Dark matter complementarity in Snowmass

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What is Snowmass?

see https://snowmass21.org

Snowmass 2021

- Particle physics community planning exercise organized by the Division of Particles and Fields (DPF) of the American Physical Society

- Snowmass goals:
  - work on/collect **new scientific studies**, mostly concerning on future directions for the field
  - **engage** the community and junior scientists
  - to prepare a collective **vision** for the **next decade of US particle physics**

- Organized in 10 Frontiers
  - Accelerator, Cosmic, Community Engagement, Computing, Energy, Instrumentation, Neutrino, Rare processes and Precision Measurements, Theory, Underground + Snowmass Young (for early career input)
  - Each Frontier has 5-10 Topical Groups (eg. dark matter!)

- The vision is taken by the Particle Physics Project Prioritization Panel (P5) as input to a 10-year strategic plan
  - P5 science drivers from Snowmass 2013: Higgs boson as tool for discovery, pursue physics associated to neutrino mass, identify the new physics of dark matter, understand dark energy and inflation, explore the unknown

The P5 website: https://www.usparticlephysics.org/p5/
The P5 process, slides by chair H. Murayama

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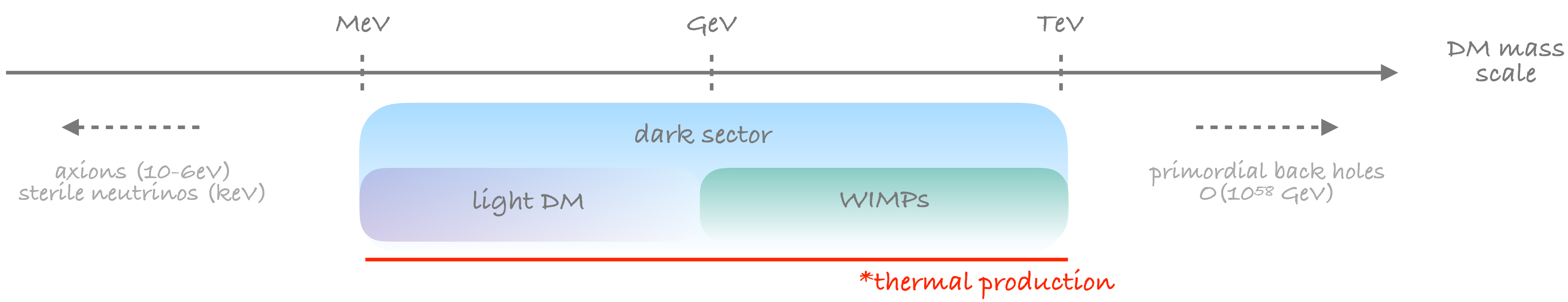
What is dark matter?

DM evidence

- *Empirical evidence of DM* from astrophysical observations at different scales
  - interacts gravitationally, long lived and neutral
  - no information about its nature (what DM could be?)
  - *only measured quantitative property is its mass abundance*
    - very large set of possible DM masses can account for observed final relic density



- Knowing so little about DM a collaboration among the frontiers is essential, we must ...

... delve deep

... search wide

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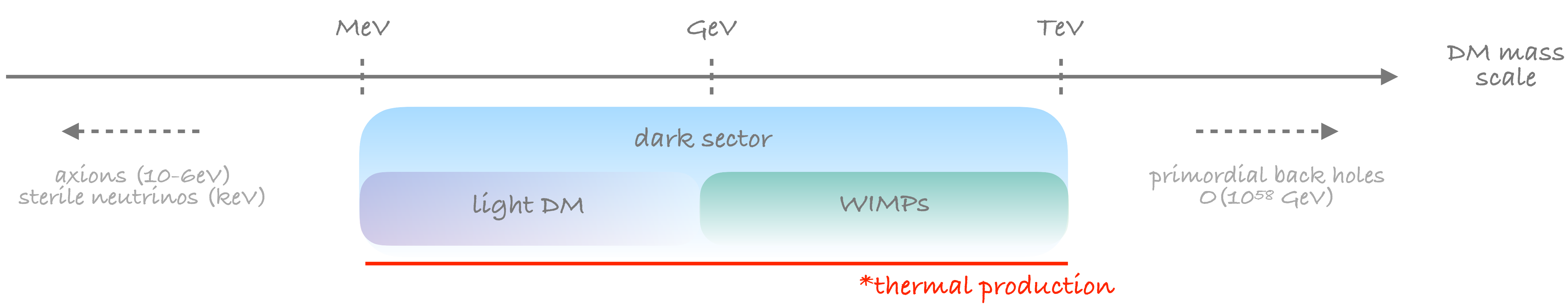

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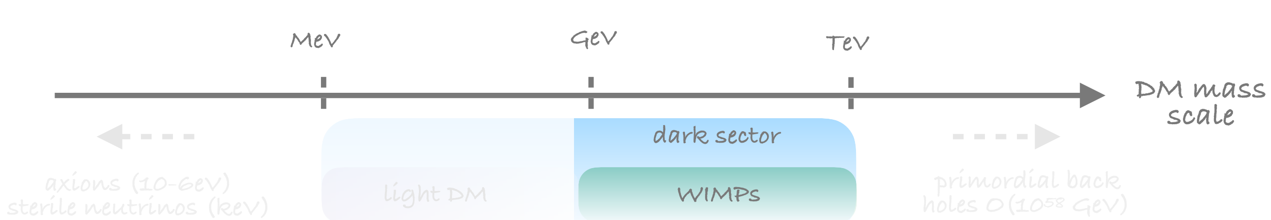

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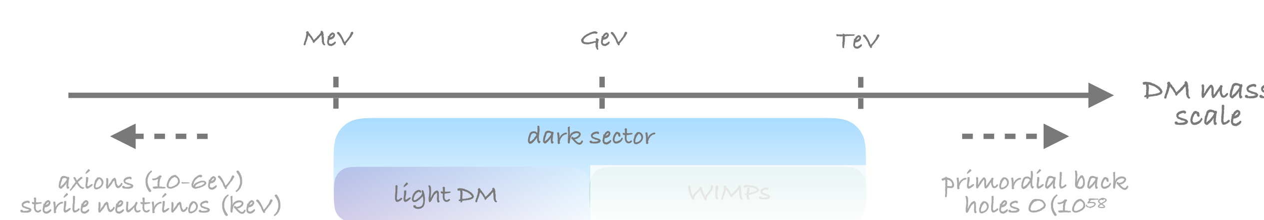
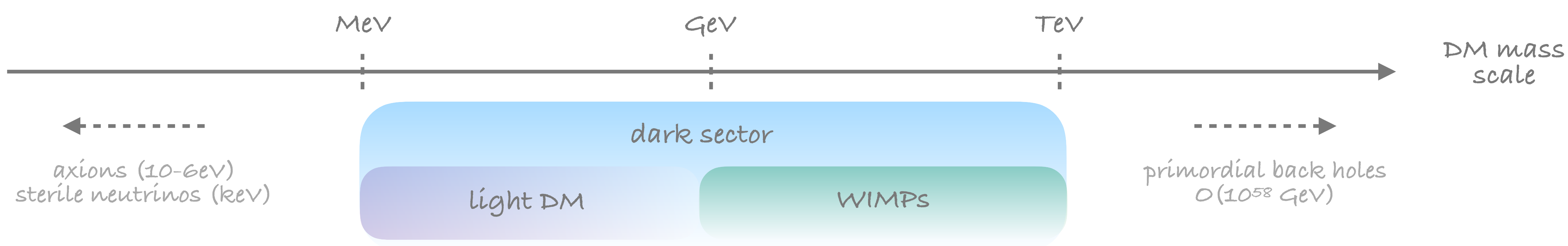


Snowmass: what is the road to discover DM?

arXiv:2210.01770



- *Over the next decade, need of unified strategy to maximize discovery potential*
  - many compelling theoretical targets from simple/minimal models will be accessible via planned and proposed experiments, colliders, and observatories across experimental frontiers
  - understanding and harnessing complementarity between techniques and technologies is essential
  - *if DM discovered*, complementarity needed to triangulate fundamental nature of DM
  - *if DM is not found*, we will still gain important information on its properties

- *What is the strategy ahead to allow DM discovery?*
  - *build a portfolio of experiments of different scales:* experiments at all scales needed to cover very broad range of theoretically motivated parameter space
  - *leverage US expertise in international projects:* coordination and cooperation across borders is critical. Build a strong US-based program and pursue opportunities for US expertise to play key role in international projects
  - *Provide support to further strengthen the theory program:* essential to make connections between experimental frontiers and guide new approaches to understand and detect DM
  - *Support inter-disciplinary collaborations and increase in the research budget:* essential to enable new ideas, new technologies, and new analyses

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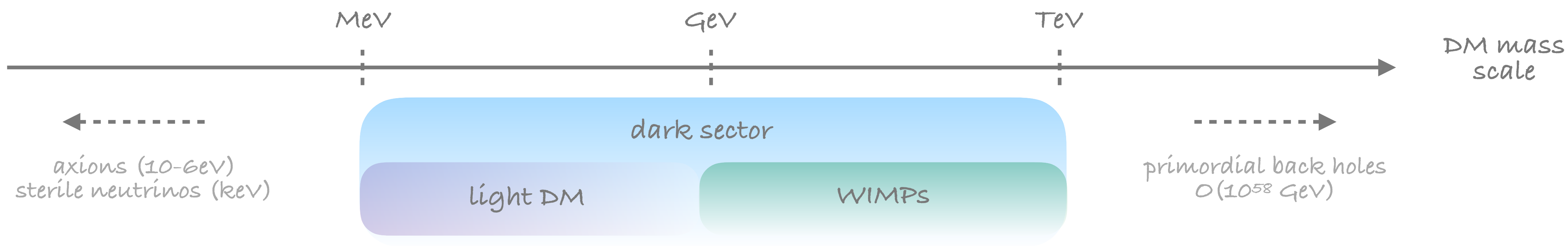

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Why complementarity?

Different DM search approaches and complementary necessary to investigate DM across Frontiers:

- Cosmic: direct and Indirect searches
- Cosmic: wavelike DM
- Cosmic: cosmic probes of DM
- Rare & precision: Dark Sectors at High
- Energy: DM at colliders
- Neutrino: DM in neutrino

- Experiments can simultaneously discover DM by detecting its relic components or producing it
  - relic DM probes give insight into DM halo properties and provide connection of new particles discovery with cosmological DM, DM production probes give insight on DM interactions and on dark-sector beyond SM
- Different experimental approaches have unique parameter-space coverage and DM properties sensitivity
  - for eg. DM detection experiments are sensitive to non-relativistic DM signals and production probes explore the physics of DM in relativistic regime
  - terrestrial experiments are sensitive to rare DM interaction processes; cosmological and astrophysical probes have unique sensitivity to properties like lifetime, DM self-interaction, etc …
- DM experiments can be co-located and/or profit from the same or similar technological infrastructure
  - wider exploration of DM with a more efficient use of shared resources

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Inputs and opinions from people outside of Snowmass?

- In the following wishlist of inputs from the community for different frontier
- Goal:
  - inform European community of efforts on dark matter complementarity within Snowmass
  - are there more recommendations that the European community would like to bring forward with respect to the ones already introduced in the whitepaper?

DM searches: roadmap and complementarity

Cosmic: direct and Indirect searches

- **Focus:** particles DM with mass eV-10^{19} GeV
  - *direct detection*: *delving deep* into heavy DM, with spin-independent reaching neutrino floor and increasing sensitivity in scenarios where the neutrino floor remains distant, *searching wide* with new techniques to probe DM in MeV and lower ranges
  - *indirect detection*: *delving deep* in TeV range with model-agnostic probes of minimal thermal relic scenario, *searching wide* in MeV range with new probe of low-energy cosmic-ray anti-deuterons

- **Roadmap:**
  - *Diverse* and continuous direct and indirect detection experiments *portfolio* at multiple scale
  - *Moderate- and large-scale experiments* allow to delve deep in GeV-TeV range, *small-scale experiments* provides ability to test expanded models range
  - *Support theory*, simulations, calibration, bkg modeling and complementary astrophysical measurements
  - *R&D* towards improved detector technologies are fundamental and crucial

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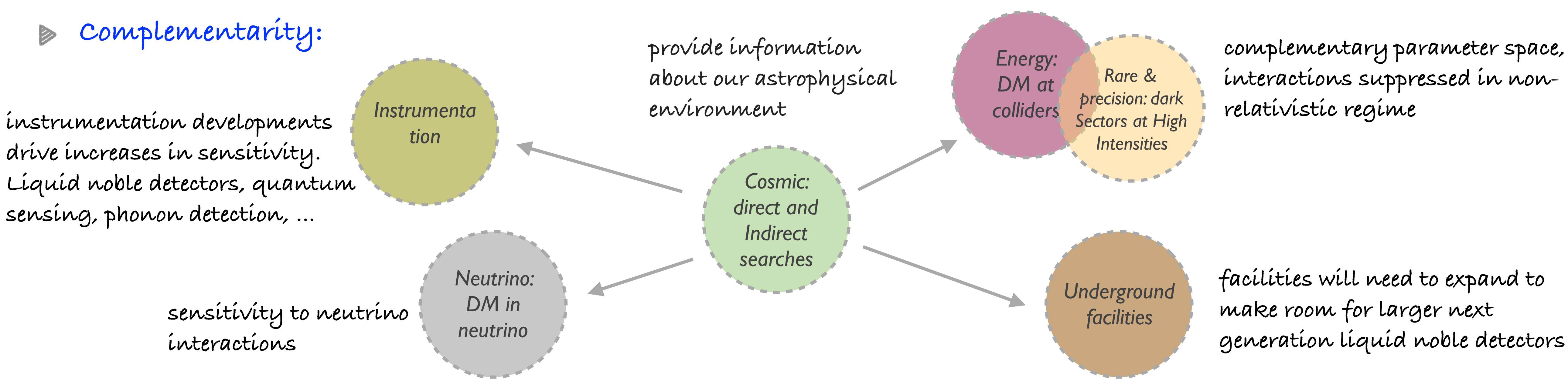

DM searches: roadmap and complementarity

Cosmic: wavelike DM

- **Focus:** wavelike DM with mass < 1eV
  - *delving deep* into QCD axion candidate DM, *searching wide* with broader models predicting axion-like particles
  - quantum measurement techniques become critical for enabling detection and explore broader scenarios
  - provide information about our astrophysical environment

- **Roadmap:**
  - *Pursue the QCD axion executing current projects*: ADMX generation-2, DMRadio-m3, ADMX-EFR
  - Collection of *small-scale experiments* to exploit different techniques, pursue opportunities for *US key-role in international projects*
  - *Support* enabling *technologies*, cross disciplinary *collaborations*, and *theory* beyond the QCD axion

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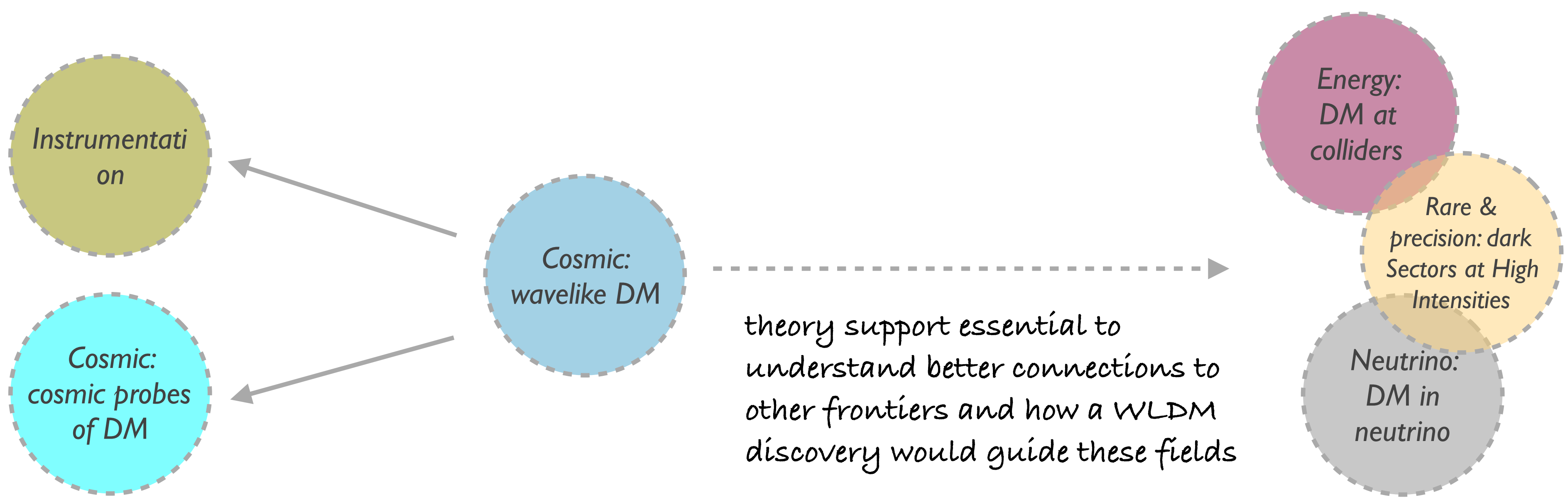
- **Complementarity:**

techniques needed have strong overlap with Rare&Precision

complementarity in constraining available QCD axion mass range



theory support essential to understand better connections to other frontiers and how a WLDM discovery would guide these fields

DM searches: roadmap and complementarity

Cosmic: cosmic probes of DM

- **Focus:** important avenue to measure the fundamental properties of DM
  - provide only known way to directly study DM fundamental properties through gravity
  - sensitive to DM mass, lifetime, self-interaction, and other dark sector particles in extreme large scales and environments inaccessible to terrestrial experiments (wide range of parameter space)
  - ability to link results of terrestrial DM experiments to cosmological measurements

- **Roadmap:**
  - Current/near-future HEP cosmology experiments have direct sensitivity to DM particle physics, cosmological studies of DM should be supported as a key component of the HEP Cosmic Frontier program
  - Construction of future cosmology experiments critical for DM understanding. HEP community should invest strategically an support design, construction, operation of these facilities to maximize their sensitivity to DM
  - Theory, simulation, observation, experiment must be supported to maximize cosmic probes sensitivity to DM

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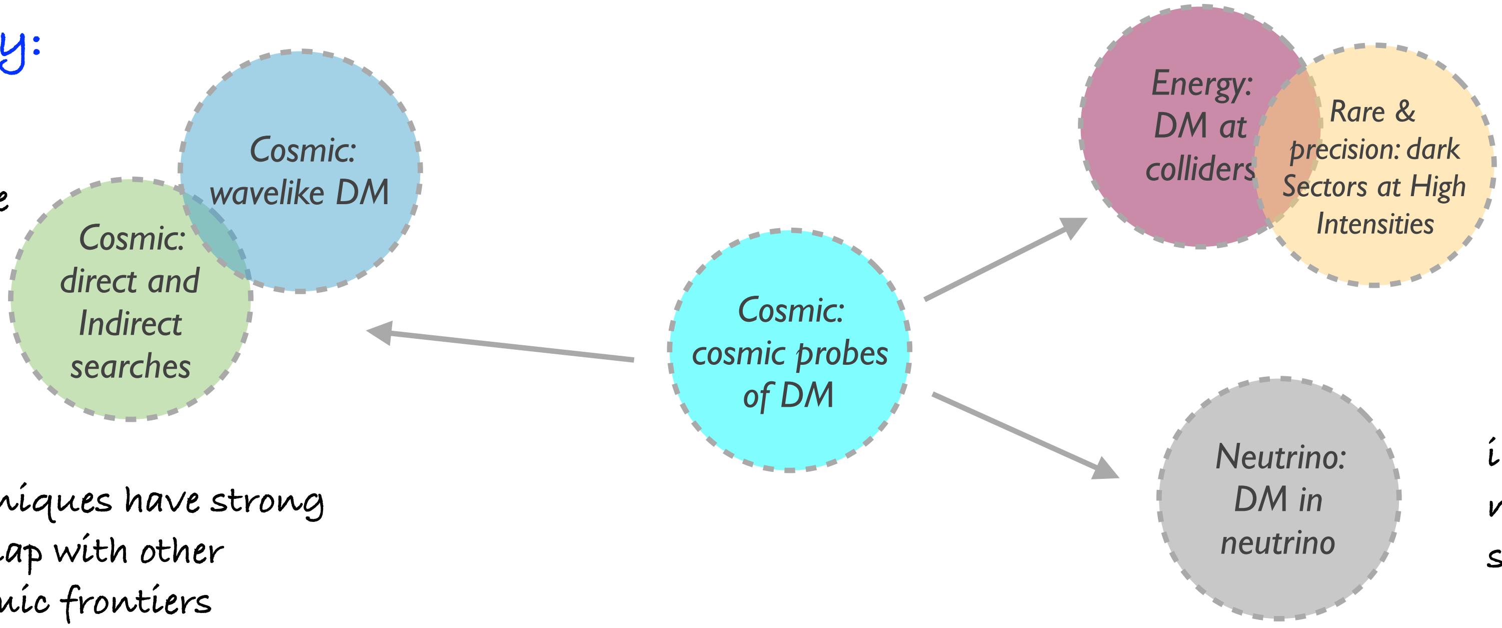
- **Complementarity:**

complementary sensitivity to particle DM and WLDM

important inputs on DM distribution



techniques have strong overlap with other Cosmic frontiers

complementary to dark mediator searches from DM self-interaction

inputs on keV mass sterile neutrinos from impact on cosmic structure formation

DM searches: roadmap and complementarity

Rare & precision: Dark Sectors at High Intensities

- **Focus:** particle DM with mass MeV-GeV
  - *search wide*, provide unique and unprecedented access to low-mass DM
  - powerful probe of thermal DM models
  - also probe of light SM-neutral dark-sector particles decaying into SM particles (long lifetimes)

- **Roadmap:**
  - *Exploit capabilities of existing large multi-purpose detectors*, in particular Belle II and LHCb
  - Broaden and invest in completion of “Basic Research Needs Dark Matter New Initiatives" (DMNI) program, *small-scale experiments essential to explore sub-GeV thermal DM and dark-sector* not accessible by large multi-purpose detectors. CCM200 and LDMX selected projects, but need to identify dark-sector future ideas
  - *Support dark sector theory efforts* to understand viable models

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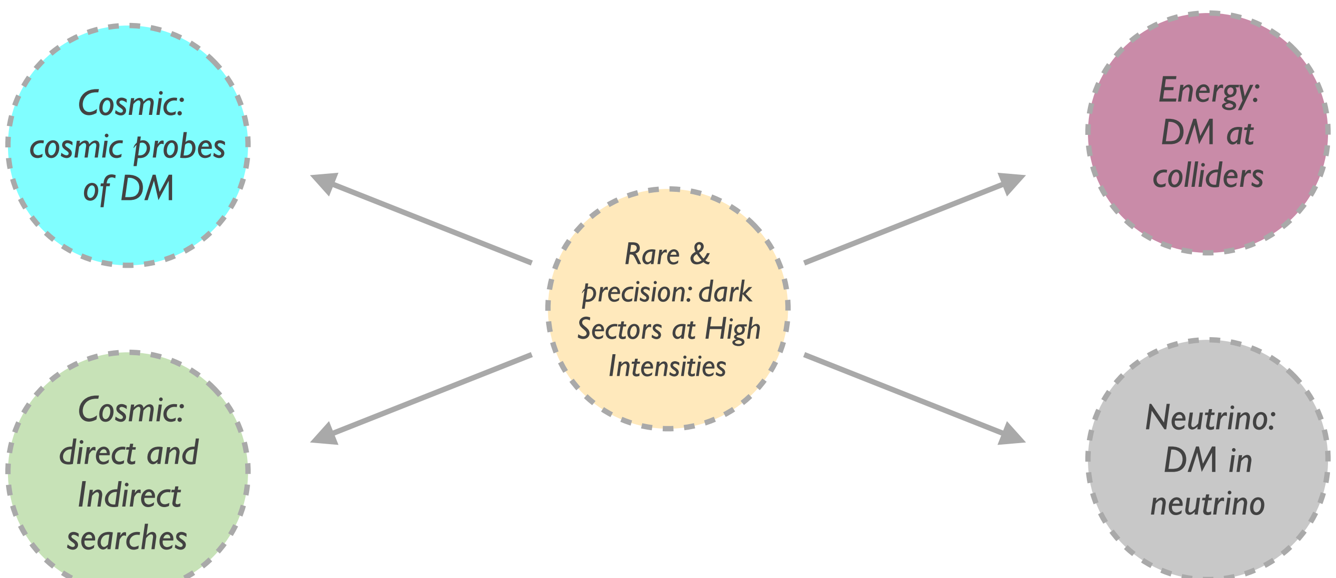
- **Complementarity:**

complementary for light-DM, with additional info from self-interactions

targeting similar light DM models, but complementary signal scaling (non-relativistic vs relativistic)



employ similar technique but focus on different mass/couplings. Can be co-located in facilities

Exploring complementary and overlapping mass ranges

DM searches: roadmap and complementarity

Energy: DM at colliders

- **Focus:** particle DM with mass GeV-TeV
  - *delving deep*, WIMP-like particles
  - *search wide*, lighter thermal DM particles, higher-mass DM-SM mediators, extended dark-sectors
  - *if DM discovered* via other frontiers, imperative to produce it and study its SM interactions in high-energy colliders controlled conditions, and vice versa to establish that the invisible particles are DM

- **Roadmap:**
  - *Immediate future: HL-LHC,* discover/exclude vast thermal DM scenarios, probe smaller dark-sector couplings
  - *Intermediate future: electron-positron collider*, further explore if DM is produced via a SM or BSM mediator especially for models favoring lepton couplings
  - *longer term: multi-TeV discovery machine,* allow higher energy scales for dark-sector physics, will reach thermal milestone for thermal DM from 3 GeV complementing lower-mass Frontier experiments

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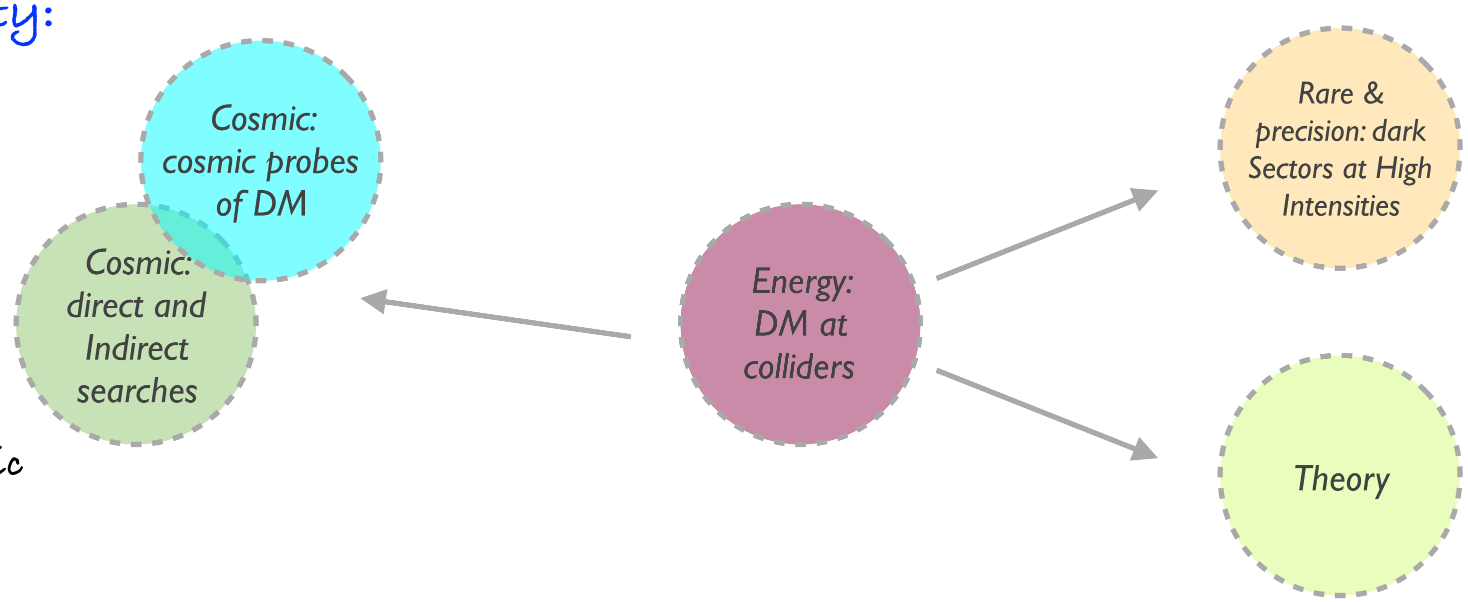
- **Complementarity:**

Exploit individual capabilities to constrain DM type(s) and their interactions

complementary signal scaling (non-relativistic vs relativistic)



Complementary focus on DM mass/couplings

Can be co-located in facilities

to relate information from multiple experiments

models details affects searched signal characteristics

DM searches: roadmap and complementarity

Neutrino: DM in neutrino

- **Focus:** understanding neutrino properties, also sensitive to DM
  - search wide, right-handed sterile neutrino, neutrino portal, probe DM and dark sector particles
  - indirectly probe or constrain DM by anomalous spectra of neutrino fluxes
  - improved understanding of neutrino fluxes, properties, cross sections can assist in understanding the bkg in DM searches with neutrino experiments and in other frontiers

- **Roadmap:**
  - Realization of DUNE in its full scope within the next decade. Will expand opportunities in DM and dark-sector searches through high intensity, high power proton beams and near/large-scale detectors
  - Advancing the understanding of neutrino backgrounds. Small-scale experiment, in collaboration with nuclear physics community, could provide precise measurements of neutrinos bkg for DM searches

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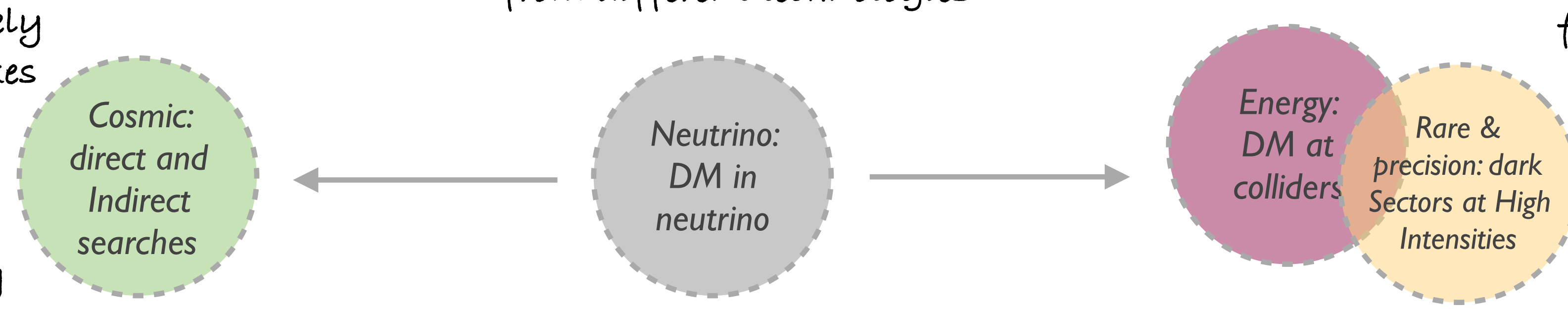
- **Complementarity:**

within the Frontier – complementary information from different technologies

contribute DM-induced neutrinos detection precisely measuring neutrinos fluxes from natural sources

complementary reach for sub-GeV DM



complemental sensitivity for boosted DM

DM search: additional critical components

- *Theory: essential to compare results from different experiments*
  - define connections between different experimental programs and Frontiers
  - motivate specific experimental directions
- *Instrumentation: new technologies often opening up new regions of parameter space for exploration*
  - promote R&D into instrumentation, development of technical workforce, tools to share common knowledge
- *Computing: essential for raw data collection, storage, data processing and analysis, results interpretation …*
  - build stronger partnerships with national supercomputing facilities, enhance industry collaborations on machine learning technique, support scalable software infrastructure tools across communities
  - essential to have efficient, well-maintained, and validated simulation infrastructure
  - promote widely-adopted data and software standards, in support of global analyses of experimental results
- *Underground facilities: needed to host experiments (eg. to evade cosmic ray backgrounds)*
  - clear need for additional underground space, tailored to needs of neutrino and DM experiments
- *Accelerator frontier: foundation of intensity-frontier and energy-frontier searches for DM and dark sectors*
  - efficiently utilize existing and upcoming facilities to explore possible rare process experiments
  - explore technically and document accelerator possibilities for energy frontier to operate in 2040
- *Community Engagement and Workforce Development:*
  - material support to enhance engagement efforts at all levels of society, also as recruiting tool for HEP
  - supported portfolio of small and medium-scale projects will also allow workforce training

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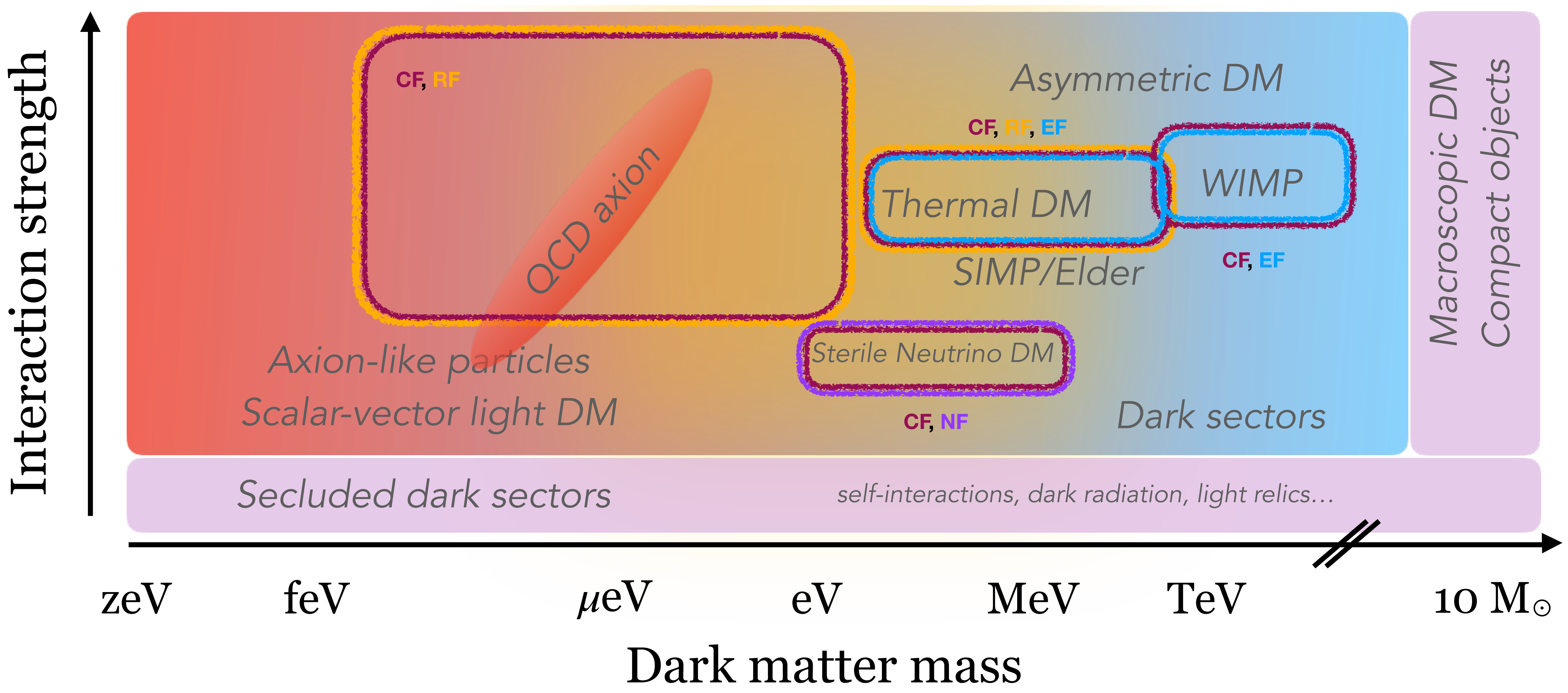
  - supported portfolio of small and medium-scale projects will also allow workforce training

DM searches: complementarity at play

- Very large set of viable theoretical scenarios that can provide DM candidates
  - possibilities span enormous ranges in DM mass and interaction strength
  - complementarity between DM searches pivotal to enable discovery of DM fundamental nature and to allow triangulation of its properties (both in case of discovery or null results)



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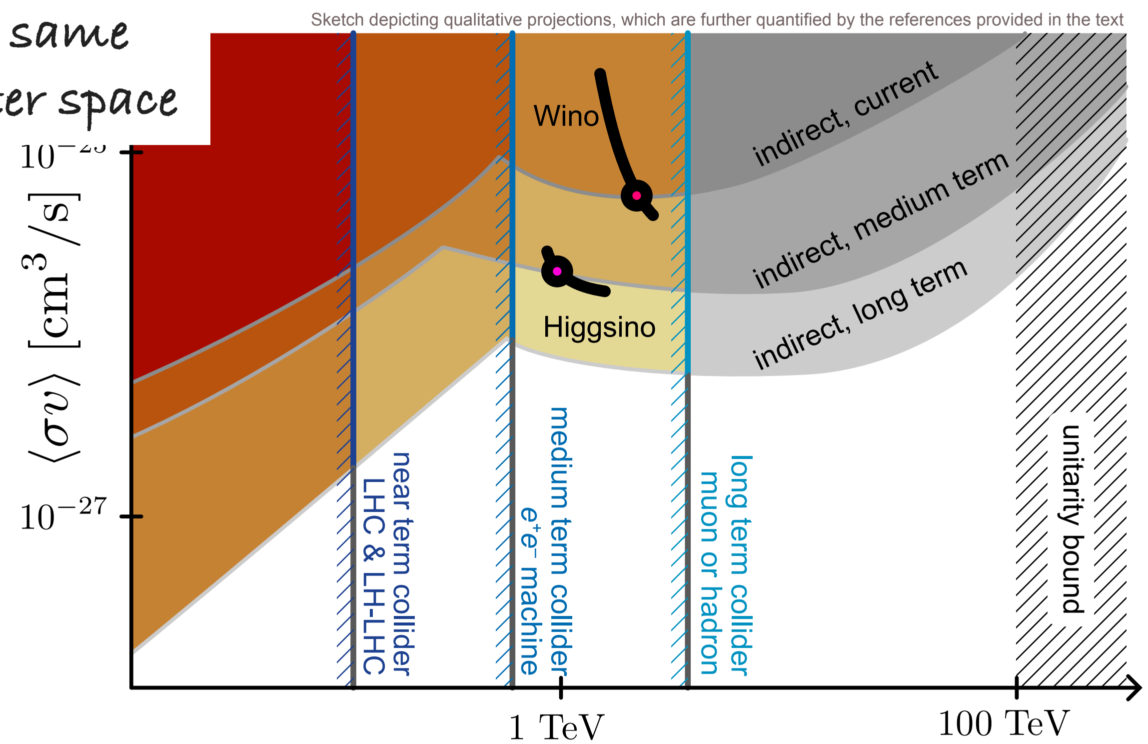
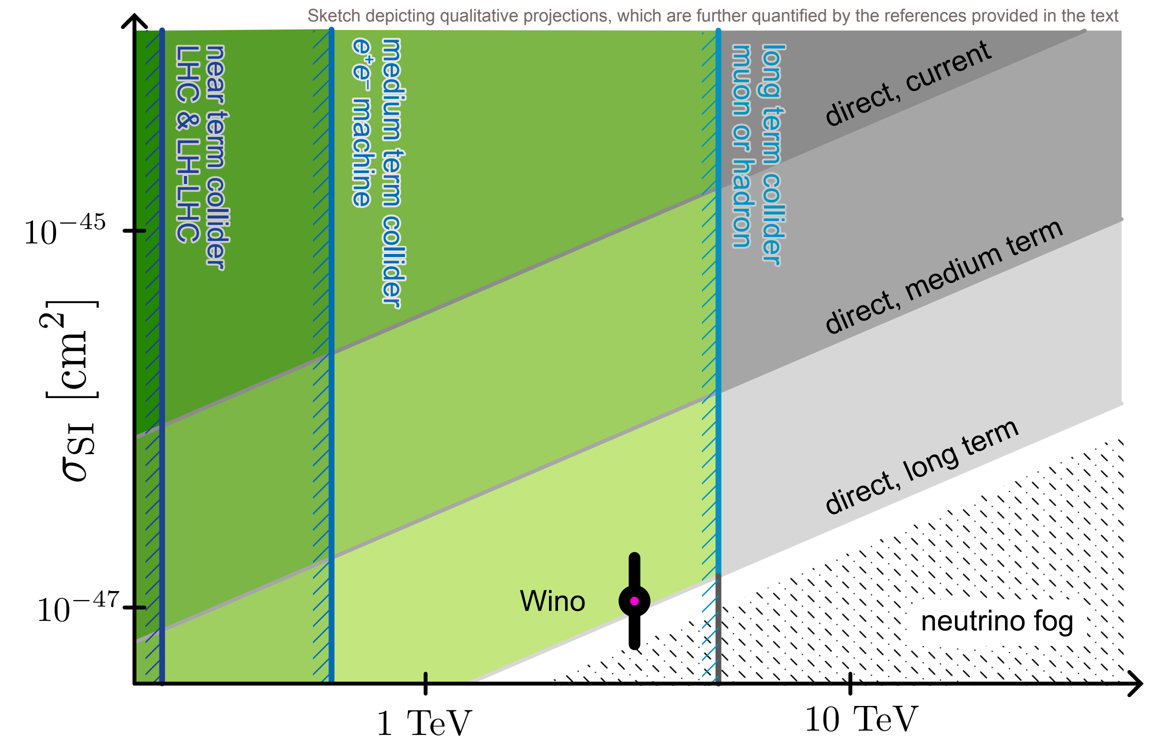
- *Case study*: WIMP DM lightest particle of multiplet interacting with SM through weak force (EWK SUSY)
  - DM Dirac (Higgsino) or Majorana(Wino) particle, m_{DM} only free parameter fixed by relic density (TeV scale, but lighter for non-thermal production), cross-sections not fully probed by current experimental effort

probing same parameter space





direct detection: DM-nucleon interactions expected to be very rare, requiring large exposure for detection.

indirect detection: signal from DM annihilation into photons or gauge bosons accessible by gamma-ray telescopes and other indirect detection experiments

colliders: can probe DM invisible signature, semi-visible decays of long-lived intermediate states (TeV scale), loop effects due to new particles (lower energies)

- *Complementarity*: in case of discovery colliders will access DM-SM interactions, and direct/indirect efforts will connect it to cosmological properties. Even no signal will allow to the planning of future generations of colliders and improve antiprotons/antinuclei production rate relevant to cosmic-ray signals of DM

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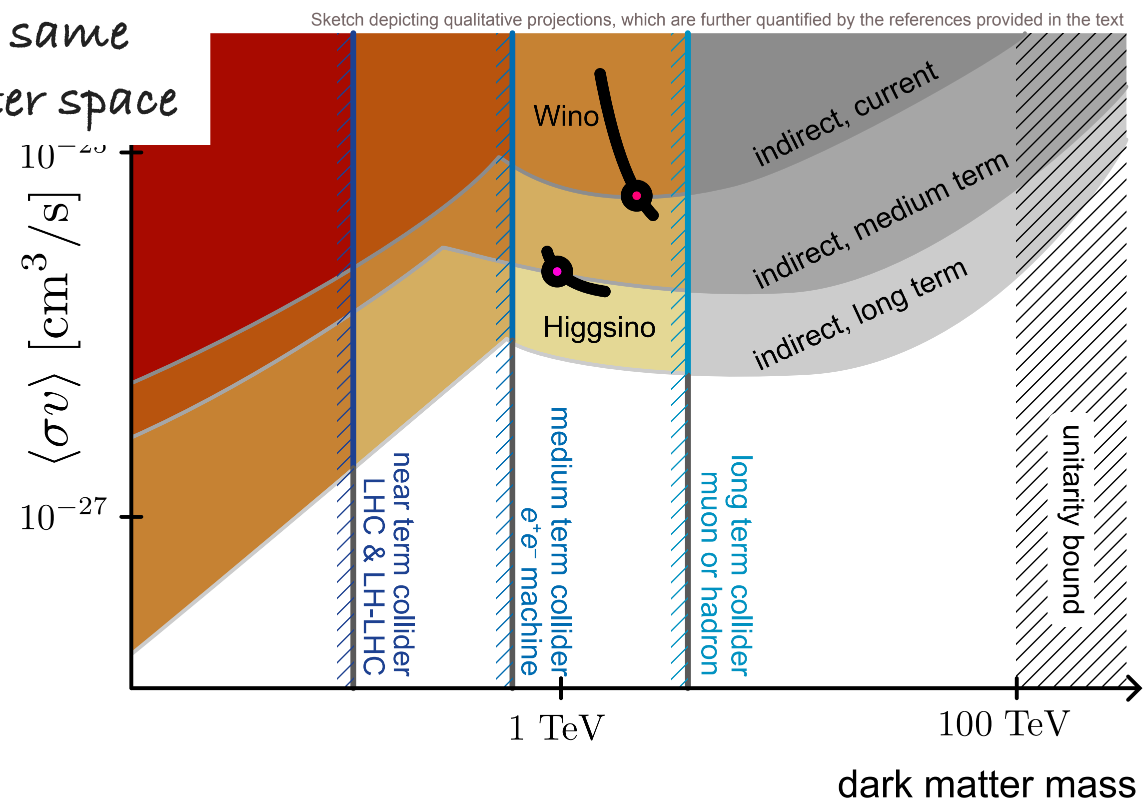

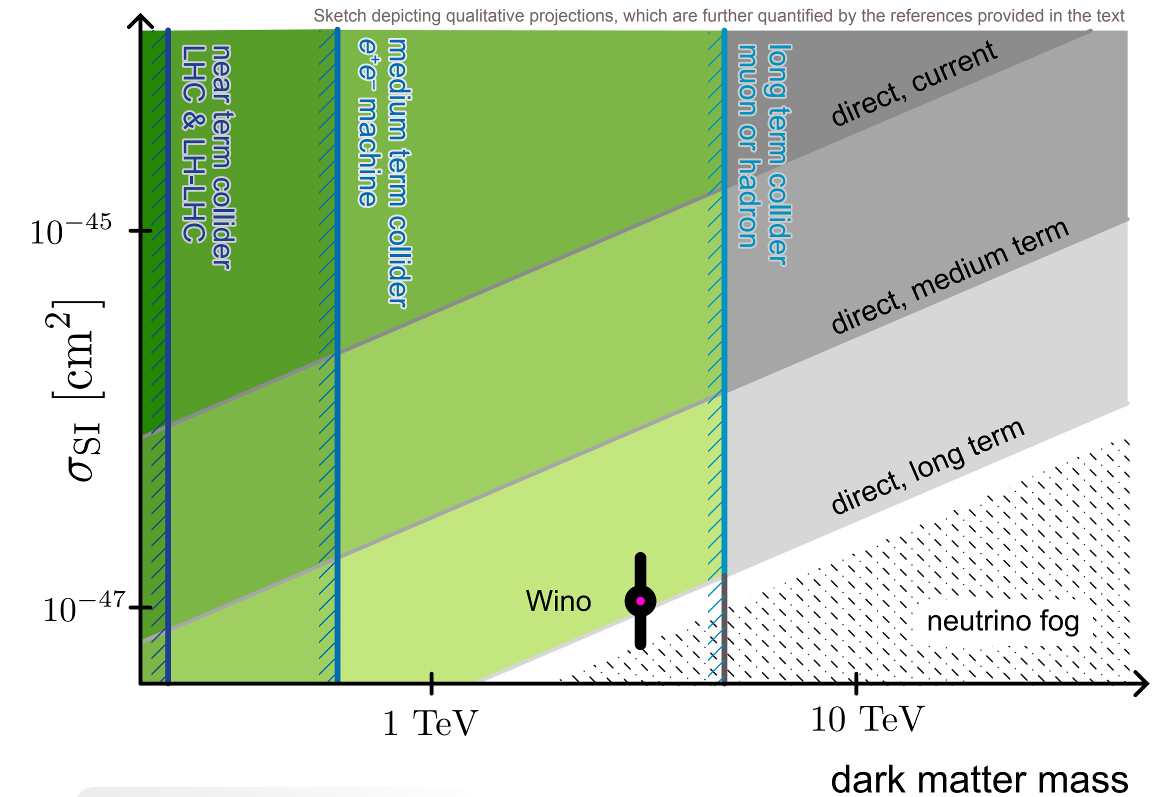

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- *Case study*: DM and additional BSM particle
  - new particle mediates DM-SM interaction with couplings comparable or weaker than weak interaction
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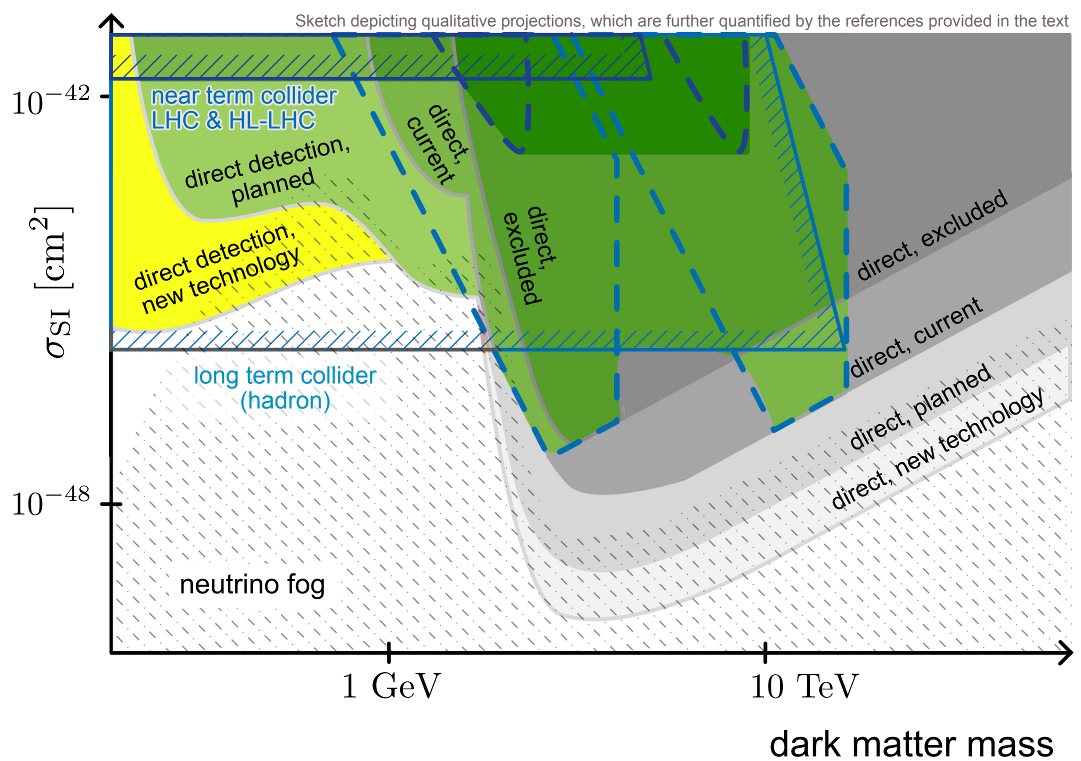
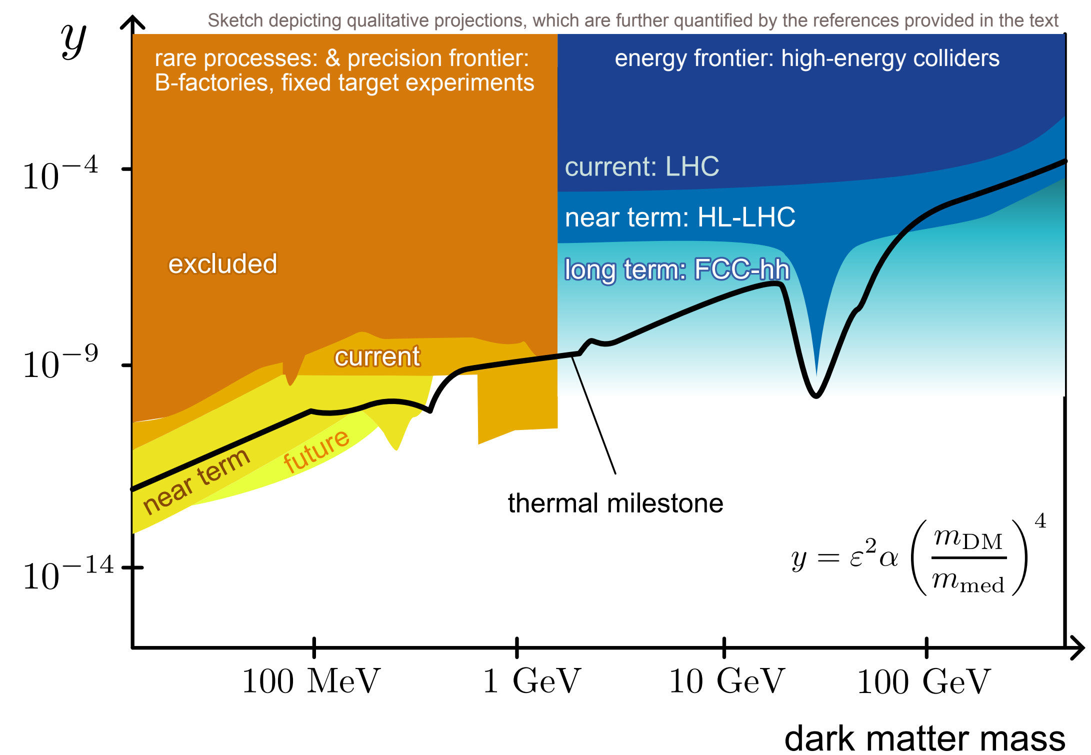
  - *eg. benchmark vector portal*, dark vector boson *(dark photon)* mediator that mixes with SM photon





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  - in portal models, both low and high mass particles are needed for theoretical consistency. Only a *combination of Cosmic, Energy and Rare&Precision Frontier experiment* can discover DM and associated particles
  - *simultaneous discovery* in these experiment is essential to determine DM candidate cosmological nature and its interactions with ordinary matter

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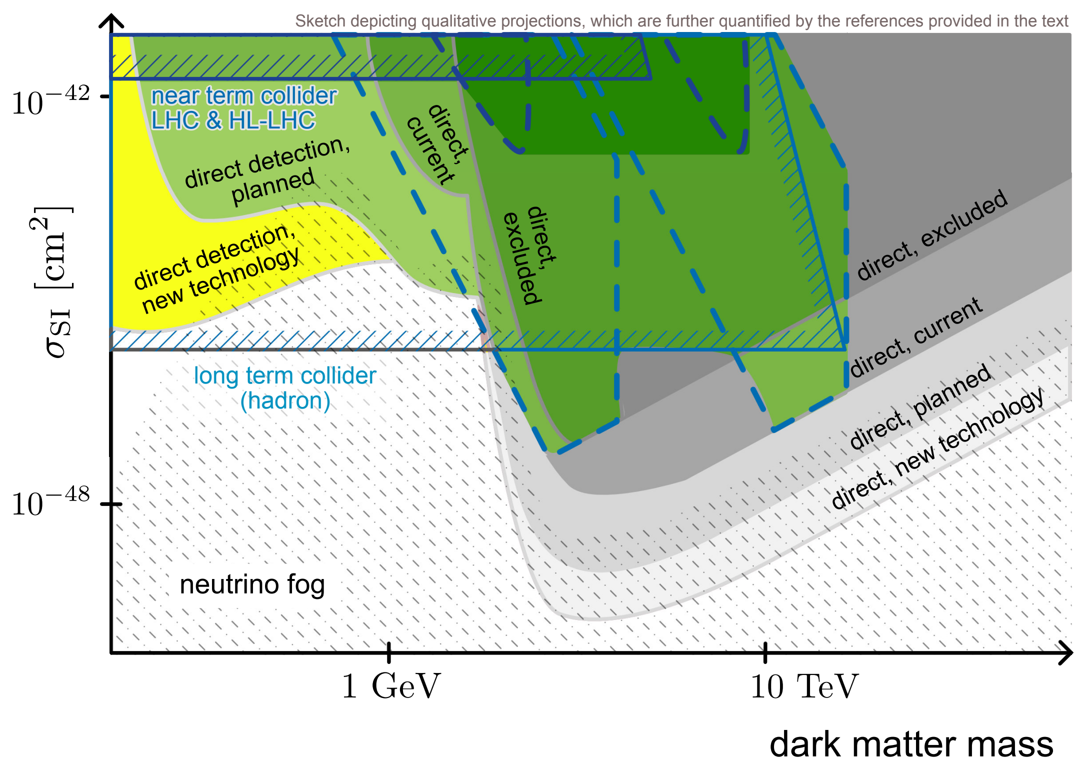

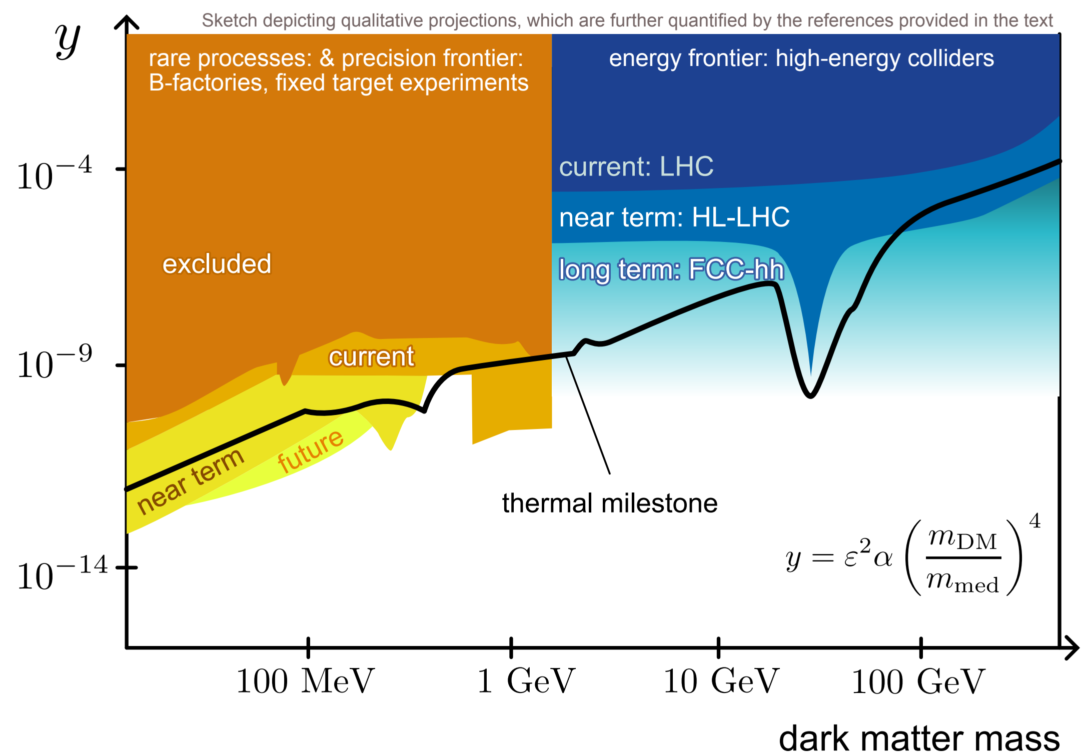

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- Complementarity: coverage of viable phase space

cosmic probes: constraints from suppression of DM structure for producing keV-mass sterile neutrinos with a “warm” initial momentum distribution

indirect detection: search for X-ray lines originating from the decay of keV mass sterile neutrinos

neutrino experiments: different dependencies on the model behavior of sterile neutrinos in the early Universe

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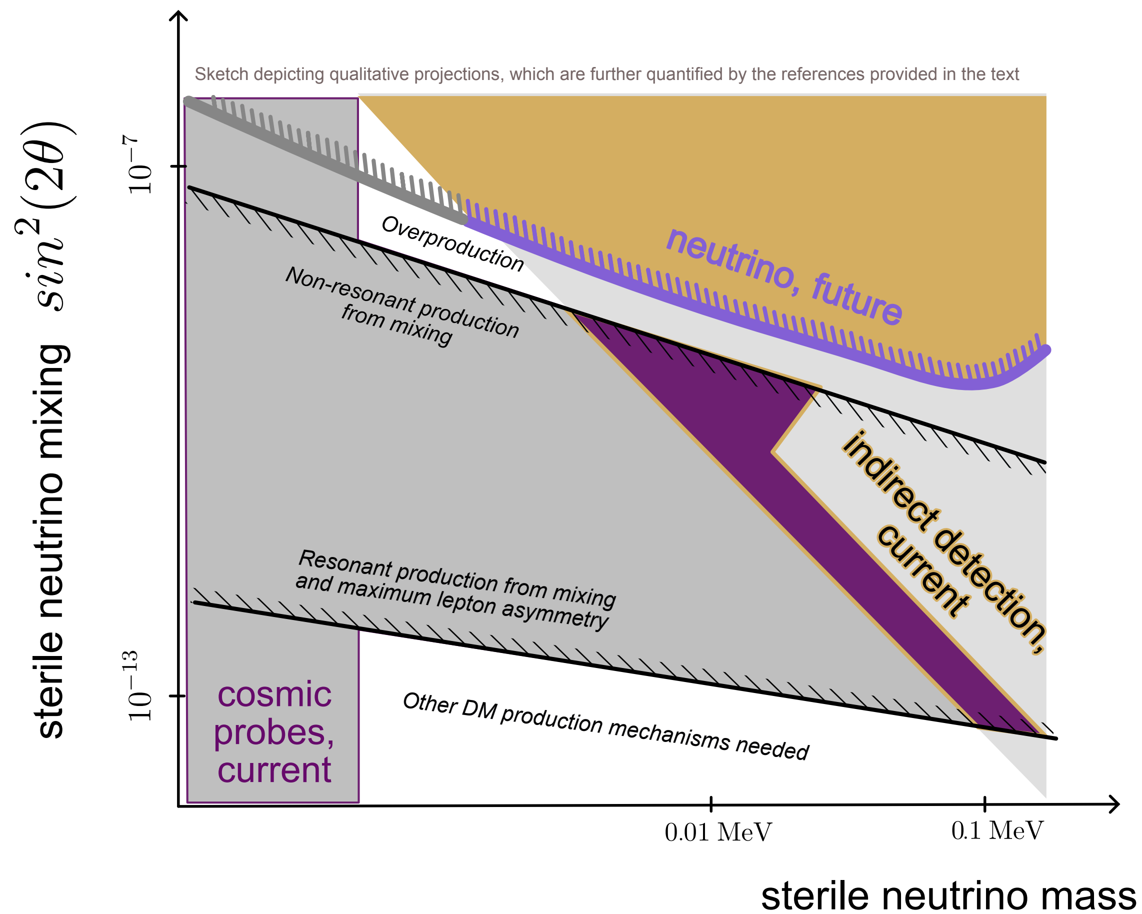

- Case study: wavelike DM
  - constraints across frontiers less stringent due to many models to be explored experimentally and theoretically
- Complementarity: in case of discovery from direct detection experiments
  - will provide measurement of DM velocity distribution in halo. This can be compared to cosmic probes results
  - precision measurement of coupling with photons can identify type of QCD axion or ALP discovered
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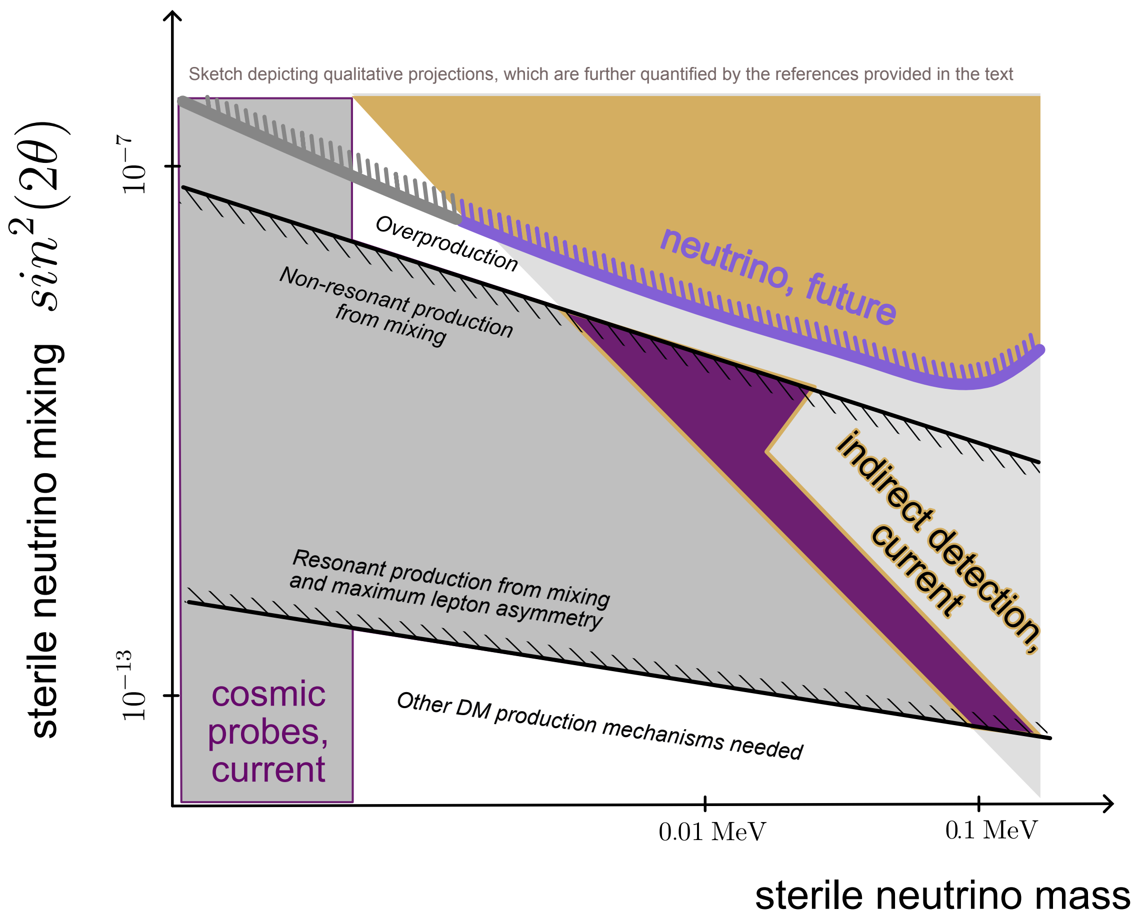

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fundamental open
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triangulate DM nature
(employing results from
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enormous theoretically
motivated space

need to delve deep and search
wide across frontiers

- Complementarity across frontiers is at the hearth of the journey to DM discovery
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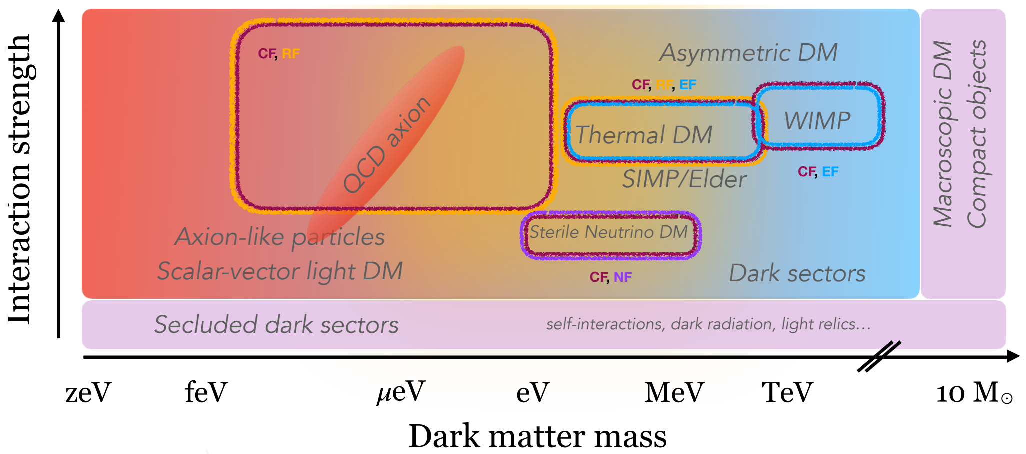

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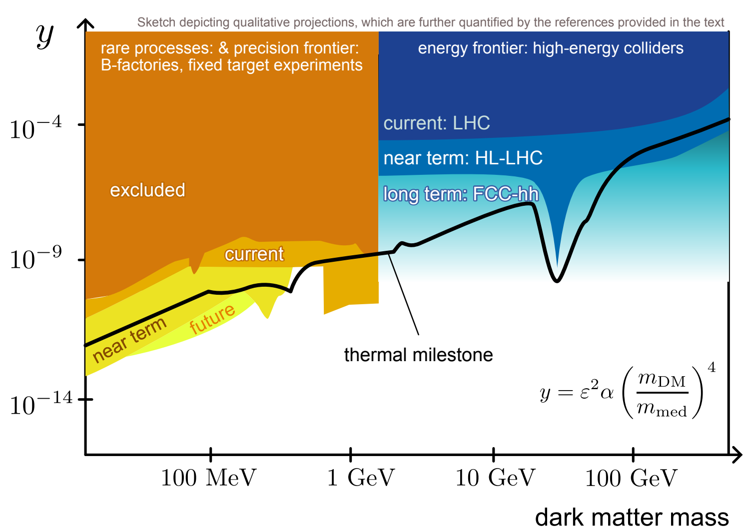

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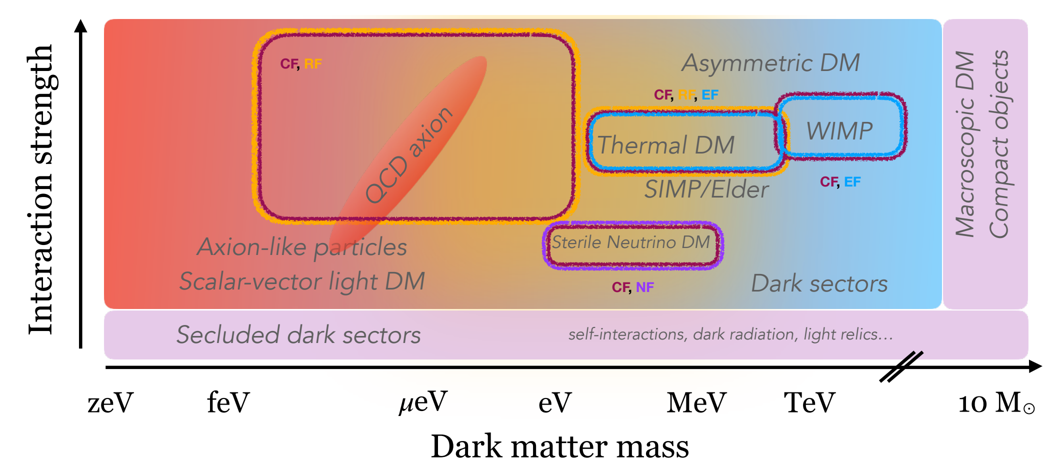

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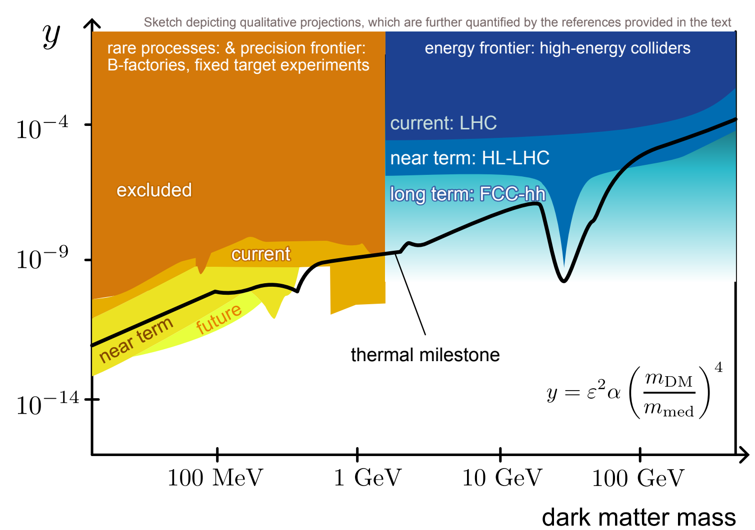

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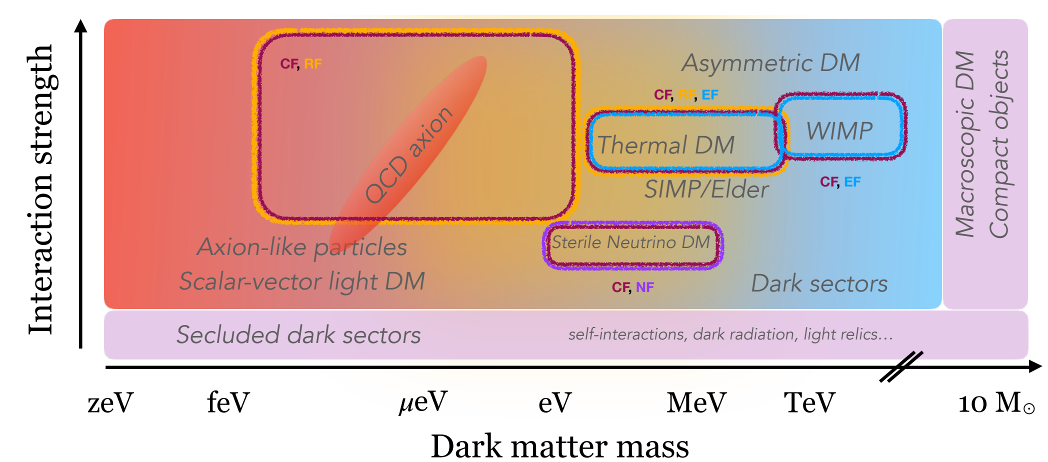

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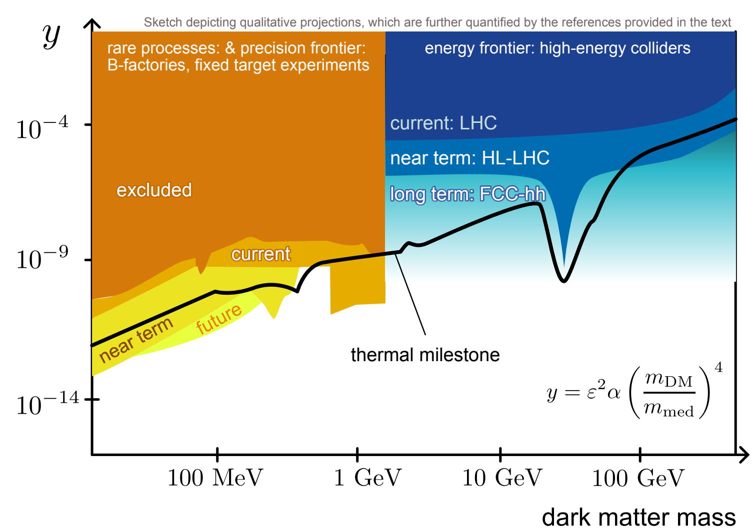

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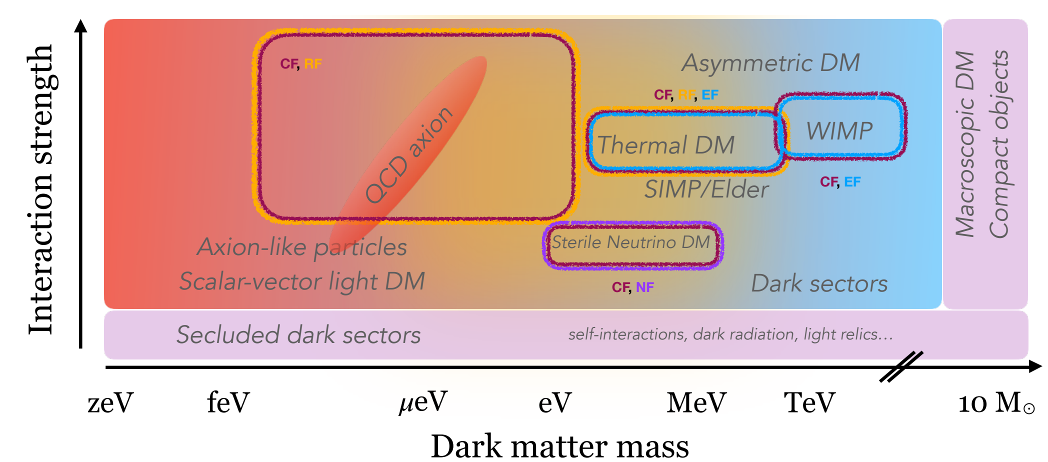

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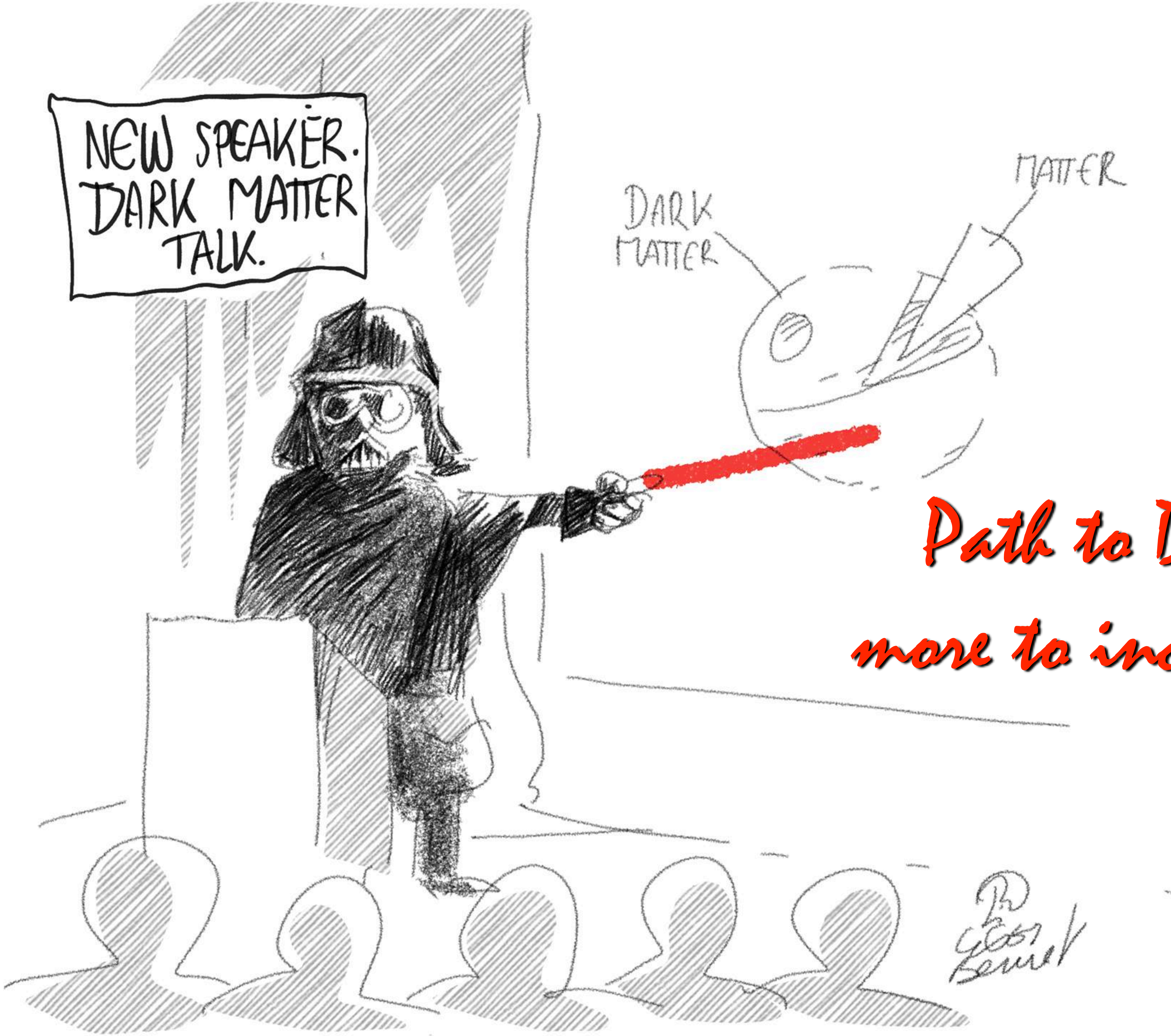
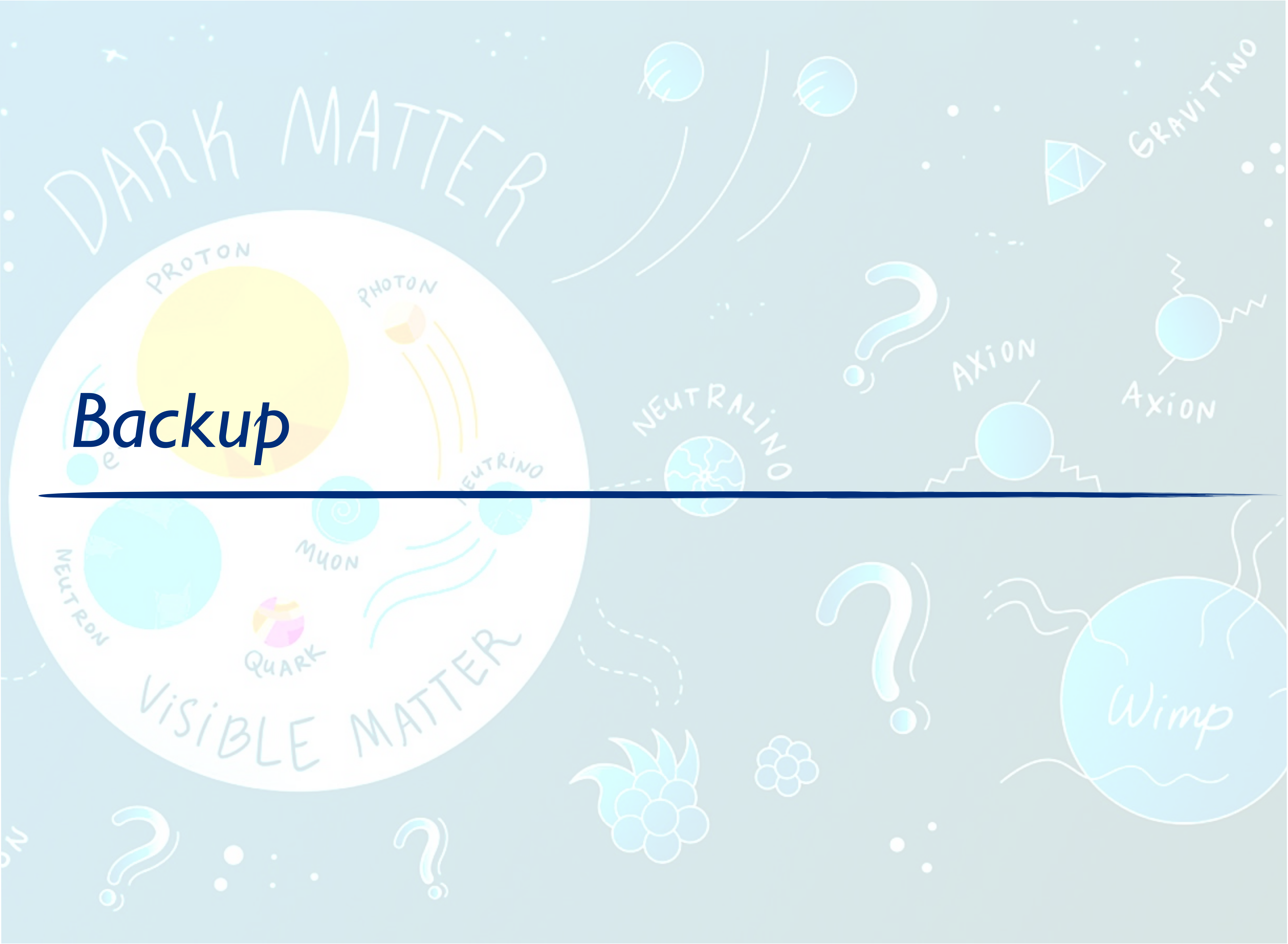
- Complementarity across frontiers is at the hearth of the journey to DM discovery
  - feedback on the roadmaps discussed?
  - other complementarity cases that should be highlighted beyond those in Snowmass document was summarized in this talk?
  - concrete suggestions from your community / experiment on how to make these roadmaps happen?



Path to DM,
more to include?

Backup


DARK MATTER
PROTON
PHOTON
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MUON
NEUTRON
QUARK
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AXION
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How can we study DM interactions?

- Assuming DM-SM interactions enables different searches:
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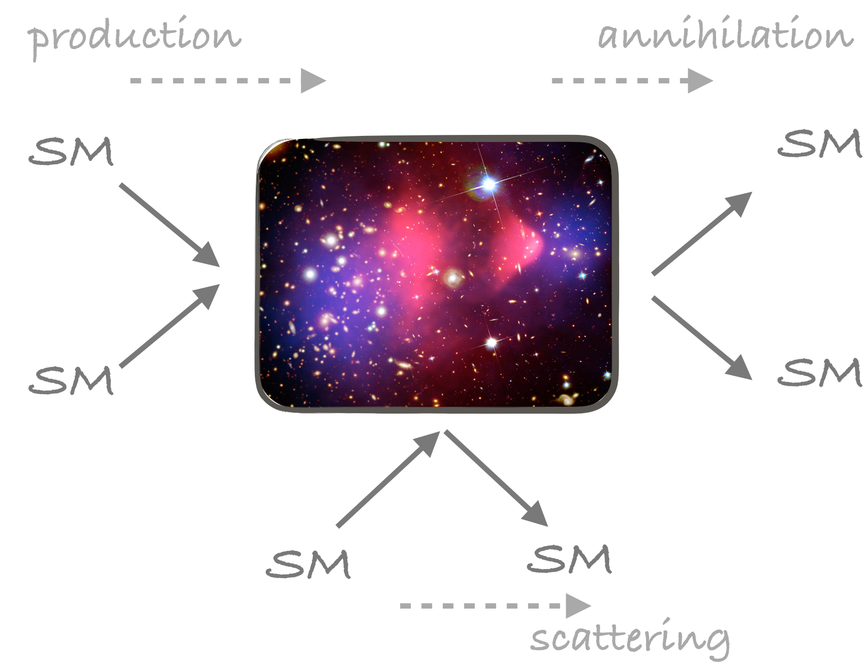
  - direct detection, nuclear recoils from DM-nuclei scattering
  - colliders, DM production



✱ Complementarity essential: eg. info about lifetime in case of DM discovery at colliders (~10^{-7}s), particle properties compared with cosmological constraints

- Example of complementarity for DM and dark-sector production

  MeV-GeV:
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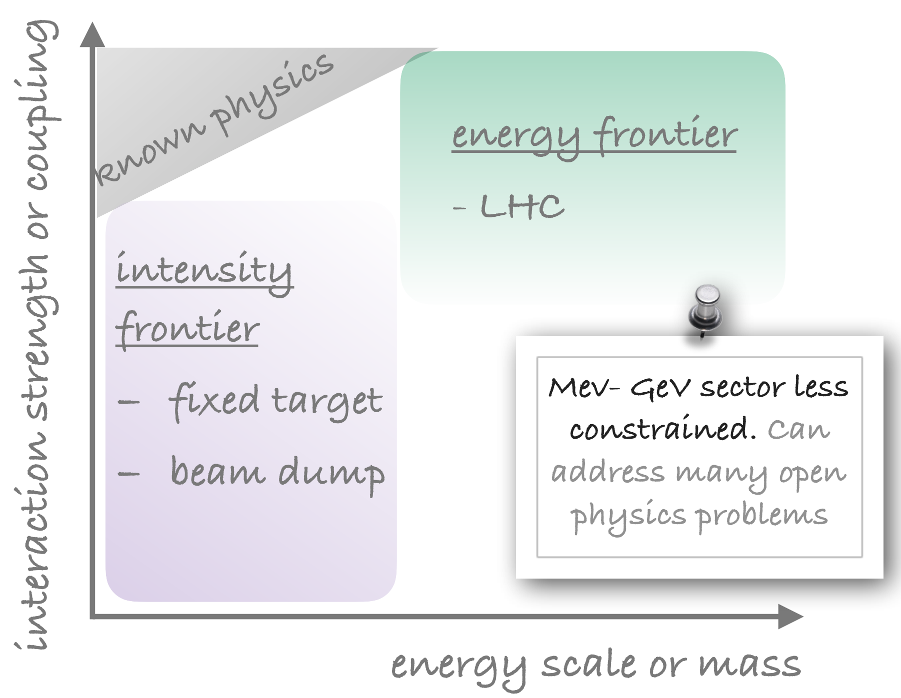
- dark sector mediators could be heavy, light, and/or long-lived

✱ rich connections and complementarity between type of experiments



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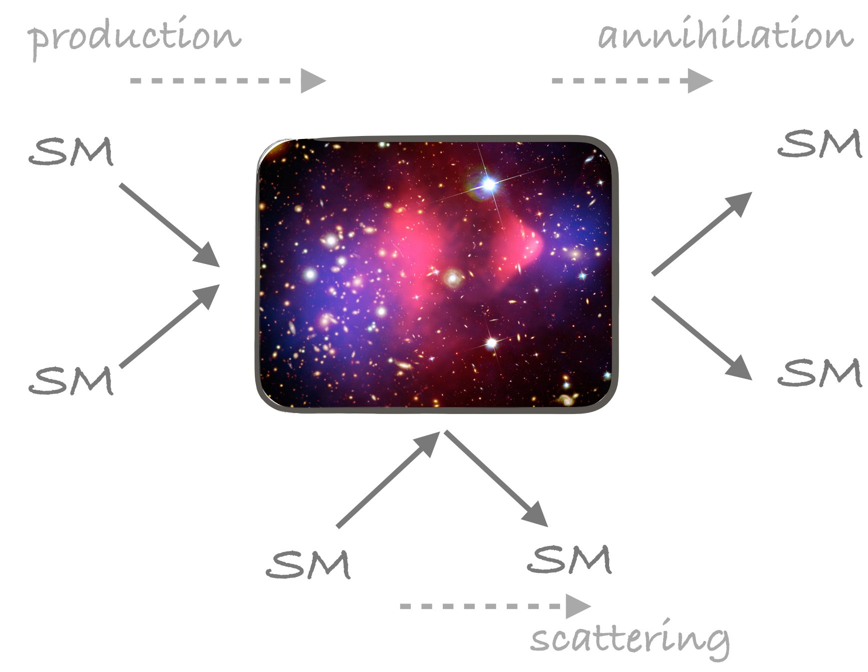

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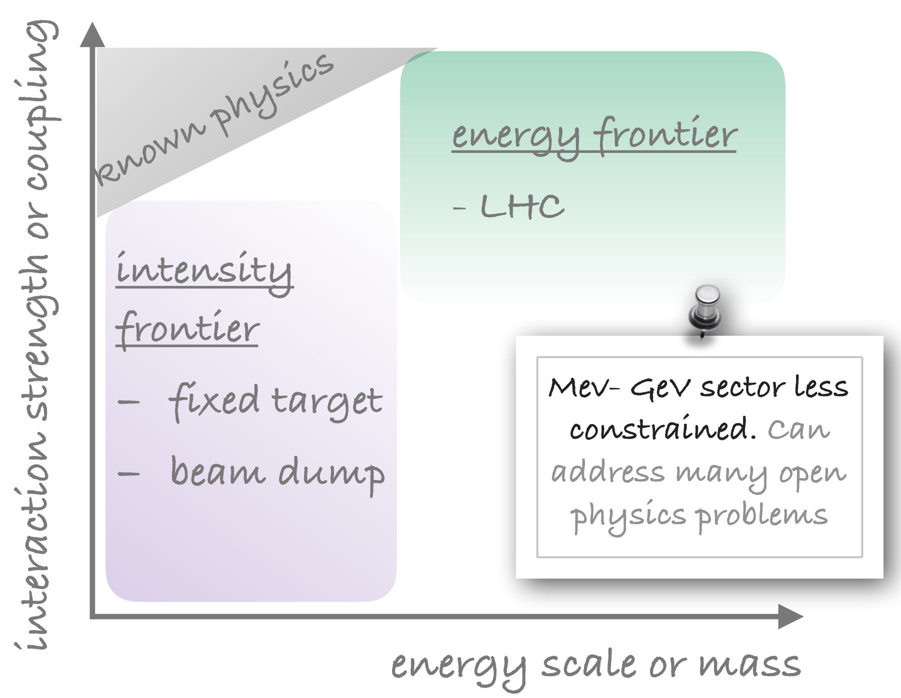

Important to identify common benchmarks to better exploit complementarity!

Snowmass: what is the road to discover DM?

arXiv:2210.01770

- *DM and visible matter have similar energy density - compelling evidence of non-gravitational interactions but … many viable DM candidates and properties*
  - no single experimental technique can probe all possibilities
  - *over last decade, broaden pursuable DM candidates through new experiments/searches* thanks to advances in technology, analysis techniques and theoretical models

- *Over the next decade, need of unified strategy to maximize discovery potential*
  - many compelling theoretical targets from simple/minimal models will be accessible via planned and proposed experiments, colliders, and observatories across experimental frontiers
  - understanding and harnessing complementarity between techniques and technologies is essential
  - *if DM discovered*, complementarity needed to triangulate fundamental nature of DM
  - *if DM is not found*, we will still gain important information on its properties

- *What is the strategy ahead to allow DM discovery?*
  - *build a portfolio of experiments of different scales:* experiments at all scales needed to cover very broad range of theoretically motivated parameter space
  - *leverage US expertise in international projects:* coordination and cooperation across borders is critical. Build a strong US-based program and pursue opportunities for US expertise to play key role in international projects
  - *Provide support to further strengthen the theory program:* essential to make connections between experimental frontiers and guide new approaches to understand and detect DM
  - *Support inter-disciplinary collaborations and increase in the research budget:* essential to enable new ideas, new technologies, and new analyses

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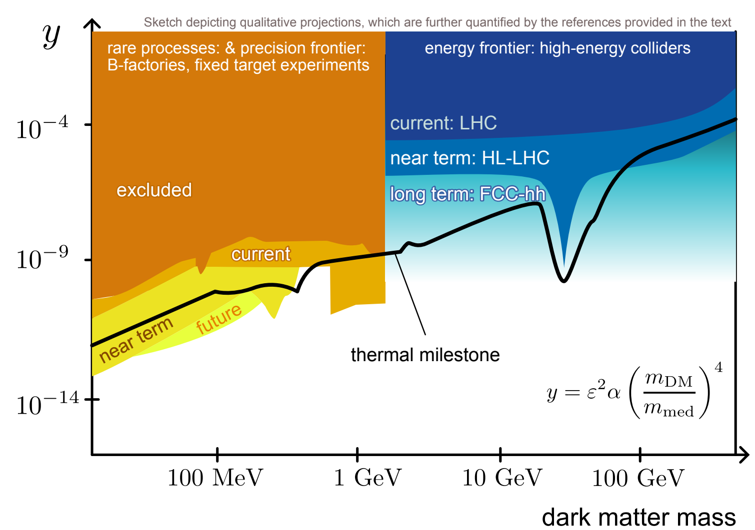

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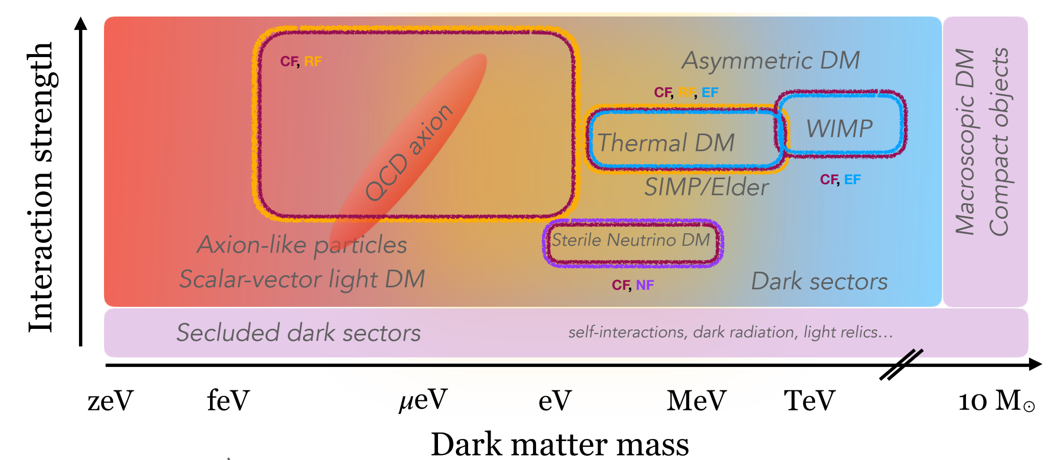

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