

Deciphering the Archaeological Record: Cosmological Imprints of Non-Minimal Dark Sectors

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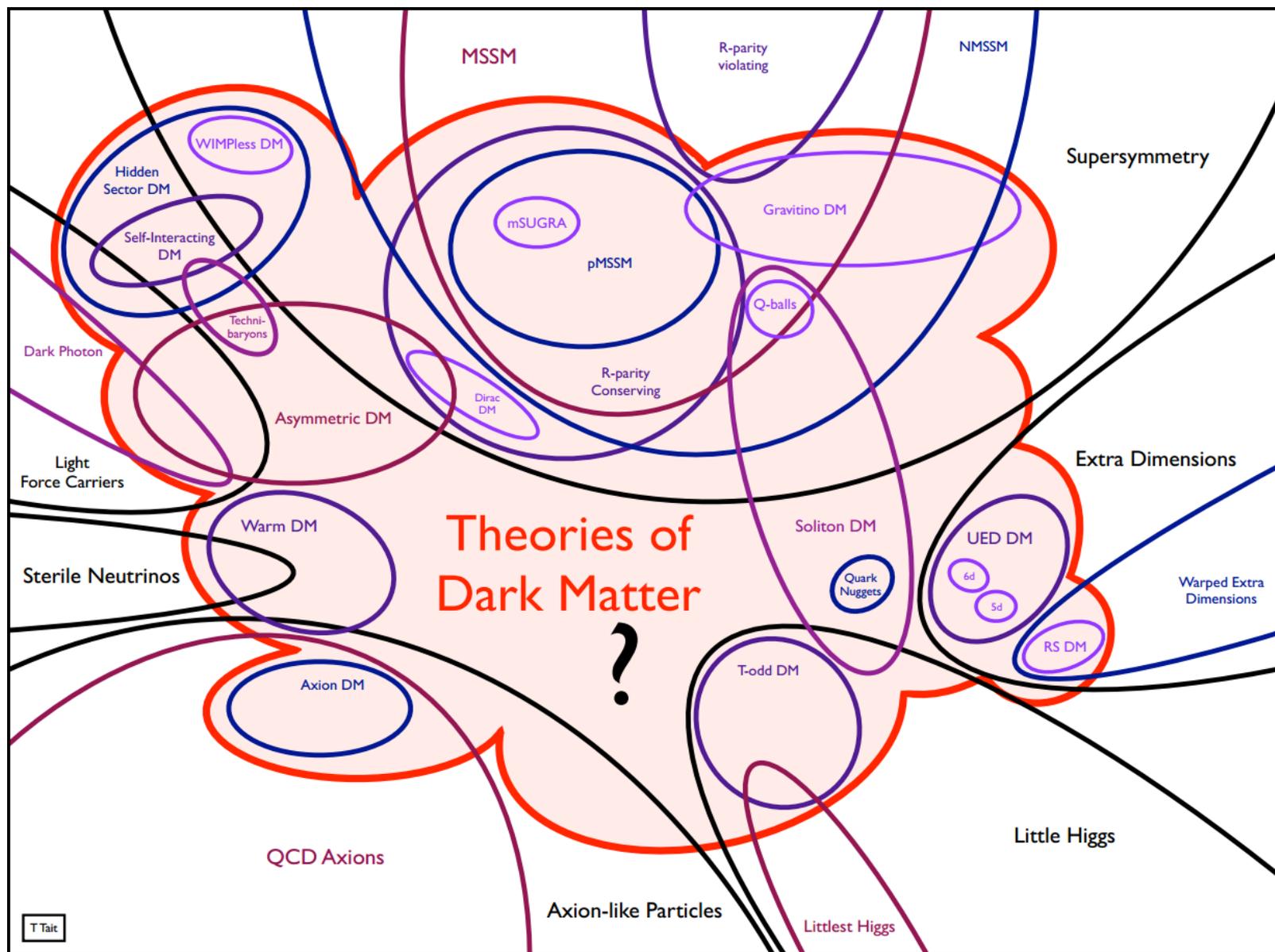
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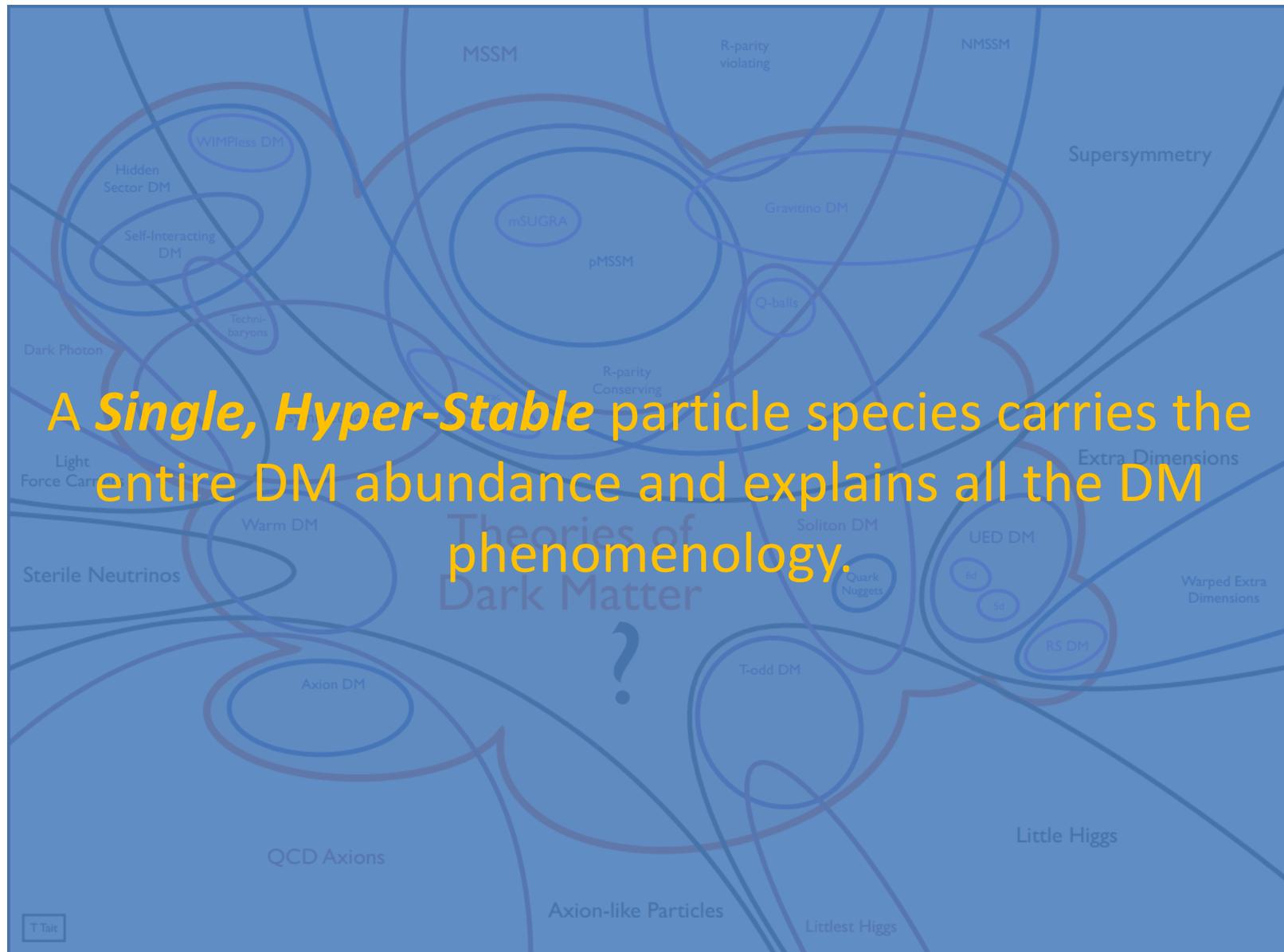
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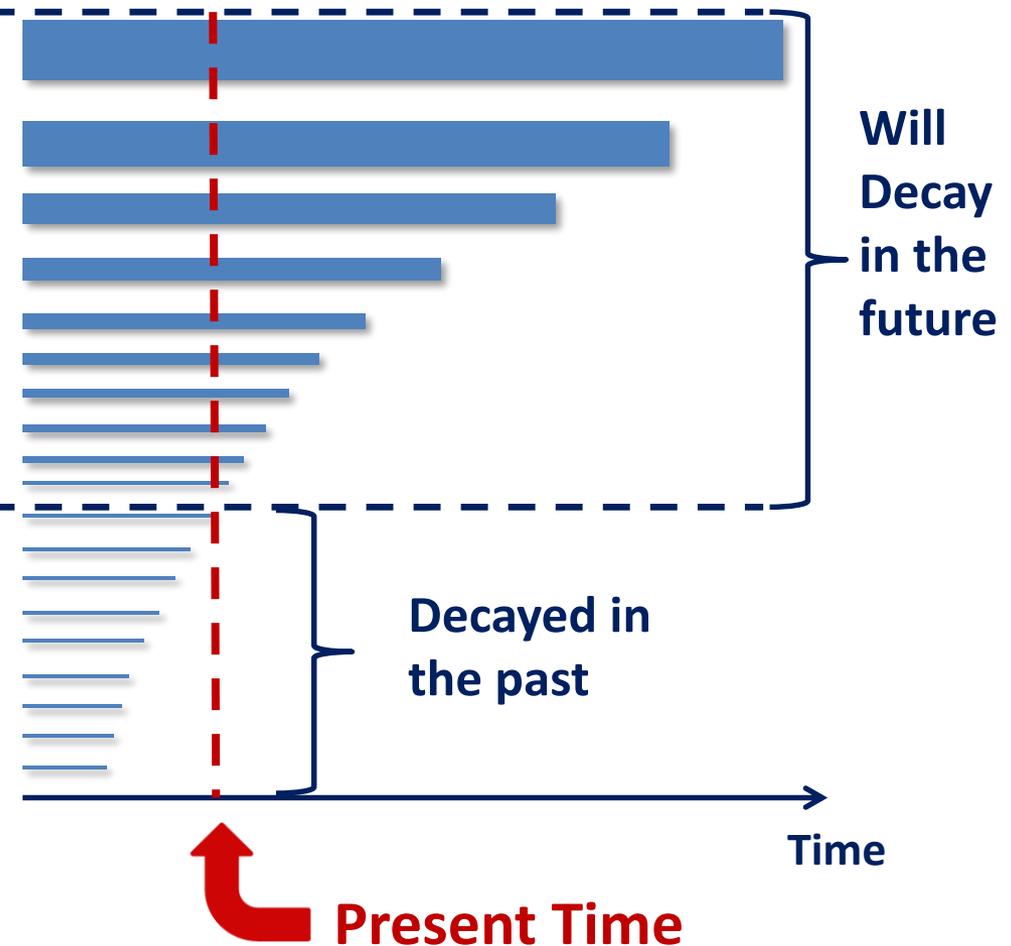
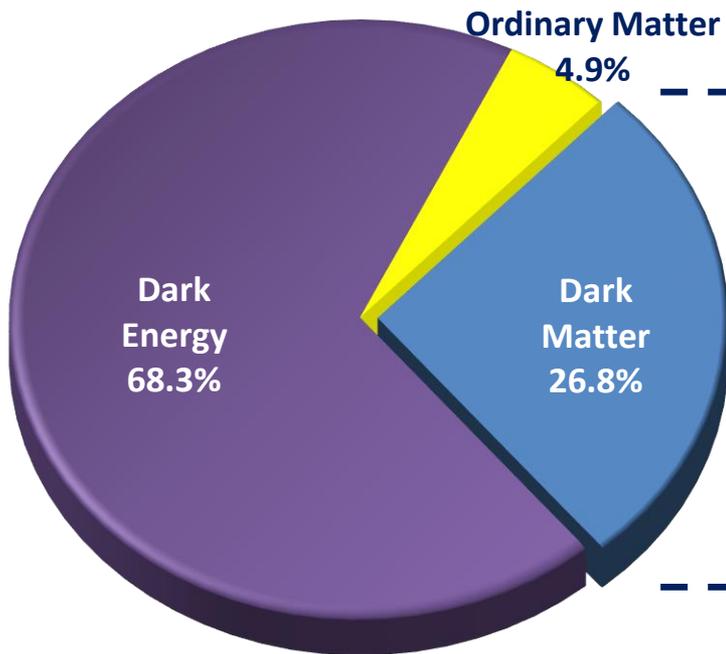
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Non-Minimal Dark Sectors:

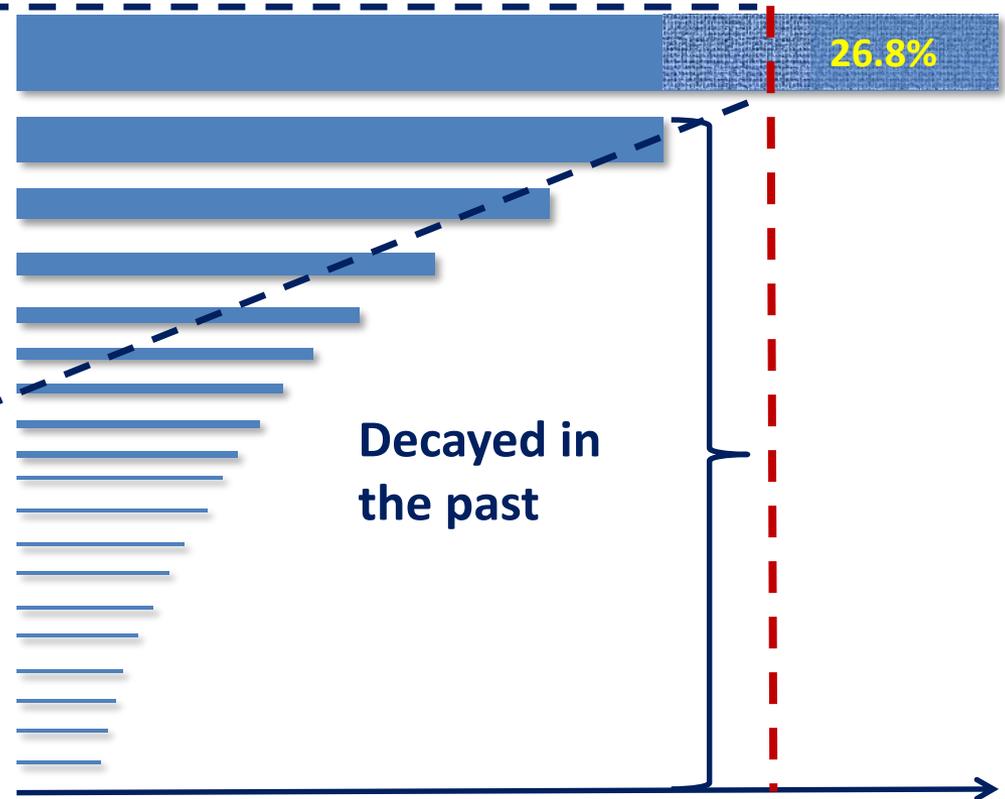
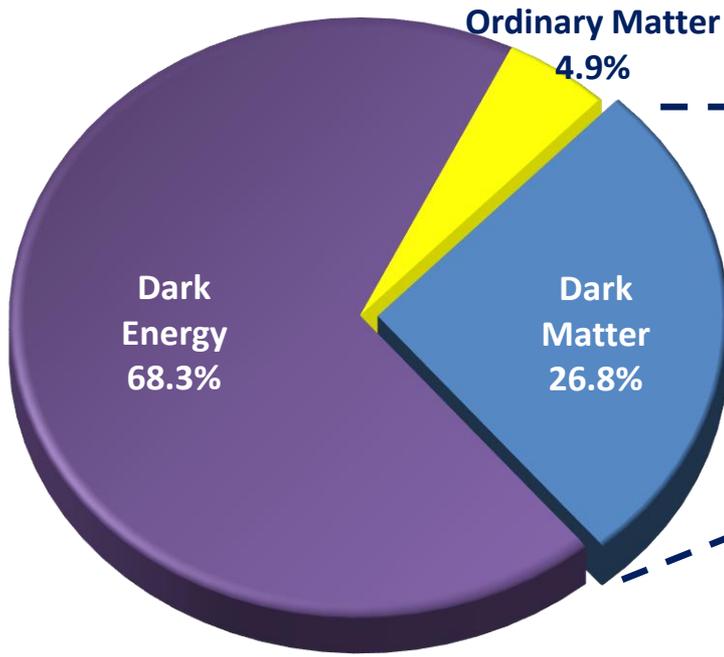
- Dark sector contains an ensemble of particle species instead of a single DM component.
- Phenomenology of dark sector is not determined by the properties of any individual constituent alone, but is determined collectively across all components.

Example 1: Dynamical Dark Matter Dienes & Thomas 2011



- DM today still consists of an ensemble of DM components
- Present-day DM pheno is thus very different from what is normally assumed in the standard WIMP paradigm and other single-component DM frameworks

Example 2: Single-Component Today with Early-Universe Imprints

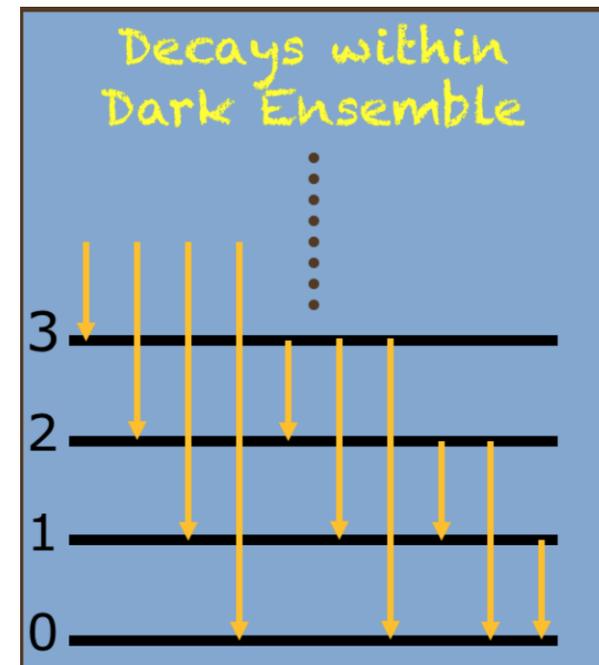


- All heavier dark sector components have already decayed prior to the present time
- Residual DM is single-component today, but decaying ensemble processes in the early universe nevertheless leave non-trivial imprints on late-time cosmology

In this work, we are focusing on scenarios in which decays occur *entirely within the dark ensemble.*

Direct consequences:

- Change particle number density of each state
- Convert mass energy into kinetic energy
- Kinetic energy is redshifted away by cosmological expansion



Essentially, all these consequences are captured by the *phase-space distribution* of each state in the ensemble:

$$f_i(p, t)$$

Phase-Space Distribution

Phase-space distribution contains almost all the relevant information about a species

$$\begin{aligned}
 n_i &\equiv g_i \int \frac{d^3 p}{(2\pi)^3} f_i(p, t) \\
 \rho_i &\equiv g_i \int \frac{d^3 p}{(2\pi)^3} f_i(p, t) E \quad \leftarrow E = \sqrt{p^2 + m^2} \\
 P_i &\equiv g_i \int \frac{d^3 p}{(2\pi)^3} f_i(p, t) \frac{p^2}{3E} \\
 w_i &\equiv \frac{P_i}{\rho_i}
 \end{aligned}$$

Boltzmann equation for distribution function when particles are decaying:

$$\begin{aligned}
 \frac{\partial f_i}{\partial t} &= H p_i \frac{\partial f_i}{\partial p_i} - f_i \sum_{\alpha} \Gamma_i^{(\alpha)} \quad \leftarrow \text{loss from decays to lighter states} \\
 &+ \frac{(1 \pm f_i)}{2E_i} \sum_{\ell, \alpha} \mathcal{N}_{\ell i}^{(\alpha)} \int [d\pi_{\ell} f_{\ell}] [d\pi_i (1 \pm f_i)]^{\mathcal{N}_{\ell i}^{(\alpha)} - 1} \\
 &\times \left\{ \prod_{m \neq i} [d\pi_m (1 \pm f_m)]^{\mathcal{N}_{\ell m}^{(\alpha)}} \right\} |\mathcal{M}|^2 . \quad \leftarrow \text{gain from decays of heavier states}
 \end{aligned}$$

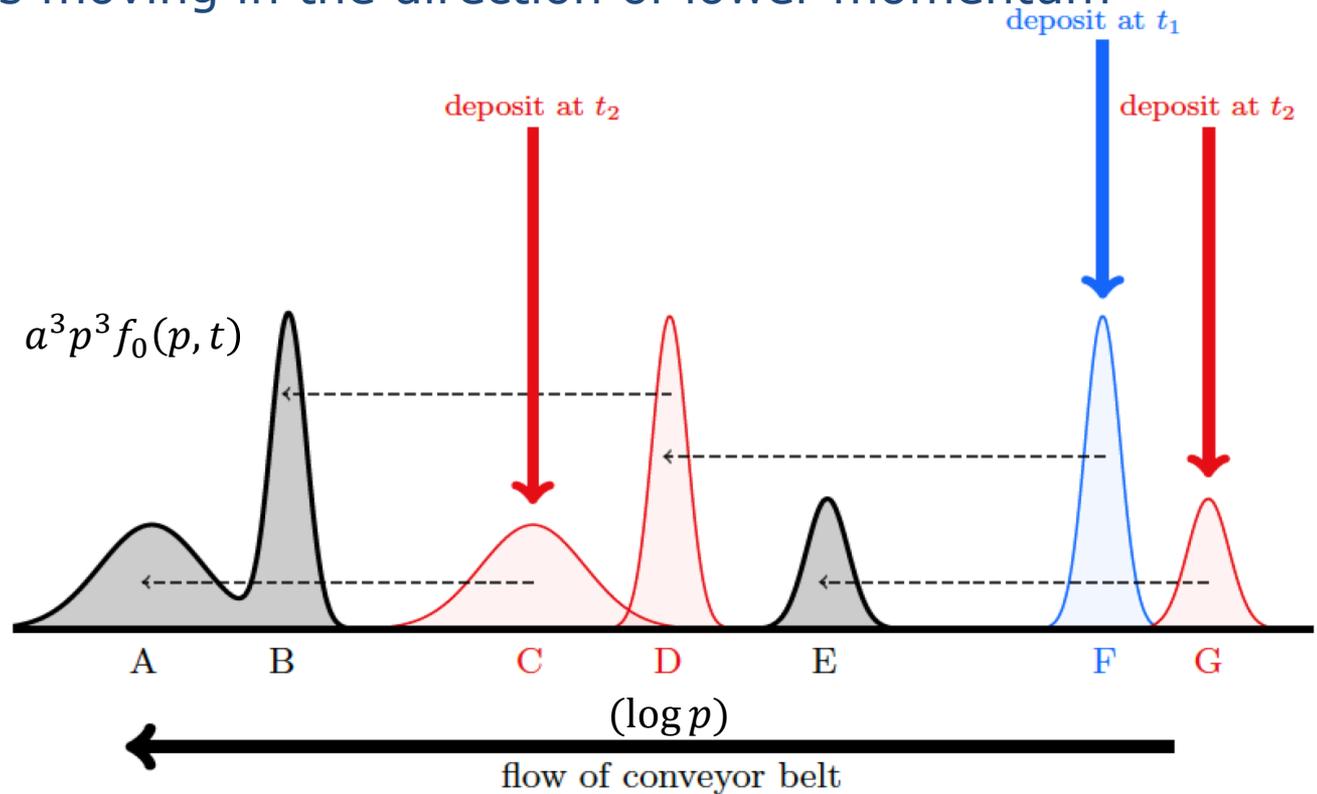
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Conveyor Belt Analogy

It is helpful to imagine a conveyor belt in the momentum space to represent cosmological evolution:

- Decays from heavier states \rightarrow Dropping Objects on a conveyor belt
- Decays into lighter states \rightarrow Unloading objects from the conveyor belt
- Redshift \rightarrow Objects moving in the direction of lower momentum

e.g. consider packets deposited at different times during cosmological history...

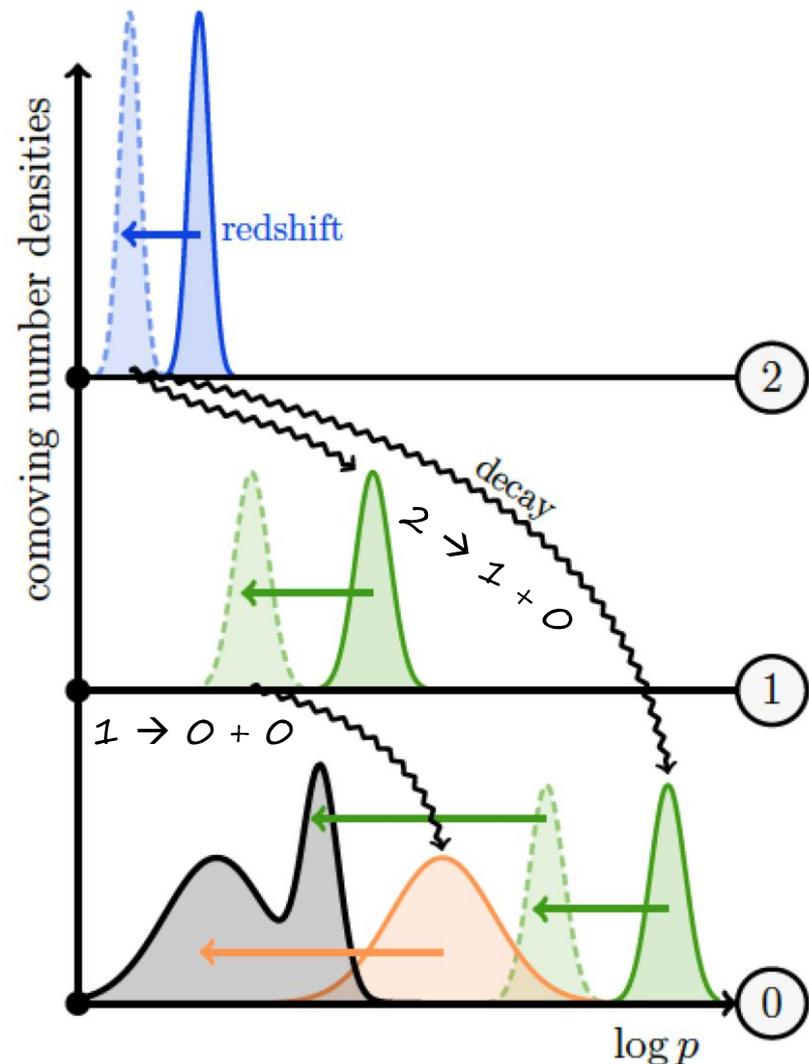


...multi-modal distribution can result at present time!

Non-trivial Phase-space Distribution

In fact, such a pattern of deposits can arise from the decays of a single heavy unimodal packet!

A non-trivial DM phase-space distribution at late times can represent the imprint of complex decay dynamics at earlier points in cosmological history.

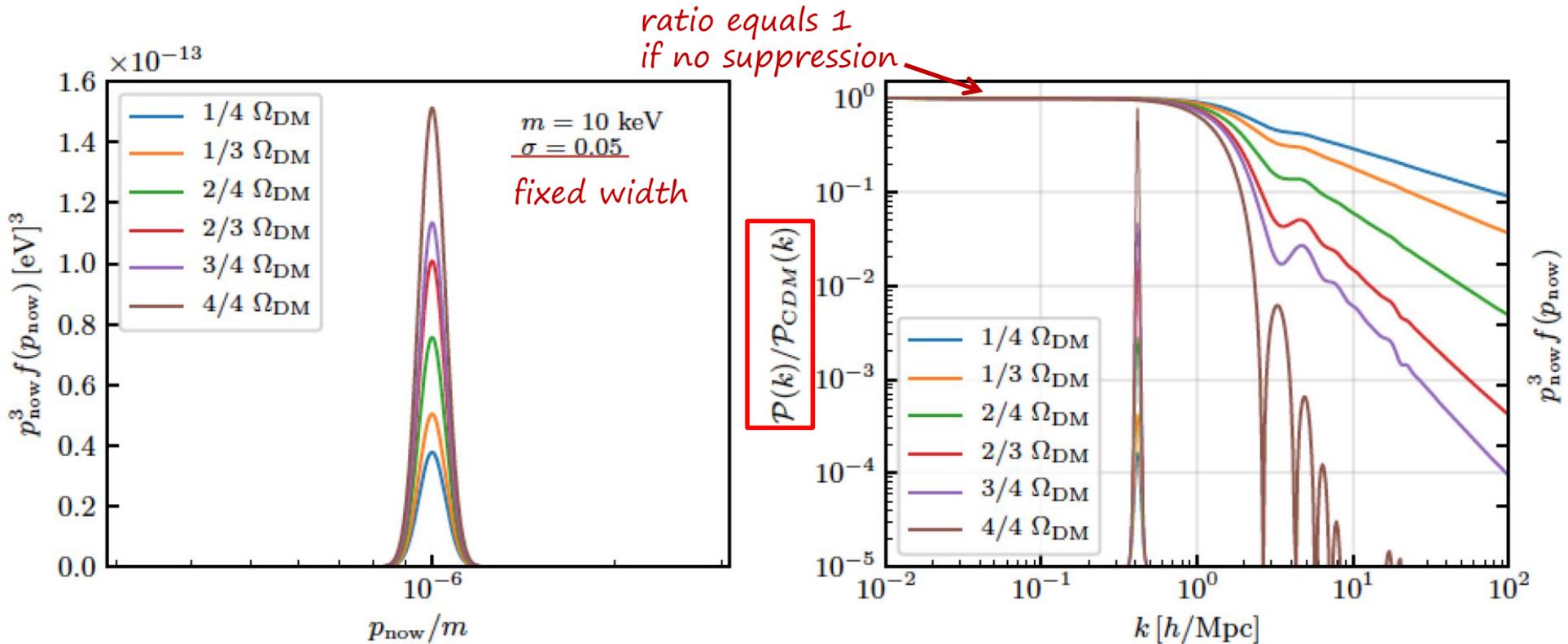


Consequences of having a non-trivial phase-space distribution

It turns out that the formation of structure in the early universe (clusters, galaxies, etc.) is sensitive to the velocities of DM!

In fact, Structure formation is suppressed if DM has non-negligible velocities!

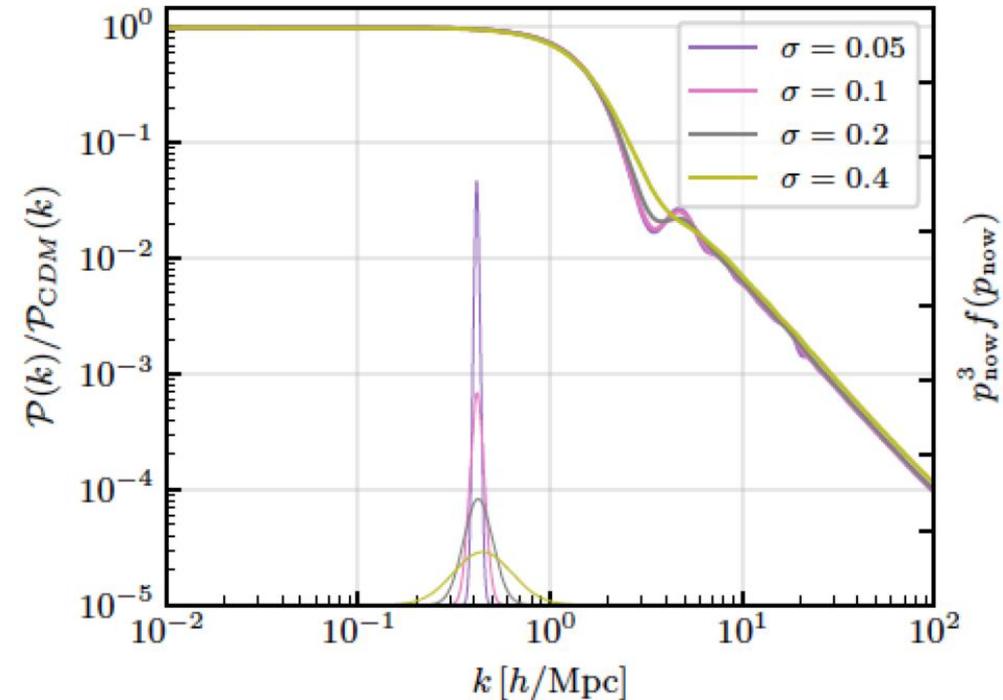
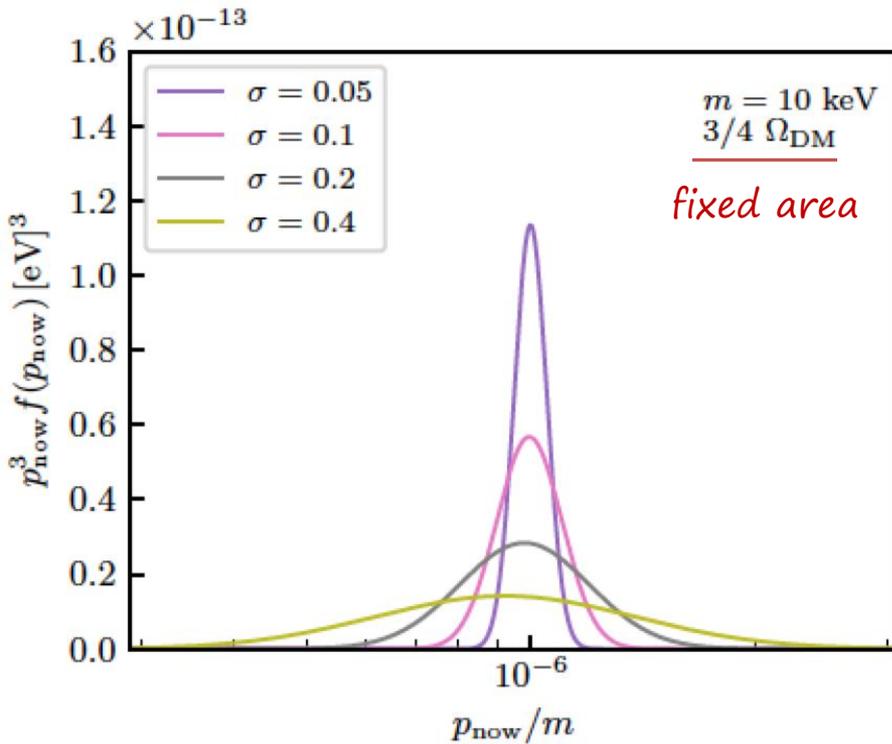
- ❖ **For this reason, the DM phase-space distribution is the central object for structure formation in the early universe!**
- ❖ **Moreover, studying the relation between DM phase-space distribution and large scale structure enables us to learn about DM from its gravitational interaction only.**
- ❖ **This therefore provides a way to learn about dark sector even when dark sector is not talking to SM sector at all, other than via gravity!**

$a^3 p^3 f_0(p) \rightarrow \mathcal{P}(k)$: Single Packet


Varying height/area with width fixed

(a complementary CDM component is added to get the total DM abundance)

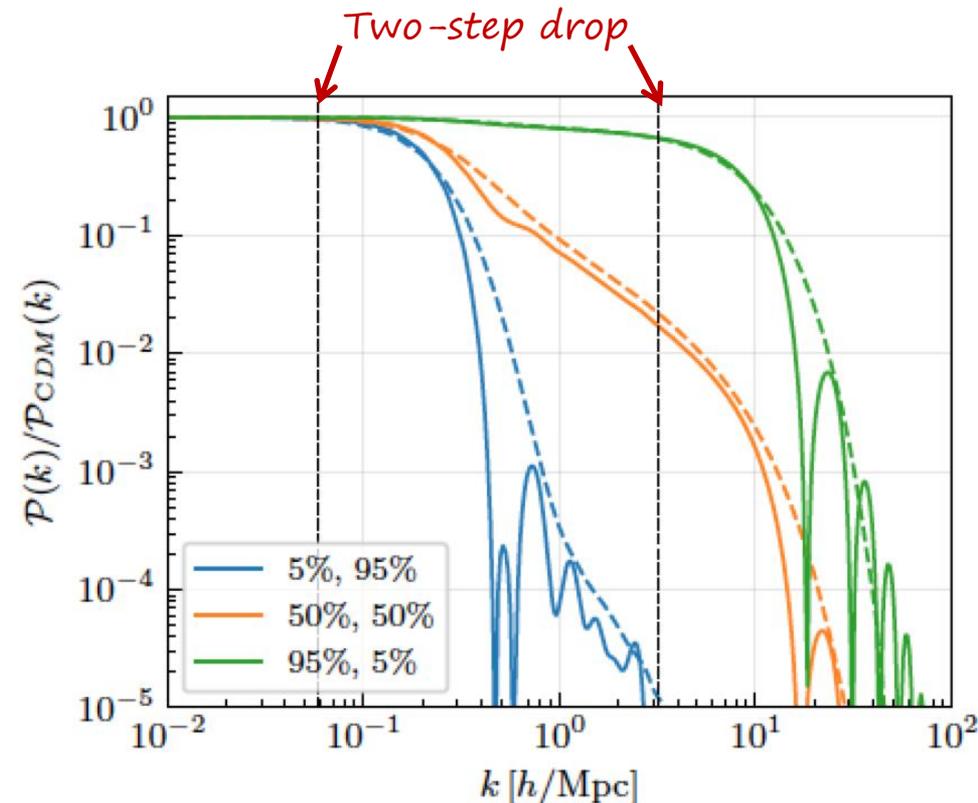
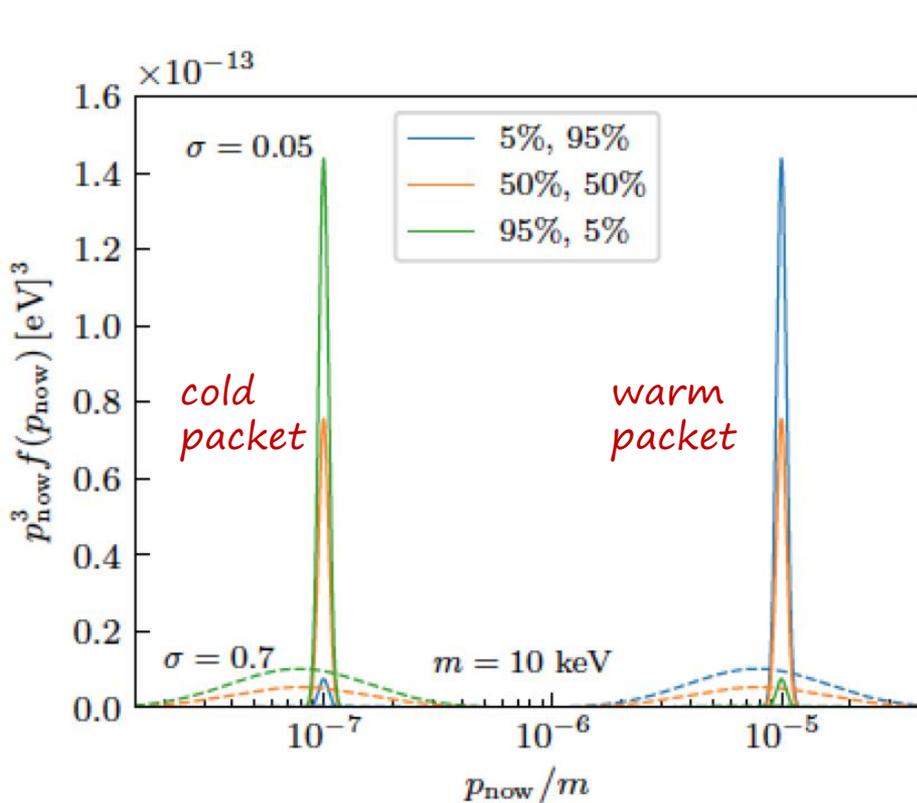
- Larger packet \rightarrow Stronger suppression
- Wiggles from DM acoustic oscillations show up and become more obvious as the height increases

$a^3 p^3 f_0(p) \rightarrow \mathcal{P}(k)$: Single Packet


Varying width with height/area fixed

(a complementary CDM component is added to get the total DM abundance)

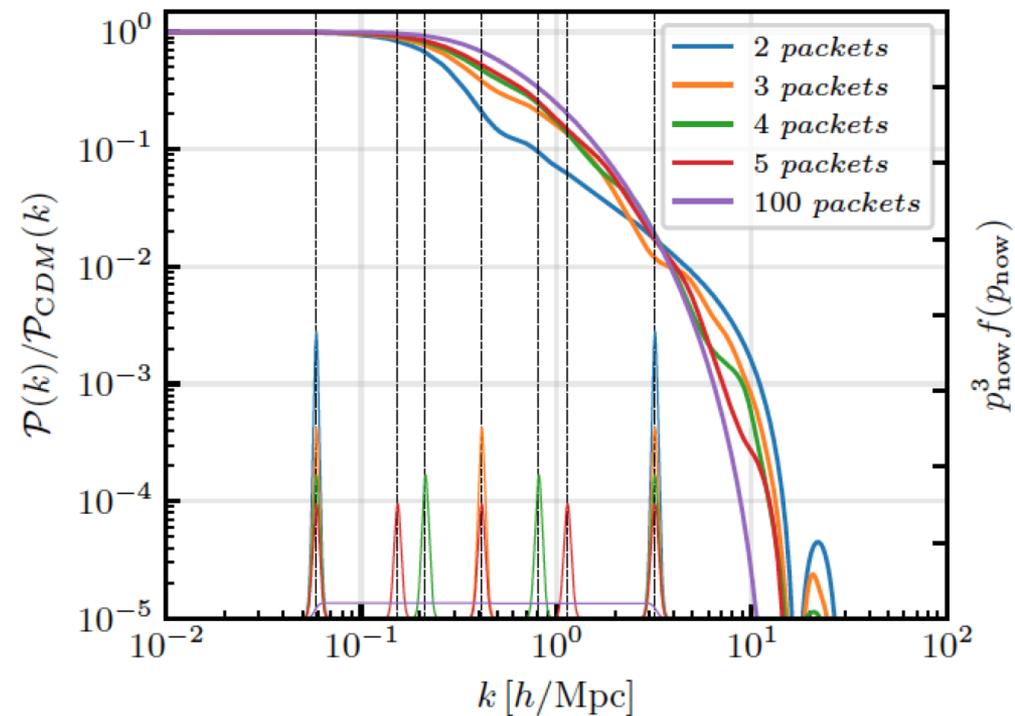
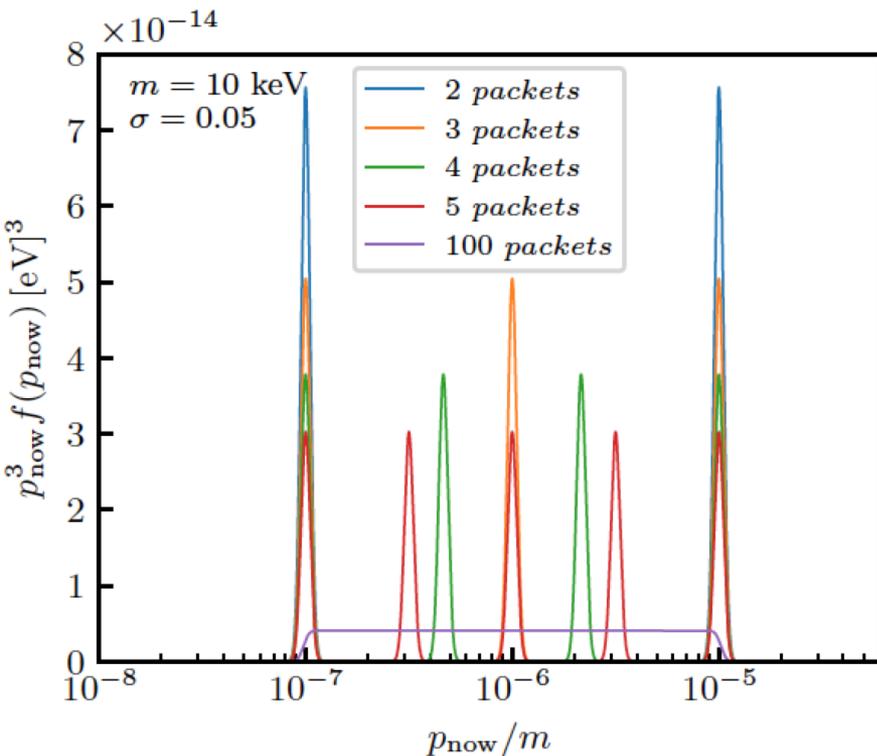
- Overall suppression is essentially unaffected by widths, but
- Wiggles smoothed out as width increases

$$a^3 p^3 f_0(p) \rightarrow \mathcal{P}(k): \text{Two Packets}$$


Varying fractions and widths

(two packets together carry the total DM abundance)

- Power spectra experience a two-step drop, first drop at k associated with the warmer packet, second at k associated with the colder packet
- Larger packet \rightarrow Larger drop
- Wiggles smoothed out as widths increase

$a^3 p^3 f_0(p) \rightarrow \mathcal{P}(k)$: Multiple Packets


From isolated packets to continuum

Start with 2 packets at 10^{-7} and 10^{-5} . Gradually add packets in between such that they are evenly distributed on log scale.

- Curves crossing each other as the k_{FSH} associated with each packet is passed
- Order of curves inverted after passing the last k_{FSH}
- Wiggles appear when packets are isolated and sharp, but become less distinct as packets increase
- In the continuum limit, wiggles are completely smoothed out

Toy Model: Parametrization

Dark ensemble consists of $N+1$ real scalars ϕ_j with $j = 0, 1, \dots, N$, and a mass spectrum:

$$m_j = m_0 + j^\delta \Delta m$$

Lagrangian:

$$\mathcal{L} = \sum_{\ell=0}^N \left(\frac{1}{2} \partial_\mu \phi_\ell \partial^\mu \phi_\ell - \frac{1}{2} m_\ell^2 \phi_\ell^2 - \sum_{i=0}^{\ell} \sum_{j=0}^i c_{\ell ij} \phi_\ell \phi_i \phi_j \right) + \dots$$

In our analysis we considered **10** levels...

The trilinear coupling:

$$c_{\ell ij} = c_0 \mu R_{\ell ij} \left(\frac{m_\ell - m_i - m_j}{\Delta m} \right)^r \left(1 + \frac{m_i - m_j}{\Delta m} \right)^{-s}$$

mass difference between parent and products
mass difference between products

Positive r \rightarrow Favor decays with more kinetic energy

Negative r \rightarrow Decays more marginal

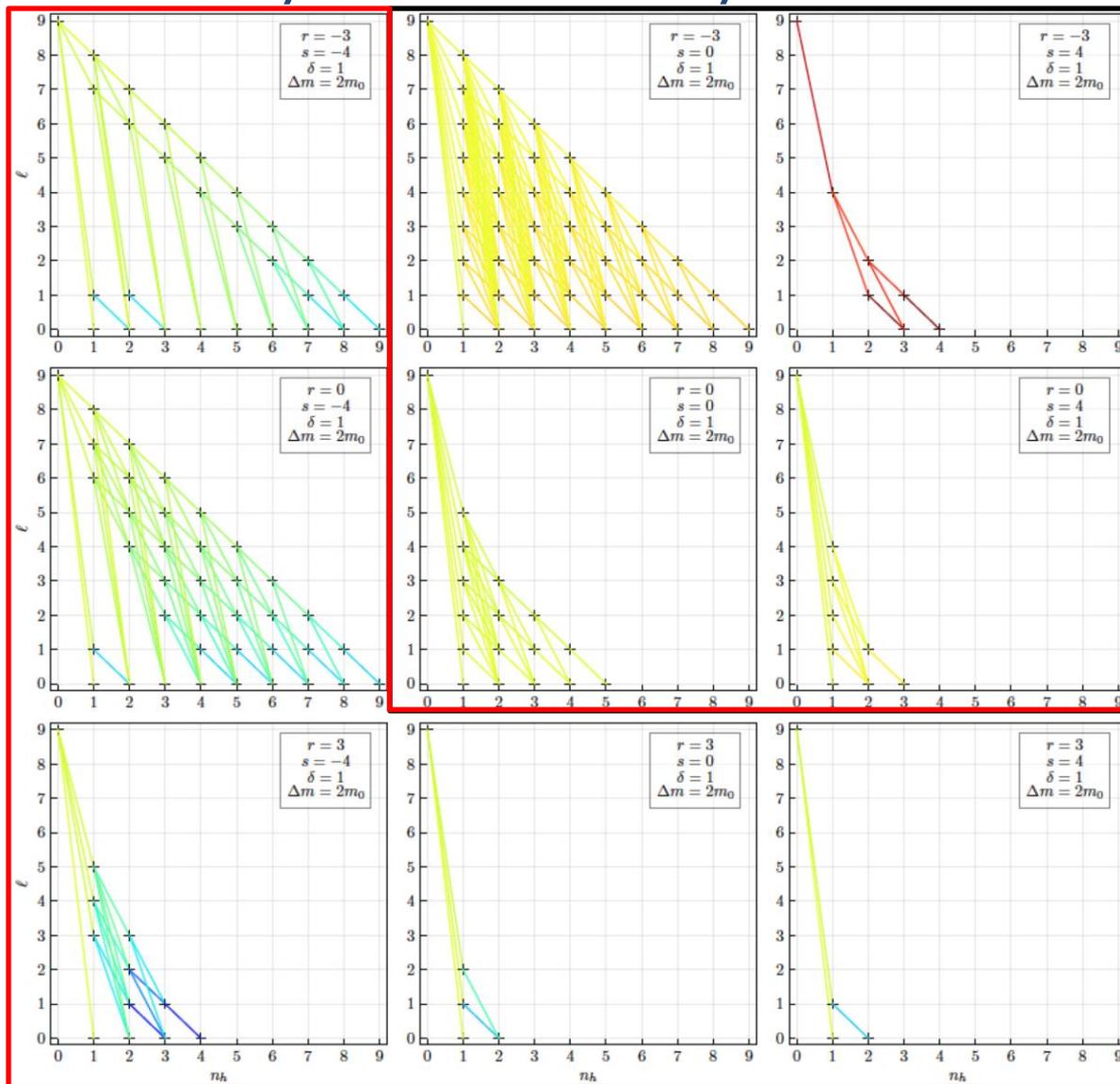
Positive s \rightarrow Decay products tend to have similar masses

Negative s \rightarrow Decay products tend to have different masses

Toy Model: Decay Chains

And we can have many different patterns of decay chains...

Timescales of a decay chain can be inferred by inverting the "slowest color"



Deposits to the ground state tend to happen around the same time

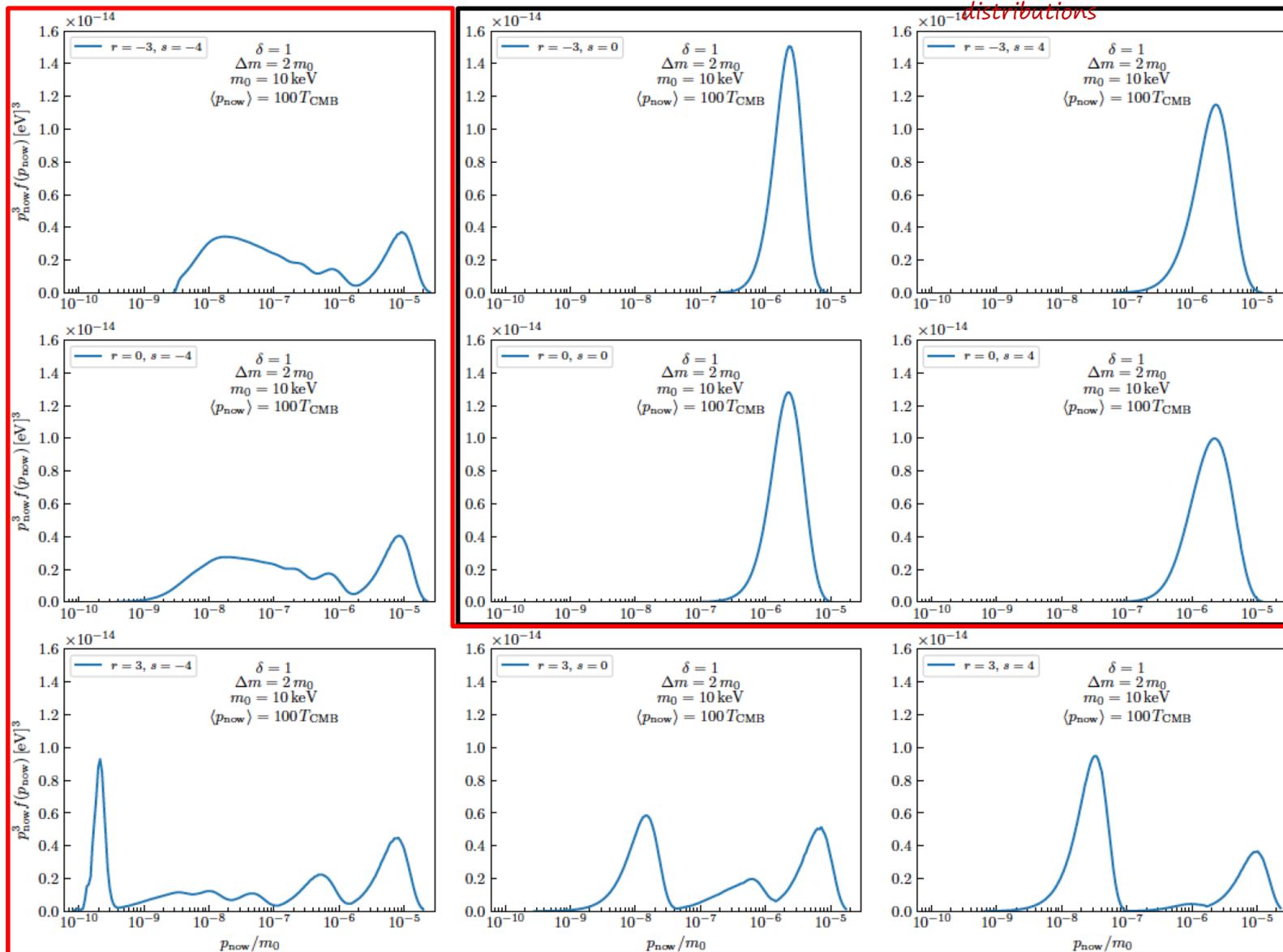
Deposits to the ground state tend to happen at different times

Normalized production rate

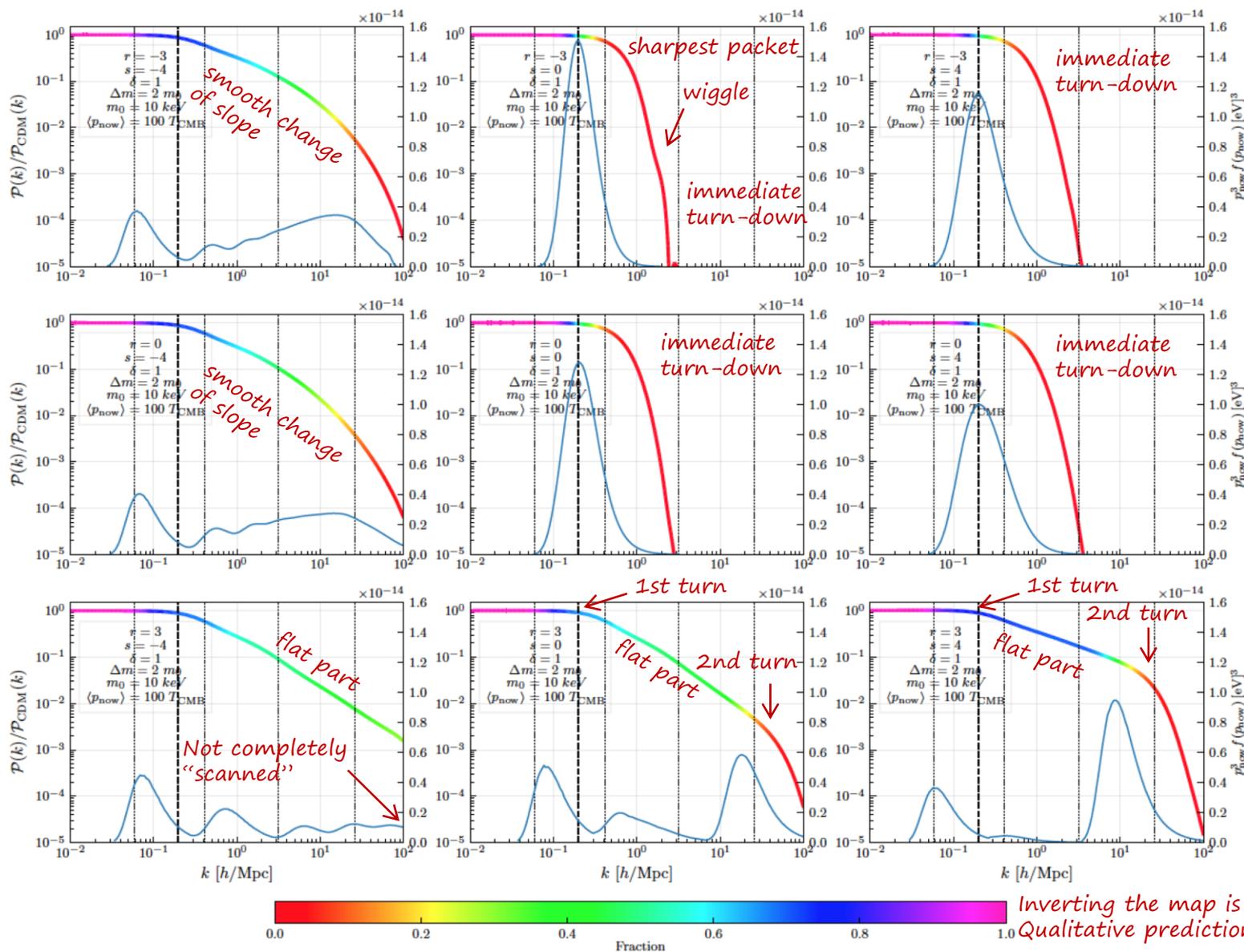
$$\frac{\sum_{\alpha} \mathcal{N}_{li}^{(\alpha)} \Gamma_{li}^{(\alpha)}}{\sum_{\alpha} \mathcal{N}_{9,0}^{(\alpha)} \Gamma_{9,0}^{(\alpha)}}$$

Measures how fast a state is being produced

Toy Model: Final Phase-Space Distribution



Toy Model: $f_0(p_{\text{now}}) \rightarrow \mathcal{P}(k)$



Conclusions

- Early universe processes such as decays in non-minimal dark sectors may leave non-trivial imprints in the phase-space distribution of the DM particles.
- Multi-modal distribution would emerge, if deposits to the ground state occur at different timescales.
- Non-trivial features in the phase-space distribution of DM can affect structure formation and can be mapped to suppression patterns in the matter power spectrum.
- Some aspects of the inverse map may be possible to explore.

Future Prospects

- Other early-universe processes that give rise to non-trivial distributions.
- Study explicit model and use the suppression patterns in matter power spectrum as observational bounds and signatures.