RF6: dark sectors at high intensity

Stefania Gori
UC Santa Cruz

Rare Processes and Precision Frontier kick-off meeting

July 27, 2020

Outline, RF6 topical group

1. Motivations and goals

- Goals of this talk
- Why dark sectors?
- Goals of the topical group

2. Structure of the group

7 sub-groups.

Organized by initial state. I.e. How is the dark particle produced?

(e^+e^- colliders, fixed target exp., Kaon exp., high energy exp., neutrino exp., …)

3. Physics opportunities

I will discuss a few experiments.
Disclaimer: not an exhaustive list

- Dark Matter production
- Production of portal-mediators that decay to SM particles
- Production of "rich" dark sectors

4. Benchmark scenarios

Conveners: Stefania Gori (sgori@ucsc.edu), Mike Williams (mwill@mit.edu)

Goals of this talk

Key questions:

* Why are Dark Sectors a compelling opportunity for the next decade?

* What are the needed theoretical developments?

* How do small and multi-purpose experiments confront the dark sector landscape?

* Which set of benchmark models comprehensively covers the interesting signatures we can look for?

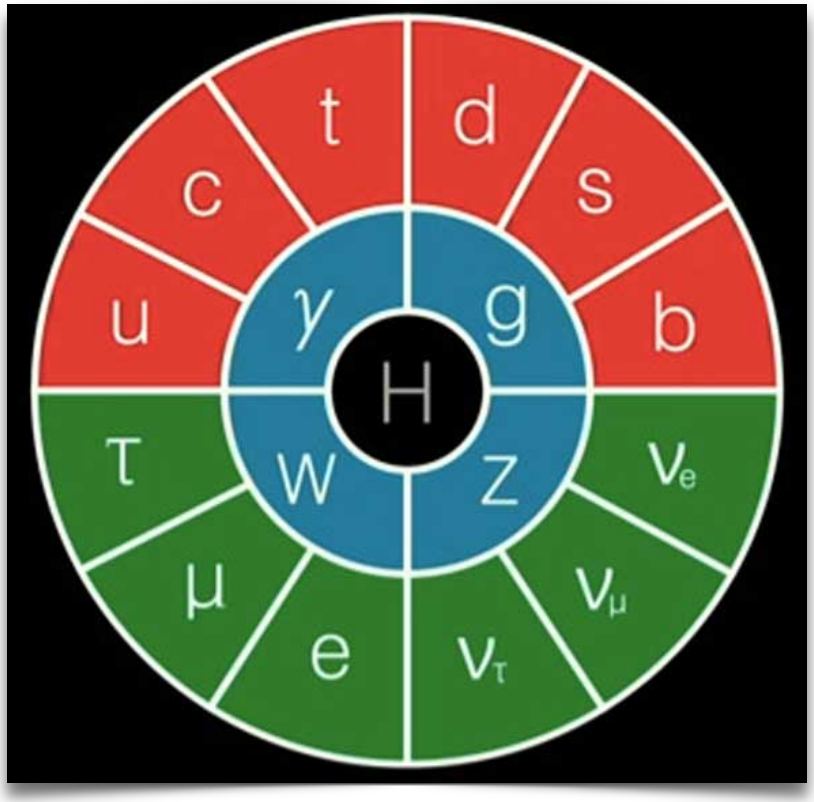
Call for new contributions and ideas

Snowmass community effort

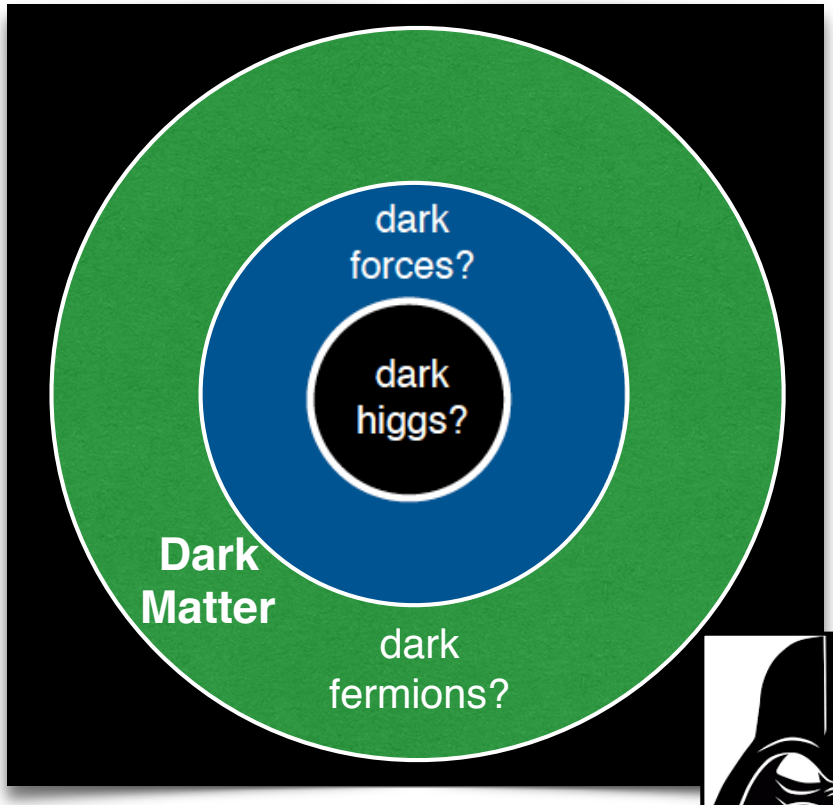
What is a dark sector?

Any particle that does not interact through the Standard Model (SM) forces.

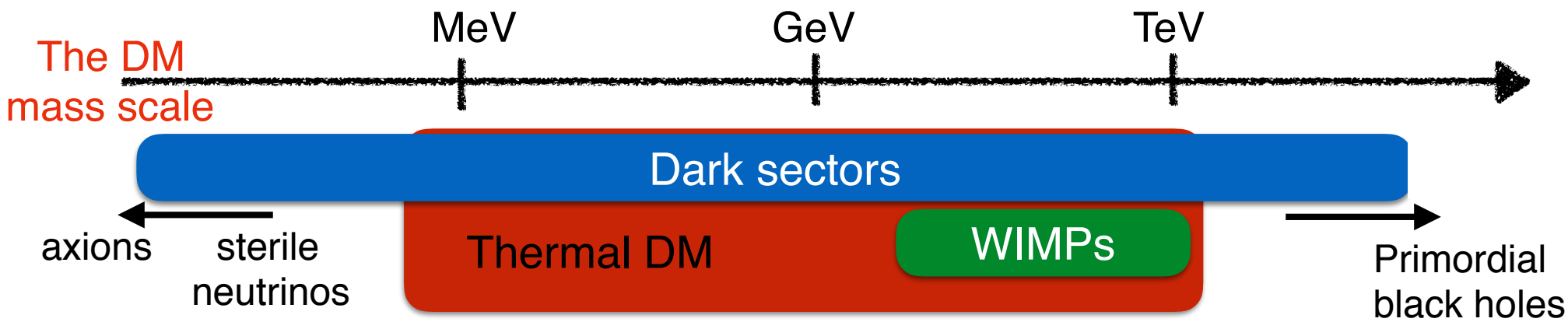
Our visible universe



The dark universe



Why a dark sector? (DM)



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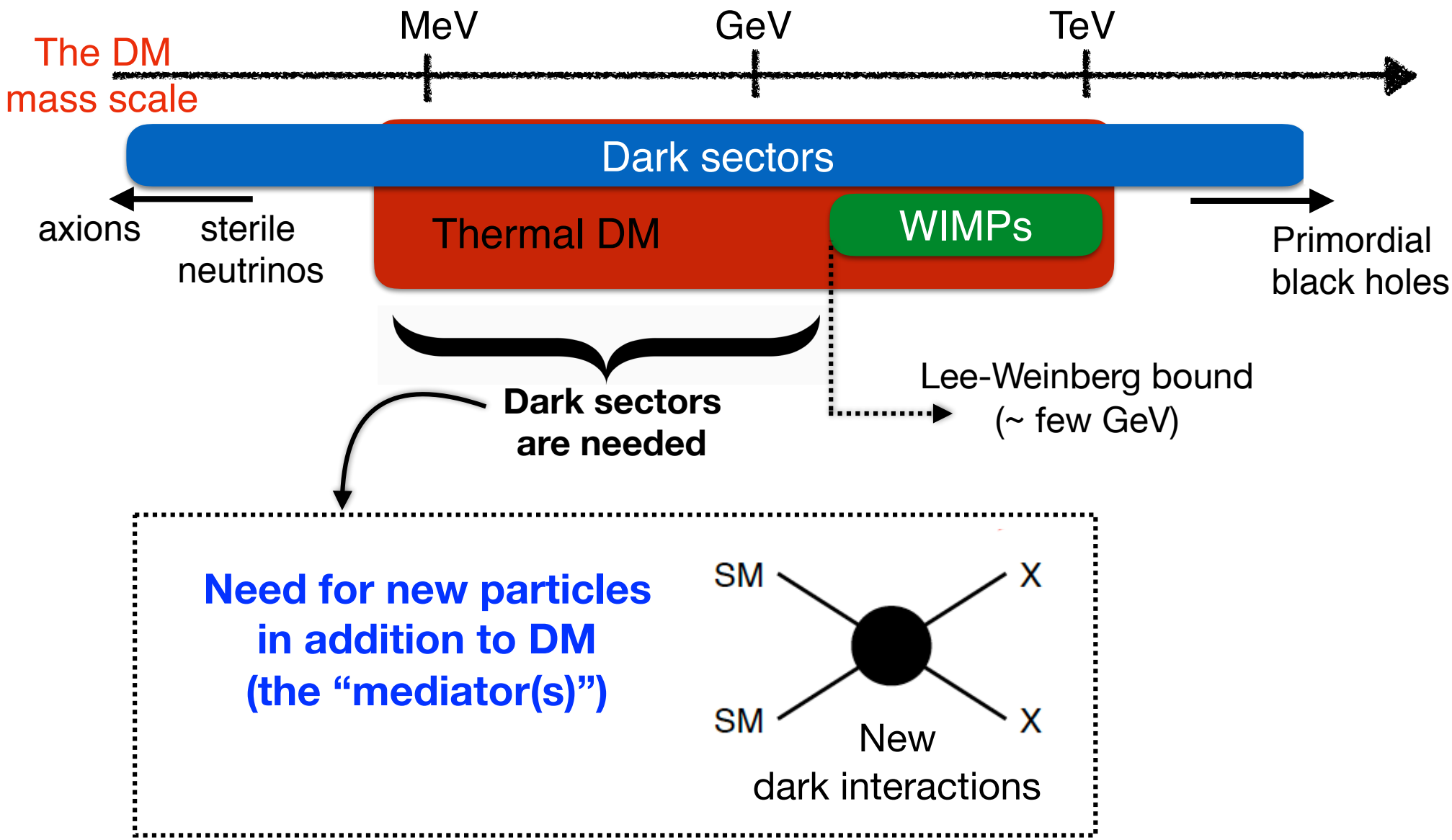


Why a dark sector? (beyond DM)

Beyond the DM motivation, many other open problems in particle physics let us think about dark particles.

Why a dark sector? (beyond DM)

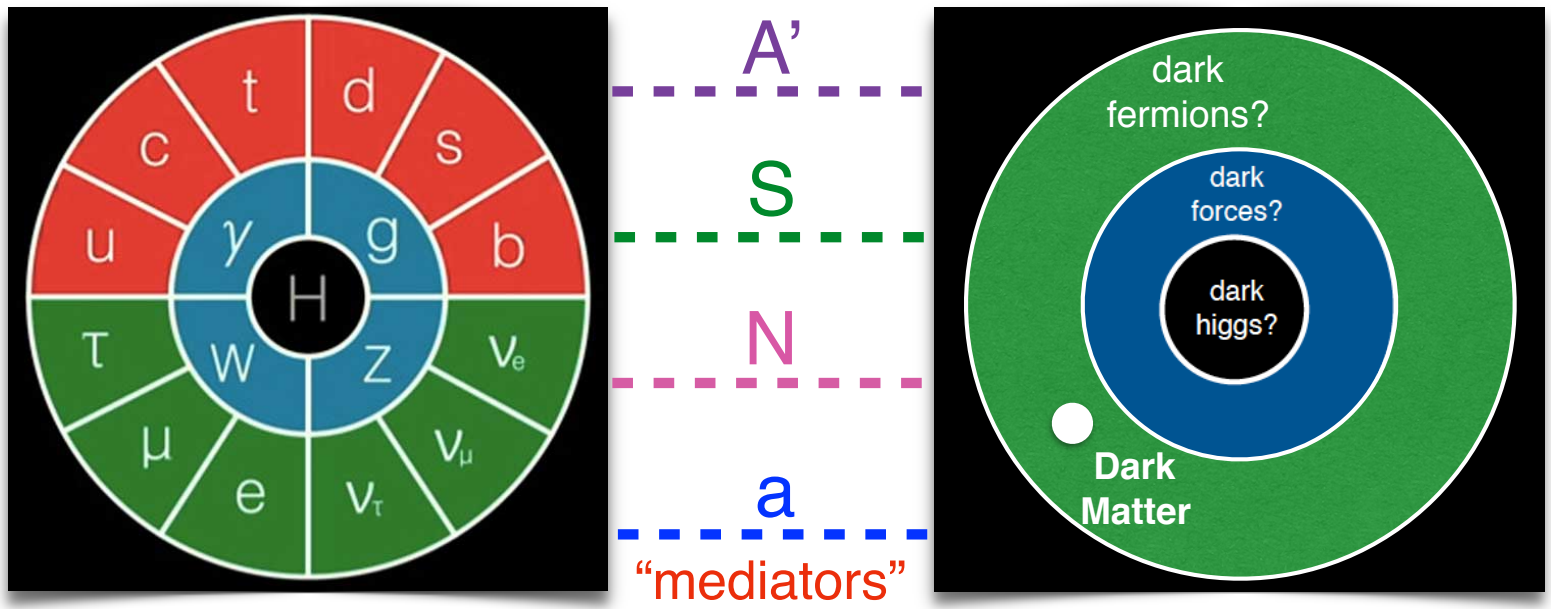
Beyond the DM motivation, many other open problems in particle physics let us think about dark particles.

- Models to address the strong CP problem. Axions and axion-like particles;
- Models to address the gauge hierarchy problem (relaxion);
- SUSY extended models (Next-to-Minimal-Supersymmetric-Standard-Model);
- Models for baryogengesis;
- Models for neutrino mass generation;
- Models addressing anomalies in data;

($(g-2)_\mu$, galactic center excess for Dark Matter, Xenon1T anomaly, B-physics anomalies, KOTO anomaly, …).

Some of these particles are naturally light thanks to approximate global symmetries.

How to gain access to the dark sector?



Only a few interactions exist that are allowed by Standard Model symmetries:

"mediators"	"portal interactions"
Dark photon	$\epsilon B^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$
Axion	$g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$

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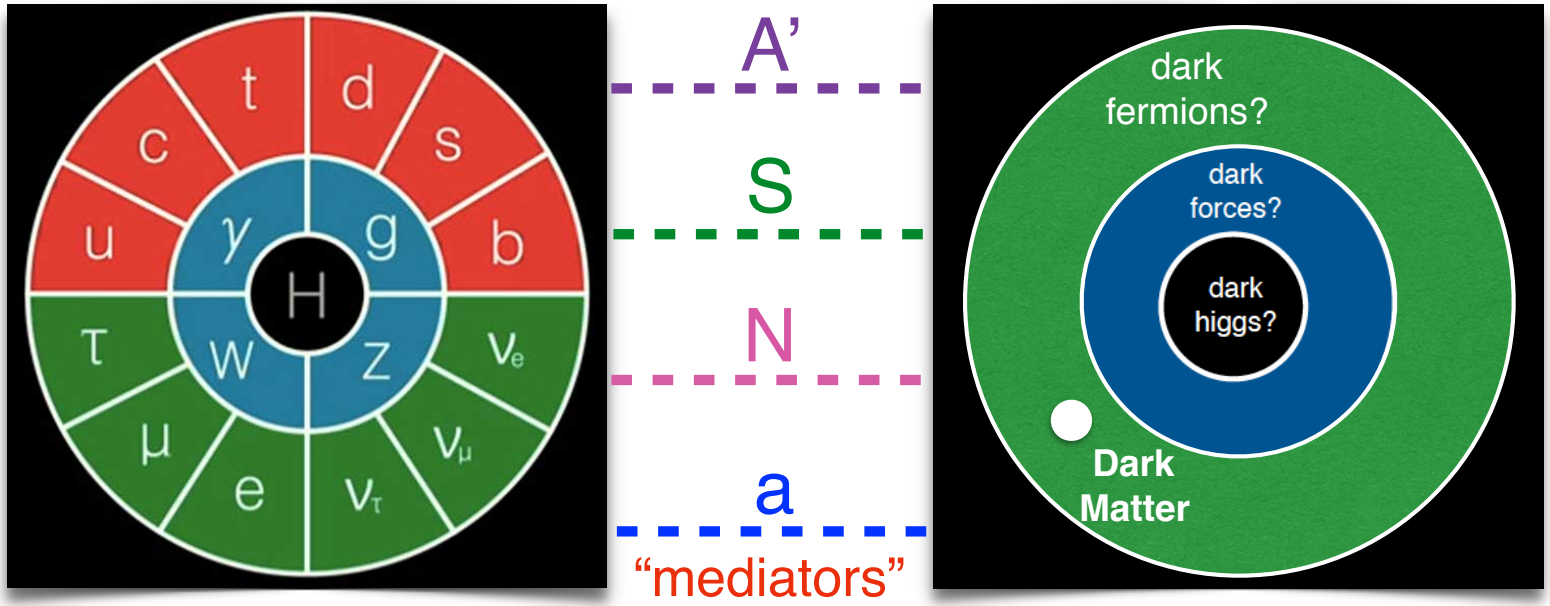

Only a few interactions exist that are allowed by Standard Model symmetries:

+ possible new dark gauge bosons obtained gauging e.g. B-L, L_μ-L_τ, …

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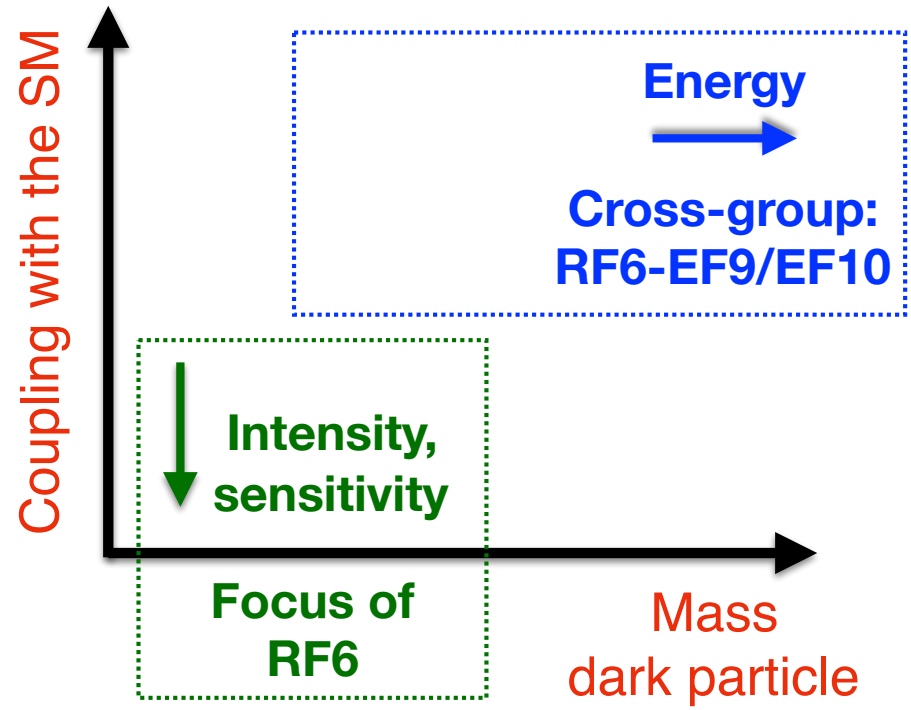
Ambitious experimental targets



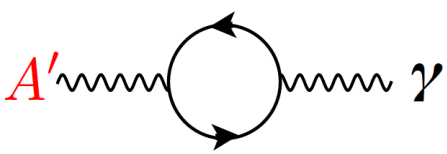
Ambitious experimental targets

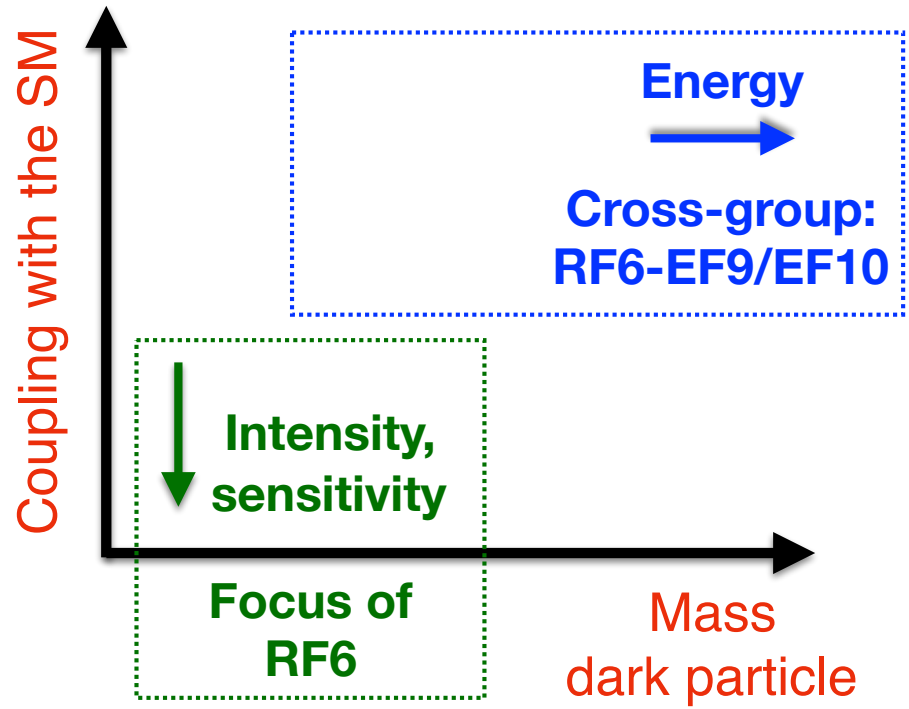
How low do we want to go in coupling?
What are our experimental targets?

A few thoughts:

- in several models, the coupling is naturally suppressed

(e.g. loop suppression, mass suppression etc)





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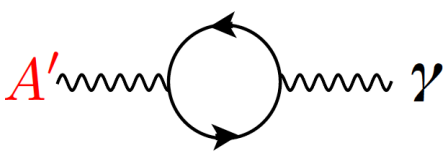
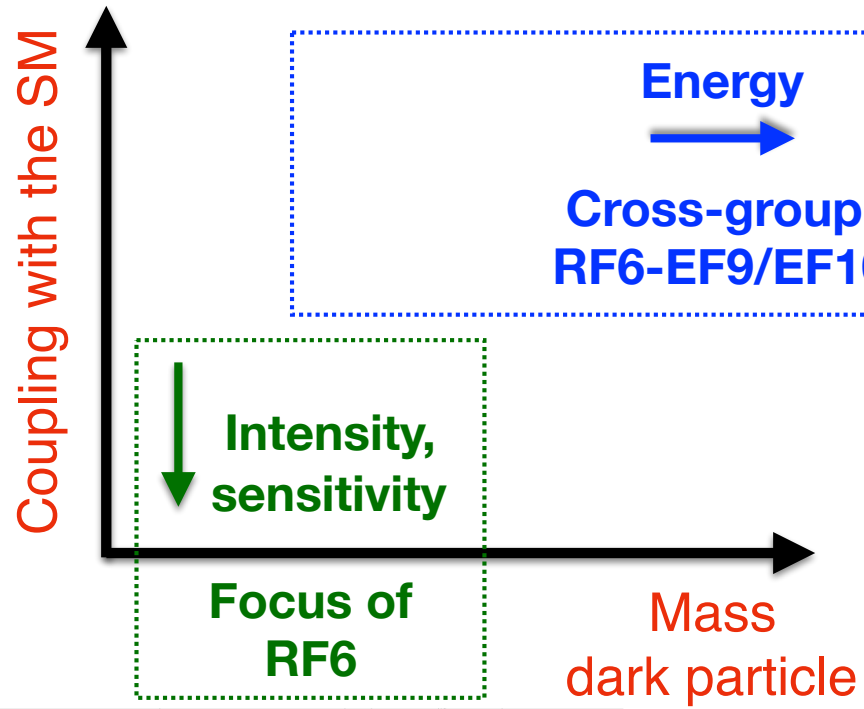
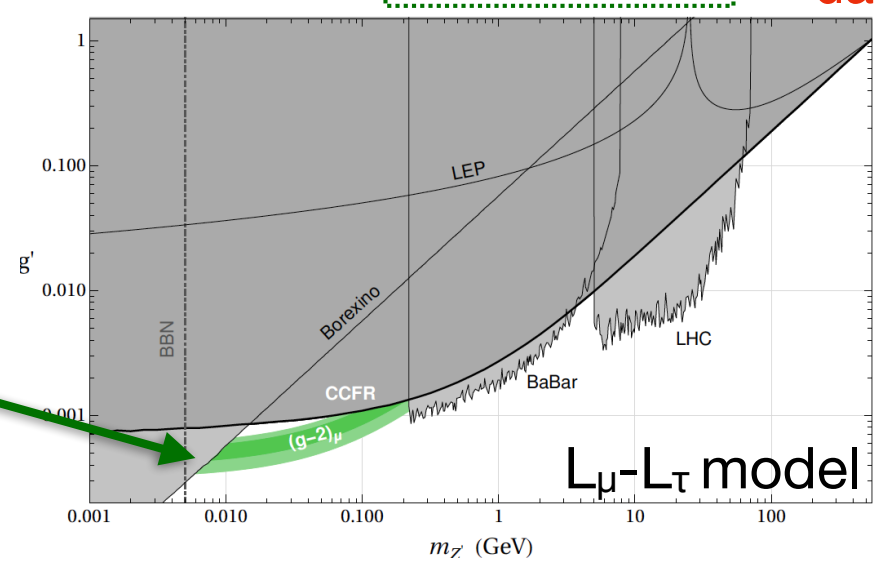


- Anomaly based targets:
e.g. $(g\text{-}2)_\mu$, KOTO, Xenon1T, …





Altmannshofer, SG, Martin-Albo, Sousa, Wallbank, 1902.06765

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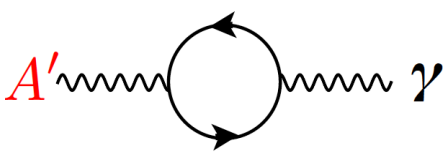

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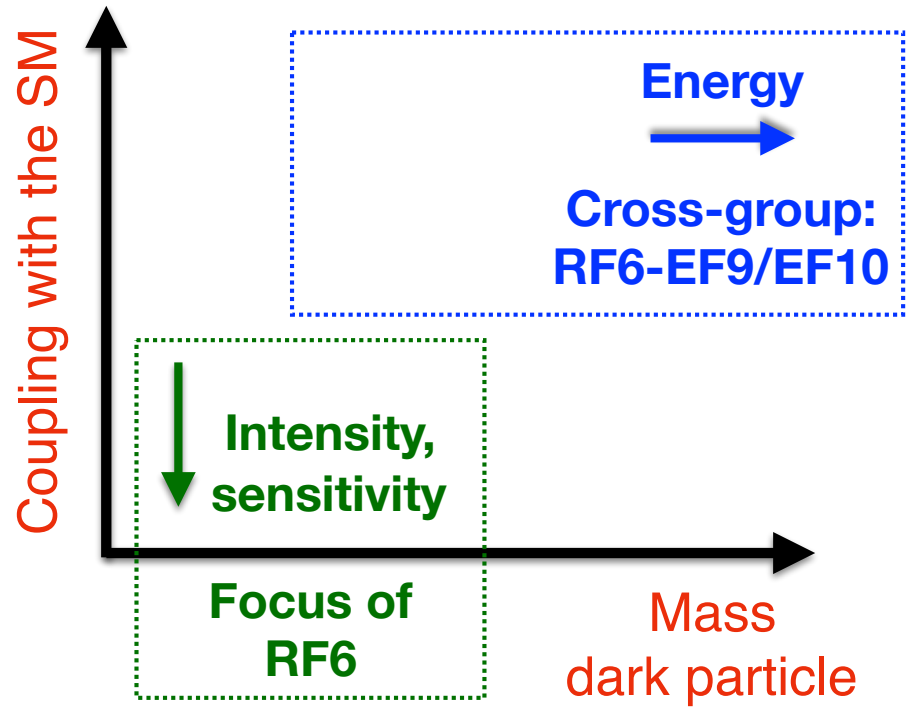
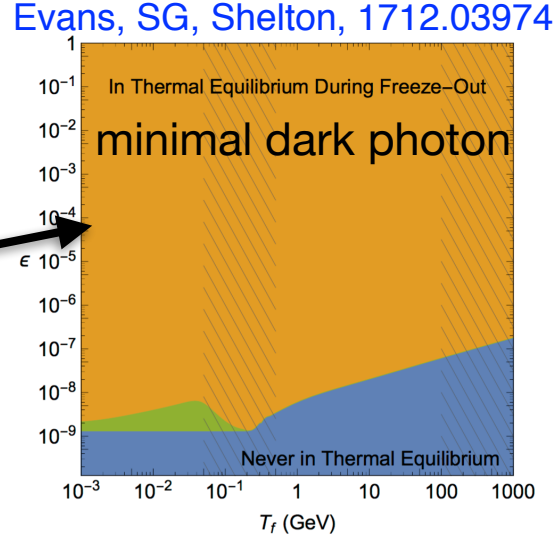
- Thermal Dark Matter target



Evans, SG, Shelton, 1712.03974



Organization of our RF6 group

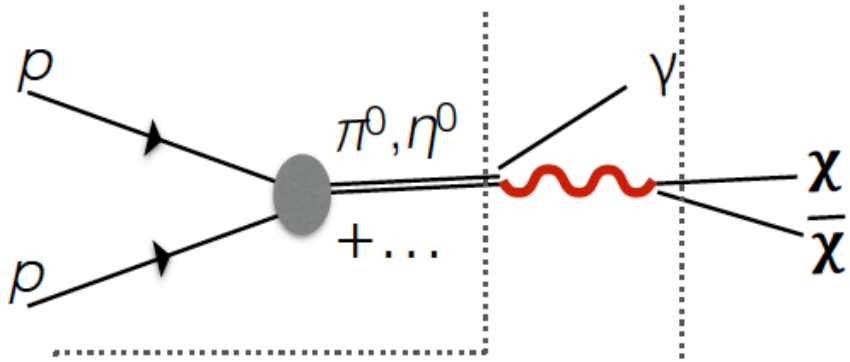
7 broad topics:

1. Theory: Brian Batell (PITT), Phillip Schuster (SLAC)
2. e^+e^- experiments: Chris Hearty (UBC)
3. Fixed-target experiments: Natalia Toro (SLAC), Phil Harris (MIT), Gordan Krnjaic (FNAL)
4. Kaon factories: Babette Dobrich (CERN), Jure Zupan (Cincinnati)
5. Low masses @ EF facilities: Phil Ilten (Cincinnati, liaison with EF7-9-10)
6. Neutrino experiments: NF3 convener Pilar Coloma (Valencia, liaising with us)
7. Other opportunities: (heavy ion experiments, pion and eta experiments, …)

Topics naturally organized by initial-state (i.e. how to produce the dark sector?)

Complementarity with cosmic frontier
(liaison: Susan Gardner (U. of Kentucky))

Many Faces of Dark Sectors



from N.Toro,
EF/RF/AF Cross-frontier
dark sector meeting,
July 16, 2021

People & facilities naturally organize by **initial-state**…

1. Theory of dark sectors
2. Dark sectors at electron-positron colliders
3. Dark sectors at fixed target / beam dump experiments (electron, positron, proton, and muon beams)
4. Dark sectors at kaon factories
5. Low-mass dark sectors at energy-frontier facilities (cross-group with EF09 - BSM: More general explorations / EF10 - BSM: Dark Matter at colliders)
6. Dark sectors at neutrino experiments (cross-group with NF03 - Neutrino physics - BSM)
7. Other experimental opportunities

x **Theories** naturally organize by **intermediate-state** "portals"

x **Science case** naturally aligned with whether **final-state** is SM, non-SM, or mixed

All three axes are important, both in mapping the physics and understanding detector design and capabilities.

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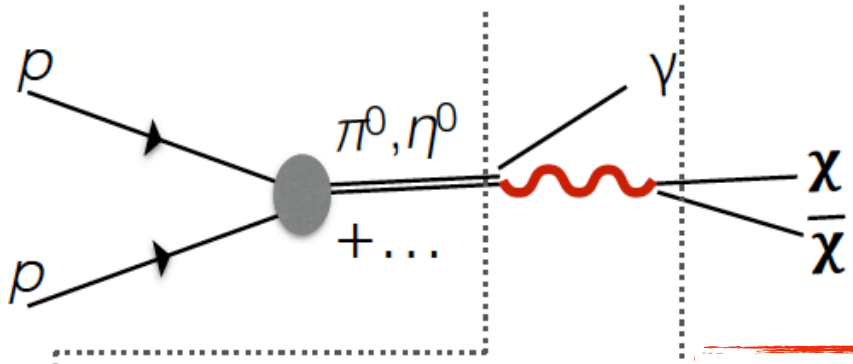

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Final states to look for

Invisible, non-SM

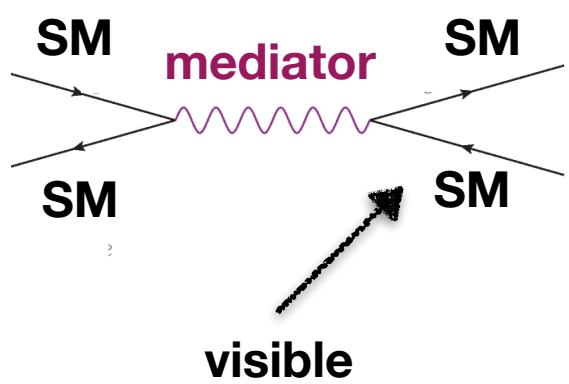
Dark Matter production

Producing stable particles that could be (all or part of) Dark Matter

Visible, SM

Production of portal-mediators that decay to SM particles

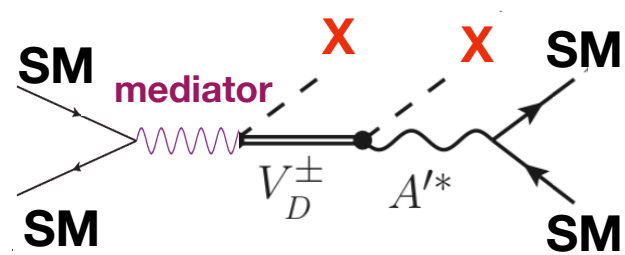
Systematically exploring the portal coupling to SM particles



Mixed visible-invisible

Production of "rich" dark sectors

Testing the structure of the dark sector



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1. Theory

Conveners: Brian Batell (PITT), Phillip Schuster (SLAC)

A non exhaustive list of topics:

- Comprehensive theory motivations for dark sectors;
- Discussion of simplified & benchmarks models for dark sectors;
- Discussion of experimental targets;
- Study of more complete theories and their connection to DM cosmology (thermal freeze-out, freeze-in, strongly interacting DM, …); Interesting recent developments here!
- Filling the gaps in theory simulations/calculations. E.g. utilize secondary beams of SM particles produced in beam dumps to probe dark sectors.

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Benchmark models & organization of the studies (1)

We want to build on the past community effort

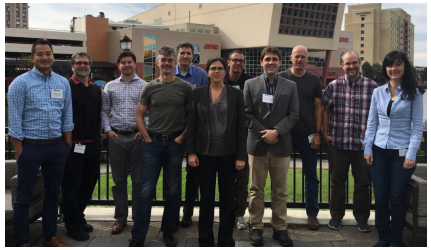
Many workshops/meetings in the last ~10 years.

Significant momentum in last few years on community-wide planning in small experiments relevant to dark matter/dark sectors, including accelerator searches.

SLAC, 2009

SLAC, 2016

Elba, 2017



DC, 2019 (accelerator panel)

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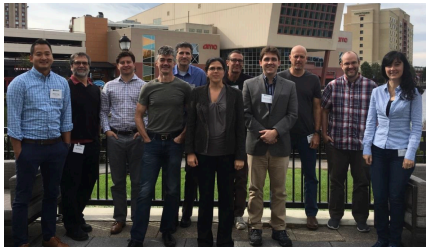

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Most recently:

- Cosmic Visions community workshop, 2017
  https://arxiv.org/pdf/1707.04591.pdf
- Basic Research Needs (BRN) workshop, 2018
  https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf
- Physics beyond colliders initiative, 2019
  https://arxiv.org/abs/1902.00260

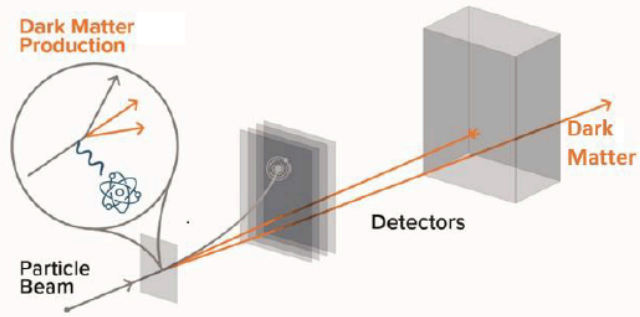
Several benchmark scenarios have been proposed and analyzed

BRN priority research directions

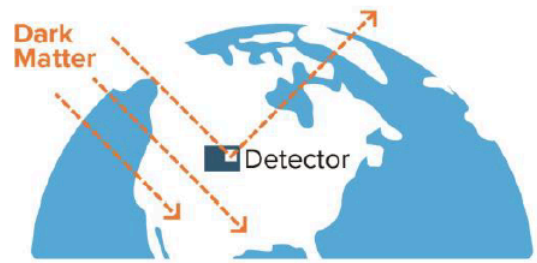
Summary of the High Energy Physics Workshop on Basic Research Needs for Dark Matter Small Projects New Initiatives

October 15 – 18, 2018

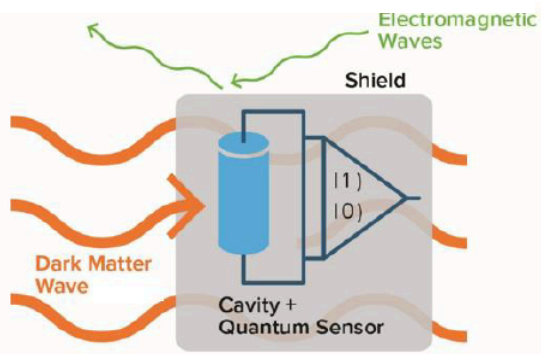
Create & Detect Dark Matter at Accelerators **PRD1**



Detect Galactic Dark Matter Underground **PRD2**



Detect Wave Dark Matter in the Laboratory **PRD3**



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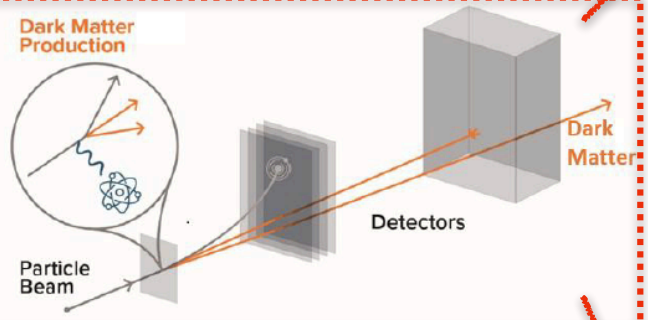

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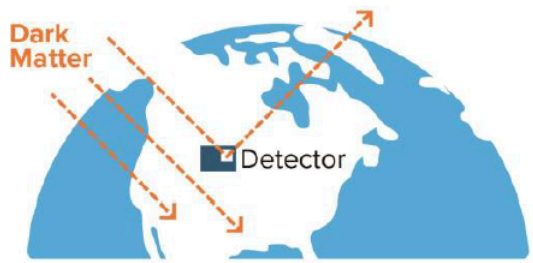

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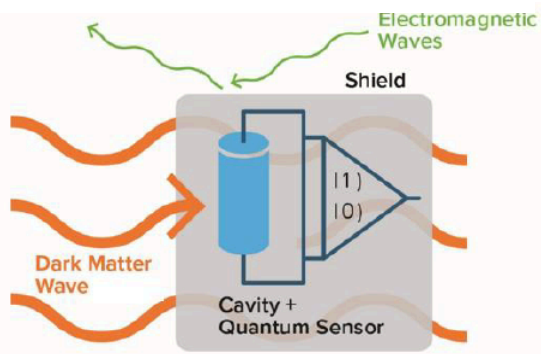

Thrust 1 (near term):

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.

Thrust 2 (near term and long term):

Explore the structure of the dark sector by producing and detecting unstable dark particles.

Benchmark models & organization of the studies (2)

Preliminary

Benchmarks in Final State x Portal Organization

	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	*m_χ vs. y [$m_{A'}/m_\chi$=3,α_D=.5]* **$m_{A'}$ vs. y** [α_D=0.5, 3 m_χ values] m_χ vs.α_D [$m_{A'}/m_\chi$=3, y=y_{fo}] m_χ vs. $m_{A'}$ [α_D=0.5, y=y_{fo}] *Millicharge m vs. q*	$m_{A'}$ vs. ϵ [decay-mode agnostic] ***$m_{A'}$ vs. ϵ [decays]***	**iDM m_χ vs. y** [$m_{A'}/m_\chi$=3,α_D=.5] (anom connection) **SIMP-motivated cascades [slices TBD]** $U(1)_{B-L\,/\,\mu-\tau\,/\,B-3\tau}$ (DM or SM decays)
Scalar	m_χ vs. sinθ [λ=0, fix m_S/m_χ, g_D] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	*m_S vs. sinθ* [λ=0] *m_S vs. sinθ* [λ=s.t. Br(H→ϕϕ ~10^{-2})]?	Dark Higgssstrahlung (w/vector) scalar SIMP models? Leptophilic/leptophobic dark Higgs?
Neutrino	e/μ/τ a la1709.07001?	*m_N vs. U_e* *m_N vs. U_μ* *m_N vs. U_τ* Think more about reasoanble flavor structures	Sterile neutrinos with new forces?
ALP	m_χ vs. fq/l [λ=0, fix m_a/m_χ, g_D] (thermal target excluded) What about f_γ, f_G?	*m_a vs. f_γ* *m_a vs. f_G* *m_a vs. f_q=f_l* (separate?) Think more about reasoanble coupling relations including $f_{W/Z}$	FV axion couplings

\+ Neutron portal? Hidden valleys (or are these out-of-scope?)? See e.g. 2003.02270

Bold = BRN benchmark, *italic=PBC benchmark.* others are new suggestions. Underline=CV benchmarks that were not used in BRN

Comments/suggestions?

2. e^+e^- experiments

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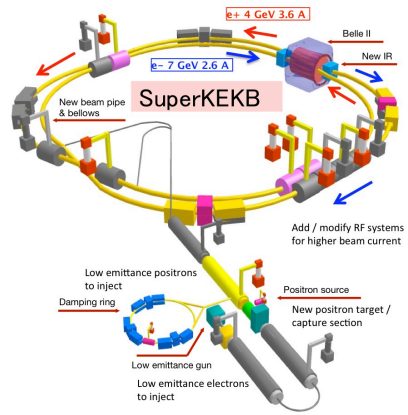
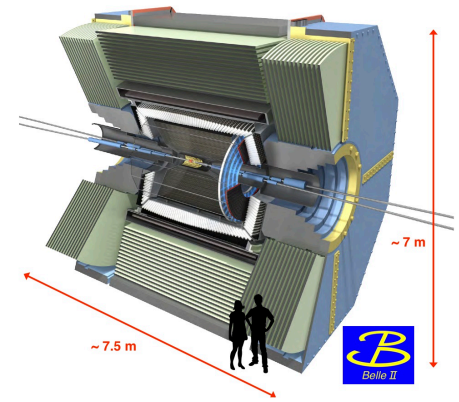
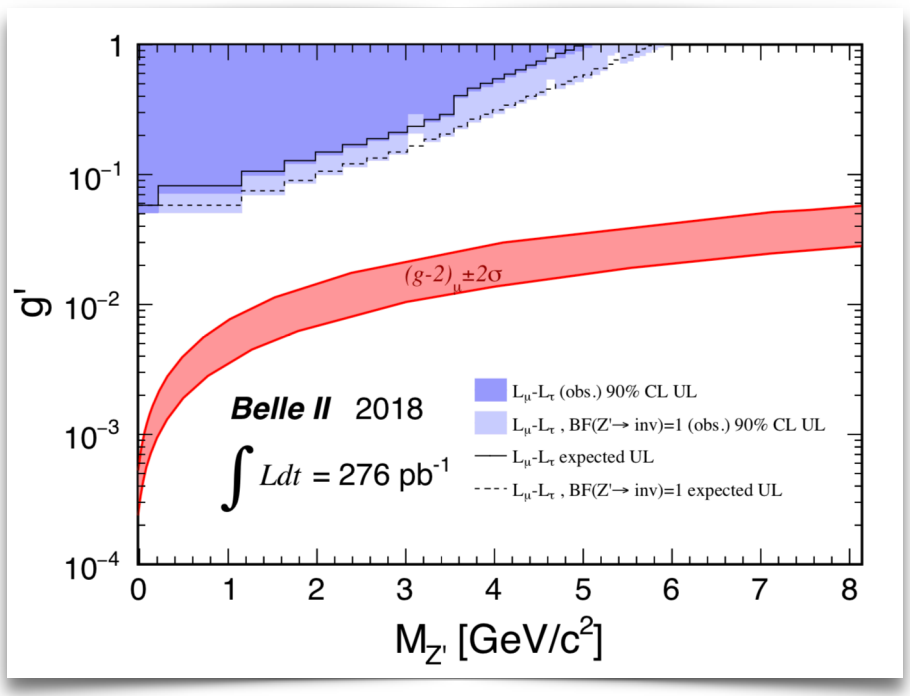
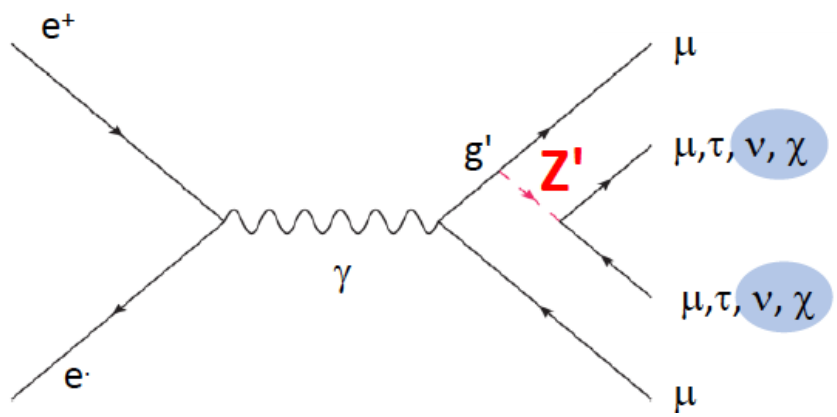
Belle-II experiment





First dark sector search is published!





Phys.Rev.Lett. 124 (2020) no.14, 141801

2. e^+e^- experiments

Conveners: Chris Hearty (UBC)

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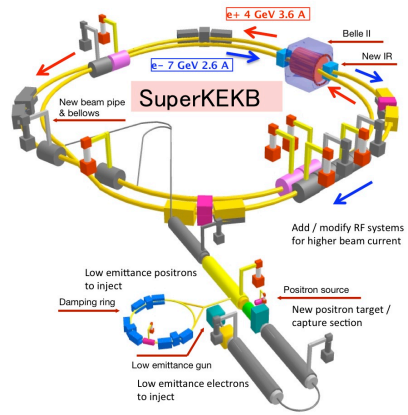
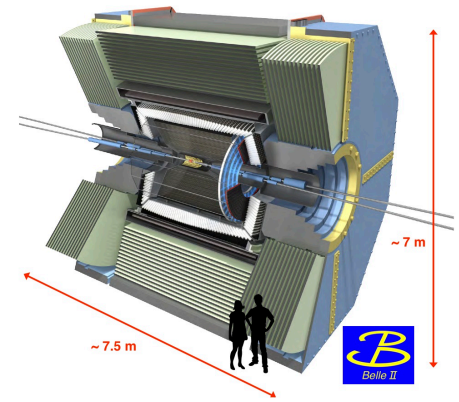
Belle-II experiment





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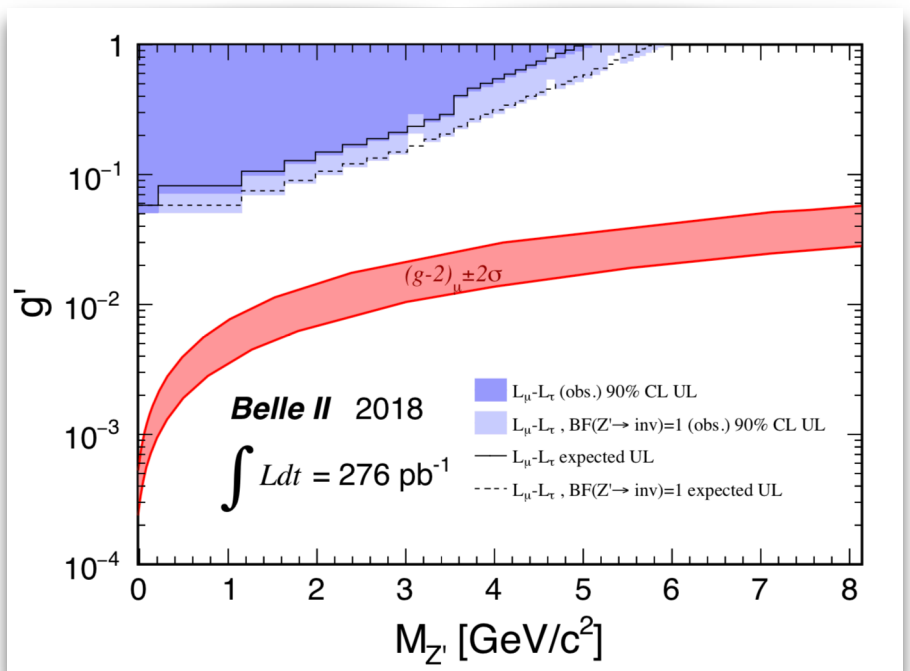

Many possible new searches

DM Production	Mediator Decay Via Portal	Structure of Dark Sector

- invisible/visible dark photons
- axion like particles
- dark scalars from B decays
- sterile neutrinos
- Inelastic Dark Matter
- …

+ searches at BES3 and Babar

3. Fixed-target exp.

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Conveners: Natalia Toro (SLAC), Phil Harris (MIT), Gordan Krnjaic (FNAL)

Several running/proposed experiments to search for prompt or long lived dark sector particles.

Let's mention a few of them.

Disclaimer: this is not an exhaustive list.

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(Partially) Visible final states

Near forward detectors. Examples:

Excellent for detecting low-mass displaced visible dark particles

p-beam: SpinQuest/DarkQuest @ Fermilab

e-beam: HPS @ JLAB

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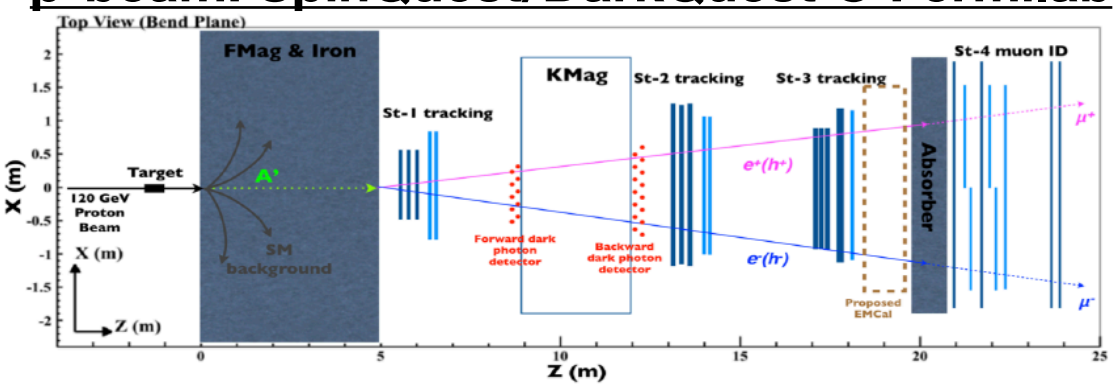
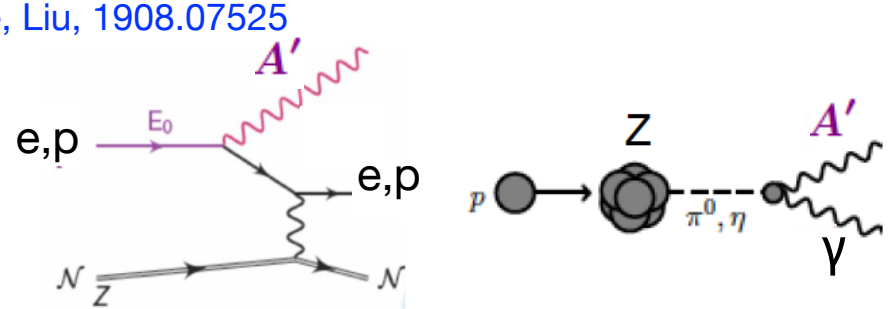


Berlin, SG, Schuster, Toro, 1804.00661

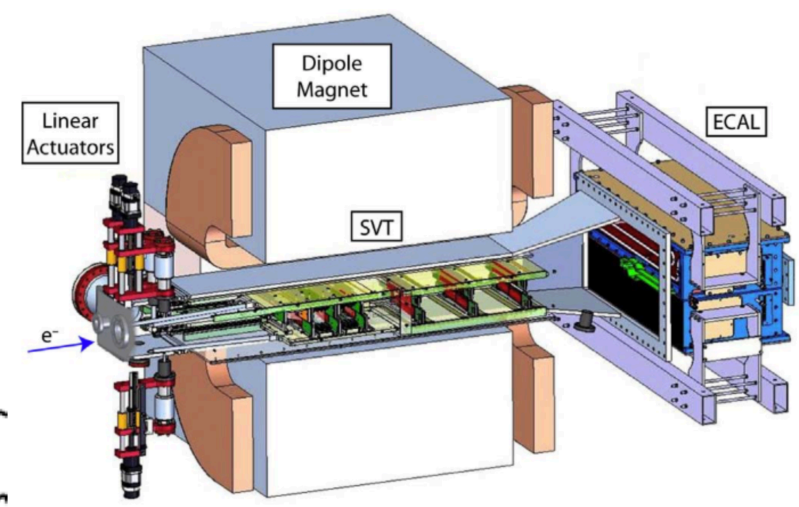
See also LongQuest proposal:

Tsai, De Niverville, Liu, 1908.07525

e.g. dark photon production:



e-beam: HPS @ JLAB



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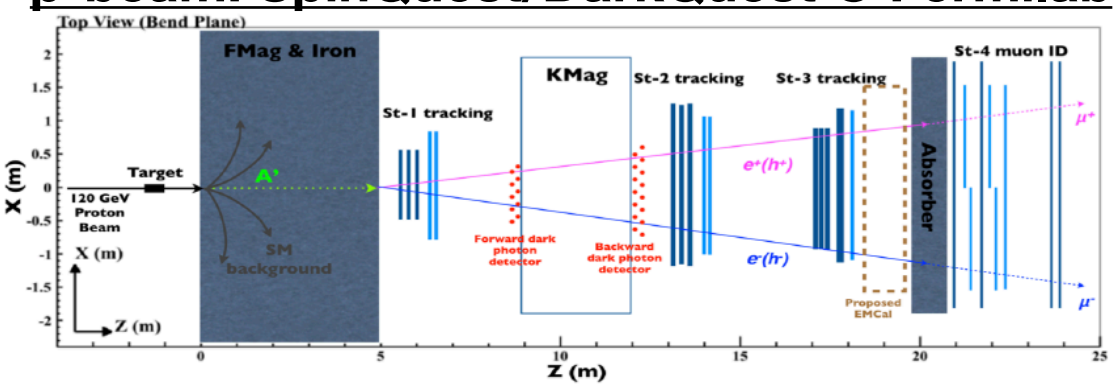


Berlin, SG, Schuster, Toro, 1804.00661

See also LongQuest proposal:

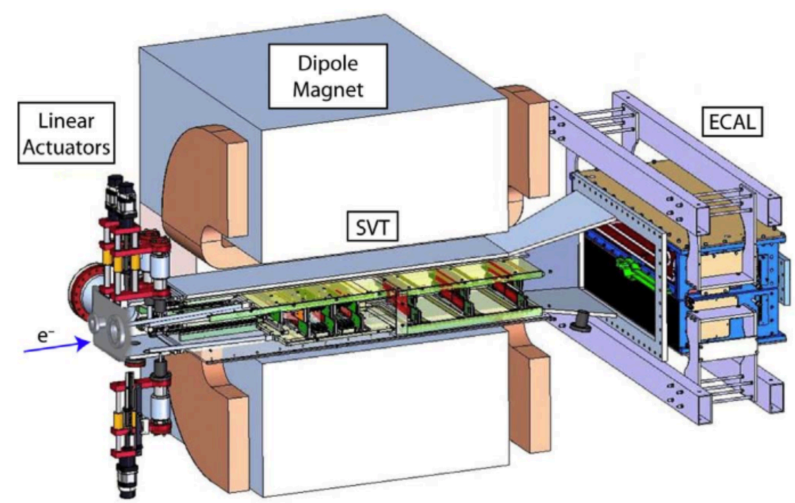
Tsai, De Niverville, Liu, 1908.07525

Complementarity with experiments looking for **prompt resonances**:

e.g. APEX, Mu3e, DarkLight

and **missing mass**: e.g. MMAPS, PADME

e-beam: HPS @ JLAB



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Invisible final states

Missing momentum or energy

Excellent for detecting low-mass invisible dark particles

DM beam dump

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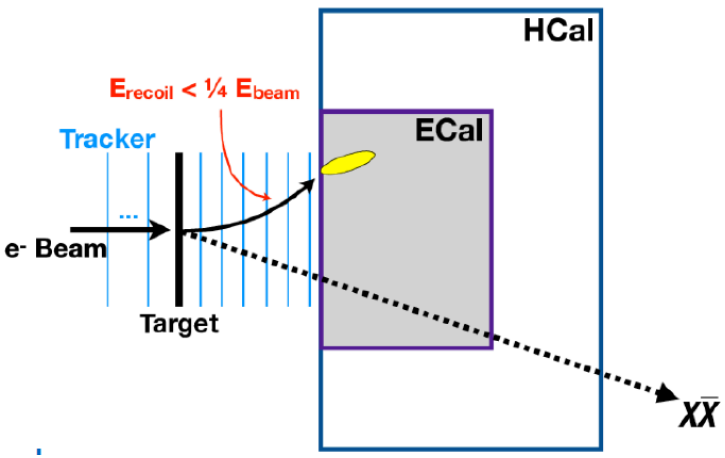
Invisible final states

Excellent for detecting low-mass invisible dark particles

Missing momentum or energy

NA64, LDMX, M3

electron and muon beams

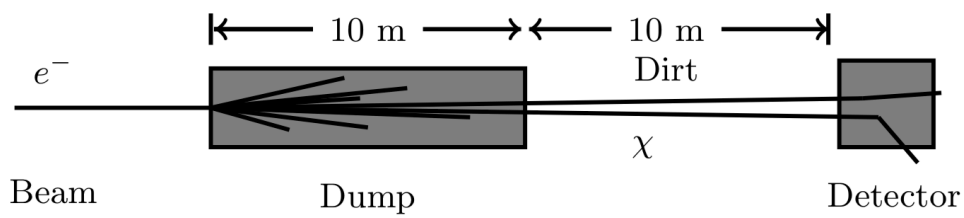


Unique capability to "image" individual beam particles

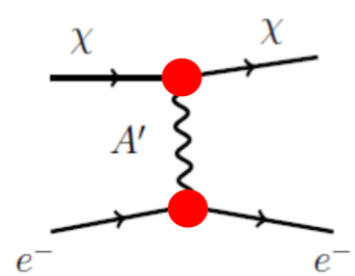
DM beam dump

BDX, DarkMESA

Izaguirre, Krnjaic, Schuster, Toro, 1307.6554



DM-detector scattering



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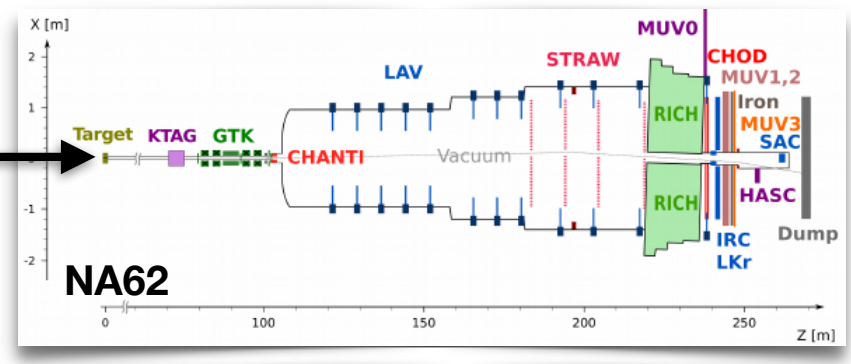
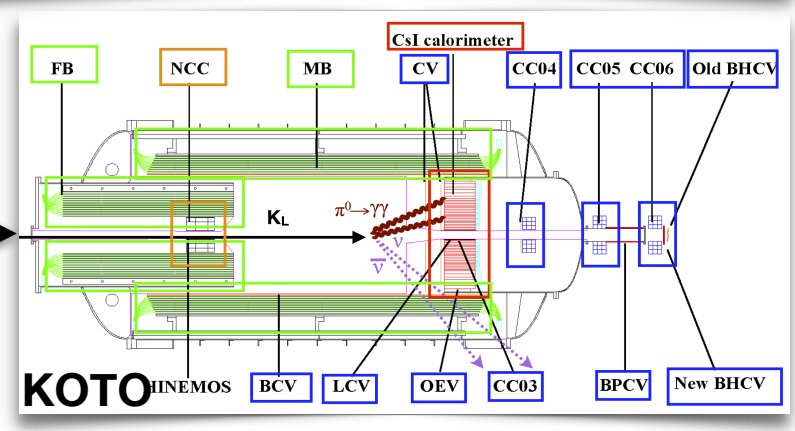
NA62 @ CERN ($K^{\pm} \rightarrow \pi^{\pm} \nu \nu$)
KOTO @ JPARC ($K_L \rightarrow \pi^0 \nu \nu$)
Future: KLEVER @ CERN ($K_L \rightarrow \pi^0 \nu \nu$)

p beam



p beam



(Interesting anomaly at KOTO)

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Production of dark particles through

1. Kaon decays
2. proton beam-target scattering
3. Decays of secondary particles

(e.g. pion decays) Frascati Phys.Ser. 69 (2019) 194-199

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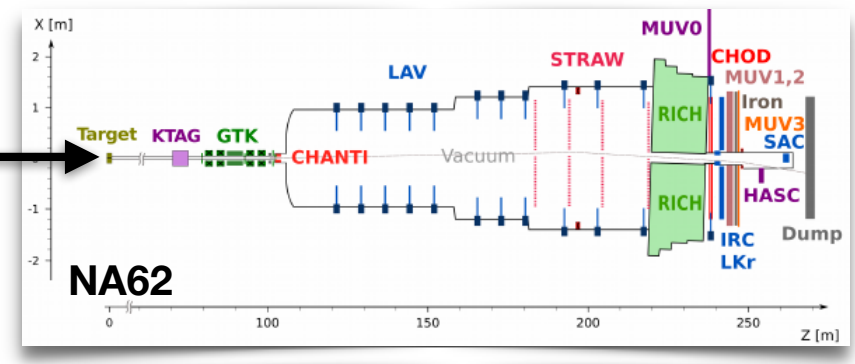

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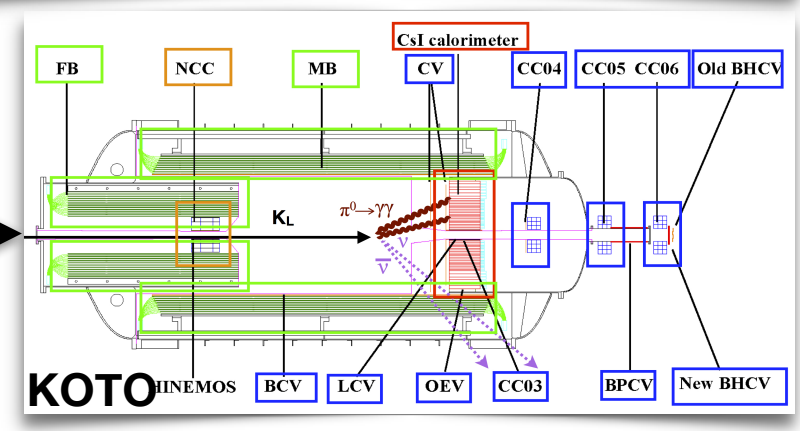

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Future: KLEVER @ CERN ($K_L \to \pi^0 \nu \nu$)

Potential for future discovery

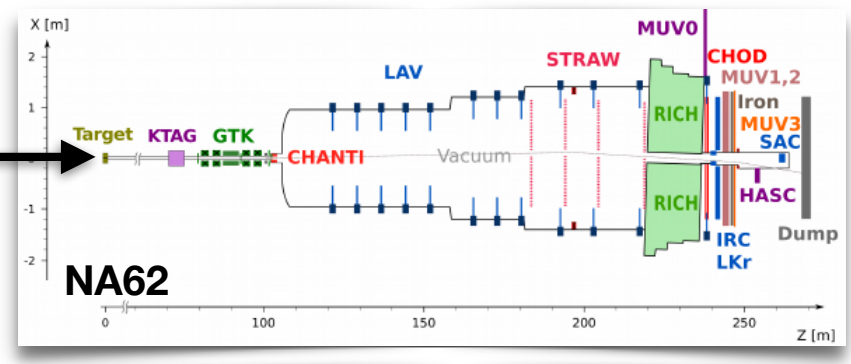
1. $K \to \pi$ + missing energy:
Dark photons + light dark matter,
Higgs portal scalar, …

1. $K \to \pi$ + visible (e^+e^-, 2γ, …):
Dark photons, axion-like-particles, …

2. Production of dark particles in the dump
(Possible beam-dump run of NA62)

3. $\pi^0 \to \gamma$ + missing energy:
Dark photons, …

p beam



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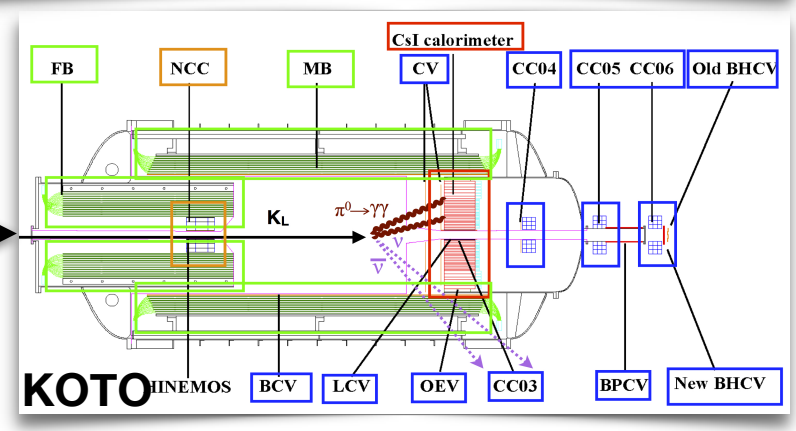

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5. EF facilities

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Collaboration with EF09/EF10

The **(HL) LHC(b)** will search for (short and long-lived) dark sector particles in a large range of masses

DM Production	Mediator Decay Via Portal	Structure of Dark Sector

In addition, several experiments have been proposed to search for long-lived dark particles:
- codex-b,
- faser-II,
- mathusla,
- milliQan

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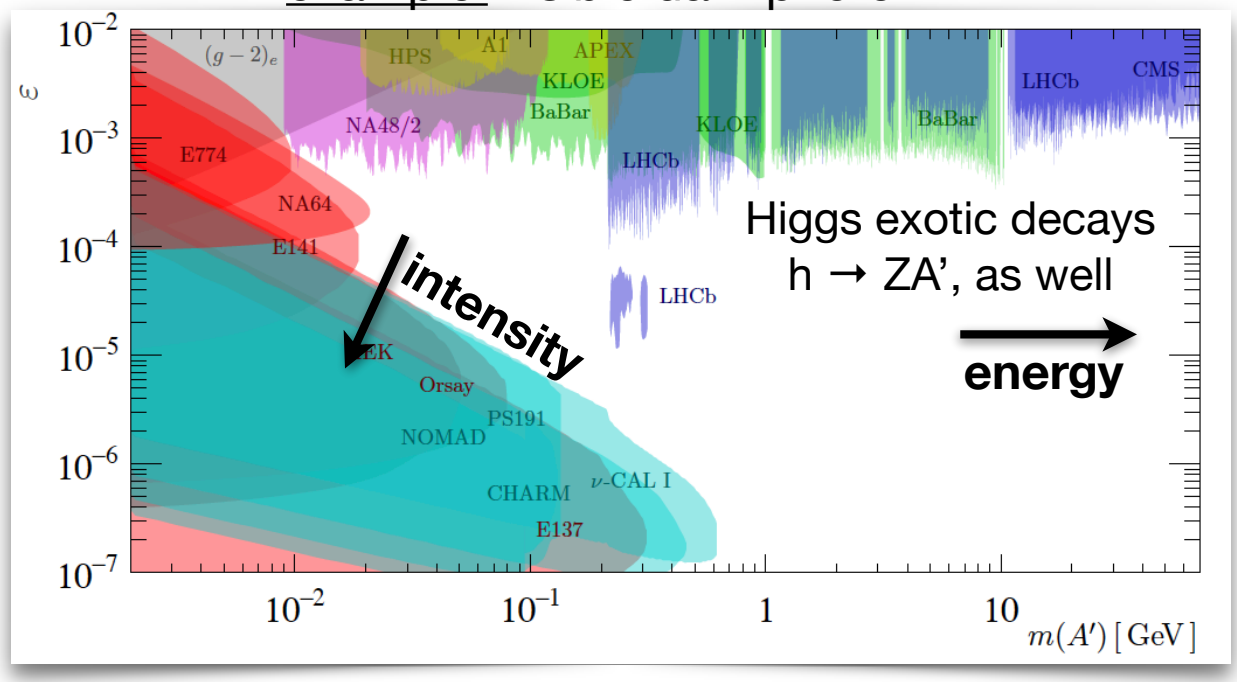
example: visible dark photon



Complementarity with high intensity

High energy + high intensity ⟶ a huge mass range can be covered!

6. Neutrino exp.

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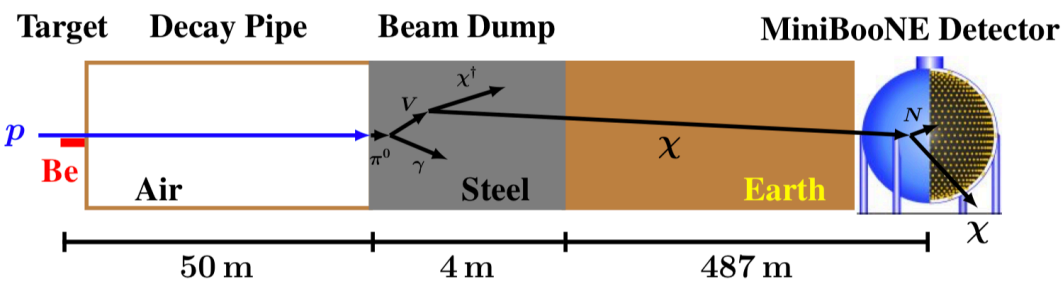
Collaboration with NF3

Neutrino (near) detectors can be used to search for dark sectors

Symbiotic neutrino/DM programs



Aguilar-Arevalo et al., 1702.02688

see also Batell, Pospelov, Ritz, 0906.5614

- DM-nucleus scattering
- DM-electron scattering

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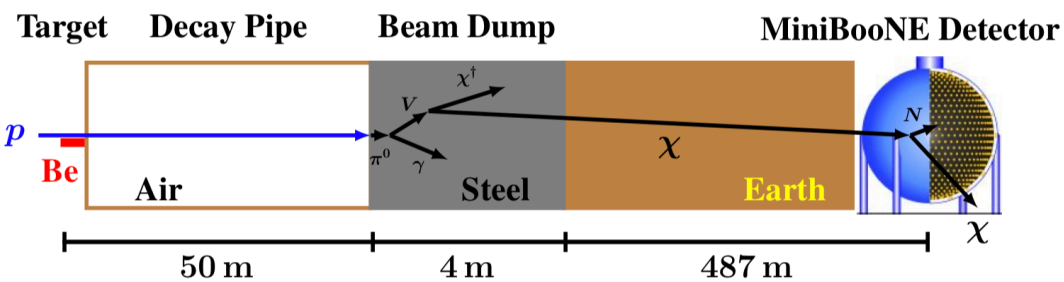

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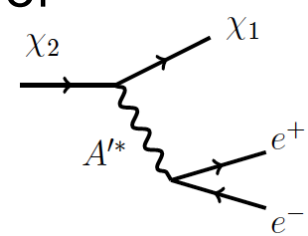
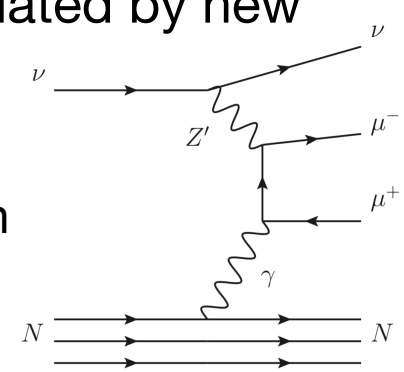
- DM-nucleus scattering
- DM-electron scattering

Observation of (semi) visible signatures

- from the production of dark particles



- from the scattering of SM neutrinos mediated by new forces



<u>example:</u>
trident production

Altmannshofer, SG, Pospelov, Yavin, 1403.1269

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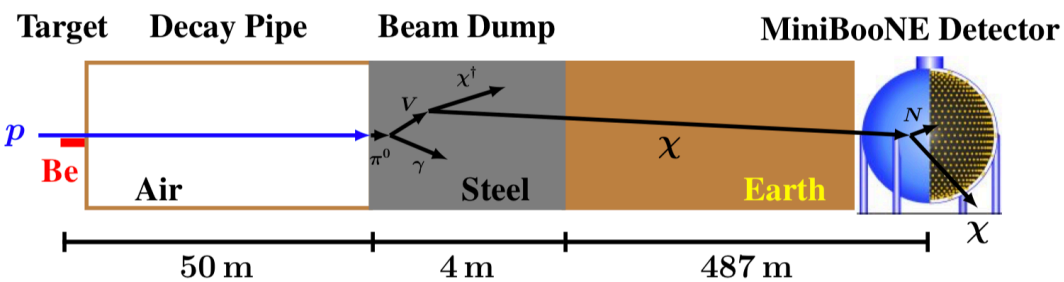
Neutrino (near) detectors can be used to search for dark sectors

Symbiotic neutrino/DM programs



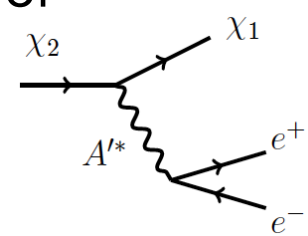
Aguilar-Arevalo et al., 1702.02688
see also Batell, Pospelov, Ritz, 0906.5614

- DM-nucleus scattering
- DM-electron scattering

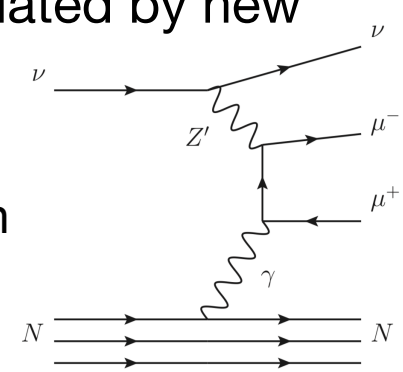
There is a variety of current/future accelerator neutrino experiments which can carry out dark sector searches:
COHERENT, CCM, NOvA, MicroBooNE, SBND, ICARUS, DUNE, …

Observation of (semi) visible signatures

- from the production of dark particles



- from the scattering of SM neutrinos mediated by new forces



<u>example:</u>
trident production

Altmannshofer, SG, Pospelov, Yavin, 1403.1269

7. Other opportunities

1. Theory: Brian Batell (PITT), Phillip Schuster (SLAC)
2. e+e- experiments: Chris Hearty (UBC)
3. Fixed-target experiments: Natalia Toro (SLAC), Phil Harris (MIT), Gordan Krnjaic (FNAL)
4. Kaon factories: Babette Dobrich (CERN), Jure Zupan (Cincinnati)
5. Low masses @ EF facilities: Phil Ilten (Cincinnati, liaison with EF7-9-10)
6. Neutrino experiments: NF3 convener Pilar Coloma (Valencia, liaising with us)
7. Other opportunities: (heavy ion experiments, pion and eta experiments, …)

Possible topics:

- dark sectors at heavy ion experiments (overlap with EF7)
- dark sectors at pion or eta factories
- neutron—dark-neutron oscillation searches
- …

- More general explorations:

physics potential enabled by the Fermilab booster upgrade (BU) and PIP2
(Fermilab plans to upgrade its accelerator infrastructure to deliver
2.4 MW 120 GeV proton beam for DUNE.
High intensity lower energy proton beams from initial acceleration stages,
PIP2 and the BU, will be available for other experiments.
The potential exists to produce lepton beams as well.)
https://indico.fnal.gov/event/23352/

Join us

Contacts:

Stefania Gori (sgori@ucsc.edu), Mike Williams (mwill@mit.edu)

(1) Brian Batell (batell@pitt.edu), Phillip Schuster (schuster@slac.stanford.edu), (2) Chris Hearty (hearty@physics.ubc.ca), (3) Natalia Toro (ntoro@slac.stanford.edu), Phil Harris (pcharris@mit.edu), Gordan Krnjaic (krnjaicg@fnal.gov), (4) Babette Dobrich (babette.dobrich@cern.ch), Jure Zupan (zupanje@ucmail.uc.edu), (5) Phil Ilten (philip.james.ilten@cern.ch), (6) Pilar Coloma (pcoloma@ific.uv.es)

Meetings:

- Cross-frontier RF6-EF9-EF10-AF5 workshop July 15-16
https://indico.fnal.gov/event/44030/timetable/#20200715
- **RF6 kickoff meeting, August 12-13**
- Snowmass Community Planning meeting, October 5-9

RF6 seeks engagement from everyone studying dark sector physics at ANY accelerator-based facility, and aims to build a comprehensive report

Subscribe:

- mailing list (SNOWMASS-RPF-06-DARK-SECTOR@fnal.gov)
- SLACK channel (#rpf-06-dark-sector)

instructions on how to subscribe at https://snowmass21.org/rare/dark

Expressions of interest: https://docs.google.com/forms/d/e/1FAIpQLSeLEgcQxYTooyS17LoR06GpZD2tXBu8QG4hQqvPTxSwTIE78w/viewform

Deadlines:

Letters of Interest (April 1 – August 31, 2020) – https://snowmass21.org/loi
Contributed Papers (April 1 – July 31, 2021) – https://snowmass21.org/submissions/

Conclusions and Q&A

- Dark Sectors represent a broad arena for new physics, with dark matter as powerful motivation (+ strong CP problem, baryogenesis, neutrino masses, …);
- Plenty of recent developments on the theory side;

- Much is unexplored;
- Bounded, reachable and motivated regions of parameter space represent exciting directions for near-term experiments.

Possible discussion topics:

- Benchmarks/signatures
- New experimental opportunities not mentioned here
- Role of theory
- add your own!