LLP-DM Overview

Linking LLP searches and experiments to DM models

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Roadmap of Dark Matter models for Run 3 Workshop
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General Principles

1. General Connection of LLPs to Hidden Sectors

Any hidden sector with more than one particle in it generically contains unstable particles. (E.g. Dark QCD)

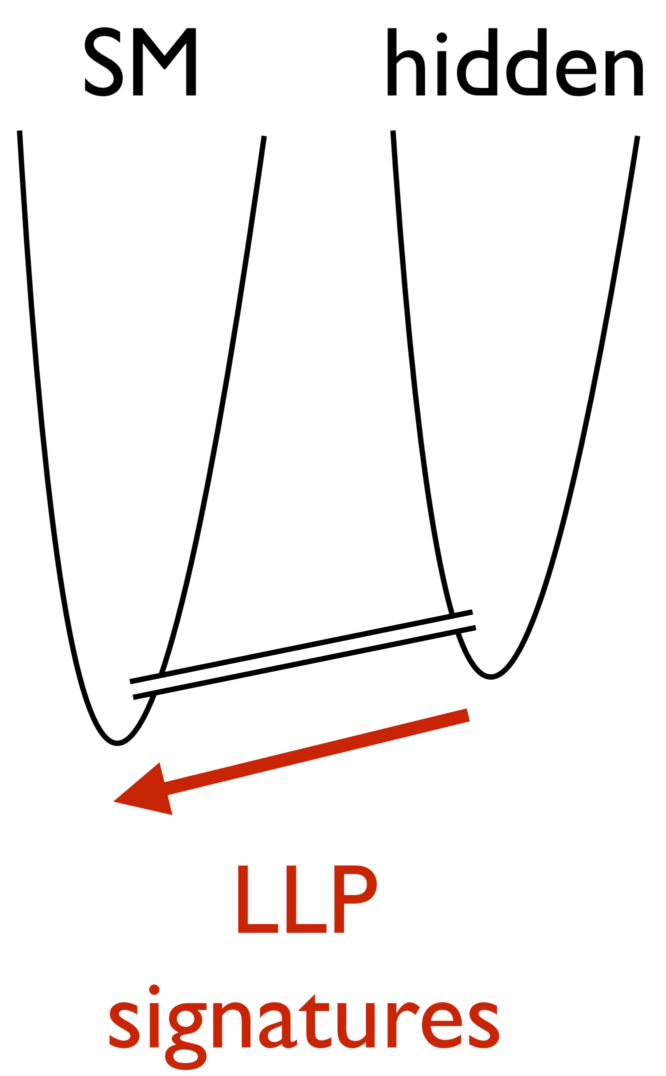
If the lightest ones are stable, they are DM candidates.

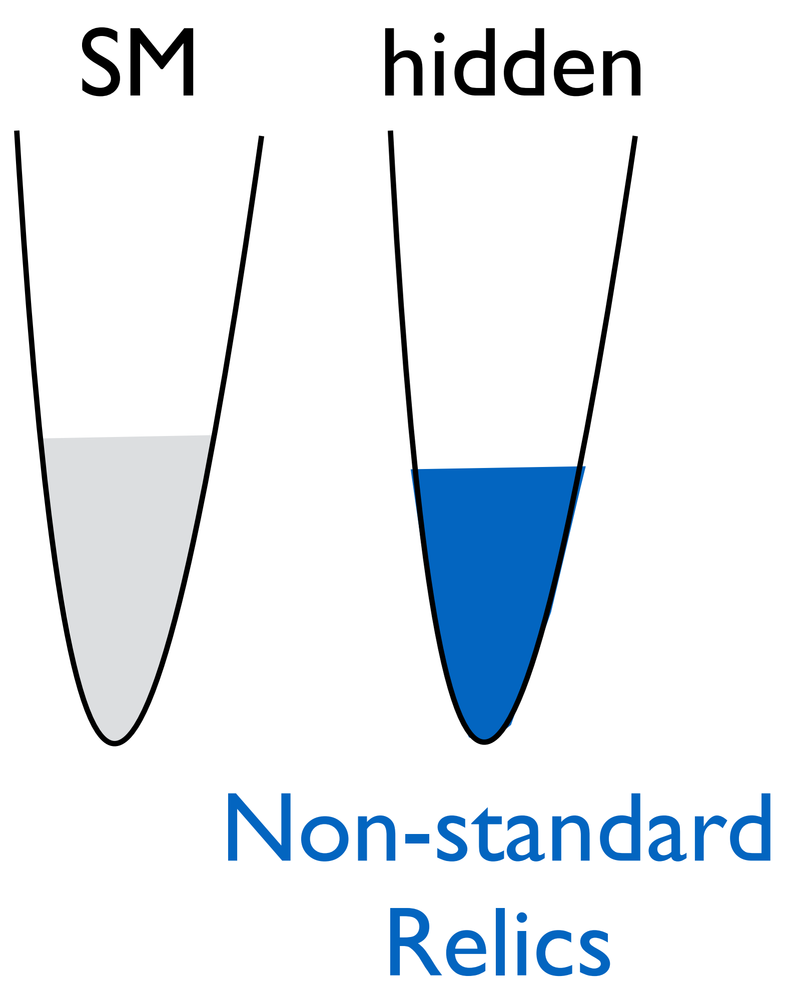
The unstable ones are often LLPs due to tiny SM portal couplings being only decay (and collider production) channel.

e.g. dark glueballs, dark photons, …

2. Two sides of the same coin

The LLP might not have a direct empirical connection to DM, but a deep theoretical one: the same kinds of models make DM or LLPs, depending on whether the stabilizing symmetry is exact or slightly broken.

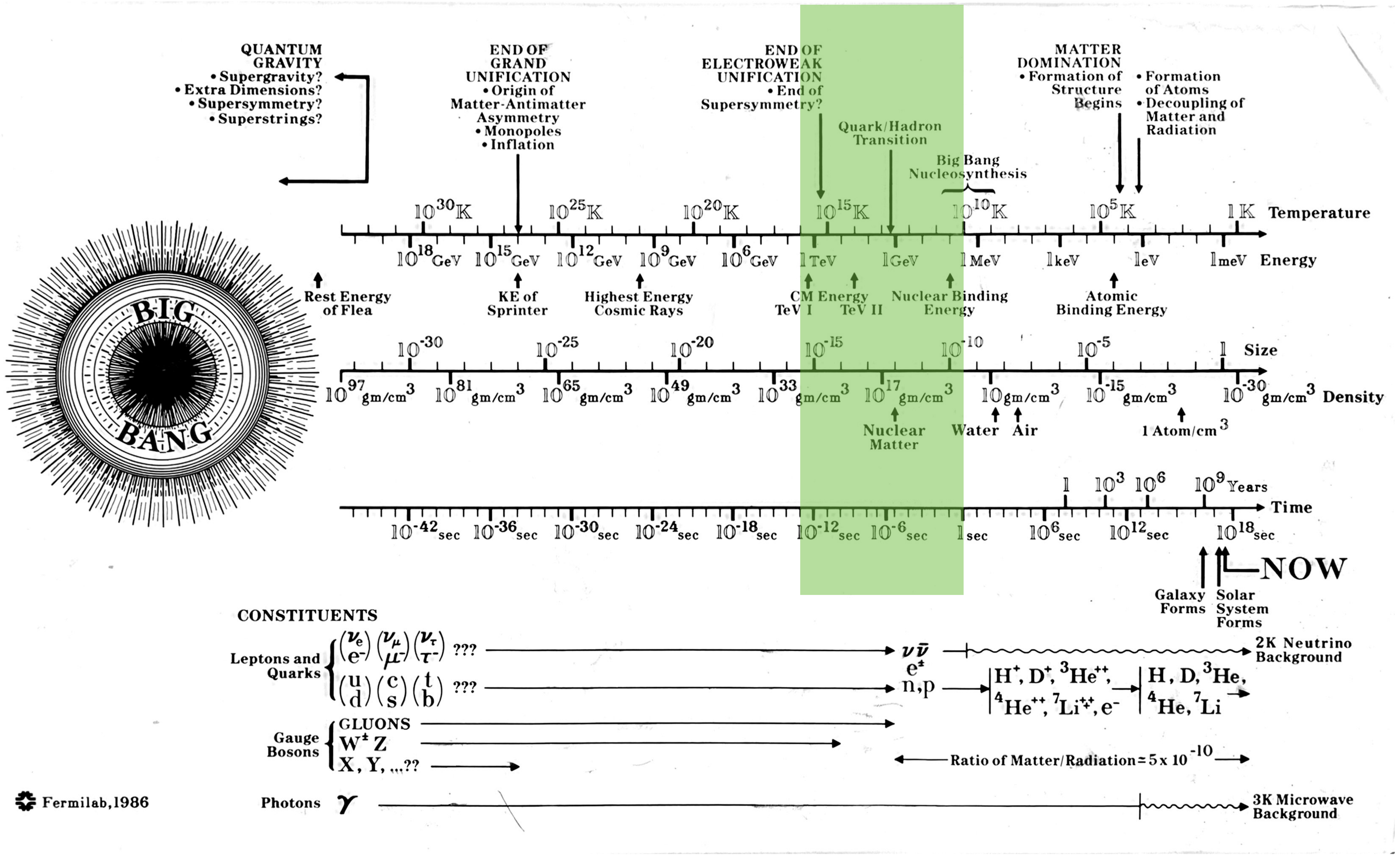




3. LLPs are cosmologically interesting "by definition"

The shortest-lived LLP for which we might reconstruct a **displaced** vertex has $c\tau \sim 0.1 \text{ mm}$
$\Rightarrow \tau \gtrsim 10^{-13} s$

To be completely cosmologically `safe', LLP should not disrupt BBN:
$\Rightarrow \tau \lesssim 1s$



In standard cosmology, these decays corresponds to a temperature range of <u>MeV - 10 TeV</u>. **A lot of interesting things can/do happen around these scales!**

4. LLP properties often instrumental in DM models

What makes a DM model?

Need **stable DM Candidate** and some way of generating the **DM abundance**.

In many such explicit models, the DM relic abundance is determined by the properties of other particles in the plasma of the Big Bang ⇒ particle = LLP!

This LLP carries the same quantum number which stabilizes DM, and decays into DM + SM final states.

The DM particle itself could be almost completely sterile (no direct detection)
⇒ LLP production and decay at colliders could be only way to ‘observe’ DM.

LLP-DM Connection: Example Mechanisms

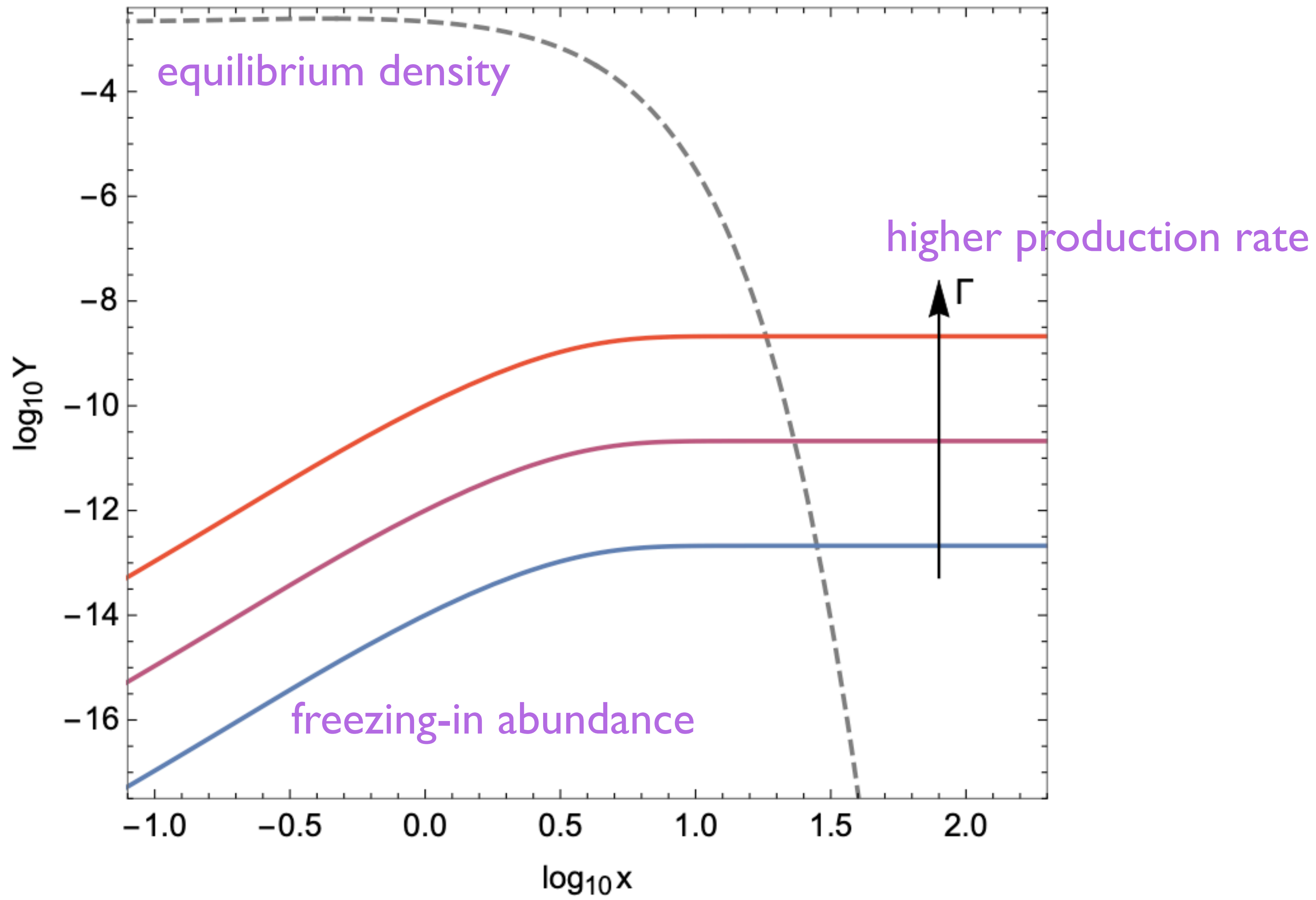
LLP-DM Connection: Example Mechanisms

1. Freeze-in DM

Freeze-in DM

Generic description of Freeze-in mechanism:

Some DM candidate X is *not* produced after inflation (or most recent reheating), but is instead produced "slowly" from suppressed interactions in the SM plasma for $T > T_{FO}$, such that X never reaches kinetic equilibrium with the SM.



1706.07442 Bernal et al review

Freeze-in DM

This is naturally realized if there is a particle "B" that decays to SM + DM:

$$B \to A_{SM} + X$$

If B is in thermal equilibrium of the plasma, but has lifetime >> H^{-1} while in equilibrium, then these decays are rare and slowly populate the DM abundance.

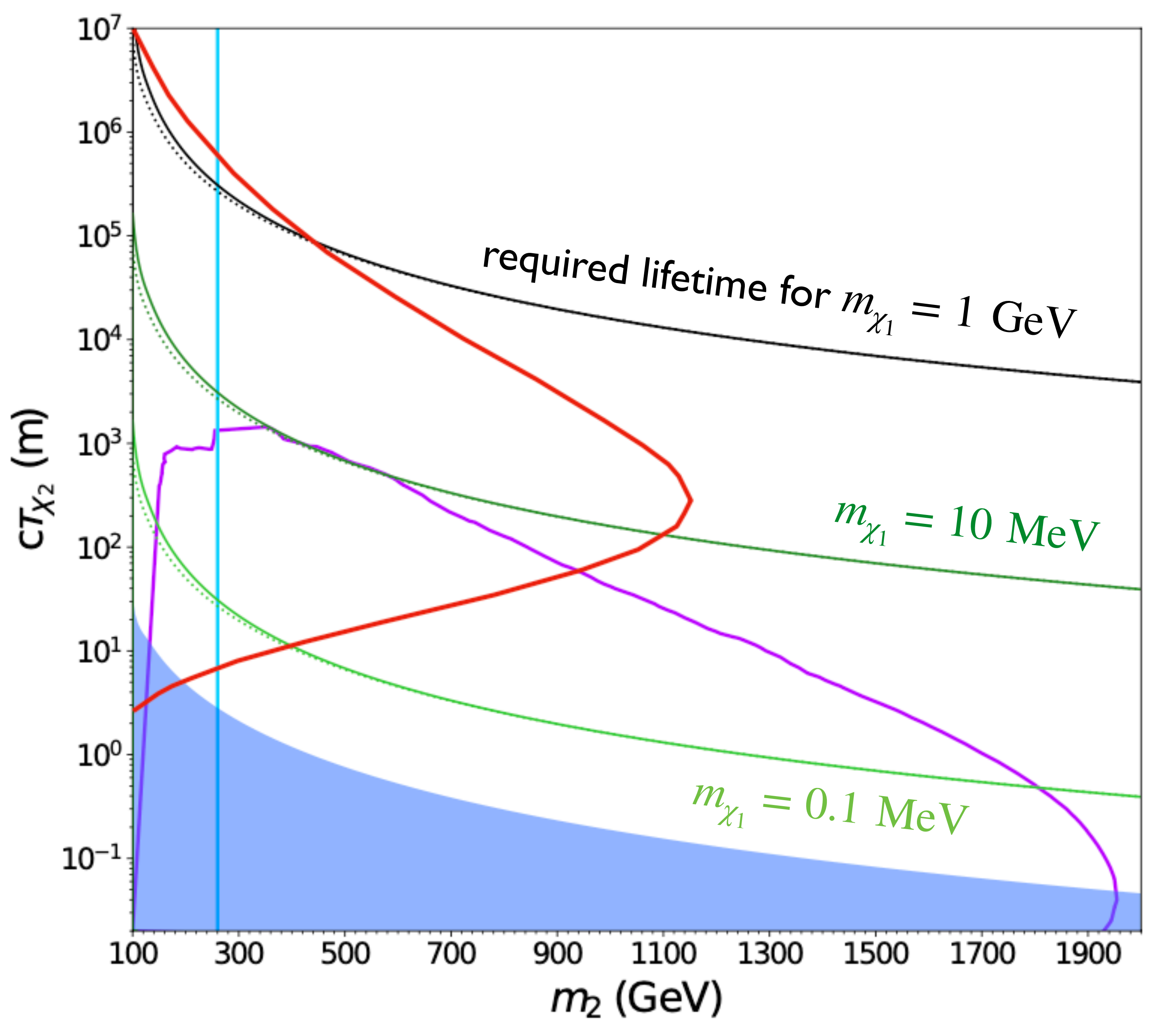
⇒ B is an LLP!

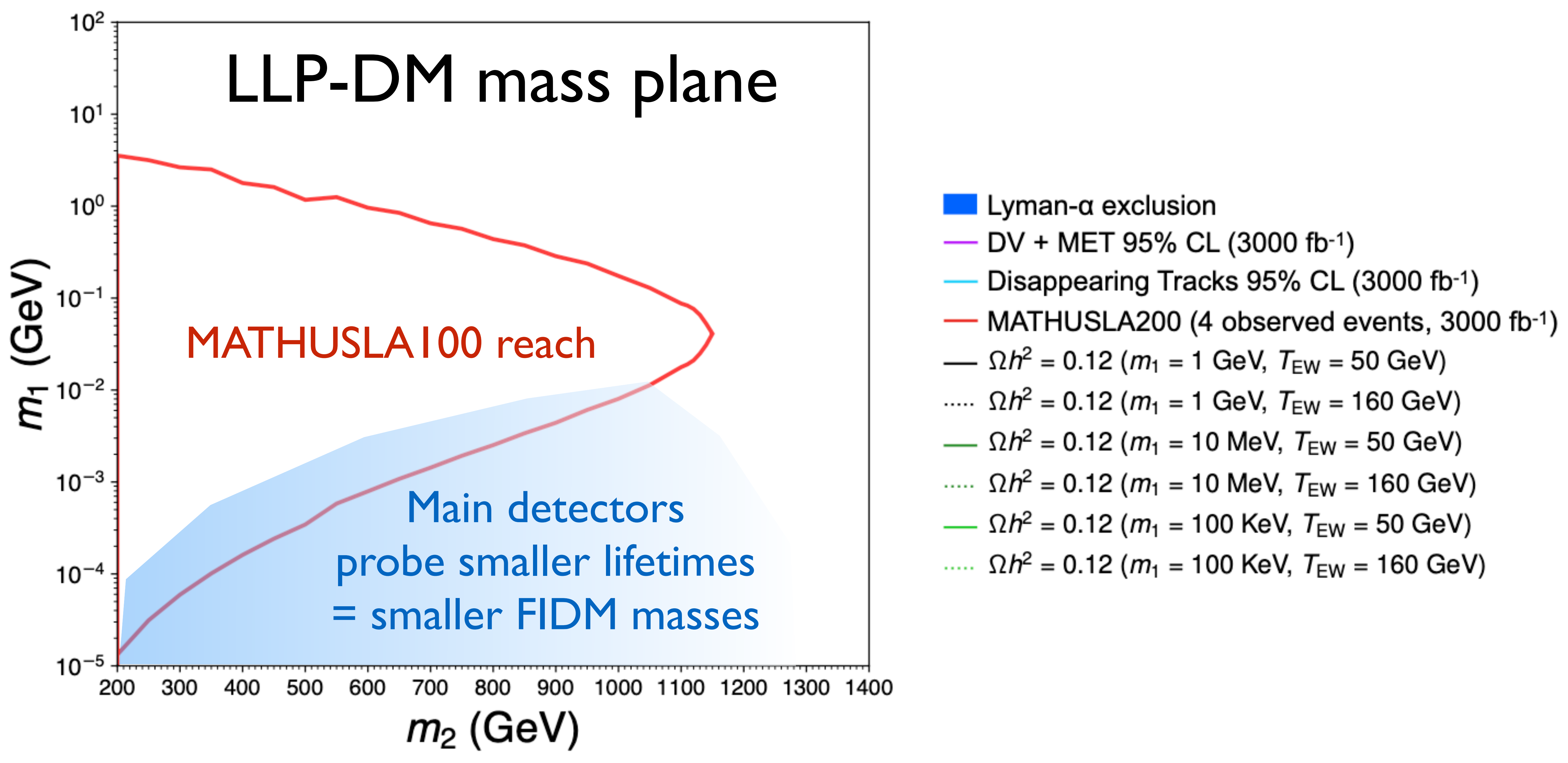
1901.09936 MATHUSLA Physics Case 1908.11387 No, Tunney, Zaldivar

Minimal Example Model

EW doublet fermion (ψ_1, ψ_2), where ψ_1 = DM and ψ_2 = LLP.

Close analogue of Higgsino-Bino or Higgsino-Axino system.





1901.09936 MATHUSLA Physics Case 1908.11387 No, Tunney, Zaldivar

LLP-DM Connection: Example Mechanisms

2. Inelastic DM

Inelastic Dark Matter

Imagine DM has to 'upscatter' into an excited state to interact with SM:

hep-ph/0101138 Tucker-Smith, Weiner

1508.03050 Izaguirre, Krnjaic, Shuve

$$X_1 + SM \to X_2 + SM$$

with $m_{X_2} = m_{X_1} + \Delta$

This mass splitting suppresses (e.g.) nuclear scatterings in direct detection experiments. For $\Delta \gtrsim 100 \text{ keV}$, there is no direct detection signal.

However, the slightly heavier state X_2 could be produced at colliders, and be long-lived due to the small mass splitting.

$\Rightarrow$ Collider production of LLP and decay to DM is the only way to observe DM.

Dark Photon Benchmark Model

Two dark Weyl fermions charged under $U(1)_D$

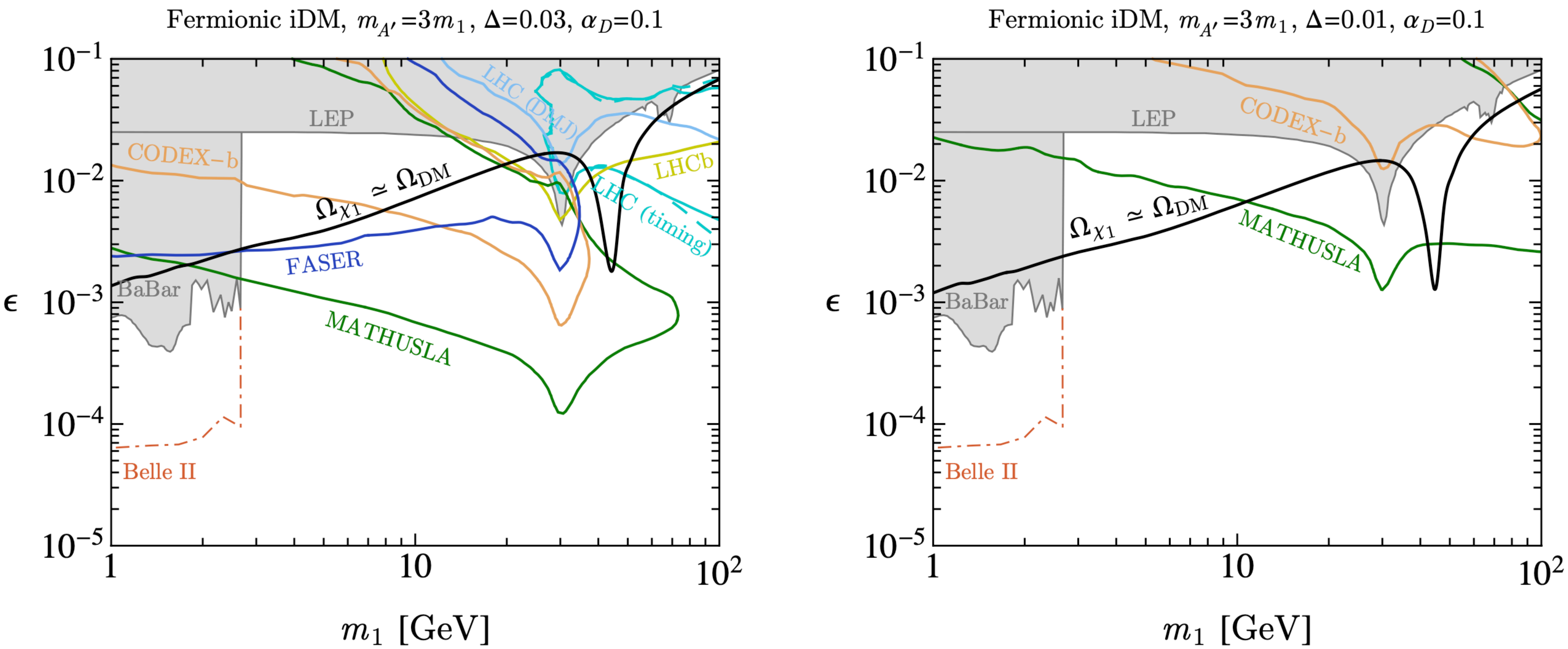
Dirac Mass + a majorana mass generated by $U(1)_D$ breaking

$\Rightarrow$ Two mass eigenstates $\chi_1, \chi_2$with small mass spliitting
$\Rightarrow$ Dark photon interaction switches mass eigenstates $ie_D A'_\mu \bar{\chi}_1 \gamma^\mu \chi_2$
$\Rightarrow$ If A' is heavier than DM states, annihilation is to SM via kinetic mixing $\epsilon F F'$

$\Rightarrow$ χ_2 is LLP with decay to $\bar{f}f\chi_1$, and lifetime determined by $(m_{A'}, \epsilon) \leftrightarrow \Omega_{\chi_1}$

Berlin, Kling 1810.01879

Dark Photon Benchmark Model



Berlin, Kling 1810.01879

LLP-DM Connection: Example Mechanisms

3. Asymmetric DM

Asymmetric DM

Review 1308.0338 Zurek

In ADM, baryons and DM have a shared 'dark/baryon number' in common, and a single shared asymmetry is distributed amongst both sectors to generate our baryon asymmetry and an asymmetric DM relic.

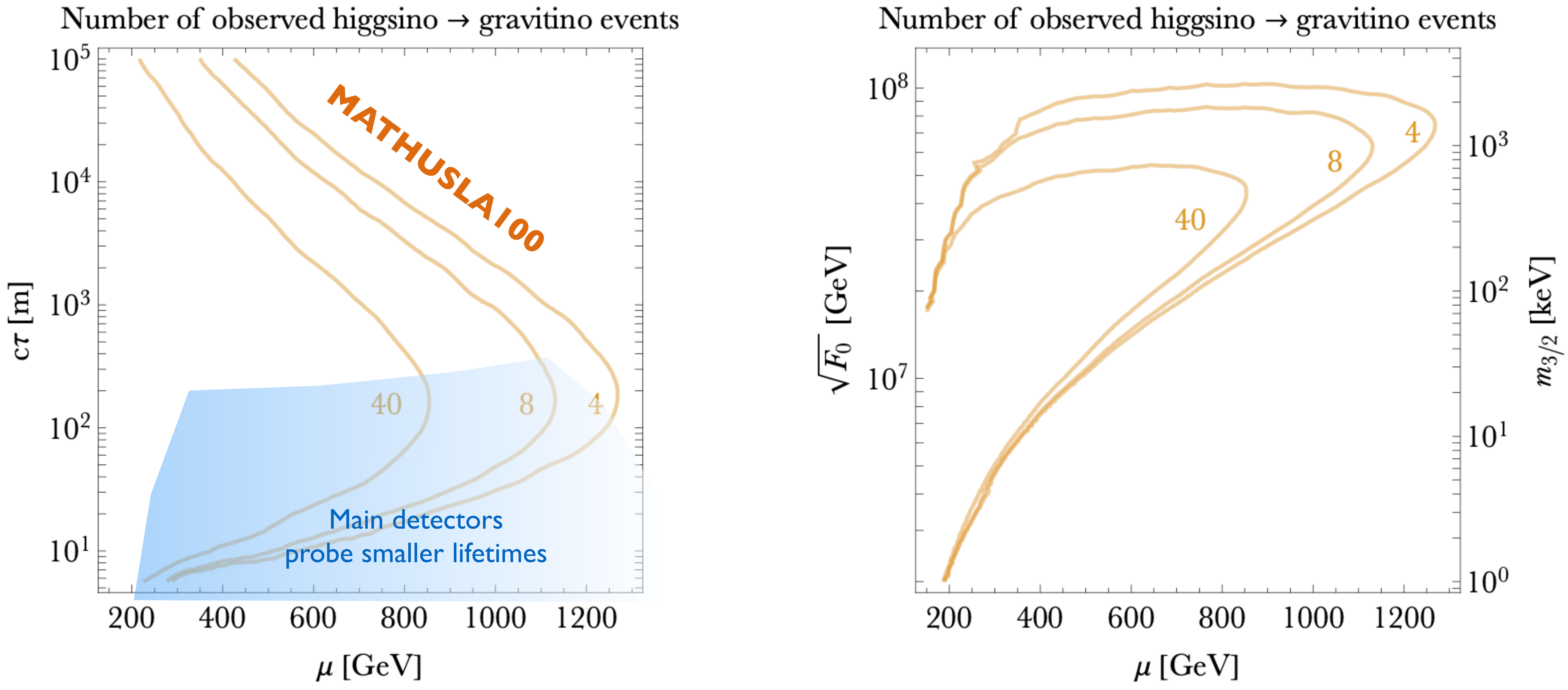
Could explain why $\Omega_{DM} \sim \Omega_b$

To transfer the asymmetry need operators like $$\mathcal{O}_{ADM} = \frac{\mathcal{O}_{B-L}\mathcal{O}_X}{M^{n+m-4}}$$

In SUSY, these operators destabilize the LSP $\Rightarrow$ ADM motivates RPV LLP searches

$$W_{\rm ADM} = X\ell H,\ \ \frac{X u_i^c d_j^c d_k^c}{M_{ijk}},\ \ \frac{X q_i \ell_j d_k^c}{M_{ijk}},\ \ \frac{X \ell_i \ell_j e_k^c}{M_{ijk}}$$

Asymmetric DM



1901.09936 MATHUSLA Physics Case

LLP-DM Connection: Example Mechanisms

4. Draining the hidden sector

Hidden Sector Freeze-out

In many models, a hidden sector generates the DM abundance via freeze-out WITHIN the hidden sector:

$\chi\chi \to \phi\phi$

where ϕ are some lighter dark states (ALPs, dark photons, scalars, …)

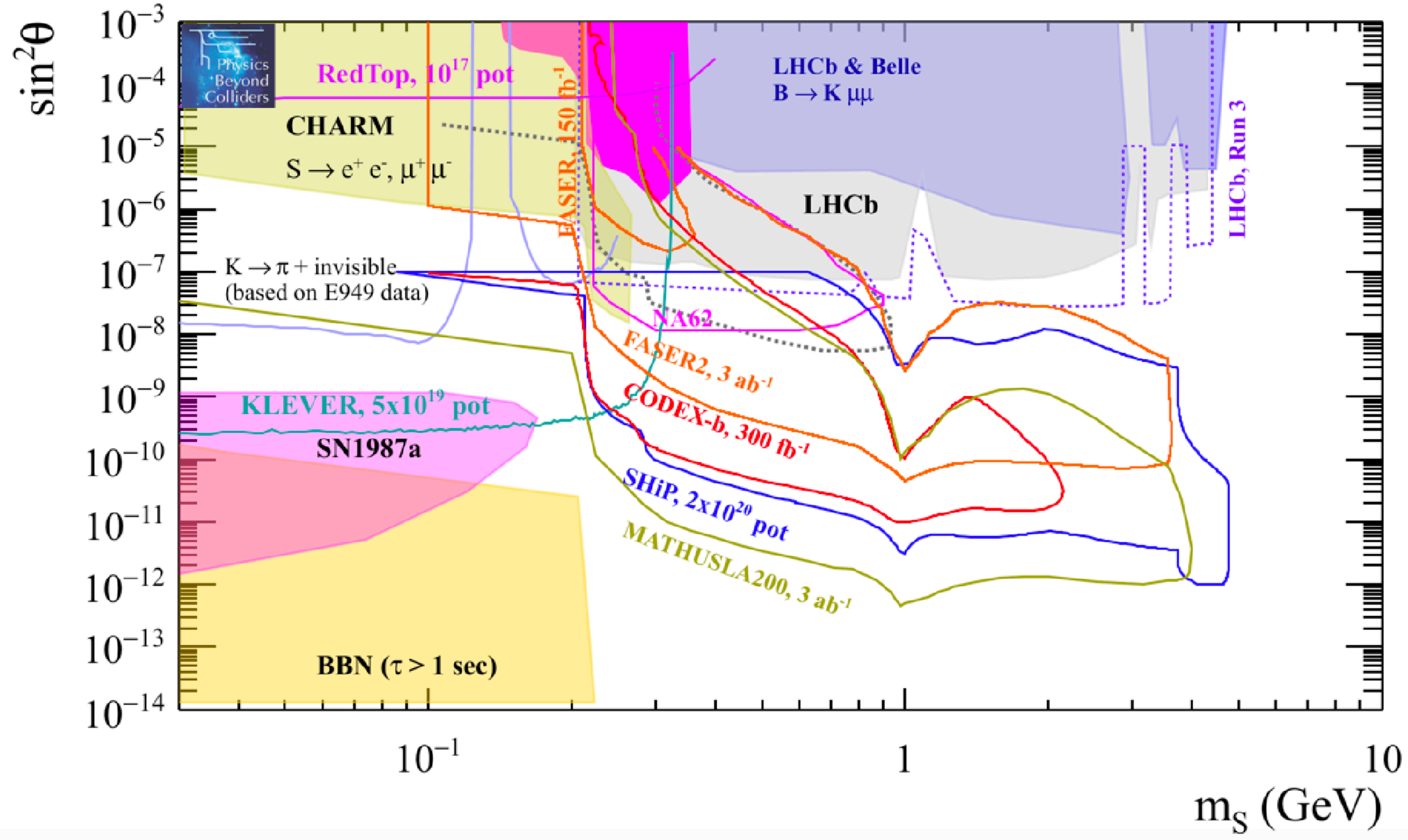
This can open up model building freedom by allowing arbitrary couplings to mediate freeze-out. But what do you do with the light final states ϕ?

ϕ might contribute to Ω_{DM} or ΔN_{eff} if stable $\Rightarrow$ decay to SM!

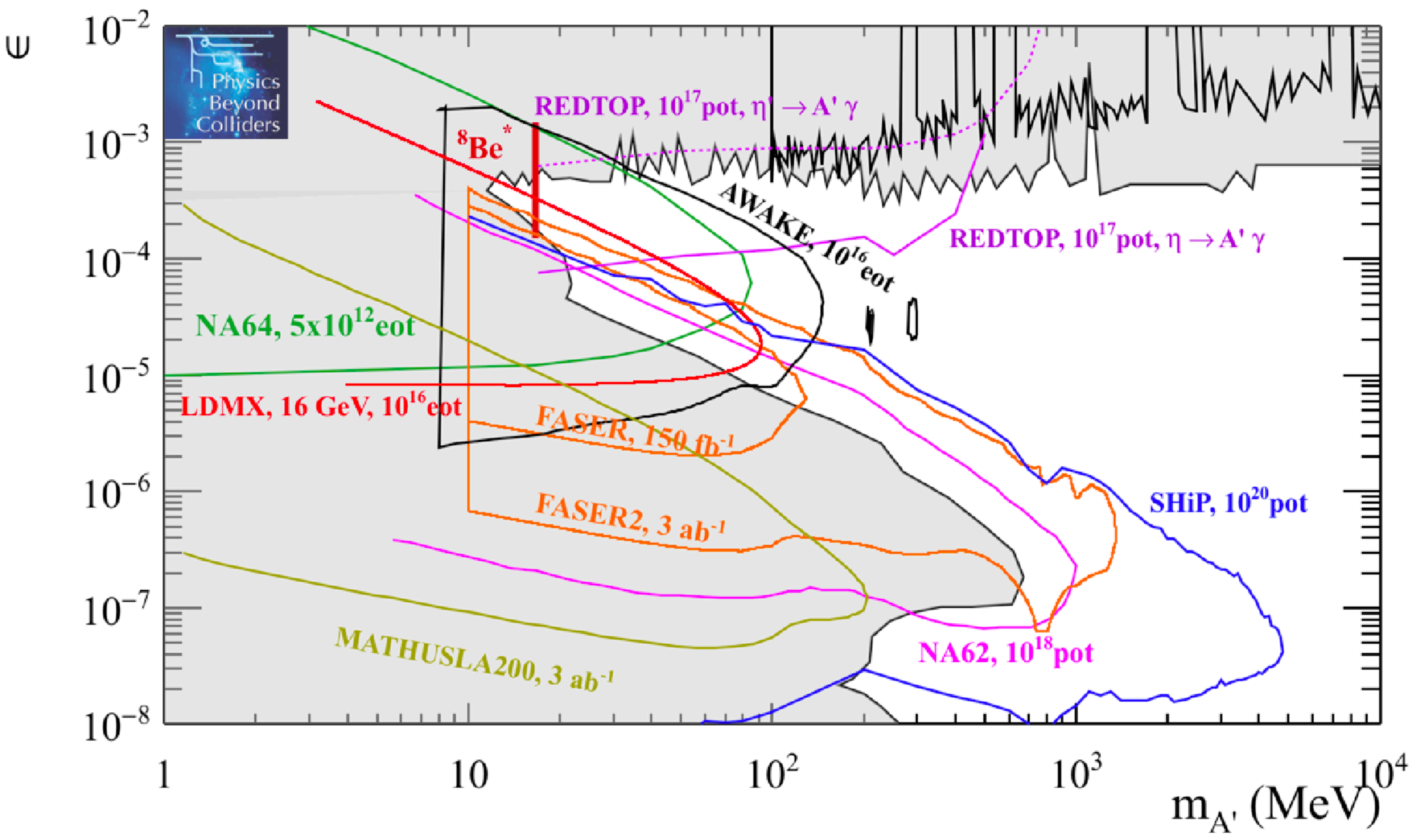
ϕ should not be populated directly from SM bath $\Rightarrow$ tiny couplings $\Rightarrow$ LLPs!

Light LLP searches = meta-stable dark radiation searches?

Dark scalar higgs portal



Dark photon kinetic mixing



1901.09966 PBC BSM WG report

LLP-DM Connection: Example Mechanisms

5. Composite/Rich Hidden Sectors

Composite Hidden Sectors

A confining dark sector gives rise to a multitude of composite IR states.

Some of those can easily be stable DM candidates, but there will always be other meta-stable states.

For mass splittings $\gtrsim 0.1 \ \mathrm{GeV}$, these LLPs decay within ~ meter.

Li, Tsai 1901.09936

Particularly motivated within SIMP/ELDER models, where $n \to 2$ annihilations set the relic abundance and which are most easily realized in composite theories.

Hochberg, Kuflik, Volansky, Wacker 1402.5143
Kuflik, Perelstein, Lorier, Tsai, 1512.04545

Fraternal Twin Higgs

Chacko, Goh, Harnik hep-ph/0506256
Craig, Katz, Strassler, Raman 1501.05310

Neutral Naturalness models solve the (little) hierarchy problem without introducing new colored states like SUSY or CH/RS models. This avoids LHC constraints, but suggests non-trivial cosmology or LLP signals.

The Twin Higgs stabilizes the Higgs with a Z2 symmetry that copies the SM to a hidden sector: hidden quarks, hidden QCD, etc.

Cosmological problems (ΔN_{eff}) can be avoided if you construct a "minimal" model with only the ingredients to solve the little hierarchy problem.

→ dark 3rd generation fermions, higgs, QCD

Craig, Katz, 1505.07113
Garcia Garcia, Lasenby, March-Russell 1505.07109
DC, Gryba, Setford, Hooper, Scholtz 2106.12578

⇒ Dark Tau can be WIMP, and dark glueballs coupling via Higgs portal are LLP

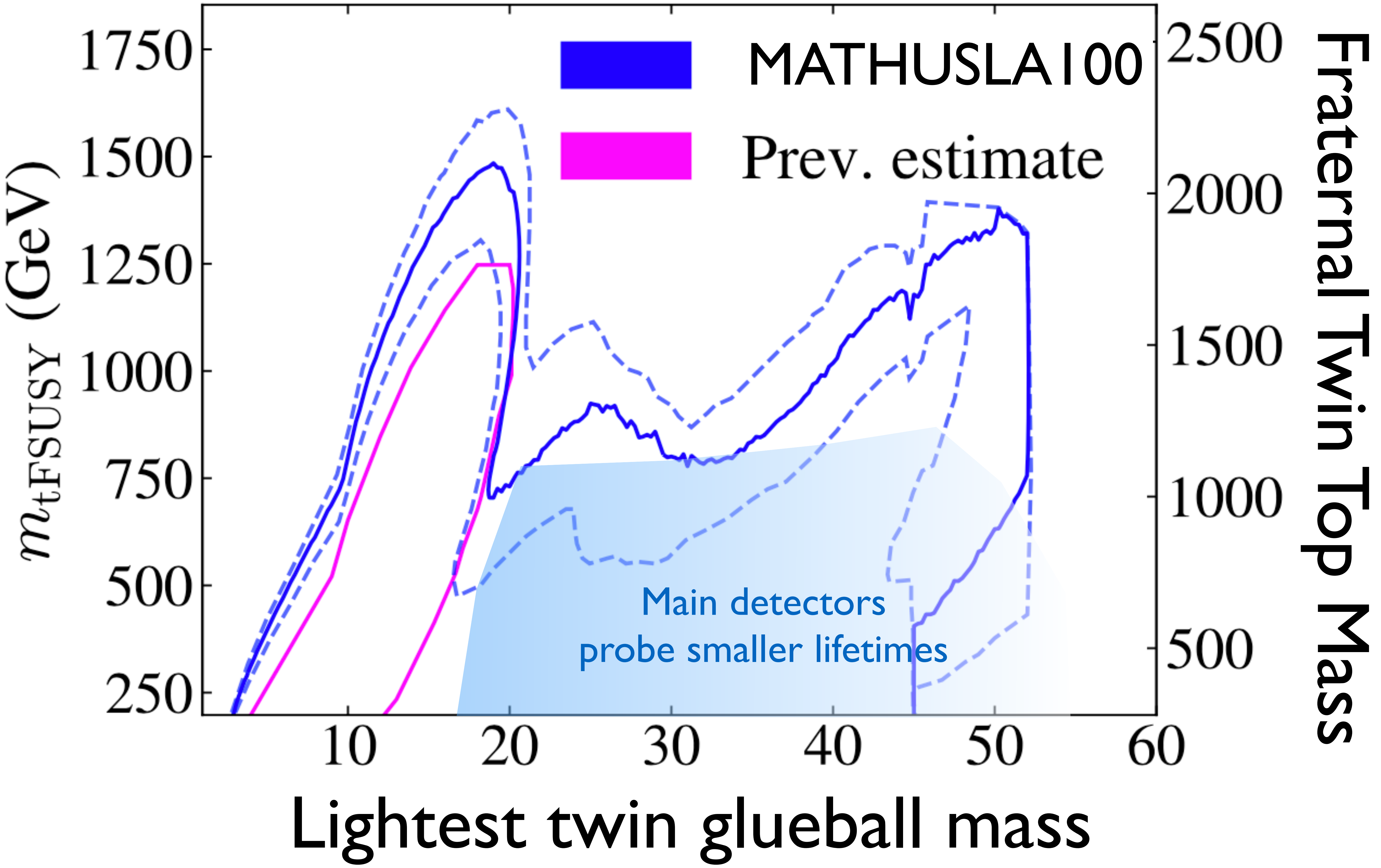
Dark Glueballs

DC, Gemmell, Verhaaren 2202.12899
Batz, Cohen, DC, Gemmell, Kribs 2310.13731

The Glueball signal of Neutral Naturalness shows up in FTH, FSUSY, …

Dark hadronization is difficult, only recently able to model.

See Caleb Gemmell's Talk!



Good example of how a motivated dark sector contains stable (twin Tau DM) and meta-stable (dark glueballs) states, and how decay of the LLPs is crucial to drain the dark sector

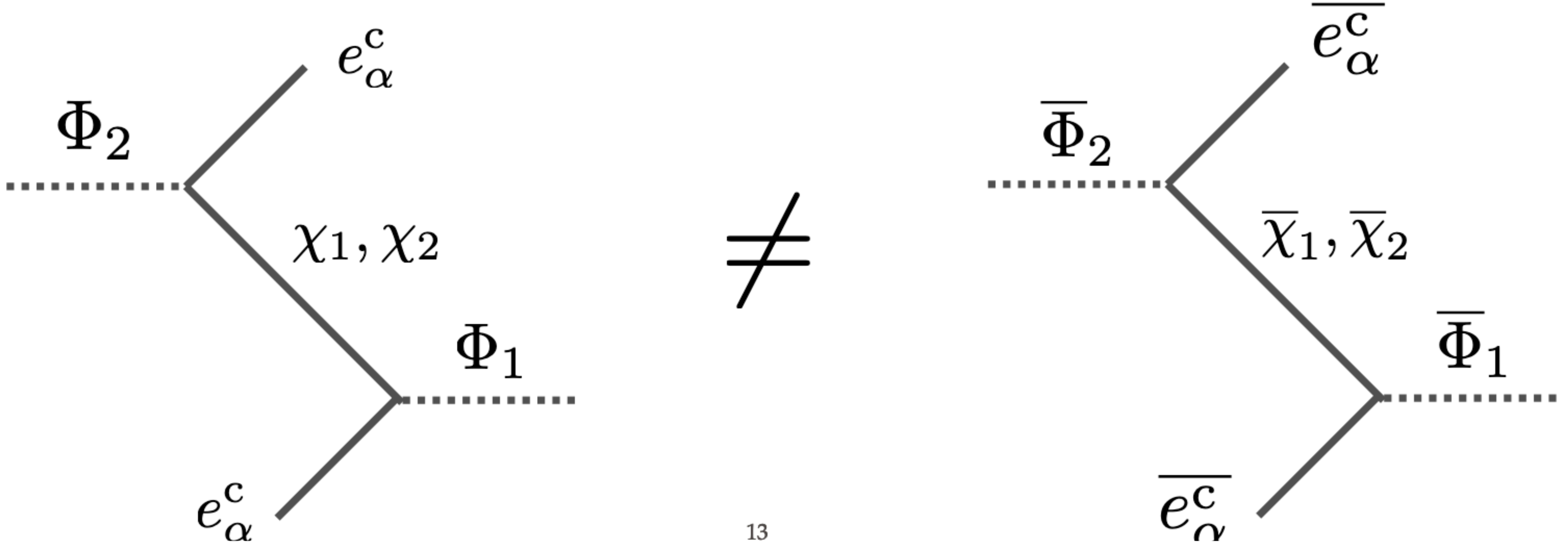
LLP-DM Connection: Example Mechanisms

6. DM from Baryogenesis

FIMP Baryogenesis

BARYOGENESIS MECHANISM

- The physics of this mechanism is most easily seen with **two scalars** and two DM particles - will get to single scalar scenario later
- Baryogenesis occurs when subset of DM scatters a second time: asymmetry << DM abundance



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Slide by Brian Shuve

B Shuve, D. Tucker-Smith, 2004.00636, +Berman, 2201.11502

FIMP Baryogenesis

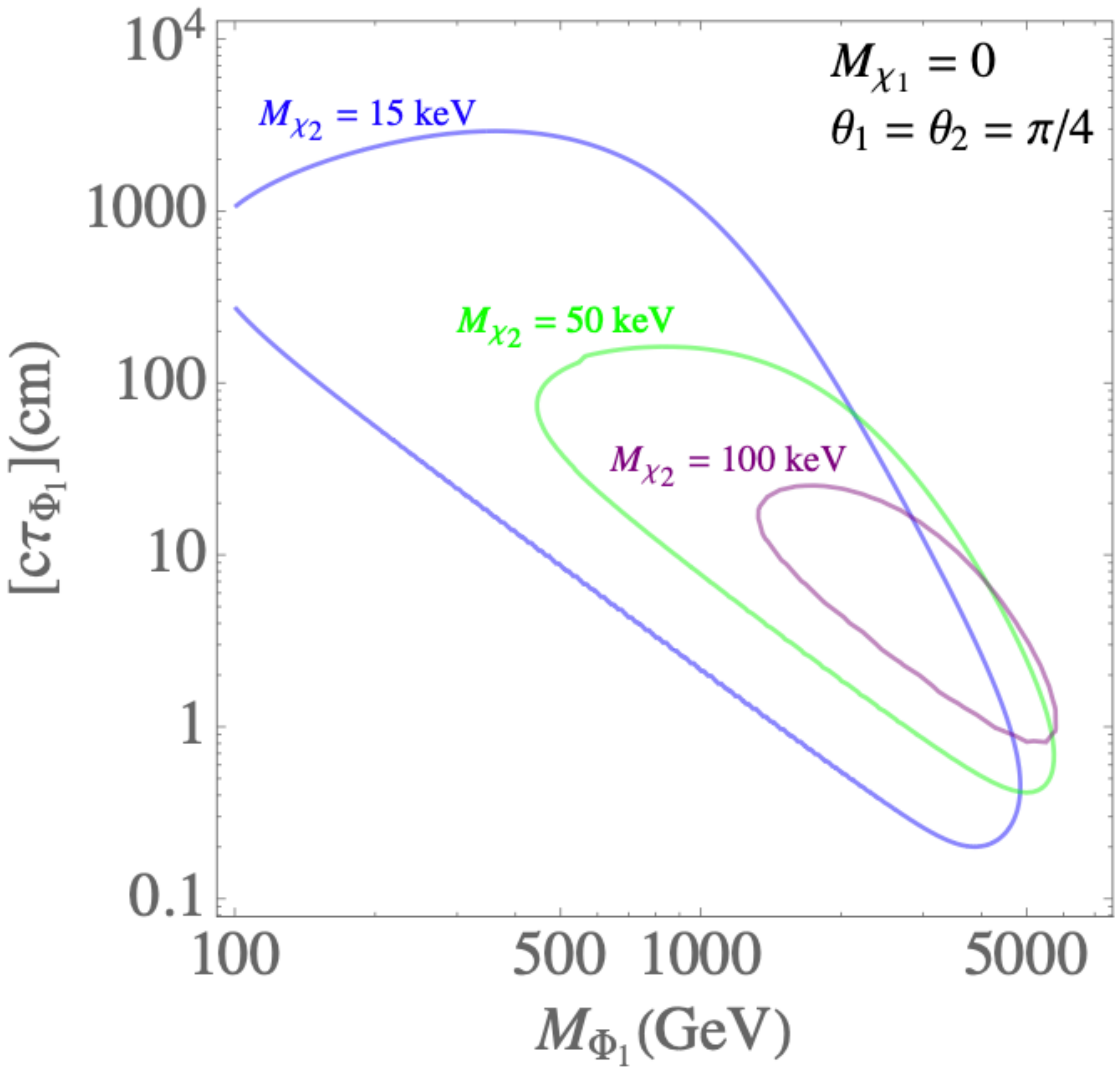
Oscillation of DM states + expansion of universe (out-of-eq condition) allows for production of DM abundance and a *much smaller* baryon abundance/asymmetry.

Interestingly, this collapses the very wide FIMP parameter space of LLP mass, LLP lifetime, and stable DM mass to

~ TeV **~ cm-m** **~** $\lesssim 100$ keV

B Shuve, D. Tucker-Smith, 2004.00636, +Berman, 2201.11502

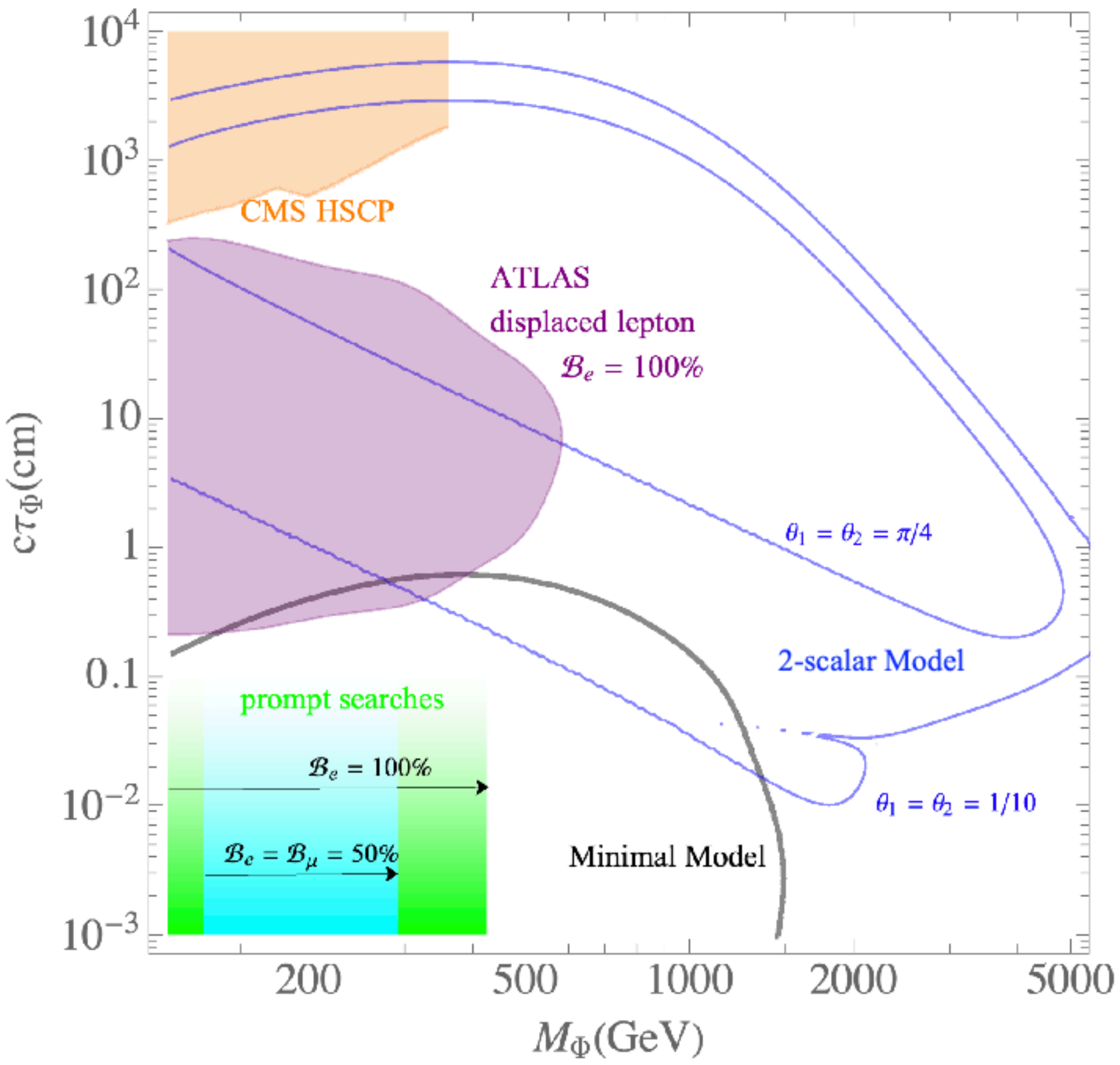
Charged LLP Properties



Roughly, this is the 'maximal' parameter space, except that single-mediator models can give rise to shorter but still macroscopic decay lengths.

Berman, Shuve, Tucker-Smith, 2201.11502

PHENO: COLLIDERS



- Gap at low mass when Φ has appreciable branching fraction to tau leptons
- Still room for new electroweak states ~100 GeV
- ~TeV limits if scalar has QCD charge

Slide by Brian Shuve

General Lessons

In these examples, what role did the LLP play?

Freeze-in: LLP being an LLP is what makes the DM

iDM: small mass splitting makes iDM mechanism and an LLP

ADM: UV-scale breaking/sharing of symmetries (to have DM/baryons come from one generated asymmetry) gives rise to small destabilizing couplings in IR → LLP

Draining Hidden Sector: taking out the garbage after the hidden sector did what we want is best done by making everything else LLPs

demonstrated in e.g. Fraternal Twin Higgs with glueball LLPs due to H portal

Composite DM often has nearby states with small mass splittings, which are LLPs.

These specific examples are just some illustrations of the general principles from beginning.

A lot more examples than I could cover

Here are some recent papers that examine the DM-LLP connection in different ways, in no particular order

2310.08883 Bandyopadhyay, Frank, Parashar, Sen "Interplay of inert doublet and vector-like lepton triplet with displaced vertices at the LHC/FCC and MATHUSLA"

2404.19057 Sáez, Lahiri, Möhling "Coscattering in the Extended Singlet-Scalar Higgs Portal"

2404.16086 Heisig, Lessa, Ramos "Probing conversion-driven freeze-out at the LHC"

2112.10784 Chu, Cui, Pradler, Shamma "Dark Freeze-out Cogenesis"

2212.11303 Allahverdi, Loc, Osiníski "Dark Matter and Baryogenesis from Visible-Sector Long-Lived Particles"

2402.18557 Allahverdi, Loc, Osiníski "Dark matter from mediator decay in early matter domination"

2312.03826 Asadi, Radick, Yu "A Duet of Freeze-in and Freeze-out: Lepton-Flavored Dark Matter and Muon Colliders"

2312.09274 Acaroglu, Blanke, Heisig, Krämer, Rathmann "Flavoured Majorana Dark Matter then and now: From freeze-out scenarios to LHC signatures"

2201.12253 Bertuzzo, Scaffidi, Taoso "Searching for inelastic dark matter with future LHC experiments"

2309.07213 Carpenter, Gilmer, Kawamura, Murphy "Taking aim at the wino-higgsino plane with the LHC"

General Conclusions (?)

Clear correspondence between LLP lifetime and cosmological era of decay.
→ This might provide a hint as to the role an LLP plays in our universe?

I was asked to map LLP searches ↔ DM parameter space, but it's hard to say general things about mass & production rates, there are many DM examples and mechanisms that give a wide range of predictions.

(Not sure if this can be meaningfully simplified beyond extremely minimal examples.)

Upshot:

LLP searches are intimately connected to DM

↔

The range of even fairly simple DM models is huge, and many of those predict LLPs.