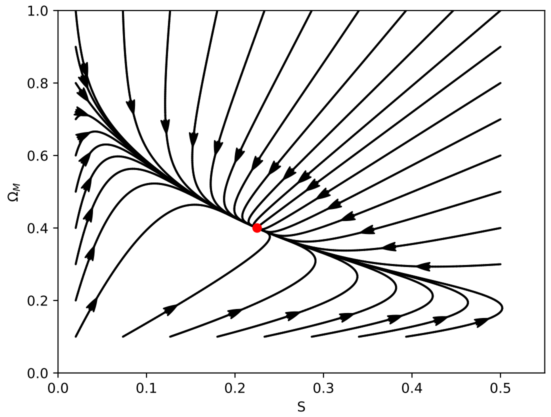
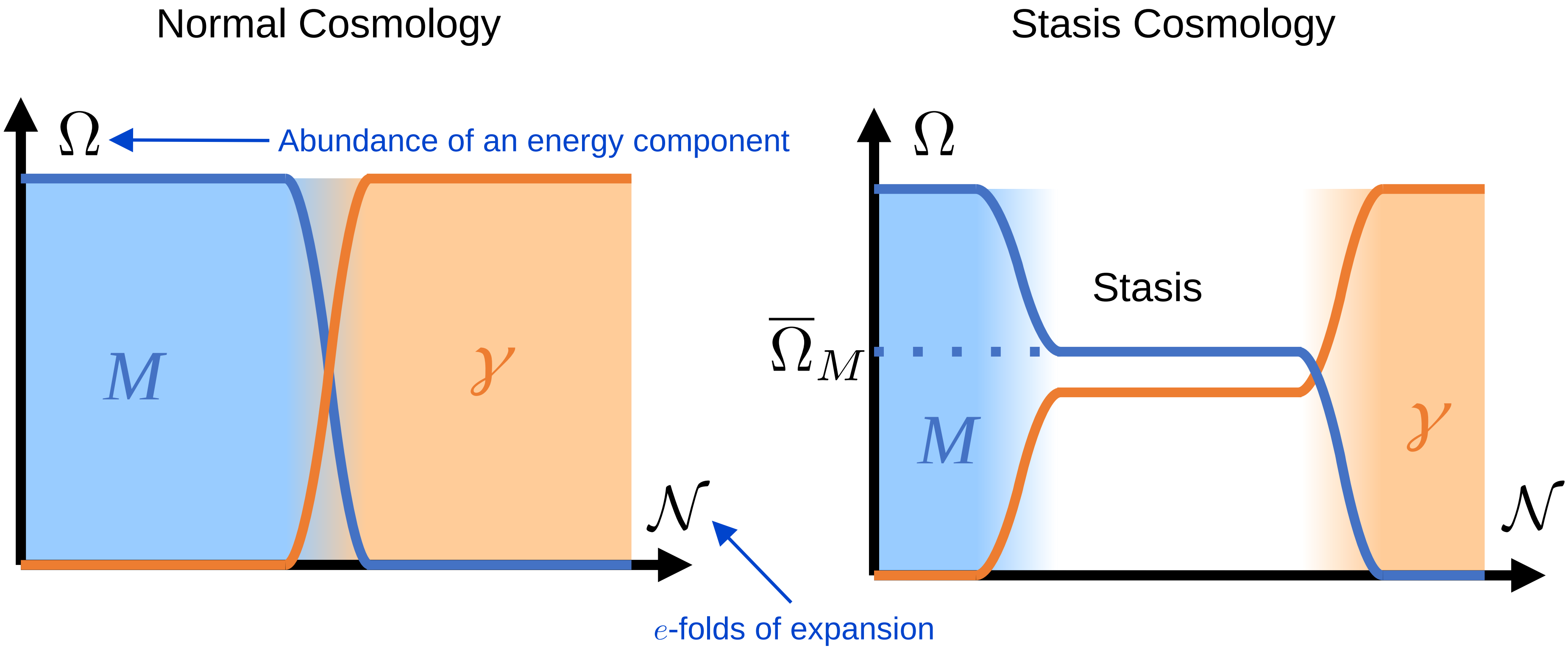
Stasis From Thermal Effects
and Other Novel Perspectives on Stasis

Jonah Barber (University of Arizona)



J B, Keith R. Dienes, Brooks Thomas
[arXiv:2405.xxxxx, arXiv:2405.xxxx(x+1)]

Intro to Stasis



Stasis in Current Literature

Stasis in current literature happens due to towers of states, which appear in many BSM theories:

- Strings
- Soft Strings
- Extra Dimensions
- PBHs

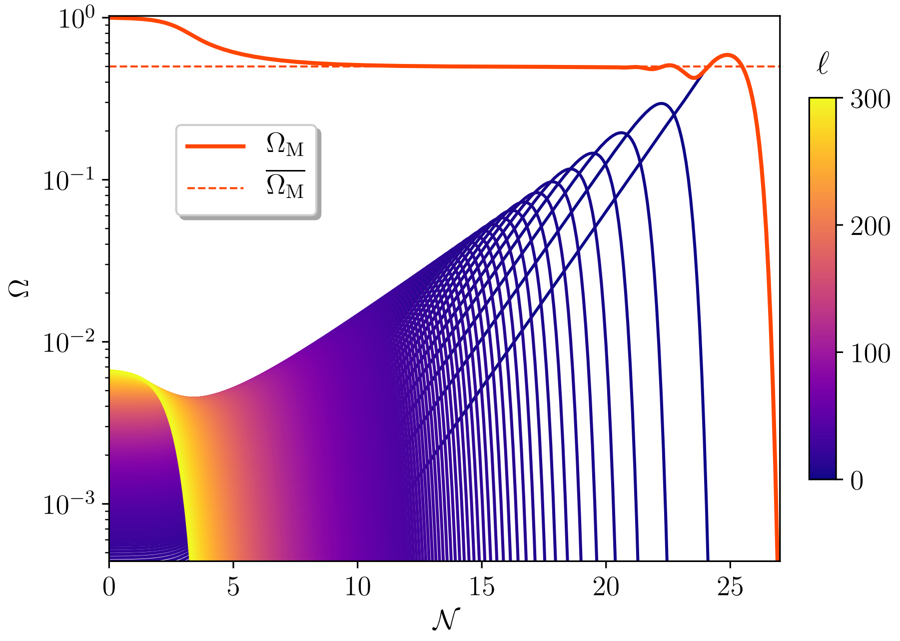


Figure from
K. R. Dienes, L. Heurtier, F. Huang, D. Kim, T. M. P. Tait, and B. Thomas, Phys. Rev. D 105, 023530 (2022), arXiv:2111.04753 [astro-ph.CO].

Can Stasis Happen Without a Tower?

YES !

Condition for Stasis to Happen

Energy Density of Matter

In general we can say: $$D_t \rho_M = -P^{(\rho)}$$

Total amount of matter decreases due to a "Pump" process.

"Comoving" Derivative:

$$D_t \rho_M = \partial_t \rho_M + 3H \rho_M$$

Condition for Stasis to Happen

Energy Density of Matter

In general we can say: $D_t \rho_M = -P^{(\rho)}$

Total amount of matter decreases due to a "Pump" process.

"Comoving" Derivative:

$$D_t \rho_M = \partial_t \rho_M + 3H\rho_M$$

Hubble Parameter

Matter abundance evolves according to: $\rho \cdot \partial_t \Omega_M = (1 - \Omega_M) H \rho_M - P^{(\rho)}$

Stasis happens when $\partial_t \Omega_M = 0$ for a long time.

Condition for Stasis to Happen

Energy Density of Matter

In general we can say: $D_t \rho_M = -P^{(\rho)}$

Total amount of matter decreases due to a "Pump" process.

"Comoving" Derivative:

$$D_t \rho_M = \partial_t \rho_M + 3H\rho_M$$

Hubble Parameter

Matter abundance evolves according to: $\rho \cdot \partial_t \Omega_M = (1 - \Omega_M) H \rho_M - P^{(\rho)}$

Stasis happens when $\partial_t \Omega_M = 0$ for a long time.

Therefore, in order to have stasis, the Pump has to have the property: $P^{(\rho)} \propto H\rho_M$

What is Hubble Up To?
The Chekhov's Friedmann Equation

The first Friedmann equation says that:

$$H \propto \sqrt{\rho}$$

Total Energy Density

If Matter or Radiation (or both) dominate the energy density, then H must decrease over time, it is not constant.

Stock Image from Wikipedia

What the Pump Actually Does

Let's examine two cases.

Decay (with tower):

$$P^{(\rho)} = \langle \Gamma \rangle \, \rho_M$$

Decay Rate, averaged over the abundances

Annihilation (assume no tower):

$$P^{(\rho)} = \langle \sigma v \rangle \, \rho_M^2$$

"Cross Volume", averaged over all collisions

What the Pump Actually Does

Let's examine two cases.

Decay (with tower):

$$P^{(\rho)} = \langle \Gamma \rangle \, \rho_M$$

Decay Rate, averaged over the abundances

Annihilation (assume no tower):

$$P^{(\rho)} = \langle \sigma v \rangle \, \rho_M^2$$

"Cross Volume", averaged over all collisions

To get Stasis:

$$\langle \Gamma \rangle \propto H$$

Hence the tower.
(The dominant abundances shift down the tower over time)

What the Pump Actually Does

Let's examine two cases.

Decay (with tower):

$$P^{(\rho)} = \langle \Gamma \rangle \, \rho_M$$

Decay Rate, averaged over the abundances

To get Stasis:

$$\langle \Gamma \rangle \propto H$$

Hence the tower.
(The dominant abundances shift down the tower over time)

Annihilation (assume no tower):

$$P^{(\rho)} = \langle \sigma v \rangle \, \rho_M^2$$

"Cross Volume", averaged over all collisions

To get Stasis:

$$\langle \sigma v \rangle \propto 1/H$$

Hence the ????.

How Could Cross Volume Change with Hubble?

What if cross volume depends on momentum?

Let: $$\sigma v = C \left| \vec{p}_{CM} \right|^q$$

some exponent

Momentum of either incoming particle in CM frame

some rate constant

How Could Cross Volume Change with Hubble?

What if cross volume depends on momentum?

Let: $$\sigma v = C \left| \vec{p}_{CM} \right|^q$$

some exponent

Momentum of either incoming particle in CM frame

some rate constant

If we assume the matter is in thermal equilibrium with itself then the average cross section is a thermal average.

Thus: $$\langle \left| \vec{p}_{CM} \right|^q \rangle \propto T^{q/2}$$

Temperature of Matter

How Could Cross Volume Change with Hubble?

What if cross volume depends on momentum?

Let: $$\sigma v = C \left|\vec{p}_{CM}\right|^q$$

some exponent

Momentum of either incoming particle in CM frame

some rate constant

If we assume the matter is in thermal equilibrium with itself then the average cross section is a thermal average.

Thus: $$\langle \left|\vec{p}_{CM}\right|^q \rangle \propto T^{q/2}$$

Temperature of Matter

It then follows: $$\langle \sigma v \rangle \propto T^{q/2}$$

Average cross volume depends on temperature! And temperature will drop over time.

Could ???? Be This Temperature Dependence In the Cross Volume?

(It’s YES again)

Could a Temperature Dependent Cross Section Lead to Stasis?

We must Satisfy: $\langle \sigma v \rangle \propto T^{q/2} \propto 1/H \propto 1/\rho^{1/2}$

Or: $T^q \propto 1/\rho$

(polishing the barrel)

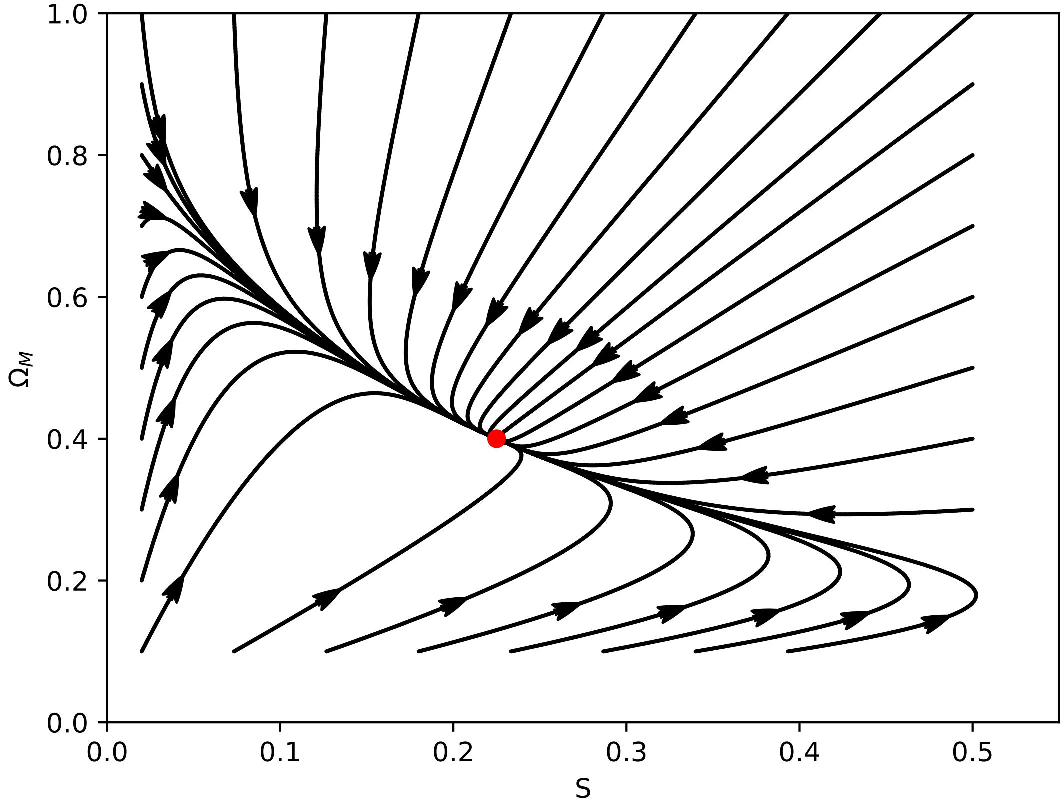
Define a new parameter: $S \equiv \rho_M T^q$ (NOT entropy)

(because ρ_M and T will both be dropping, q will have to be negative, so we call S the “coldness”)

In order to have $\langle \sigma v \rangle \propto 1/H$, S must be constant.

The Result: Thermal Stasis

$$q = -2$$



Thermal stasis can happen whenever:

$$-6 + 2\sqrt{3} < q < -3/2$$

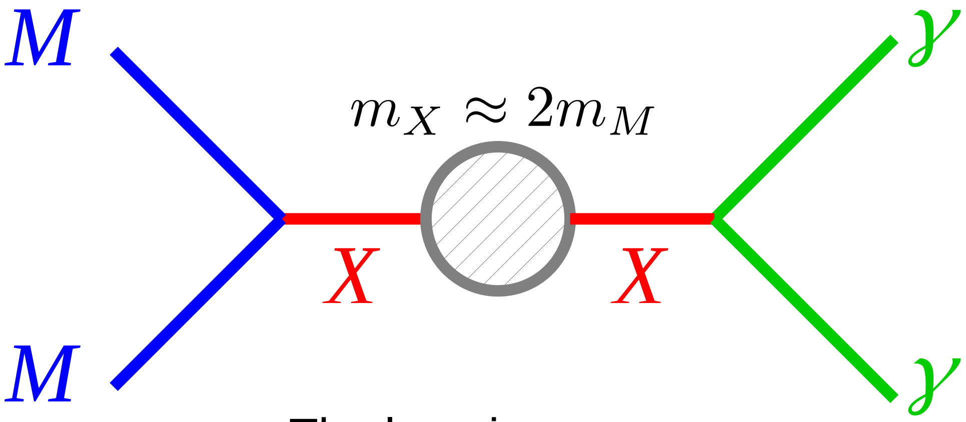
The plot shows shows that this Stasis is an attractor (just like the tower Stases).

What About a QFT Model?

The property we need is:

$$\sigma v \propto |\vec{p}_{CM}|^{-2}$$

This diagram can do it.

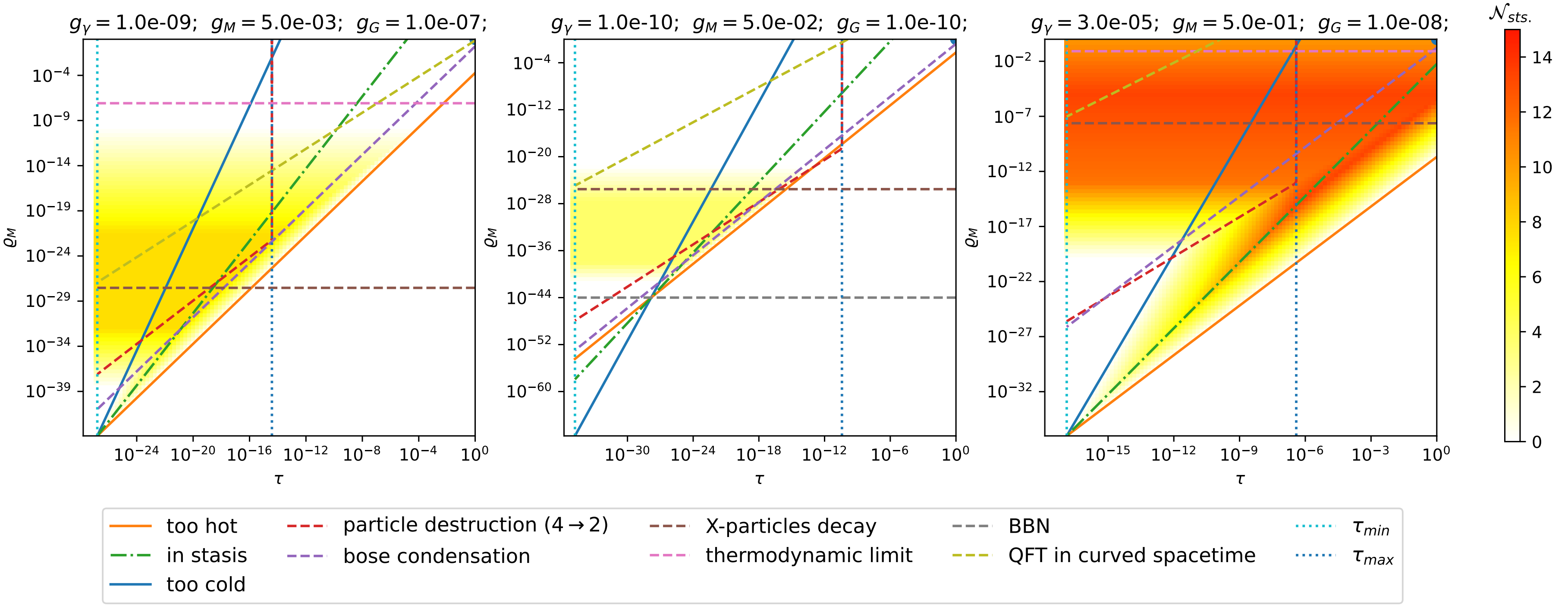


The loop is important even for small couplings.

Constraints on Stasis with Our Model

- Density must be above that of BBN.
- Temperature must be in a range set by the propogator.
- A $4M \to 2M$ process must be weak.
- Initial Density/Temperature must be able to reach the Stasis balance (set by S).
- Any primordial X particles must have decayed.
- QFT in curved spacetime must not interfere with the propagator.
- There must not be Bose Condensation of the matter.
- We must be in the Thermodynamic limit, with lots of particles per Hubble volume.

Duration of Stasis with our Model



Stasis can last more than a (bakers) dozen e-folds.

What Is the Connection Between Thermal Stasis and Tower Stasis?

In general, Let: $$P^{(\rho)} = Z\rho_M^n$$

Decay:

$$P^{(\rho)} = \langle\Gamma\rangle\,\rho_M$$
$$n = 1$$

Annihilation:

$$P^{(\rho)} = \langle\sigma v\rangle\,\rho_M^2$$
$$n = 2$$

What Is the Connection Between Thermal Stasis and Tower Stasis?

In general, Let: $P^{(\rho)} = Z \rho_M^n$

Decay:

$$P^{(\rho)} = \langle \Gamma \rangle \, \rho_M$$

$$n = 1$$

Let:

$$n_{\text{eff}} \equiv \frac{d \log(P^{(\rho)})}{d \log \rho_M}$$

Annihilation:

$$P^{(\rho)} = \langle \sigma v \rangle \, \rho_M^2$$

$$n = 2$$

What Is the Connection Between Thermal Stasis and Tower Stasis?

In general, Let: $P^{(\rho)} = Z\rho_M^n$

Decay:

$$P^{(\rho)} = \langle\Gamma\rangle\, \rho_M$$
$$n = 1$$

Let:

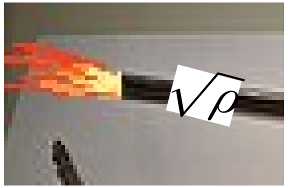
$$n_{\rm eff} \equiv \frac{d\log(P^{(\rho)})}{d\log\rho_M}$$

Annihilation:

$$P^{(\rho)} = \langle\sigma v\rangle\, \rho_M^2$$
$$n = 2$$

Decays along tower deform $n_{\rm eff}$

Thermal effects deform $n_{\rm eff}$



It happens because: $H\rho_M \propto \rho_M^{3/2}$

$$n_{\rm eff} = \frac{3}{2}$$

Both Stases are different manifestations of the same underlying $n_{\rm eff} = 3/2$ stasis.

Conclusion

- Towers of states are not necessary for stasis.
- A Temperature-dependent cross section can lead to stasis.
- All Stases appear to share a common $\rho_M^{3/2}$ scaling.

Papers to appear soon! Thank you.