Deciphering the Structure of the Dark Sector from the Matter Power Spectrum: *A Concrete Example*

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The logic flow:

early-universe dynamics

dark-matter phase-space distribution $f(p)$

matter power spectrum $P(k)$

Can we invert this to learn about early-universe dynamics from the observable $P(k)$?

The logic flow:


early-universe dynamics


dark-matter phase-space distribution $f(p)$


matter power spectrum $P(k)$

?

?

?

The focus of this talk:

- What *<u>can</u>* we learn from $P(k)$?
- To what extent is an inversion possible?

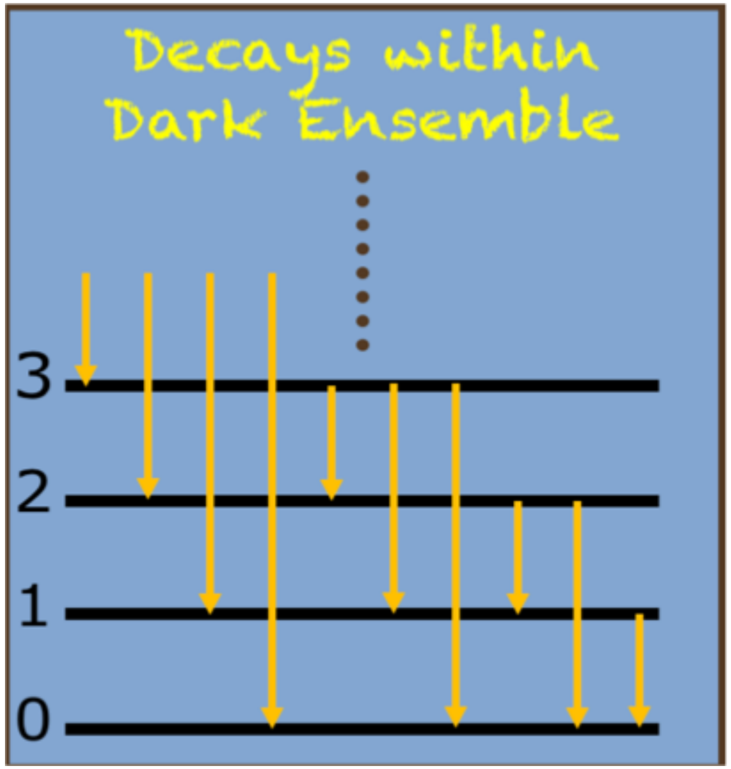
Multiple different early-universe dynamics could result in the same $f(p)$

An example…

We focus on scenarios in which decays occur ***entirely within the dark ensemble***, a.k.a. ***intra-ensemble decay***

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 the dynamics is captured by the evolution of the *phase-space distribution* of each state in the ensemble:

$$f_i(p,t)$$

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:

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

The trilinear coupling:

mass difference between parent and products

mass difference between products

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

Positive r → Decays with more kinetic energy
Negative r → Decays more marginal (less phase space)

Positive s → Decay products tend to have similar masses
Negative s → Decay products tend to have different masses

In our analysis we considered ***N=9*** ***(10 states)***

Toy Model: Parametrization

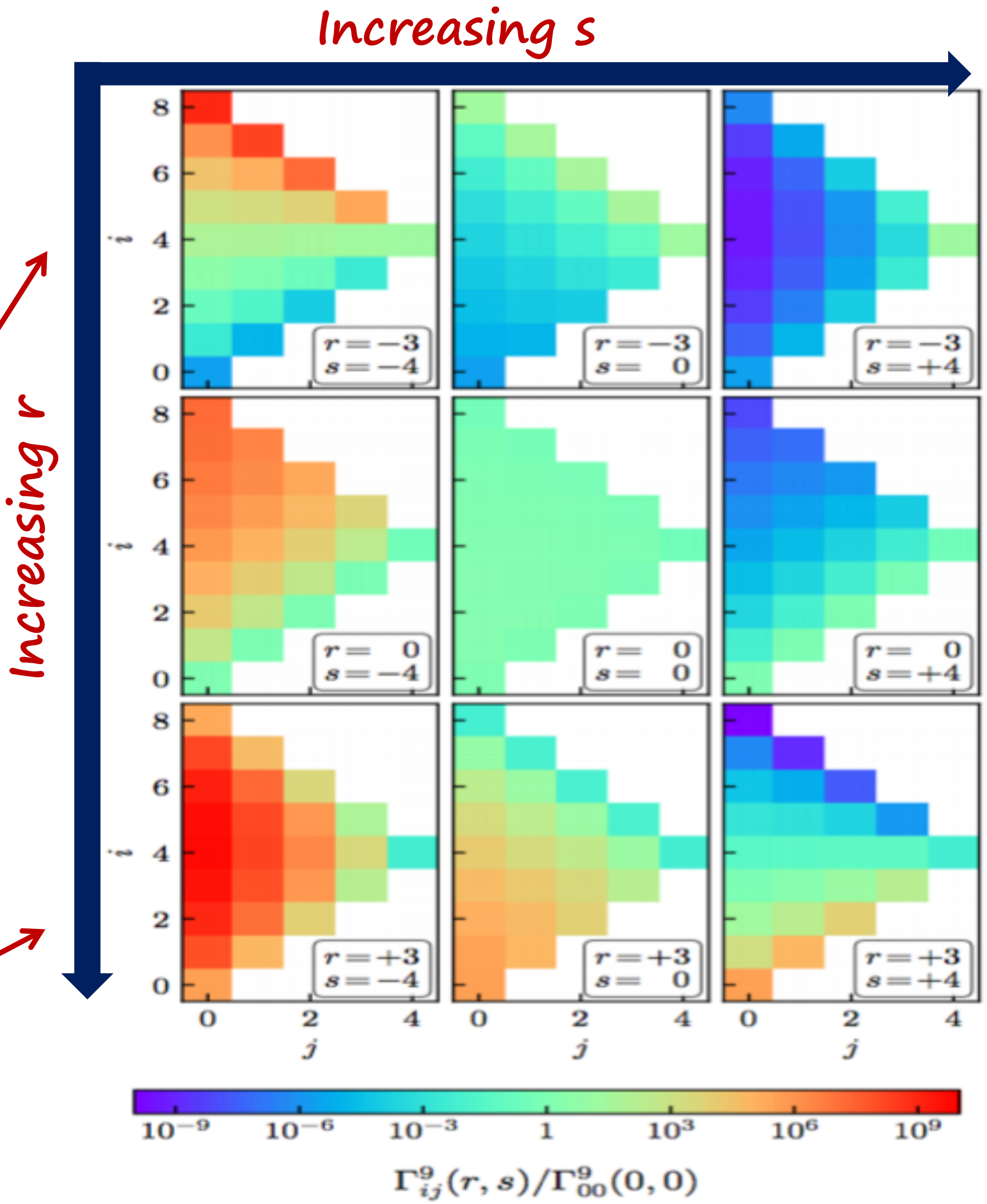
Given the explicit Lagrangian we can calculate the decay widths from a given parent state to a given pair of daughter states:

$$\phi_\ell \rightarrow \phi_i + \phi_j$$

For $\ell = 9$, we have…

Tend to minimize kinetic energy and symmetry
e.g. $\phi_9 \rightarrow \phi_8 + \phi_0$

Tend to produce light states but favor asymmetry
e.g. $\phi_9 \rightarrow \phi_4 + \phi_0$



Tend to minimize kinetic energy but favor symmetry
e.g. $\phi_9 \rightarrow \phi_4 + \phi_4$

Tend to produce the lightest states
e.g. $\phi_9 \rightarrow \phi_0 + \phi_0$

Toy Model: Decay Chains

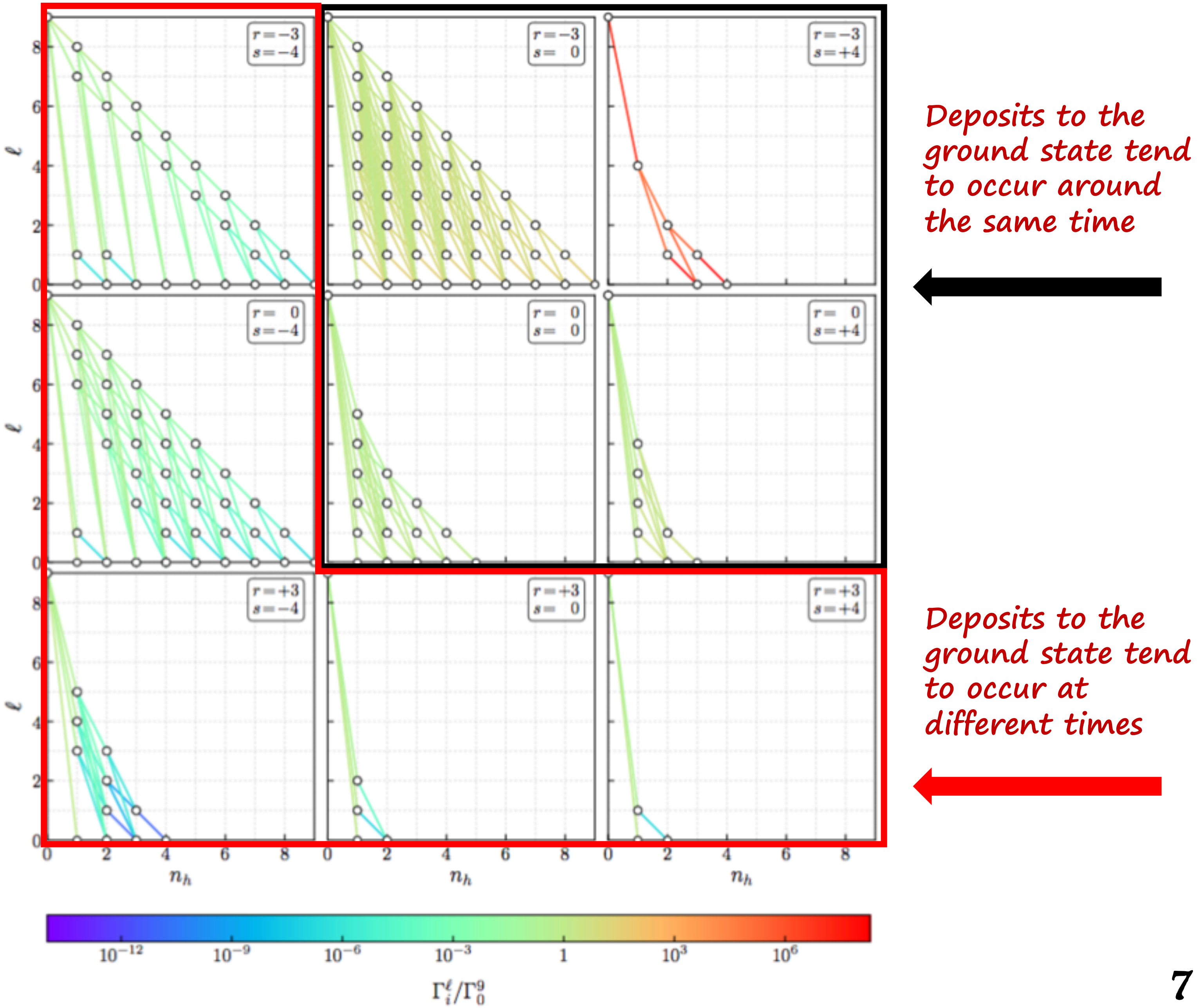
Now, let us assume decays start at

$$\ell = 9$$

we can have many different patterns of decay chains…

How to read?

- Color of each segment measures how fast a state is being produced, warmer color → faster production
- Timescales of a decay chain can be inferred by inverting the "slowest color"



Toy Model: Final Phase-Space Distribution

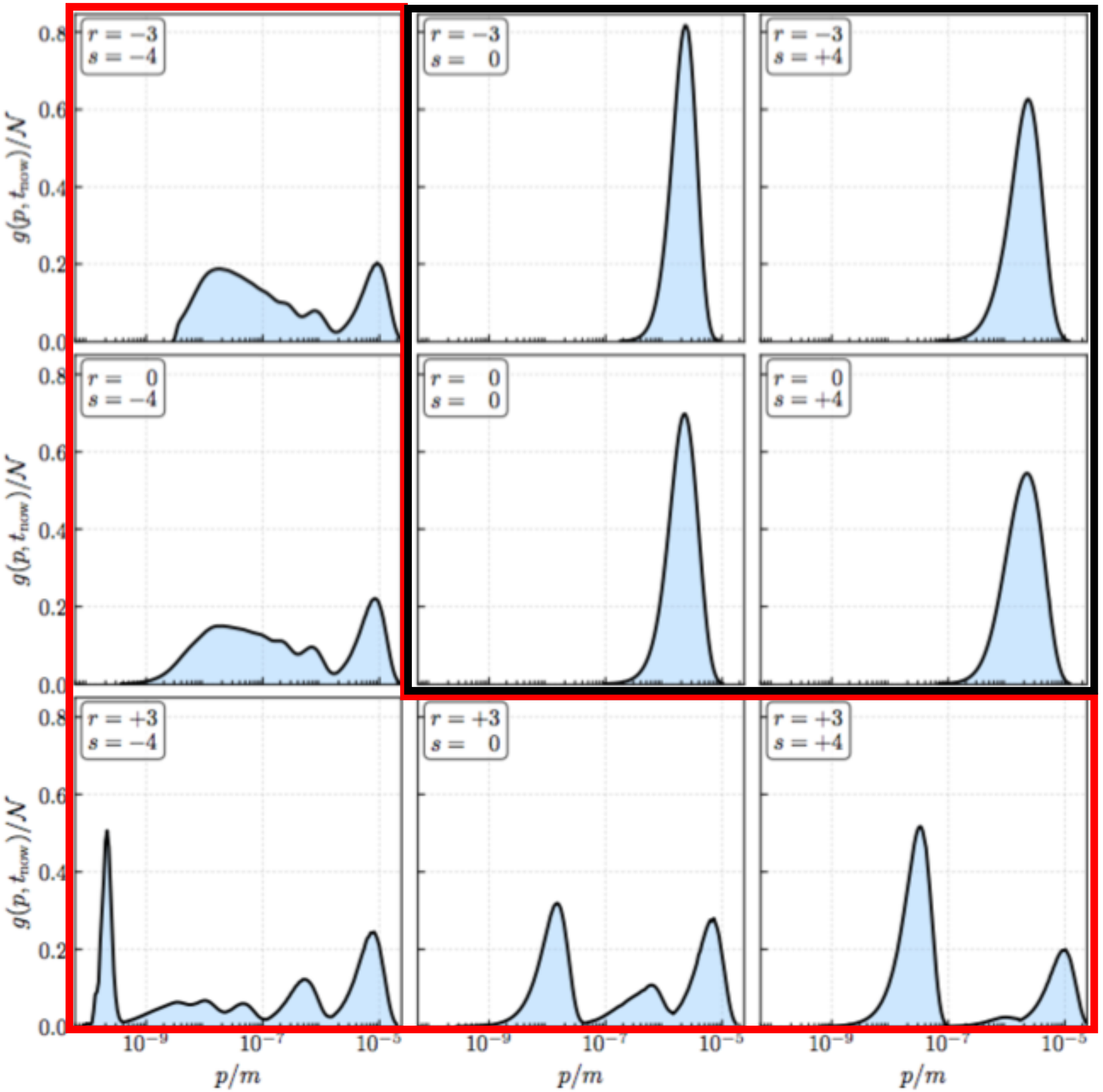
$g(p)$ is phase-space distribution w.r.t. $\log p$

$$N(t) = \frac{g_{\rm int}}{2\pi^2} \int_{-\infty}^{\infty} d\log p \; g(p,t) \equiv \frac{g_{\rm int}}{2\pi^2} \mathcal{N}(t)$$

A rich variety of distributions emerges!

As expected!

- *Cases in which decay chains that land on the ground state at similar timescales tend to produce unimodal distributions*
- *Multi-modal distributions could result if timescales of different decay chains differ significantly*



unimodal distributions

multi-modal distributions

Toy Model: $g(p) \to P(k)$

Matter power spectrum $P(k)$ obtained by feeding $g(p)$ to CLASS code

Plot the squared transfer function

$$T^2(k) \equiv P(k)/P_{\rm CDM}(k)$$

to show relative suppression

Map $g(p)$ to $\tilde{g}(k)$ by mapping p to $k_{\rm hor}$

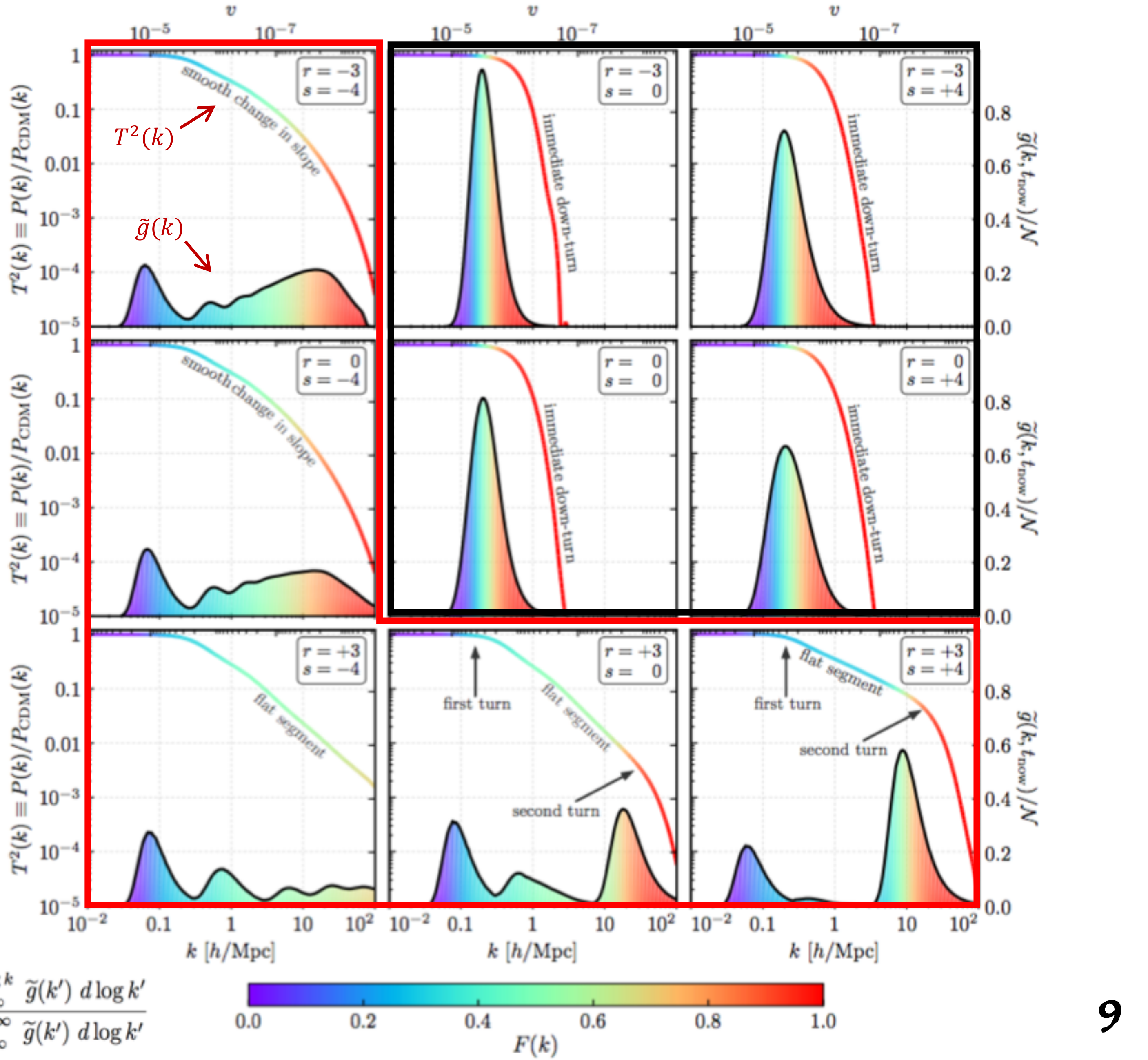
Rainbow colors correspond to ***hot fraction function*** $F(k)$: fraction of DM particles with

$$k_{\rm hor} < k$$

As we sweep through the k-space from left to right, equivalently, we are scanning the distribution from higher momentum to lower momentum!

Slope of $T^2(k)$ indeed appears to ***correlate*** with $F(k)$

$$k_{\rm hor}(p) \equiv \xi \left[\int_{t_{\rm prod}}^{t_{\rm now}} \frac{p/a(t)}{\sqrt{p^2/a(t)^2 + m^2}} \frac{dt}{a(t)} \right]^{-1}$$



$$F(k) \equiv \frac{\int_{-\infty}^{\log k} \tilde{g}(k')\, d\log k'}{\int_{-\infty}^{+\infty} \tilde{g}(k')\, d\log k'}$$

Toy Model: Reconstruction Conjecture

To what extent can we "***resurrect***" the DM phase-space distribution from the transfer function?

Recall our conjecture…

$$\frac{\tilde{g}(k)}{\mathcal{N}} \approx \frac{1}{2}\left(\frac{9}{16}+\left|\frac{d\log T^2}{d\log k}\right|\right)^{-1/2}\left|\frac{d^2\log T^2}{(d\log k)^2}\right|$$

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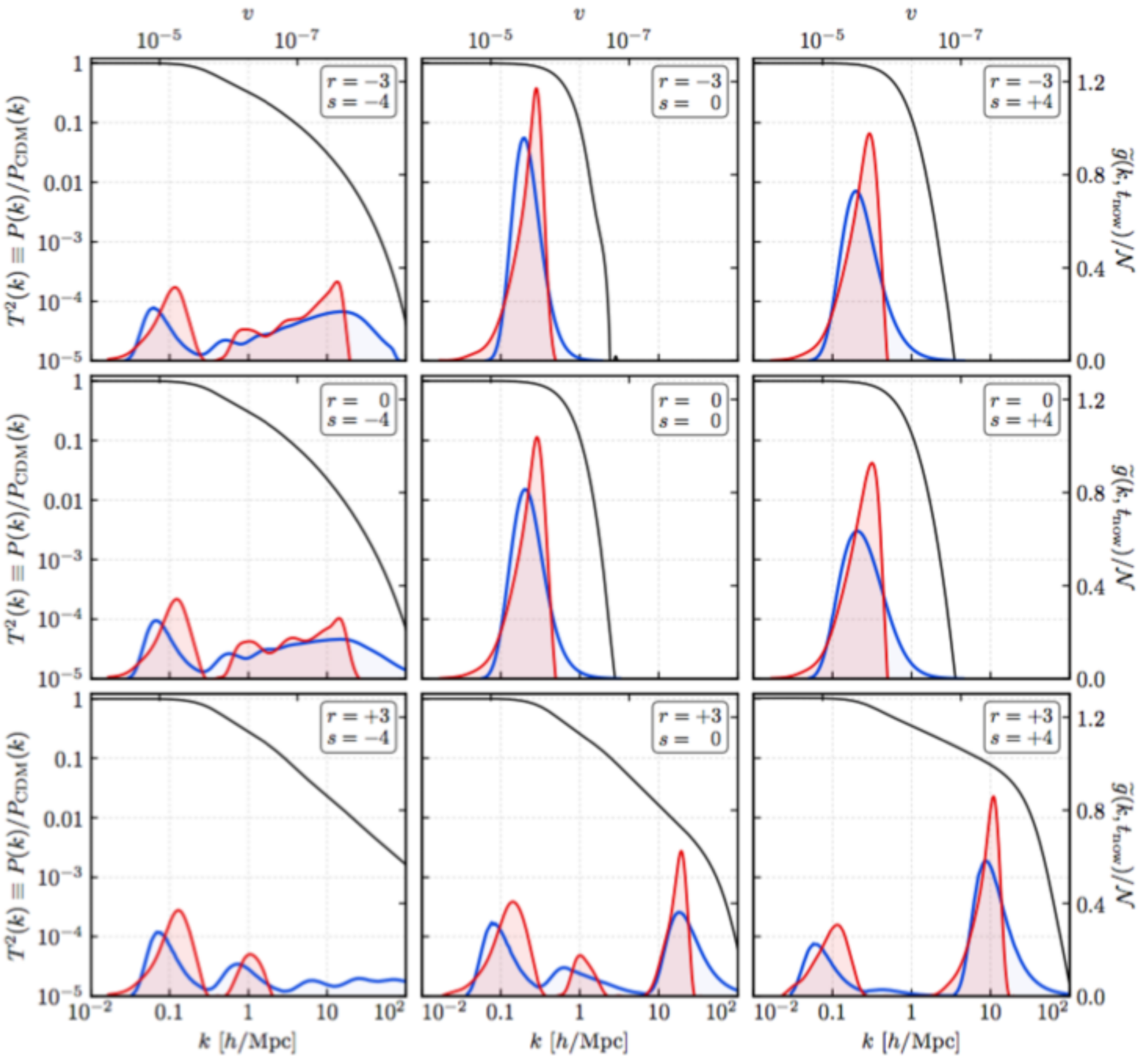
Blue: original DM distribution in k-space
Red: reconstruction directly from $T^2(k)$



Archaeological reconstruction is surprisingly accurate for a **variety** of possible DM distributions.
Able to resurrect the **salient features** of the original distribution!

Summary

- A non-minimal dark-sector toy model that can exhibit various interesting and complicated early-universe dynamics with intra-ensemble decays.
- Decays in non-minimal dark sectors can leave identifiable patterns in $g(p)$ which are further imprinted on $P(k)$.
- The reconstruction conjecture allows us to resurrect salient features of $g(p)$.
- Our approach provides a way to learn about dark-sector dynamics even if the dark sector has no direct couplings to the SM.

Future Directions

- Incorporate effects that might come from couplings to SM. Could potentially affect evolution of phase-space distributions in additional subtle ways.
- Incorporation of observational bounds (Lyman α, etc.), in progress.
- Refine reconstruction conjecture for greater accuracy.
- We have thus far studied only the linear power spectrum. Can this analysis be extended to non-linear regime (relevant for higher k)?
- What are the effects on structure formation if decays persist in late-time universe?