Phenomenological Implications of Dynamical Dark Matter

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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

The Dark Matter Problem: Abundance vs. Stability

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: $\Omega_\chi \vdots\ \Omega_{\rm CDM} \approx 0.23$.
- 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 ~10^{17} s)

Consequences

- Such "hyperstability" is the **<u>only</u>** 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": $\Omega_{\rm CDM}$ changes only due to Hubble expansion, etc.

Dynamical Dark Matter

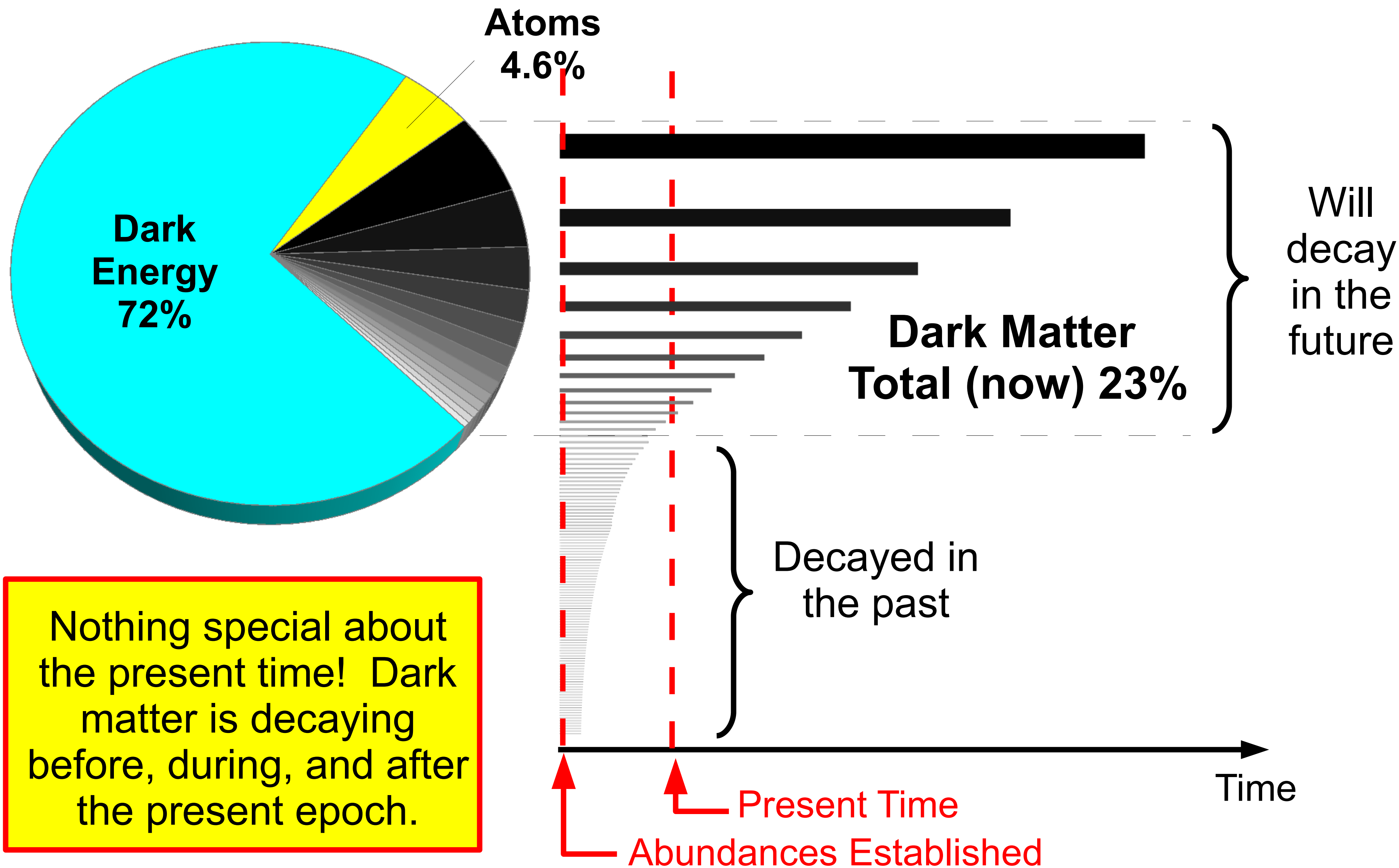
K. Dienes, BT [arXiv:1106.4546, arXiv:1107.0721]

Dynamical Dark Matter (DDM) is an alternative framework for addressing thge dark-matter problem <u>without</u> imposin of hyperstability.

In particular, in DDM scenarios...

- The dark-matter candidate is an **<u>ensemble</u>** 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 **<u>balanced against decay rates</u>** 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 **<u>non-trivial time-dependence</u>** beyond that associated with the expansion of the universe.

DDM Cosmology: The Big Picture



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

The all-important questions:

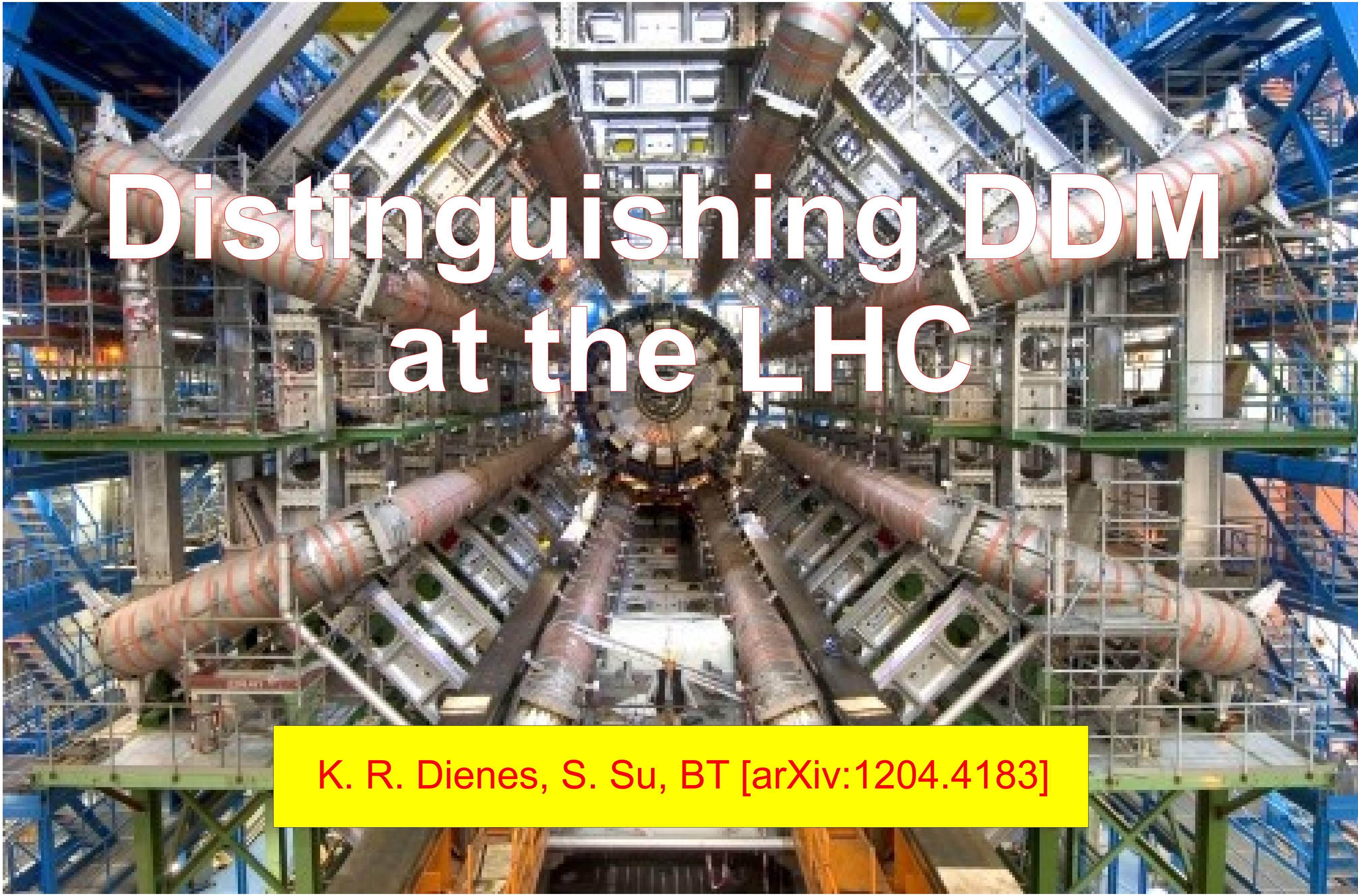
(No untestable theory shall pass!)

How can we detect DDM ensembles in practice?

How can we distinguish these ensembles from other DM candidates experimentally?

In this talk, I'll examine some of the phenomenological consequences that can arise within the DDM framework and discuss the prospects for **detecting** and **distinguishing** DDM ensembles...

- At colliders
- At direct-detection experiments
- Indirectly, via cosmic-ray signatures



Distinguishing DDM at the LHC

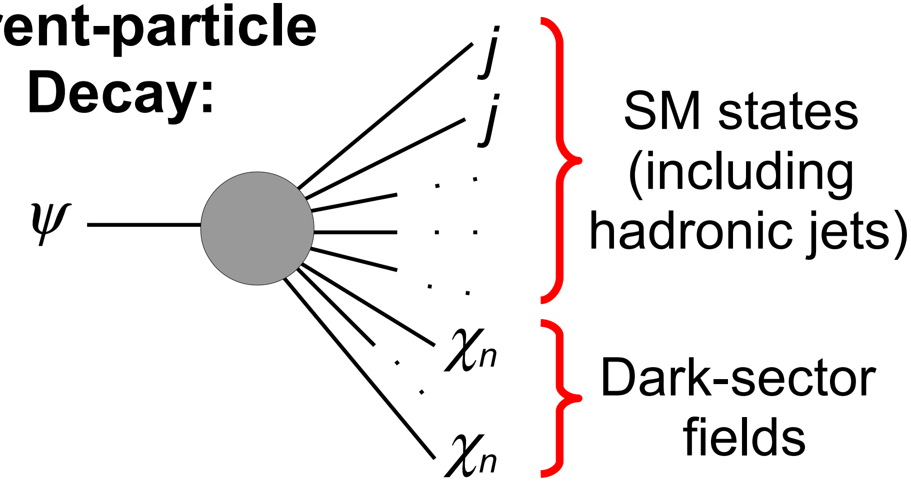
K. R. Dienes, S. Su, BT [arXiv:1204.4183]

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:



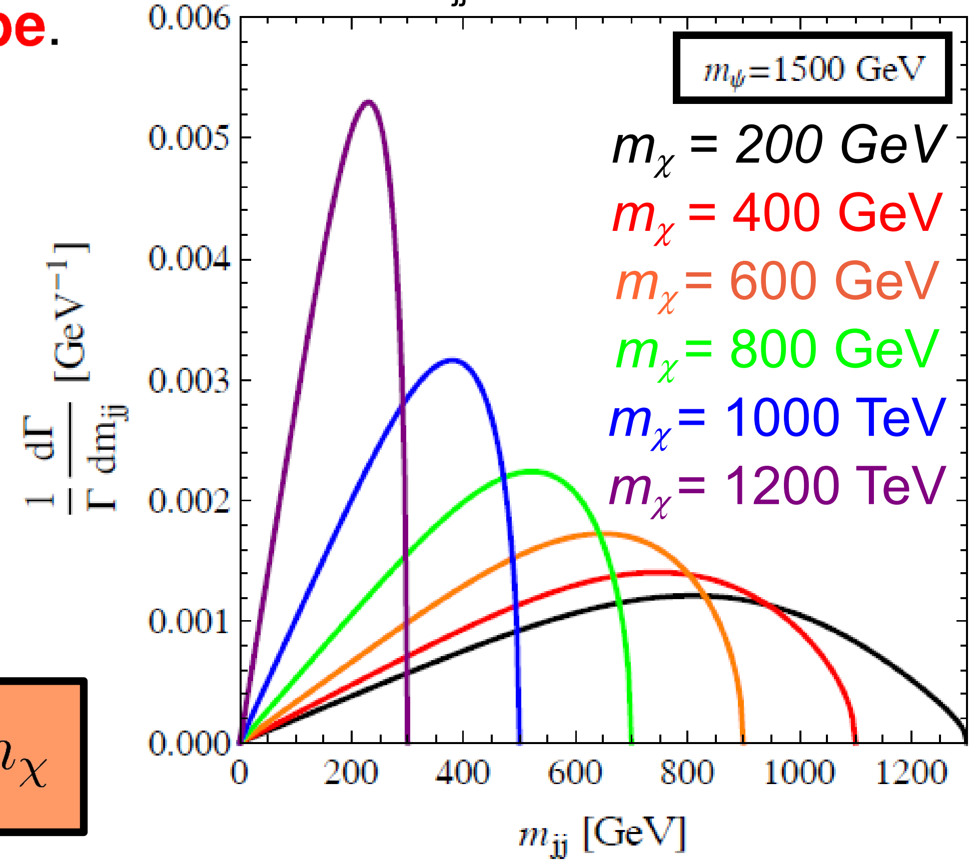
As we shall see, such information can be used to distinguish DDM ensembles from traditional DM candidates on the basis of LHC data.

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:

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

m_{jj} Distributions



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 $O_n^{(\alpha)}$:

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.:

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

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

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

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

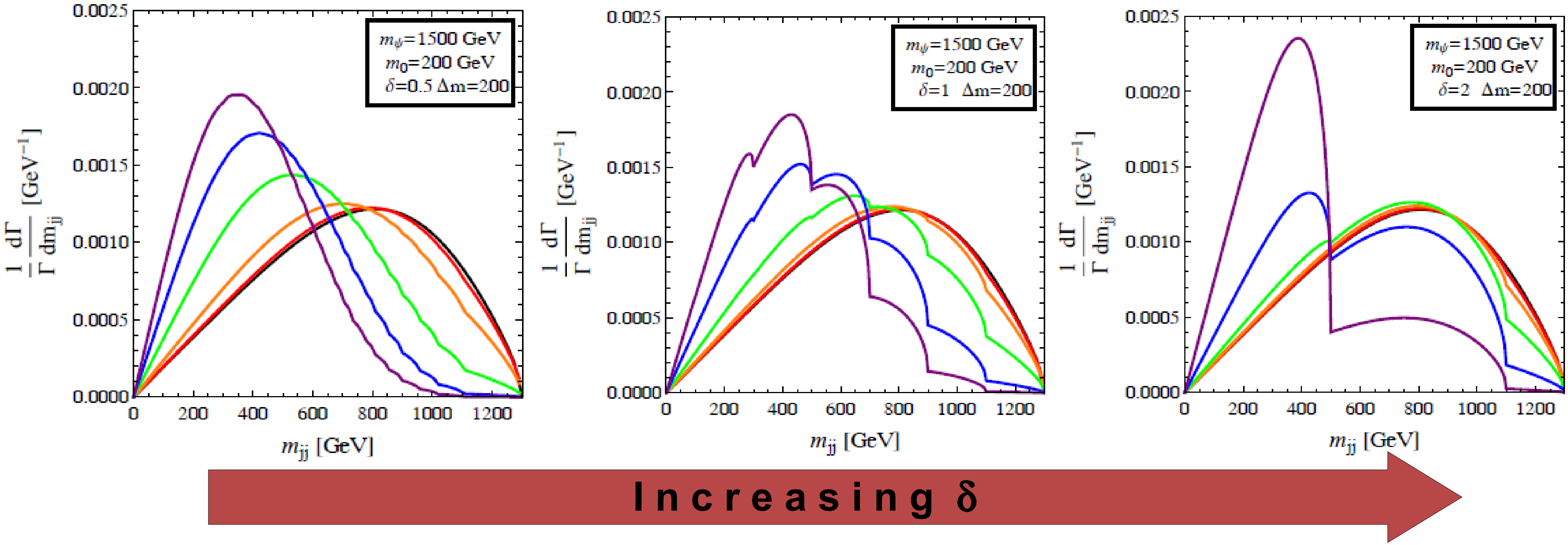
γ: scaling indices for couplings between ψ and the dark-sector fields χ_n.

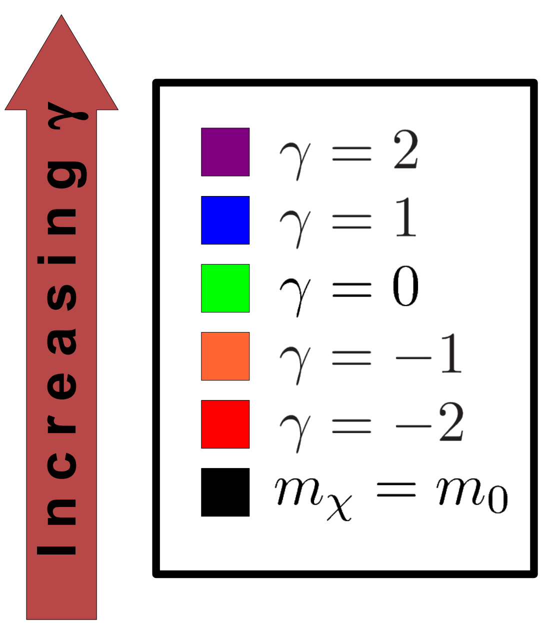
m_0 : mass of lightest constituent

δ: scaling index for the density of states

Δm : mass-splitting parameter

Kinematic Distributions from DDM Ensembles





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.

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

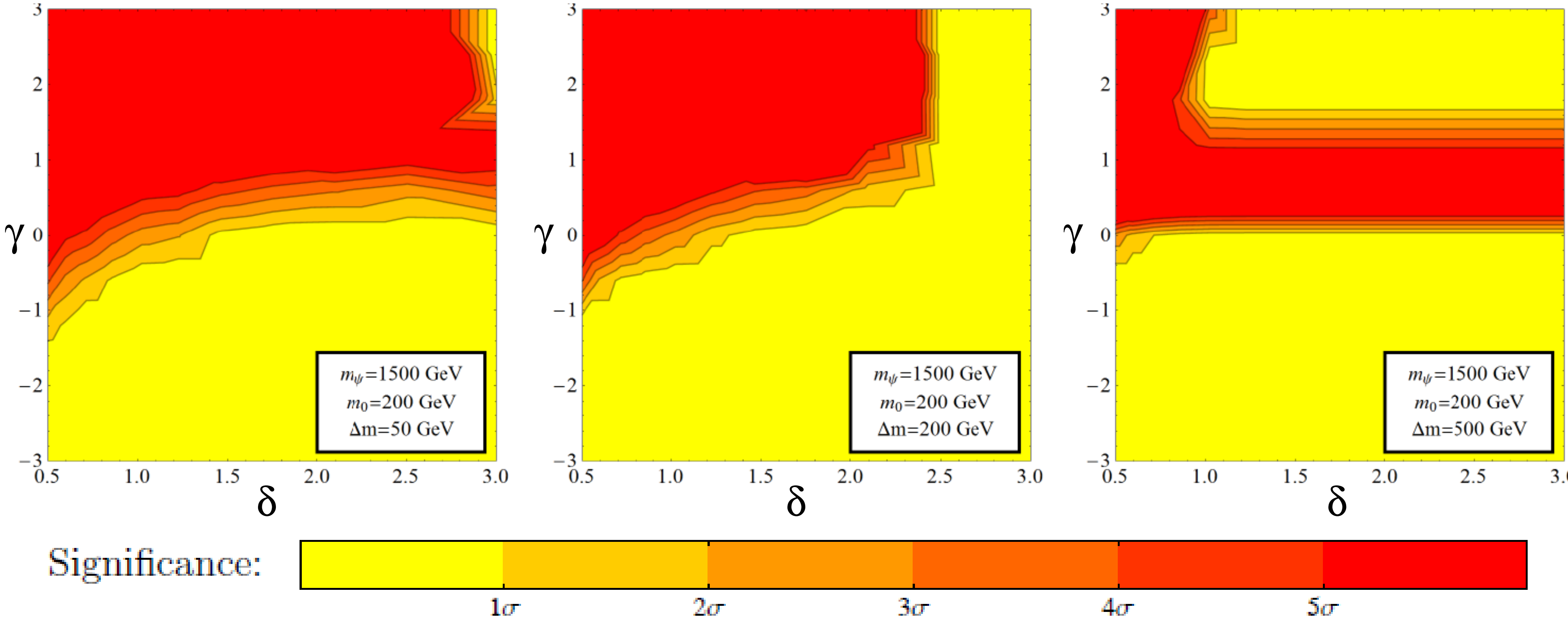
$$\chi^2_{\text{min}} = \min_{m_\chi} \left\{ \chi^2(m_\chi) \right\}$$

- 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., $pp \rightarrow \psi\psi$ for TeV-scale parent, L_{int} < 30 fb^{-1})

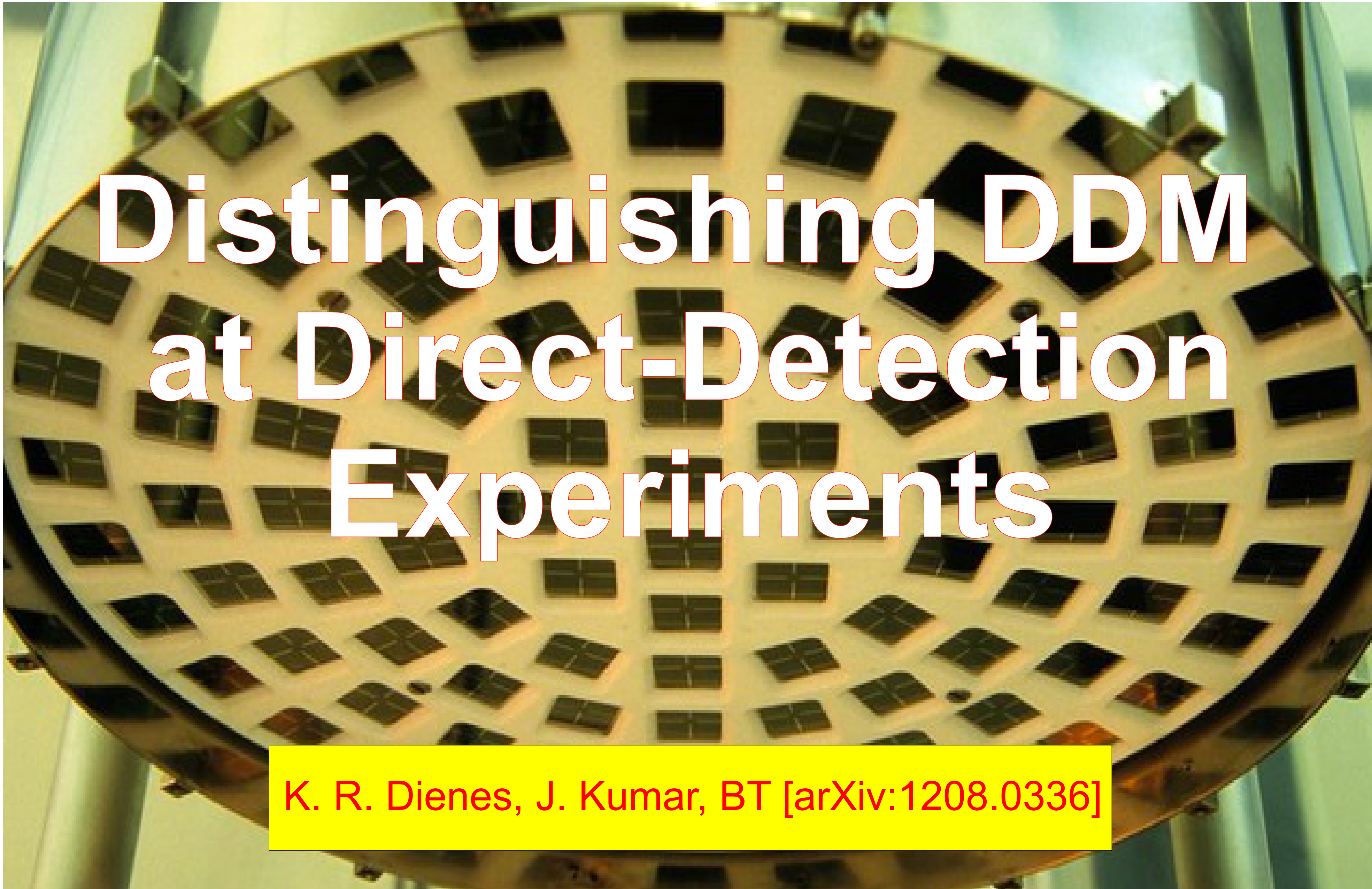
$\Delta m = 50$ GeV $\qquad$ $\Delta m = 200$ GeV $\qquad$ $\Delta m = 500$ GeV



The upshot:

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

Distinguishing DDM at Direct-Detection Experiments



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

Direct Detection of DDM

- Direct-detection experiments offer another possible method for distinguishing DDM ensembles from traditional DM candidates.
- After the initial observation an excess of signal events at such an experiment, the shape of the **recoil-energy spectrum** associated with those events can provide additional information about the properties of the DM candidate.
- A number of factors impact the shape of the recoil-energy spectrum in a generic dark-matter scenario. **Particle physics**, **astrophysics**, *and* **cosmology** all play an important role.

$$\frac{dR}{dE_R} = \sum_j \frac{\sigma_{Nj}^{(0)}}{2m_j\mu_{Nj}^2} F^2(E_R)\rho_j^{\mathrm{loc}} \int_{v_{\min}^{(j)}}^{v_{\mathrm{esc}}} \frac{f_j(v)}{v}\,dv$$

χ_j-nucleus scattering cross-section

Form factor

Local energy density of χ_j

Halo-velocity distribution for χ_j

Mass of χ_j

Reduced mass of χ_j-nucleon system

Particle physics

Nuclear physics

Astrophysics and cosmology

Direct Detection of DDM

In this talk, I'll adopt the following standard assumptions about the particles in the DM halo as a definition of the "**standard picture**" of DM:

- Total local DM energy density: $\rho_{\rm tot}^{\rm loc} \approx 0.3~{\rm GeV/cm}^3$.
- Maxwellian distribution of halo velocities for all χ_j.
- Local circular velocity $v_0 \approx 220$ km/s, galactic escape velocity $v_e \approx 540$ km/s.
- Woods-Saxon form factor.
- Spin-independent (SI) scattering dominates.
- Isospin conservation: $f_{pj} = f_{nj}$.
- Local DM abundance $\propto$ global DM abundance: $\rho_j^{\rm loc}/\rho_{\rm tot}^{\rm loc} \approx \Omega_j/\Omega_{\rm tot}$.

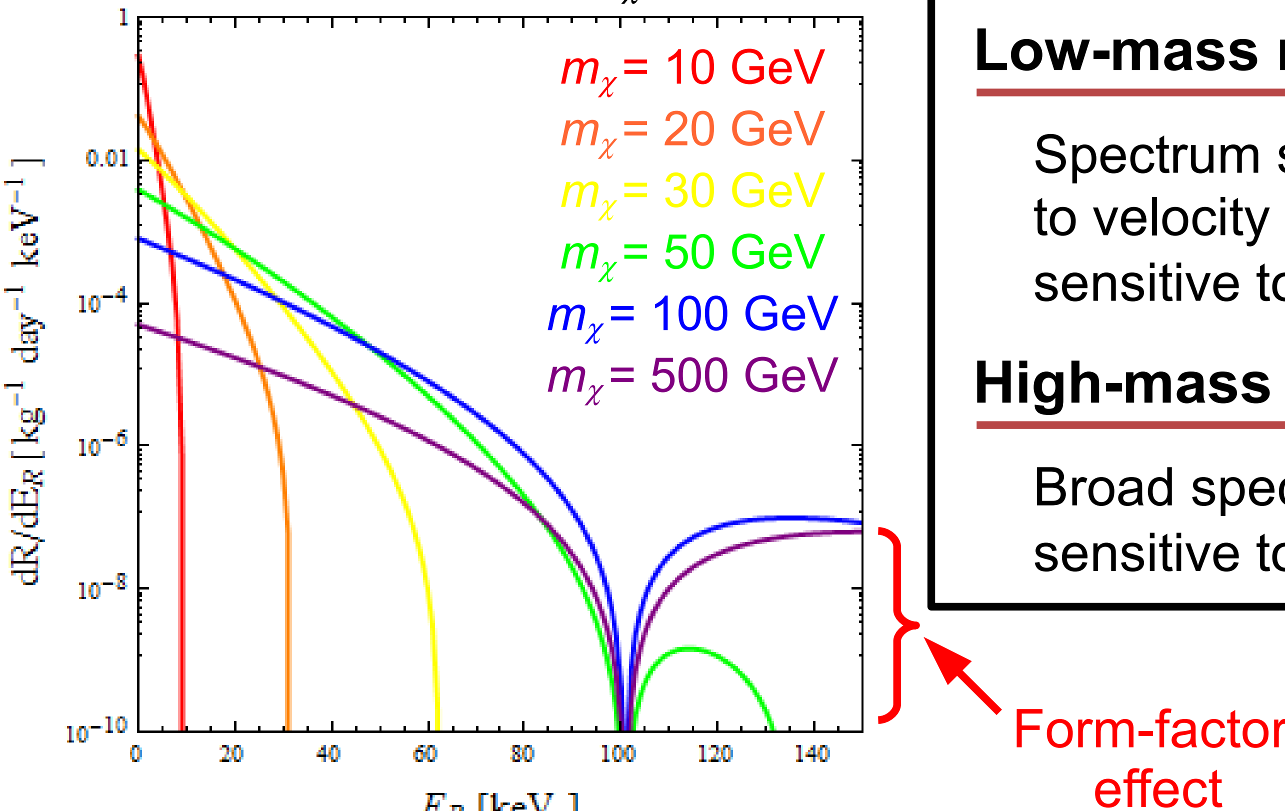
Departures from this standard picture (isospin violation, non-standard velocity distributions, etc.) can have important experimental consequences.

Here, we examine the consequences of replacing a traditional DM candidate with a DDM ensemble, with all other things held fixed.

Recoil-Energy Spectra: Traditional DM

- Let's begin by reviewing the result for the spin-independent scattering of a traditional DM candidate χ off a an atomic nucleus N with mass m_N.
- Recoil rate exponentially suppressed for $E_R \gtrsim 2m_\chi^2 m_N v_0^2/(m_\chi+m_N)^2$

Target material: Xe
Normalization: $\sigma_{N\chi}$ = 1 pb



Two Mass Regimes:

Low-mass regime: $m_\chi \lesssim$ 20 - 30 GeV

Spectrum sharply peaked at low E_R due to velocity distribution. Shape quite sensitive to m_χ.

High-mass regime: $m_\chi \gtrsim$ 20 - 30 GeV

Broad spectrum. Shape not particularly sensitive to m_χ.

Direct Detection of DDM Ensembles

- Cross-sections depend on effective couplings between the χ_j and nuclei.

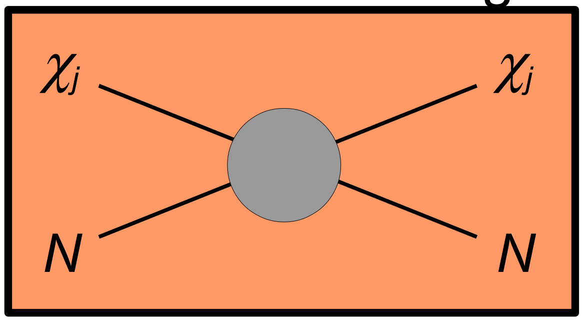
- Both **elastic and inelastic scattering** can in principle contribute significantly to the total SI scattering rate for a DDM ensemble.

- In this talk, I'll focus on elastic scattering: $\chi_j N \rightarrow \chi_j N$.

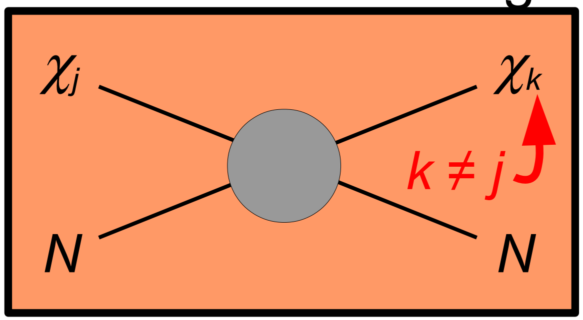
(For potential implications of inelastic scattering within the DDM framework, see talk by David Yaylali.)

- For concreteness, I'll focus on the case where the abundances Ω_j of the χ_j and their couplings to nucleons scale like:

Elastic Scattering



Inelastic Scattering

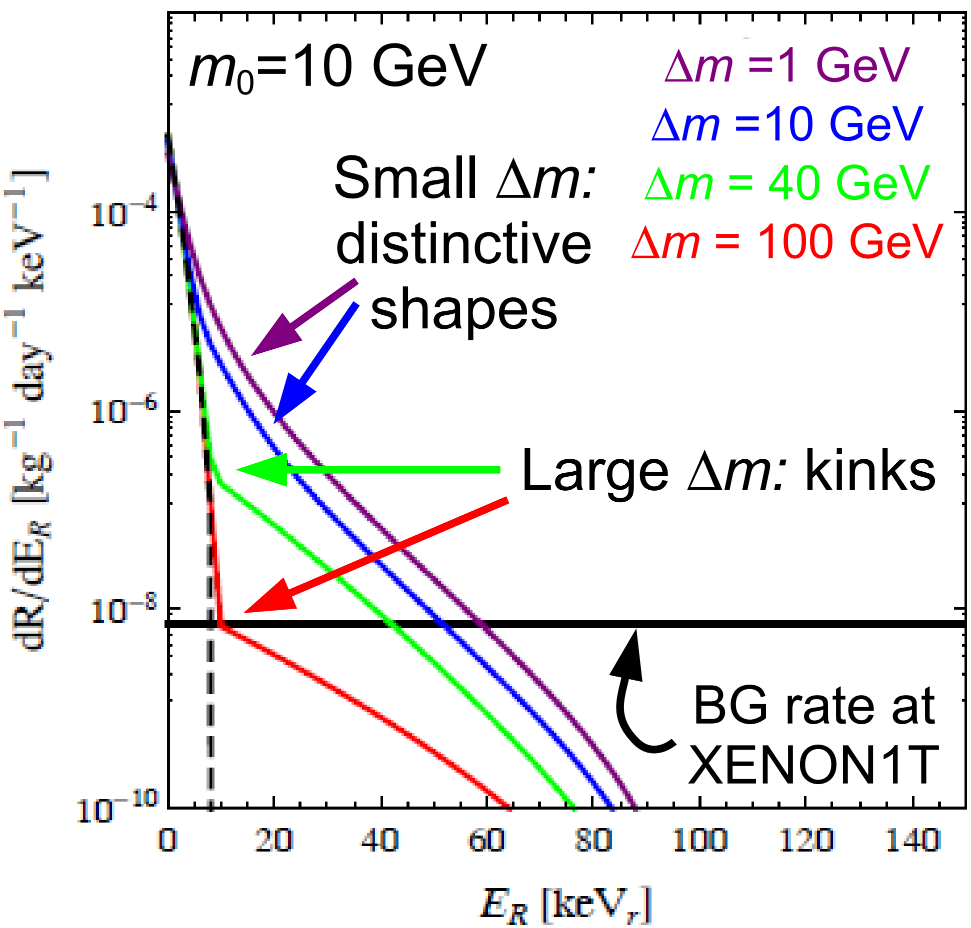


$$\Omega_j = \Omega_0 \left(\frac{m_j}{m_0} \right)^{\alpha}$$

$$f_{nj} = f_{n0} \left(\frac{m_j}{m_0} \right)^{\beta} \quad \Rightarrow \quad \sigma_{nj}^{(\mathrm{SI})} = \frac{4\mu_{nj}^2}{\pi} f_{nj}^2$$

Recoil-Energy Spectra: DDM

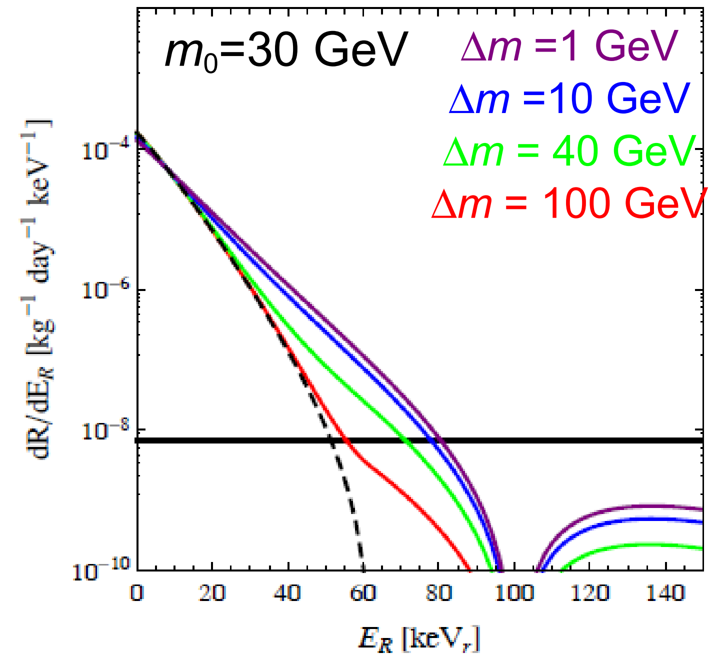
- **Distinctive features** emerge in the recoil-energy spectra of DDM models, especially when one or more of the χ_j are in the low-mass regime.
- As m_0 increases, more of the χ_j shift to the high-mass regime. Spectra increasingly resemble those of traditional DM candidates with $m_\chi \approx m_0$.

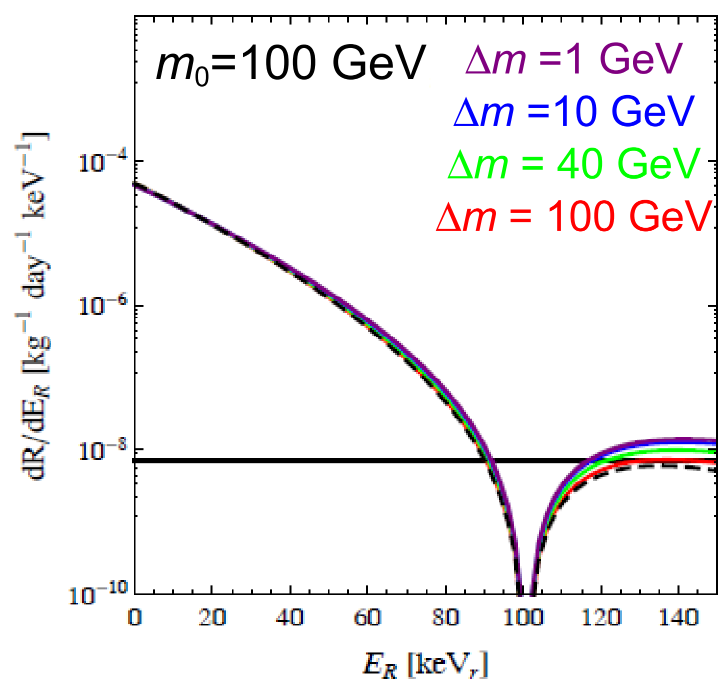


α = -1.5
β = -1
δ = 1

Xe target

Rate normalized to that of χ with $\sigma_\chi^{(SI)}$=10^{-9} pb





How well can we hope distinguish a departure from the standard picture of DM due to the presence of a DDM ensemble on the basis of direct-detection data?

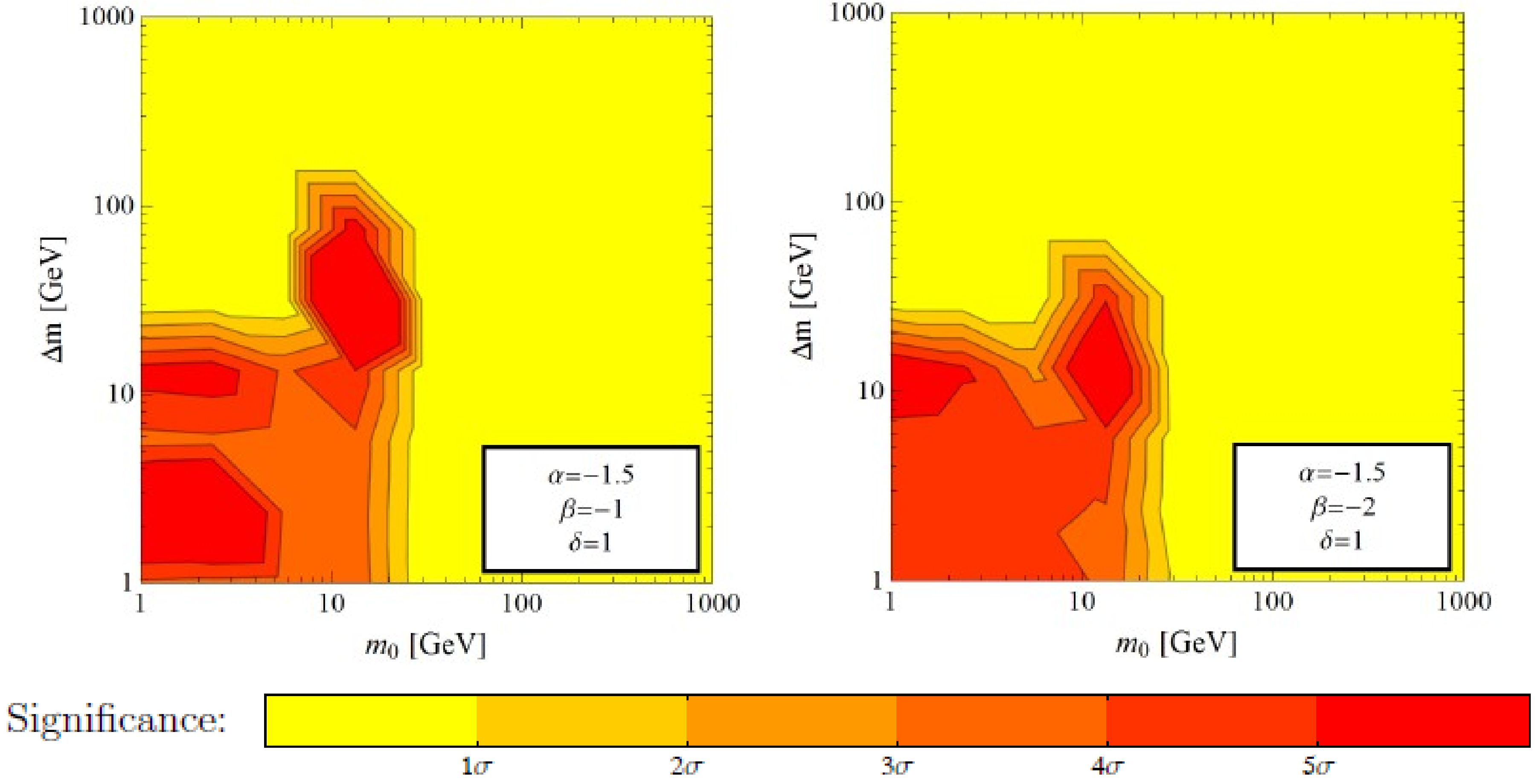
Consider a detector with similar attributes to those anticipated for the next generation of noble-liquid experiments (XENON1T, LUX/LZ, PANDA-X, et al.)

- Liquid-xenon target
- Fiducial volume ~ 5000 kg
- Five live years of operation.
- Energy resolution similar to XENON100
- Acceptance window: 8 keV < E_R < 48 keV

Assume an excess of N_e ~ 1000 total signal events (consistent with most stringent current limits).

- Compare the recoil-energy spectrum for a given DDM ensemble to those of traditonal DM candidates which yield the <u>**same total event rate**</u>.
- As in our LHC analysisThe minimum χ^2_{min} from these comparisons quantifies the degree to which the DDM model can be distinguished from traditional DM candidates, under standard astrophysical assumptions.

Distinguishing DDM Ensembles: Results



The upshot:

In a variety of situations, it should be possible to distinguish characteristic features to which DDM ensembles give rise at the next generation of direct-detection experiments.

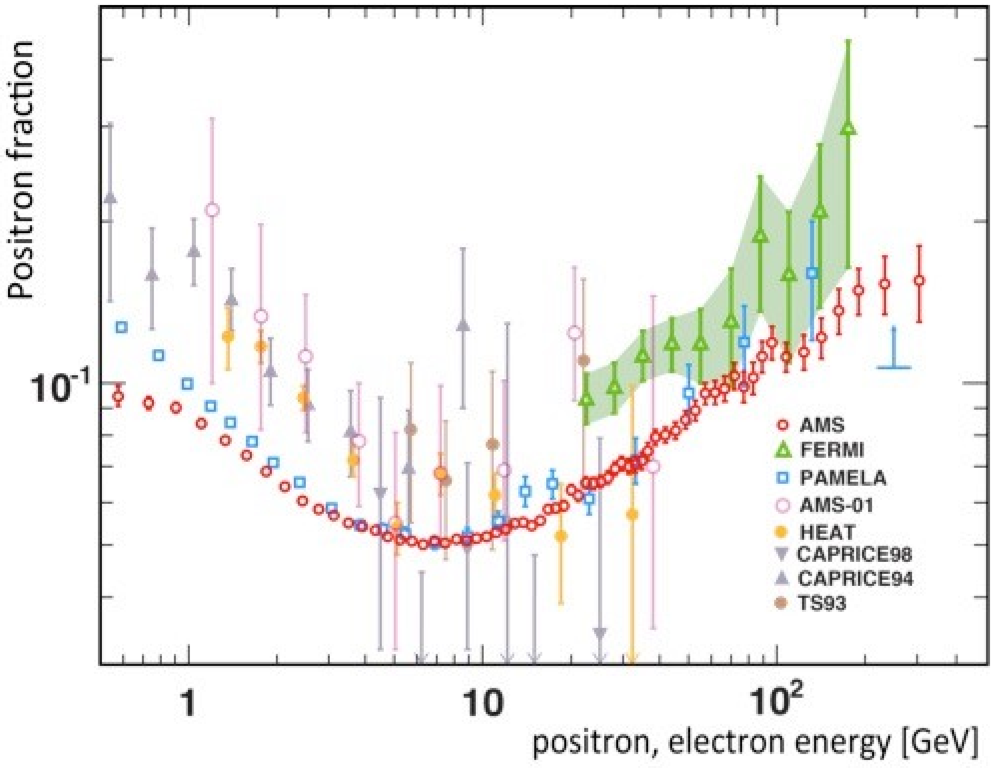
Distinguishing DDM with Cosmic-Ray Detectors

K. R. Dienes, J. Kumar, BT [arXiv:1305.xxxx]

The Positron Puzzle

PAMELA, AMS-02, and a host of other experiments have reported an **excess of cosmic-ray positrons**.

Annihilating or decaying dark-matter in the galactic halo has been advanced as a possible explanation of this data anomaly.



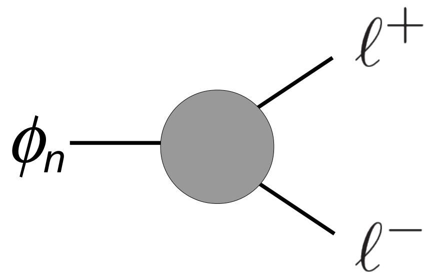
Dark-matter candidates whose annihilations or decays reproduce the observed positron fraction typically run into other issues:

- Limits on the continuum gamma-ray flux from FERMI, etc.
- Limits on the cosmic-ray antiproton flux from AMS-01, etc.
- Cannot simultaneously reproduce the total $e^{\pm}$ flux from FERMI, etc.
- Leave imprints in the CMB not observed by WMAP/PLANCK.

DDM ensembles can actually go a long way toward reconciling these tensions.

DDM Ensembles and Cosmic Rays

For concreteness, consider the case in which the ensemble constituents ϕ_n are scalar fields which couple to pairs of SM fermions.



Leptonic decays (preferred by antiproton-flux constraints)

$$\ell^\pm = \{e^\pm, \mu^\pm, \tau^\pm\}$$

Provides best fit to combined $e^\pm$ flux.

$$\mathcal{L}_{\rm int} = \frac{c_n m_\ell}{\Lambda} \phi_n \bar{\ell}\ell + \text{h.c.}$$

Distributing the dark-matter relic abundance across the ensemble yields a spectrum of lepton injection energies softens the $e^\pm$ spectrum

Parametrizing the ensemble

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

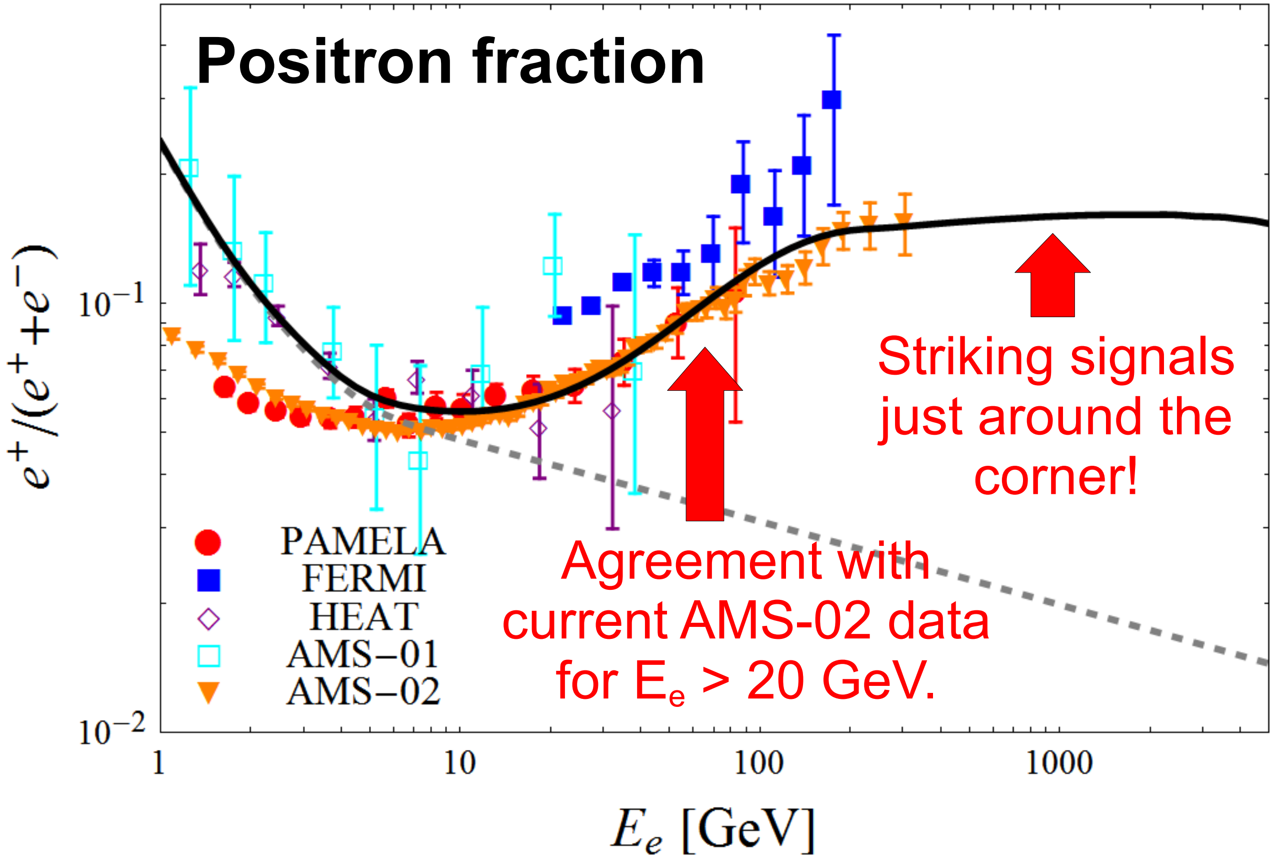
Couplings: $$c_n = c_0 \left(\frac{m_n}{m_0}\right)^\xi$$

Abundances: $$\Omega_n = \Omega_0 \left(\frac{m_n}{m_0}\right)^\alpha$$

$$\Gamma_n \sim \frac{m_\ell^2 m_0}{\Lambda^2} \left(\frac{m_n}{m_0}\right)^\gamma$$

where $\gamma \equiv 1 + 2\xi$

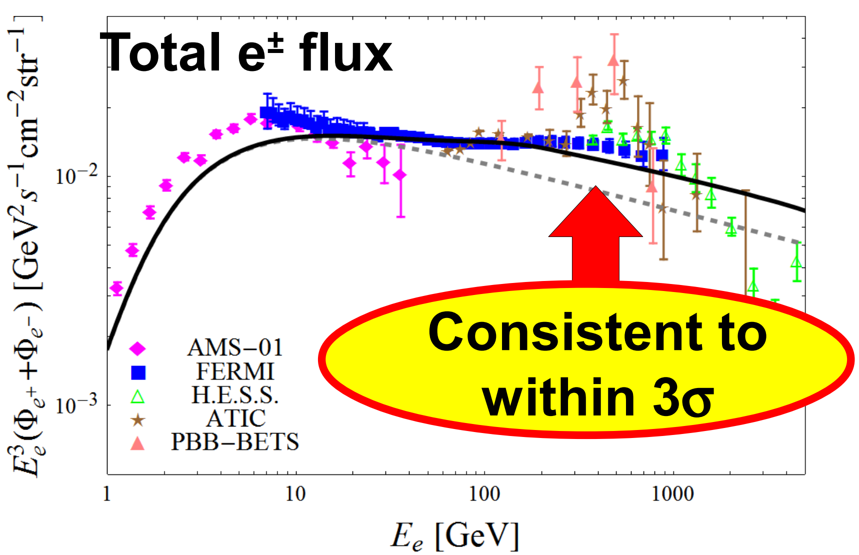
Turndown

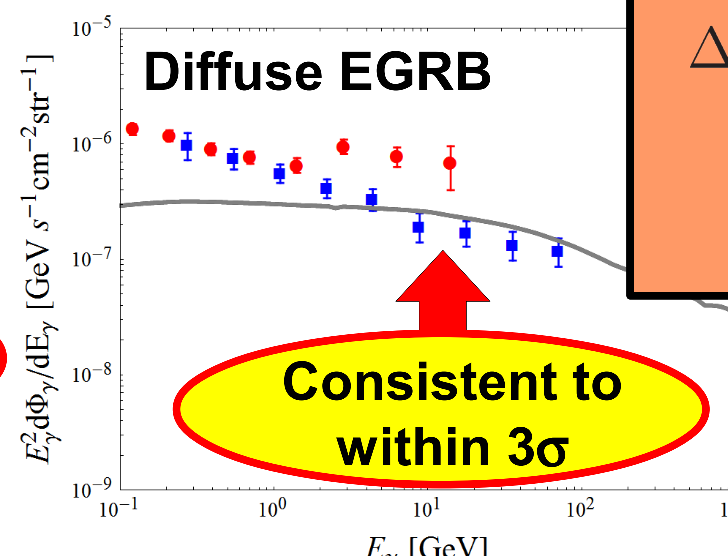


Due to this softening, DDM ensembles can reproduce current AMS-02 data while at the same time satisfying gamma-ray constraints.

Ensembles which do this typically also yield striking features – **plateaus** or **soft turn-downs** – in the positron fraction at higher energies.

$$m_0 = 500 \text{ GeV}$$
$$\Delta m = 1 \text{ GeV}$$
$$\alpha = -2$$
$$\gamma = 0.875$$
$$\delta = 1$$





Summary

DDM is an alternative framework for dark-matter physics in which stability is replaced by **a balancing between lifetimes and abundances** across a vast **ensemble** of particles which collectively account for Ω_{CDM}.

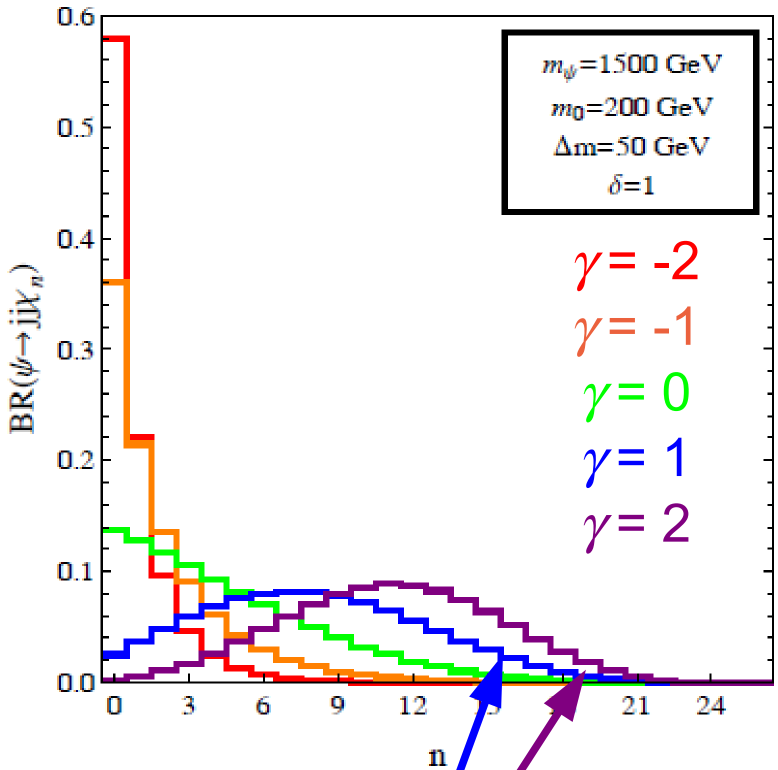
Such DDM ensembles give rise to **distinctive experimental signatures** which can serve to distinguish them from traditional dark-matter candidates. These include:

- Imprints on kinematic distributions of SM particles at colliders.
- Distinctive features in the recoil-energy spectra observed at direct-detection experiments.
- Unusual features in cosmic-ray e^+ and e^- spectra at high energies.

Many more phenomenological handles on DDM and on non-minimal dark sectors in general remain to be eplored!

Extra Slides

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.:

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

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

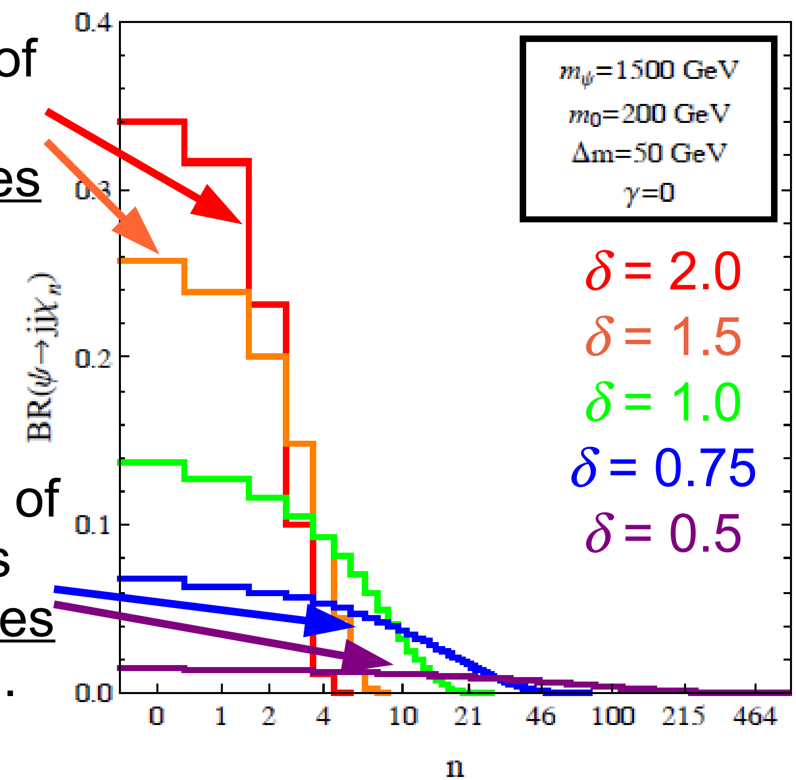
Density of states decreases with n.

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

…but phase space always decreases with n.

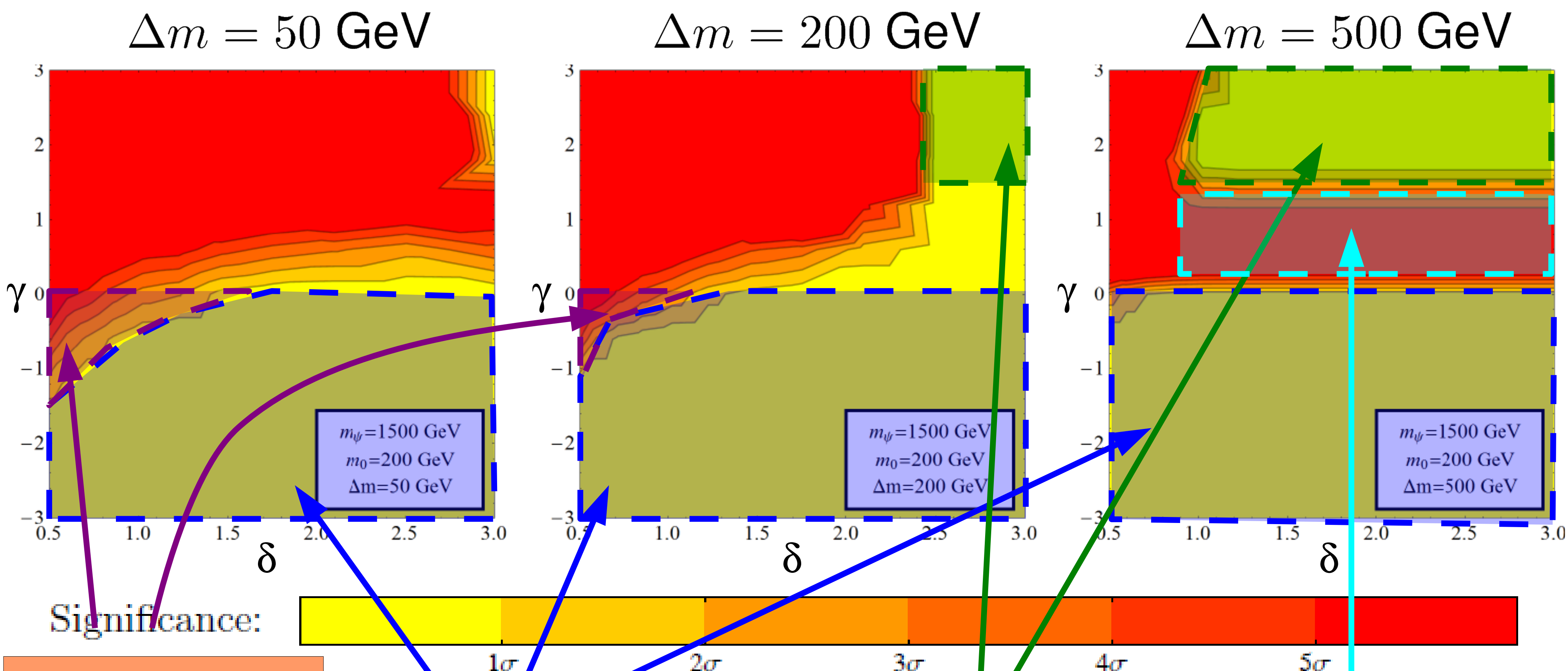
- **Branching fractions** of ψ to the different χ_n controlled by Δm, δ, and γ.

Density of states increases with n.



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})



Density of states large enough to overcome γ suppression for small δ.

BRs to all χ_n with $n > 1$ suppressed: lightest constituent dominates the width of ψ.

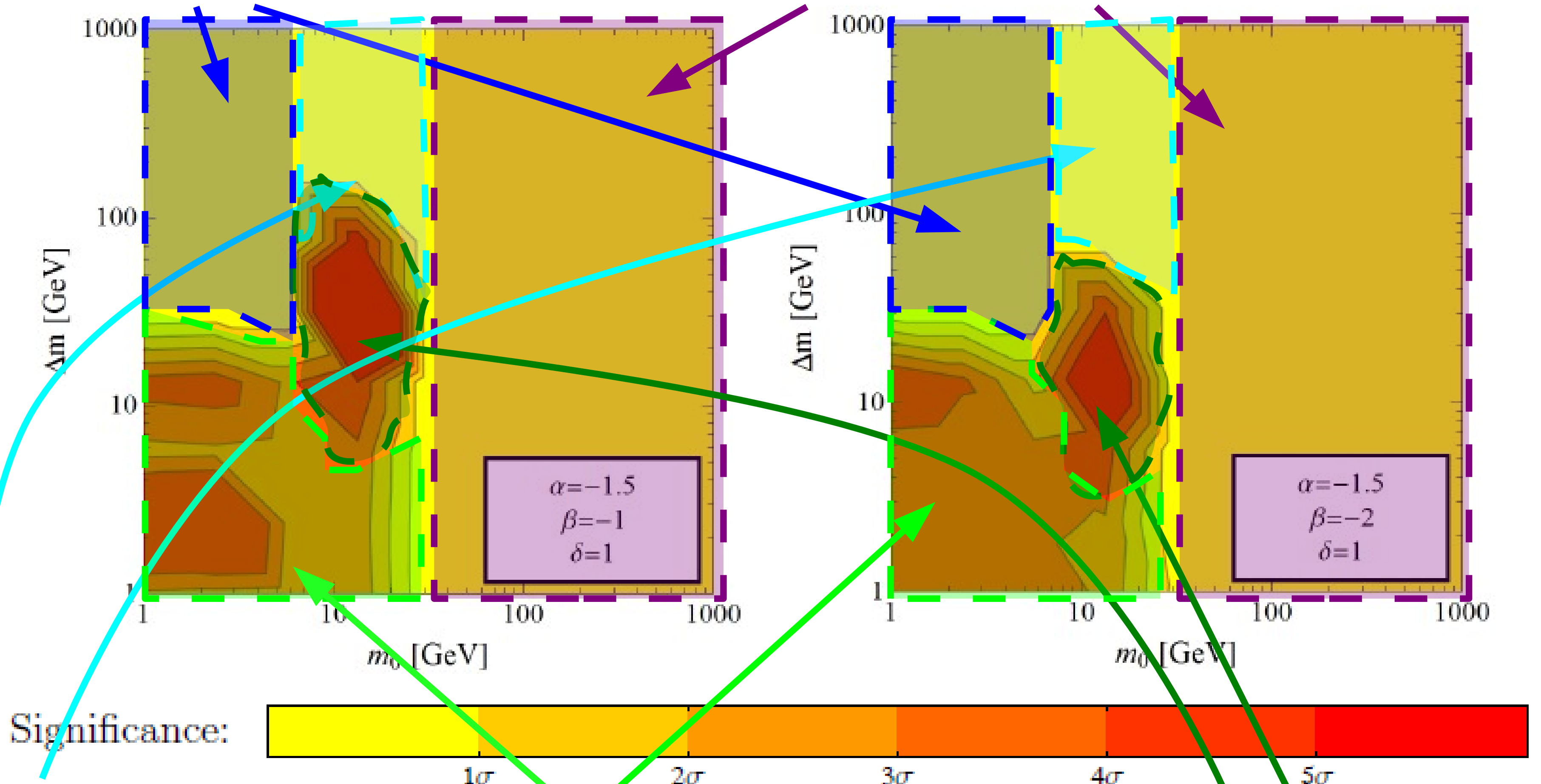
Next-to-lightest constituent χ_1 dominates the width of ψ.

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

Distinguishing DDM Ensembles: Results

χ_0 contributes mostly at $E_R < E_R^{min}$, all other χ_j in high-mass regime

All χ_n in high-mass regime: little difference between their dR/dE_R contributions



Only χ_0 contributes perceptible to overall rate: looks like regular low-mass DM

Multiple χ_j in low-mass region: distinctive dR/dE_R spectra

χ_0 in low-mass regime, all χ_j with $j \geq 1$ in high-mass regime: kink in dR/dE_R spectrum