Experimental searches for DM and Neutrinoless Double Beta Decay

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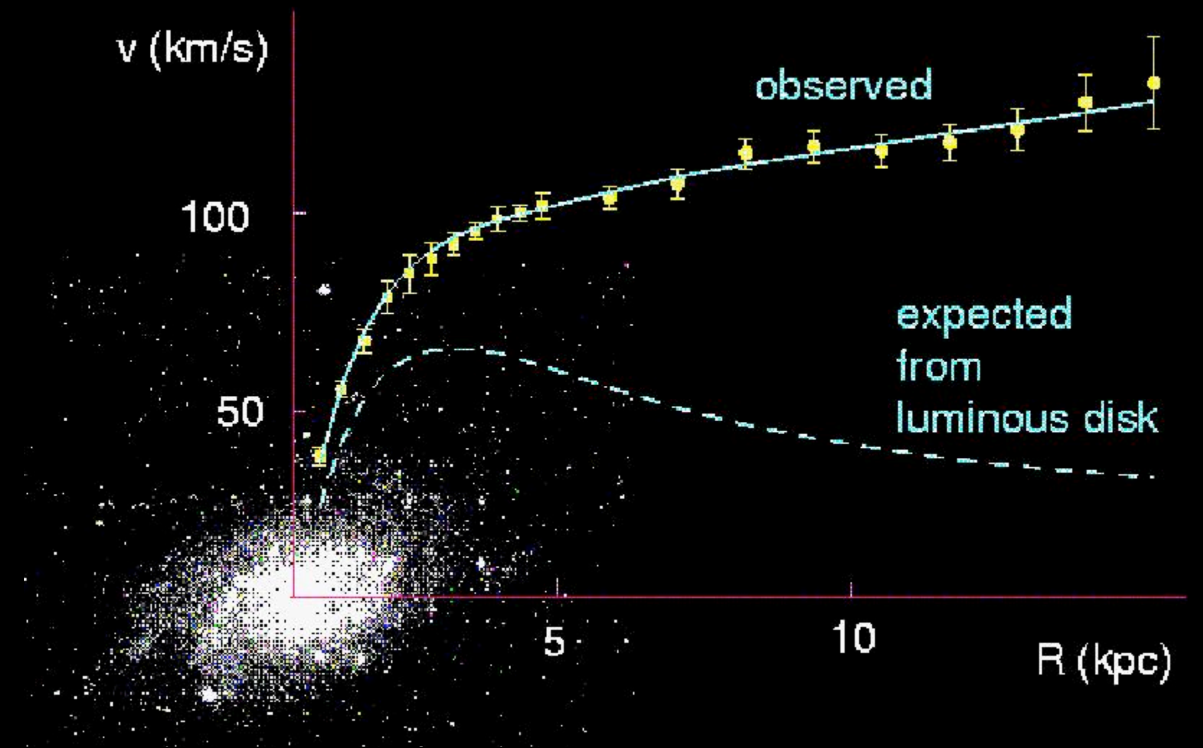
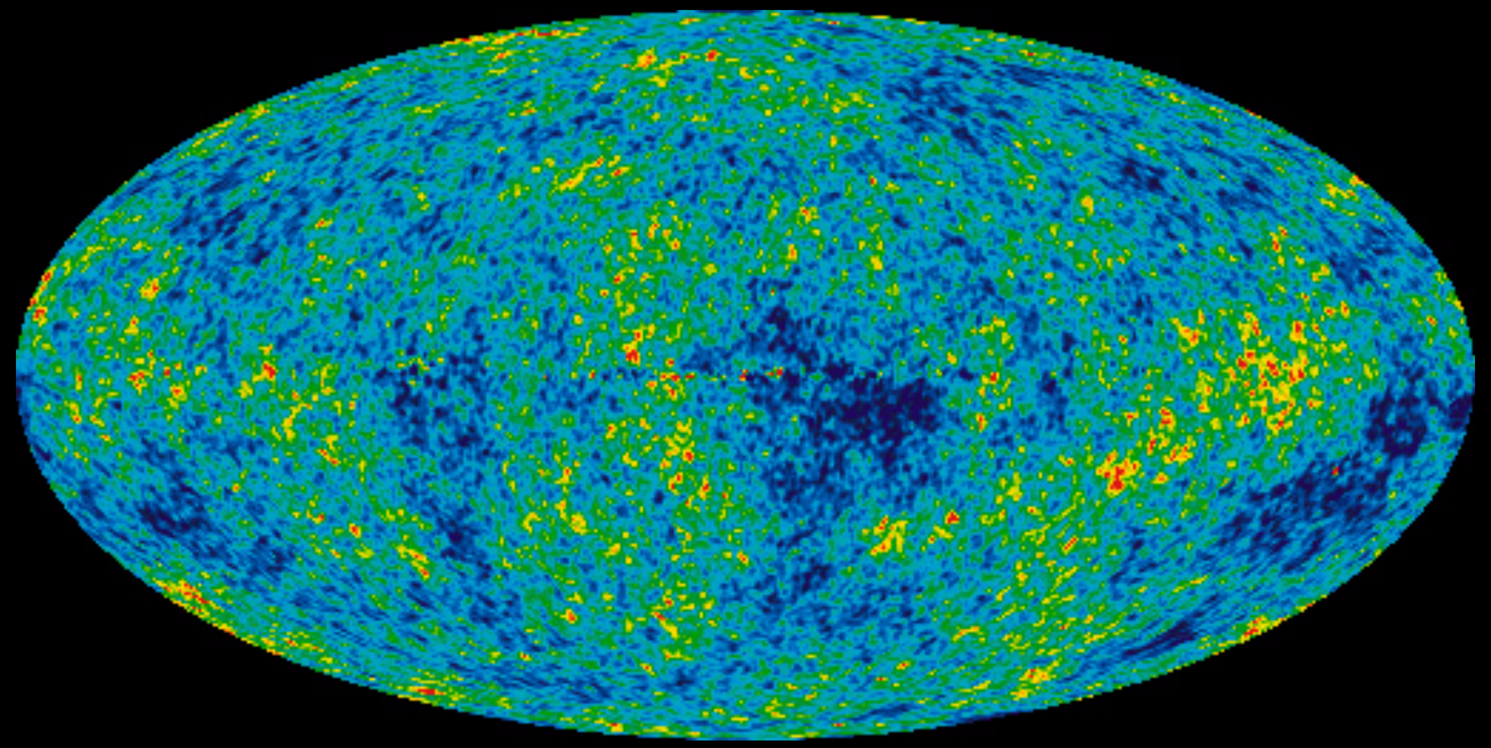
Much astrophysical evidence for Dark Matter

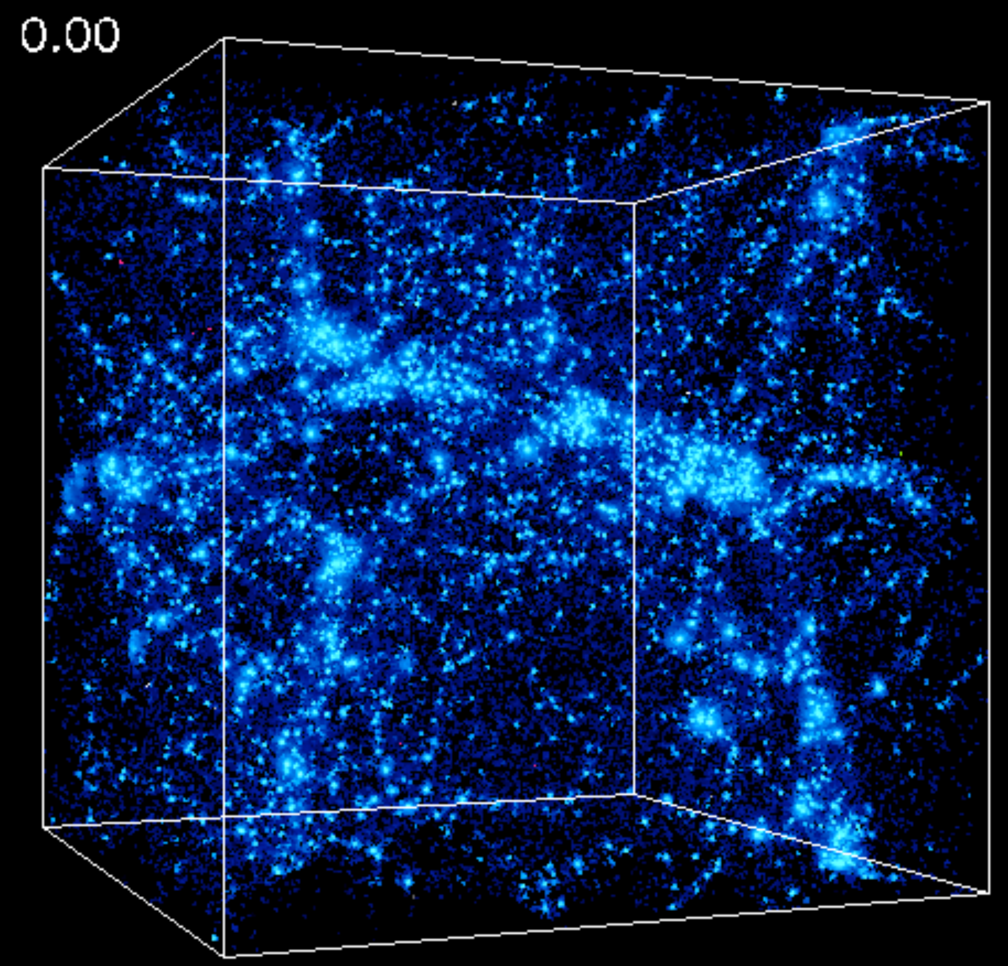


Rotational Curves


Anisotropy in CMB

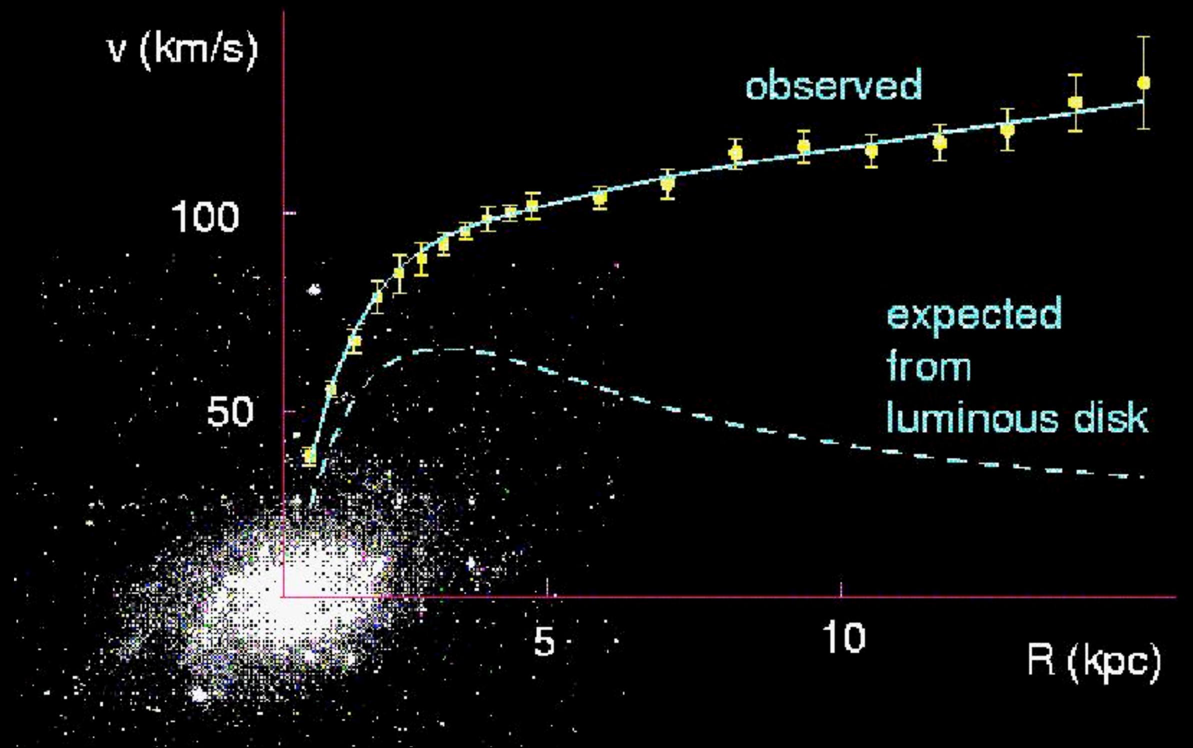

Weak Lensing


Galaxy Clusters



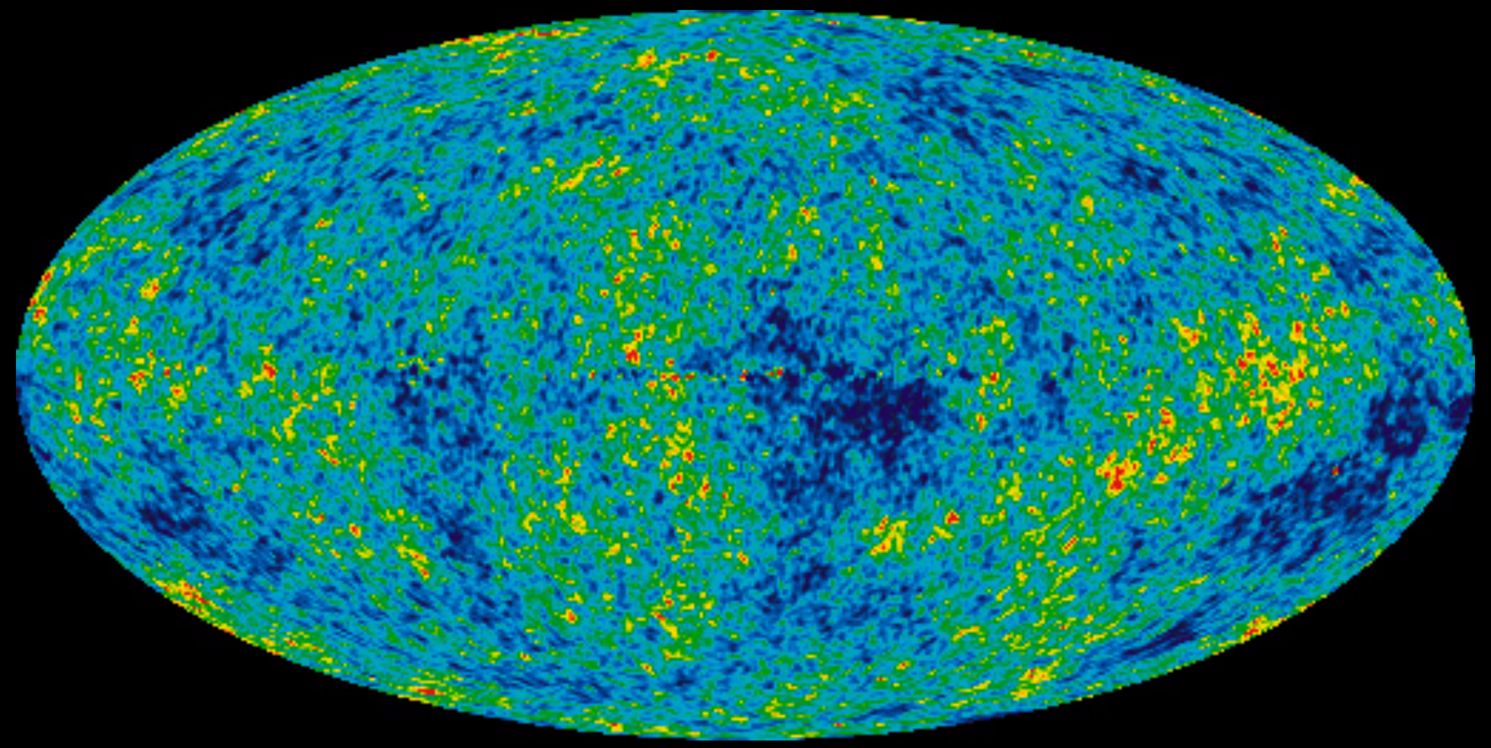
Large Scale Structure

Much astrophysical evidence for Dark Matter



Rotational Curves

On **all** distance scales in the Universe!



Anisotropy in CMB

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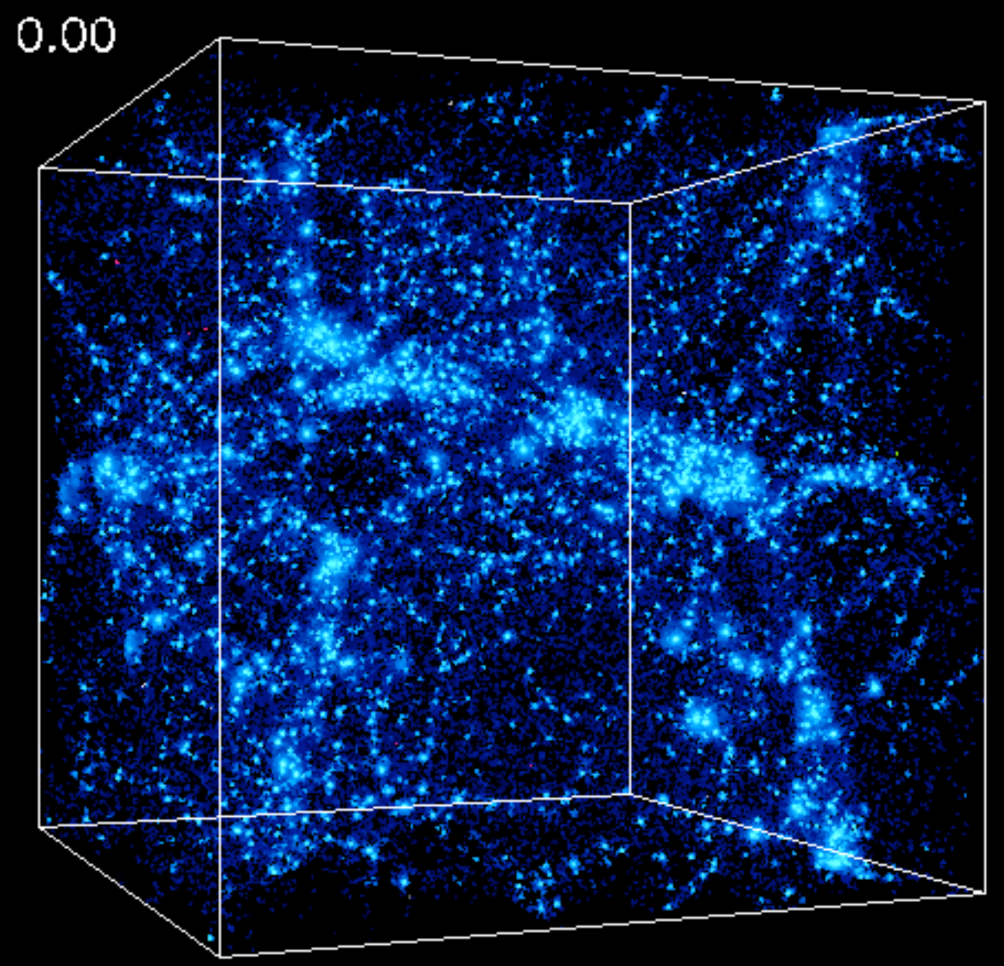


Large Scale Structure

Dark Matter Candidates

Bertone, Tait, Nature 562, 51

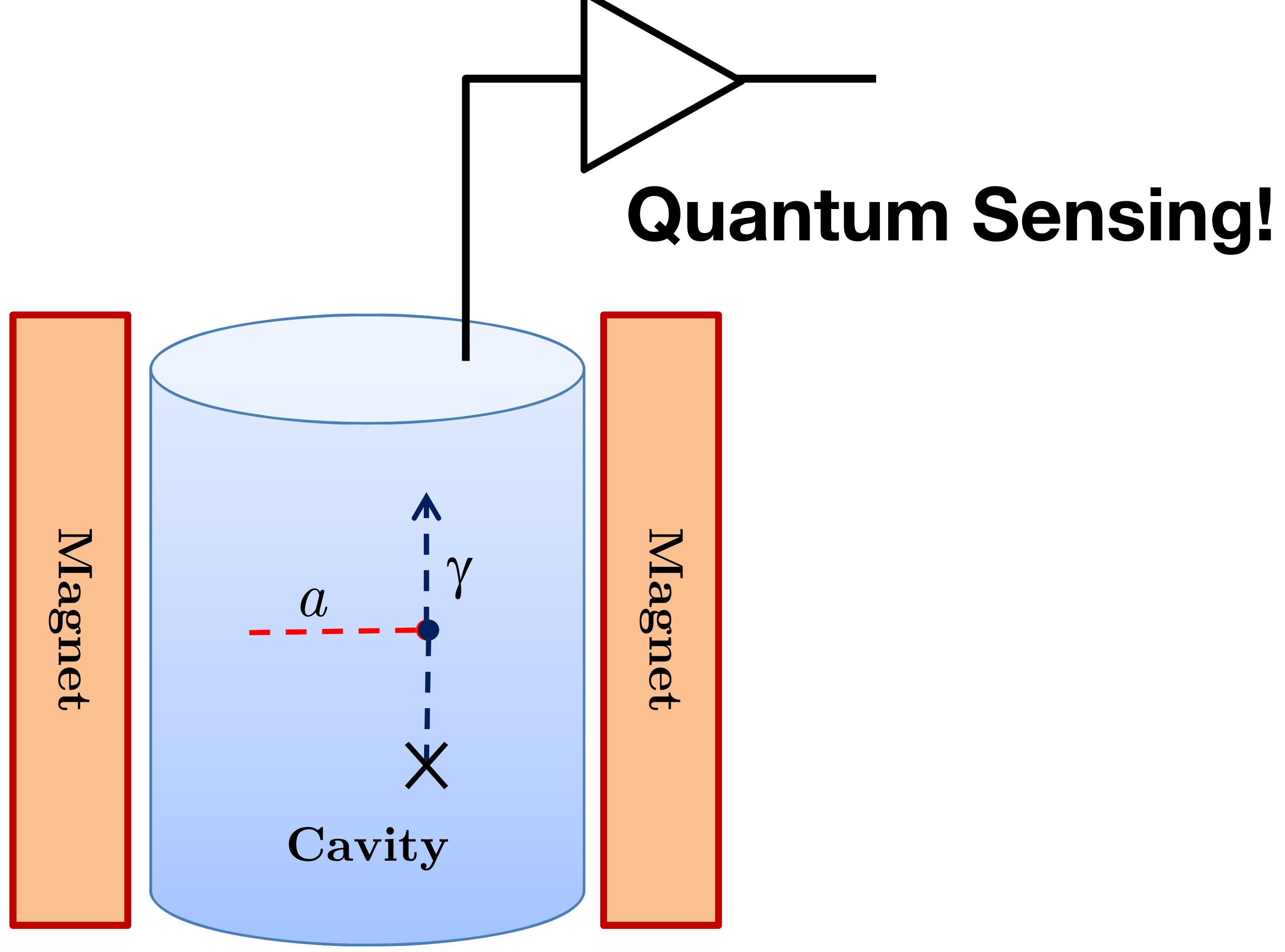
Dark Matter Candidates

Bertone, Tait, Nature 562, 51

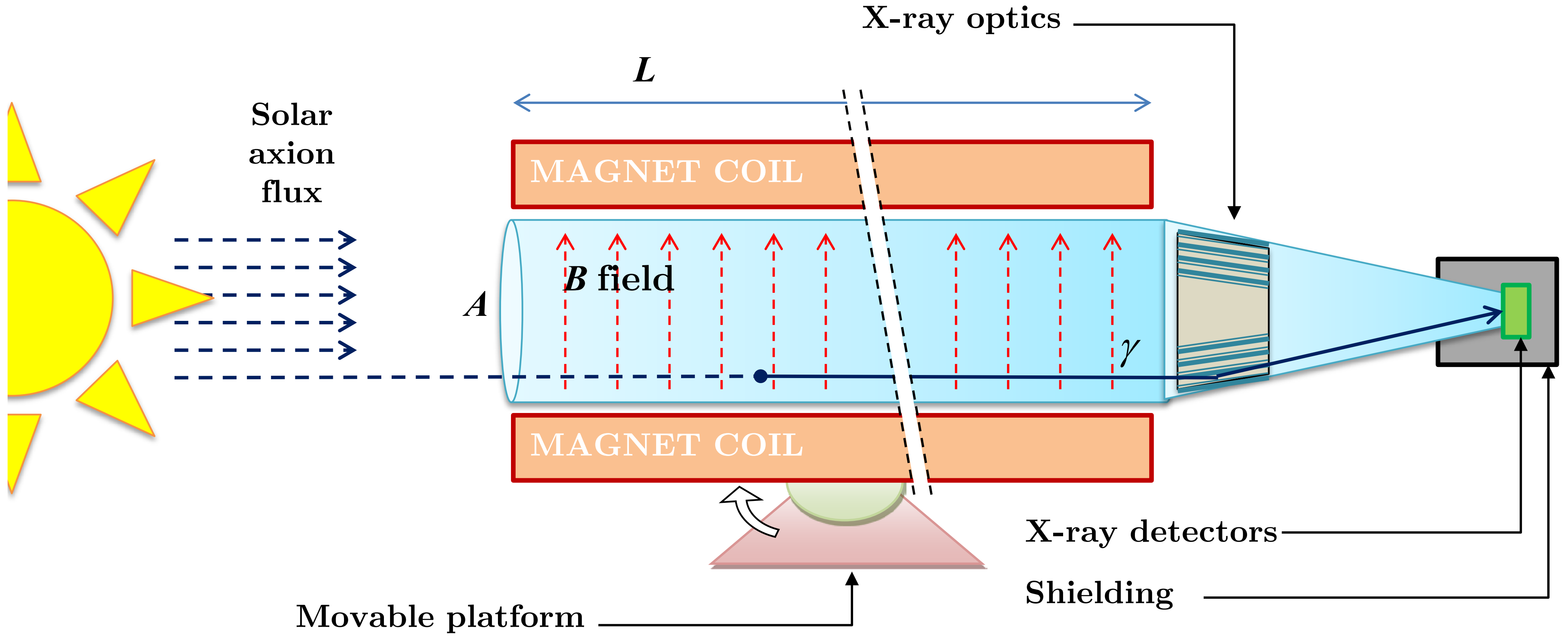
Axions

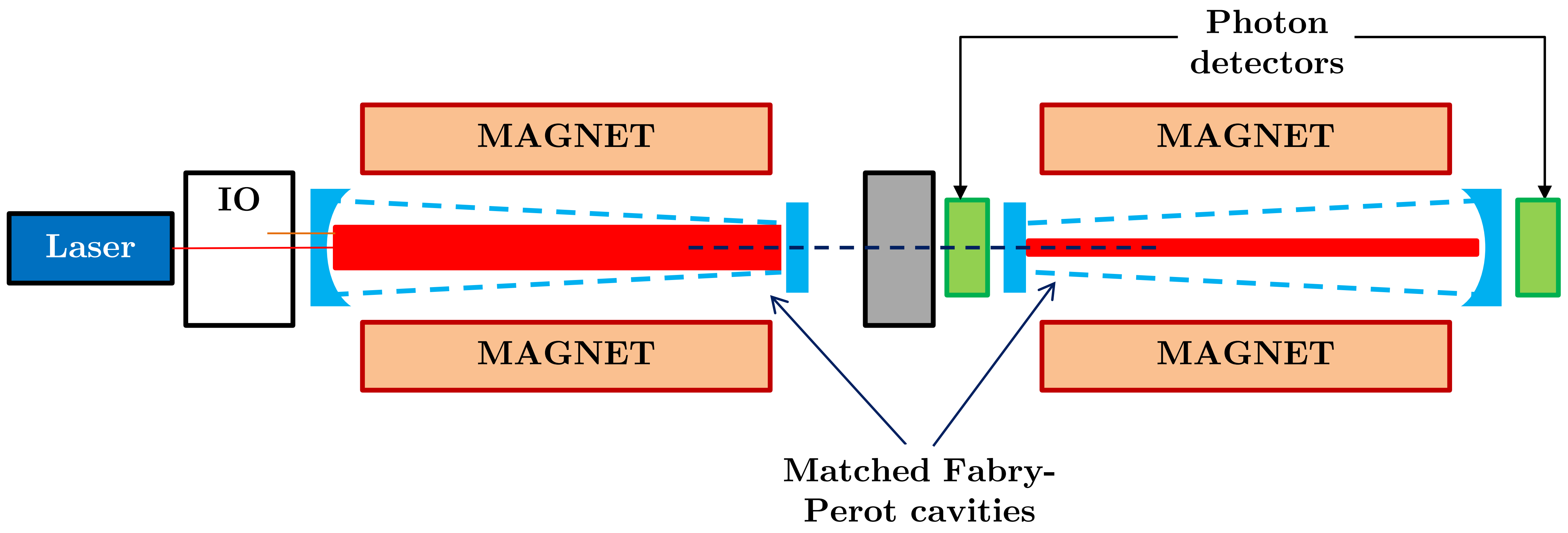
QCD Axion: good DM and strong-CP solution candidate

Axion-like-Particle (ALP): good DM candidate

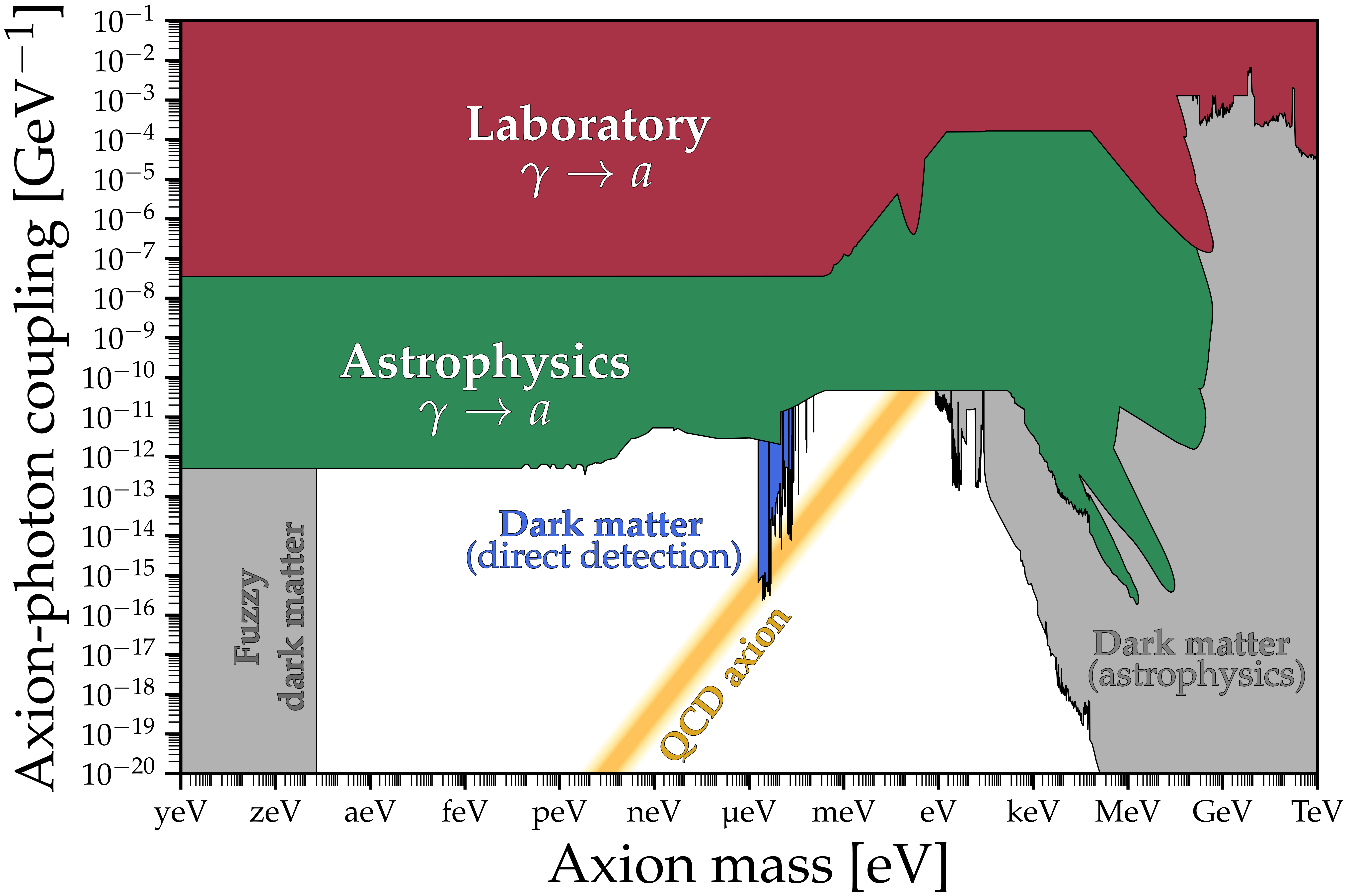


- **Axions from Dark Matter Halo**
  - Haloscopes: look for axion conversion to photons in B-field
  - Experiments: ADMX, MADMAX, CASPEr, …
- **Axions from the Sun**
  - Helioscopes: axion-photon or axion-electron coupling
  - Experiments: CAST, IAXO, but also EDELWEISS, **XENON**, LZ, GERDA, CUORE, …
- **Axions in the lab**
  - “Shining through walls”: photon regeneration
  - Experiments: ALPS, …



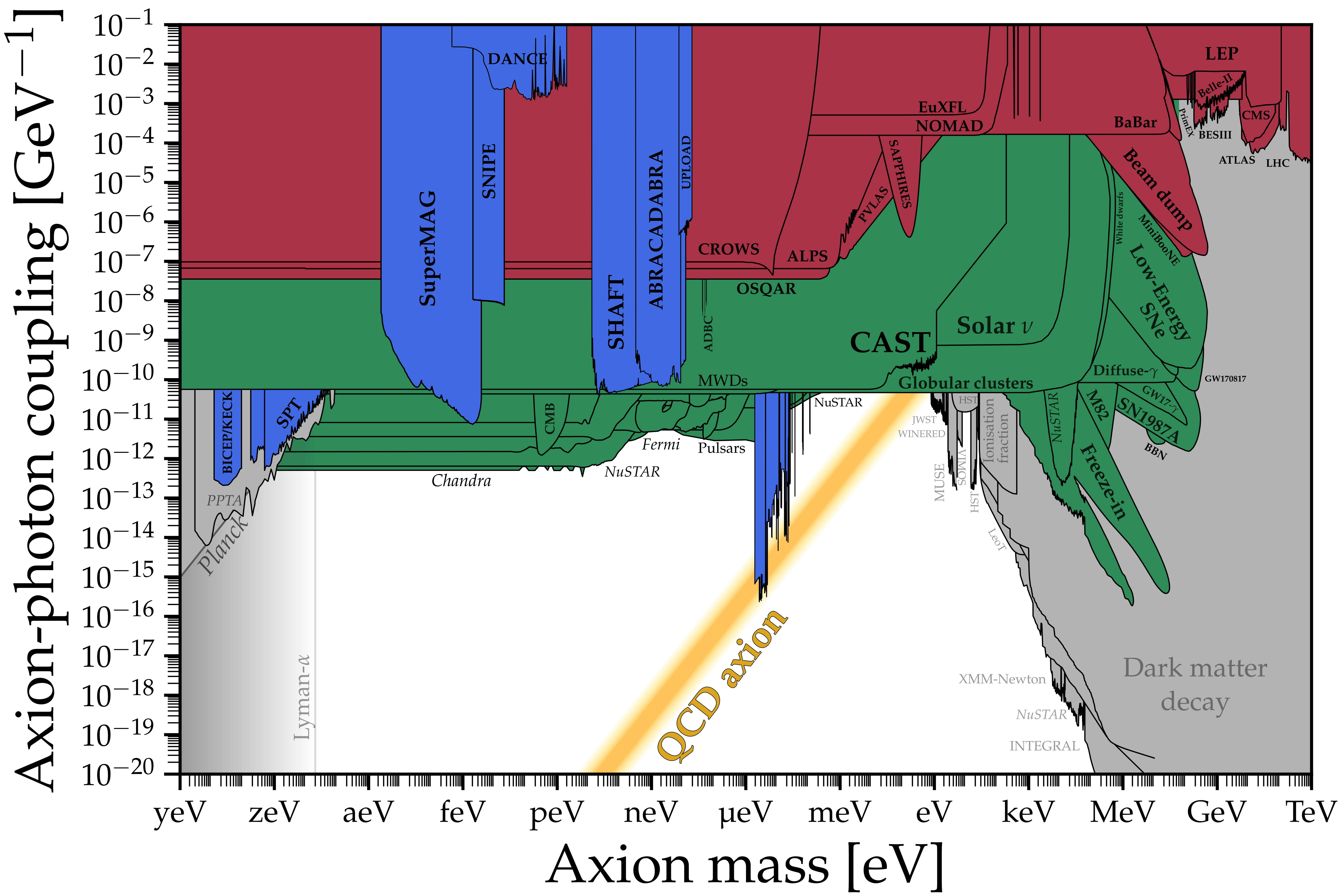


Axion Landscape



https://cajohare.github.io/AxionLimits/docs/ap.html

Axion Landscape



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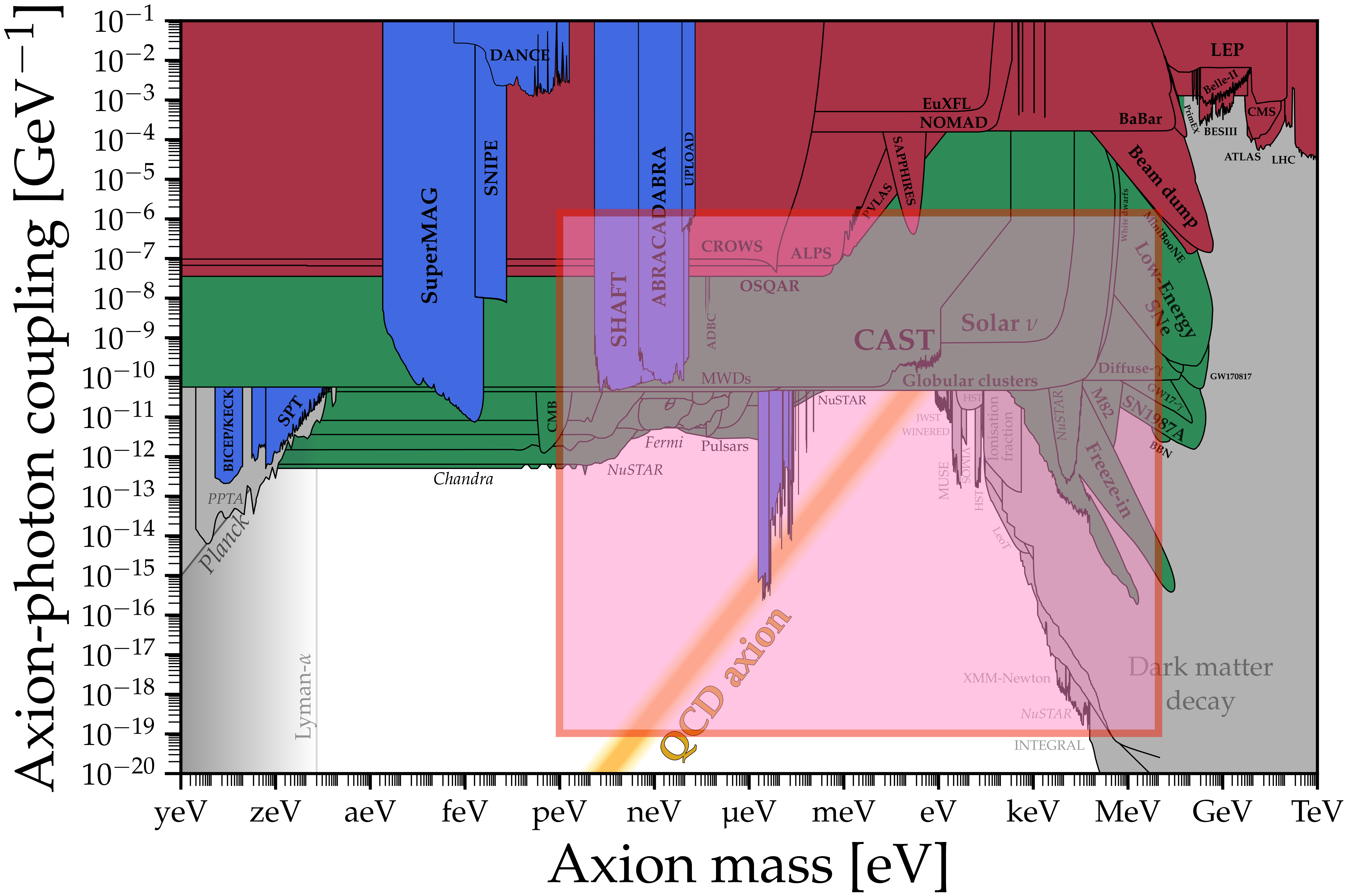
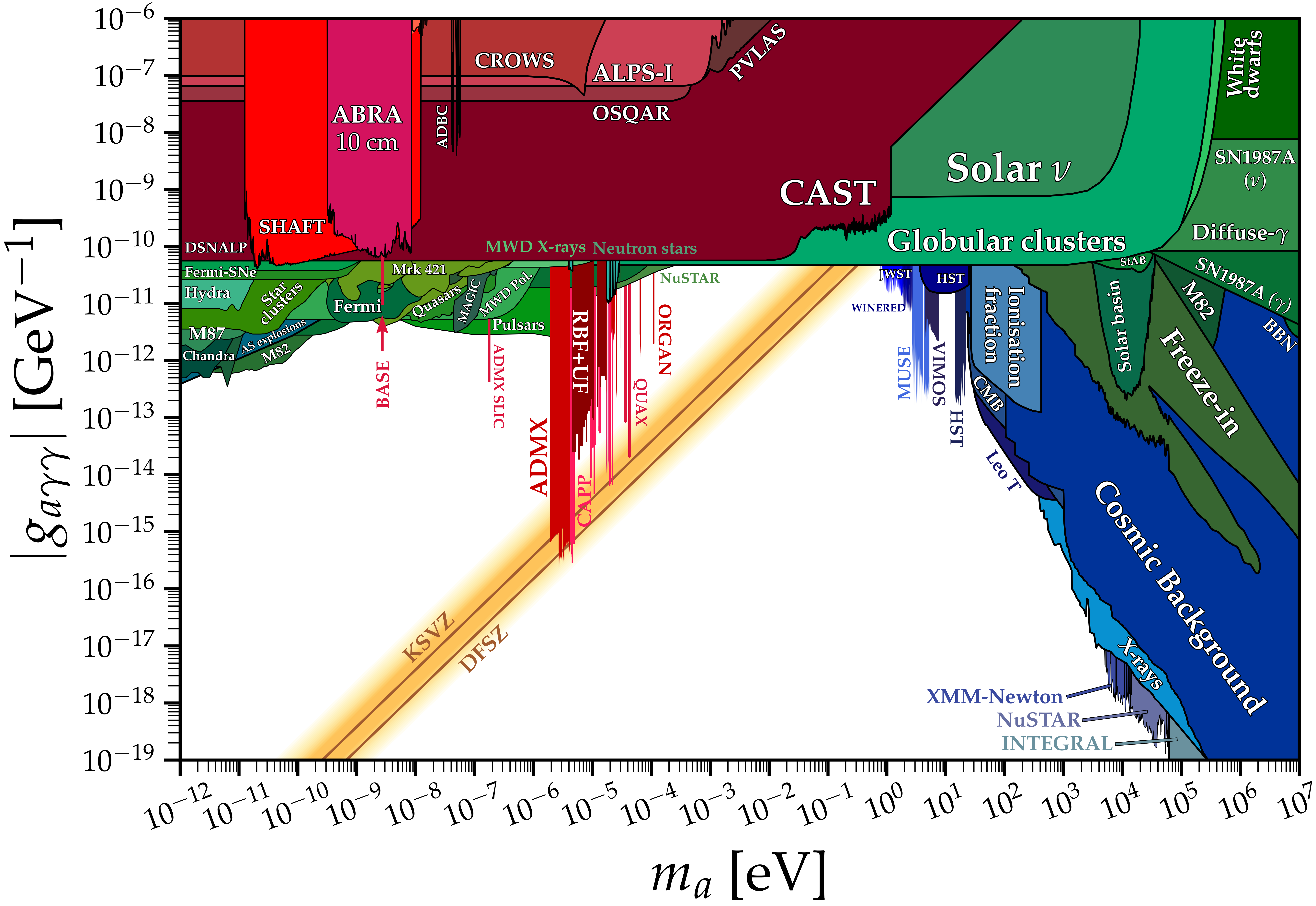
Axion Landscape

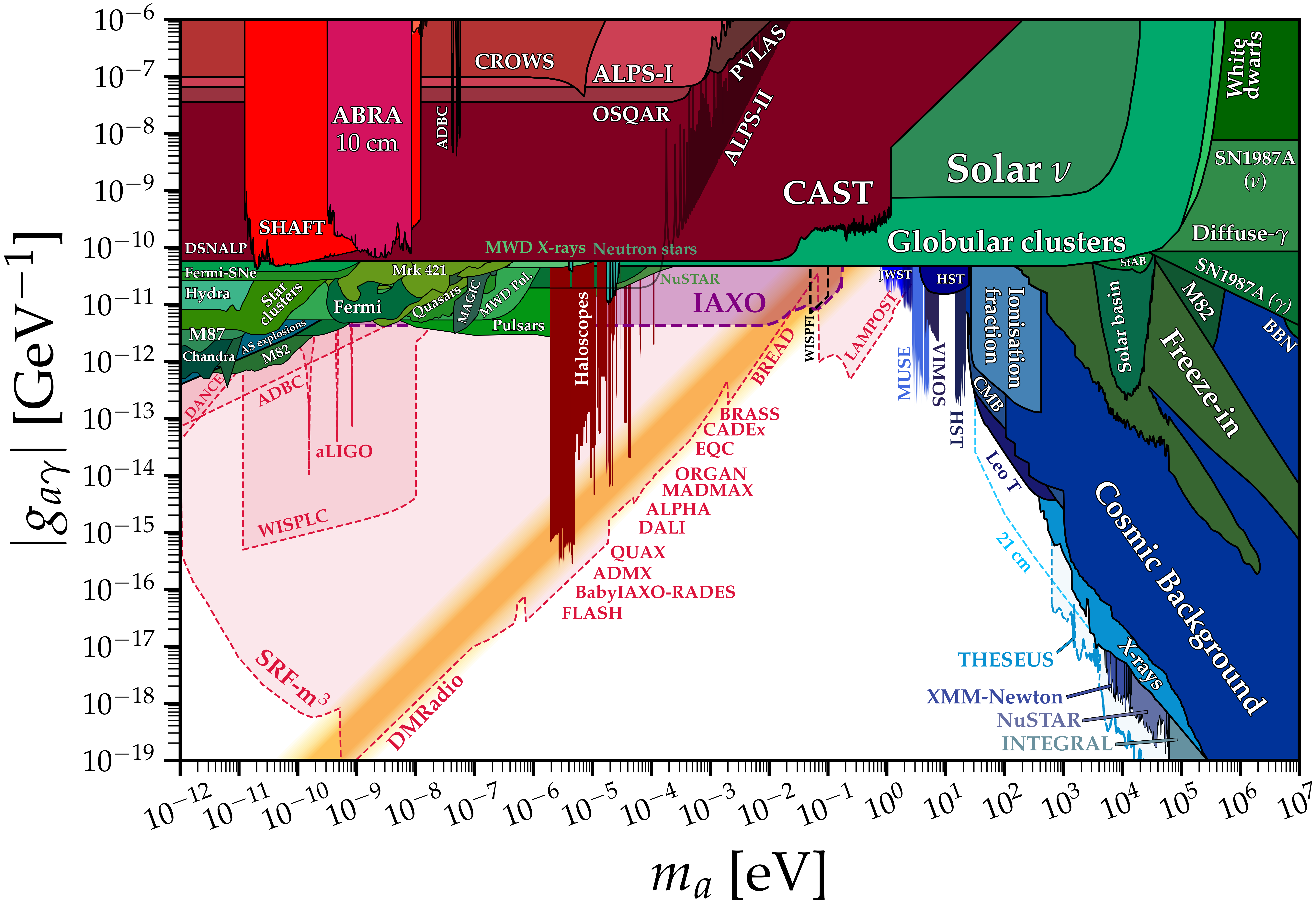


https://cajohare.github.io/AxionLimits/docs/ap.html

Axion Landscape: QCD Axion

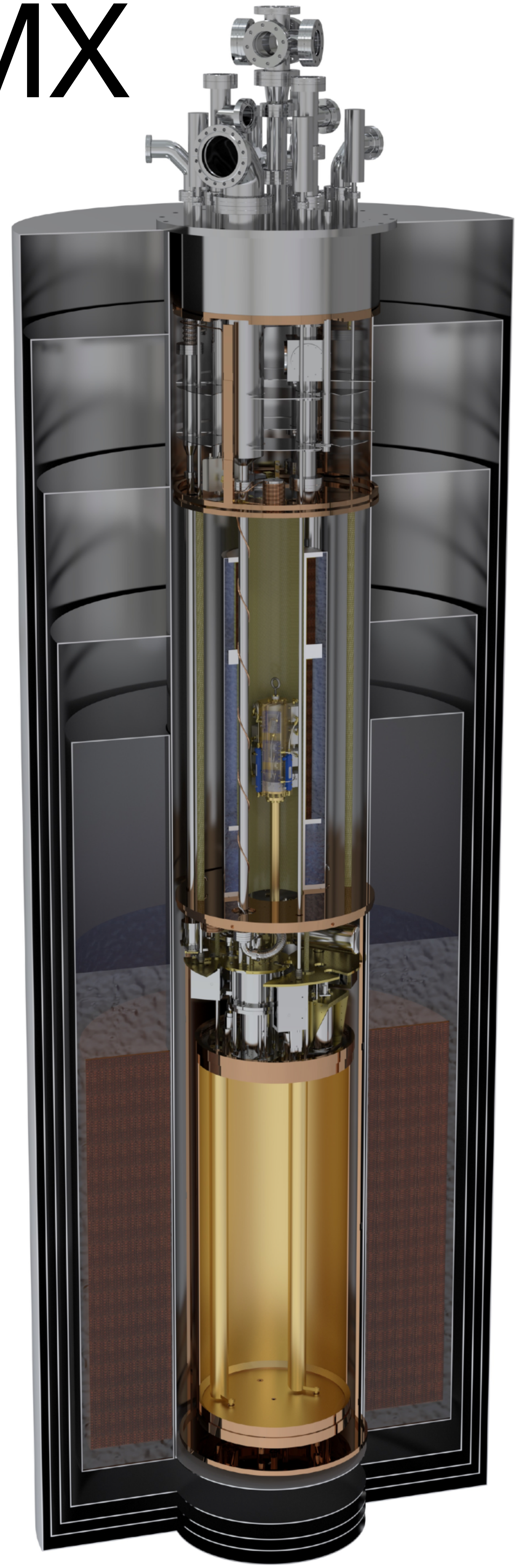


Axion Landscape: QCD Axion



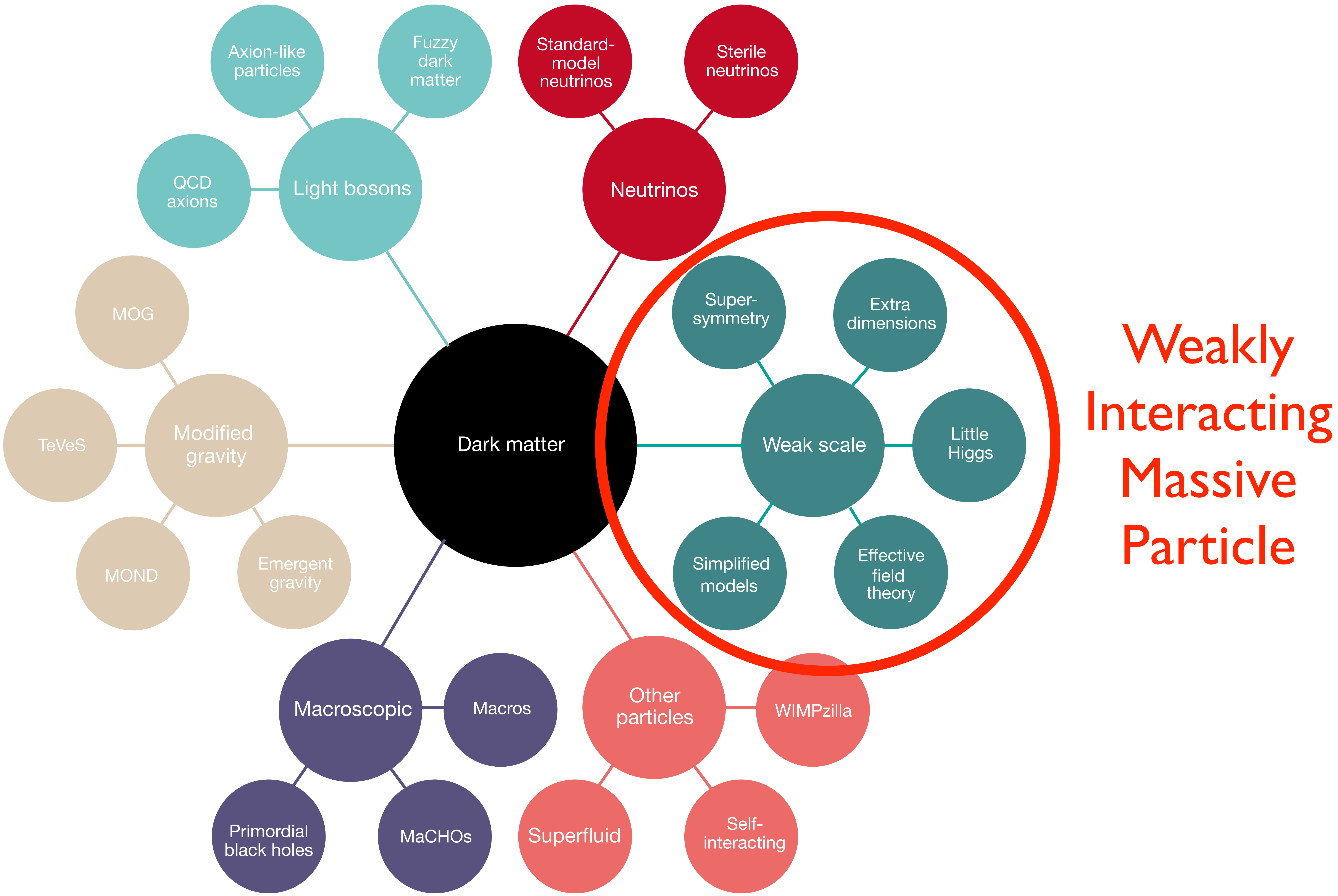
Example axion haloscope: ADMX

- ADMX Experiment as example of Haloscope
- Large volume 8.5T superconducting magnet
- No special lab required
- High-Q cavity, tunable @ 2-4 GHz → 8 - 16 μeV m_a
- SQUID and other quantum sensing readout technology
- Similar tech in Europe: QUAX, FLASH

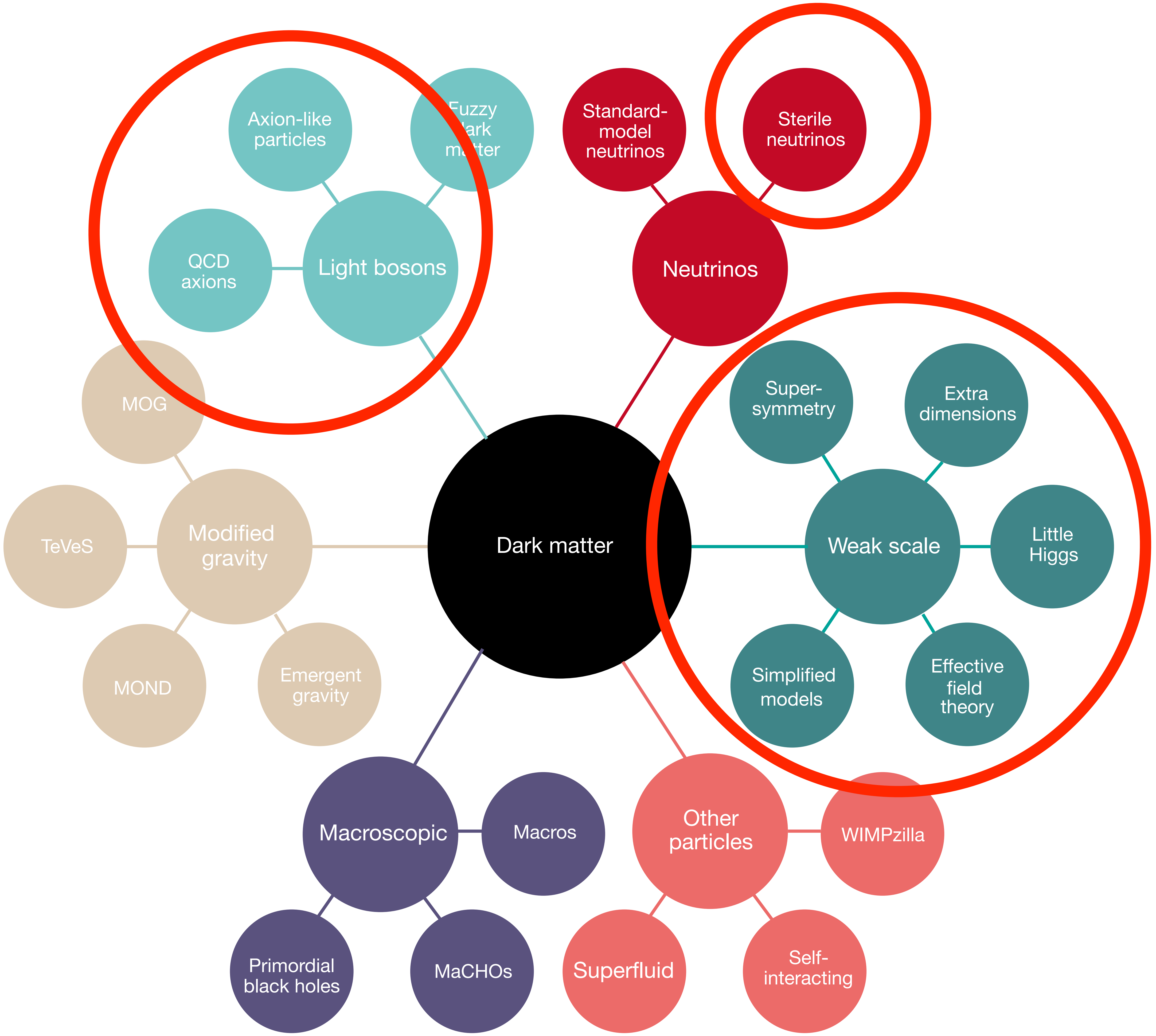


Dark Matter Candidates

Dark Matter Candidates



Dark Matter Candidates



Patrick Decowski - Nikhef/UvA

DM → Rare Event Searches & Measurements

XLZD = XENON + LZ + DARWIN

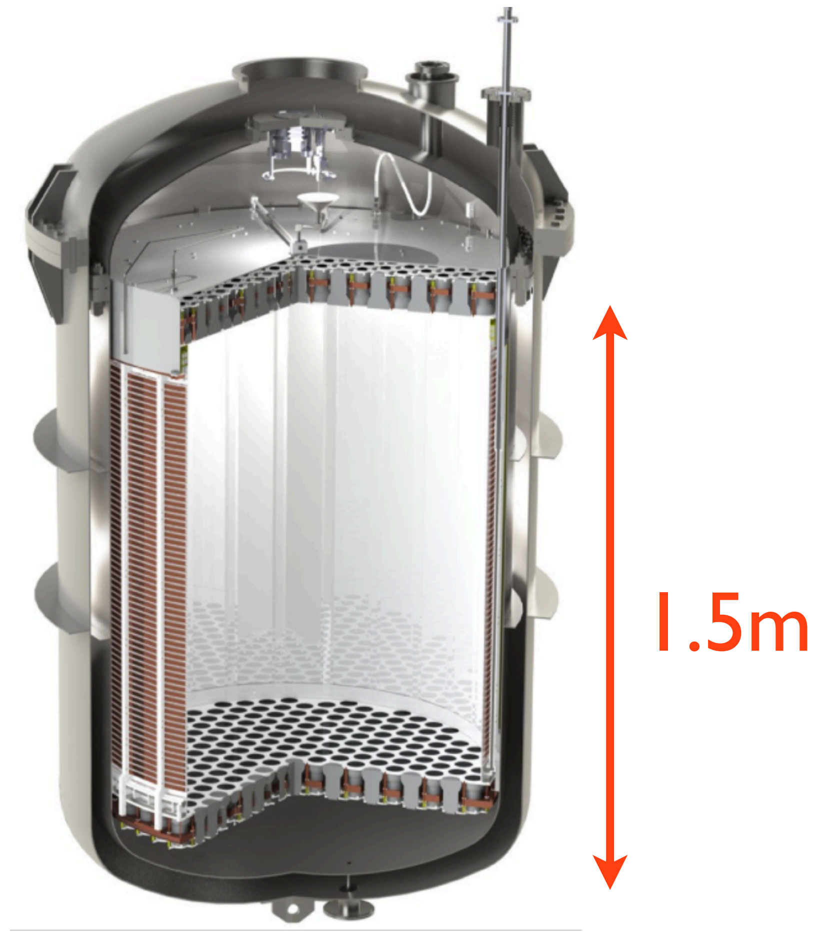
- Joined forces with competing LZ experiment
    - XLZD Collaboration
- Ultra-sensitive liquid xenon rare event observatory
- 60t LXe mass
- Submitted a Design Book

XLZD Design Book, arXiv:2410.17137, submitted to EPJC

White Paper: J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001, arXiv:2203.02309

XLZD: largest feasible dual-phase LXe detector

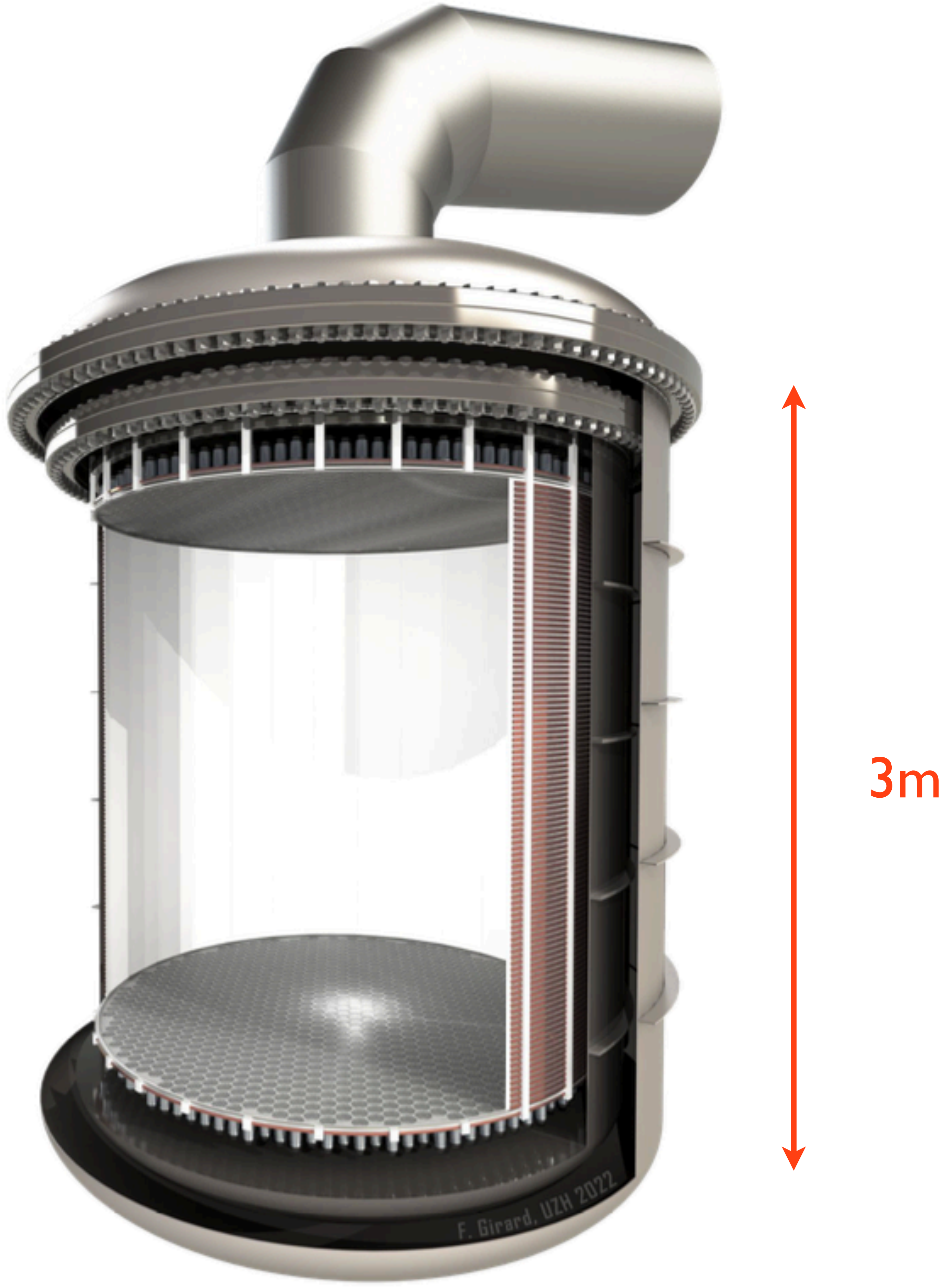
XENONnT (or LZ)



8.5t of LXe

Scale all dimensions by 2x

XLZD



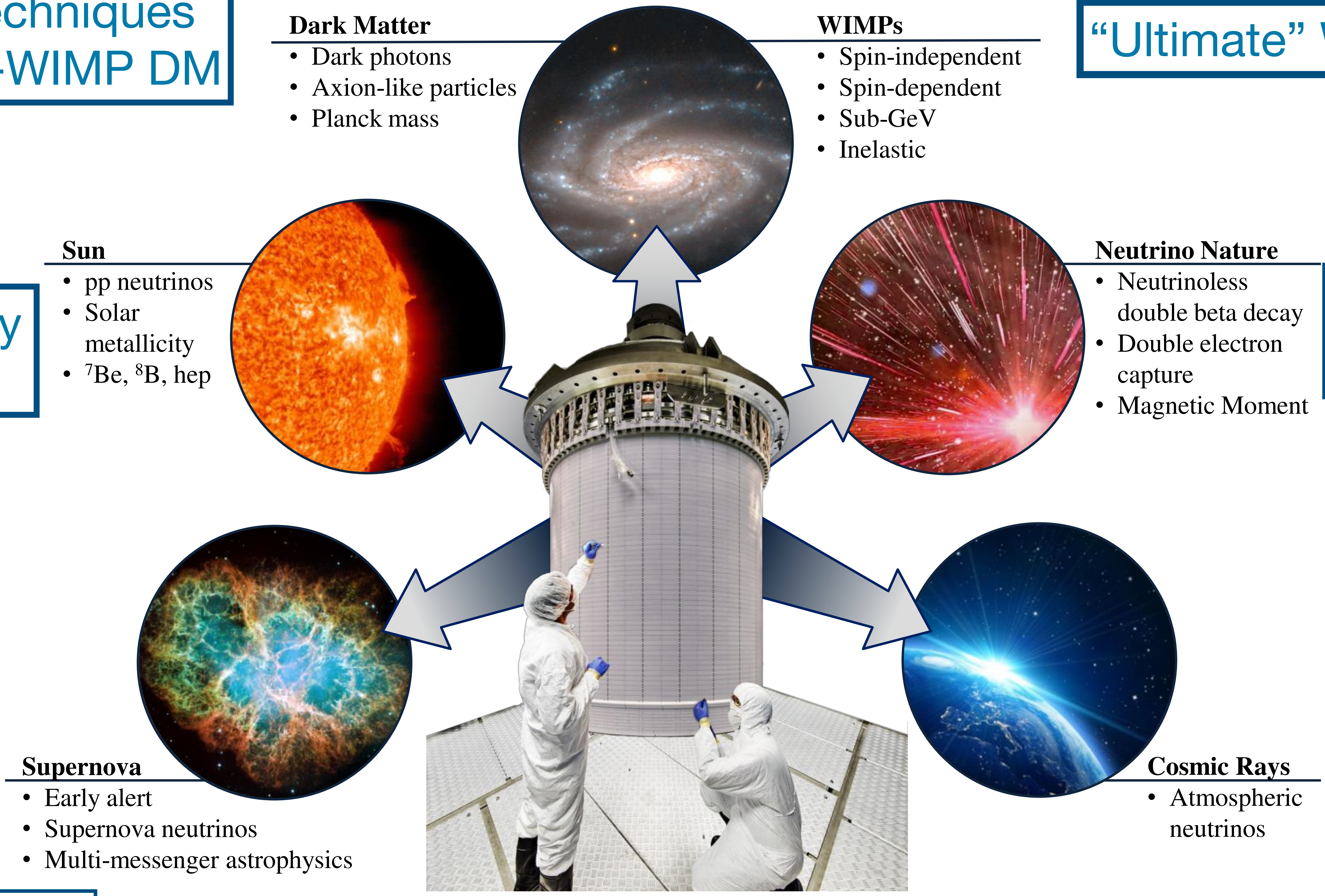
60t of LXe (+ reduce BG by ~10x)

Ultra-low BG + new techniques allow to search for non-WIMP DM

“Ultimate” WIMP DM detector

Low-E complementarity with DUNE

Competitive with dedicated 0v2b exp



Atmospheric E_ν < 100 MeV

Detailed measurements if/when galactic SN occurs

Large liquid xenon mass and ultra-low backgrounds expand number of available physics channels

White Paper: J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001, arXiv:2203.02309

XLZD Collaboration Formed

October-December 2024: Moved from a Consortium to Collaboration

450 collaborators and 72 institutions

XLZD XENON + + DARWIN

Institutional Board
Chair: Carter Hall (Maryland)
…

All of XENON and most of LZ

Co-spokespersons
Marc Schumann (Freiburg)
Dan Akerib (SLAC)

Executive Board
Patrick Decowski (Nikhef)
…

XLZD Management

WG1: Science
Co-lead: Tina Pollmann
…

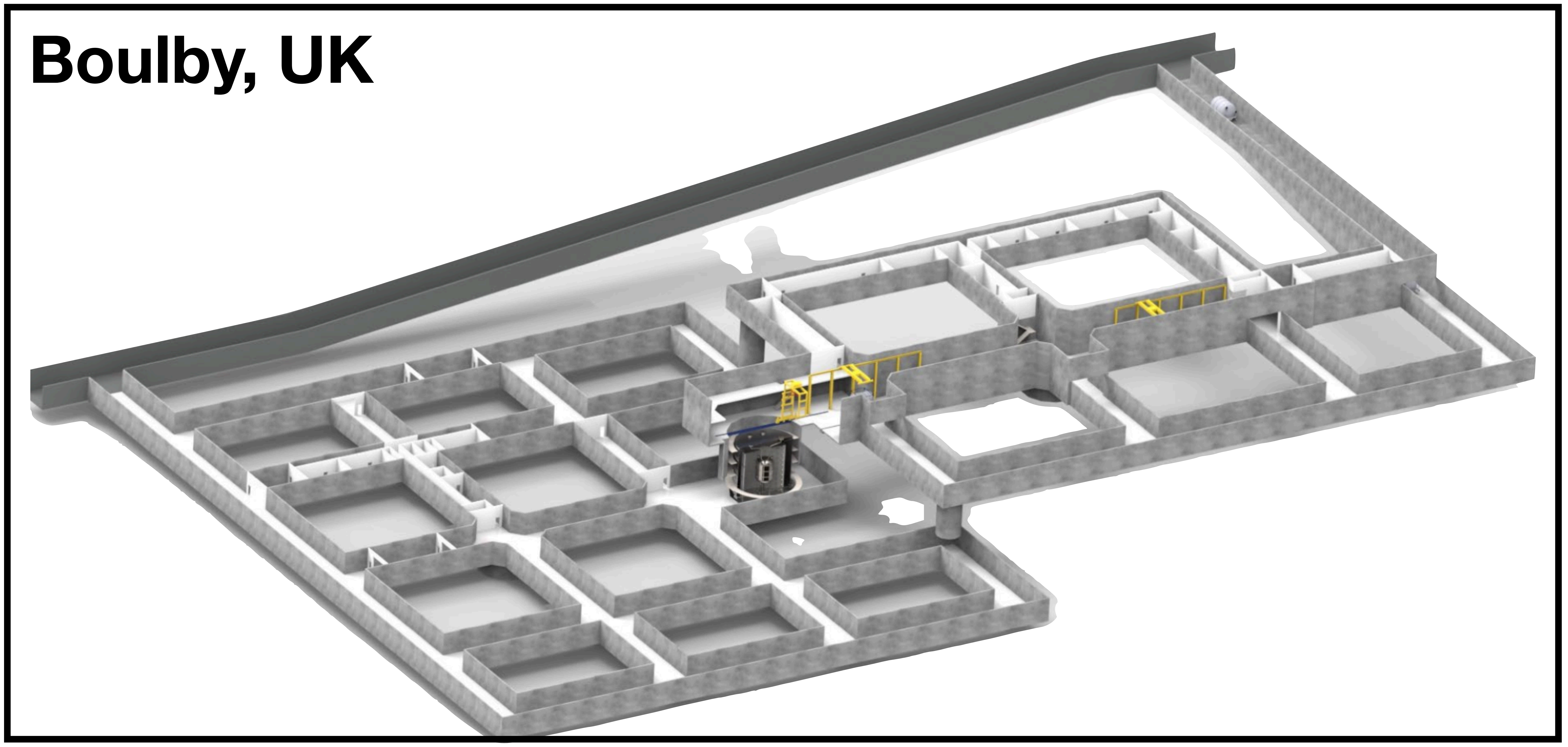
WG2: Detector Perf.
…

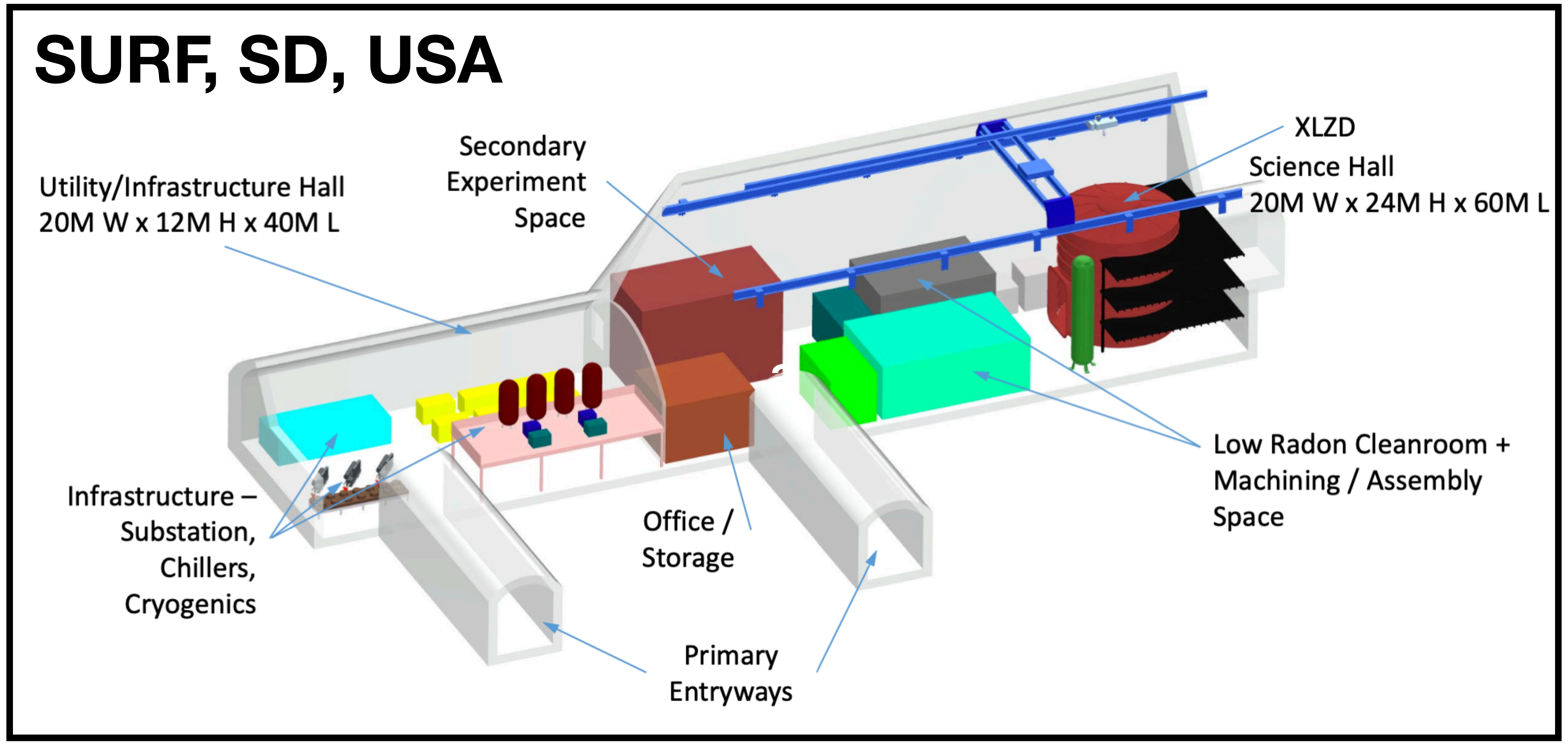
WG3/4: R&D
…

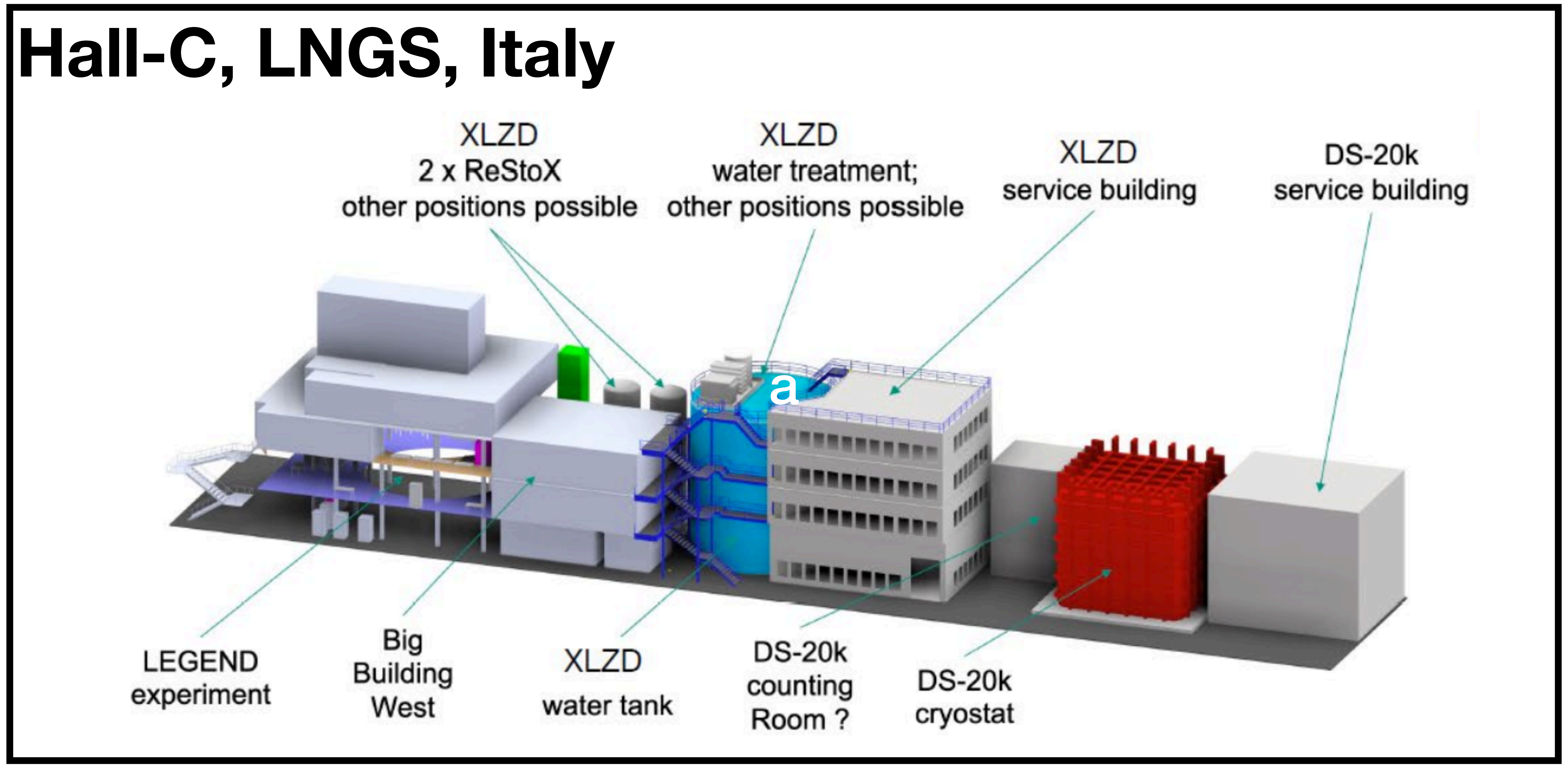
WG5: Siting
A.P. Colijn
…

Ambition is to build XLZD by 2031

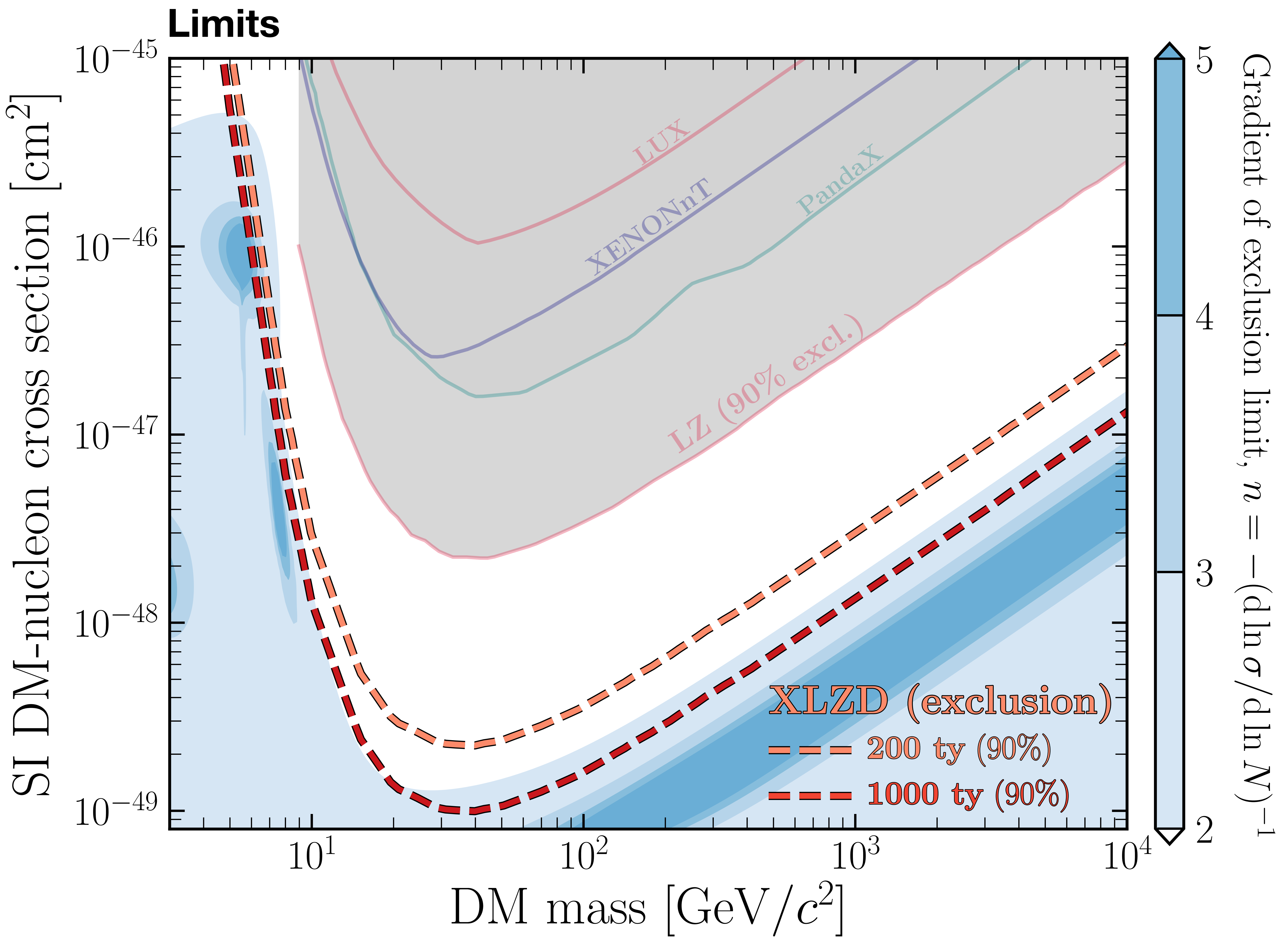
Three possible Sites

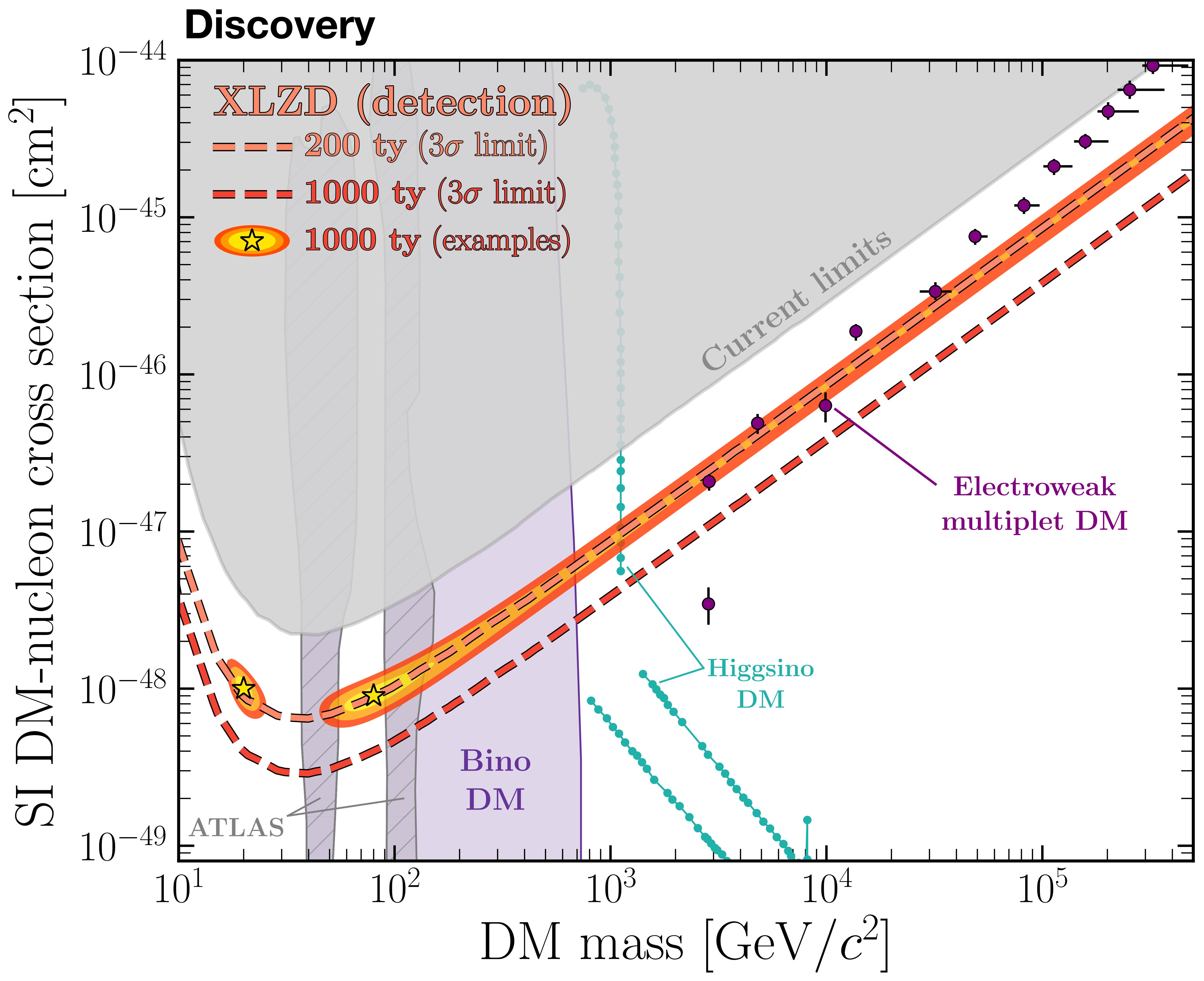






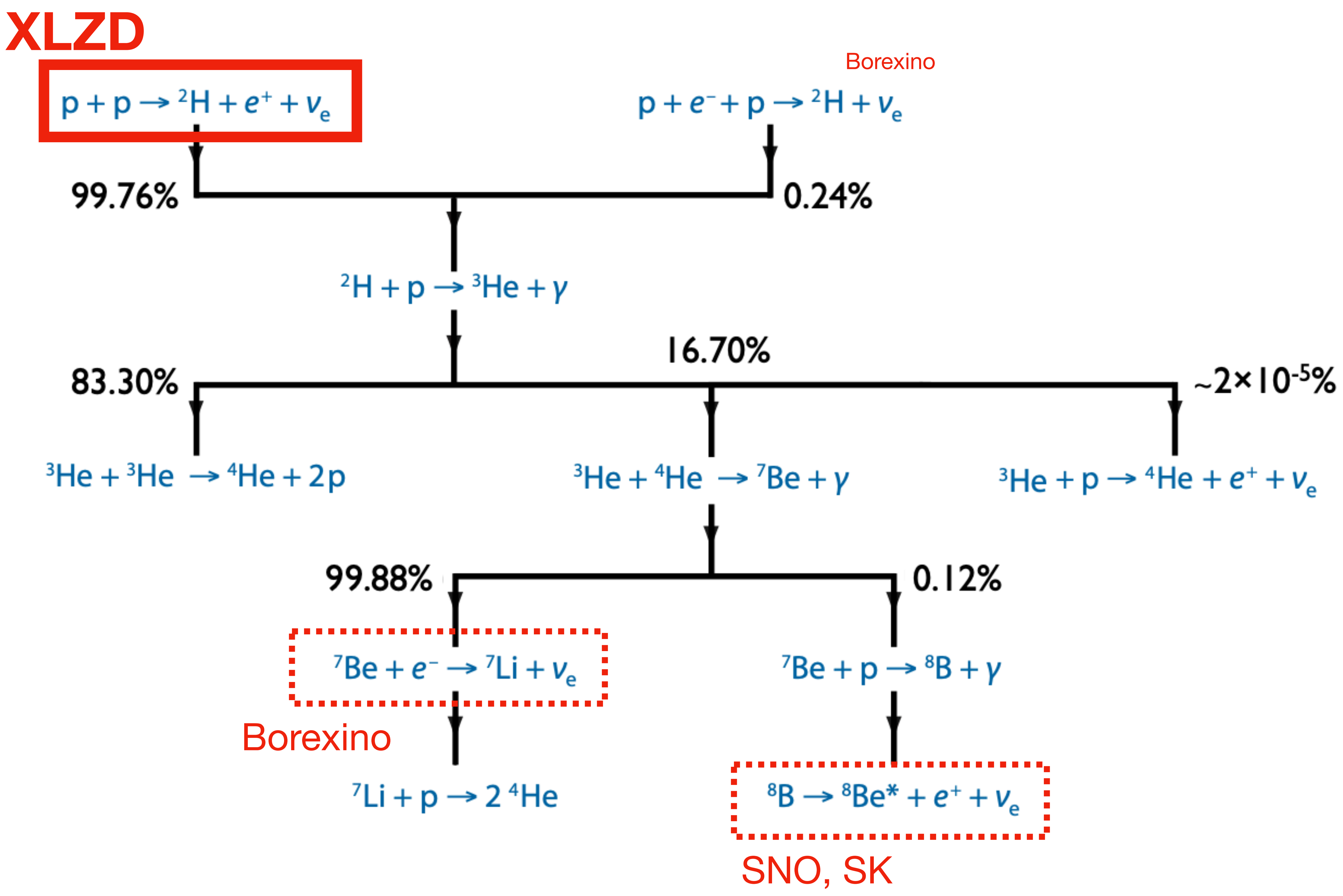
Reach of XLZD

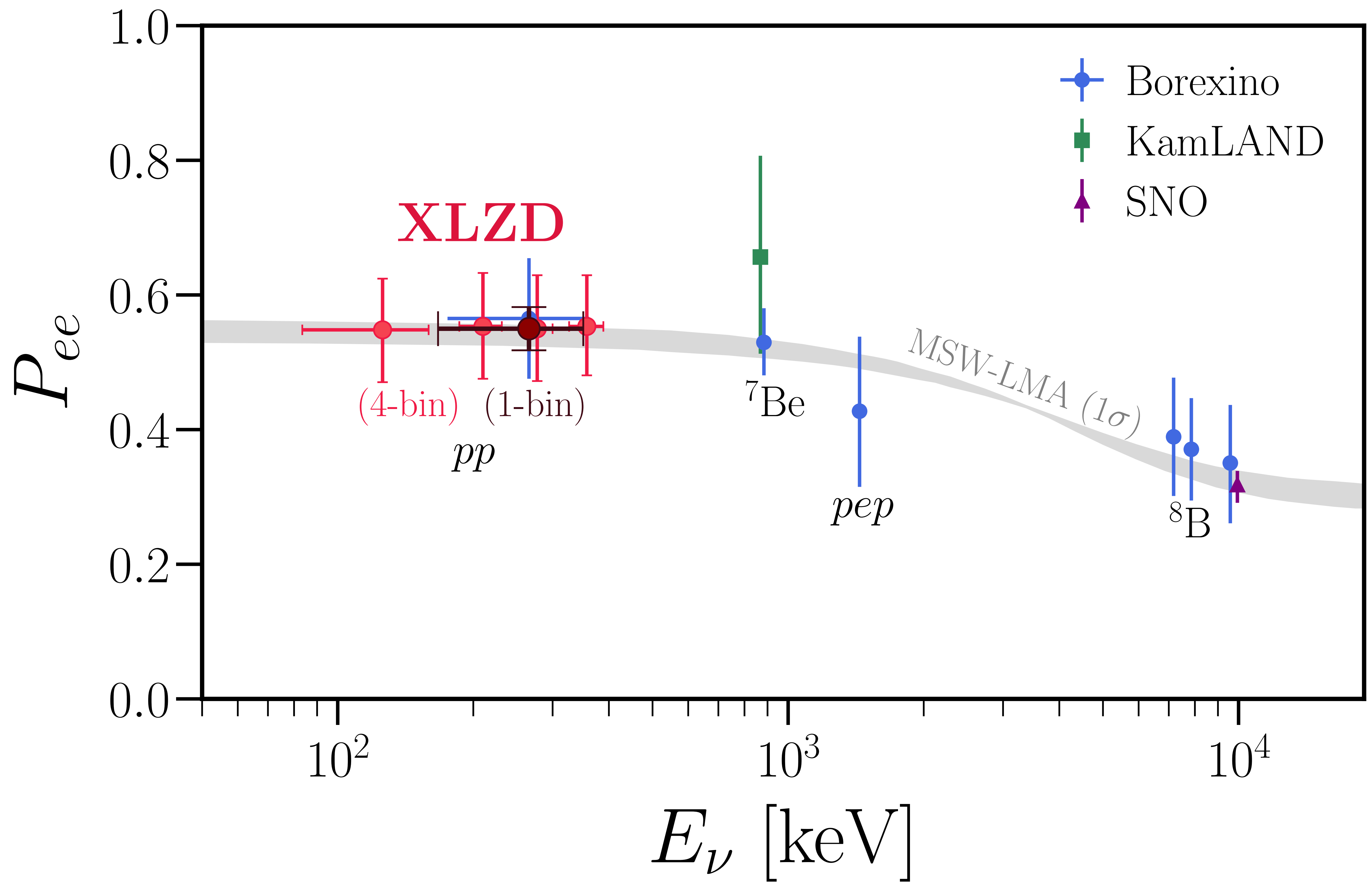




XLZD will cover ALL accessible WIMP parameter space above a few GeV mass

XLZD will measure Solar Neutrinos



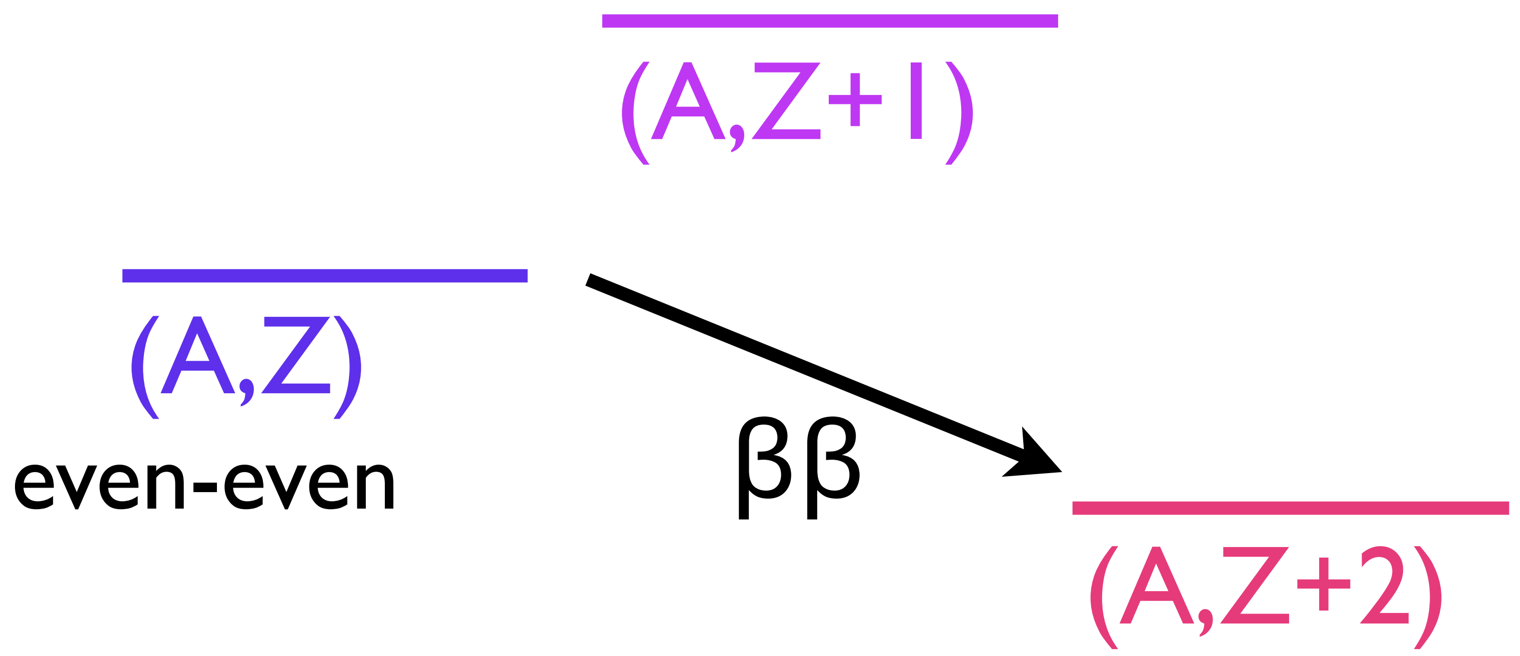


4% measurement of P_{ee}, testing LMA-MSW model

Neutrinoless Double Beta Decay

Double Beta Decay

^{136}Xe



A second-order process only detectable if first-order beta decay is energetically forbidden

Rare, but Standard Model Process:

$$2\nu 2\beta : (A, Z) \rightarrow (A, Z+2) + e^- + e^- + \overline{\nu}_e + \overline{\nu}_e$$

^{76}Ge

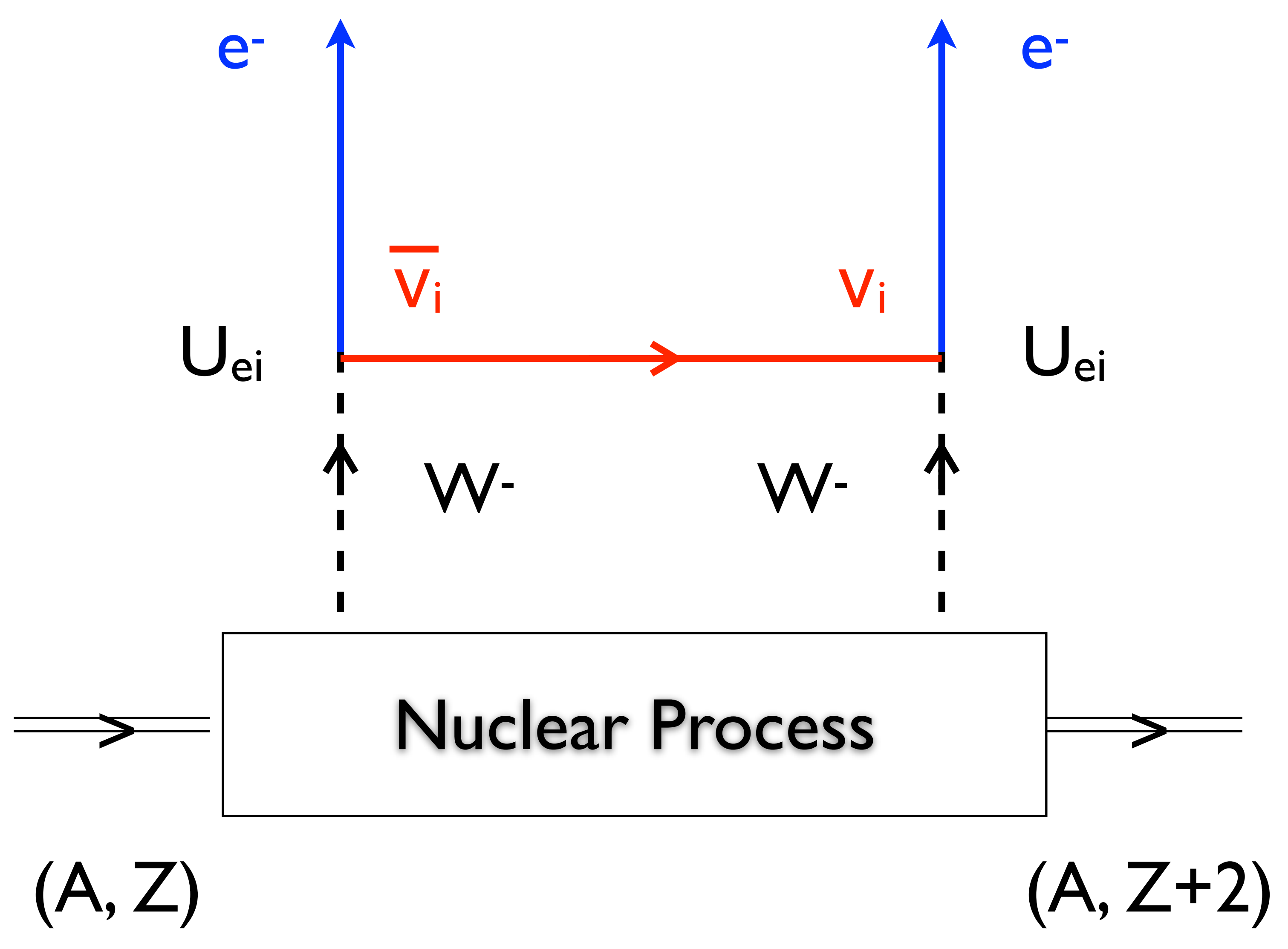
^{82}Se

^{100}Mo

^{130}Te

...

Neutrinoless Double Beta Decay



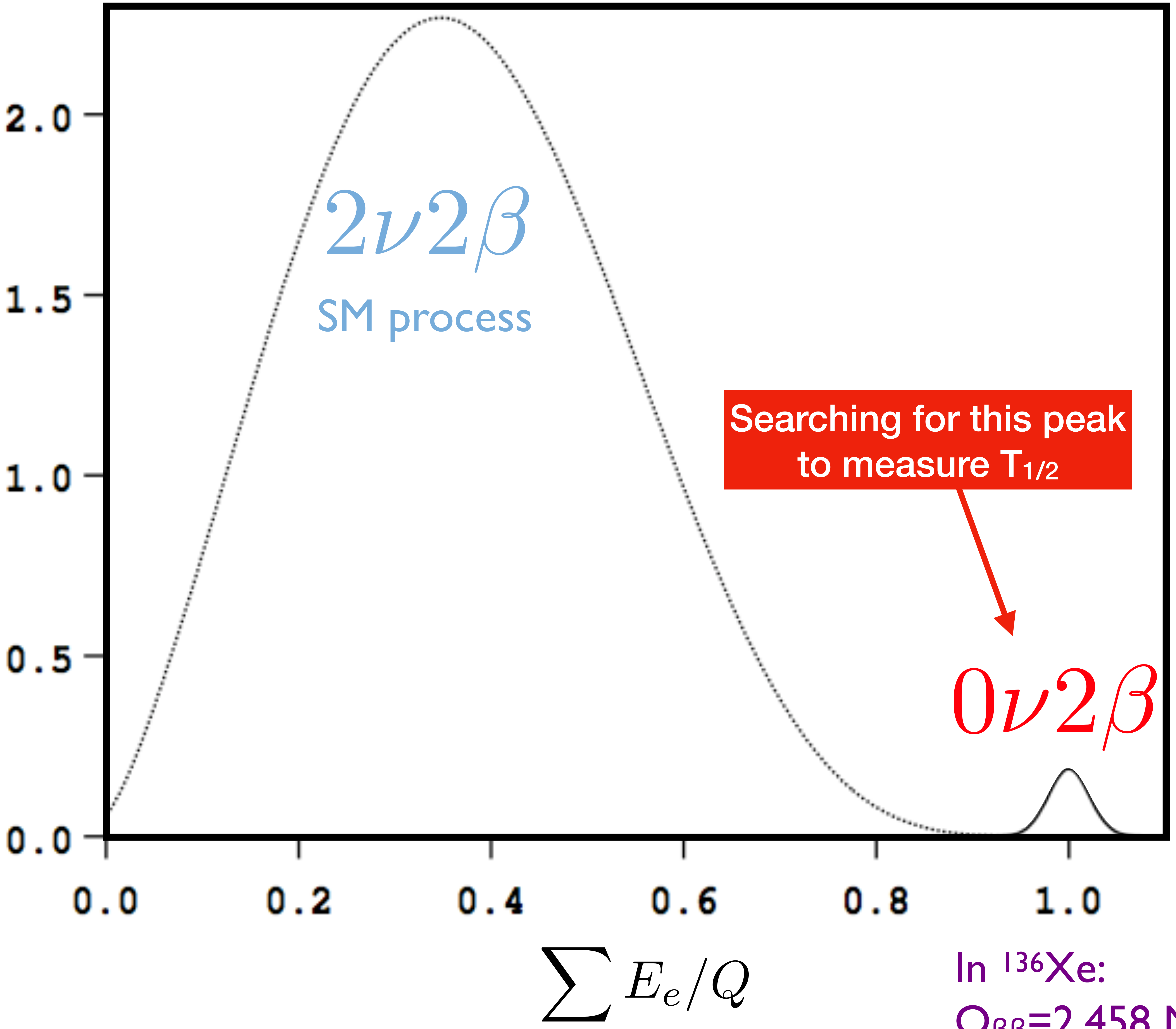
Is ν Majorana?

$$M_\nu \neq 0$$
$$|\Delta L| = 2$$

$$0\nu2\beta : (A, Z) \rightarrow (A, Z+2) + e^- + e^-$$

- Extremely rare radioactive process
- Requires massive Majorana neutrino
- Lepton Number Violation
  - Model dependent - Standard interpretation: light Majorana ν + SM interactions
- Measure of neutrino mass scale → effective Majorana mass $\langle m_{\beta\beta} \rangle$

Detecting 0ν2β Decay



In ^{136}Xe:
$Q_{\beta\beta}$=2.458 MeV

$$T^{0\nu}_{1/2} \propto \epsilon \frac{a}{A}\sqrt{\frac{Mt}{b\Delta E}}$$

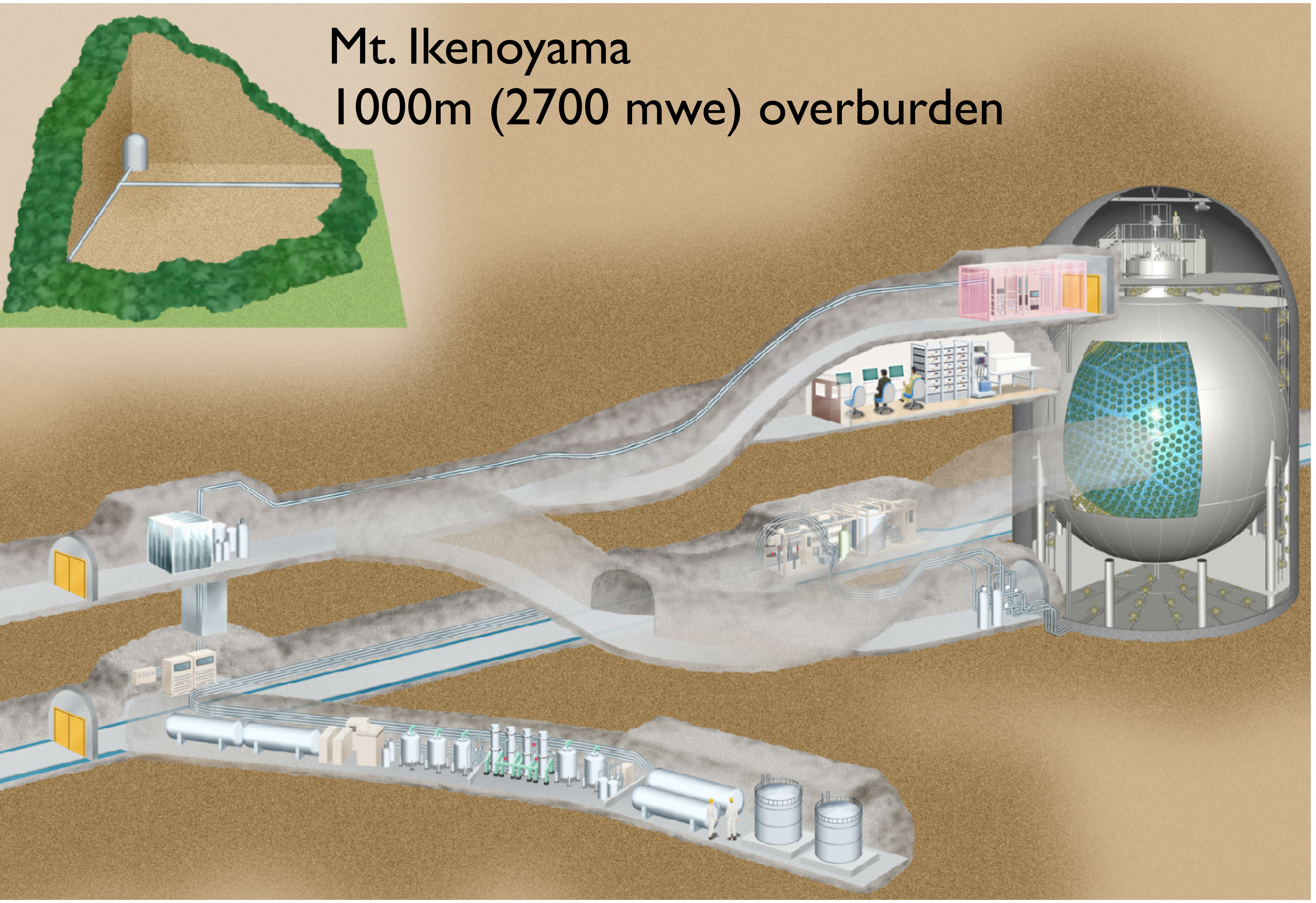
Detector Mass, Exposure, BG and Energy Resolution

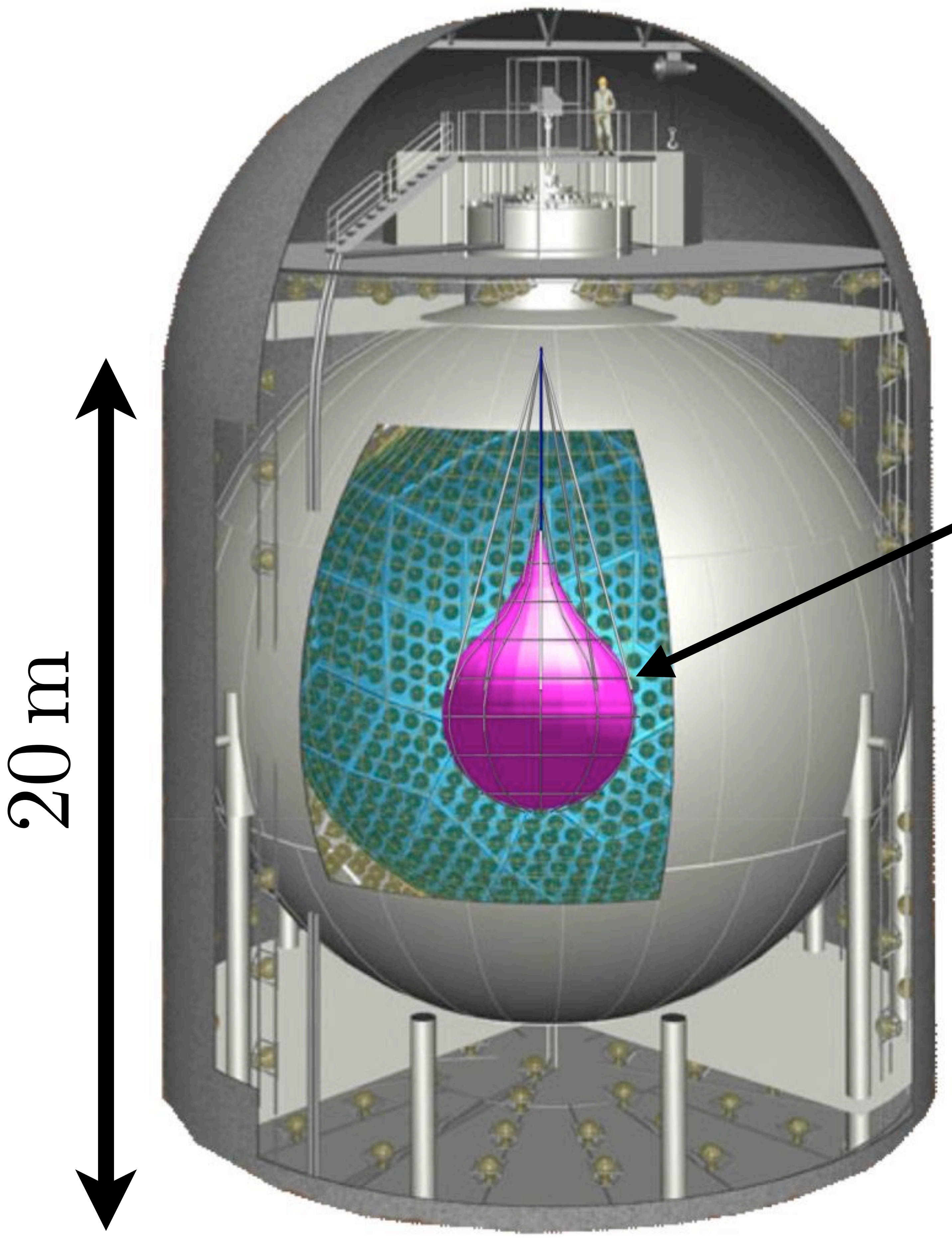
Half-life relates to $\langle m_{\beta\beta}\rangle$

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Phase Space and Nuclear Matrix Elements from Theory

KamLAND-Zen at Kamioka in Japan





745 kg of ^{136}Xe dissolved in Liquid Scintillator

New results with KamLAND-Zen 800 data recorded from Jan 2019 to Jan 2024:
Exposure of 2.1 ton-years → largest ever

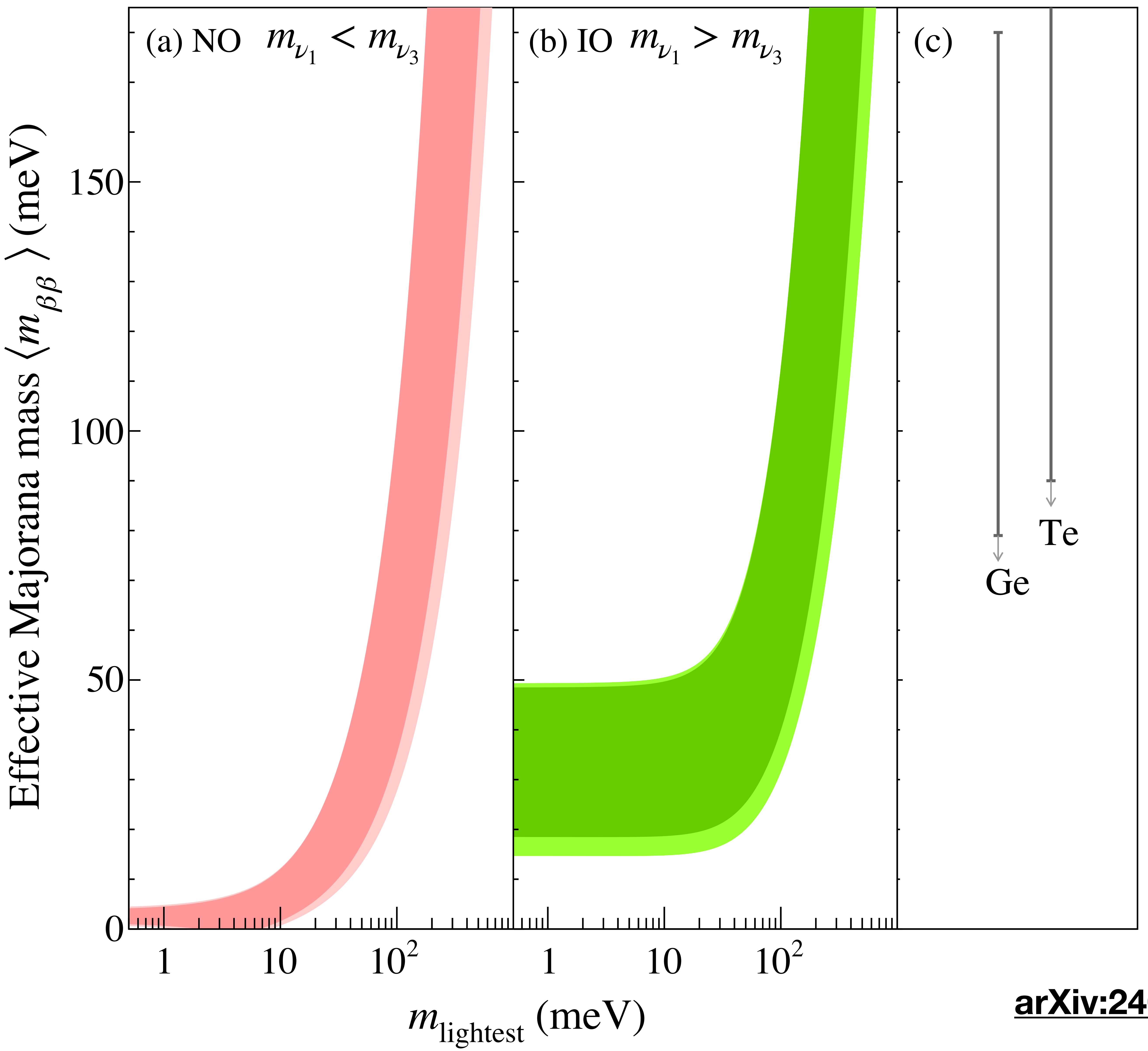
arXiv:2406.11438

Effective Majorana Mass

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

$T_{1/2} > 3.8 \times 10^{26}$ yr

Exp. $\langle m_{\beta\beta}\rangle$ limits



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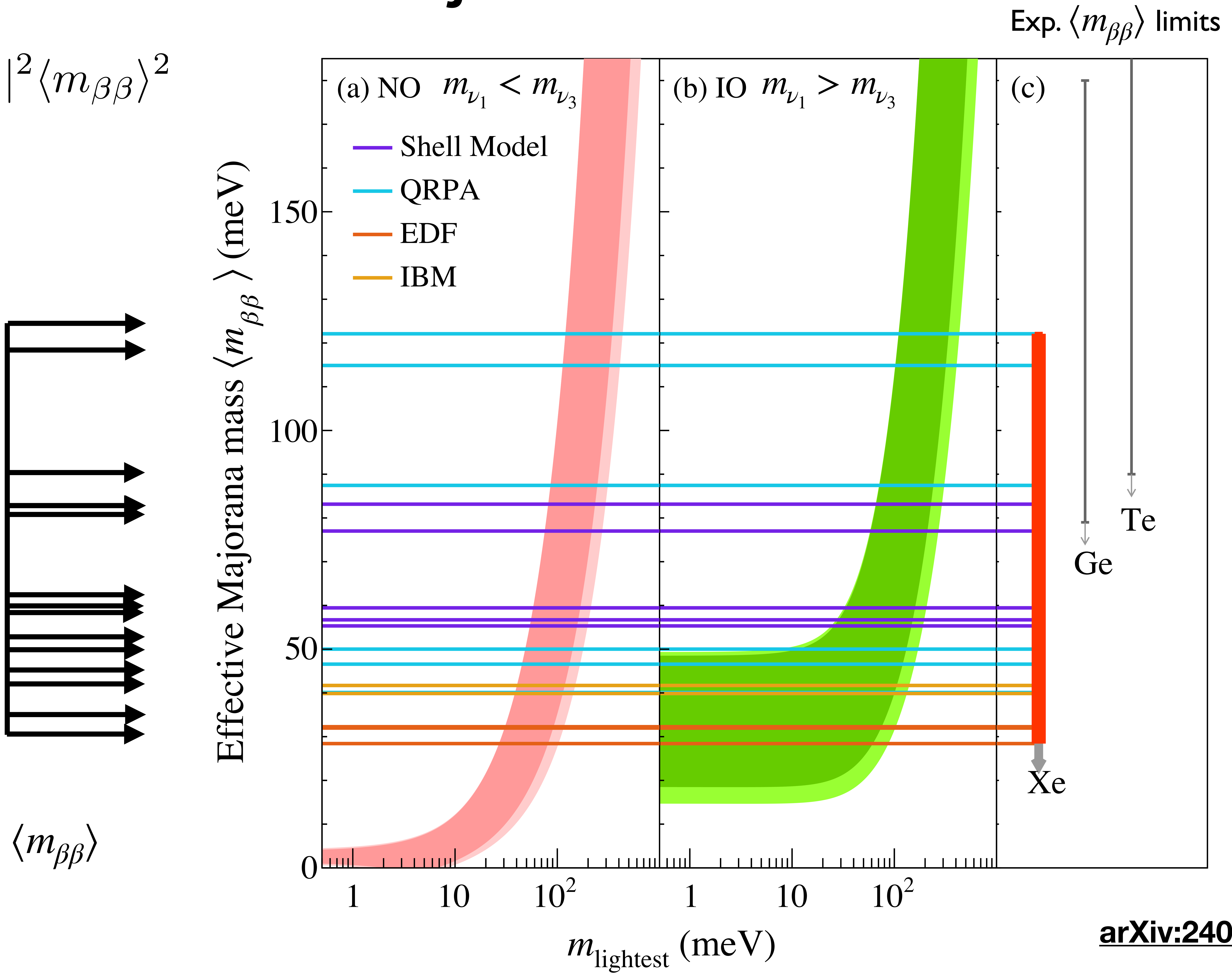
$\langle m_{\beta\beta}\rangle$ excl. limit depends on Nuclear Matrix Elements



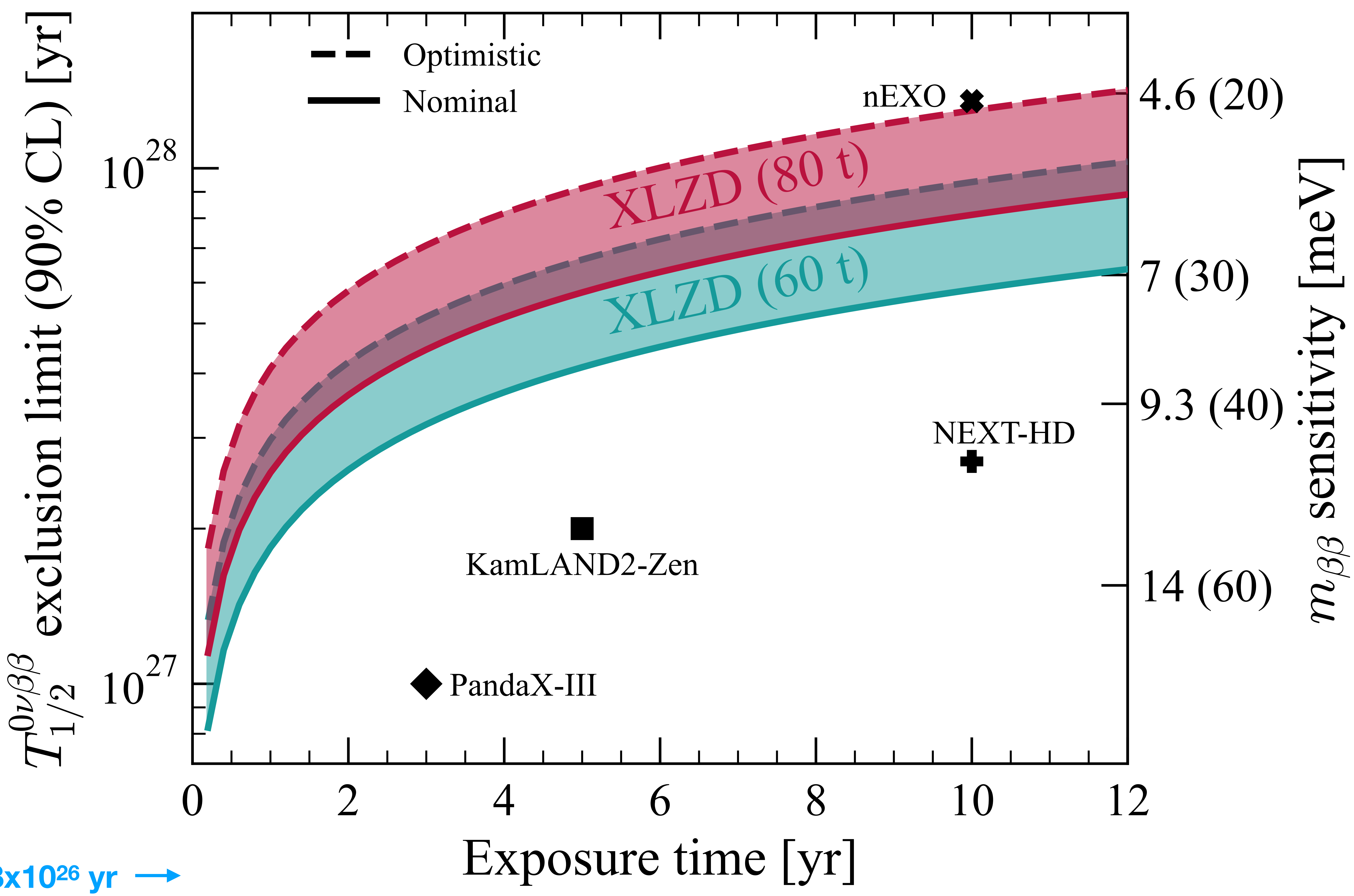
Most stringent limit on $\langle m_{\beta\beta}\rangle$

For some NMEs we probe Inverted Ordering ν-mass

arXiv:2406.11438

XLZD will also be a 0v2β detector!

60t natural Xe @ 8.9% ^{136}Xe n.a. → 5.3 t of ^{136}Xe
[this is not possible with an Ar detector!]



KLZ limit 3.8x10^{26} yr →

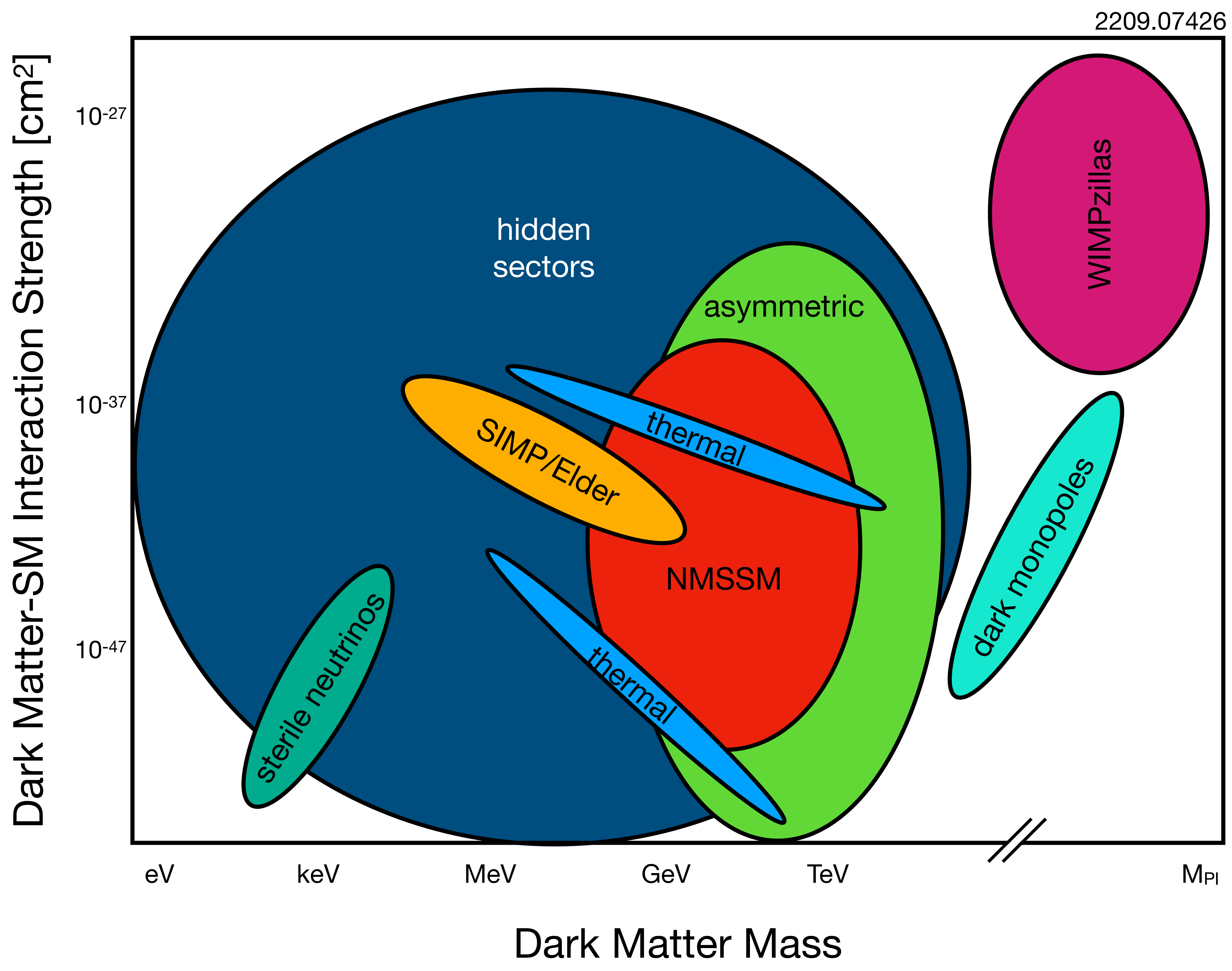
Conclusions

- A number of astroparticle and non-accelerator experiments will target important beyond the standard model questions
- Many small-scale axion experiments
- Neutrinoless double-beta decay experiments: KamLAND2-Zen, LEGEND, CUPID etc.
- XLZD Observatory (~2031) will be
  - "Ultimate" WIMP DM experiment
  - Competitive neutrinoless double-beta decay experiment
  - Solar neutrino physics, Supernovae, …

Sentence

“The European Particle Physics Strategy Update and CERN should embrace a diverse portfolio including astroparticle and non-accelerators experiments to study elementary particles over a broad range of distance scales and energies.”

Cartoon of Models



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Cartoon of Models