LLP UBIQUITY

New Physics with Exotic and Long-Lived Particles
Joint ICISE-CBPF Workshop, Quy Nhon, Vietnam

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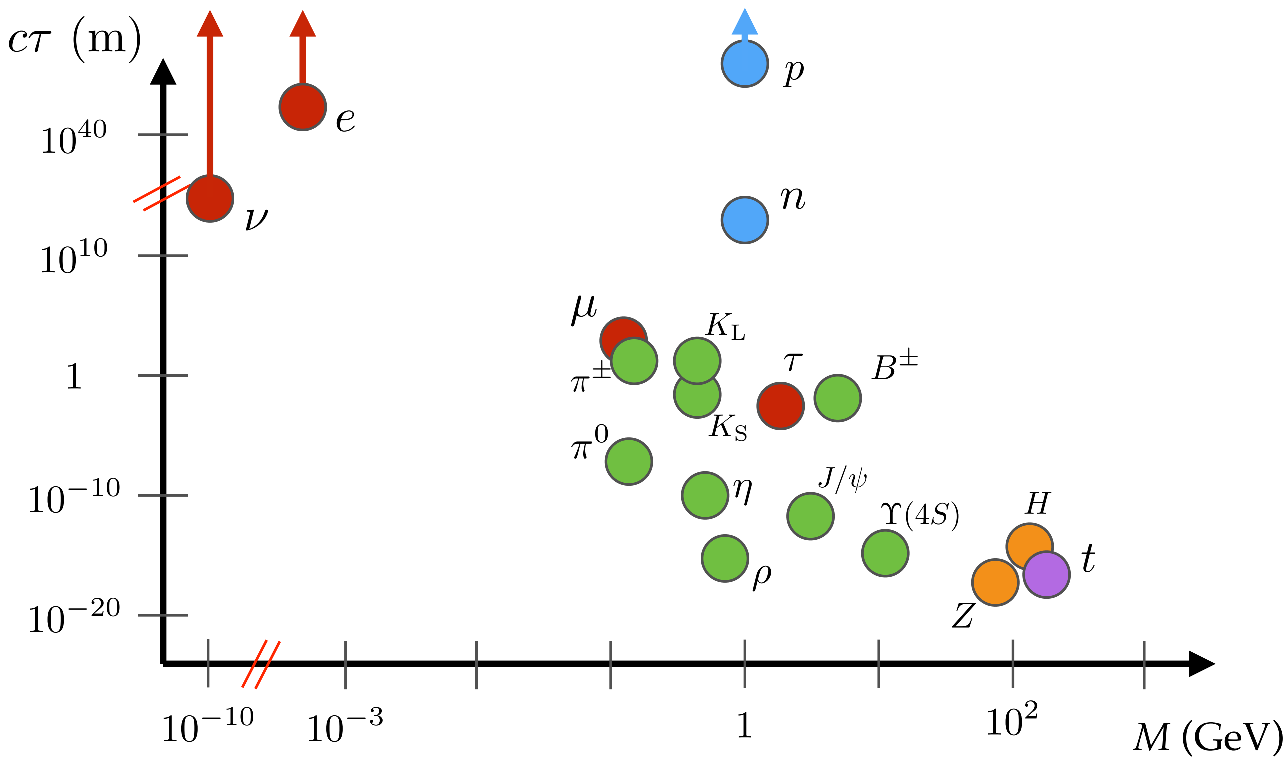
INTRODUCTION

- We have already discovered many Long-Lived Particles



Alimena et al. (eds. Beacham, Shuve) (2019)

- In fact, LLPs have played an essential role in many of the conceptual breakthroughs that established the standard model of particle physics: *e*, *p*, *n*, μ, *K*, ν, …

INTRODUCTION

- The next breakthrough in particle physics is likely to involve LLPs
  - LLPs are ubiquitous in BSM theories, especially those with cosmological significance
  - LLPs can be detected through a huge variety of signatures
  - Many of these signals are truly spectacular – a few events can be a discovery
  - For existing experiments, we have not yet reached the full LLP discovery potential
  - And LLPs present many opportunities for new and clever experiments (and new and clever experimentalists!)

INTRODUCTION

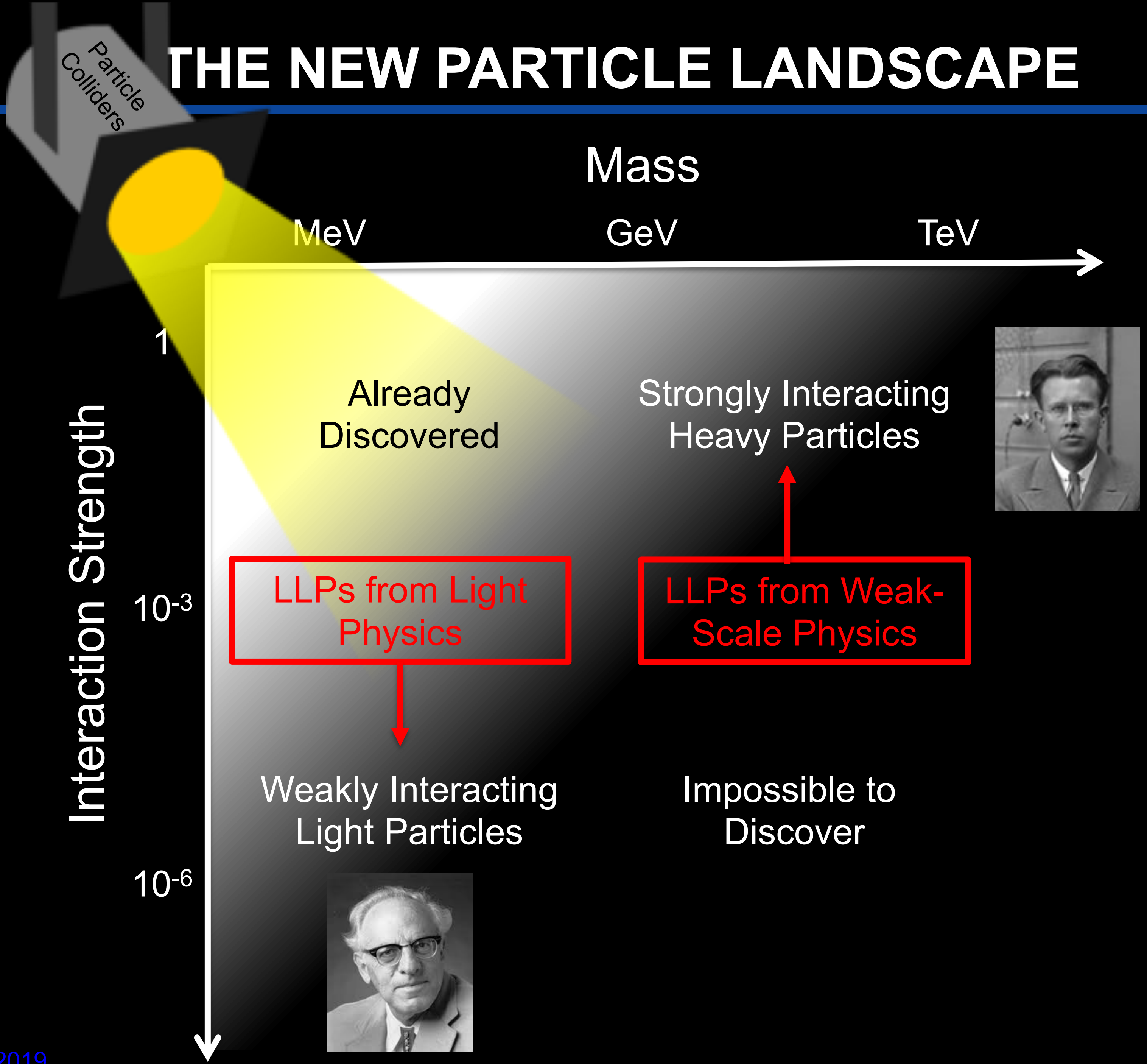
- This is by now a huge field and it is impossible to give a proper theory overview. Here I will present a small sampling of theoretical ideas that have led to my personal optimism about LLPs.

- In many cases, LLPs scenarios are "too flexible"; couplings, mass splittings can be tuned to be arbitrarily small and voila – LLP! This is fine (we should look where we can look at this point), but for a short talk…

- Also cosmology provides both a motivation for LLPs and a way to focus the discussion.

- So here I will attempt to highlight scenarios in which LLPs have some independent reason to be long-lived and have some interesting cosmological implications.

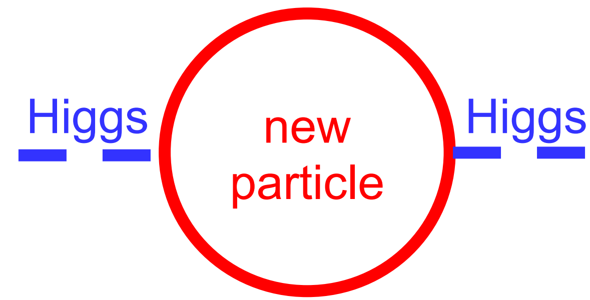
THE NEW PARTICLE LANDSCAPE



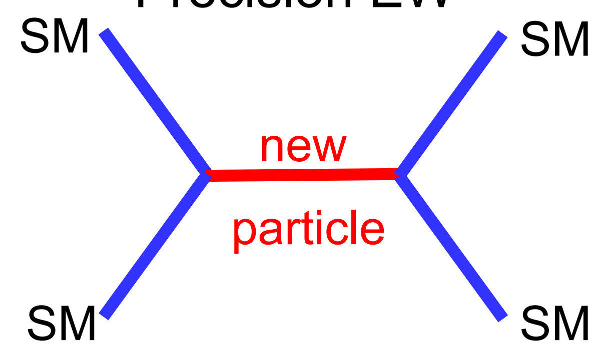
LLPs FROM
WEAK- SCALE PHYSICS

WEAK-SCALE PHYSICS AND LLPs

- Why should there be LLPs at the weak scale? After all, the natural decay length is $c\tau \sim c/m_W \sim 10^{-17}$ m!



- But hierarchy problem → new physics at 100 GeV, and precision EW → no new physics below few TeV in 4-pt ints.

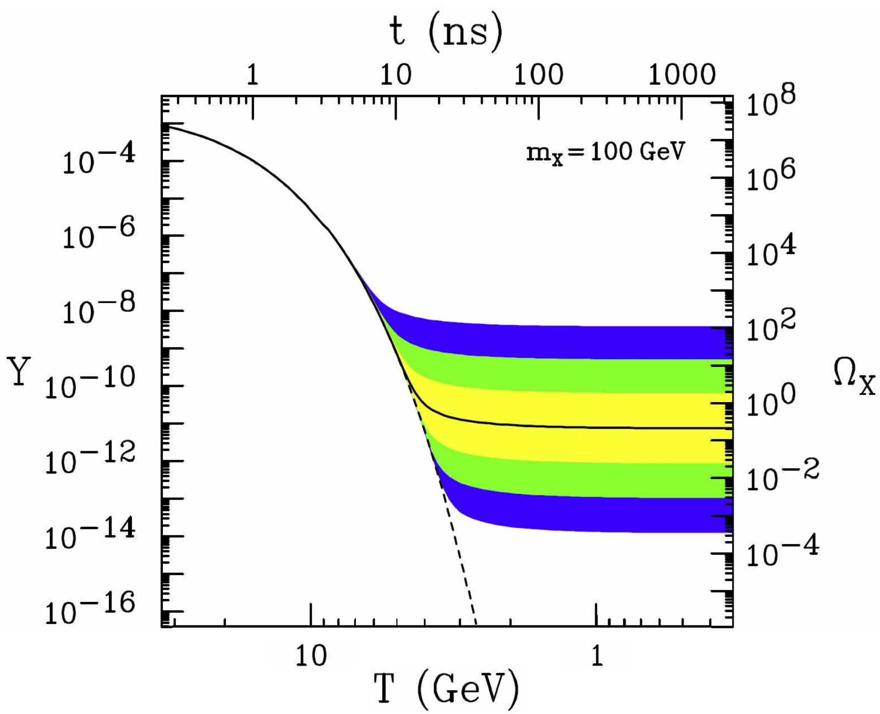


- Simple solution: impose a discrete parity, so all interactions require pairs of new particles.
- This makes the lightest new particle stable. This is a general argument. It may be augmented in specific contexts, e.g., in SUSY, *p* decay → *R*-parity → stable LSP.

Cheng, Low (2003); Wudka (2003); Farrar, Fayet (1974)

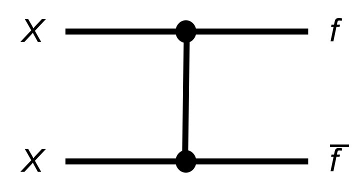
WEAK-SCALE PHYSICS AND COSMOLOGY

- What good is a stable weak-scale state? Dark matter!



- The resulting relic density is

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



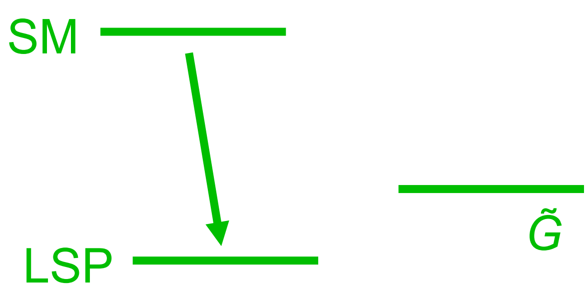
- For a WIMP, $m_X \sim 100$ GeV and $g_X \sim 0.6$ → $\Omega_X \sim 0.1$

- This simple coincidence, the WIMP Miracle, ties together weak-scale physics, LLPs, and cosmology, and has led to the prominence of missing E_T searches and DM at colliders.

LLPs IN STANDARD SUSY

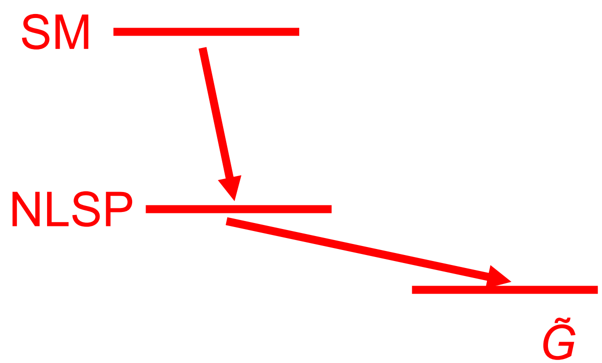
- But this focus on missing E_T is a vast oversimplification.
- Consider standard (gravity-mediated) supersymmetry. The gravitino has mass ~ 100 GeV, couplings ~ M_W/M_{Pl} ~ 10^{-16} .

- $\tilde{G}$ not LSP



- Assumption of most of literature

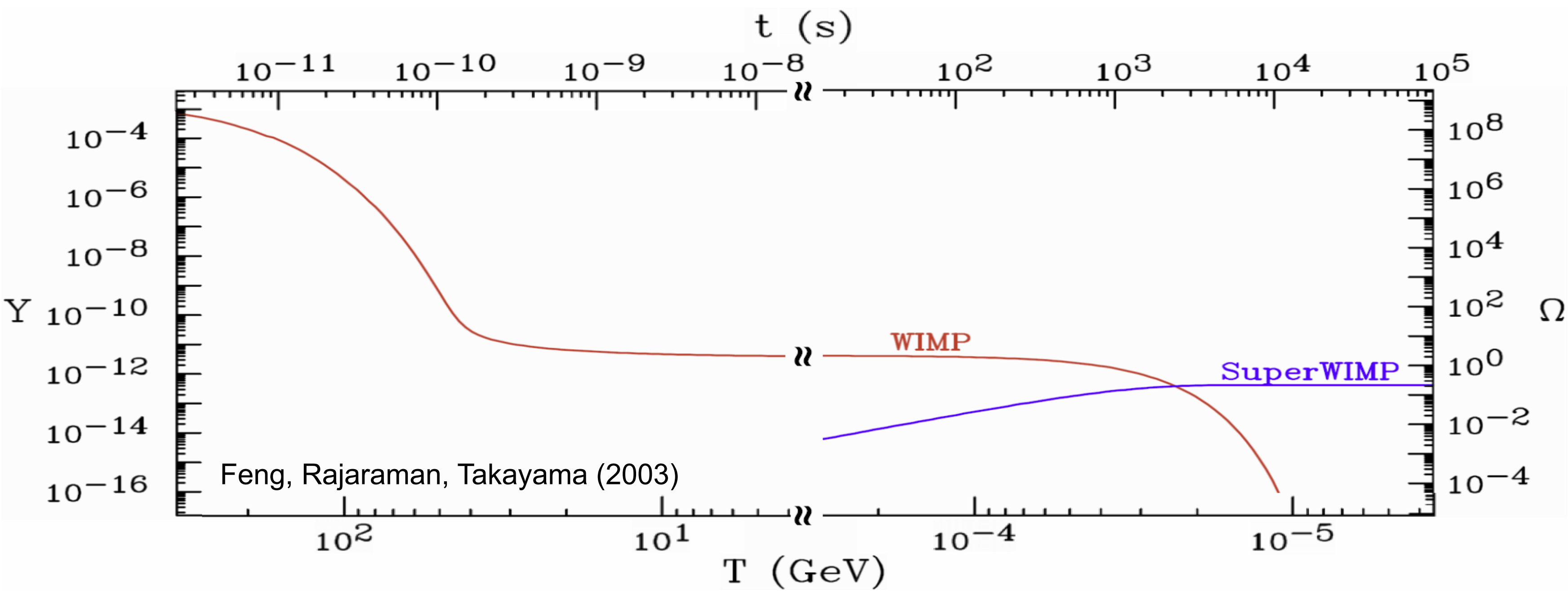
- $\tilde{G}$ LSP



- Completely different cosmology and particle physics

LLPs IN SUPERWIMP SCENARIOS

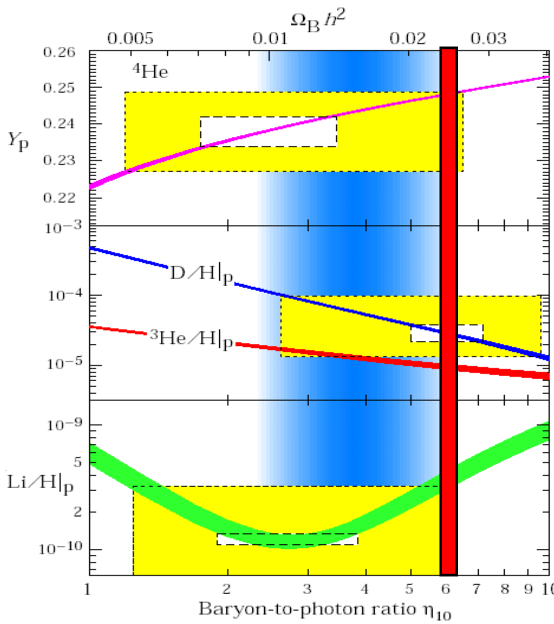
- In the $\tilde{G}$ LSP scenario, WIMPs freeze out as usual, but then decay to $\tilde{G}$ after M_{Pl}^2/M_W^3 ~ seconds to months.



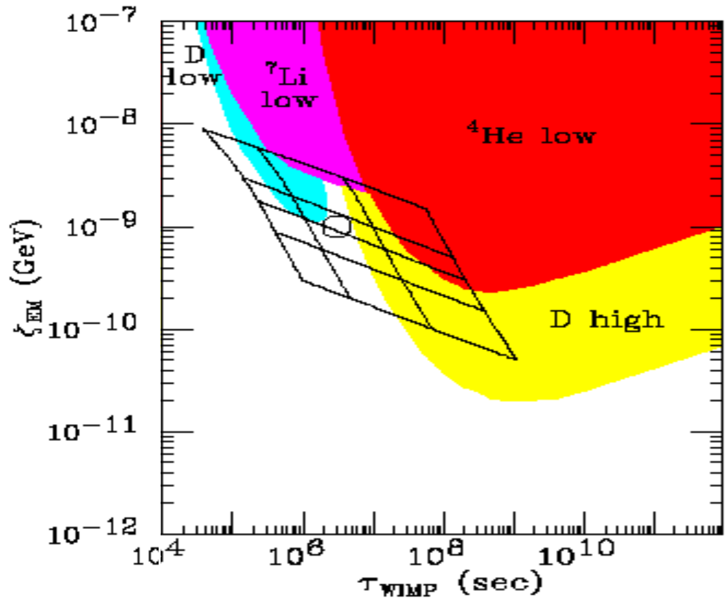
- The gravitino is superWIMP DM, naturally has the right relic density. But now the WIMP can be charged, implying metastable charged LLPs at colliders.

LLPs AND BBN

- Decays to superWIMPs can impact light element abundances



Fields, Sarkar, PDG (2002)



Feng, Rajaraman, Takayama (2003)

- BBN excludes $\chi \rightarrow Z\tilde{G}$, but $\tilde{l} \rightarrow l\tilde{G}$ may be ok and may even fix the longstanding lithium anomaly! It is not true that BBN categorically excludes LLP lifetimes > 1s.

- Late decays may also distort the CMB, resolve small-scale structure: many interesting cosmological imprints.

Feng, Rajaraman, Takayama (2003); Kaplinghat (2004); Cembranos et al. (2004); …

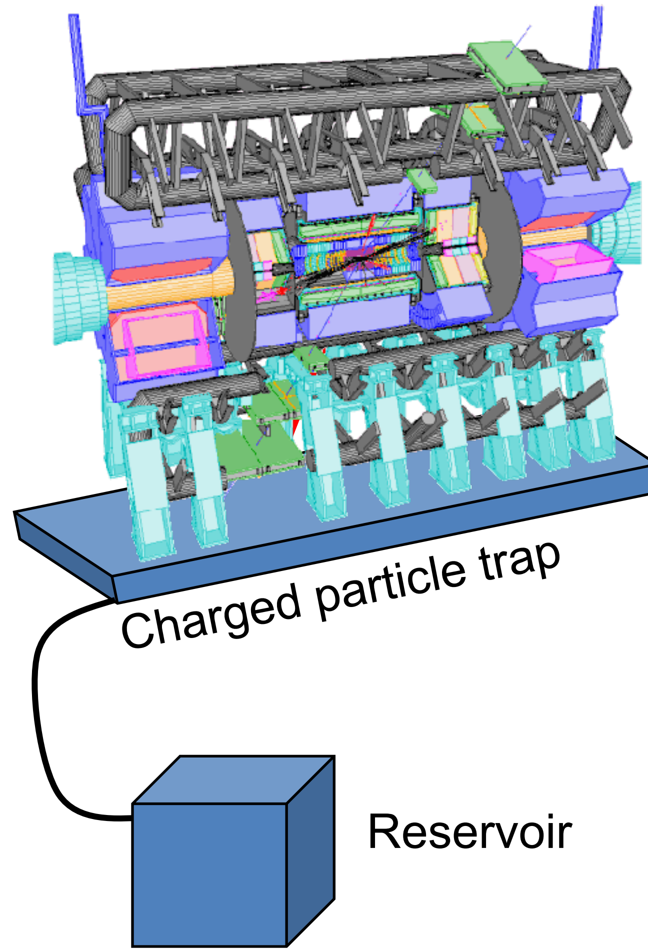
LLPs AND ADD-ON DETECTORS

- If we see metastable charged LLPs, we know they must decay.
- We can collect these particles and study their decays.
- Several ideas have been proposed
  - Catch sleptons in a 1m thick water tank (up to 1000/year) and then move them to a quiet place to observe their decays

    Feng, Smith (2004)
  - Catch sleptons in LHC detectors

    Hamaguchi, Kuno, Nakawa, Nojiri (2004)
  - Dig sleptons out of detector hall walls

    De Roeck, Ellis, Gianotti, Moortgat, Olive, Pape (2005)



LLPs IN GAUGE-MEDIATED SUSY

- Scenarios with gauge-mediated SUSY breaking are among the most famous of those predicting LLPs.

Dine, Nelson, Nir, Shirman (1994, 1995); Dimopoulos, Dine, Raby, Thomas (1996); …

- NLSPs decay to light $\tilde{G}$ LSPs. The $\tilde{G}$ mass and the NLSP decay length are correlated. For $\tilde{G}$ masses ~ keV (motivated, with caveats, by $\tilde{G}$ DM), the decay lengths are macroscopic

$$c\tau_{\rm NLSP} \approx 50\ {\rm cm} \left(\frac{200\ {\rm GeV}}{m_{\rm NLSP}}\right)^5 \left(\frac{m_{\tilde{G}}}{\rm keV}\right)^2$$

	Neutralino NLSP	Slepton NLSP
Prompt	Prompt photons	Multi-leptons
Intermediate	Displaced photons Displaced conversion	Displaced lepton Track kinks
Long-Lived	Missing E_T	Time-of-flight High dE/dx

LLPs IN ANOMALY-MEDIATED SUSY

- Scenarios with anomaly-mediated SUSY breaking give additional interesting LLPs signals

Randall, Sundrum (1998); Giudice, Luty, Murayama, Rattazzi (1998); …

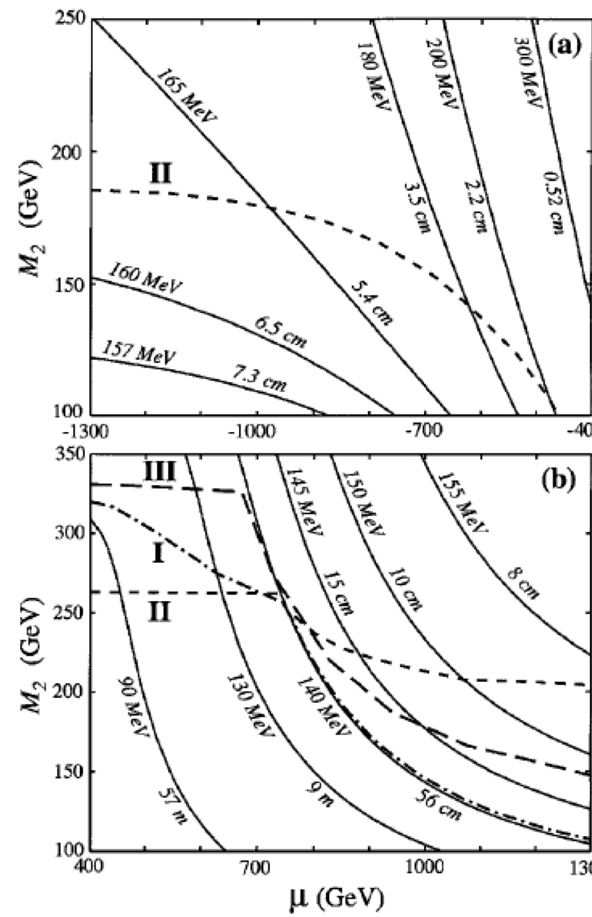
- The LSPs are a highly degenerate Wino triplet with $\Delta m_{loop} >> \Delta m_{tree}$

- Typically, there are 2-body decays

$$\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \pi^+$$

and disappearing tracks after ~10cm

- In exotic cases, there can be even greater degeneracy, leading to very long decay lengths and 3-body decays $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 (e^+ \nu_e, \mu^+ \nu_\mu)$



Feng, Moroi, Randall, Strassler, Su (1999)

LLPs IN OTHER WEAK-SCALE MODELS

- By considering a few standard models of weak-scale physics, we have motivated a plethora of possible LLP signatures.
- Of course, there are many other motivated weak-scale models with LLPs.
- In SUSY: e.g., R-parity violating SUSY and compressed SUSY, which have become more motivated as generic, sub-TeV SUSY becomes excluded.
- Extra dimensional scenarios typically have similar possibilities (e.g., viewing universal extra dimensions as bosonic supersymmetry), and naturally compressed spectra.
- Many other motivations and cosmological connections: leptogenesis, neutrino masses, etc.

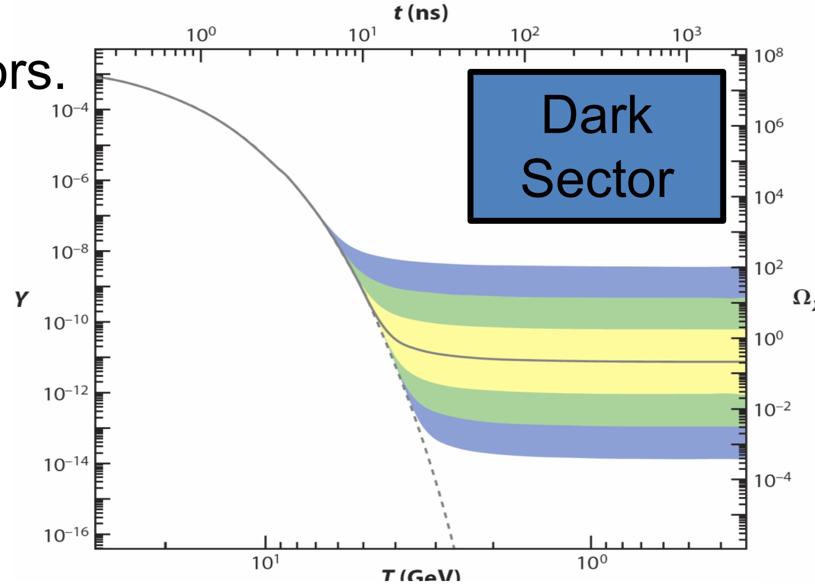
LLPs FROM LIGHT PHYSICS

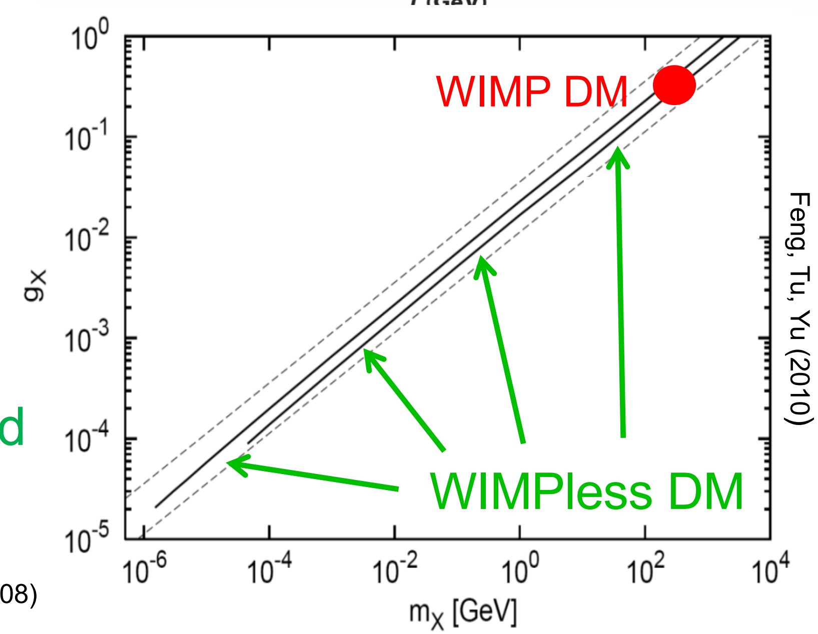
DARK SECTORS

- In recent years, dark matter → dark sectors. What do we know about its properties?
- In general, nothing. But suppose DM freezes out in the dark sector just as we discussed above for WIMPs in the visible sector:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

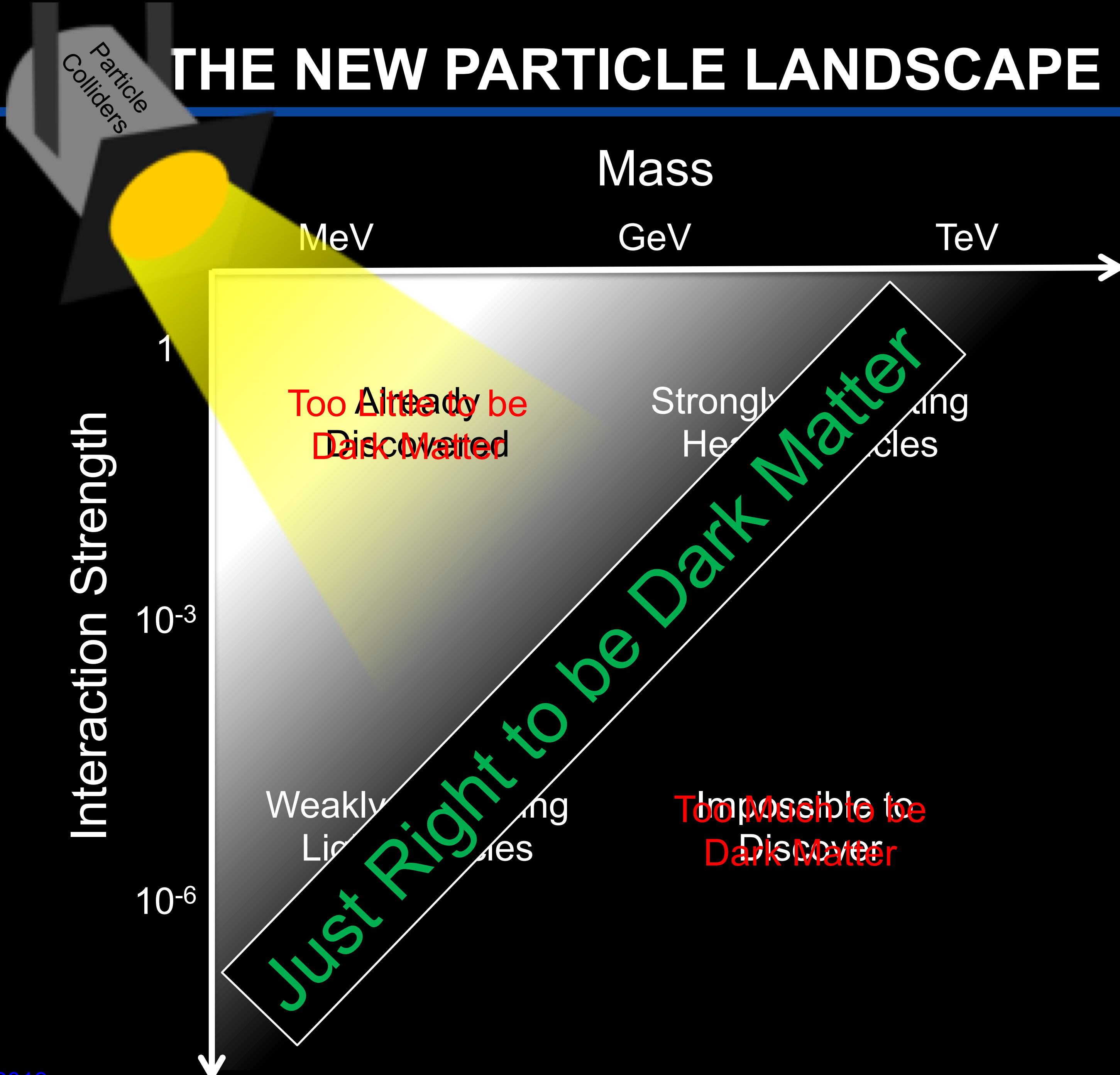
- WIMP Miracle: $g_X \sim 1$, $m_X \sim 100$ GeV → right abundance.
- WIMPless Miracle: But with a dark sector, we don't need to fix $g_X \sim 1$. The dark sector can have lighter particles and weaker interactions and still have the right abundance.





Boehm, Fayet (2003); Feng, Kumar (2008)

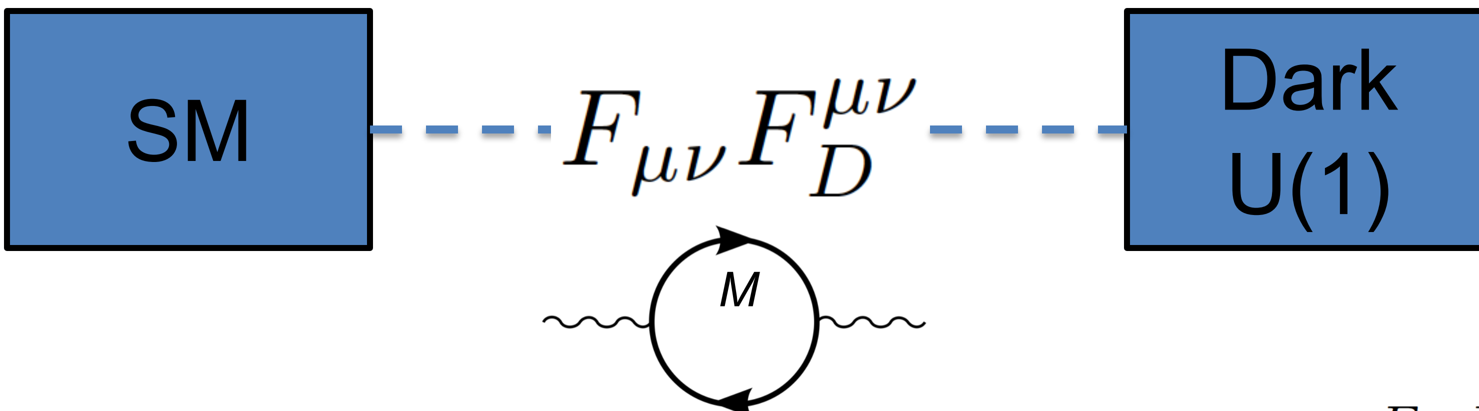
THE NEW PARTICLE LANDSCAPE



PORTALS

- Dark sectors need not talk with us. But if they do, what are the most likely non-gravitational interactions?

- Suppose the dark sector has U(1) electromagnetism. There are infinitely many possible SM-dark sector interactions, but one is induced by arbitrarily heavy mediators:



- It is "most likely" because it is non-decoupling. Cf. $\dfrac{F_{\mu\nu}F_D^{\nu\alpha}F_\alpha^\mu}{M^2}$

- It is also naturally small, since it is induced by a loop.

Okun (1982), Galison, Manohar (1984), Holdom (1986)

DARK PHOTON, DARK HIGGS, STERILE NUS

- This provides an organizing principle that motivates specific examples of new, weakly interacting light particles. There are just a few options:

- Spin 1 SM - - - - $F_{\mu\nu}F_D^{\mu\nu}$ - - - - Dark Force

→ dark photon, couples to SM fermions with suppressed couplings proportional to charge: εq_f. Holdom (1986)

- Spin 0 SM - - - $h^\dagger h \phi_D^\dagger \phi_D$ - - - Dark Scalar

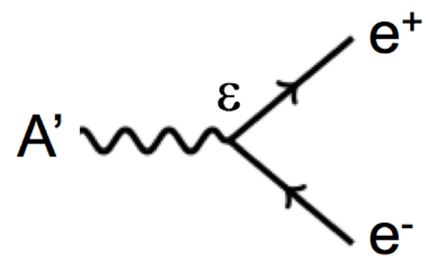
→ dark Higgs boson, couples to SM fermions with suppressed coupling proportional to mass: $\sin\theta\, m_f$. Patt, Wilczek (2006)

- Spin 1/2 SM - - - $hL\psi_D$ - - - - Dark Fermion

→ sterile neutrino, mixes with SM neutrinos with suppressed mixing $\sin\theta$.

LIGHT LLP DECAYS

- The advent of dark sectors, along with axion-like particles, light gauge bosons, etc., has highlighted a new class of LLPs. Consider a neutral particle with energy E ~ TeV, mass m ~ 100 MeV, coupling $\varepsilon \sim 10^{-5}$.
- It passes through matter essentially without interacting: radiation length is (10 cm) $\varepsilon^{-2} \sim 10^9$ m, the distance to the moon!
- It may decay to visible particles, but only after traveling a long distance.



Velocity near the speed of light

$$v \approx 1$$

Rest lifetime enhanced by small mass, small ε

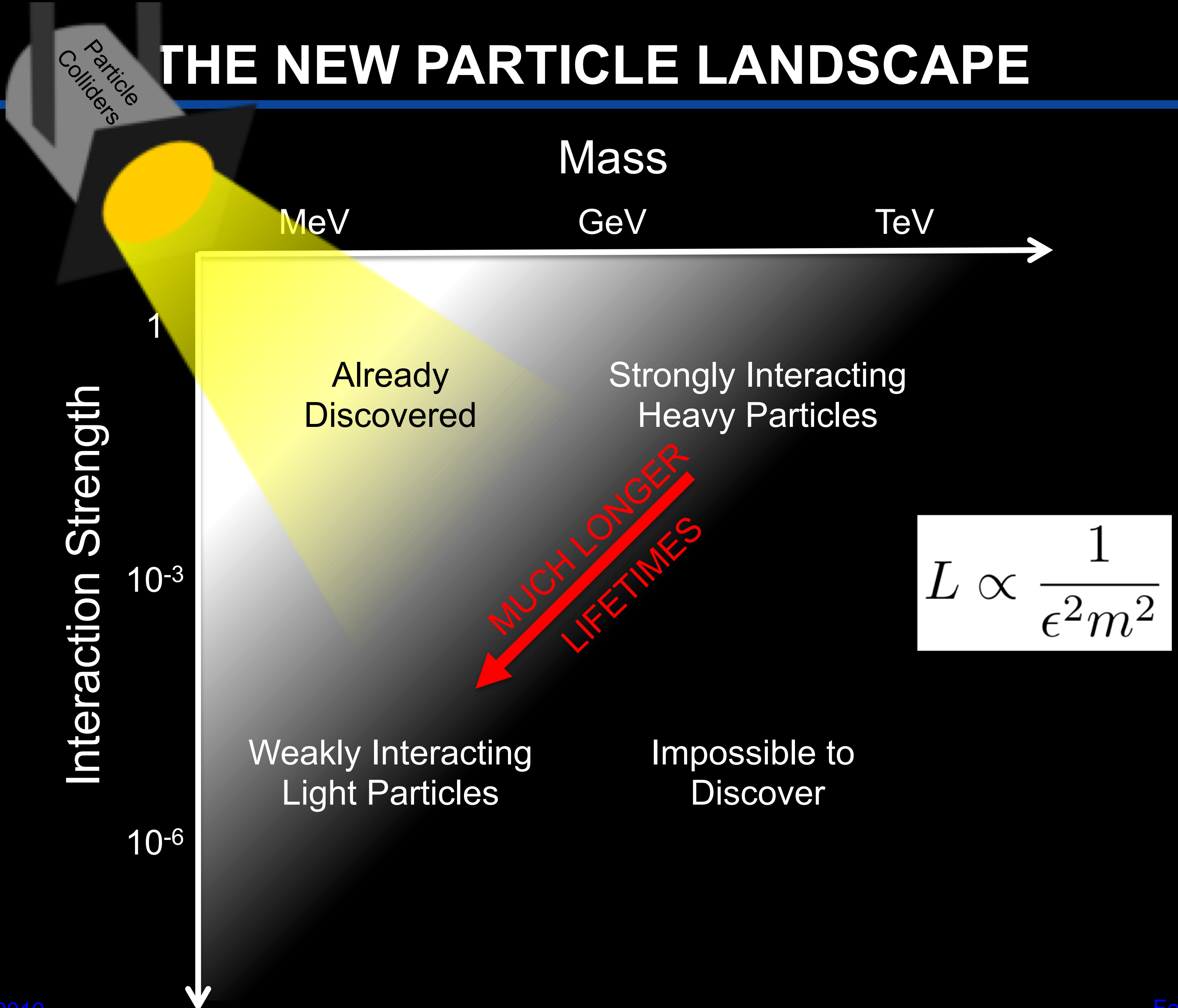
$$\tau \propto \frac{1}{\epsilon^2 m}$$

Lifetime further enhanced by time dilation

$$\gamma \propto \frac{E}{m}$$

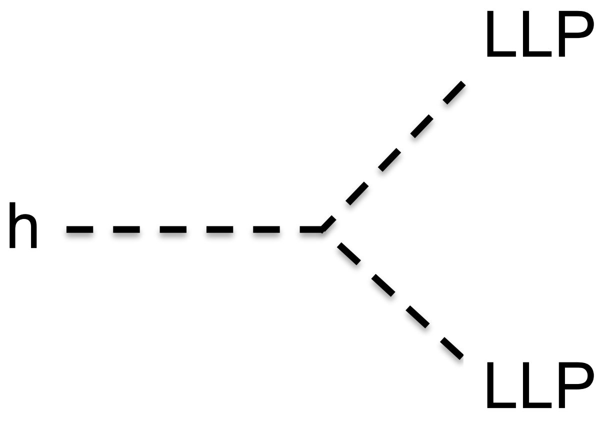
$$L = v\tau\gamma \sim (100\ \mathrm{m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{100\ \mathrm{MeV}}{m}\right]^2 \left[\frac{E}{\mathrm{TeV}}\right]$$

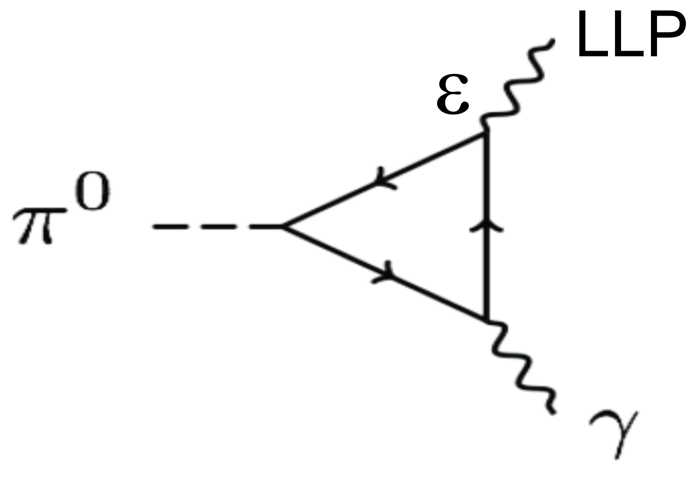
THE NEW PARTICLE LANDSCAPE



LIGHT LLP PRODUCTION

- The advent of light and weakly interacting particles greatly increases the possible modes of production.
- Production in weak-scale processes remains interesting.
- But now production through light SM particle decays is also possible, opening up the floodgates to experiments at both the energy frontier and the intensity frontier.





THERMAL TARGETS: VISIBLE DECAYS

- If $m_{LLP} < 2m_{DM}$, the LLP will decay to the SM, and the most promising signal is visible particle-anti-particle pairs.

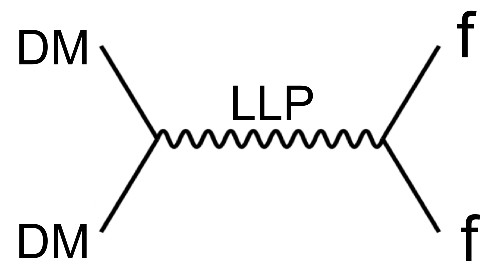
- The introduction of dark sector-SM interactions modifies DM freeze out, since the DM can annihilate to the SM.

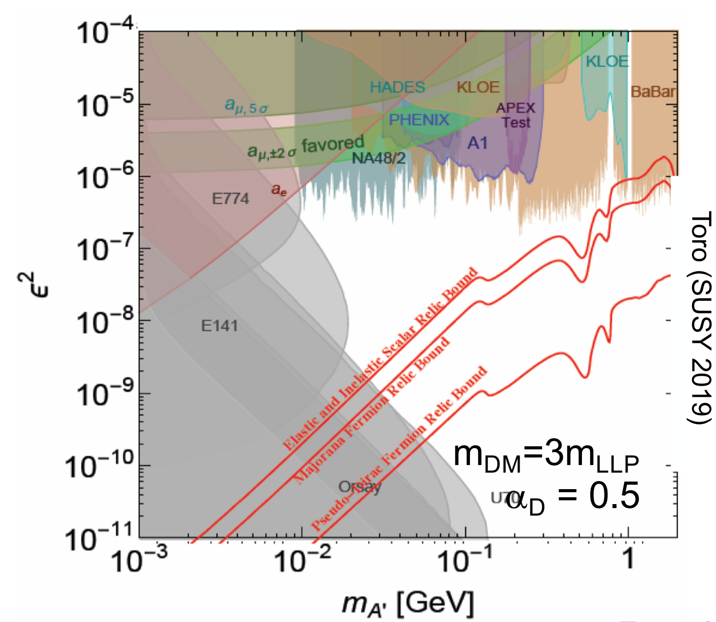
- To determine the thermal relic targets, must work in a definite model.

- E.g., for dark photons decaying visibly to SM particles, the thermal targets focus attention on

  masses m ~10 MeV – many GeV

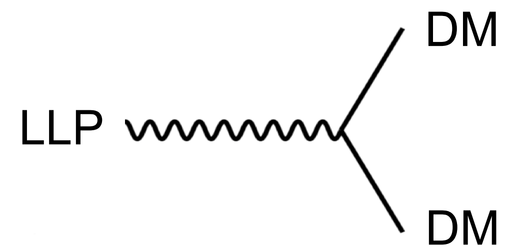
  couplings $\varepsilon \sim 10^{-5} - 10^{-3}$



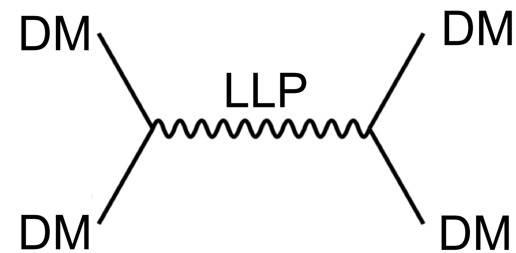


THERMAL TARGETS: VISIBLE DECAYS

- If $m_{LLP} > 2m_{DM}$, the LLP will typically decay invisibly to DM, and the most promising signal is missing mass or missing energy.



- Again freeze out sets some thermal relic targets, but there is a new possibility: resonant annihilation for $m_{LLP} \sim 2m_{DM}$.

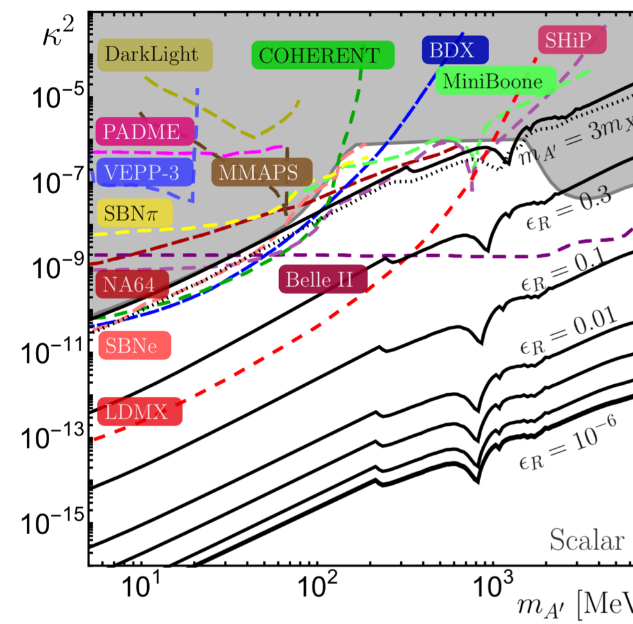


- For dark photons decaying invisibly to DM, the thermal targets are again typically around

  masses m ~10 MeV – manu GeV

  couplings $\varepsilon \sim 10^{-5} - 10^{-3}$

- But for even 10% fine-tuning, e.g., $m_{LLP} \sim 2.2\ m_{DM}$, the thermal targets can shift down to couplings $\varepsilon \sim 10^{-7} - 10^{-5}$, beyond any proposed experiment.



Feng, Smolinsky (2017)

SUMMARY

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  - LLPs are ubiquitous in BSM theories, especially those with cosmological significance
  - LLPs can be detected through a huge variety of signatures
  - Many of these signals are truly spectacular – a few events can be a discovery
  - For existing experiments, we have not yet reached the full LLP discovery potential
  - And LLPs present many opportunities for new and clever experiments (and new and clever experimentalists!)