Motivation for Accelerator-Based Dark Sector Searches

Natalia Toro

Accelerator-based Dark Sector Searches Agora

April 22, 2022

Goals for This Talk

- What are dark sectors, and why are they exciting?
- Why are **small and multi-purpose Intensity Frontier* accelerator-based experiments** essential to confront this landscape?

*in a broad sense – e.g. including neutrino experiments, LHCb, Belle II, forward auxiliary detector proposals at LHC, …

What is a Dark Sector?

Simply:

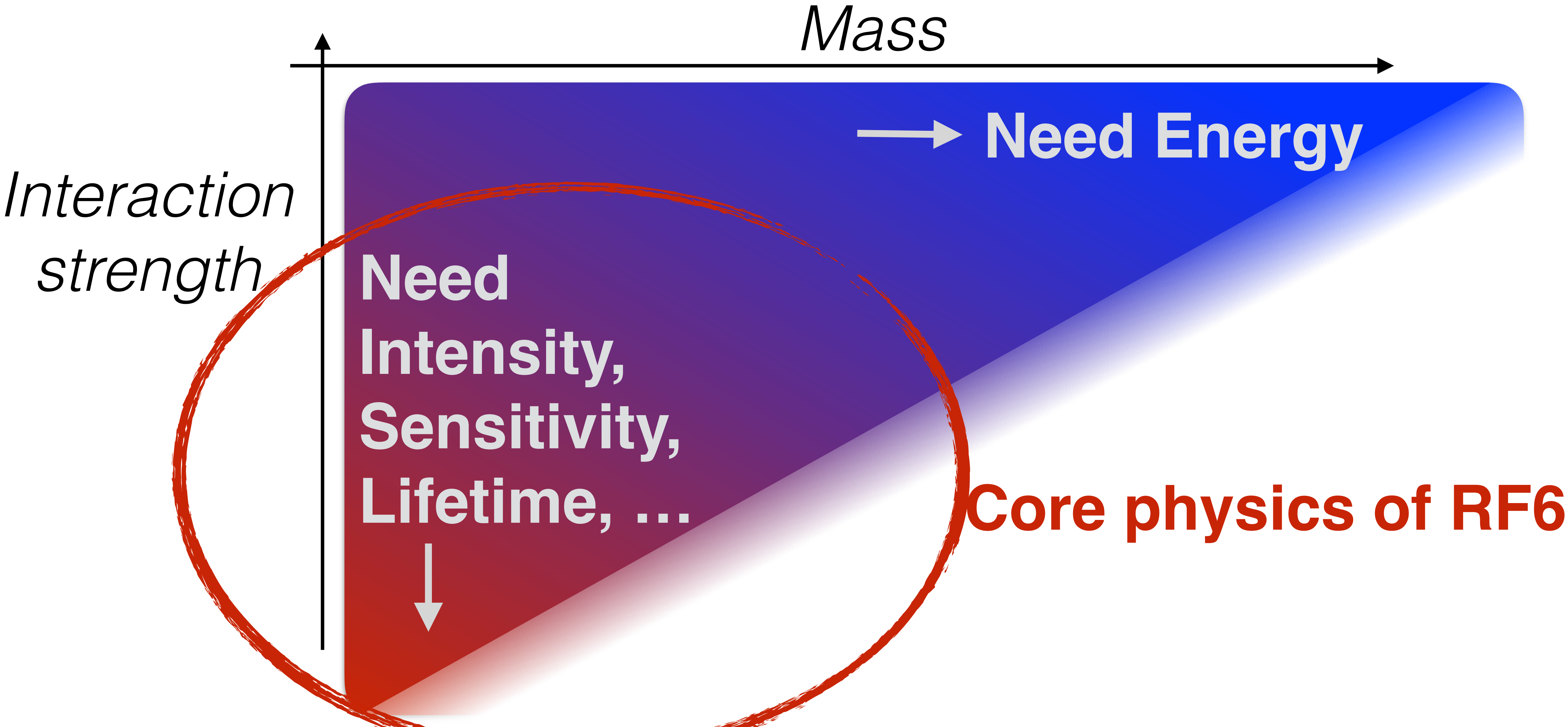
New physics neutral under Standard Model forces (EM, weak, strong)

Typically focus on **low mass scales** ($\lesssim$ GeV) where any new physics must be SM-neutral – hence a dark sector

What is a Dark Sector?

Simply:

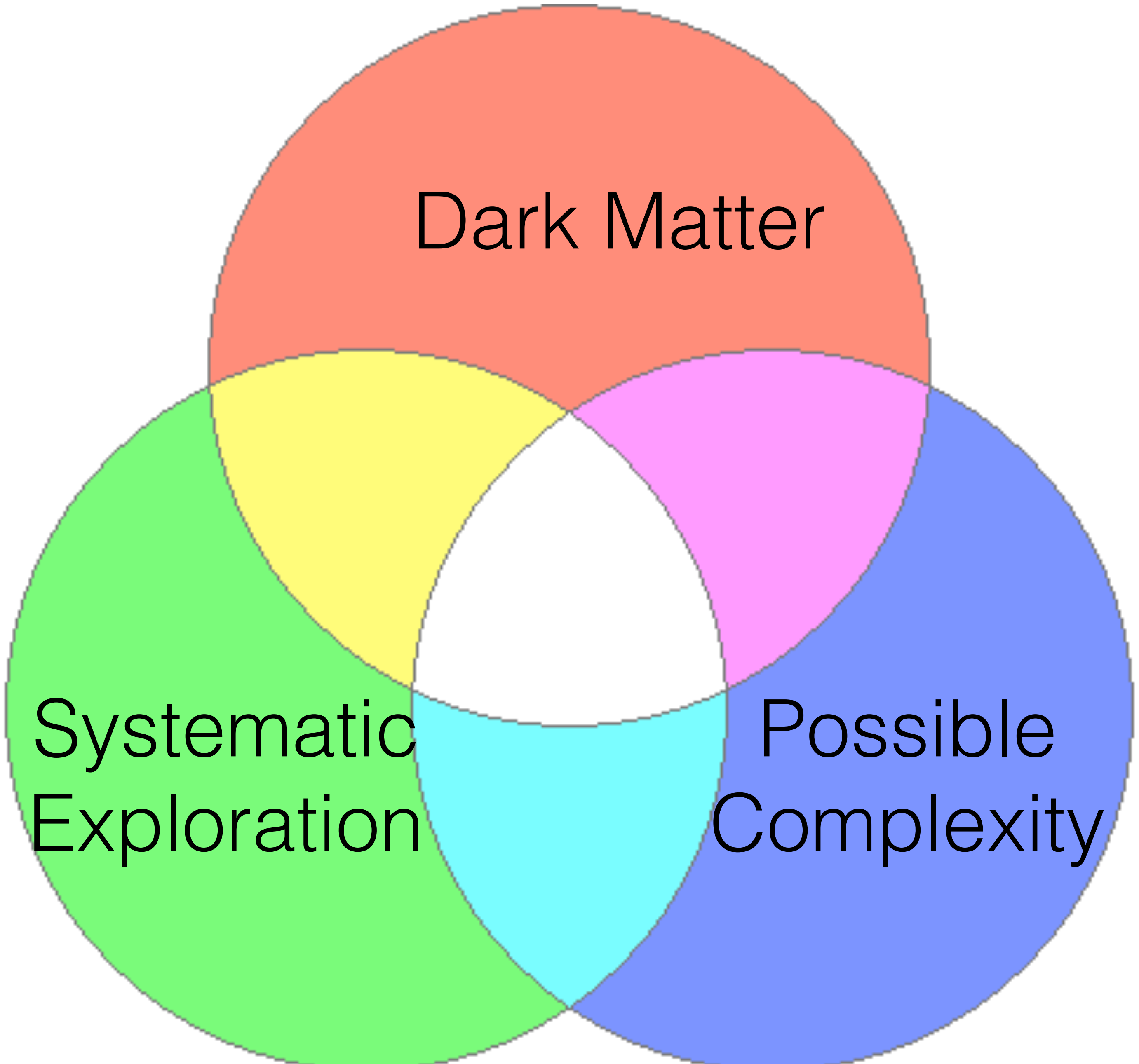
New physics neutral under Standard Model forces (EM, weak, strong)



Why Dark Sectors?

A rich new window for physics beyond the Standard Model and dark matter in particular

Three intertwined motivations – each shedding different light on searches and possible signals



Why Dark Sectors?

A rich new window for physics beyond the Standard Model, including dark matter

Three intertwined motivations:

- Viable, predictive, and discoverable models of light **dark matter** are a key motivation and anchor
- Symmetries of Standard Model provide a framework for **systematic exploration** of weakly-coupled new physics
- These arguments motivate possibility of **complexity in dark sector**, which we could discover experimentally

Dark Sectors <2020

- Many grassroots workshops since ~2009:
  - Dark Forces and Dark Sectors @ SLAC,
    Dark Interactions @ BNL, DM at Accelerators in Italy
- Significant momentum in last few years on community-wide planning in small experiments relevant to dark matter, including accelerator searches for dark sectors

:1707.04591v1 [hep-ph] 14 Jul 2017

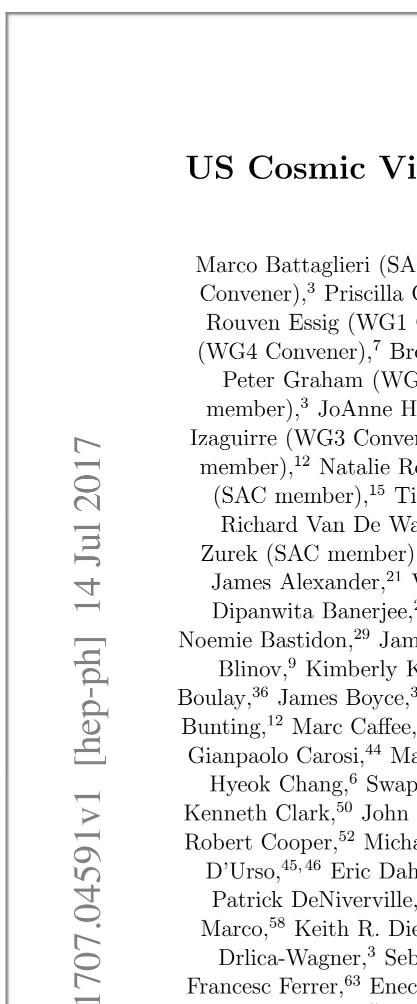
US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

Marco Battaglieri (SAC co-chair),[1] Alberto Belloni (Coordinator),[2] Aaron Chou (WG2 Convener),[3] Priscilla Cushman (Coordinator),[4] Bertrand Echenard (WG3 Convener),[5] Rouven Essig (WG1 Convener),[6] Juan Estrada (WG1 Convener),[3] Jonathan L. Feng (WG4 Convener),[7] Brenna Flaugher (Coordinator),[3] Patrick J. Fox (WG4 Convener),[3] Peter Graham (WG2 Convener),[8] Carter Hall (Coordinator),[2] Roni Harnik (SAC member),[3] JoAnne Hewett (Coordinator),[9,8] Joseph Incandela (Coordinator),[10] Eder Izaguirre (WG3 Convener),[11] Daniel McKinsey (WG1 Convener),[12] Matthew Pyle (SAC member),[12] Natalie Roe (Coordinator),[13] Gray Rybka (SAC member),[14] Pierre Sikivie (SAC member),[15] Tim M.P. Tait (SAC member),[7] Natalia Toro (SAC co-chair),[9,16] Richard Van De Water (SAC member),[17] Neal Weiner (SAC member),[18] Kathryn Zurek (SAC member),[13,12] Eric Adelberger,[14] Andrei Afanasev,[19] Derbin Alexander,[20] James Alexander,[21] Vasile Cristian Antochi,[22] David Mark Asner,[23] Howard Baer,[24] Dipanwita Banerjee,[25] Elisabetta Baracchini,[26] Phillip Barbeau,[27] Joshua Barrow,[28] Noemie Bastidon,[29] James Battat,[30] Stephen Benson,[31] Asher Berlin,[9] Mark Bird,[32] Nikita Blinov,[9] Kimberly K. Boddy,[33] Mariangela Bondì,[34] Walter M. Bonivento,[35] Mark Boulay,[36] James Boyce,[37,31] Maxime Brodeur,[38] Leah Broussard,[39] Ranny Budnik,[40] Philip Bunting,[12] Marc Caffee,[41] Sabato Stefano Caiazza,[42] Sheldon Campbell,[7] Tongtong Cao,[43] Gianpaolo Carosi,[44] Massimo Carpinelli,[45,46] Gianluca Cavoto,[22] Andrea Celentano,[1] Jae Hyeok Chang,[6] Swapan Chattopadhyay,[3,47] Alvaro Chavarria,[48] Chien-Yi Chen,[49,16] Kenneth Clark,[50] John Clarke,[12] Owen Colegrove,[10] Jonathon Coleman,[51] David Cooke,[25] Robert Cooper,[52] Michael Crisler,[23,3] Paolo Crivelli,[25] Francesco D'Eramo,[53,54] Domenico D'Urso,[45,46] Eric Dahl,[29] William Dawson,[44] Marzio De Napoli,[34] Raffaella De Vita,[1] Patrick DeNiverville,[55] Stephen Derenzo,[13] Antonia Di Crescenzo,[56,57] Emanuele Di Marco,[58] Keith R. Dienes,[59,2] Milind Diwan,[11] Dongwi Handiipondola Dongwi,[43] Alex Drlica-Wagner,[3] Sebastian Ellis,[60] Anthony Chigbo Ezeribe,[61,62] Glennys Farrar,[18] Francesc Ferrer,[63] Enectali Figueroa-Feliciano,[64] Alessandra Filippi,[65] Giuliana Fiorillo,[66]

Cosmic Visons community workshop 2017 (~mini-Snowmass)

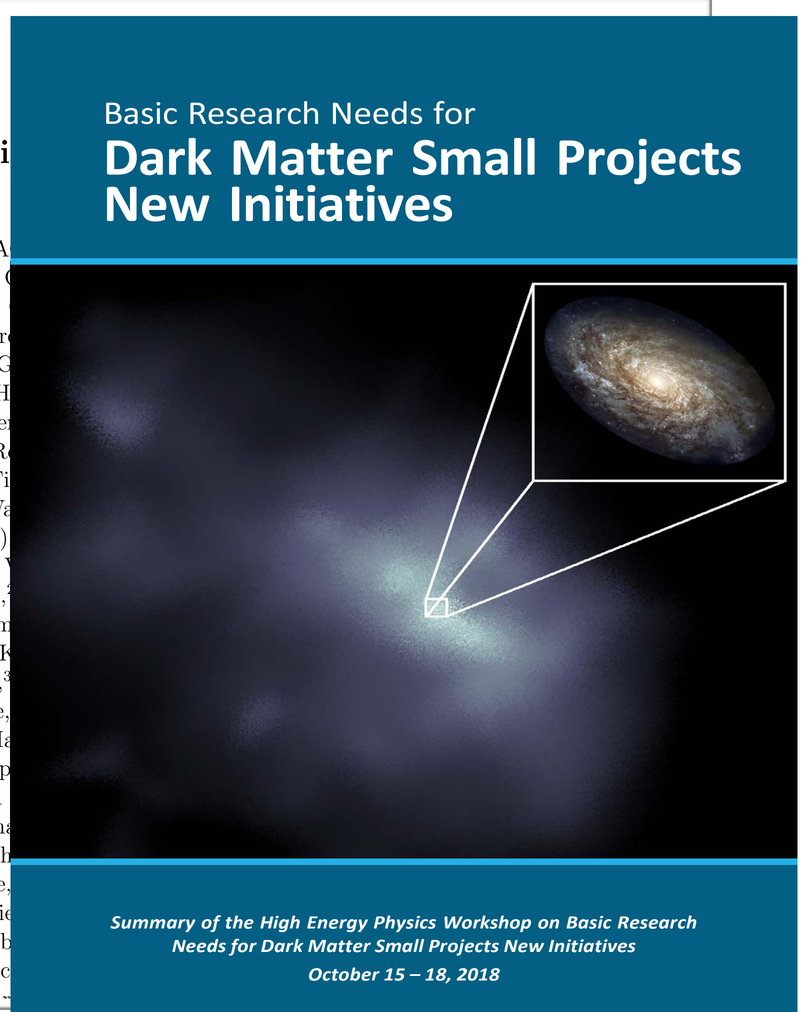
Dark Sectors <2020

- Many grassroots workshops since ~2009:
  - Dark Forces and Dark Sectors @ SLAC,
    Dark Interactions @ BNL, DM at Accelerators in Italy
- Significant momentum in last few years on community-wide planning in small experiments relevant to dark matter, including accelerator searches for dark sectors


US Cosmic Vi

Marco Battaglieri (SA
Convener),[3] Priscilla C
Rouven Essig (WG1
(WG4 Convener),[7] Br
Peter Graham (WG
member),[3] JoAnne H
Izaguirre (WG3 Conve
member),[12] Natalie R
(SAC member),[15] Ti
Richard Van De Wa
Zurek (SAC member)
James Alexander,[21]
Dipanwita Banerjee,
Noemie Bastidon,[29] Jam
Blinov,[9] Kimberly K
Boulay,[36] James Boyce,
Bunting,[12] Marc Caffee,
Gianpaolo Carosi,[44] M
Hyeok Chang,[6] Swap
Kenneth Clark,[50] John
Robert Cooper,[52] Mich
D'Urso,[45,46] Eric Dah
Patrick DeNiverville,
Marco,[58] Keith R. Di
Drlica-Wagner,[3] Seb
Francesc Ferrer,[63] Enec

:1707.04591v1 [hep-ph] 14 Jul 2017



Cosmic Visons community workshop 2017 (~mini-Snowmass)

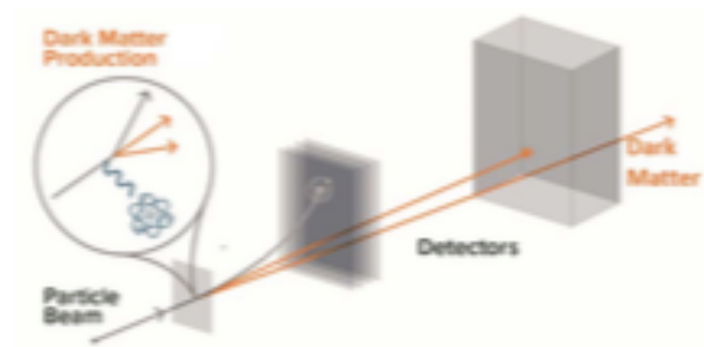
Basic Research Needs (BRN) workshop 2018: *non-FACA* panels charged by DOE with identifying priority **science** in Dark Matter scope, achievable with small US-based experiments

BRN Priority Research Directions

Summary of the High Energy Physics Workshop on Basic Research Needs for Dark Matter Small Projects New Initiatives
October 15 – 18, 2018

PRD 1

Create & Detect Dark-Matter Particles at Accelerators

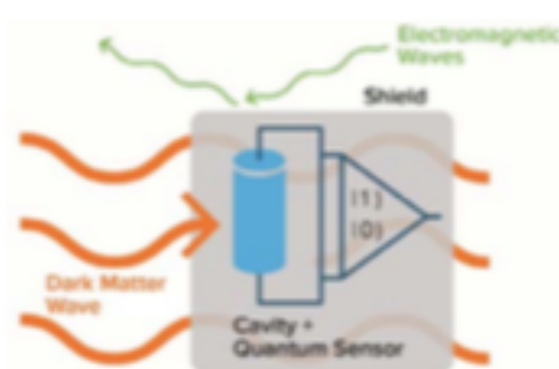


PRD 2

Detect Galactic Particle Dark Matter Underground

PRD 3

Detect Galactic Wave Dark Matter in the Laboratory



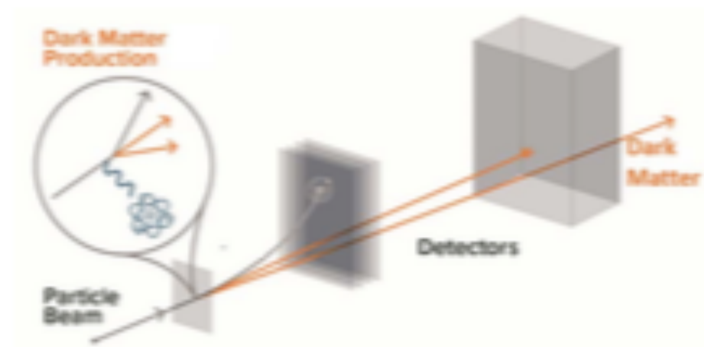
Success!
Experiments in all 3 PRDs received planning funds through 2019 FOA

BRN Priority Research Directions

Summary of the High Energy Physics Workshop on Basic Research Needs for Dark Matter Small Projects New Initiatives
October 15 – 18, 2018

PRD 1

Create & Detect Dark-Matter Particles at Accelerators

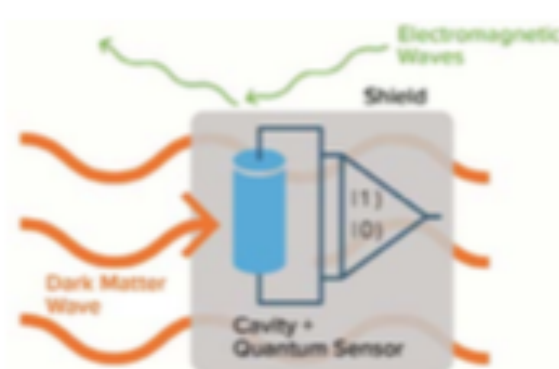


PRD 2

Detect Galactic Particle Dark Matter Underground

PRD 3

Detect Galactic Wave Dark Matter in the Laboratory



Success!
Experiments in all 3 PRDs received planning funds through 2019 FOA

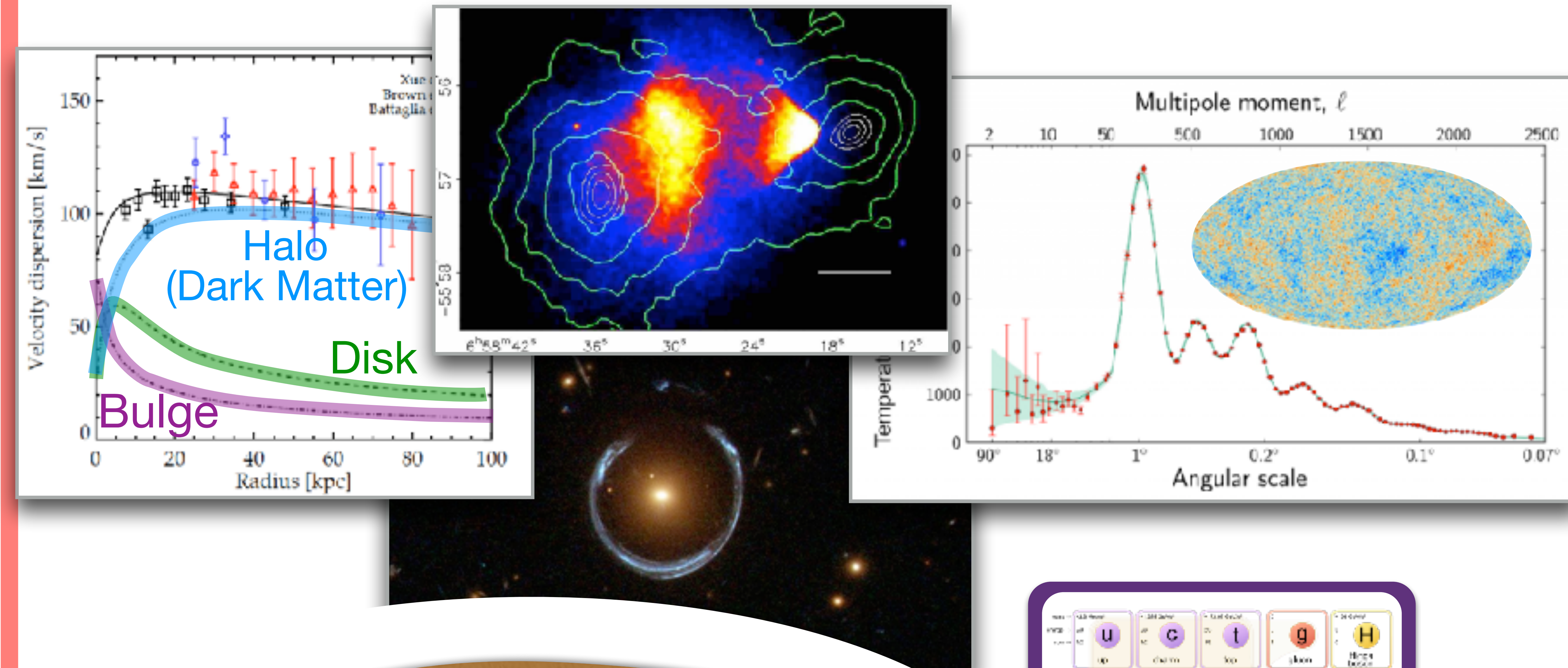
Thrust 1 (near term): Through 10- to 1000-fold improvements in sensitivity over current searches, use particle beams to explore interaction strengths singled out by thermal dark matter across the electron-to-proton mass range.

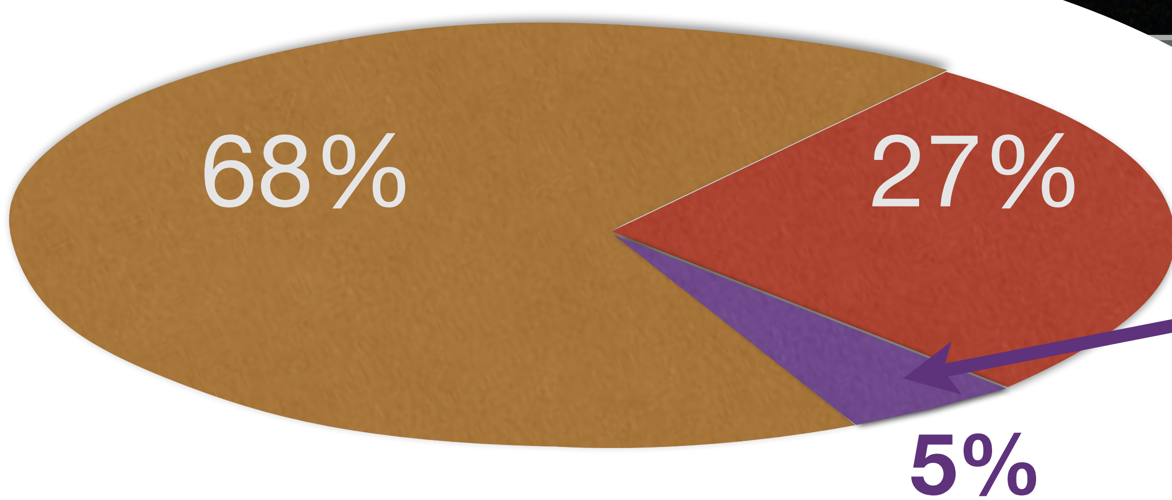
CCM, LDMX

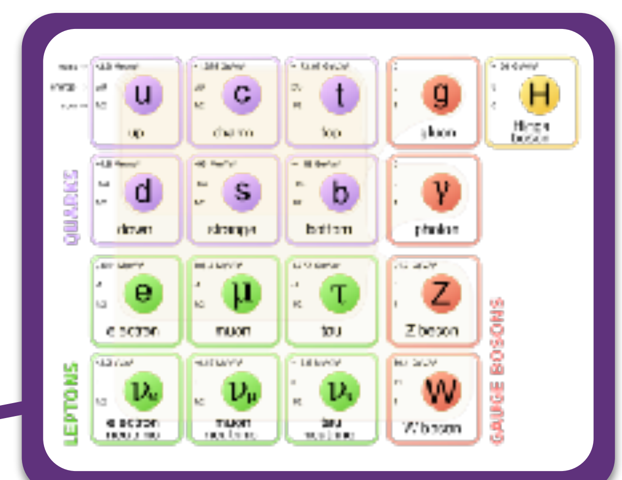
Thrust 2 (near and long term): Explore the structure of the dark sector by producing and detecting unstable dark particles.

non-DMNI funding

The Balance of the Universe

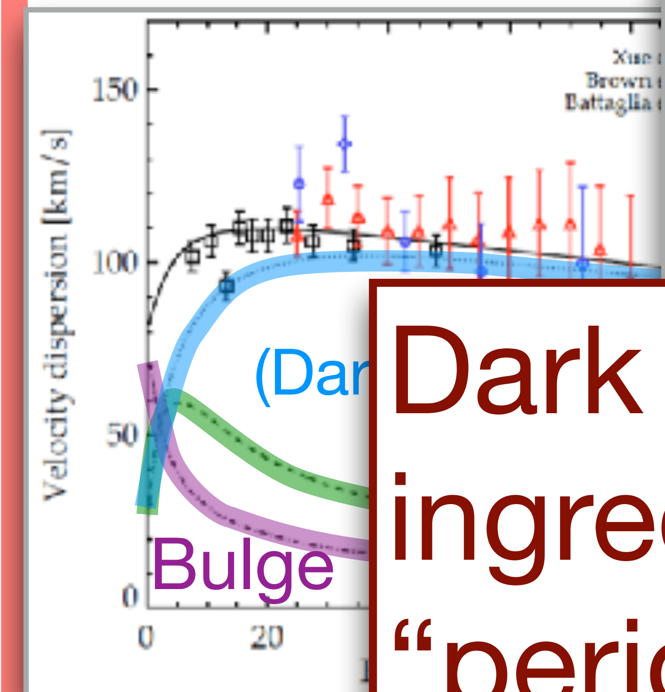


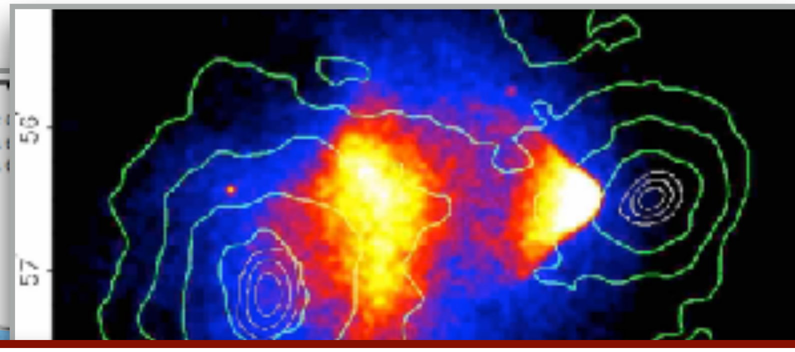


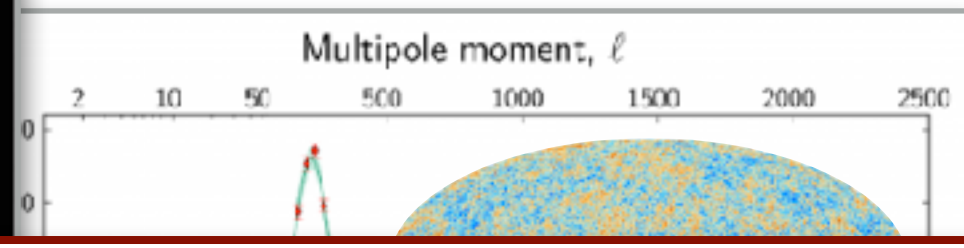


Known Matter
(the Standard Model)

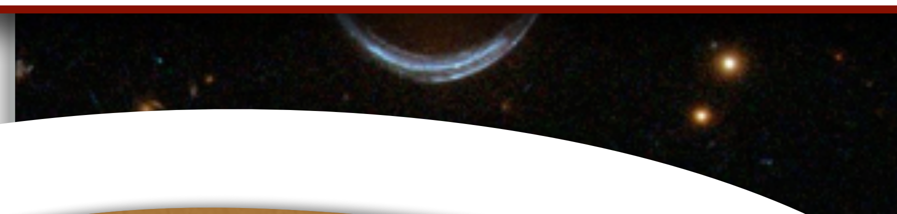
The Balance of the Universe

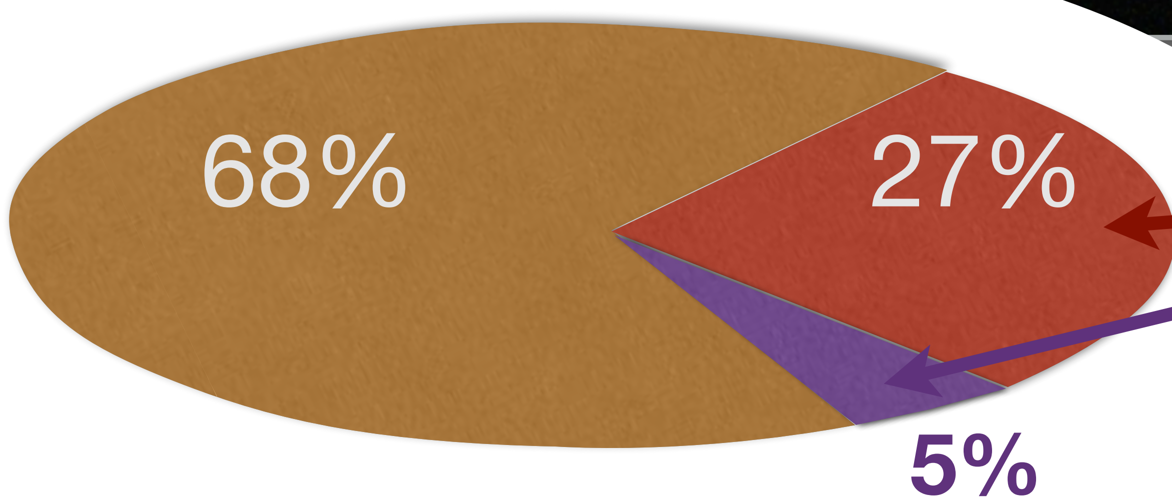


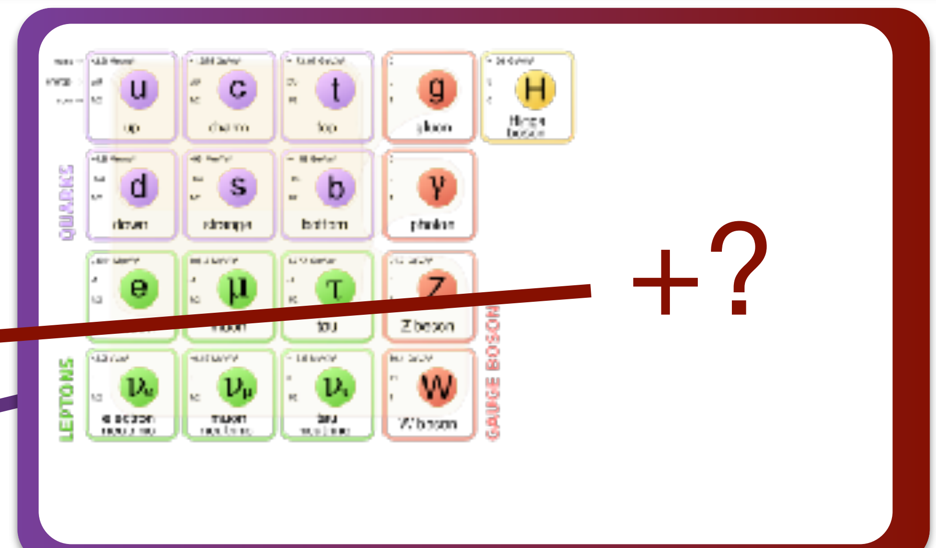




Dark Matter is made of unfamiliar ingredient(s) – must extend the "periodic table" of the Standard Model!







Dark Matter

Cosmological evidence → bulk properties of dark matter:

- mass density ρ_{DM}
- cosmological longevity $\tau_{DM} \gtrsim 10^{18}$ s
- low pressure $p_{DM} \ll \rho_{DM}$
- decoupled from baryonic plasma before recombination
- …

These imply **bounds** on particle properties, but not **measurements**… and direct searches to date just strengthen these bounds

Dark Matter Particle Properties

Constituent Mass?

10^{-22} eV ⟷ 10^{19} eV

Non-gravitational interactions?

Boson or Fermion?

Conserved charge?

Dark Matter Particle Properties

Bulk properties can inform guesses

Constituent Mass?

10^{-22} eV ⟷ 10^{19} eV

Non-gravitational interactions?

Boson or Fermion?

Conserved charge?

Dark Matter Particle Properties

Bulk properties can inform guesses

Constituent Mass?

10^{-22} eV ⟷ 10^{19} eV

Non-gravitational interactions?

Boson or Fermion?

Conserved charge?

Yes? (it's cosmologically stable)

Dark Matter Particle Properties

Bulk properties can inform guesses

Constituent Mass?

10^{-22} eV ⟷ 10^{19} eV

Non-gravitational interactions?

Yes? (to explain how it got here)

Boson or Fermion?

Conserved charge?

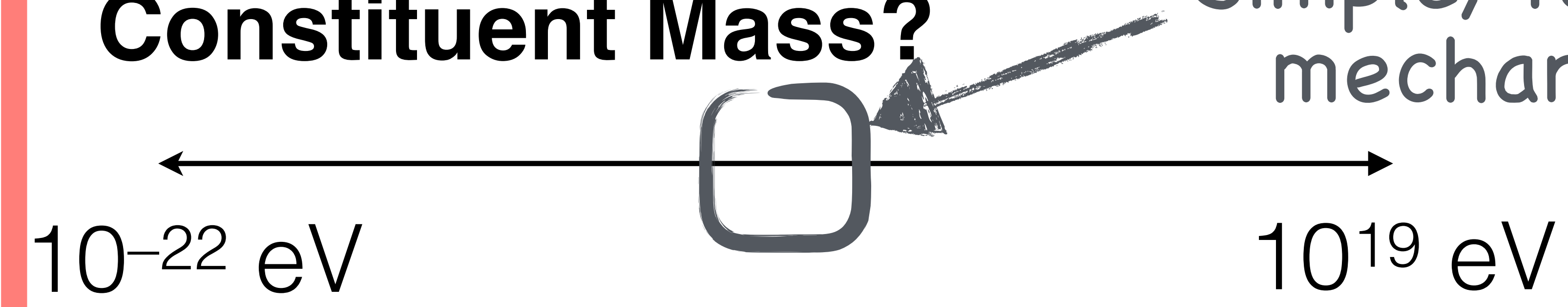
Yes? (it's cosmologically stable)

Dark Matter Particle Properties

Bulk properties can inform guesses

Constituent Mass?

Simple, familiar production mechanisms work here



Non-gravitational interactions?

Yes? (to explain how it got here)

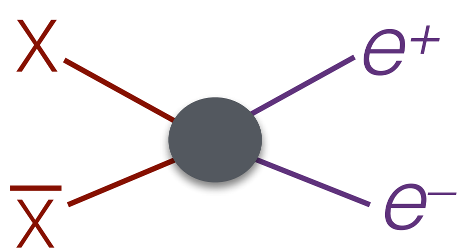
Boson or Fermion?

Conserved charge?

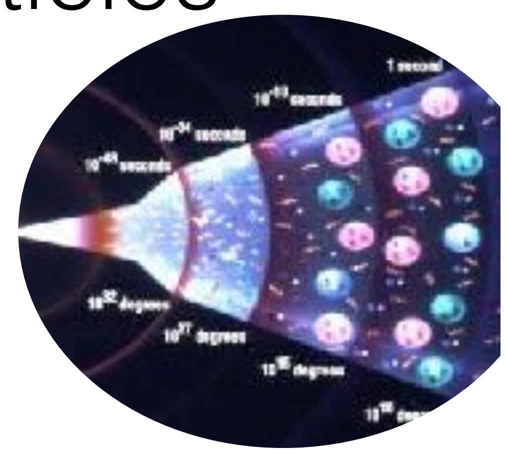
Yes? (it's cosmologically stable)

Thermal Freeze-Out

- Simple explanation of DM origin from hot bath of Standard Model particles

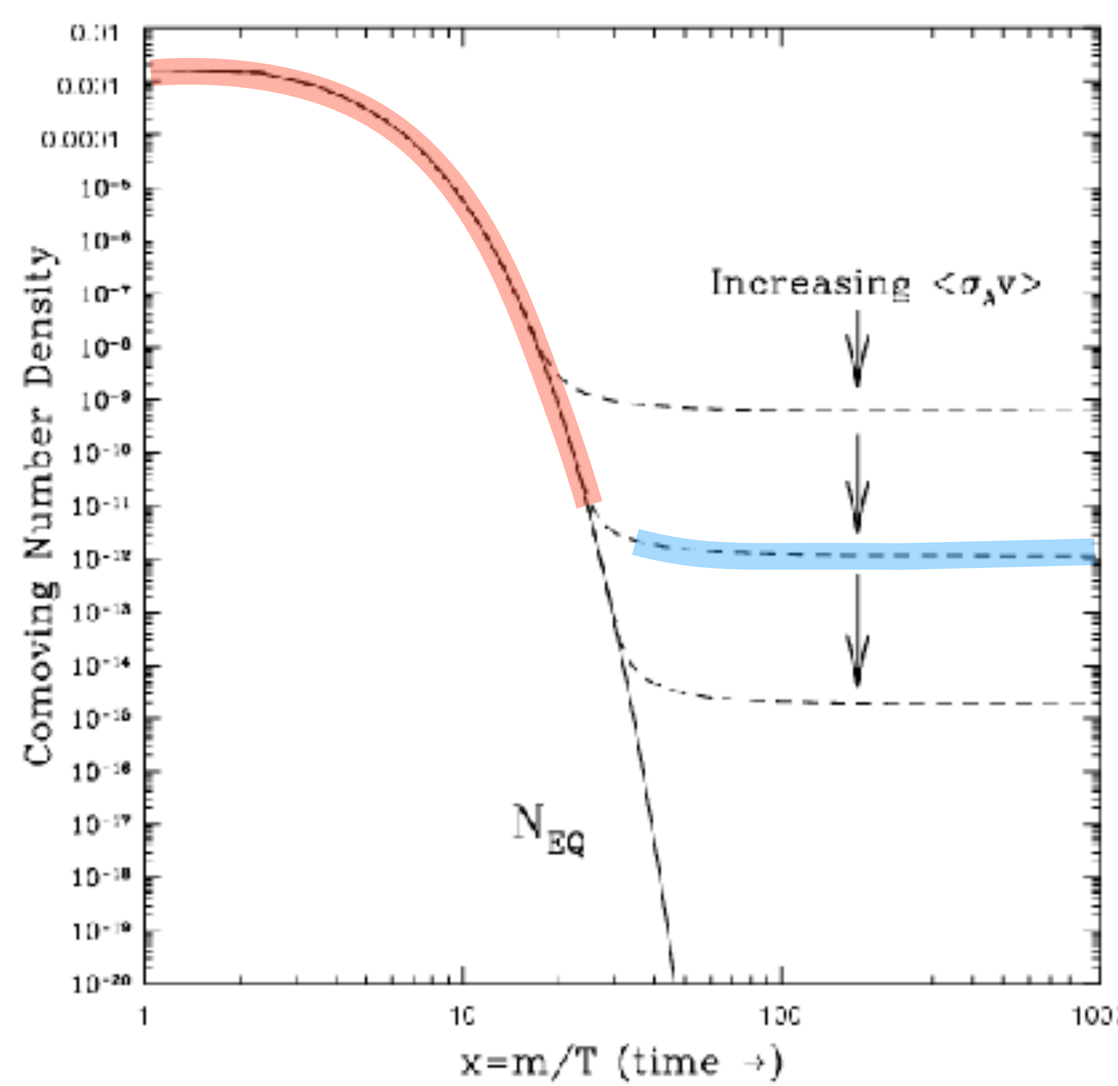


vs.



$\Gamma_A \sim n_{DM} \sigma_A v$

$\Gamma_{exp} \sim H$

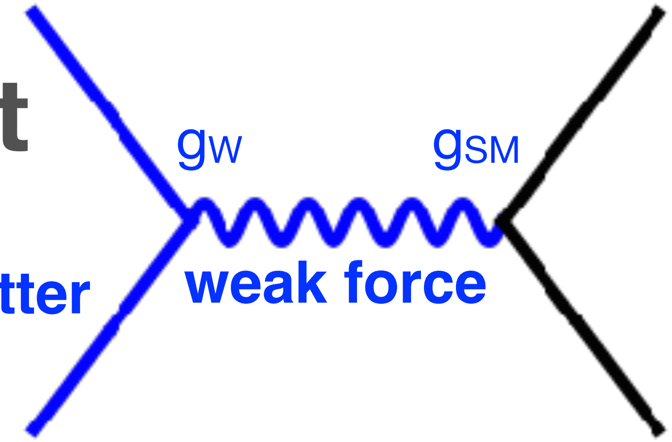


- Implies **close, direct, recent** contact between DM and SM

- Therefore, especially predictive: standard cosmology $+ \rho_{DM} \Rightarrow \sigma_A$

A Strong Candidate: The WIMP

Simple, familiar particle content



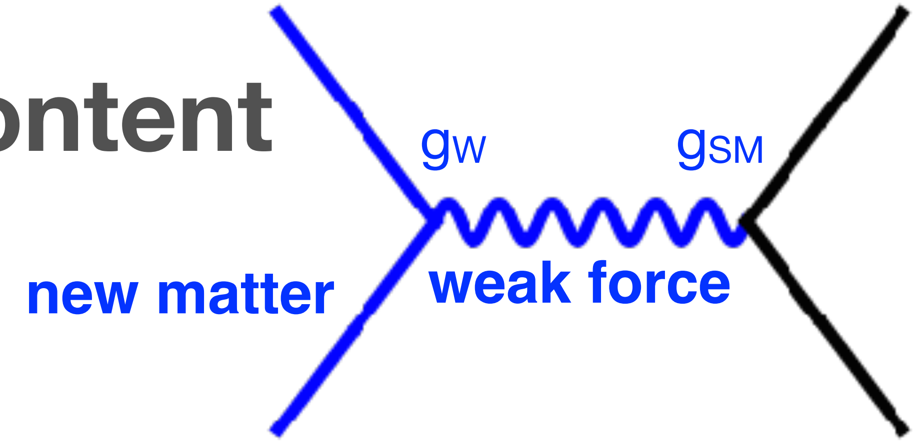
DM from a new row in Standard Model table

	$\mathbf{U}(1)_Y$	$SU(2)_L$	$SU(3)_C$
L	$-1/2$	$\mathbf{2}$	-
e^c	$+1$	-	-
Q	$+1/6$	$\mathbf{2}$	$\mathbf{3}$
u^c	$-2/3$	-	$\bar{\mathbf{3}}$
d^c	$+1/3$	-	$\bar{\mathbf{3}}$
h	-1/2	$\mathbf{2}$	-

Dark Matter | Systematic Exploration | Rich Possibilities

A Strong Candidate: The WIMP

Simple, familiar particle content



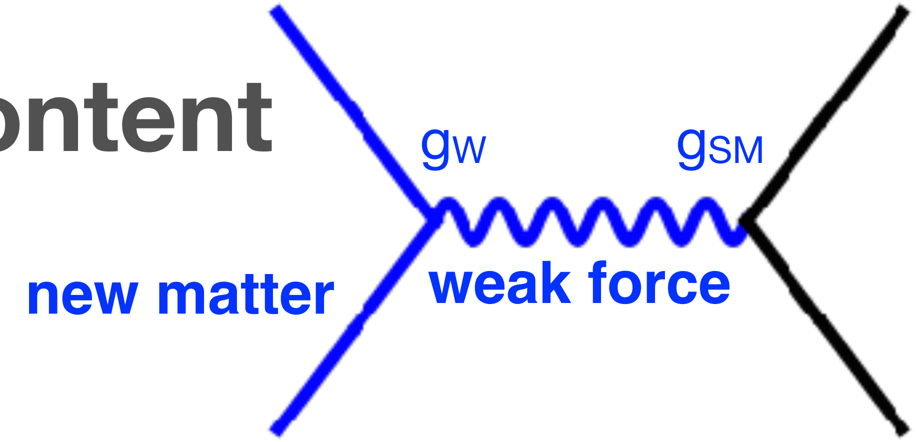
DM from a new row in Standard Model table

	$\mathbf{U}(1)_Y$	$SU(2)_L$	$SU(3)_C$
L	$-1/2$	$\mathbf{2}$	-
e^c	$+1$	-	-
Q	$+1/6$	$\mathbf{2}$	$\mathbf{3}$
u^c	$-2/3$	-	$\bar{\mathbf{3}}$
d^c	$+1/3$	-	$\bar{\mathbf{3}}$
h	-1/2	$\mathbf{2}$	-
WIMP	X	X	

EM-neutral component of new weak multiplet

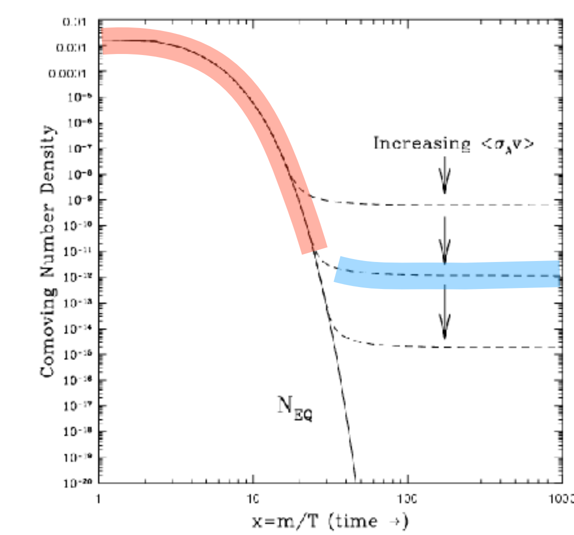
A Strong Candidate: The WIMP

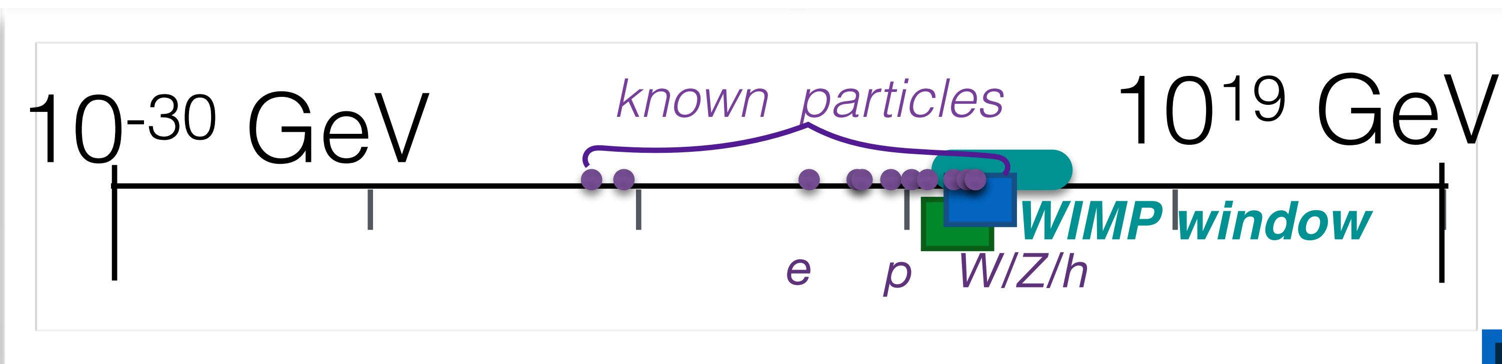
Simple, familiar particle content



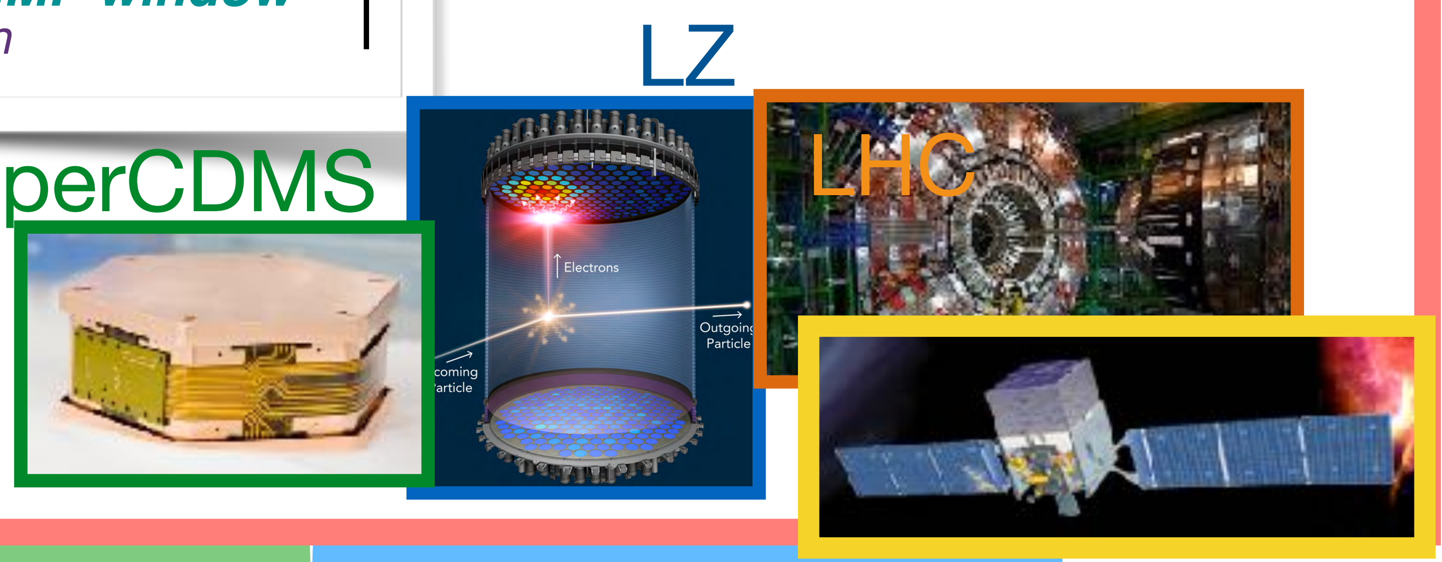
Simple, predictive cosmology

Weak-scale mass and coupling yield ballpark <σAv> matching abundance





Strong experimental program

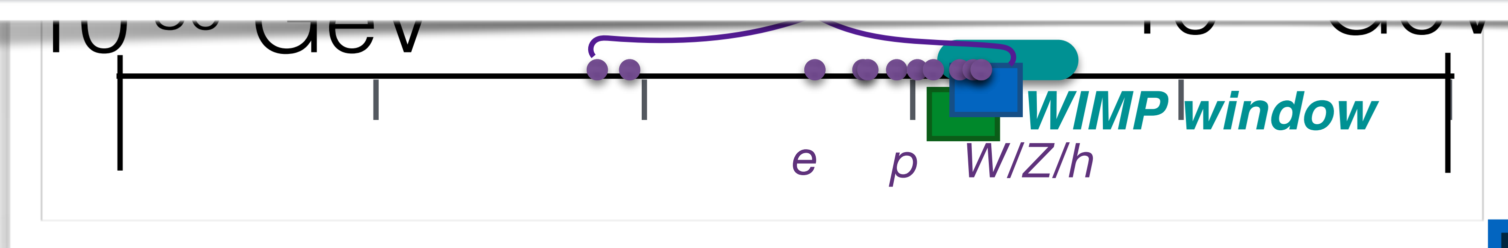


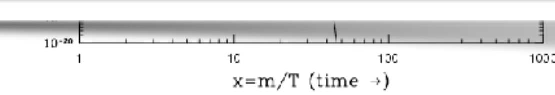
A Strong Candidate: The WIMP

Simple, familiar particle content

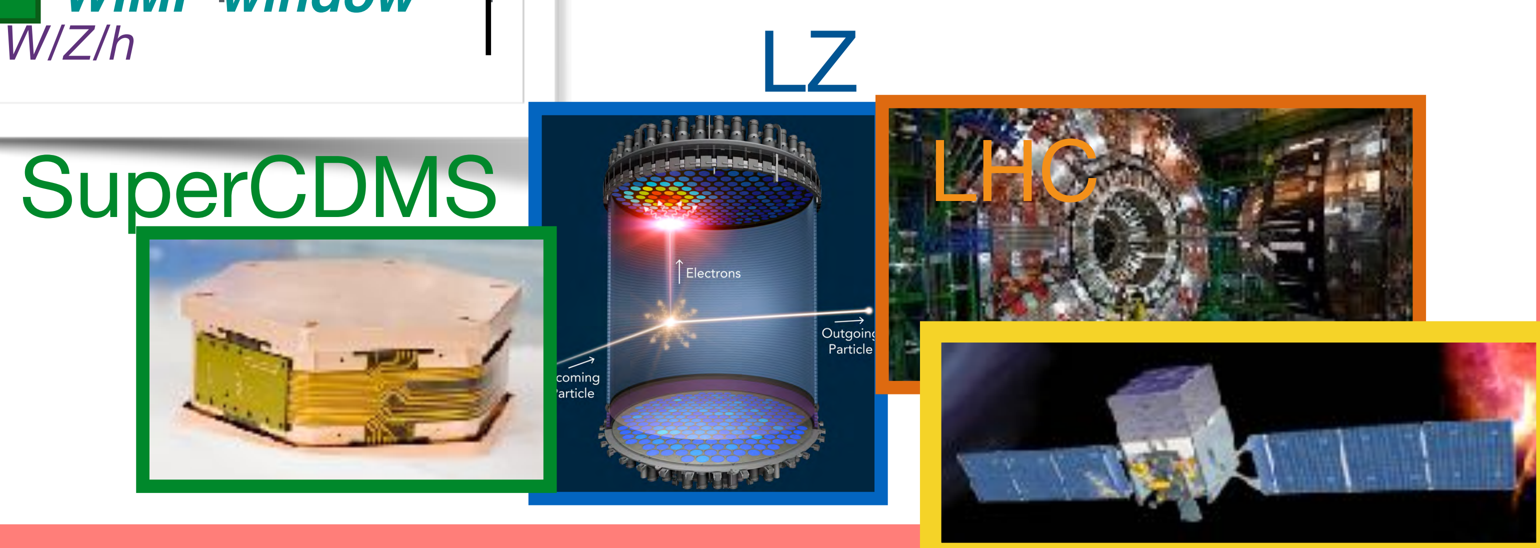
Weak-force assumption is under pressure from data!

Next steps in WIMP searches are important – **and** it's time to broaden the lamppost





Strong experimental program



WIMPs→ Dark Sectors

Simple, familiar particle content

DM from a new **column** in SM table?

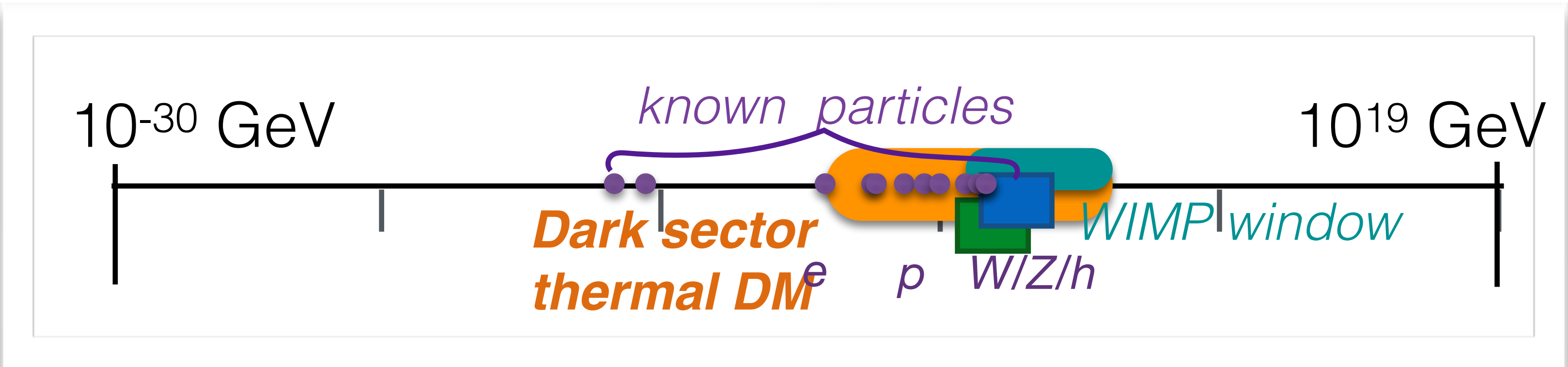
	$\mathbf{U}(1)_Y$	$SU(2)_L$	$SU(3)_C$	Dark Force
L	$-1/2$	$\mathbf{2}$	-	–
e^c	$+1$	-	-	–
Q	$+1/6$	$\mathbf{2}$	$\mathbf{3}$	–
u^c	$-2/3$	-	$\bar{\mathbf{3}}$	–
d^c	$+1/3$	-	$\bar{\mathbf{3}}$	–
h	-1/2	$\mathbf{2}$	-	–
DM				X

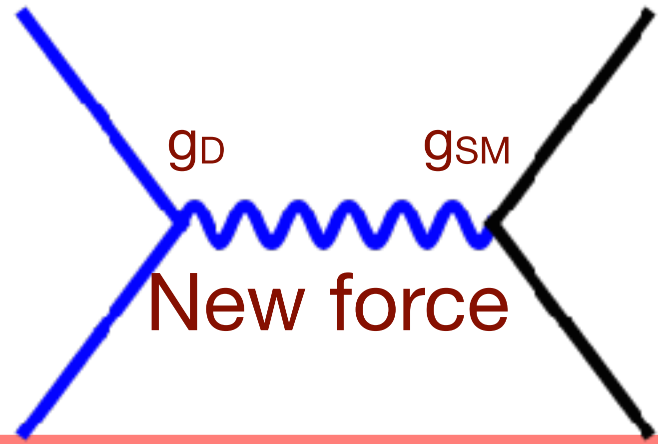
WIMPs→ Dark Sectors

Simple, familiar particle content

Immediate rewards for DM charged under new force

- Stable due to new conserved charge
- Dark because no common charges with SM
- Nontrivial miracle: Generic, small cross-talk ("portals") between SM and dark sector extends WIMP-like thermal freeze-out to lighter DM





Dark Matter | Systematic Exploration | Rich Possibilities

Organizing Dark Sectors

with an Abundance Mindset

- Setting aside dark matter – how do you find a dark sector?
- How much does the search depend on the precise content of the dark sector
(e.g. Does it have just one matter species?
Is it as complex as the SM?)

Organizing Dark Sectors

with an Abundance Mindset

Standard Model Sector

	$\mathbf{U}(1)_Y$	$SU(2)_L$	$SU(3)_C$
L	$-1/2$	$\mathbf{2}$	-
e^c	$+1$	-	-
Q	$+1/6$	$\mathbf{2}$	$\mathbf{3}$
u^c	$-2/3$	-	$\bar{\mathbf{3}}$
d^c	$+1/3$	-	$\bar{\mathbf{3}}$
h	-1/2	$\mathbf{2}$	-

?

Dark Sector

	$\mathbf{U}(1)_X$	$SU(N)_A$	$SU(M)_B$
a	Q_a	$\square$	
b	Q_b		
c	Q_c	$\square$	$\square$
d	Q_d		$\bar{\square}$
$\ldots$			

- Interactions relevant at low energies are those whose coupling has non-negative mass dimension (operator dimension ≤ 4)
- Interactions must be Lorentz-invariant, **SM** gauge-invariant, and **HS** gauge-invariant

Organizing Dark Sectors

with an Abundance Mindset

Standard Model Sector

	$\mathbf{U}(1)_Y$	$SU(2)_L$	$SU(3)_C$
L	$-1/2$	$\mathbf{2}$	-
e^c	$+1$	-	-
Q	$+1/6$	$\mathbf{2}$	$\mathbf{3}$
u^c	$-2/3$	-	$\bar{\mathbf{3}}$
d^c	$+1/3$	-	$\bar{\mathbf{3}}$
h	-1/2	$\mathbf{2}$	-

?

Dark Sector

	$\mathbf{U}(1)_X$	$SU(N)_A$	$SU(M)_B$
a	Q_a	$\Box$	
b	Q_b		
c	Q_c	$\Box$	$\Box$
d	Q_d		$\bar{\Box}$
$\ldots$			

SM gauge-invariant dimension $d_{SM} \leq 3$

x

Same-Lorentz-structure DS gauge-invariant dimension $d_{HS} \leq 4 - d_{SM}$

Organizing Dark Sectors

Standard Model Sector — **?** — **Dark Sector**

$B_{\mu\nu}$

$|h|^2$

hL

$q_i \bar{f}_i \gamma_\mu f_i$

x

Same-Lorentz-structure DS gauge-invariant dimension $d_{HS} \leq 4 - d_{SM}$ (if it exists)

Organizing Dark Sectors

Standard Model Sector — **?** — **Dark Sector**

e.g. $B_{\mu\nu}$ x $\epsilon/2\, F'^{\mu\nu}$

(mixed kinetic term with dimensionless coeff **ϵ**)
...if dark sector has a **massive** Abelian gauge boson

Holdom, Okun 1980s

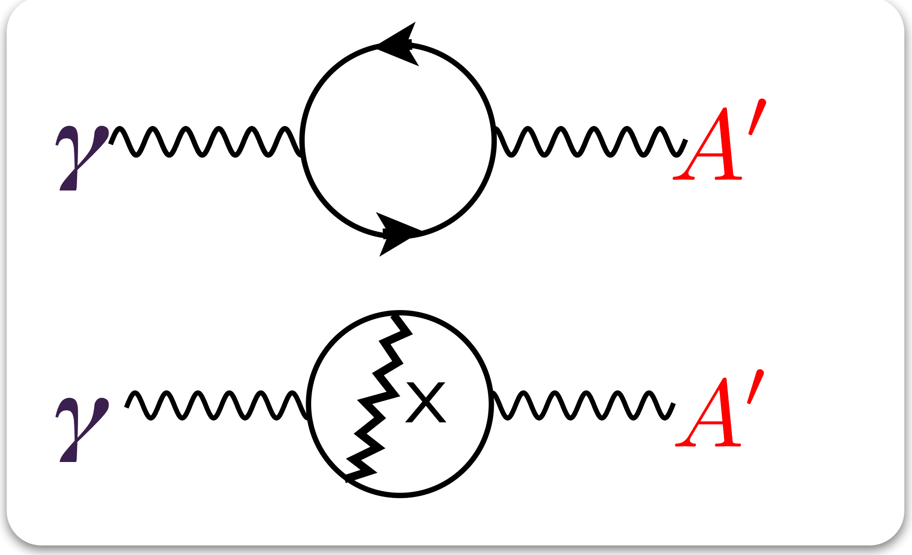
The Scale of Mixing

"Everything not forbidden is compulsory" – Gell-Mann

$$\frac{\epsilon}{2} B_{\mu\nu} F'^{\mu\nu}$$

Loops of heavy particles charged under both U(1)s generate small couplings

$$\epsilon \sim \frac{g_D e}{16\pi^2} \times \log(\dots) \sim 10^{-2} - 10^{-6}$$



Non-perturbative effects can generate smaller couplings

The Portals

Standard Model Sector — **?** — **Dark Sector**

e.g. $B_{\mu\nu}$ x $\epsilon/2\, F'^{\mu\nu}$

Similarly, dark scalars and neutral fermions can mix with SM Higgs and neutrinos:

$|h|^2$ x $\mu S + \lambda|\phi|^2$

hL x $y_N N$

"portal mediators"

$q_i \bar{f}_i \gamma_\mu f_i$ gV^μ Gauge SM global symmetry (not product structure)

Portals as Building Blocks

Just 3 interaction types dictate SM coupling to *generic* DS
→ lab and cosmological production

$$B_{\mu\nu} \quad \times \quad \epsilon/2\, F'^{\mu\nu}$$

$$|h|^2 \quad \times \quad \mu S + \lambda|\phi|^2$$

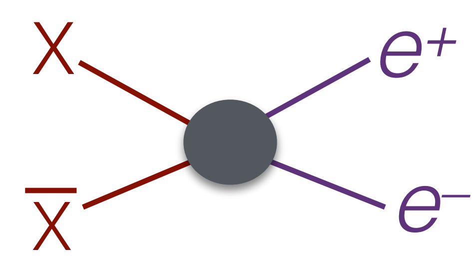
$$hL \quad \times \quad y_N N$$

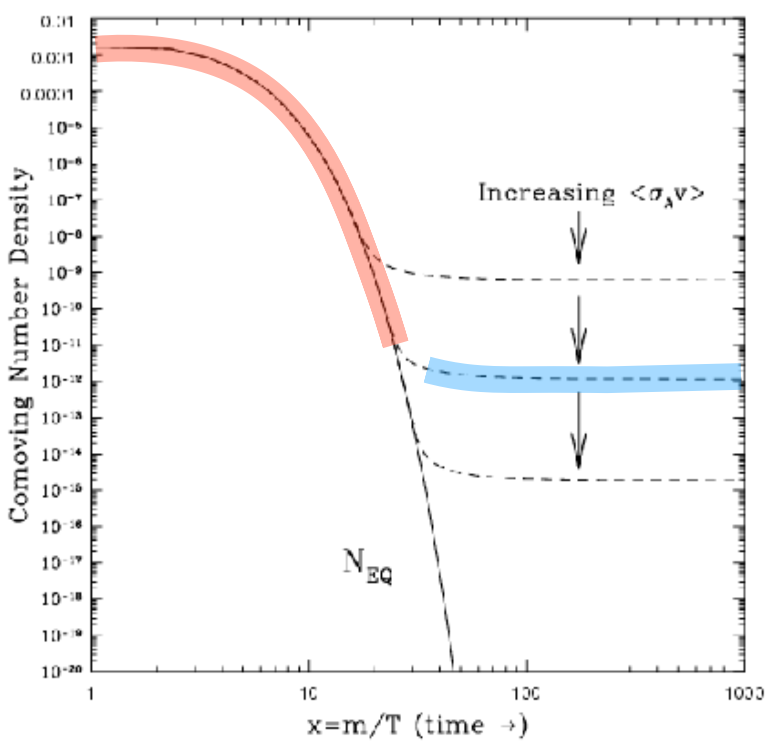
Dark photon and Higgs couple weakly to SM matter, inheriting SM flavor structure (***Q*_EM** / ***Y*_L,U,D**)

Lepton portal is like sterile neutrino, with new flavor structure

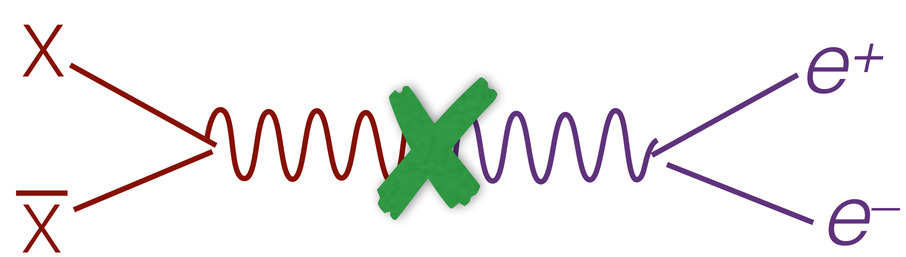
Portals to Dark Matter

Dark matter annihilation to SM matter was a core ingredient of thermal freeze-out, with **cross-section fixed by DM abundance**



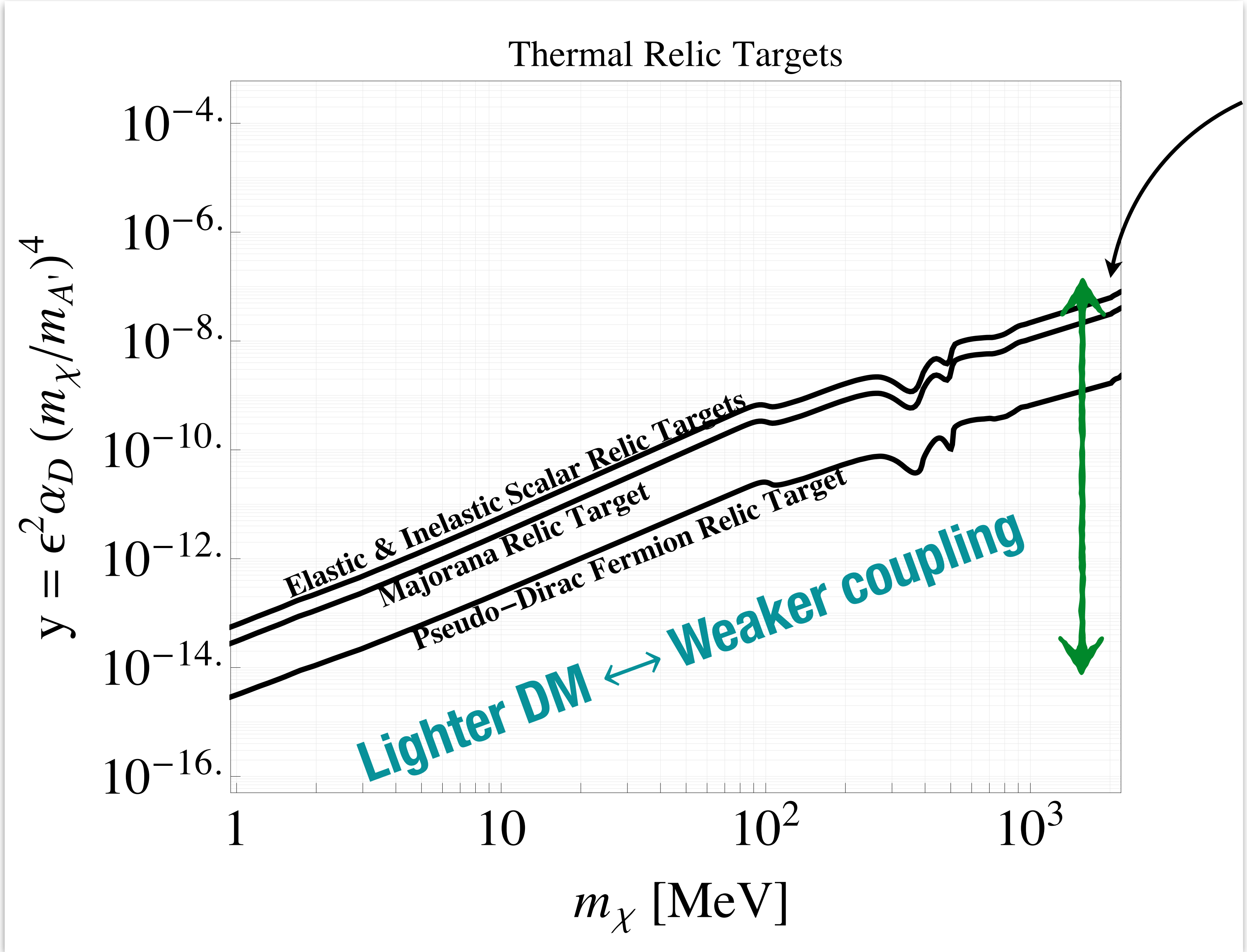


Portals mediate this annihilation!



Effectively, new force weakly coupled to SM matter

Portals to Dark Matter

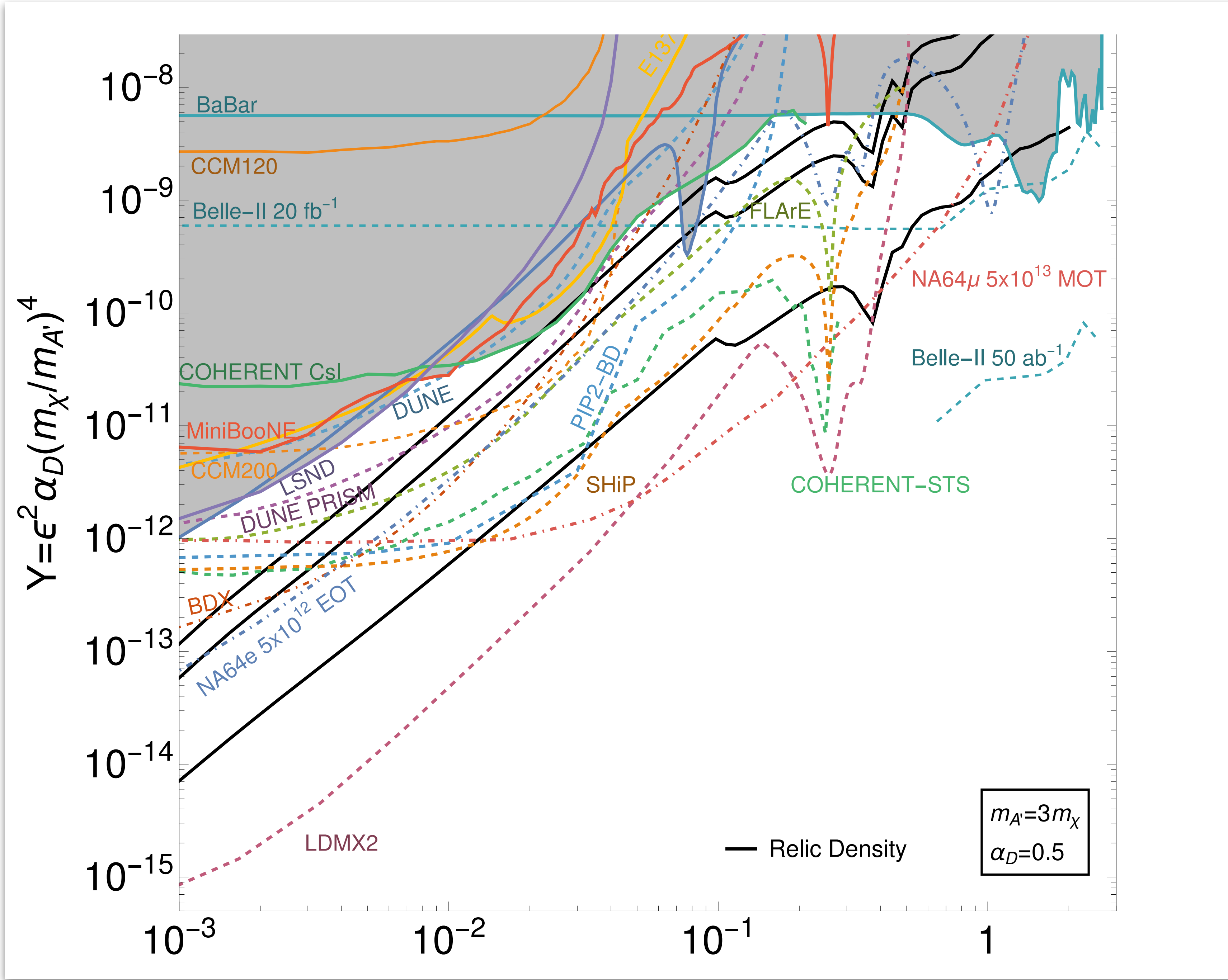


Interaction strengths needed for freeze-out are…

…consistent with expectation for perturbative kin. mixing

$\epsilon_{1\text{–}2\ \text{loop}}^2 \times \left(\begin{smallmatrix}\text{couplings \&} \\ \text{mass ratios}\end{smallmatrix}\right)$

Portals to Dark Matter



Interaction strengths needed for freeze-out are…

…within a factor of 10-1000 of current experiments' sensitivity over most of the mass range

…accessible with the next generation of planned and DMNI-supported experiments! (see Stefania's talk)

Scalar portal ruled out by data

Neutrino portal also supports predictive and testable models (somewhat less explored)

Why Dark Sectors?

A rich new window for physics beyond the Standard Model, including dark matter

Three intertwined motivations:

- Viable, predictive, and discoverable models of light **dark matter** are a key motivation and anchor
- Symmetries of Standard Model provide a framework for **systematic exploration** of weakly-coupled new physics
- These arguments motivate possibility of **complexity in dark sector**, which we could discover experimentally

Portals On their Own

If mediator is lighter than any dark-sector matter (or the dark sector is minimal – i.e. just a portal mediator) then **mediator decays** also set by portal couplings.

$B_{\mu\nu}$ x $\epsilon/2\, F'^{\mu\nu}$

$|h|^2$ x $\mu S + \lambda|\phi|^2$

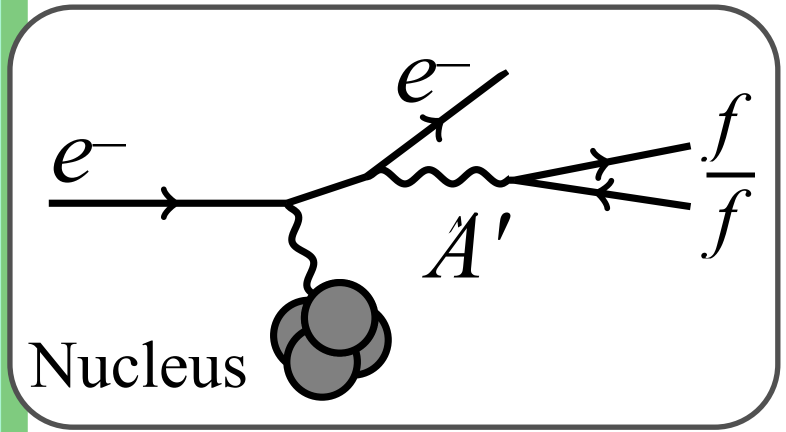
hL x $y_N N$

Portals On their Own

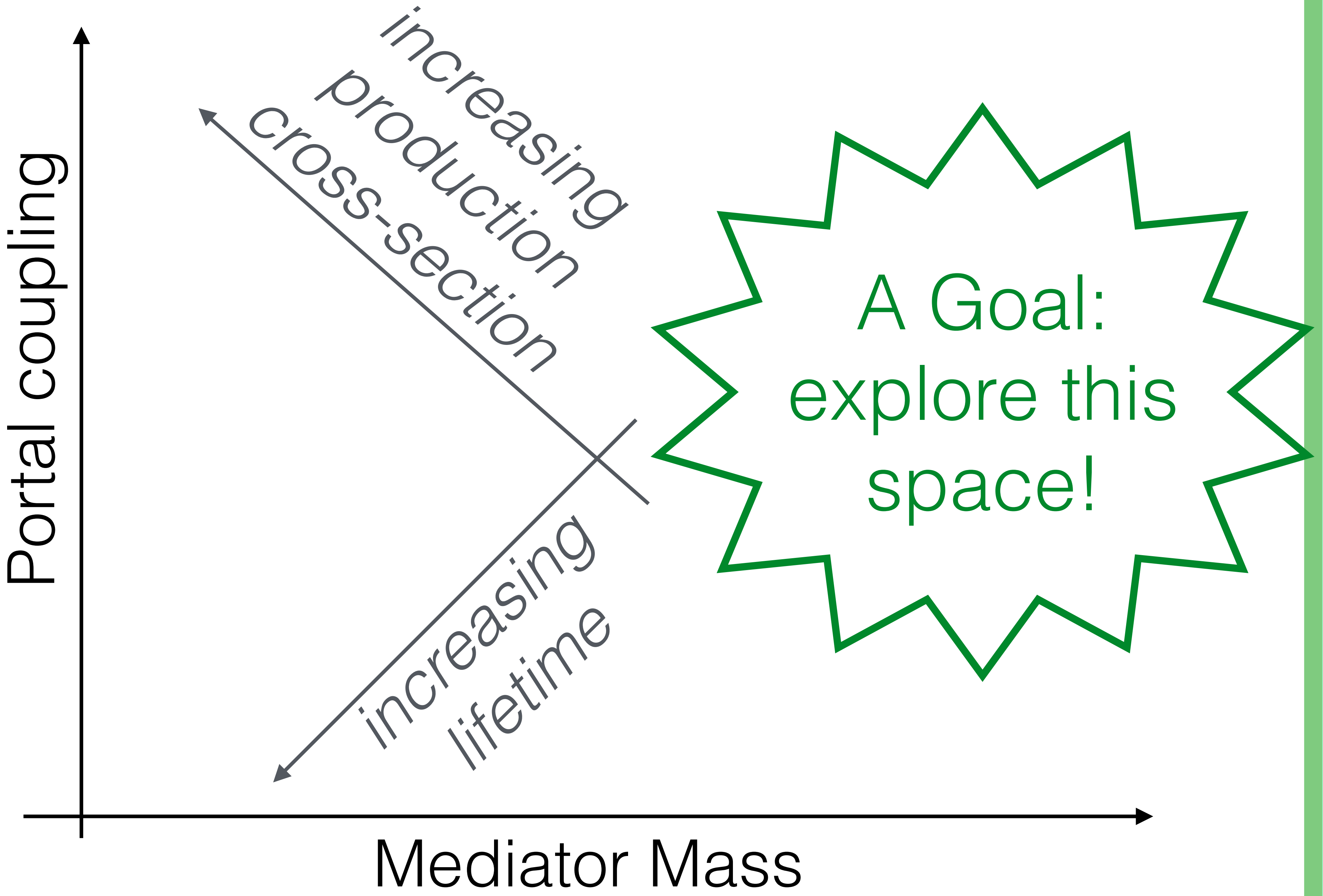
A Range of Signals

Example:

$$\frac{\epsilon}{2} B_{\mu\nu} F'^{\mu\nu}$$



+ analogues for other portals & production mechanisms

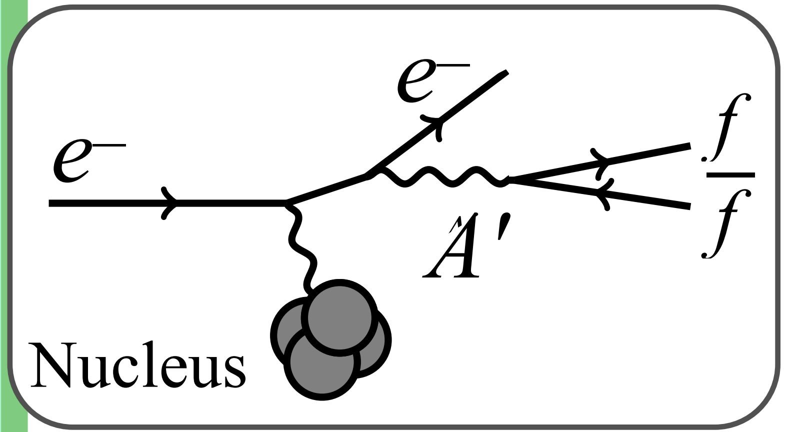


Portals On their Own

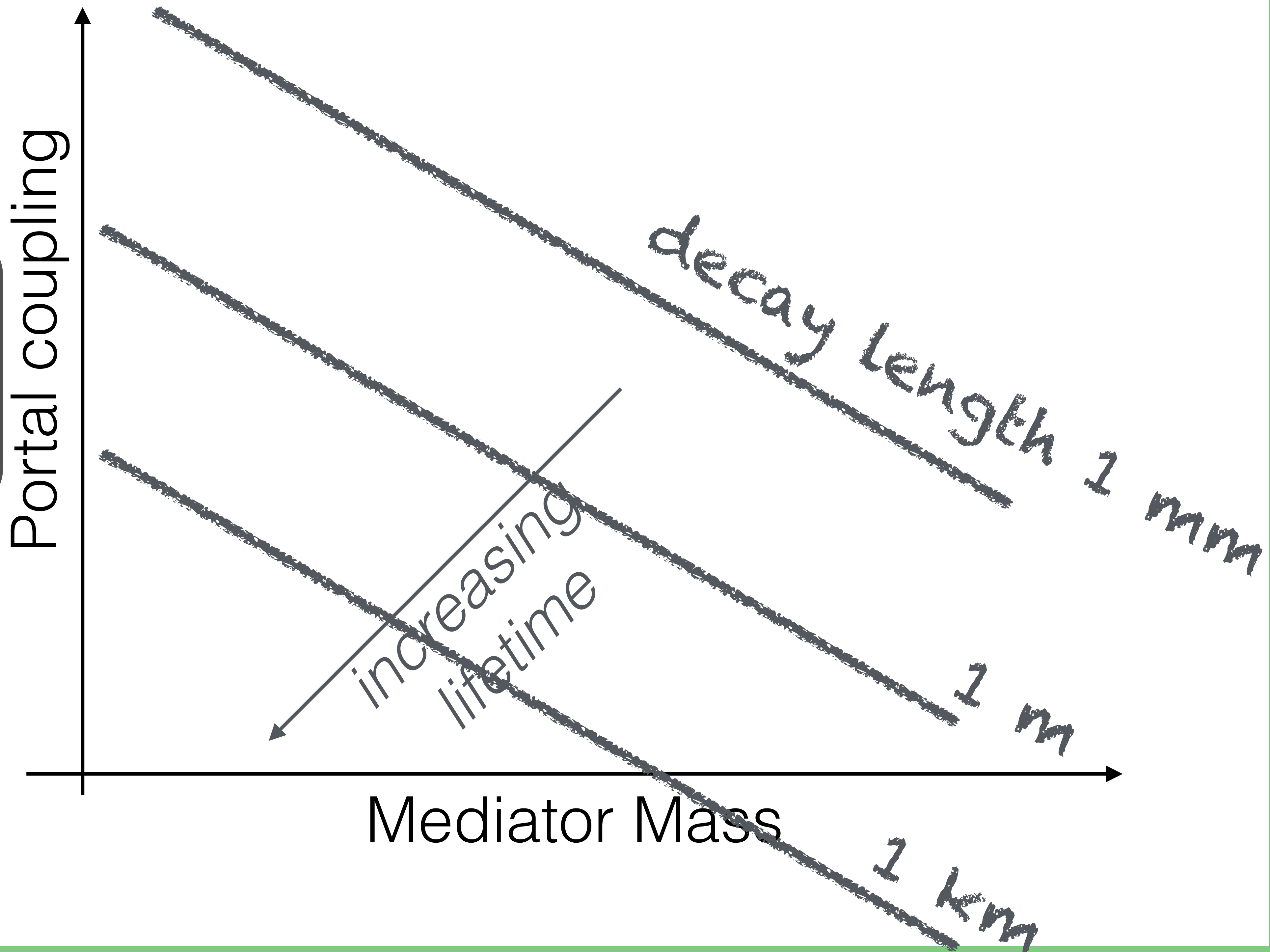
A Range of Signals

Example:

$$\frac{\epsilon}{2} B_{\mu\nu} F'^{\mu\nu}$$

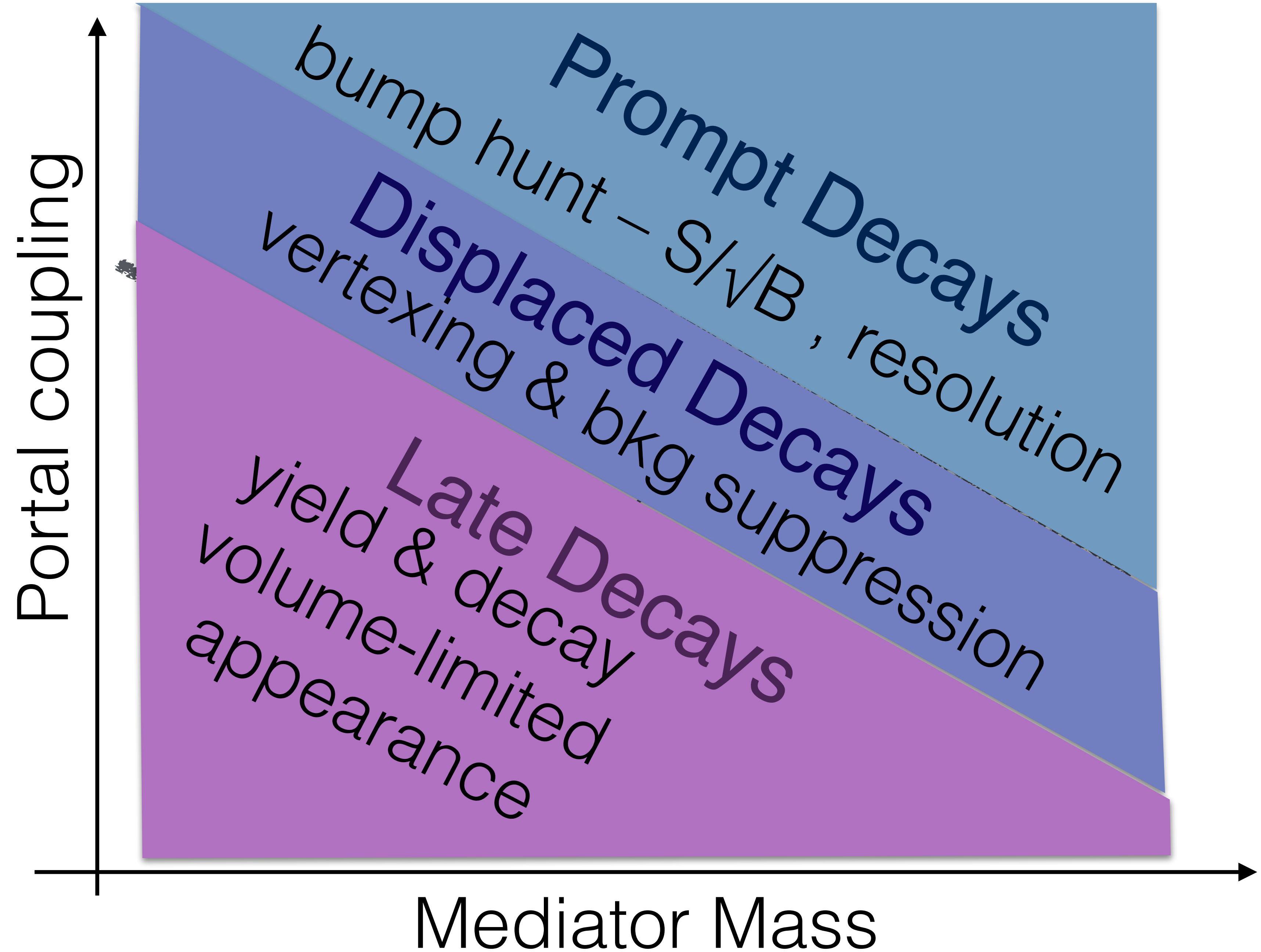


+ analogues for other portals & production mechanisms



Portals On their Own

Lifetime
→
sensitivity drivers

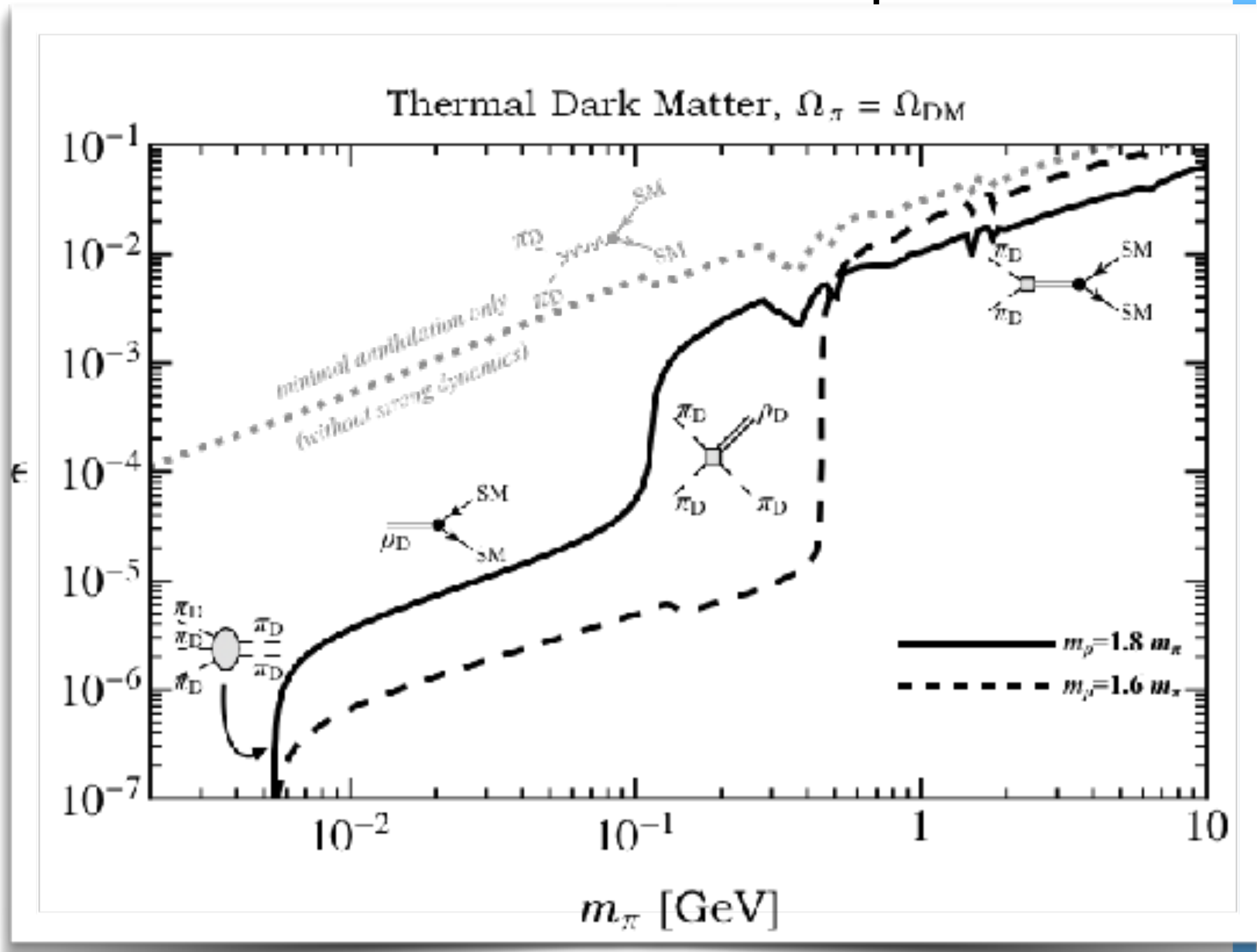


Thinking Broadly

What if There's More?

- Robustness to complicated dark sectors is important!
- In DM models, DM is stab-ilized by "being the lightest". But heavier **excited states** can play important roles in DM freeze-out **and** searches.

(e.g. SIMP cosmology studied in 1801.05805)

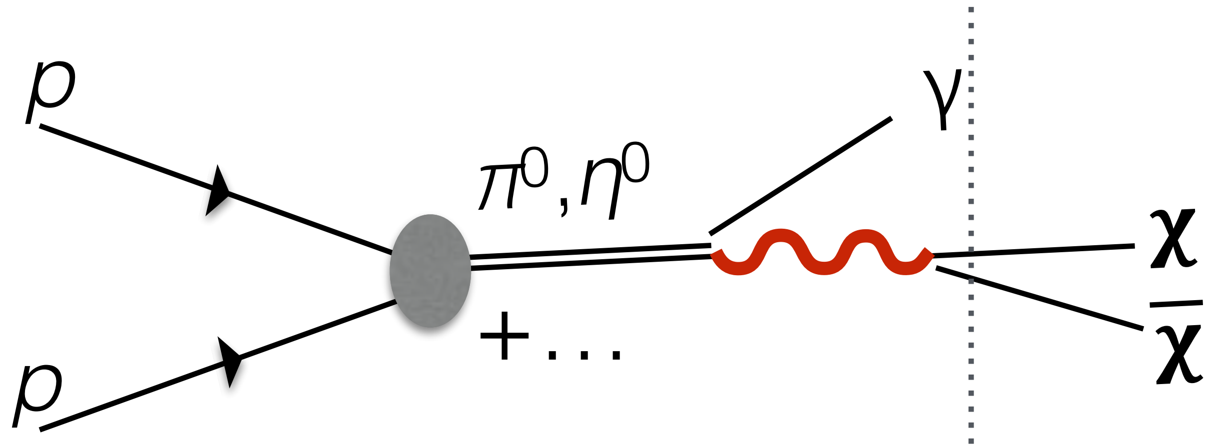


Thinking Broadly

Beyond Dark Matter

- Outside of DM motivation, multi-stage visible decays ar also possible
- Finally, generalizations of the basic portals are motivate by several anomalies in data

What you Look For Depends on What You Want to Find



Facilities & portals dictate initial & intermediate states – but each motivation points towards a different type of final state

Explore **predictive DM models** (mainly) by **producing DM particles**

non-SM

Systematically study **minimal couplings** to dark sectors via **mediator decays to SM**

SM

Hunt for **complexity in the dark sector** through **mixed visible/invisible decay chains**

mixed

Goals for This Talk

- What are dark sectors, and why are they exciting?

- Why are **small and multi-purpose Intensity Frontier* accelerator-based experiments** essential to confront this landscape?

*in a broad sense – e.g. including neutrino experiments, LHCb, Belle II, forward auxiliary detector proposals at LHC, …

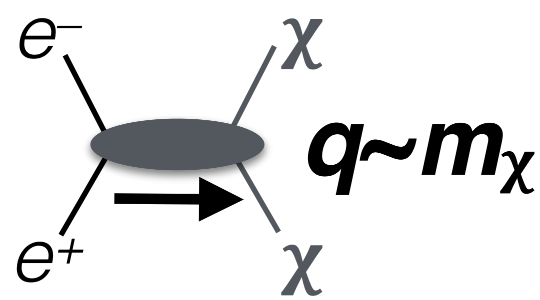
Why Accelerators?

- Fundamentally complementary to direct detection!

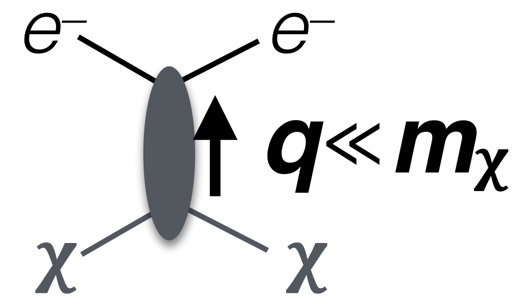
1. Address different questions
   - Accelerators can explore the whole dark sector, direct detection only sees stable parts
   - Direct detection probes cosmological abundance & stability, accelerators do not
   - Measure different properties – and even more powerful when you can use both.
2. Different kinematics (non-relativistic halo vs. relativistic production) → Different parametric sensitivity

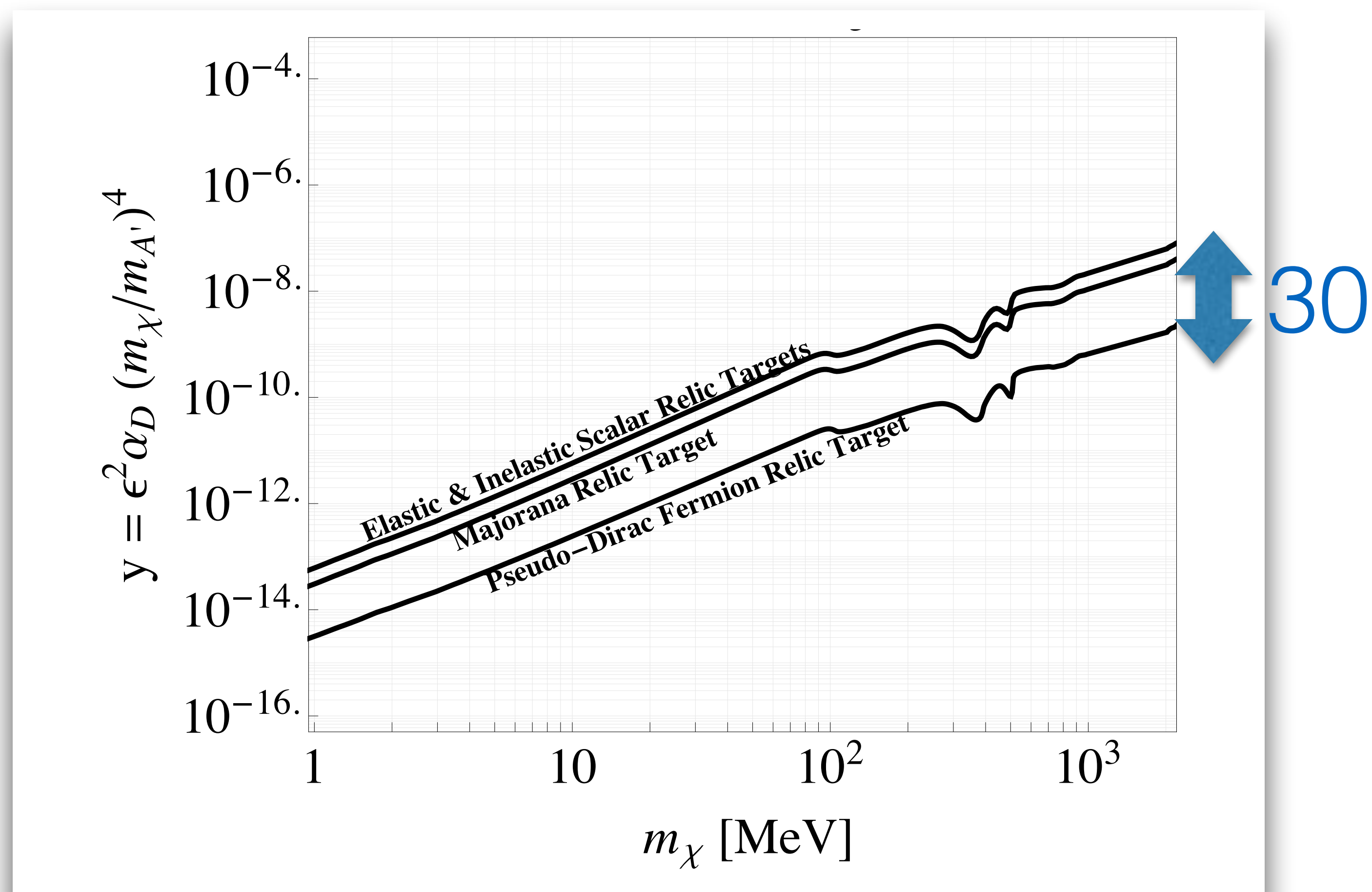
Kinematics Matters

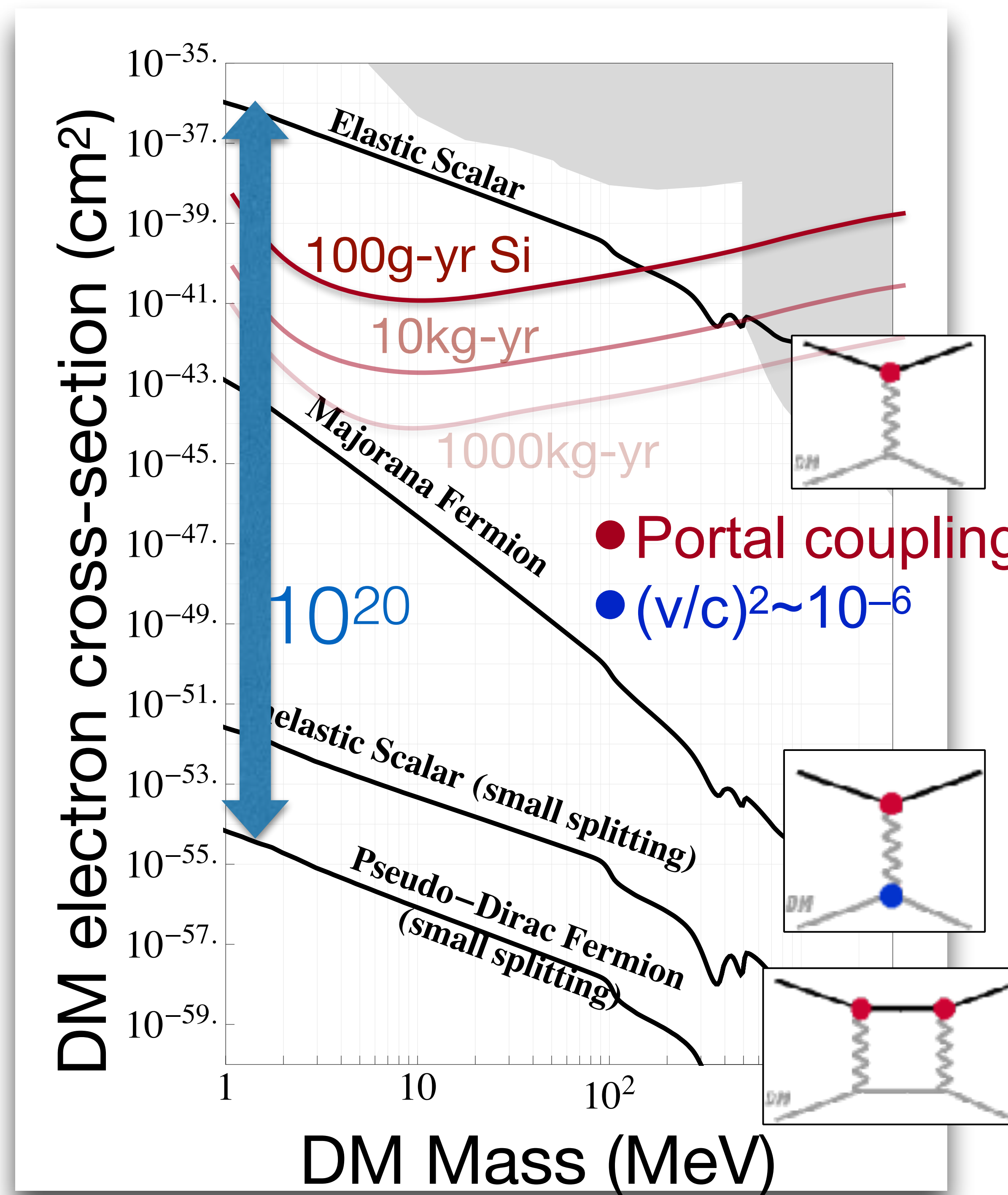
Accelerator Production



Direct Detection







Kinematic similarity to freeze-out temperature ⇒ narrow band

But note q≪m_χ **enhances** other models' signals ⇒ need both!

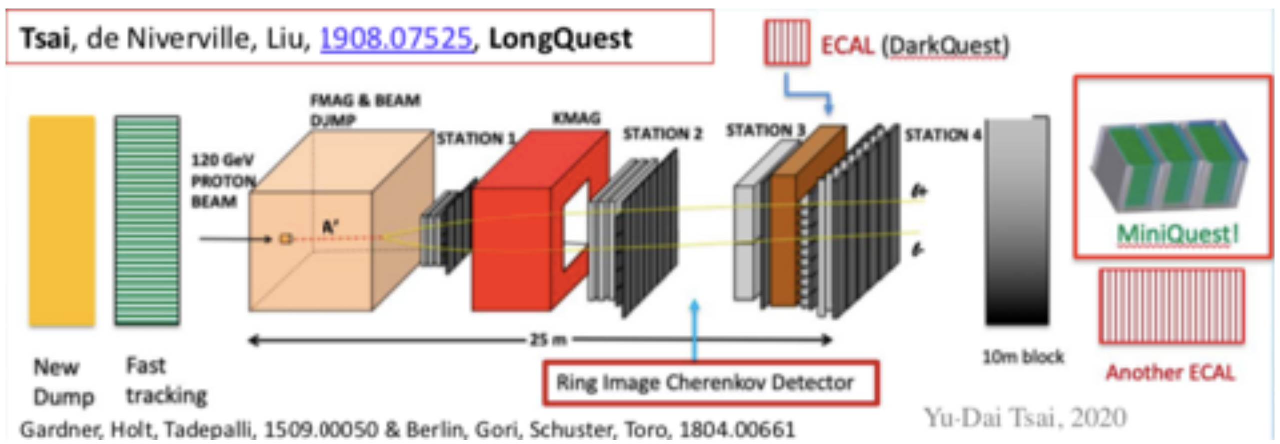
Why Intensity?

- Physics crosses frontiers, but also cares about details! **Low- and high-energy experiments,** as well as **small and multi-purpose experiments**, complement each other *because* they have different strengths.

- A few examples of enabling capabilities & configurations for dark-sector discovery experiments

Near, Forward, Specialized Detectors

p beam: DarkQuest/LongQuest/SpinQuest



e beam: HPS

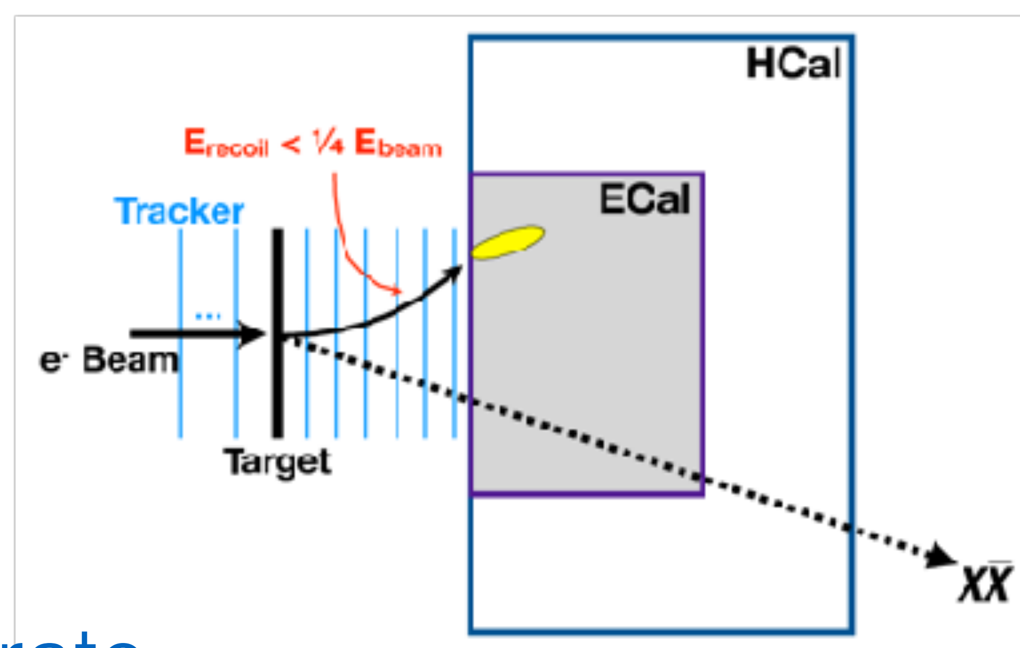
Excellent for low-mass displaced vtx sensitivity

- HPS and LHCb VELO at LHC hug sides of beam to measure shorter decays

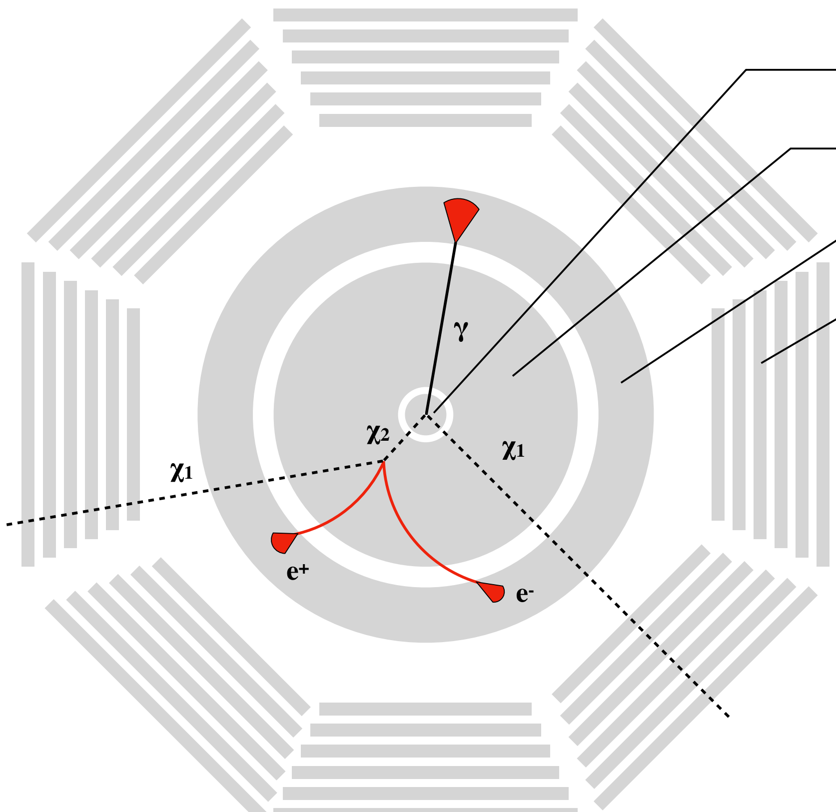
---

Unique capability to "image" individual beam particles for DM search *a la* NA64, LDMX

- rely on low bunch charge
  ⇒ motivates high repetition rate



Friendlier Environment for Low-Energy Final-States

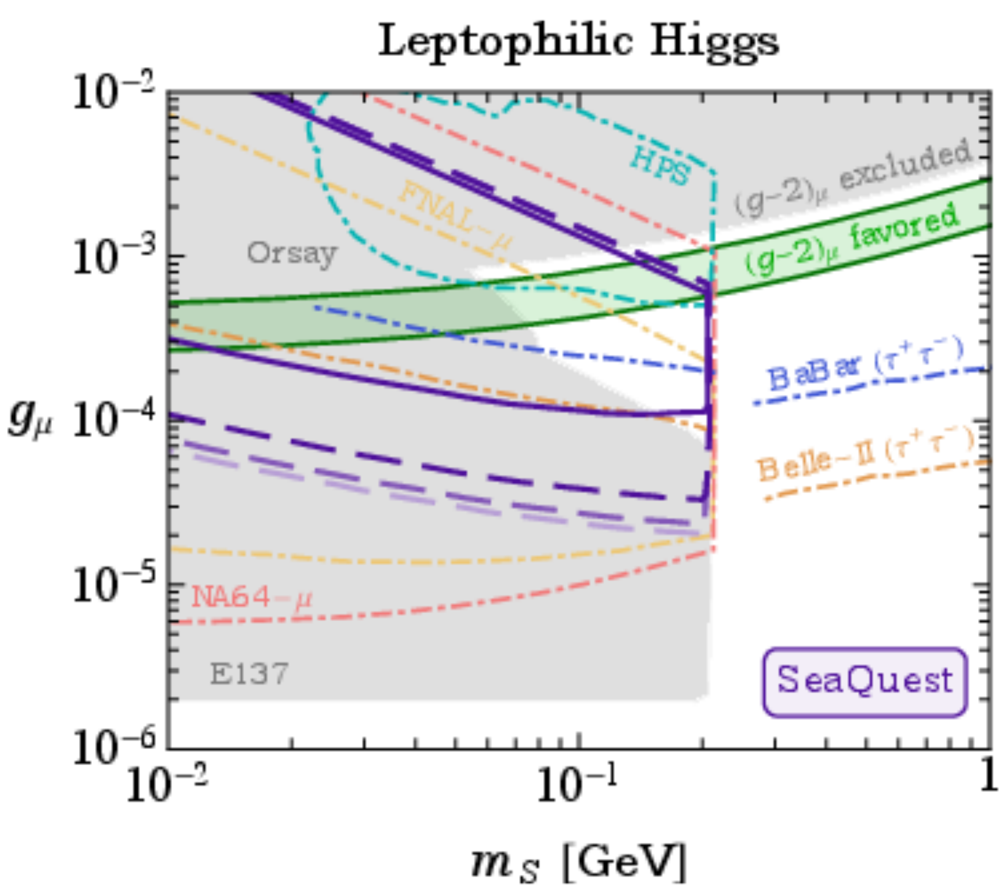


- Belle-II inelastic DM production search [1911.03176] exploits **O(50 MeV)** energy & pair-mass thresholds

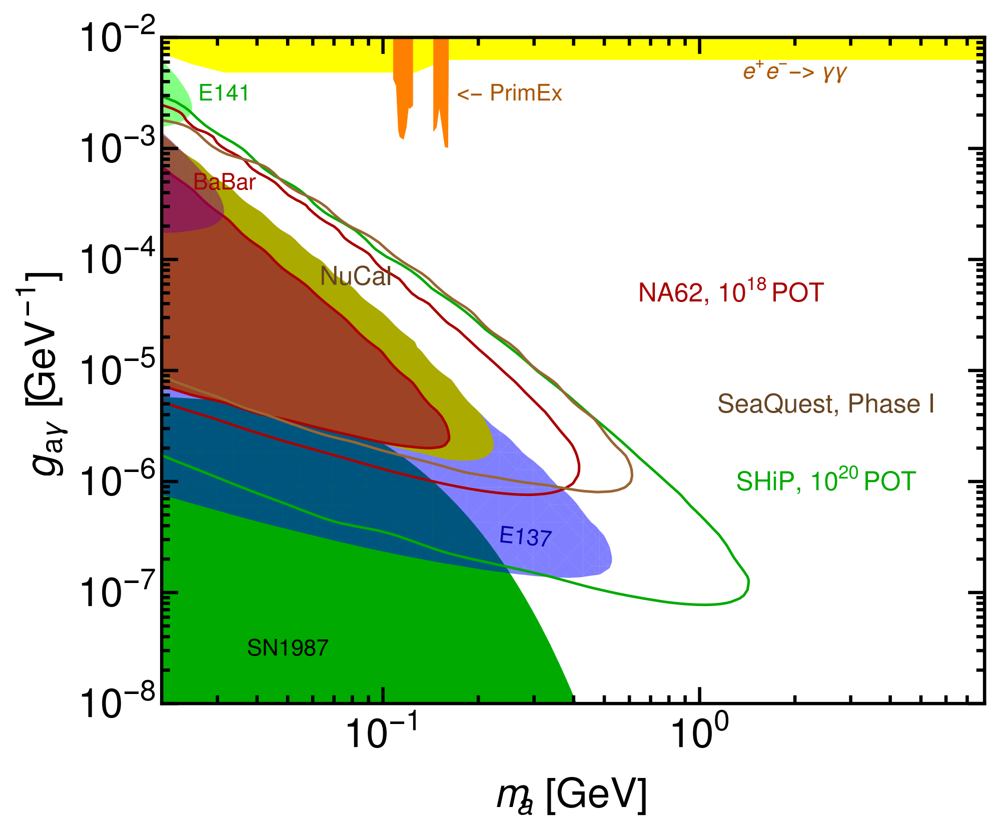
(buried in pile-up at LHC)

Secondary Beams

Collimated showers of secondary particles can seed reactions for which primary beam particle has insufficient coupling

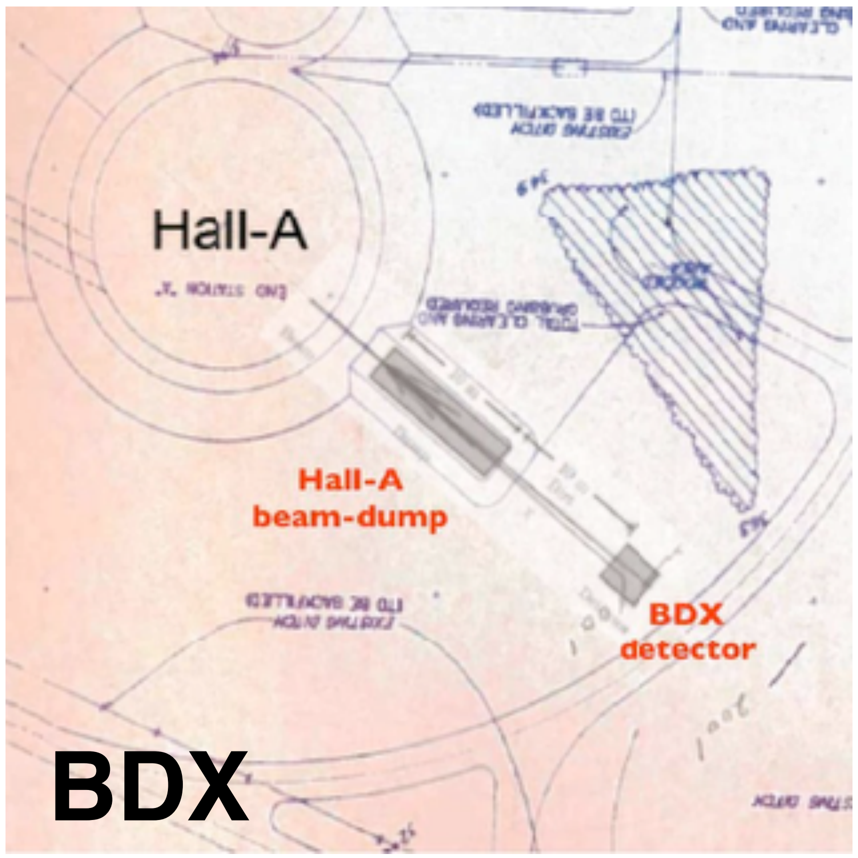


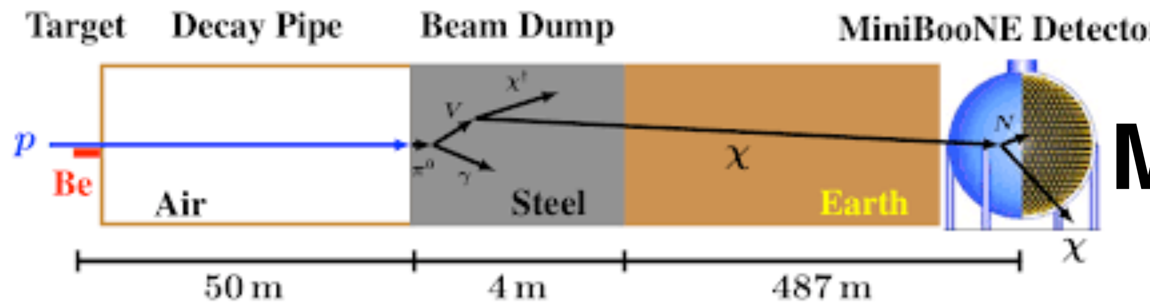
1804.00661 Berlin, Gori, Schuster, NT
leptophilic Higgs from secondary muons



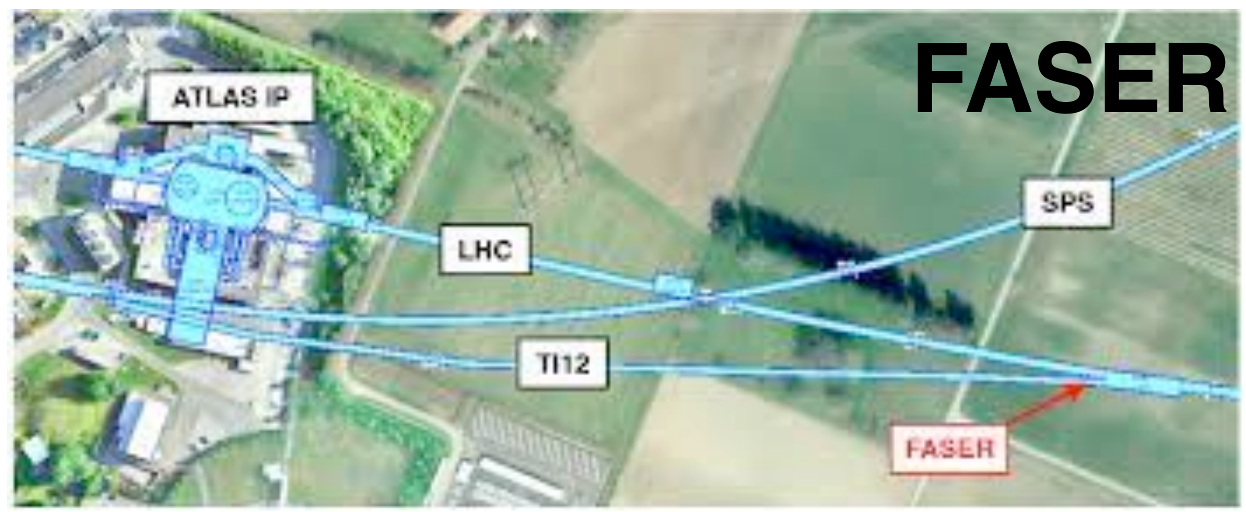
1904.02091 Döbrich,Jaeckel, Spadaro
ALPs from secondary photons

Long Baselines & Large Instrumented Volumes



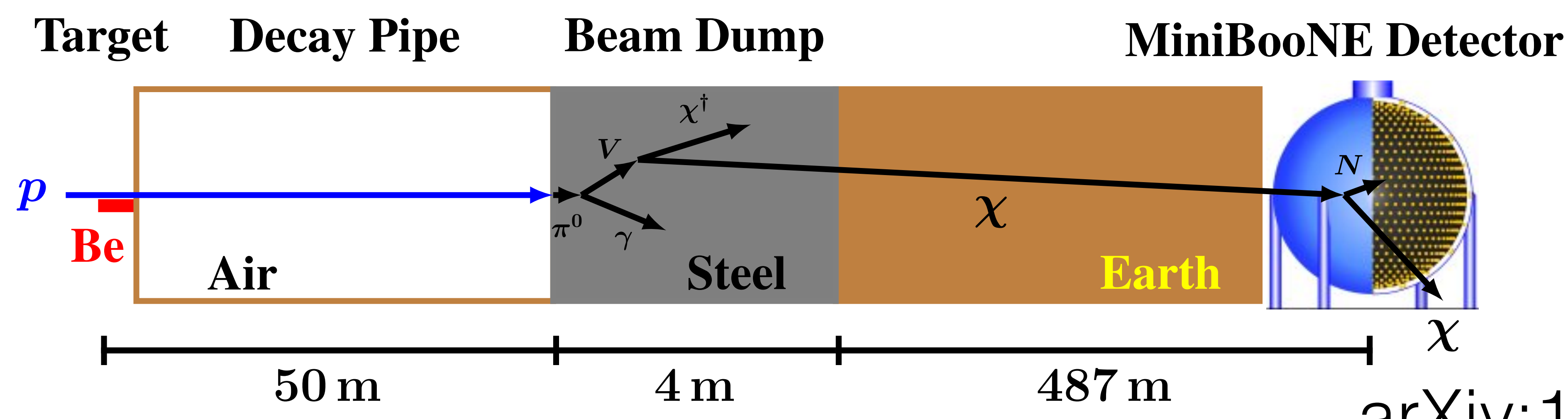


Mini-BooNE DM



Strong synergy with Energy and Neutrino Frontiers – see Brian Battel and Jonathan Feng's talks

High Luminosities



arXiv:1807.06137

- e.g. 10^{20} (10^{23}) protons on target at MiniBooNE (COHERENT)
  - Typical proton travels 10s of cm through the dump → luminosities at the level of 10^4–10^7 ab^{-1}
  - Similar story for electron beam dumps, w/ distinct shielding, background, detector size trade-offs
- This extreme luminosity allows searches for signals with inherently tiny efficiency like dark matter scattering in downstream detector.

Road to Discovery

- Accelerator-based experiments are needed to explore the parameter space of predictive thermal DM models; they give complementarity insights into the particle physics of the dark sector

- The broad range of signals that can arise from dark sectors calls for targeted experimental designs

Conclusion

- Dark Sectors, with **dark matter** as powerful motivation, represent a **rich new window** for physics beyond the Standard Model.

- High-impact parameter-space – including thermal dark matter milestones – can be explored within the decade!

- Small-scale accelerator-based experiments and creative analyses of multi-purpose experiments are key to exploring this physics and mutually complementary