Dynamical Dark Matter

Theoretical Overview

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[arXiv:1106.4546, 1107.0721, 1203.1923] with Keith Dienes
[arXiv:1204.4183] with Keith Dienes and Shufang Su
[arXiv:1205.xxxx] with Keith Dienes and Jason Kumar

Dark Matter: The Conventional Wisdom

In most dark-matter models, the dark sector consists of one stable dark-matter candidate χ (or a few such particles). Such a dark-matter candidate must therefore...

- account for essentially the entire dark-matter relic abundance observed by WMAP: $\Omega_\chi \approx \Omega_{CDM} \approx 0.23$.
- Respect observational limits on the decays of long lived relics (from BBN, CMB data, the diffuse XRB, etc.) which require that χ to be *extremely* stable:

$$\tau_\chi \gtrsim 10^{26}\ s$$

(Age of universe: only $\sim 10^{17}$ s)

Consequences

- Such "hyperstability" is the **only** way in which a single DM candidate can satisfy the competing constraints on its abundance and lifetime.
- The resulting theory is essentially "frozen in time": Ω_{CDM} changes only due to Hubble expansion, etc.

Dynamical Dark Matter (DDM)

- The dark-matter candidate is an **ensemble** consisting of a vast number of constituent particle species whose collective behavior transcends that of traditional dark-matter candidates.
- Dark-matter stability is not a requirement; rather, the individual abundances of the constituents are **balanced against decay rates** across the ensemble in manner consistent with observational limits.
- Cosmological quantities like the total dark-matter relic abundance, the composition of the dark-matter ensemble, and even the dark-matter equation of state exhibit a **non-trivial time-dependence** beyond that associated with the expansion of the universe.

This talk:

- General features of the DDM framework
- Characterizing the cosmology of DDM models
- Methods for distinguishing DDM ensembles from traditional DM candidates at the LHC, direct-detection experiments, etc.

Talk in this afternoon's Extra-Dimensions session:

- An explicit realization of the DDM framework which satisfies all applicable constraints

General Features of the DDM Framework

For concreteness, consider the case in which the components of the DDM ensemble are scalar fields:

$$\phi_i, \; i = \{1, \ldots, N\} \text{ with } N \gg 1$$

with

Masses: m_i
Decay widths: Γ_i

In a FRW universe, these fields evolve according to

$$\ddot{\phi}_i + (3H + \Gamma_i)\dot{\phi}_i + m_i^2 \phi_i = 0$$

Hubble parameter: $H(t) \sim 1/t$

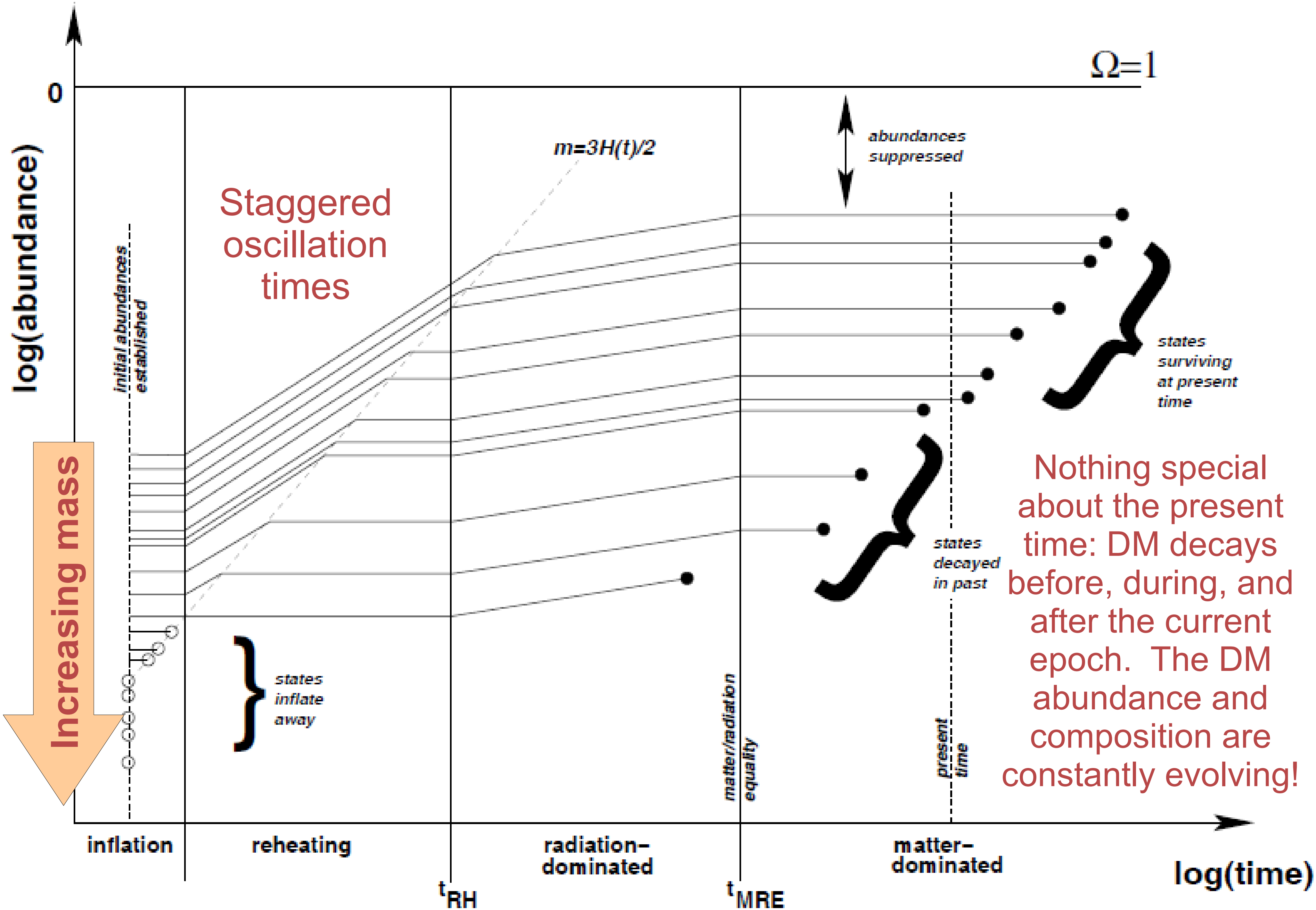
- Each scalar transitions from overdamped to underdamped oscillation at a time t_i, when:

$$3H(t_i) = 2m_i \;\Rightarrow\; t_i \sim 1/m_i$$

Heavier states "turn on" first.

This leads to a dark sector which evolves like...

Dynamical Dark Matter: the Big Picture



Characterizing DDM Ensembles

- The cosmology of DDM models is principally described in terms of three fundamental (**time-dependent**) quantities:

1 Total relic abundance:

$$\Omega_{\text{tot}}(t) = \sum_{i=0}^{N} \Omega_i(t)$$

2 Distribution of that abundance:

(One useful measure)

$$\eta(t) \equiv 1 - \frac{\Omega_0}{\Omega_{\text{tot}}}$$

where

$$\Omega_0 \equiv \max\{\Omega_i\}$$

The interpretation:

$$0 \le \eta \le 1 \quad \begin{cases} \eta = 0 \\ \eta > 0 \end{cases}$$

$\eta = 0$ → One dominant component (standard picture)

$\eta > 0$: Quantifies depature from traditional DM

3 Effective equation of state:

$$p = w_{\text{eff}}\,\rho_{\text{tot}}$$

Not always $w = 0$!

$$w_{\text{eff}}(t) = -\left(\frac{1}{3H}\frac{d\rho_{\text{tot}}}{dt} + 1\right)$$

Characterizing DDM Ensembles

- Unlike traditional dark-matter candidates, a DDM ensemble has no well-defined mass, decay width, or set of scattering cross-sections.
- The natural parameters which describe such a dark-matter candidate are those which describe **the internal structure of the ensemble** itself and describe how quantities such as the constituent-particle masses, abundances, decay widths, and cross-sections scale with respect to one another across the ensemble as a whole.

For example:

$$\Omega(\Gamma) = A\,(\Gamma/\Gamma_0)^{\alpha}$$

$$n_\Gamma(\Gamma) = B(\Gamma/\Gamma_0)^{\beta}$$

Density of states per unit width Γ

The properties of the ensemble are naturally expressed in terms of the coefficients A and B and the **scaling exponents** α and β.

e.g., if we take: $\Omega_i(t) \approx \Omega_i \Theta(\tau_i - t)$

$$\sum_i \rightarrow \int n_\tau(\tau) d\tau \quad \text{with} \quad n_\tau = \Gamma^2 n_\Gamma$$

We obtain the general result:

$$\frac{d\Omega_{\rm tot}(t)}{dt} \approx -\sum_i \Omega_i \delta(\tau_i - t) \approx -AB\Gamma_0^2(\Gamma_0 t)^{-\alpha-\beta-2}$$

And from this result follow...

General expressions for our three fundamental quantities:

	For $x \equiv \alpha + \beta \neq 1$	For $x \equiv \alpha + \beta = 1$
$\Omega_{\text{tot}}(t)$	$\Omega_{\text{CDM}} + \frac{AB\Gamma_0}{(1+x)} \left[(\Gamma_0 t)^{1+x} - \Gamma_0 t_{\text{now}})^{1+x} \right]$	$\Omega_{\text{CDM}} - AB\Gamma_0 \ln(\Gamma_0 t)$
$w_{\text{eff}}(t)$	$\frac{(1+x)w_*}{2w_* + (1+x+2w_*)(t/t_{\text{now}})^{1+x}}$ where $w_* = \frac{AB\Gamma_0}{2\Omega_{\text{CDM}}(\Gamma_0 t_{\text{now}})^{1+x}}$	$\frac{w_*}{1 - 2w_* \ln(t/t_{\text{now}})}$ where $w_* = \frac{AB\Gamma_0}{2\Omega_{\text{CDM}}}$
$\eta(t)$	$\frac{2w_* + [\eta_*(1+x) - 2w_*](t/t_{\text{now}})}{2w^*_{\text{eff}} + (1+x+2w^*_{\text{eff}})(t/t_{\text{now}})^{1+x}}$	$\frac{\eta_* - 2w_* \ln(t/t_{\text{now}})}{1 - 2w_* \ln(t/t_{\text{now}})}$

Now let's examine an example of how this works for a particular example of a DDM ensemble that arises **naturally** in many extensions of the SM (including string theory)...

Scalars in extra dimensions:

- For concreteness, consider a scalar field Φ propagating in a single extra spacetime dimension compactified on a S_1/Z_2 orbifold of radius R. The SM fields are restricted to a brane at y=0.
- The action can in principle include both **bulk-mass** and **brane-mass** terms:

$$S = \int d^4x dy \left[\frac{1}{2}\partial_P \Phi^* \partial^P \Phi - \frac{1}{2}M^2|\Phi|^2 - \frac{1}{2}\delta(y)m^2|\Phi|^2 + \mathcal{L}_{\text{int}}\right]$$

Non-renormalizable interactions suppressed by some heavy scale f_ϕ

KK-mode Mass-Squared Matrix

$$\mathcal{M}^2_{k\ell} = \left(\frac{k\ell}{R^2} + M^2\right)\delta_{k\ell} + r_k r_\ell m^2$$

- Brane mass indices **mixing** among the KK modes: mass eigenstates ϕ_λ are linear combinations of KK-number eigenstates ϕ_i:

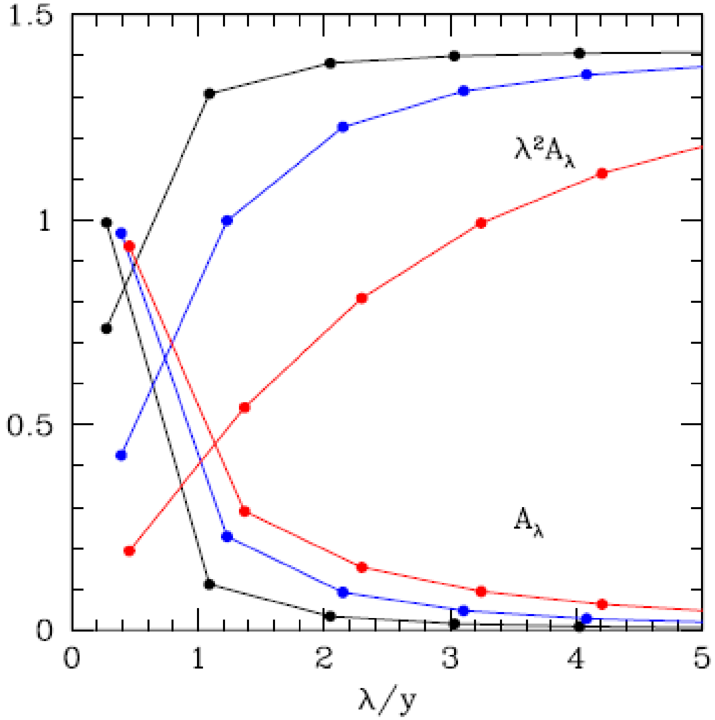
$$|\phi_\lambda\rangle = A_\lambda \sum_{k=0}^{\infty} \frac{r_k \tilde{\lambda}^2}{\tilde{\lambda}^2 - k^2 y^2} |\phi_k\rangle$$

$y = 1/mR$

where $\tilde{\lambda} \equiv \sqrt{\lambda^2 - M^2}/m$

$$A_\lambda \equiv \frac{\sqrt{2}}{\tilde{\lambda}} \frac{1}{\sqrt{1 + \pi^2/y^2 + \tilde{\lambda}^2}}$$

Mixing factor: suppresses couplings of light modes to brane states.



Balancing from Mixing

The ϕ_λ decay to SM fields on the brane:

Linear combination of ϕ_λ that couples to brane states

Decay widths:

$$\Gamma_\lambda \sim \frac{\lambda^3}{\hat{f}_\phi^2}\langle\phi_\lambda|\phi'\rangle^2 = \frac{\lambda^3}{\hat{f}_\phi^2}\left(\tilde{\lambda}^2 A_\lambda\right)^2$$

Relic abundances (from misalignment):

If the 5D field has a shift symmetry $\Phi \rightarrow \Phi$ + [const.] above the scale at which m is generated, $\phi_{k=0}$ can have a **misaligned vacuum value**:

$$\Omega_\lambda(t_\lambda) \sim \frac{\lambda^2\theta^2\hat{f}_\phi^2|\langle\phi_\lambda|\phi_{k=0}\rangle|^2}{H^2 M_P^2}\left(\frac{t_\lambda}{t}\right)^{\kappa_\lambda} = \frac{\theta^2\hat{f}_\phi^2}{H^2M_P^2}\lambda^2 A_\lambda^2\left(\frac{t_\lambda}{t}\right)^{\kappa_\lambda}$$

Overlap with zero mode

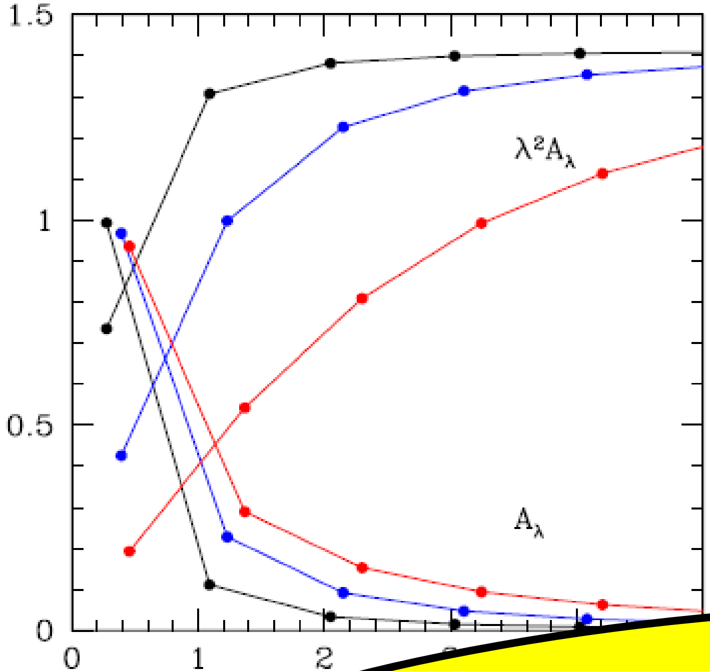
Oscillation-time factor

Staggered: $t_\lambda \sim 1/\lambda$

Simultaneous: $t_\lambda \sim$ const.

A natural balance between Ω_λ and Γ_λ!

$$\begin{aligned} \text{instantaneous}: &\quad \Omega_\lambda\Gamma_\lambda^{2/3} \sim \text{constant} \\ \text{staggered (RD era)}: &\quad \Omega_\lambda\Gamma_\lambda^{7/6} \sim \text{constant} \\ \text{staggered (reheating/MD era)}: &\quad \Omega_\lambda\Gamma_\lambda^{4/3} \sim \text{constant} \end{aligned}$$



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ment):

If t

Ω_λ(

For more details and an explicit model of this sort which satisfies all phenomenological constraints, see talk in this afternoon's "Extra Dimensions I" session.

Overlap with zero mode

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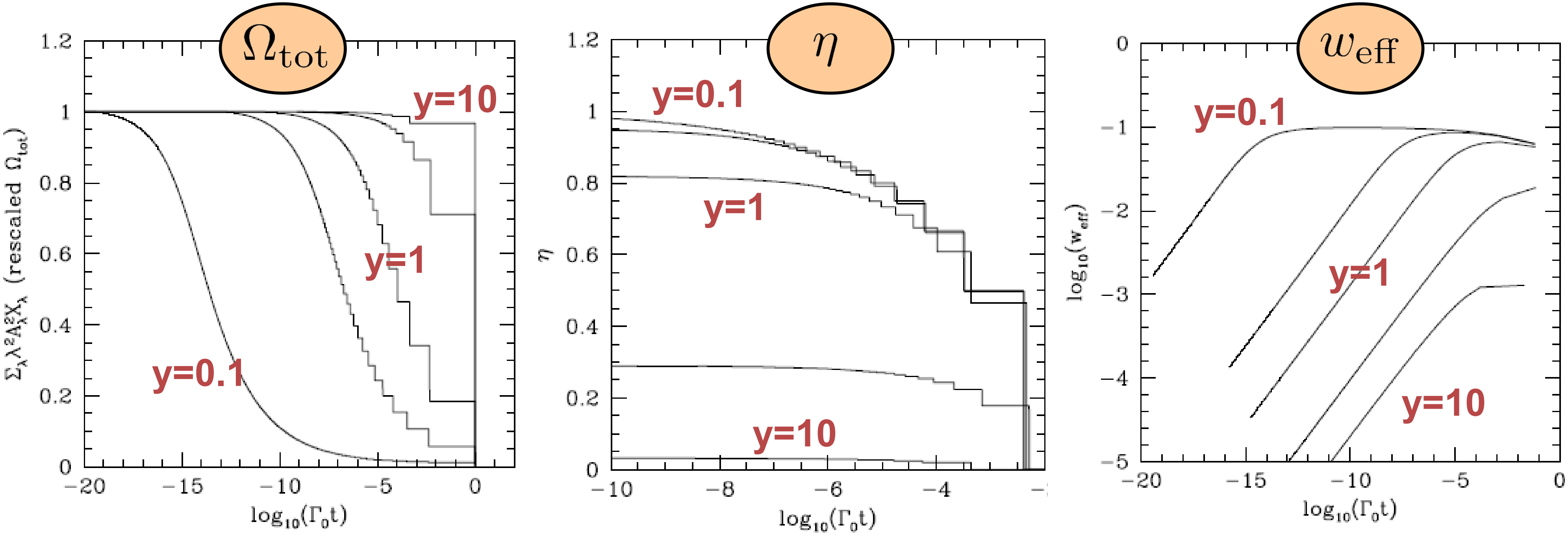
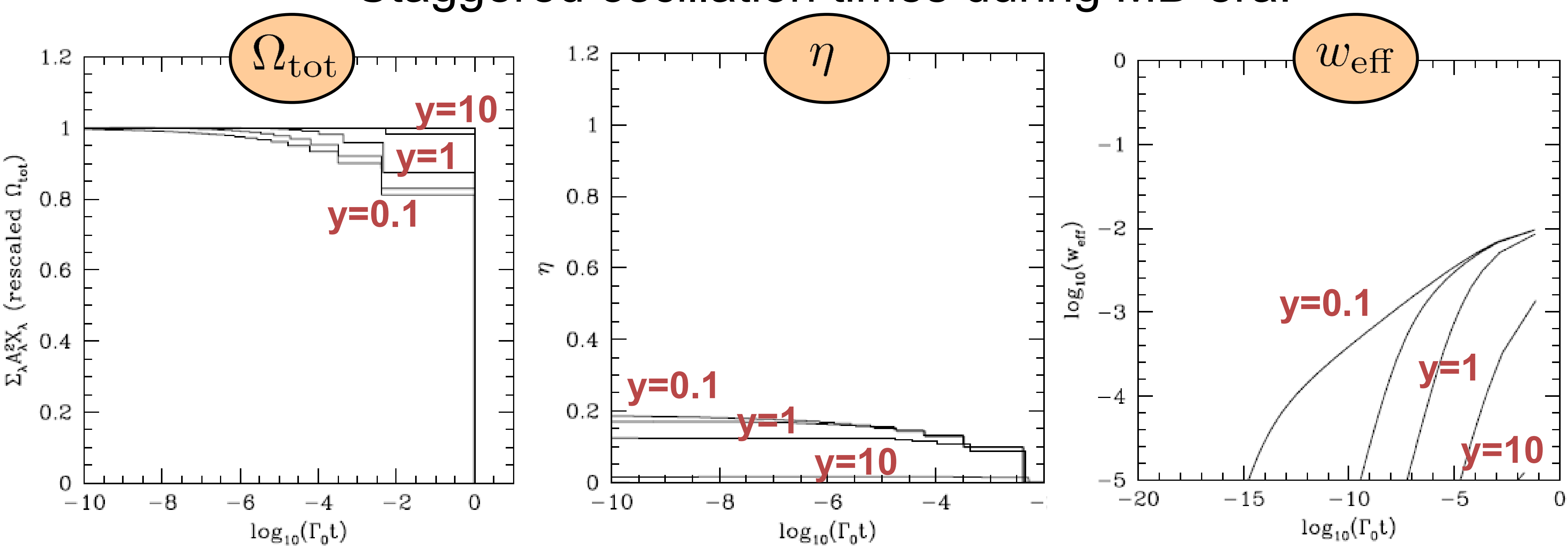
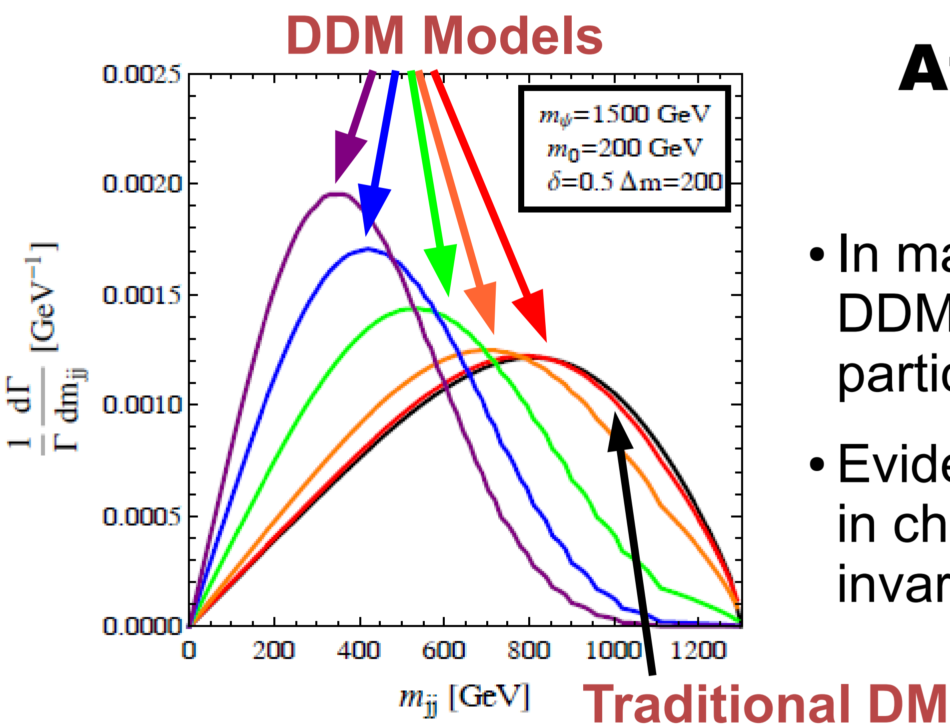
Simultaneous oscillation:



Staggered oscillation times during MD era:



Discovering (and Differentiating) DDM



At the LHC, ...

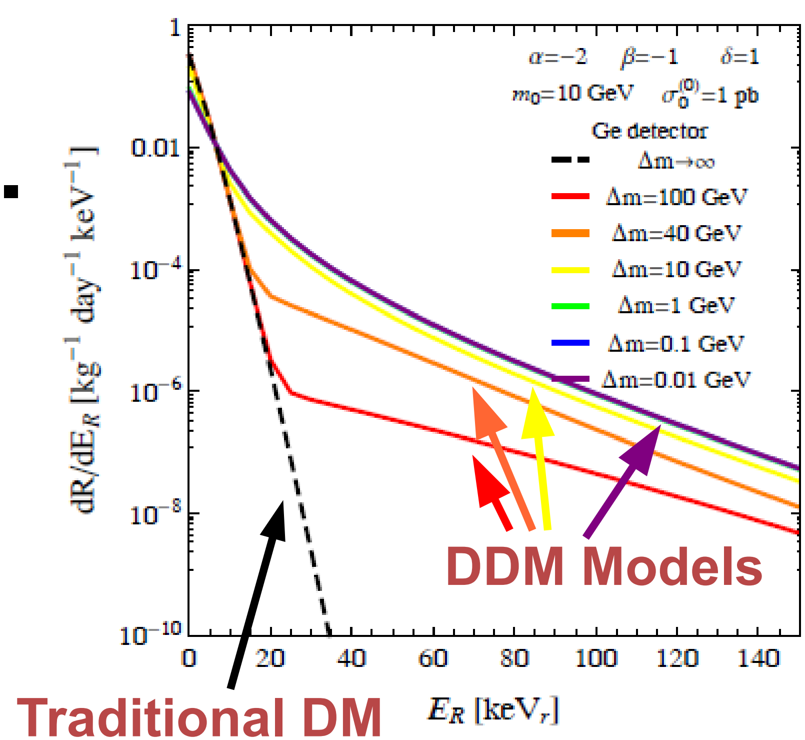
K. Dienes, S. Su, BT [arXiv:1204.4183]

- In many DDM models, constituent fields in the DDM ensemble can be produced alongside SM particles by the decays of additional heavy fields.
- Evidence of a DDM ensemble can be ascertained in characteristic features imprinted on the invariant-mass distributions of these SM particles.

at direct-detection experiments, ...

K. Dienes, J. Kumar, BT [arXiv:1205.xxxx]

- DDM ensembles can also give rise to distinctive features in recoil-energy spectra.



and perhaps in other contexts as well (indirect detection via γ rays? neutrinos?). **Many** possibilities have yet to be explored!

Summary

- Dynamical dark matter (DDM) is a new framework for addressing the dark-matter question.
- In this framework, stability is replaced by **a balancing between lifetimes and abundances** across a vast **ensemble** of particles which collectively account for Ω_{CDM}.
- This scenario is well-motivated in string theory and field theory.
- Simple, **explicit models** exist which satisfy all applicable phenomenological constraints. (See talk in "Extra Dimensions I" session this afternoon.)
- DDM ensembles can give rise to **distinctive signatures** at colliders, direct-detection experiments, etc. which permit one to distinguish them from traditional dark-matter candidates.

… indeed, the full range of phenomenological consequences of the DDM framework is just beginning to be explored!