Dynamical Dark Matter

Part II: Phenomenological Implications

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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
[arXiv:1306.2959] also with Jason Kumar
[arXiv:1405.xxxx] also with Shufang Su

Dynamical Dark Matter (DDM)

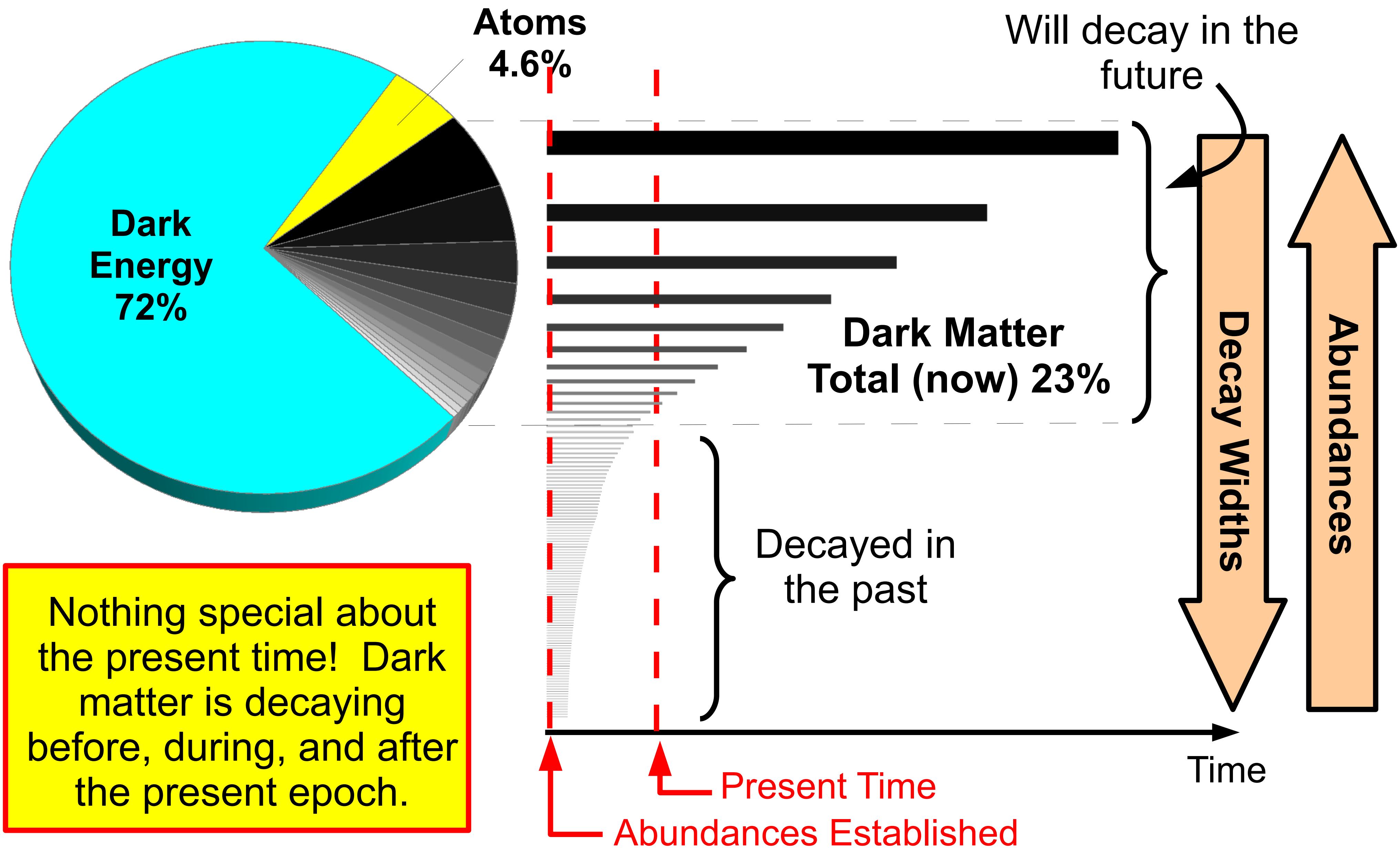
To recap, within the DDM framework...

- 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.

DDM Cosmology: The Big Picture



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

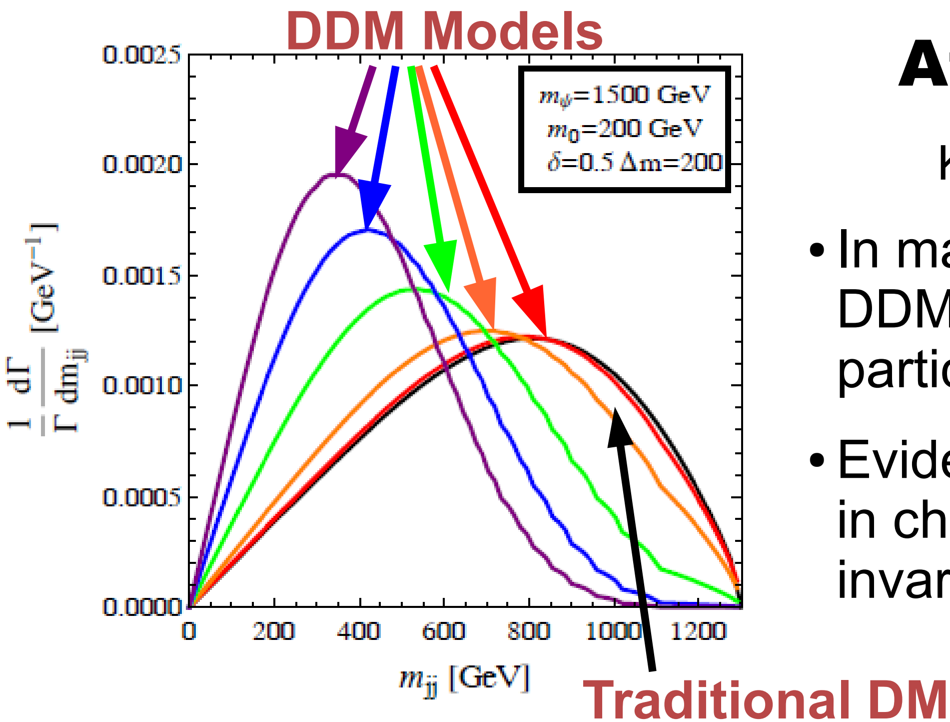
In Keith's talk, he discussed...

- The general Features of the DDM framework
- How to characterize the cosmology of DDM models

In *this* talk, I'll be discussing...

- The phenomenological consequences of DDM and some of the experimental signatures that can arise within the DDM framework
- Methods for distinguishing DDM ensembles from traditional DM candidates experimentally
    - At colliders
    - At direct-detection experiments
    - At indirect-detection experiments

Discovering and Differentiating DDM



At the LHC, ...

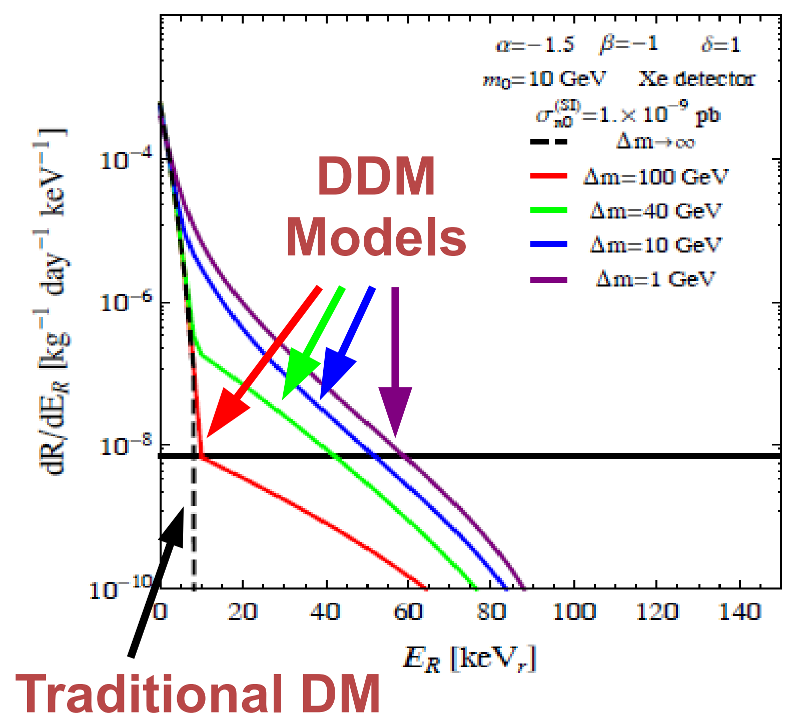
K. R. Dienes, S. Su, BT [arXiv:1204.4183]

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

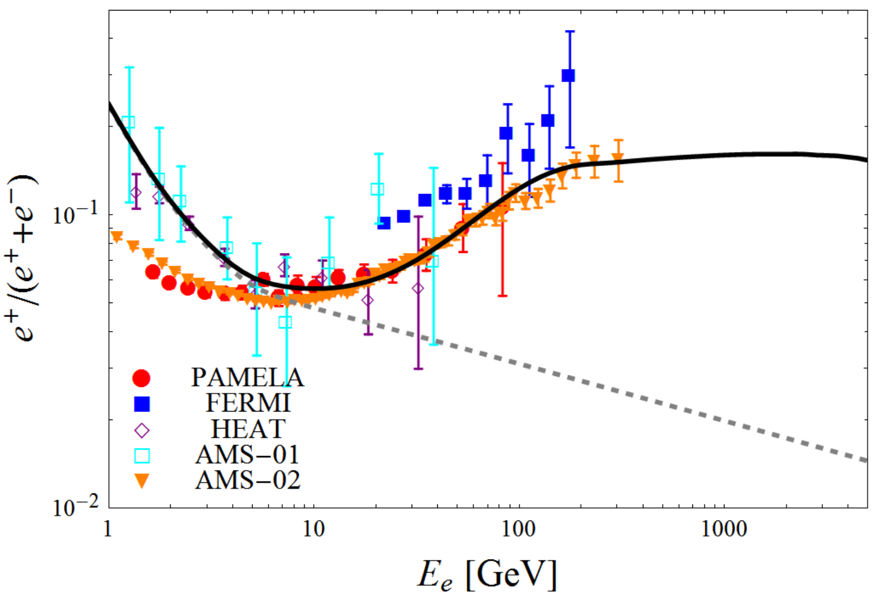
- DDM ensembles can also give rise to distinctive features in recoil-energy spectra.



... and at indirect-detection experiments.

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

- DDM ensembles can reproduce the observed positron data from AMS while satisfying constraints from other astrophysical constraints on decaying dark matter.
- Moreover, DDM models of the poistron excess give rise to concrete predictions for the behavior of the positron fraction at high energies.



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

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

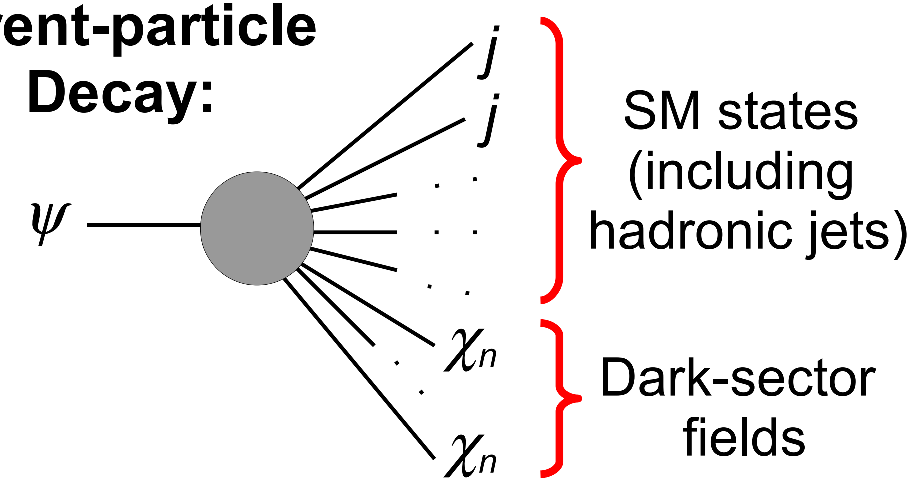
Distinguishing DDM at the LHC

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:

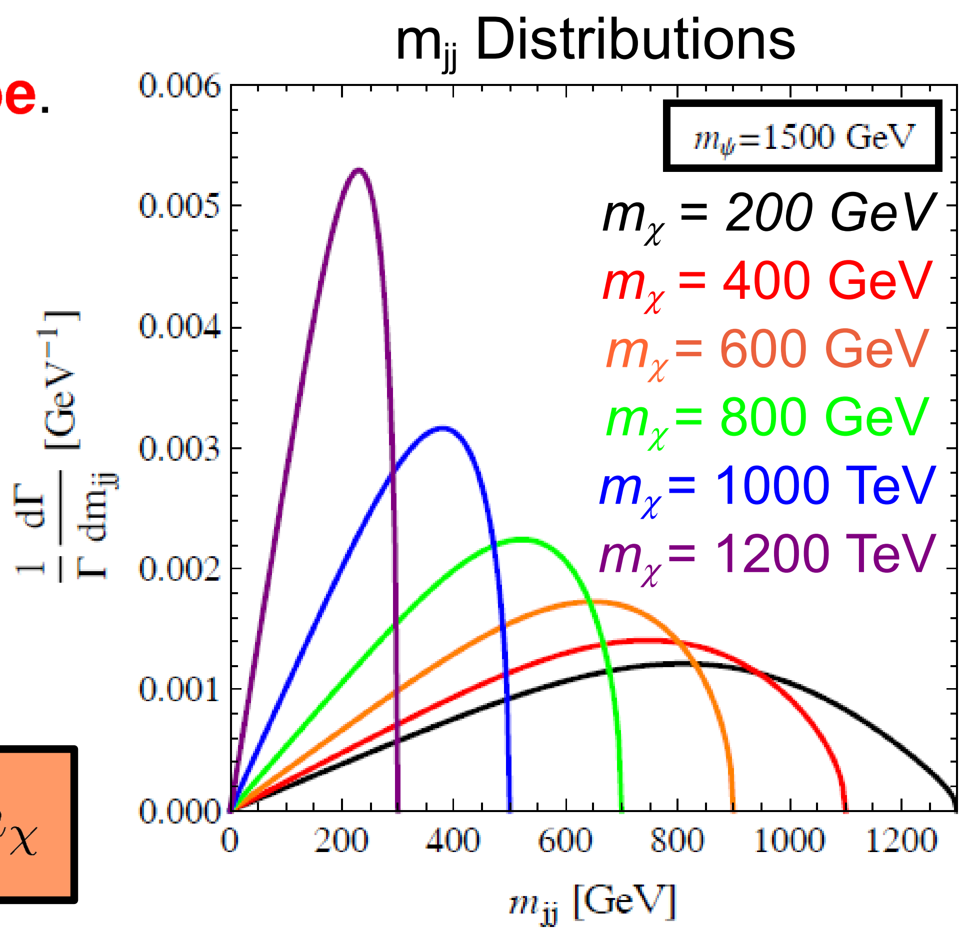


As we shall see, such information can be used to distinguish DDM ensembles from traditional DM candidates on the basis of LHC data.

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:

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



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:

γ_α : scaling indices for couplings

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

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

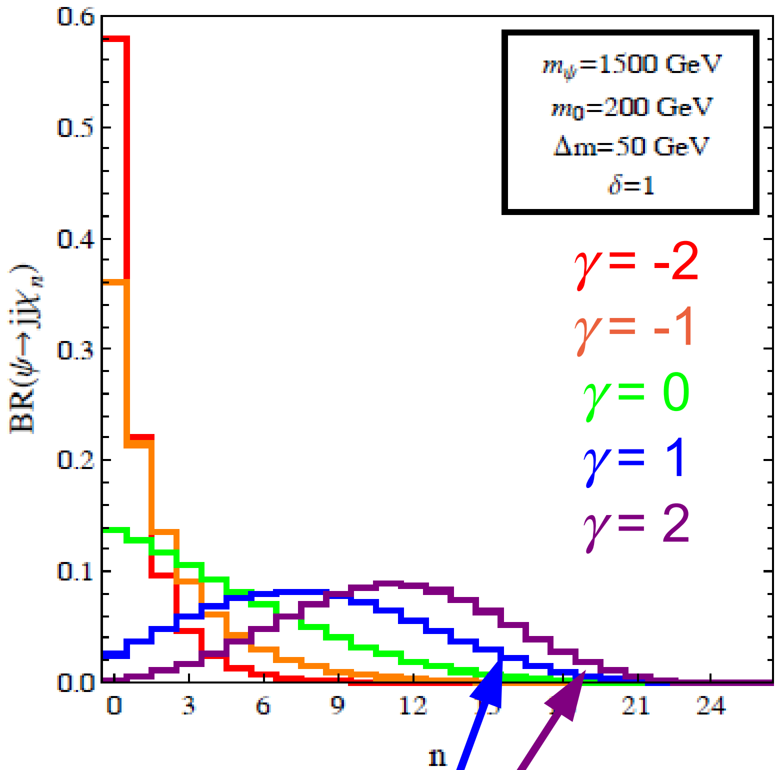
Including coupling between ψ and the dark-sector fields χ_n.

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.:

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

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

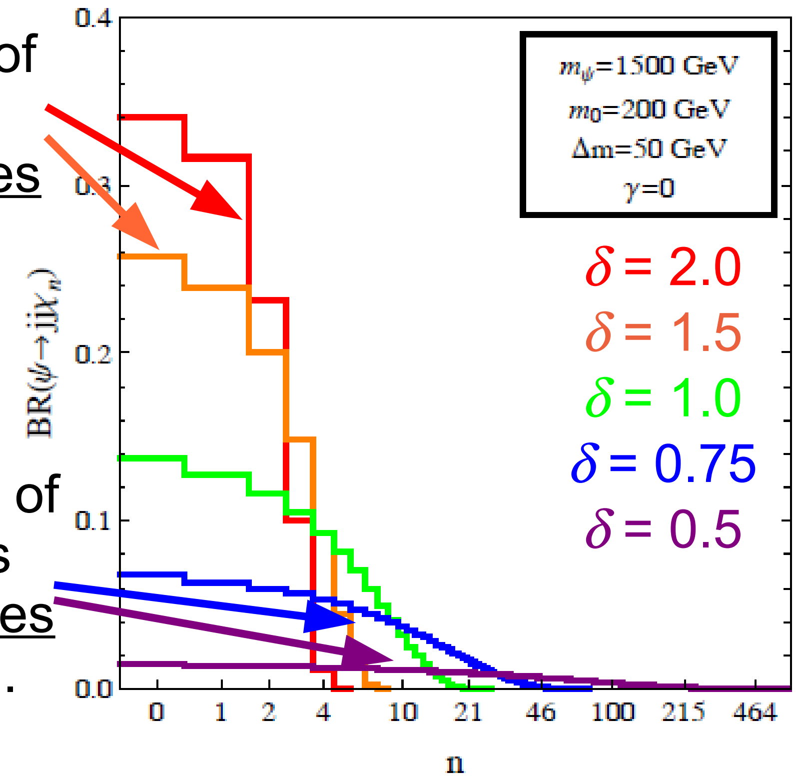
Coupling stength increases with n for γ>0...

…but phase space always decreases with n.

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

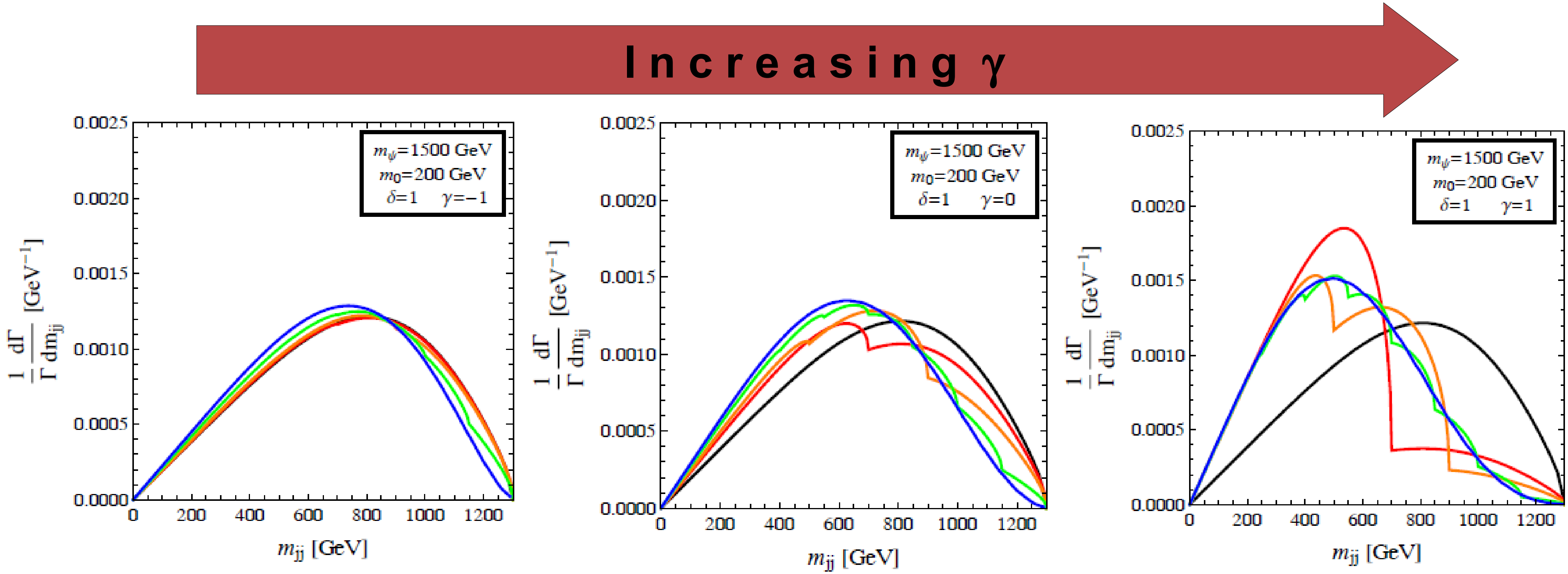
Density of states decreases with n.

Density of states increases with n.



DDM Ensembles & Kinematic Distributions

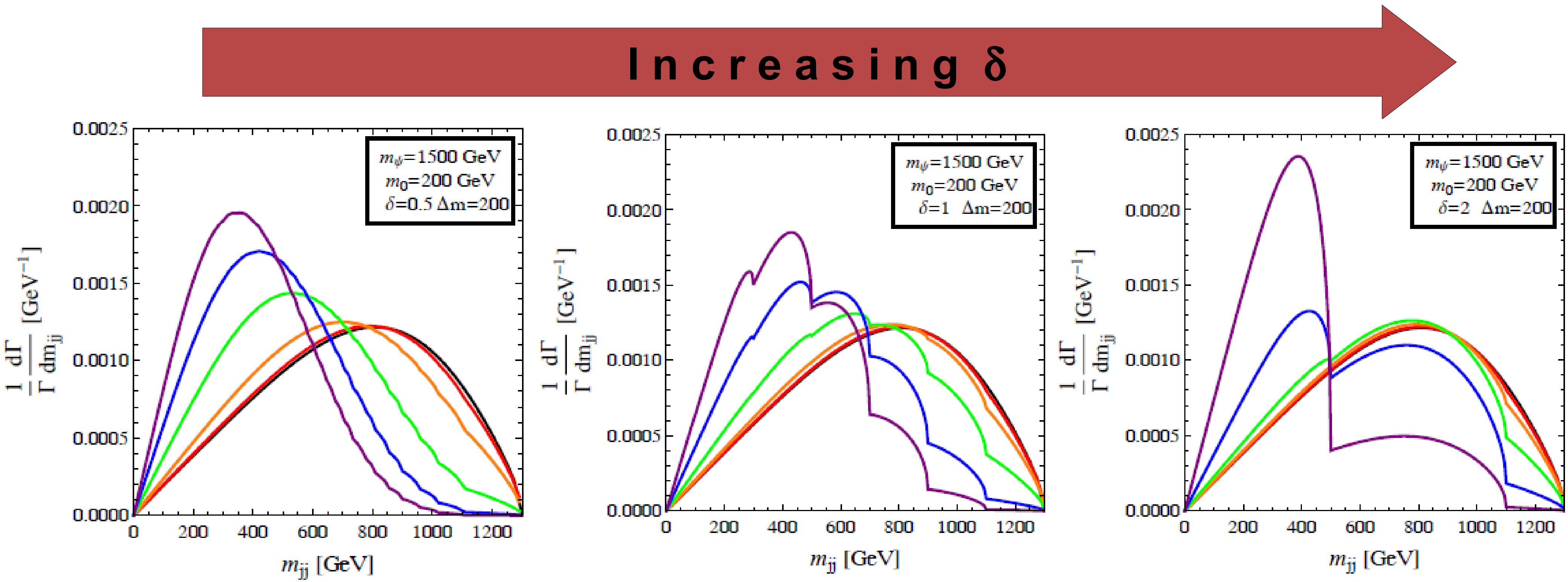
- Evidence of a DDM ensemble can be ascertained from characteristic features imprinted on the kinematic distributions of these SM particles.

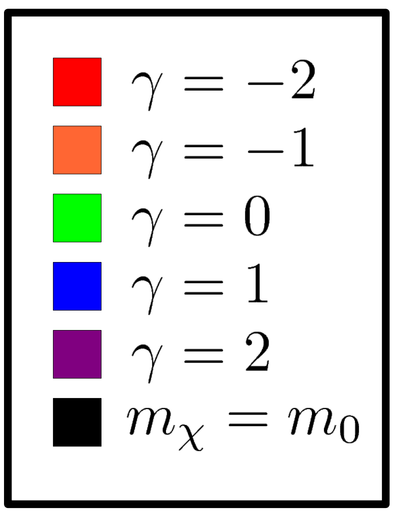


- (red) $\Delta m = 600$ GeV
- (orange) $\Delta m = 400$ GeV
- (green) $\Delta m = 150$ GeV
- (blue) $\Delta m = 20$ GeV
- (black) $m_\chi = m_0$

- 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.

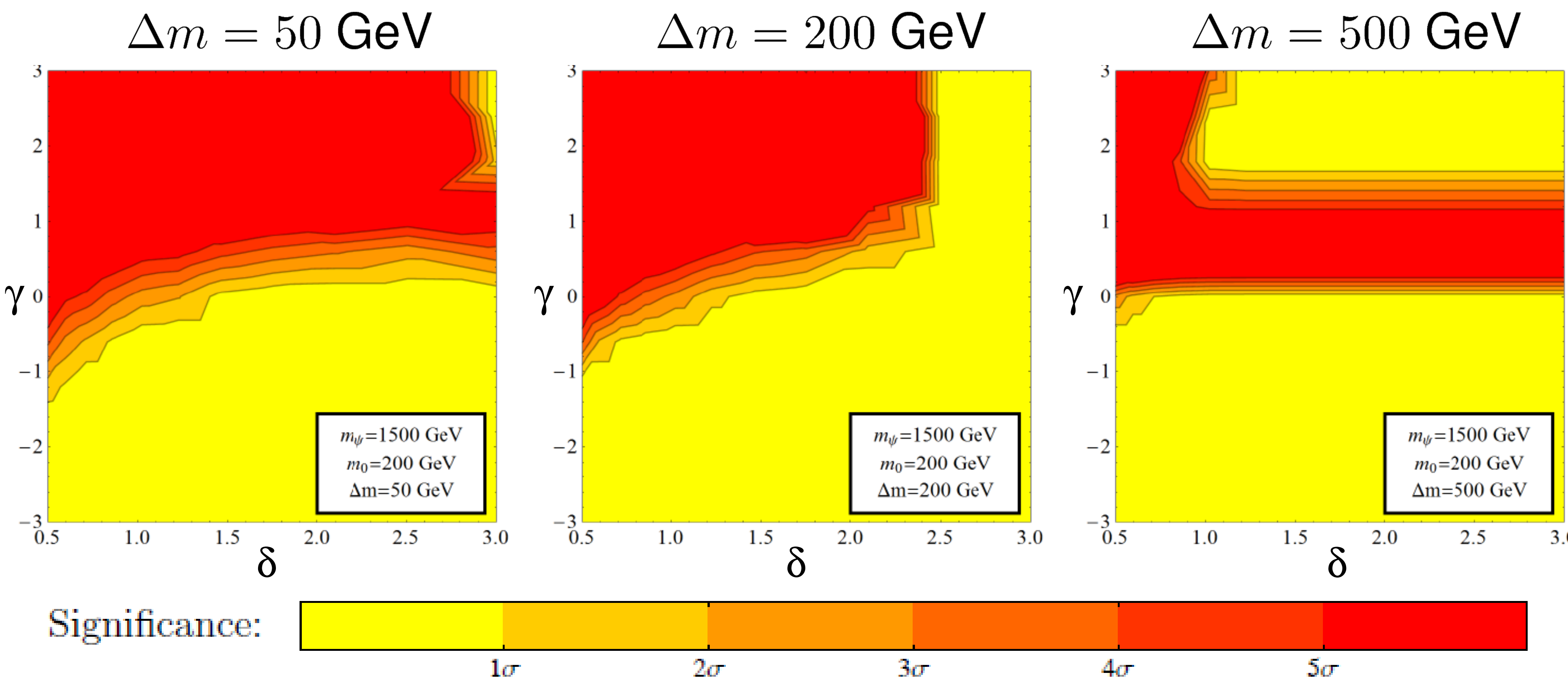
$$\chi^2(m_\chi) = \sum_k \frac{[X_k - \mathcal{E}_k(m_\chi)]^2}{\sigma_k^2}$$

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

- 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})

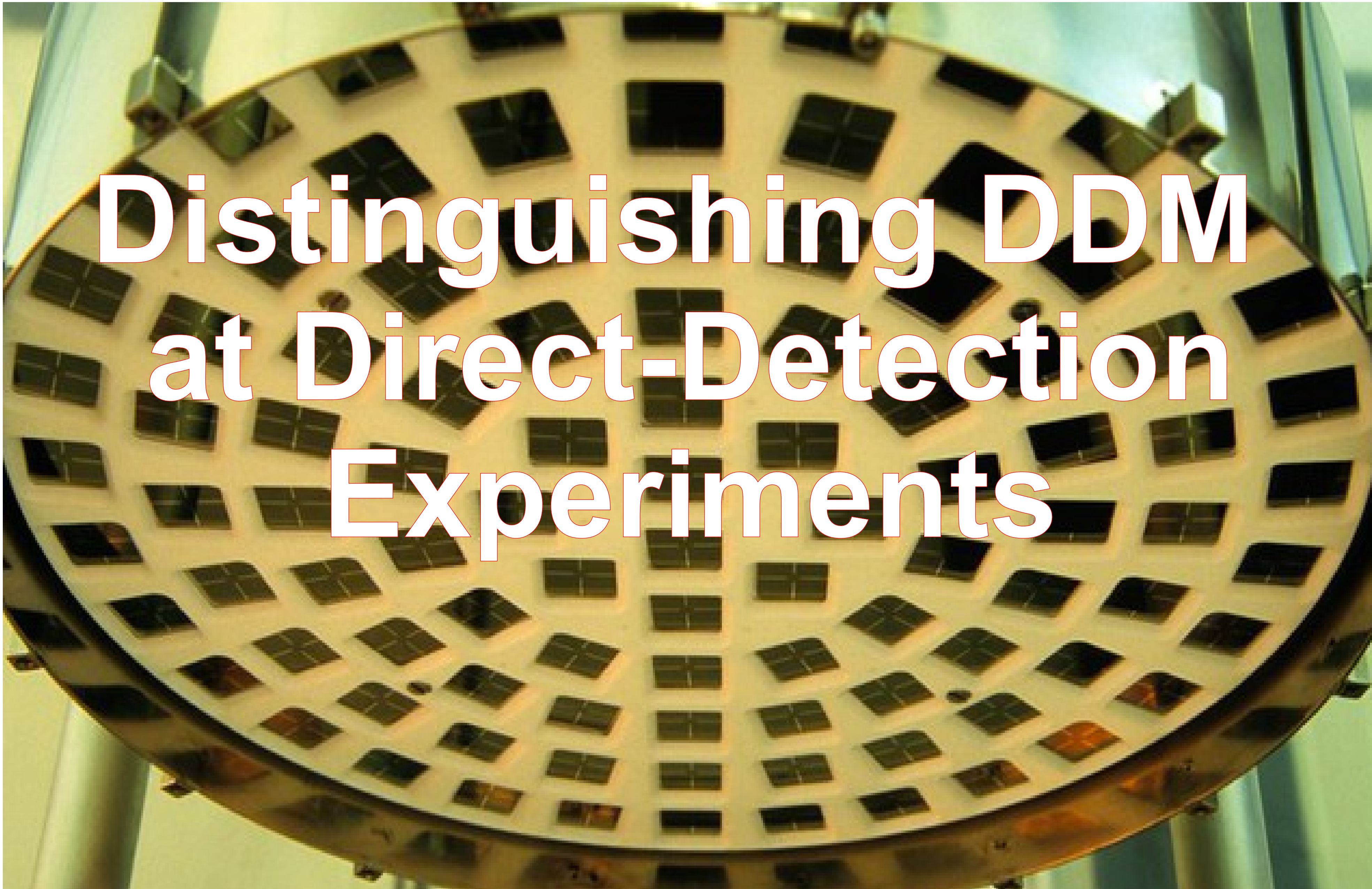


The Main Message:

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

Analysis of the prospects in other detection channels coming soon! [Dienes, Su, BT]

Distinguishing DDM at Direct-Detection Experiments



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.

$$\frac{dR}{dE_R} = \sum_j \underbrace{\frac{\sigma^{(0)}_{Nj}}{2m_j\mu^2_{Nj}}}_{\textbf{Particle physics}} \underbrace{F^2(E_R)}_{\textbf{Nuclear physics}} \underbrace{\rho_j^{\mathrm{loc}} \int_{v_{\mathrm{min}}^{(j)}}^{v_{\mathrm{esc}}} \frac{f_j(v)}{v}\,dv}_{\textbf{Astrophysics and cosmology}}$$

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

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: $\rho_j^{\rm loc}/\rho_{\rm tot}^{\rm loc} \approx \Omega_j/\Omega_{\rm tot}$.

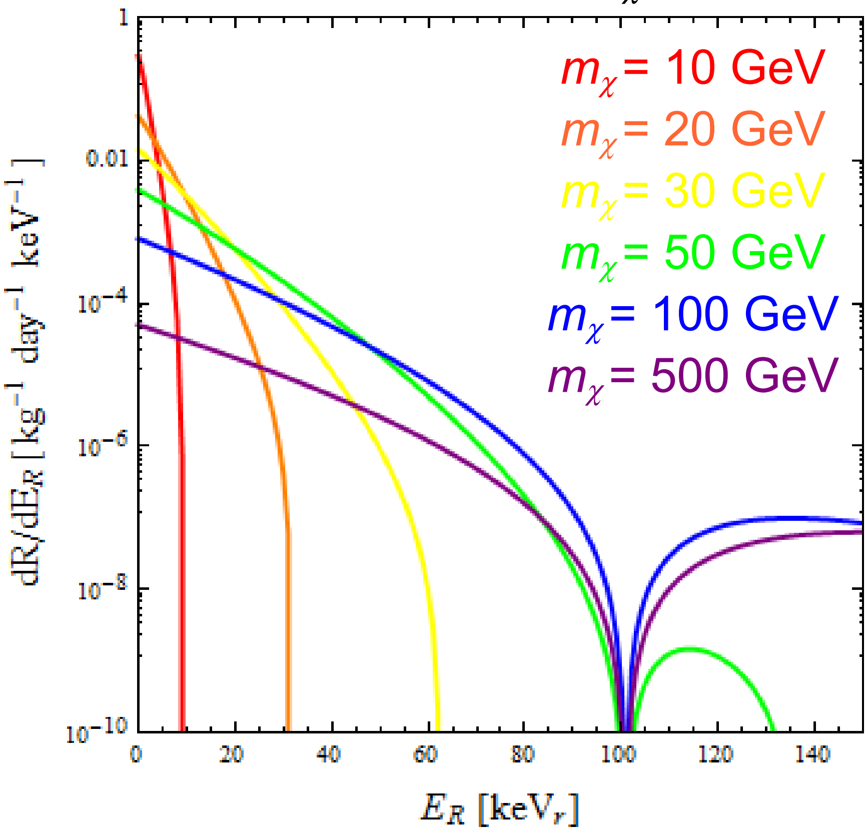
Departures from this standard picture (isospin violation, non-standard velocity distributions, etc.) can have important experimental consequences.

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



Form-factor effect

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.

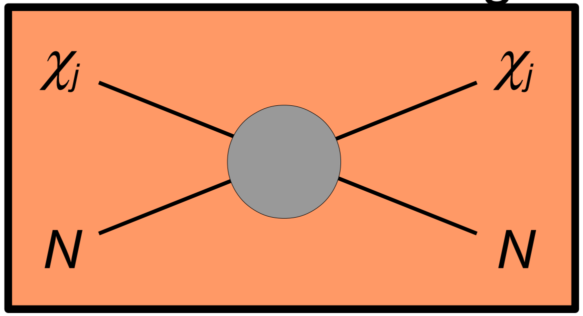
DDM Ensembles and Particle Physics

- 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 concreteness, I'll focus on the case where the couplings between the χ_j and nucleons scale like:

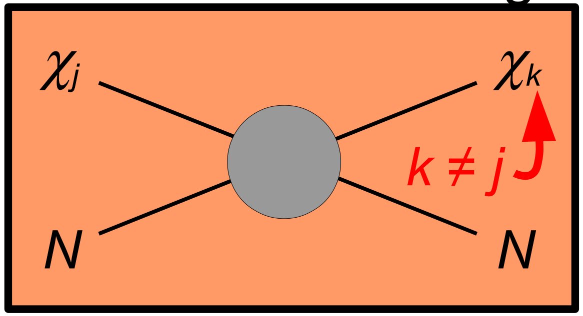
$$f_{nj} = f_{n0}\left(\frac{m_j}{m_0}\right)^{\beta} \quad \Rightarrow \quad \sigma_{nj}^{(\mathrm{SI})} = \frac{4\mu_{nj}^2}{\pi} f_{nj}^2$$

  - However, note that inelastic scattering has special significance within the DDM framework:

Elastic Scattering



Inelastic Scattering



- Possibility of **downscattering** ($m_k < m_j$) as well as upscattering ($m_k > m_j$) within a DDM ensemble.
- Scattering rates for $\chi_j N \rightarrow \chi_k N$ place lower bounds on rates for decays of the form $\chi_j \rightarrow \chi_k$ + [SM fields] and hence bounds **on the lifetimes** of the χ_j.

DDM Ensembles and Cosmology

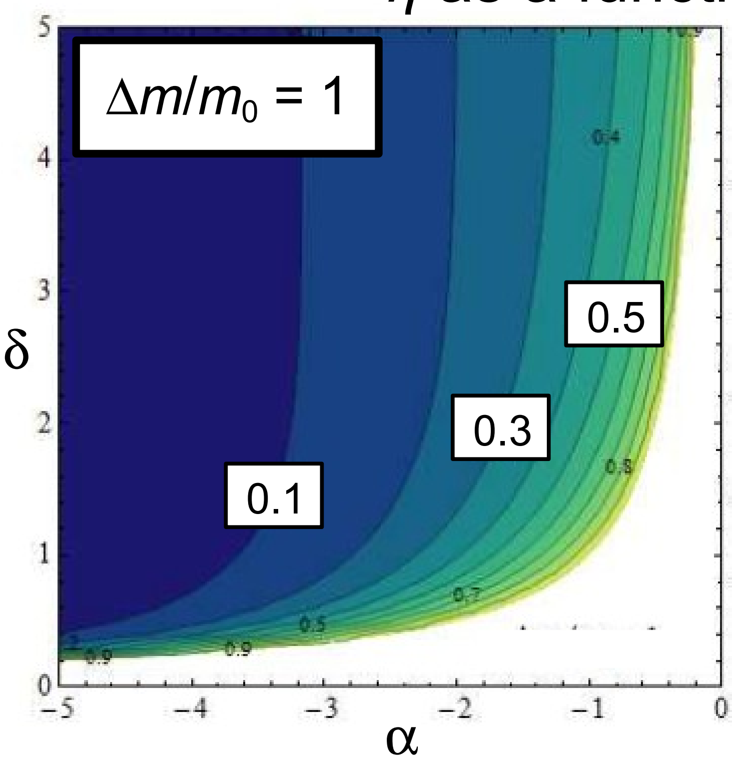
- In contrast to the collider analysis presented above, direct detection involves **a cosmological population** of DM particles, and thus aspects of DDM cosmology.
- Recall that the cosmology of a given DDM ensemble is primarily characterized by the two parameters η and $\Omega_{\rm tot}$.
- For concreteness, consider the case where $m_j = m_0 + n^\delta \Delta m$ and the present-day abundances Ω_j scale like:

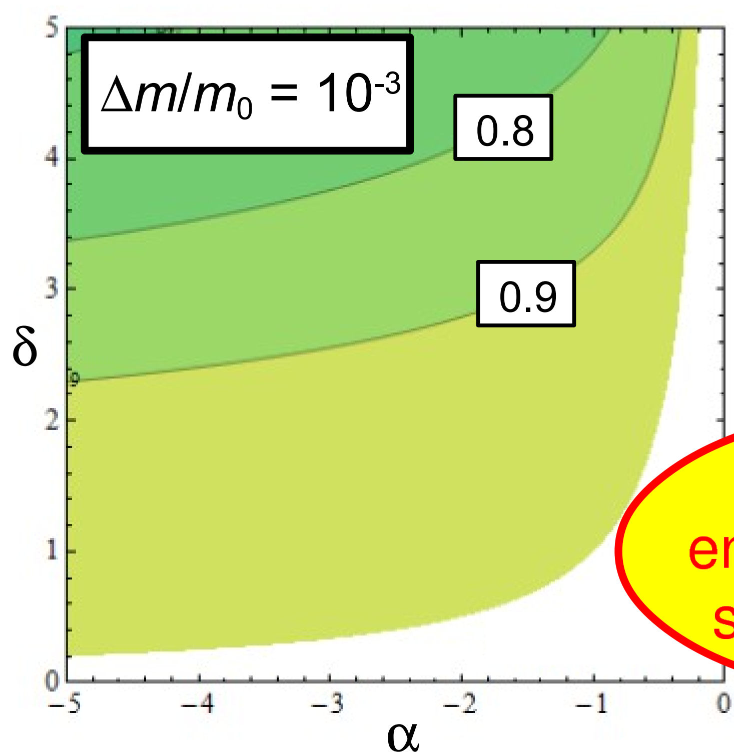
$$\Omega_{\rm tot} = \sum_j \Omega_j$$

$$\eta = 1 - \frac{\Omega_0}{\Omega_{\rm tot}}$$

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

η as a function of α and δ

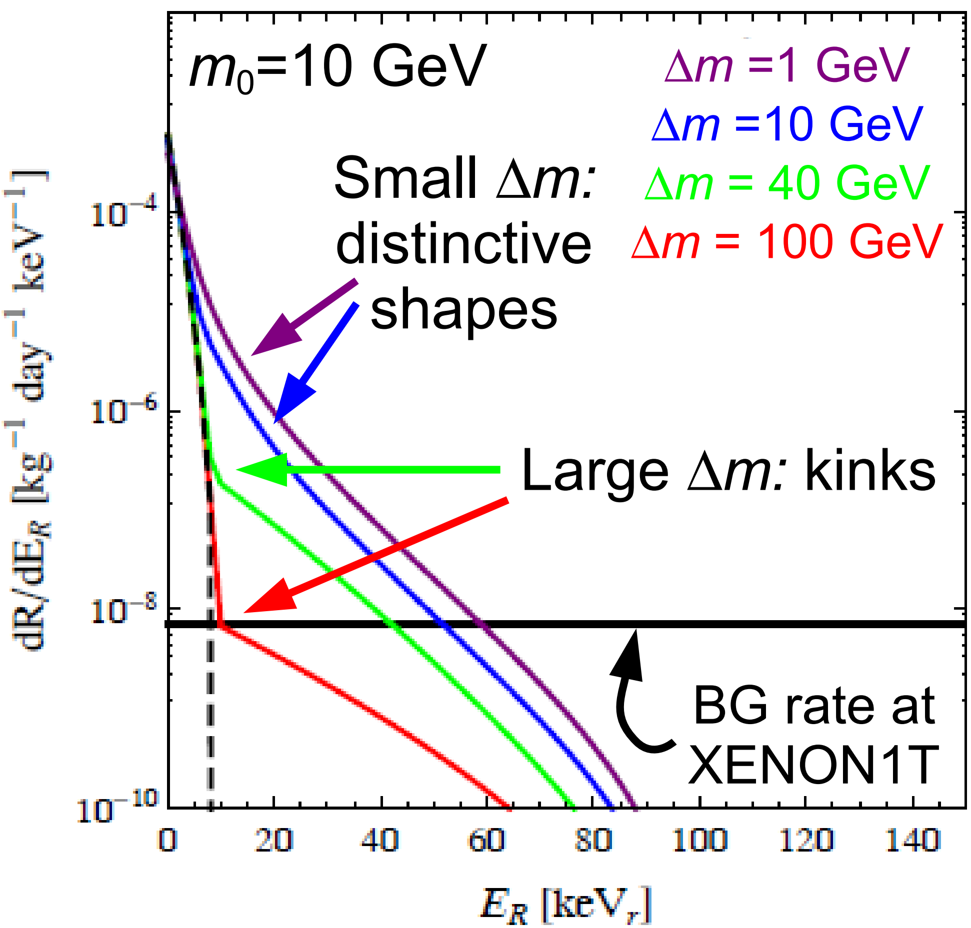




$\eta \sim \mathcal{O}(1)$: the full ensemble contributes significantly to $\Omega_{\rm tot}$.

Recoil-Energy Spectra: DDM

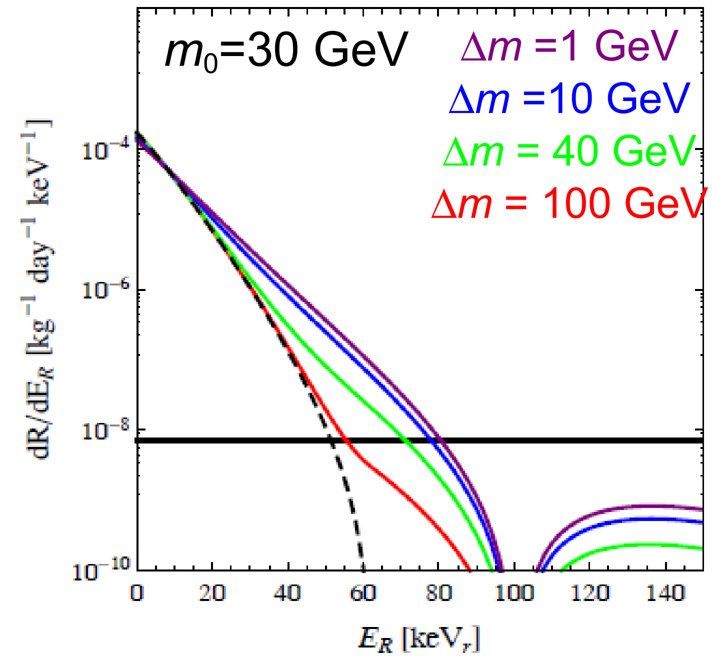
- **Distinctive features** emerge in the recoil-energy spectra of DDM models, especially when one or more of the χ_j are in the low-mass regime.
- As m_0 increases, more of the χ_j shift to the high-mass regime. Spectra increasingly resemble those of traditional DM candidates with $m_\chi \approx m_0$.

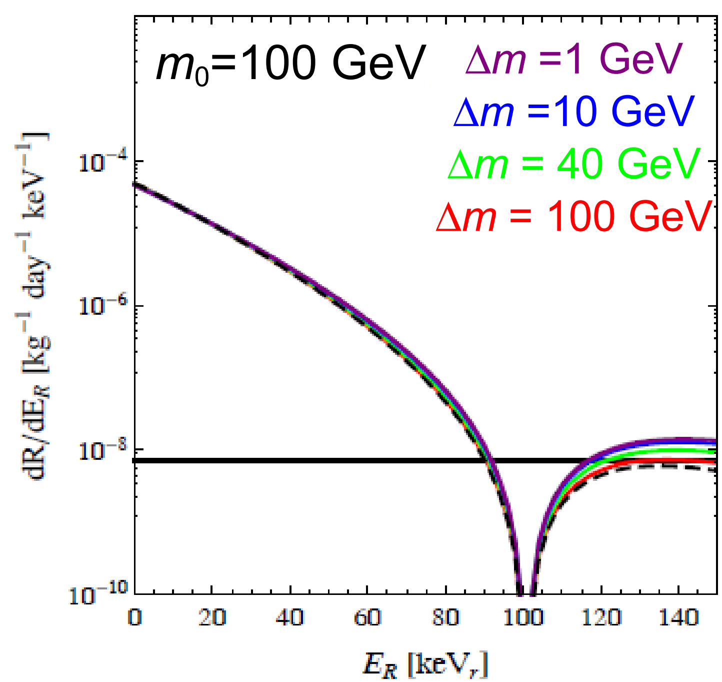


α = -1.5
β = -1
δ = 1

Xe target

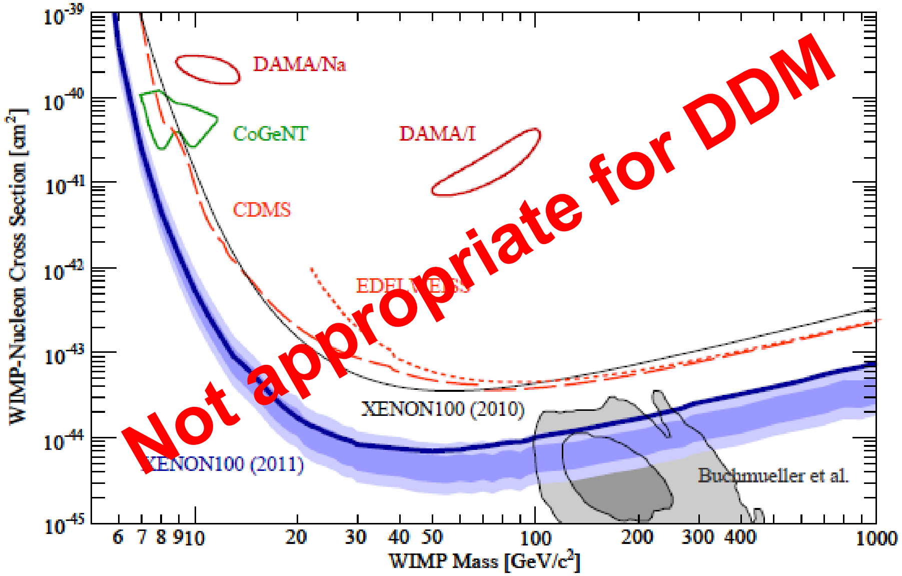
Rate normalized to that of χ with $\sigma_\chi^{(SI)}$=10^{-9} pb



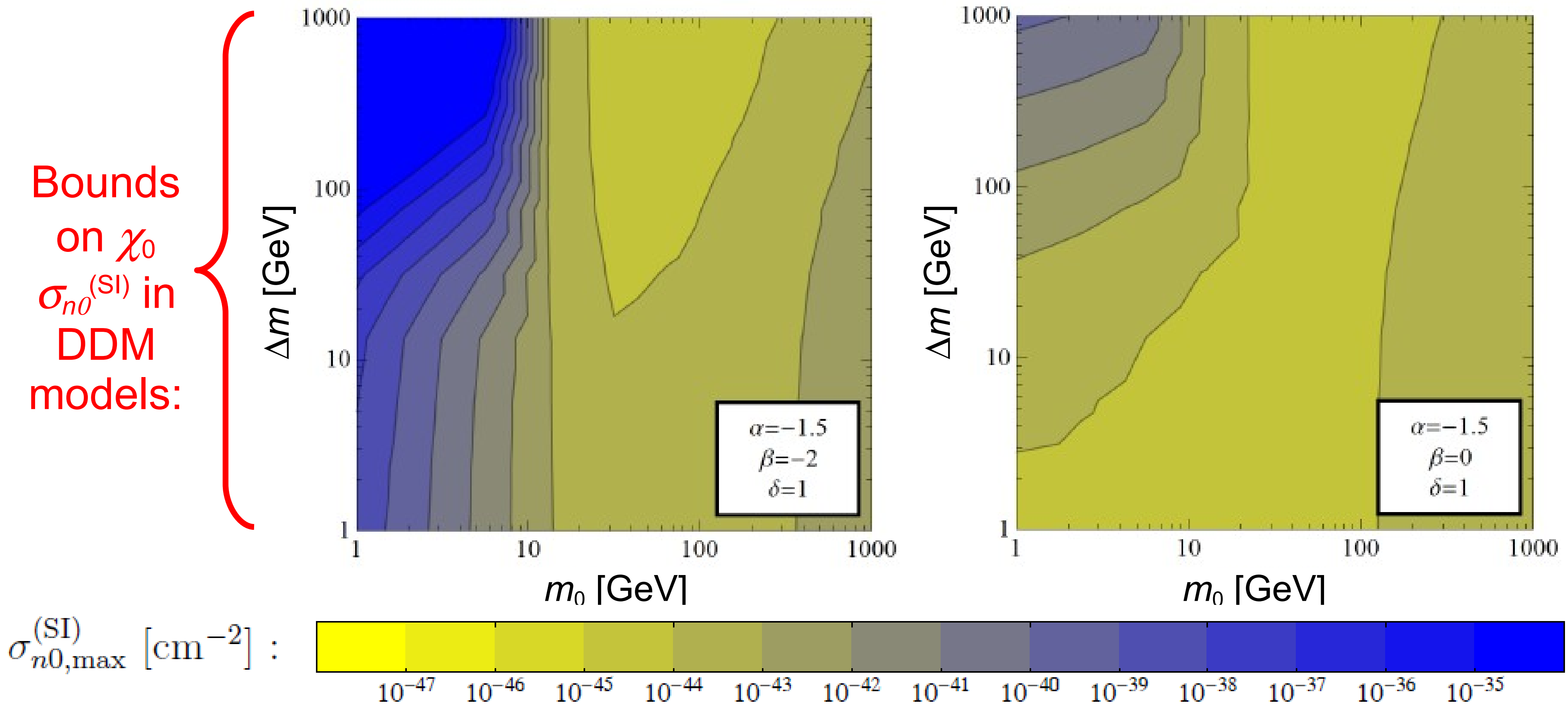


Constraining Ensembles:

- Experimental limits constrain DDM models just as they constrain traditional DM models.
- A DDM ensemble has no well-defined mass or interaction cross-section: limits *cannot* be phrased as bounds on m_χ and $\sigma_\chi^{(SI)}$.
- Most stringent limits from XENON100 data.



Bounds on χ_0 $\sigma_{n0}^{(SI)}$ in DDM models:



How well can we 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 the case in which a *particular* experiment, characterized by certain attributes including...

Target material(s)	Fiducial Volume	Signal acceptance
Detection method	Data-collection time	Recoil-energy window

…reports a statistically significant excess in the number of signal events.

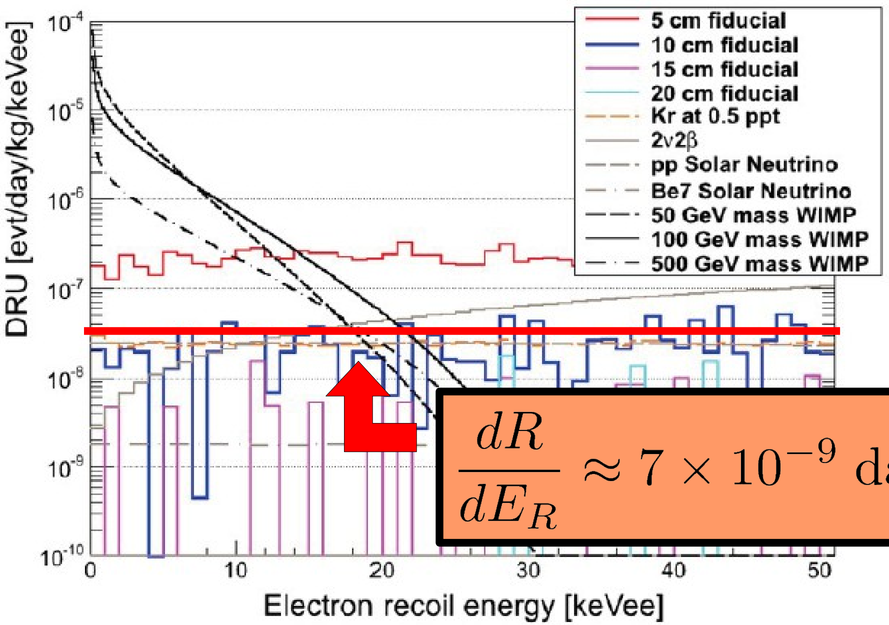
The Procedure (much like in our collider analysis):

- Compare the recoil-energy spectrum for a given DDM ensemble to those of traditonal DM candidates which yield the **same total event rate** at a given detector.
- Survey over traditional DM candidates with different m_χ and define a χ^2 statistic for each m_χ to quantify the degree to which the corrsponding recoil-energy spectrum differs from that associated with the DDM ensemble.
- The minimum $\chi^2_{\rm min}$ of these quantifies the degree to which the DDM model can be distinguished from traditional DM candidates, under standard astrophysical assumptions.

As an example, consider a detector with similar attributes to those anticipated for the next generation of noble-liquid experiments (XENON1T, LUX/LZ, PANDA-X, et al.). In particular, we take:

- 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

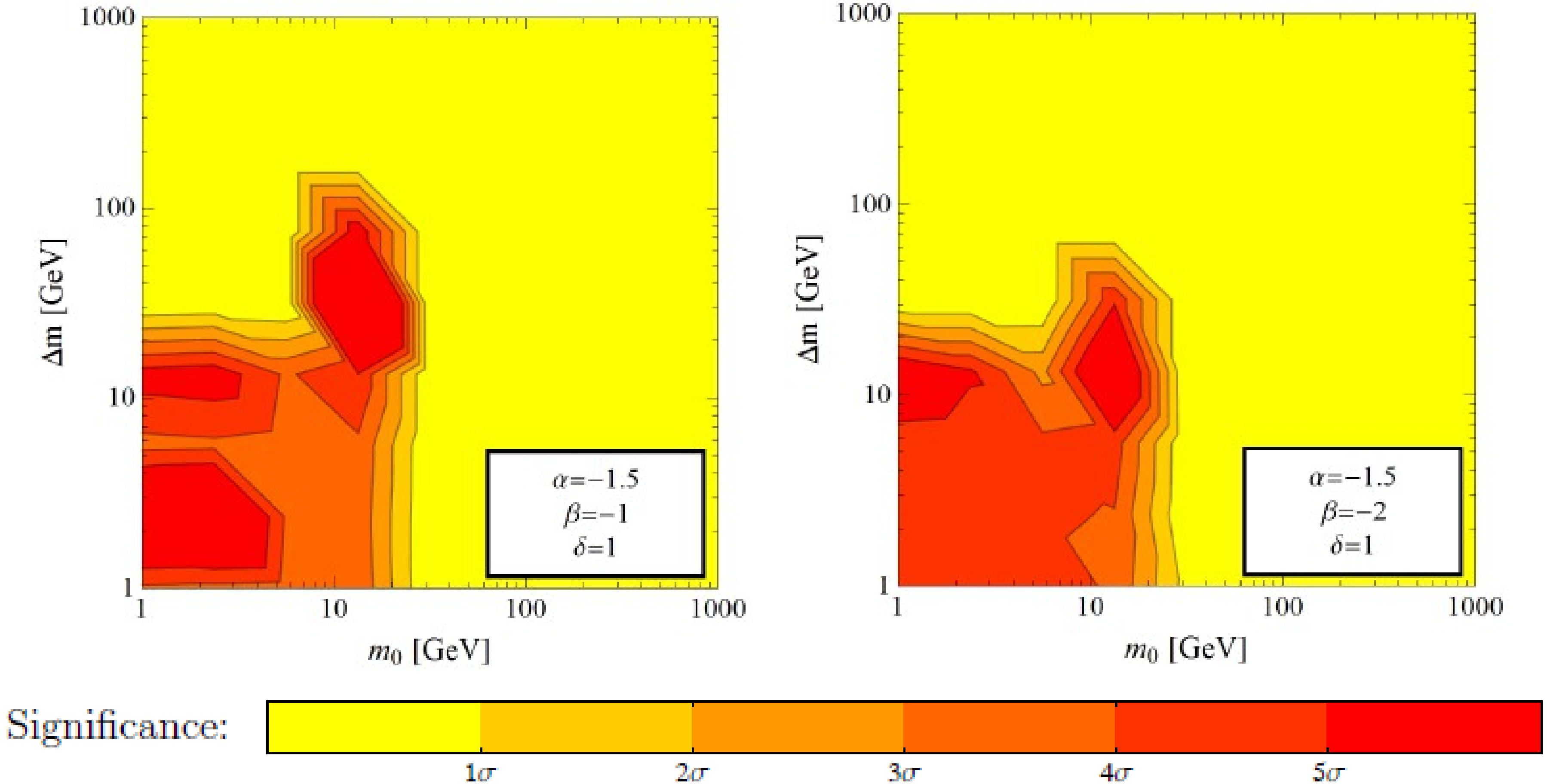
Background Contribution



$$\frac{dR}{dE_R} \approx 7 \times 10^{-9}\ \mathrm{day}^{-1}\mathrm{kg}^{-1}\mathrm{keV}_{\mathrm{nr}}^{-1}$$

- N_e ~ 1000 total signal events observed (consistent with most stringent current limits from XENON100).
- Background dR/dE_R spectrum essentially flat

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.

- The best prospects are obtained in cases where multiple χ_j are in the low-mass regime: $m_j \lesssim 30$ GeV.
- A 5σ significance of differentiation is also possible in cases in which only χ_0 is in the low-mass regime and a kink in the spectrum can be resolved.

CAUTION

Discrepancies in recoil-energy spectra from standard expectations can arise due to several other factors as well (complicated halo-velocity distribution, velocity-dependent interactions, etc.). Care should be taken in interpreting such discrepancies in the context of any particular model.

However,

By comparing/correlating signals from **multiple experiments** it should be possible to distinguish between a DDM interpretation and many of these alternative possibilities.

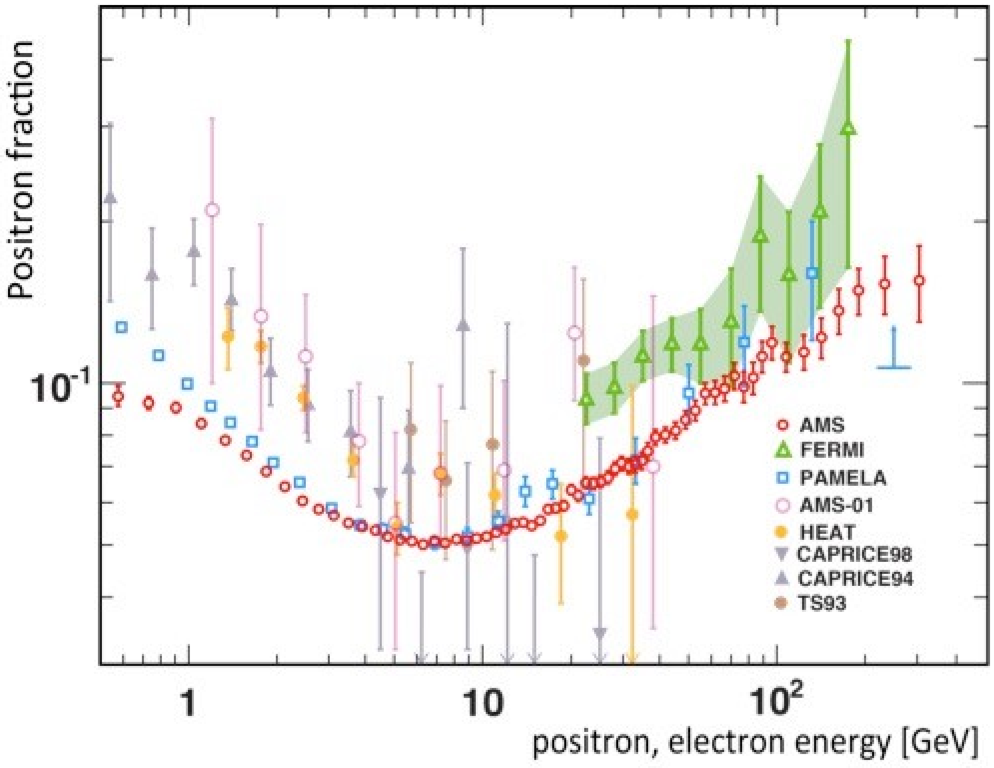
Distinguishing DDM with Cosmic-Ray Detectors

K. R. Dienes, J. Kumar, BT [arXiv:1305.2959]

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.



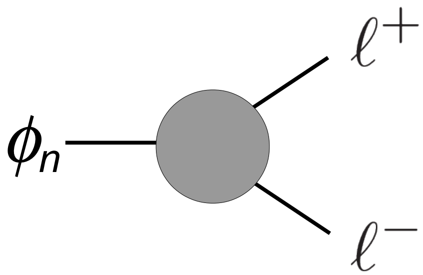
Dark-matter candidates whose annihilations or decays reproduce the observed positron fraction typically run into other issues:

- Limits on the continuum gamma-ray flux from FERMI, etc.
- Limits on the cosmic-ray antiproton flux from PAMELA, 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.

e.g.,
$$\mathcal{L}_{\rm int} = \frac{c_n}{\Lambda} (\partial_\mu \phi_n)\, \overline{\ell} \gamma^\mu \ell$$

Distributing the dark-matter relic abundance across the ensemble yields a spectrum of lepton injection energies

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

Surveying the Parameter Space

- In surveying the parameter space of our DDM model, we adopt the following criteria for consistency with observational limits:

  - Consistency with the combined $e^+ + e^-$ flux spectrum observed by FERMI to within 3σ.
  - Consistency with the diffuse extragalactic gama-ray flux observed by FERMI (the most stringent gamma-ray constraint on decaying dark-matter models of this sort).
  - Conistency with PAMELA limits on the antiproton flux to within 3σ (*easily* satisfied for leptophilic DDM ensembles).
  - Consistency with projected Planck CMB reionization limits.

- For each choice of α, γ, and m_0, we survey over values of $\tau_0 \equiv 1/\Gamma_0$ and identify the value which provides the best fit to the AMS positron-fraction data (using a χ^2 statistic) and simultaneously satisfies the above criteria.

- We are primarily interested in the **"continuum" regime**, in which the mass splitting between all relevant modes is much smaller than the energy resolution of the AMS detector. We therefore focus on the benchmark values $\Delta m = 1$ GeV, $\delta = 1$.

As a result of the softening of the $e^{\pm}$ injection spectra, DDM ensembles can reproduce AMS positron-fraction data while simultaneously satisfying these other additional constraints.

Decays primarily to $\mu^+\mu^-$ strongly preferred

The best fit to AMS data is obtained for:

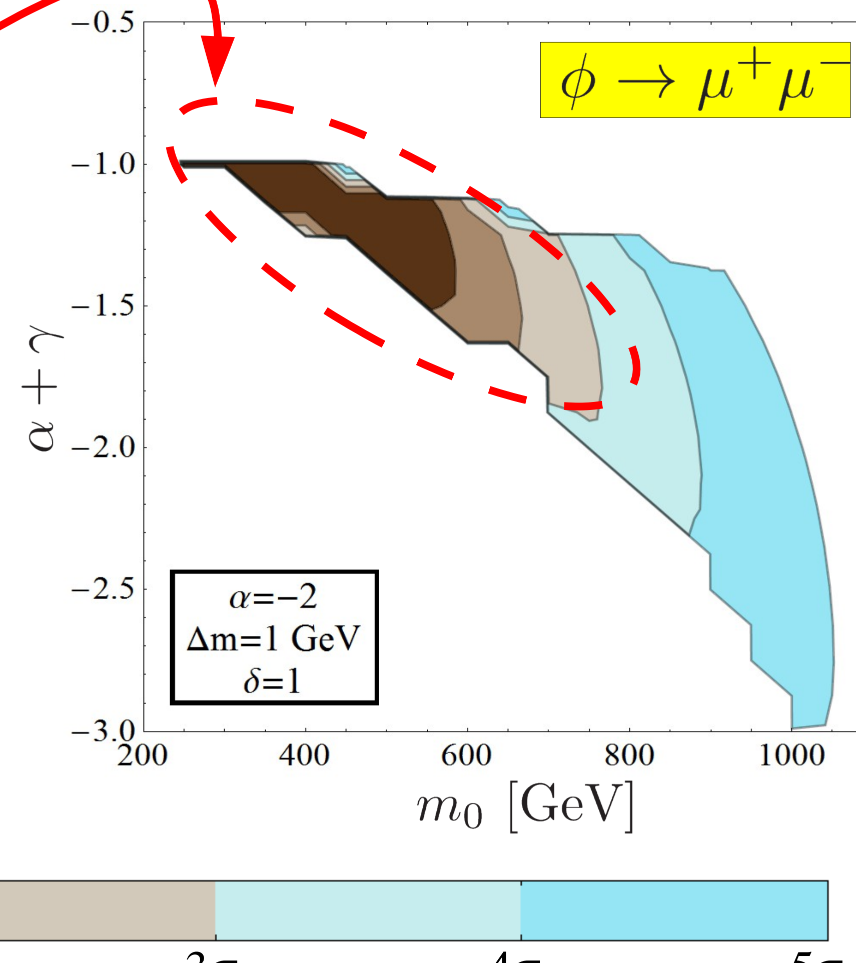
$200\ \mathrm{GeV} \lesssim m_0 \lesssim 800\ \mathrm{GeV}$

...and thus when a substantial number of enemble constituents are reasonably light.

This helps ease tensions with gamma-ray constraints relative to traditional dark-matter models with m_χ ~ 1-3 TeV.

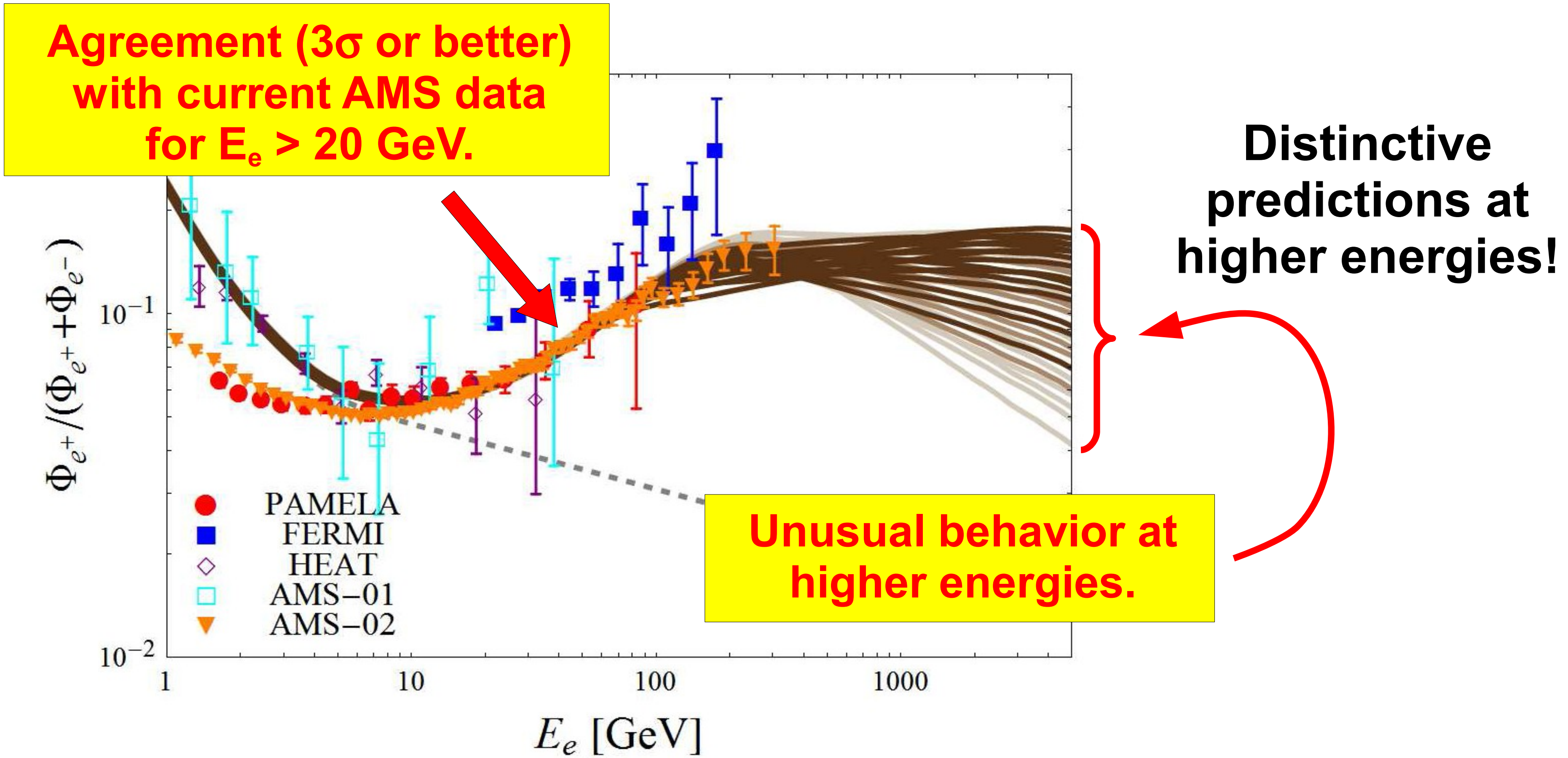
Such light ensemble constituents are also far easier to detect via complementary probes of the dark sector (e.g., colliders).

Discrepancy from AMS Positron Fraction



(White region: either > 5σ discrepancy or else ruled out by other constraints)

Positron Fractions from DDM Ensembles



The positron-fraction curves associated with DDM models in the continuum regime yield a concrete prediction for the positron fraction at $E_{e\pm}$ < 350 GeV :

In stark contrast to the pronounced downturn anticipated for typical dark-matter models, DDM models in this regime predict a **plateau** or a **gradual decline** in the positron fraction at high energies.

DDM vs. Pulsars

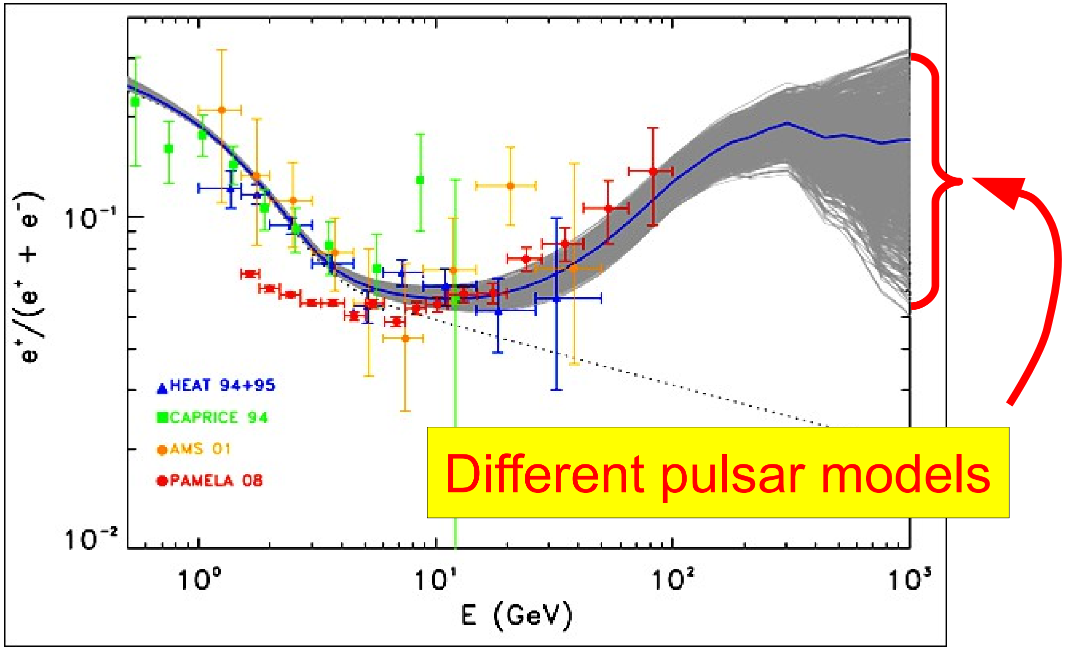
Q: Can't a population of pulsars reproduce the same positron-fraction curves?

A: Yep. Sure can.

Q: Can't a population of pulsars also reproduce essentially any curve you want?

A: Yep. Sure can.

The point is that a large number of positron-fraction curves which one might have thought could only be reproduced by pulsars ***also*** **have a natural dark-matter interpretation in terms of DDM ensembles!**



- Probing **anisotropies** in the e^+ and e^- fluxes could potentially help distinguish between pulsar populations and DDM ensembles.
- Successful DDM models of the positron excess include many light ensemble constituents which could potentially be dectected using other, **complementary probes** of the dark sector.

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:

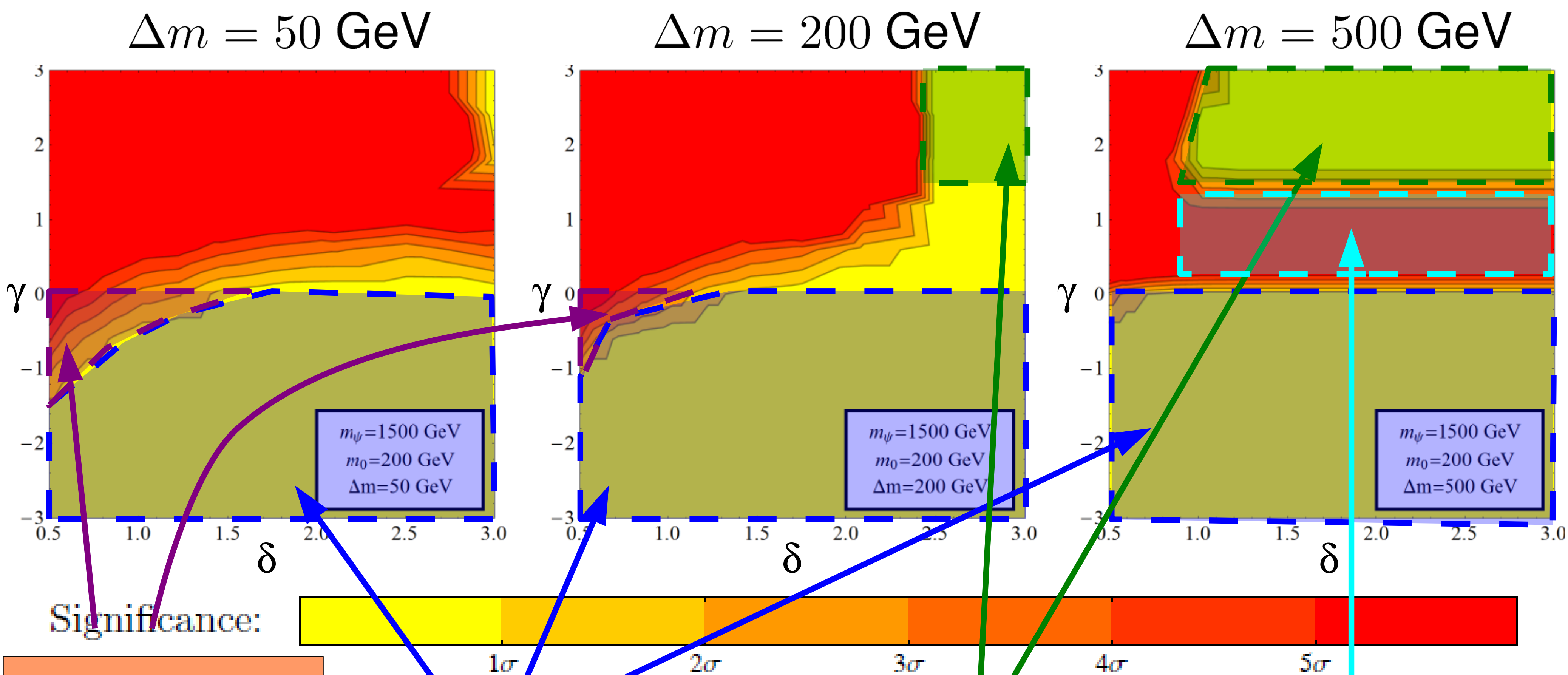
- Imprints on kinematic distributions of SM particles at colliders.
- Distinctive features in the recoil-energy spectra observed at direct-detection experiments.
- Unusual features in cosmic-ray e^+ and e^- spectra at high energies.

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

Extra Slides

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.

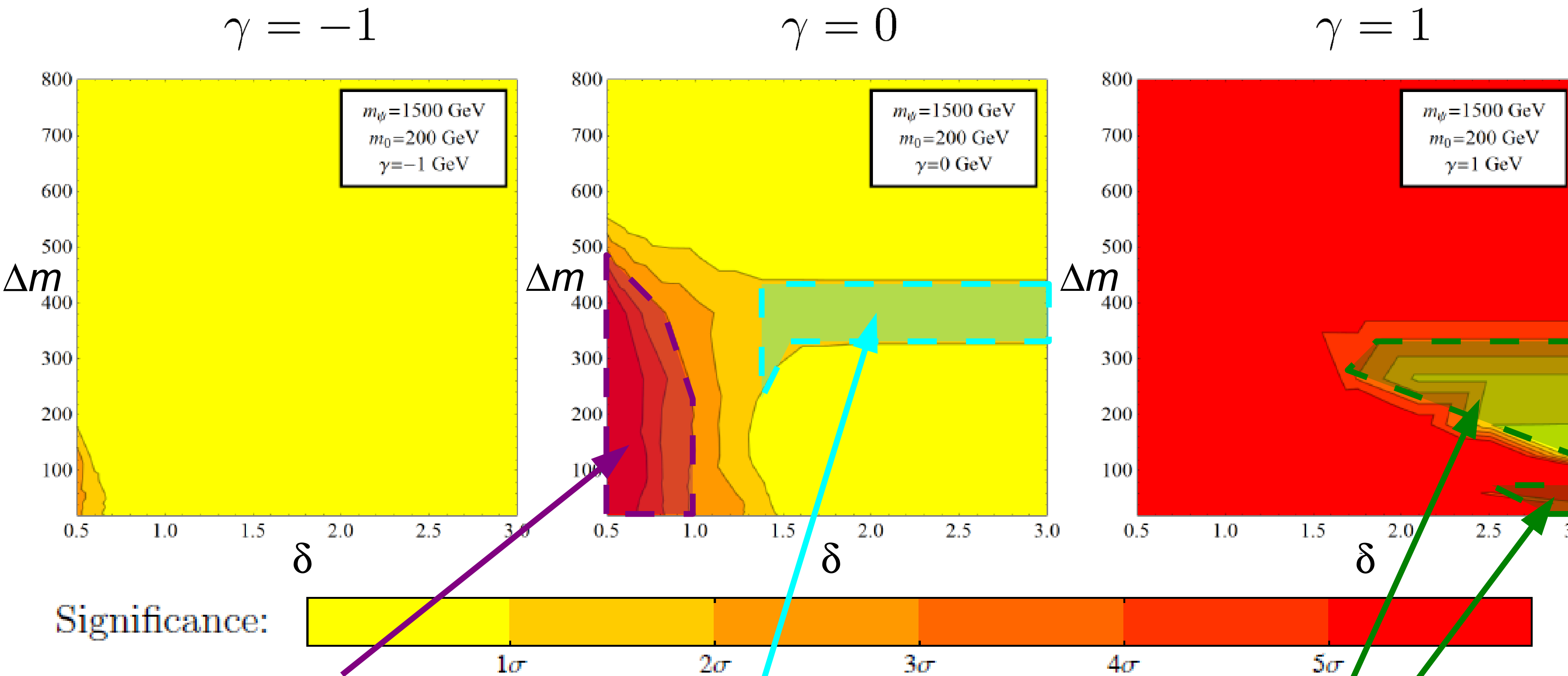
BRs to all χ_n with n > 1 suppressed: lightest constituent dominates the width of ψ.

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

BR(ψ jjχ_0) ≈ BR(ψ jjχ_1): two distinct m_{jj} peaks.

Distinguishing DDM Ensembles: Results

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



Large number of states accessible for small Δm, δ

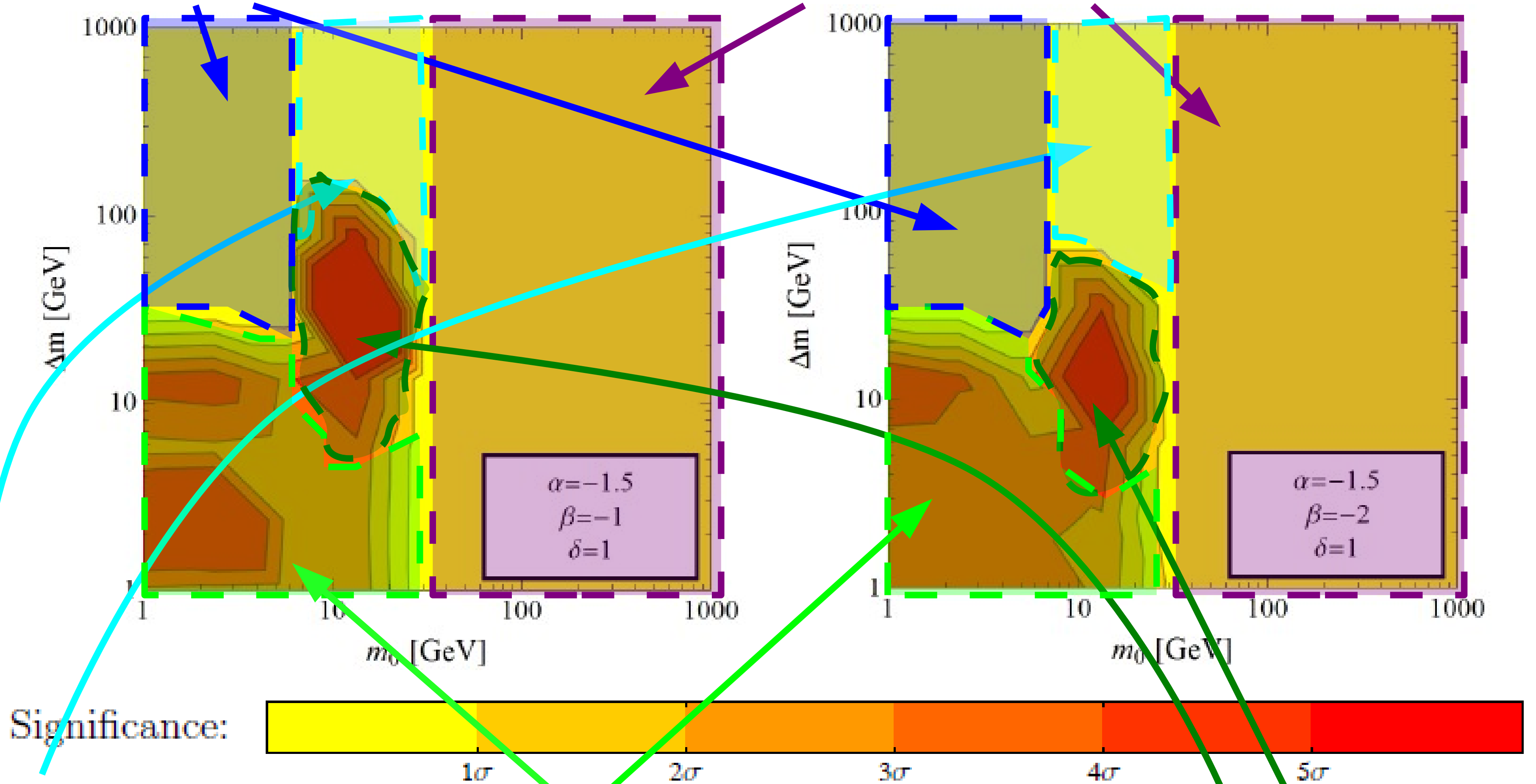
BR(ψ $jj\chi_0$) ≈ BR(ψ $jj\chi_1$): two distinct m_{jj} peaks.

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

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 perceptibly 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

Reionization Limits

- High-energy photons, electrons, and positrons produced from dark-matter decay can alter the reionization history of the universe, thereby leaving observable imprints on the CMB.

- Limits from Planck, WMAP, etc., on such imprints essentially constrain the total energy injection from dark-matter decays:

$$\xi \equiv \sum_{n=0}^{n_{\max}} \Omega_n \Gamma_n \lesssim 3 \times 10^{-26}\ \mathrm{s}^{-1}$$

Projected Planck limit
(including polarization data)

Excluded Region