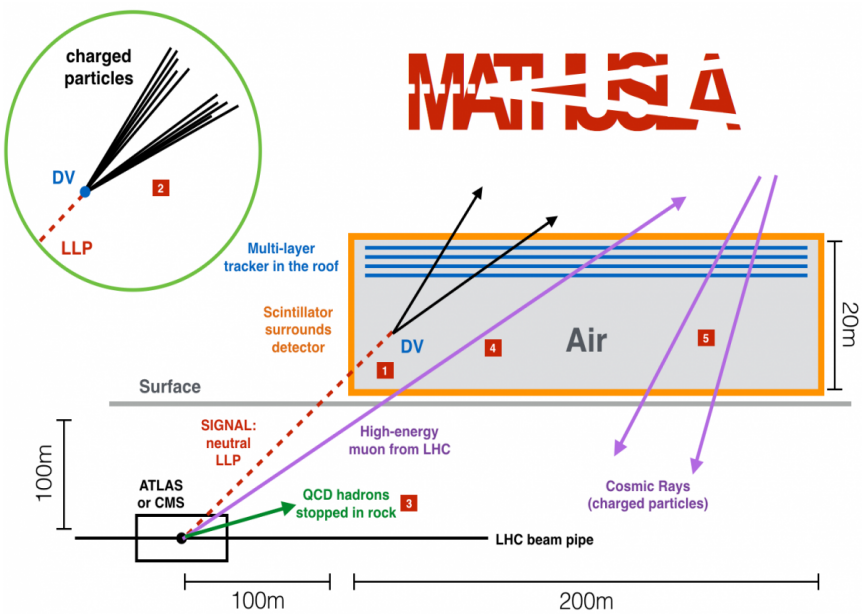
Dynamical Dark Matter at the Lifetime Frontier



Brooks Thomas

LAFAYETTE COLLEGE

Based on work done in collaboration with:

- **David Curtin and Keith Dienes [arXiv:1806.07396, arXiv:1809.11021].**

Section in MATHUSLA white paper

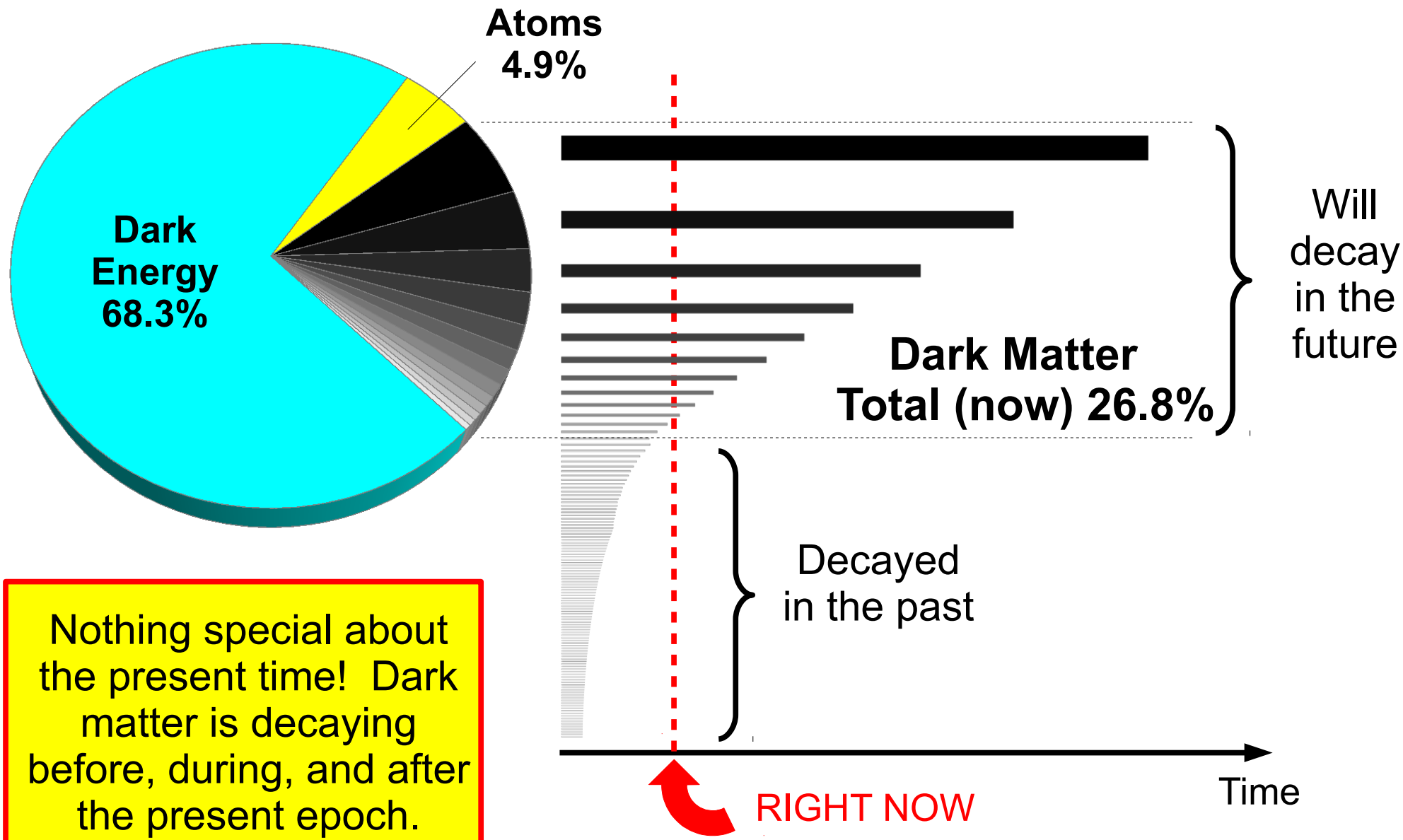
Dynamical Dark Matter

- Observational constraints impose a **stringent bound** ($\tau_\chi \gtrsim 10^{28}\,\mathrm{s}$) on the lifetimes of traditional dark-matter candidates χ which decay to visible-sector states over a large mass range $\mathcal{O}(100\,\mathrm{keV}) \lesssim m_\chi \lesssim \mathcal{O}(\mathrm{EeV})$.
- Such "hyperstability" is therefore a requirement in traditional dark-matter scenarios.
- **Dynamical Dark Matter** (DDM) is an alternative framework for dark-matter physics which provides a novel way of evading this hyperstability requirement, thereby enlarging the theory space of viable dark-matter scenarios. [Dienes, BT, '11]

In DDM scenarios...

- The dark-matter candidate is an **ensemble** consisting of a potentially vast number of constituent particle species.
- The individual abundances of the constituents are **balanced against decay rates** across the ensemble such that constraints are satisfied.
- The DM abundance and equation of state also exhibit a **non-trivial time-dependence** beyond that associated with Hubble expansion.

A Snapshot of the Cosmic Pie: Past, Present, and Future

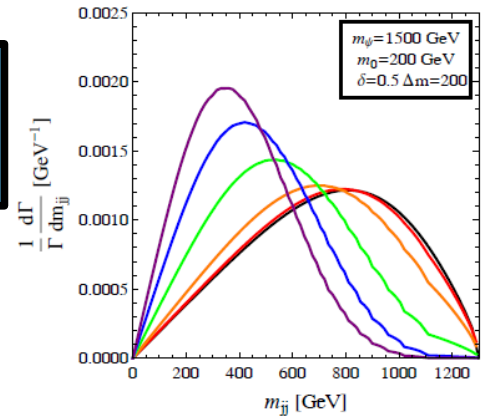


Nothing special about the present time! Dark matter is decaying before, during, and after the present epoch.

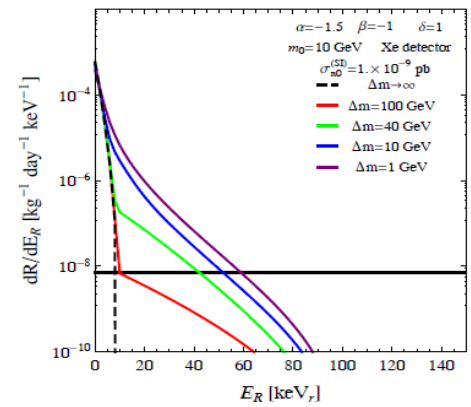
DDM: Phenomenological Consequences

- Concrete realizations of the DDM framework often also give rise to **distinctive signatures** at colliders, direct-detection experiments, or indirect-detection experiments. These include...

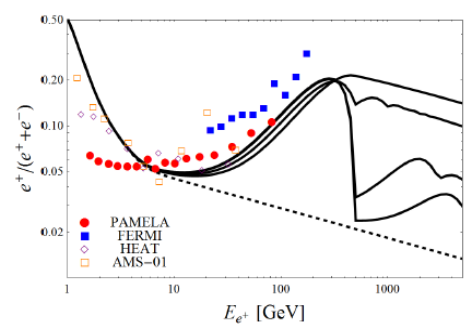
Marked differences in kinematics of visible particles at colliders. [Dienes, Su, BT '12]



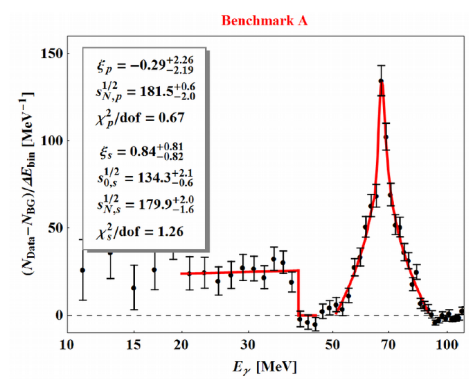
Distinctive energy distributions for nuclear recoils at direct-detection experiments. [Dienes, Kumar, BT '12]



Cosmic-ray fluxes consistent with data at low energies, but which exhibit strange behavior at high energies [Dienes, Kumar, BT '13]



Characteristic correlations between spectral features at future gamma-ray telescopes [Boddy, Dienes, Kim, Kumar Park, BT '16]



Scaling Relations

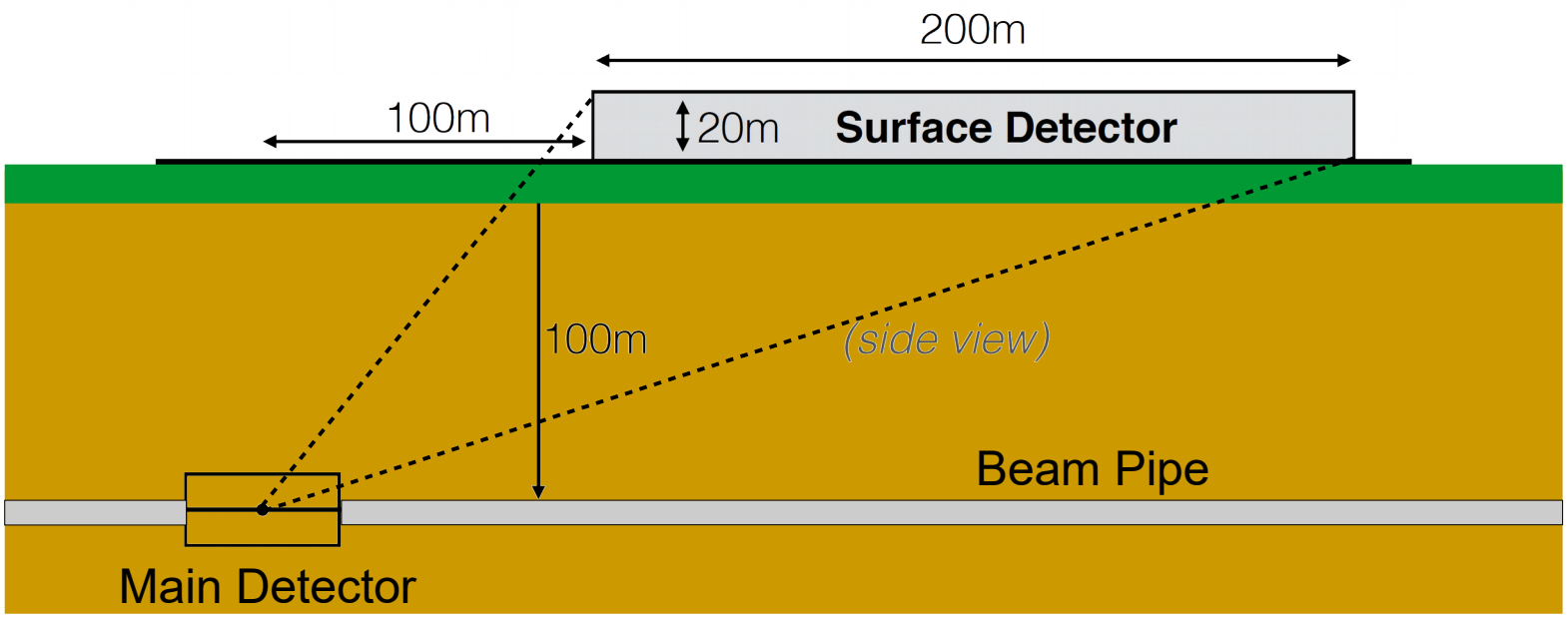
- A DDM ensemble is ***not*** simply an arbitrary collection of dark states.
- Its structure is determined by an ***organizing principle*** which specifies the properties of those states in terms of only ***a few underlying parameters***.

- This organizing principle gives rise to a set of ***scaling relations*** which describe how the masses, abundances, decay widths, etc., of the DM particles scale in relation to one another other across the ensemble:
- The structure of the ensemble specified by these scaling relations often includes not only cosmologically stable states which contribute to Ω_{DM} today, but states with ***far shorter lifetimes*** as well.

Measuring the properites of these less stable states therefore translates into concrete predictions about the dark matter.

DDM at the Lifetime Frontier

- Realizations of the DDM framework often include not only cosmologically stable states, which contribute to Ω_{DM} today, but also states with far shorter lifetimes.
- Detectors such as MATHUSLA, which augment the detection capabilities of the main LHC detectors, could probe the structure of a DDM ensemble by its less stable constituents.



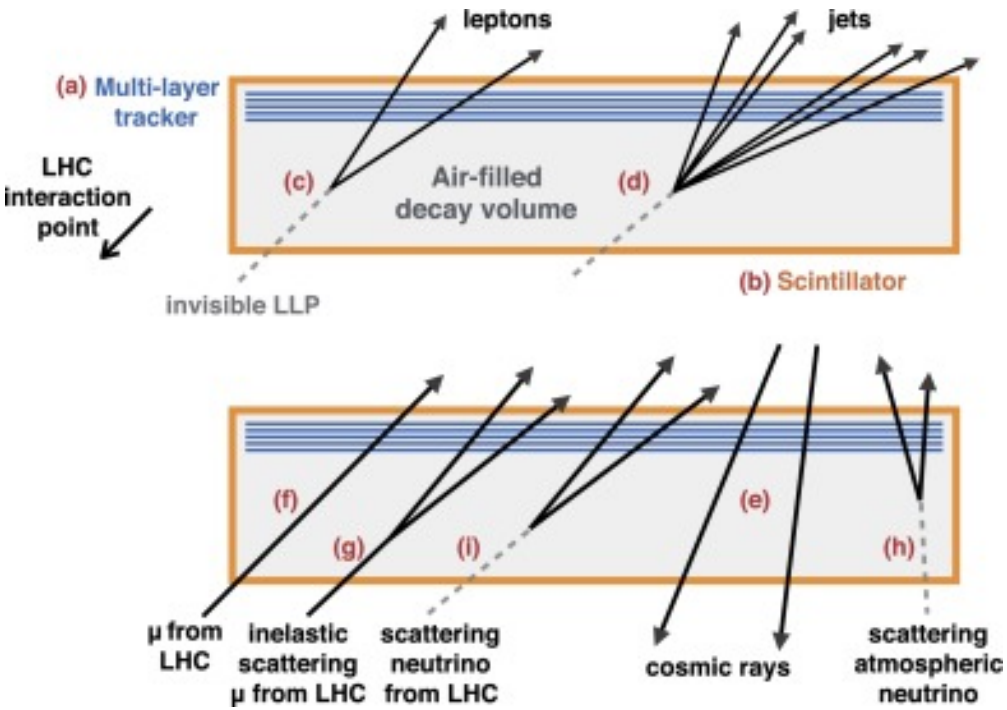
MAssive **T**iming **H**odoscope for **U**ltra **S**table neutra**L** p**A**rticles

[J. P. Chou, D. Curtin, H. Lubatti '16]

Advantages of MATHUSLA

- Design proposal involves a $(200\ \mathrm{m}) \times (200\ \mathrm{m}) \times (20\ \mathrm{m})$ decay volume.
- Similar geometric acceptance for LLP decays as the main LHC detectors.
- However, MATHUSLA does not have that same complicated triggering requirements or background issues as the main detectors.
- Excellent background rejection: near-perfect signal efficiency.

  [J. P. Chou, D. Curtin, H. Lubatti '16]
- A mere ~ 4 LLP events at the HL-LHC would be sufficent for discovery.



The Scaling Relations

- How DDM manifests itself at MATHUSLA involves an interplay between the scaling relations which govern the ensemble.
- Example model: ensemble of DM particles χ_n with masses m_n, where $n = 0, 1, 2, ..., N$.

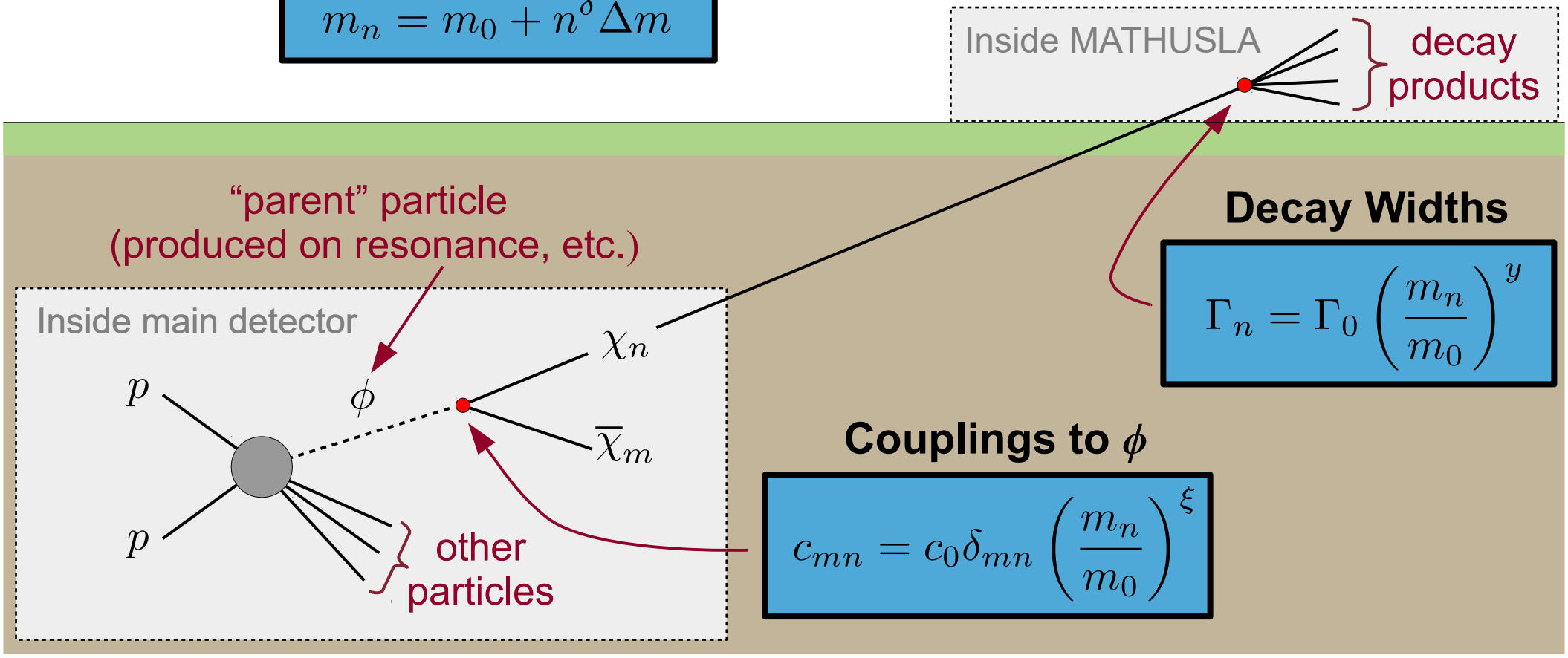
Abundances

$$\Omega_n = \Omega_0 \left(\frac{m_n}{m_0}\right)^{\gamma}$$

(not really relevant here)

Mass Spectrum

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



Decay Widths

$$\Gamma_n = \Gamma_0 \left(\frac{m_n}{m_0}\right)^{y}$$

Couplings to ϕ

$$c_{mn} = c_0 \delta_{mn} \left(\frac{m_n}{m_0}\right)^{\xi}$$

Important Questions

- How many ensemble constituents contribute significantly to the MATHUSLA signal?

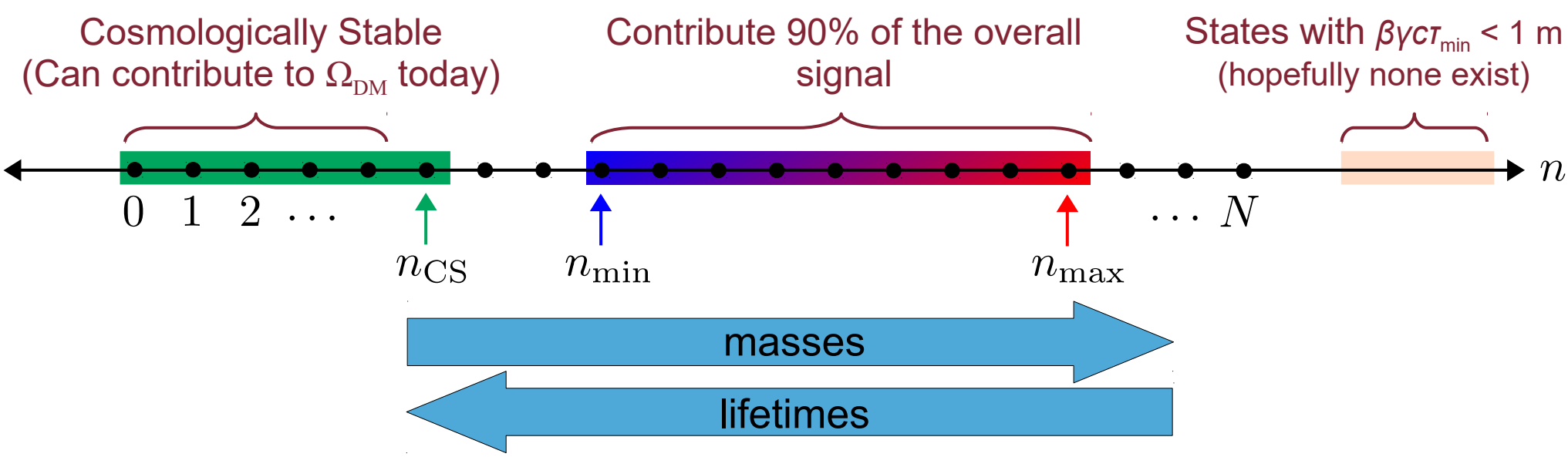
  ➡ Define $n_{\min}$ and $n_{\max}$ to delimit the range of states that contribute 90% of the overall signal rate.

- How many constituents are cosmologically stable?

  ➡ Let n_{CS} be the n value of the shortest-lived cosmologically-stable χ_n.

- Are there constituents which would characteristically decay within the main detector? (If there are, we would presumably have seen them.)

  ➡ Determine lowest n for which $\beta\gamma c\tau_{\min} < 1\ \mathrm{m}$. Should be greater than N.



Detection Prospects: Sanity Check

- Consider an example model in which ϕ couples directly to quark-antiquark pairs and can be produced at threshold via quark fusion.
- Choose coupling c_0 such that the total branching fraction for all decays of the form $\phi \to \chi_m \chi_n$ is $\mathrm{BR}_{\chi\chi} = 0.5$.
- For $m_\phi \approx 2\ \mathrm{TeV}$, we find that $\sigma_\phi \times \mathrm{Br}_{\chi\chi} \sim 100\ \mathrm{fb}$. This is (just) sufficient for a discovery at MATHUSLA.

Significantly larger m_ϕ ➡ $\sigma_\phi \times \mathrm{BR}_{\chi\chi} \ll 100\,\mathrm{fb}$

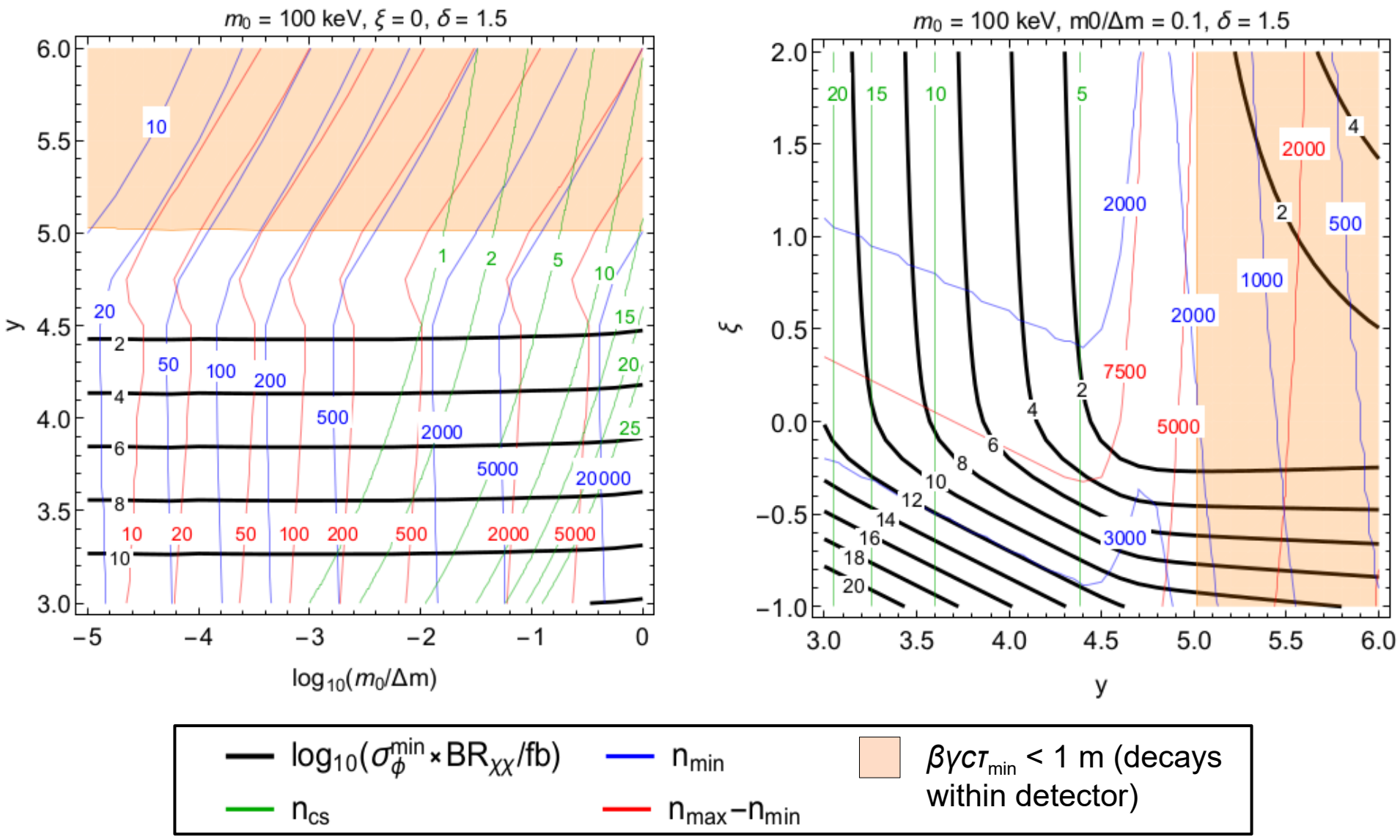
(signal unobservable)

Significantly smaller m_ϕ ➡ Ruled out by ATLAS/CMS searches in monojet + MET, dijet channels

Demonstrates that MATHUSLA is indeed capable of probing realistic DDM scenarios.

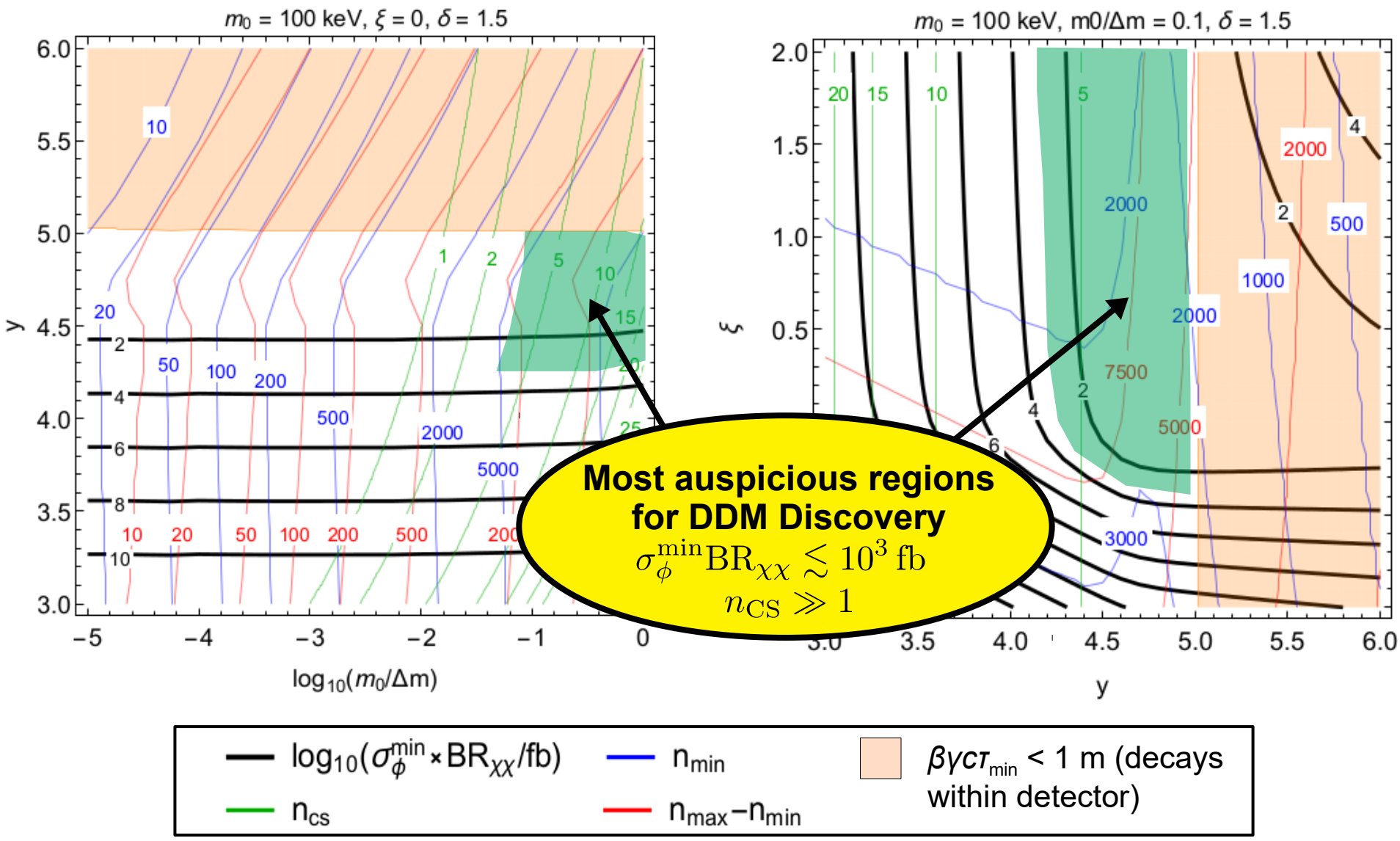
- Moroever, for this reason, we take $m_\phi = 2\ \mathrm{TeV}$, as our benchmark value in what follows.

The Reach of MATHUSLA within DDM Parameter Space



- Contours show minimum value of $\sigma_\phi \times \mathrm{BR}_{\chi\chi}$ within parameter space required in order to observe ~ 4 LLP events are during the HL-LHC run.

The Reach of MATHUSLA within DDM Parameter Space



- Contours show minimum value of $\sigma_\phi \times \mathrm{BR}_{\chi\chi}$ within parameter space required in order to observe ~ 4 LLP events are during the HL-LHC run.

Summary

- DDM ensembles often include not only cosmologically-stable states that serve as dark matter today, but also far less stable states that ***manifest as LLPs***.
- These LLPs can lead to signals at dedicated detectors like MATHUSLA.
- We have explored the reach of MATHUSLA within the parameter space of DDM scenarios and identified particularly auspicious regions within that parameter space within which a significant number of cosmologically-stable χ_n contribute to $\Omega_{\rm DM}$ today, while ***a discovery is possible*** at MATHUSLA due to the less stable χ_n.
- The properties of all ensemble constituents are determined by the same set of scaling relations. Thus, measuring the properties of the LLPs allows us to make ***concrete predictions*** about the properties of the dark matter.
- In principle, ***correlations between signals*** at MATHUSLA and signals at the main LHC detector can yield even more information about the structure of the ensemble.