CAP Congress 2023 - UNB Fredericton - June 2023

Light Sub-GeV Dark Matter at Accelerators

Adam Ritz

University of Victoria

Work over several years with B. Batell, A. Berlin, P. deNiverville, S. Foroughi, D, McKeen, M. Pospelov, P. Schuster, N. Toro

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(A Decade of) Light Sub-GeV Dark Matter at Accelerators*

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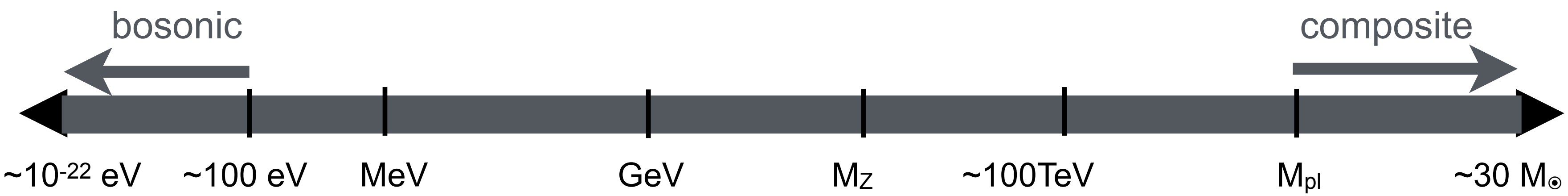
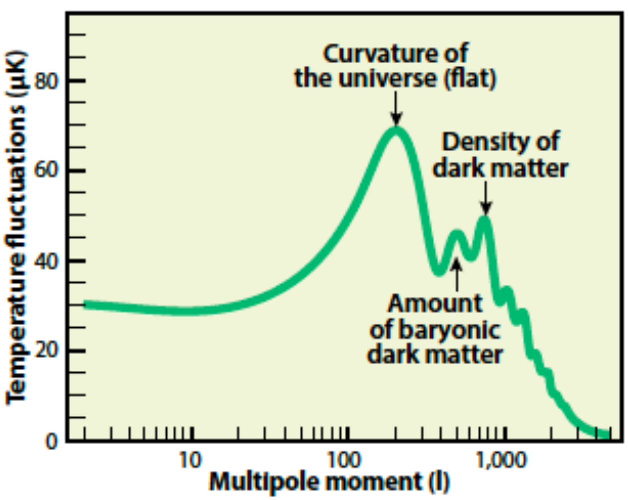
* Disclaimer for historical incompleteness!

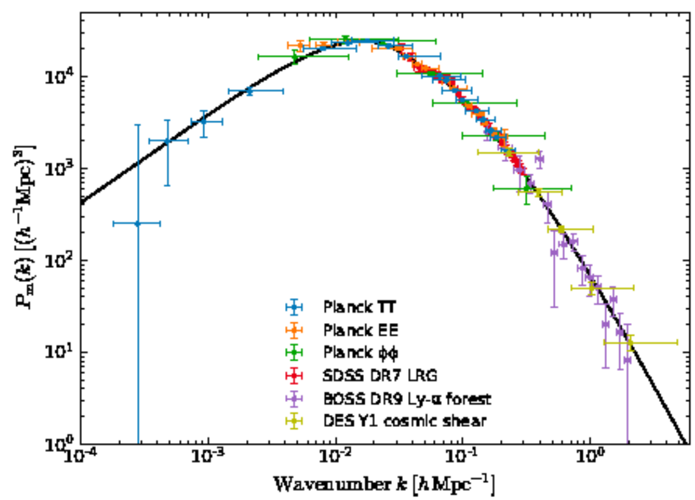
Cold dark matter landscape



- Gravitational evidence for DM from multiple cosmological & astrophysical scales (CMB, LSS, Lensing, etc)
- Empirical evidence for dark matter (and neutrino mass) arguably points to a dark/hidden sector (but not directly to a specific mass scale)

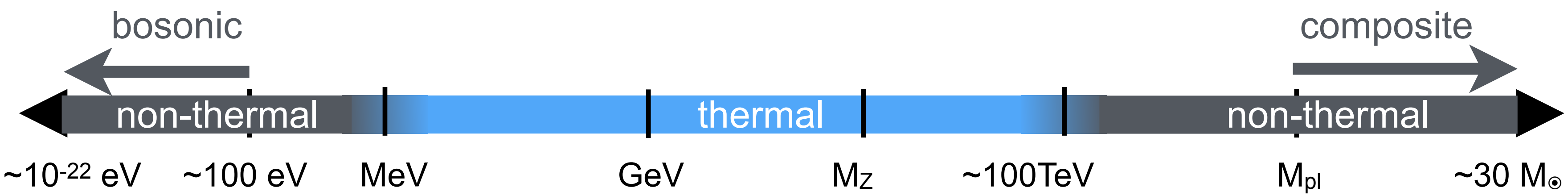


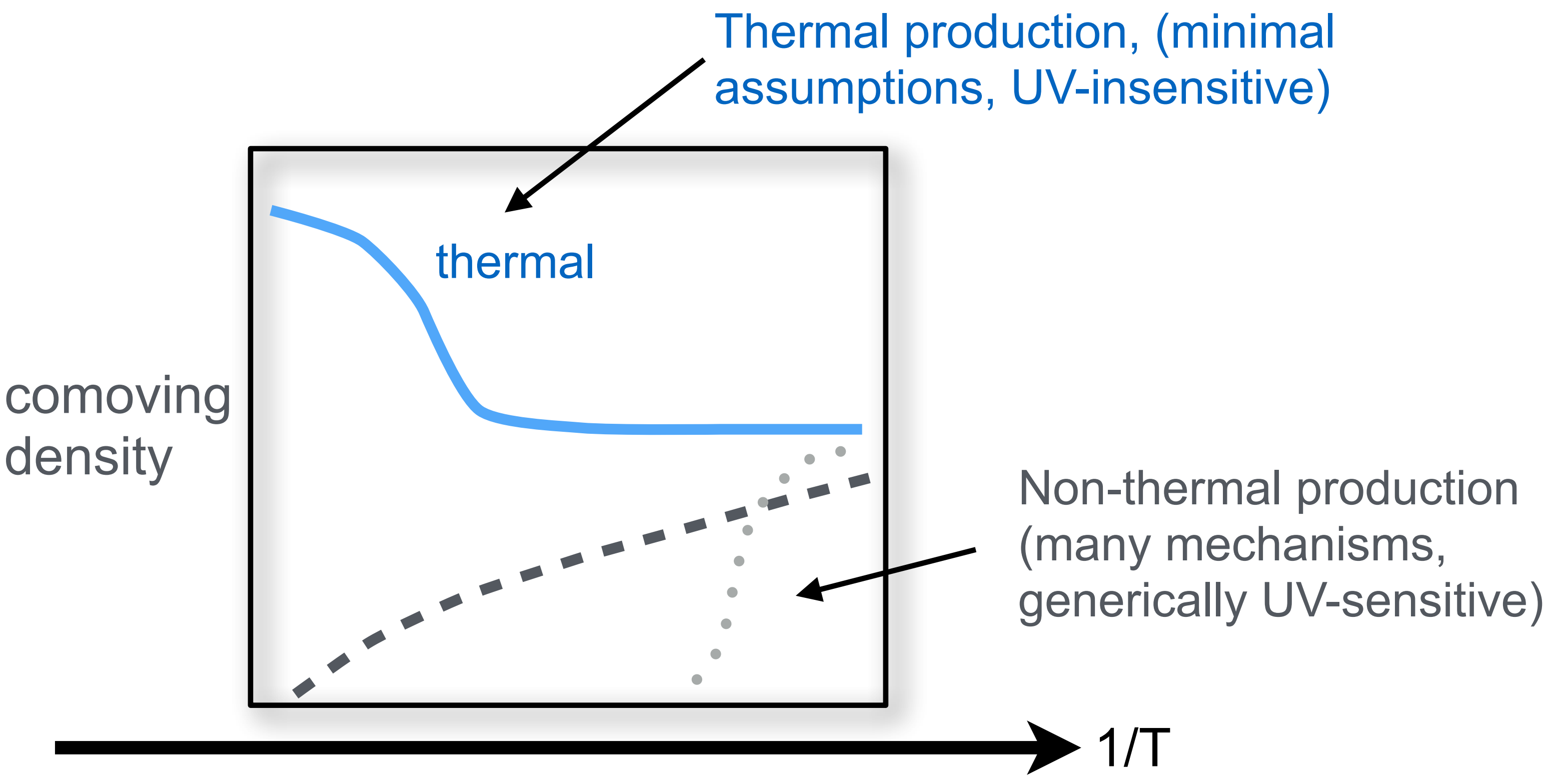
- $\rho_{CDM} \sim 5\rho_{baryons}$
- Cold enough…
- Dark enough…
- Structure growth prior to recombination…



➠ **Empirical evidence for DM (and neutrino mass) allows a vast mass range for new physics, so what are the appropriate theory priors?**

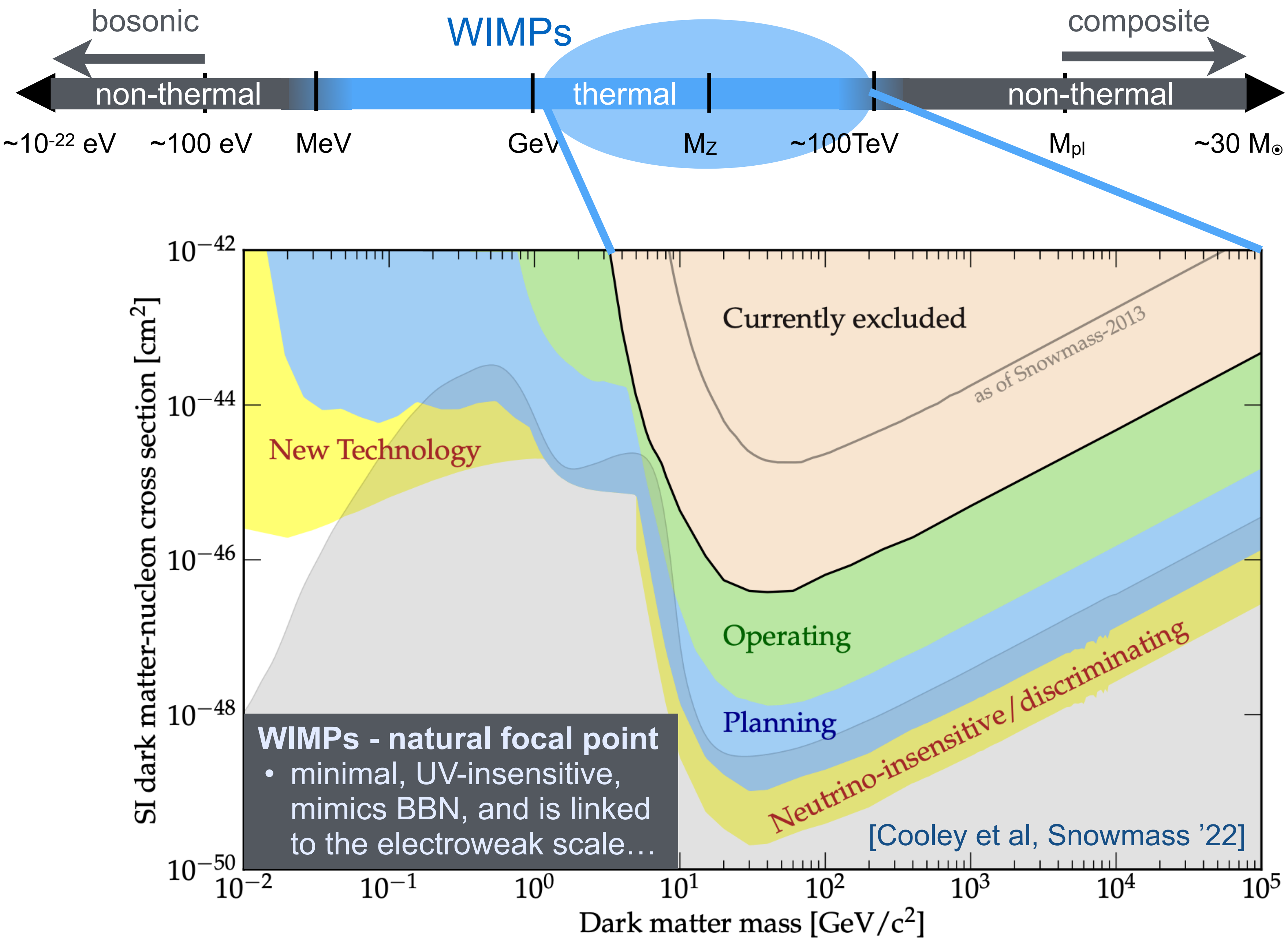
Cold dark matter landscape



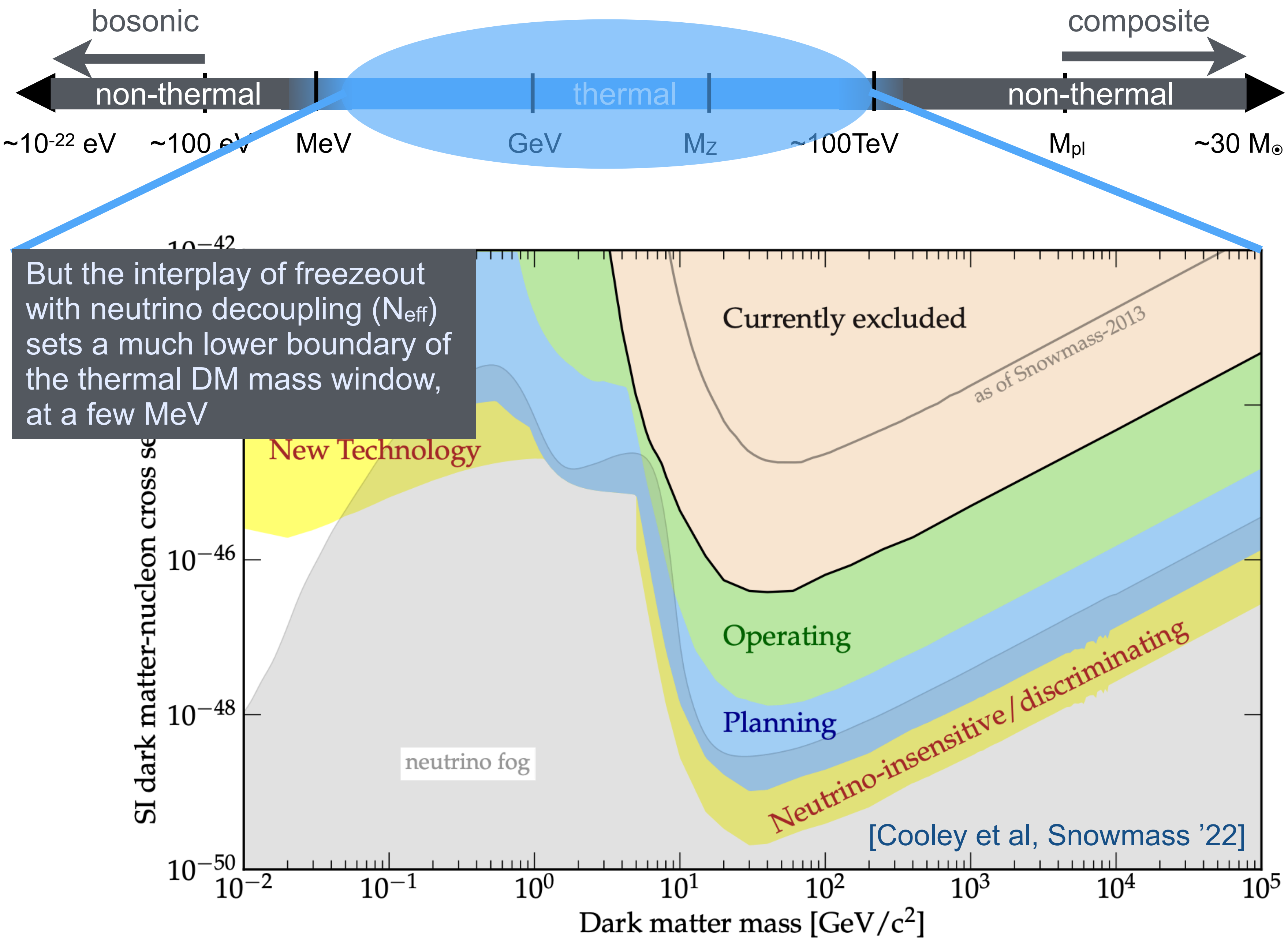


DM thermal history in the early universe

Cold dark matter landscape

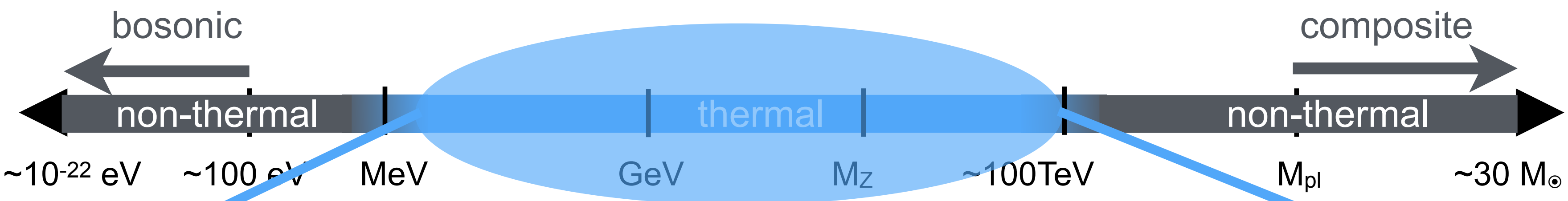


Cold dark matter landscape



But the interplay of freezeout with neutrino decoupling (N_{eff}) sets a much lower boundary of the thermal DM mass window, at a few MeV

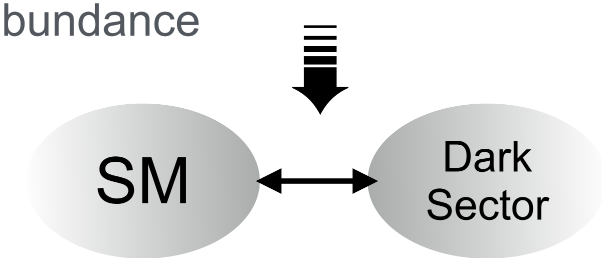
Cold dark matter landscape

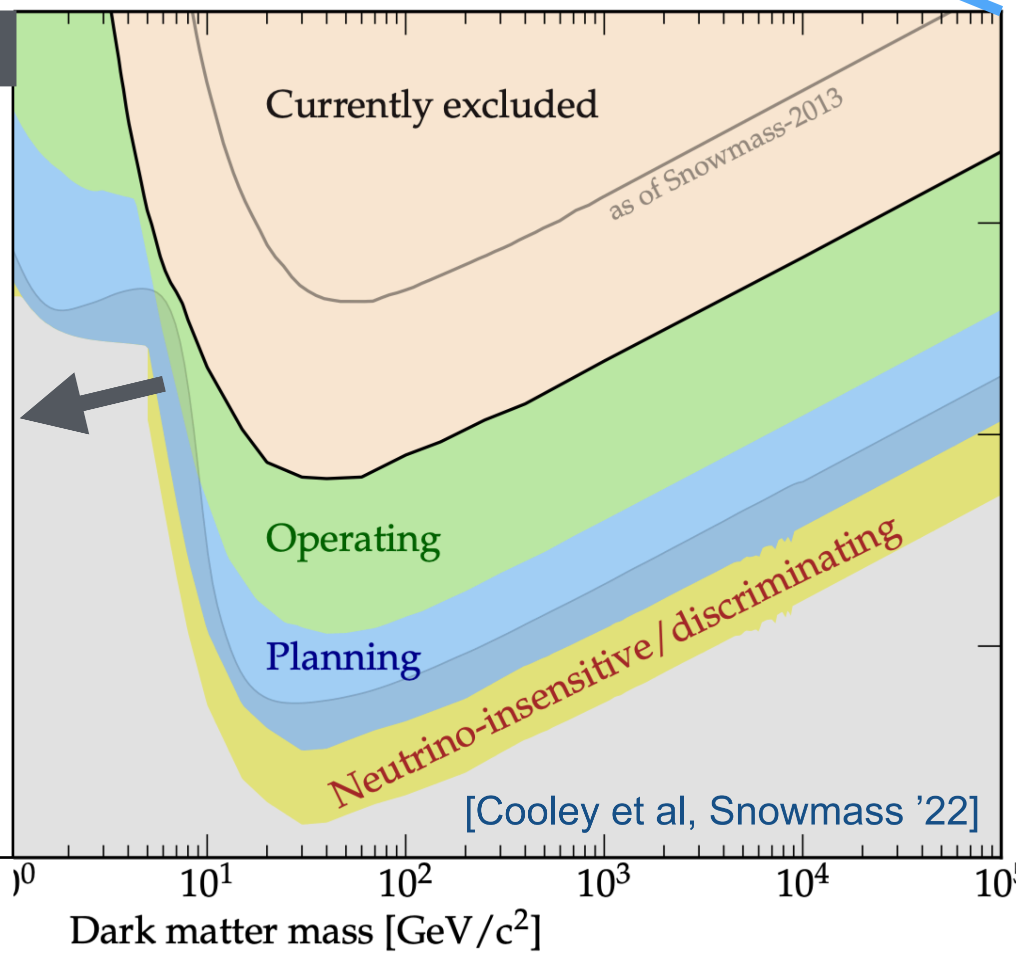


Sub-GeV thermal relic

$$\langle \sigma_{\rm ann} v \rangle \propto \frac{m_{\rm DM}^2}{m_{\rm med}^4} \sim 1 \text{ pb}$$

Lee-Weinberg bound ➠ light mediators are required for freeze out with the required relic abundance





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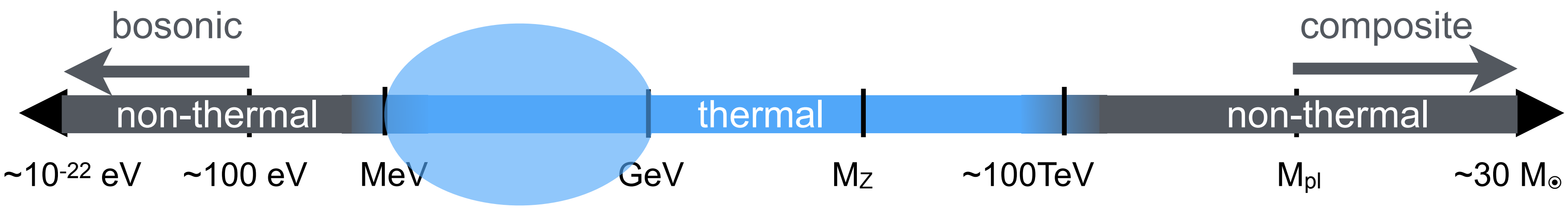

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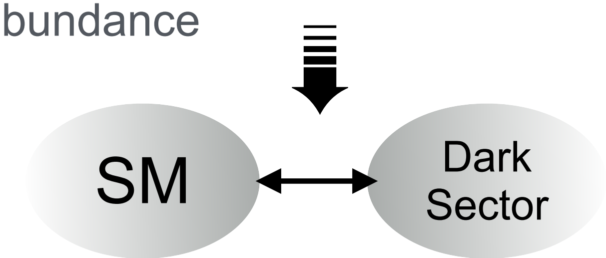


EFT for mediators to a (neutral) dark sector

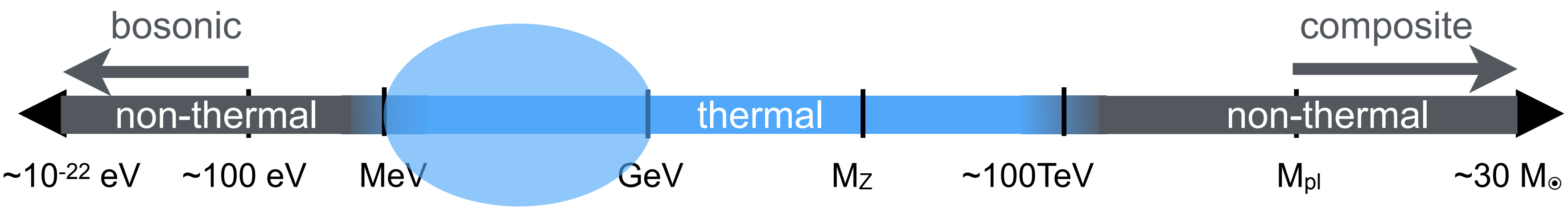
There are just three UV-complete relevant or marginal "portals" to a SM-neutral dark sector, unsuppressed by a (possibly large) new physics scale Λ

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{\rm (SM)} \mathcal{O}_l^{\rm (med)} = \mathcal{L}_{\rm portals} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j -$$

Vector portal — **Higgs portal** — **Neutrino portal**

Cold dark matter landscape



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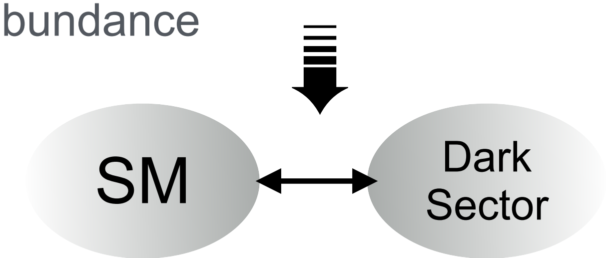

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Vector portal | **Higgs portal** | **Neutrino portal**

Focus for this talk - thermal DM (scalar, fermion in dark sector) charged under U(1)’ vector portal

Accelerator-based strategy for light DM

To test this scenario, return to an old hypothesis - is CDM more like the CνB (abundant, but with KE too low for direct detection recoil thresholds)?

➠ Muon neutrinos were instead discovered at BNL in a fixed target experiment, via production and (weak) scattering of a *relativistic* beam

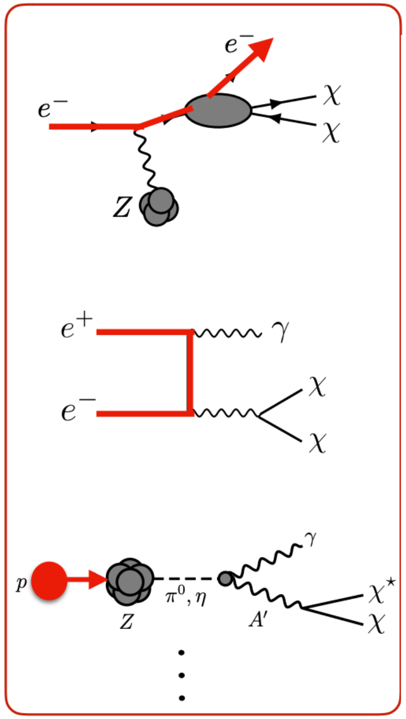
OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 15, 1962)

➠ **accelerator-based search strategy**

Low DM mass, and low dimension portal couplings ➠ High-luminosity medium energy colliders (B-factories) and e-beam and p-beam fixed target experiments



[Krnjaic et al, Snowmass ’22]

Accelerator-based strategy for light DM

To test this scenario, return to an old hypothesis - is CDM more like the CNB (abundant, but with KE too low for direct detection recoil thresholds)?

- Muon neutrinos were instead discovered at BNL in a fixed target experiment, via production and (weak) scattering of a *relativistic* beam

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(Received June 15, 1962)

- **accelerator-based search strategy**

- **probe the full kinematics of thermal freezeout of dark sector DM + mediator**

Invisible, non-SM

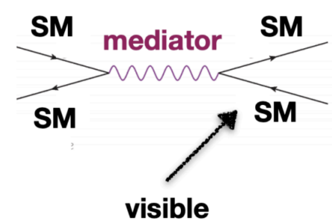
Dark Matter production

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

Visible, SM

Production of portal-mediators that decay to SM particles

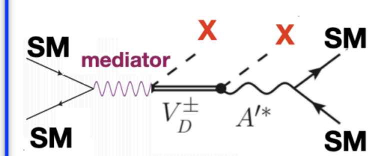
Systematically exploring the portal coupling to SM particles



Mixed visible-invisible

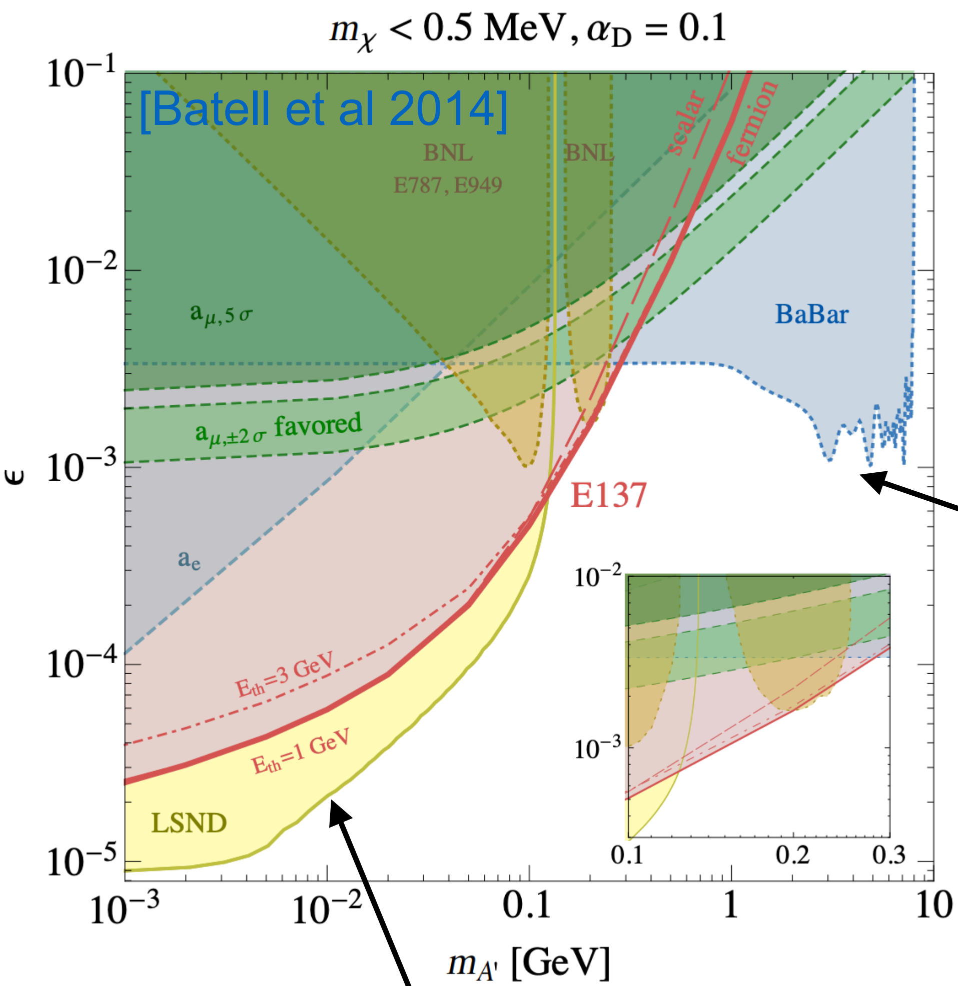
Production of "rich" dark sectors

Testing the structure of the dark sector



[Gori, Williams, Snowmass RF6 '22]

Status a decade ago (vector portal DM)



Initial efforts to recast existing data and analyses by theorists

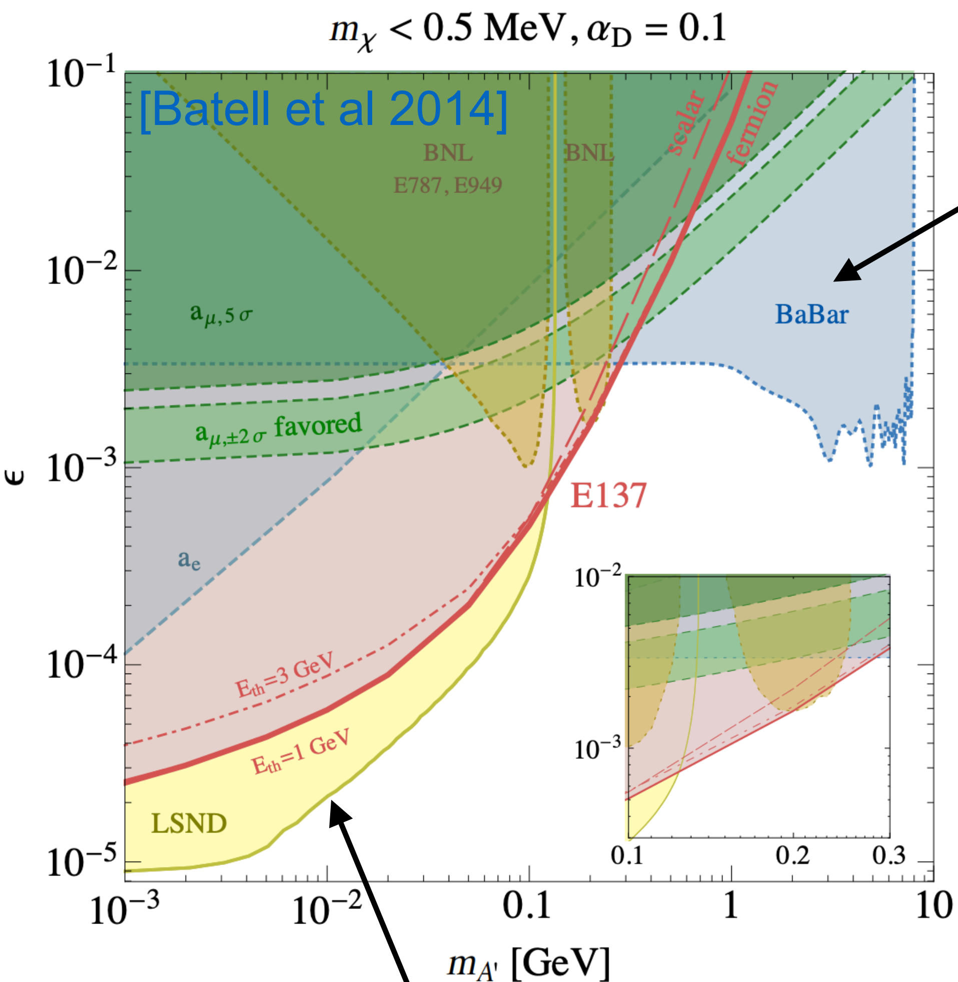
Recast of BaBar monophoton (missing E) data [Essig et al 2013]

Signal rate ~ ε^2

Recast of LSND e-scattering data [deNiverville, Pospelov & AR 2011]

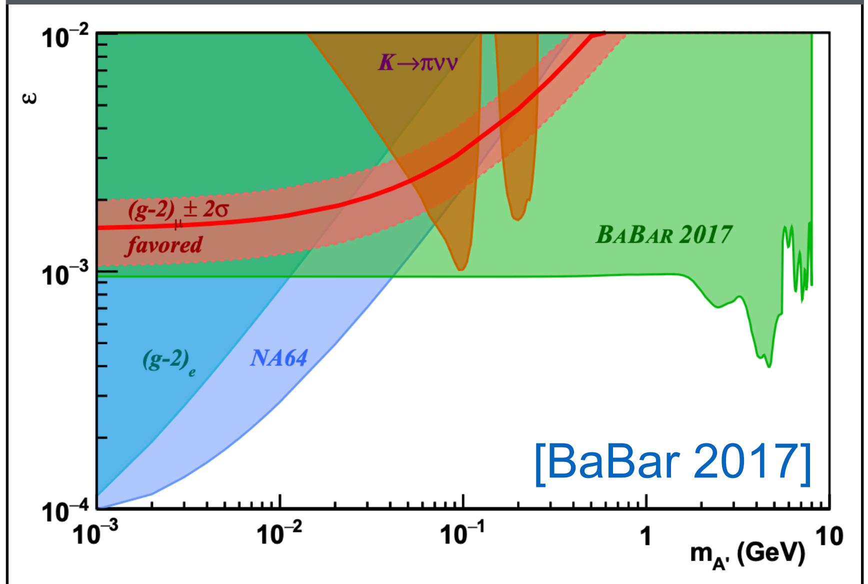
Signal rate ~ ε^4

Status a decade ago (vector portal DM)



Recast of BaBar monophoton (missing E) data [Essig et al 2013]

Analysis of the full dataset by BaBar improved this limit in 2017



Recast of LSND e-scattering data [deNiverville, Pospelov & AR 2011]

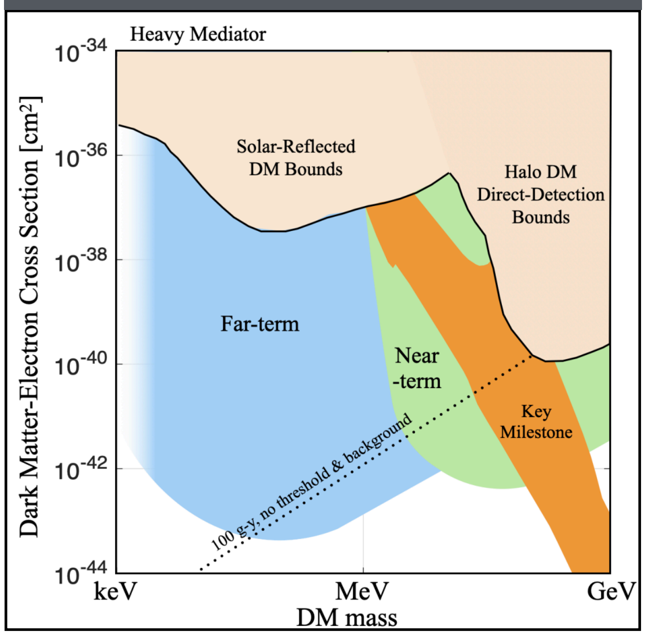
"New" experiments…

A broad target mass range (MeV-GeV) provides an incentive to explore new technologies, and low-cost synergies with existing (e.g. neutrino) experiments

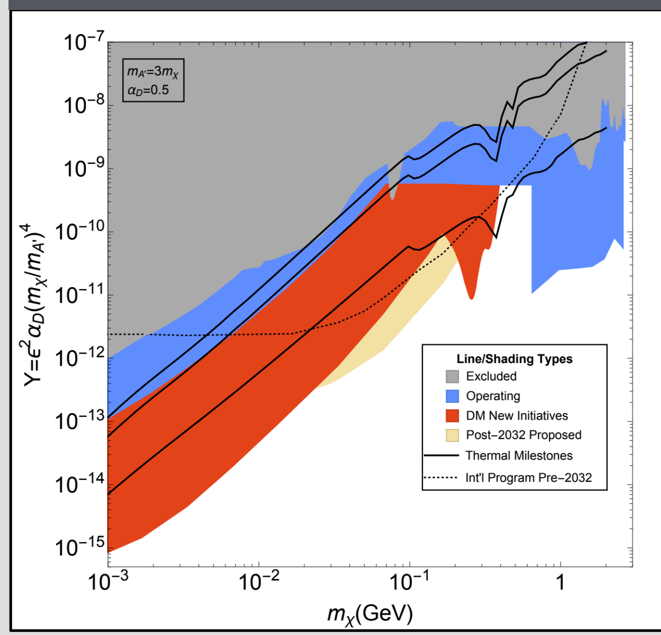
Complementary kinematics

Focus of this talk

Direct detection via (non-rel) electron scattering

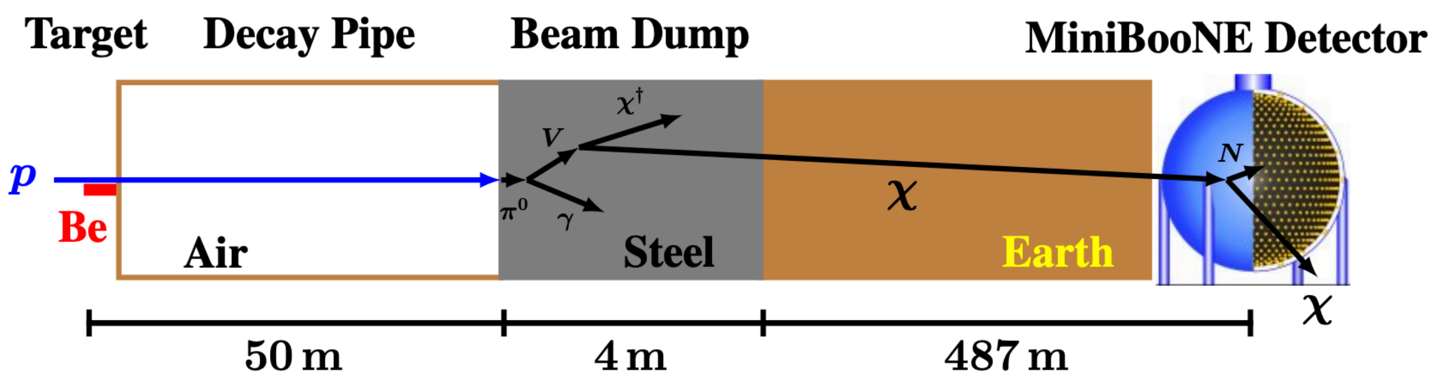


Accelerator-based missing E/mtm or (rel) scattering



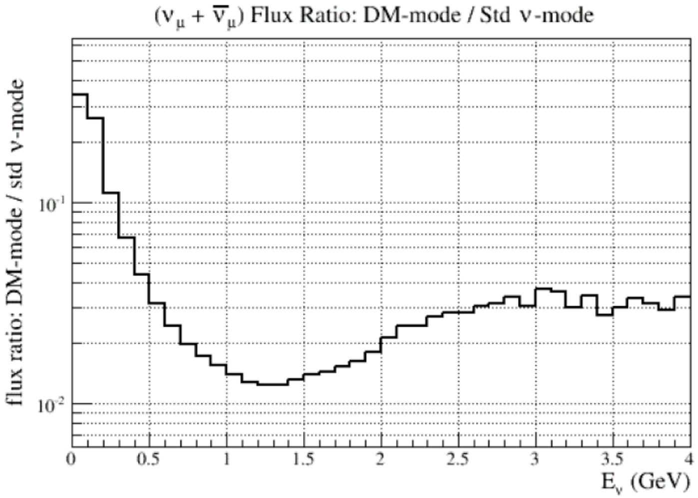
Neutrino beams & scattering - MiniBooNE

Proposal: Synergy with the neutrino short- and long-baseline program, using the (near) detector as a dark matter detector, looking for recoil, but now for a relativistic beam [Batell, Pospelov & AR 2009, deNiverville, Pospelov & AR 2011, Dharmapalan et al 2012]



Neutrino "background" can be reduced significantly:

- p-beam off-target (factor ~70 reduction)
- Timing (10ns delay for DM, pulsed beams)
- Recoil energy cuts (forward e-scattering)



MiniBooNE proposal to FNAL PAC

[Dharmapalan et al 2012]

PAC presentation in Jan 2014

A Proposal to Search for Dark Matter with MiniBooNE

Submitted to the FNAL PAC Dec 16, 2013

The MiniBooNE Collaboration

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The Theory Collaboration

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University of Chicago, Chicago, IL, 60637

P. deNiverville, M. Pospelov, & A. Ritz
University of Victoria, Victoria, BC, V8P 5C2

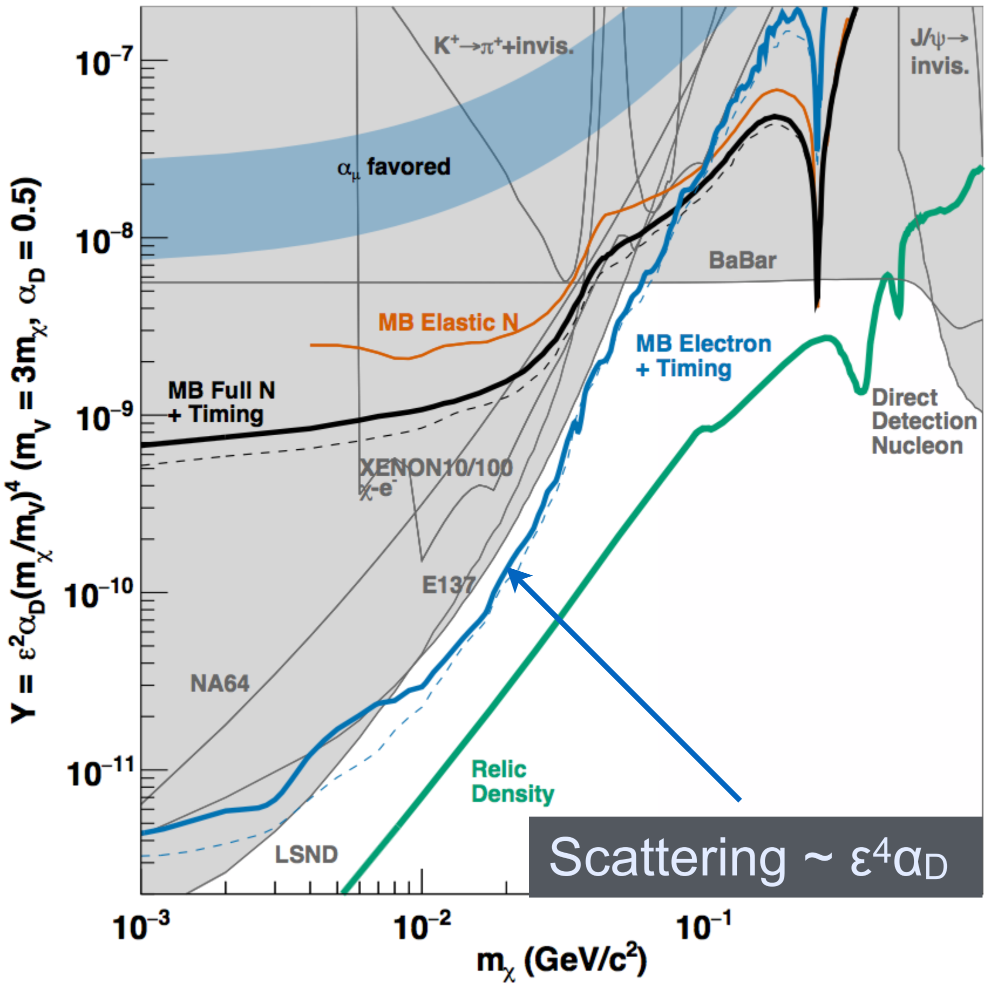
D. McKeen
University of Washington, Seattle, WA, 98195

✓ - beam dump run approved initially for 12 months, but ultimately extended until MicroBooNE switched on

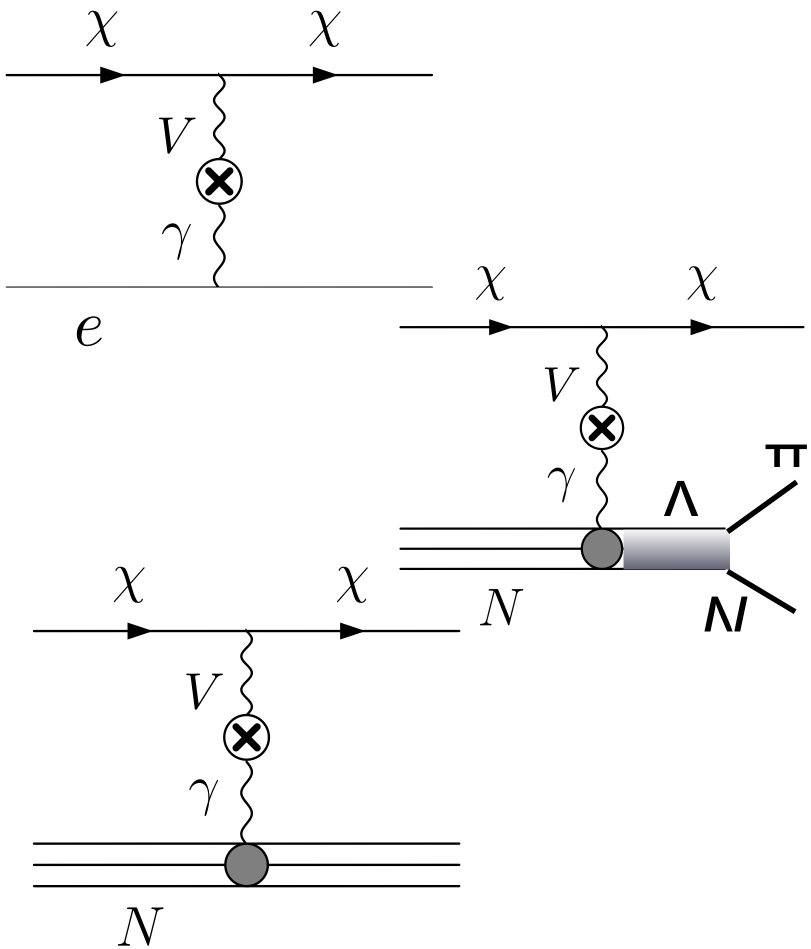
Request 2 x 10^{20} POT in 2014 with beam off-target

MiniBooNE results

Scattering signatures mimic neutral current neutrino interactions

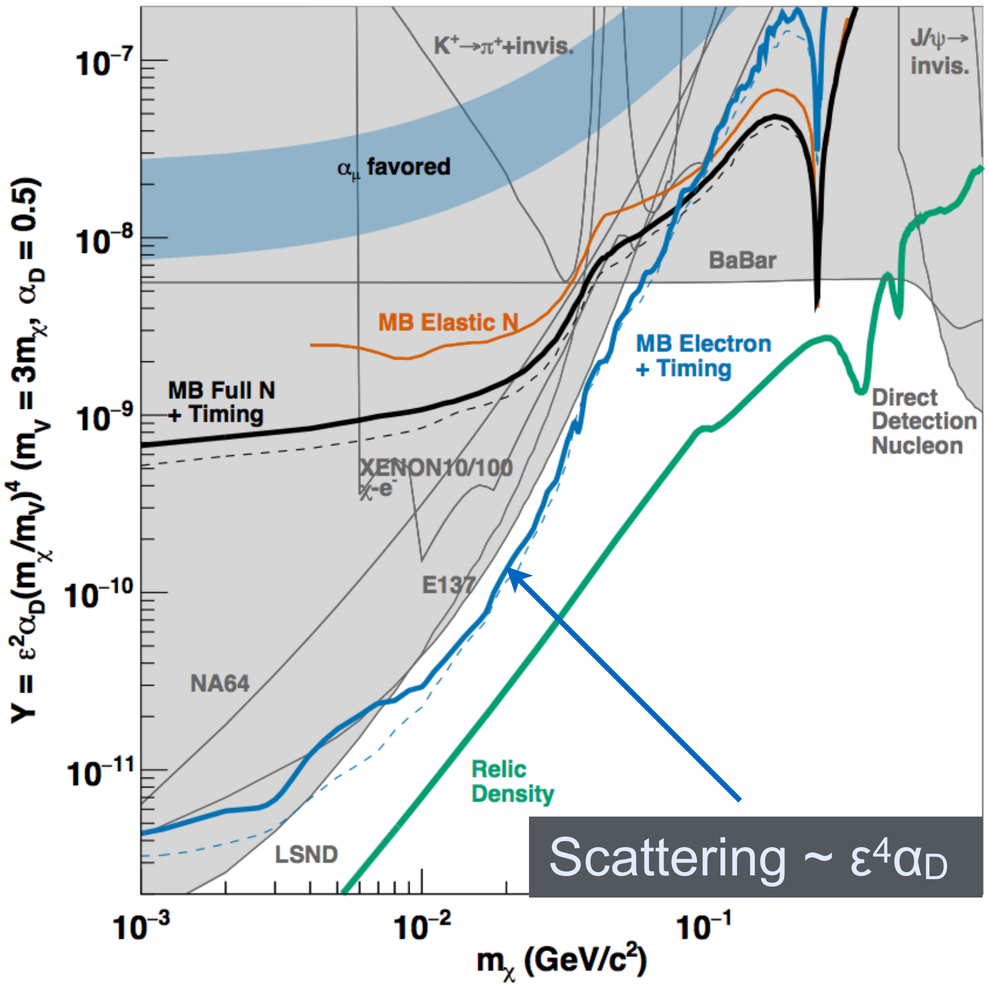


[MiniBooNE 2018]



MiniBooNE (& COHERENT) results

Scattering signatures mimic neutral current neutrino interactions

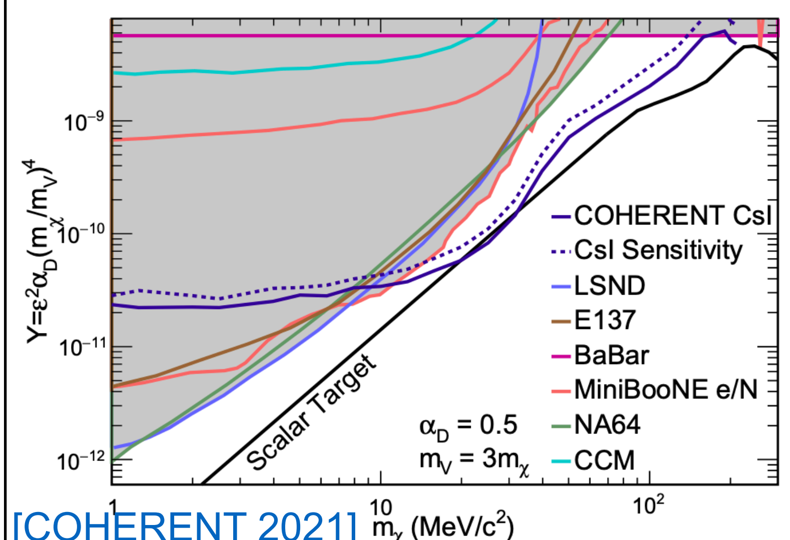


Scattering ~ $\varepsilon^4\alpha_D$

[MiniBooNE 2018]

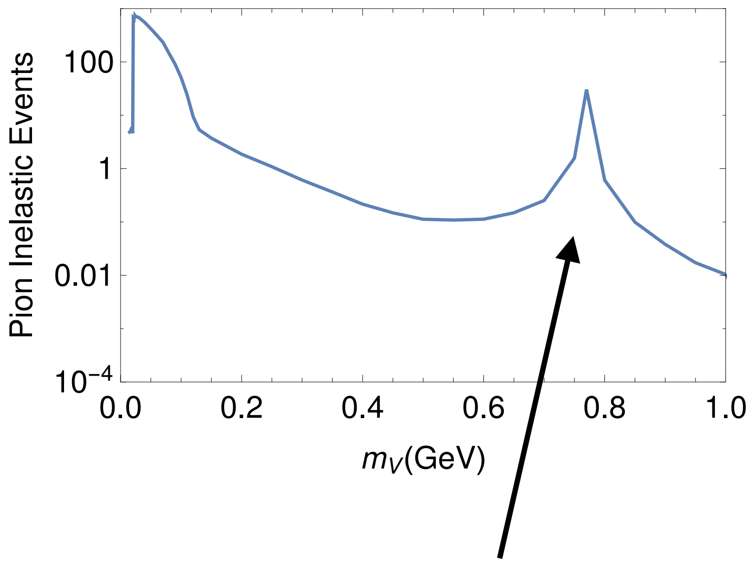
Small improvement in sensitivity, but this was a full experimental analysis, not a theoretical recast (as for the LSND limit), and pioneered a number of tools for background reduction

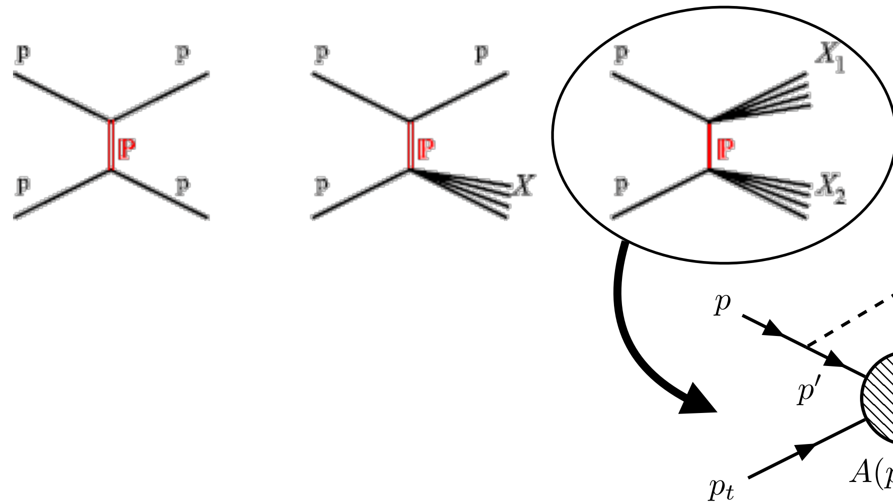
Improved higher-mass sensitivity using similar techniques in 2021 from COHERENT CsI (at SNS)



[COHERENT 2021]

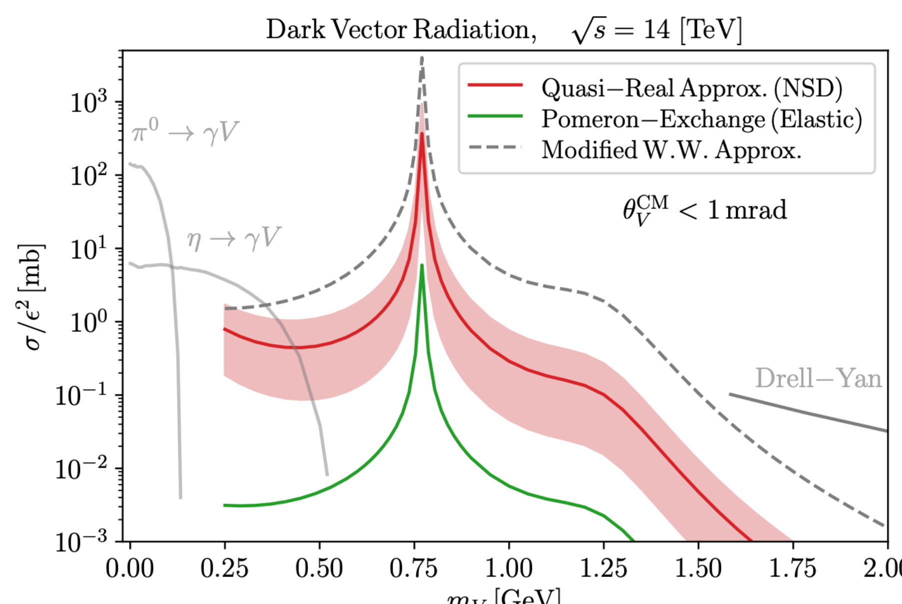
Neutrino Beams - production rate





Revisiting A' production in proton bremsstrahlung, including the ρ/ω resonance region

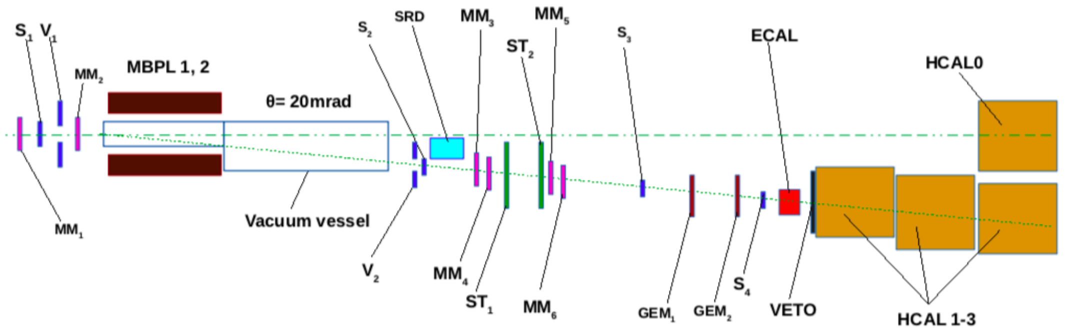
[Foroughi-Abari, AR '21 + work in progress]

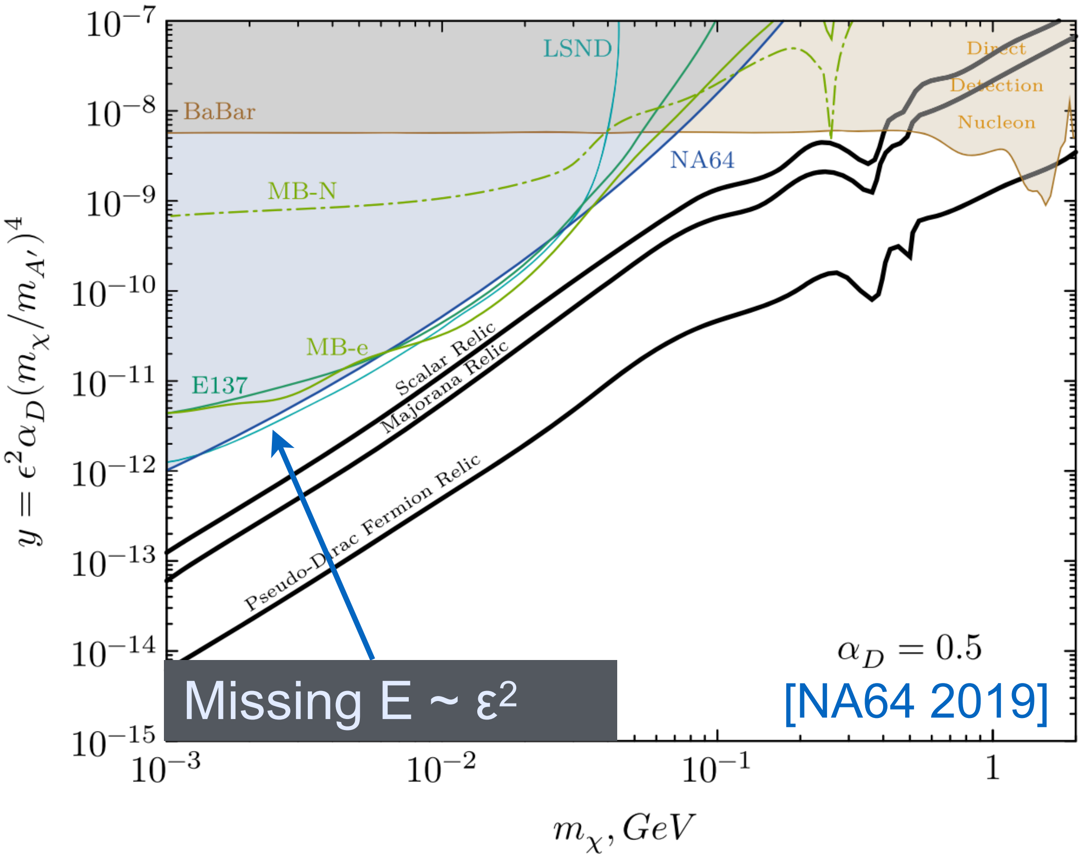


Missing mass - NA64

The signal rate for production and missing mass is ~ ε^2

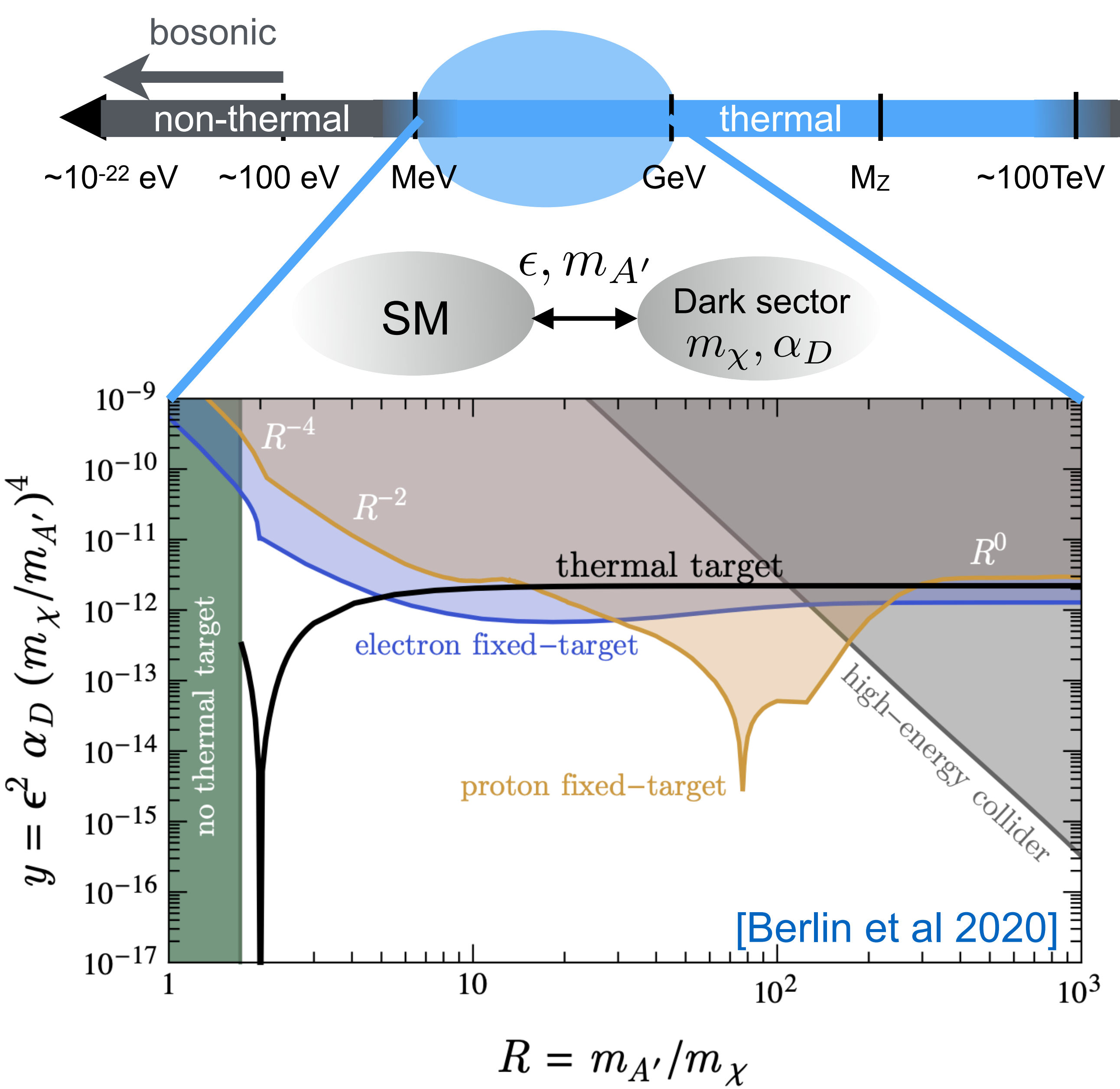
Proposal for NA64 approved for CERN north area with operations starting in 2016





Improvement on E137, MB-e and LSND limits, relying purely on the A'-electron coupling

Sub-GeV thermal DM landscape today

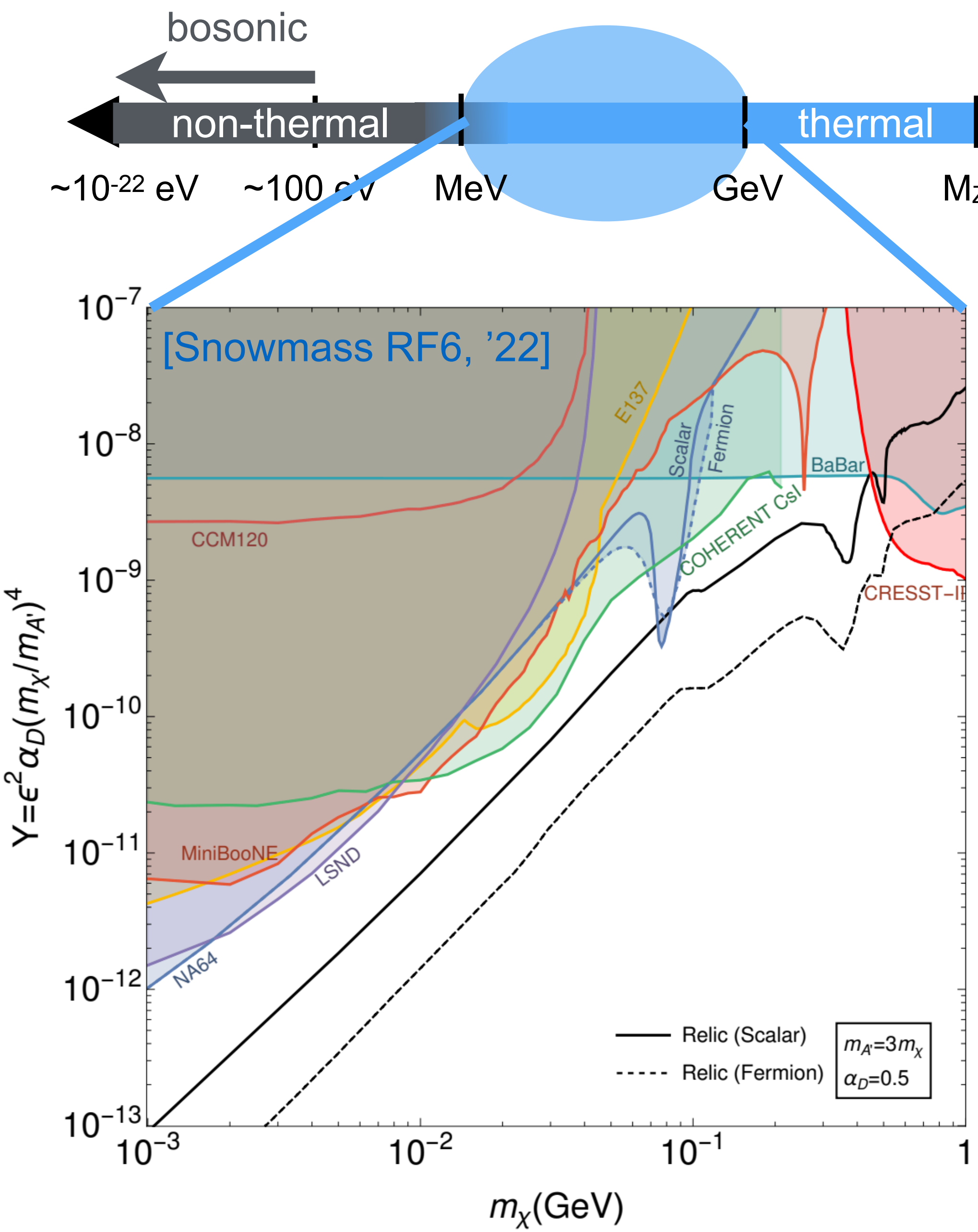


Invisible, non-SM

Dark Matter production

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

Sub-GeV thermal DM landscape today



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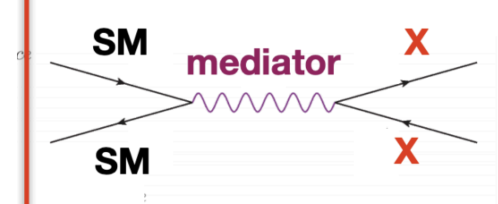

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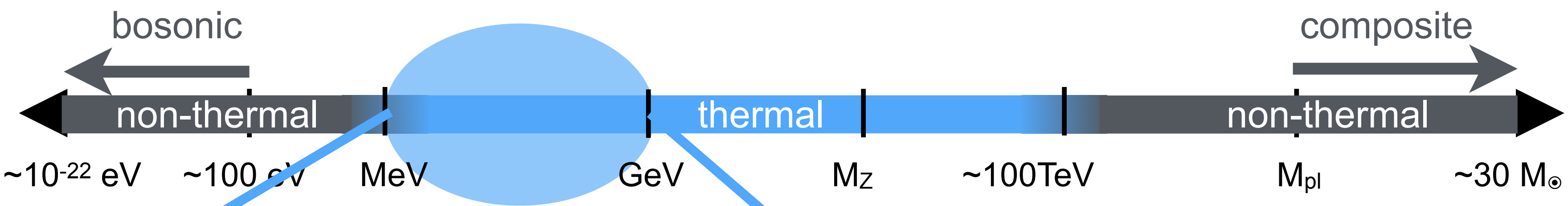

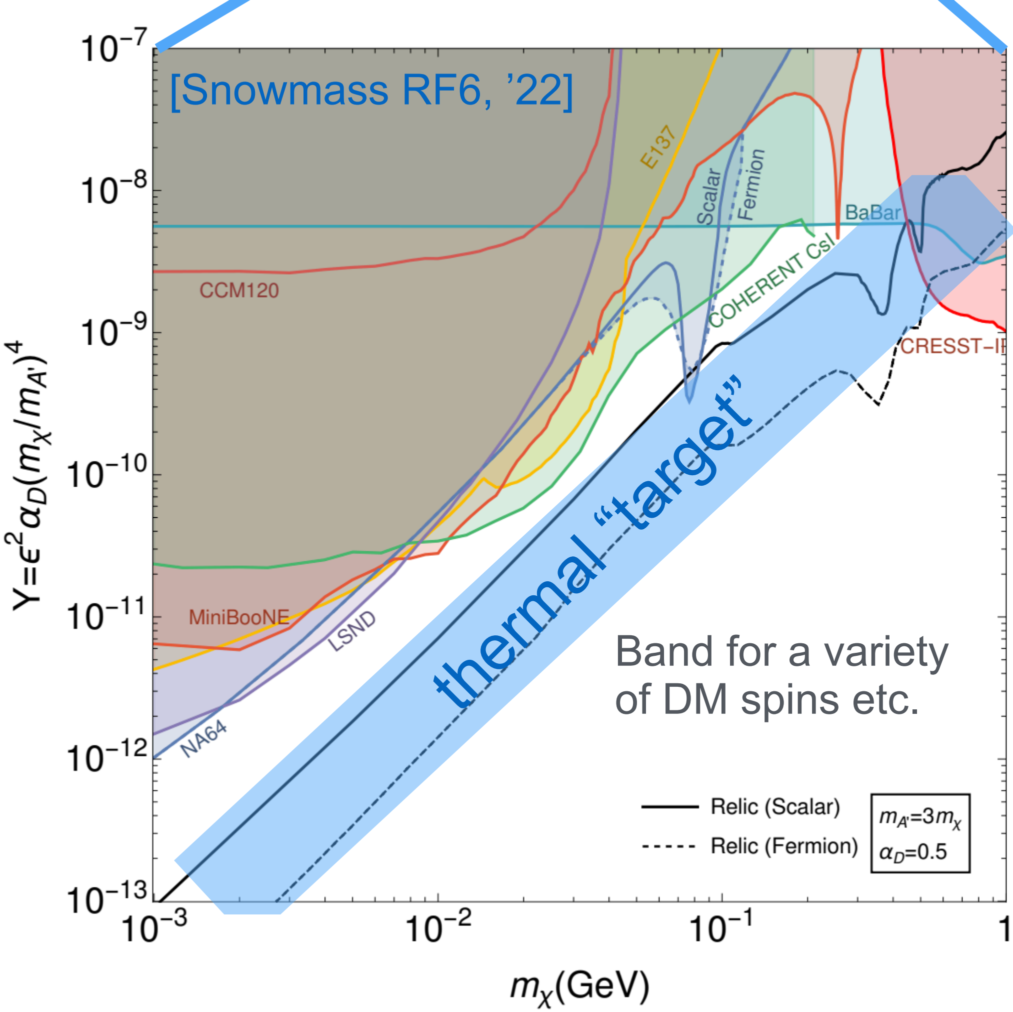

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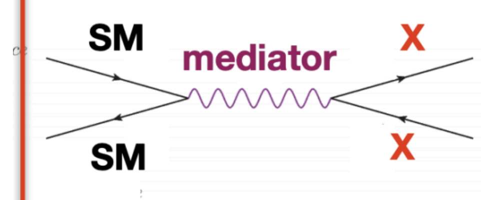
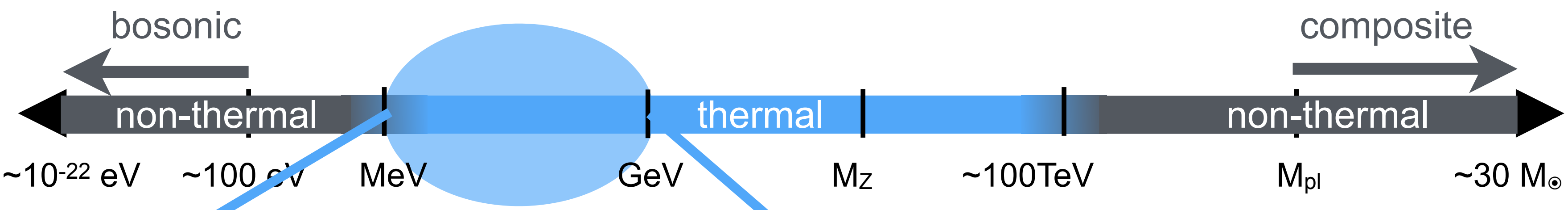
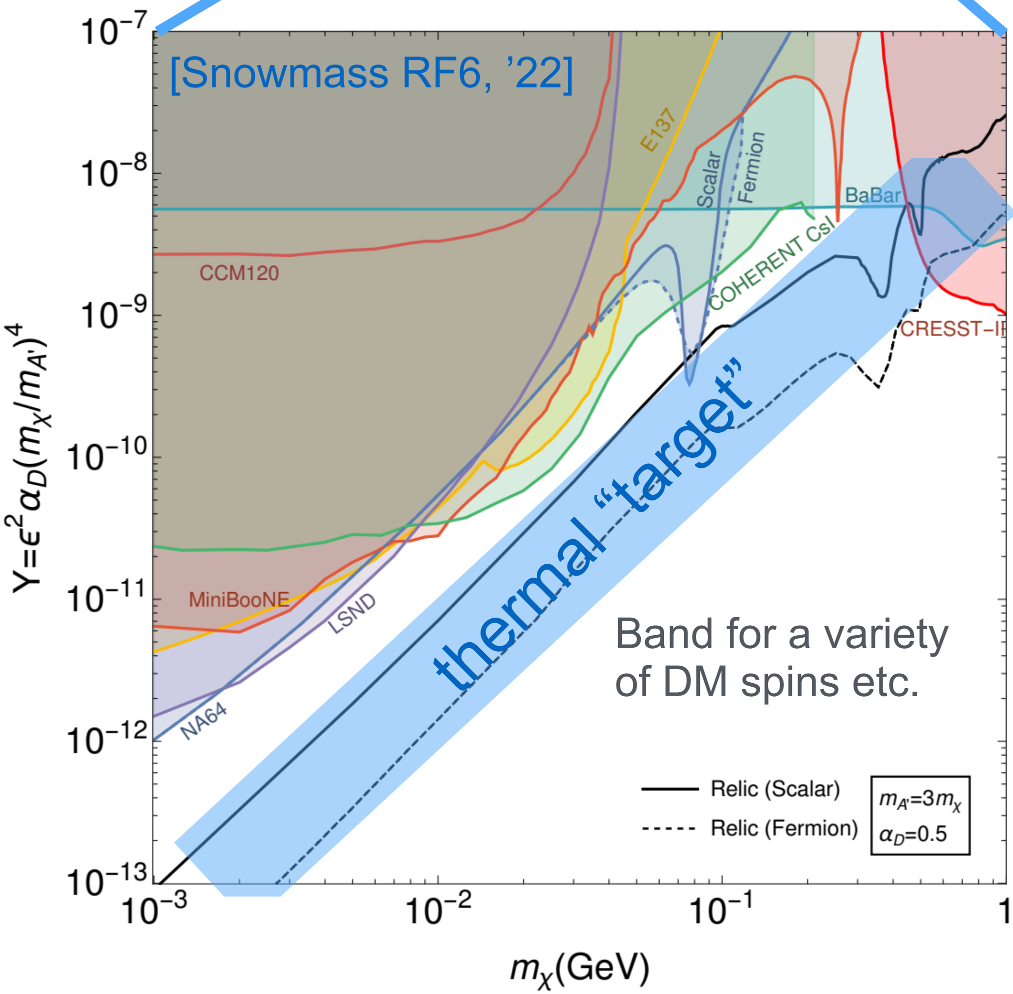
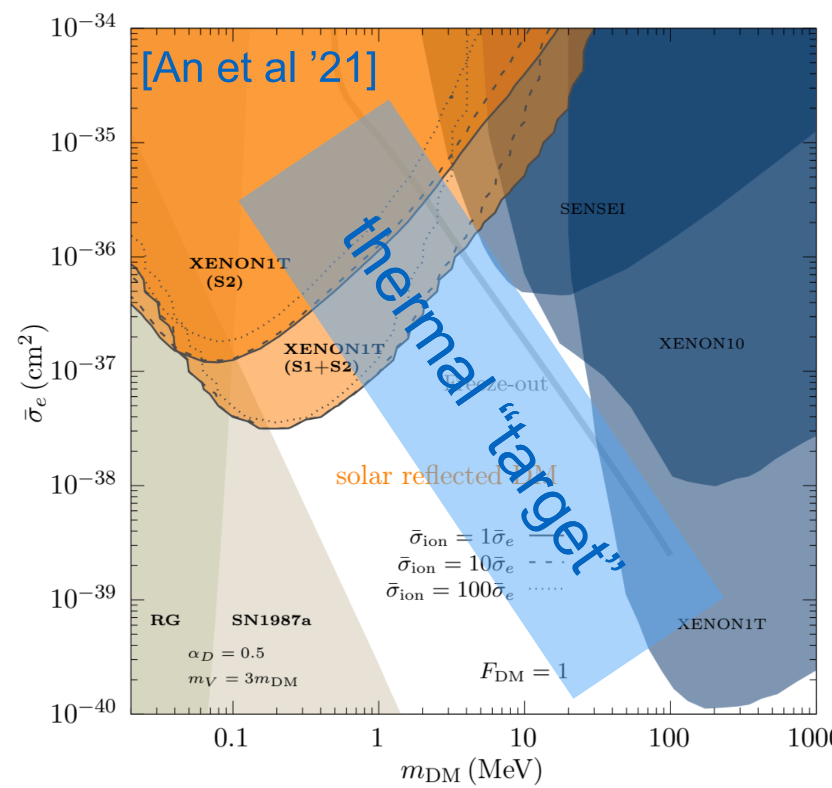


Sub-GeV thermal DM landscape today

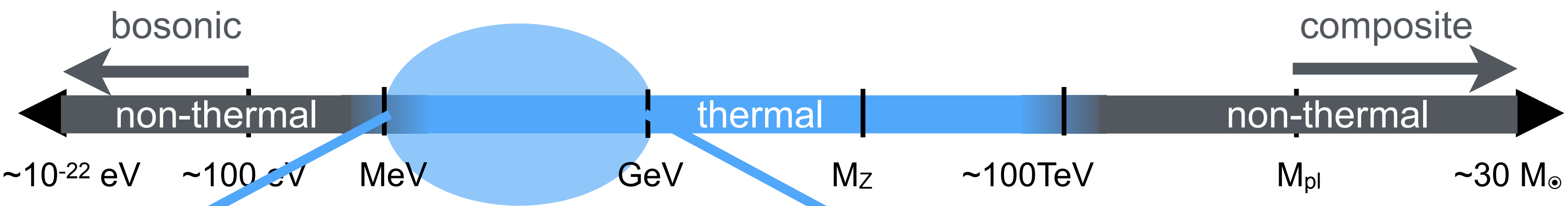


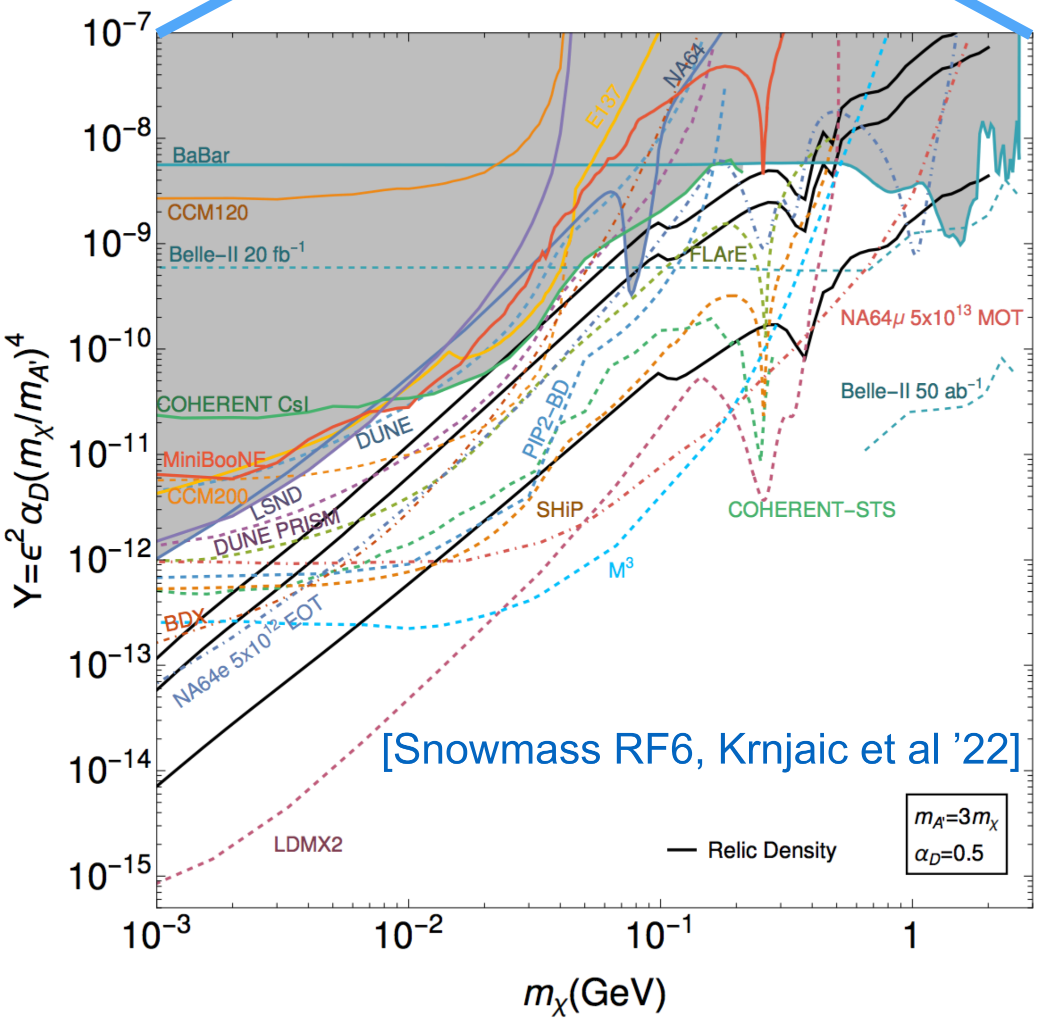


Complementary thermal target for next-gen low mass direct detection, (and improved sensitivity to N_{eff})
[Snowmass WP Essig et al, '22]



Sub-GeV thermal DM landscape today





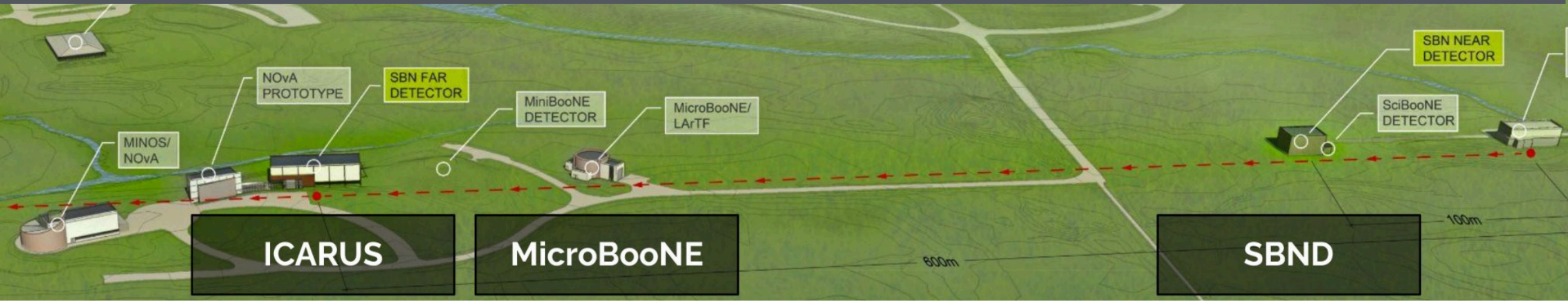
Multiple expts/proposals at various developmental stages

- KEK (Belle II) [S. Longo, talk in W1-1]
- SLAC (LDMX)
- CERN
- FNAL
- LANL
- SNS
- JLab
- Mainz
- …

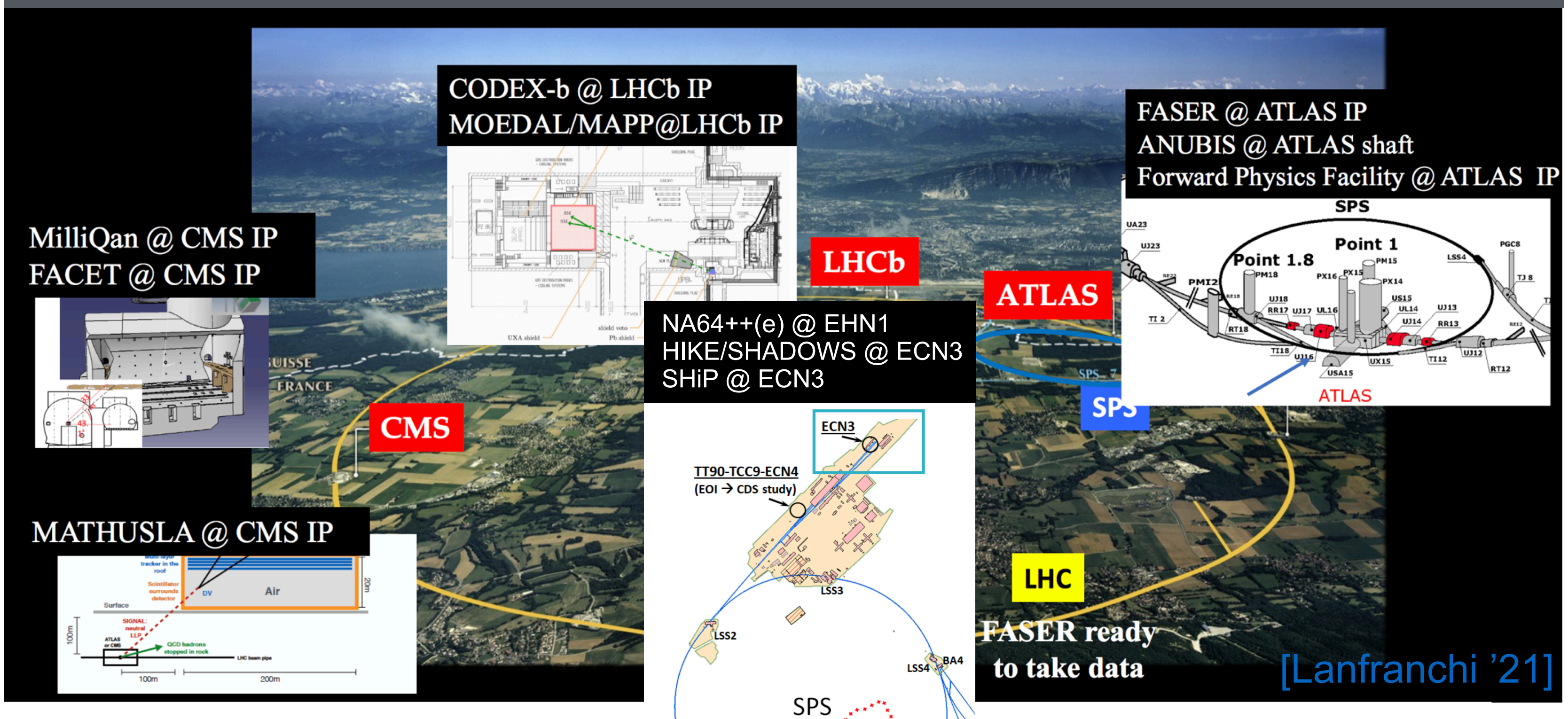
Plus analyses of multiple Vector, Higgs, HNL, ALP portal mediators (PBC benchmarks)

Fermilab & CERN

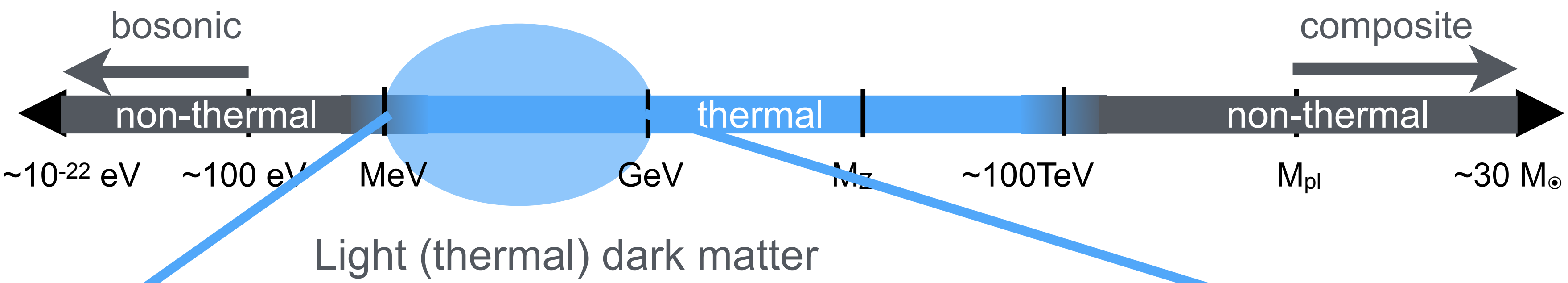
Synergistic with new FNAL short-baseline neutrino program



Multiple proposals to broadly probe LLPs (PBC benchmarks) at CERN



Summary



High-luminosity accelerators have the kinematics to test facets of thermal freezeout in MeV-GeV DM models, a complementary probe to direct detection (N- or e-scattering)

- The effort to broadly search for light DM coupled to the Standard Model via the renormalizable mediator portals has progressed a long way over the past decade.

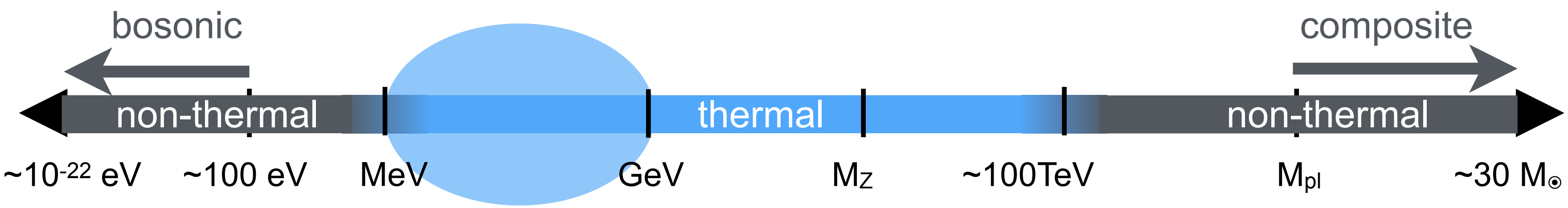
Natural interplay with long and short baseline neutrino program, which can be pursued further with next-gen facilities

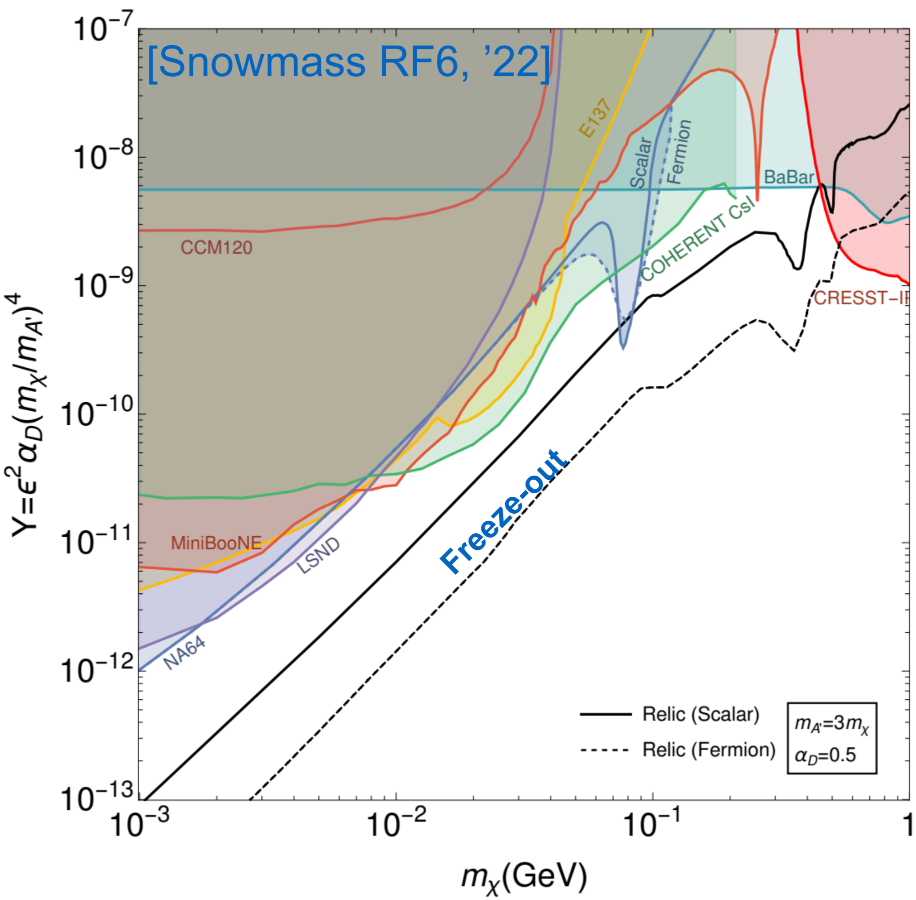
Dedicated plans/proposals at multiple labs (CERN, Fermilab, SLAC, LANSCE, KEK, Mainz, JLab) over the coming decade

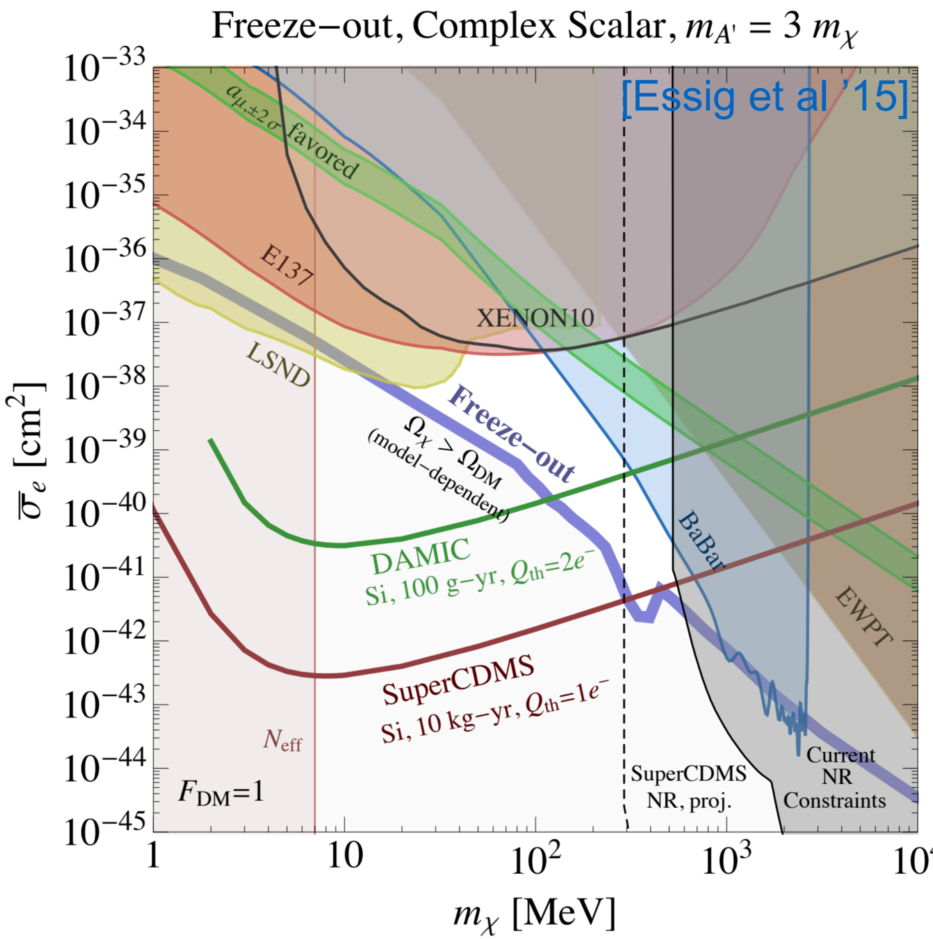
+ Many complementary efforts on low-mass direct detection, e.g. via e-scattering

Backup Slides

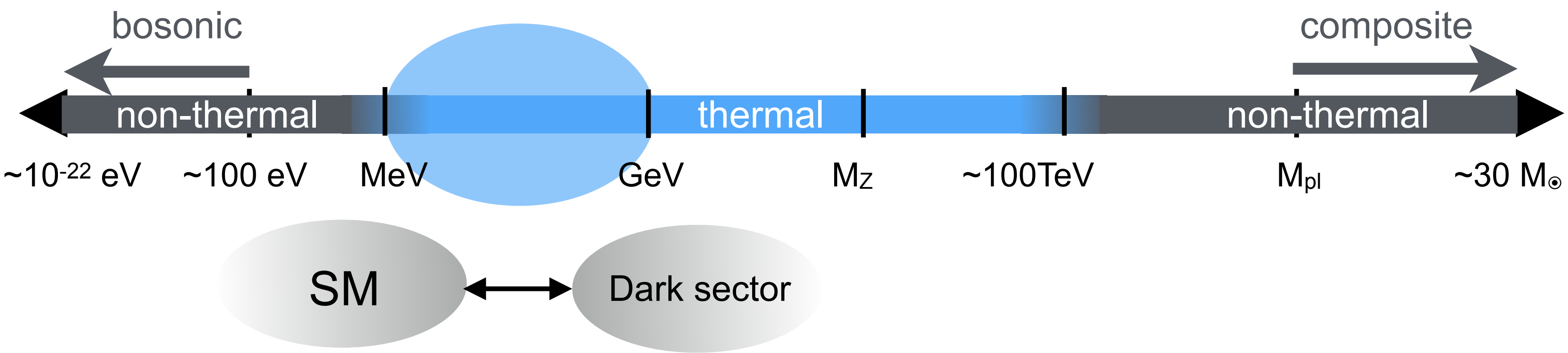
Sub-GeV thermal DM - Y vs σ_e







Dark sectors - PBC benchmarks



Broader more systematic framework for light dark sectors and LLPs, covering all low dimension portal mediators, and *focusing on visible decay signatures*

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})}$$

CERN PBC benchmark cases

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j$$

BC 1-3 | BC 4-5 | BC 6-8

$$+ \frac{1}{f_a} \left(\mathrm{tr}(G\tilde{G}) + c_F F\tilde{F} + c_\psi \partial_\mu j^\mu_{A\psi} \right) a + \mathcal{O}(\dim \geq 5)$$

BC 9-11