Snowmass 2021: Dark matter at colliders

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2021/10/27 - Snowmass EF 10 topical group

Quick re-introduction to EF10

Organization of work around benchmarks

The DM @ Colliders community is quite broad and **shares work** with many other **TGs and Frontiers**
→ we want to be as **inclusive** as possible while keeping an eye on **big picture**

1. Studies of **common DM benchmarks** agreed-upon with other groups/frontiers
   - Leads to "big picture" plots e.g. comparing other experiments
     - Similar to what was done for the European Strategy Briefing Book
   - Our contributors have been working towards providing **technical help** to the collaborations and interested parties
     - e.g. model repository, common code pipelines (potentially with CompF07?)
       - Interest within EF10, where some contributors work within this project
2. Studies that **highlight potential differences wrt common benchmarks**
   - Not necessarily comprehensive in terms of experimental coverage
   - E.g. highlight different complementarity or different signatures
3. Studies that **point out novel / less-explored DM models** (mostly joint with EF09)
   - E.g. highlighting uncovered phase space

List of focused questions from Snowmass EF10 (DM @ Colliders)

1. How can we best test the **WIMP** paradigm?
    - Through the simplest/minimal WIMP models (EW multiplets) and their extensions
    - Using simple mediator models (s-channels/t-channels) already used for collider searches
    - Through the Higgs portal, since the Higgs boson is the most relevant portal operator between SM and DM and there are connections to precision measurements

2. How can we best explore **beyond-WIMP** scenarios?
    - Using portals that privilege light dark sectors / dark matter
    - Focusing on less-explored signatures of dark sectors that can highlight present/future blind spots

3. How to best exploit **synergies & complementarity** between DM@colliders & other TGs and Frontiers
    - In terms of different experiments / observations answering the same physics question on the nature of DM
    - In terms of detector, data acquisition and trigger design [e.g. IF04 kick-off]

EF10 goals recap: testing the WIMP paradigm

1. **Electroweak multiplets [meeting 04/06/20, 02/07/20]**
   - Electroweak multiplet: higgsino/wino(minimal DM). Mediator: W/Z/h.
   - Target: TeV(and above)-scale DM masses, motivated by relic density

Common benchmarks with EF08/CF

2. **Simplified mediator models [meeting 18/06/20]**
   - S-channel and t-channel mediators. (This meeting)
   - Well established benchmarks for LHC, simple benchmarks for comparisons
   - Main target: DM masses < ½ mediator mass.

Common benchmarks with EF09/RF06/CF

3. **Higgs portal [upcoming meeting]**
   - Well motivated coupling between SM to the dark world
   - Main target: DM masses < ½ Higgs mass.

Common benchmark with Higgs EFs

EF10 goals recap: beyond WIMPs

[joint EF09-10/RF05/AF06 meeting 16-17/07]

1. (Very) different DM masses and couplings with respect to the WIMP
   a. Strongly interacting DM, light DM (< GeV)
      i. E.g. dark QCD benchmarks *LOI*

Common benchmarks in discussion with EF09/RF05, also to be discussed with CF

2. Different portals with respect to LHC simplified models:
   a. dark photon and generic dark scalar/pseudoscalar (including rare decays)
      i. Develop connections between these portals and DM simplified models
      See this talk by N. Toro at the "LLP preparatory meeting" (EF8-10/RF05/AF06)
      ii. Understand how to present them coherently - see this talk by N. Toro at EF10 meeting

Next steps

Tentative plan for the future

- Resuming monthly meetings
  - Next meetings: **September 22, Oct 27, and Nov 17**

- To potential contributors: don't hesitate to bring updates to our attention
  (even though we will inquire for progress with LOI authors)
  - We can only include in final whitepapers what we know about!

- Discussions for DM complementarity plots also expected to resume once Cosmic Frontier restarts (September onwards)

- Discussion ongoing for a joint EF-8/9/10 workshop in early 2022

Backup slides

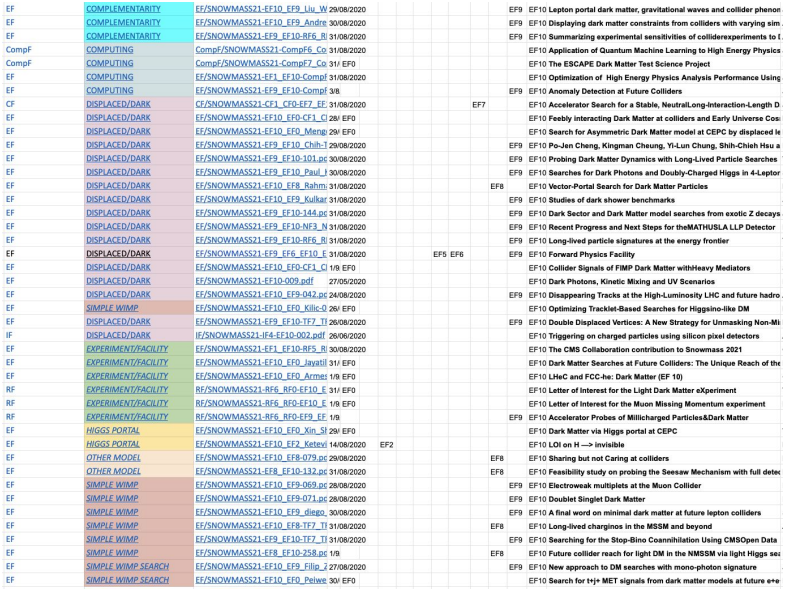
Before the break: work on LOIs

44 LOIs so far [EF10 LOIs: links and titles]

Mostly cross-listed with EF09/CF

Roughly grouped by topics:

- WIMP (9) *Covered in September 10 biweekly meeting.*
- Alternative models (2) *Covered in September 10 biweekly meeting.*
- Displaced, dark sector (17)
- Higgs portal (2)
- Directly related to a facility. (5) *Covered in Sept 23rd meeting*
- Computing. (4)
- Complementarity between different probes (4)
  Covered in Sept 23rd meeting



EF	COMPLEMENTARITY	EF/SNOWMASS21-EF10_EF9_Liu_W	29/08/2020					EF9	EF10 Lepton portal dark matter, gravitational waves and collider phenon
EF	COMPLEMENTARITY	EF/SNOWMASS21-EF10_EF9_Andre	30/08/2020					EF9	EF10 Displaying dark matter constraints from colliders with varying sim
EF	COMPLEMENTARITY	EF/SNOWMASS21-EF9_EF10-RF6_R	31/08/2020					EF9	EF10 Summarizing experimental sensitivities of colliderexperiments to D
CompF	COMPUTING	CompF/SNOWMASS21-CompF6_Co	31/08/2020						EF10 Application of Quantum Machine Learning to High Energy Physics
CompF	COMPUTING	CompF/SNOWMASS21-CompF7_Co	31/ EF0						EF10 The ESCAPE Dark Matter Test Science Project
EF	COMPUTING	EF/SNOWMASS21-EF1_EF10-CompF	31/08/2020						EF10 Optimization of High Energy Physics Analysis Performance Using
EF	COMPUTING	EF/SNOWMASS21-EF9_EF10-CompF	3/8					EF9	EF10 Anomaly Detection at Future Colliders
CF	DISPLACED/DARK	CF/SNOWMASS21-CF1_CF0-EF7_EF	31/08/2020				EF7		EF10 Accelerator Search for a Stable, NeutralLong-Interaction-Length D
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10_EF0-CF1_Cl	28/ EF0						EF10 Feebly interacting Dark Matter at colliders and Early Universe Cos
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10_EF0_Meng	29/ EF0						EF10 Search for Asymmetric Dark Matter model at CEPC by displaced le
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10_Chih-T	29/08/2020					EF9	EF10 Po-Jen Cheng, Kingman Cheung, Yi-Lun Chung, Shih-Chieh Hsu a
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10-101.pc	30/08/2020					EF9	EF10 Probing Dark Matter Dynamics with Long-Lived Particle Searches
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10_Paul_J	30/08/2020					EF9	EF10 Searches for Dark Photons and Doubly-Charged Higgs in 4-Leptor
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10_EF8_Rahm	31/08/2020				EF8		EF10 Vector-Portal Search for Dark Matter Particles
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10_EF9_Kulkar	31/08/2020					EF9	EF10 Studies of dark shower benchmarks
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10-144.pc	31/08/2020					EF9	EF10 Dark Sector and Dark Matter model searches from exotic Z decays
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10-NF3_N	31/08/2020					EF9	EF10 Recent Progress and Next Steps for theMATHUSLA LLP Detector
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10-RF6_R	31/08/2020					EF9	EF10 Long-lived particle signatures at the energy frontier
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF6_EF10_E	31/08/2020		EF5	EF6		EF9	EF10 Forward Physics Facility
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10_EF0-CF1_Cl	1/9 EF0						EF10 Collider Signals of FIMP Dark Matter withHeavy Mediators
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10-009.pdf	27/05/2020						EF10 Dark Photons, Kinetic Mixing and UV Scenarios
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10_EF9-042.pc	24/08/2020					EF9	EF10 Disappearing Tracks at the High-Luminosity LHC and future hadro
EF	SIMPLE WIMP	EF/SNOWMASS21-EF10_EF0_Kilic-0	26/ EF0						EF10 Optimizing Tracklet-Based Searches for Higgsino-like DM
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10-TF7_TI	26/08/2020					EF9	EF10 Double Displaced Vertices: A New Strategy for Unmasking Non-Mi
IF	DISPLACED/DARK	IF/SNOWMASS21-IF4-EF10-002.pdf	26/06/2020						EF10 Triggering on charged particles using silicon pixel detectors
EF	EXPERIMENT/FACILITY	EF/SNOWMASS21-EF1_EF10-RF5_R	30/08/2020						EF10 The CMS Collaboration contribution to Snowmass 2021
EF	EXPERIMENT/FACILITY	EF/SNOWMASS21-EF10_EF0_Jayatil	31/ EF0						EF10 Dark Matter Searches at Future Colliders: The Unique Reach of the
EF	EXPERIMENT/FACILITY	EF/SNOWMASS21-EF10_EF0_Armes	1/9 EF0						EF10 LHeC and FCC-he: Dark Matter (EF 10)
RF	EXPERIMENT/FACILITY	RF/SNOWMASS21-RF6_RF0-EF10_E	31/ EF0						EF10 Letter of Interest for the Light Dark Matter eXperiment
RF	EXPERIMENT/FACILITY	RF/SNOWMASS21-RF6_RF0-EF10_E	1/9 EF0						EF10 Letter of Interest for the Muon Missing Momentum experiment
RF	EXPERIMENT/FACILITY	RF/SNOWMASS21-RF6_RF0-EF9_EF	1/9					EF9	EF10 Accelerator Probes of Millicharged Particles&Dark Matter
EF	HIGGS PORTAL	EF/SNOWMASS21-EF10_EF0_Xin_SI	29/ EF0						EF10 Dark Matter via Higgs portal at CEPC
EF	HIGGS PORTAL	EF/SNOWMASS21-EF10_EF2_Ketevi	14/08/2020	EF2					EF10 LOI on H --> invisible
EF	OTHER MODEL	EF/SNOWMASS21-EF10_EF8-079.pc	29/08/2020				EF8		EF10 Sharing but not Caring at colliders
EF	OTHER MODEL	EF/SNOWMASS21-EF8_EF10-132.pc	31/08/2020				EF8		EF10 Feasibility study on probing the Seesaw Mechanism with full detec
EF	SIMPLE WIMP	EF/SNOWMASS21-EF10_EF9-069.pc	28/08/2020					EF9	EF10 Electroweak multiplets at the Muon Collider
EF	SIMPLE WIMP	EF/SNOWMASS21-EF10_EF9-071.pc	28/08/2020					EF9	EF10 Doublet Singlet Dark Matter
EF	SIMPLE WIMP	EF/SNOWMASS21-EF10_EF9_diego	30/08/2020					EF9	EF10 A final word on minimal dark matter at future lepton colliders
EF	SIMPLE WIMP	EF/SNOWMASS21-EF10_EF8-TF7_TI	31/08/2020				EF8		EF10 Long-lived charginos in the MSSM and beyond
EF	SIMPLE WIMP	EF/SNOWMASS21-EF9_EF10-TF7_TI	31/08/2020					EF9	EF10 Searching for the Stop-Bino Coannihilation Using CMSOpen Data
EF	SIMPLE WIMP	EF/SNOWMASS21-EF8_EF10-258.pc	1/9				EF8		EF10 Future collider reach for light DM in the NMSSM via light Higgs se
EF	SIMPLE WIMP SEARCH	EF/SNOWMASS21-EF10_EF9_Filip_Z	27/08/2020					EF9	EF10 New approach to DM searches with mono-photon signature
EF	SIMPLE WIMP SEARCH	EF/SNOWMASS21-EF10_EF0_Peiwe	30/ EF0						EF10 Search for t+j+ MET signals from dark matter models at future e+e

We answered ~all LOIs individually

- Useful to build a discourse with the proponents, and to match-make with SEC members who contacted us

Recordings and notes available in the spreadsheet

What happened during the break?

Our feeling: people (us included) really took a Snowmass break
→ mostly worked on other things (still relevant for Snowmass)

We did not organize a conversation meeting - mostly because main EF10 contributors were busy/left

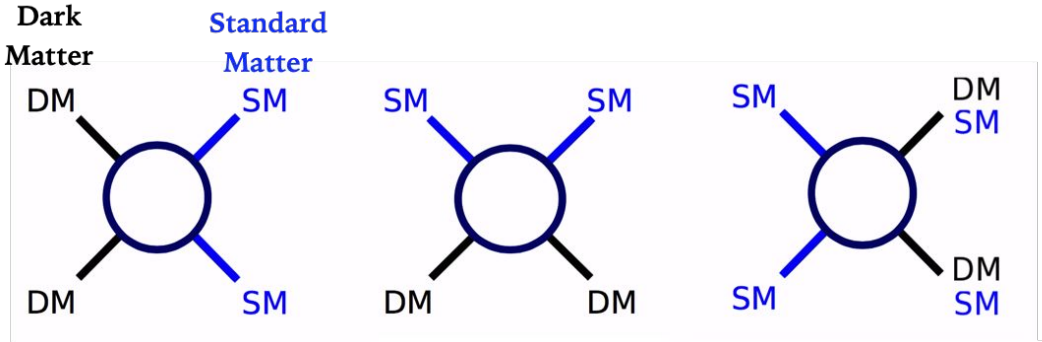
Parallel efforts were encouraged and followed, naming the most relevant/active:

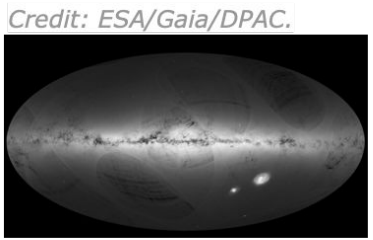
- Snowmass *Dark Showers group* (joint with EF09) - Suchita Kulkarni [th], Marie-Helene Genest [exp]
  - Had a number of meetings on new publications / benchmark discussions (~ every 3 weeks)
  - Organized a tutorial/workshop with experts during the Long Lived Particles Community Workshop
  - Talk by Suchita Kulkarni today
- WIMPs at muon colliders
  - There have been several studies on the search for WIMP dark matter (focusing on the so called Minimal Dark Matter scenario) at muon collider (with various energy and luminosity options), as well as a few more on-going work.
  - While it may not be as complete as the study for the 100 TeV pp collider for the briefing book, a set of basic results are available now to paint a big picture on this topic.
  - Talks by M. Costa and J. Zurita today
- WIMPs and lighter DM at hadron/lepton colliders → see also next slide
  - Some of our main contributors graduated, some are back as PhD students starting in September, some are new
  - One of the postdoc leaders of whitepaper also moving on to new jobs (!colliders) but want to keep contributing once Snowmass restarts
  - Talks by A. Albert today
- New Wino/Higgsino studies with monojet signature ongoing - Andie Wall & Elliott Lipeles

DM@colliders in the broader Snowmass context

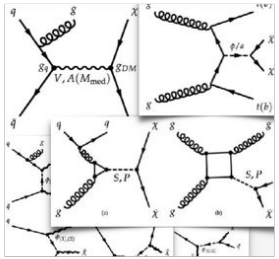
Observations, experiments and theories all needed for DM discovery

- DD/ID can discover DM with cosmological origin
- Colliders / accelerators can produce DM and probe the dark interaction
- Observations motivating DM come from astrophysics / gravitational interactions
- Theoretical frameworks are necessary to put different observations in context





Astrophysics

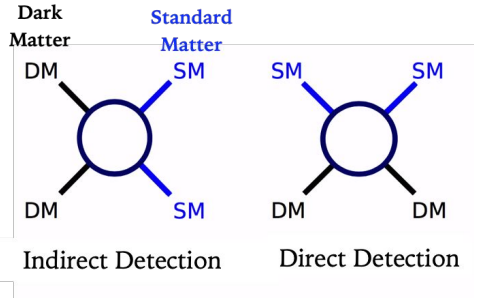


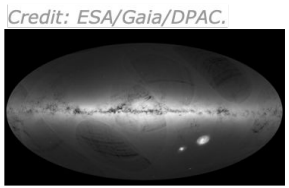
Theory

DM @ Colliders: continued exploration of *different experimental signatures of DM* at *different energy scales* (MeV -- TeV), motivated by many *different DM models* (WIMP-like, SUSY, dark sectors…)

DM@colliders in the broader Snowmass context

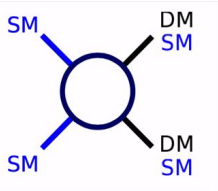
Observations, experiments and theories all needed for DM discovery





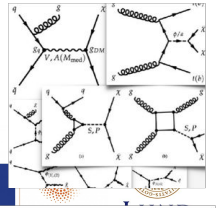
Astrophysics

Cosmic Frontier 01 (particle-like DM)
CF02 (wave-like DM)
CF03 (cosmic probes of DM)
Underground Frontier
Neutrino Frontier



Colliders & accelerators

EF10 (this TG), EF02, EF03, EF08, EF09
(+ others for backgrounds)
Rare & precision Frontier 06 (dark sectors at accelerators)
Accelerator Frontier 05 (accelerators for dark sectors)



Theory

Theory Frontier 07 (collider phenomenology)
TF07 (BSM model building)
TF09 (Astro-particle physics & cosmology)
(+ others for backgrounds)

Nearly all the physics in EF10 is **synergistic** with other groups / frontiers

→ keeping in sync & communicating often is part of our day-to-day work

Testing the WIMP paradigm: three main directions

1. **Electroweak multiplets [meeting 04/06, 02/07]**
   - Electroweak multiplet: higgsino/wino(minimal DM). Mediator: W/Z/h.
   - Target: TeV-scale DM masses, motivated by relic density

Common benchmarks to be discussed with EF08 (after LOIs)

2. **Simplified mediator models [meeting 18/06]**
   - S-channel and t-channel mediators.
   - Well established benchmarks for LHC, simple benchmarks for comparisons
   - Target: DM masses ~ GeV-scale and above

Common benchmarks in discussion with EF09/RF05, to be discussed with CF

3. **Higgs portal [upcoming meeting]**
   - Well motivated coupling between SM to the dark world
   - Target: DM masses ~GeV-scale and above

Common benchmark to be discussed with EF02

Ongoing work on simple WIMP models

Electroweak multiplet WIMP

EF/SNOWMASS21-EF10_EF9-069.pdf - **Electroweak multiplets at the Muon Collider**
EF/SNOWMASS21-EF10_EF0_Armesto_LHeC_BSM10-180.pdf **LHeC and FCC-he: Dark Matter (EF 10)**
EF/SNOWMASS21-EF10_EF9-071.pdf, **singlet + doublet WIMP simplified model**
EF/SNOWMASS21-EF10_EF9_diego_redigolo-104.pdf **- Electroweak multiplets at the Muon Collider**
EF/SNOWMASS21-EF10_EF8-TF7_TF0-CompF2_CompF0_Kulkarni_Suchita-139.pdf **- Long lived charginos**
EF/SNOWMASS21-EF9_EF10-TF7_TF0_Haipeng_An-237.pdf **- stop-bino coannihilation with open data**
EF/SNOWMASS21-EF8_EF10-258.pdf **- light dark matter in NMSSM via light higgs and electroweakino searches**
EF/SNOWMASS21-EF10_EF0_Peiwen_WU-103.pdf **- top+jet+MET at future e+e- colliders**
EF/SNOWMASS21-EF10_EF0_Kilic-051.pdf **- Optimizing Higgsino searches**

Higgs portals:

EF/SNOWMASS21-EF10_EF2_Ketevi_Assamagan-035.pdf ***LOI on H —> invisible***
EF/SNOWMASS21-EF1_EF2_Patrick_Janot-172.pdf **- H -> invisible at the FCC-ee**
EF/SNOWMASS21-EF10_EF0_Xin_Shi-080.pdf **- DM via Higgs portal at CEPC**

Full list of LOIs and recording here (please contact us if we missed yours due to the cross-listing form limitations!)

Ongoing work on DM simplified models

DM Simplified models at colliders

EF/SNOWMASS21-EF10_EF0_Peiwen_WU-103.pdf - **Search for t + j + MET signals from dark matter models at future ee collider**

EF/SNOWMASS21-EF10_EF9_Filip_Zarnecki-054.pdf - **New approach to DM searches with mono-photon signature**

EF/SNOWMASS21-EF10_EF9_Andreas_Albert-094.pdf - **Displaying dark matter constraints from colliders with varying simplified model parameters**

EF/SNOWMASS21-EF9_EF10-RF6_RF0-CF1_CF3_Boyu_Gao-160.pdf - **Summarizing experimental sensitivities of collider experiments to Dark Matter models and comparison to other experiments**

Future collider and experiment (they group more than one search)

HL-LHC ATLAS: EF/SNOWMASS21-EF0_EF0-RF0_RF0_ATLASCollaboration-195.pdf

HL-LHC CMS: EF/SNOWMASS21-EF1_EF10-RF5_RF7_CMSCollaboration-109.pdf

Muon collider: EF/SNOWMASS21-EF10_EF0_Jayatilaka-225.pdf

LHeC: EF/SNOWMASS21-EF10_EF0_Armesto_LHeC_BSM10-180.pdf

CLIC: EF/SNOWMASS21-EF0_EF0_CLICphysics-170.pdf

Lepton colliders: EF/SNOWMASS21-EF0_EF0-TF0_TF0-AF0_AF0-244.pdf

Also: theory (general BSM overviews)

Energy Frontier BSM Wishlist

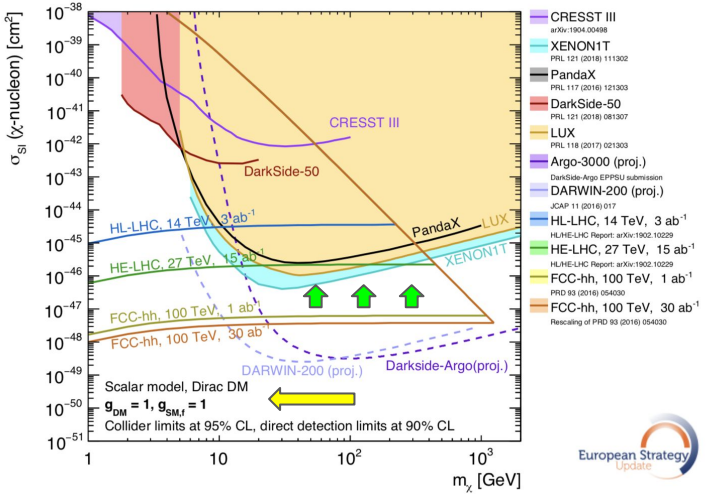
Full list of LOIs and recording here (please contact us if we missed yours due to the cross-listing form limitations!)

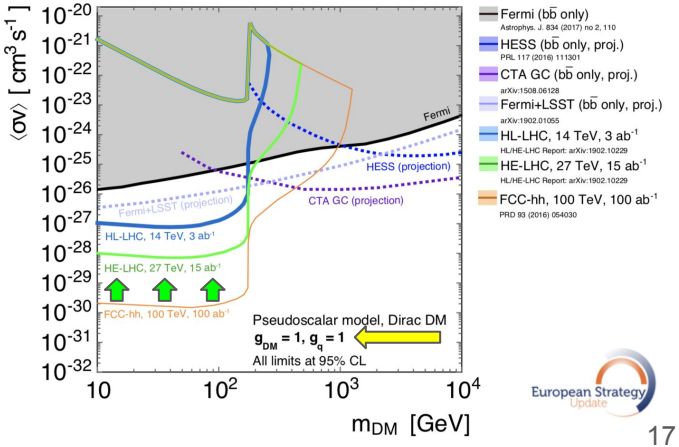
Ongoing work on complementarity

http://cds.cern.ch/record/2691414/files/Briefing_Book_Final.pdf

From European Strategy BSM and DM working groups:

- Plots including collider / direct / indirect detection results, using a simple WIMP-like model scenario (pseudo/scalar SM-DM mediator with fixed o(1) couplings)
- After discussions with other communities, will be updating plots to lower coupling hypotheses to better connect to other DM searches e.g. accelerator-based
  - See this LOI (w/Dark Matter Working Group) and this LOI (plots of heavier WIMPs by EF10)





Other synergies emphasized by European Strategy

- What can we learn from:
  - **Non-collider** experiments (for dark sector searches)
  - **Astrophysics** and **nuclear** physics
- How can we work together towards the same physics goals:
  - In collaboration with **theory, instrumentation & computing** (see also ESCAPE project / HSF / IRIS-HEP (US))

Some initial questions on possible joint summary plots

Need discussion between EF/CF/RF/NF/TF (topical workshop(s)?)

- Are simple WIMP models / simplified models [Dark Matter Working Group] / portals [Physics Beyond Colliders] a framework we want to agree upon for summary plots? (Widely used by the collider community already)

- Exclusion areas plotted by colliders don't impose any relic density constraints on exclusion areas from simplified models → is this making the constraints incompatible?

- Is extending collider limits for thermal relics below 1 GeV in summary plots theoretically sound, and welcome by other communities?

- What is the best way to display uncertainties for the experiments involved?

Conclusions and outlook from CPM

1. Lively community → broad program of DM@Collider studies within EF10
   - Work on common "big picture" benchmarks alongside unexplored models/signatures

2. Future discovery of / constraints on DM requires a broad physics perspective
   - Coordinate with other Topical Groups and frontiers
   - Would like to update the DM Complementarity Snowmass 2013 whitepaper with an even more global picture of DM (including accelerators and large astro surveys)
     i. See session #150, tomorrow at 12:15
   - Willing to start this journey with CF/EF/RF with joint meetings for joint summary plots!

3. Important to consider *tools* to answer questions about physics of DM
   - Necessary to plan for reinterpretable / reusable searches & measurements (already at the LHC) [potential collaborations with CompF07]
   - Follow detector, data acquisition and trigger design [e.g. IF04 kick-off]

Join us, give input

Webpage of EF 10: https://snowmass21.org/energy/dark_matter

Slack channel: #ef10-dark_matter under https://snowmass2021.slack.com

Email list: SNOWMASS-EF-10-DARK_MATTER@FNAL.GOV

Instructions on how to join: https://snowmass21.org/energy/start#communications

List of all EF10 LOIs (title / authors): Spreadsheet with presentation recordings (more will be added)