Dynamical Dark Matter

An Alternative Framework for Dark-Matter and Its Collider Implications

Dark Matter at a Future Hadron Collider Workshop
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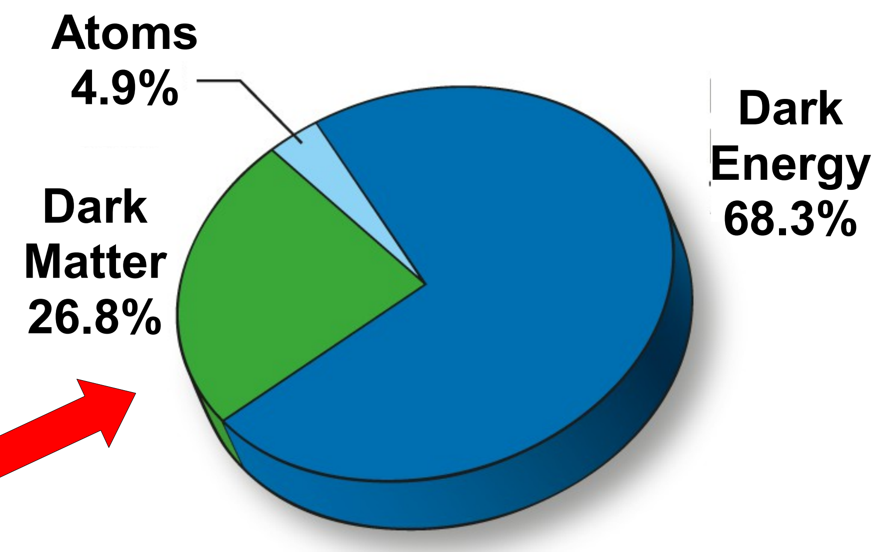
(Colorado College)

Based on work done in collaboration with Keith Dienes:

[arXiv:1106.4546]
[arXiv:1107.0721]
[arXiv:1203.1923]
[arXiv:1204.4183] also with Shufang Su
[arXiv:1208.0336] also with Jason Kumar
[arXiv:1306.2959] also with Jason Kumar
[arXiv:1406.4868] also with Jason Kumar
[arXiv:1407.2606] also with Shufang Su & David Yaylali
[arXiv:1512.xxxxx] also with Fei Huang & Shufang Su
[arXiv:1512.xxxxx] also with Jacob Fennick & Jason Kumar

What We Do Know About Dark Matter:

Not a lot (which is why it's an interesting subject!), but experimental data have taught us some important things:



The "Cosmic Pie" (Today)

- It makes up about a quarter of the energy budget of the universe.

  [CMB Measurements (COBE, WMAP, Planck), high-redshift supernovae, Galaxy clusters]

- Most of it isn't normal, baryonic matter.

  [Baryon acoustic oscillations, large-scale structure]

- It acts more or less like cold (i.e., non-relativistic) particles.

  [Large-scale structure, nucleosynthesis, merging clusters (e.g. the Bullet Cluster)]

- Its interactions with normal, baryonic matter are very weak.

  [Large- and small-scale structure, direct detection, collider data, merging clusters, etc.]

- In addition, over the past few years, a puzzling assortment of **data anomalies** and **putative signals** have been advanced as possible clues about the nature of the dark matter:

Excesses in the number of signal events at a number of direct-detection experiments (CDMS-II, DAMA, etc.).

Excess in the flux of high-energy e^+ (and e^-) in cosmic rays (PAMELA, FERMI, AMS-2, etc.).

Tensions (?) between observational data and the properties of dark-matter haloes predicted by numerical simulations of small-scale structure.

Excesses in the observed photon flux at energies around $E_\gamma \sim (1 - 10)$ GeV from the galactic galactic center and from dwarf galaxies.

- Many theoretical models developed to address other theoretical issues (such as the hierarchy problem or the strong-CP problem) also provide a dark-matter candidate for free.
- However, these simple, elegant solutions to the dark-matter problem are often difficult to reconcile with these data anomalies and putative signals.

These data anomalies have therefore provided a strong motivation for considering alternatives to the standard picture of dark matter suggested by these constructions.

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/Planck: $\Omega_\chi \approx \Omega_{CDM} \approx 0.26$.
- 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 ~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.

Is hyperstability really the only path to a viable theory of dark matter?

No. There is another.

...and it follows from this fundamental observation:

A given dark-matter component need not be stable if its abundance at the time of its decay is sufficiently small.

Indeed, a sufficiently small abundance ensures that the disruptive effects of the decay of such a particle will be minimal, and that all constraints from BBN, CMB, etc., will continue to be satisfied.

Thus, as we shall see, a natural alternative to hyperstability involves a **balancing of decay widths against abundances**:

- States with larger abundances must have smaller decay widths, but states with smaller abundances can have larger decay widths.
- As long as decay widths are balanced against abundances across the entire dark sector, all phenomenological constraints can be satisfied!

Dynamical Dark Matter

Dynamical Dark Matter (DDM) is a more general framework for dark-matter physics in which these constraints can be satisfied *without* imposing hyperstability.

In particular, in DDM scenarios...

- 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, because...
- Dark-matter stability is not a requirement; rather, the individual abundances of the constituents are **balanced against decay widths** 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.

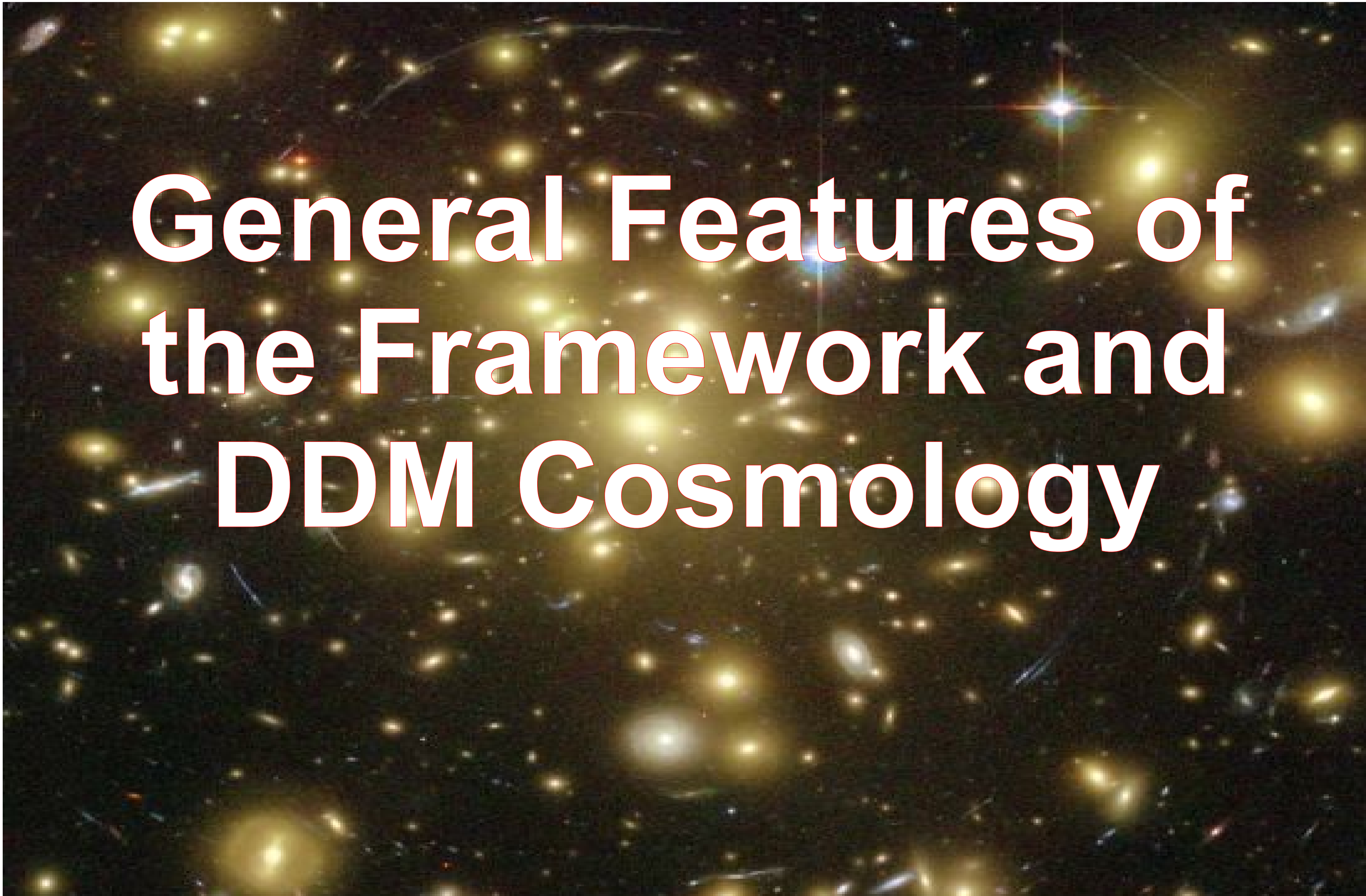
In this talk, I'll...

1. Provide a theoretical overview of the DDM framework.

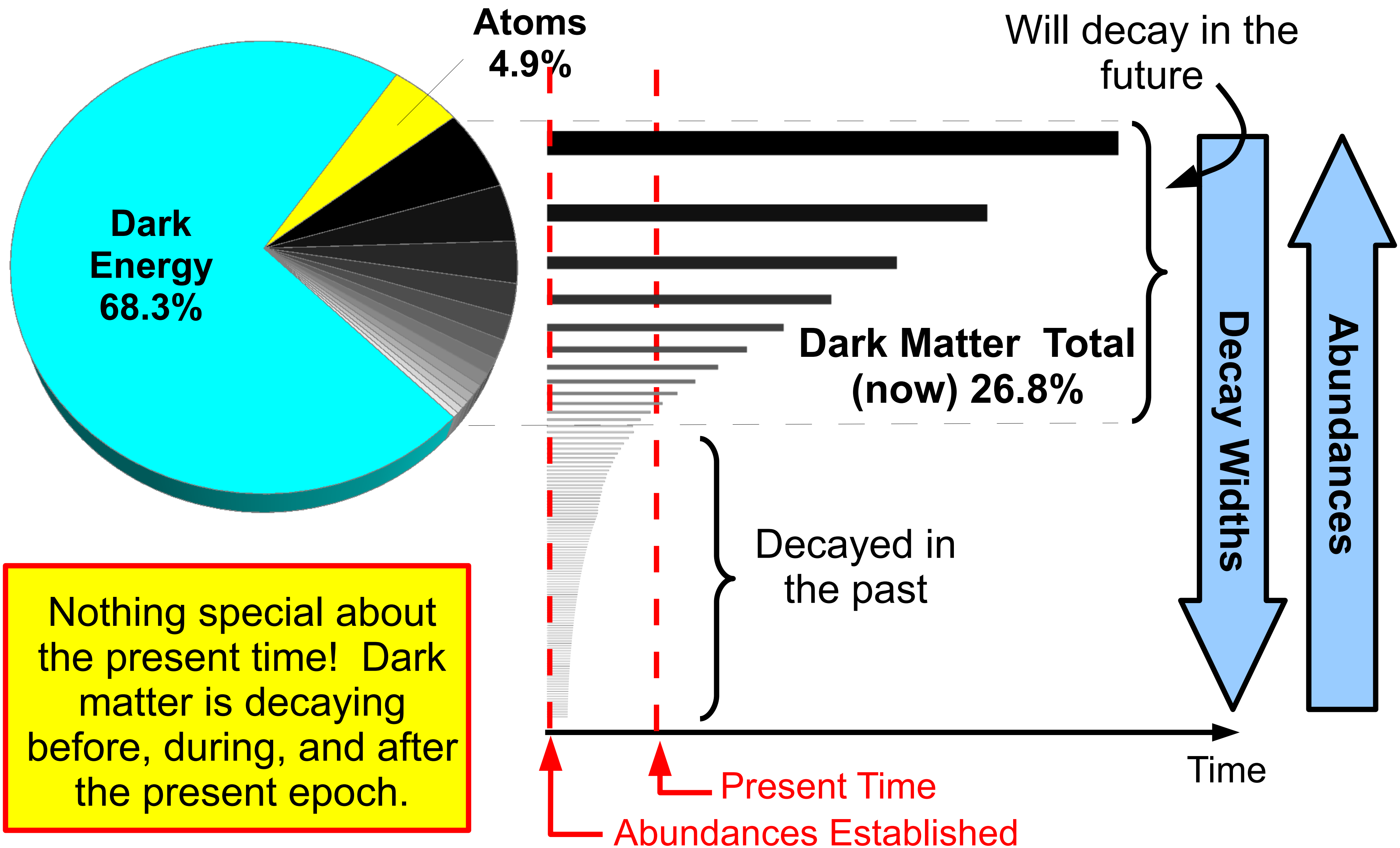
2. Discuss how to characterize the non-trivial cosmology which arises in DDM models.

3. Provide a few examples of explicit realizations of the DDM framework.

4. Discuss the phenomenological implications of the DDM framework – including methods for distinguishing DDM ensembles from traditional DM candidates at the LHC and at future colliders.


General Features of
the Framework and
DDM Cosmology

DDM Cosmology: The Big Picture



Nothing special about the present time! Dark matter is decaying before, during, and after the present epoch.

This is clearly a very different approach to the dark-matter problem...

...and one that requires a lot of rethinking about how we characterize the dark sector:

Rethinking constraints:

- Standard phenomenological bounds on the properties of dark-matter candidates are typically calculated assuming a single particle species (or a small number thereof) with a single, well-defined mass, lifetime, and set of couplings to Standard-Model fields.
- Within the DDM framework, the corresponding **bounds may be quite different** and need to be reexamined.

Rethinking how to express those constraints:

- Moreover, because of their aggregate nature, DDM ensembles **can't be parametrized in the same way** as traditional dark-matter candidates (WIMPS, etc.). The way experimental results are typically expressed in the literature isn't often readily applicable to DDM ensembles. New ways of expressing those results are needed!

Rethinking prejudices about complexity:

- As I'll demonstrate, DDM ensembles do indeed arise naturally in many top-down models of new physics (including theories with **extra dimensions**, **strongly-coupled theories**, and **string theory**).

- In such theoretically-motivated scenarios, the masses, lifetimes, couplings, etc. of the individual particles in the ensemble are all determined by only **a few** underlying parameters.

(Ensemble with an organizing principle)

Such dark-matter models are therefore no more complicated or fine-tuned than traditional models of the dark sector.

- Indeed, the measure of how minimal a theory is not the number of ***particles*** it contains, but rather the number of free ***parameters***!

The Cosmology of DDM Ensembles: An Example

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

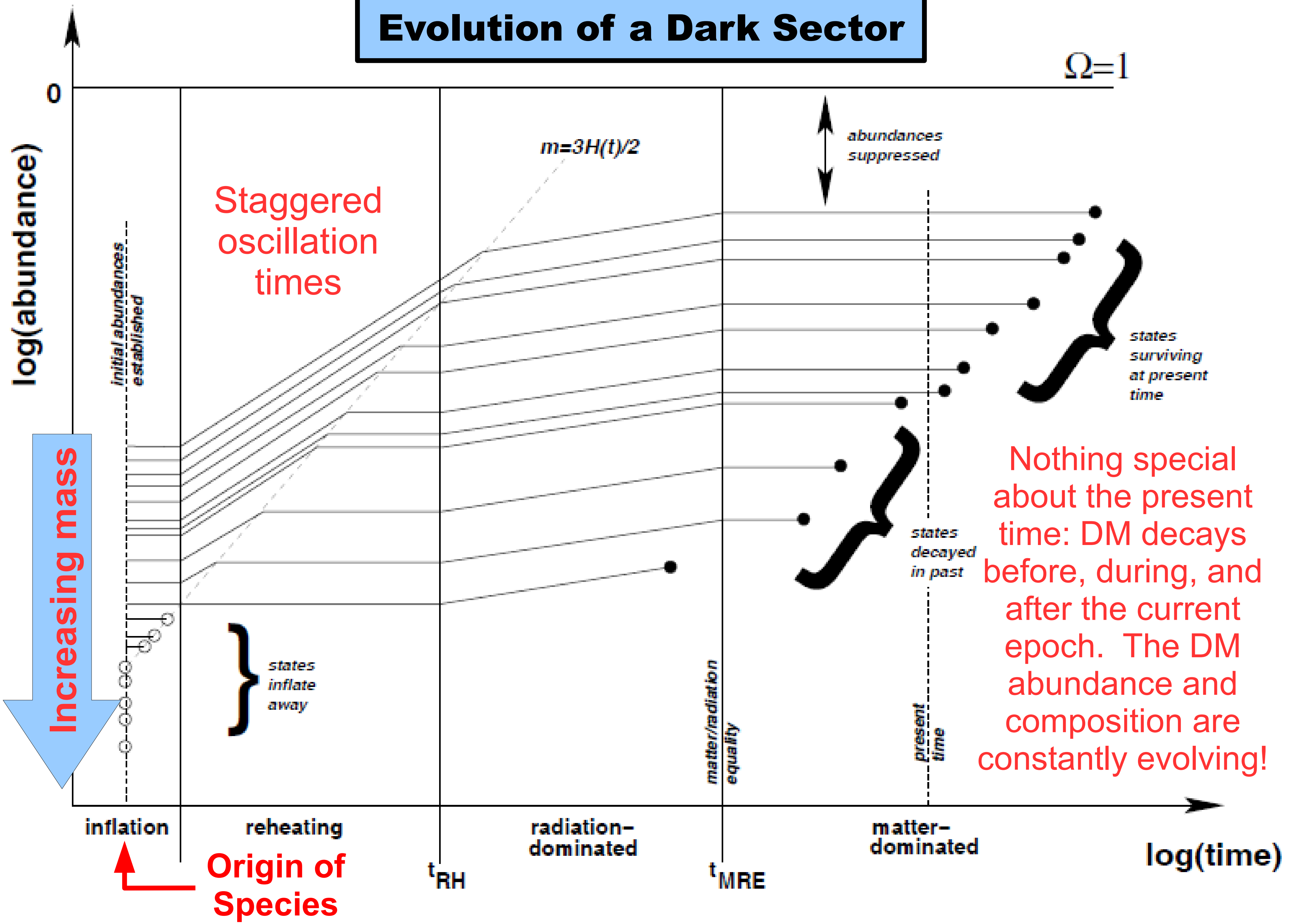
- Each scalar transitions from overdamped to underdamped oscillation at a time t_i, when:

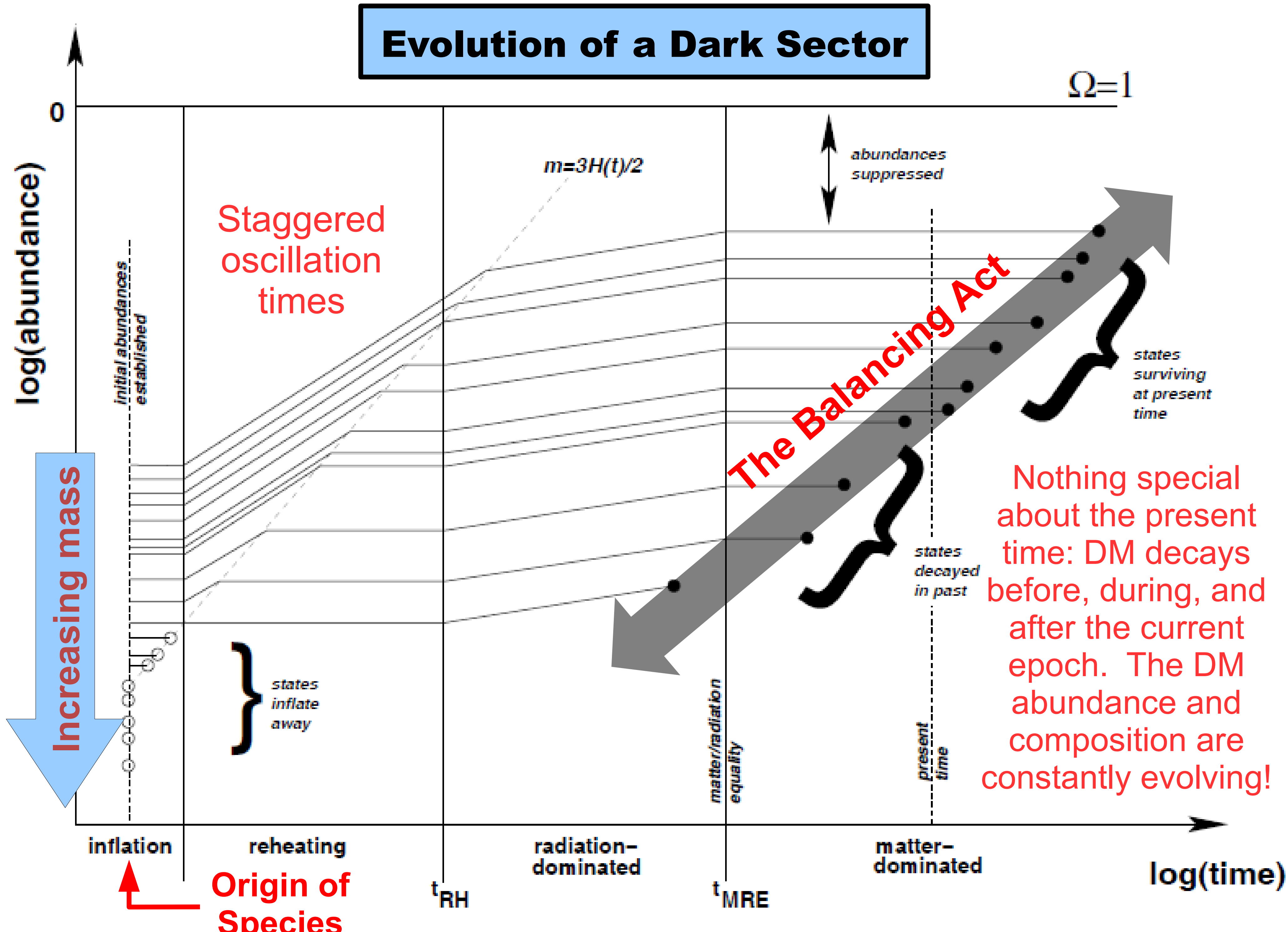
$$3H(t_i) = 2m_i \quad \Rightarrow \quad t_i \sim 1/m_i$$

Heavier states "turn on" first.

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

Evolution of a Dark Sector





Evolution of a Dark Sector
Ω=1
0
log(abundance)
m=3H(t)/2
abundances suppressed
Staggered oscillation times
initial abundances established
The Balancing Act
states surviving at present time
states decayed in past
Increasing mass
states inflate away
Nothing special about the present time: DM decays before, during, and after the current epoch. The DM abundance and composition are constantly evolving!
matter/radiation equality
present time
inflation
reheating
radiation-dominated
matter-dominated
log(time)
Origin of Species
t_RH
t_MRE

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:

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

$\eta = 0$ → 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 decay 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: $\Omega_i(t) \approx \Omega_i \Theta(\tau_i - t)$

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

We obtain the general result:

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

And from this result follow...

General expressions for our three fundamental quantities:

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

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)...

Explicit Models of DDM

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 $x_5=0$.

- The action can in principle include both **bulk-mass** and **brane-mass** terms:

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

KK-mode Mass-Squared Matrix

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

Non-renormalizable interactions suppressed by some heavy scale f_ϕ

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

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

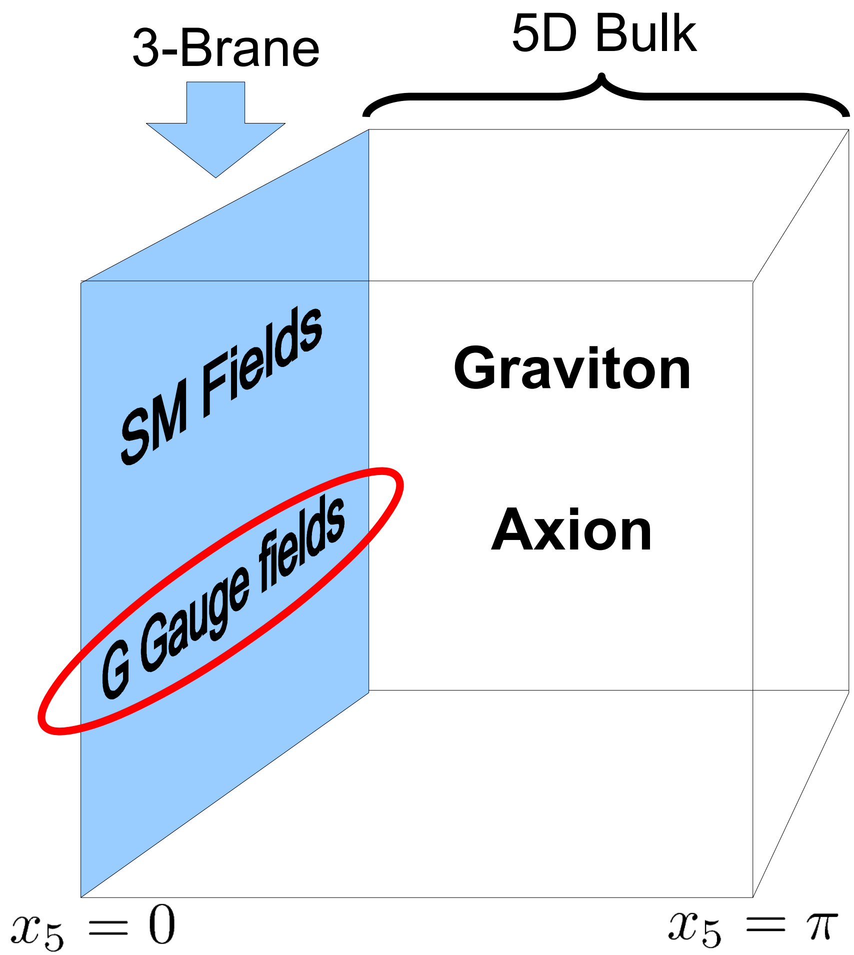
$y = 1/mR$

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.

Concrete Example: (Generalized) Bulk Axion



- Consider a 5D theory with the extra dimension compactified on S_1/Z_2 with radius $R = 1/M_c$.
- Global $U(1)_X$ symmetry broken at scale f_X by a bulk scalar → bulk axion is PNGB.
- SM and an **additional gauge group** G are restricted to the brane. G confines at a scale Λ_G. Instanton effects lead to a **brane-mass** term m_X for the axion.

Axion mass matrix:

$$\begin{pmatrix} m_X^2 & \sqrt{2}m_X^2 & \sqrt{2}m_X^2 & \cdots \\ \sqrt{2}m_X^2 & 2m_X^2 + M_c^2 & 2m_X^2 & \cdots \\ \sqrt{2}m_X^2 & 2m_X^2 & 2m_X^2 + 4M_c^2 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

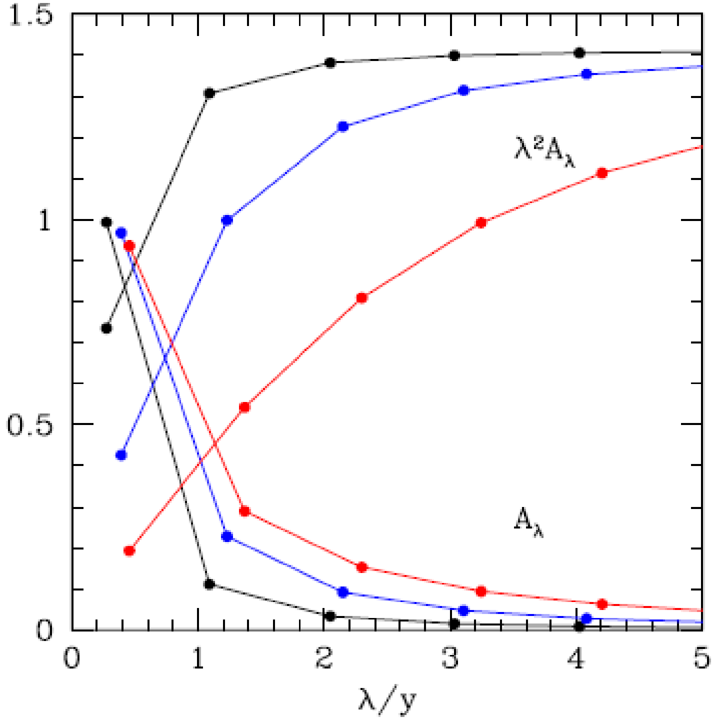
So indeed, when $y \equiv M_c/m_X$ is small, substantial mixing occurs:

Mass eigenstates $(\widetilde{\lambda} \equiv \lambda/m_X)$

$$a_\lambda = \sum_{n=0}^{\infty} U_{\lambda n} a_n \equiv \sum_{n=0}^{\infty} \left(\frac{r_n \widetilde{\lambda}^2}{\widetilde{\lambda}^2 - n^2 y^2} \right) A_\lambda a_n$$

"Mixing Factor"

$$A_\lambda = \frac{\sqrt{2}}{\widetilde{\lambda}} \left[1 + \widetilde{\lambda}^2 + \pi^2/y^2 \right]^{-1/2}$$



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:

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

Relic abundances (from misalignment):

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

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

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!

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

The Three Fundamental Questions:

1. "Does the relic abundance come out right?"

$$\Omega_{\text{tot}} \equiv \sum_\lambda \Omega_\lambda$$

must match

$$\Omega_{\text{DM}}^{\text{WMAP}} h^2 = 0.1131 \pm 0.0034$$

[Komatsu et al.; '09]

2. "Do a large number of modes contribute to that abundance, or does the lightest one make up essentially all of Ω_{DM}?"

In other words, is $\eta \sim \mathcal{O}(1)$

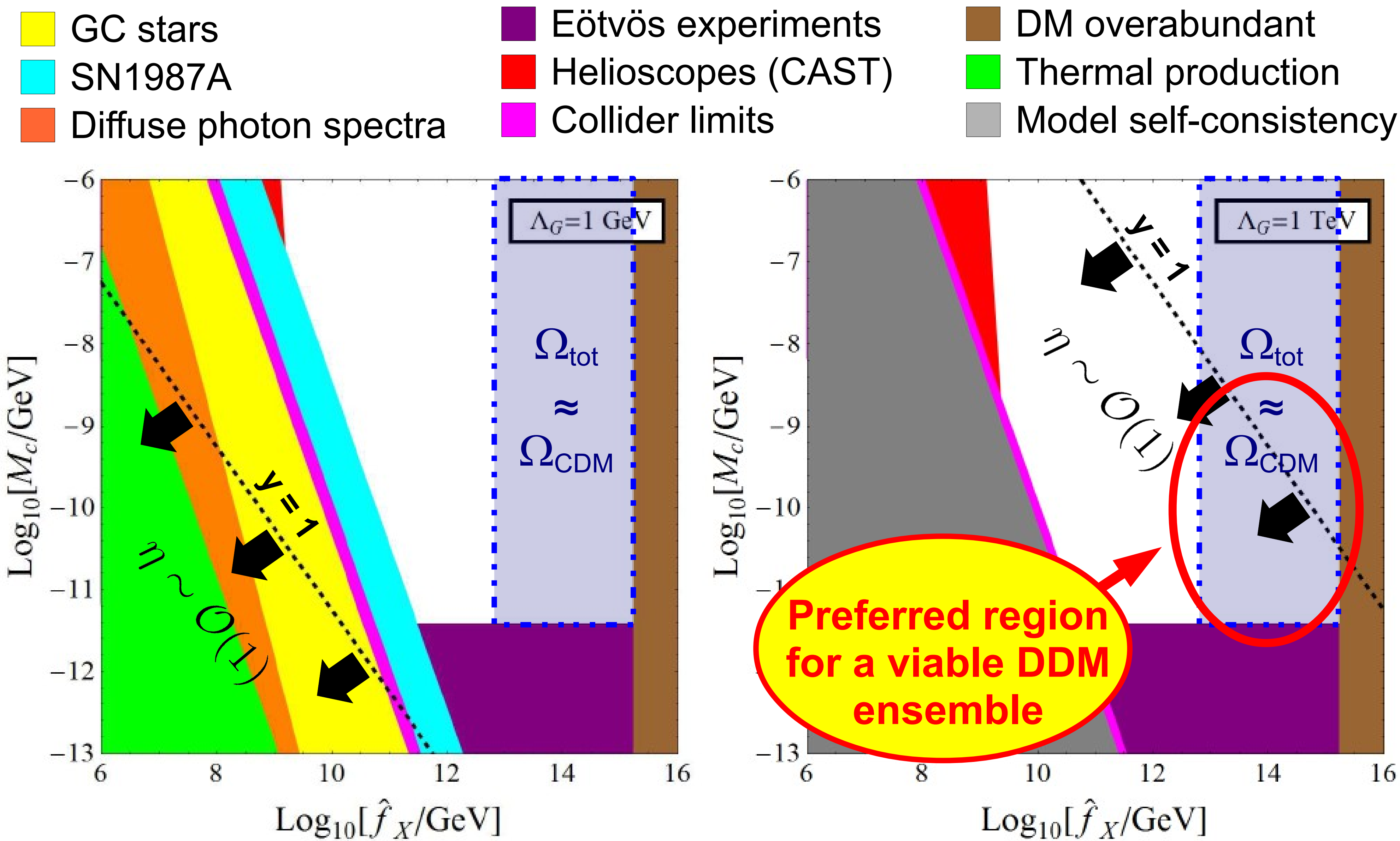
so that the full tower contributes nontrivially to Ω_{DM}?

3. "Is the model consistent with all of the applicable experimental, astrophysical, and cosmological constraints?"

Thanks to the properties of the mixing factor A_λ, the answer to all three questions can indeed (simultaneously) be in the affirmative!

The Result: A Viable DDM Ensemble

- While a great many considerations constrain scenarios involving light bulk axions, they can all be simultaneously satisfied while $\Omega_{tot} \approx \Omega_{CDM}$ and $\eta \sim O(1)$.



Constraints on Axion Models of DDM

- While a great many considerations constrain scenarios involving light bulk axions, they can all be simultaneously satisfied while $\Omega_{tot} \approx \Omega_{CDM}$ and $\eta \sim \mathcal{O}(1)$.

- GC stars
- SN1987A
- Diffuse photon spectra
- Eötvös experiments
- Helioscopes (CAST)
- Collider limits
- DM overabundant
- Thermal production

...and of course, there's also:

- Isocurvature perturbations
- Exotic hadron decays
- Light-shining-through-walls experiments
- Microwave-cavity detectors (ADMX)
- Light-element abundances (BBN)
- Late entropy production
- Inflation and primordial gravitational waves

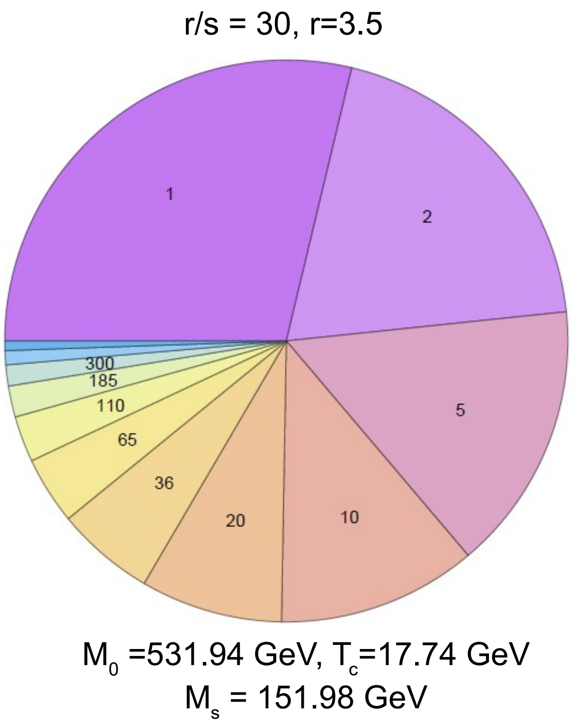
Within the region of parameter space in which $\Omega_{tot} \sim \Omega_{CDM}$, these are satisfied too!

Other Natural Contexts for DDM Ensembles:

Strongly-Coupled Theories

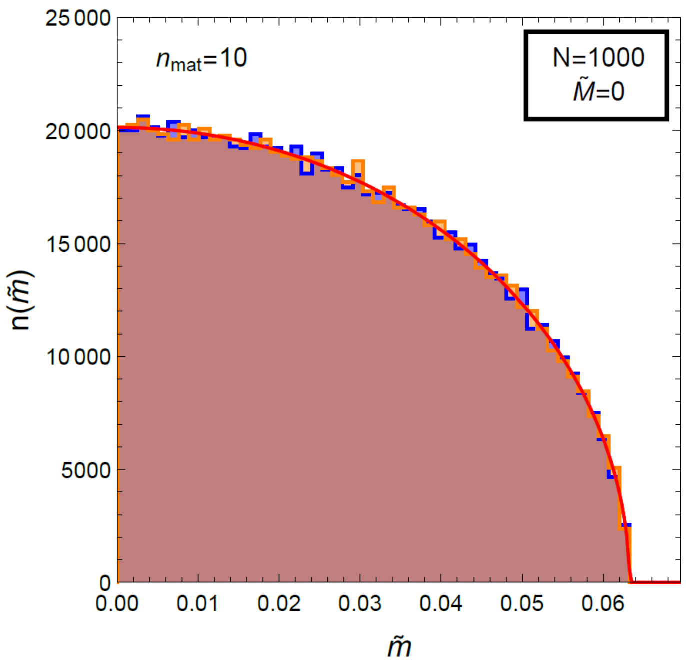
K. R. Dienes, F. Huang, S. Su, BT [arXiv:1512.xxxxx]

- Ensemble constituents are bound-state “hadronic” resonances associated with the confining phase of a strongly-coupled hidden sector.
- These resonances display a Hagedorn-like spectrum.



Theories with Large Hidden-Sector Groups

K. R. Dienes, J. Fennick, J. Kumar, BT [arXiv:1512.xxxxx]



- Naturally arise in grand unified theories, F-theory, string theory, etc.
- Ensemble constituents are the component fields within a multiplet of a large-rank symmetry group which is spontaneously broken.
- A robust statistical prediction for the mass spectrum arises in the limit in which the number of component fields is large.


Distinguishing DDM
at Hadron Colliders

- The first step in the study of DM at colliders is simply to observe an excess in one (or more) of the characteristic channels (with large $\not{E}_T$).
- However, once a signal of dark matter is initially identified in collider data, the questions then become:

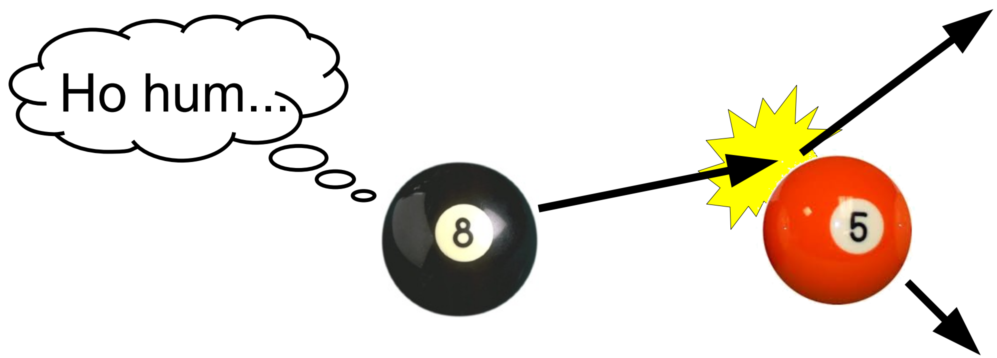
What information can we extract about the properties of the dark matter from collider data?

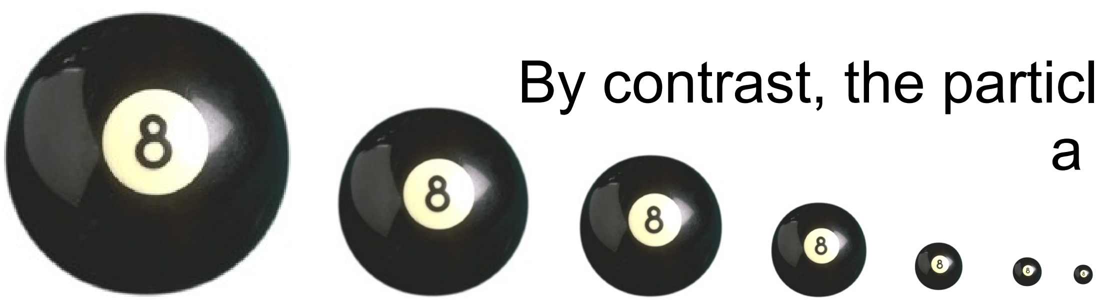
Can we distinguish DDM ensembles from more traditional DM candidates on the basis of that data?

Q: **How can we tell dark ensembles and traditional dark-matter candidates apart?**

A: In a number of ways, but the simplest and most straightforward has to do with **kinematics**.

Traditional dark-matter candidates have a well-defined mass. Leads to predictable kinematics at colliders, direct-detection experiments, etc.





By contrast, the particles in a DDM ensemble have a **broad spectrum** of different masses and couplings.

Indeed, the **kinematic** aspects of how dark ensembles interact with normal matter are profoundly different!

These considerations lead to a number of ways for discovering and distingushing DDM ensembles:

At colliders:

Through distinctive features in the kinematic distributions of Standard-Model particles.

K. R. Dienes, S. Su, BT
[arXiv:1204.4183]
[arXiv:1406.2606]

At direct-detection experiments:

Through distinctive features in the energy spectra of recoiling nuclei.

K. R. Dienes, J. Kumar, BT
[arXiv:1208.0336]

At indirect-detection experiments:

Through distinctive features in the spectra of particular cosmic-ray particles.

K. R. Dienes, J. Kumar, BT
[arXiv:1306.2959]

These are just three examples **observable effects** to which DDM ensembles can give rise that can serve to distinguish them from traditional DM candidates experimentally.

Let's turn to examine some of the phenomenological possibilities inherent in the DDM framework in greater detail.

- A number of strategies and tools have been developed in an effort to distinguish non-minimal dark sectors at colliders in particular scenarios:

• Distinguishing between different DM stabilization symmetries.	Agashe, Kim, Toharia, Walker [1003.0899]; Agashe, Kim, Walker, Zhu [1012.4460]
• M_{T2} variants for determining DM-particle masses in two-component DM systems.	Barr, Gripaios, Lester [1012.4460]; Konar, Kong, Matchev, Park [0911.4126]
• Analyis of cusp and endpoint structures in kinematic distributions.	Han, Kim, Song [1206.5633,1206.5641]

...and many more!

And there's *another* subtlety:

- Searching for non-minimaliy in the dark sector typically requires analysis of the **full distributions** of particular kinematic variables.

- Distribution-based searches involve additional subtelties that bump-hunting searches do not. For example, understanding **correlations between kinematic variables** becomes far more critical – and might mean the difference between seeing and missing a signal of non-minimality in the dark-sector!

Searching for Signs of DDM at the LHC

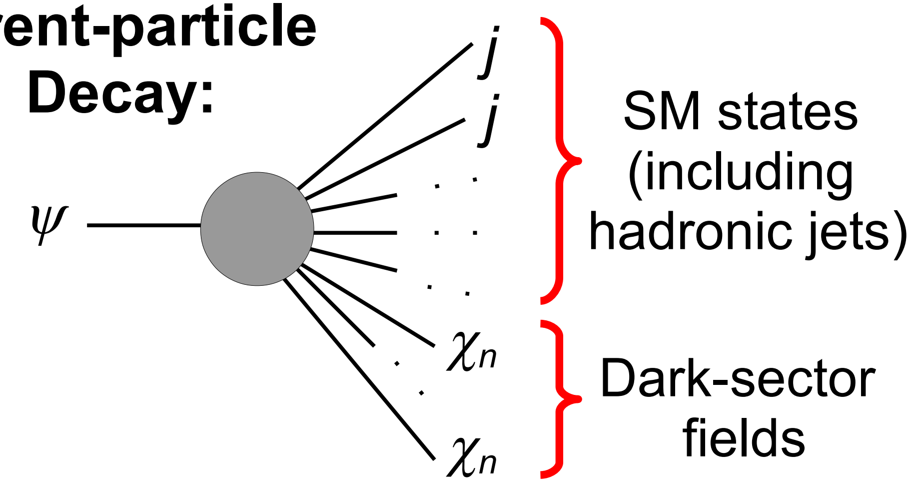
- In a wide variety of DM models, dark-sector fields can be produced via the decays of some heavy **"parent particle"** ψ.

- Strongly interacting ψ can be produced copiously at the LHC. $SU(3)_c$ invariance requires that such ψ decay to final states including not only dark-sector fields, but **SM quarks and gluons** as well.

- In such scenarios, the initial signals of dark matter will generically appear at the LHC in channels involving jets and $\not{E}_T$.

Further information about the dark sector or particles can **also** be gleaned from examining the **kinematic distributions** of visible particles produced alongside the DM particles.

Parent-particle Decay:

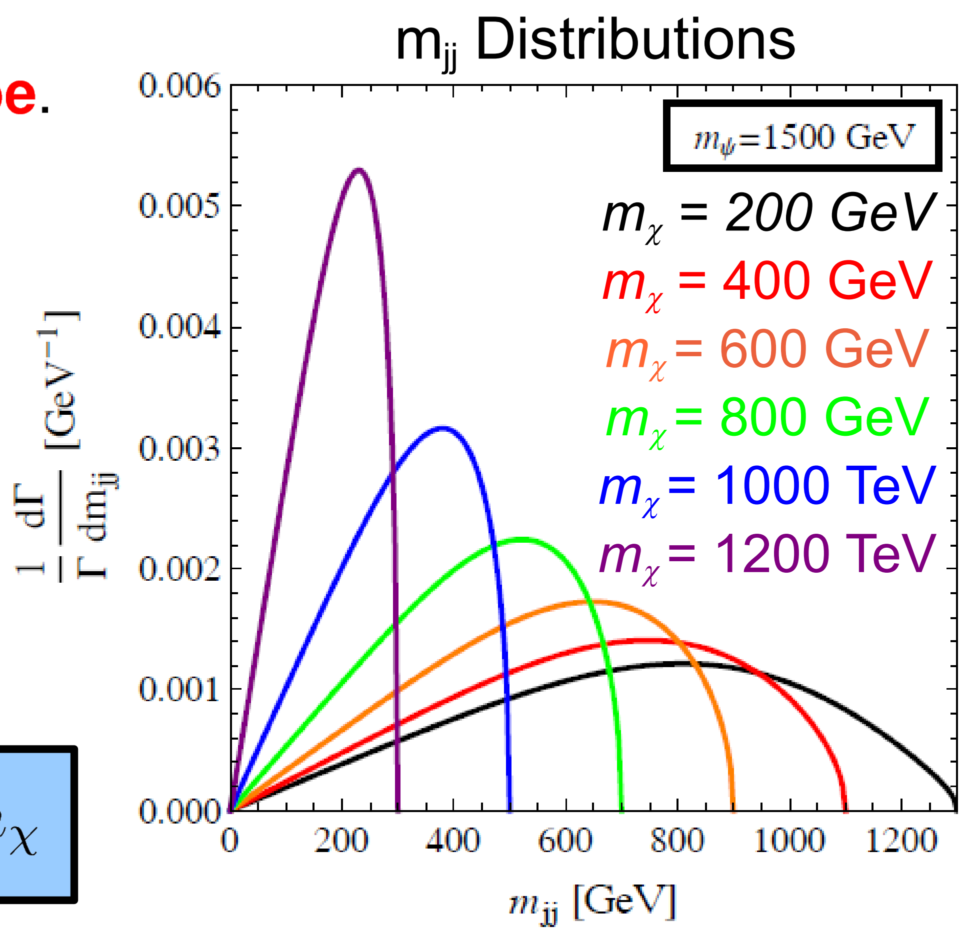


As we shall see, such information can be used to distinguish DDM ensembles from traditional DM candidates on the basis of LHC data.

Traditional DM Candidates

- Let's begin by considering a dark sector which consists of a traditional dark-matter candidate χ — a **stable** particle with a mass m_χ.
- For concreteness, consider the case in which ψ decays primarily via the **three-body** process $\psi \to jj\chi$ (no on-shell intermediary).
- Invariant-mass distributions for such decays manifest a **characteristic shape**.
- Different coupling structures between ψ, χ, and the SM quark and gluon fields, different representations for ψ, *etc.* have only a small effect on the distribution.
- m_{jj} distributions characterized by the presence of a **mass "edge"** at the kinematic endpoint:

$$m_{jj} \leq m_\psi - m_\chi$$



Parent Particles and DDM Daughters

In general, the constituent particles χ_n in a DDM ensemble and other fields in the theory through some set of effective operators $O_n^{(\alpha)}$:

$$\mathcal{L}_{\text{eff}} = \sum_{\alpha} \sum_{n=0}^{N} \frac{c_{n\alpha}}{\Lambda^{d_\alpha - 4}} \mathcal{O}_n^{(\alpha)} + \ldots$$

As an example, consider a theory in which the masses and coupling coefficients of the χ_n scale as follows:

$$c_{n\alpha} = c_{0\alpha} \left(\frac{m_n}{m_0} \right)^{\gamma_\alpha}$$

$$m_n = m_0 + n^{\delta} \Delta m$$

γ_α : scaling indices for couplings

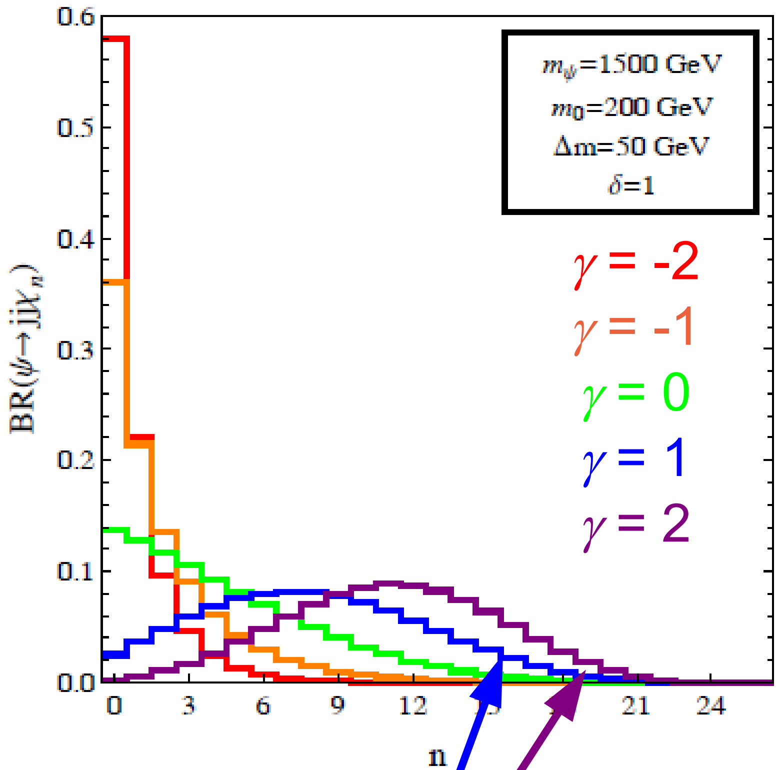
Including coupling between ψ and the dark-sector fields χ_n.

m_0 : mass of lightest constituent

δ : scaling index for the density of states

Δm : mass-splitting parameter

Parent-Particle Branching Fractions



- Once again, let's consider the simplest non-trivial case in which ψ couples to each of the χ_n via a four-body interaction, e.g.:

$$\mathcal{L}_{\text{eff}} = \sum_n \left[\frac{c_n}{\Lambda^2} (\overline{q}_i t^a_{ij} \psi^a)(\overline{\chi}_n q_j) + \text{h.c.} \right]$$

- Assume partent's total width Γ_ψ dominated by decays of the form $\psi \to jj\chi_n$.

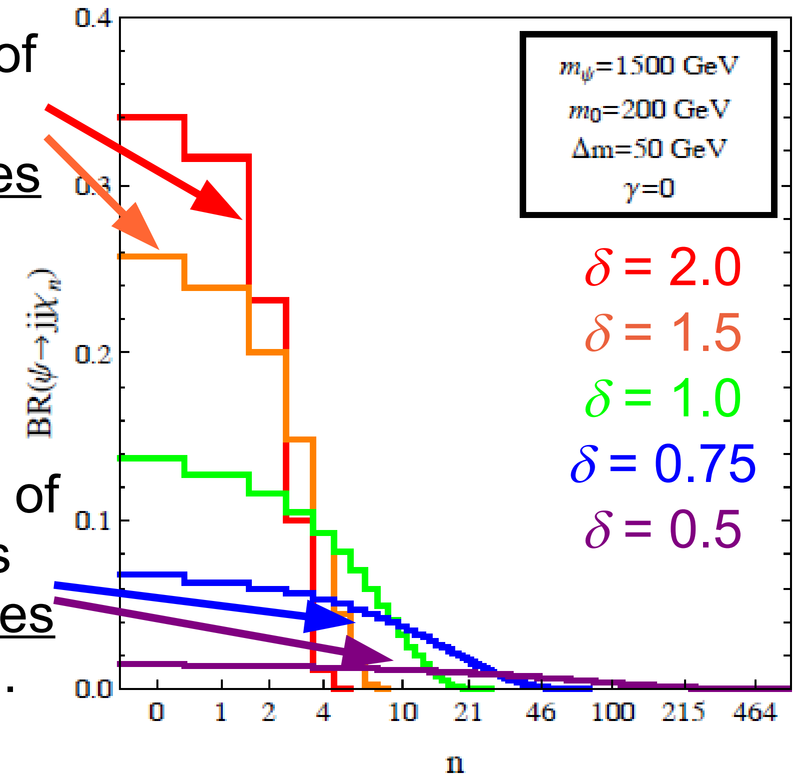
Coupling stength increases with n for γ>0...

…but phase space always decreases with n.

- **Branching fractions** of ψ to the different χ_n controlled by Δm, δ, and γ.

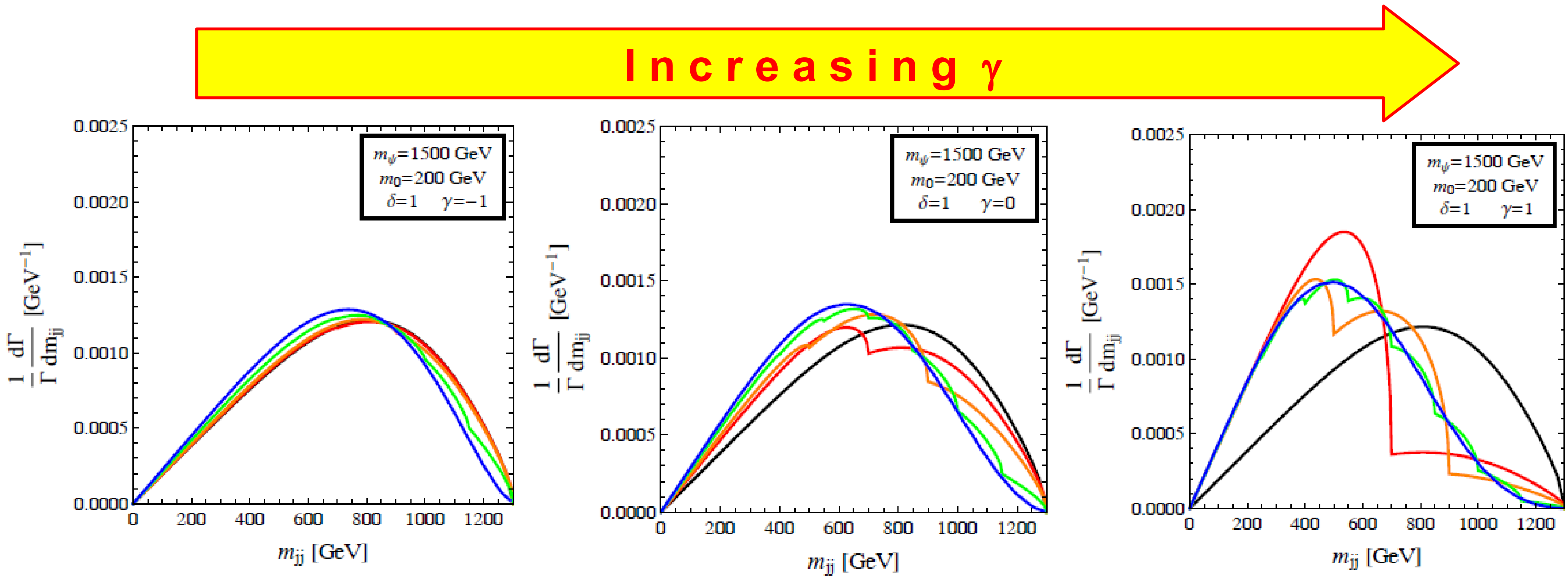
Density of states decreases with n.

Density of states increases with n.



DDM Ensembles & Kinematic Distributions

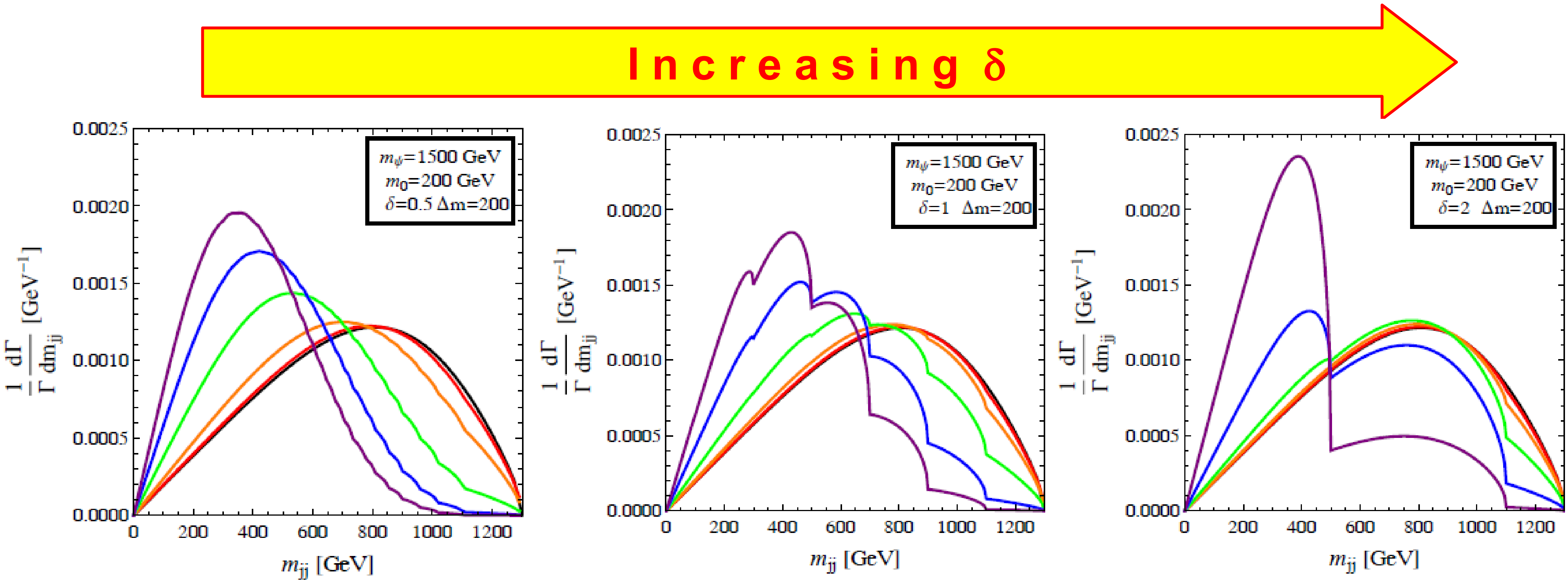
- Evidence of a DDM ensemble can be ascertained from characteristic features imprinted on the kinematic distributions of these SM particles.

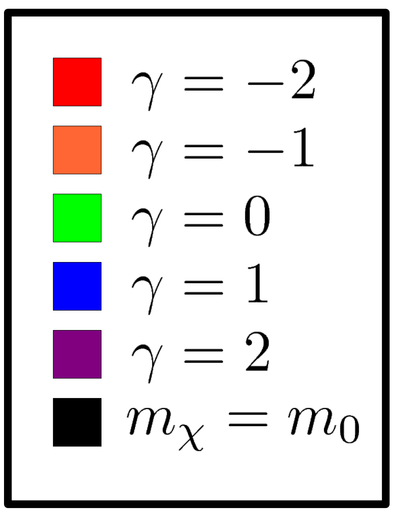


- $\Delta m = 600$ GeV (red)
- $\Delta m = 400$ GeV (orange)
- $\Delta m = 150$ GeV (green)
- $\Delta m = 20$ GeV (blue)
- $m_\chi = m_0$ (black)

- For example, in the scenarios we're considering here, the (normalized) dijet invariant-mass distribution is given by

$$\frac{1}{\Gamma_\psi}\frac{d\Gamma_\psi}{dm_{jj}} = \sum_{n=0}^{n_{\max}} \left(\frac{1}{\Gamma_{\psi n}}\frac{d\Gamma_{\psi n}}{dm_{jj}} \times \mathrm{BR}_{\psi n} \right)$$





Two Characteristic Signatures:

1. Multiple distinguishable peaks

Large δ, Δm: individual contributions from two or more of the χ_n can be resolved.

2. The Collective Bell

Small δ, Δm: Individual peaks cannot be distinguished, mass edge "lost," m_{jj} distribution assumes a characteristic shape.

But the REAL question is...

How well can we distinguish these features in practice?

In other words: to what degree are the characteristic kinematic distributions to which DDM ensembles give rise truly **distinctive**, in the sense that they cannot be reproduced by **any** traditional DM model?

The Procedure:

- Survey over traditional DM models with different DM-candidate masses m_χ and coupling structures.
- Divide the into bins with width determined by the invariant-mass resolution Δm_{jj} of the detector (dominated by jet-energy resolution ΔE_j).
- For each value of m_χ in the survey, define a χ^2 statistic $\chi^2(m_\chi)$ to quantify the degree to which the two resulting m_{jj} distributions differ.

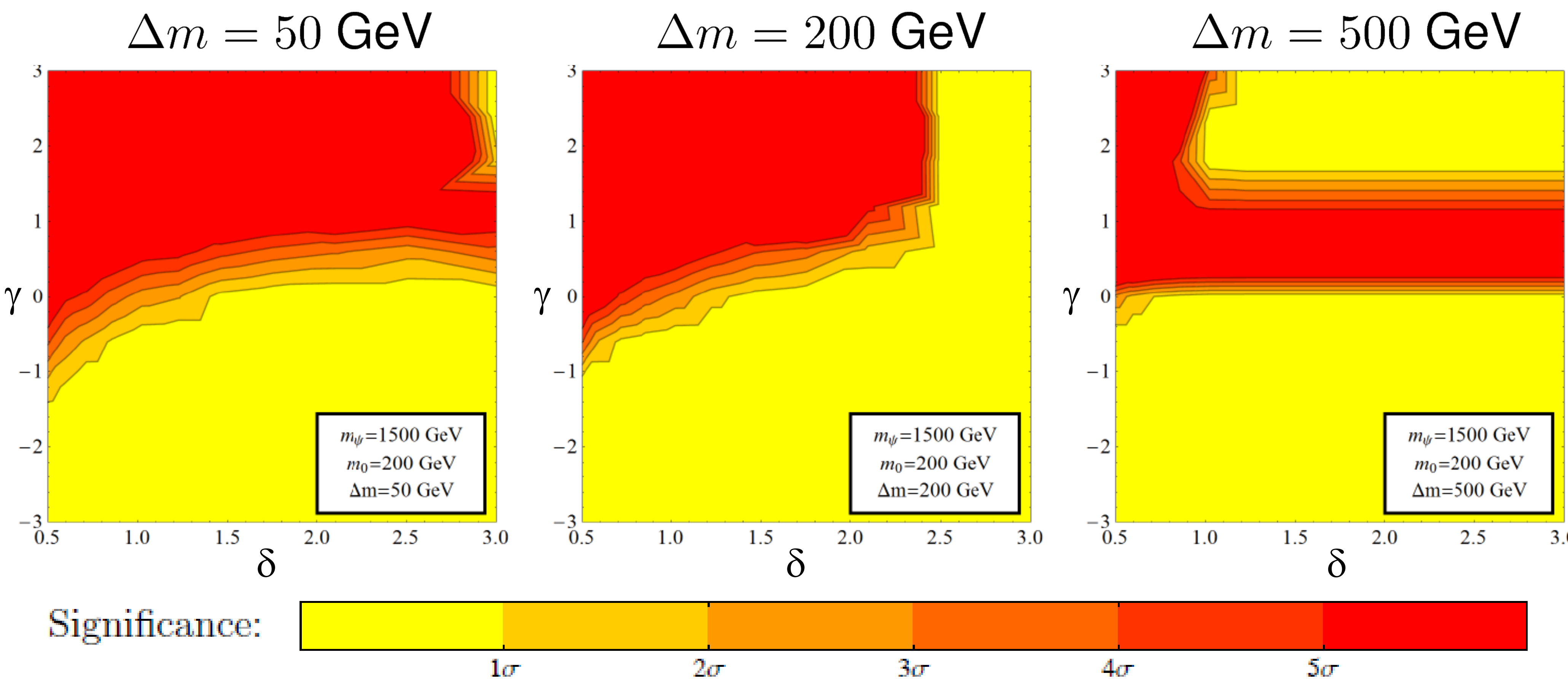
$$\chi^2(m_\chi) = \sum_k \frac{[X_k - \mathcal{E}_k(m_\chi)]^2}{\sigma_k^2}$$

$$\chi^2_{\min} = \min_{m_\chi}\left\{\chi^2(m_\chi)\right\}$$

- The **minimum** χ^2 value from among these represents the degree to which a DDM ensemble can be distinguished from **any** traditional DM candidate.

Distinguishing DDM Ensembles: Results

Results for N_e = 1000 signal events (e.g., $pp \to \psi\psi$ for TeV-scale parent, L_{int} < 30 fb^{-1})



The Main Message:

DDM ensembles can be distinguished from traditional DM candidates at the 5σ level throughout a substantial region of parameter space.

Cuts and Correlations in Distribution-Based Searches

It is well known that **correlations between collider variables** can have an important impact on data-analysis strategies for any collider analysis:

- Cuts imposed on one kinematic variable (e.g., for purposes of background reduction) will affect the shape of the distribution of any other variable with which it is non-trivially correlated.
- Such cuts can potentially **wash out distinctive features** in these distributions which provide signs of dark-sector non-minimality.
- Alternatively, in certain special cases, they can actually **amplify** the distictiveness of these distributions.

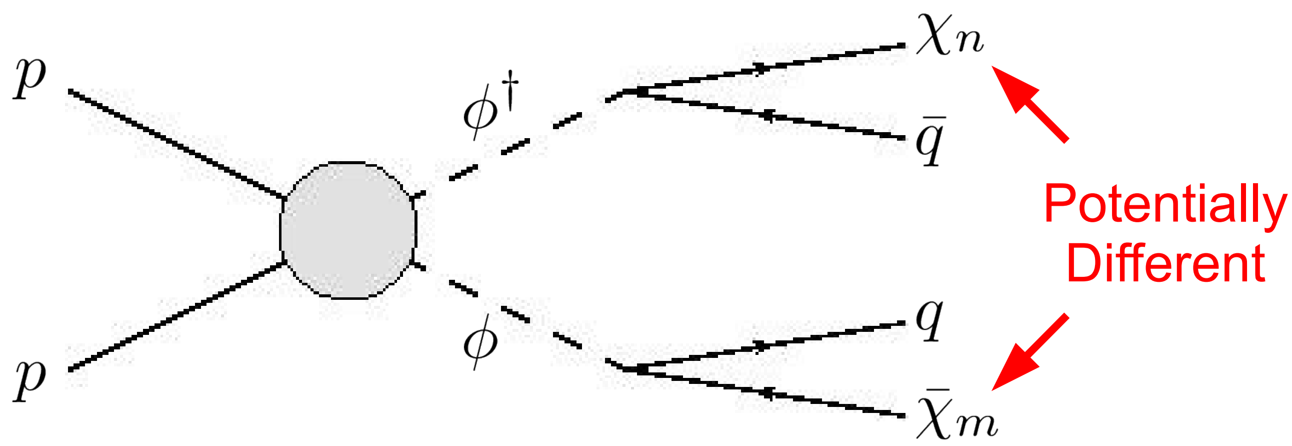
Our primary goal is to investigate the impact of such correlations in developing and optimizing search strategies for non-minimal dark sectors at colliders.

In each case, assume some heavy, strongly-interacting "parent" particle ϕ which decays to dark-sector states χ_n via the interaction Lagrangian

$$\mathcal{L}_{\text{int}} = \sum_{n=0}^{N} \sum_{q} \left[c_{nq} \phi^\dagger \overline{\chi}_n q_R + \text{h.c.} \right]$$

Search Channel:

$$pp \to jj + \not{E}_T$$



Parametrizing the DDM ensemble:

Toy model with scaling behavior for masses and couplings motivated by realstic DDM models: (Dienes, BT [1107.0721,1203.1923])

Mass spectrum: $m_n = m_0 + n^\delta \Delta m$

Coupling spectrum: $c_n = c_0 \left(\frac{m_n}{m_0} \right)^\gamma$

Standard Collider Variables

(for dijet events)

- Missing energy $\not{E}_T$
- p_{T_1} and p_{T_2} (transverse momenta of the leading two jets)
- $H_{T_{jj}} \equiv \sum_{i=1}^{2} p_{T_i}$ (scalar sum of p_{T_1} and p_{T_2})
- $H_T \equiv \not{E}_T + \sum_{i=1}^{N} p_{T_i}$
- $\alpha_T \equiv |p_{T_2}|/m_{jj}$ Randall, Tucker-Smith [0806.1049]; CMS [PAS SUS-09-001]
- $|\Delta\phi_{jj}|$ (difference in azimuthal angle between $\vec{p}_{T_1}$ and $\vec{p}_{T_2}$)
- Transverse mass M_{T_1} (formed from $\vec{p}_{T_1}$ and $\vec{\not{p}}_T$)
- Standard M_{T2} variable Lester, Summers [hep-hp/9906349]

Compare signal distibutions of these variables from different scenarios in order to identify the most auspicious strategies for distinguishing non-minimal dark sectors.

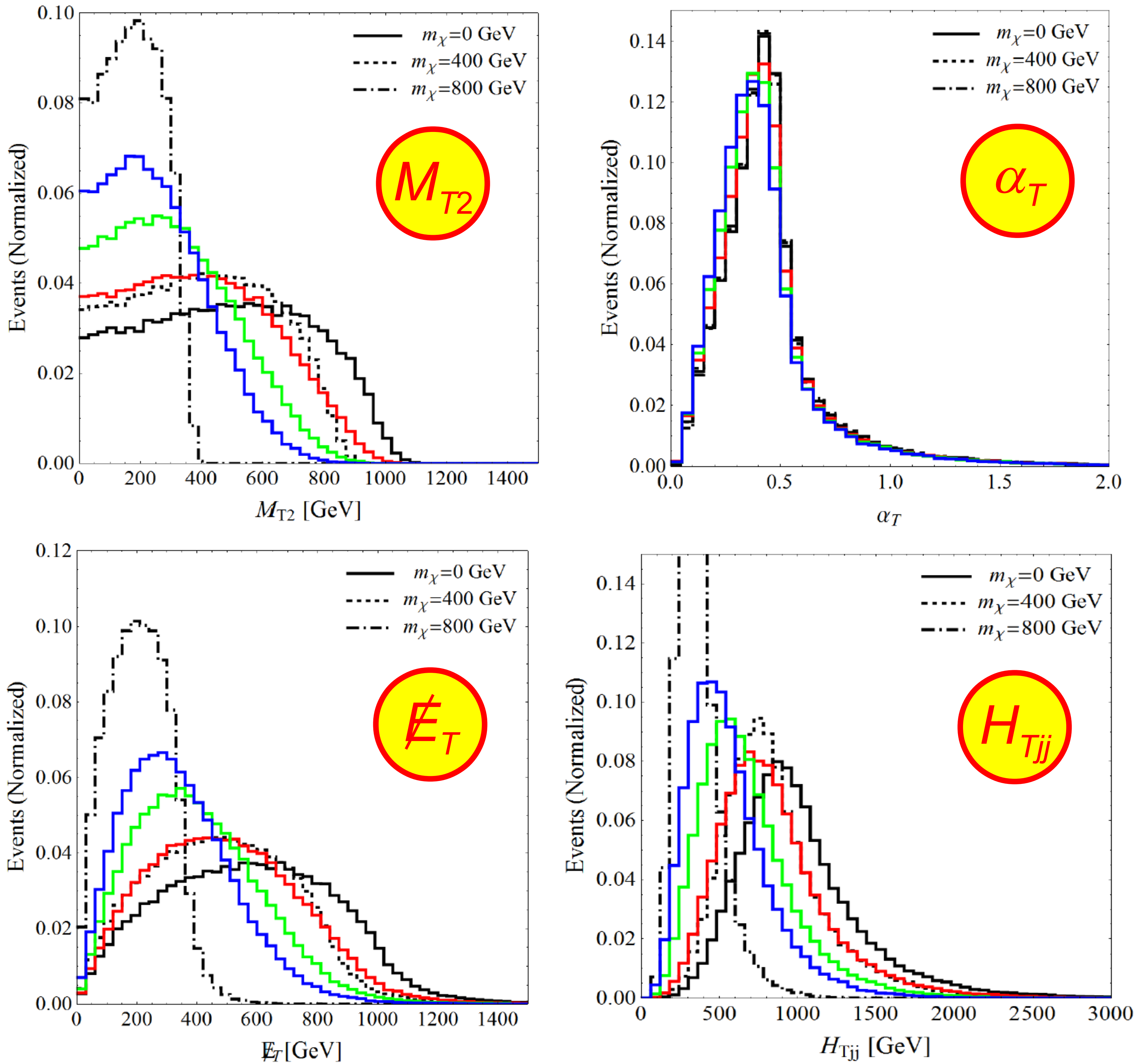
The Distributions:

Example shown here:

$$m_0 = 200\text{ GeV}$$
$$m_\phi = 1\text{ TeV}$$
$$\Delta m = 50\text{ GeV}$$
$$\delta = 1$$

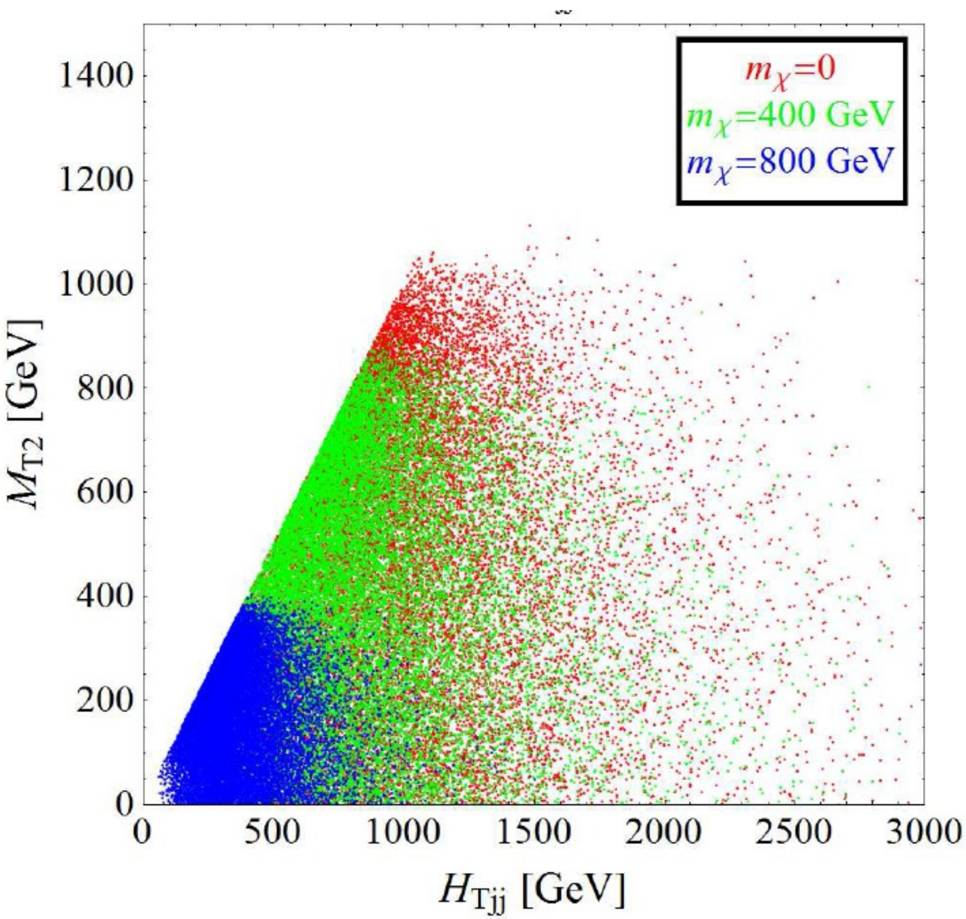
with

γ = 0
γ = 1
γ = 2



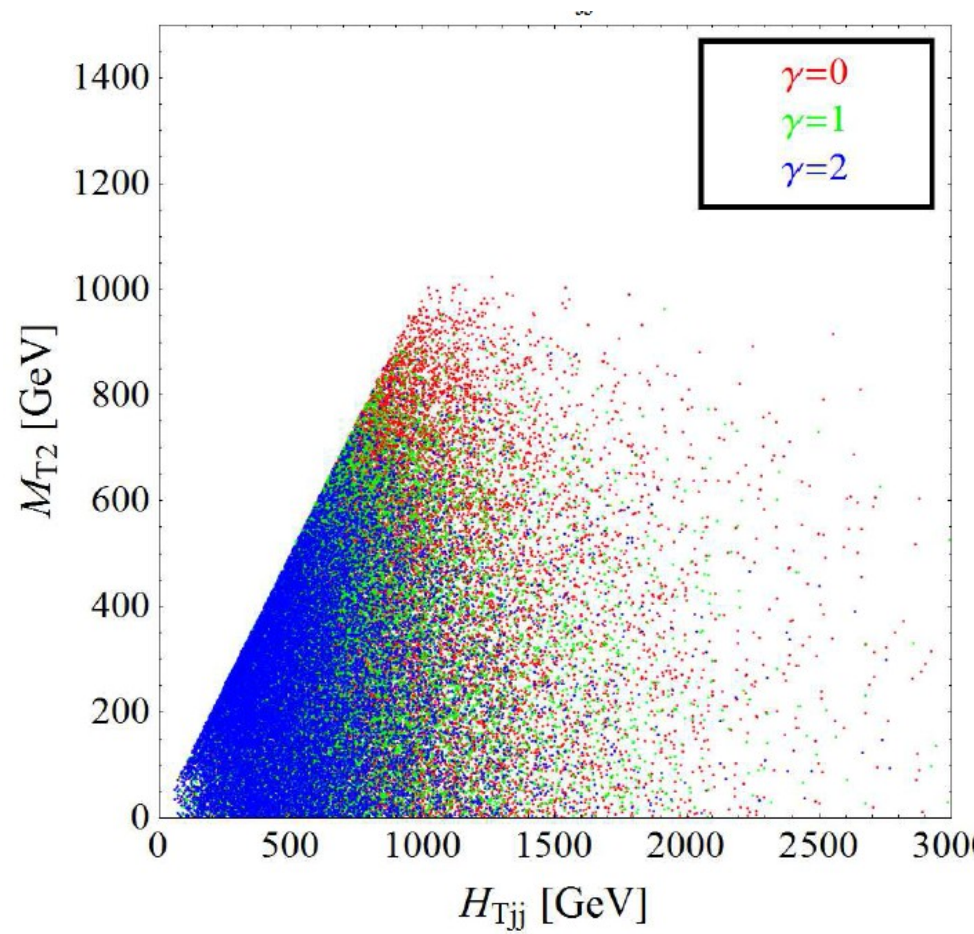
Unhelpful Correlations: $H_{T_{jj}}$ vs. M_{T2}

Traditional Dark-Matter Candidates



$m_\phi = 1$ TeV

Dynamical Dark-Matter Models

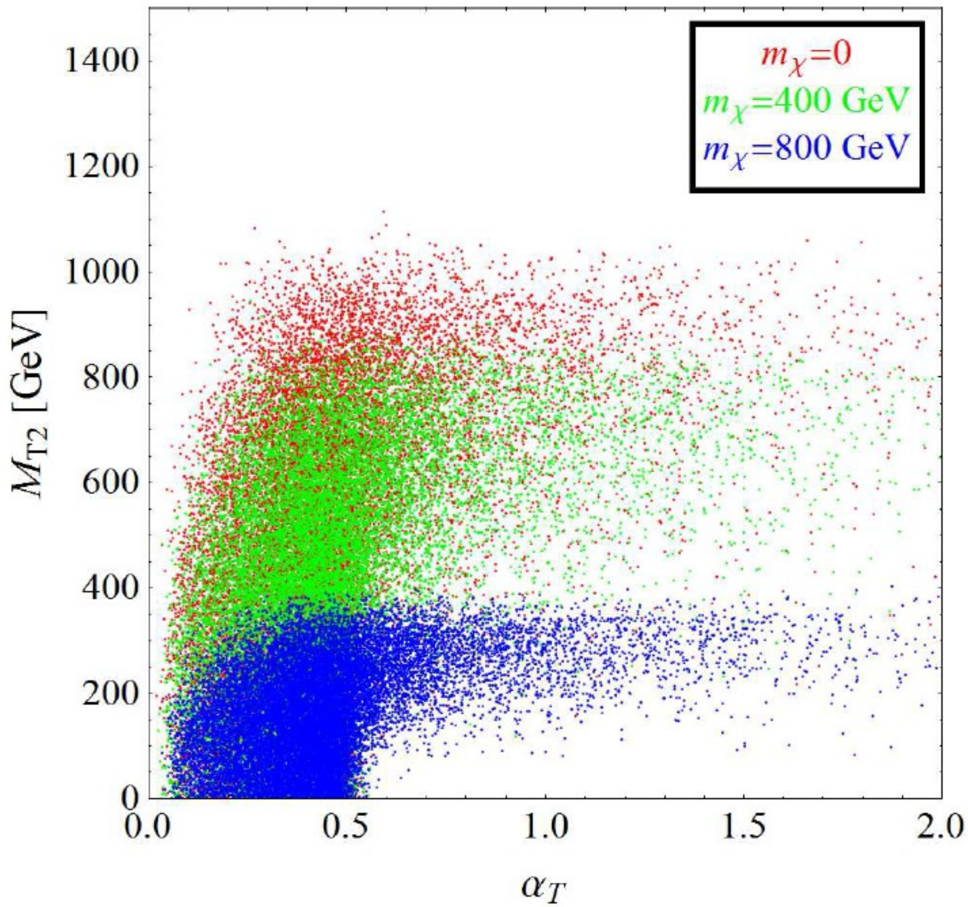


$m_0 = 100$ GeV $m_\phi = 1$ TeV

$\Delta m = 50$ GeV $\delta = 1$

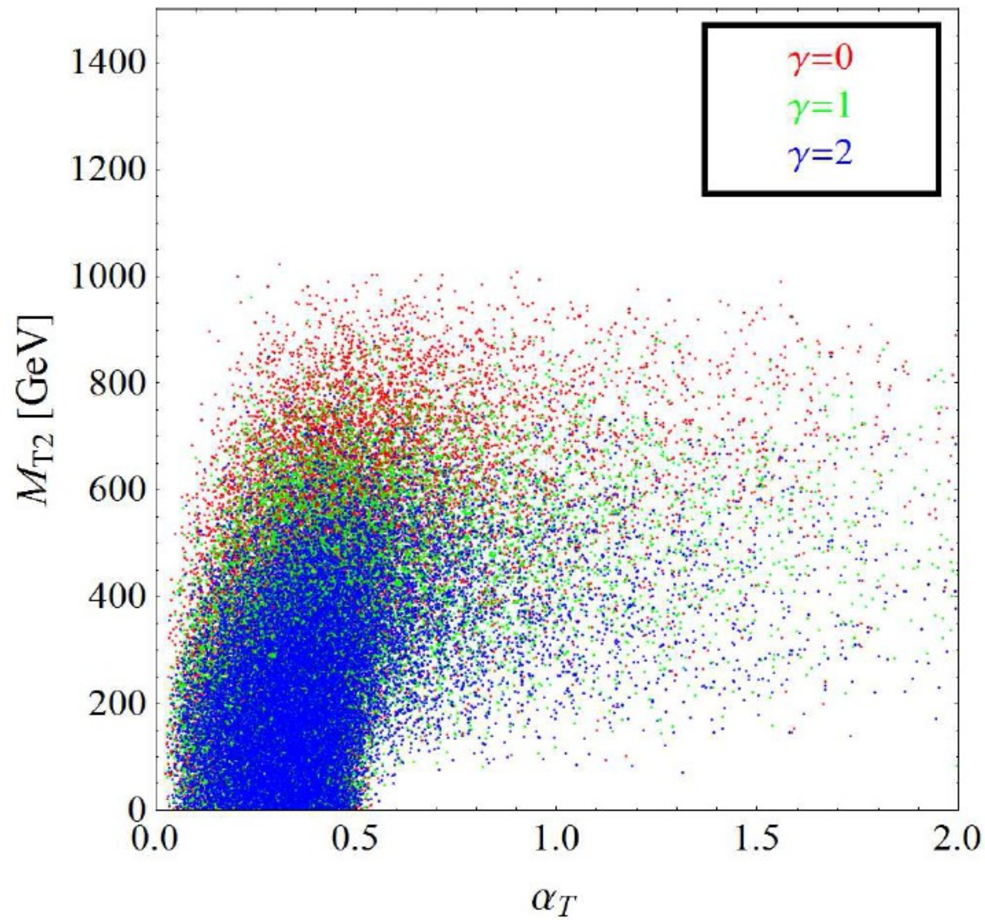
Helpful Correlations: α_T and M_{T2}

Traditional Dark-Matter Candidates



$m_\phi = 1$ TeV

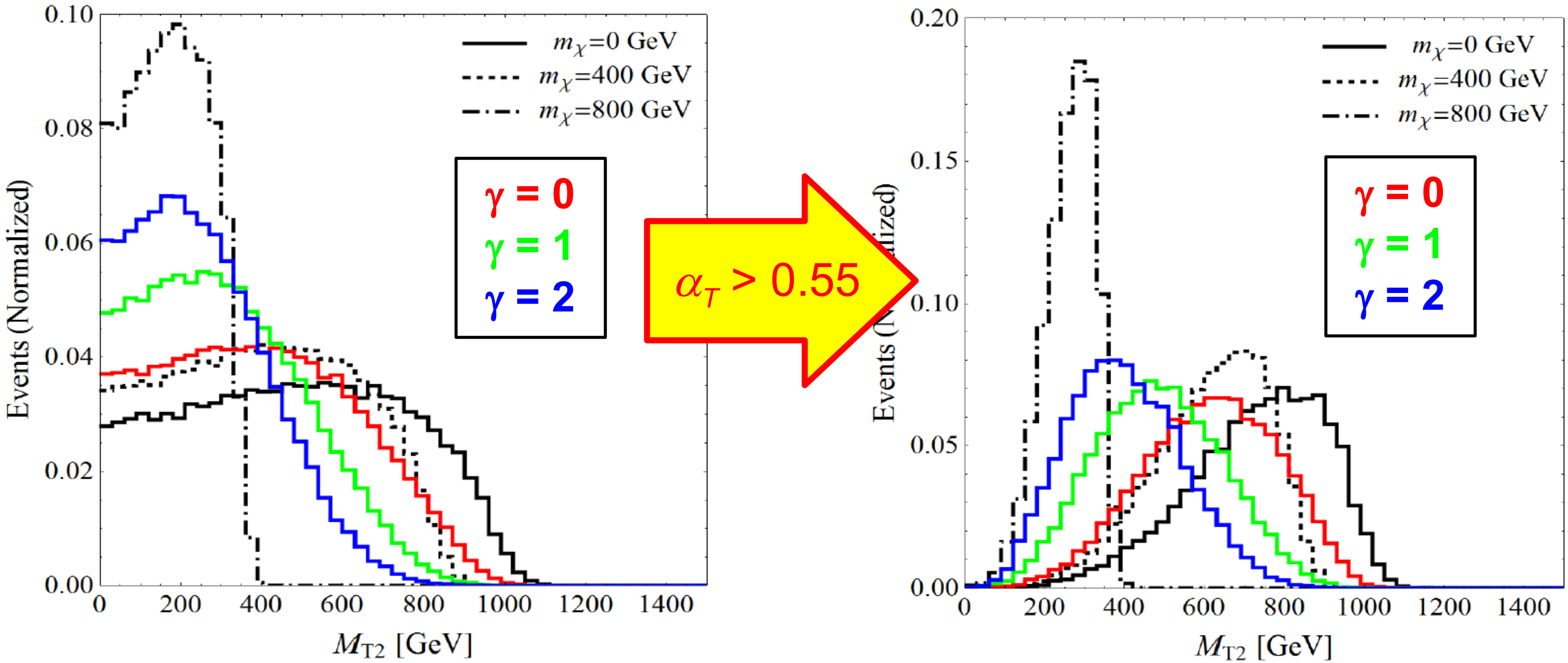
Dynamical Dark-Matter Models



$m_0 = 100$ GeV $\quad m_\phi = 1$ TeV

$\Delta m = 50$ GeV $\quad \delta = 1$

The Effect of the Cut



$m_0 = 200$ GeV $\quad m_\phi = 1$ TeV $\quad \Delta m = 50$ GeV $\quad \delta = 1$

Indeed, our α_T cut has a **dramatic effect** on the distinctiveness of the M_{T2} distributions associated with non-minimal dark sectors!

Similar effect on other kinematic distributions.

Quantifying distinctiveness

As before, our goal is to assess to what degree the kinematic distributions associated with non-minmal dark sectors **truly** distinctive, in the sense that they cannot be reproduced by **any** traditional DM model.

Thus, we adopt a similar procedure as before:

- Survey over traditional DM models with different DM-candidate masses m_χ and coupling structures.
- Divide the distribution into appropriately-sized bins.
- For each value of m_χ in the survey, define the goodness-of-fit statistic $G(m_\chi)$ to quantify the degree to which the two resulting m_{jj} distributions differ.

likelihood ratio

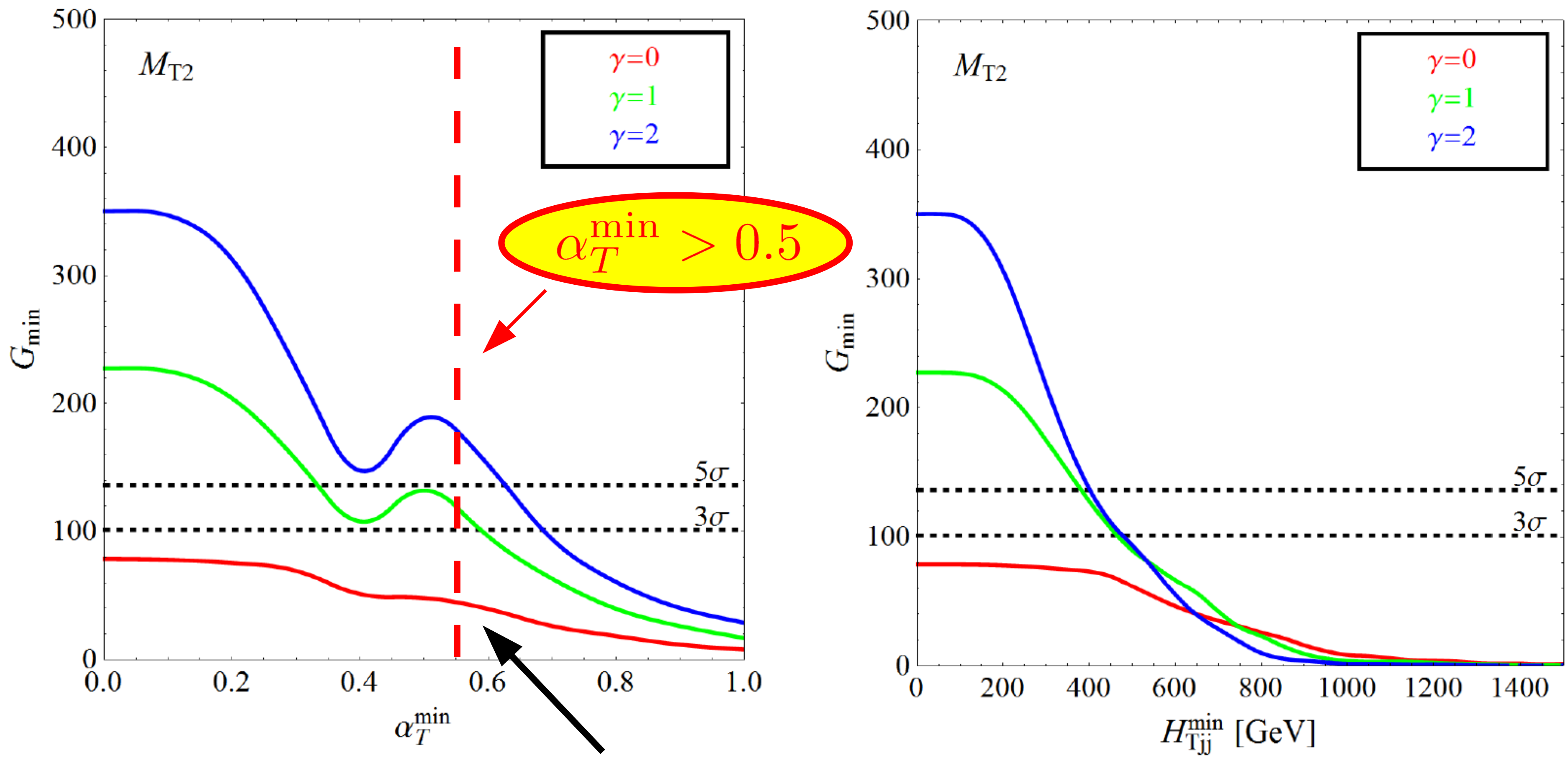
$$G(m_\chi) = -2\ln\lambda(m_\chi)$$

$$G_{\min} = \min_{m_\chi}\{G(m_\chi)\}$$

- The **minimum** $G(m_\chi)$ from among these represents the degree to which a DDM ensemble can be distinguished from **any** traditional DM candidate.

Distinguishing Power: M_{T2} Distributions

(as a function of applied cuts)

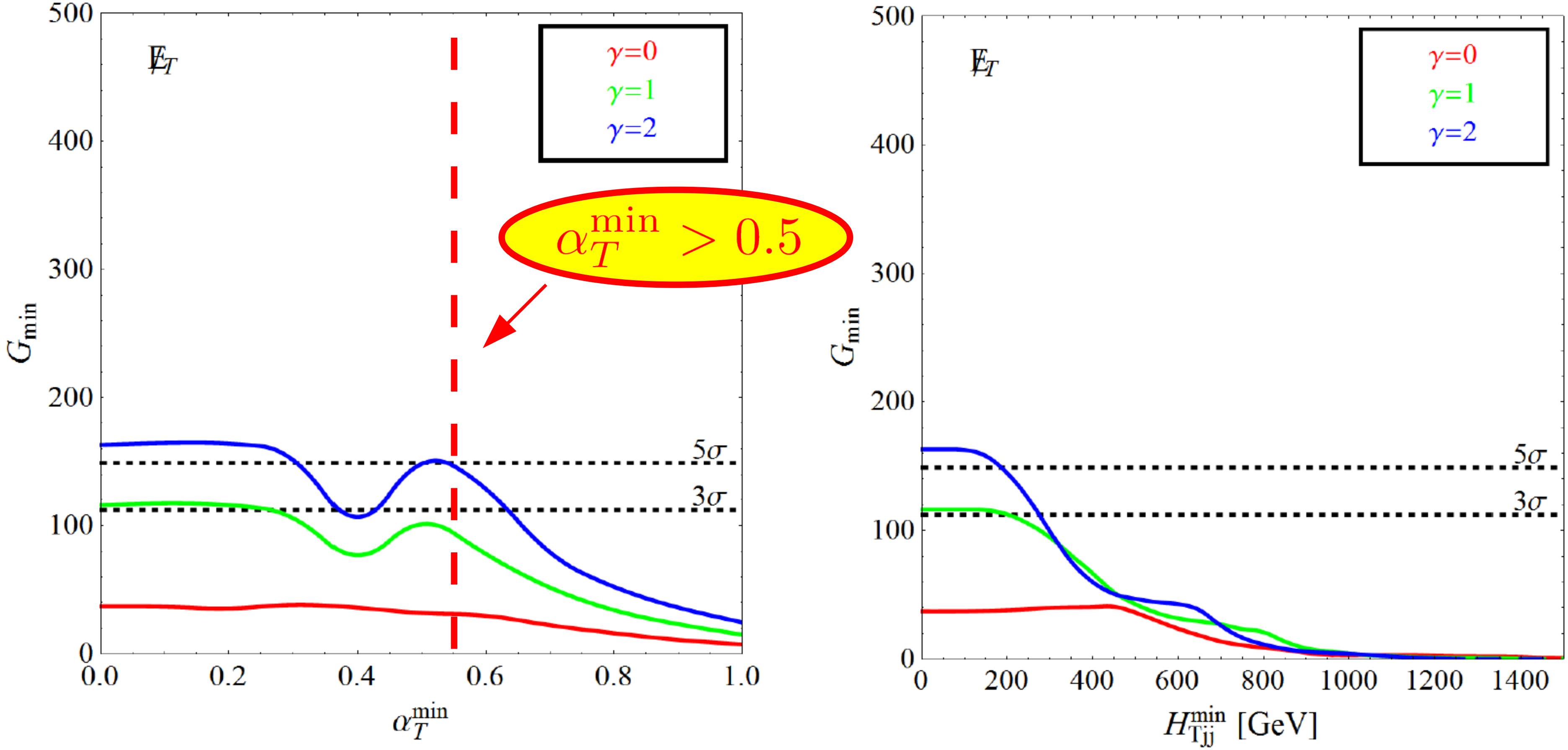


A well-chosen cut on α_T actually serves to **amplify** the distinctiveness of the singal distributions, despite the loss in statistics!

An α_T cut on this order is also helpful in reducing residual QCD backgrounds.

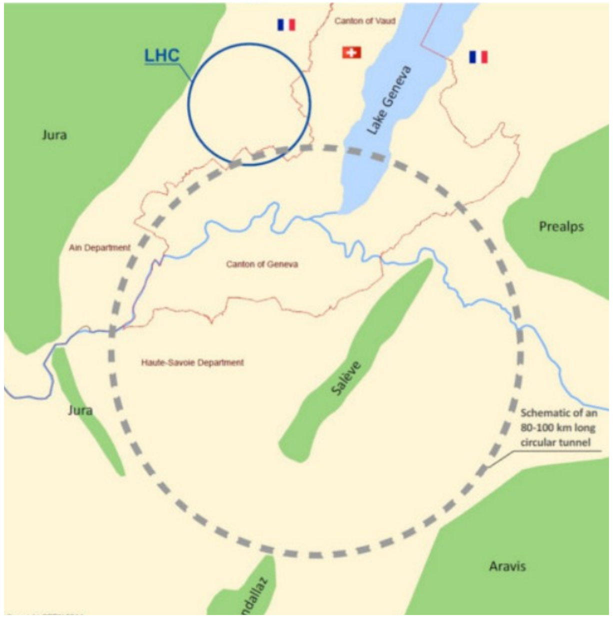
Distinguishing Power: $\not{E}_T$ Distributions

(as a function of applied cuts)



Similar results to those obtained for M_{T2} distributions, but with slightly less sensitivity.

Advantages of a 100 TeV Collider



- In DDM scenarios, the dark-matter candidate is not merely a single dark-matter particle, but an ensemble of particles with a broad range of masses.
- The experimental goal is therefore not merely to detect an excess in some particular channel, but to characterize the entire mass spectrum of the ensemble, including the heavier, more unstable components.

- Event rates at colliders are independent of cosmological abundance, unlike signals at direct- and indirect-detection experiments. Essential for probing studying the properties of the heavier states in the ensemble, whose abundances are typically suppressed.

Summary

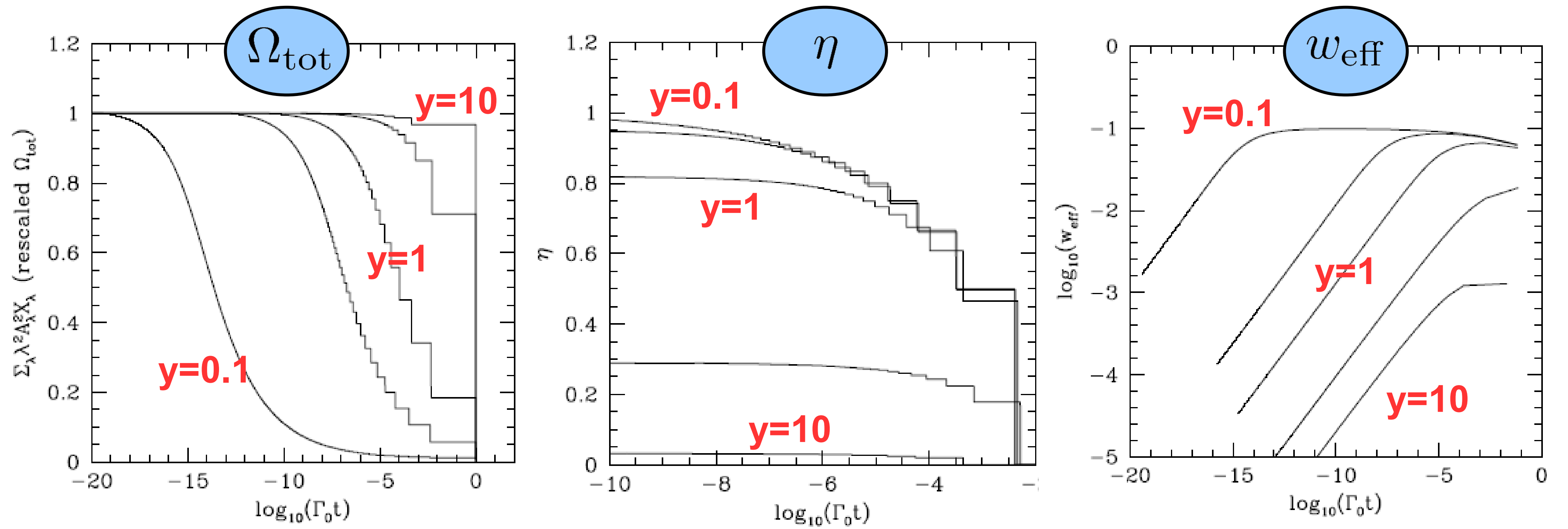
- Dynamical Dark Matter represents an alterative approach to the dark-matter problem in which the usual requirement of dark-matter stability is replaced by a **balancing of decay widths against abundances** across an ensemble constituent particles.
- These ensembles arise naturally in a number of BSM contexts.
- DDM ensembles can give rise to **distinctive experimental signatures** which permit one to distinguish them from traditional dark-matter candidates.

Signatures at hadron colliders typically manifest themselves in the shapes of **kinematic distributions** – for example, of variables such as $\not{E}_T$ and M_{T2}.

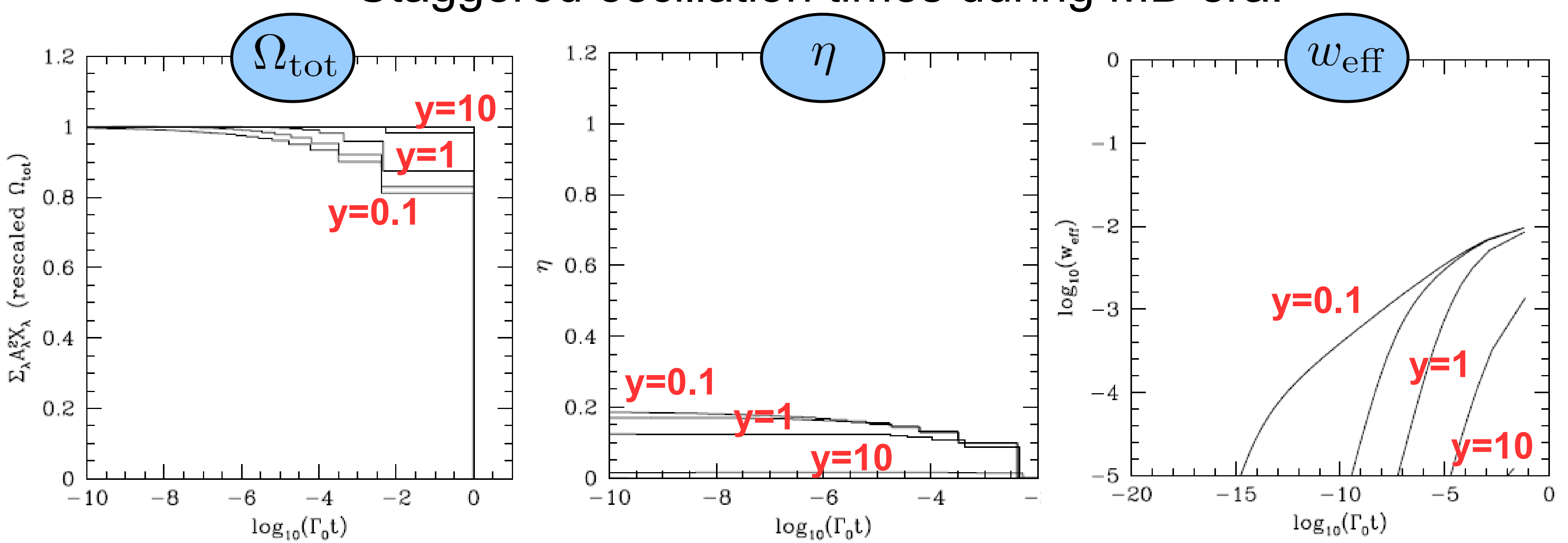
- Cuts imposed on the data (for background reduction, etc.) can distort these distributions due to non-trivial **correlations** between collider variables.
- Appropriately chosen cuts on particular variables such as α_T can actually **enhance** the distinctiveness of these distributions.

Extra Slides

Simultaneous oscillation:

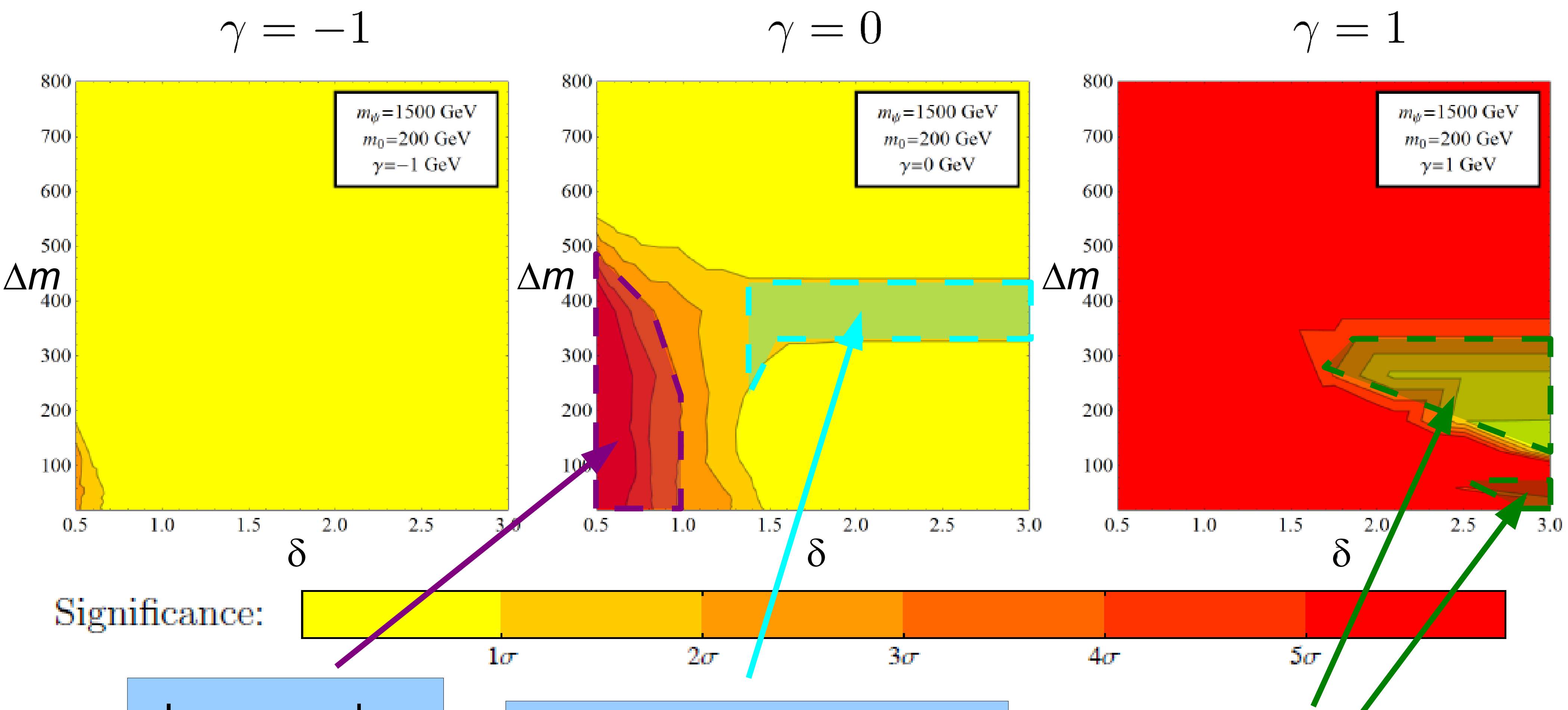


Staggered oscillation times during MD era:



Distinguishing DDM Ensembles: Results

Results for N_e = 1000 signal events (e.g., $pp \rightarrow \psi\psi$ for TeV-scale parent, L_{int} < 30 fb^{-1})



Large number of states accessible for small Δm, δ

BR($\psi \rightarrow jj\chi_0$) ≈ BR($\psi \rightarrow jj\chi_1$): two distinct m_{jj} peaks.

Only χ_0 and χ_1 kinematically accessible. One or the other dominates the width of ψ.