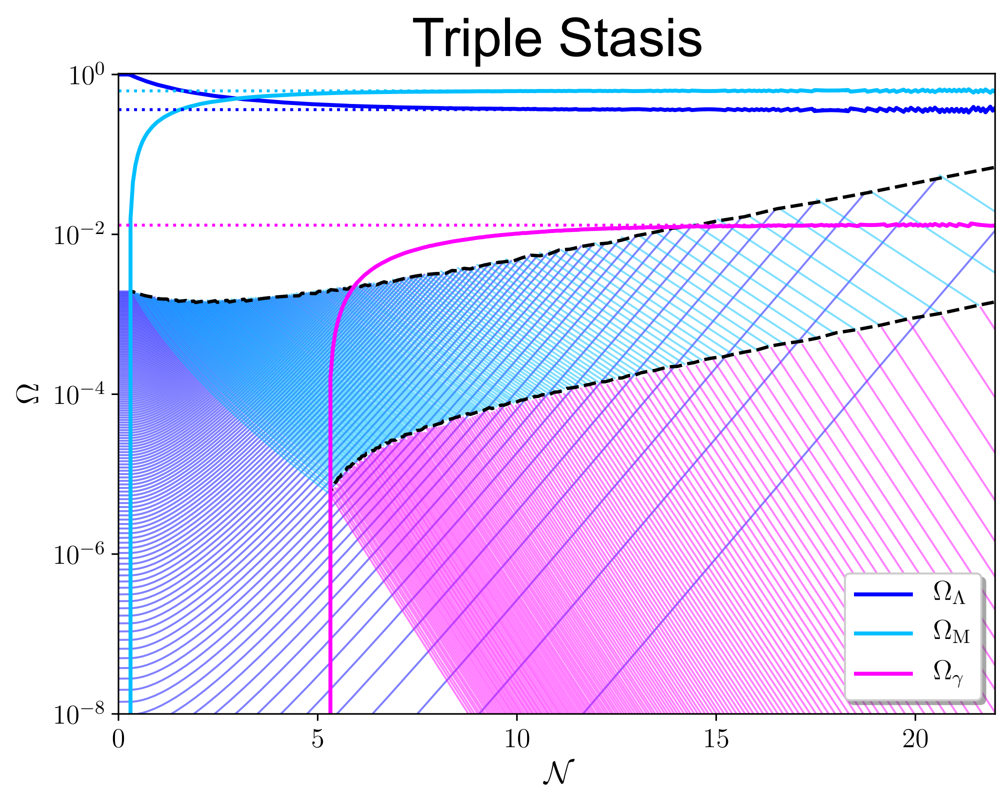


Other Realizations of Stasis

- While I'll be concentrating of stases that involve matter and radiation for the remainder of this talk, I want to emphasize that stasis is a very general phenomenon.
- For example, stasis can also involve **vacuum energy**. A natural realization of such a stasis involves a tower of oscillating scalar fields with a spectrum of masses m_ℓ which transition from overdamped behavior ($w_\ell \approx -1$) to underdamped ($\langle w \rangle \approx 0$) behavior when $3H(t) \approx 2m_\ell$. **[Dienes, Heurtier, Huang, Tait, BT '23; Dienes, Heurtier, Huang, Tait, BT '24]**
- It is also possible for a stasis to develop involves **more than two components**.

  [Dienes, Heurtier, Huang, Tait, BT '23]
- In certain situations, stasis can also arise due to the **annihilation** of non-relativistic particles into radiation.

  [Barber, Dienes, BT '24]



Beyond the Background Cosmology

- In terms of the homogeneous background cosmology (the evolution of a and ρ_{crit}), a stasis epoch **mimics an epoch of perfect-fluid domination** (PFD) wherein the fluid has an equation-of-state parameter $w_{\text{PF}} = \overline{w}$.

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- More specifically, let's consider a "**spectator" component** χ with the following properties:
  - Behaves like massive matter: $w_\chi = 0$.
  - Has $\rho_\chi \ll \rho_{\text{crit}}$ during the epoch of interest and thus no appreciable impact on the background cosmology.
  - Interacts with other components only through gravity.
- In other words, χ behaves like a population decoupled (e.g. frozen-out) **dark-matter** particles.

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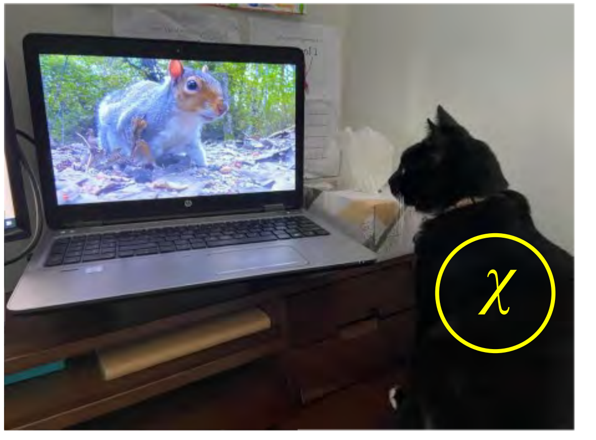

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- In other words, χ behaves like a population decoupled (e.g. frozen-out) **dark-matter** particles.
- We'll now examine at how density perturbations for χ – and in particular its density contrast $\delta_\chi \equiv \Delta\rho_\chi/\rho_\chi$ – evolves during a **matter/radiation stasis** with $0 < \overline{w} < 1/3$. As we'll see, the results differ significantly from the corresponding results for PFD!

Spectator Density Contrast

A In order to answer this question, let's first begin by reviewing some general aspects of how δ_χ (or its Fourier transform $\delta_{k\chi}$) evolves.

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

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- The solution (applying boundary conditions at early times) is:

$$\delta_{k\chi} = \frac{2\Phi_{k0}}{1+\langle w\rangle} + \int_0^a db S_{k\chi} G_{k\chi}(a,b)$$

Φ_k at early times

Green's Function

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Green's Function

- The evolution of Φ_k follows from the Einstein equation:

Sum over cosmological components X

Background energy density of X

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

Source Term

Effective equation-of-state parameter $\langle w \rangle \equiv \sum_X \Omega_X w_X$

Effective sound speed of X $c_{sX} \equiv \sqrt{\Delta p_X / \Delta \rho_X}$

Perfect-Fluid Domination

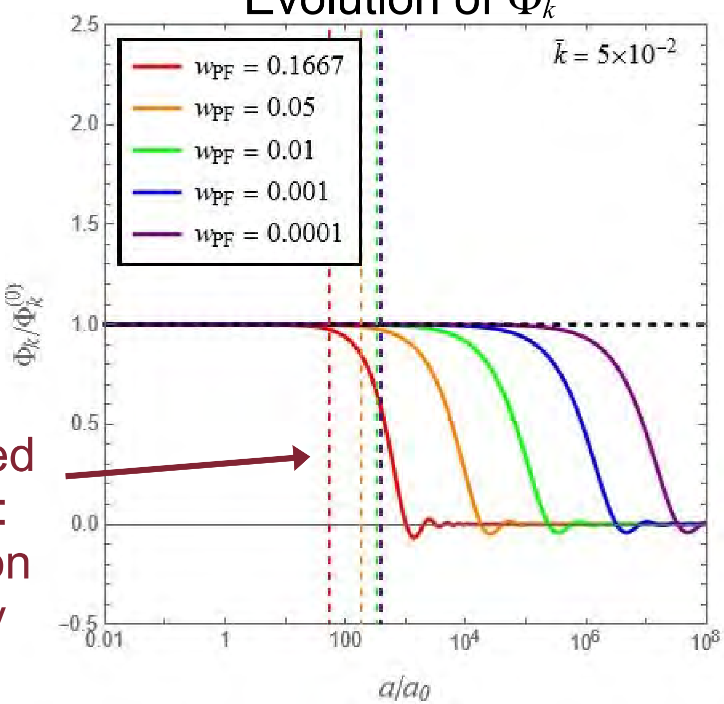
- First, let's consider a PFD epoch in which the equation of state for the perfect fluid is $p = w_{\rm PF}\rho$, where $w_{\rm PF}$ is a constant. **[Redmond, Trezza, Erickcek '18]**
- In this case, $\langle w\rangle \approx w_{\rm PF}$ and $c^2_{s\rm PF} = w_{\rm PF}$.

Vanishes

$$\boxed{\Phi_k'' + \frac{(7+3\langle w\rangle)}{2a}\Phi_k' + \frac{\langle w\rangle k^2}{a^4H^2}\Phi_k = \cancel{\frac{4\pi G}{a^2H^2}\sum_X \rho_X\delta_{kX}\left(\langle w\rangle - c^2_{sX}\right)}}$$

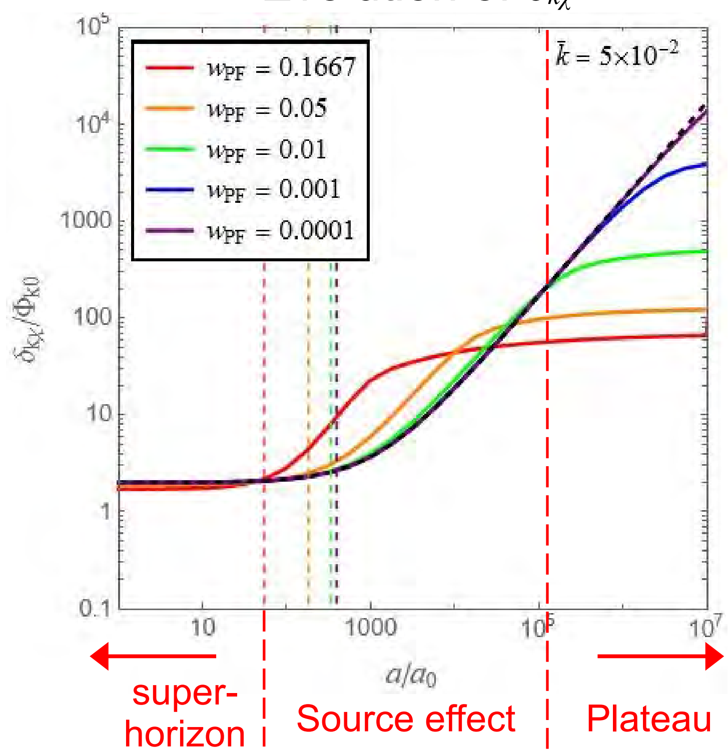
- The resulting sourceless equation yields:

Evolution of Φ_k



Dashed lines: horizon entry

Evolution of $\delta_{k\chi}$



Matter/Radiation Stasis

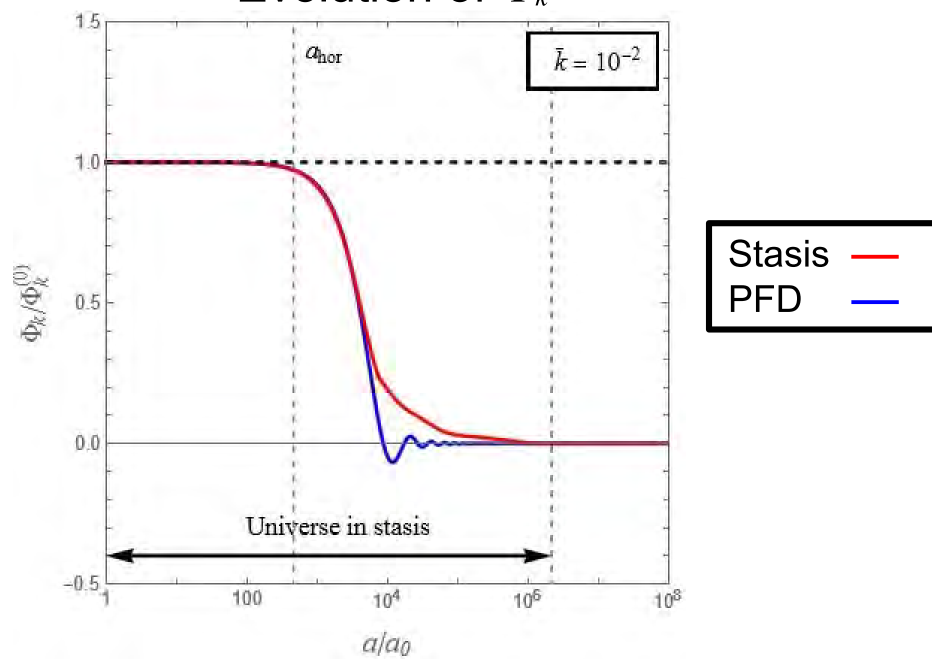
- Now let's consider the situation during an epoch of matter/radiation stasis epoch.
- In this case, there are **two** components with non-negligible Ω_X. Matter with $c_{sM}^2 = w_M = 0$ and radiation with $c_{s\gamma}^2 = w_\gamma = 1/3$.

Doesn't generally vanish

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

- The equations of motion for Φ_k and the perturbations in the stasis sector are therefore non-trivially **coupled** during stasis.
- These effects can dramatically impact on how $\delta_{k\chi}$ evolves!

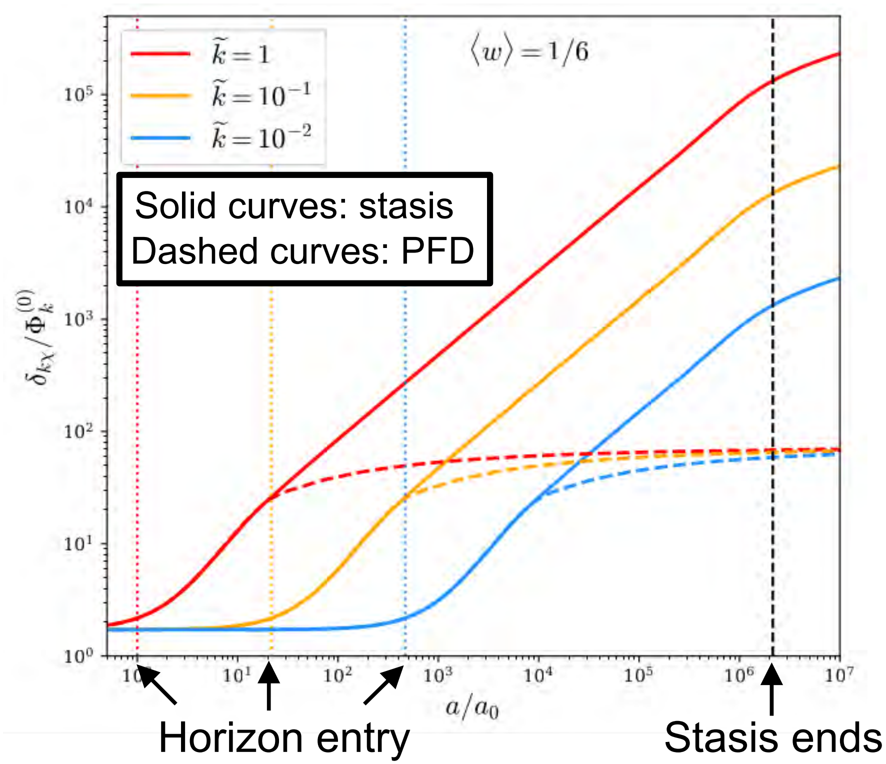
Evolution of Φ_k

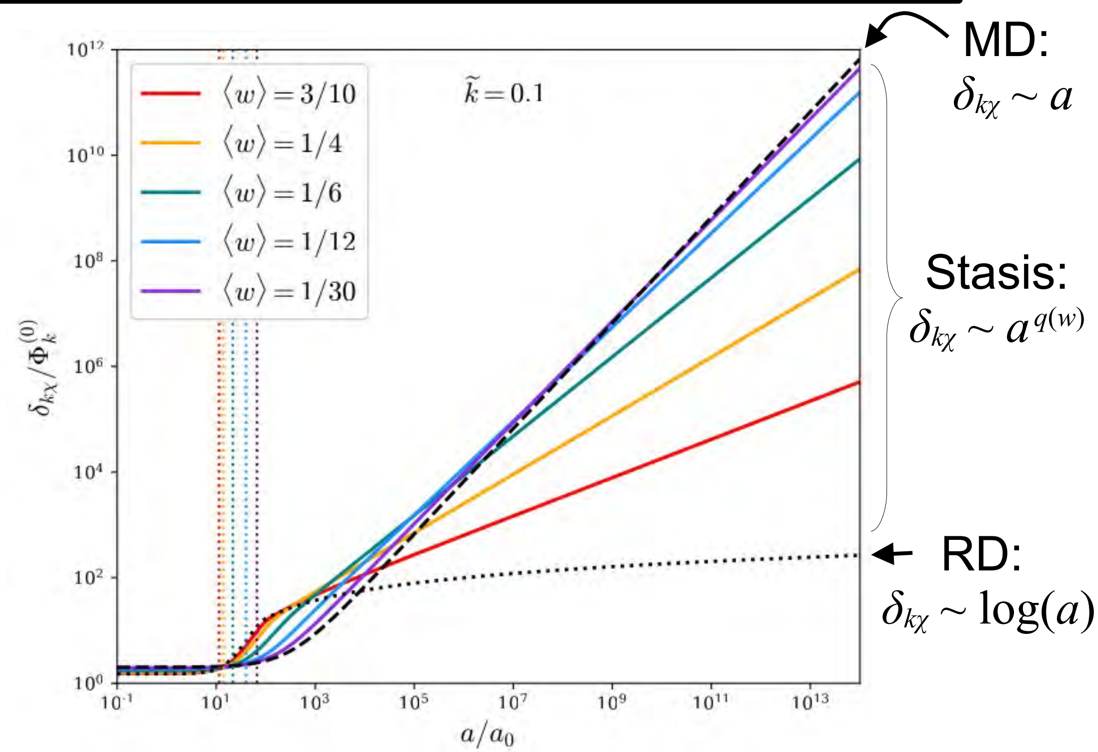


Growth Through Stasis

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

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





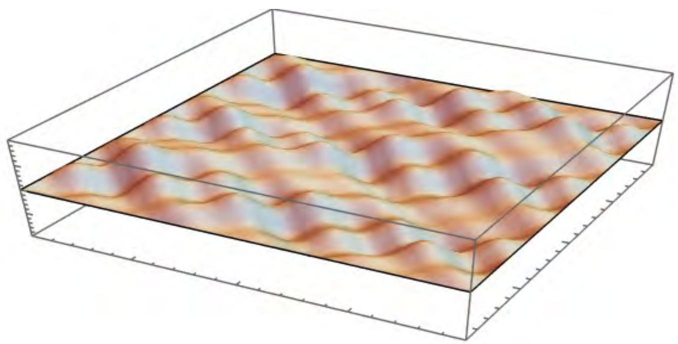
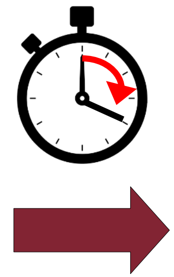
- During an EMDE, $\delta_{k\chi}$ grows linearly with a.

[Erickcek, Sigurdson '11; Fan, Ozsoy, Watson '14; Erickcek '15]

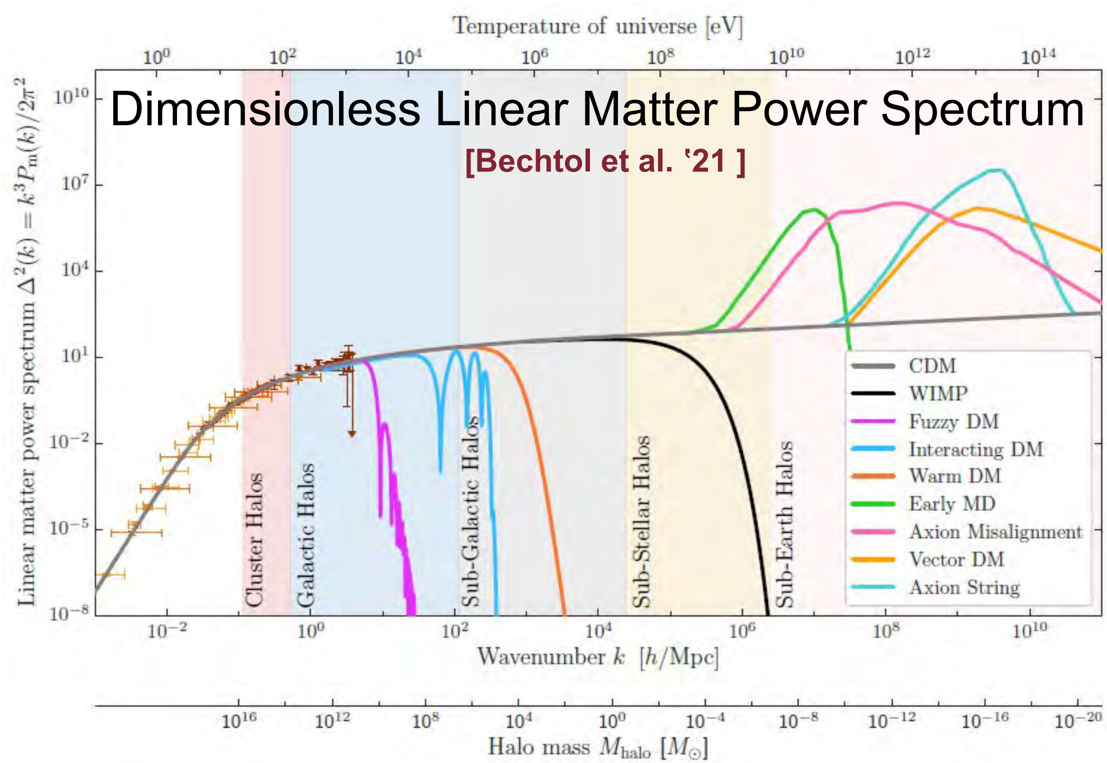
- Thus, even at the perturbation level, stasis **interpolates** between radiation and matter domination!

Why All This Matters

- 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** $P(k) = |\delta_{km}|^2$ relative to the standard cosmology across different ranges of k can have a observational consequences for **cosmic structure**.
- In the stasis case, they could lead to the formation of **microhalos** – small, dense clumps of matter.



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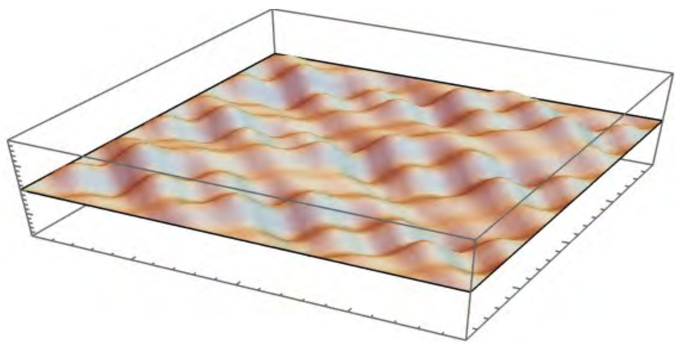

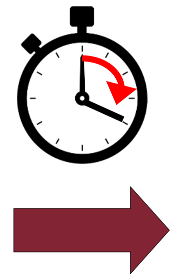

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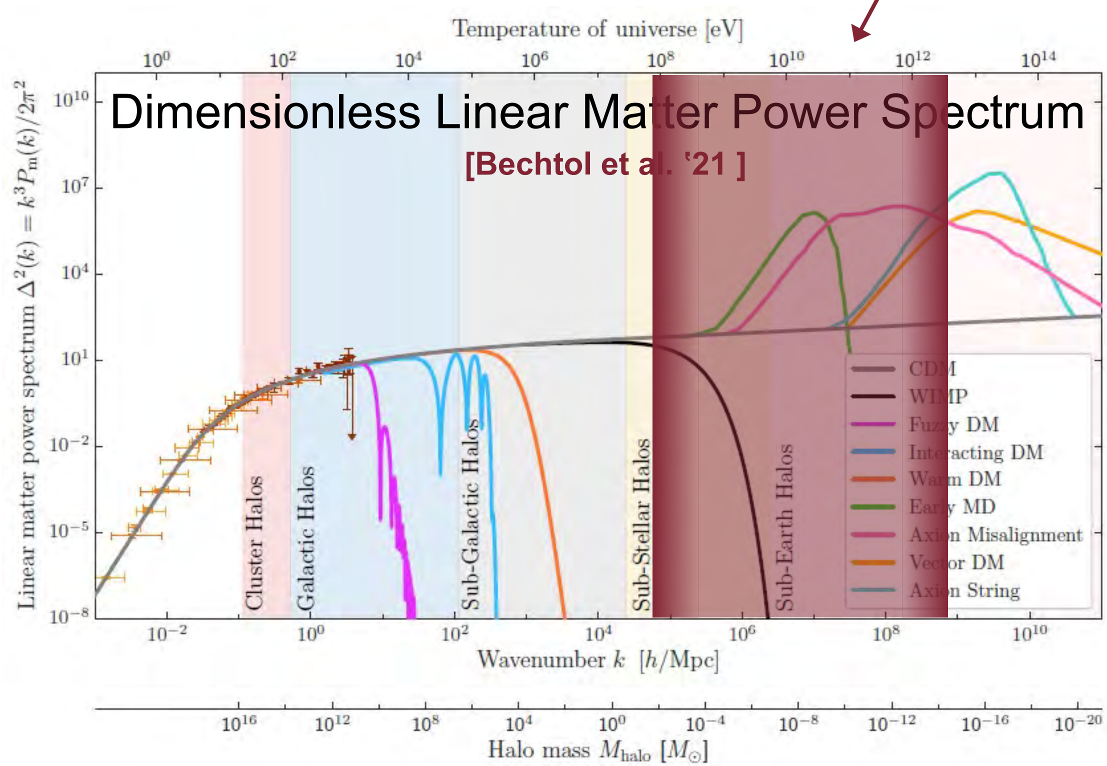

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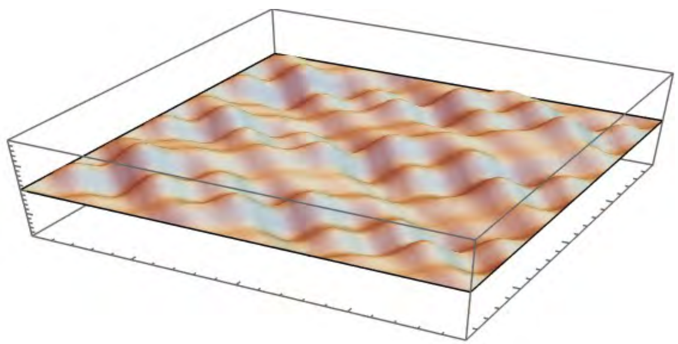

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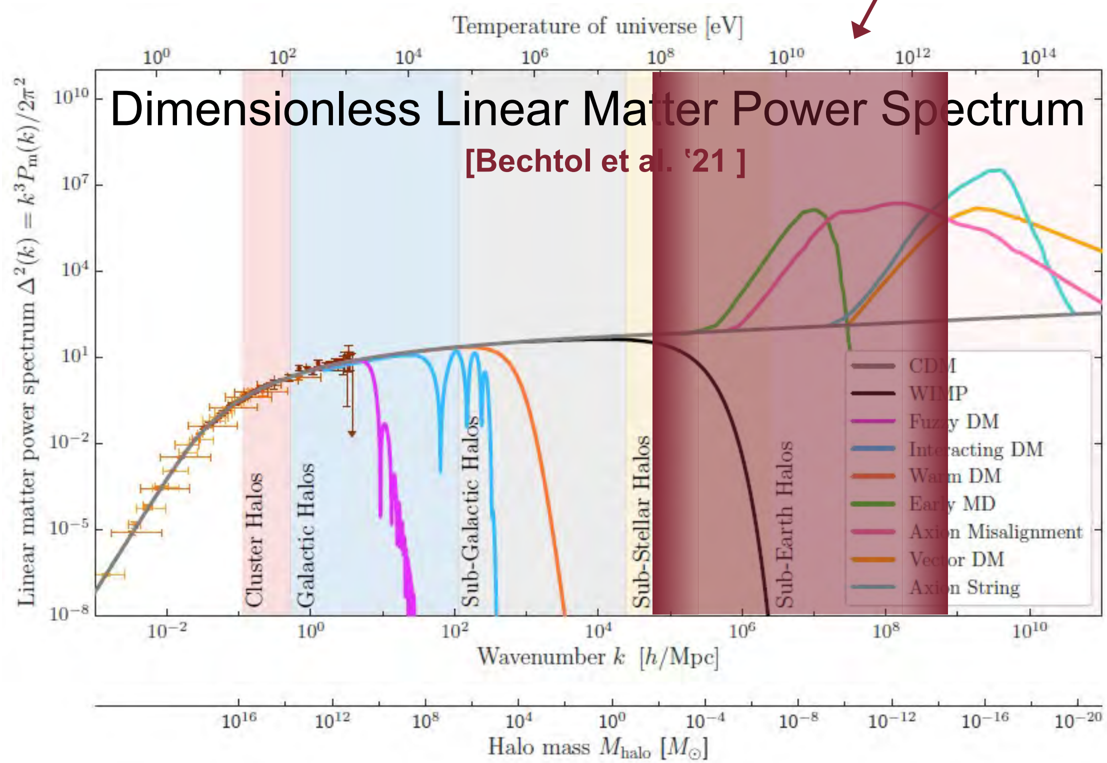


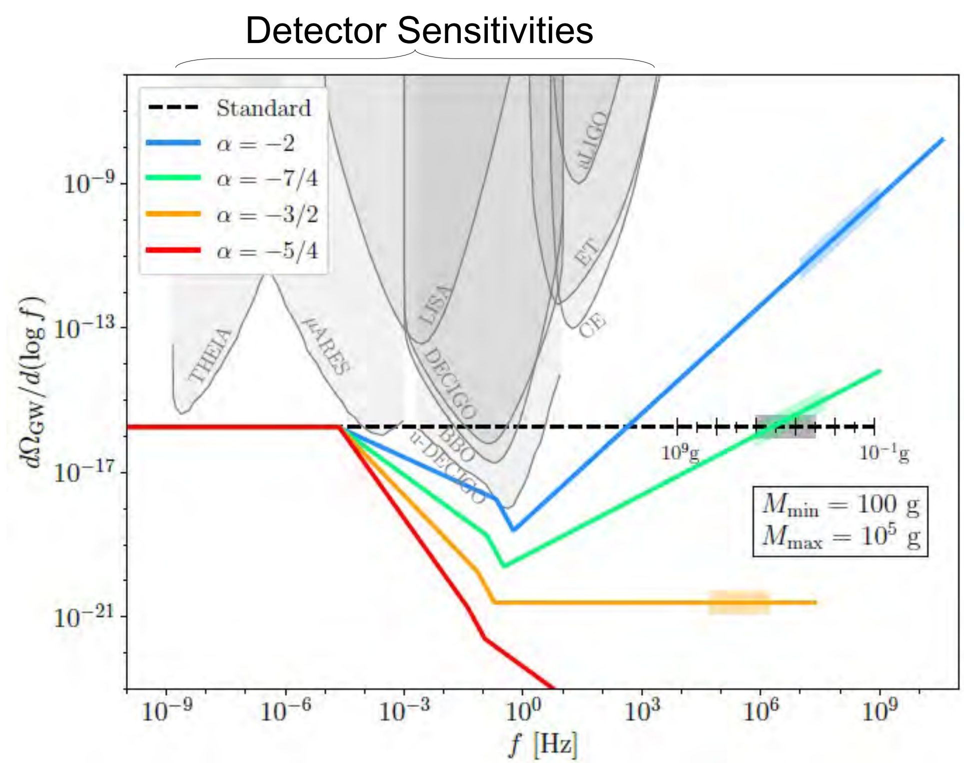
Other Observational Signatures of Stasis

- In addition to its effect on the matter power specturm, stasis can also have a number of additional potentially observable consequences.
  - Stasis modifies the predictions for the **CMB observables** r and n_s that follow from a given inflationary model. [Dienes, Huang, Heurtier, Kim, Tait, BT '22]
  - Stasis can modify the spectrum of the **stochastic gravitational-wave background** in characteristic ways. [Dienes, Huang, Heurtier, Kim, Tait, BT '22]
  - A stasis involving vacuum energy and matter can lead to accelerated expansion – and potentially even to phenomenologically viable models of **cosmic inflation**.

[Dienes, Heurtier, Huang, Tait, BT '24]

See Lucien Heurtier's plenary talk from Monday.

Effect on the SGWB



Summary

- ***Stable, mixed-component cosmological eras*** – *i.e.* ***stasis eras*** – can have a variety of implications for observational cosmology.
- The evolution of density perturbations is modified during stasis. For example, we've seen that the density contrast $\delta_{k\chi}$ for a spectator matter component grows like a power law with an exponent $0 < q(\overline{w}) < 1$.
- In this way, this power-law growth **interpolates** between the behaviors that $\delta_{k\chi}$ exhibits during matter domination and radiation domination.
- This power-law growth can lead to **enhanced structure on small scales**, including potentially the formation of microhalos.
- Stasis can give rise to a variety of other observational signatures as well.