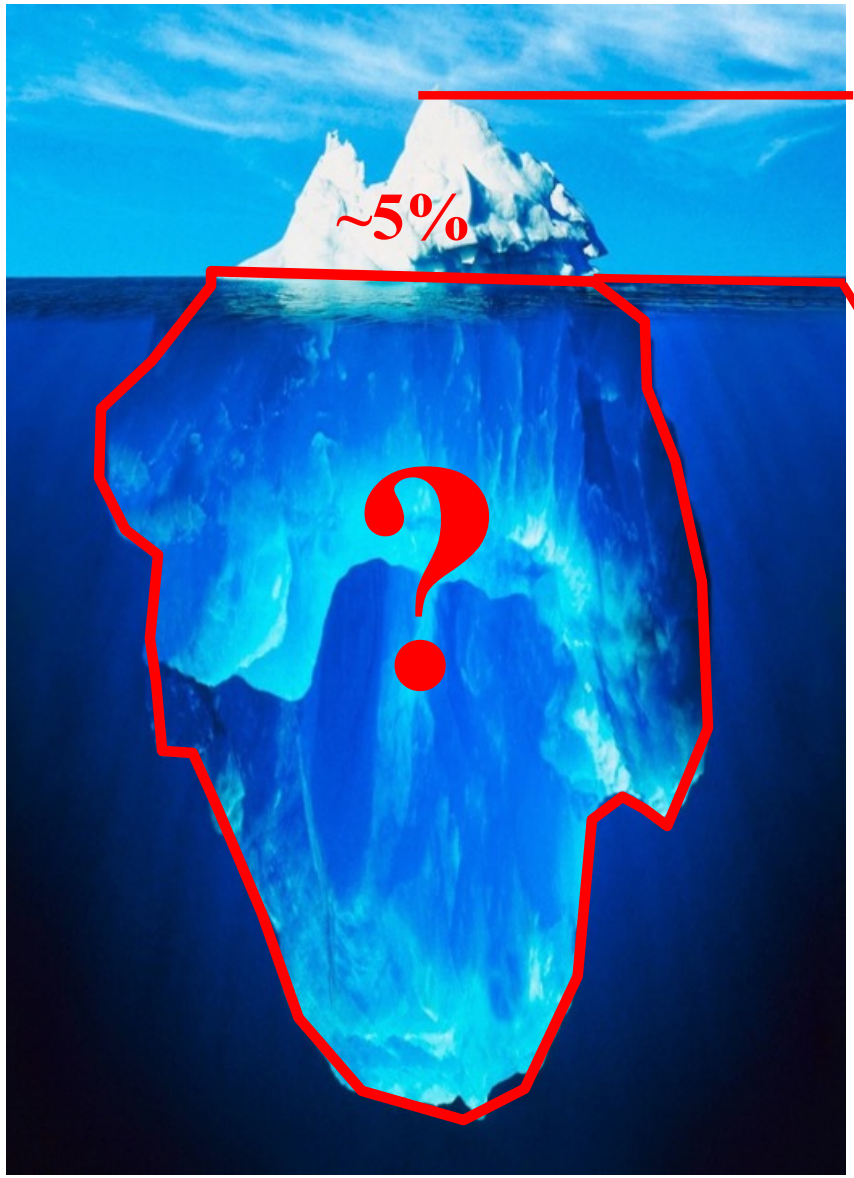
Dark Matter

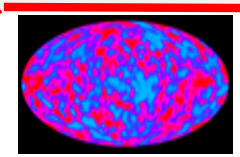
KAT Community Meeting - Karlsruhe, Oct. 16-18, 2024

Astroparticle Physics in Germany – Long-Term Strategy 2024

DM@KAT: Manfred Lindner, Federica Petricca

The Science Case





radiation: 0.005%

chemical elements:
(not H & He) 0.025%

stars:0.8%

H &He: gas 4%

neutrinos = CνB: 0.17%

black holes: PBH or LBH

dark matter: 26.8%

dark energy: 68.3%

Gravity

Modified GR

MOND
simple one scale modification
→ fails...

Other
is the EP fundamental or effective?

BHs

today's BHs

a suitable population (mass, number) of primordial black holes

Particles

BSM physics motivated
↔ SM problems

- neutrinos
- WIMPs:
  ...neutralino
  ...other
- axions
- sterile ν's
- ...

Models with correct abundance

- WIMPs
- dark photons
- ALPs
- other new particles

thermal production (WIMP miracle, ...)
non-thermal (decay, out-of-equilibrium, ...)

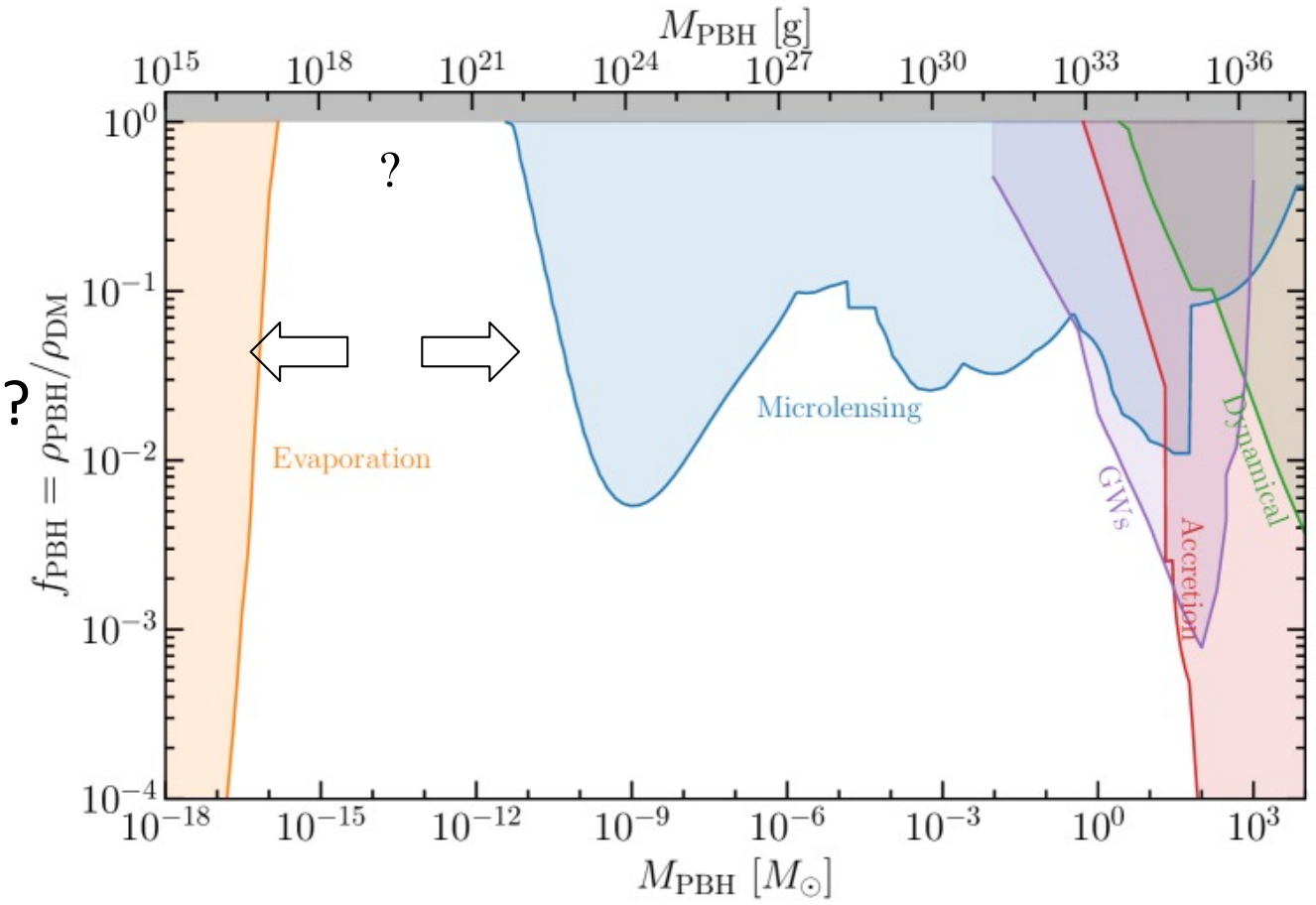
→ theory: both phenomenological & formal
i) potential solutions ii) preferred candidates iii) exclusions

Primordial Black Holes as a Dark Matter

PBH's can form in the early Universe
collapse of large density perturbations during radiation domination
small PBHs evaporate
bigger PBHs accrete

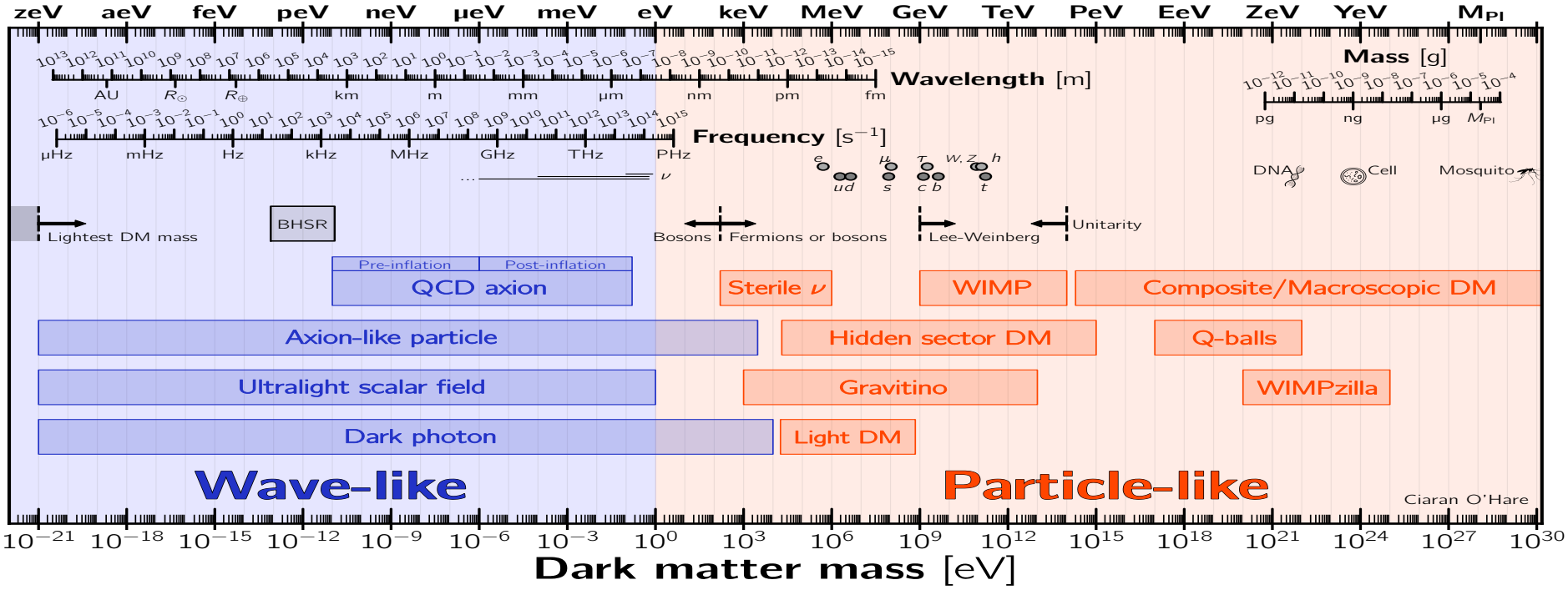
➔ which masses?
➔ evolution
➔ under/over density?

➔ constraints
➔ could all be PBH?



Green, arXiv:2402.15211

Particle Dark Matter



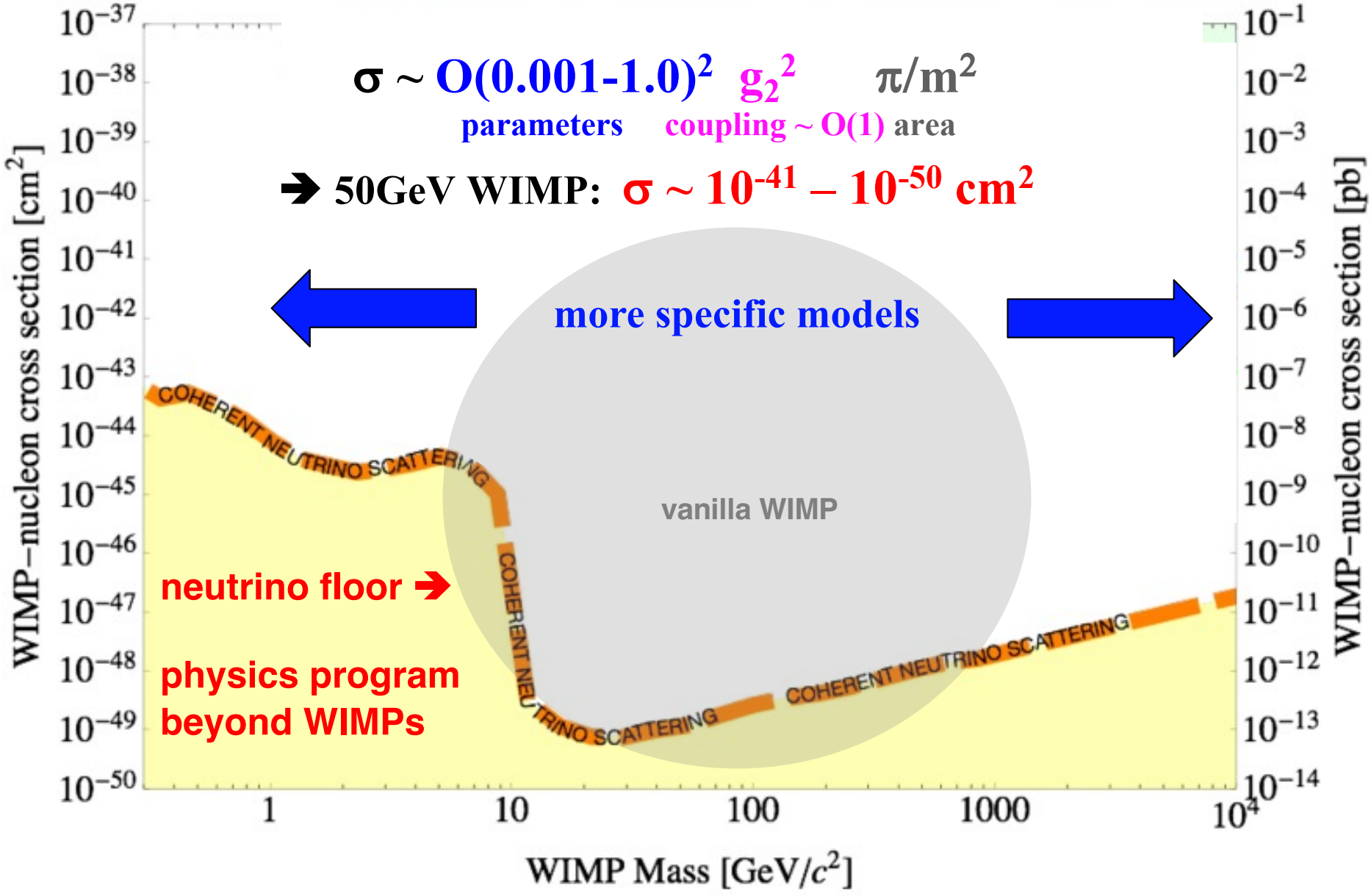
- many candidates, 51 orders of magnitude, one or a cocktail? ➔ **what to look for?**

→ motivated by other facts / problems: WIMPs, axions, sterile neutrinos

→ theoretical beauty... , your personal preference...

Vanilla WIMP Territory

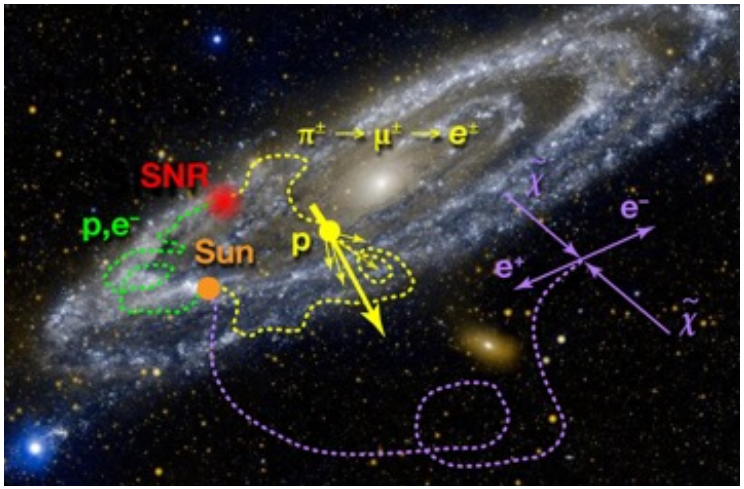
"size" of a particle: $\pi\lambda^2 = \pi/m^2$ ➔ σ = area ✖ coupling



(Heavy) Particle-Like DM Hunting

known Standard Model (SM) particles interact with WIMPs: assumptions…

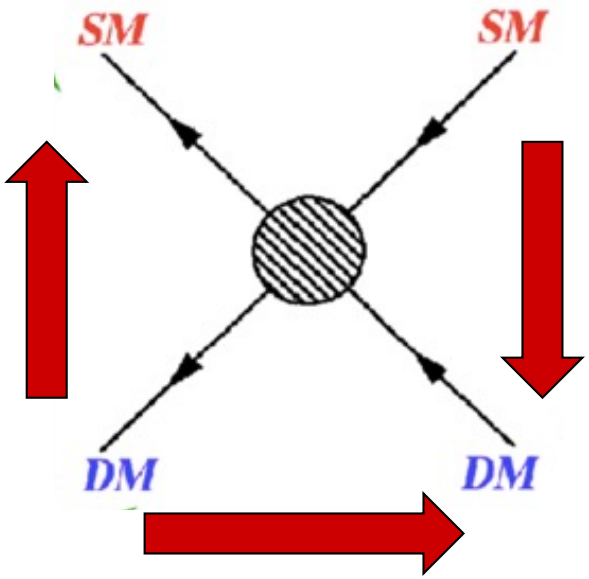
indirect detection



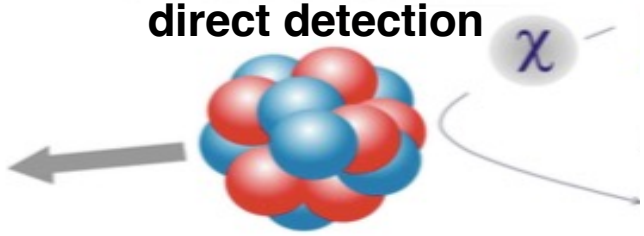
FERMI, PAMELA, AMS, HESS, IceCube, CTA, HAWC…

astronnomical uncertainties...

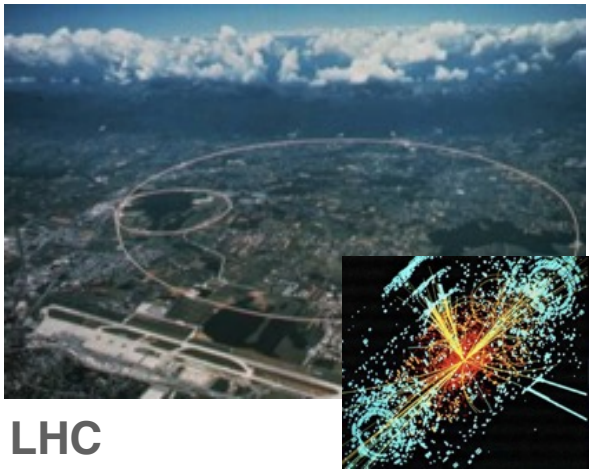
→ signal without doubt DM?



direct detection



colliders



LHC

may detect new particles, but is it DM (lifetime, abundance)?

So far nothing seen…

- → SUSY & higher scale
- → other SB motivated WIMPs
- → new ideas/candidates

WIMP wind : ~232km/s from Cygnus

- → modelling
- → rare event backgrounds

→ direct detection!

Dark Matter: Research Fields & Funding

KAT. Komitee für Astro. Teilchen. Physik

KET Komitee für Elementarteilchenphysik

R D S

KAT constituencies:
Theory
Neutrino properties
Low energy neutrino astrophysics
Cosmic rays
Gamma astronomy
High energy neutrino astrophysics
Gravitational waves
Nuclear astrophysics
Dark Matter

KHUK

+international partners...

Bundesministerium für Bildung und Forschung

Länder

HELMHOLTZ GEMEINSCHAFT

MAX PLANCK GESELLSCHAFT

erc

Particle Dark Matter @Germany

Axion experiments
➔ particle physics

KET Komitee für Elementarteilchenphysik

- **MadMax**
  MPP, DESY, MPIfR, RWTH Aachen, Hamburg, Tübingen
- **ALPSII**
  DESY, Mainz, Hannover, Hamburg
- **(Baby) IAXO**
  DESY, Heidelberg, Siegen, Bonn, Mainz, Hamburg, MPP

This meeting:

KAT. Komitee für Astro. Teilchen. Physik

- **COSINUS** test DAMA/Libra claim → MPP
- **DeLight**
- **CRESST**
- **XENON**
- **future: DARWIN → XLZD**

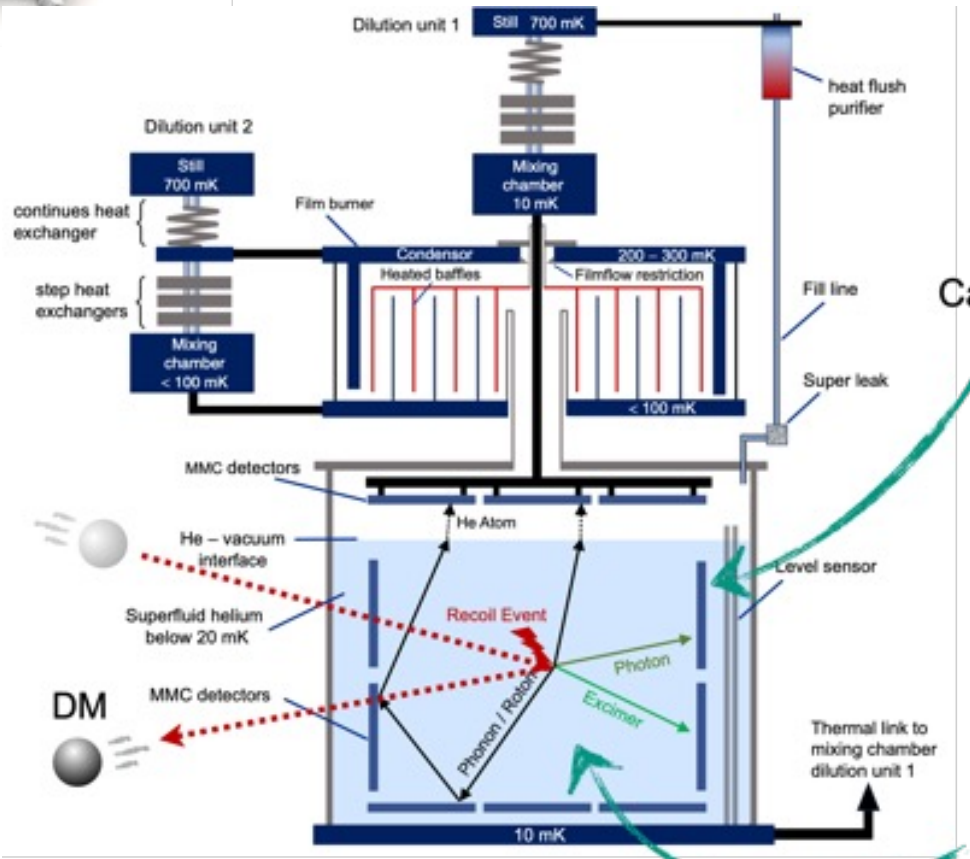
light DM ⇕ heavy DM

DELight

KIT
Karlsruhe Institute of Technology

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

universität freiburg

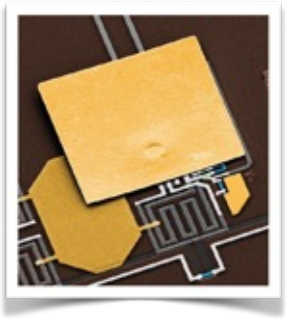


Ultra-sensitive heat/energy sensors

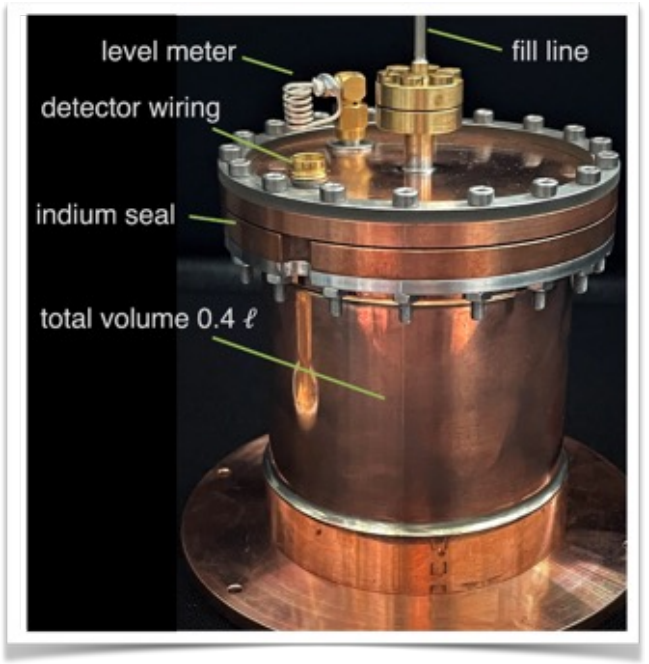
(Magnetic Micro-Calorimeters: MMCs)

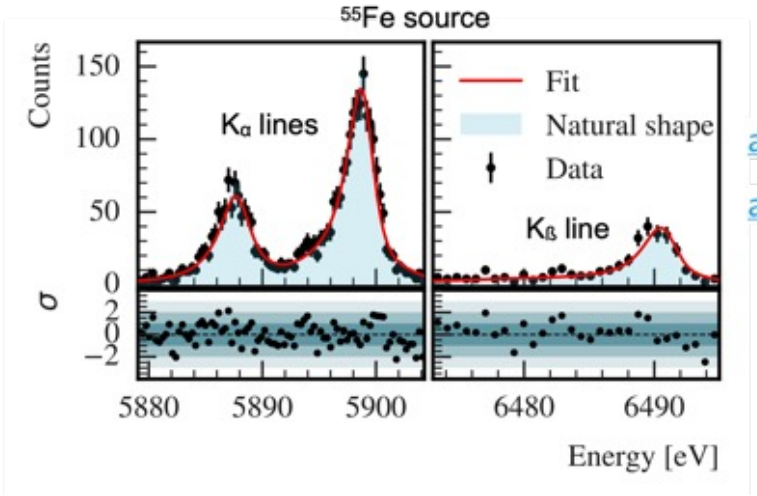
Superfluid ^{4}He

(~ 10 liters in phase-I)



R&D and design ongoing
- DELight v0 cell
- existing MMCs as test-bed

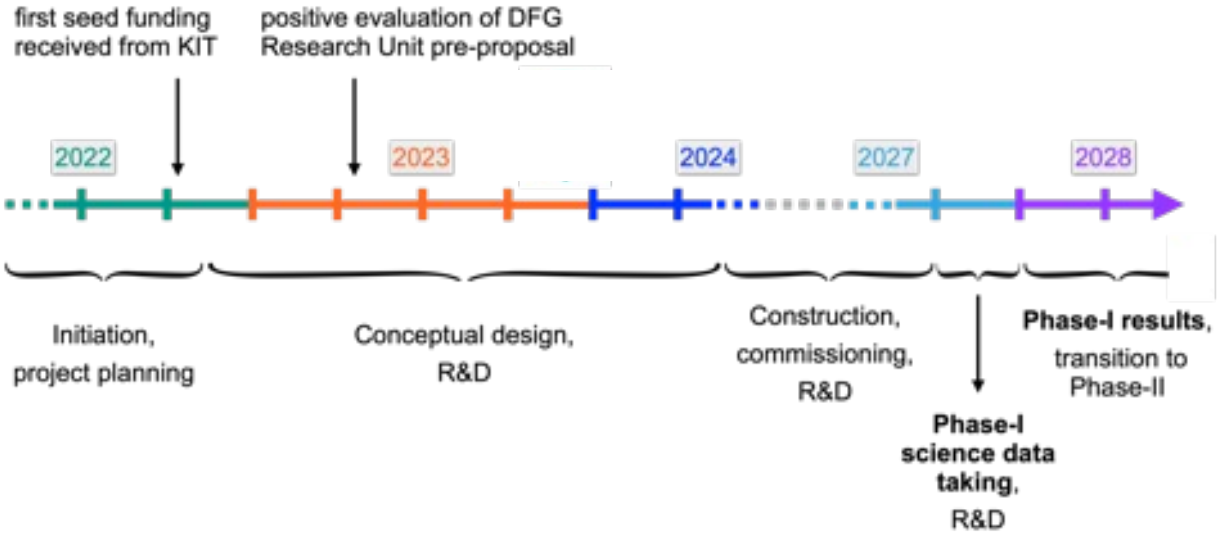


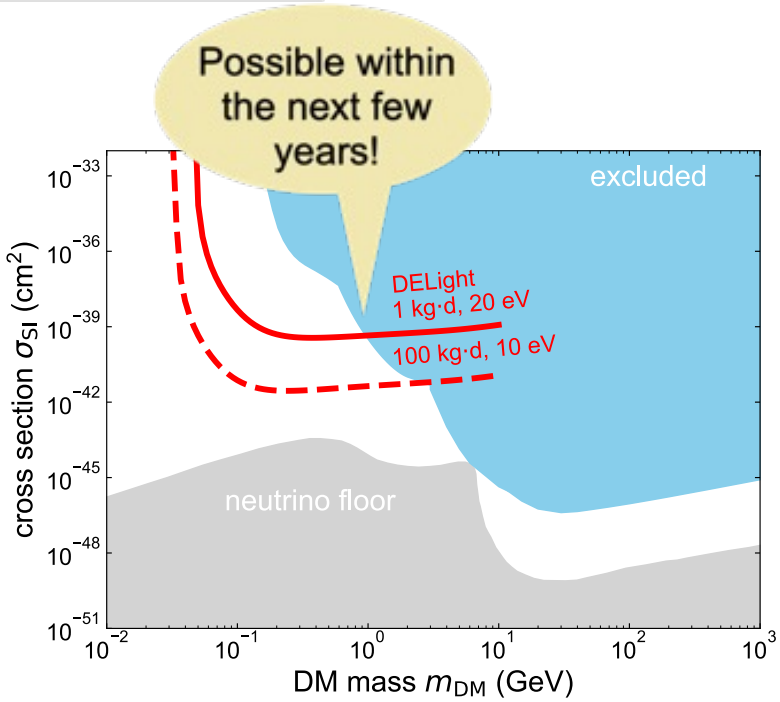


arXiv:2310.08698

arXiv:2310.08512

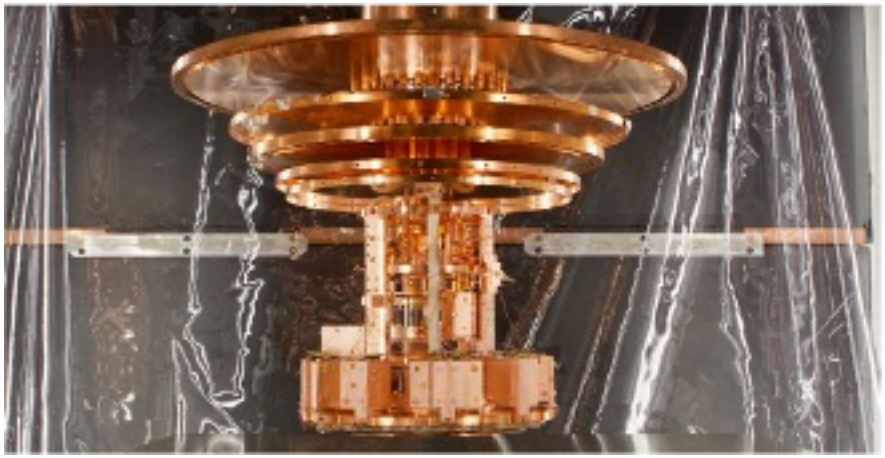
$$\Delta E_{FWHM} = \left(1.25 \pm 0.17_{(stat)}{}^{+0.05}_{-0.07\,(syst)}\right)\ eV$$





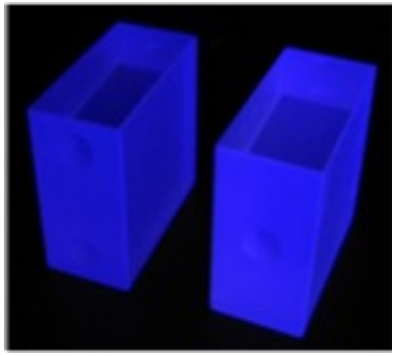
CRESST

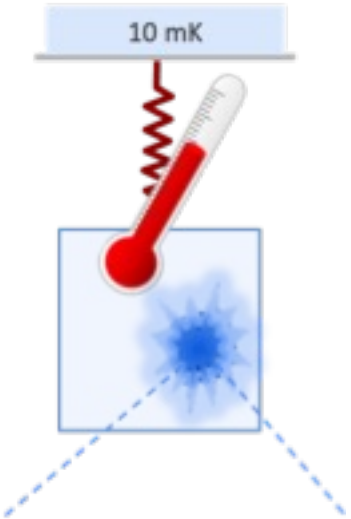
Cryogenic Rare Event Search with Superconducting Thermometers



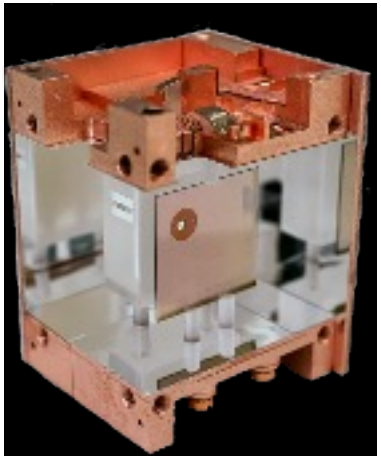
Science goal:
Direct detection of low mass dark matter (complementary to XENON)

Technical realization
Cryogenic *O*(10mk) calorimeters
Quantum-enabled Transition Edge Sensors for temperature read-out



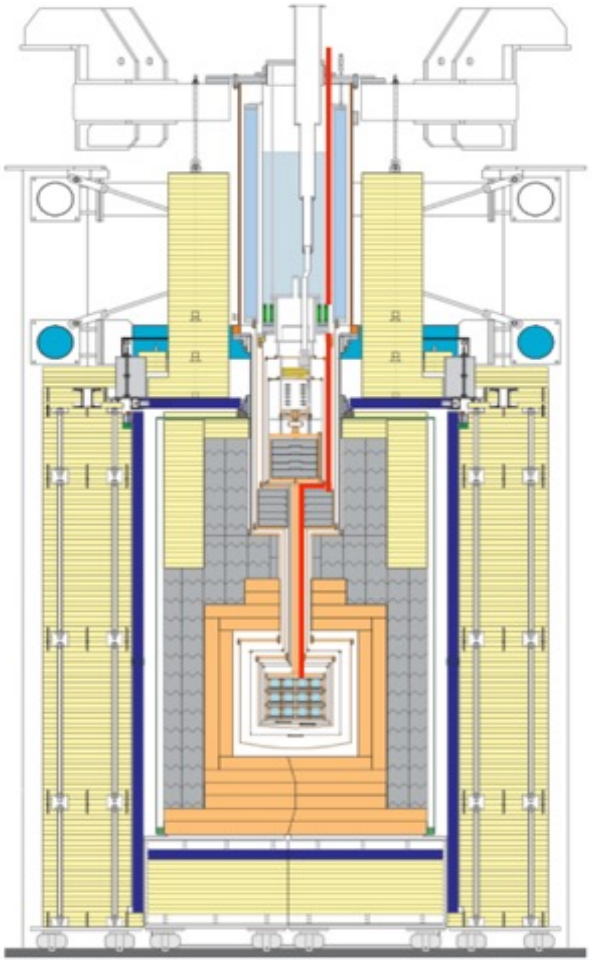


Highlights:
World-leading limits on low-mass dark matter
Lowest nuclear recoil thresholds



Strong German involvement:
MPP, TUM, Tübingen, Uni Heidelberg
Spokesperson: F. Petricca (MPP)

CRESST Timeline



CRESST sensitivity upgrade program:

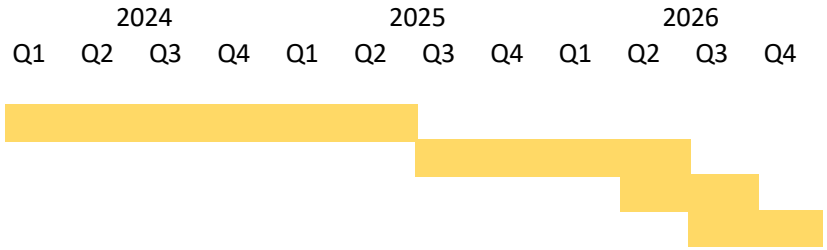
- Performance improvement (lower threshold): done
- Background reduction: ongoing
- Exposure increase: to be completed

New readout chain (288 channels) already funded by agencies and procured
New readout electronics being produced
Installation planned after the end of ongoing data-taking

→ compensate ageing of current readout that limits the number of useable channels

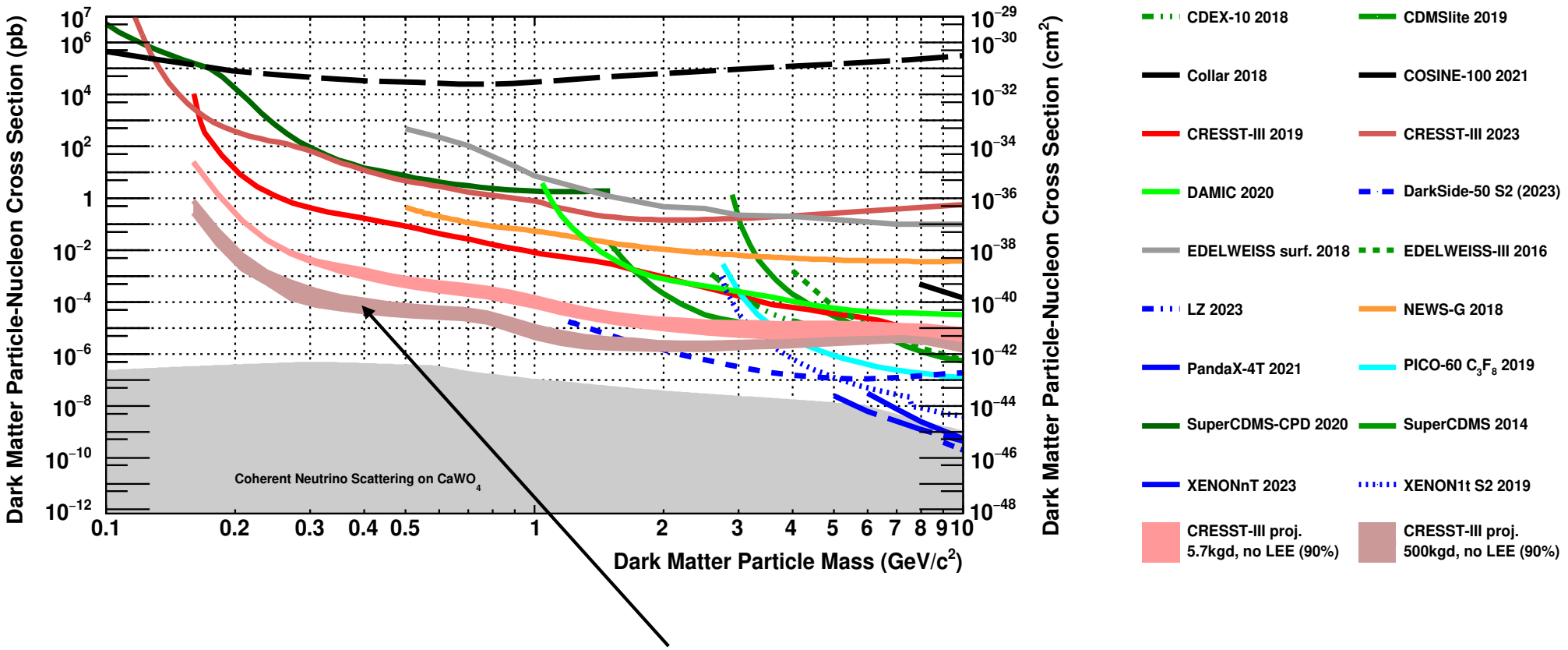
- Improving test capabilities
- increase reachable exposure

CRESST experiment @ LNGS
Run37
Upgrade
Testing / commissioning cryostat
Commissioning new detectors



2024	2025	2026	2027	2028	2029	2030
data taking		setup upgrade	data taking			

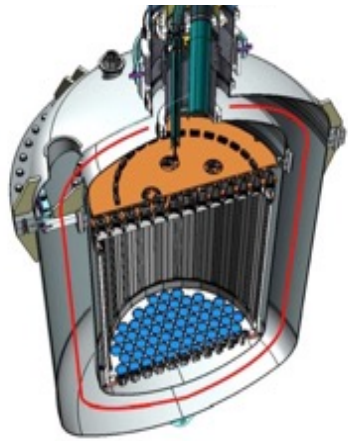
CRESST Sensitivity



~ 2 years of data taking in upgraded setup

The XENON Dark Matter Program

The XENON program at Gran Sasso, Italy (3600 mwe)

	XENON10	XENON100	XENON1T & XENONnT	
				
Period	**2005-2007**	**2008-2016**	**2012-2018**	**2019-202n**
Total (active) mass	25 kg (14kg)	161 kg (62 kg)	3200 kg (2t)	~8600 kg (5.9t)
Drift length	15 cm	30 cm	100 cm	150 cm
Status	Completed (2007)	Completed (2016)	Completed (2019)	Running
σ_{SI} limit (@50 GeV/c²)	8.8×10^{-44} cm²	1.1×10^{-45} cm²	1.6×10^{-47} cm²	$\sim 10^{-48}$ cm²
BG level	600 [t d keV]-1	5.3 [t d keV]-1	0.2 [t d keV]-1	0.04 [t d keV]-1

200+ members, 29 institutes, 12 countries

Very strong roles ←→ essential German contributions:

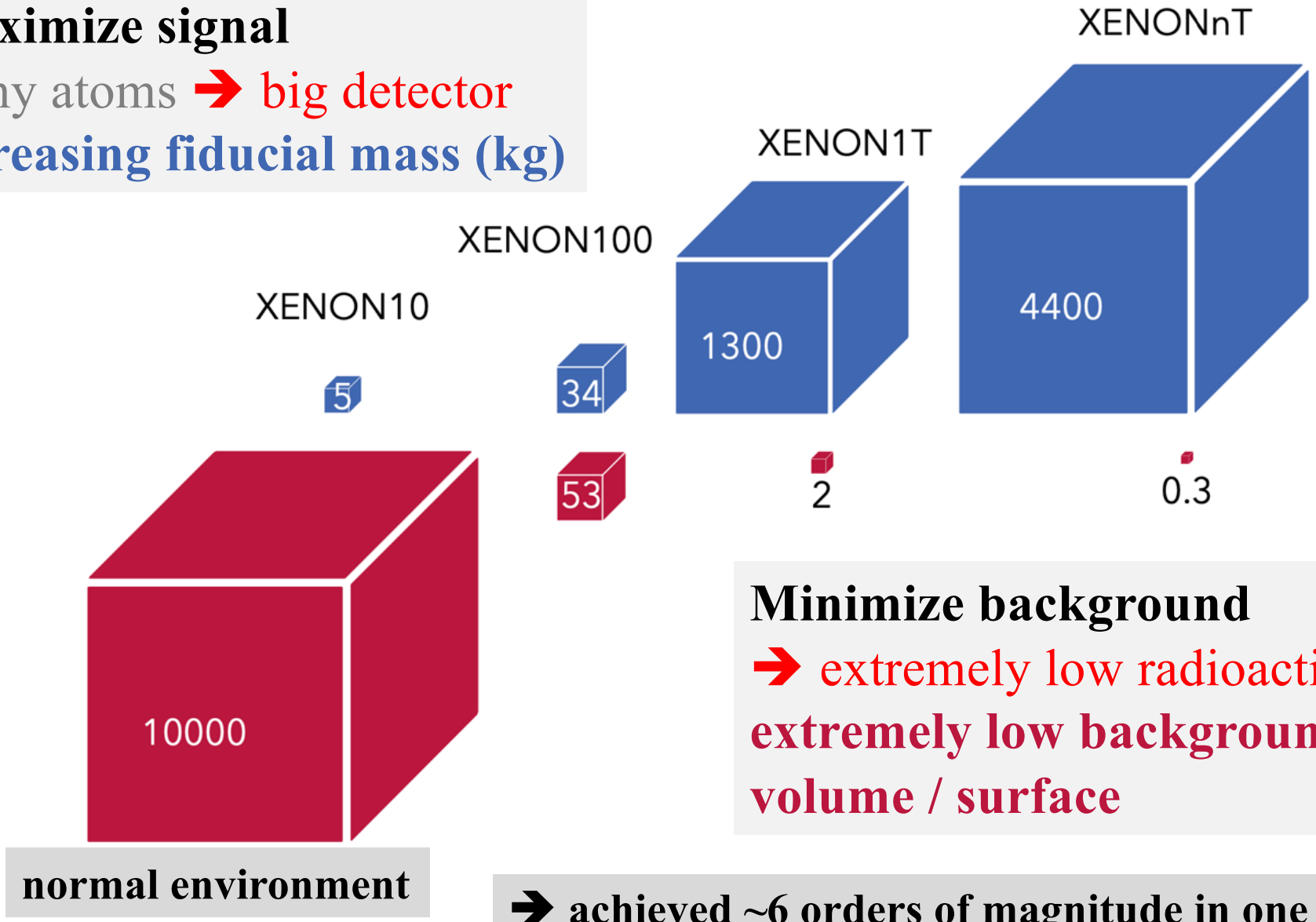
- Co-spokesperson
- Chair of Collaboration Board
- Analysis Coordinator
- Several task group leaders

Evolution: Detector Mass and Background

Maximize signal

many atoms ➔ big detector

increasing fiducial mass (kg)



normal environment

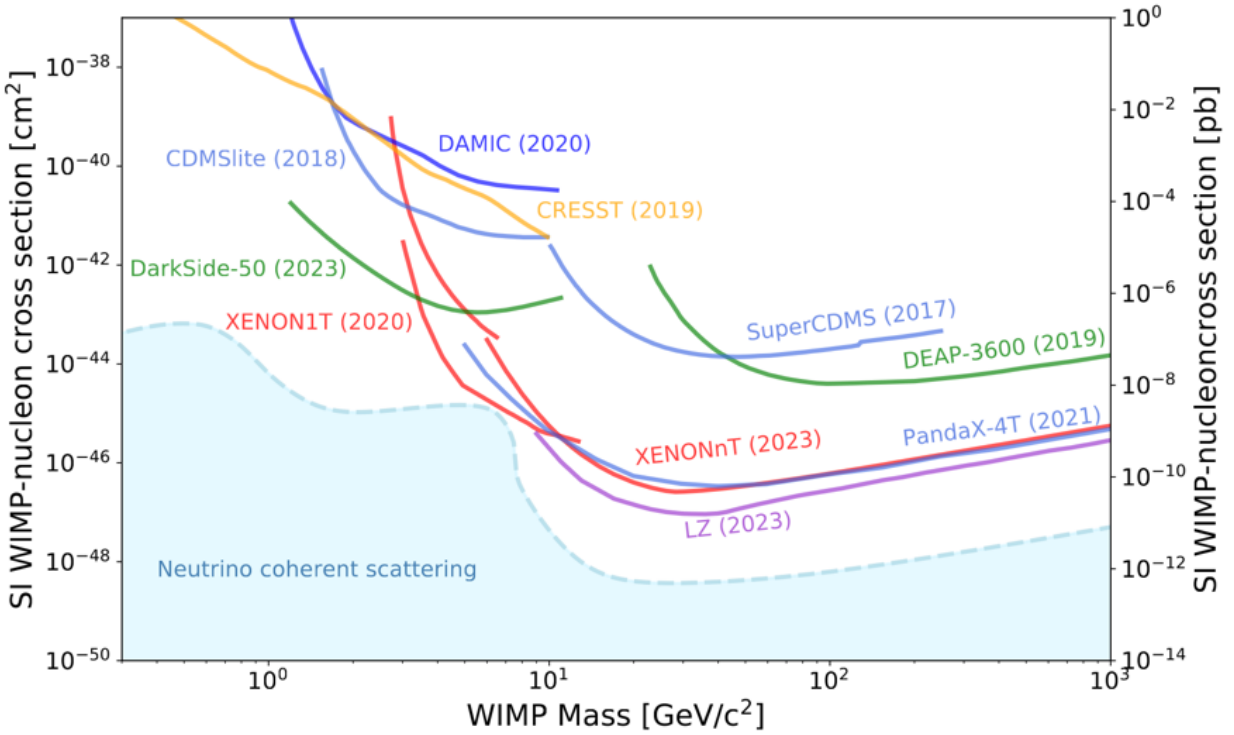
Minimize background

➔ extremely low radioactivity

extremely low backgrounds

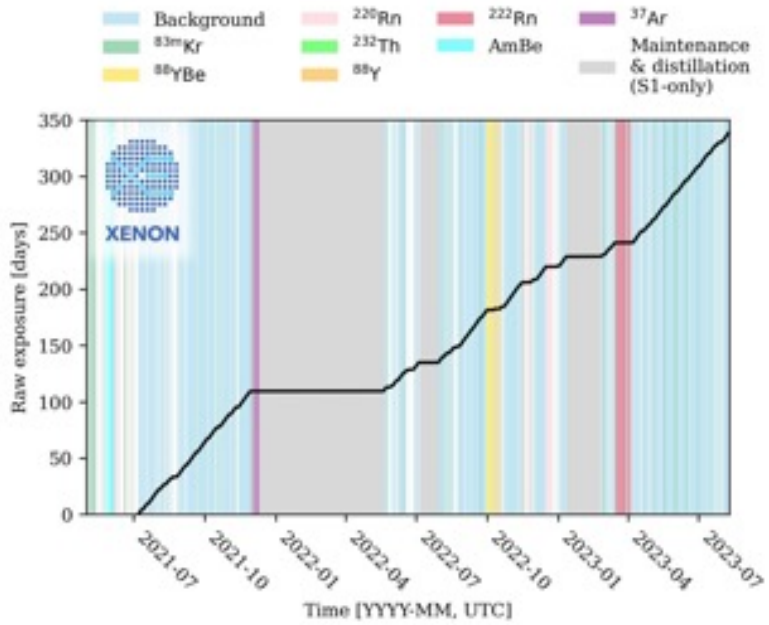
volume / surface

➔ **achieved ~6 orders of magnitude in one decade**



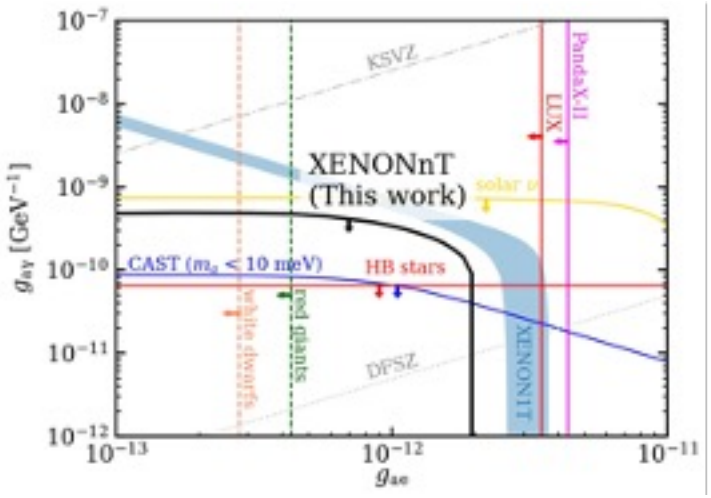
PDG24: Limits on the SI WIMP cross section

+ recent new result from LZ
+ XENONnT:
  - first observation of solar ν's via CEνNS @2.73σ
  - new WIMP result soon



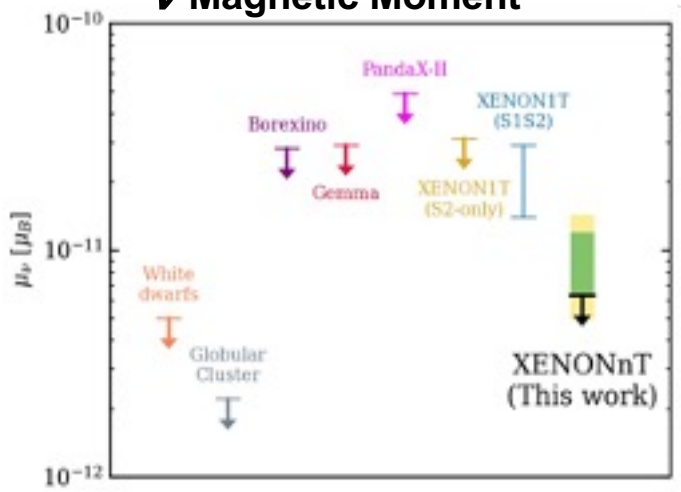
XENONnT Limits on other New Physics

Solar Axions



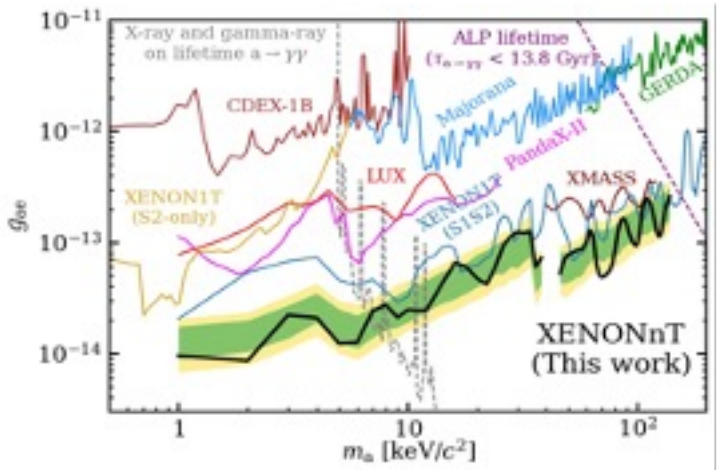
Limit on 14.4 keV peak for ^{57}Fe solar axions is < 20 events/(t*y)

ν Magnetic Moment

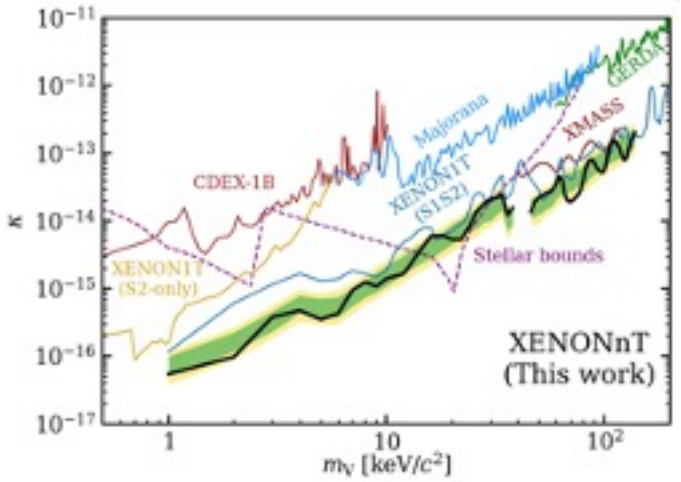


μ_ν < 6.3 10^{-12} μ_B, most stringent DD imit

Axion-like particles



Dark Photon



Phys.Rev.Lett. 129 (2022) 16, 161805

DARWIN → XLZD

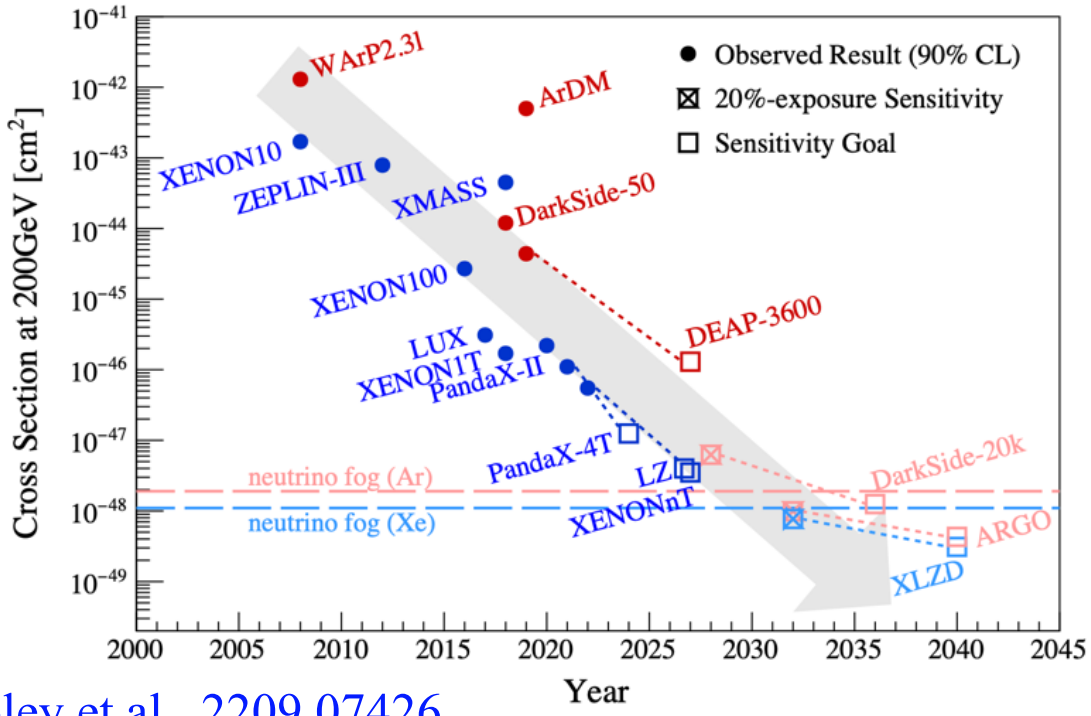
DARWIN = XENON + others

XLZD = merger of XENON, LZ, DARWIN and others

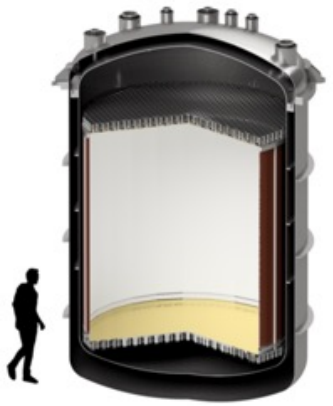
→ collaboration recently fully established: 73 institutes

8 German institutes: KIT, MPIK, Freiburg, Mainz, Münster, Heidelberg, Darmstadt und Dresden

→ FIS application



Cooley et al., 2209.07426



mass: 75 t Lxe (60t)
drift length ca. 300 cm

The Strategic Perspective

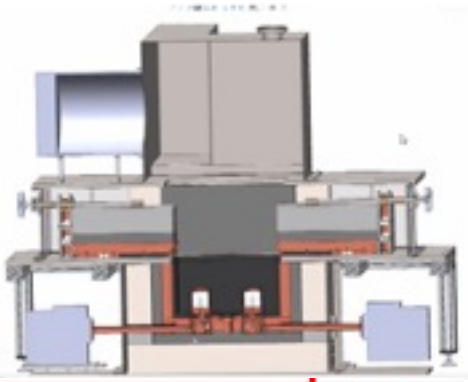
Xenon gas is the main cost factor
XENONnT: Total invest ca. 35-40M€ - out of this ca. 30 M€ for 10t xenon gas
XLZD: 250M€ - similar ratio of gas / other hardware

Important to remember: Xenon is a commodity
- can be sold later
- can serve as strategic reserve (essential for chip industry)
- re-use existing xenon gas form XENON and LZ = 10+10 = 20 tons

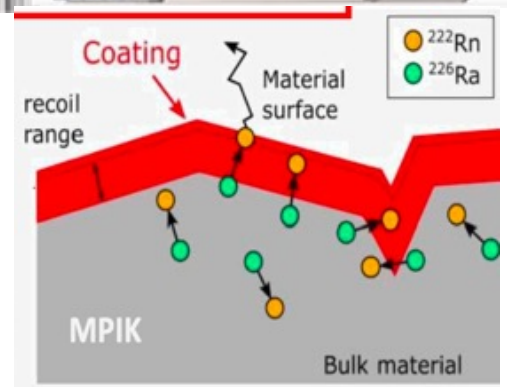
- **German groups alread own 4.4 t of Xe gas** (historic average ca. 3M€ / ton) mostly in XENONnT, partly for R&D at home institutions
- **Contributed a significant fraction of hardware in XENON1T and XENONnT** ½ of the PMTs, TPC, distillation, n-veto, μ-veto, DAQ, RGMS, screening…
- **Possible XLZD locations:** LNGS, Boulby, SURF, Kamioka, SNOLAB
- **Germany in XLZD:**
  - 20-25% of people
  - similar fraction of the invest → time integrated ca. 60 M€ (mostly xenon to be sold)
  - leading roles ←→ key expertise

German R&D and Pre-Investements

- **Freiburg:**
  800kg xenon gas
  plus ~1.5 M€:
  * PANCAKE Test Platform
    full diameter test system



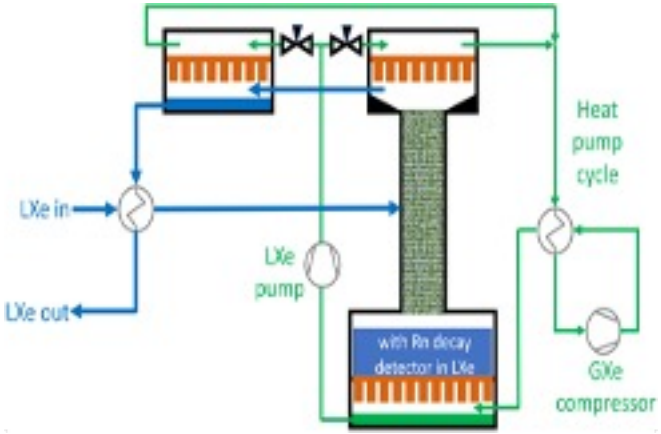
- **MPIK:**
  3000kg xenon gas
  plus ~1.5 M€:
  * RGMS (Rare Gas MS): Kr@Xe at ppq
  * Auto-RGMS: Fully automated RGMS
  * Improvements of GeMPIs for γ-screening
  * GeMPI-Neo: next generation γ-screening (~15 cts/d/kg)
  * Auto-Ema: Automated Rn screening facility
  * Radon mitigation by surface coating
    reduction up to ~1000 achieved



- **KIT:**
  260kg xenon gas
  * Electrodes R&D: HV test setups, TPC “MOTION” (ca. 80 kg lXe)
  * Computing: prototype Analysis Platform realized in 2023, with access to batch & storage at KIT Scientific Computing Centre (GridKA)

- **Mainz:**
  200kg xenon gas
  * Neutron Veto: water Cherenkov detector w/ Gd-sulfate, GS recovery
  * ^{37}Ar low-energy ER internal line source @ TRIGA (XENON1T/nT)
  * Facility for electrode scanning (upgrade to DARWIN/XLZD size)
  * XeLiPS test facility
  * low-energy NR response, MainzTPC

- **Münster**
  200kg xenon gas
  Development and demonstration of
  * a new mid-scale Rn removal system
  * a Kr concentrator (lossless online Kr removal)
  * running one system
    with Kr and Rn removal
    together with LXe purification,
    analytics and calibration
  * 2 cryogenic distillation systems for Kr and Rn removal existing (XENONnT)
  * 2 new ones under construction (LowRad)



On-going DARWIN R&D funded by BMBF, ERC, MPG, HGF

➔ very strong strategic position of German groups alone and in combination:

PANCAKE (Freiburg) + large size electrode development (KIT)

➔ development and test of a very critical component

cryogenic distillation systems (Münster) + Rn coating (MPIK)

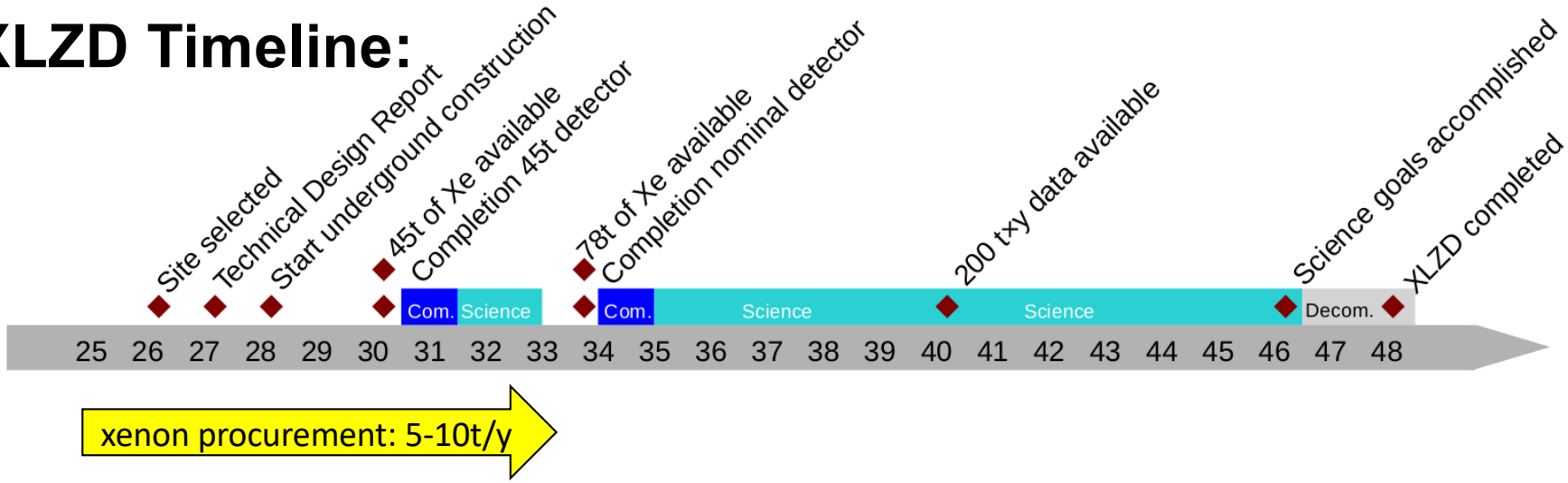
➔ technology to reduce the limiting Radon background

neutron veto (Mainz)

➔ essential for any future detector

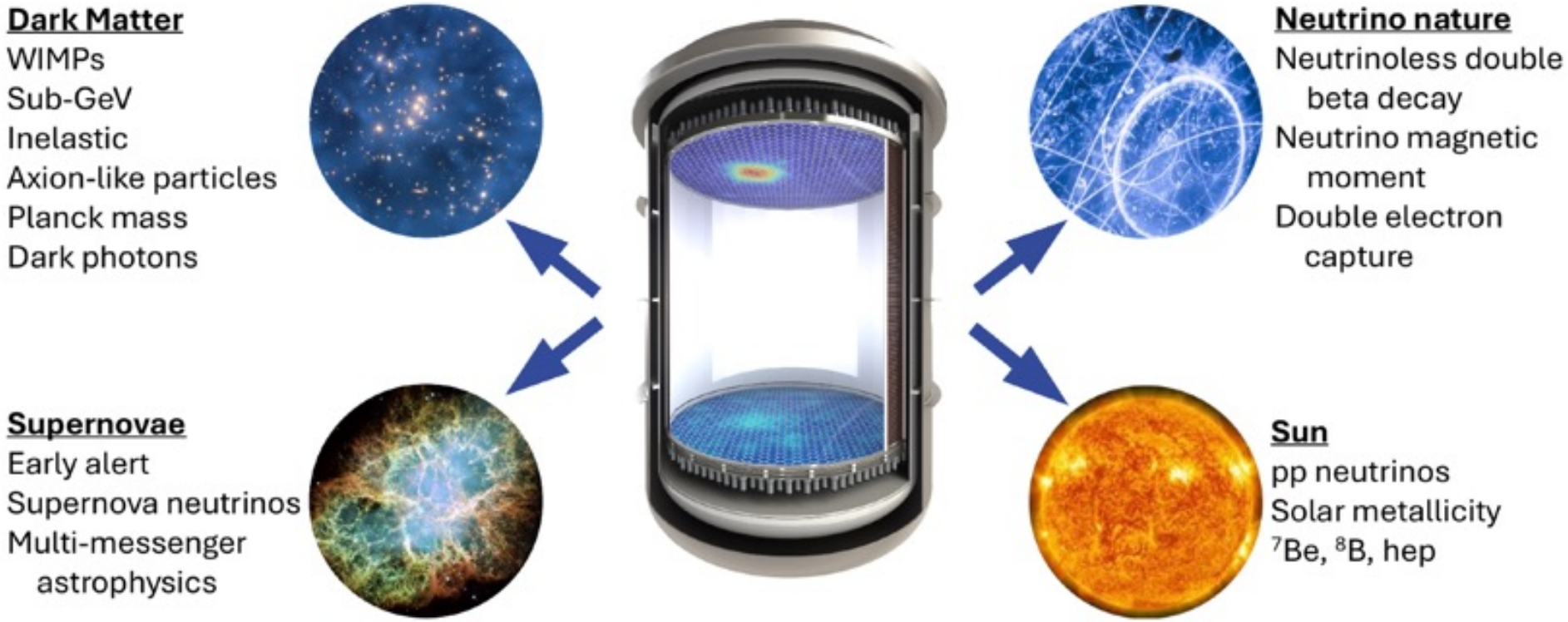
in addition: various powerful / essential low background mitigation techniques

XLZD Timeline:



The Science Case of XLZD

Physics case for a large liquid xenon detector: JoPG, arXiv:2203.02309 (600 authors)



➔ **XLZD: An Observatory for Rare Physics**

Emerging topic: CEvNS at DM detectors (XLZD) + COHERENT+ESS + reactor experiments
Now: onset of signal
Future: large statistics ➔ impressive list of extra physics topics

Conclusions on Dark Matter

One of the most important topics in fundamental physics

- New particles, gravity or both?
- Both sides contribute already a bit (neutrinos, black holes)
- Many theoretical ideas / motivations and detection methods
- **Direct detection important: Discover/verify DM in the Universe**

- **Particle DM**

  - axions @KET
  - KAT: COSINUS, DeLight, CRESST, XENON, XLZD
  - **big new project: XLZD = merger of XENON, LZ, DARWIN**
    * utilize 10+10 tons of existing xenon → total goal 50-80
    * total invest: 250 M€ - integrated German fraction 60M€ (xe gas...)
    * **strong German role:** key technologies and essential expertise
    * **excellent science potential**: DM, solar ν's, CEνNS, SN, 0νββ, ...

Discussion