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Particle Physics 5YP 2025-2030: Theory Perspective

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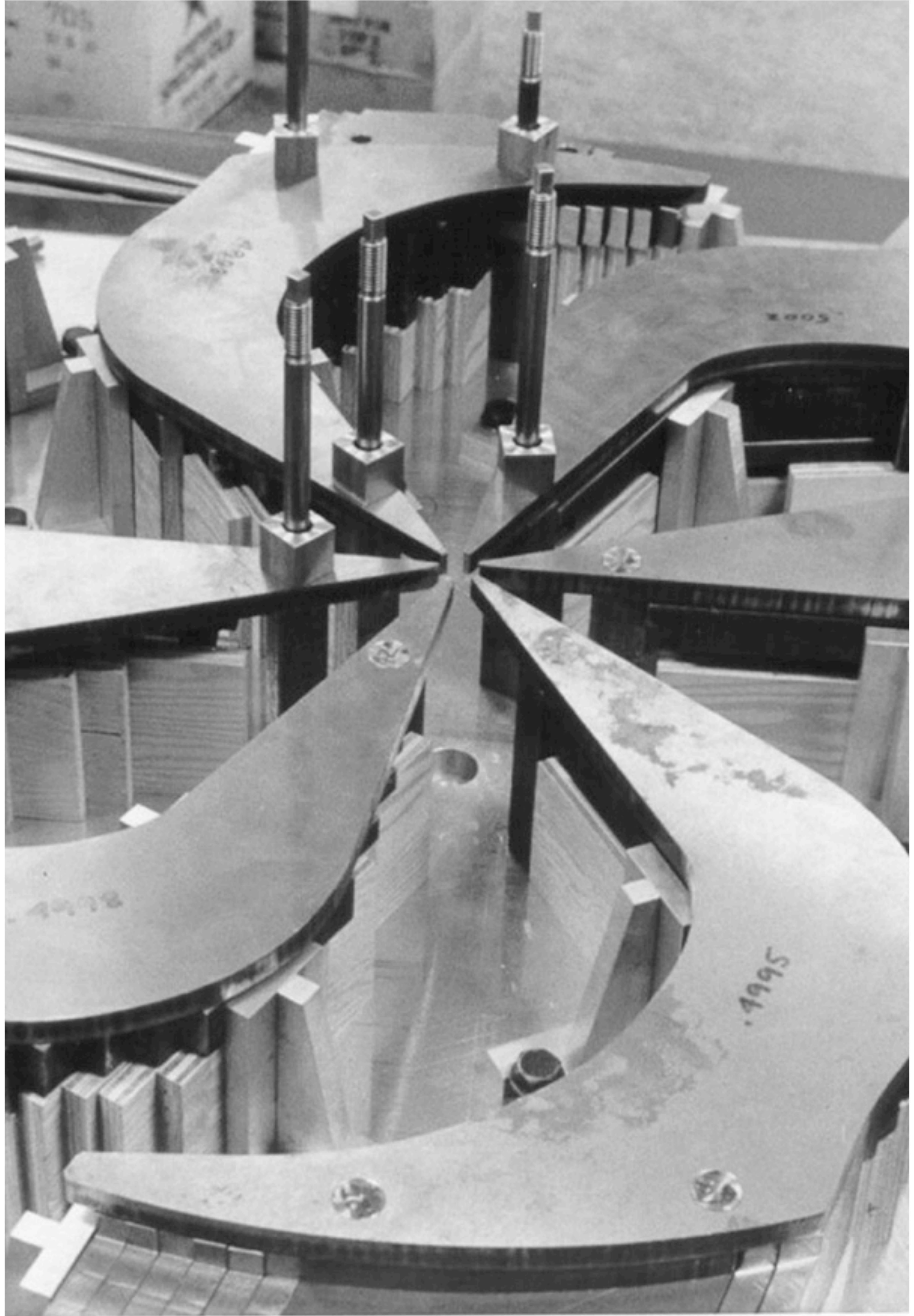

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Discovery, accelerated

Outline

- Colliders
- Neutrinos
- Dark Matter
- Precision and Intensity
- And more?

Colliders

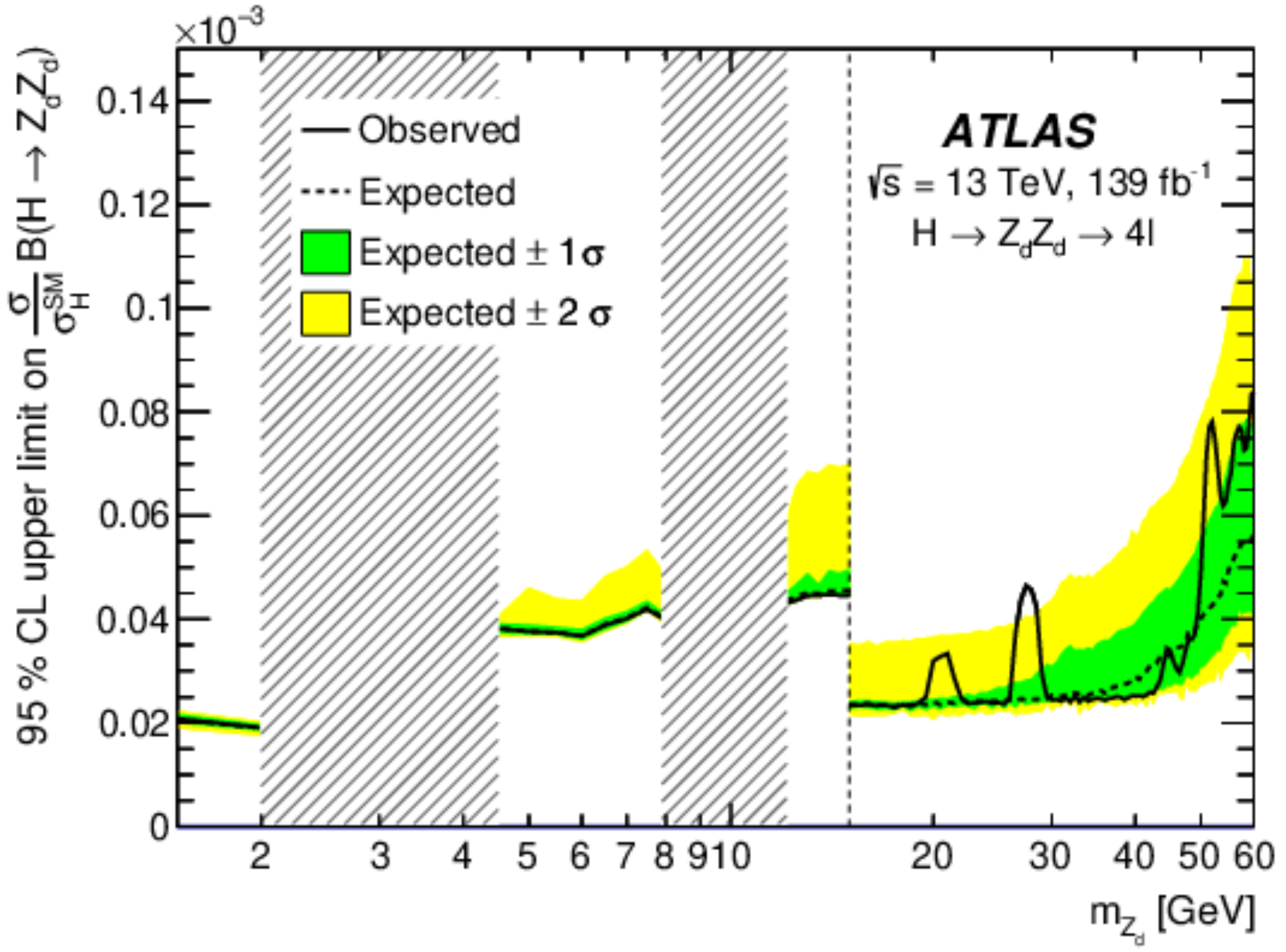
- Main players will be High Luminosity LHC and Belle II.

- HL-LHC will greatly expand the sensitivity to “non-strong” new physics.

  e.g. electroweak superpartners, exotic leptons (muon g-2?), new Higgses

- More luminosity will also allow for high precision and detailed Higgs measurements.

  e.g. rare Higgs decay channels, Higgs width, di-Higgs?



- ATLAS Run II (2110.13673) result for $h \to Z_d + Z_d$
- assumes Z_d is a “visible” dark photon
- $\mathrm{BR} < 3 \times 10^{-5}$!!!

Colliders

- Precision HL-LHC measurements can be interpreted within SMEFT:

  SMEFT = SM plus all (reasonable) dimension-6+ operators

  - Captures the impact of just about any new physics effects on SM → SM processes **provided** the new physics is fairly heavy ($M^2 > s, |t|, |u|$)

  - Major recent advances in the theoretical treatment of SMEFT!

- "Valued-added" sensitivity to new long-lived particles with far detectors like FASER and MATHUSLA

- New understanding of QCD jets using AI tools and new theoretical methods.

- Belle-II complements HL-LHC with excellent sensitivity to lighter ($m < 10\,\mathrm{GeV}$) new physics.

- HL-LHC and Belle-II will also be important tools for flavour and precision electroweak physics.

Colliders

- What comes after HL-LHC?
- Linear Collider (ILC) seems like it's in rough shape.
- New circular collider in China may be impacted by geopolitics…
- Future Circular Collider at CERN seems like the most robust possibility, ee then pp stages.
- Strong push by some for a muon collider (*e.g.* 2007.15684), excellent for Higgs and more.

Neutrinos

- Understanding neutrino properties will require a broad range of energies and techniques.

  e.g. HyperK, DUNE, IceCube variations, P-ONE, KATRIN, nEXO, LEGEND, cosmology,…

- HyperK and DUNE are the major players in CP angle, mass hierarchy determination.

- They are both potentially sensitive to many other phenomena and this deserves more study.

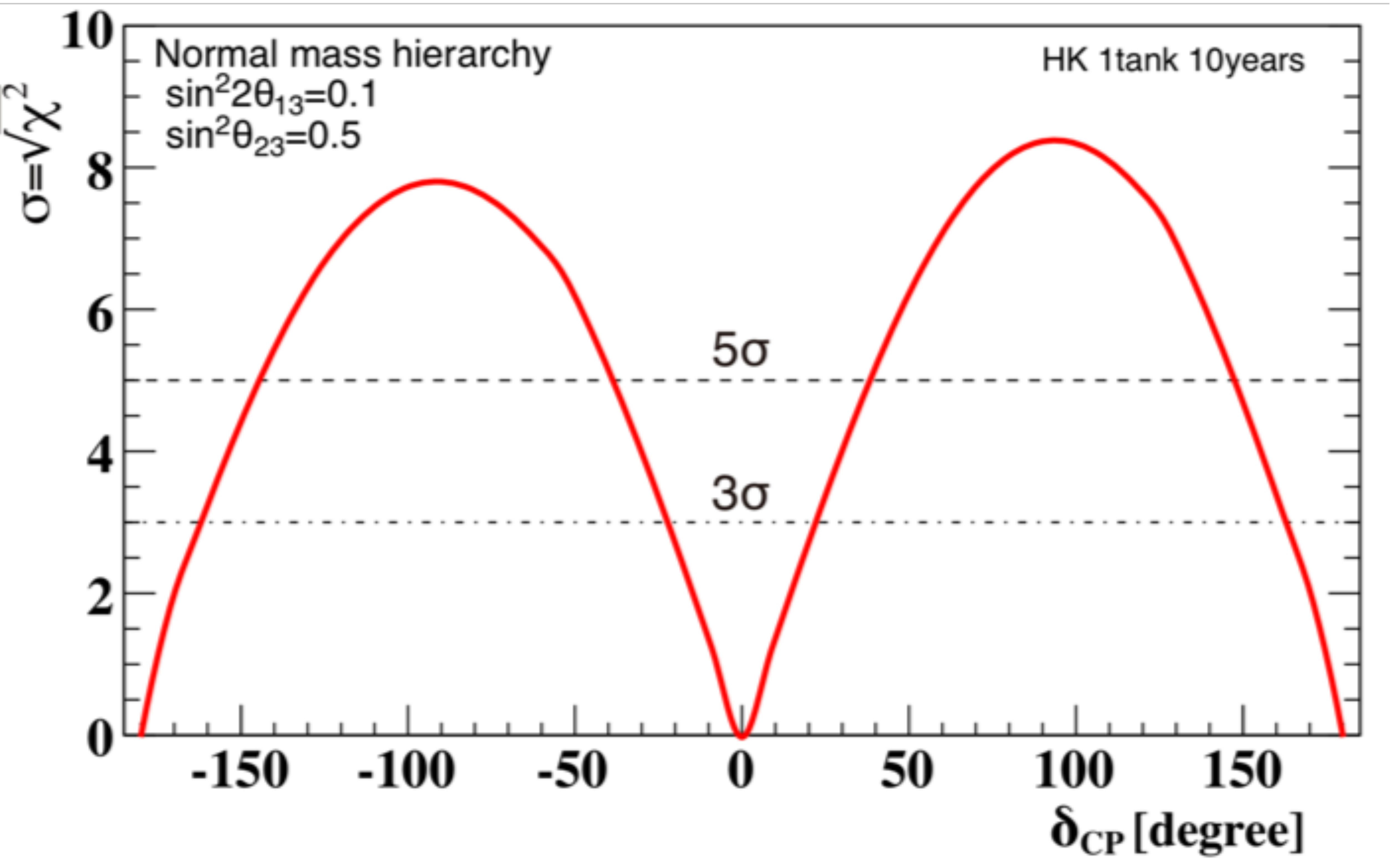
  e.g. nucleon decay, dark sectors, non-standard neutrinos, …

- Cosmology has important implications for absolute neutrino masses and can probe non-standard interactions but challenging systematics.

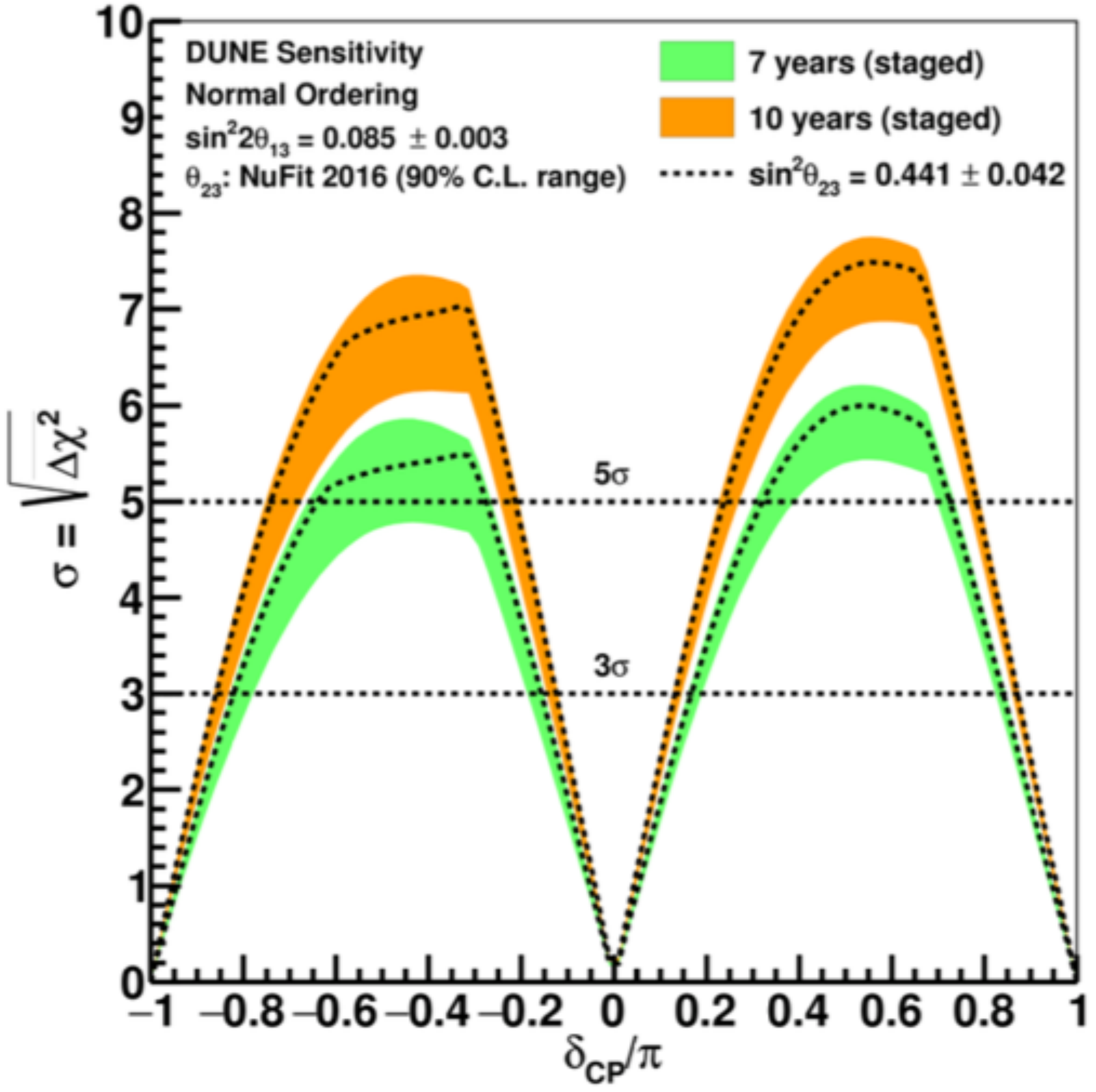
  Direct experimental tests in KATRIN and $0\nu\beta\beta$ are essential as well.

- Note: if neutrinos are Dirac, won't have anything to say about NH vs. IH!

Neutrinos - CP Violation



Hyper-K
1805.04163

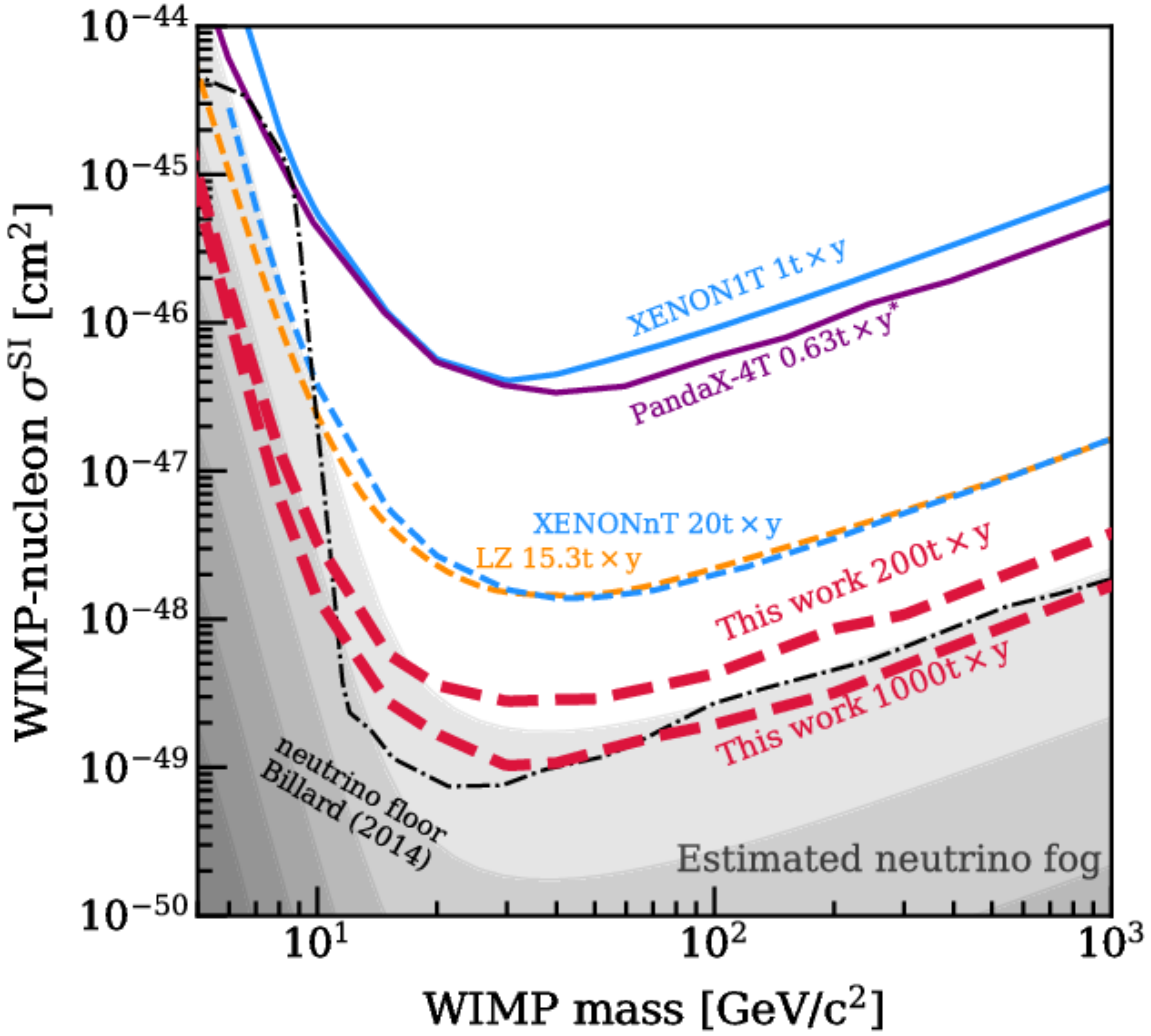


DUNE
PoS NuFact 2017, 052 (2017)

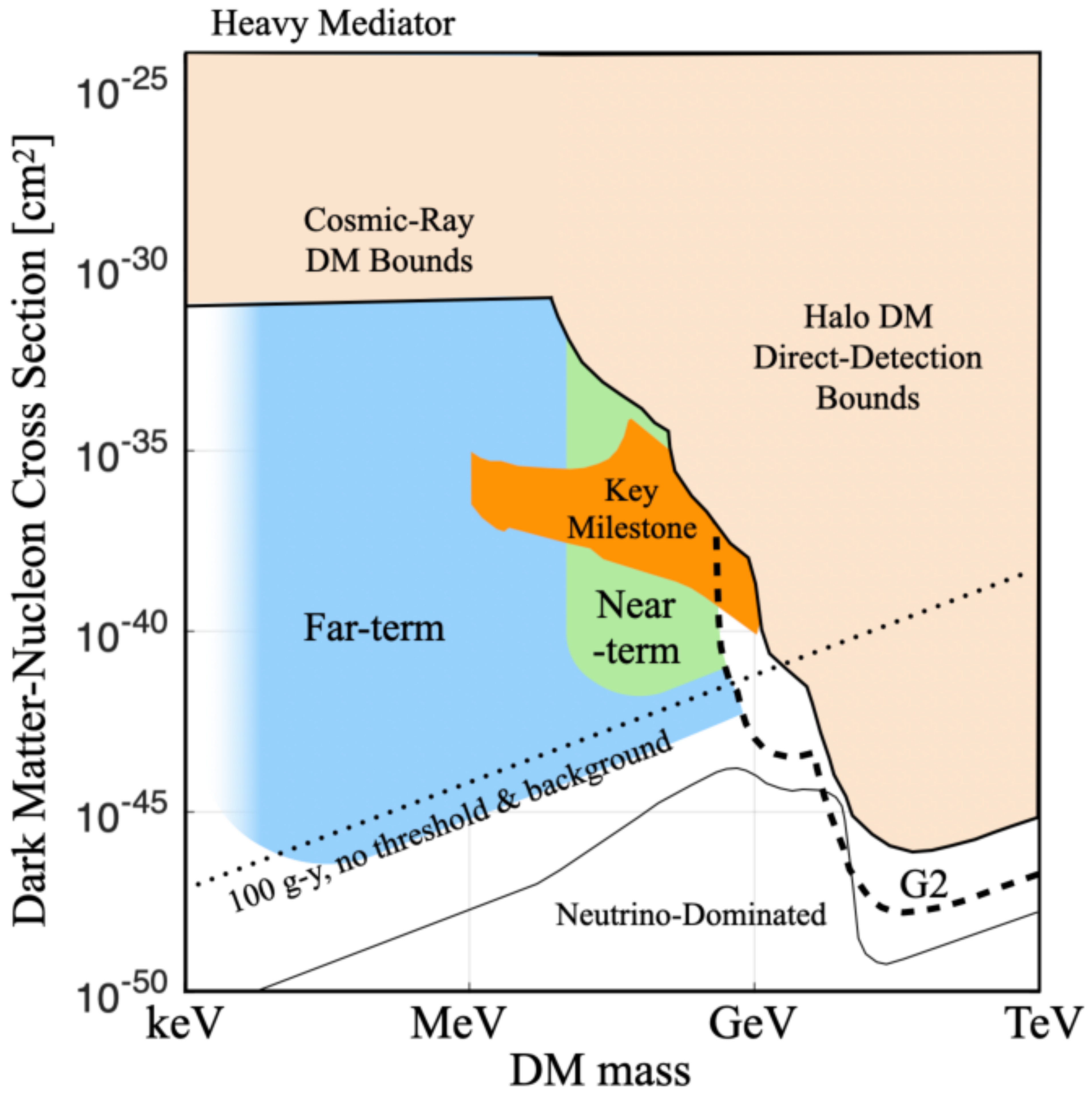
Dark Matter

- Direct searches for DM can be classified into three broad categories:
  - **WIMP-like: mass above 1 GeV, weakish interaction strength with SM**
    - will be dominated by large-scale Xe (XENONnT, LZ, PandaX-4T) and Ar (DarkSide 50k)
    - progress towards the “neutrino floor” in future with DARWIN (Xe) and ARGO (Ar)
  - **Light DM: mass between 1 keV — 1 GeV, weakish interaction strength with SM**
    - searches rely on more complicated responses than elastic nuclear scattering, smaller scale
    - SuperCDMS, NEWS-G, SENSEI, DAMIC, lots of proposed ideas using fancy materials
  - **Ultralight DM: sub-keV light bosons with very tiny interaction strengths with SM**
    - detection relies on extreme precision, many new ideas but not fully implemented
    - methods are often specific to the candidate of interest

Dark Matter - Nuclear Targets

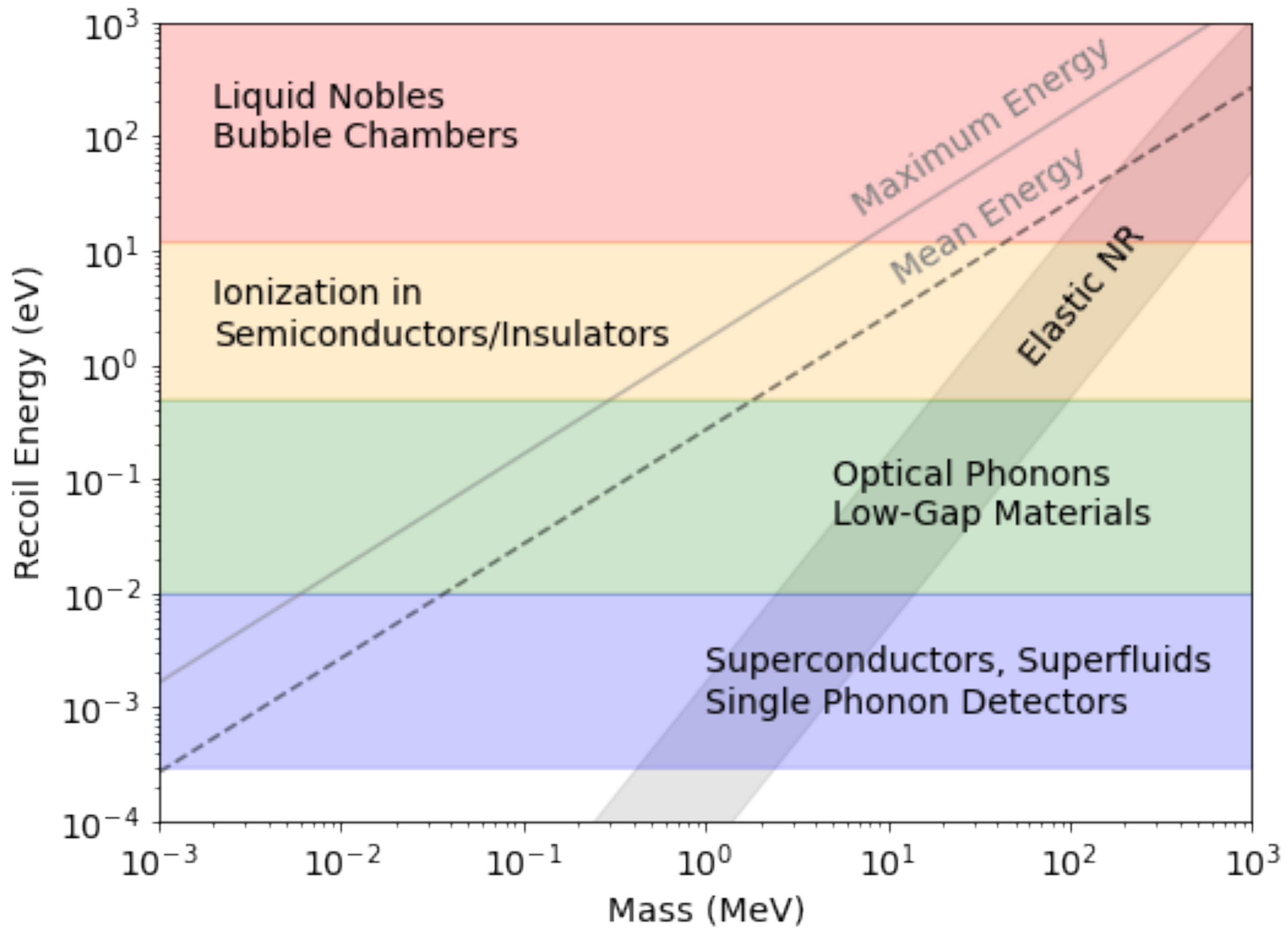


Large Scale Xenon
2203.02309

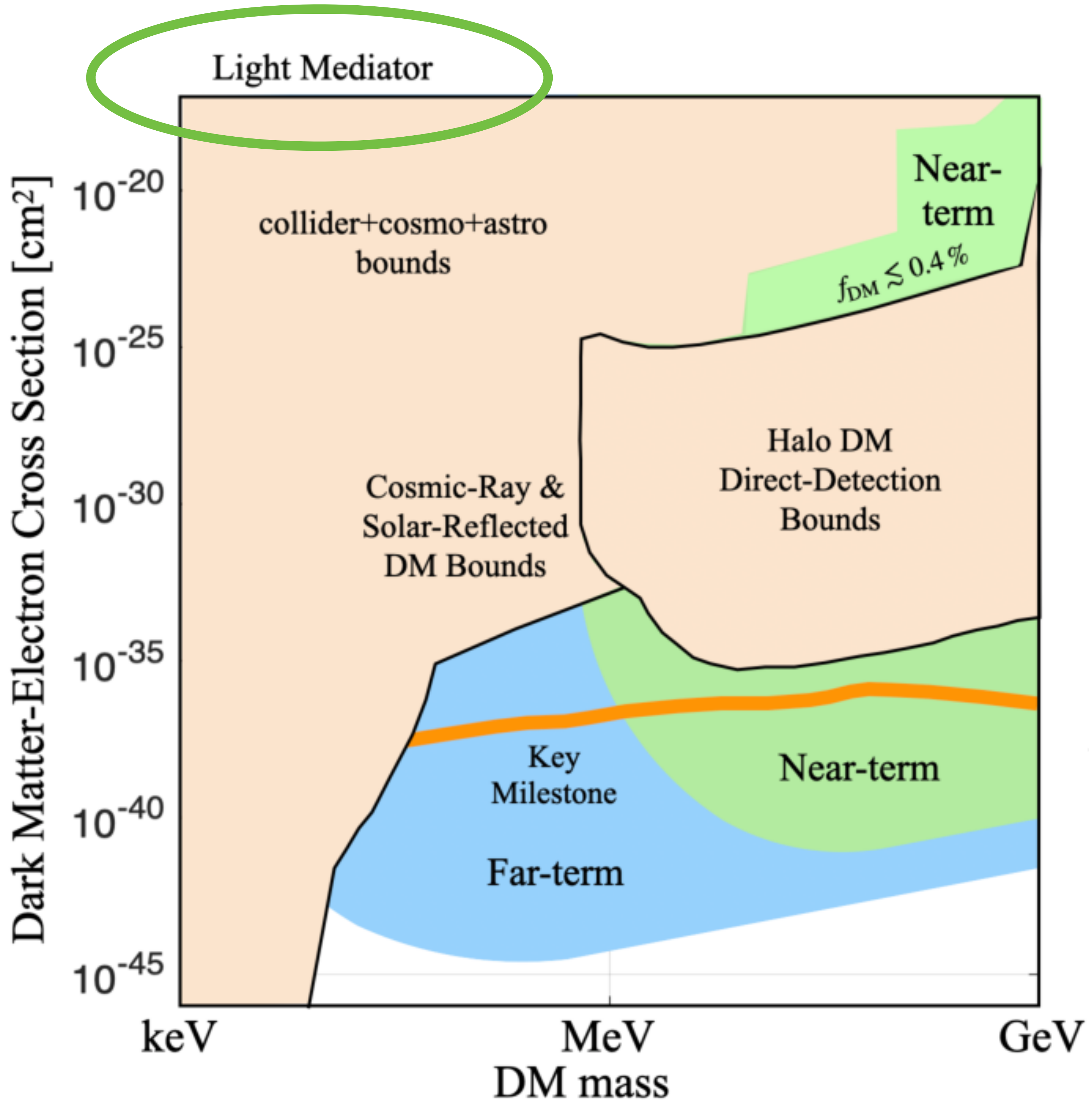


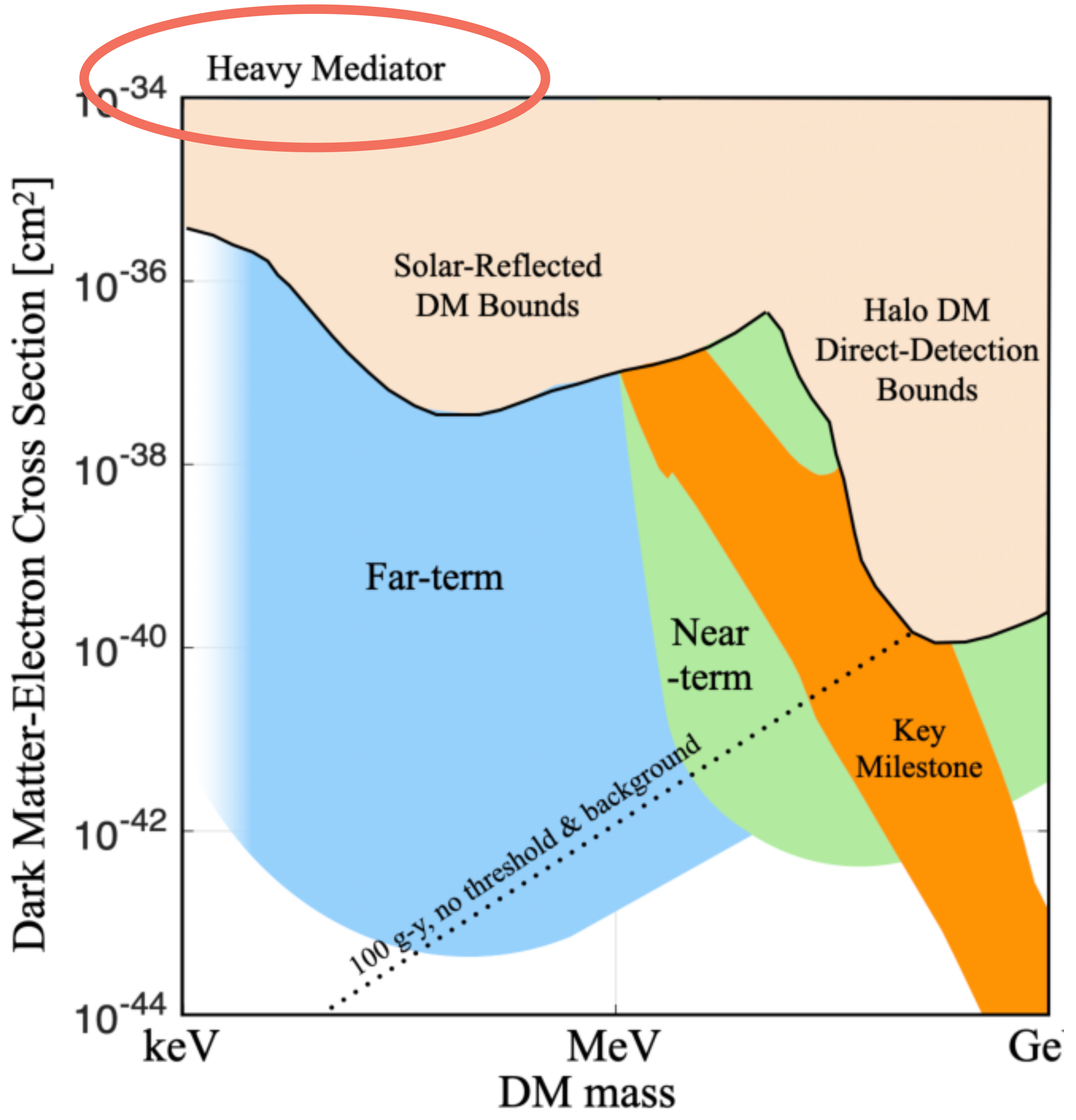
Light DM on Nuclei
2203.08297

Dark Matter - Electron Targets



DM Kinematics
2203.08297





Light DM on Electrons
2203.08297

Dark Matter and More

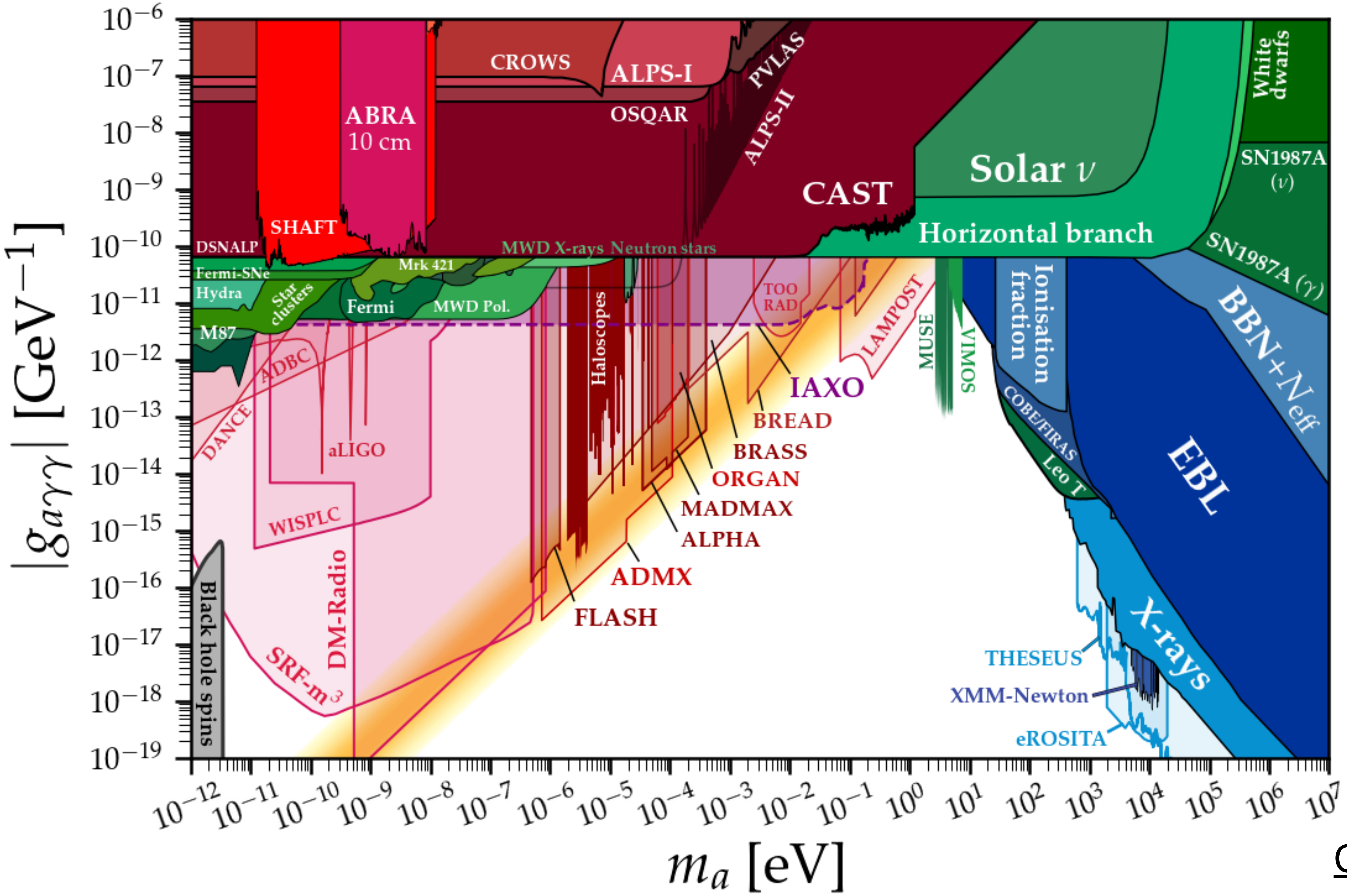
- Direct searches are complemented by collider and indirect searches.
- Collider searches typically require DM with weak interactions to be heavier than $m_{\mathrm{DM}} \gtrsim 50\,\mathrm{GeV}$.
- Indirect detection (*e.g.* cosmic rays, gamma rays, CMB) also constrains minimal freeze-out production mechanism for DM with masses below this.
- Lighter thermal DM ($m_{\mathrm{DM}} \lesssim 10\,\mathrm{GeV}$) requires new interactions to get the right relic density.

  $\rightarrow$ dark sectors connected to dark matter!
- Dark sector searches are addressed well by LHC, Belle II, and high-intensity lower-energy experiments like DarkLight, NA62, SeaQuest, SHiP, …

Precision

- High precision can detect tiny deviations from the SM from very heavy (or light) new physics.
- Searches for new sources of CP violation may give clues to the excess of matter over antimatter.
  (*e.g*. UCN nEDM, RadM EDM, many other experiments…)
- Charged lepton flavour violation is often correlated with explanations to muon (g-2).
- Extreme precision is the best way to look for ultralight new physics such as wavelike DM.
  - axions in EM cavities (ADMX), LC circuits (DMRadio, ABRACADABRA,…), SRF cavities (Fermilab)
  - oscillating EDMs or fundamental constants from wavelike (oscillating) DM
  - gravitational waves?

Precision - Axion DM



C. O'Hare, 2022

And More…

- Major advances in many fields adjacent to “particle physics”:
  - CMB temperature, polarization, and frequency measurements
  - cosmic structure via 21cm lines and large surveys
  - gravitational waves: LIGO, LISA, DECIGO, BBObserver, …
  - new accelerator technologies
  -

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Thank you
Merci

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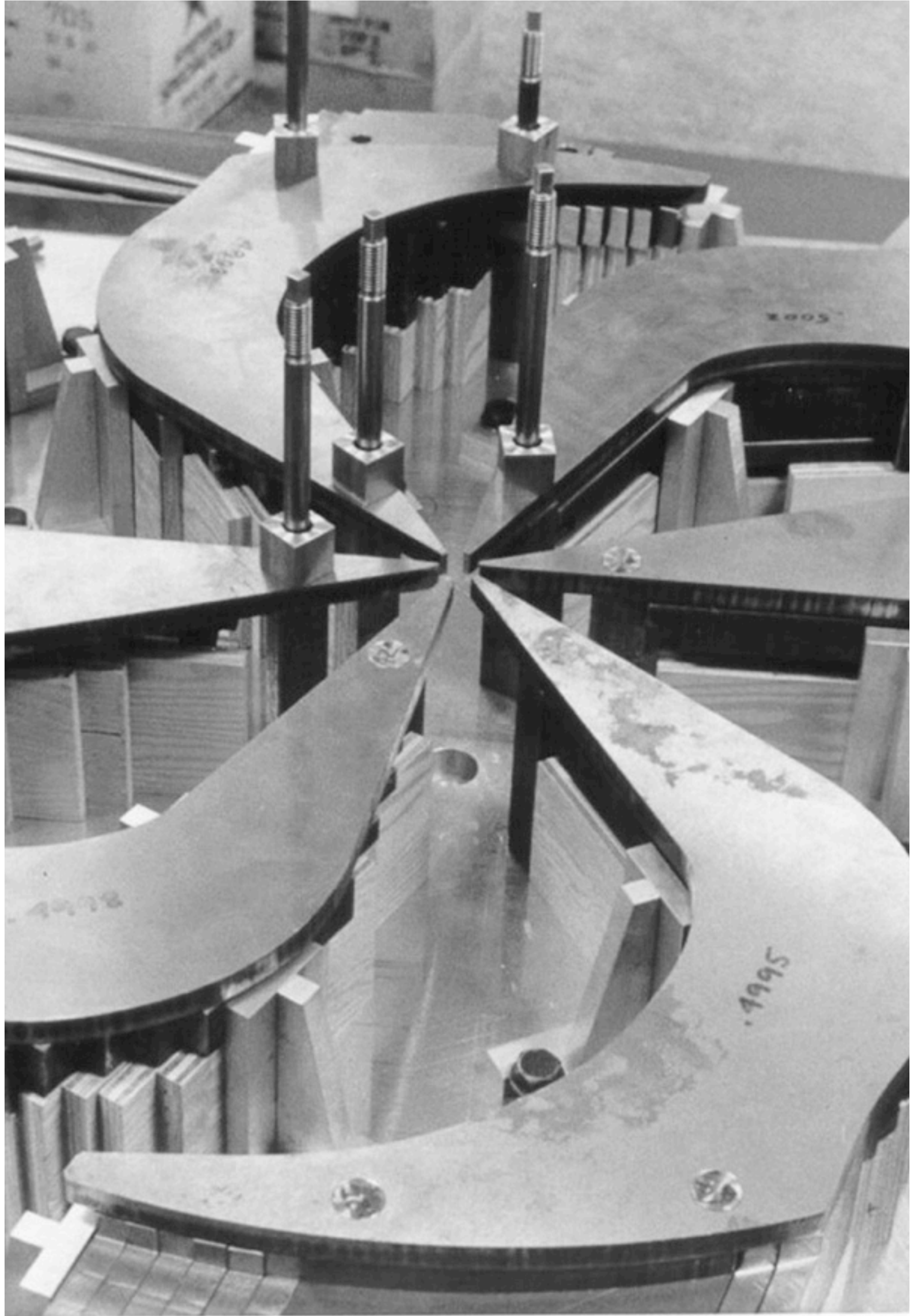

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