ACCELERATOR SEARCHES FOR THE DARK SECTOR

The Almost Invisibles: Exploring the Weakly Coupled Universe

SLAC Summer Institute

Jonathan Feng, UC Irvine, 17-18 August 2020

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LECTURE 1

INTRODUCTION

- Before we begin, we should acknowledge the temerity of the title of these two lectures: "Accelerator Searches for the Dark Sector."

- Why should these completely human-made experiments on Earth have any hope of telling us about what the universe looks like a Gpc away?

Accelerators
Particle Physics
L ~ 10^{-18} m

Dark Sector
Cosmology
L ~ 10^{25} m

- In fact, it is one of the great wonders of our field that there are reasons for optimism.
  – The existence of the dark sector is now one of the strongest reasons to expect not only that new particles exists, but also that new particles will appear at the particle experiments we are now building.
  – General arguments have motivated a huge number of new ideas for experiments at accelerators and colliders in the coming years.

OUTLINE

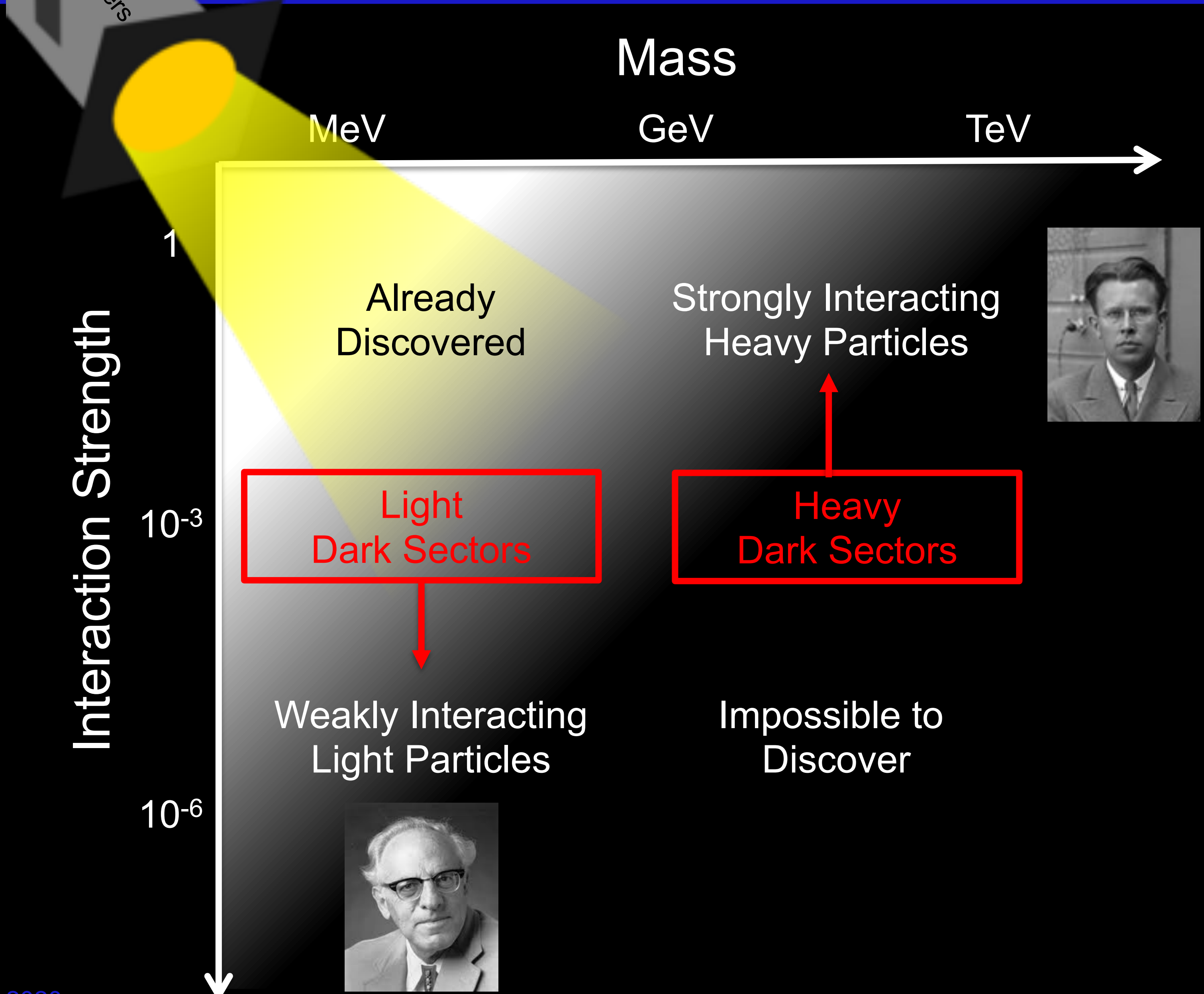
I: Particle Physics and the Relic Density of Dark Matter

II: Heavy Dark Sectors at Accelerators

III: Light Dark Sectors at Accelerators

I: Particle Physics and the Relic Density of Dark Matter

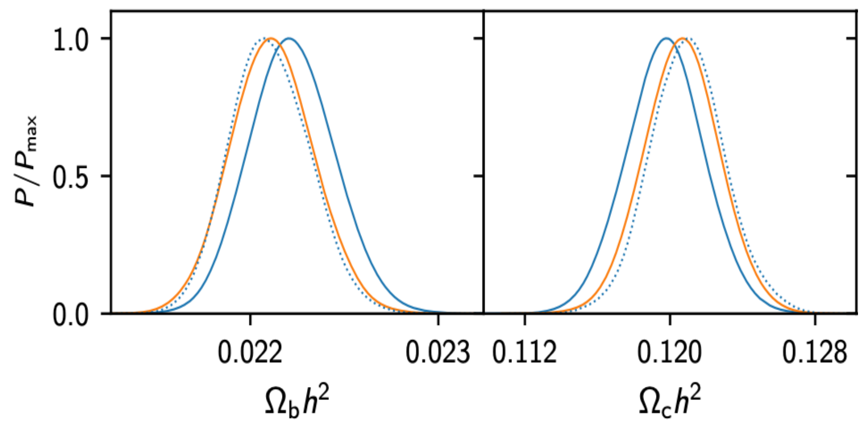
THE NEW PARTICLE LANDSCAPE



DARK MATTER'S RELIC DENSITY

- We know little about dark matter and the dark sector.
- The one thing we do know *precisely* is the dark matter's relic density: $\Omega_{\rm DM}h^2 = 0.1200 \pm 0.0012.$

  Planck Collaboration (2018)



- What can we learn from this about dark matter's particle properties?
  - Generically: nothing.
  - But if we assume dark matter is produced through thermal freezeout: a lot.

THERMAL FREEZE OUT

See Tim Tait's Lectures

(1) Assume a new heavy particle *X* is initially in thermal equilibrium:

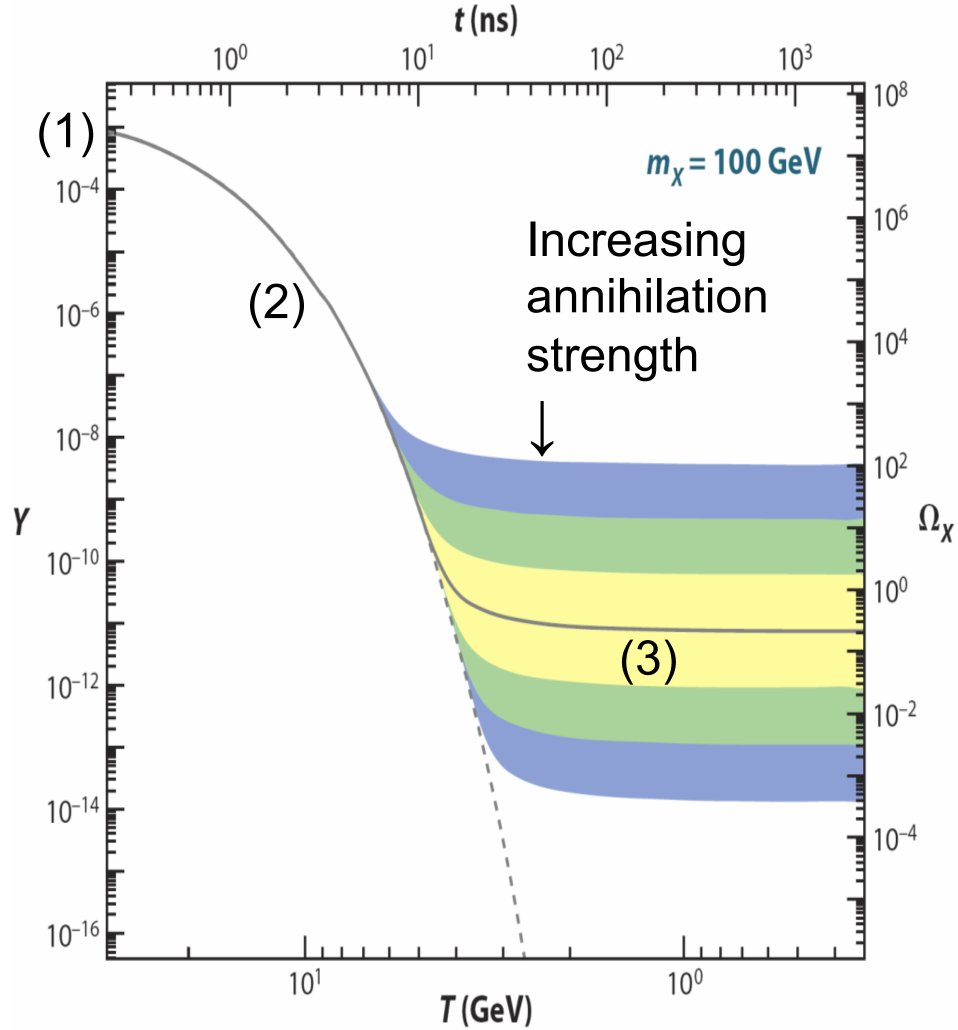
$$XX \leftrightarrow qq$$

(2) Universe cools:

$$XX \underset{\not\leftarrow}{\rightarrow} qq$$

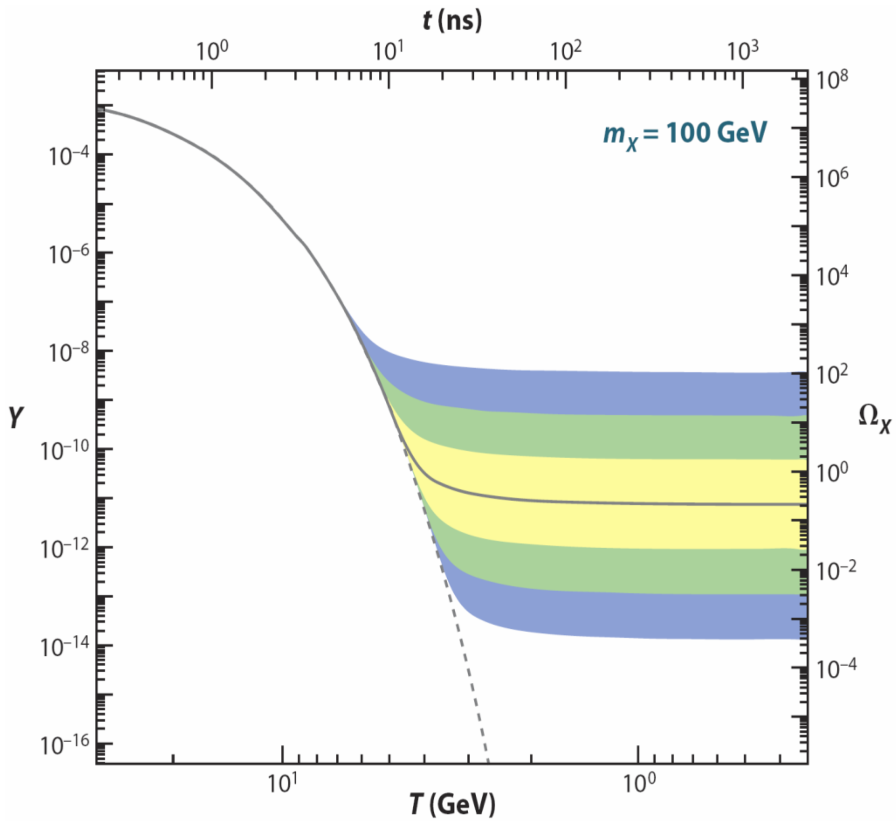
(3) Universe expands:

$$XX \underset{\not\leftarrow}{\not\rightarrow} qq$$



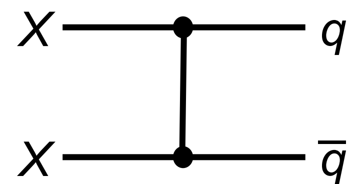
Zeldovich et al. (1960s)

THE WIMP MIRACLE



- It turns out that the relation between Ω_X and annihilation strength is wonderfully simple:

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



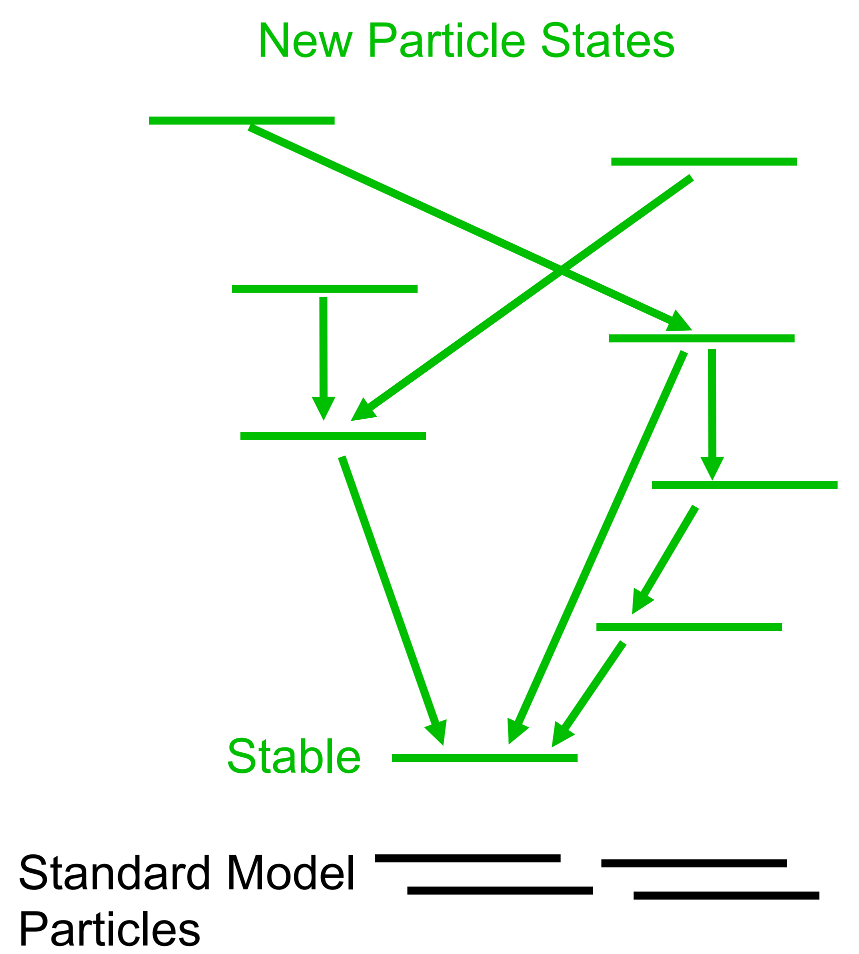
where we've assumed that the annihilation is characterized by a single mass scale.

- Keeping track of the constants, we find $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$.

- This is remarkable: particles with the right thermal relic density are now at the energy frontier! The LHC is a big DM search experiment.

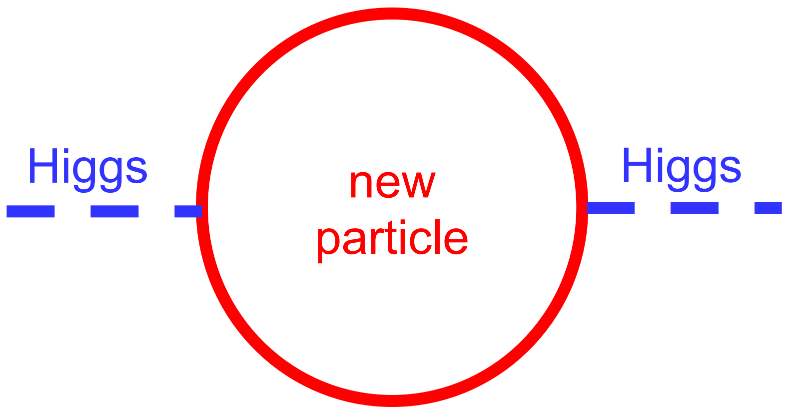
WIMP STABILITY

- The WIMP Miracle is well appreciated. But its success relies another less well-advertised "miracle."
- DM must be stable.
- How natural is this? *A priori*, not very: the only stable particles we know about are very light.

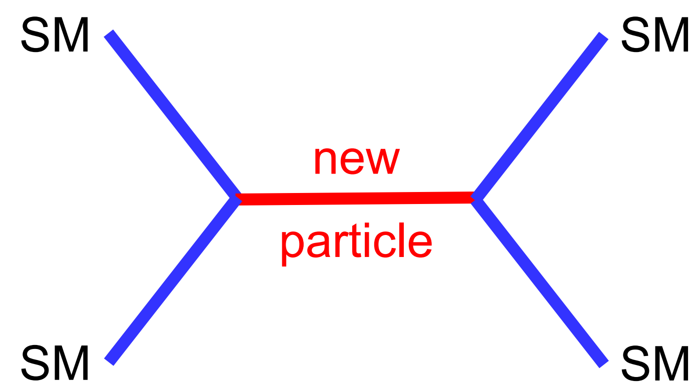


THE DISCRETE WIMP MIRACLE

Gauge Hierarchy requires



Precision EW excludes



In some cases, there are even stronger reasons to exclude these 4-particle interactions (e.g., proton decay in SUSY)

- Simple solution: impose a discrete parity, so all interactions require *pairs* of new particles. This also makes the lightest new particle stable: Discrete Symmetry ↔ Stability

Cheng, Low (2003); Wudka (2003)

- Remarkable coincidence: particle physics independently motivates particles that are stable enough to be dark matter

DARK SECTORS

- The WIMP Miracle relies on the choice of gauge coupling $g_X \sim 1$. This is a reasonable choice, since it is true of all known gauge forces, and since EM and strong interactions are largely excluded, leads to DM with weak SU(2) interactions: weakly-interacting massive particles (WIMPs).

- But all evidence for dark matter is gravitational. It may therefore have only gravitational interactions with standard model particles.

- Alternatively, it may have highly suppressed, but non-negligible, interactions with standard model particles with couplings $g_X \ll 1$. We will see that this in fact emerges quite naturally in models with dark sectors, which contain not just dark matter, but also possibly additional matter and forces.

Visible Sector
SM

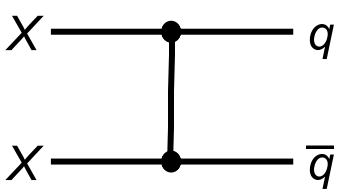
Dark Sector
DM + Other Particles

WIMPLESS MIRACLE

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

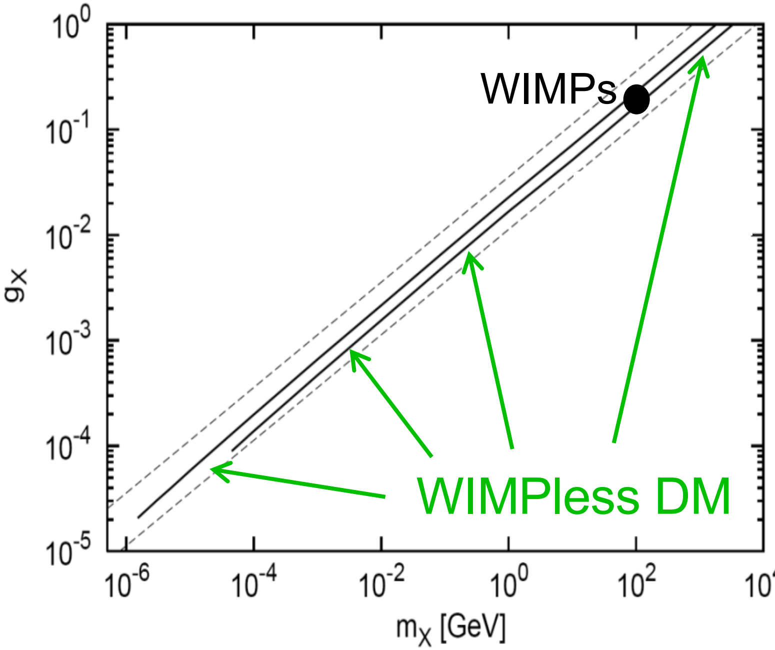
- Recall the WIMP miracle: the relation between Ω_X and annihilation strength is wonderfully simple:

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



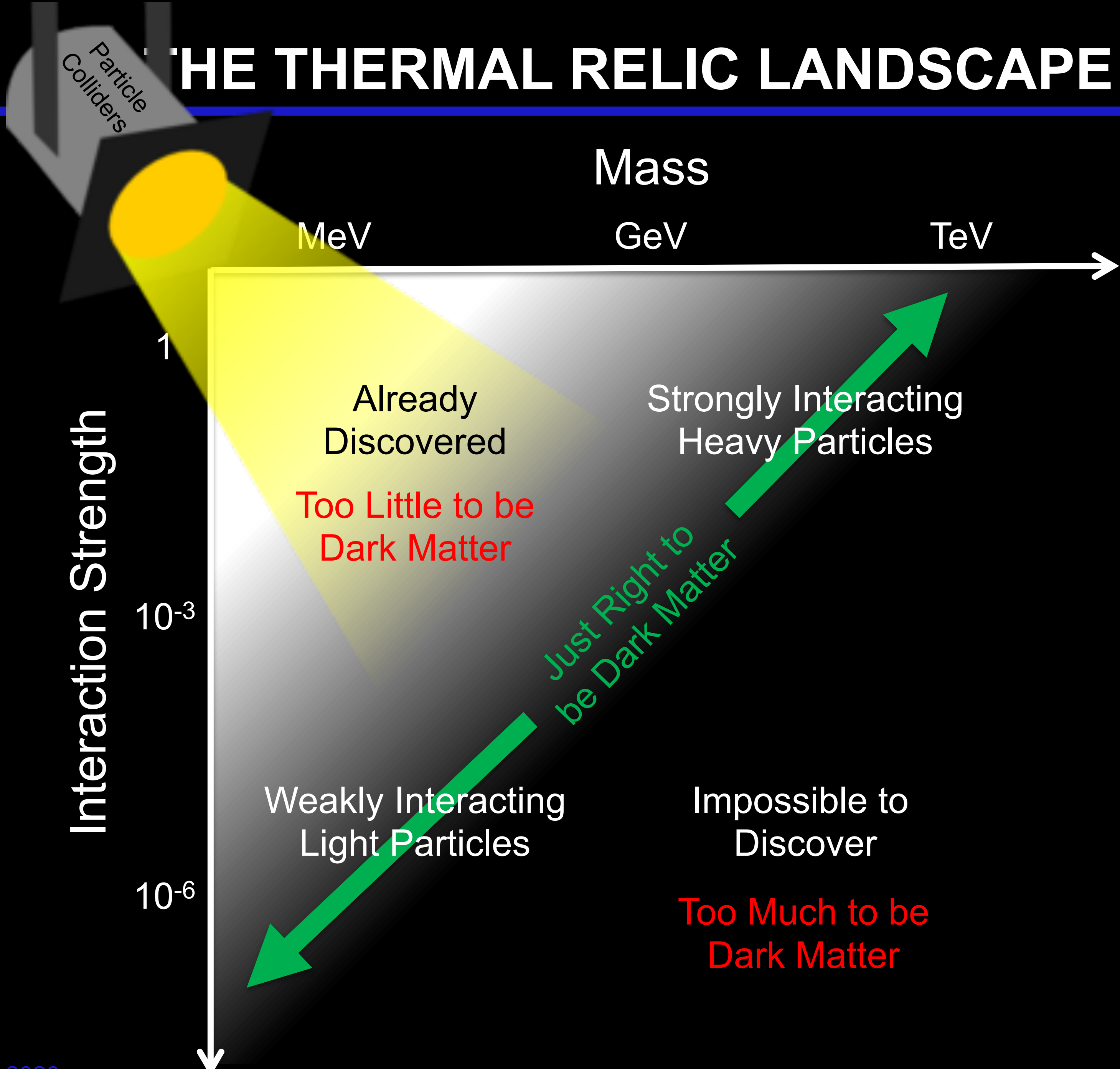
$m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

- With a dark sector, the coupling g_X doesn't have to be ~ 1



- WIMPless miracle: with dark sectors, light, weakly-coupled DM can also have the correct thermal relic density, opening up a whole new set of dark matter and dark sector signals, all within standard cosmology.

THE THERMAL RELIC LANDSCAPE



I. SUMMARY

- We know little about dark matter, but we know its relic density precisely.
- If dark matter is produced through thermal freezeout, this relic density tells us about its particle properties, and remarkably, it favors particles with masses and couplings that are not yet excluded, but are within reach of current and near future experiments.
- There is a continuum of ideas, but roughly they break into two classes:

	Heavy	Light
Typically referred to as	WIMP Dark Matter	Dark Sectors
Typical coupling	~1	$\sim 10^{-6}$ to 10^{-3}
Typical mass range	100 GeV to TeV	MeV to GeV
Typically probed at the	Energy Frontier	Intensity and Energy Frontiers

- Note: there are many caveats, exceptions, and extensions to what I have presented above. Some will be discussed below, some are still unexplored.

II: Heavy Dark Sectors at Accelerators

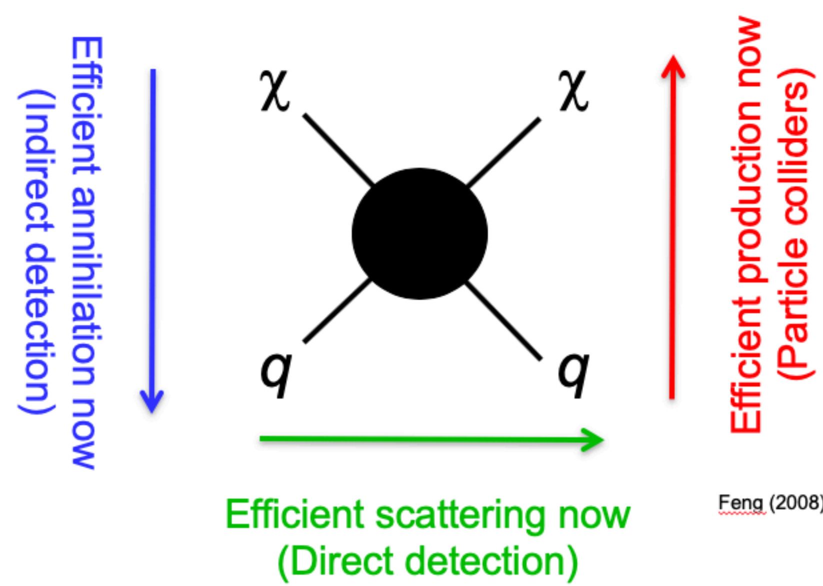
PARTICLE COLLIDERS

- If dark matter particles (and other particles associated with dark matter) have masses in the 100 GeV to TeV range, they are not easy to make. Two options:

- Use nature to make them (e.g., in the Big Bang)
  - Indirect Detection
  - Direct Detection
  - UHE Cosmic Rays

- Use particle colliders (not just accelerators, fixed target experiments), to reach the highest possible center-of-mass energies.

See Tracy Slatyer's Lectures

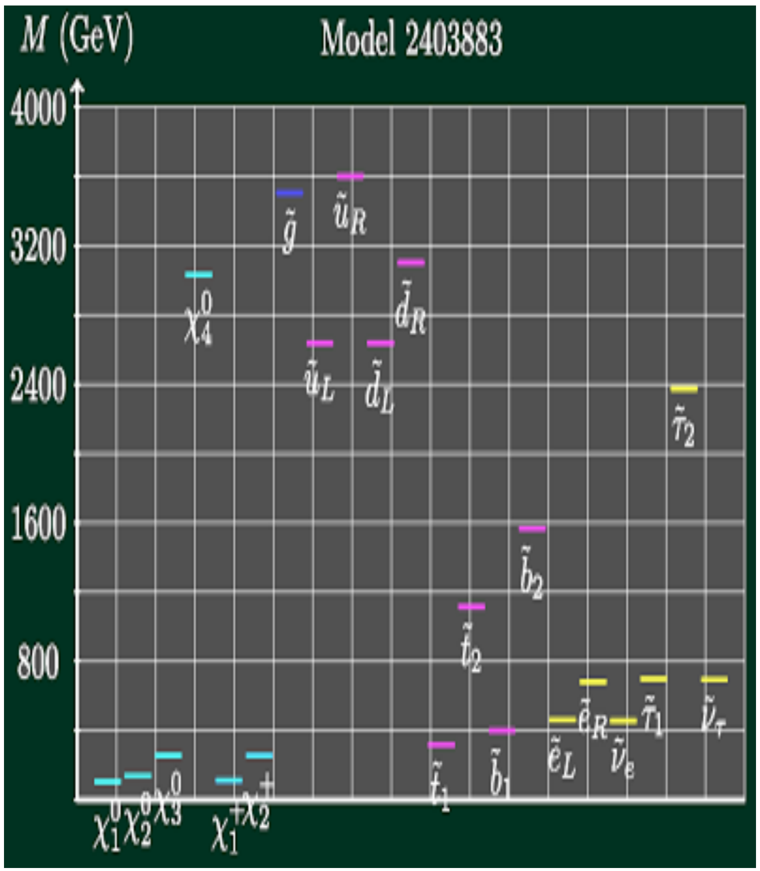


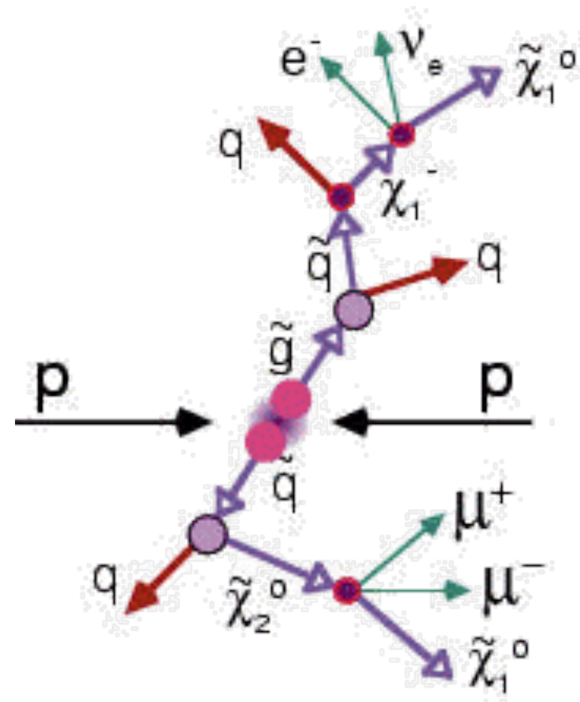
See Tim Tait's Lectures

See Jodi Cooley's Lectures

MISSING E_T

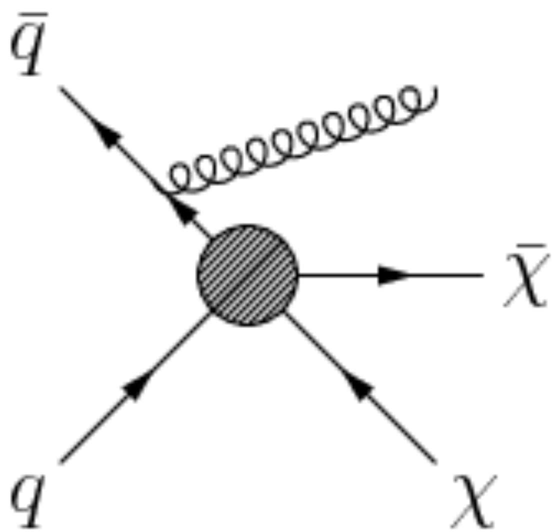
- Consider full models (e.g., SUSY), or simplified models. Produce other particles that decay to DM, look for missing E_T signatures.





MONO-X

- Alternatively, produce the DM directly, but in association with something else that can be seen. Model the blob as an effective operator, look for mono-X, where X = photon, jet, W, Z, h, b, t, ….



Birkedal, Matchev, Perelstein (2004)

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

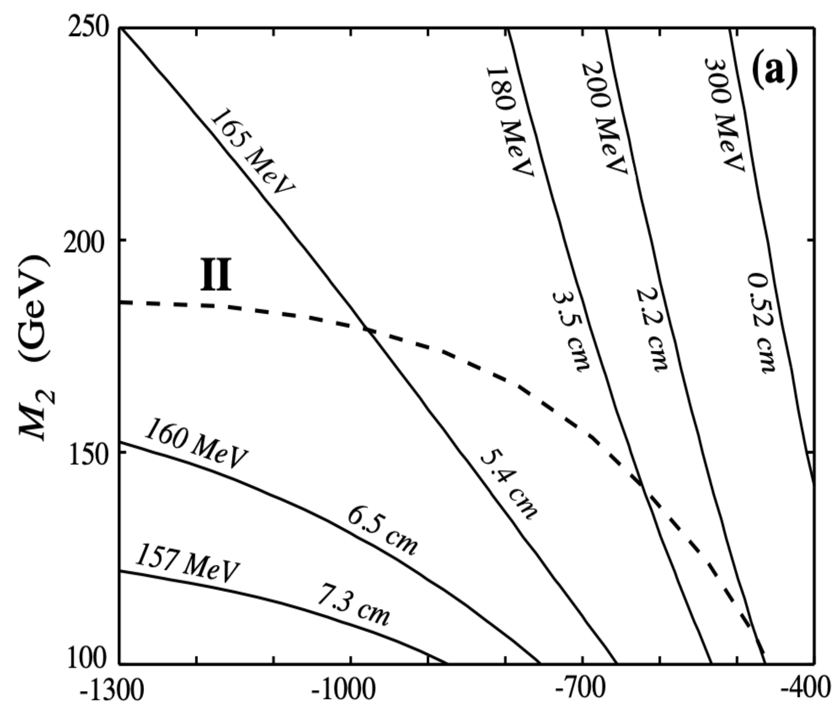
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)
Bai, Fox, Harnik (2010)

WINO DM AND DISAPPEARING TRACKS

- Although missing E_T and mono-X are by far the most-studied signatures of DM, there are actually many others. To give a flavor of these, and to prepare us for the wonderful zoo of interesting signatures to be discussed next for light dark sectors, let's give a few examples.

- DM may be the neutral Wino, the SUSY partner of an SU(2) gauge boson.

- The neutral Wino is part of an SU(2) triplet $(\tilde{W}^-, \tilde{W}^0, \tilde{W}^+)$
  - SU(2) symmetry: complete degeneracy
  - SU(2) breaking: Δm ~ 160 MeV
  - Leading decay is $\tilde{W}^\pm \rightarrow \tilde{W}^0 \pi^\pm$ with a long decay length $c\tau$
  - Signature: the charged Wino is produced, but then decays to DM and an extremely soft pion, so "disappears" after ~10 cm

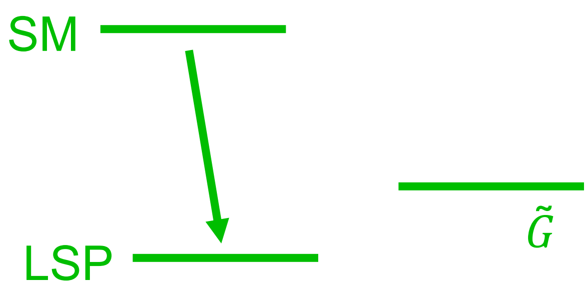


Feng, Moroi, Randall, Strassler, Su (1999)

GRAVITINO DM AND LONG-LIVED PARTICLES

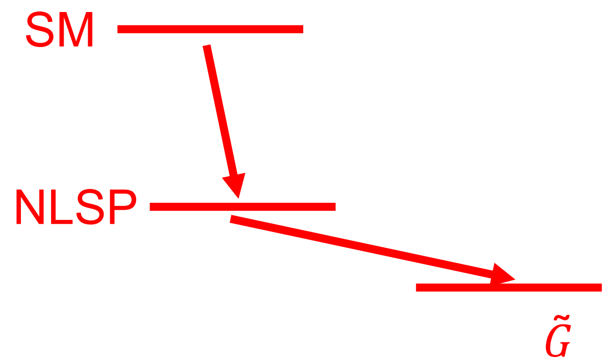
- In all supersymmetric models, the graviton has a superpartner, the gravitino $\tilde{G}$. Its mass can be anything from eV to PeV, but its couplings are typically extremely weak (as expected for the graviton's partner).

- $\tilde{G}$ not LSP



- Assumption of most of literature

- $\tilde{G}$ LSP

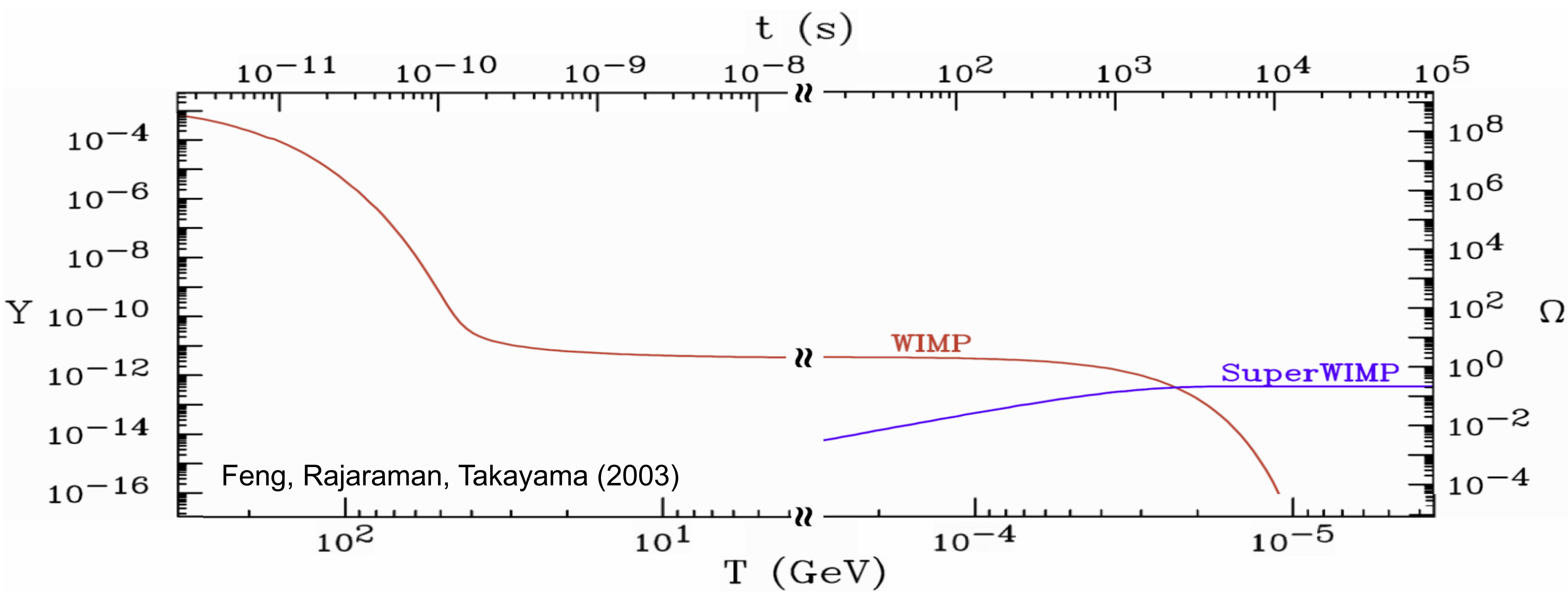


- Completely different cosmology and particle physics

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

SUPERWIMP DARK MATTER

- In gravity-mediated SUSY, the $\tilde{G}$ has mass ~ 100 GeV, but extremely weak couplings $M_W/M_{\rm Pl}$ ~ 10^{-16}. If the $\tilde{G}$ is the LSP, WIMPs freeze out as usual, but then decay to $\tilde{G}$ after $t \sim M_{\rm Pl}^2 / M_W^3$ ~ seconds to months.



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

METASTABLE CHARGED PARTICLES

- If we see long-lived charged particles, e.g., sleptons, we know they can't be DM, must decay.

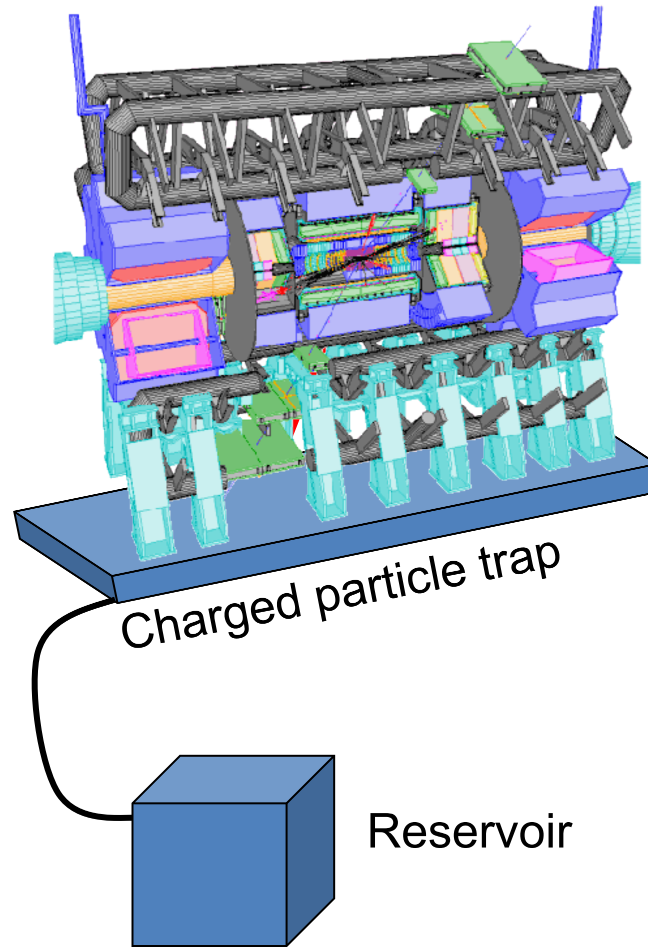
- We can collect these particles and study their decays.

- Several ideas have been proposed

  – Trap sleptons a 1m thick water tank (a supplementary detector!) 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)



II. SUMMARY

- Heavy dark matter leads to many interesting signals at colliders.
- Classic signatures: missing E_T and mono-X.
- But ”exotic” signatures are also well-motivated. Some examples
  - Wino DM: disappearing tracks
  - Gravitino DM: metastable charged particles
- Dark matter does not simply motivate missing E_T at colliders. The interplay of cosmology and particle physics is far richer than that, and we should be on the lookout for qualitatively new signatures and opportunities at accelerators and colliders.

III: Light Dark Sectors at Accelerators

DARK SECTORS

- This is how we have traditionally thought about dark matter:

Standard Model

Dark Matter

- But this is probably closer to the truth:

Visible Sector
Standard Model

Dark Sector
DM + Other Particles

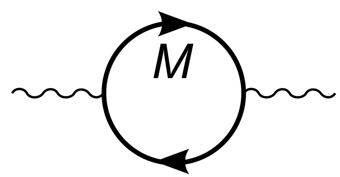
- What are the consequences of a dark sector containing dark matter, but also additional matter and forces?

DARK PHOTONS

- A dark sector need not interact with us, except through gravity. But if it does, what are the most likely non-gravitational interactions?

- Suppose the dark sector has its own electromagnetism. There are infinitely many possible SM-dark sector interactions, but one is special:

Visible Sector SM, $U(1)_{EM}$	$\frac{1}{2} \epsilon F^{\mu\nu} F_{D\mu\nu}$	Dark Sector DM, $U(1)_D$



- This term is allowed by all symmetries, and loop-induced by mediators.

- Moreover, it has mass dim 4, and so is non-decoupling. Cf. $\frac{F_{\mu\nu} F_D^{\nu\alpha} F_\alpha^\mu}{M^2}$.
  It is “most likely” because it is induced even by heavy mediators.

- Since it is loop-induced, we expect $\epsilon \sim 10^{-3}$ or smaller.

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

DARK PHOTONS

- In more detail, suppose the Dark Sector contains a massive U(1) gauge boson, and the SM-dark sector interaction is generated as noted before:

Visible Sector
SM, $U(1)_{EM}$

$$\frac{1}{2}\epsilon\, F^{\mu\nu}F_{D\mu\nu}$$

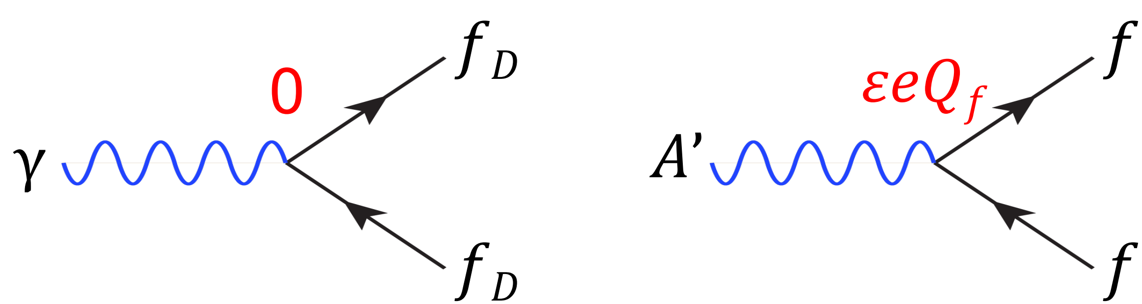
Dark Sector
DM, $U(1)_D$

$$-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$-\frac{1}{4}F_D^{\mu\nu}F_{D\mu\nu} + mA_D^{\mu}A_{D\mu}$$

- We can eliminate the mixing term by redefining fields: Try it! (For help, see the appendix of 1602.01465.) You will find that in the end, the physical states are the massless SM photon γ and a massive "dark photon" A'.

- The γ does not couple to dark sector particles. The A' couples to SM particles proportional to their SM charges, but suppressed by ε.



PORTALS

- The dark photon is a "portal" particle, connecting the SM and dark sector. We can look for other dim 4 interactions. There are only 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: $\varepsilon e Q_f$. 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 $\sin\theta$.

LECTURE 2

DARK PHOTON LAGRANGIAN

- Define field strengths $F_X^{\mu\nu} \equiv \partial^\mu X^\nu - \partial^\nu X^\mu, \quad X = A, B, C, D$

- The Lagrangian for the massless SM U(1) gauge boson C and a massive dark sector U(1) gauge boson D, including kinetic mixing, is

$$\mathcal{L} = -\frac{1}{4} F_{C\mu\nu} F_C^{\mu\nu} - \frac{1}{4} F_{D\mu\nu} F_D^{\mu\nu} + \frac{1}{2} \epsilon F_{C\mu\nu} F_D^{\mu\nu} + \frac{1}{2} m_D^2 D_\mu D^\mu + C_\mu J_{\rm SM}^\mu + D_\mu J_{\rm dark}^\mu$$

- To remove the mixing and go to the physical basis, define

$$D = \frac{1}{\sqrt{1-\epsilon^2}} B \qquad C = A + \frac{\epsilon}{\sqrt{1-\epsilon^2}} B$$

- The resulting Lagrangian is

$$\mathcal{L} = -\frac{1}{4} F_{A\mu\nu} F_A^{\mu\nu} - \frac{1}{4} F_{B\mu\nu} F_B^{\mu\nu} + \frac{1}{2} \frac{m_D^2}{1-\epsilon^2} B_\mu B^\mu + \left(A_\mu + \frac{\epsilon}{\sqrt{1-\epsilon^2}} B_\mu \right) J_{\rm SM}^\mu + \frac{1}{\sqrt{1-\epsilon^2}} B_\mu J_{\rm dark}^\mu$$

  where A is the SM photon γ, and B is the dark photon A'.

- Note that the photon is massless and doesn't couple to the dark current. But the dark photon does couple to the SM current.

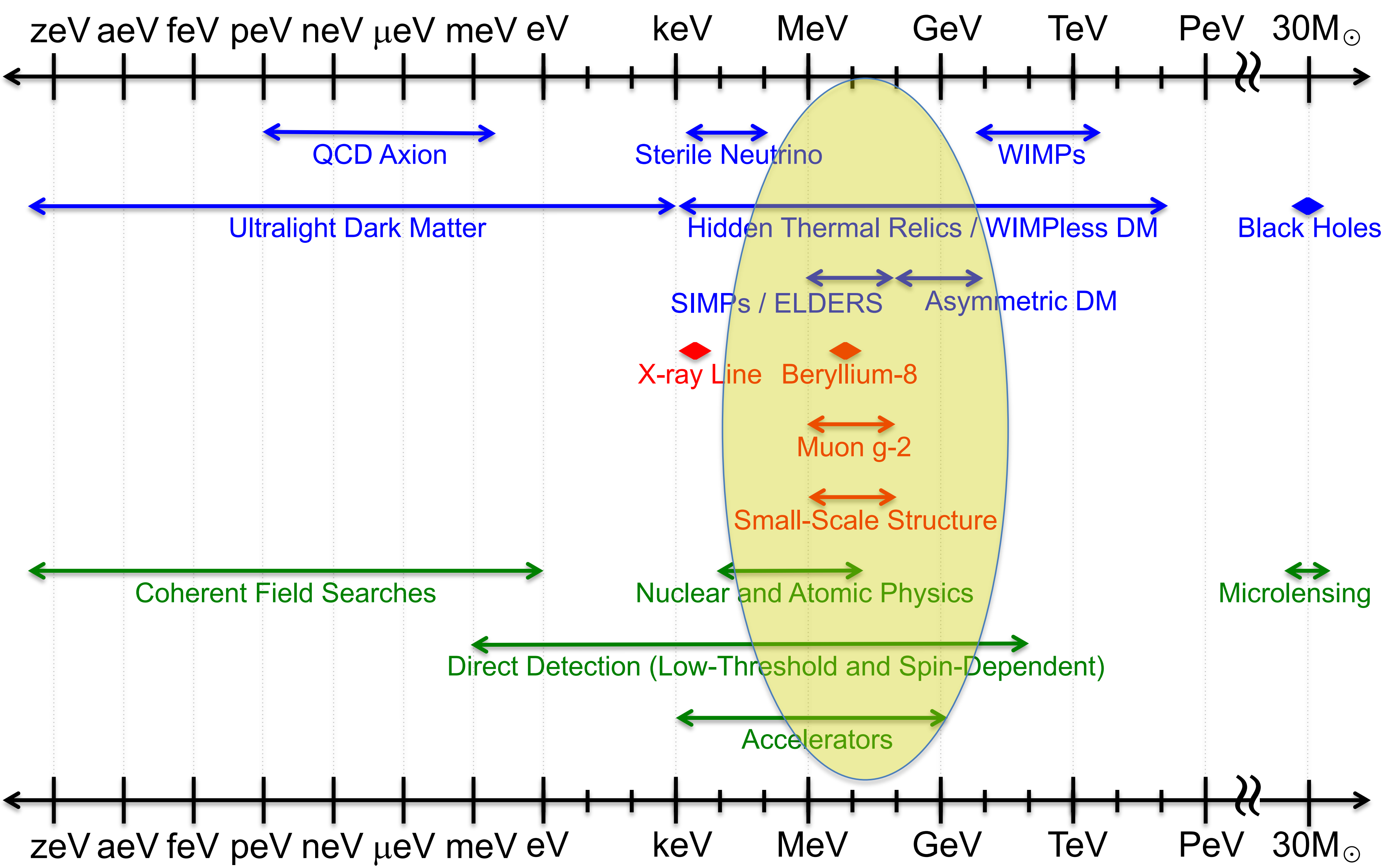
PORTAL PARAMETER SPACE

- By focusing on the renormalizable interactions between the SM and the dark sector, we now have identified 3 favored portal particles
  - Dark photons
  - Dark Higgs bosons
  - Dark fermions (sterile neutrinos, heavy neutral leptons)

- Each is very simply characterized by only two new parameters
  - m, the new particle's mass
  - ε (or $\sin\theta$), the new particle's coupling / interaction strength

- Before discussing the many possible accelerator probes, let's get oriented in this parameter space by discussing some of the well-known targets for future experiments
  - Muon g-2 anomaly
  - The ^{8}Be and ^{4}He ATOMKI anomalies
  - Self-interacting dark matter
  - The thermal relic density

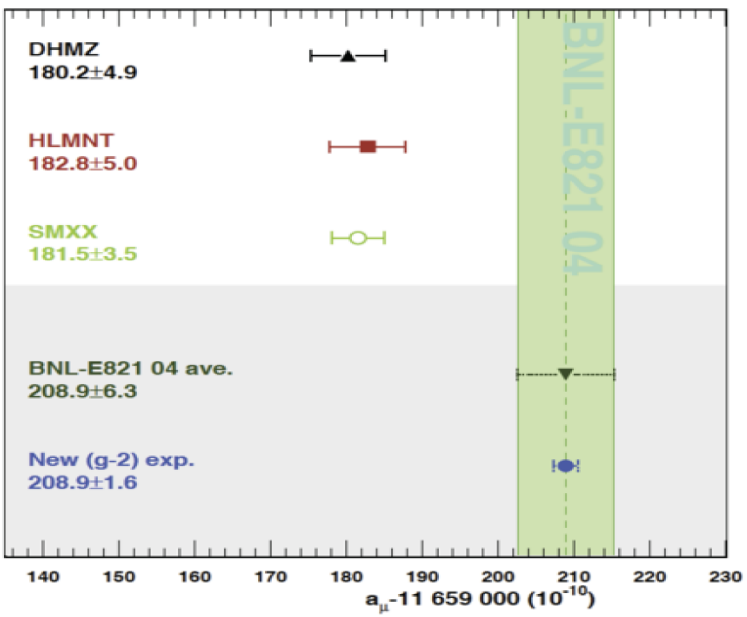
Dark Sector Candidates, Anomalies, and Search Techniques



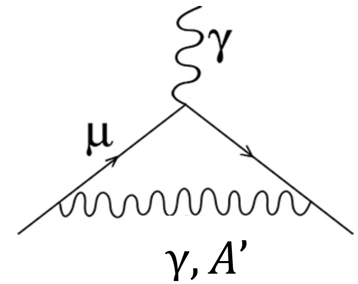
Cosmic Visions Report (2017)

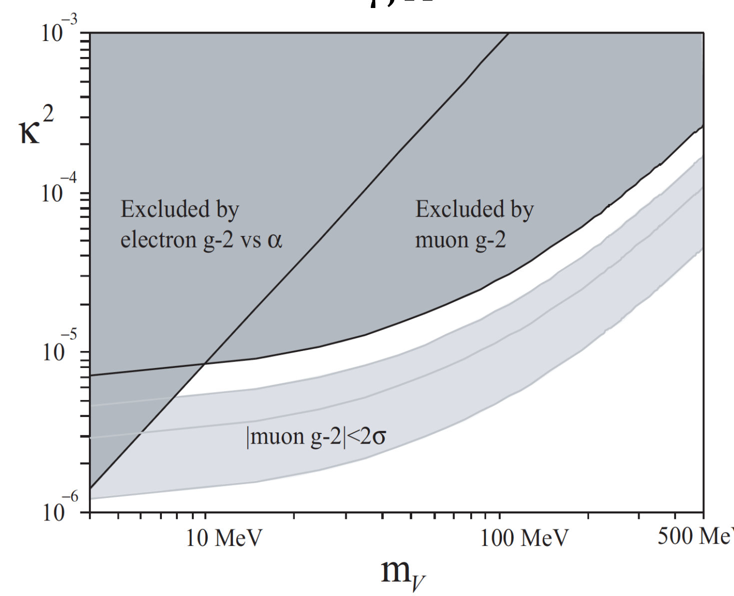
THE MUON'S ANOMALOUS MAGNETIC MOMENT

- The 3.7σ discrepancy between the SM and experiment can be resolved by MeV-GeV particles with $\varepsilon \sim 10^{-3}$. The dark photon is no longer a viable solution, but other particles with similar masses and couplings are.



Hagiwara et al. (2017); Aoyama et al. (2020)

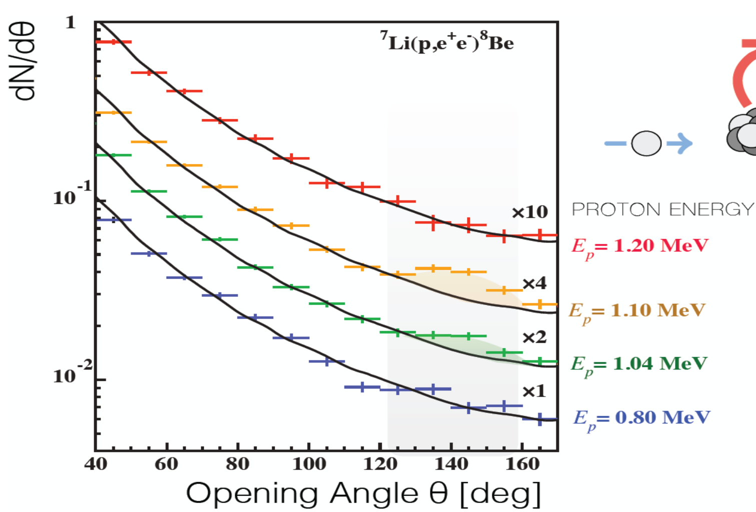


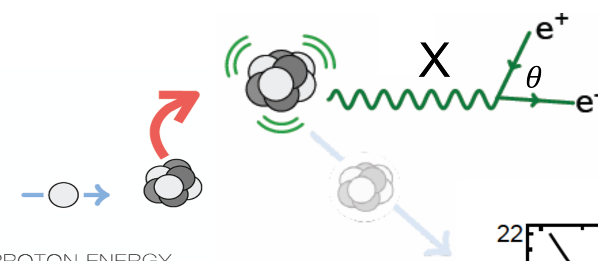


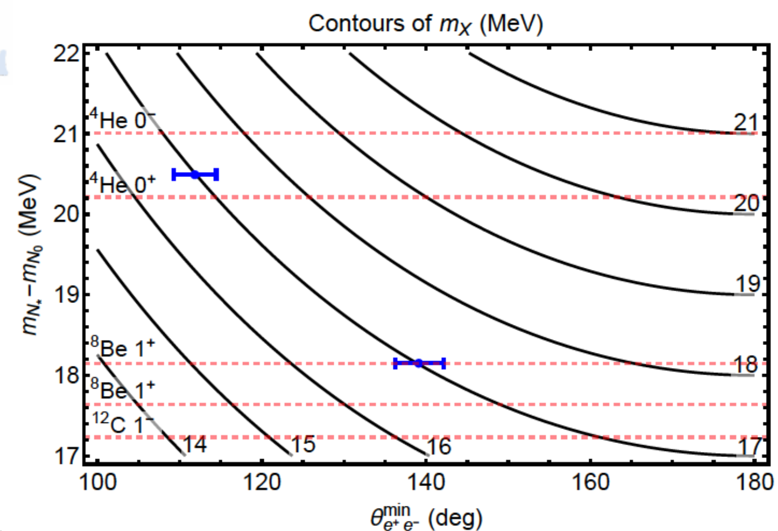
Boehm, Fayet (2003); Pospelov (2008)

THE ^{8}Be and ^{4}He ATOMKI ANOMALIES

- A 7σ anomaly in the decays of excited ^{8}Be nuclei can be explained by a new particle with mass 17 MeV and couplings ~ 10^{-4} - 10^{-3}.
- A new 7σ anomaly in the decays of excited ^{4}He nuclei can be explained by the same new particle.







Krasznahorkay et al. (2015, 2019)
Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, Tait (2016)
Feng, Tait, Verhaaren (2020)

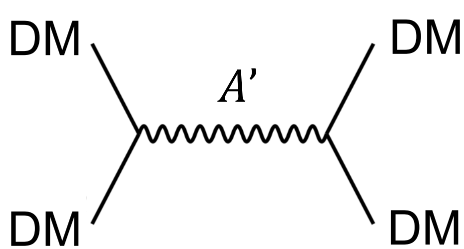
SELF-INTERACTING DARK MATTER

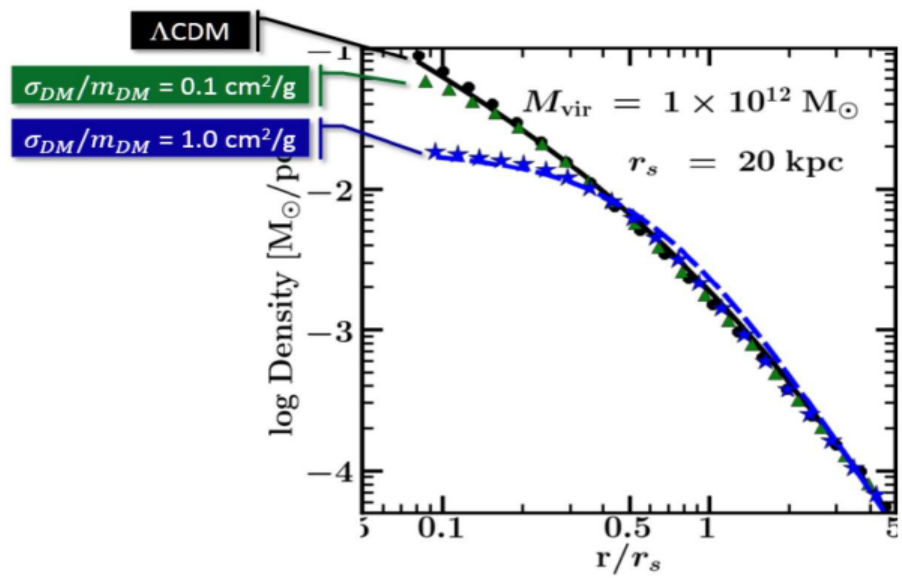
- There are indications from small-scale structure that dark matter may be strongly self-interacting.

- For example, there appear to be halo profiles that are not as cuspy as predicted by standard cold dark matter.

- To make a difference, the required self-interaction cross section is

$$\frac{\sigma}{m} \sim \frac{\text{cm}^2}{\text{g}} \sim \frac{\text{barn}}{\text{GeV}} \sim (100\ \text{MeV})^{-3}$$

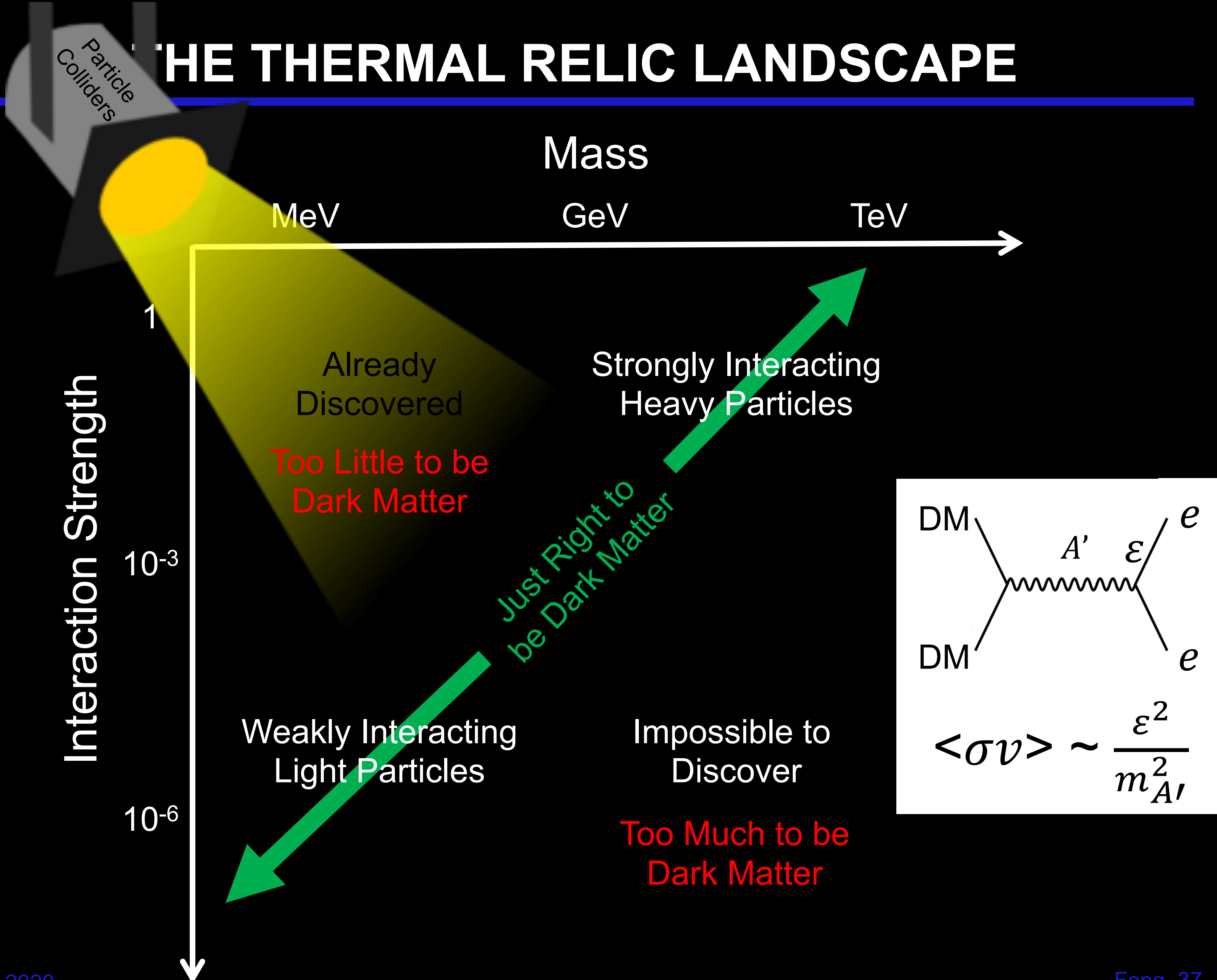




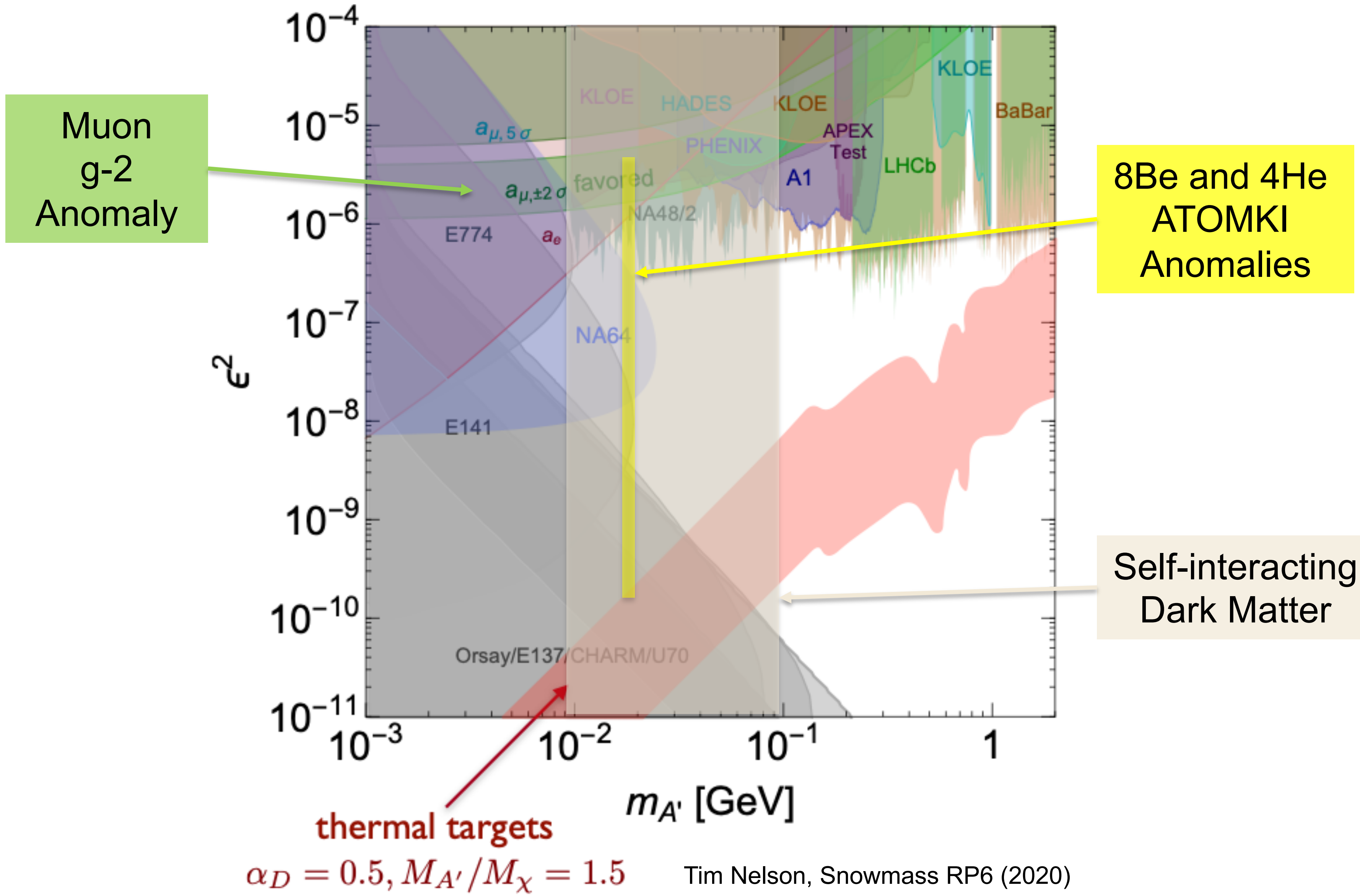
Tulin, Yu (2017)
Rocha et al. (2012), Peter et al. (2012); Vogelsberger et al. (2012); Zavala et al. (2012)

- This can be explained by a characteristic dark sector mass scale of ~ 10-100 MeV.

THE THERMAL RELIC LANDSCAPE



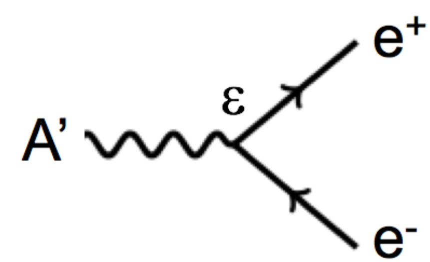
TARGETS IN DARK PHOTON PARAMETER SPACE



Tim Nelson, Snowmass RP6 (2020)

DARK PHOTON DECAY

- How can we look for portal particles at colliders? As an example, consider again the case of a dark photon.
- It passes through matter essentially without interacting: radiation length is (10 cm) ε^{-2} ~ 10^9 m, the distance to the moon!
- It decays 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

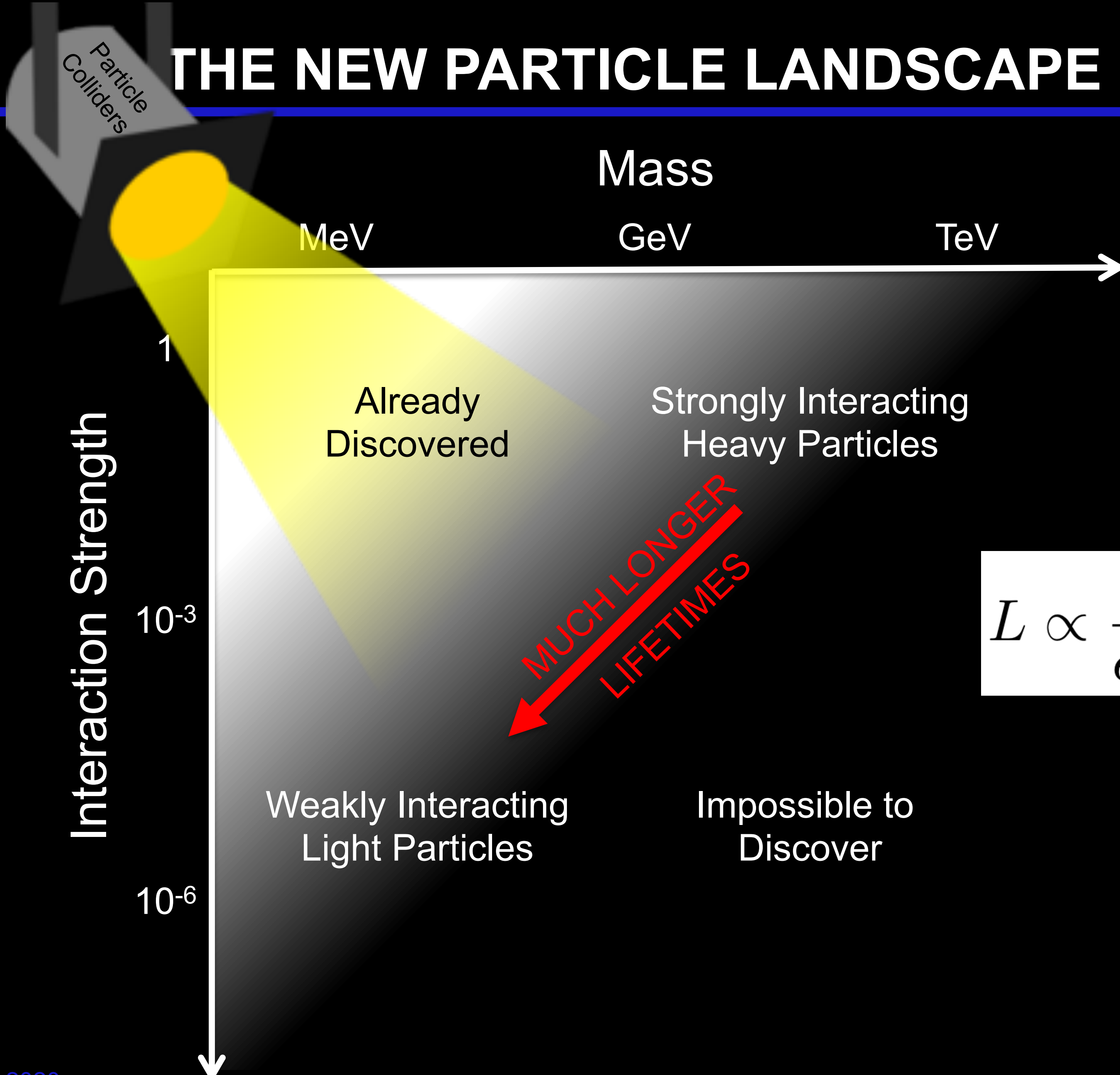
$$\tau \propto \frac{1}{\epsilon^2 m}$$

Lifetime further enhanced by time dilation

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

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

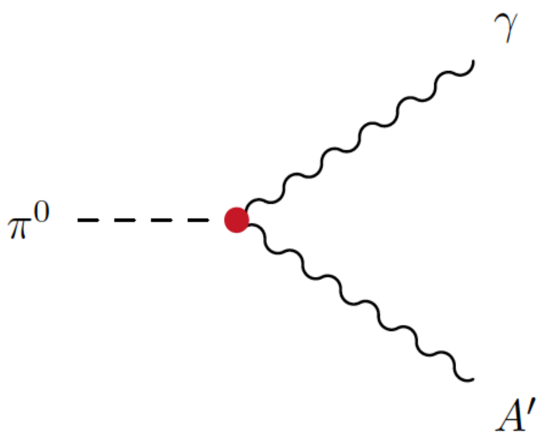
THE NEW PARTICLE LANDSCAPE



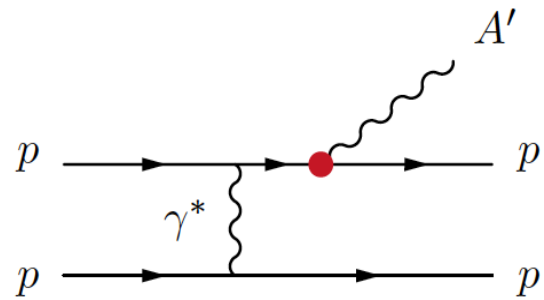
$$L \propto \frac{1}{\epsilon^2 m^2}$$

DARK PHOTON PRODUCTION

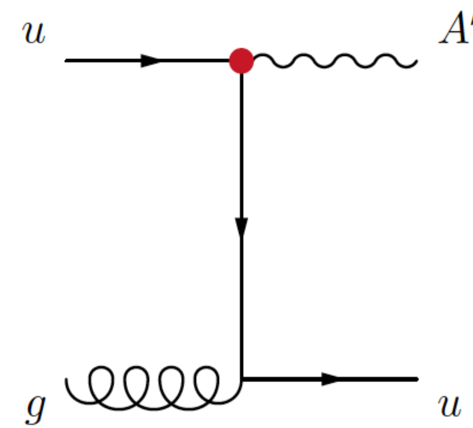
- There are many processes that may produce dark photons: take any SM process with a SM photon and replace the SM photon with a dark photon. For example:



Meson decay



Dark bremsstrahlung

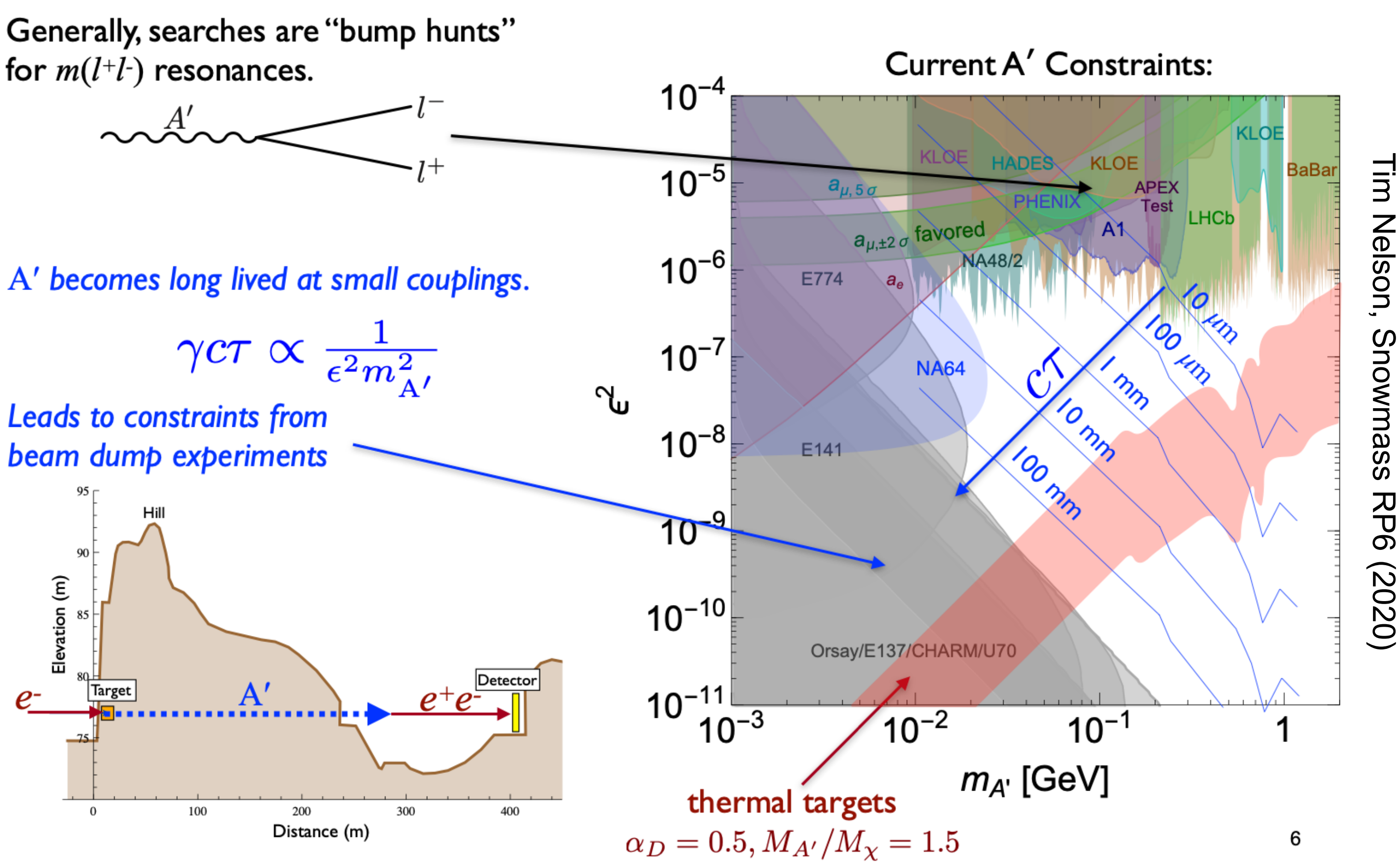


Hard scattering

- This opens up the floodgates to experimental probes at both the energy and intensity frontiers. Here mention just a small sampling, try to give an impression of the diversity of existing and planned experiments.

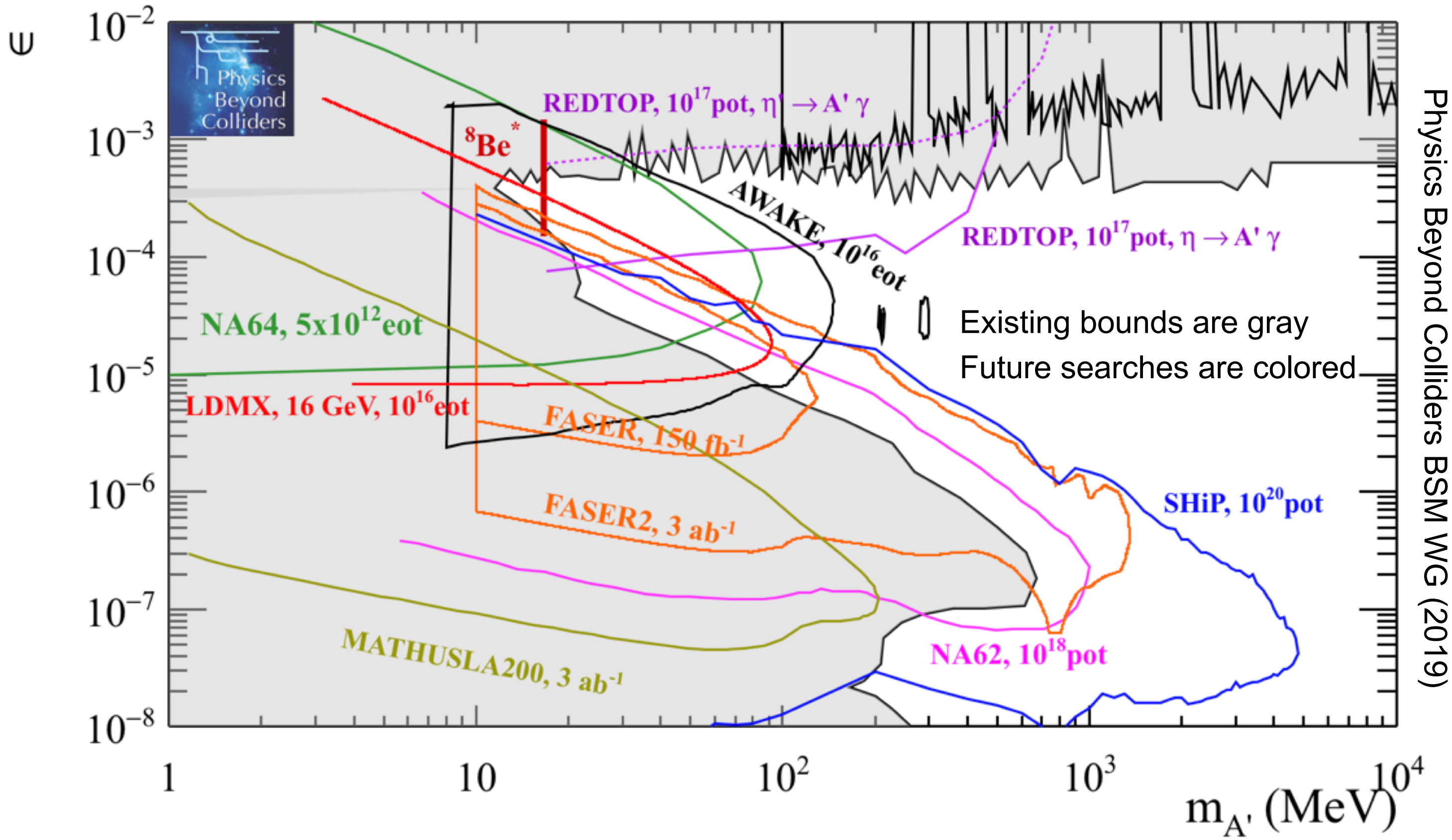
EXISTING CONSTRAINTS ON DARK PHOTONS

- For high ε, constraints are from bump hunts. These fail when ε becomes too small and the production rate is low, but they exclude ε above 10^{-3}.
- For low ε, constraints are from beam dump experiments. These fail when ε becomes too high and the decays are too short.



FUTURE PROBES OF DARK PHOTONS

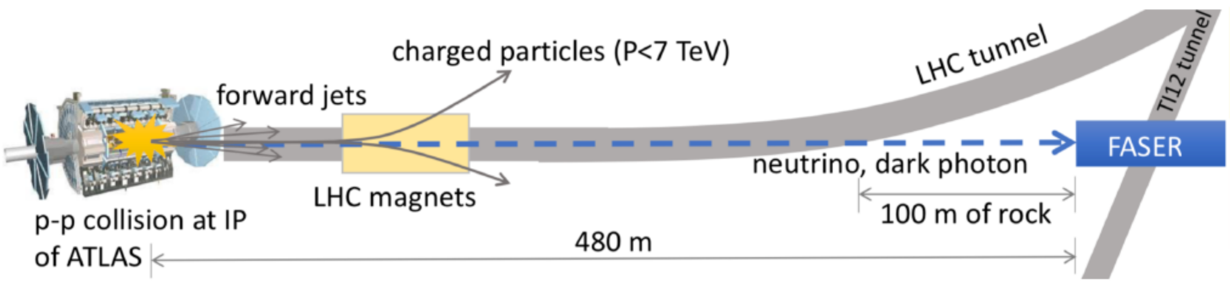
- Many improved bump hunts (e.g., Belle II) and beam dumps (e.g., NA62, DarkQuest, SHiP).
- Also new qualitatively different proposals: REDTOP, proposed for CERN PS, probing rare decays of $\eta, \eta \rightarrow \gamma\ (A' \rightarrow e^+e^-)$; and FASER, located in the far-forward region of ATLAS at the LHC.



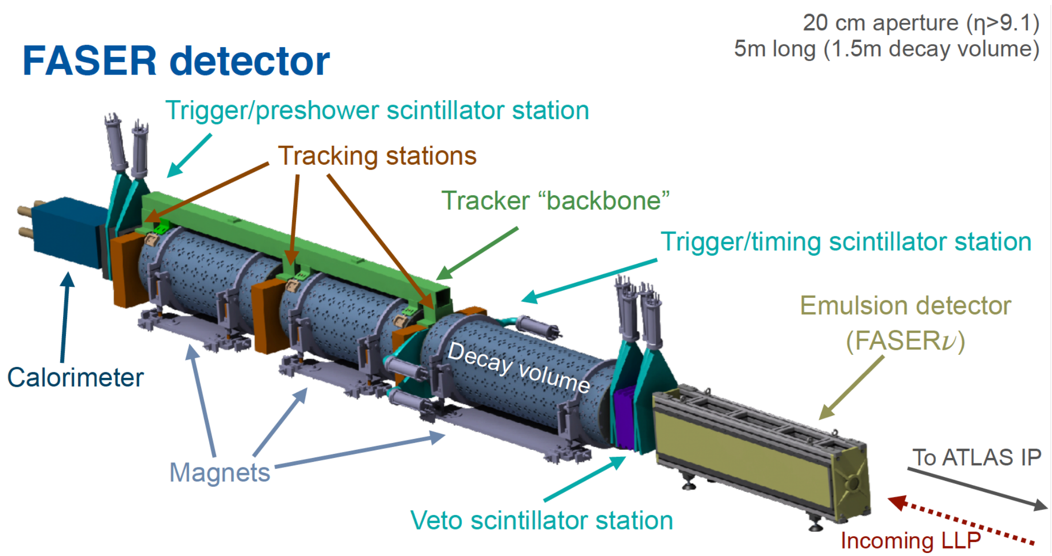
FASER @ CERN

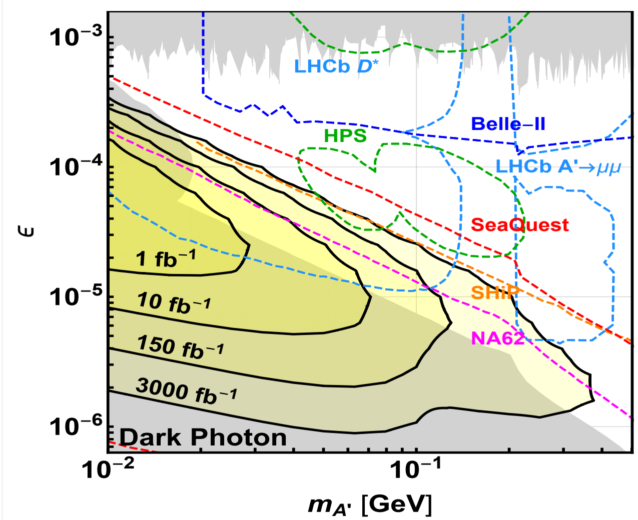
- Located in a side tunnel off the LHC beamline 480 m from ATLAS, currently under construction to begin in LHC Run 3 from 2021-24.

ForwArd Search ExpeRiment



Will probe new parameter space with just 1 fb^{-1} of data in Run 3, test the ^{8}Be anomaly.



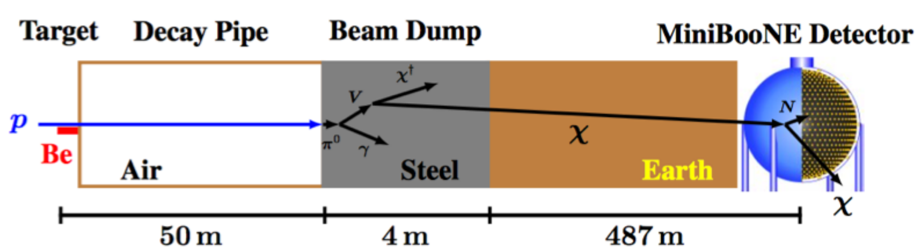


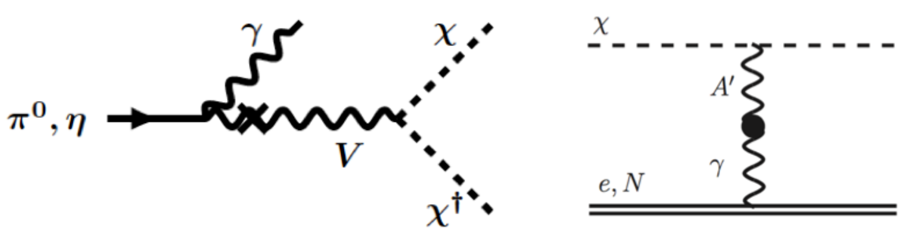
Michaela Queitsch-Maitland, ICHEP (2020)

INVISIBLY DECAYING DARK PHOTONS

- If $m_{LLP} > 2m_{DM}$, the LLP will typically decay into the dark sector, presumably to DM, leading to invisible decays.
- Can look for look for the resulting DM to scatter, much like one would look for neutrino production and scattering.

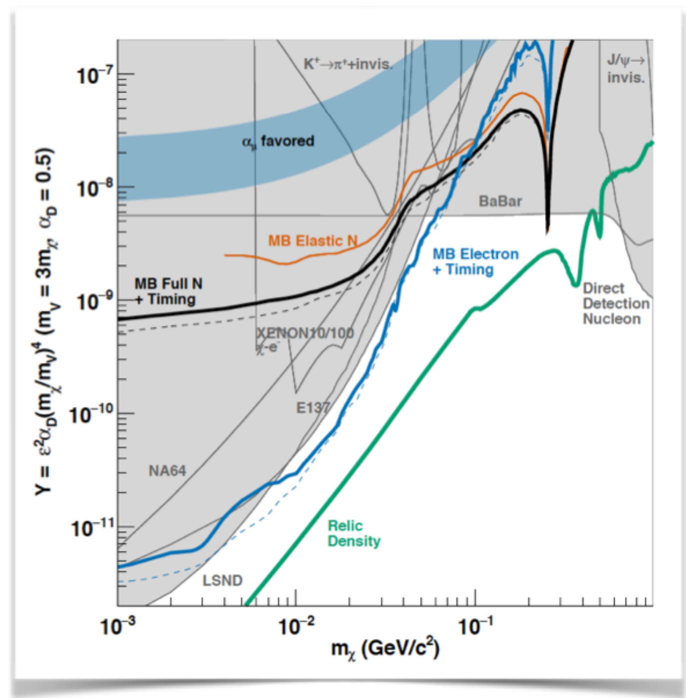
MiniBooNE-DM @ FNAL





DM production

DM scattering

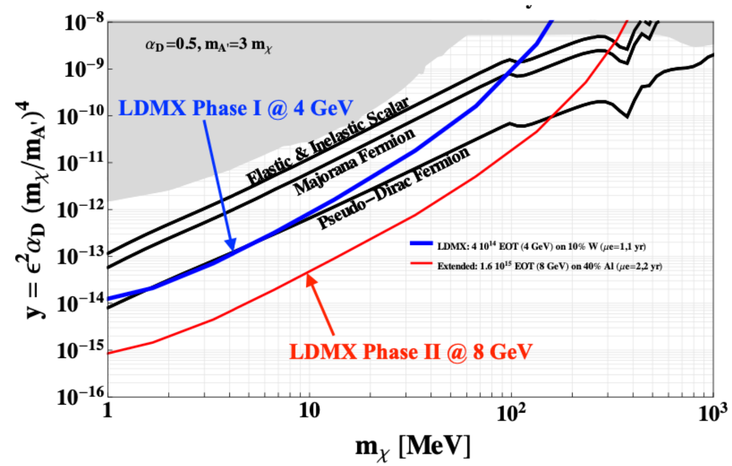


Brian Batell, Snowmass RP6 (2020)

[Aguilar-Arevalo et al. (MiniBooNE-DM) '18]

LDMX @ SLAC

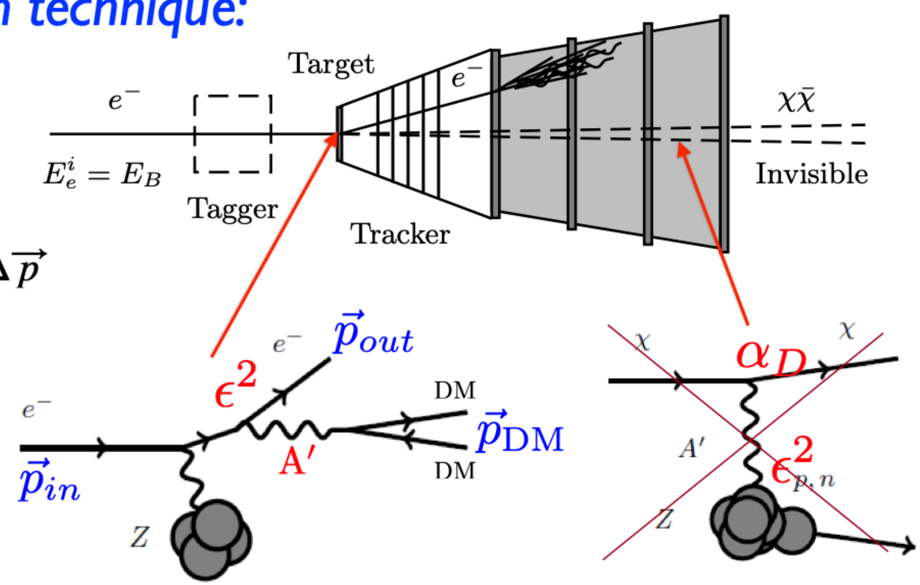
- Alternatively, can look for missing energy or momentum. Without having to see the DM scattering, can probe deep into parameter space, cover the typical thermal relic region.



Missing energy/momentum technique:

- one electron at a time, to uniquely associate e^-_{out} with e^-_{in} (only electrons are clean enough)
- look for events with large ΔE or $\Delta \vec{p}$
- no other products of reaction (something invisible produced)

$$N \propto \epsilon^2$$



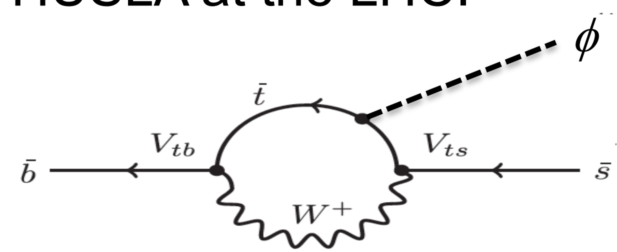
$$\vec{p}_{\rm in} = \vec{p}_{\rm out} + \vec{p}_{\rm DM}$$

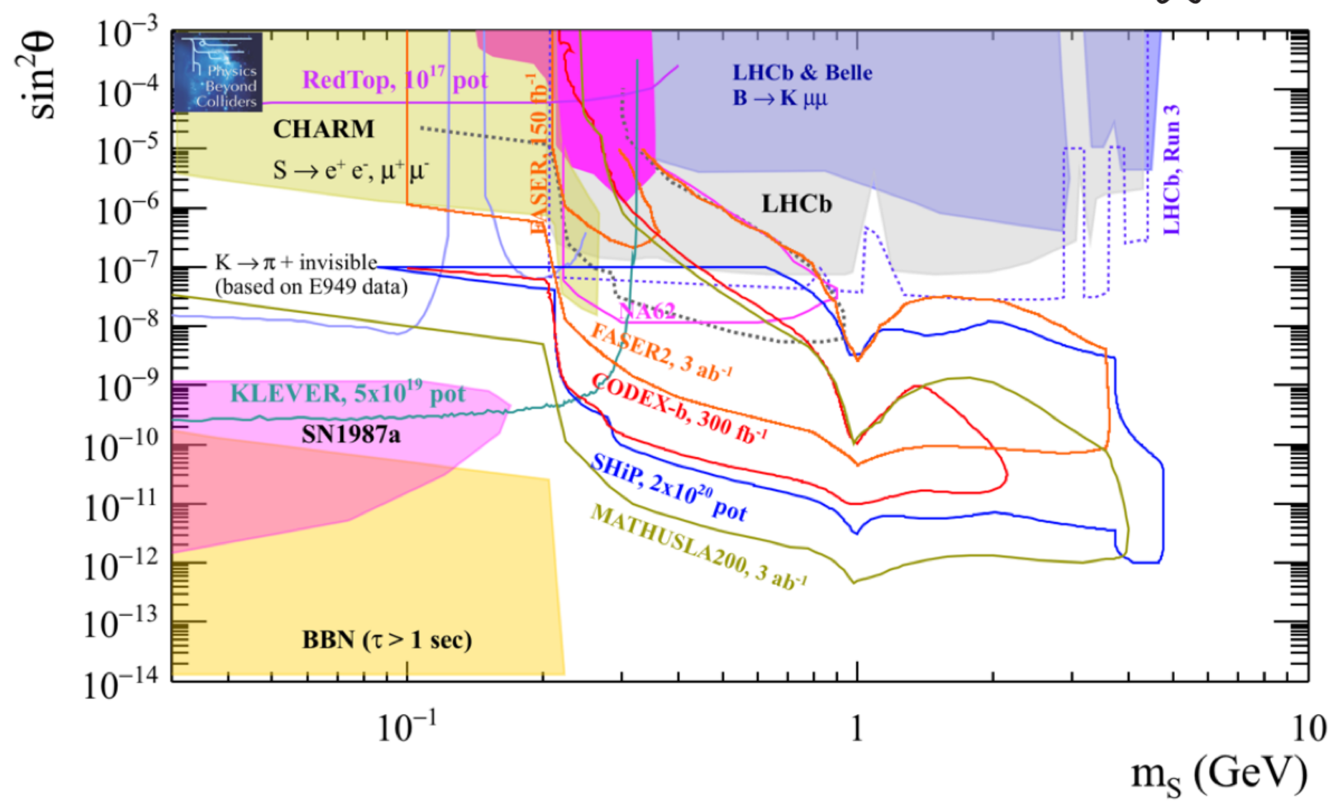
Tim Nelson, Snowmass RP6 (2020)

DARK HIGGS BOSONS

- Dark Higgs boson couplings are proportional to Yukawa couplings. Best probes are from decays of B mesons, produced in very high energy collisions: e.g., FASER, Codex-b, and MATHUSLA at the LHC.

$$B(B \to \phi) \gg B(K \to \phi) \gg B(\eta, \pi \to \phi)$$



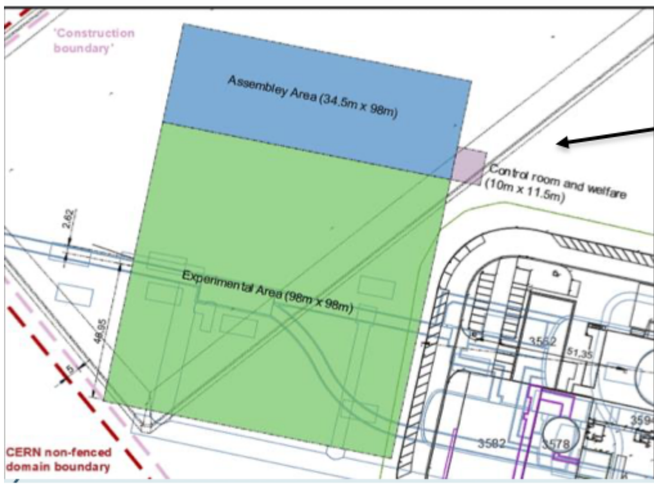


Physics Beyond Colliders BSM WG (2019)

MATHUSLA @ CERN

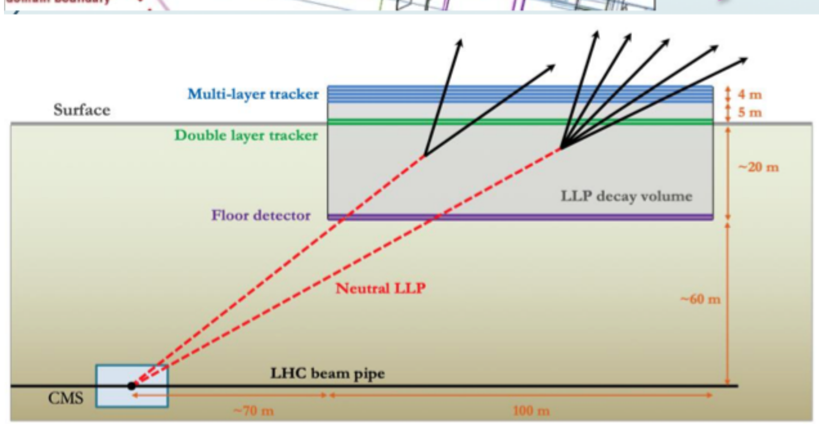
- A large detector proposed for the surface near CMS at the LHC.

MATHUSLA at P5



Large area **surface** detector above CMS IP dedicated to detection of ultra long-lived particles - air decay volume with **tracking chambers.**

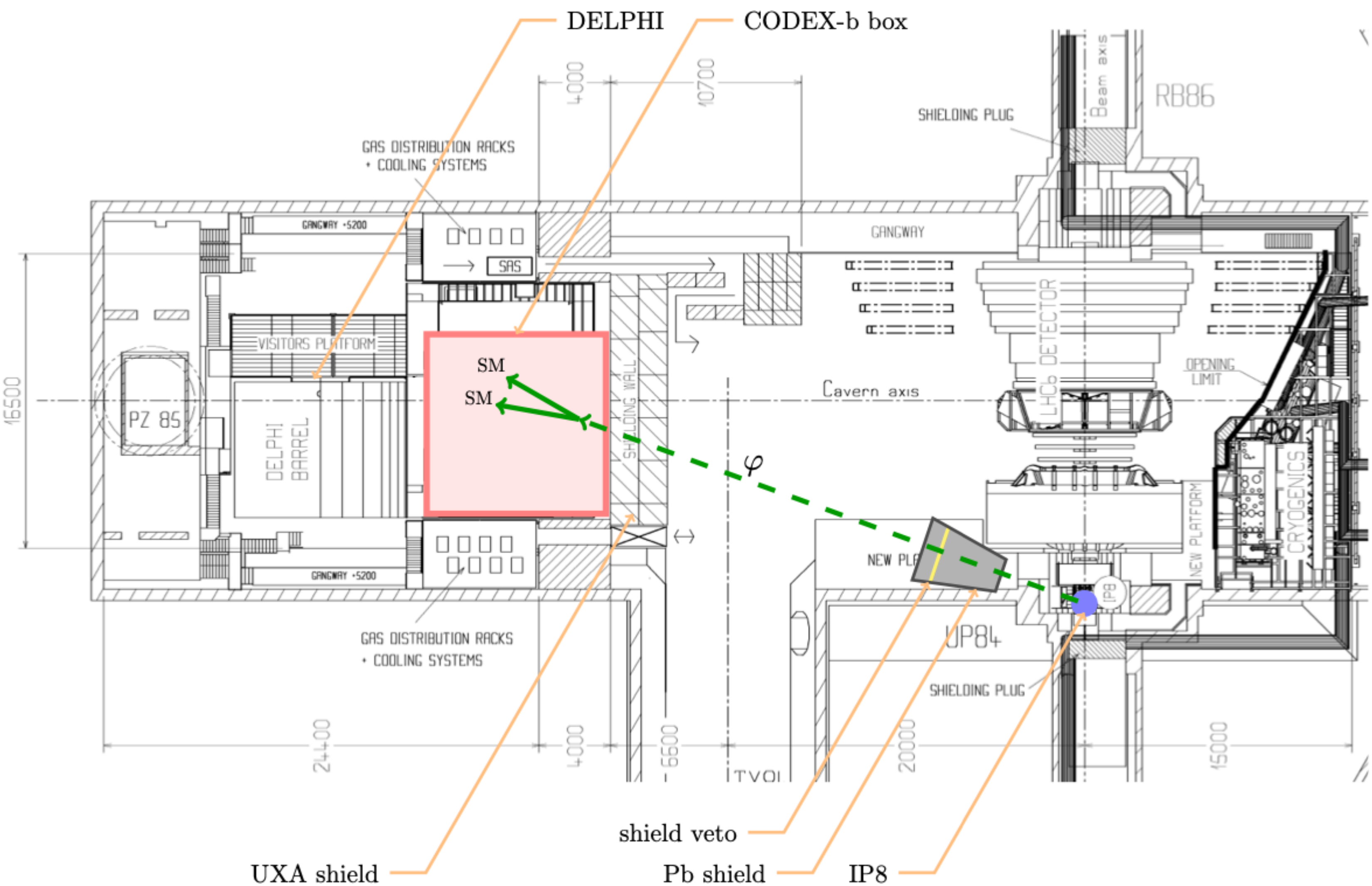
- ❑ Decay volume 100m²X25m
- ❑ Robust tracking and good background rejection - five tracking scintillator layers at top and two more ~ 5 m below top layers
- ❑ Two scintillator layer of floor detectors to reject cosmic ray inelastic backscattering, muon decays and interactions near the surface.
- ❑ Detector planes consist of extruded scintillators coupled to SiPMs - provides good time/space resolution needed for cosmic ray rejection and vertex reconstruction.
- ❑ Cosmic ray rate ~ 1.7 MHz
- ❑ Test installed at P1 above ATLAS to understand muon rate from LHC pp collisions and cosmic ray backgrounds that result in upward going tracks (inelastic backscattering and muon decays) – arXiv:2005.02018



Henry Lubatti, Snowmass LLP (2020)

CODEX-B @ CERN

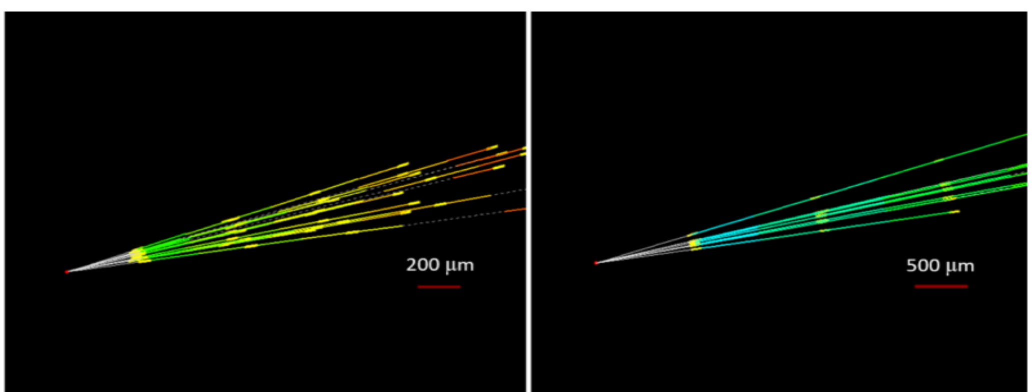
- A large detector proposed for the surface near CMS at the LHC.



Simon Knapen, Snowmass LLP (2020)

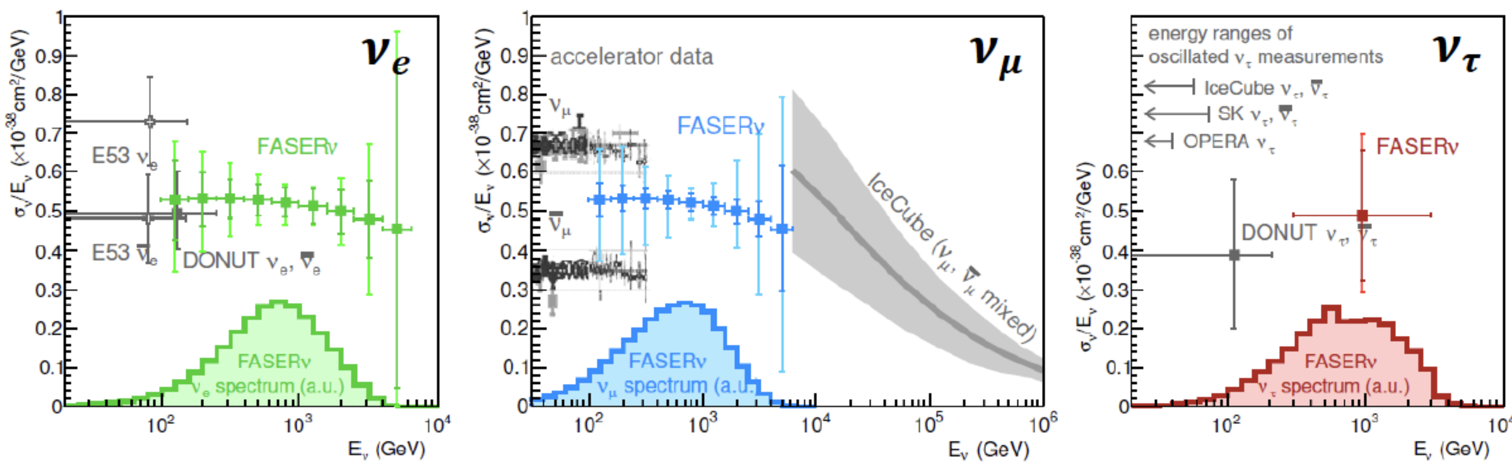
NEUTRINOS AT COLLIDERS

- An “almost invisibles” success story, currently in progress.
- No collider neutrino has ever been detected.
- 1984: de Rujula and Ruckl: to detect neutrinos, look in the forward direction: high energy, high cross section.
- 2018: FASER pilot ~30 kg emulsion detectors were placed on the beam collision axis and collected 12.5 fb^{-1} of data in 6 weeks.
- 2020: Expect ~10 neutrino interactions. Several neutral vertices identified, likely to be neutrinos. Analysis ongoing, expected in coming months.



NEUTRINOS AT COLLIDERS

- 2021-24: FASERν will collect data with 1.3 ton tungsten/emulsion in Run 3
  - Detect ~1000 ν_e, ~10,000 ν_μ, and ~10 ν_τ.
  - Probe neutrino properties at energies E_ν ~ TeV, first direct exploration of this energy range for all 3 flavors.



FASER Collaboration 1908.02310 (2019)

- 2027-36: With Forward Physics Facility, can upgrade to ~10 tons in HL-LHC
  - Detect ~100,000 ν_e, ~1,000,000 ν_μ, and ~1000 ν_τ at TeV energies.
  - Study production, propagation, and interactions for all 3 ν flavors, lepton universality, ν oscillations, ν_τ magnetic moment, NSI, neutrino tridents, …
  - This will open up a new world of TeV neutrino physics at colliders.

III. SUMMARY

- Dark sectors open up many new opportunities for probing new physics at accelerators.

- Most likely interactions of the standard model with the dark sector are through portal particles: dark photons, dark Higgs bosons, sterile neutrinos (heavy neutral leptons, dark fermions).

- In these models, there are enormous untouched regions of parameter space, all characterized by light, very weakly-interacting particles with long lifetimes.

- Many other candidates and many new experimental opportunities at both the intensity and energy frontiers. For more, see
  - US Cosmic Visions: New Ideas in Dark Matter [arxiv:1707.04591 hep-ph]
  - Physics Beyond Colliders at CERN: BSM Report [arxiv:1901.09966 hep-ex]
  - Snowmass RP6 Kickoff Meeting, [https://indico.fnal.gov/event/44819]