Light MeV-scale dark matter at accelerators

Adam Ritz

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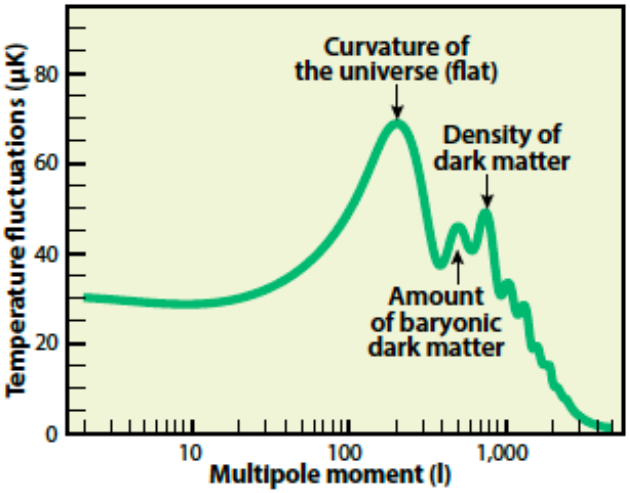
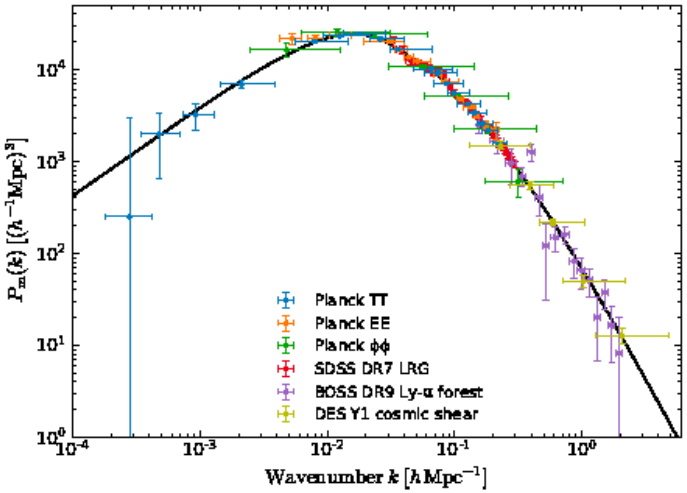
Cold dark matter landscape

Empirical evidence for dark matter (and neutrino mass) arguably points to a dark/hidden sector (but not directly to a specific mass scale)

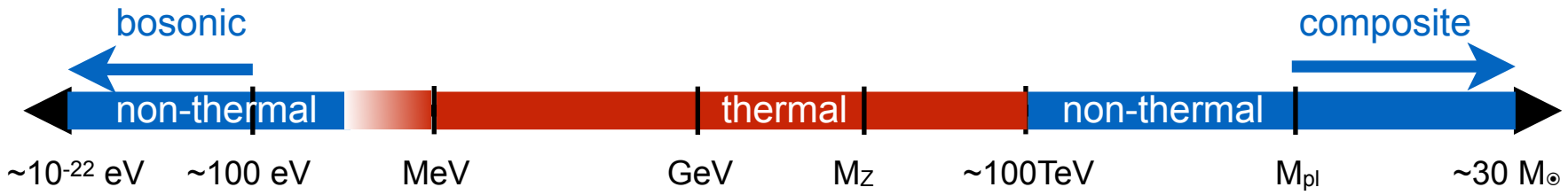
- Gravitational evidence from multiple cosmological & astrophysical scales (CMB, LSS, Lensing, etc)
  - Relic density ~ 5 x baryons
  - Cold enough…
  - Dark enough…

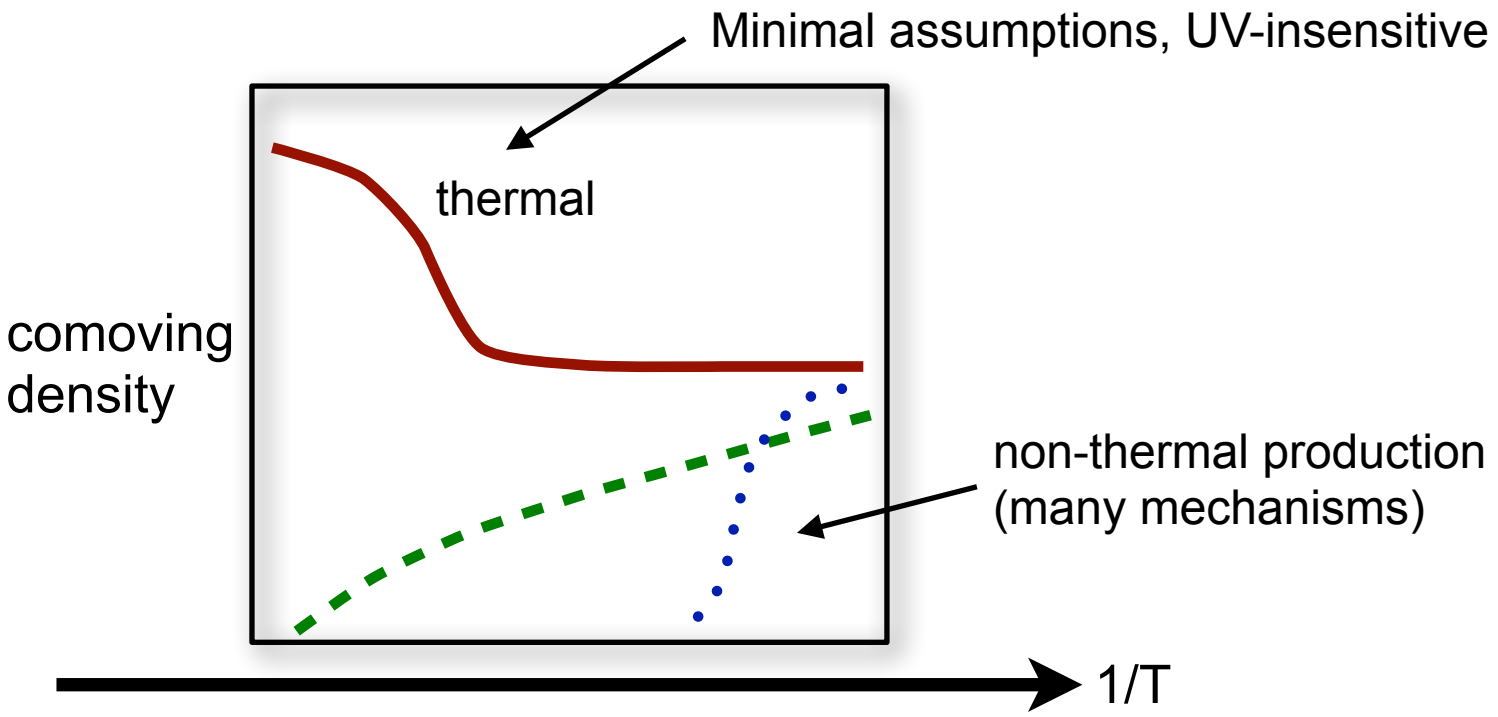




➠ a huge parameter space a priori, so what theoretical guidance is there?

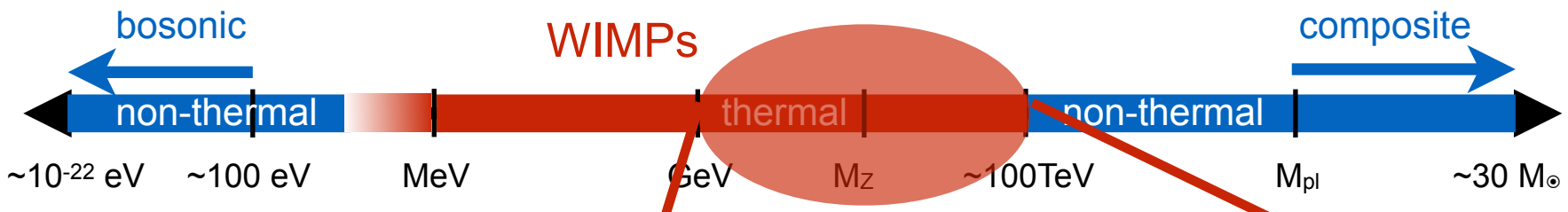
Cold dark matter landscape





DM thermal history in the early universe

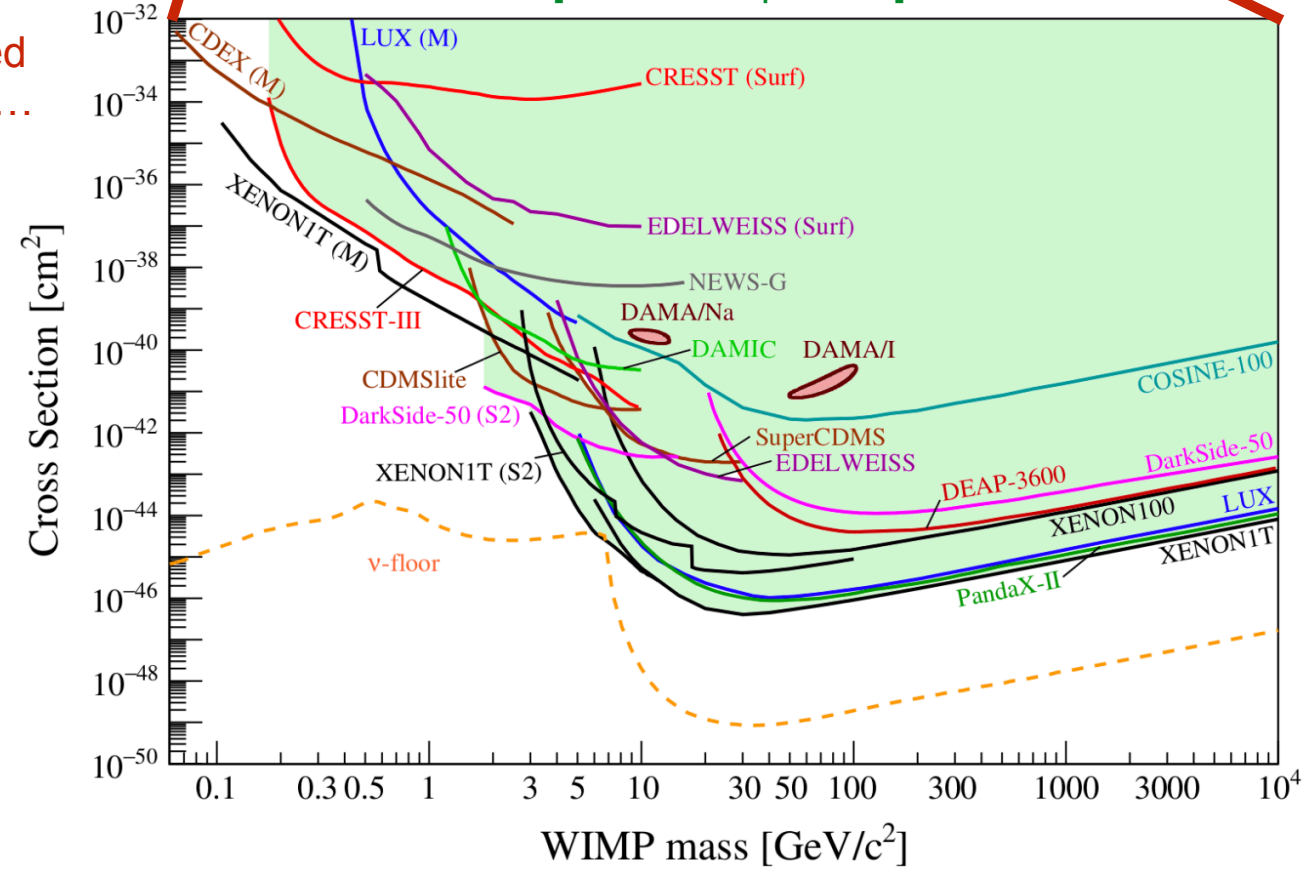
Cold dark matter landscape



WIMPs

- minimal, UV-insensitive production mechanism, mimics BBN, and is linked to the electroweak scale…
- Natural focal point

[APPEC Report '21]



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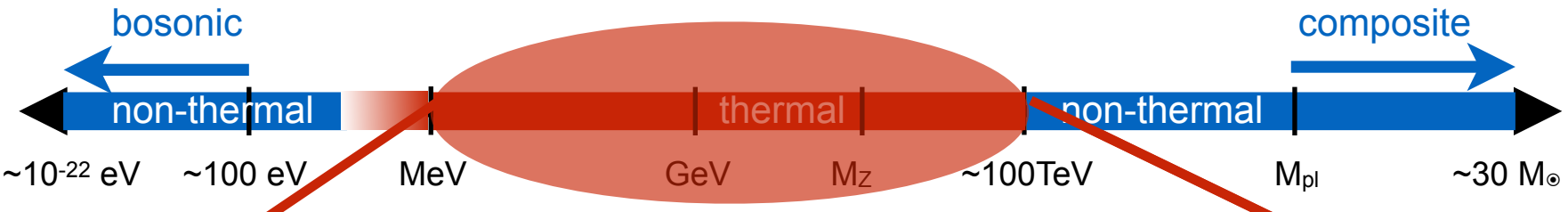
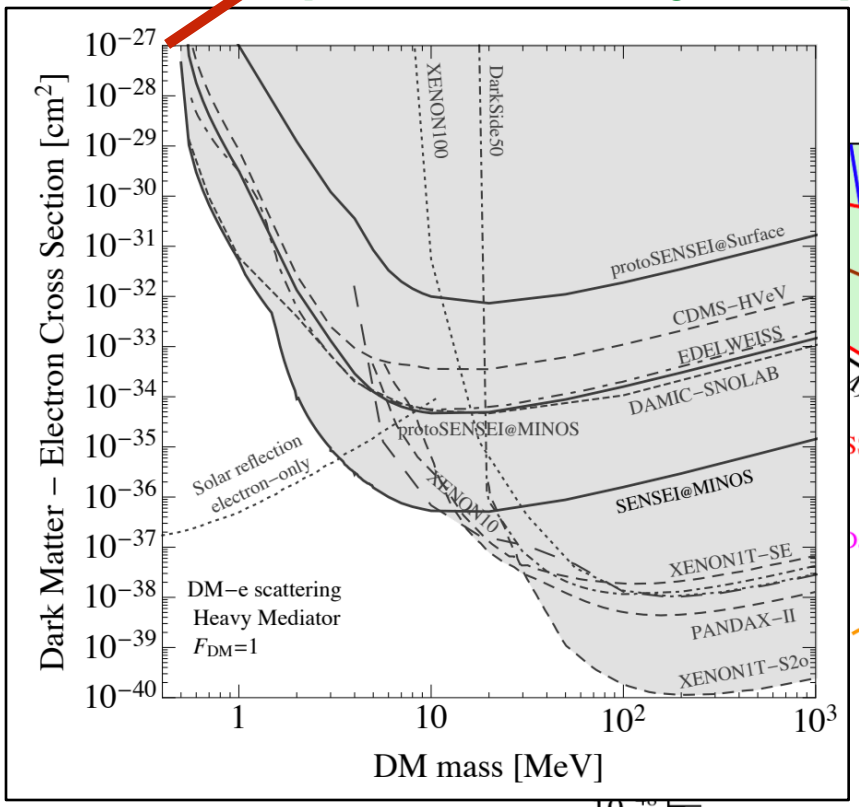
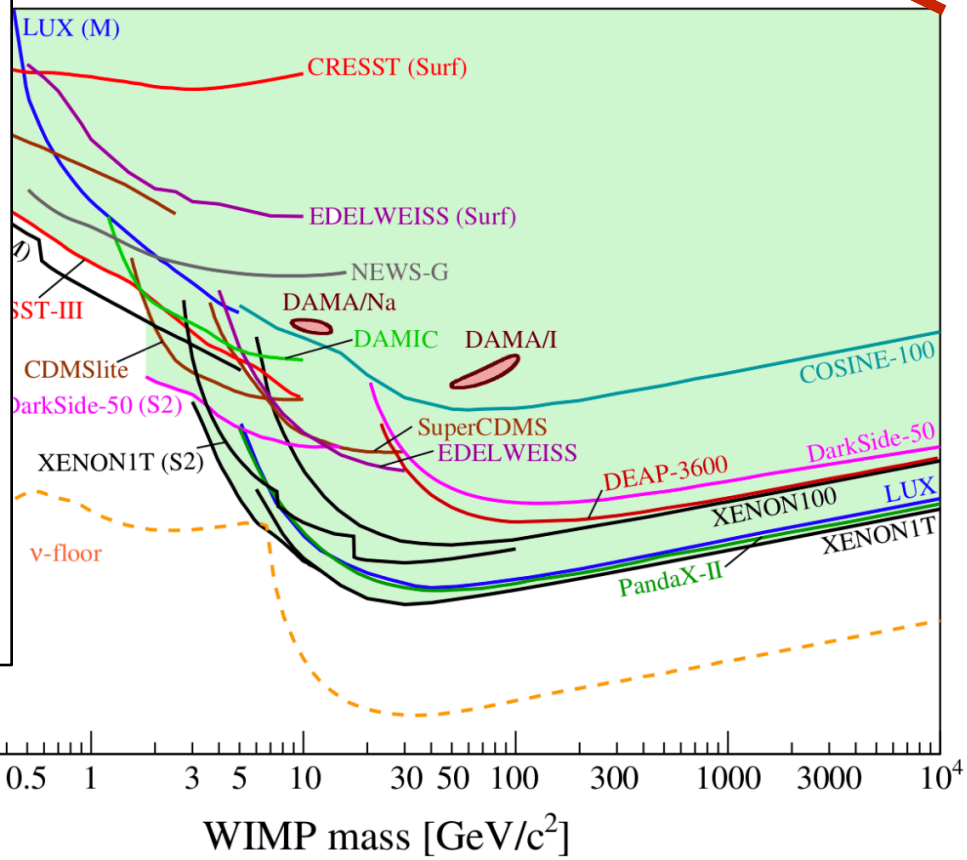


[Snowmass CF, Essig et al '22]

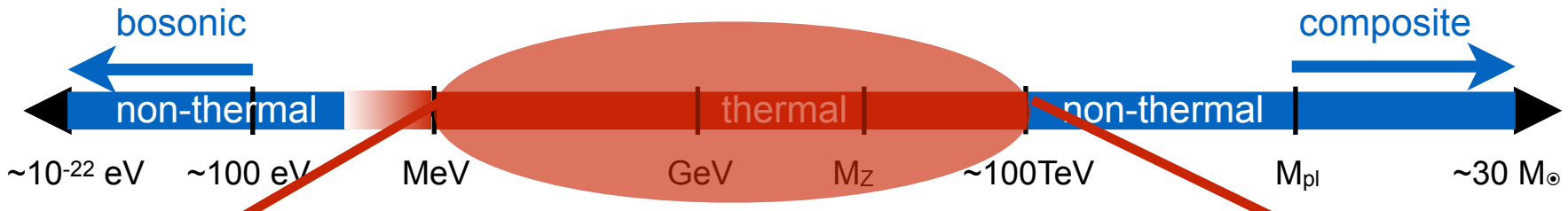


[APPEC Report '21]



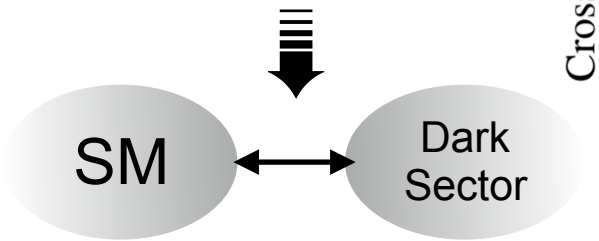
Direct detection sensitivity down to ~1 MeV mass via electron scattering

Cold dark matter landscape

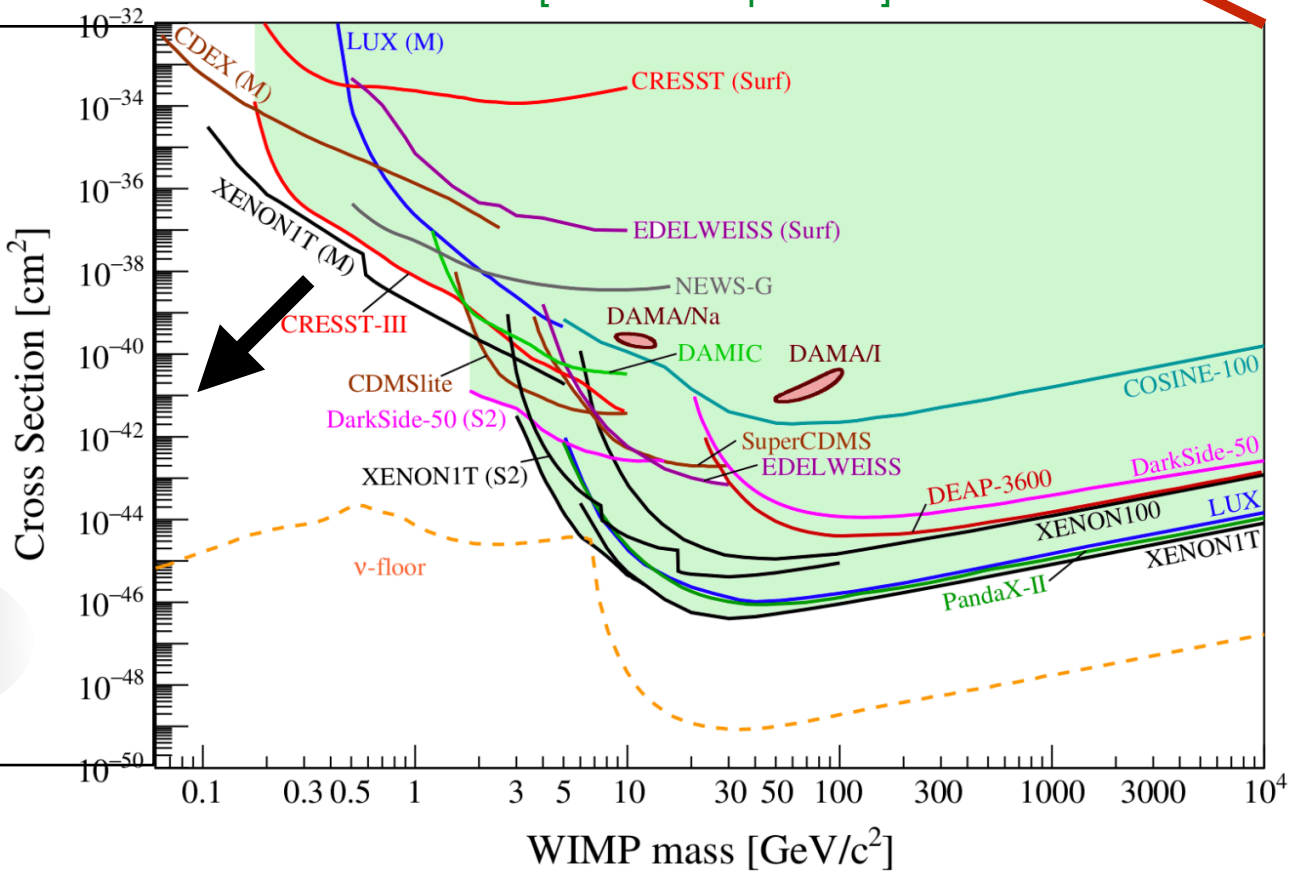


Sub-GeV thermal relic

- $\sigma_{ann} \propto m_{DM}^2/m_{med}^4$ so Lee-Weinberg bound ➠ light mediators are required for freeze out with the required relic abundance



[APPEC Report '21]



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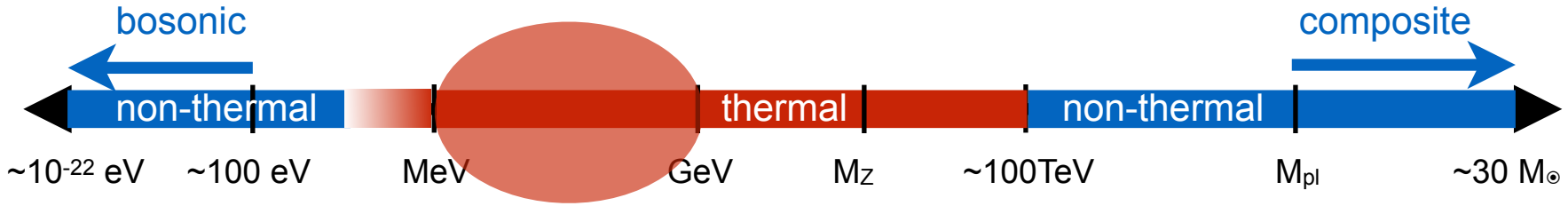

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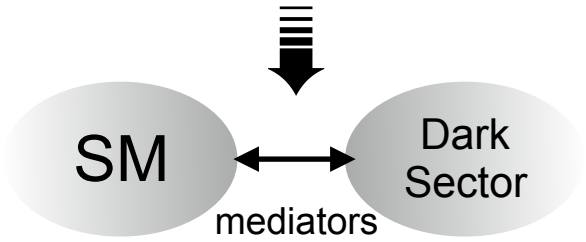


EFT for a (neutral) dark sector

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

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

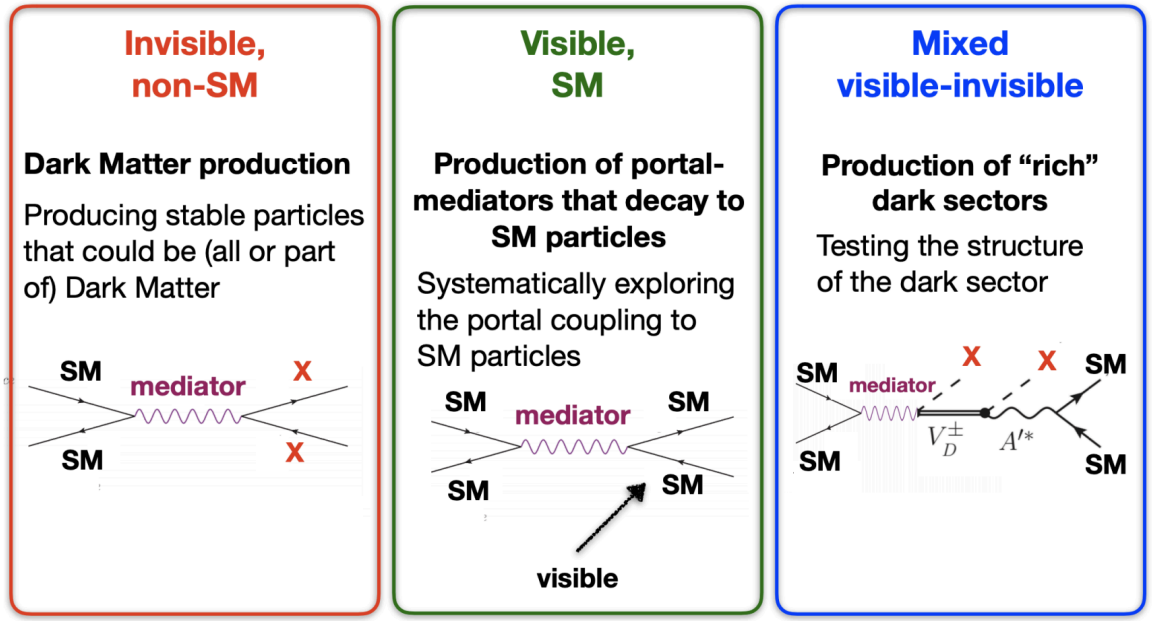
$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j +$$

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

Accelerator-based strategy

Is CDM like the CvB (abundant, but E too low for detector recoil thresholds)?

➠Recalling the discovery channel of muon neutrinos, this suggests an accelerator-based search strategy (full kinematics of thermal freezeout)



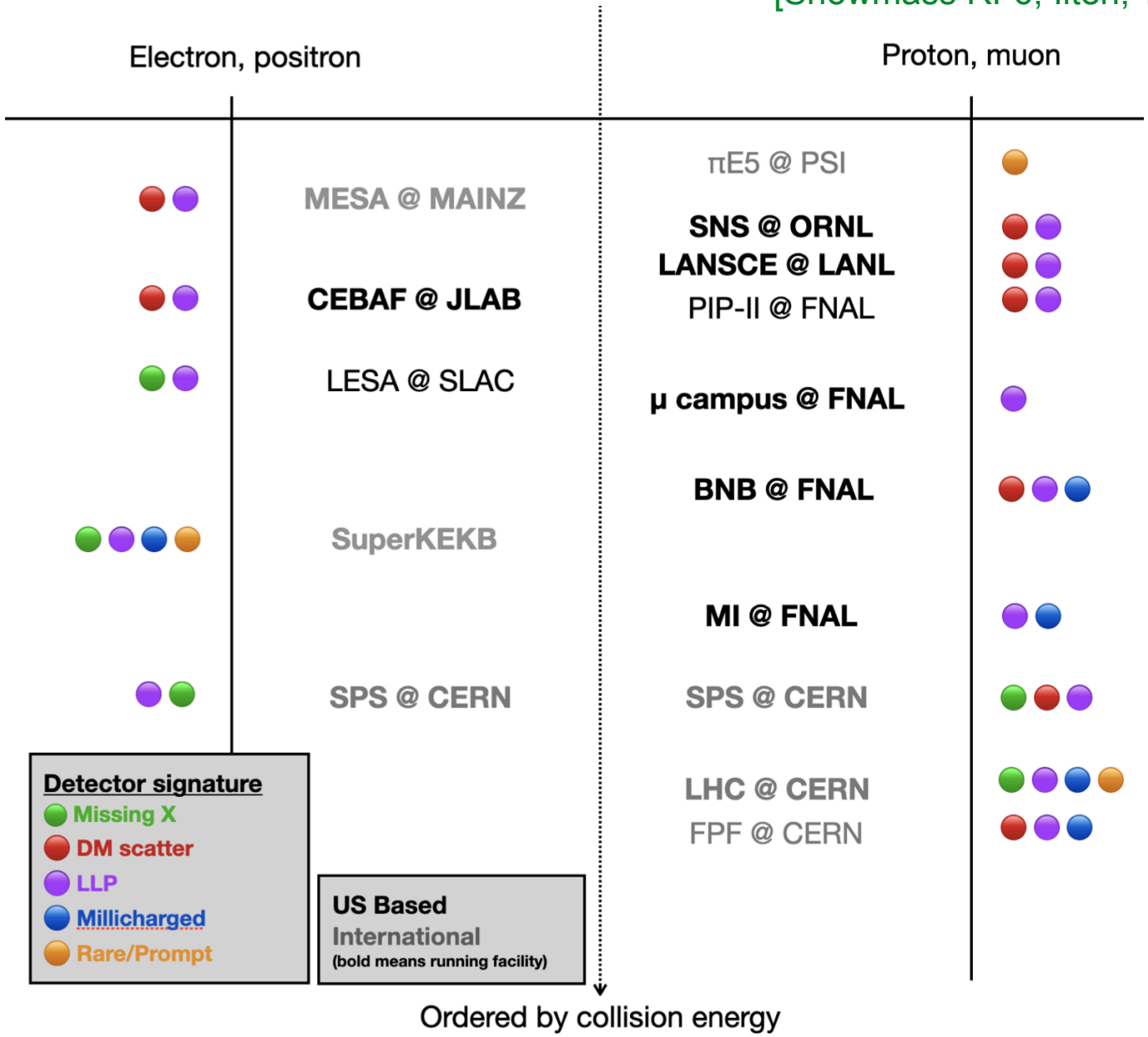
Stefania Gori, Mike Williams

Exploration of signatures associated with various portals (mediators)

- Electron/positron beams
- Proton beams
- Muons

Broad experimental program underway/planned

[Snowmass RF6, Ilten, Tran et al '22]



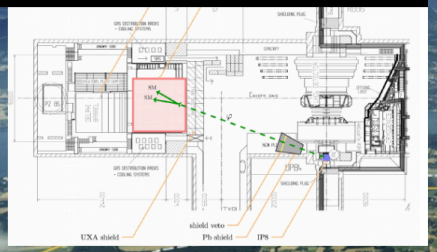
Broad experimental program underway/planned

[Lanfranchi '21]

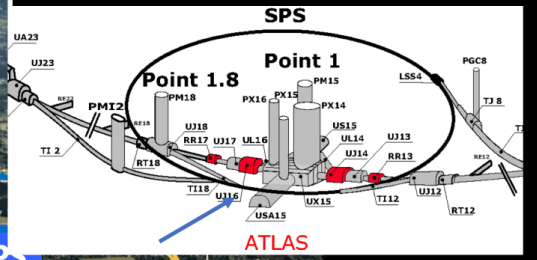
Physics Beyond Colliders

FIPs @ CERN –The Long-Lived Particle detectors at the LHC IPs

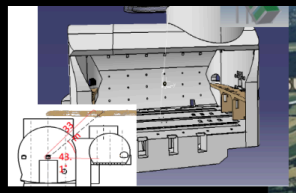
CODEX-b @ LHCb IP
MOEDAL/MAPP@LHCb IP



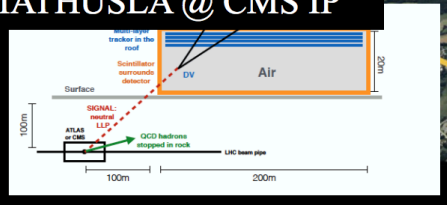
FASER @ ATLAS IP
ANUBIS @ ATLAS shaft
Forward Physics Facility @ ATLAS IP



MilliQan @ CMS IP
FACET @ CMS IP



MATHUSLA @ CMS IP



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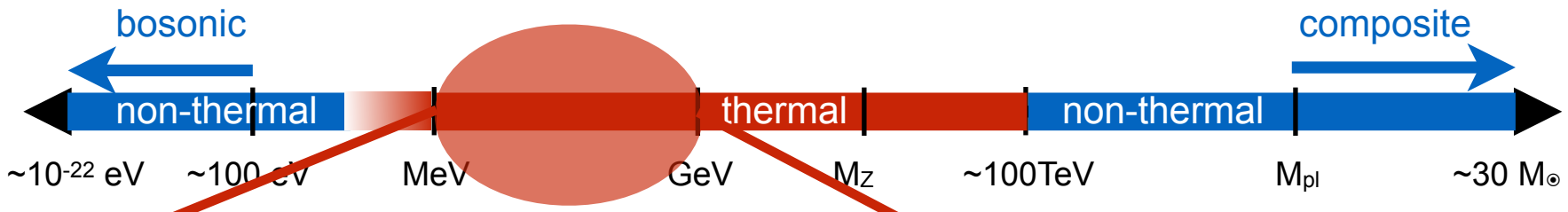
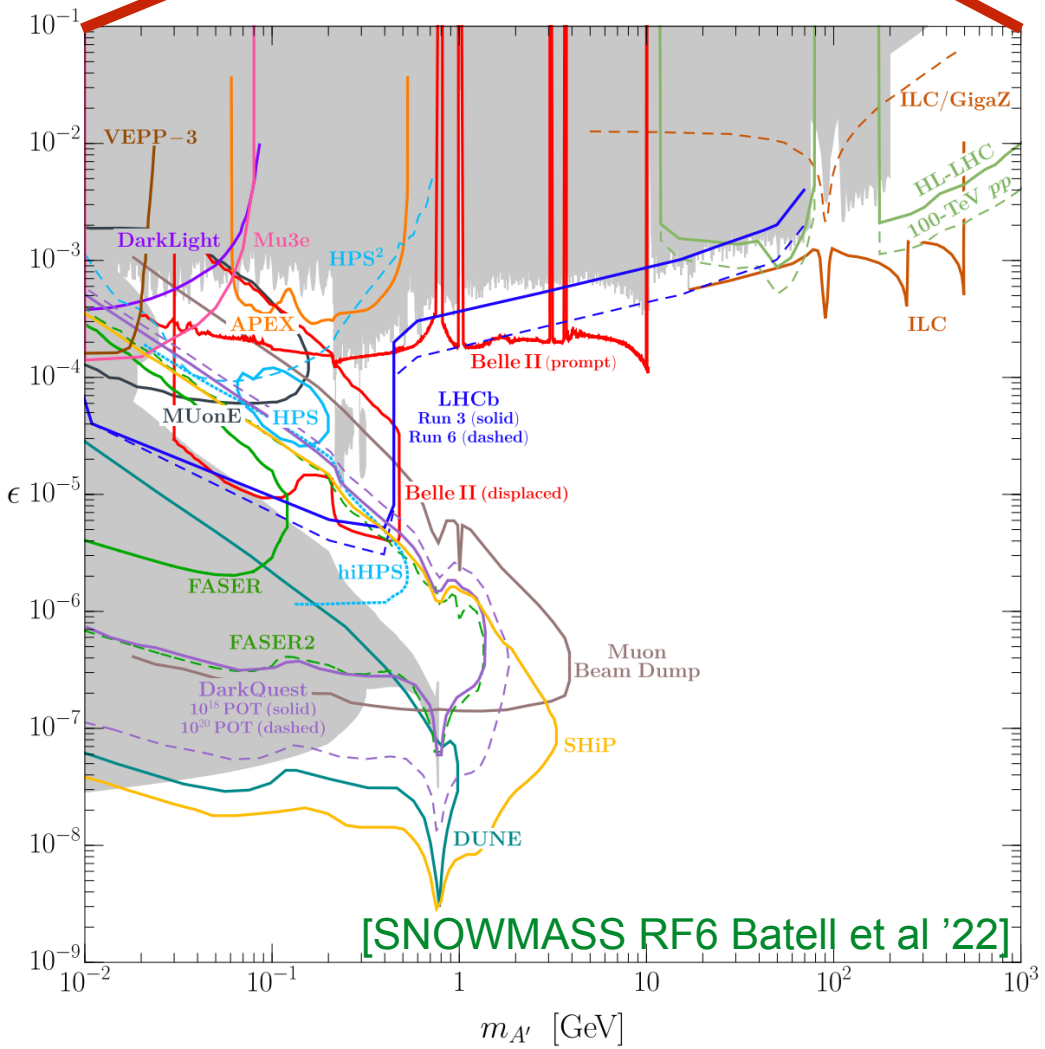


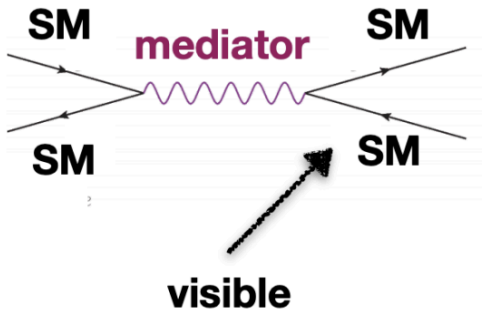


[SNOWMASS RF6 Batell et al '22]

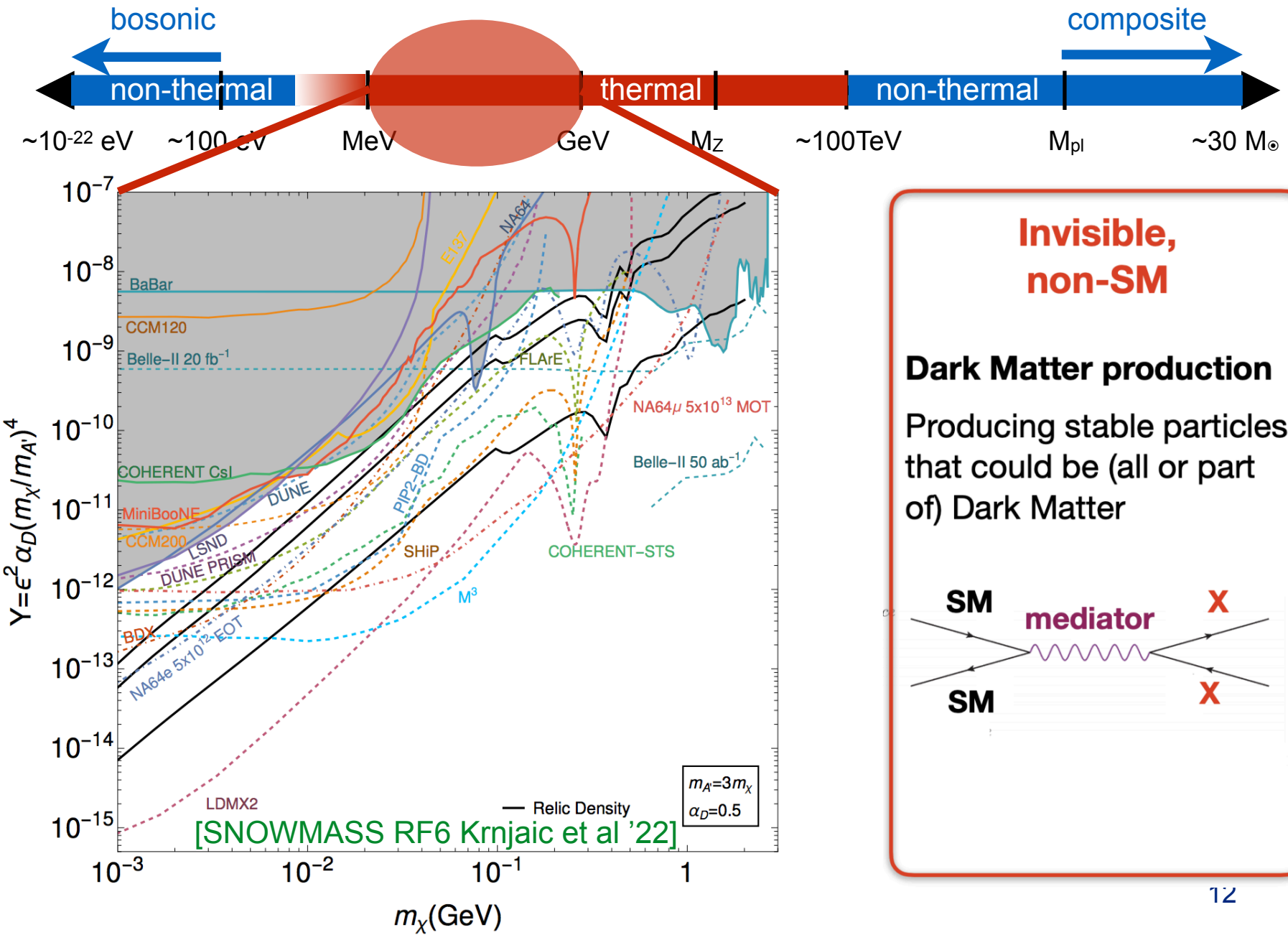
Visible, SM

Production of portal-mediators that decay to SM particles

Systematically exploring the portal coupling to SM particles



Cold dark matter landscape

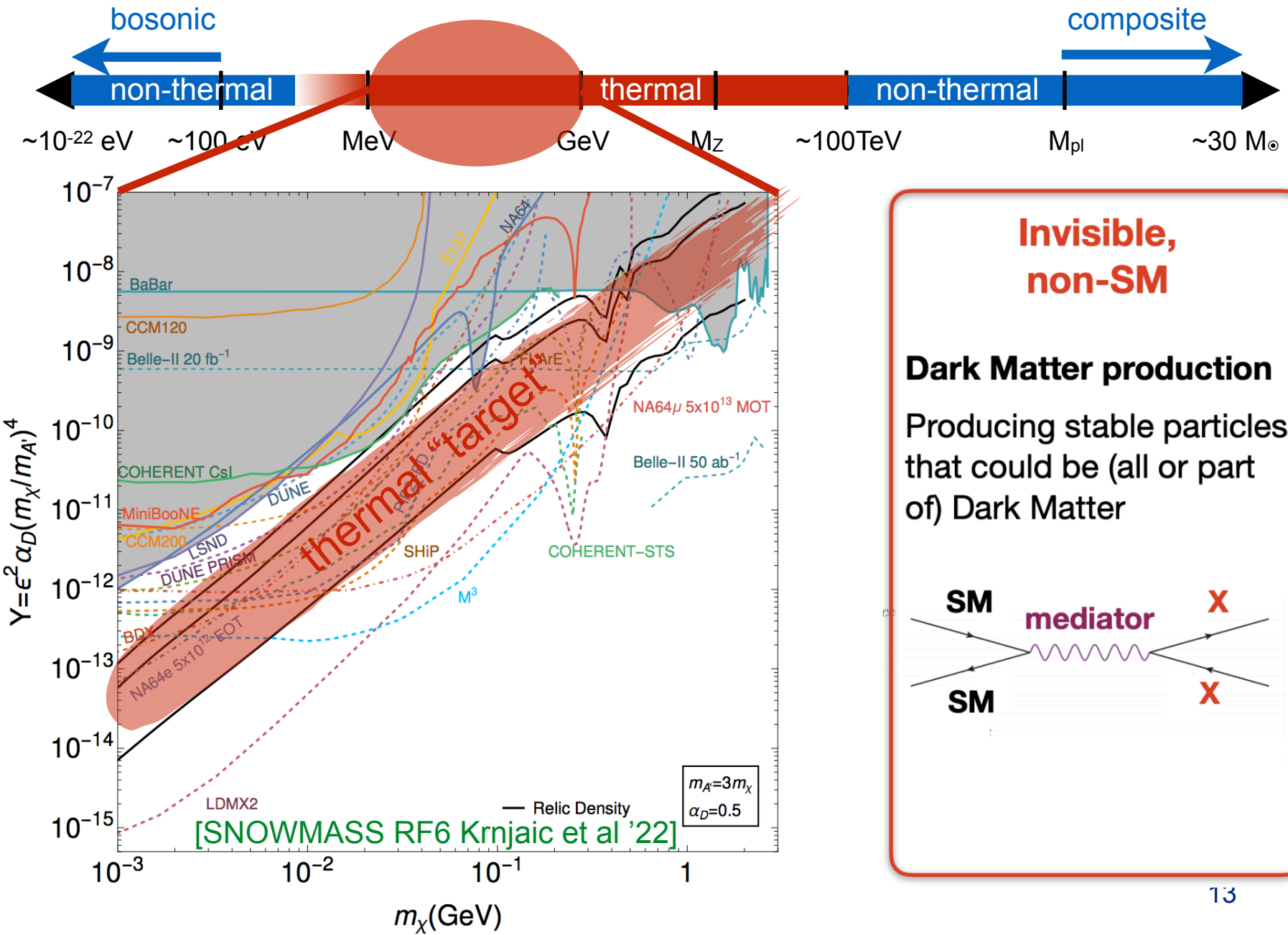


Invisible, non-SM

Dark Matter production

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

Cold dark matter landscape



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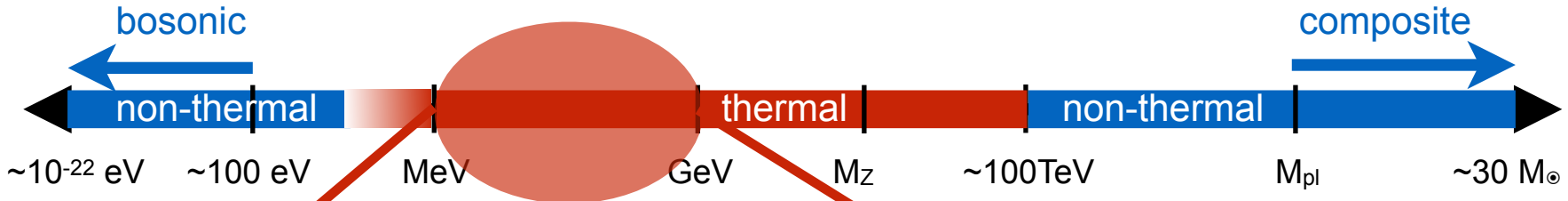

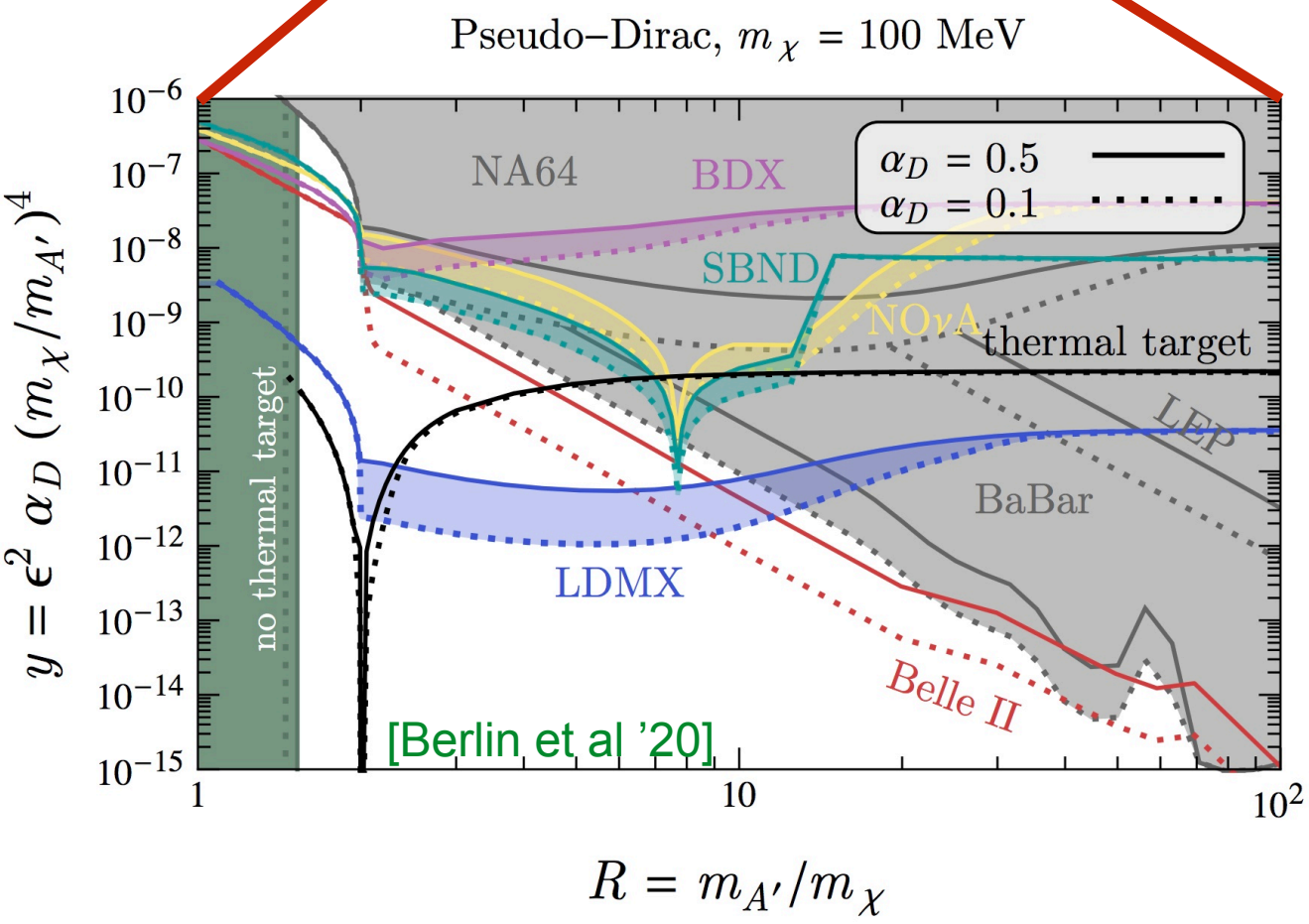

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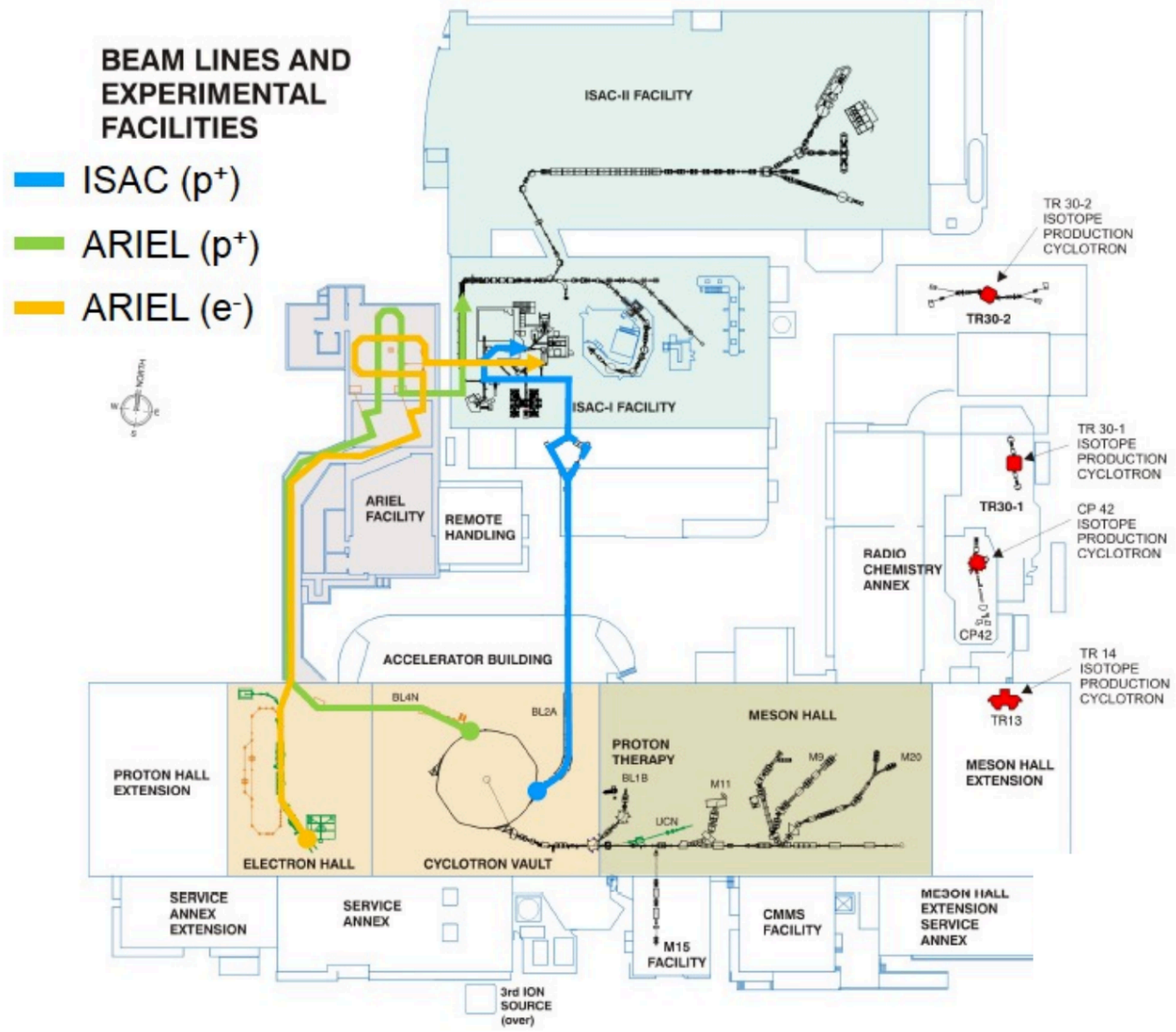
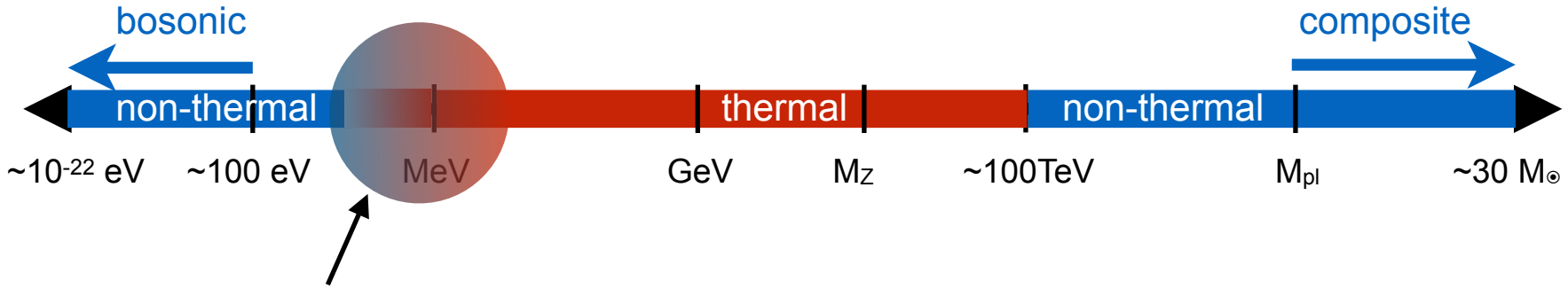
TRIUMF - e AND p beams



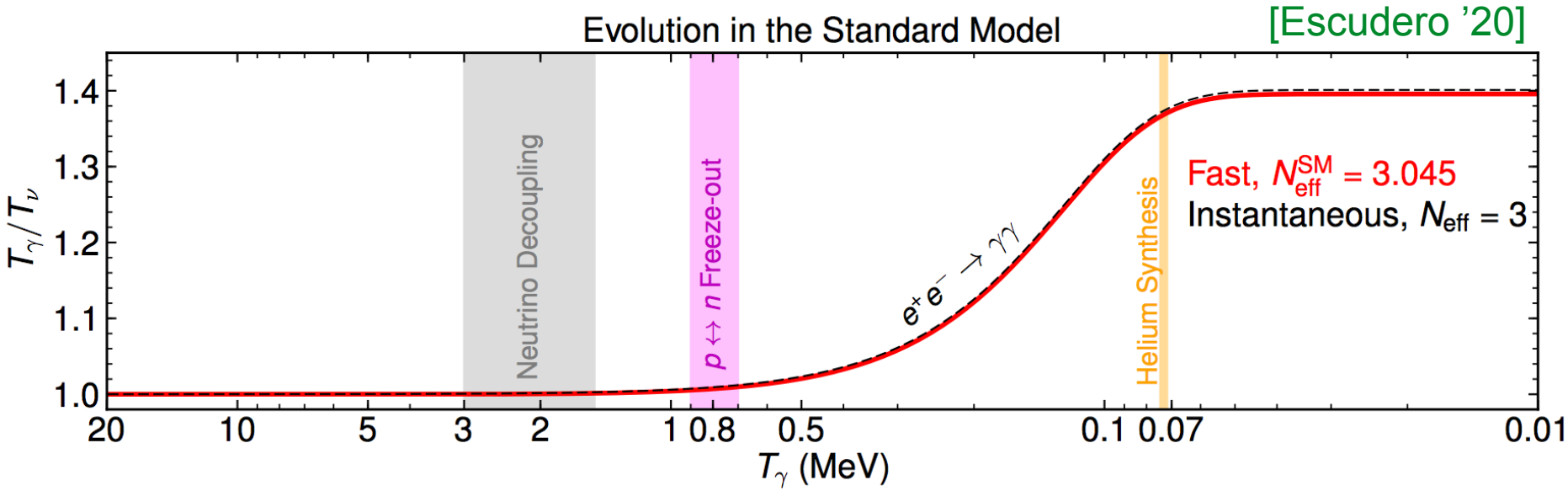
TRIUMF has both proton ***and*** electron beams

- high intensity, but relatively low energy
- ***suited to NP searches at the MeV-scale***…

Thermal DM near the MeV threshold

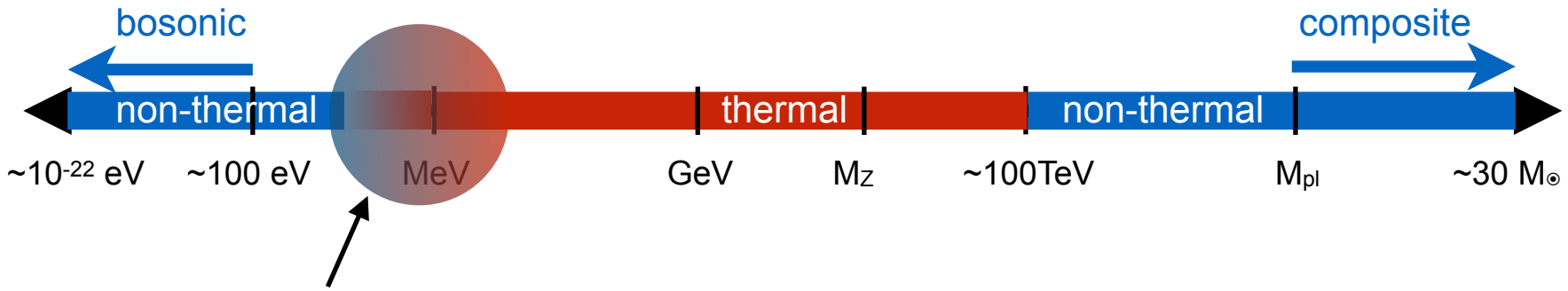


MeV-scale thermal DM - interplay with neutrino decoupling & nucleosynthesis sets the lower end of the mass window



Precision CMB and BBN (and structure formation) data → constrain new dofs

Thermal DM near the MeV threshold



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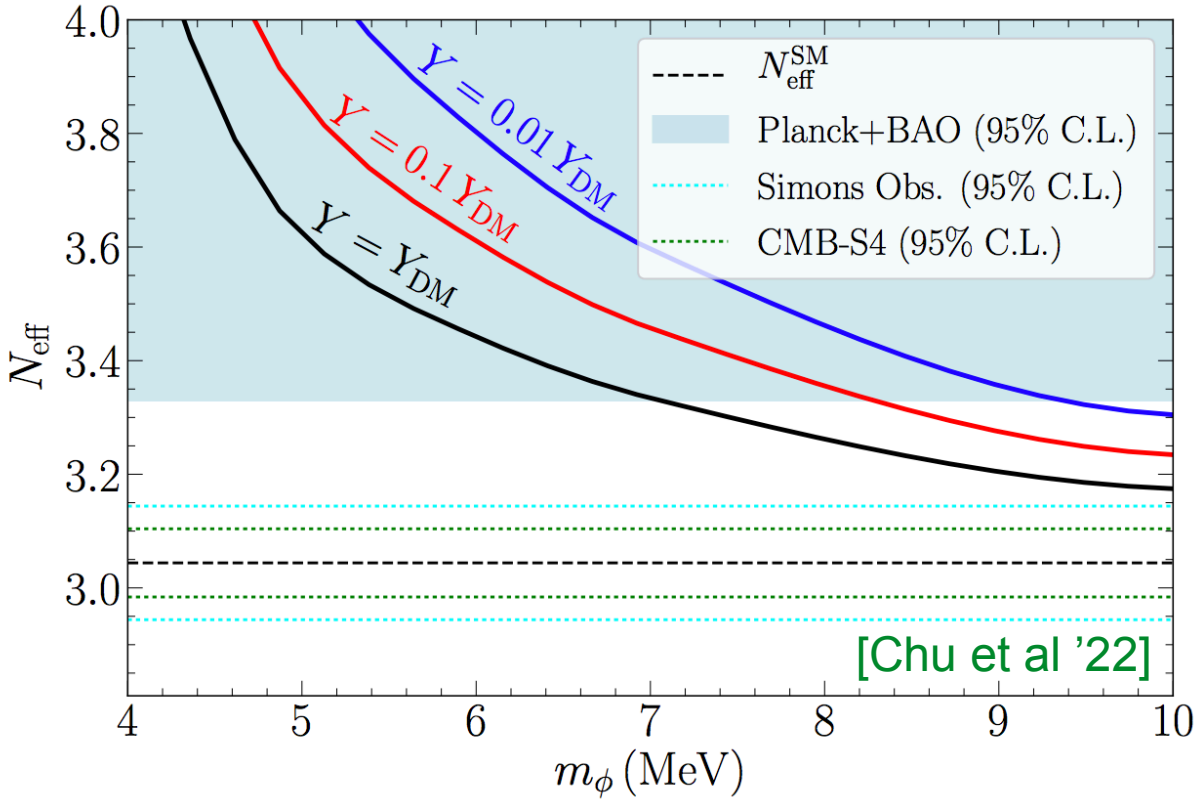
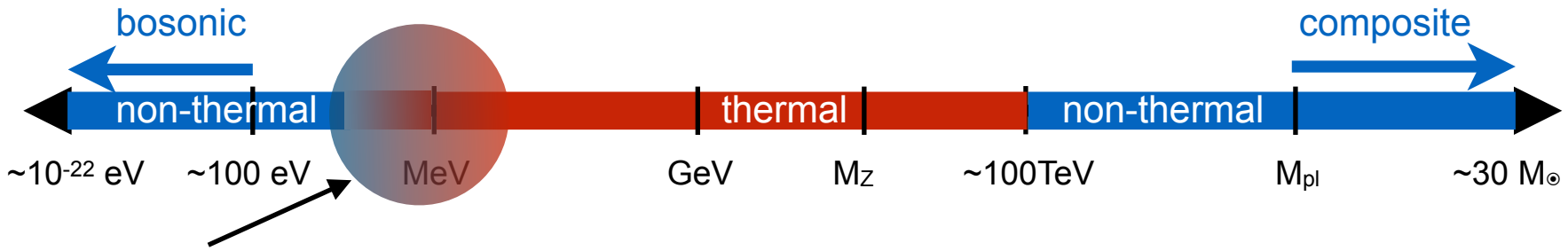
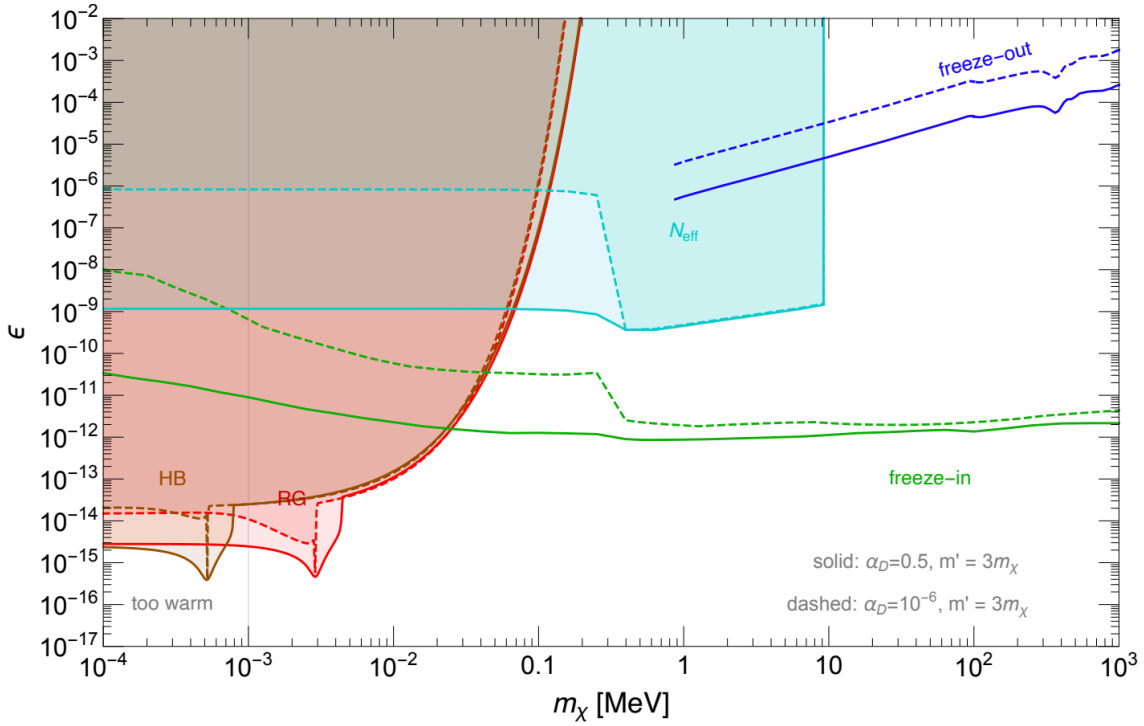


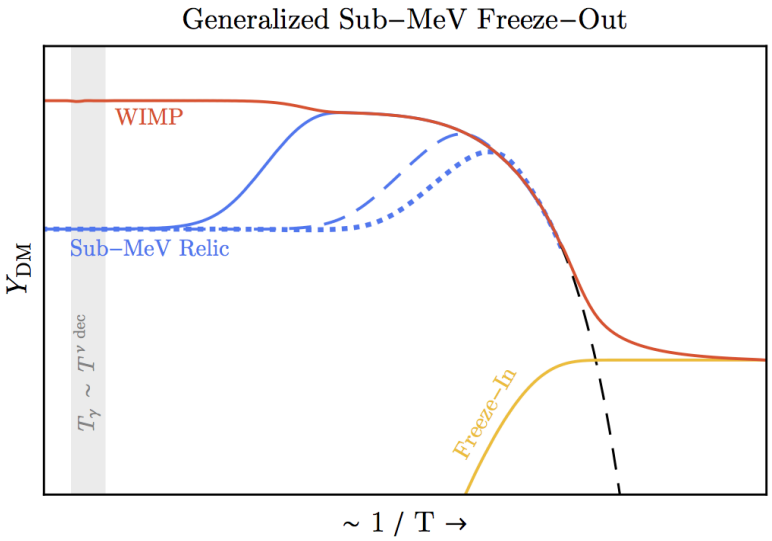
Beyond thermal DM - freeze-in



Non-thermal production can be UV-insensitive, e.g. freeze-in, while softening constraints from N_{eff}, but couplings are small, less accessible to accelerators

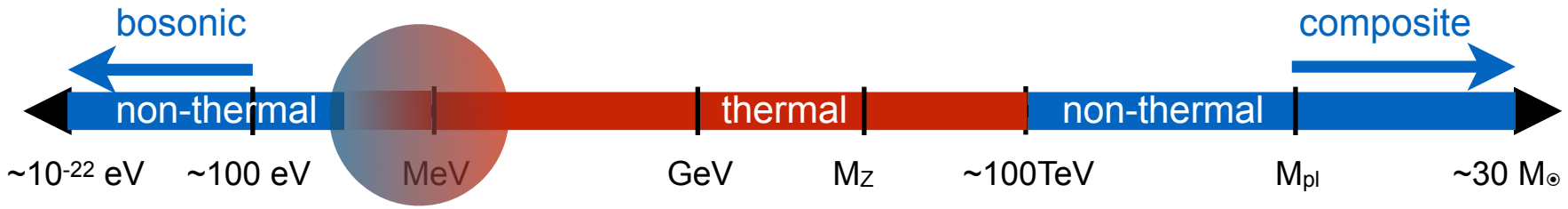


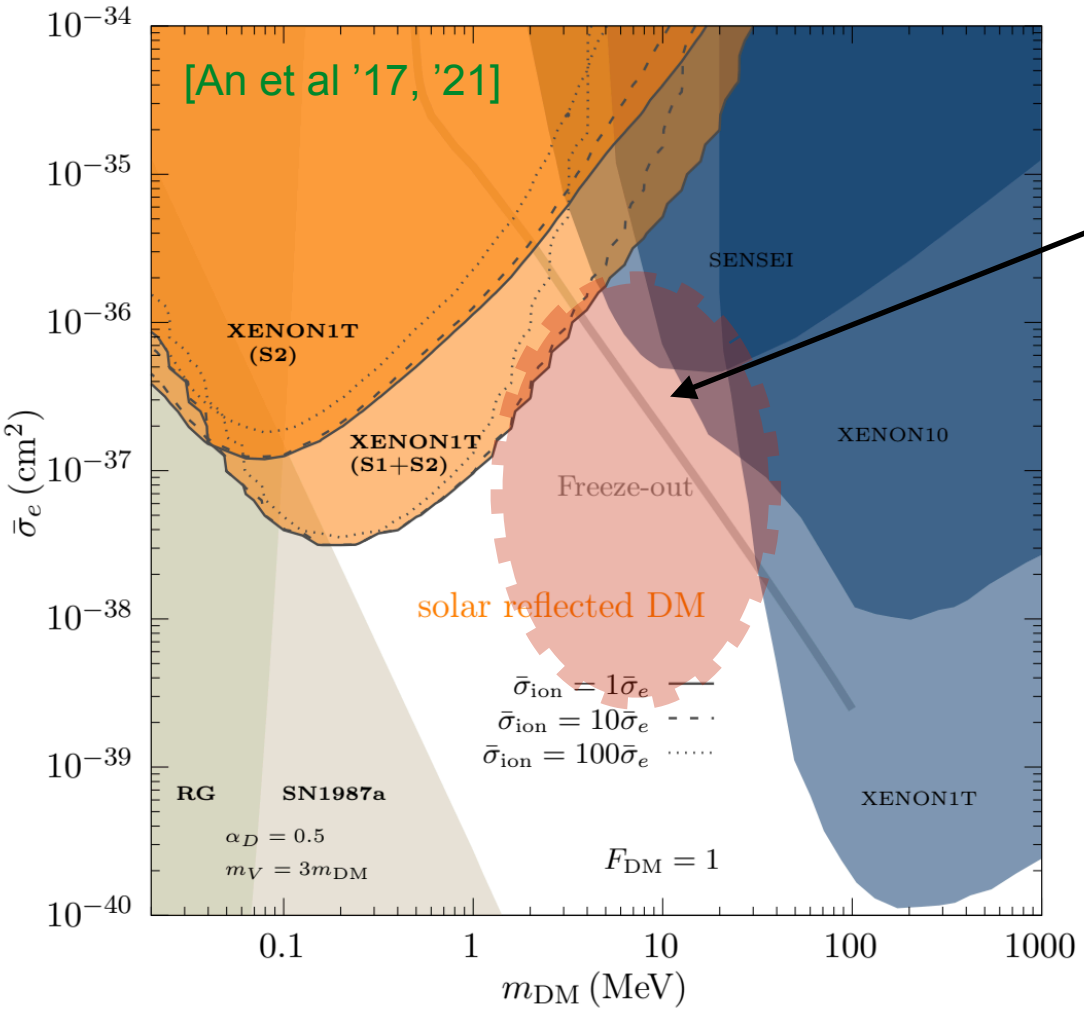
[Chang et al '19]



[Berlin, Blinov '18]

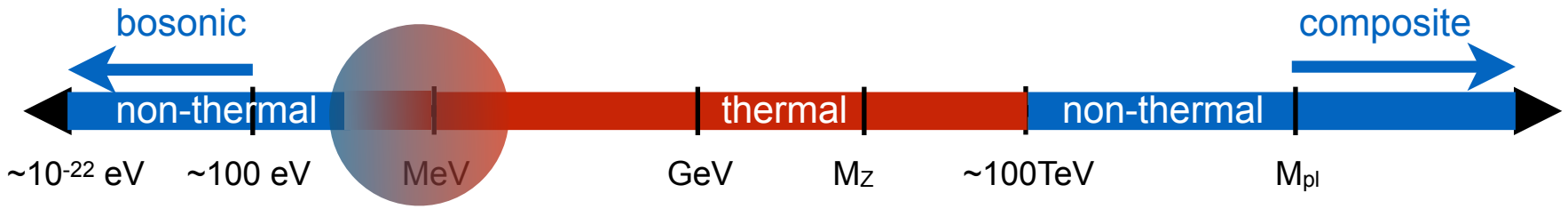
Thermal DM near the MeV threshold

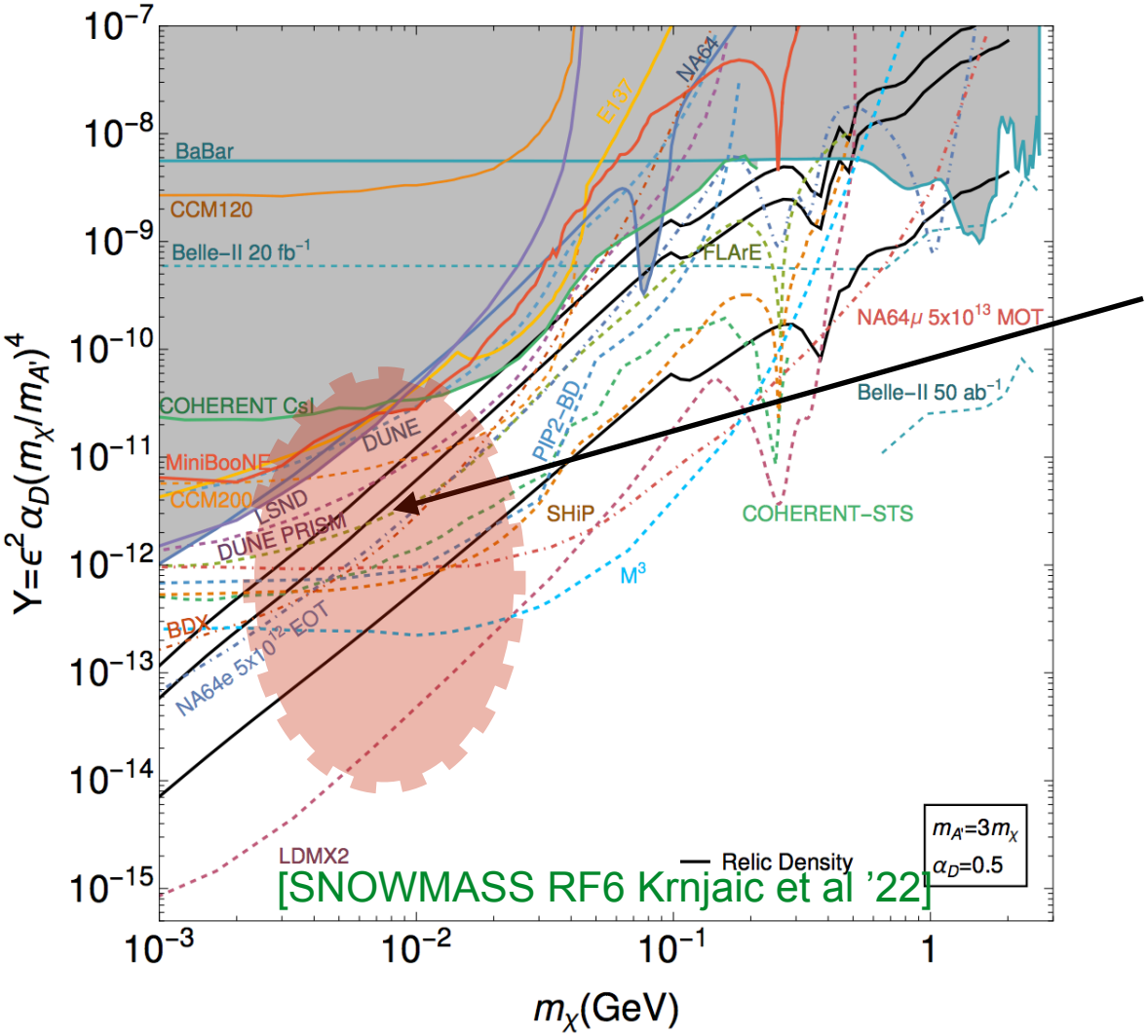




Target for next-gen direct detection, and improved sensitivity to $N_{\rm eff}$

Thermal DM near the MeV threshold

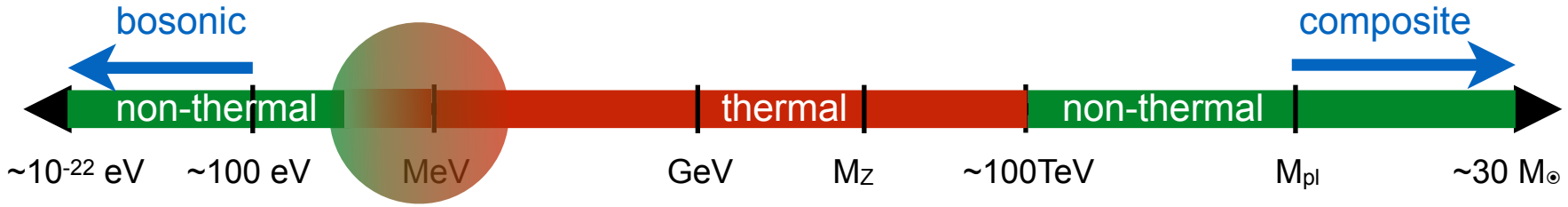




[SNOWMASS RF6 Krnjaic et al '22]

Also a target for accelerators with e-beams (NA64, LDMX, …) and p-beams (CCM, PIP2-BD, …)

Summary



- High-luminosity accelerators have the kinematics to test facets of thermal freezeout in MeV-GeV DM models, complementary to direct detection (via N- or e-scattering)
  - Proposals at multiple facilities (CERN, Fermilab, SLAC, KEK, Mainz, JLab) to build on efforts over the past decade

- TRIUMF (with e- and p-beams) is well-positioned to explore the low O(MeV) range, but model are constrained due to a complex interplay with early universe cosmology (neutrino, e^+/e^- freezeout and BBN)
  - MeV-scale DM still presents an intriguing target, with hints from long-standing anomalies such as the galactic 511 keV excess