Direct Dark Matter searches

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University of Birmingham


The NGC 6503 galaxy. Credit: NASA/ESA HST

38th Conference on Recent Developments in HEP and Cosmology
June 14, 2022, Thessaloniki, Greece

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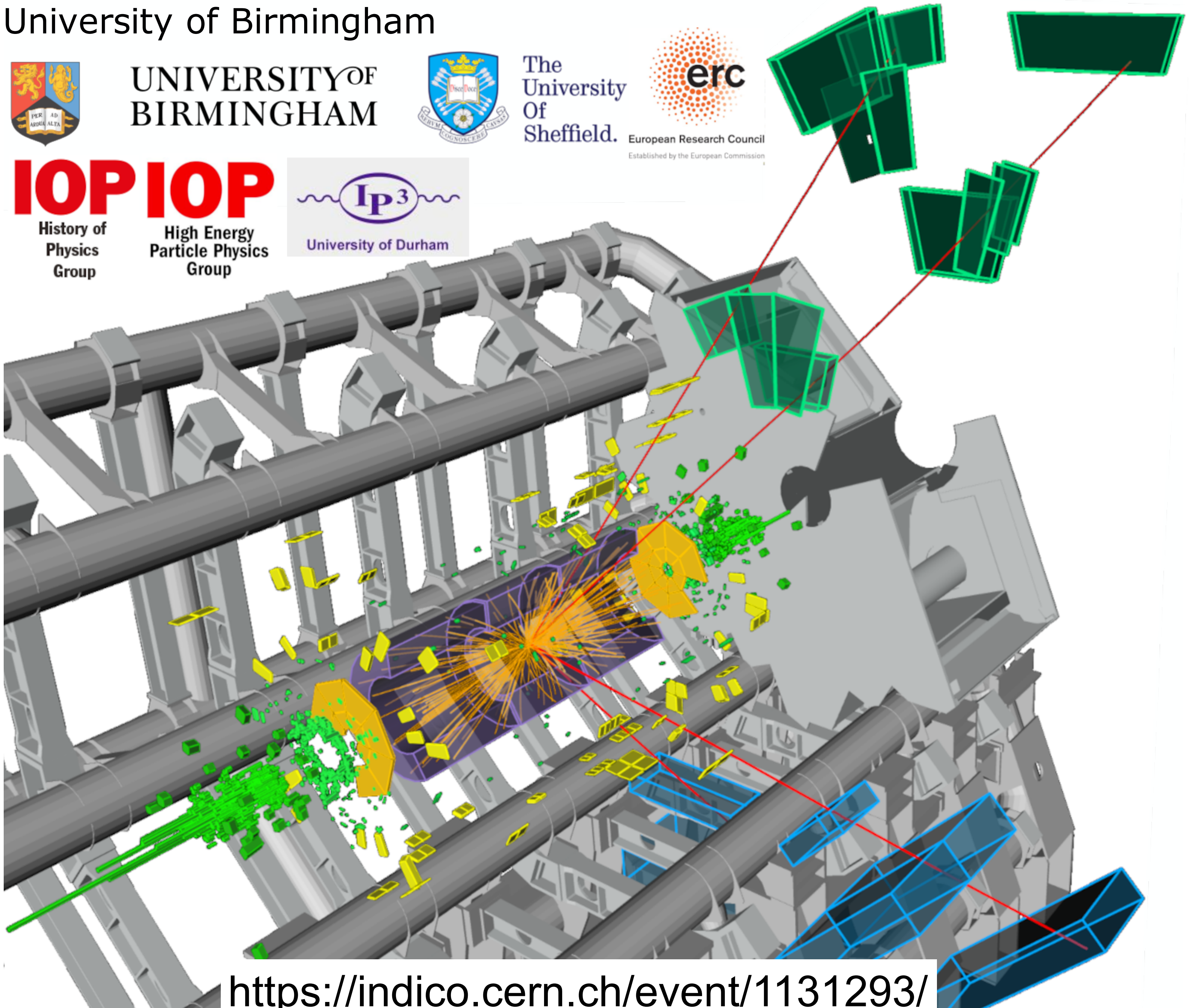
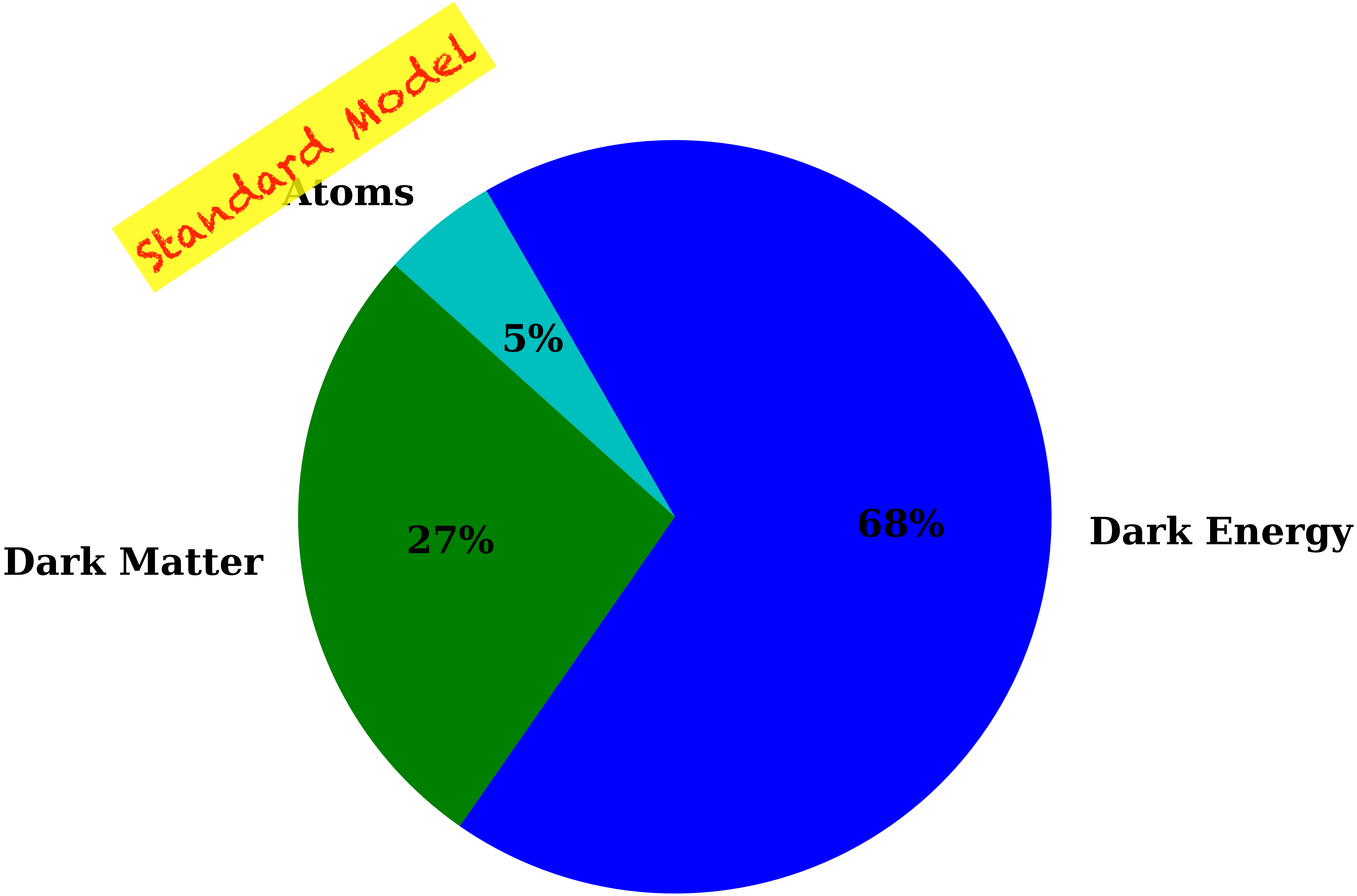
HiggsDiscovery@10
Symposium for the 10 years from the Higgs boson observation

June 30 and July 1, 2022
University of Birmingham

UNIVERSITY OF BIRMINGHAM · The University Of Sheffield. · erc European Research Council Established by the European Commission · IOP History of Physics Group · IOP High Energy Particle Physics Group · IP3 University of Durham



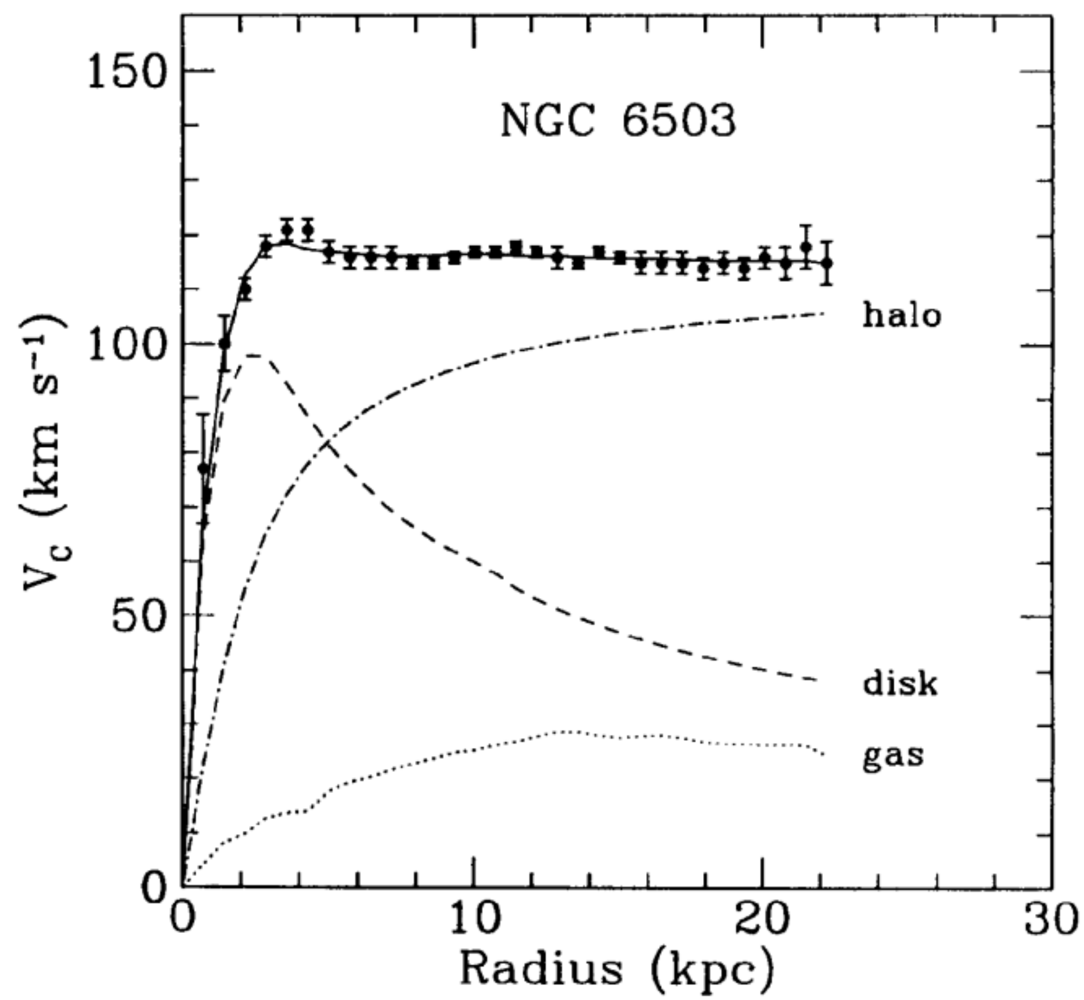
https://indico.cern.ch/event/1131293/

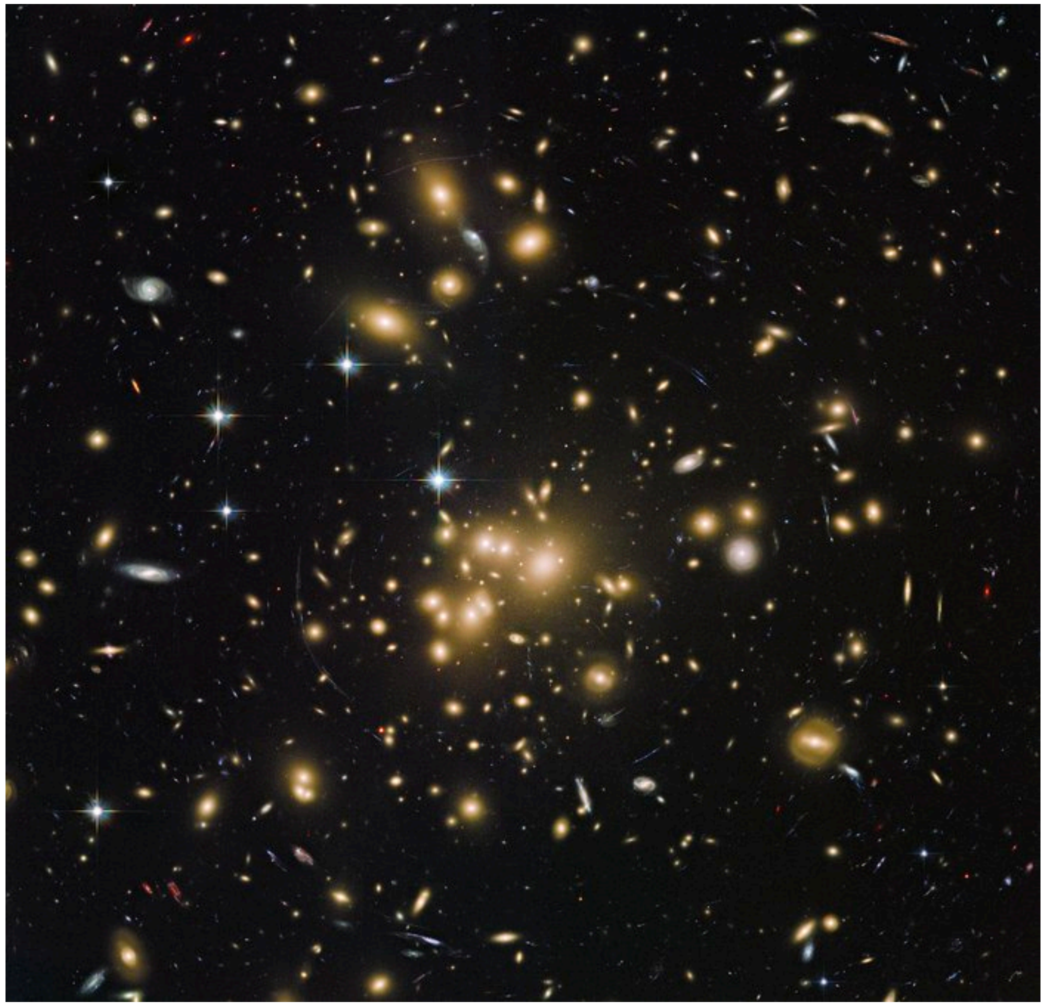

Standard Model
Atoms
5%
Dark Matter
27%
68%
Dark Energy

Evidence for Dark Matter

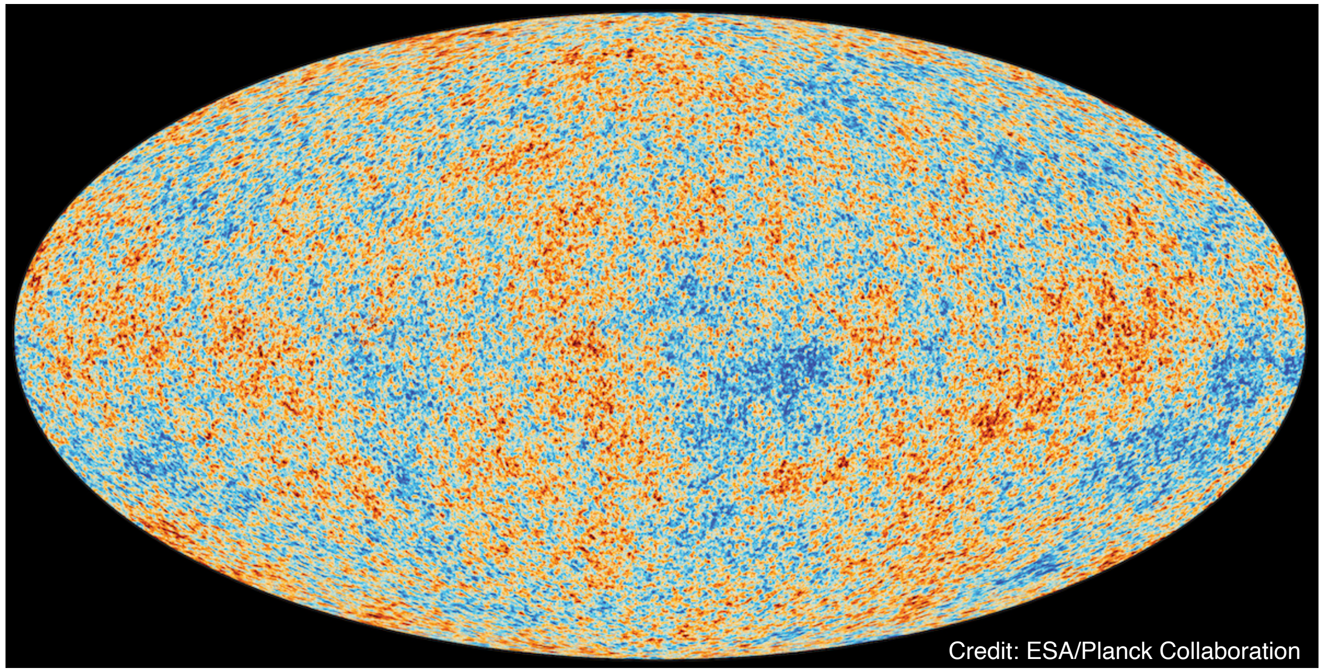
- **Ample evidence over different distance scales**
  - Galactic rotation curves
  - Clusters of galaxies
  - Early and late cosmology
    - Cosmic microwave background
    - Large scale structure formation
  - Bing Bang Nucleosynthesis

Mon. Not. R. Astr. Soc. 249 (1991) 523.





The Abell 1689 galaxy cluster. Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), J. Blakeslee (Herzberg Research Centre, Dominion Astrophysical Obs.), and H. Ford (JHU)



Credit: ESA/Planck Collaboration

Dark Matter: what do we know

- **What we know about Dark Matter**
  - Non-Baryonic
  - Mostly “cold”
  - Electrically neutral (or milli-charged?)
  - “Weakly” interacting
  - $\Omega_{DM}h^2 = 0.120 \pm 0.001$
  - Stable or $\tau_{DM} \gg \tau_U$

Dark Matter Particle (X^0)

X^0 mass: $m = ?$
X^0 spin: $J = ?$
X^0 parity: $P = ?$
X^0 lifetime: $\tau = ?$
X^0 scattering cross-section on nucleons: $?$
X^0 production cross-section in hadron colliders: $?$
X^0 self-annihilation cross-section: $?$

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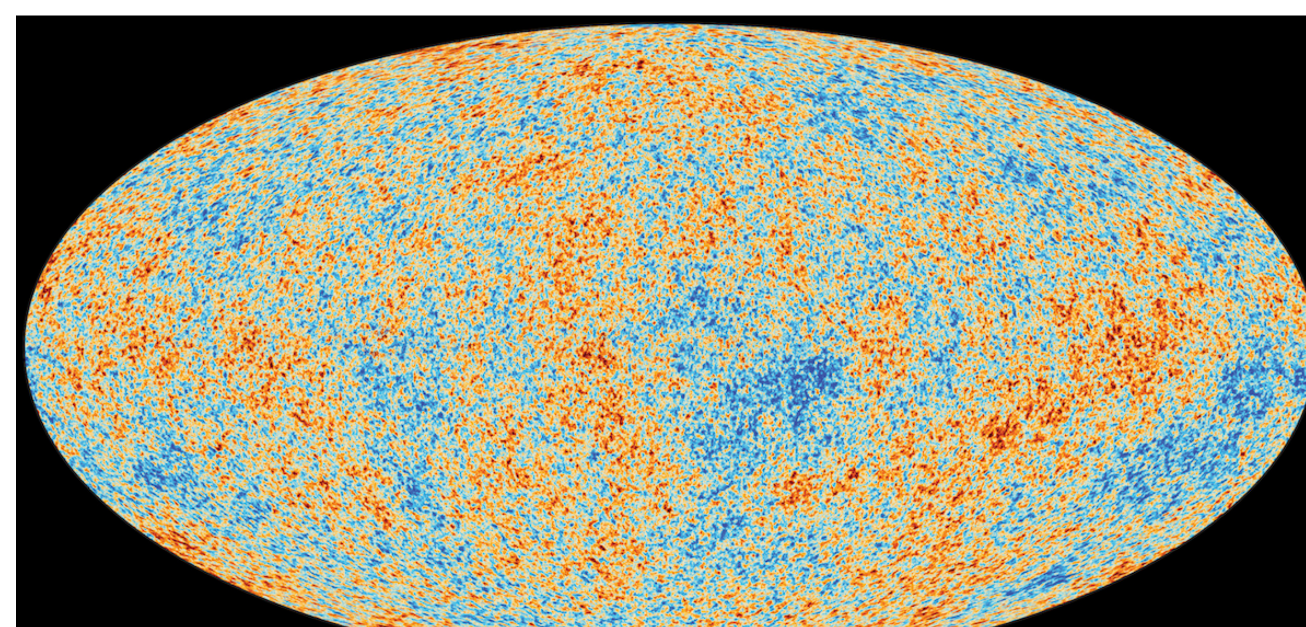

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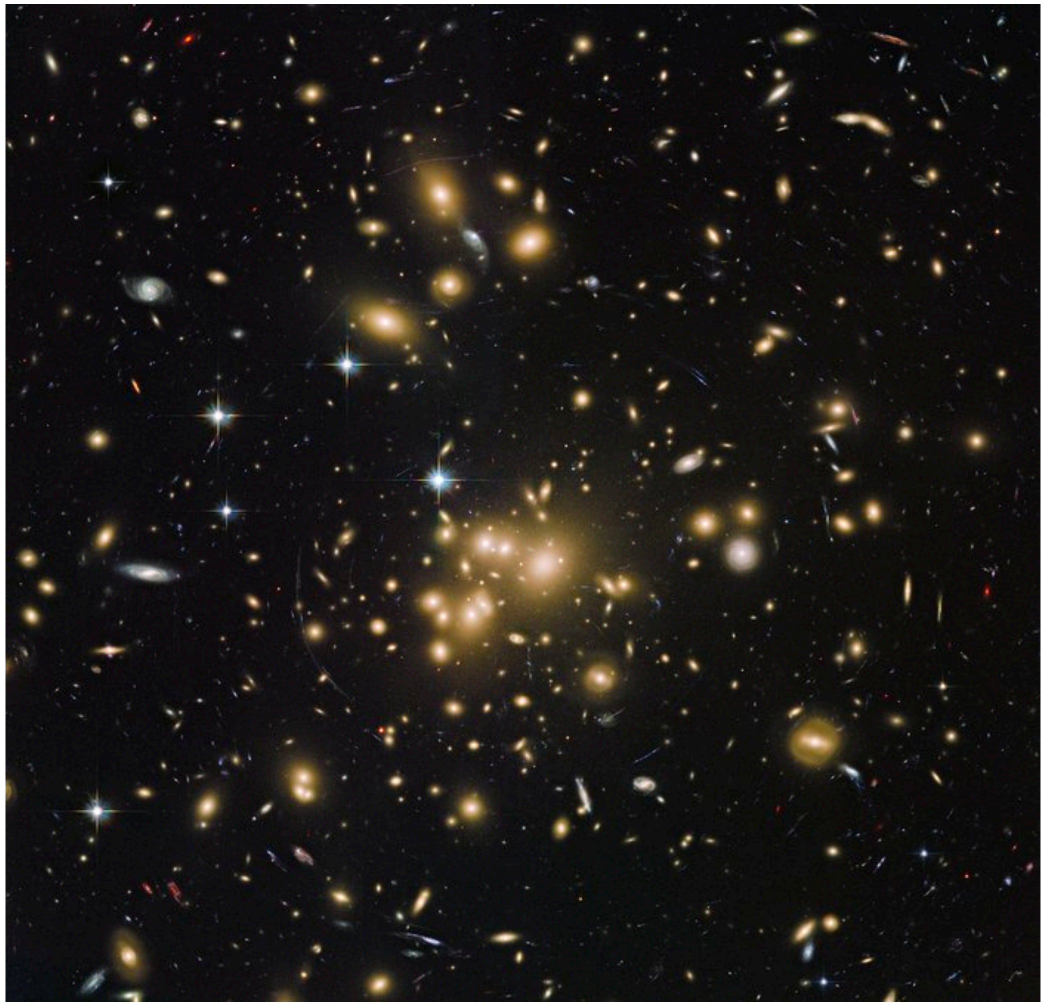
X^0 self-annihilation cross-section: ?

No known particle fits the bill!



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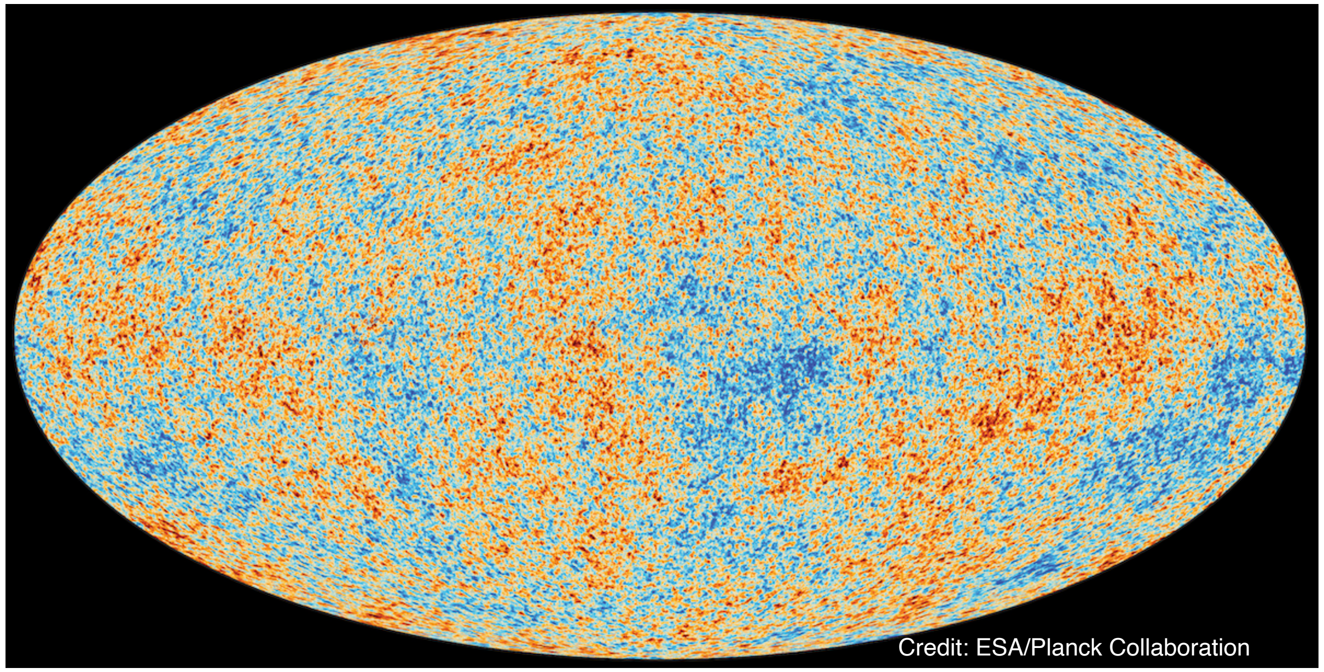

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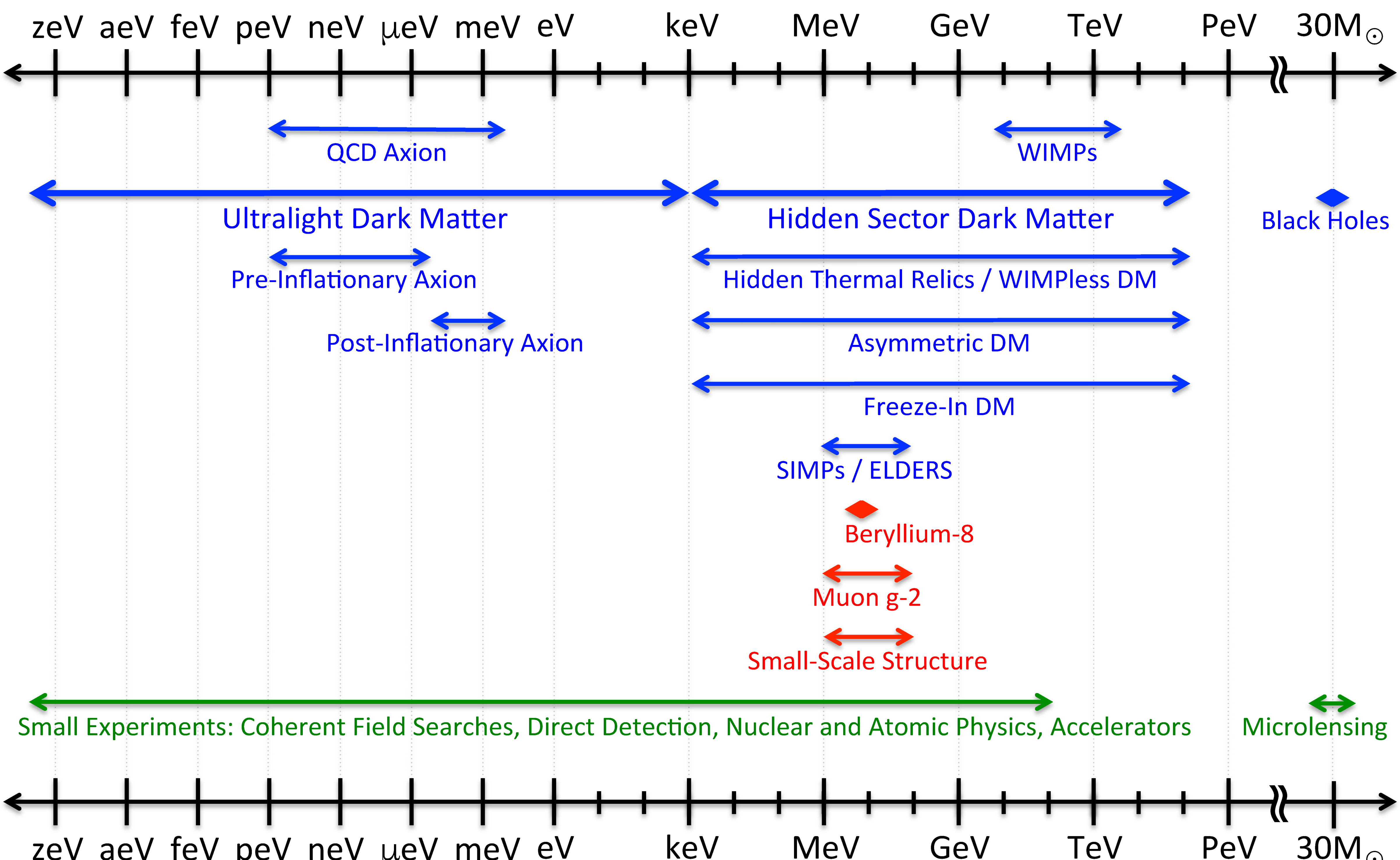
Wide field of possibilities!

Dark Sector Candidates, Anomalies, and Search Techniques



Cosmic visions
arXiv:1707.04591

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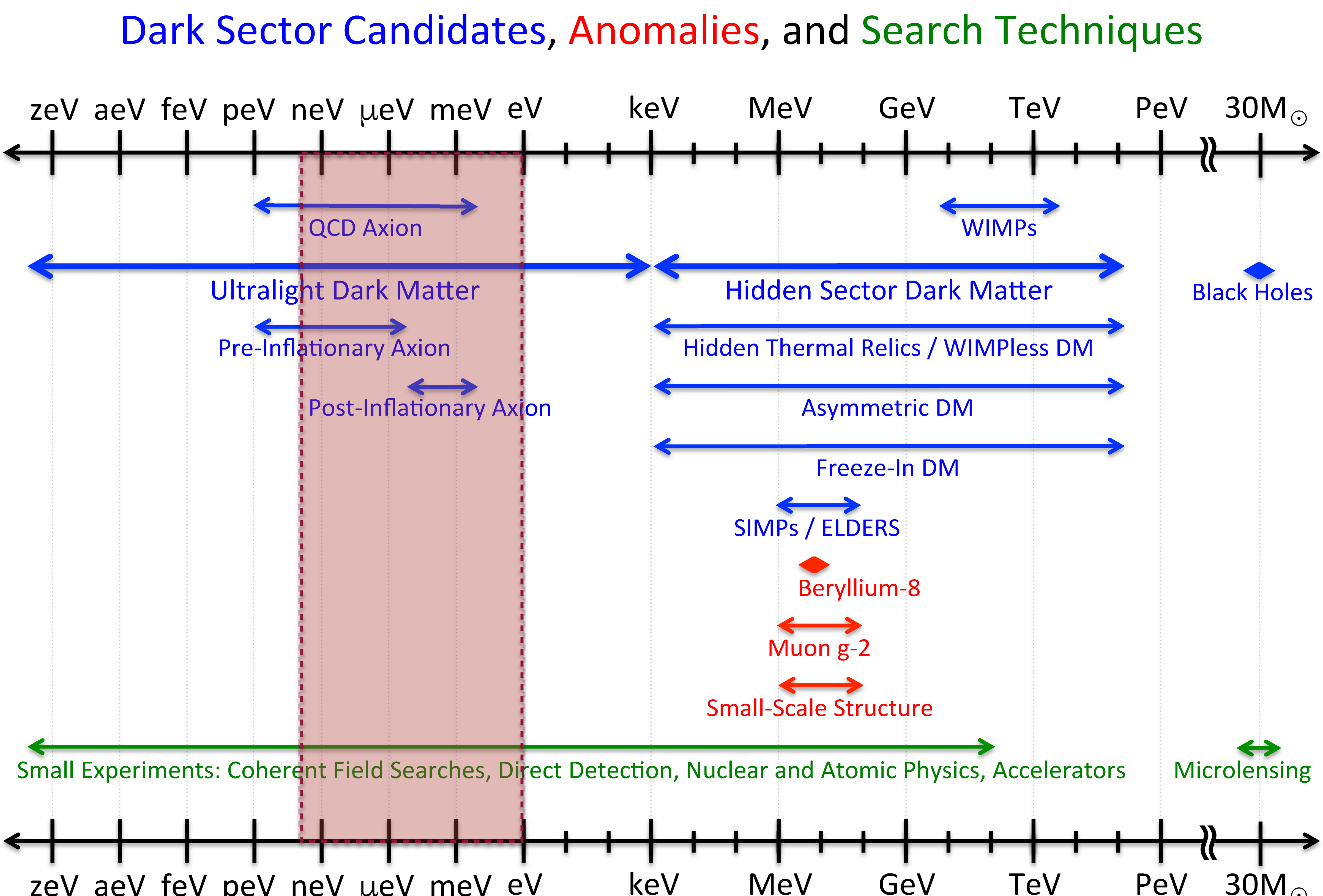

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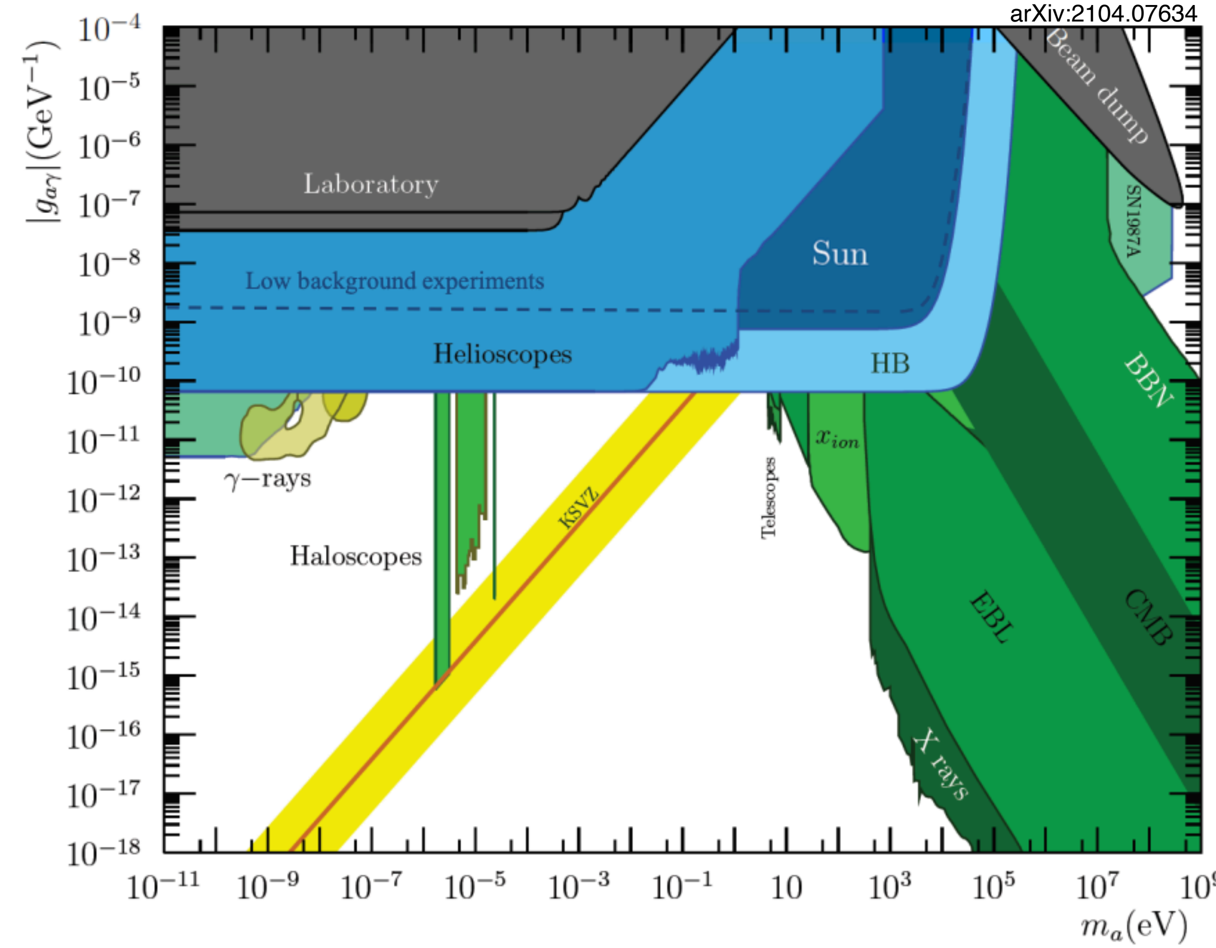
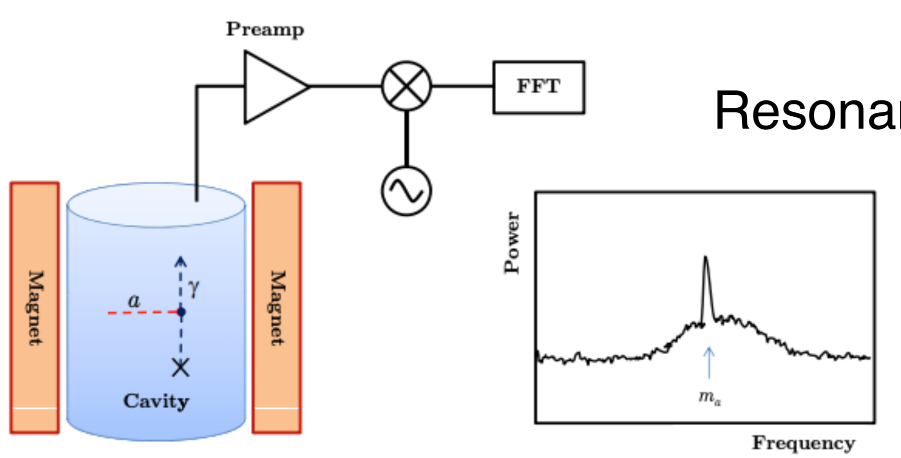
Axions and ALP searches

- **Mostly relying on axion-photon coupling**
- **Haloscopes**
  - DM Axion/ALP field coupling to static B-field
  - Direct DM search
- **Helioscopes**
- **Laboratory experiments**
  - Axions produced on-site
  - Light shinning through the wall (LSW)

arXiv:2104.07634

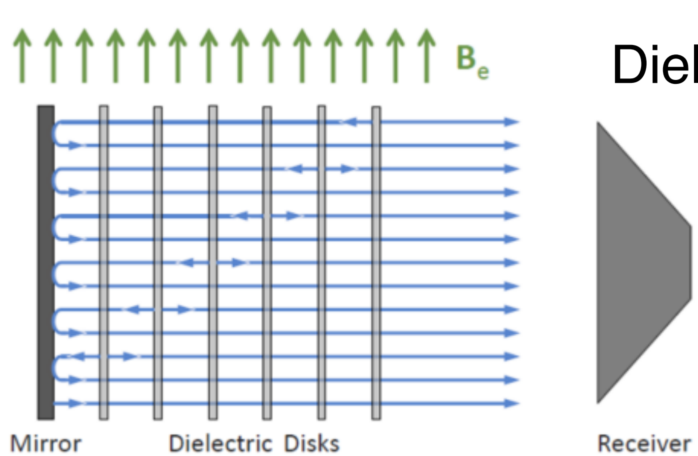


Resonant Cavities



Prog. Part. Nucl. Phys. 102 (2018) 89

Dielectric



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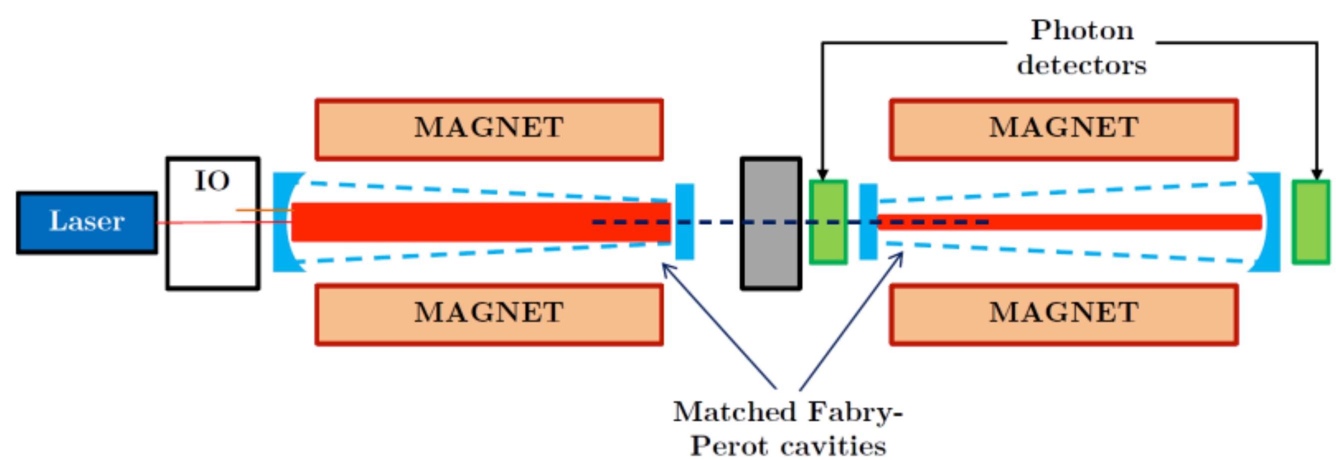


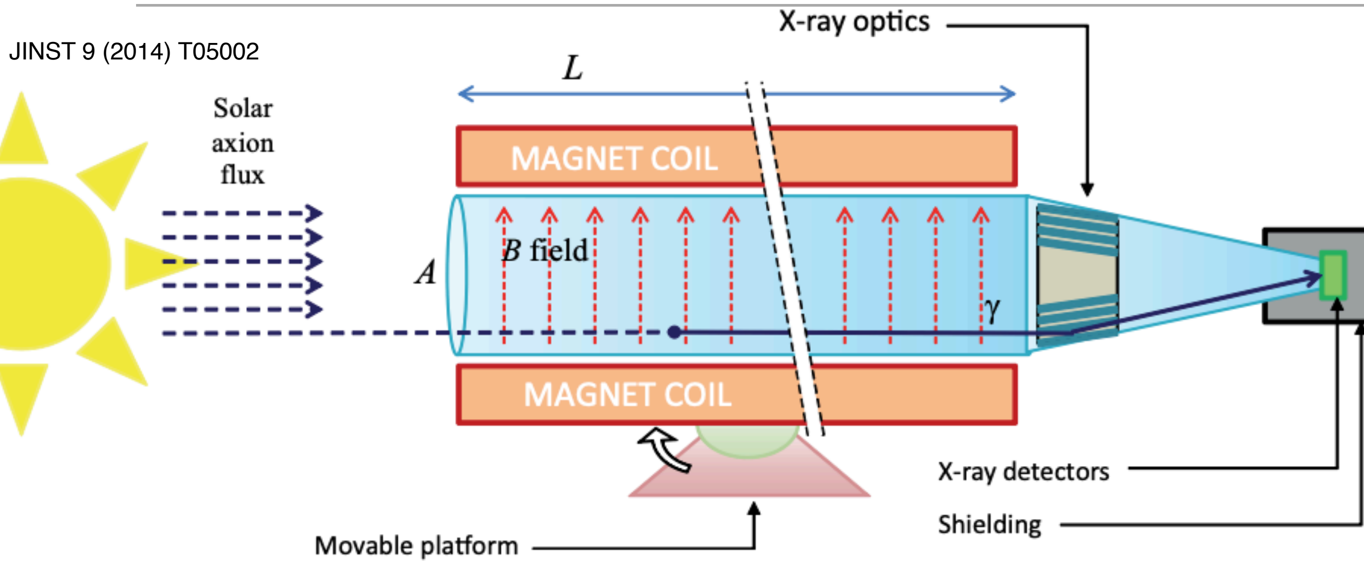
Prog. Part. Nucl. Phys. 102 (2018) 89

Experiment	status	B (T)	L (m)	Input power (W)	β_P	β_R	$g_{a\gamma}[\mathrm{GeV}^{-1}]$
ALPS-I [433]	completed	5	4.3	4	300	1	5×10^{-8}
CROWS [435]	completed	3	0.15	50	10^4	10^4	9.9×10^{-8}(*)
OSQAR [434]	ongoing	9	14.3	18.5	-	-	3.5×10^{-8}
ALPS-II [436]	in preparation	5	100	30	5000	40000	2×10^{-11}
ALPS-III [437]	concept	13	426	200	12500	10^5	10^{-12}
STAX1 [438]	concept	15	0.5	10^5	10^4	-	5×10^{-11}
STAX2 [438]	concept	15	0.5	10^6	10^4	10^4	3×10^{-12}

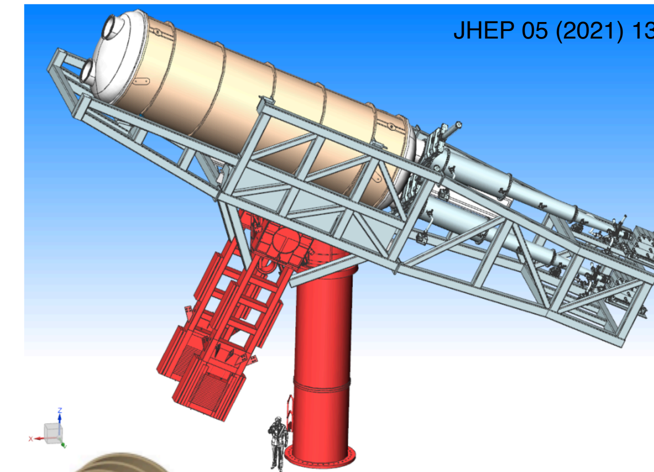
Prog. Part. Nucl. Phys. 102 (2018) 89

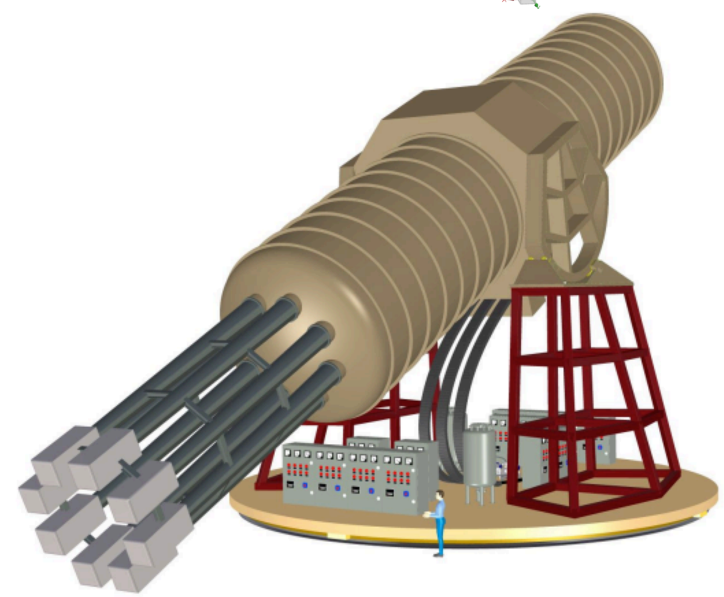
International AXion Observatory

JINST 9 (2014) T05002

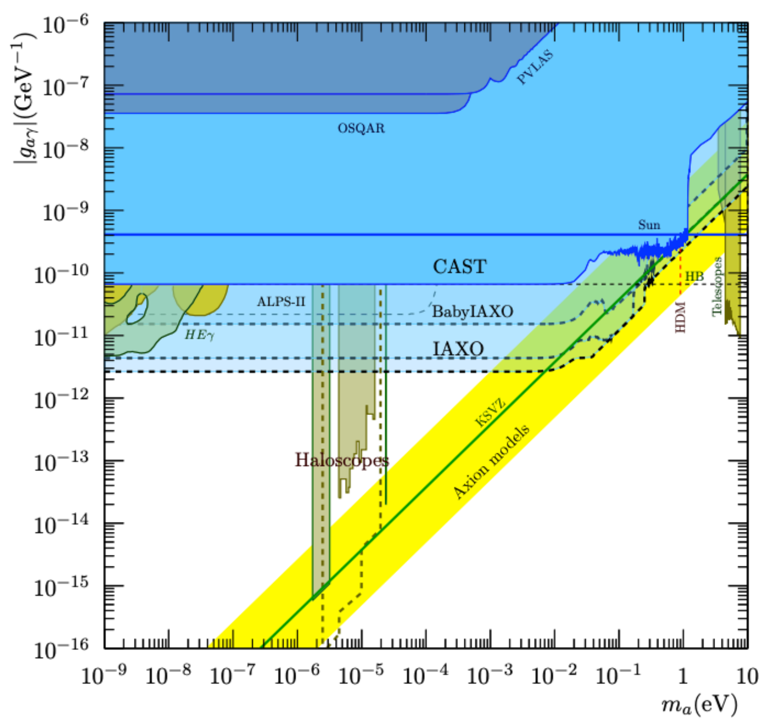


JHEP 05 (2021) 137





- **Next (4th) generation Helioscope**
  - Building on the success of CAST
    - Following the BNL and Tokyo experiments
  - Search for axions/ALPS produced in the sun
    - Inverse-Primakoff effect $(a + \gamma^* \rightarrow \gamma)$
  - 21 institutes from 8 countries
  - babyIAXO to be hosted at DESY

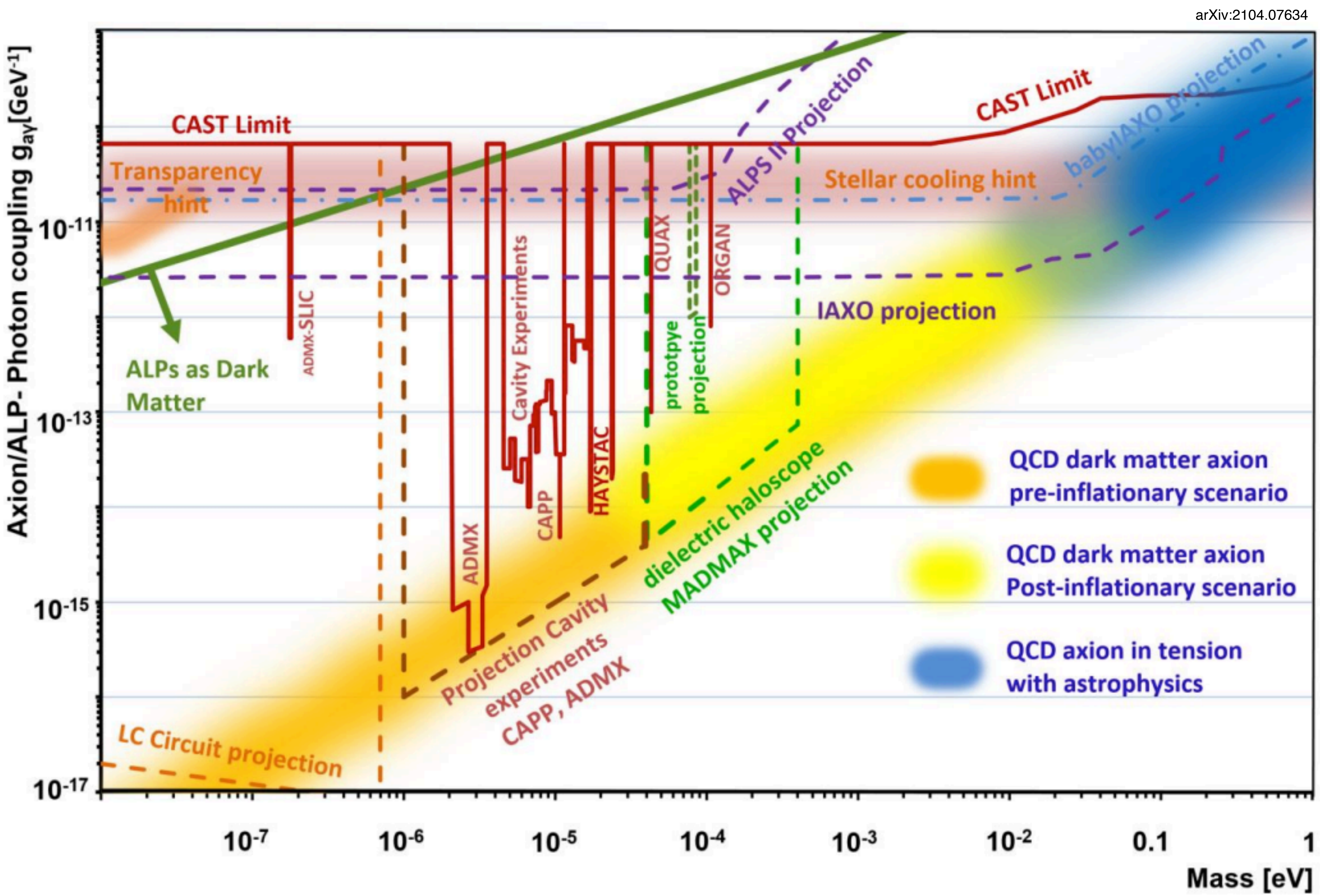


$$g_{a\gamma}^4 \propto (BL)^{-2} A^{-1} \times (t\epsilon_t)^{-1/2} \times a^{-1/2}\epsilon_0^{-1} \times b^{1/2}\epsilon_d^{-1}$$

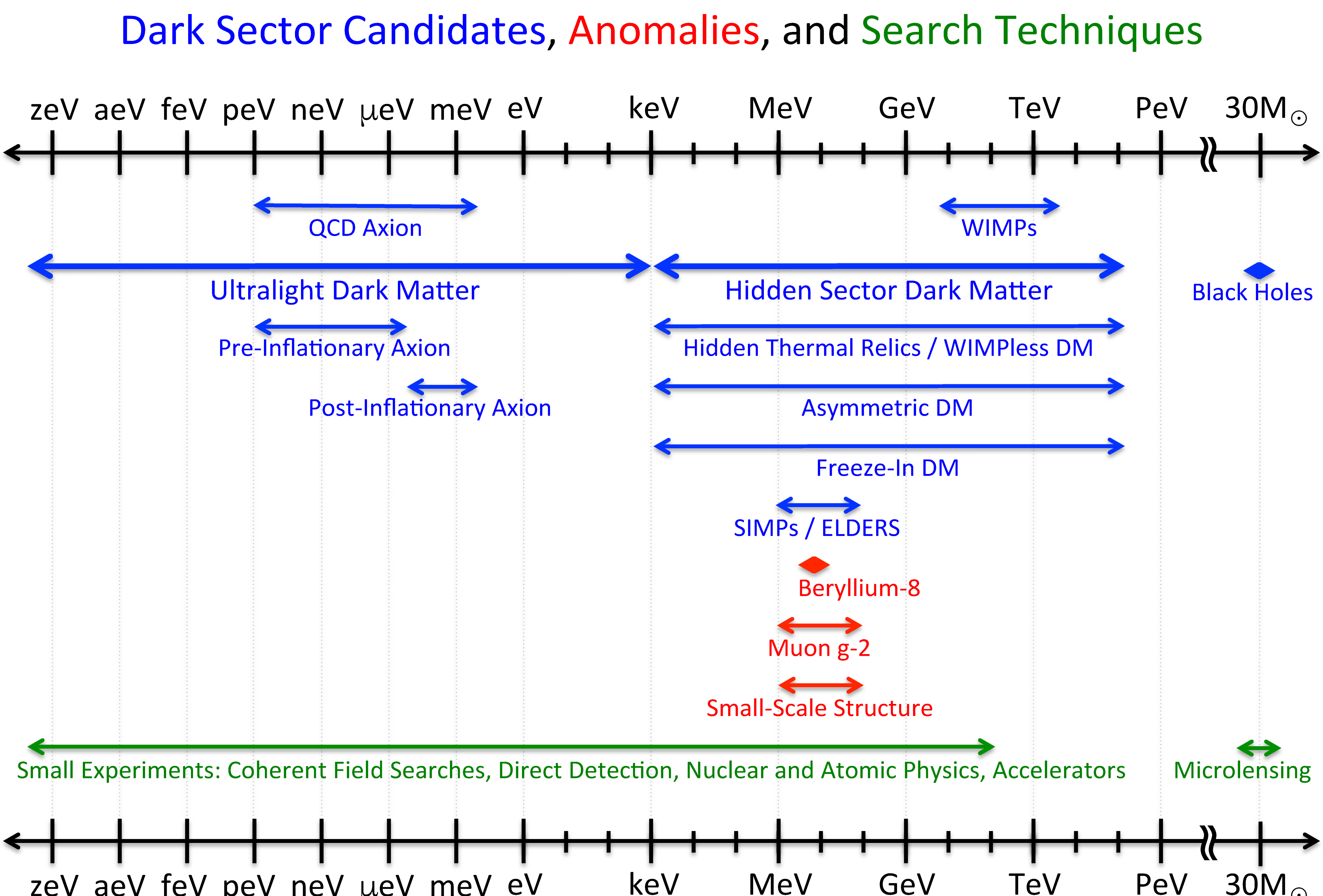
Parameter	Units	CAST	BabyIAXO	IAXO	IAXO+
B	T	9	~2	~2.5	~3.5
L	m	9.26	10	20	22
A	m^2	0.003 (*)	0.77	2.3	3.9
f_M	T^{2}m^4	21	~230	~6000	~24000
b	keV^{-1} cm^{-2} s^{-1}	1×10^{-6} (**)	1×10^{-7}	10^{-8}	10^{-9}
ϵ_d		~ 0.6	0.7	0.8	0.8
ϵ_o		0.3	0.35	0.7	0.7
a	cm^2	0.15	2×0.3	8×0.15	8×0.15
ϵ_t		0.12	0.5	0.5	0.5
t	year	~ 1	1.5	3	5

JHEP 05 (2021) 137

Axions and ALP searches prospects



Wide field of possibilities!



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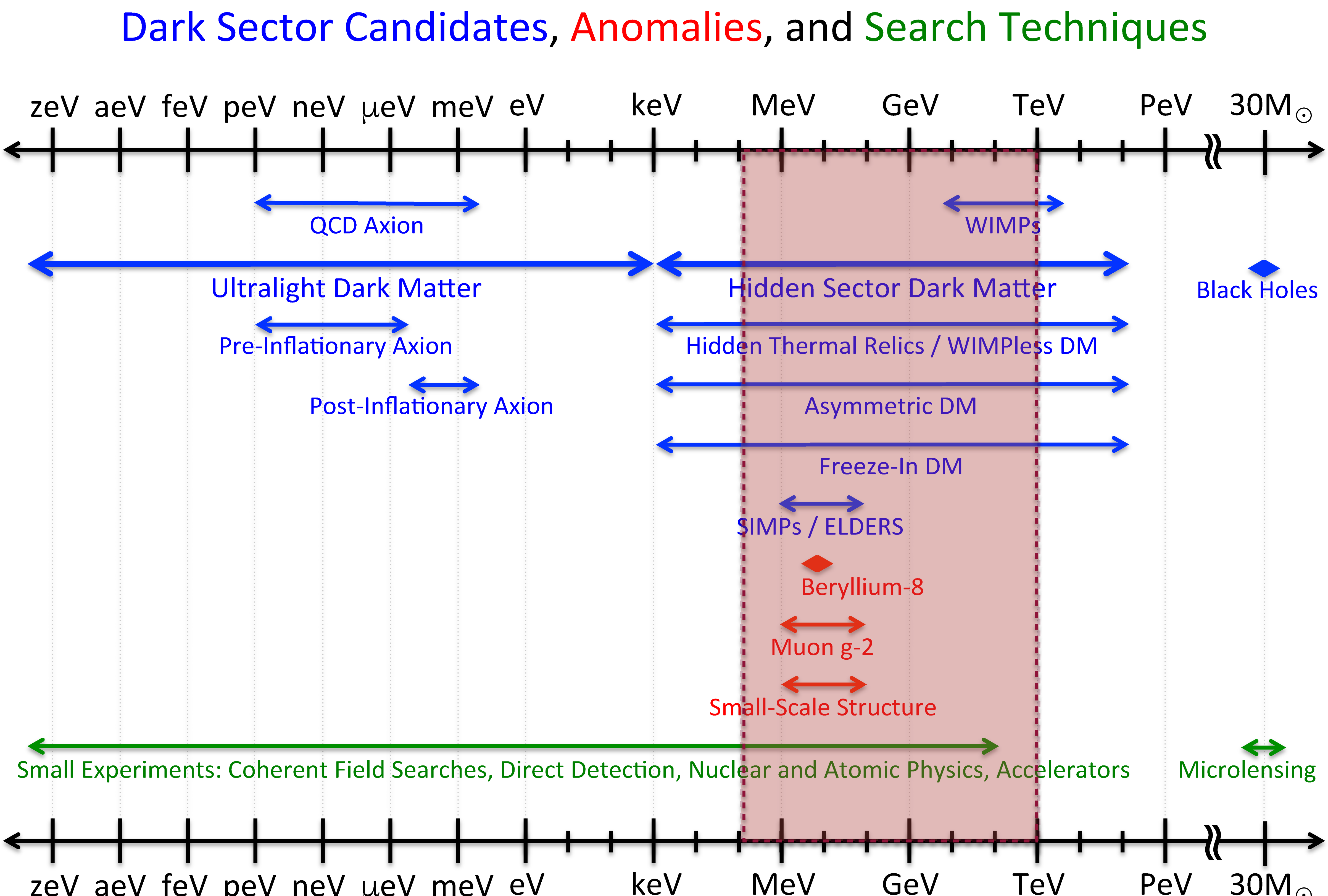

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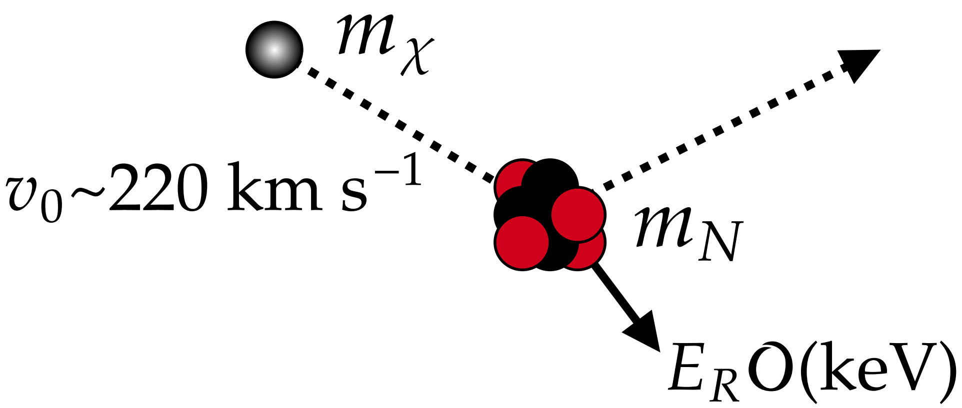
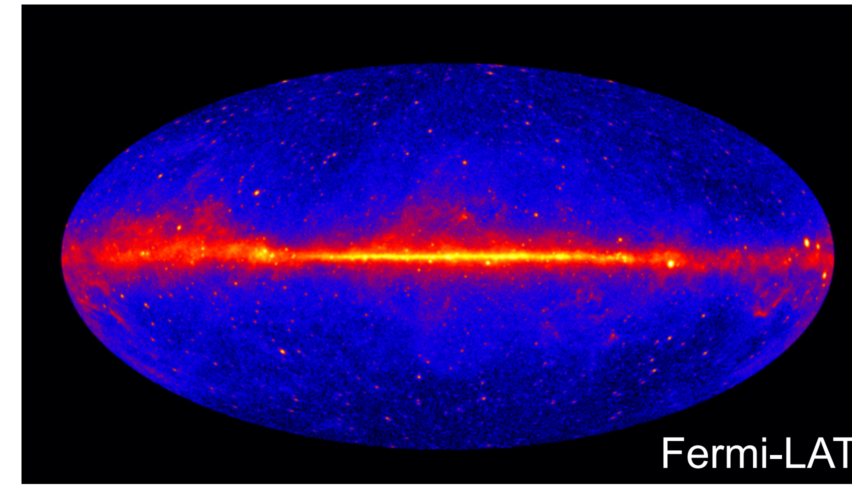
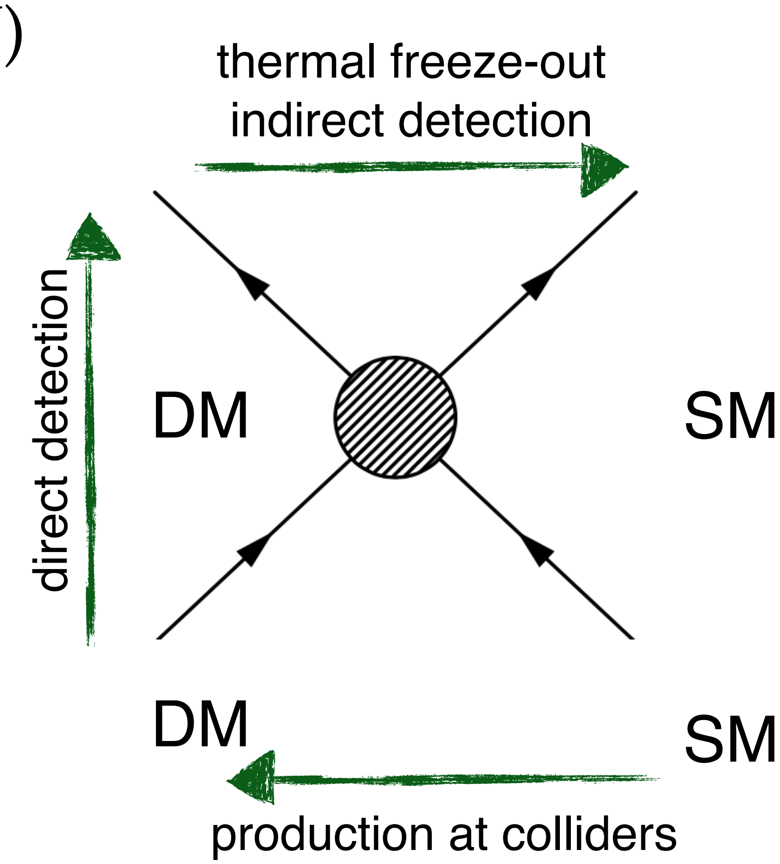
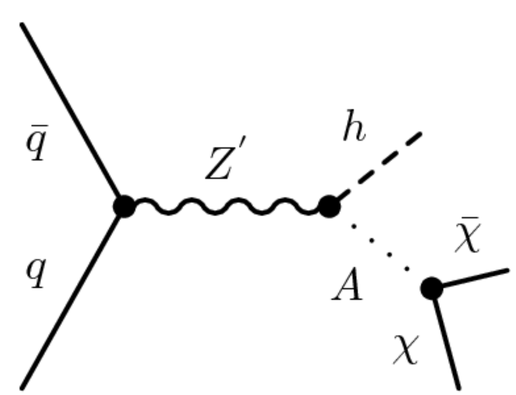
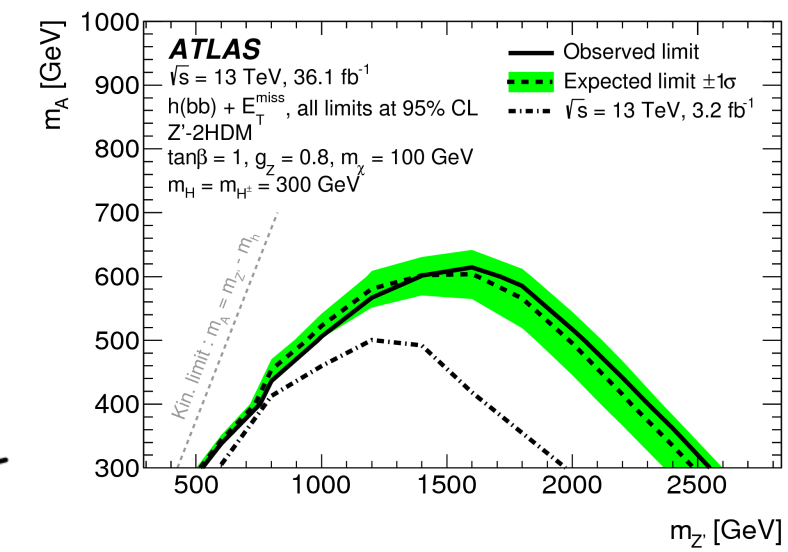
Dark Matter Detection











Phys. Rev. Lett. 119 (2017) 181804

Standard Halo Model

- **Standard Halo Model**
  - Spherical
  - Isotropic
  - Maxwell velocity distribution
  - No substructure

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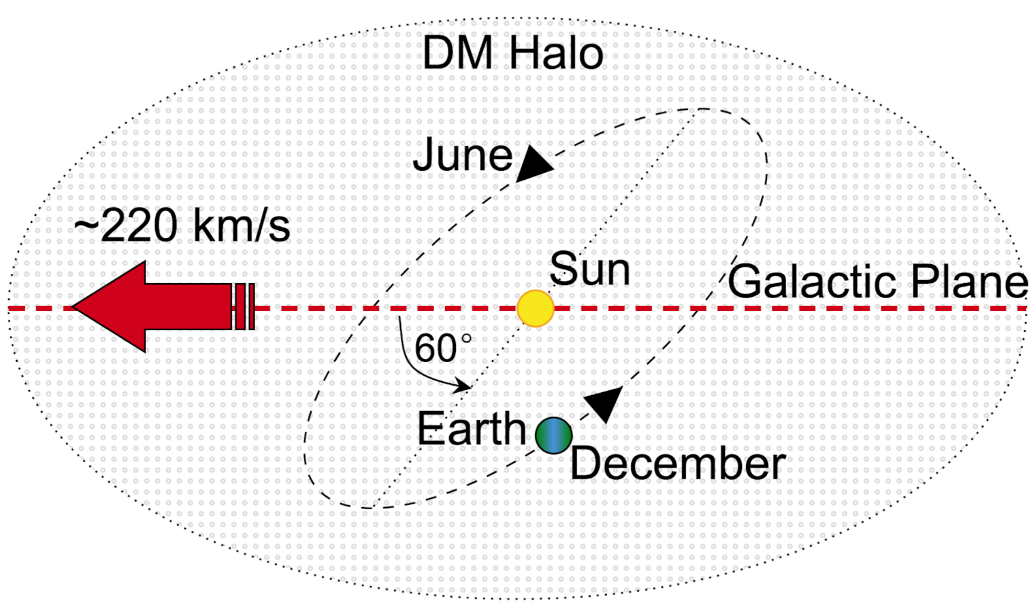
- **Locally…**
  - DM density is $\rho \sim 0.3\text{-}0.4$ GeV cm^{-3}
  - Solar system travelling through “DM Wind”
  - Flux: $10^7/m_\chi$ GeV cm^{-2}s^{-1}
  - Motion of Earth → velocity time dependent
  - Annual modulations in DM flux



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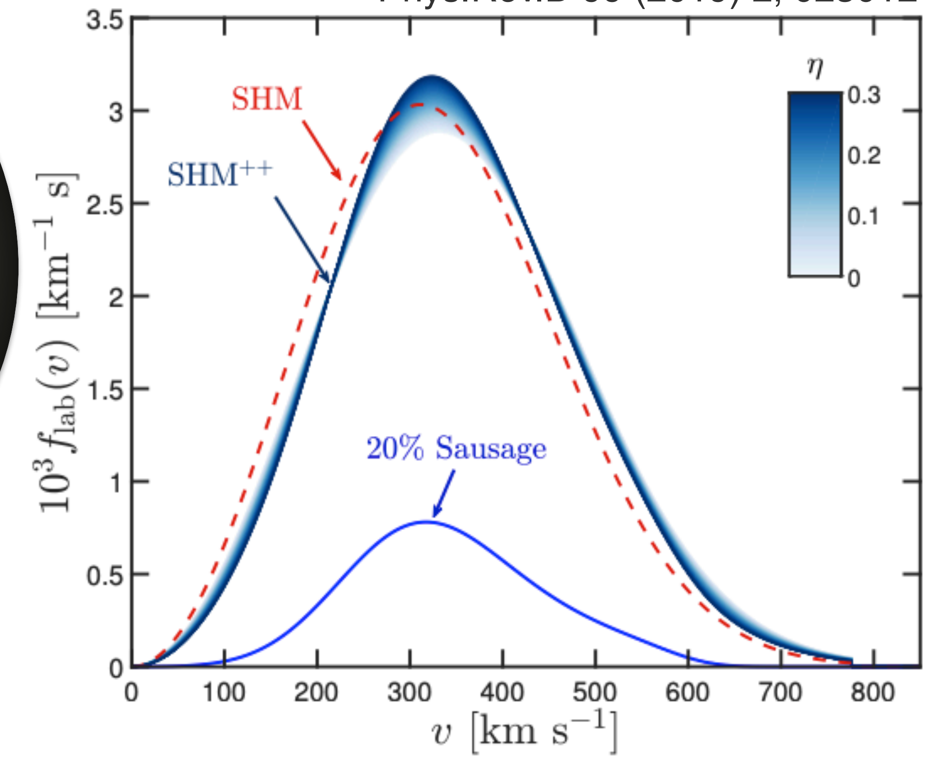
Phys.Rev.D 99 (2019) 2, 023012



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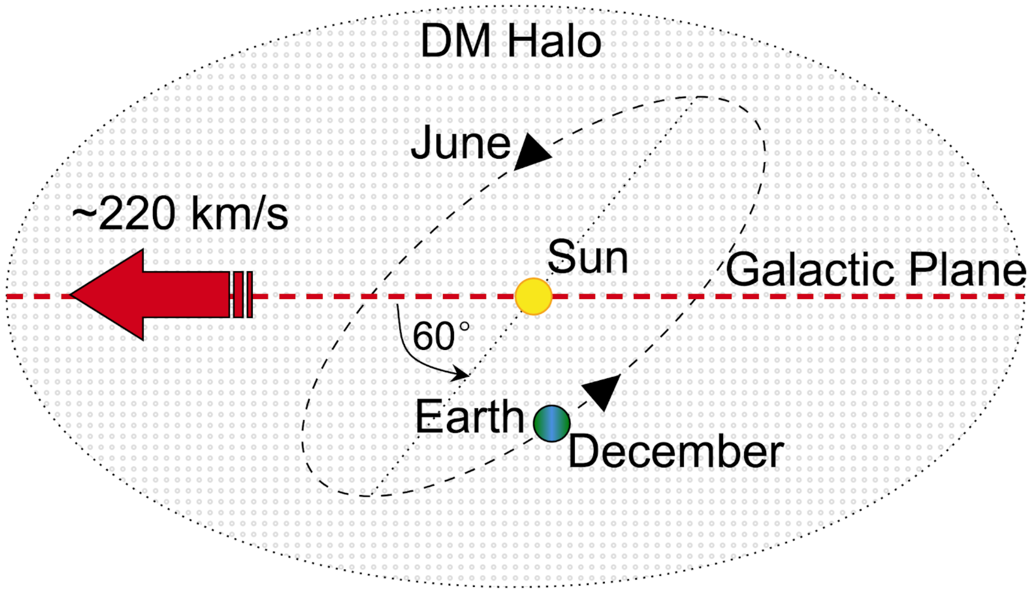
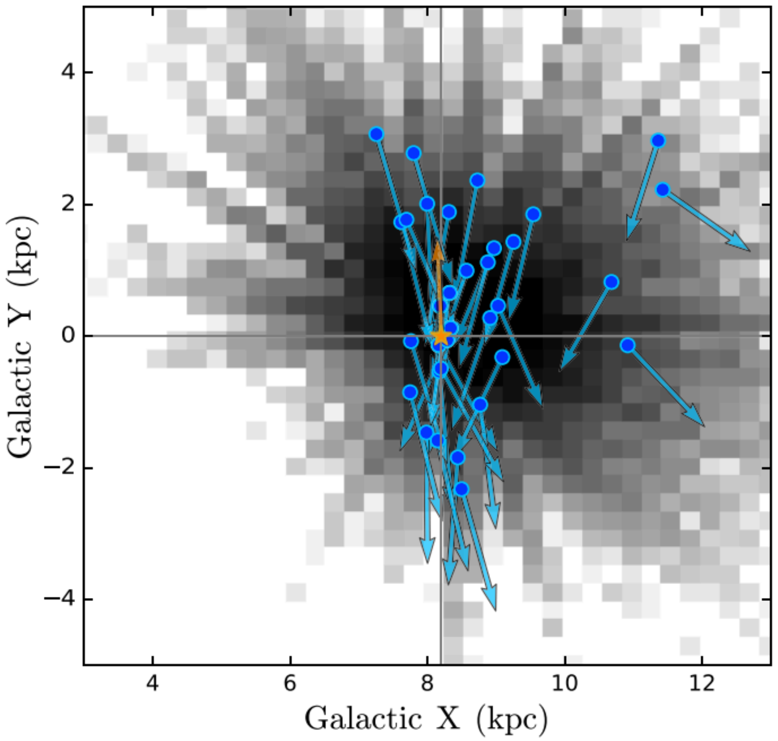
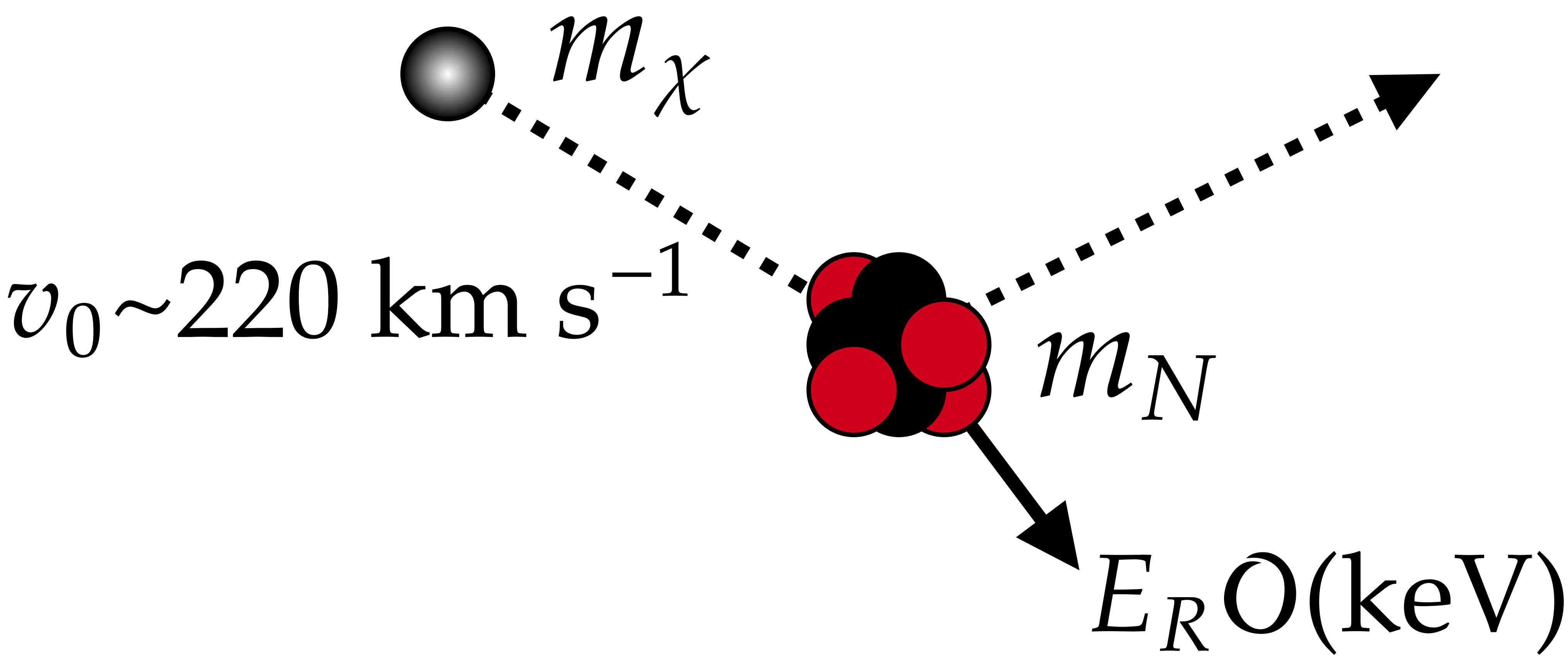




PRD 98 (2018) 10, 103006

Gaia sheds new light on DM in our neighbourhood

Dark Matter Direct Detection



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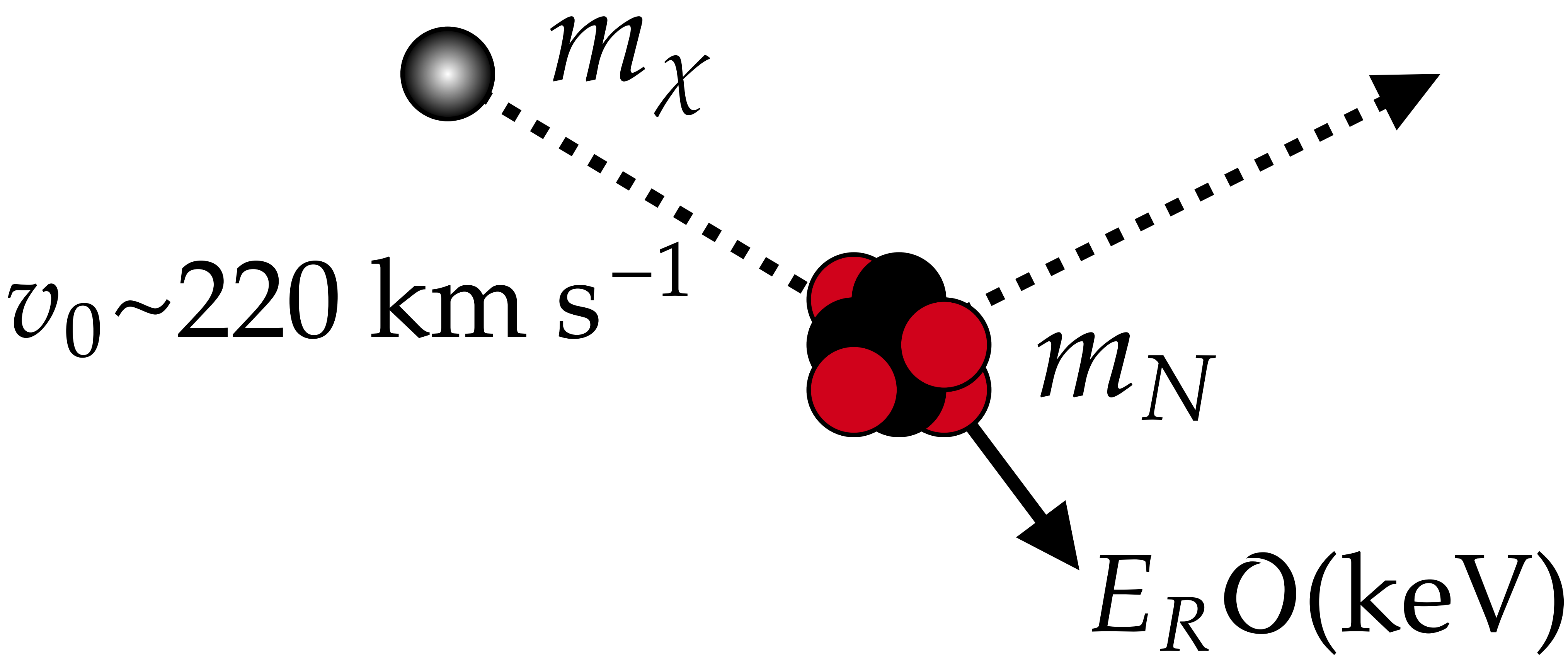
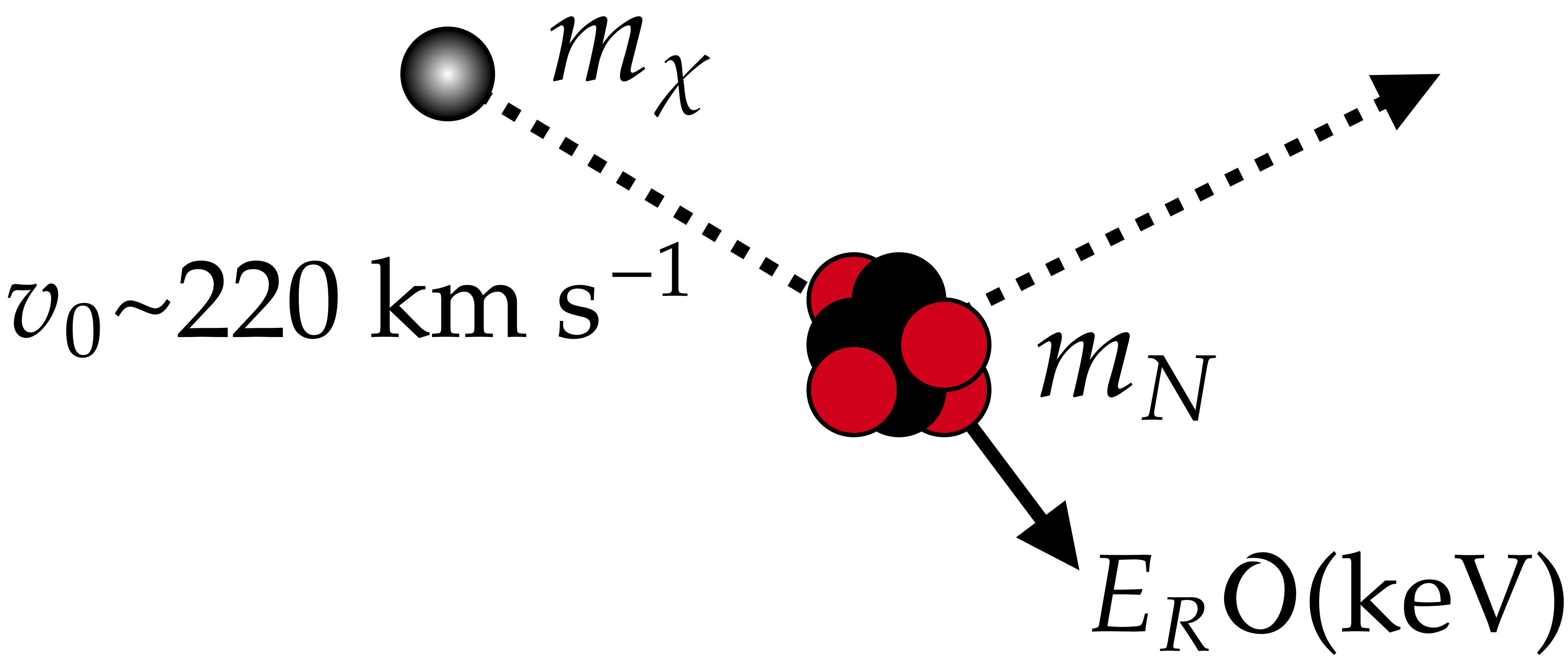


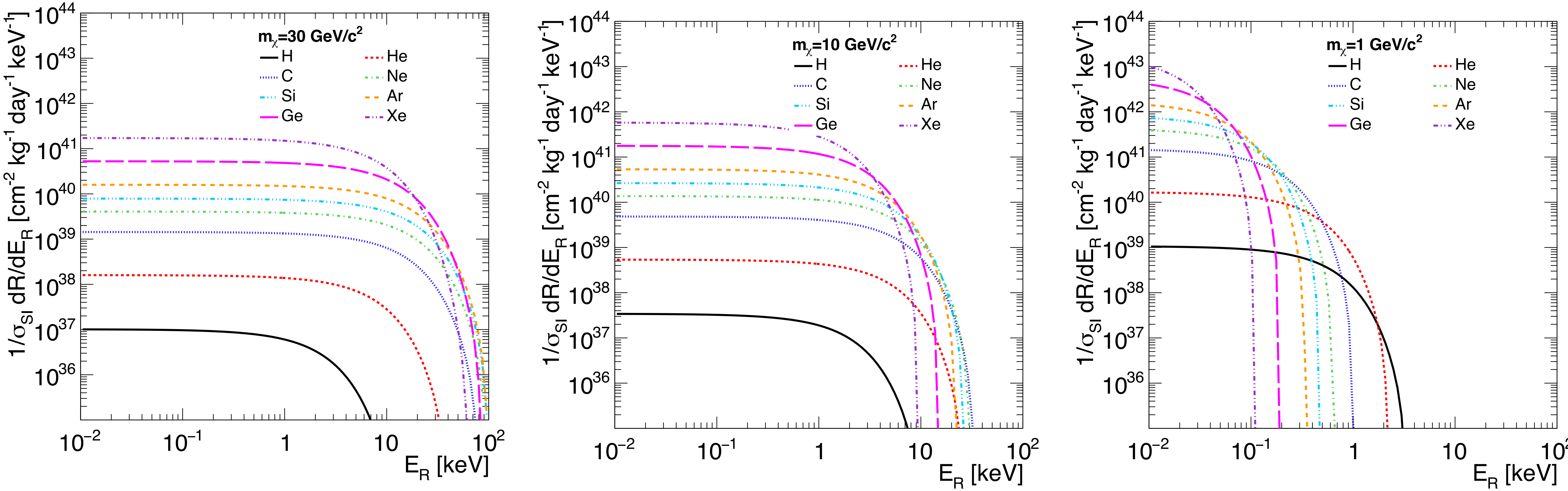
- **Many handles to confirm possible signals**
  - Recoil energy distribution
  - Seasonal flux variation
  - Directional detection

Dark Matter Direct Detection



- **Experimental challenges**
  - Rare events searches
  - Low recoil energies
  - Large backgrounds

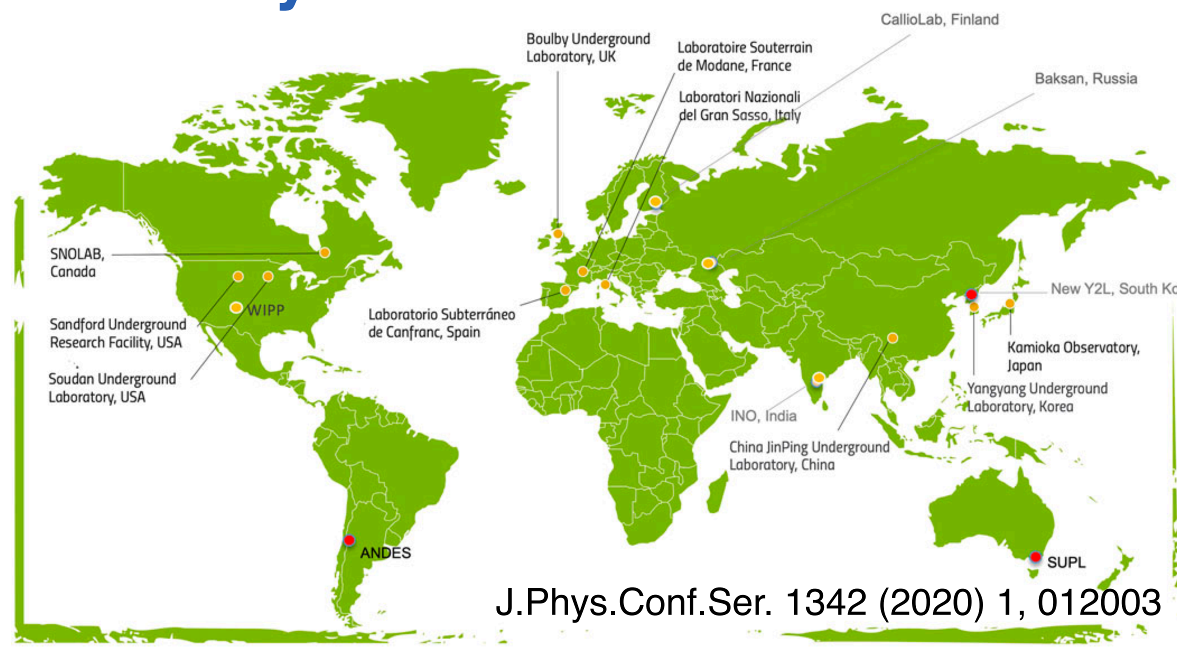
Recoil energy distribution



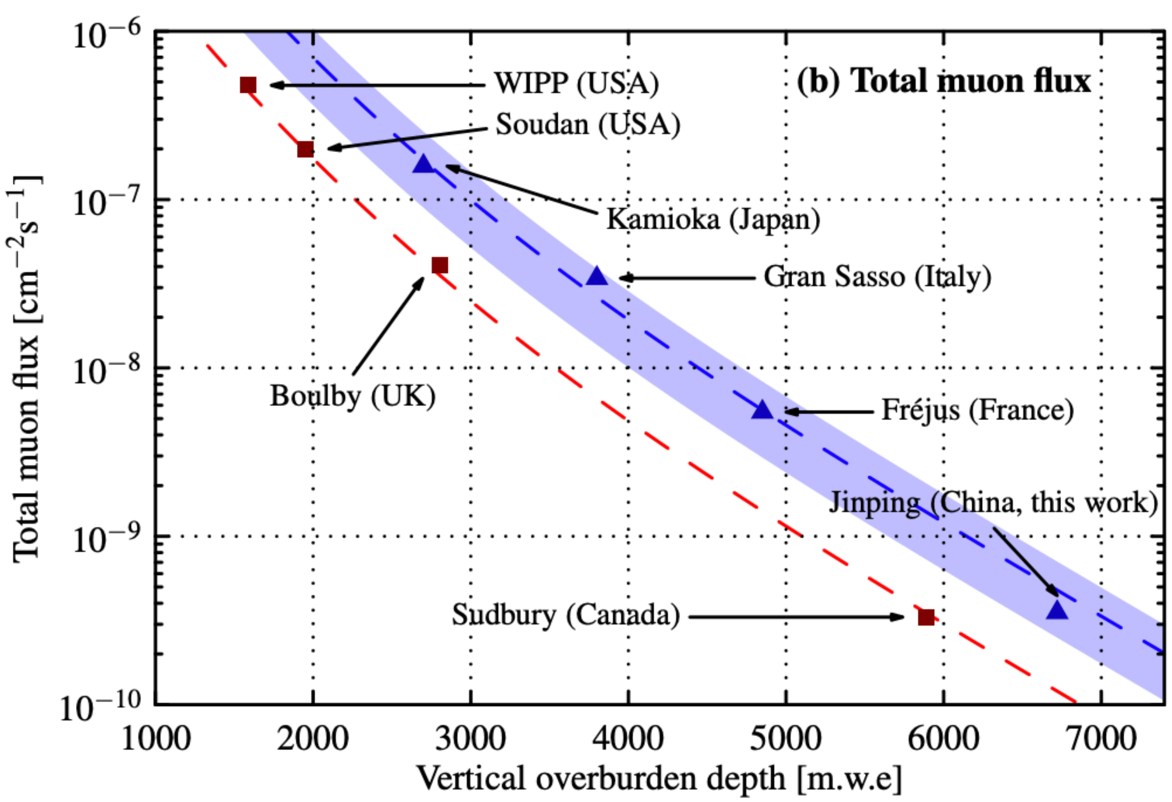
Decreasing DM mass

Deep underground laboratories

- **Low background requirements: suppress cosmic rays**
  - >10 laboratories in operation worldwide
  - Material screening facilities
    - HPGe, α-counting, ICP-MS
  - Copper electroformation
  - Exchange of expertise among laboratories
  - Multidisciplinary research
    - Geophysics, Biology



J.Phys.Conf.Ser. 1342 (2020) 1, 012003



Chin.Phys.C 45 (2021) 2, 025001

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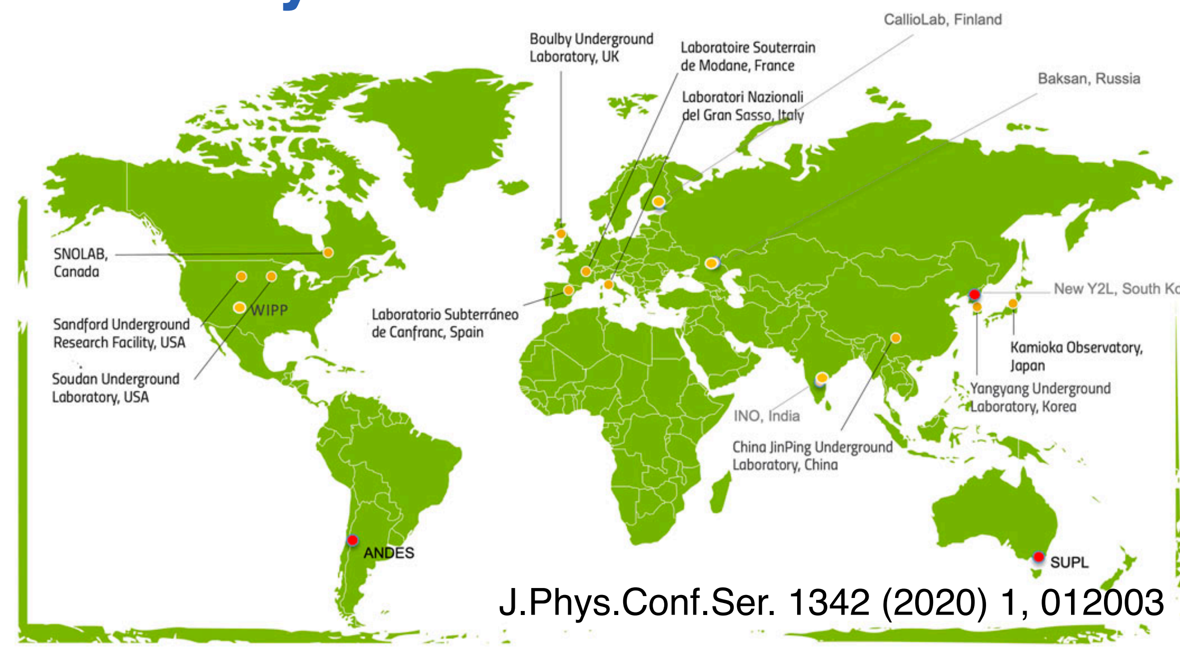

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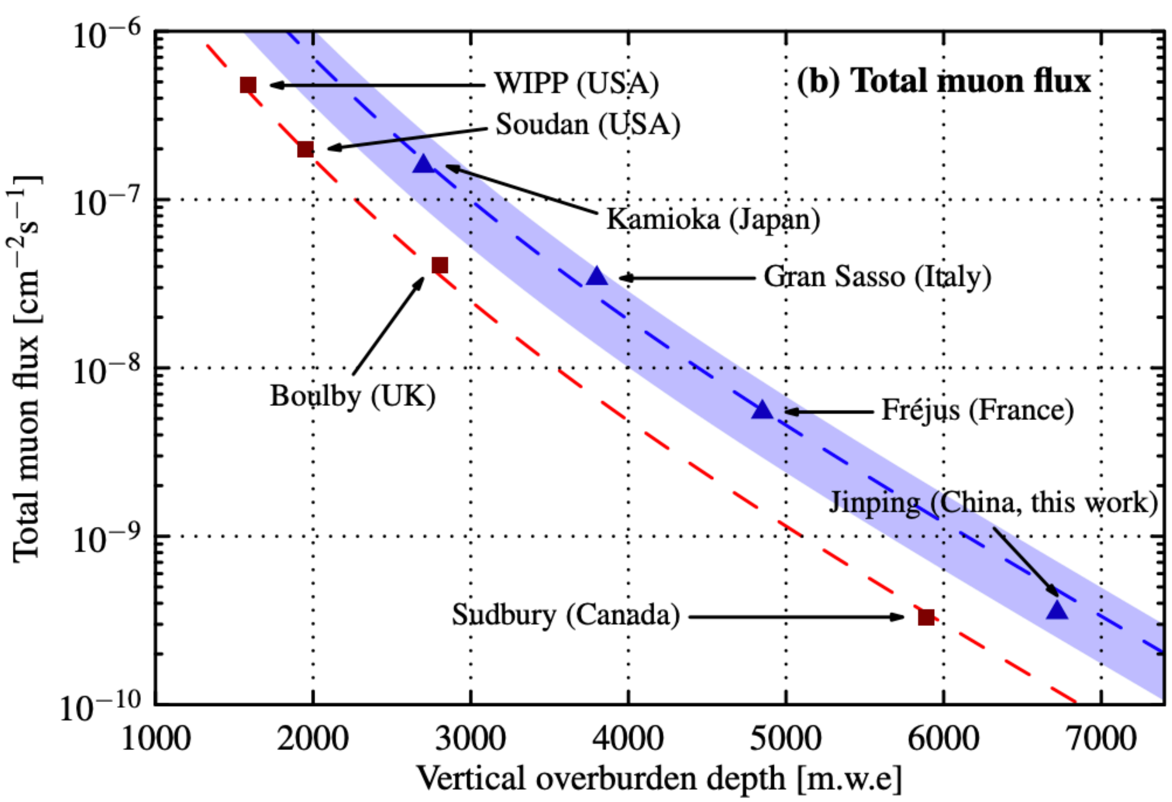

Chin.Phys.C 45 (2021) 2, 025001

	SNOLab	LNGS	LSC	Boulby	LSM	Callio Lab	Baksan	SURF	CJPL-I/II	Kamioka	Y2L
Date of creation	2003 (1991)	1987	2010	1989	1982	1995	1967	2007 (1967)	2009/ 2014	1983	2003 A6 2014 A5
Personnel	100	106	12	6	12	13	227	125	20	94	4
Surface U/S [m^2]	5350/ 3100	17000/ 95000	1600/ 2550	1700/ 400	400	220	1600/ 10000	1900/ 190	8000	15000/ 3000	300/ 60
Volume [m^3]	30000	**180000**	10000	7200	3500	1000*	23000	7160	4000/ **300000**	150000	5000
Depth [m]	2070	1400	850	1100	1700	1440	1700	1500	2400	1000	700
Access [V or H]	V	H	H	V	H	V / drive in	H	H	H	H	Drive in
Makeup Air [m^3/h]	12000	35000-60000	20000	300	5500	3600	1440	510000	_	6000	3300
Air change/day	10	5-8	48	24	38	7	_	144 (LUX)	_	6	15
Muon flux [m/m^2/s]	3.1 10^{-6}	3 10^{-4}	3 10^{-3}	4 10^{-4}	4.6 10^{-5}	1 10^{-4}	3 10^{-5}	5.3 10^{-5}	2 10^{-6}	10^{-3}	4 10^{-3}
Radon [Bq/m^3]	130	80	100	**<3**	15	70	40	300	40	80	40
Cleanliness	2000 or better	Only in sector	Only in sector	10000	ISO9	Only in sector	Only in sectors	3000	Only in sectors	Only in sectors	Only in sectors

A. Ianni, TAUP'17

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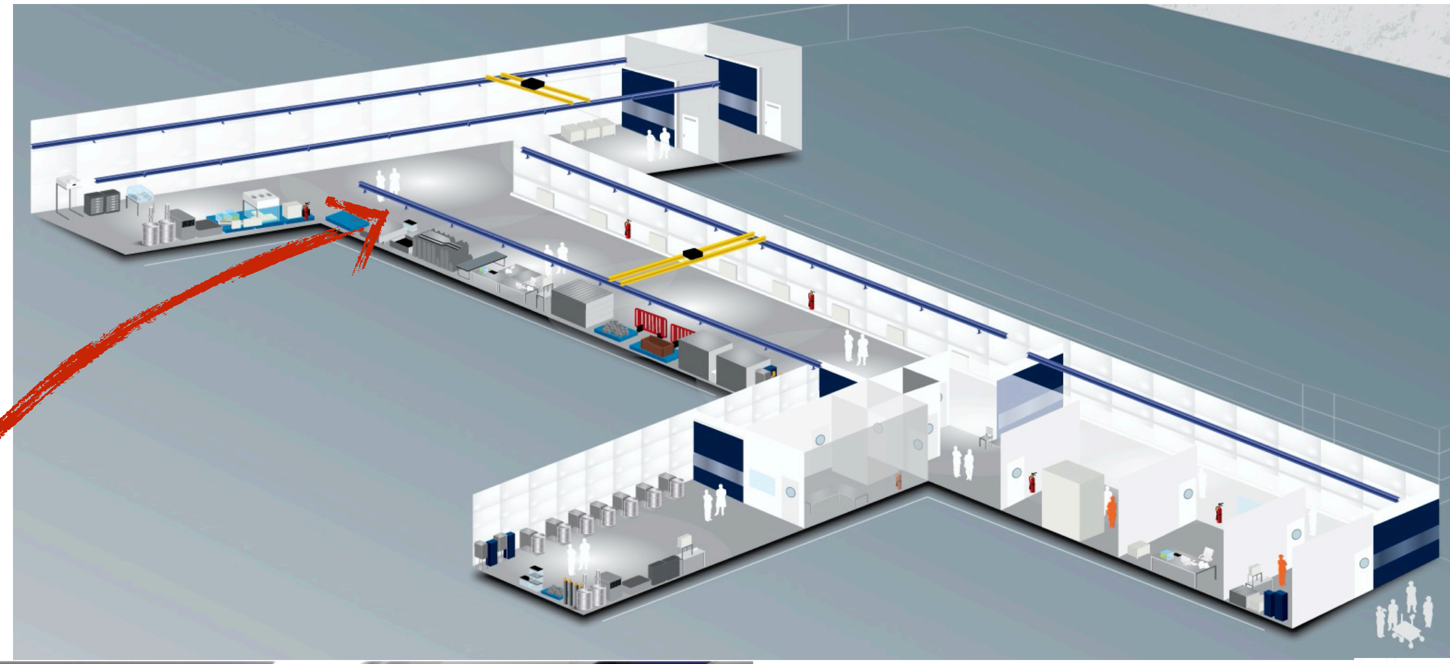


BOULBY UNDERGROUND LABORATORY

UKRI Science and Technology Facilities Council

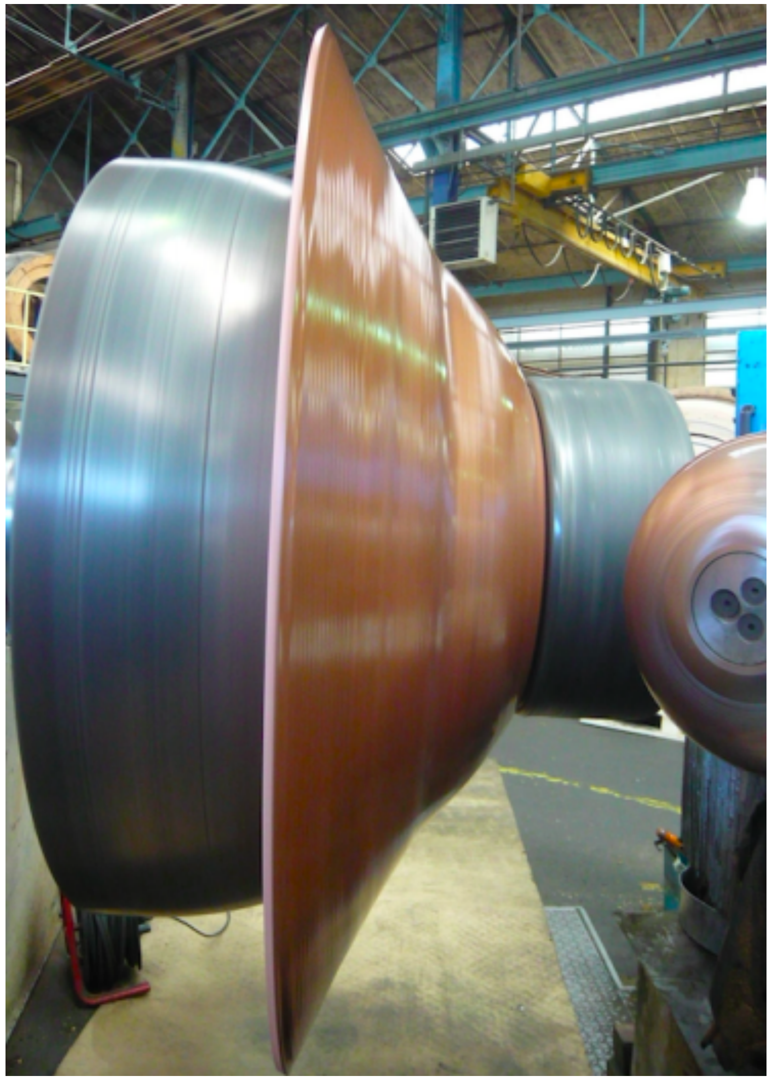
10
10
10
10
10
Total muon flux [cm^{-2}s^{-1}]

Chir

A. Ianni, TAUP'17

High purity materials

- **Copper common material for rare event experiments**
  - Strong enough to build gas vessels
  - No long-lived isotopes (^{67}Cu $t_{1/2}$=62h)
  - Low cost/commercially available at high purity
- **Backgrounds**
  - Cosmogenic: ^{63}Cu(n,α)^{60}Co from fast neutrons
  - Contaminants: ^{238}U/^{232}Th decay chains



4N Aurubis AG Oxygen Free Copper (99.99% pure)

- Spun into two hemispheres
- Electron-beam welded together

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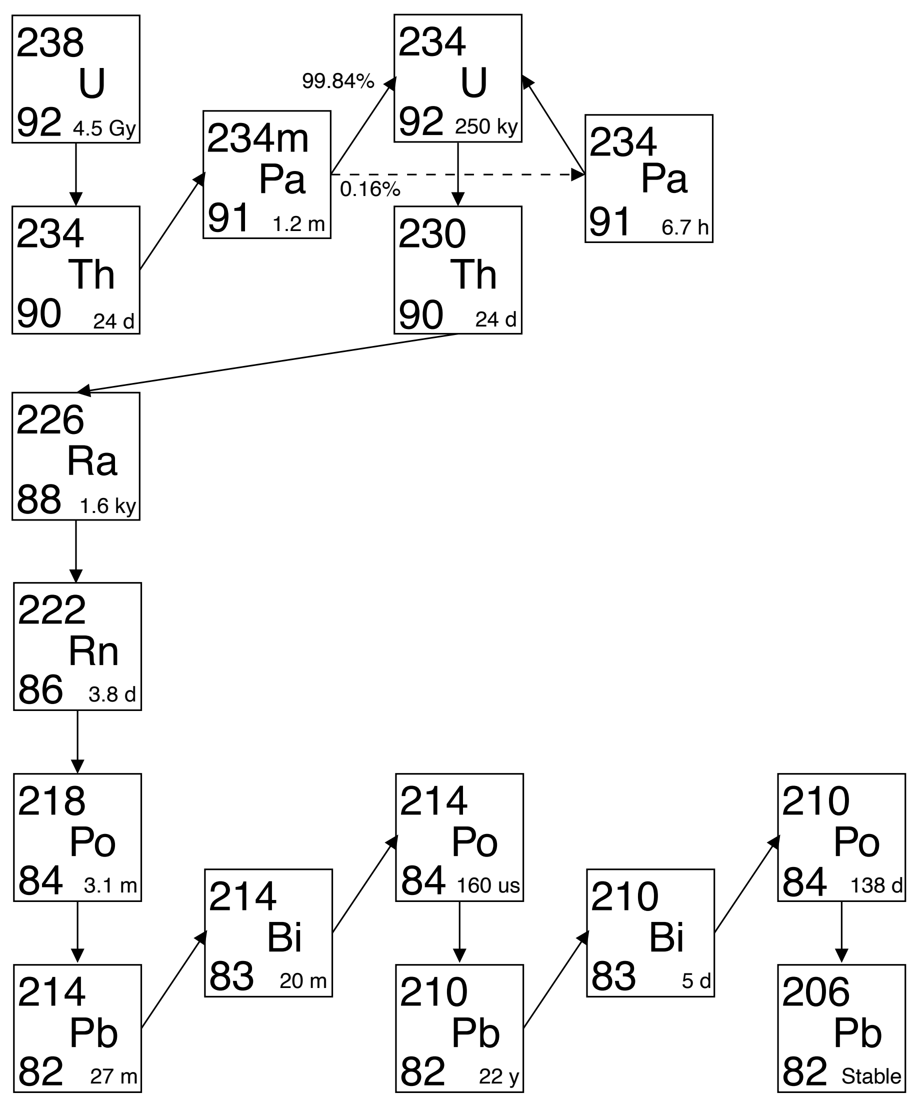

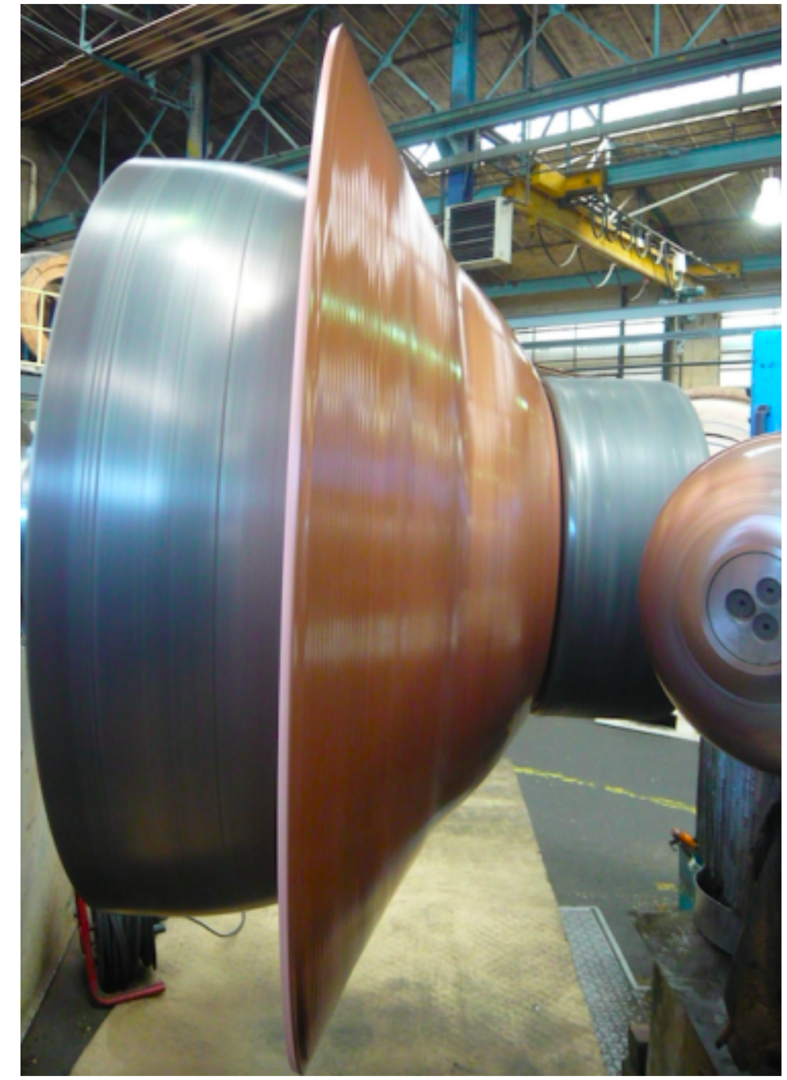

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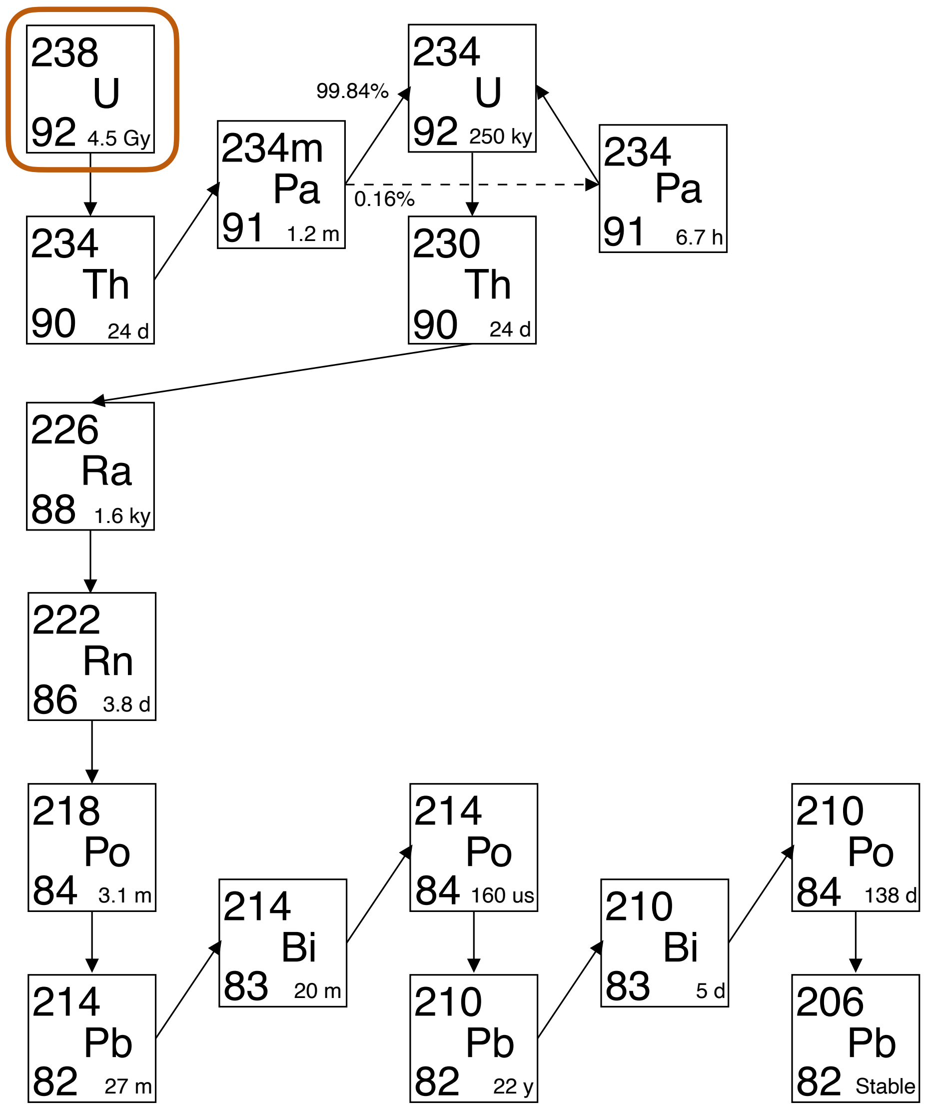
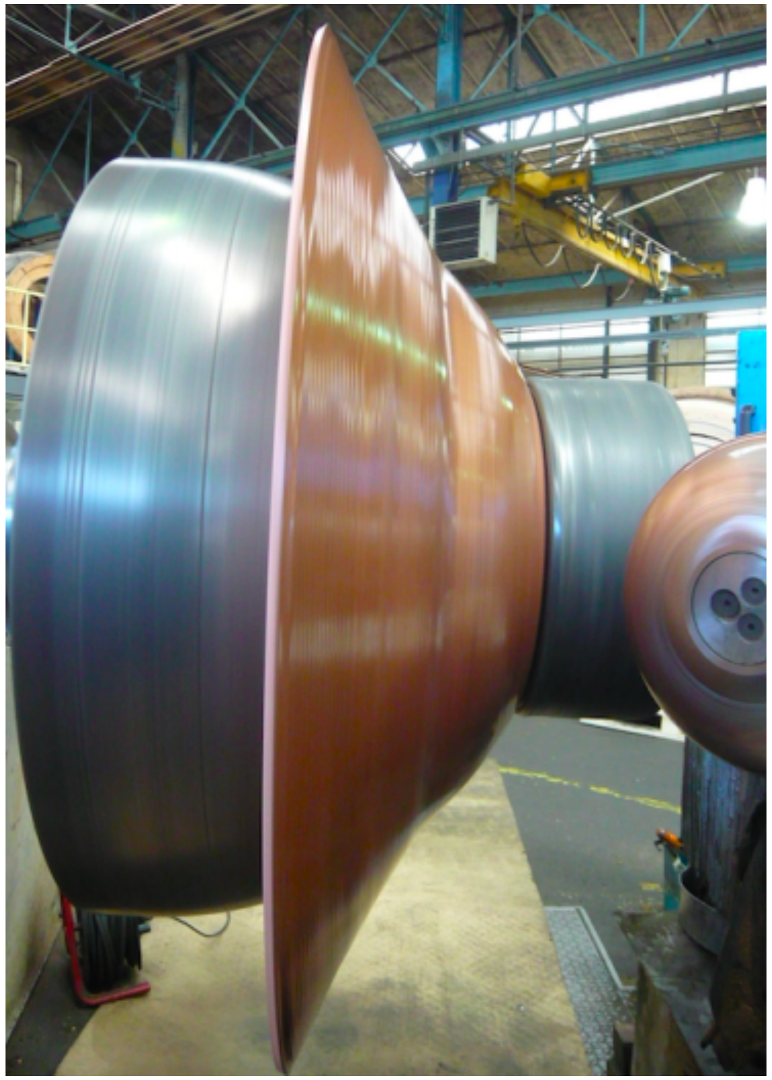
directly measured with mass spectrometers ~10 µBq/kg





4N Aurubis AG Oxygen Free Copper (99.99% pure)
- Spun into two hemispheres
- Electron-beam welded together

High purity materials

- **Copper common material for rare event experiments**
  - Strong enough to build gas vessels
  - No long-lived isotopes (^{67}Cu $t_{1/2}$=62h)
  - Low cost/commercially available at high purity
- **Backgrounds**
  - Cosmogenic: ^{63}Cu(n,α)^{60}Co from fast neutrons
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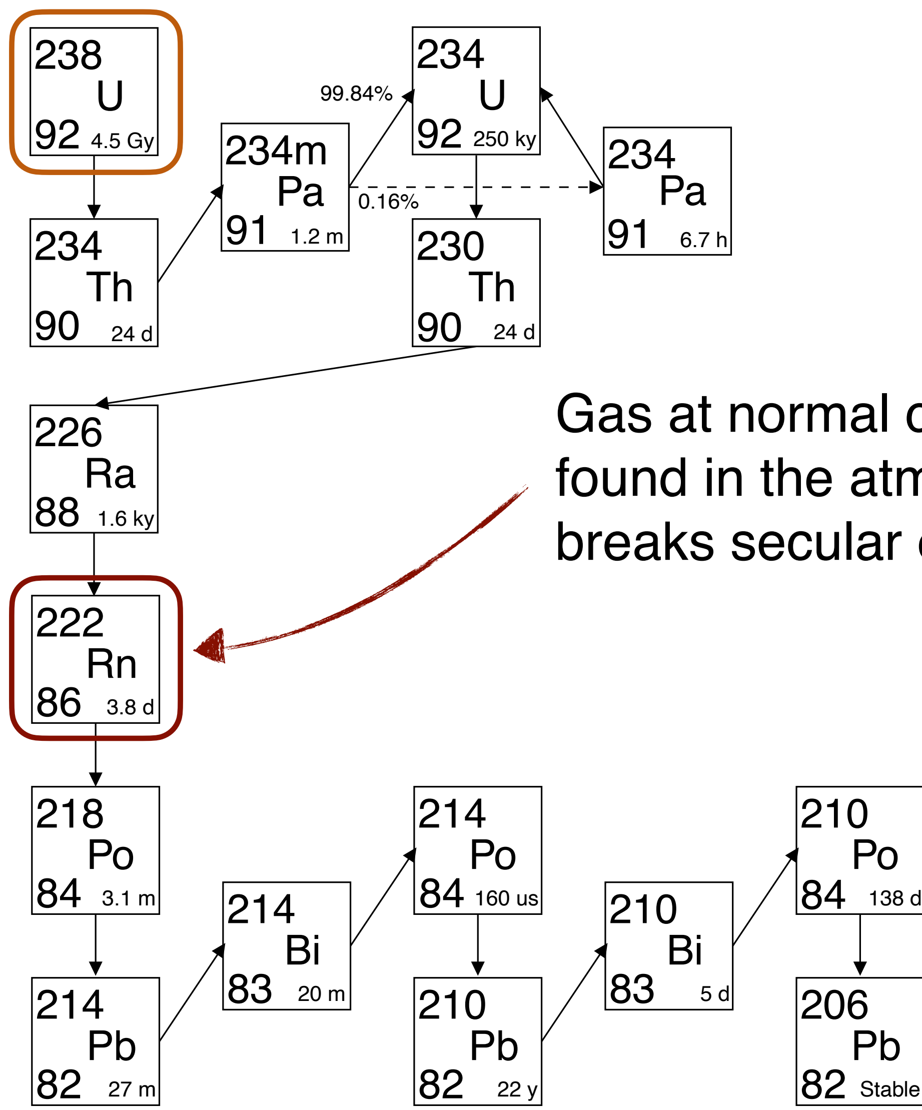
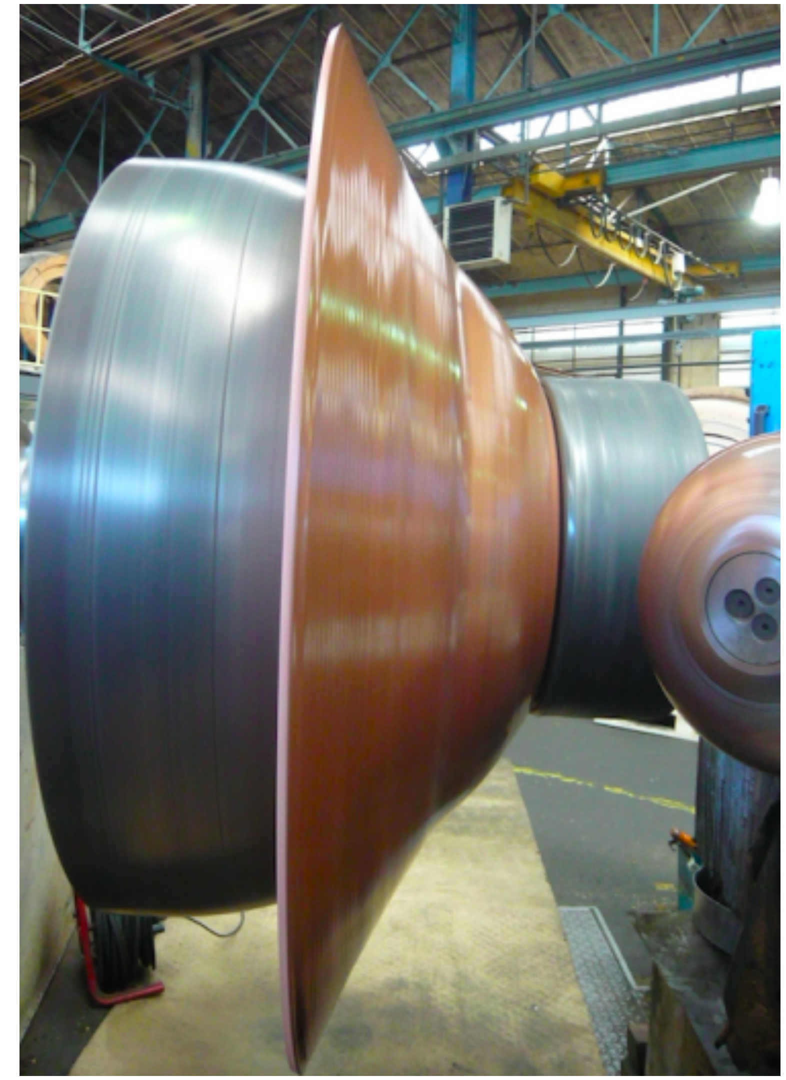


Gas at normal conditions: found in the atmosphere breaks secular equilibrium



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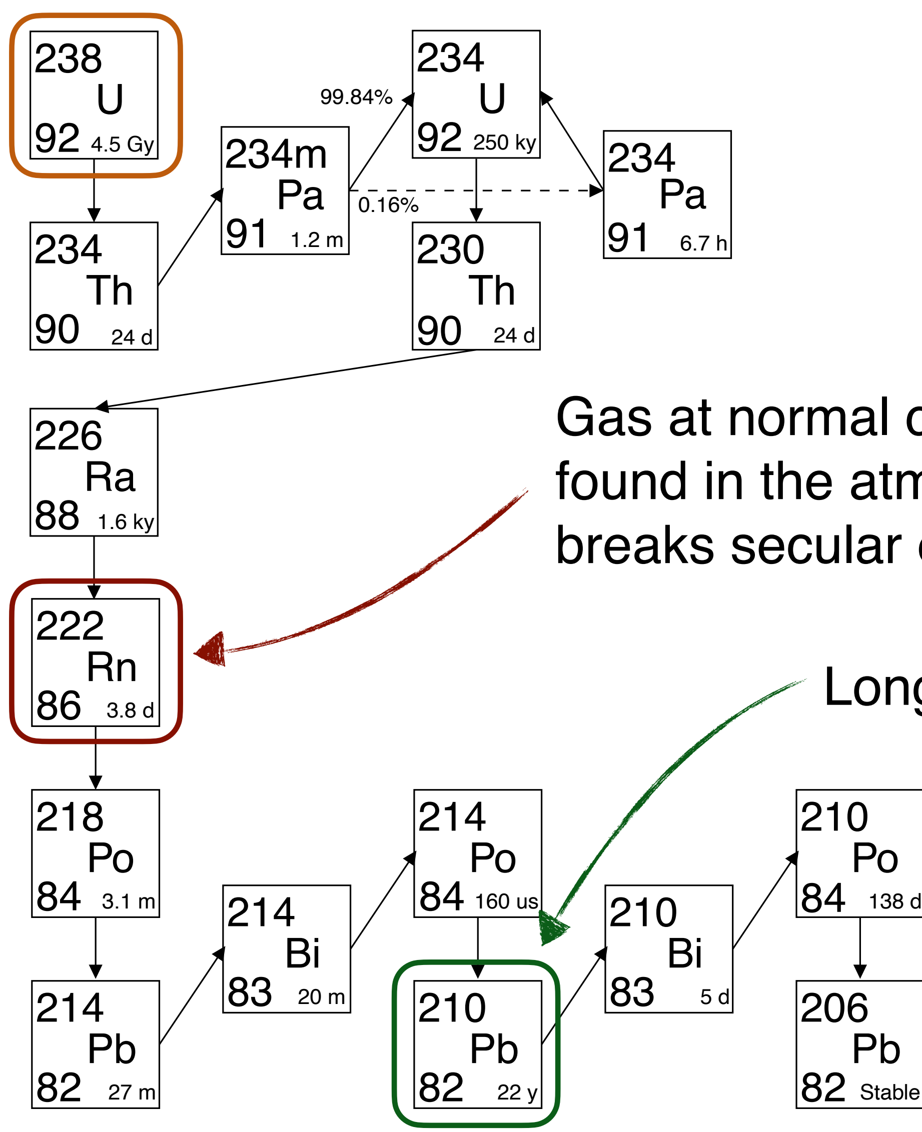
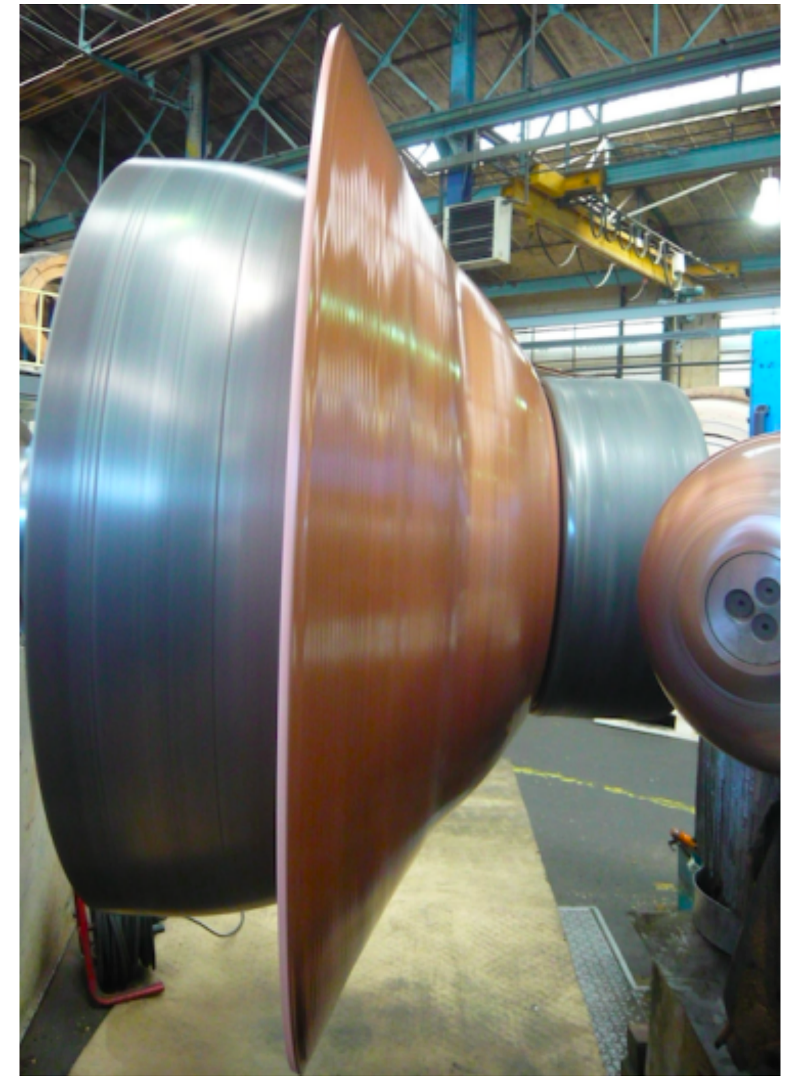


Gas at normal conditions: found in the atmosphere breaks secular equilibrium

Long-lived!



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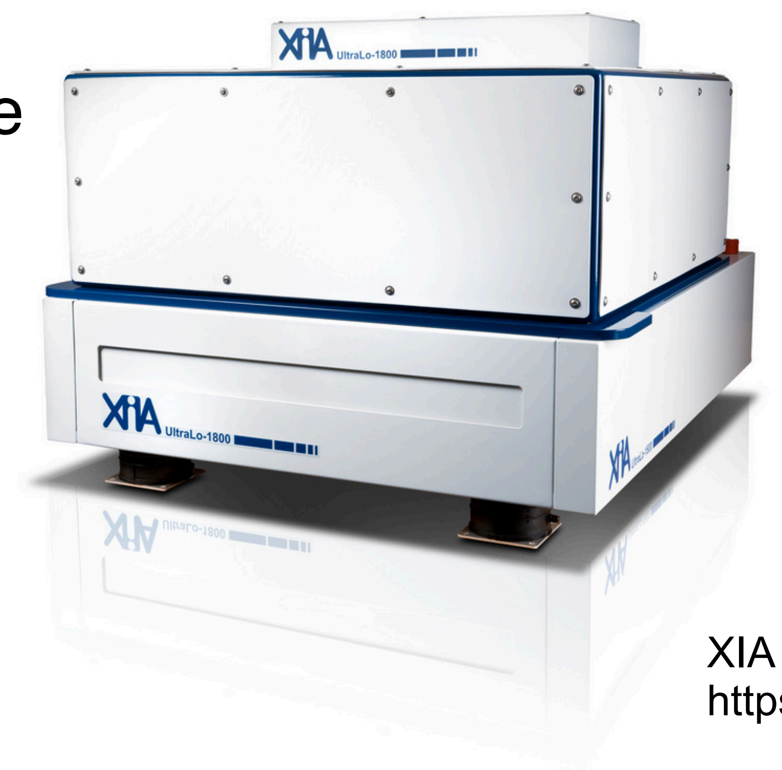
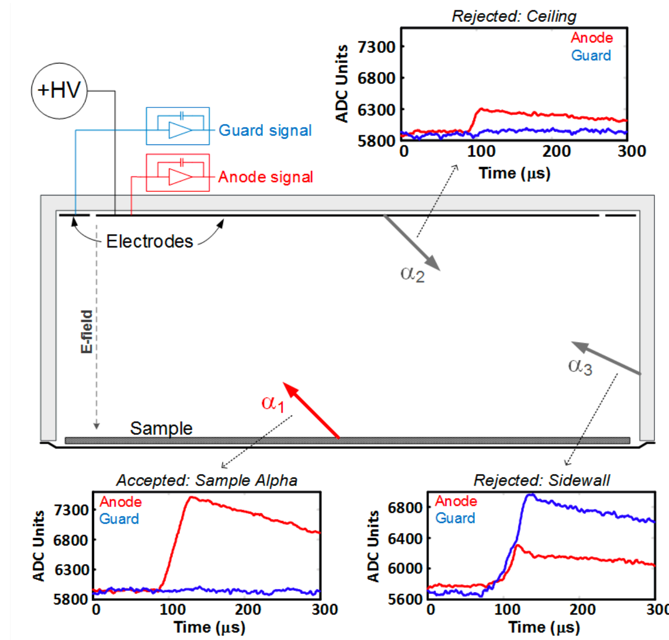
High purity materials

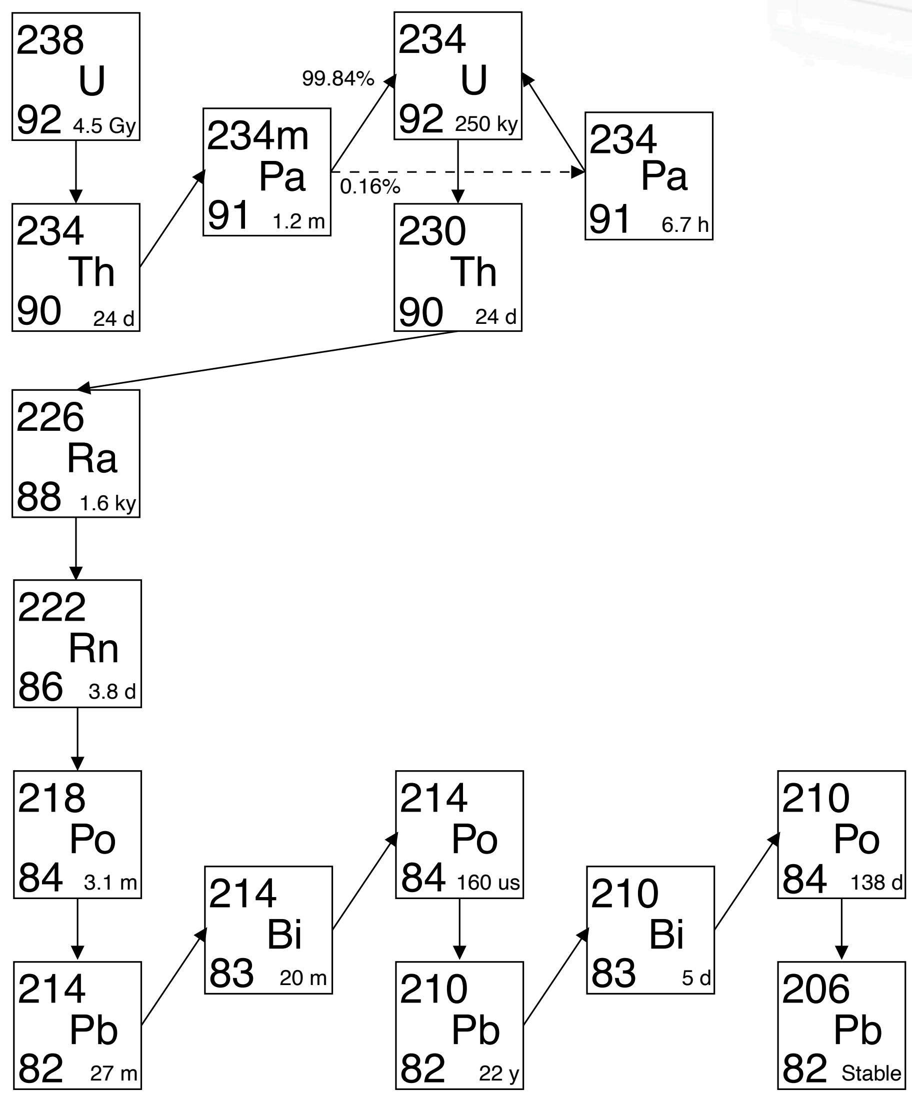
- **Low background α-particle counting**
  - Background suppression through pulse shape discrimination

Recent development





XIA UltraLo-1800
https://www.xia.com/ultralo-theory.html



NIM A 988 (2021) 164844

High purity materials

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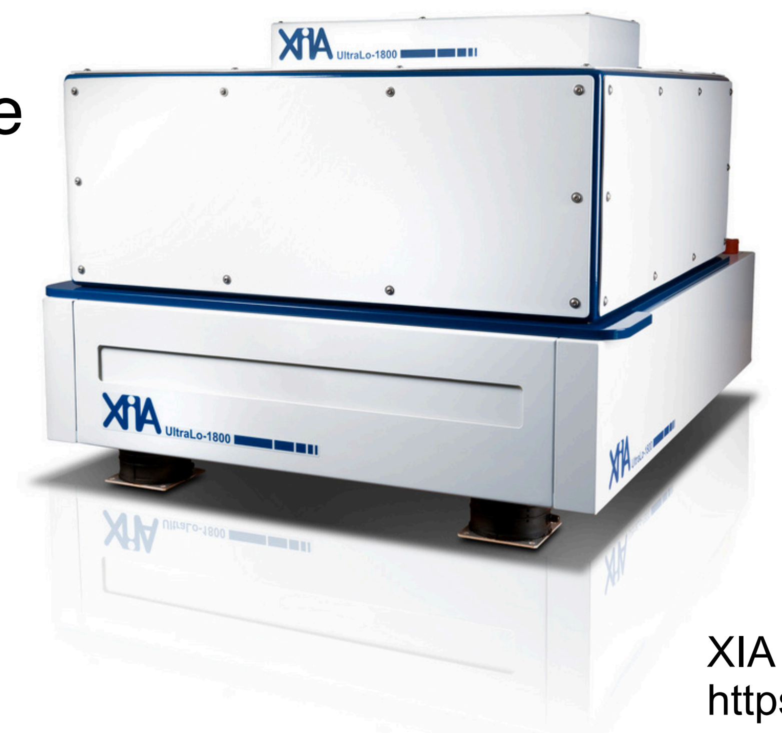

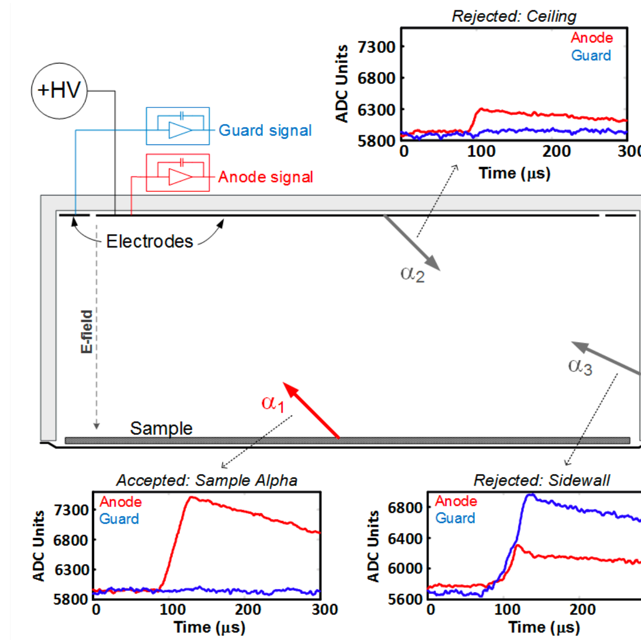

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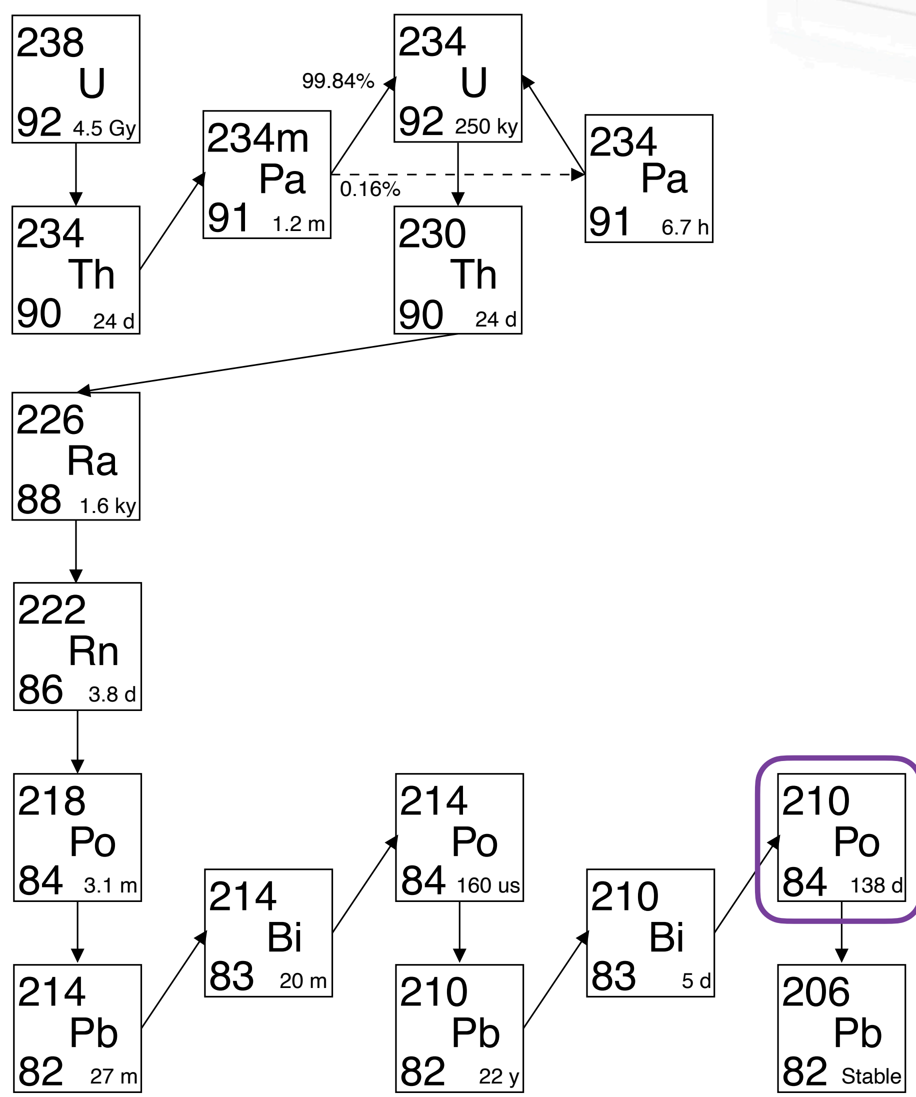

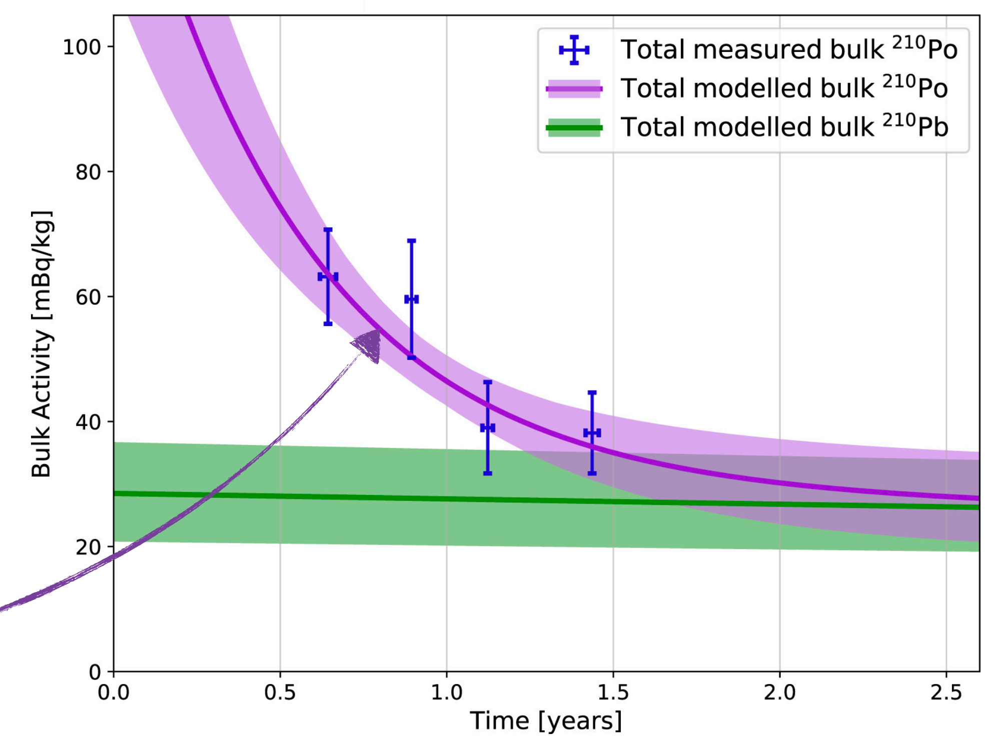

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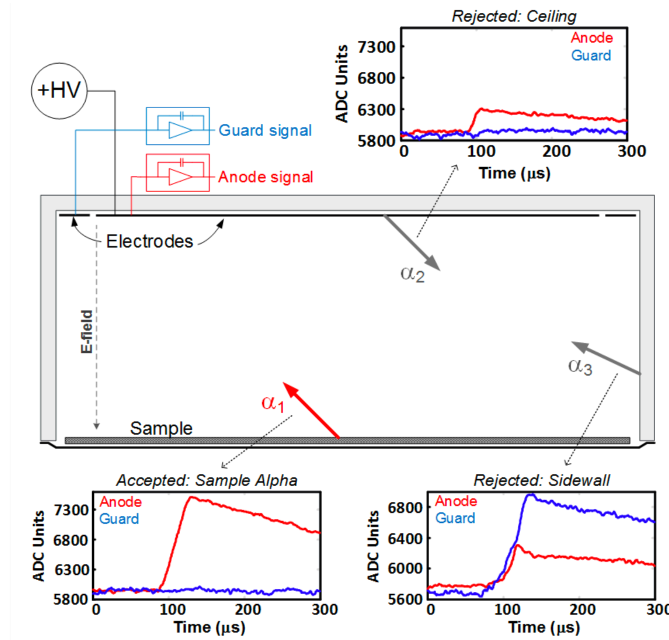

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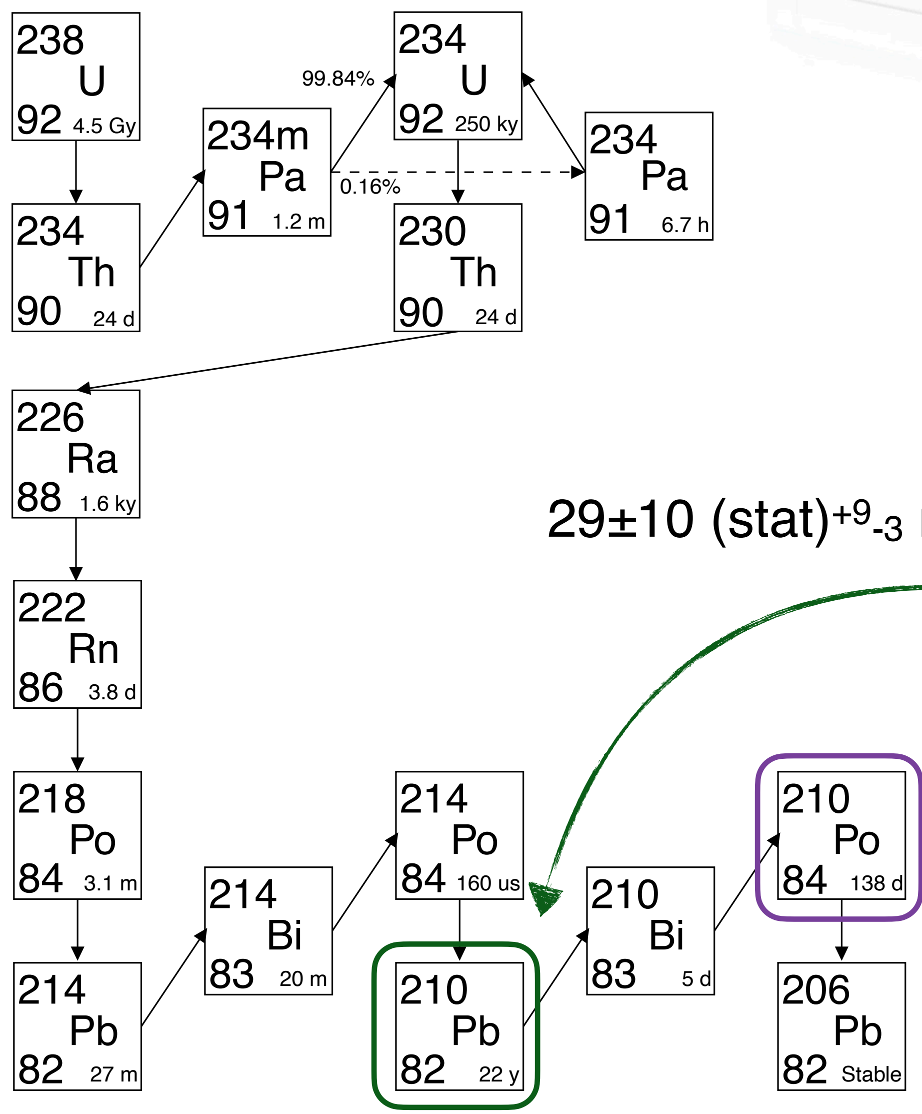
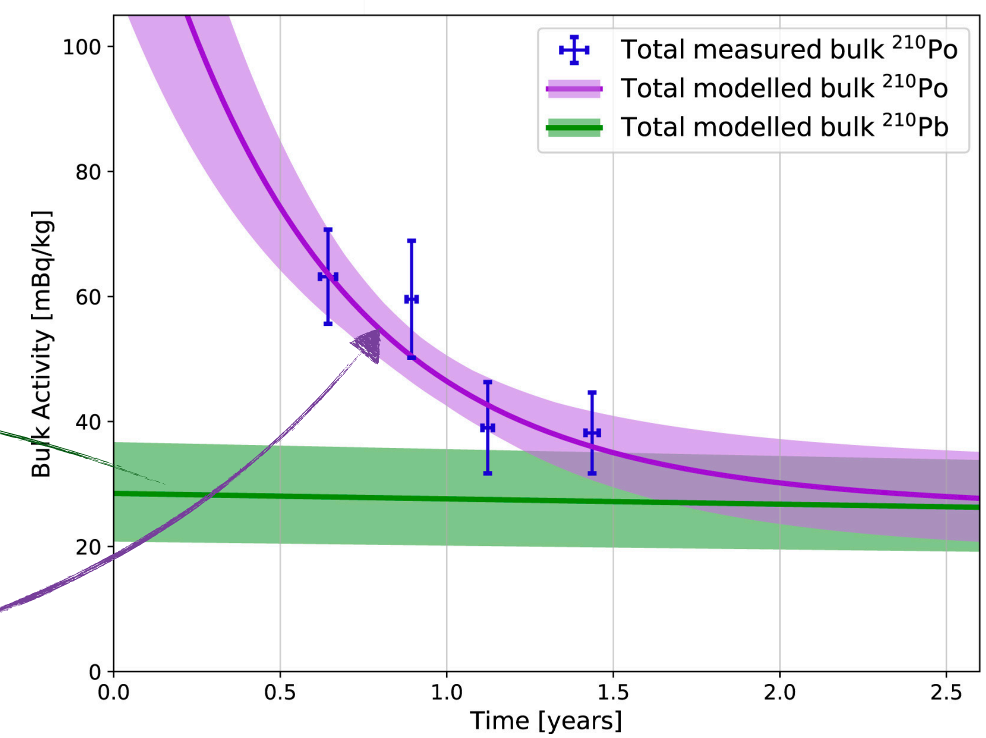


$29 \pm 10\ (\text{stat})^{+9}_{-3}$ mBq/kg



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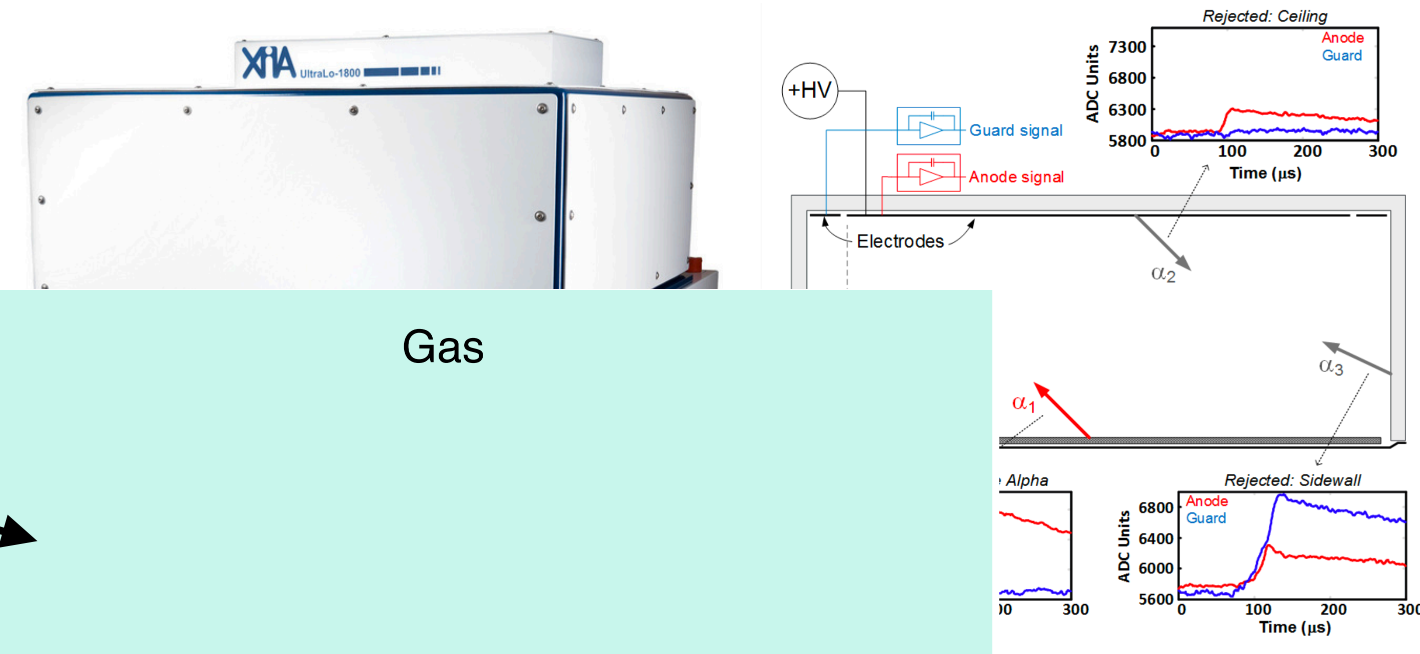
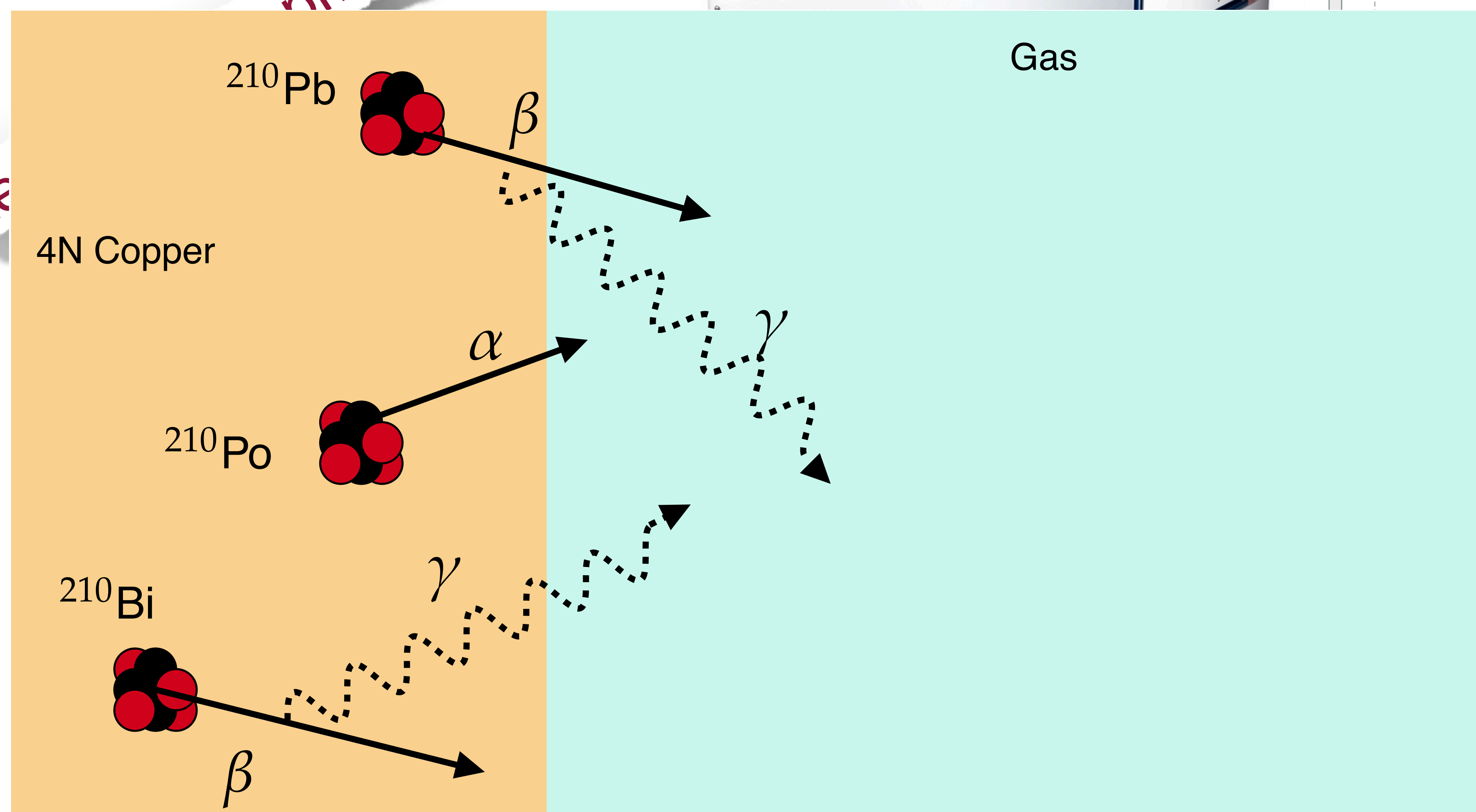
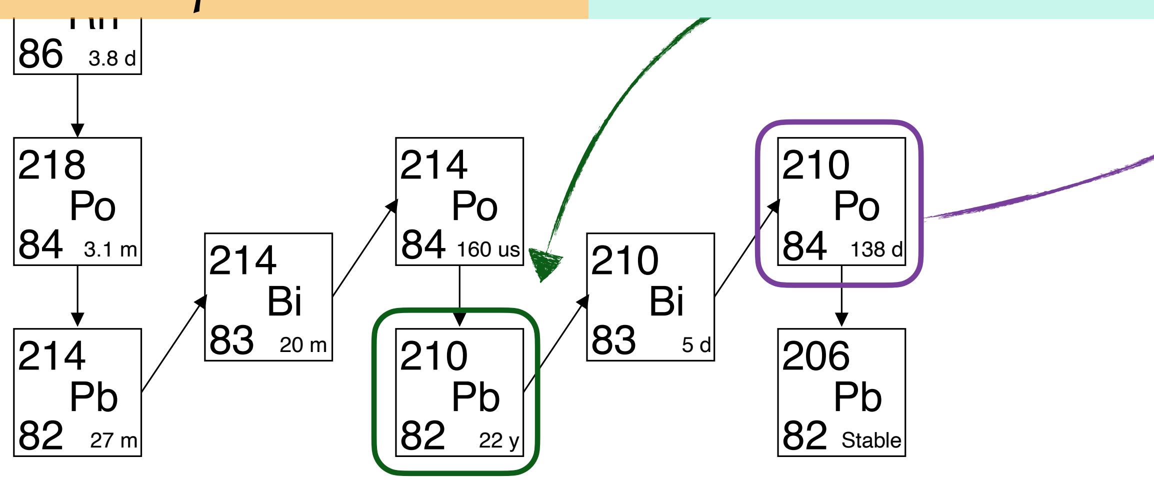
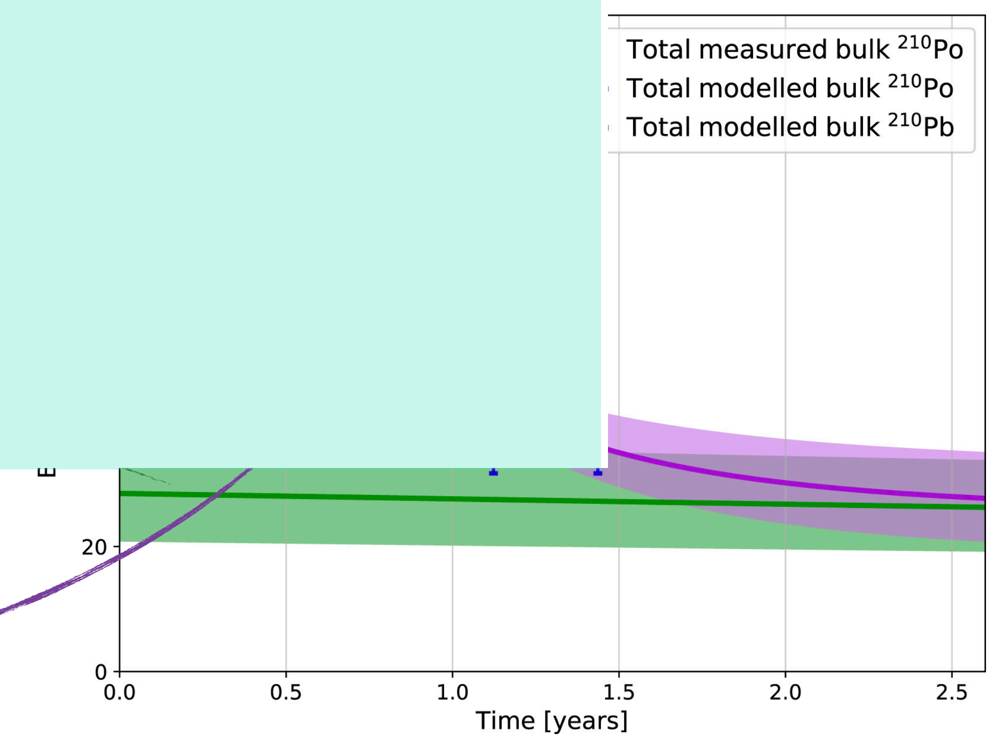


om/ultralo-theory.html







NIM A 988 (2021) 164844

Copper Electroplating

Internal shield: add a layer of extremely radio-pure copper

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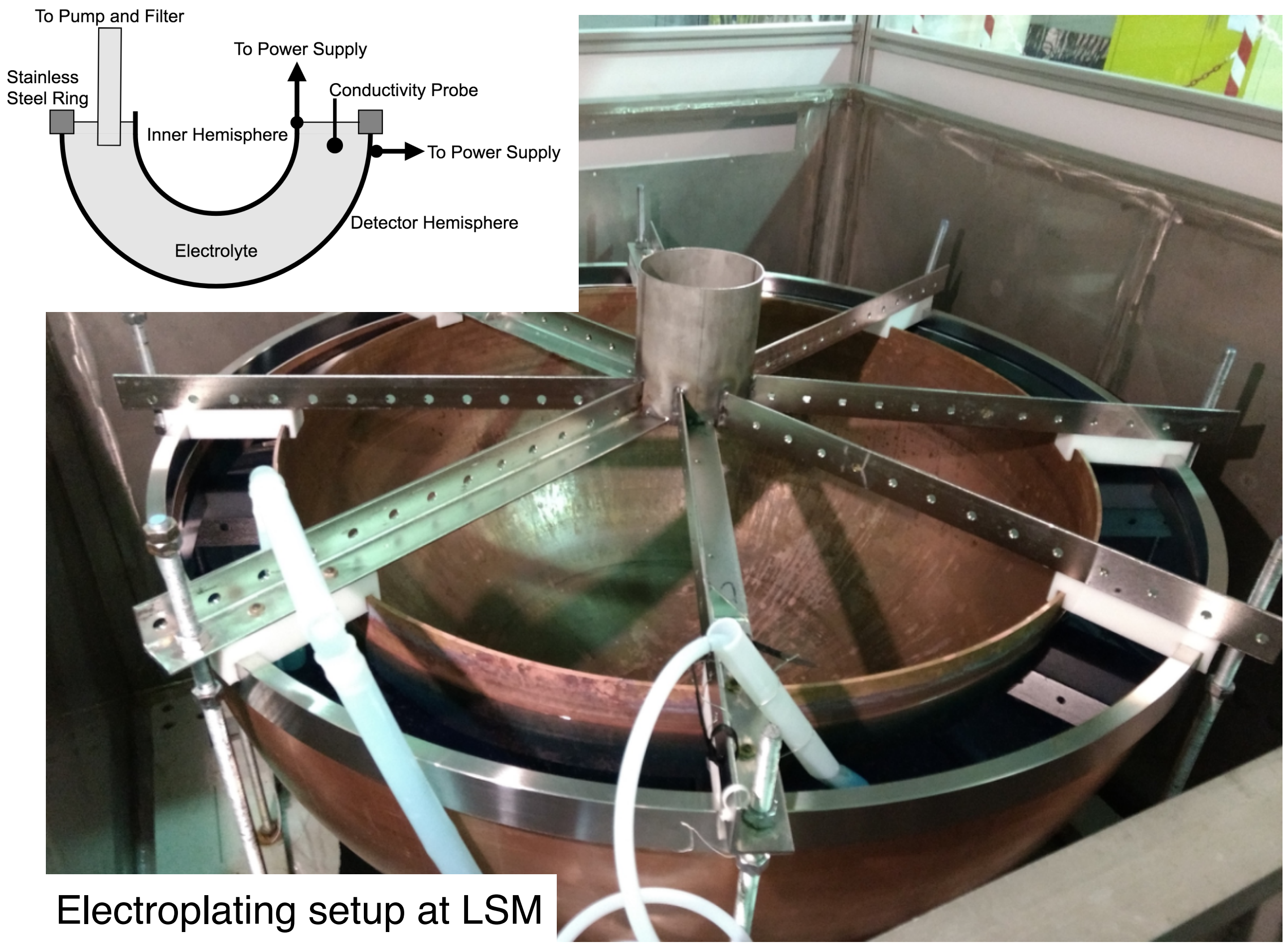

Electroplating setup at LSM

NIM A 988 (2021) 164844

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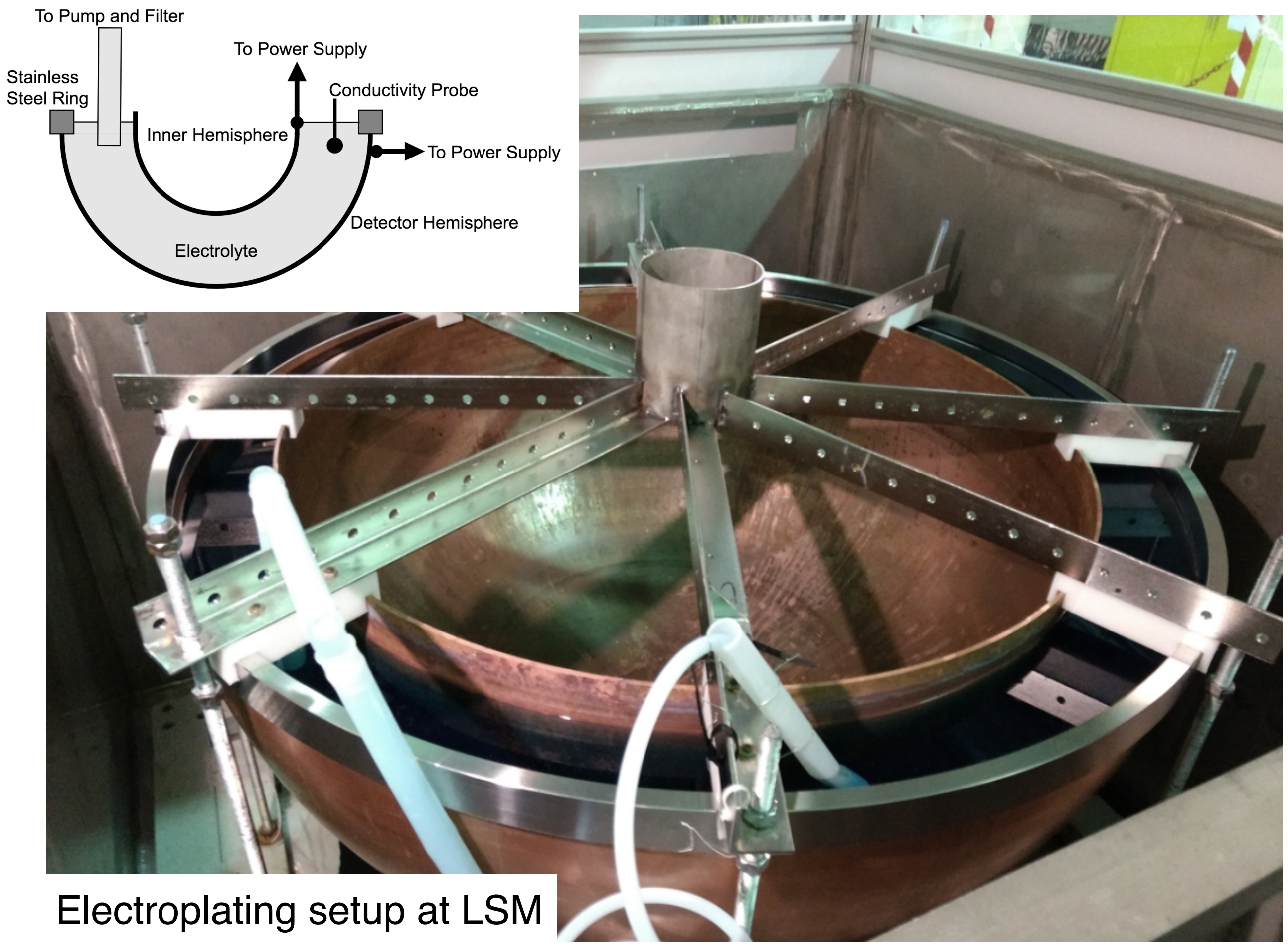

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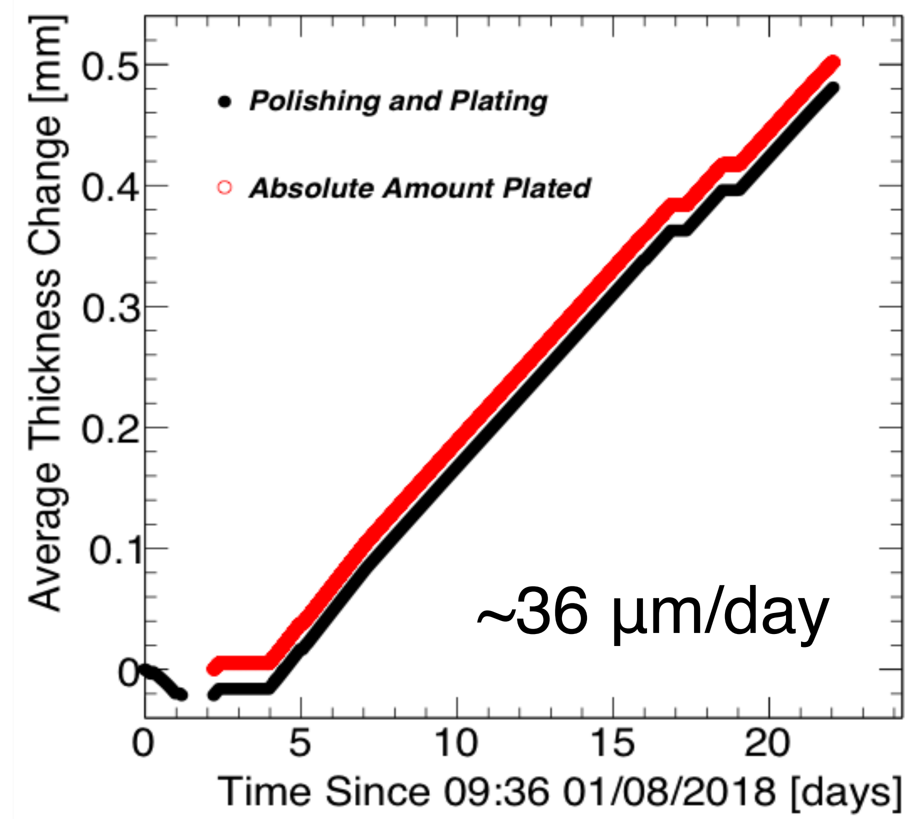

NIM A 988 (2021) 164844

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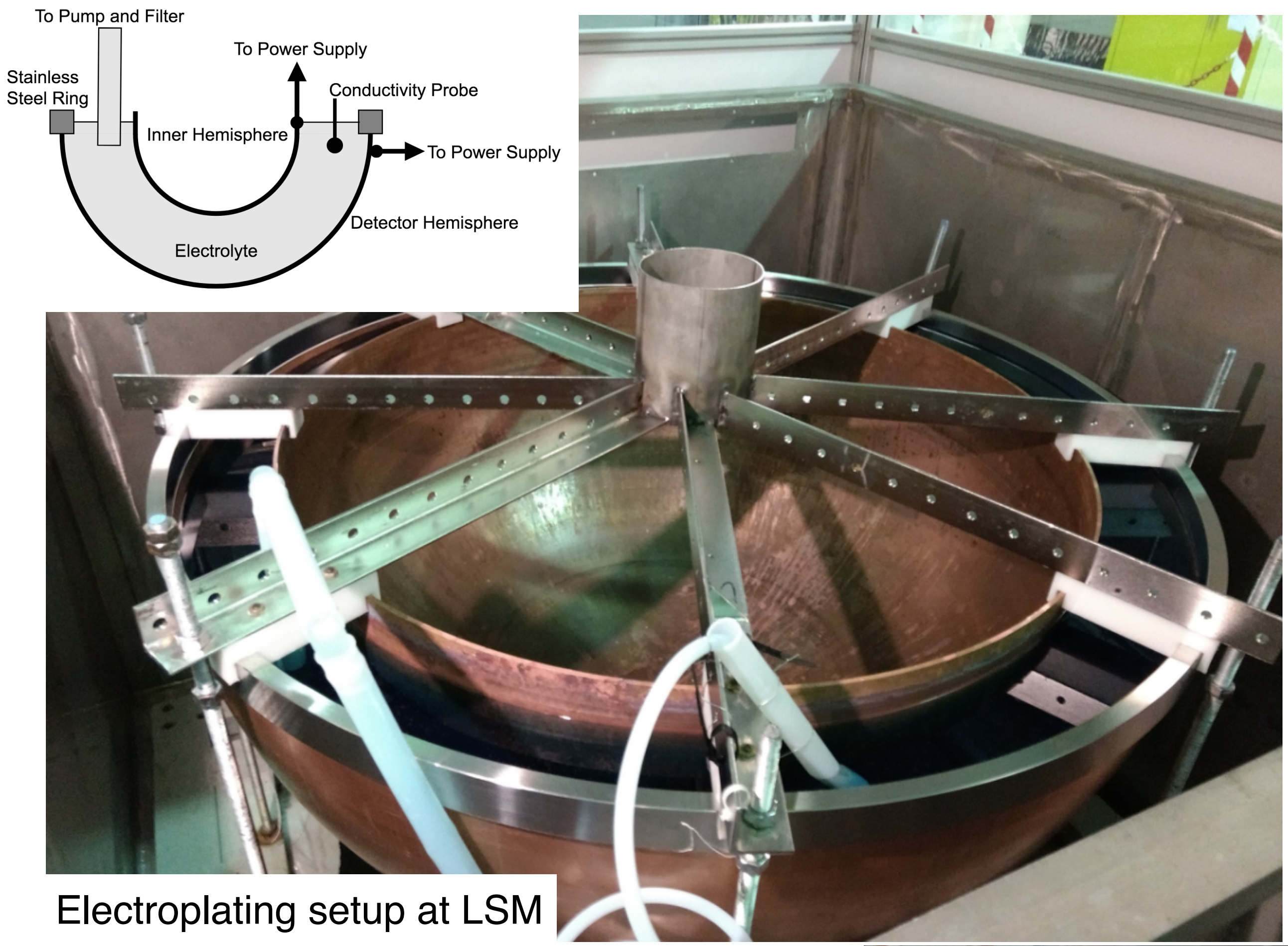

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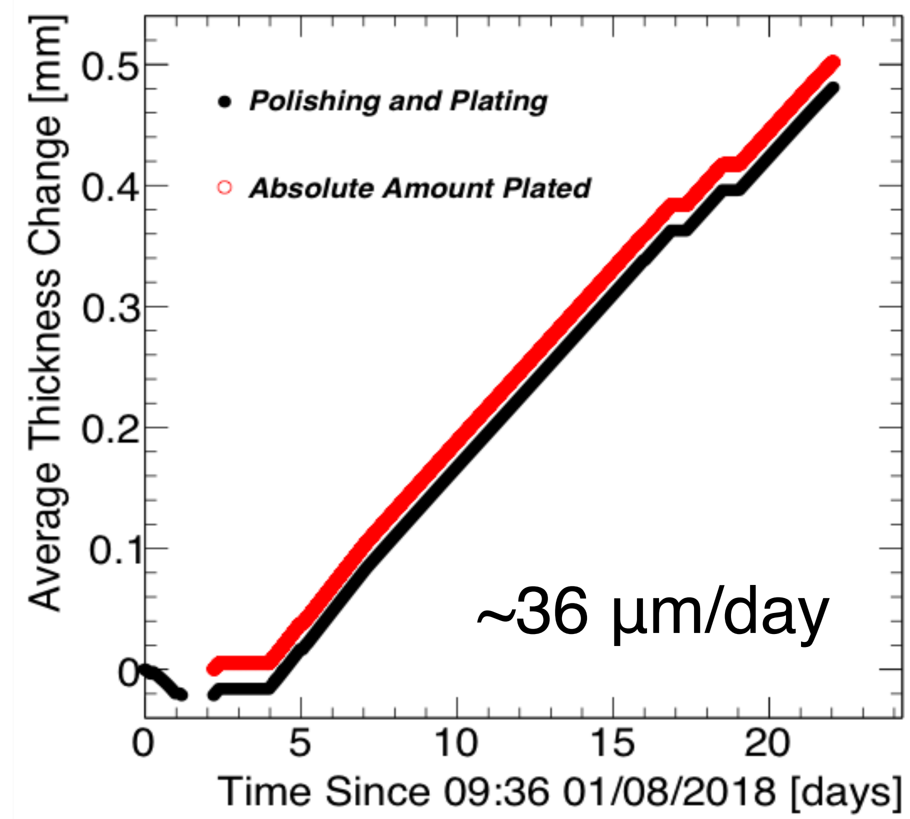
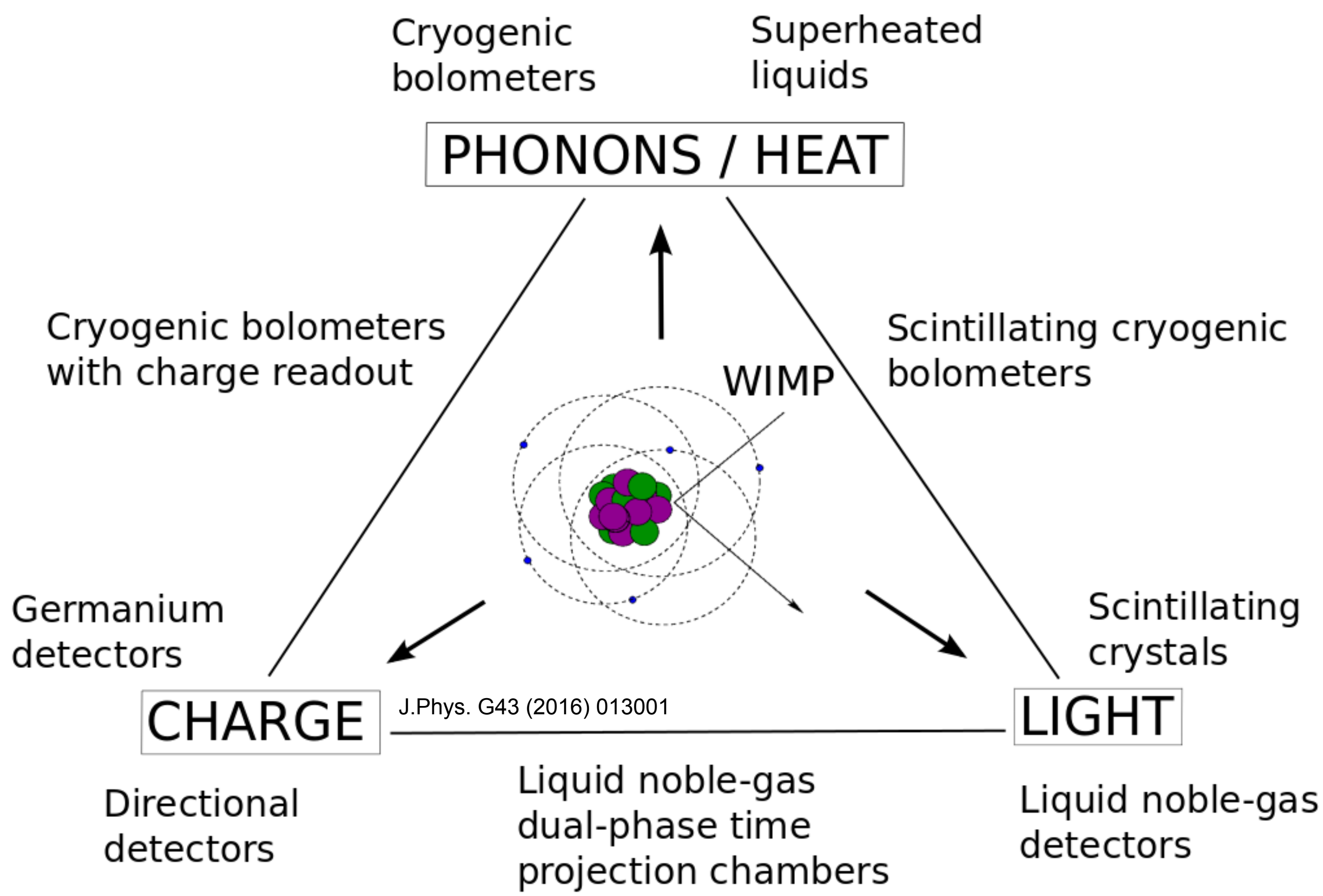


Sample	Weight [g]	^{232}Th [µBq/kg]	^{238}U [µBq/kg]
C10100 Cu (Machined)	-	8.7 ± 1.6	27.9 ± 1.9
Cu Electroformed	-	< 0.119	< 0.099
Hemisphere 1	0.256	< 0.58	< 0.26
Hemisphere 2	0.614	< 0.24	< 0.11

NIM A 988 (2021) 164844

Direct Detection Signals



- **Nuclear recoil deposits energy in several forms**
- **Experiments sensitive to one or more of these**
  - Multiple signals → background suppression

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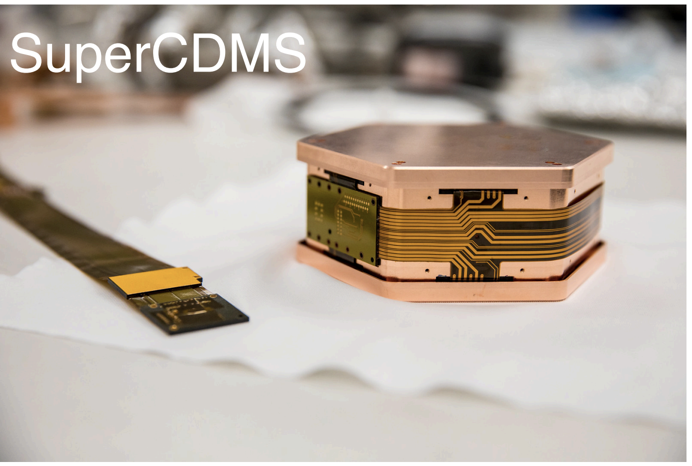
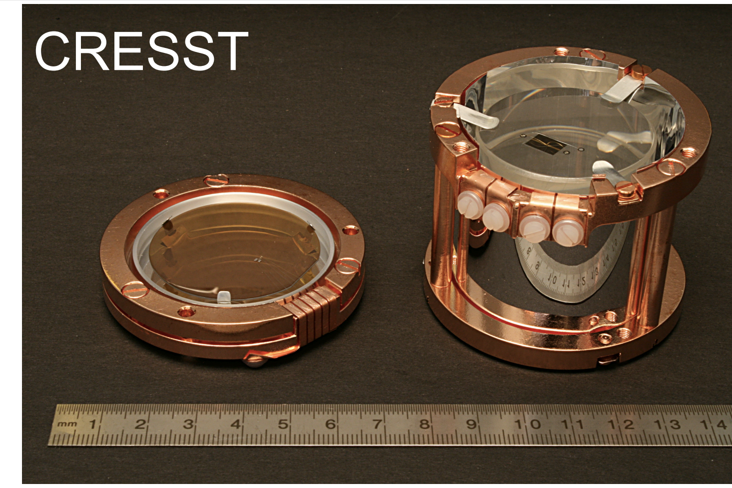
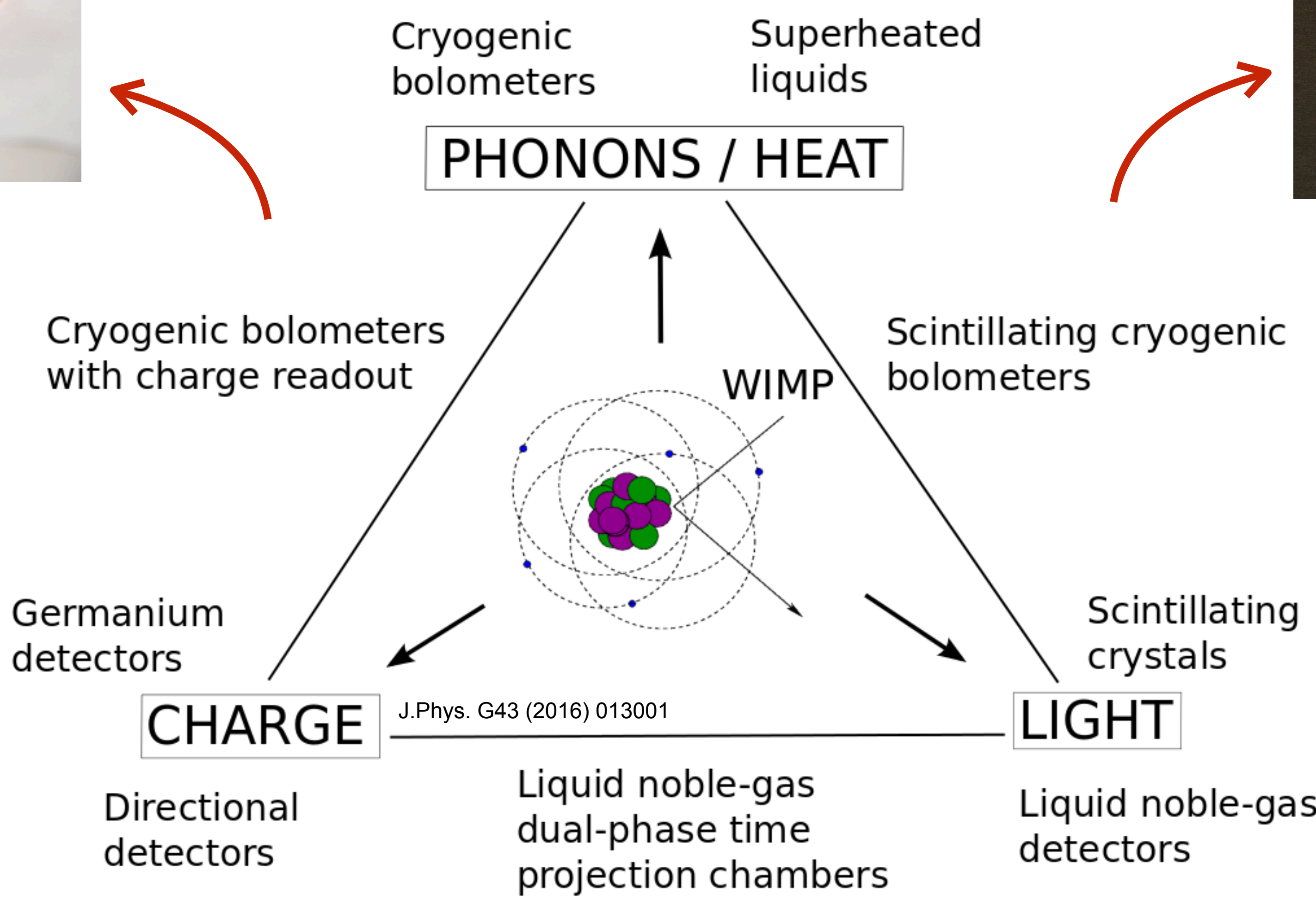


Ge, Si:
SuperCDMS
EDELWEISS



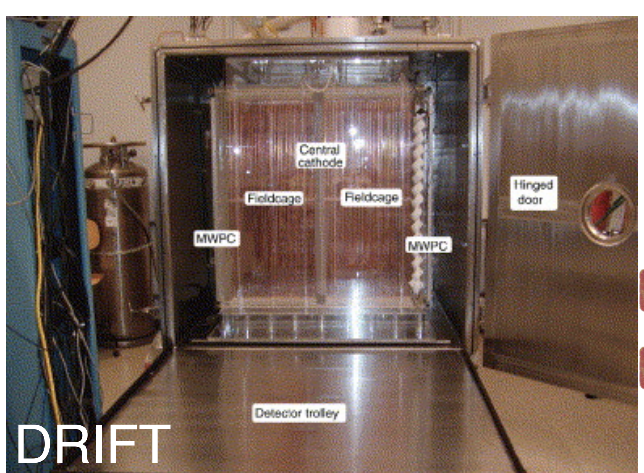
CaWO$_4$: CRESST
NaI: COSINUS



Ar: DEAP-3600
CsI: KIMS
NaI: ANAIS
DAMA/LIBRA,
COSINE, SABRE

C$_3$F$_8$: PICO
Ge: CDEX
Si: DAMIC, SENSEI
Ar, Ne: TREX-DM
He:SF$_6$: DRIFT/CYGNUS
Ag, Br, C: NEWSdm
H, He, Ne: NEWS-G

Xe: LZ, PandaX-4T, XENONnT, DARWIN
Ar: DarkSide-50, DarkSide-20k, ARGO



XENON-1T

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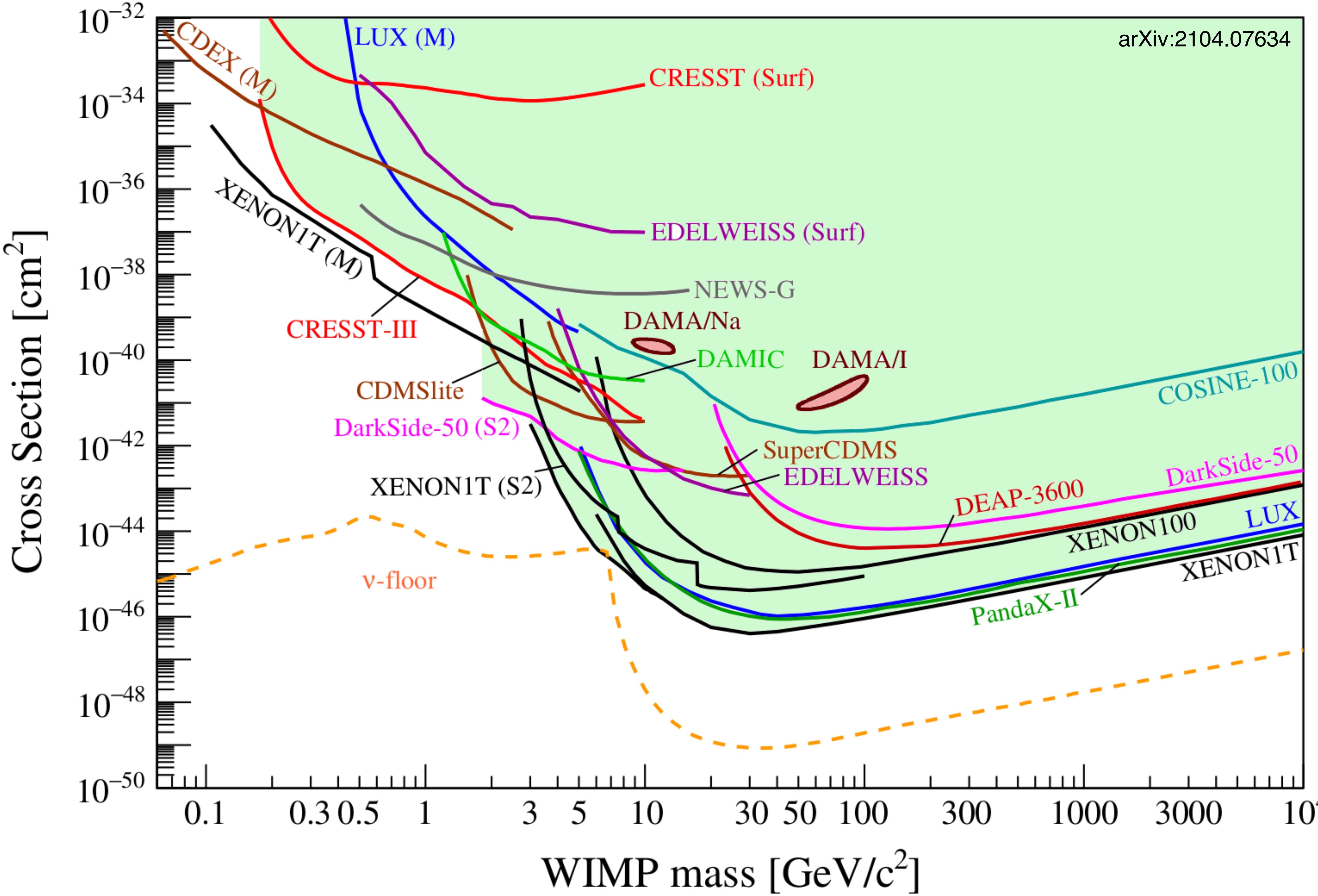
Landscape of Direct Detection searches



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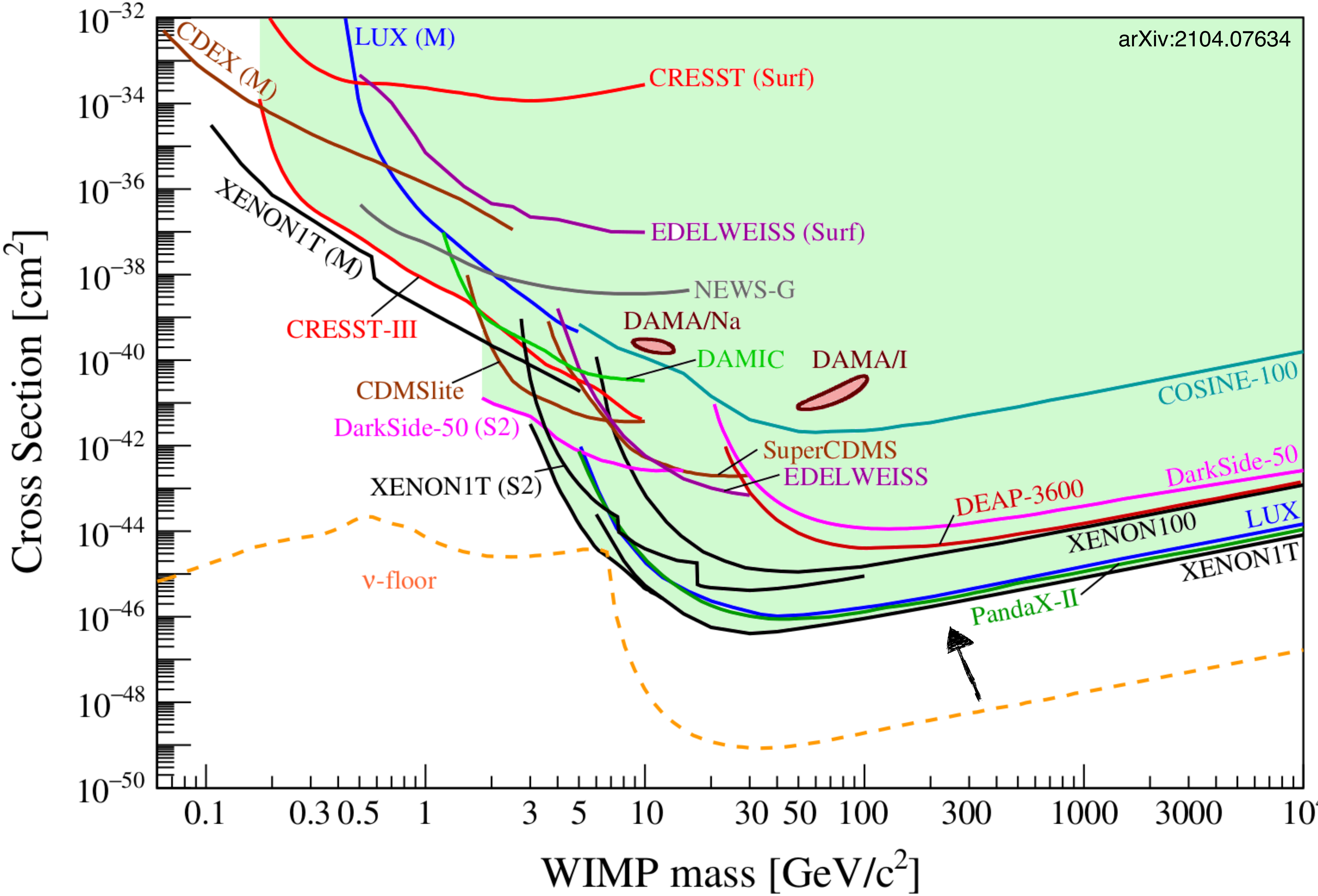

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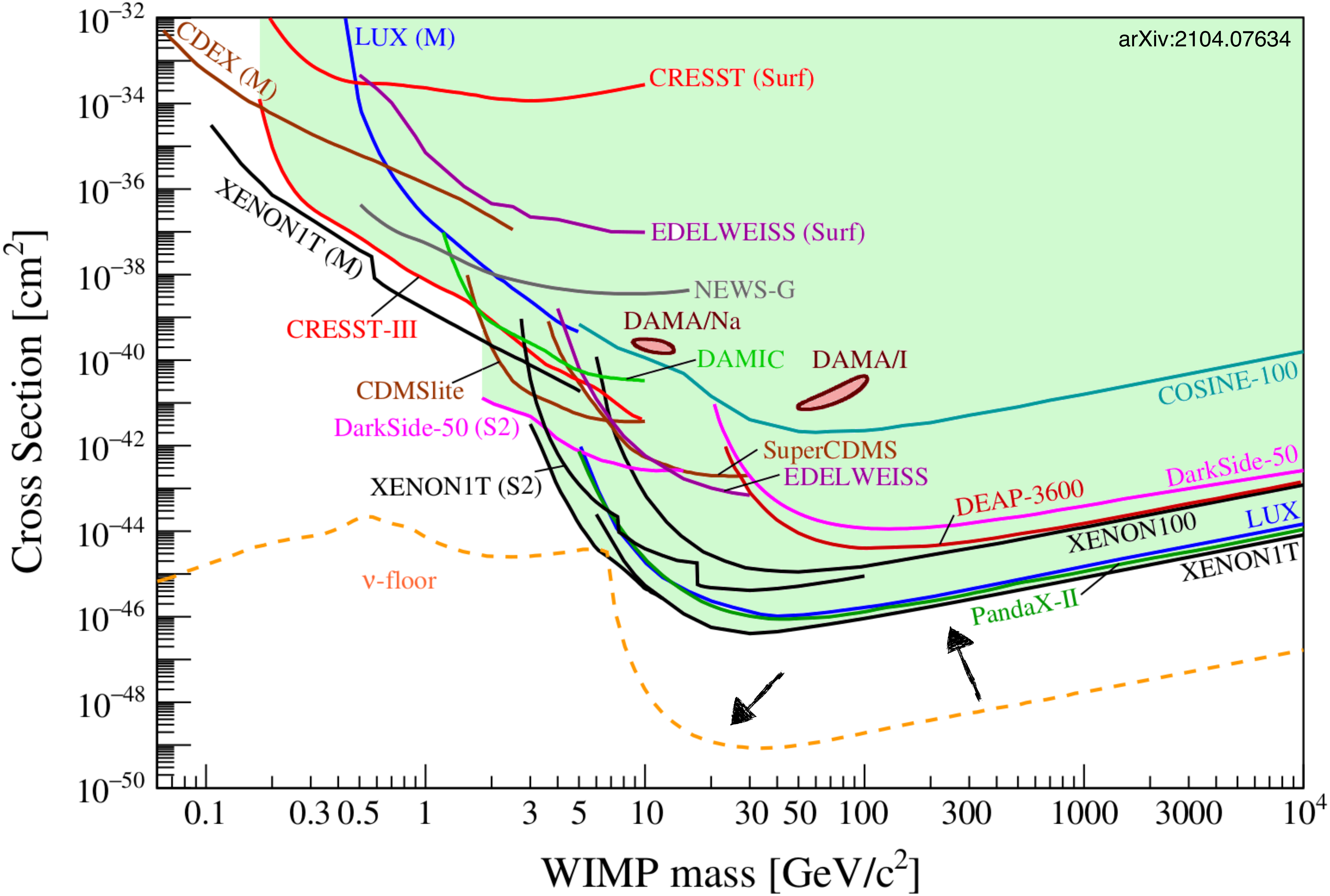
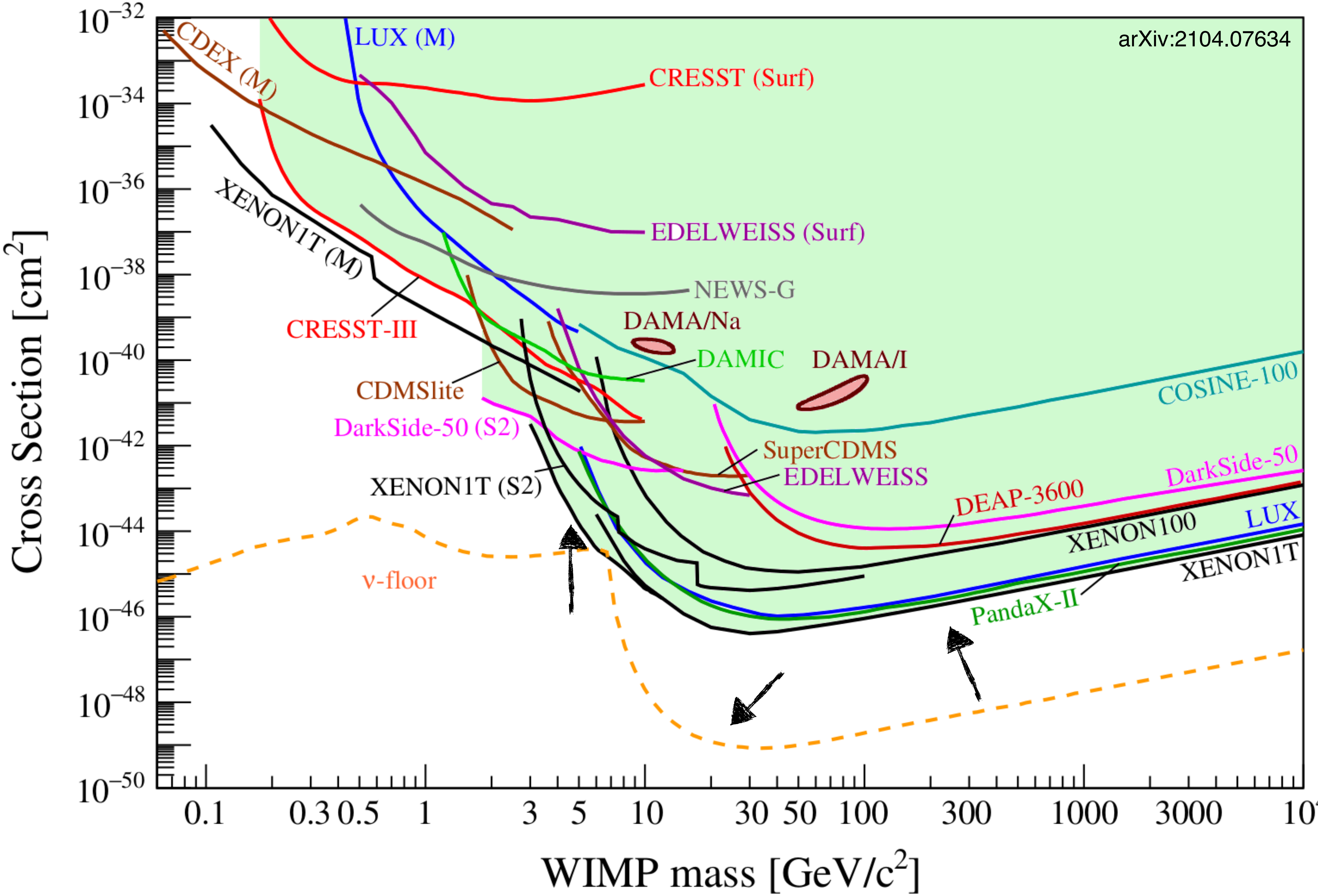


UNIVERSITY OF BIRMINGHAM

Landscape of Direct Detection searches



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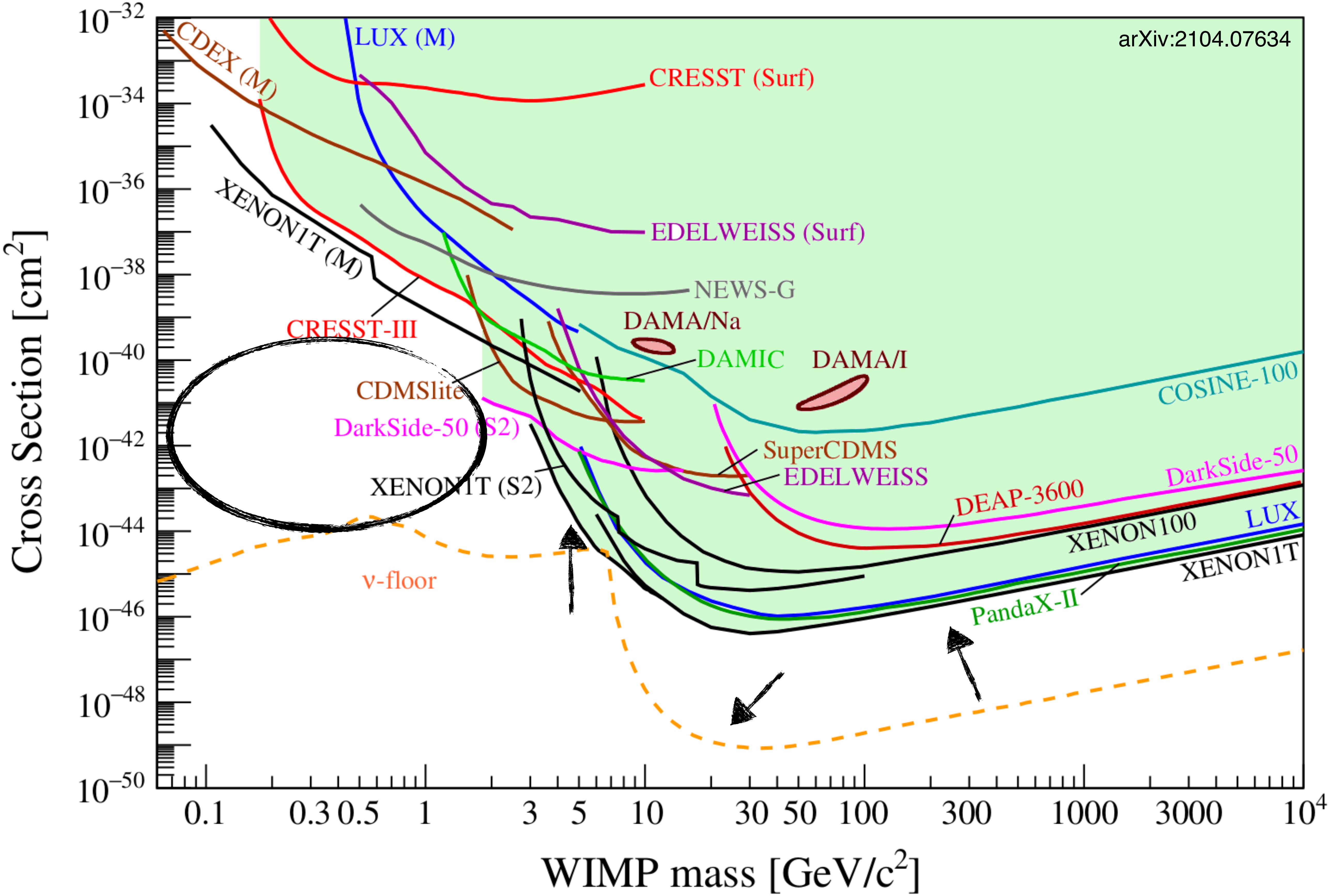

UNIVERSITY OF BIRMINGHAM

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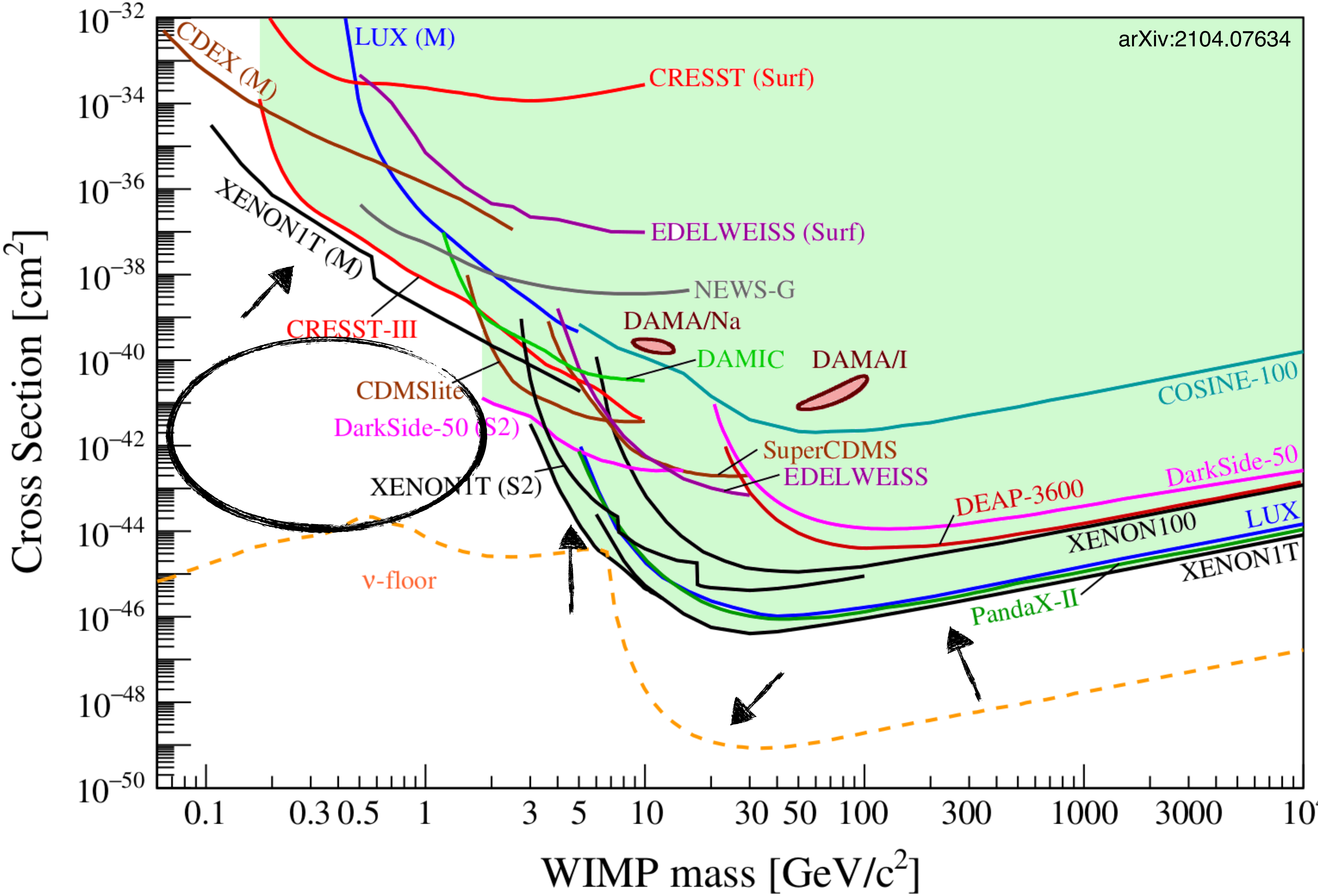

UNIVERSITY OF BIRMINGHAM

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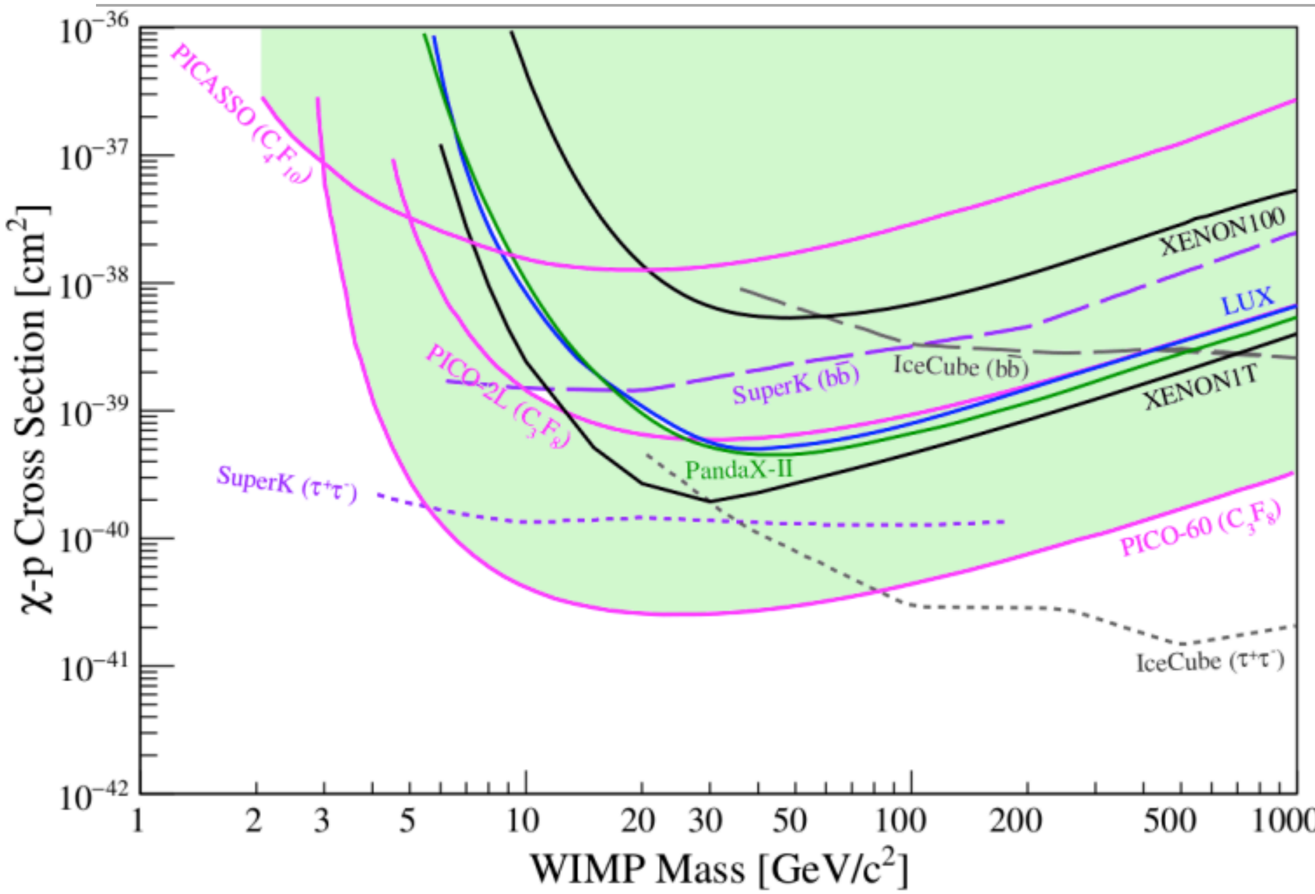

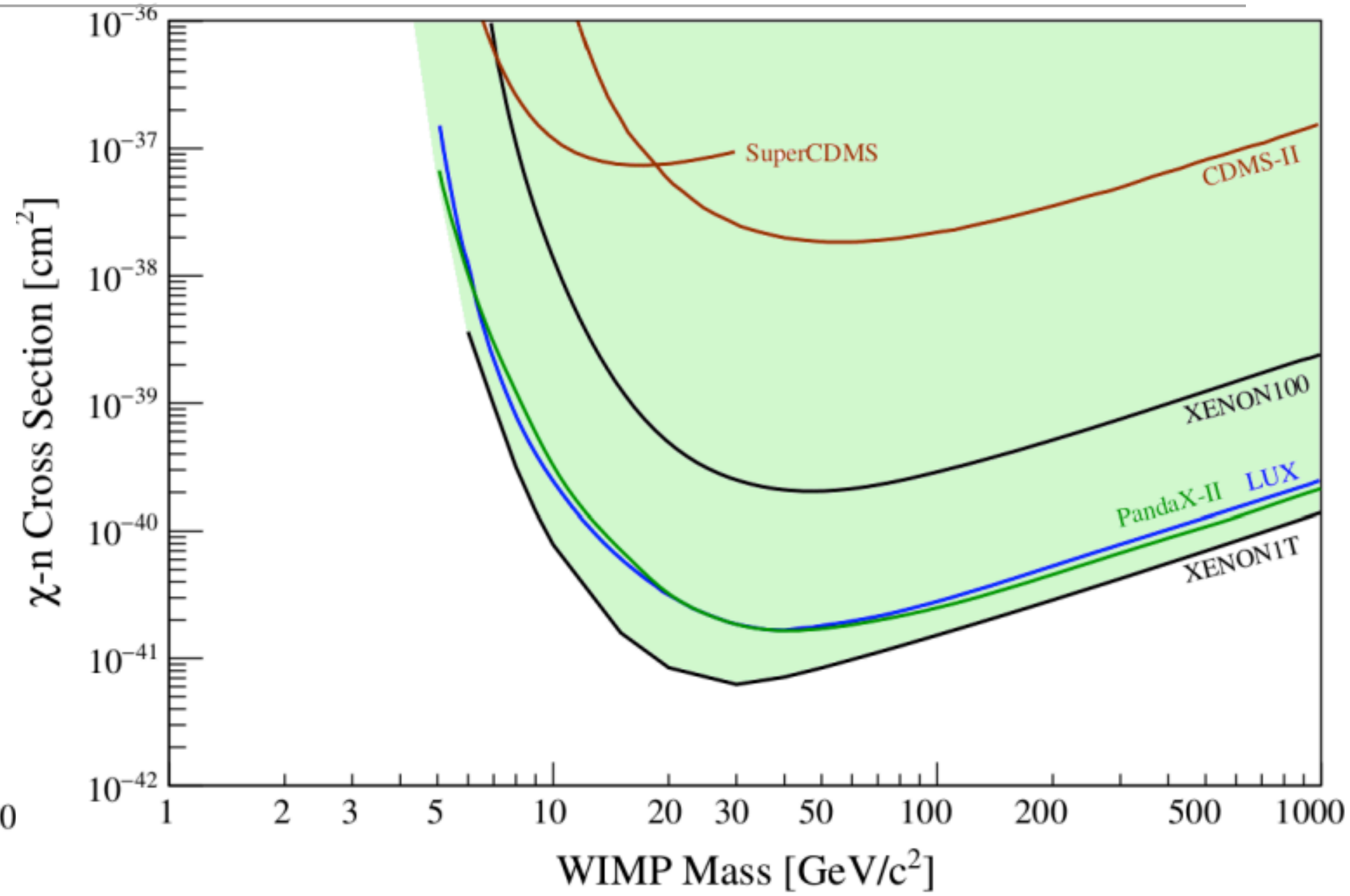

Isotope	Z	Abundance	Spin	Unpaired Nucleon	Relative Strength
^{19}F	9	100.0%	1/2	proton	100
^{23}Na	11	100.0%	3/2	proton	12
^{27}Al	13	100.0%	5/2	proton	22
^{29}Si	14	4.7%	1/2	neutron	11
^{73}Ge	32	7.7%	9/2	neutron	34
^{127}I	53	100.0%	5/2	proton	24
^{129}Xe	54	26.4%	1/2	neutron	47
^{131}Xe	54	21.2%	3/2	neutron	18

J.Phys.G 46 (2019) 10, 103003

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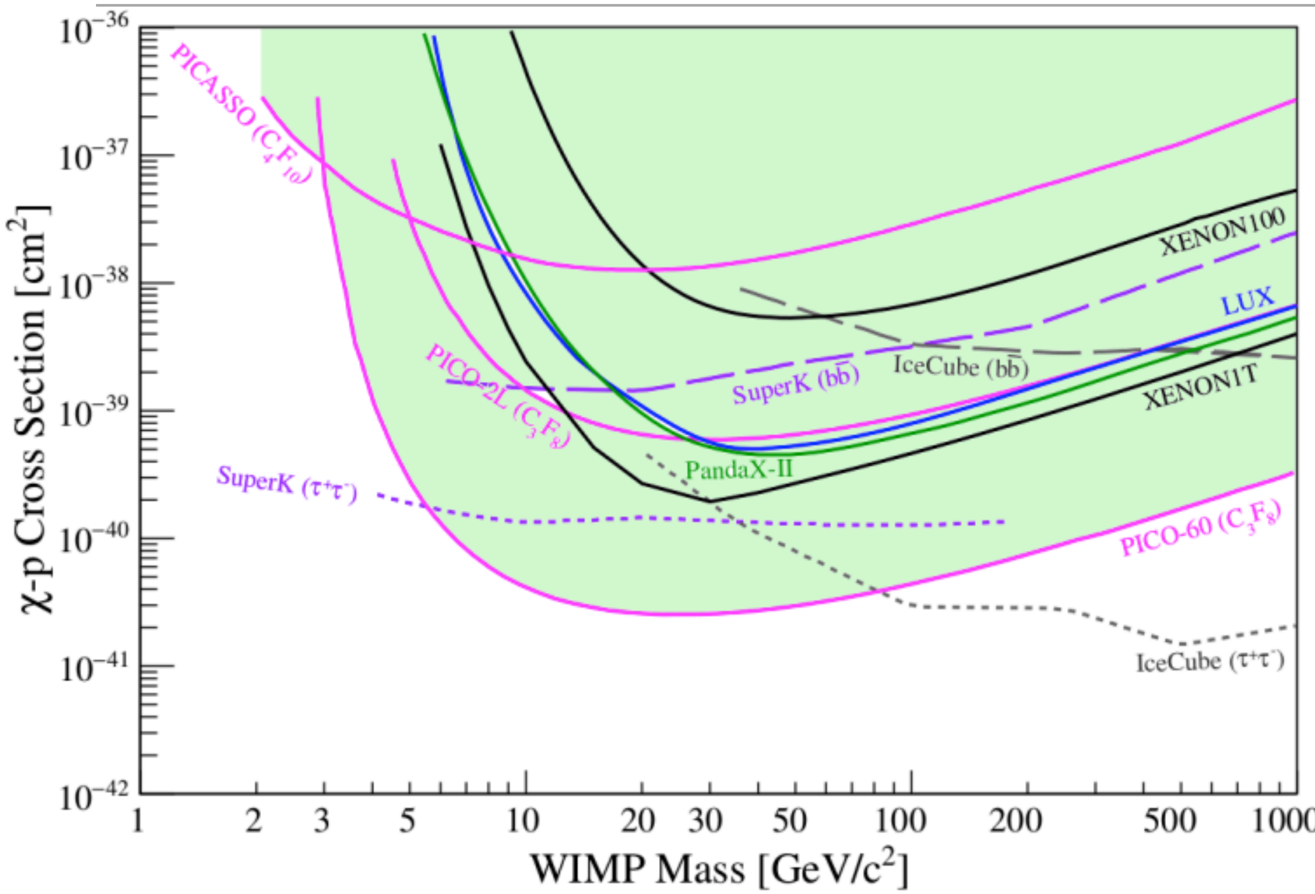

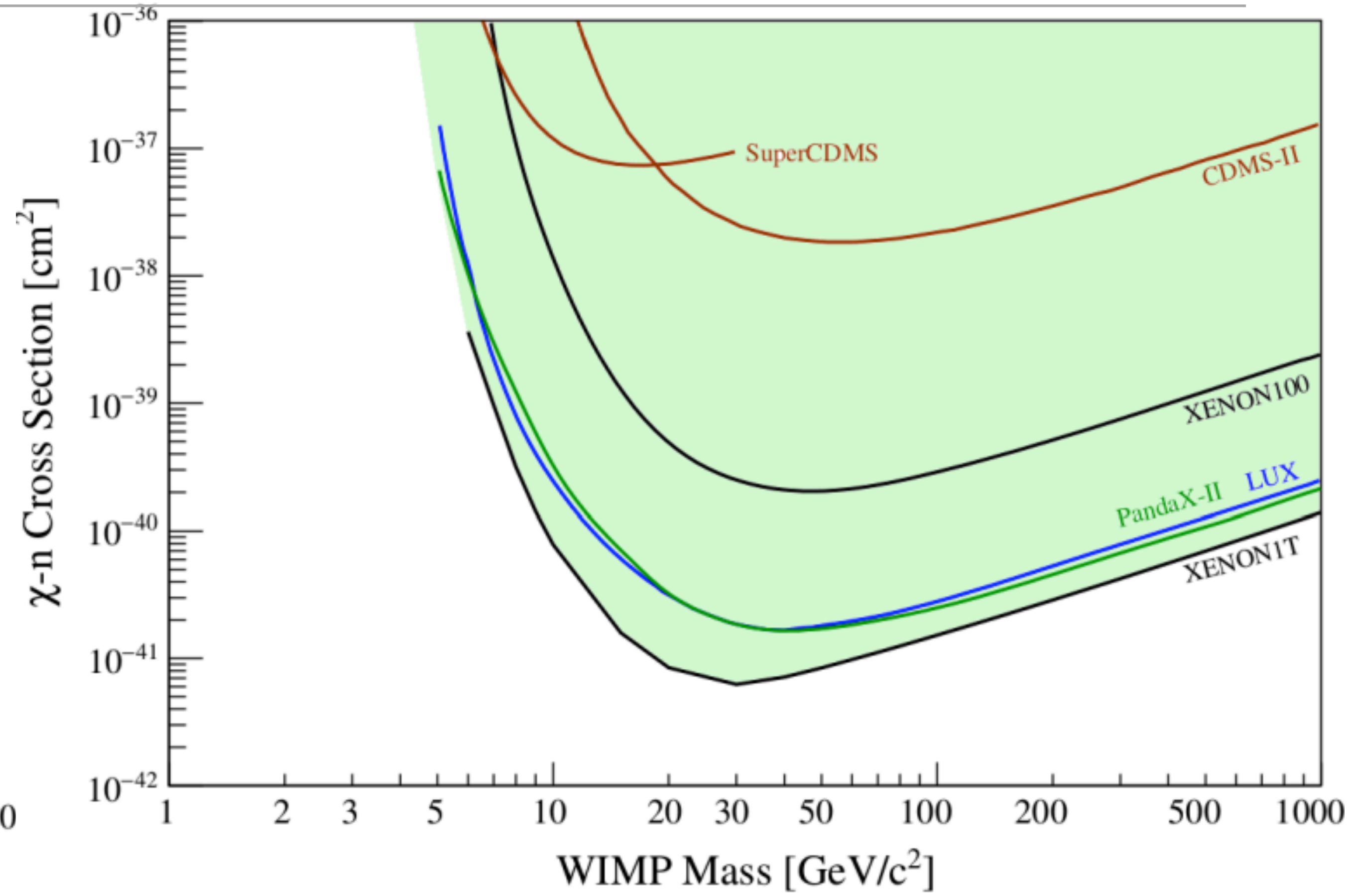

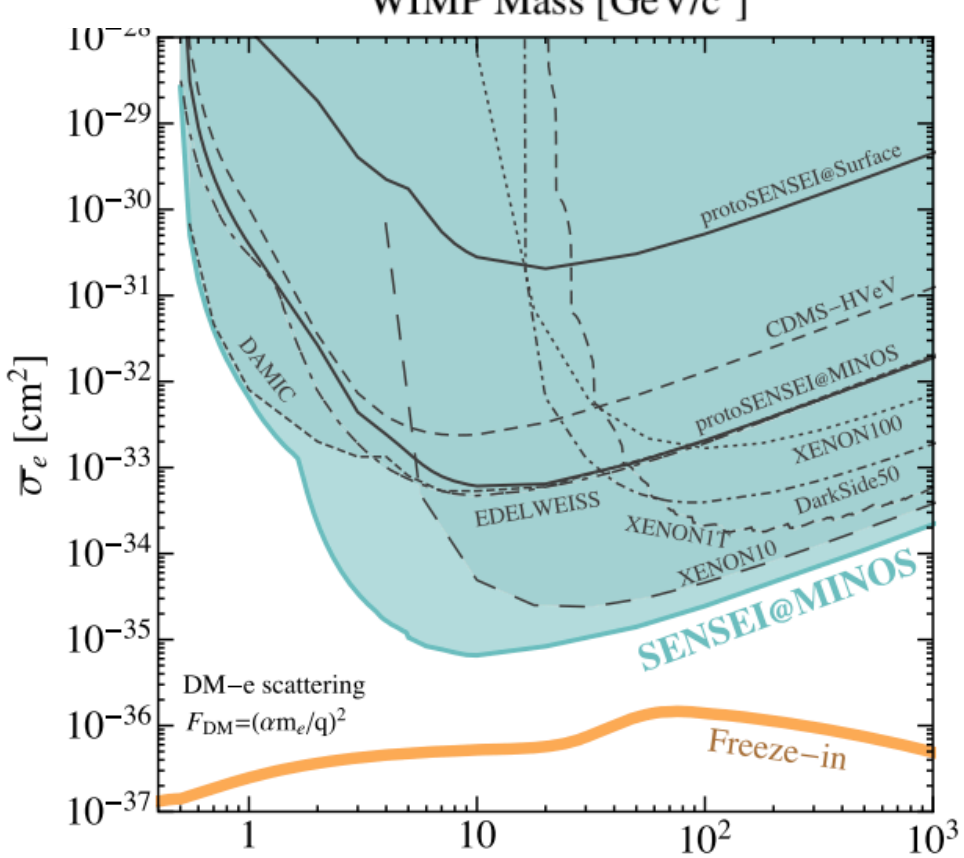

PRL125, 171802 (2020)

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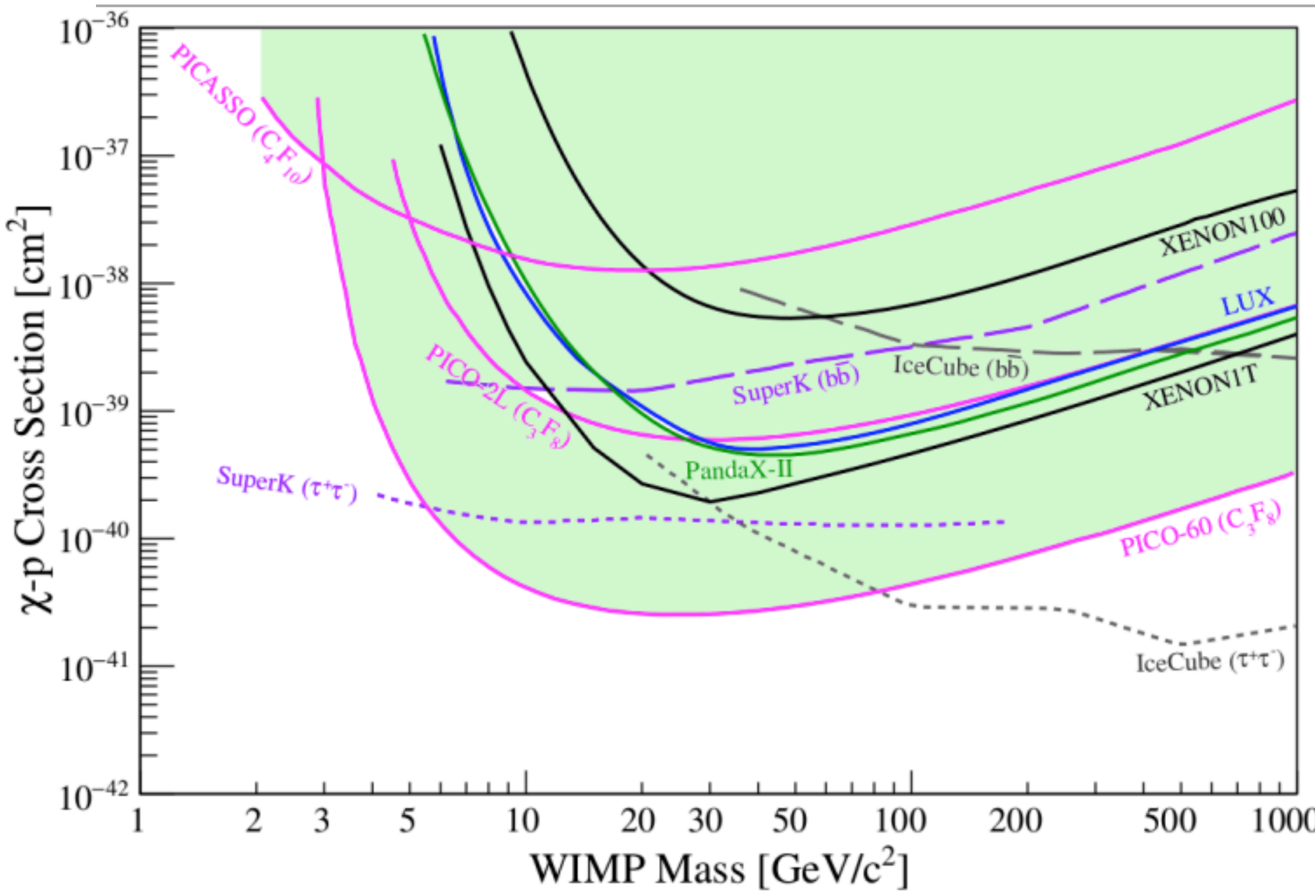

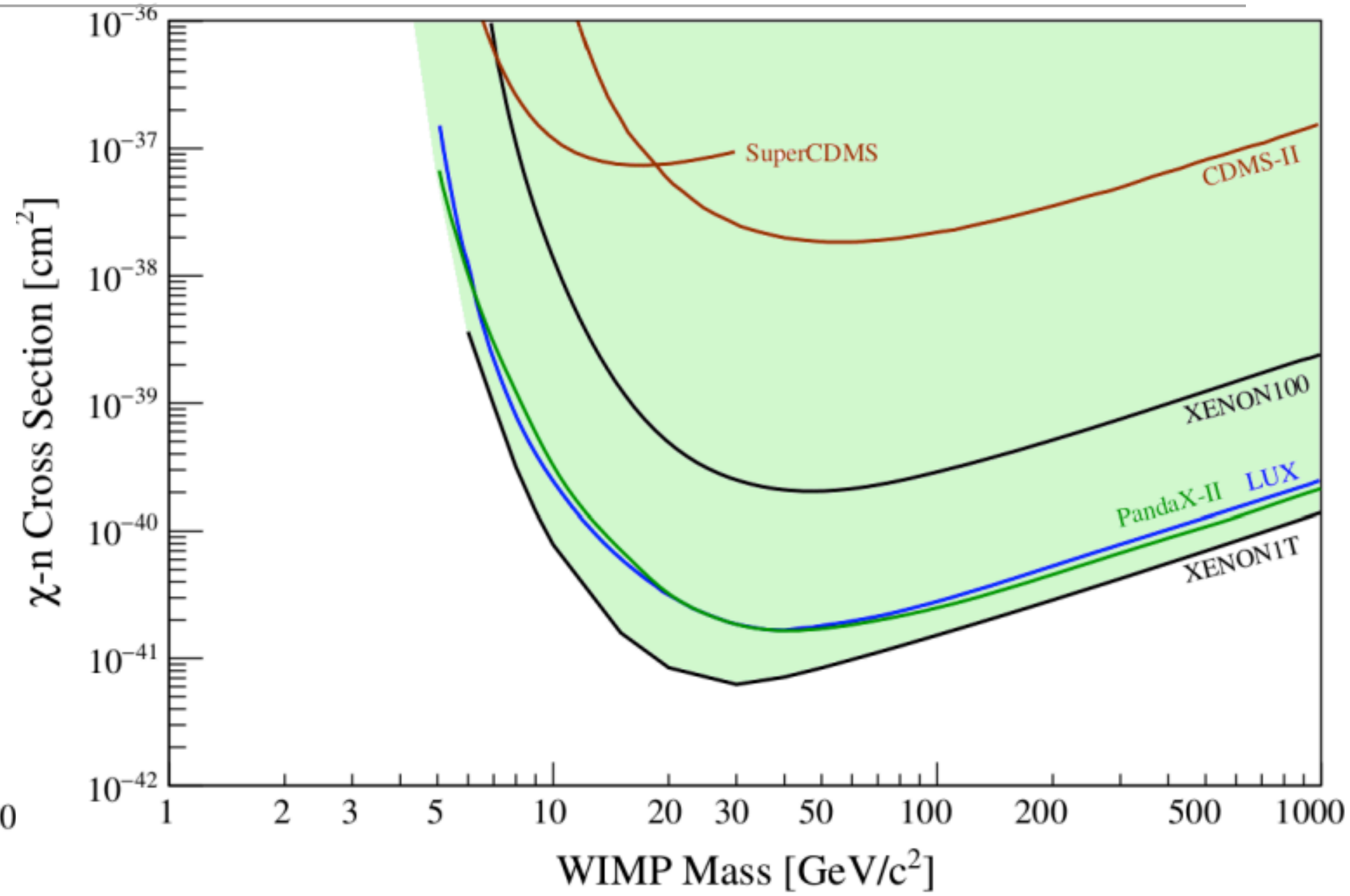

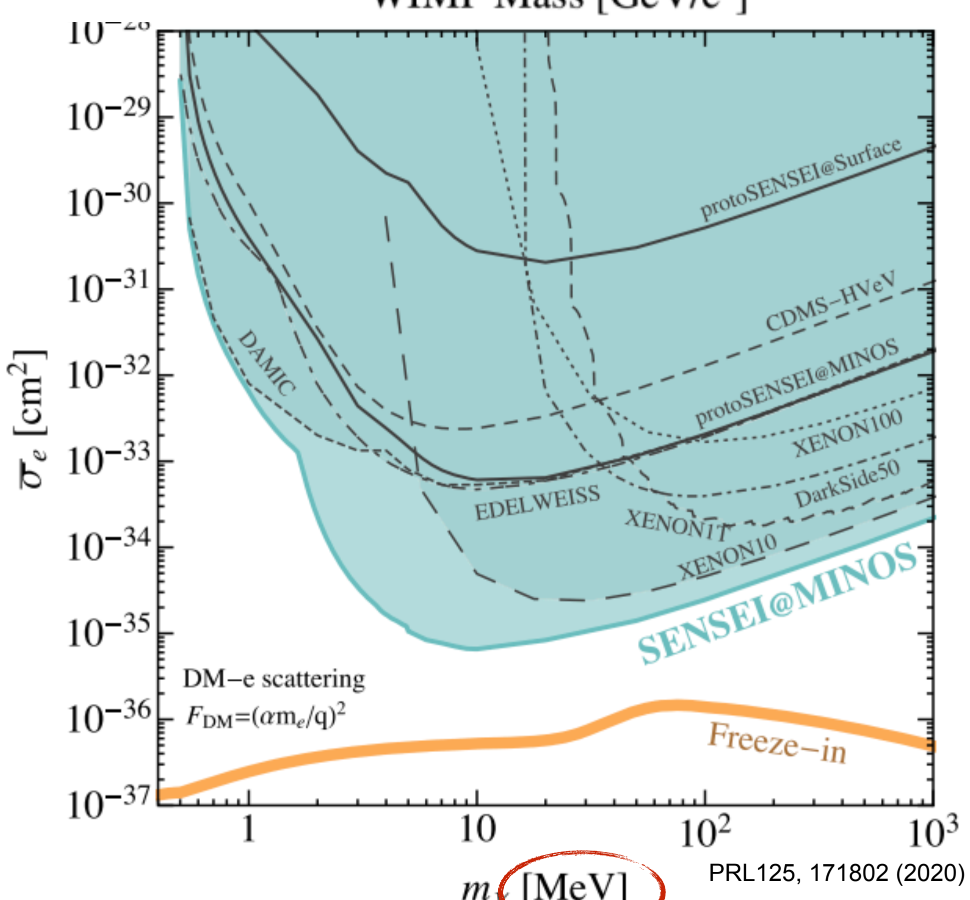

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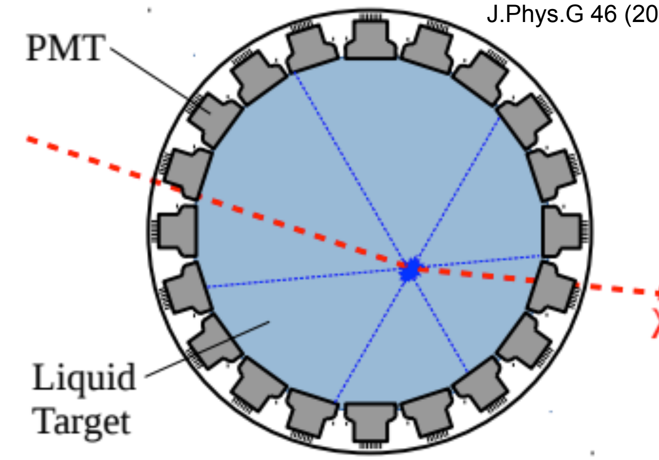
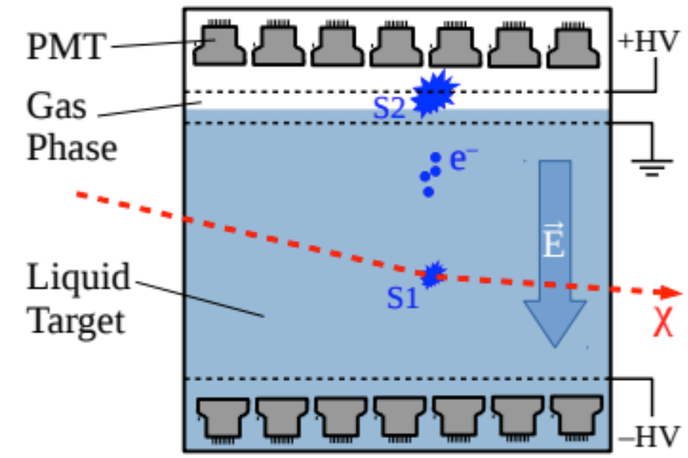
Liquified Noble Gas Detectors

- **Single and two-phase Ar and Xe detectors**
  - High density
    - Massive and compact DM targets
    - Exceeding tonne-scale already
  - Scintillation: 128 nm Ar, 178 nm Xe
  - Xe: efficient self-shielding, no long-lived isotopes, discrimination with S2/S1
  - Ar: pulse shape discrimination for electron/nuclear recoils
  - Energy threshold mostly depends on light read-out (1keV)
    - Low mass searches using S2 only

J.Phys.G 46 (2019) 10, 103003





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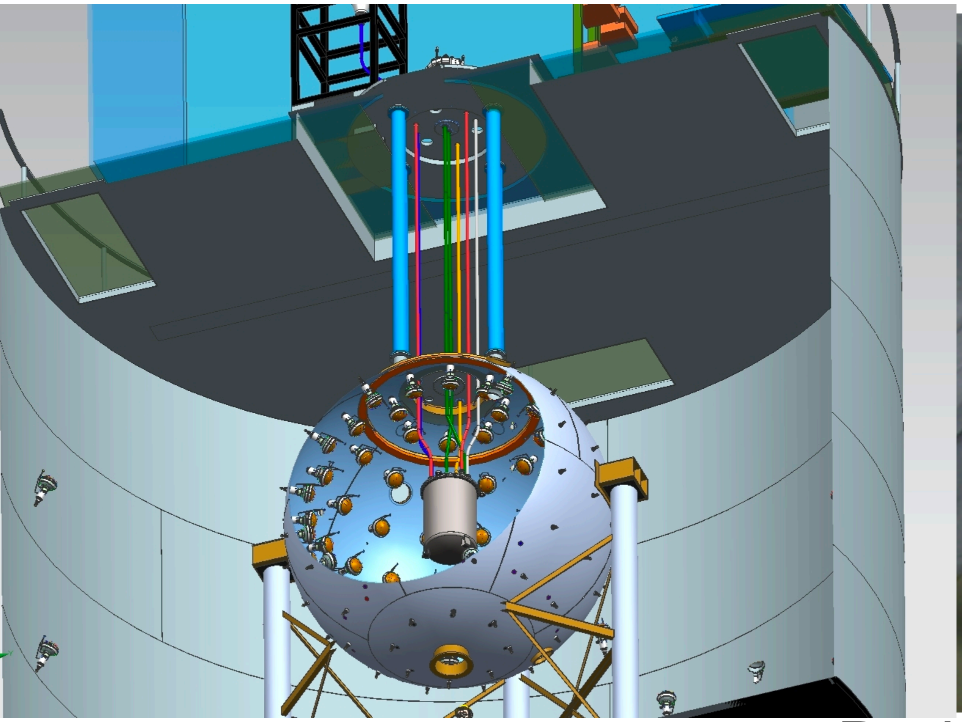
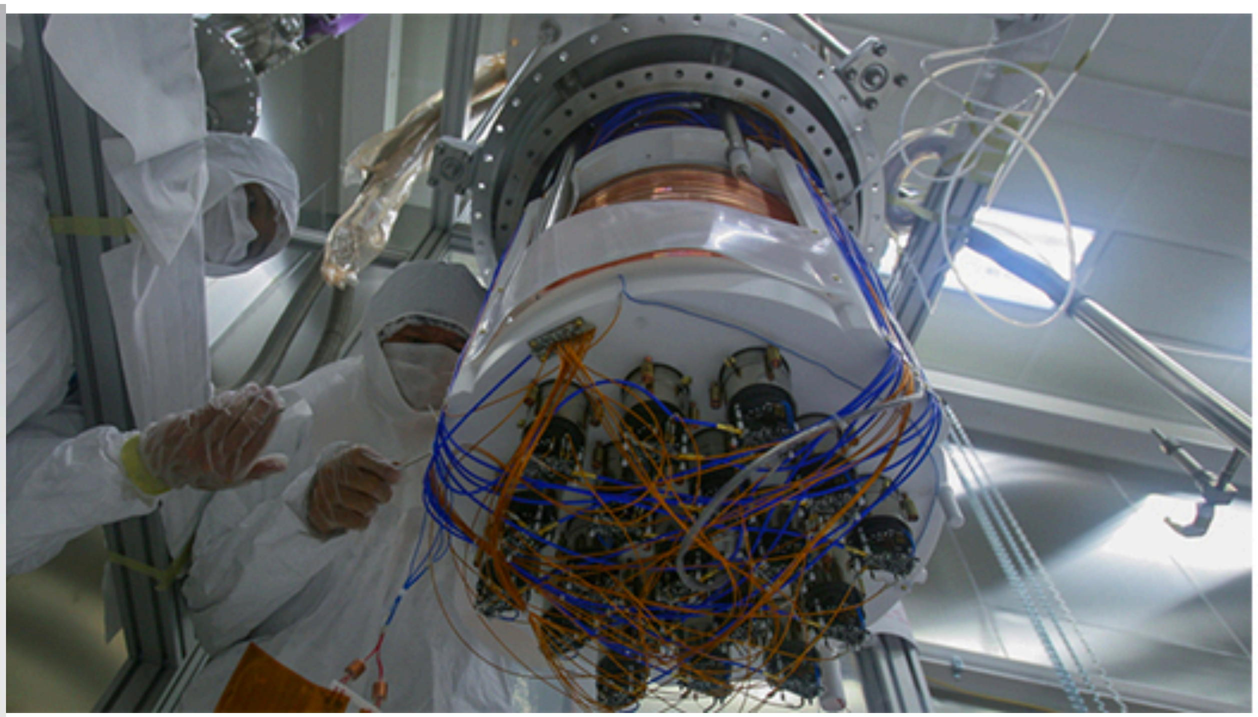




DarkSide-50

LZ

Xenon Detectors

XENON 10 (LNGS)
ZEPLIN (Boulby)

10 kg

2010

XENON 100 (LNGS)

100 kg

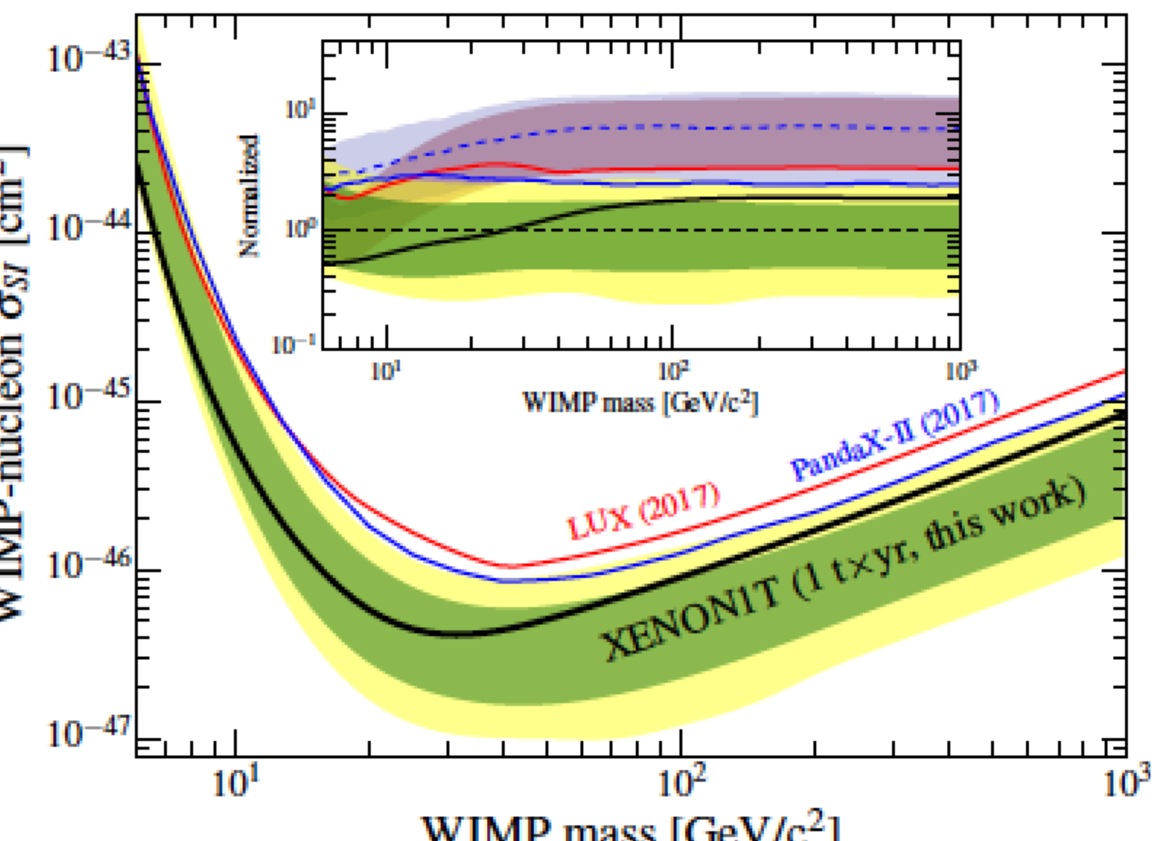
LUX (250 kg, SURF),

PANDA-X (500 kg, CJPL)

XMASS (0.8t, Kamioka)

2015

arXiv:1805.12565



1000 kg

XENON 1T (1t, LNGS)

PandaX-4:(4t, CJPL)
XENONnT: (6t, LNGS)
LZ: (7t, SURF)

2020

10000 kg

***Future: DARWIN**: 50 t*

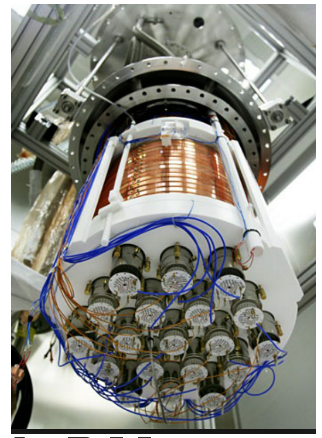
Argon Detectors

Rubbia C., CERN-EP-INT-77-08 (1977)

2010 **WARP**

10 kg

DS-50 (50 kg, LNGS)

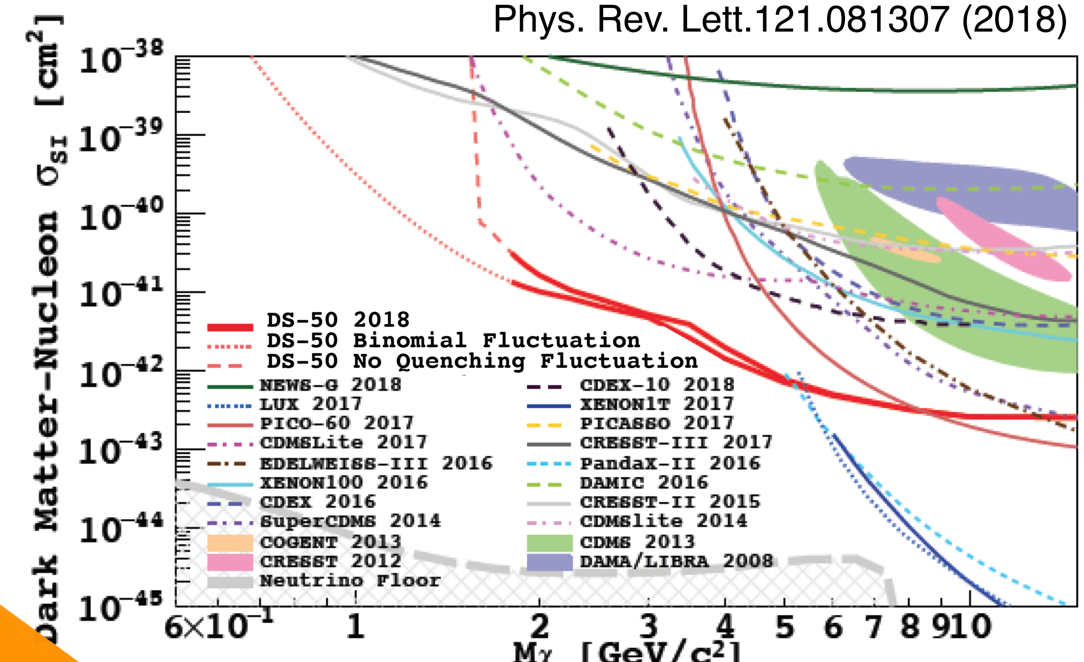


ArDM (1t, LSC)

100 kg

DS-50: leading SI limit at 1-5 GeV/c² for WIMP-nucleus and WIMP-e scattering

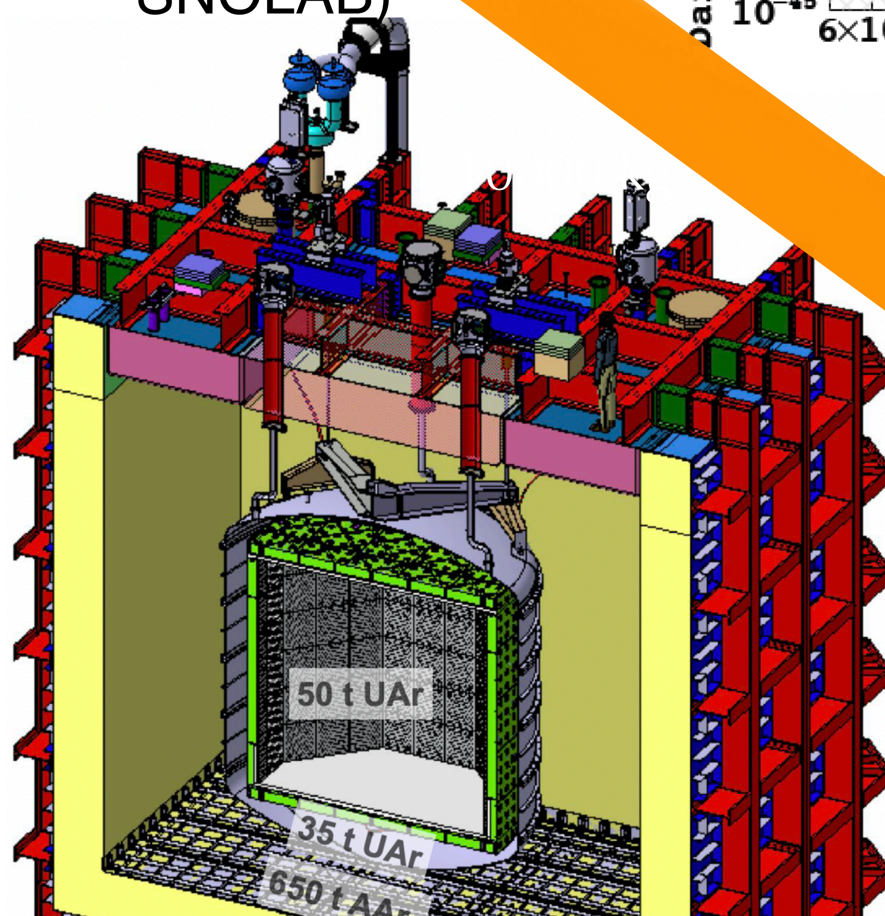
Phys. Rev. Lett.121.081307 (2018)



1,000 kg 2015

DEAP-3600 (3.6t, SNOLAB)

DEAP-3600: demonstrated "S1" particle ID, and ultrapure acrylic cryostat (x100 lower radioactivity)



Global Argon Dark Matter Collaboration formed

10,000 kg

2020

DarkSide-20k (50t, LNGS)

100,000 kg

ARGO kt-scale

APPEC

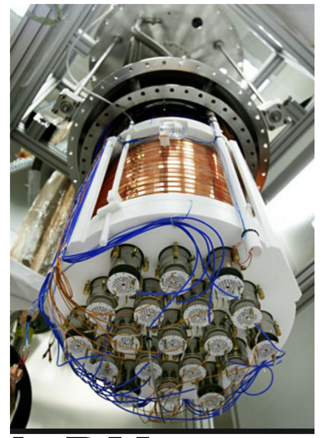
Slide: J. Monroe (RHUL)

Argon Detectors

Rubbia C., CERN-EP-INT-77-08 (1977)

10 kg 2010 **WARP**

DS-50 (50 kg, LNGS)

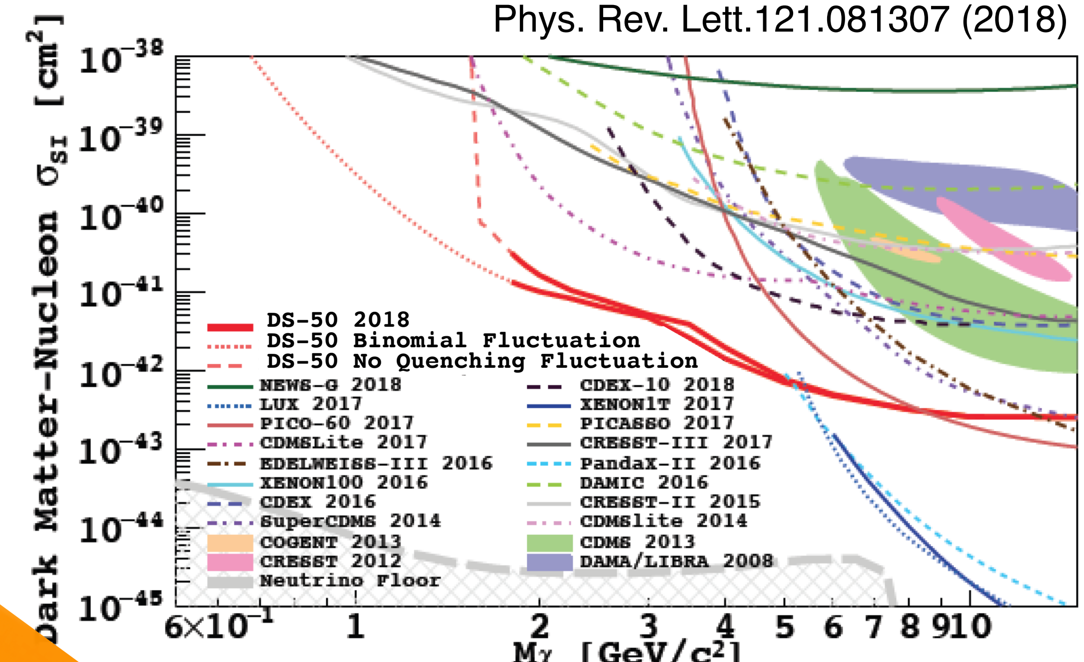


ArDM (1t, LSC)

100 kg

DS-50: leading SI limit at 1-5 GeV/c² for WIMP-nucleus and WIMP-e scattering

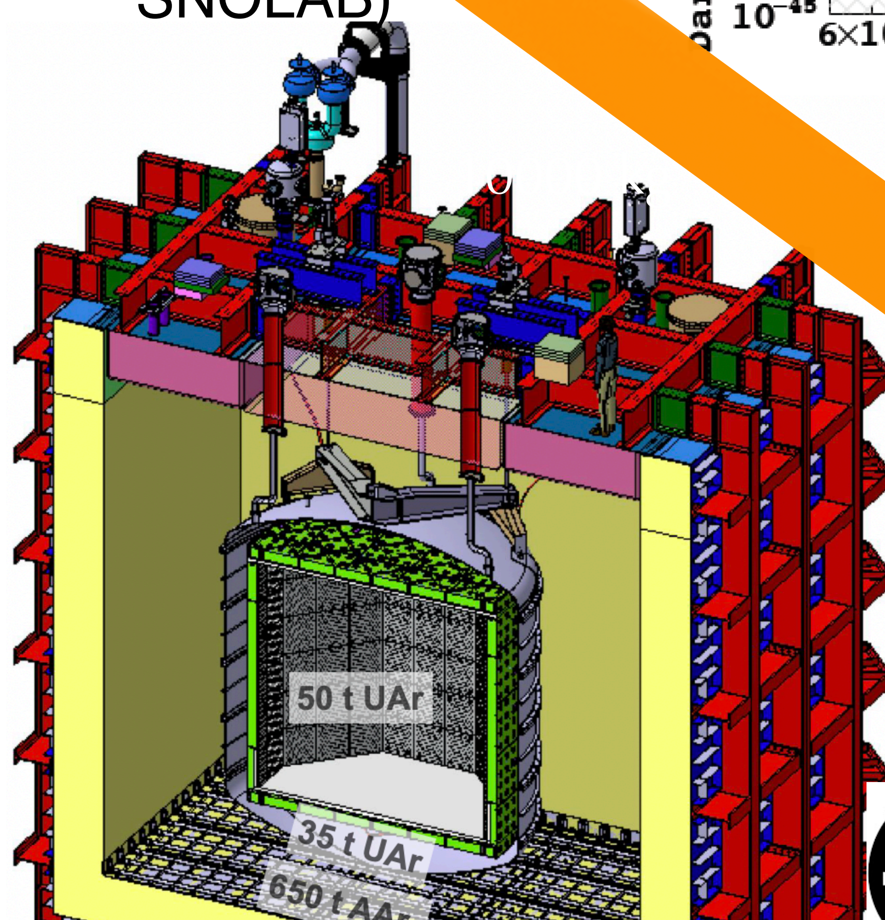
Phys. Rev. Lett.121.081307 (2018)



1,000 kg 2015

DEAP-3600 (3.6t, SNOLAB)

DEAP-3600: demonstrated "S1" particle ID, and ultrapure acrylic cryostat (x100 lower radioactivity)



Global Argon Dark Matter Collaboration formed

10,000 kg 2020

APPEC

DarkSide-20k (50t, LNGS)

100,000 kg

ARGO kt-scale

DARKSIDE

See talk by I. Manthos

Slide: J. Monroe (RHUL)

NaI experiments

- **Long standing annual modulation signal from DAMA/LIBRA**
  - Test DAMA/LIBRA anomaly with NaI(Tl)
  - No evidence for annual modulation
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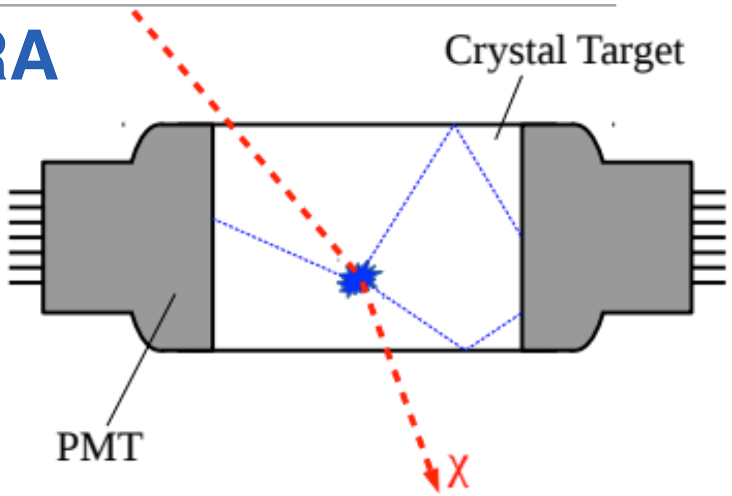

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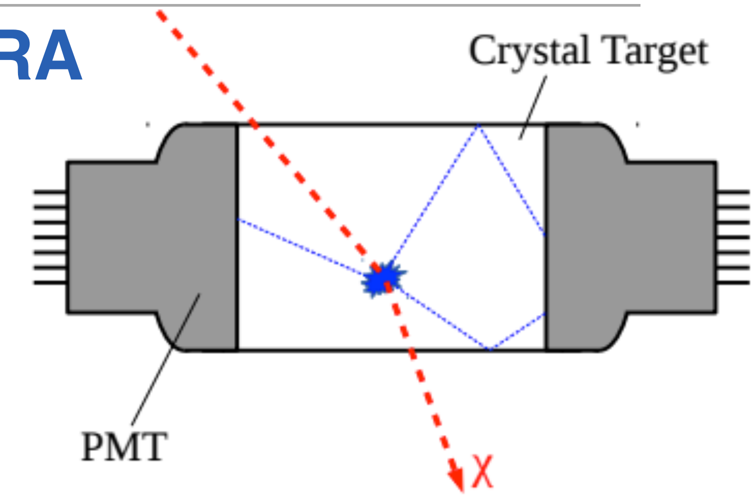

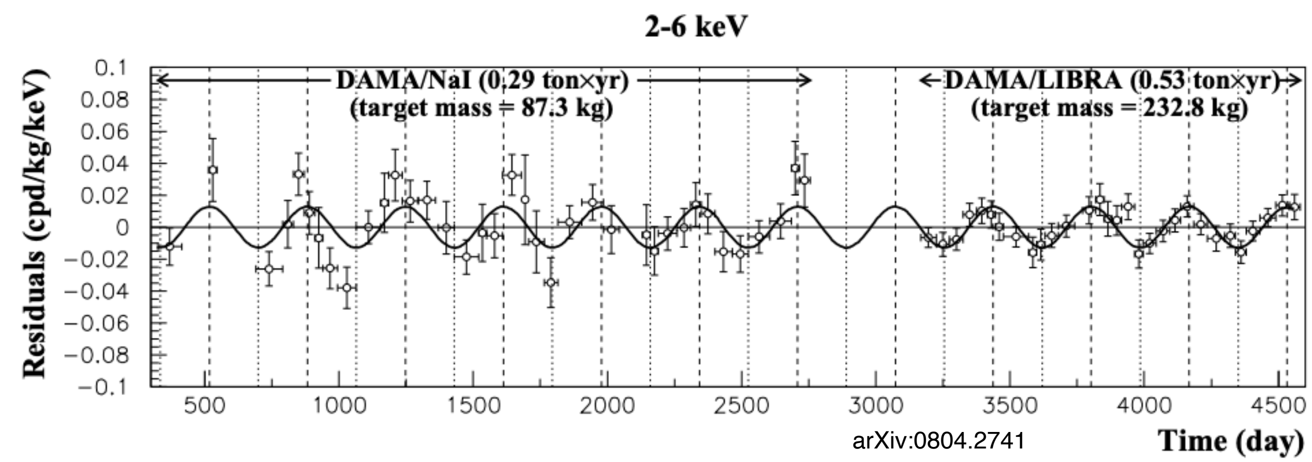

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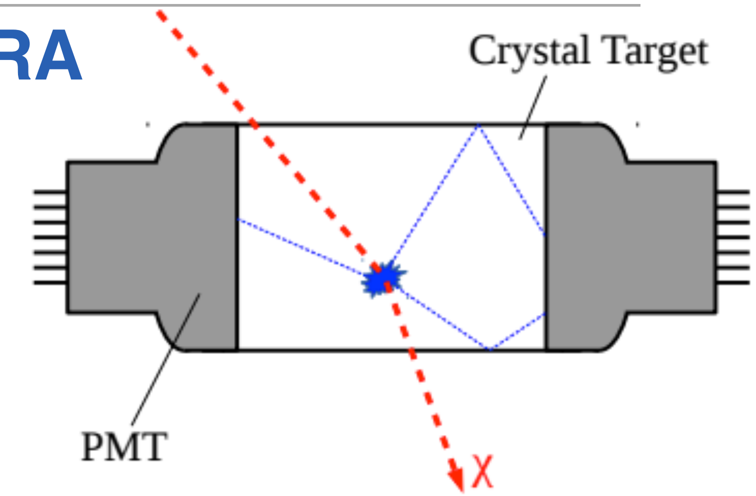
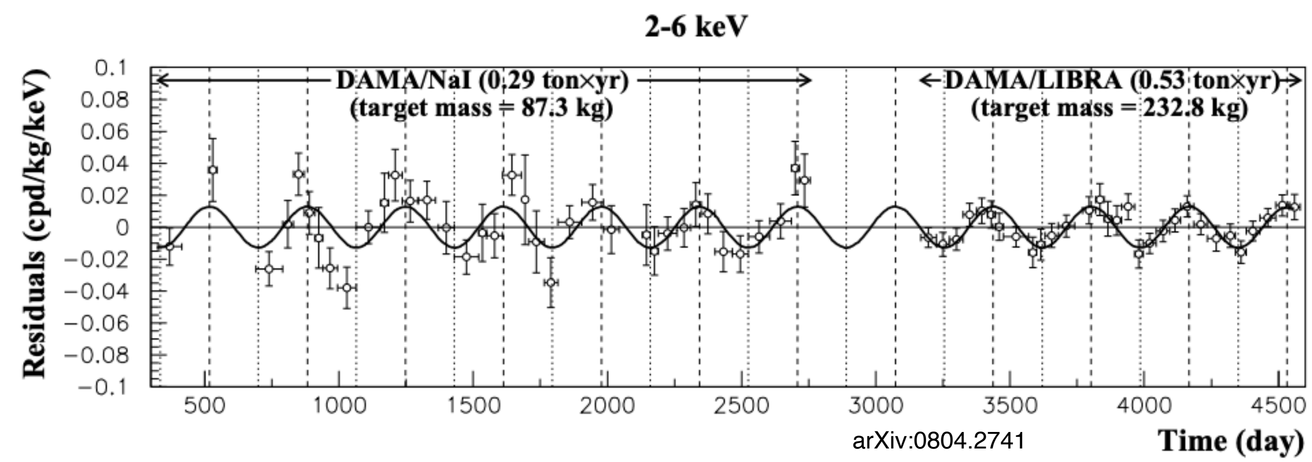
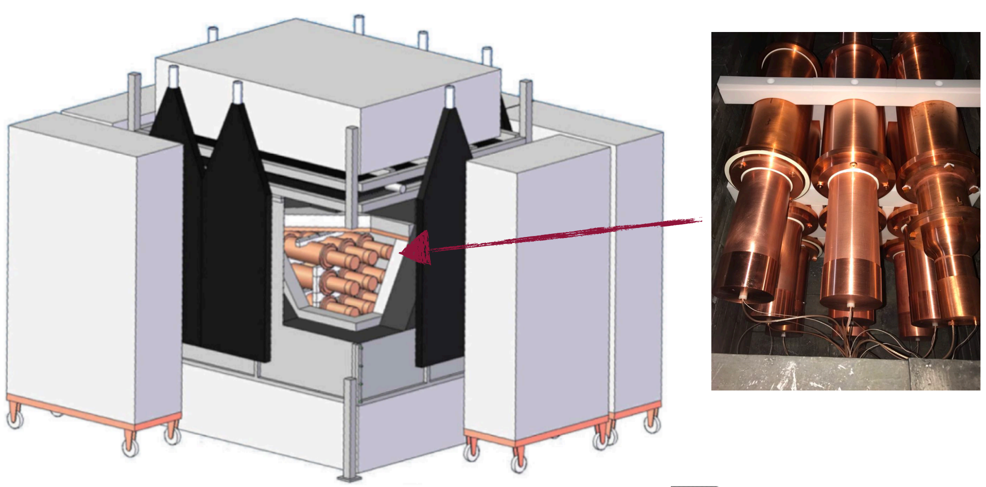
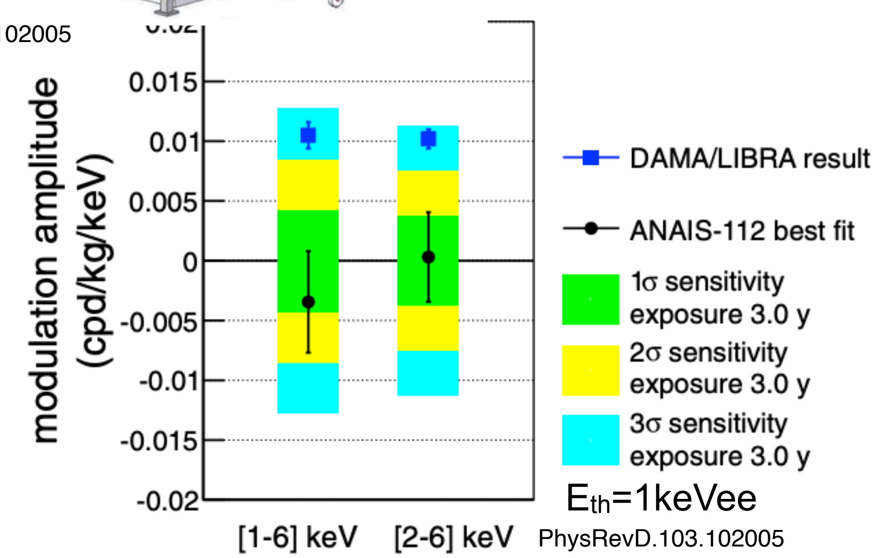




arXiv:0804.2741



PhysRevD.103.102005



E_{th}=1keVee

PhysRevD.103.102005

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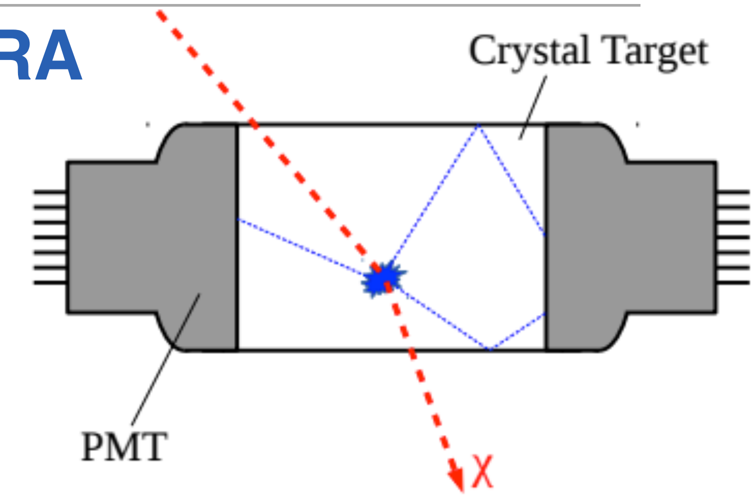

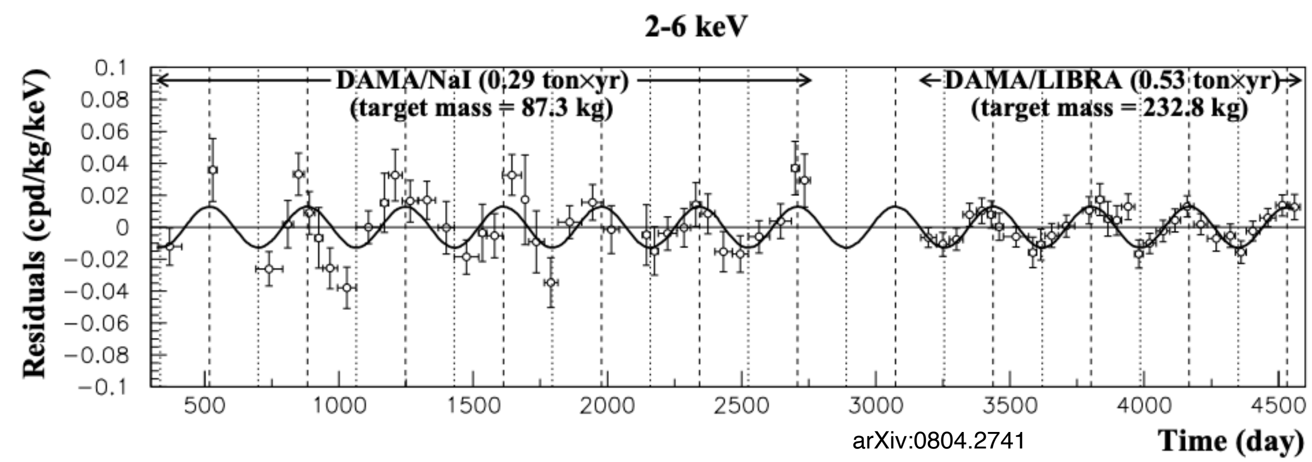

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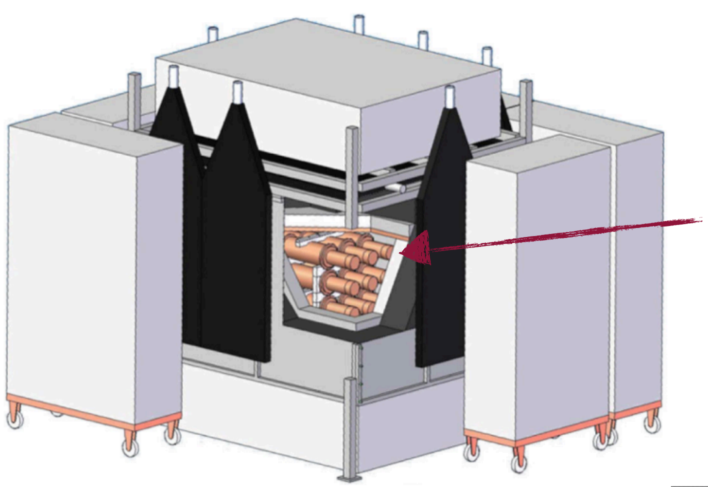
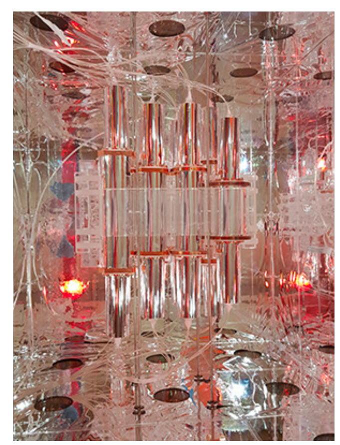
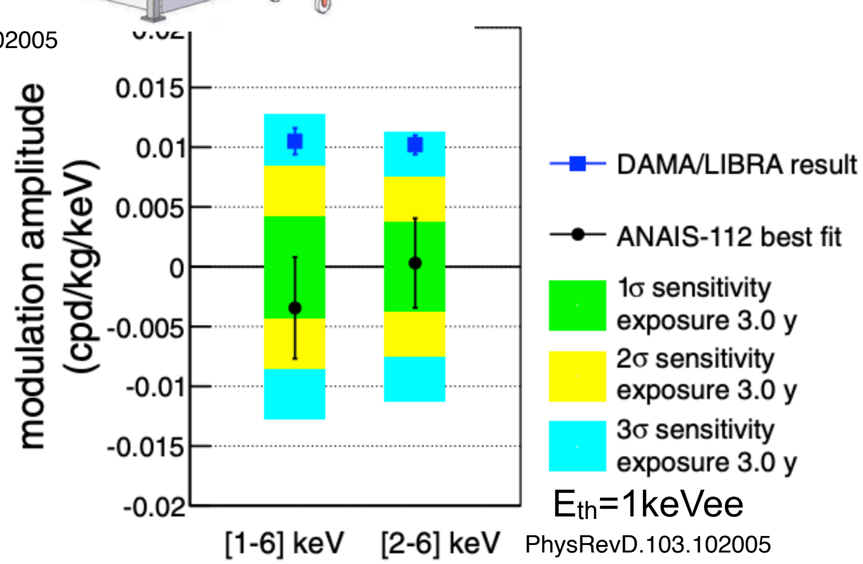


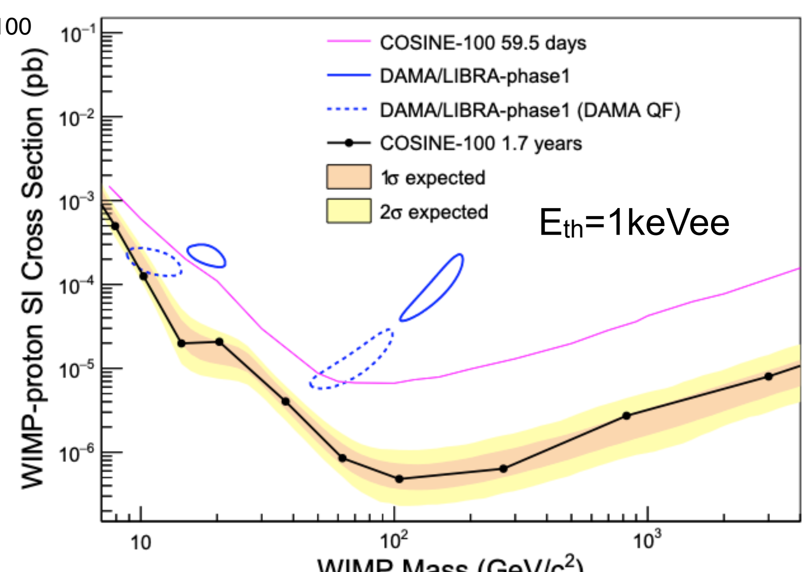


PhysRevD.103.102005

COSINE-100



PhysRevD.103.102005



Sci.Adv. 7 (2021) 46, abk2699

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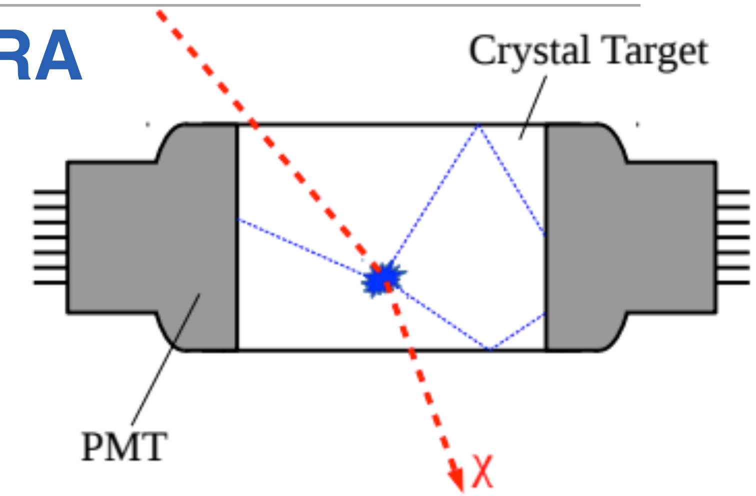

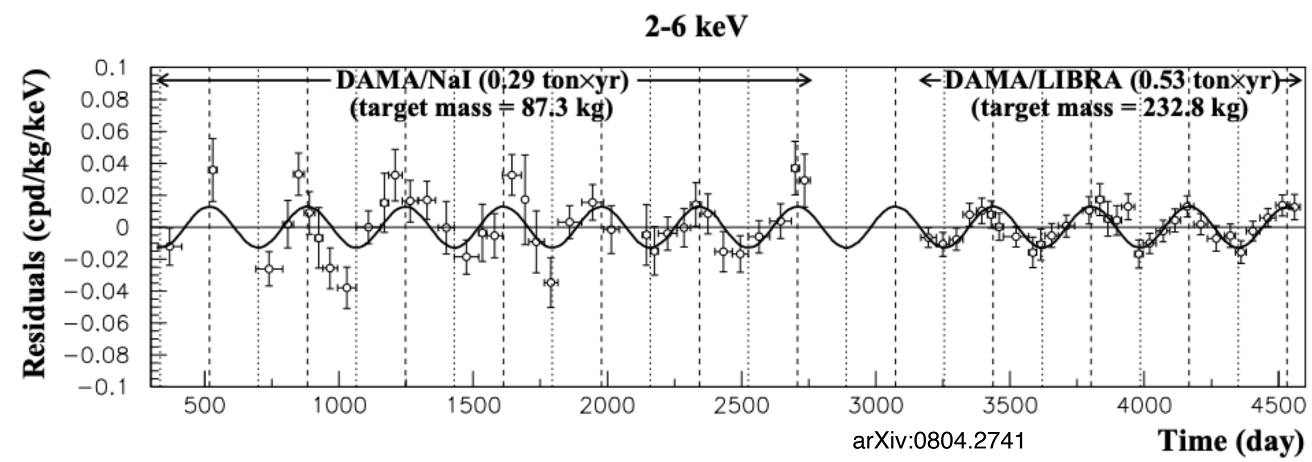

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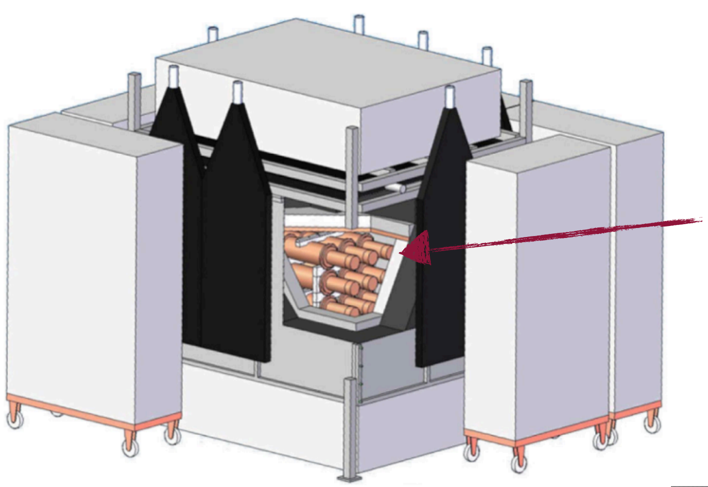
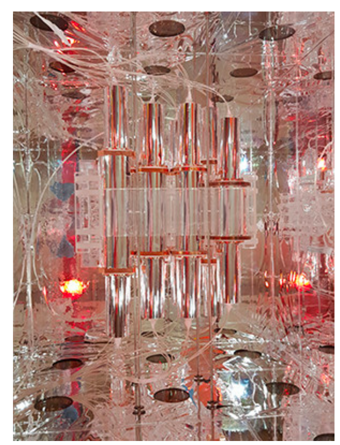
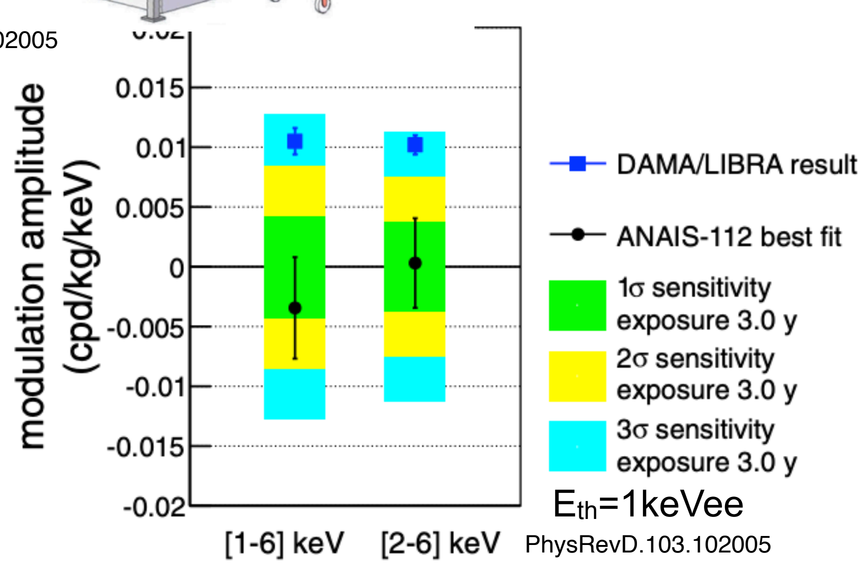


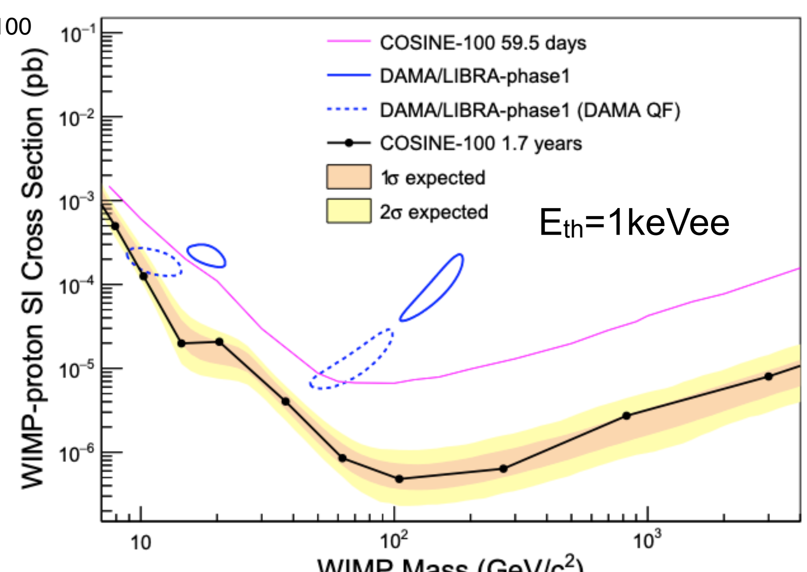


PhysRevD.103.102005

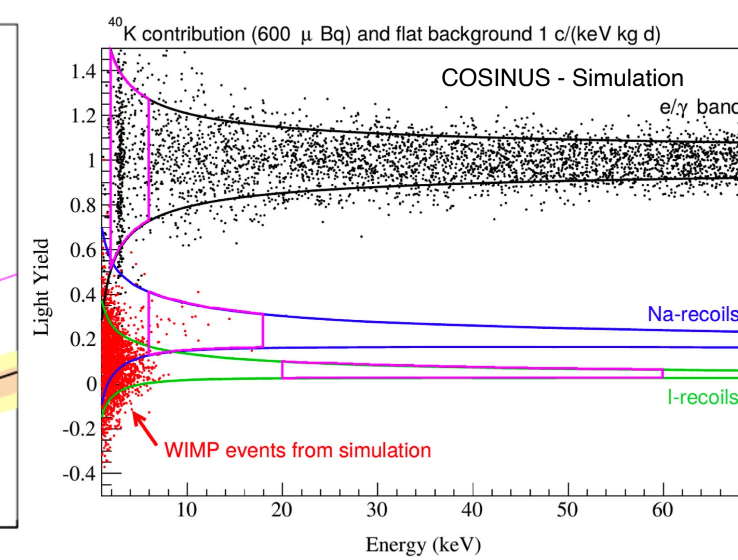
COSINE-100



PhysRevD.103.102005



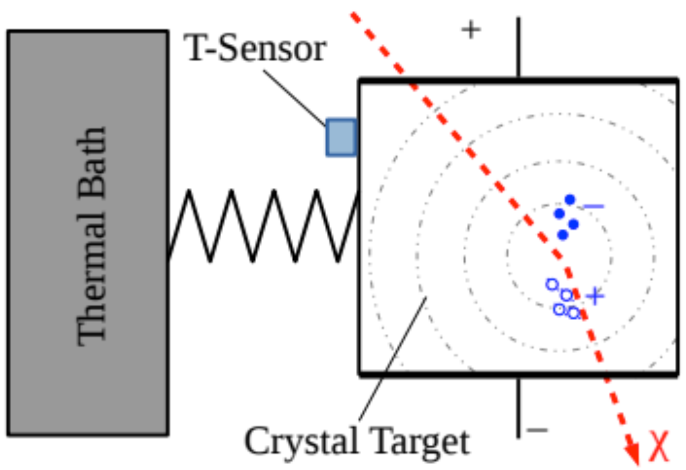
Sci.Adv. 7 (2021) 46, abk2699



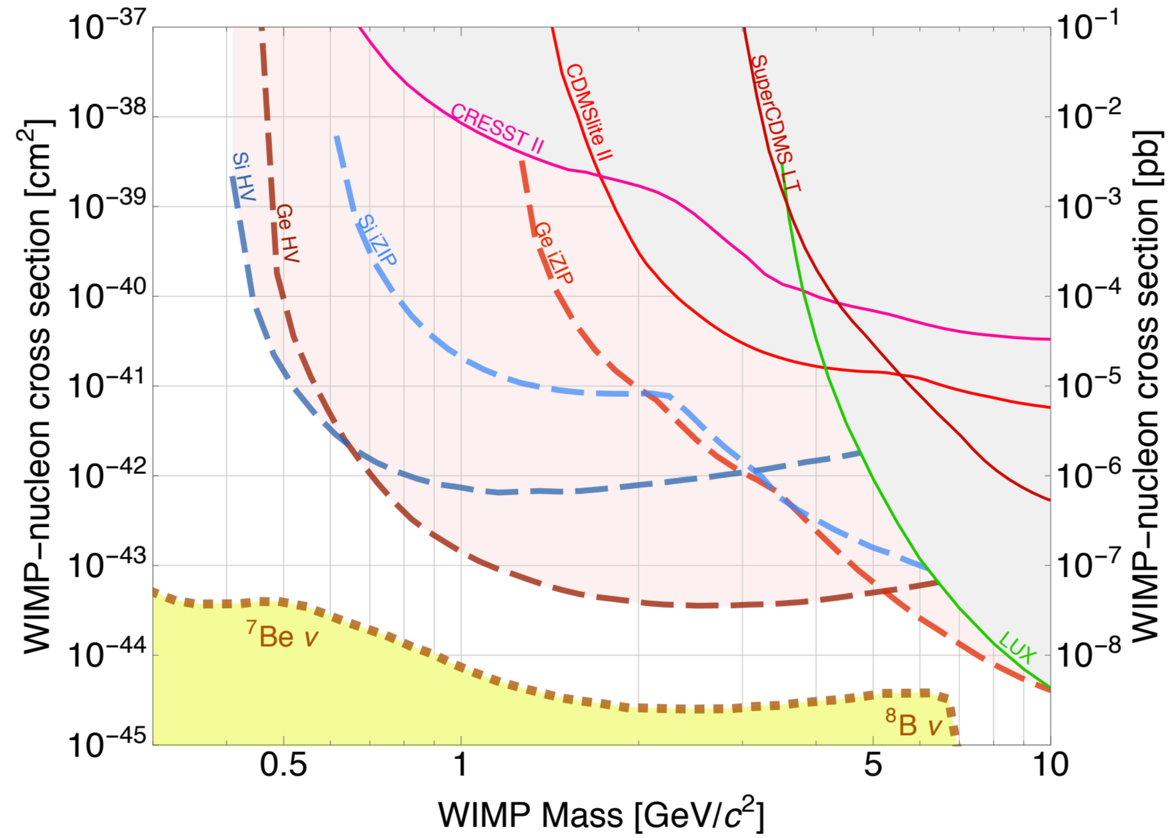
Nucl.Instrum.Meth.A 845 (2017) 359

Cryogenic detectors

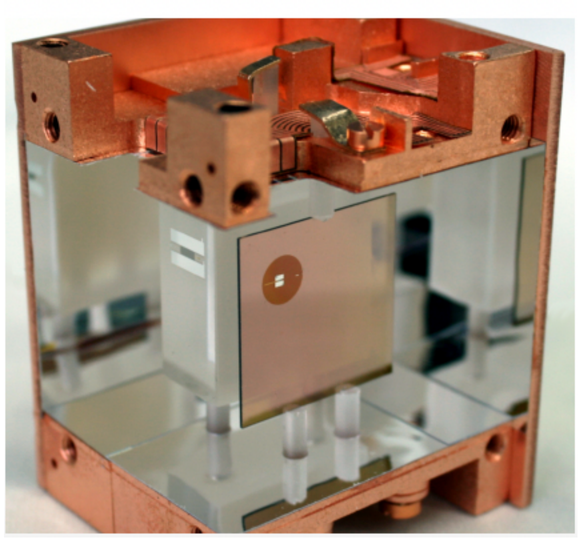
- **Cyogenic bolometers operating at O(10mK)**
  - Sub-keV (< 100 eV) energy thresholds
  - Phonons and/or ionisation/light
    - Some background discrimination
  - Probe light dark matter



Phys.Rev.D 95 (2017) 8, 082002

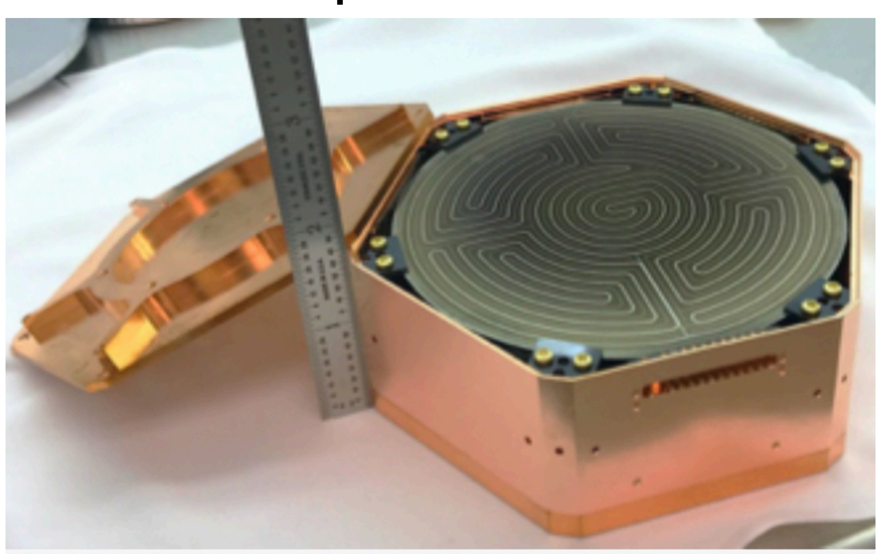


CRESST



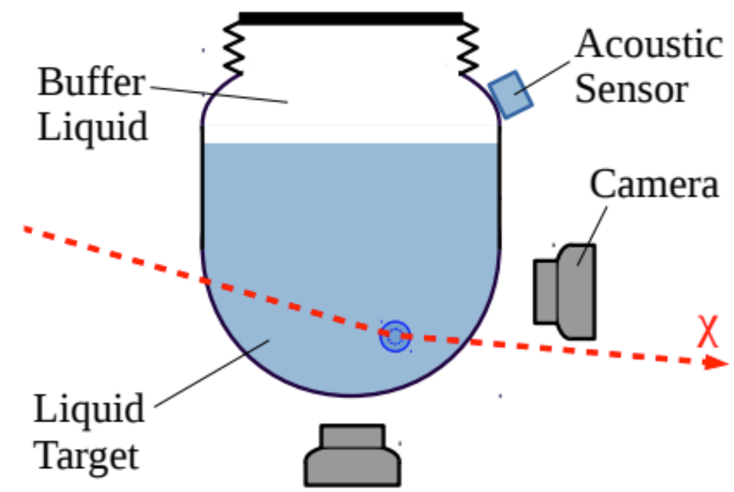
EDELWEISS

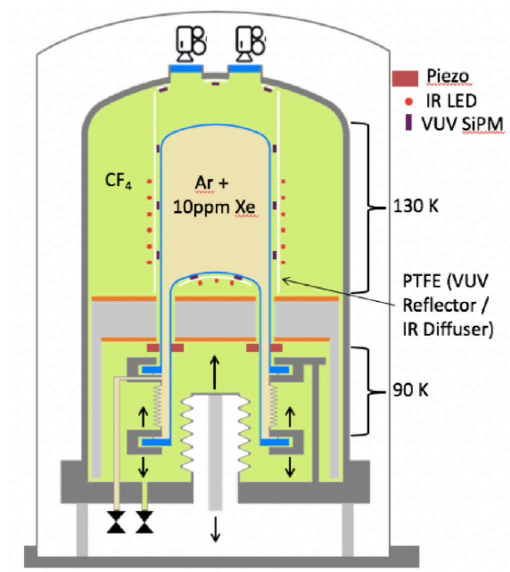
SuperCDMS

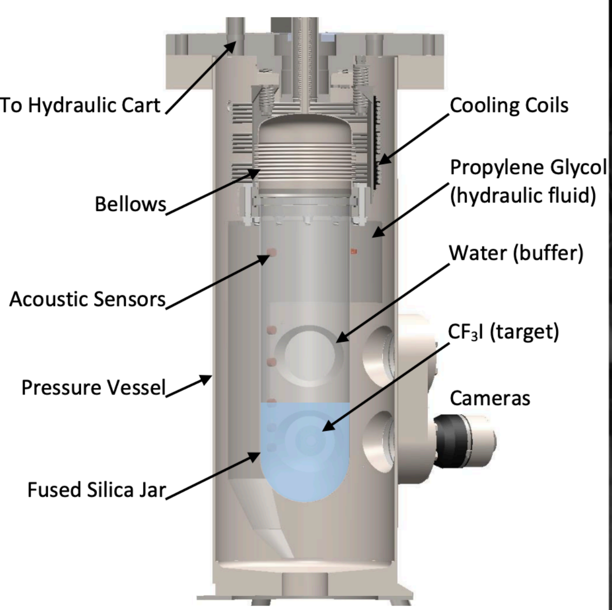


Bubble chambers

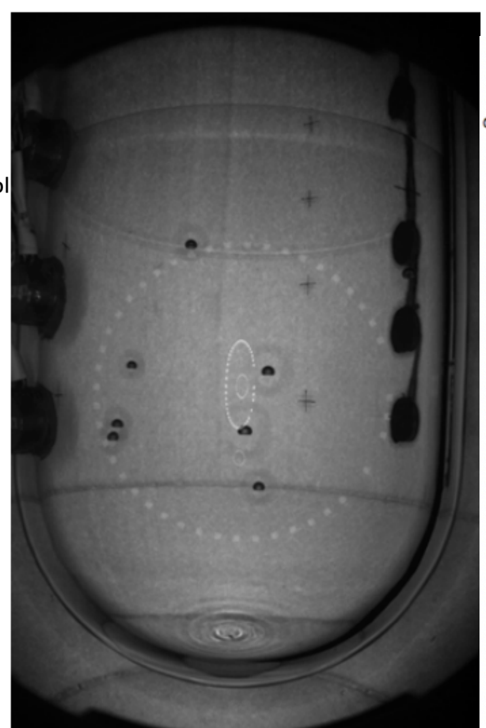
- **PICO**
  - Superheated liquid C_3F_8
  - Acoustic and visual readout for background rejection
  - PICO-500 at SNOLAB: under design, installation/ data in 2022/23
- **New: the scintillating bubble chamber (SBC)**
  - Superheated 10 kg Xe-doped LAr, cooled to 130K
  - Piezoelectric sensors + cameras readout + SiPMs for scintillation signal







arXiv:1510.07754



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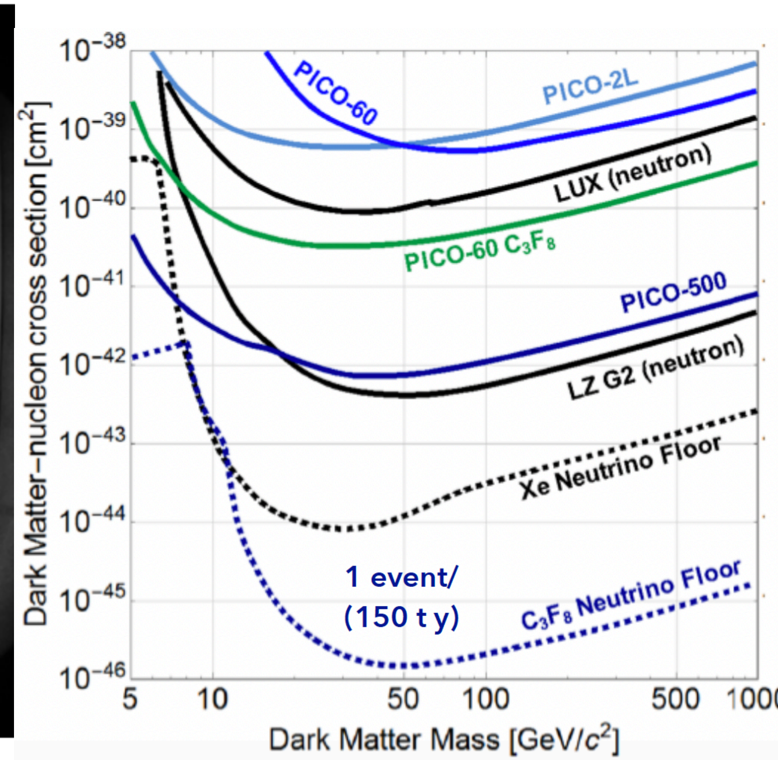
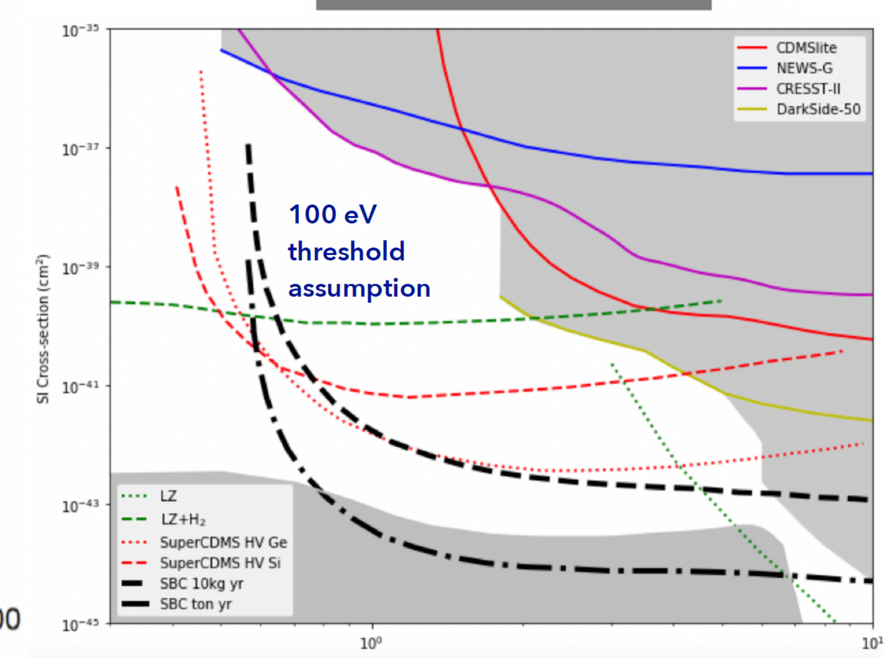
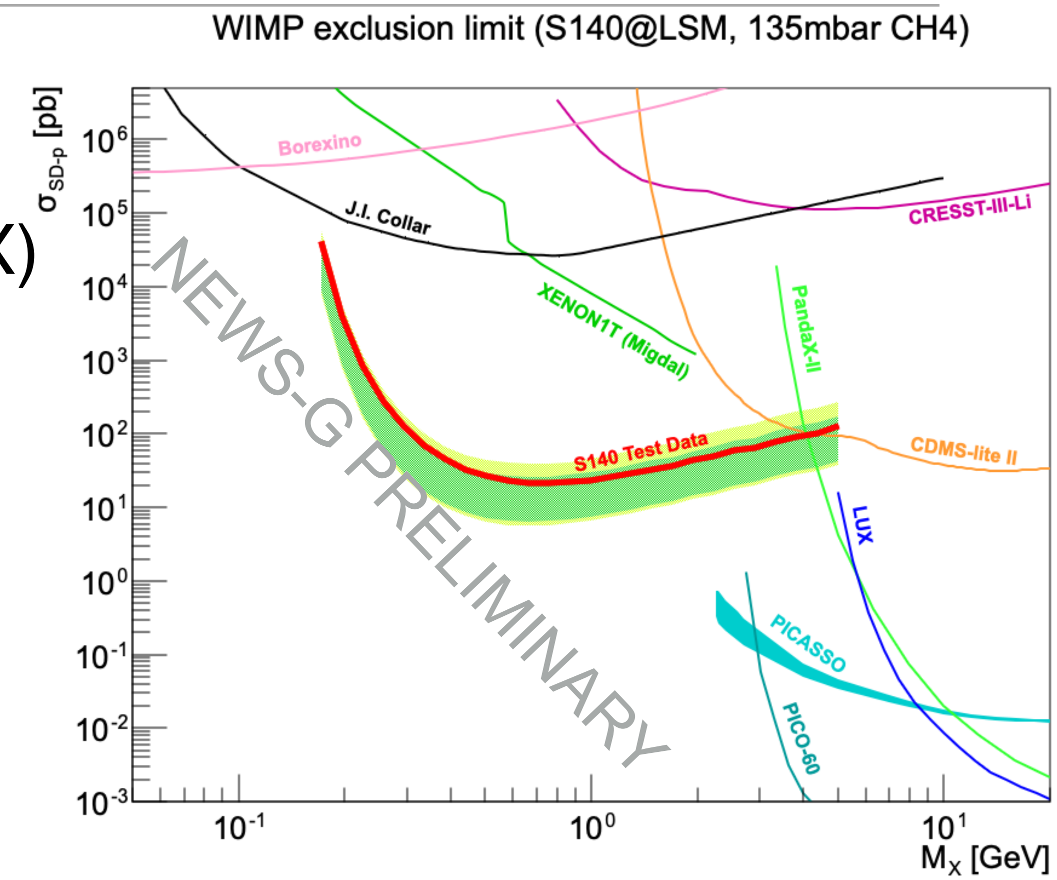
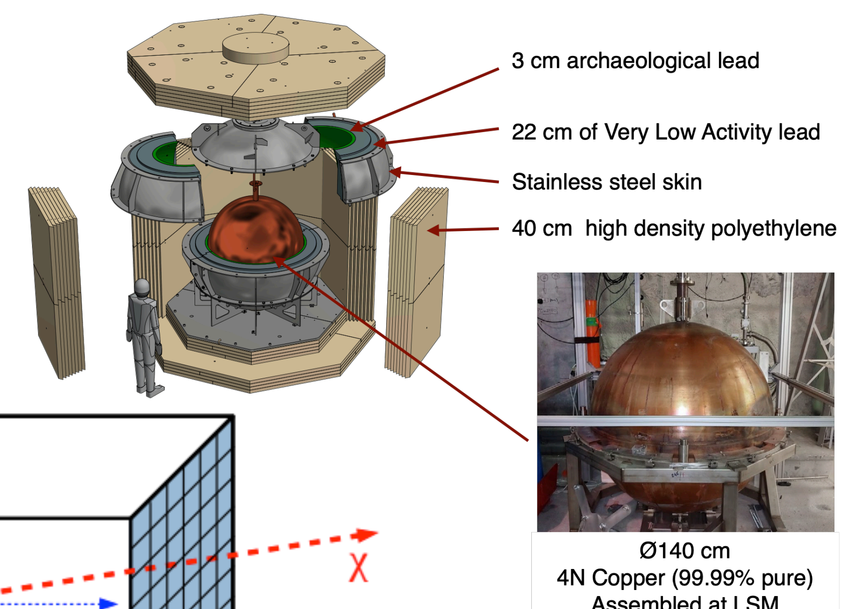


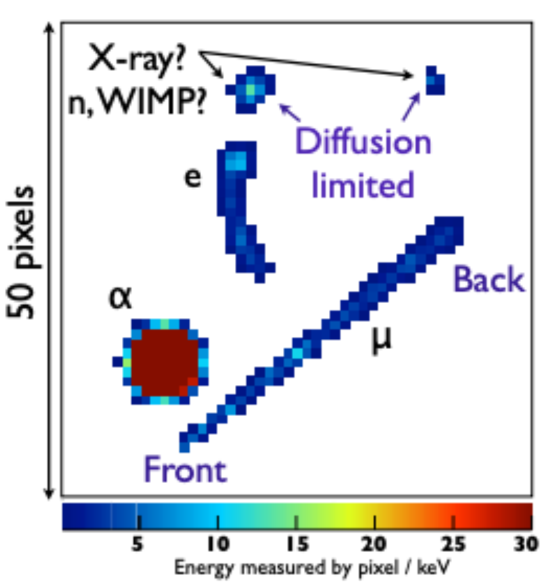


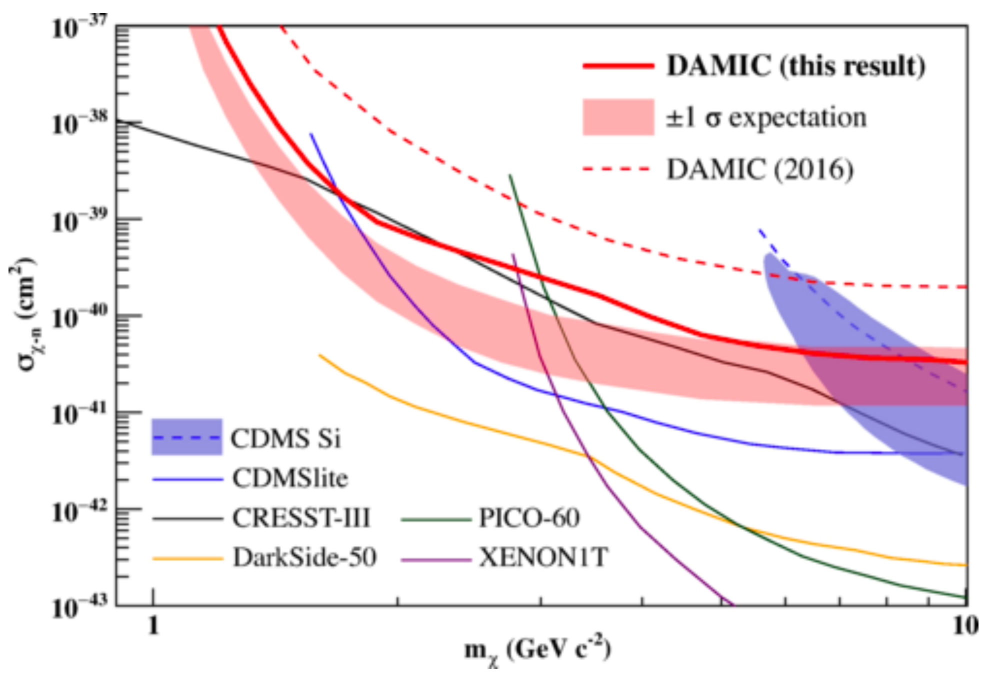
Ionisation detectors

- **Both solid state and gaseous detectors**
  - Point contact HPGe detectors: low energy threshold and (potentially) large total mass (CDEX)
  - Si CCDs: low ionisation energy, low noise, and particle ID (DAMIC-M, SENSEI)
  - NEWS-G: spherical proportional counter, light targets, pulse shape discrimination vs surface events, low energy threshold
- **Directional detectors**
  - Gas (DRIFT, CYGNUS), nuclear emulsion (NEWSdm), graphene
  - Requirement: angular resolution + head/tail id

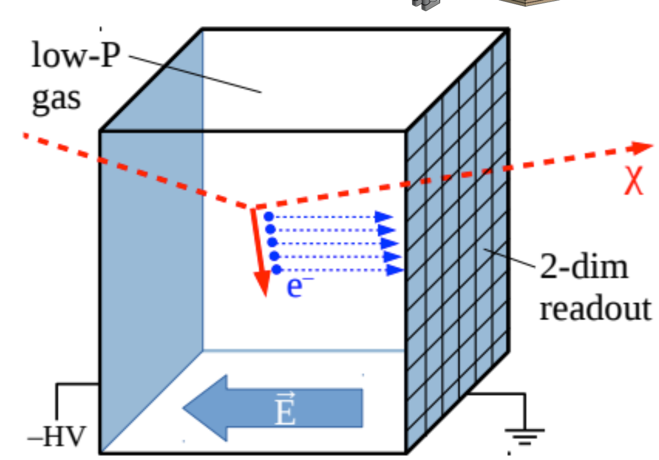








Phys. Rev. Lett. 125, 241803



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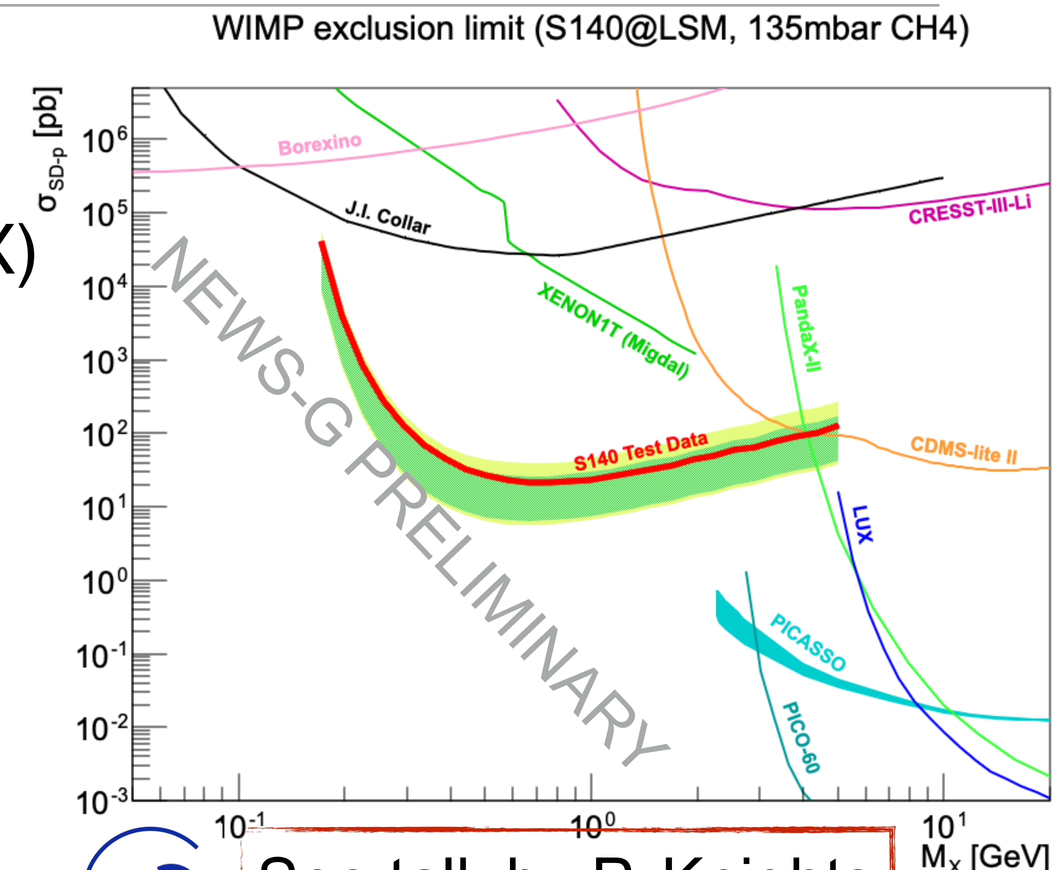
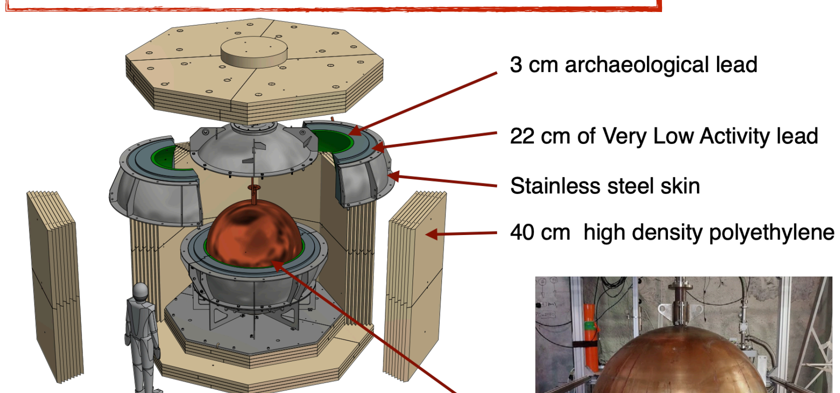
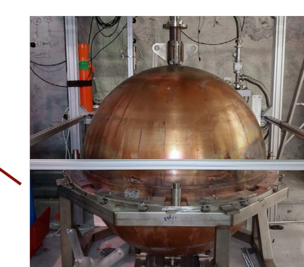
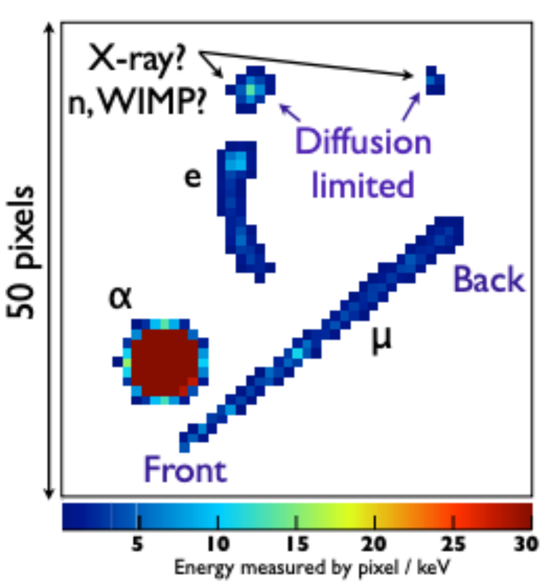


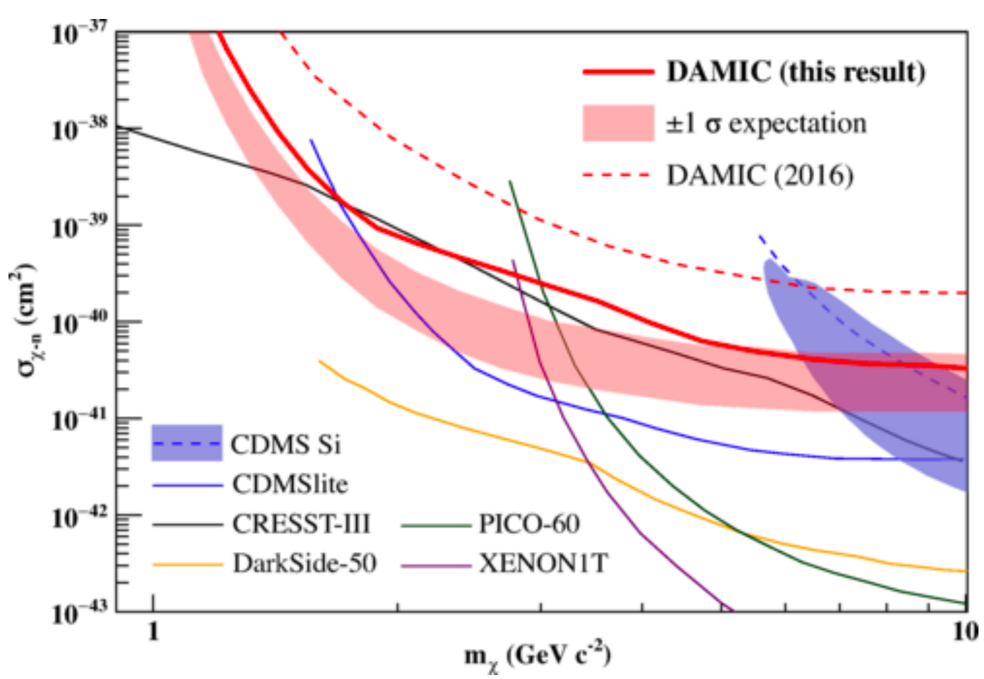
See talk by P. Knights





Ø140 cm
4N Copper (99.99% pure)
Assembled at LSM





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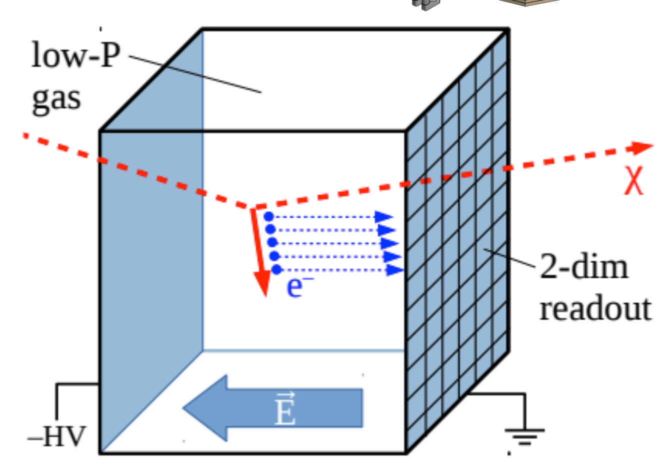
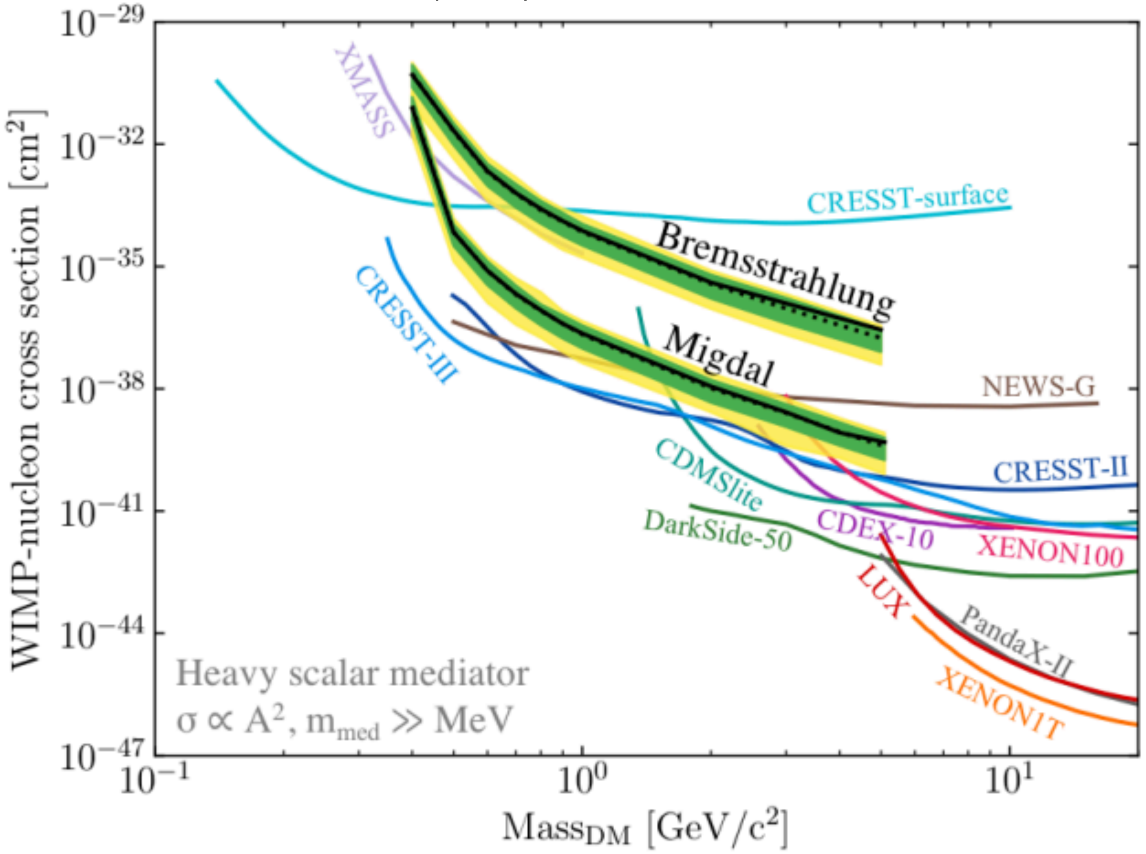


Migdal effect: Light DM with heavy targets

LUX: PRL 122 (2019) 13, 131301
Also Xenon1T: PRL 123 (2019) 24, 241803



- Analysed by Arkady Migdal
  - Nuclear scattering (1939)
  - α and β± decays (1941)
- Relevance for DM searches
  - Ibe et al. JHEP03(2018)194

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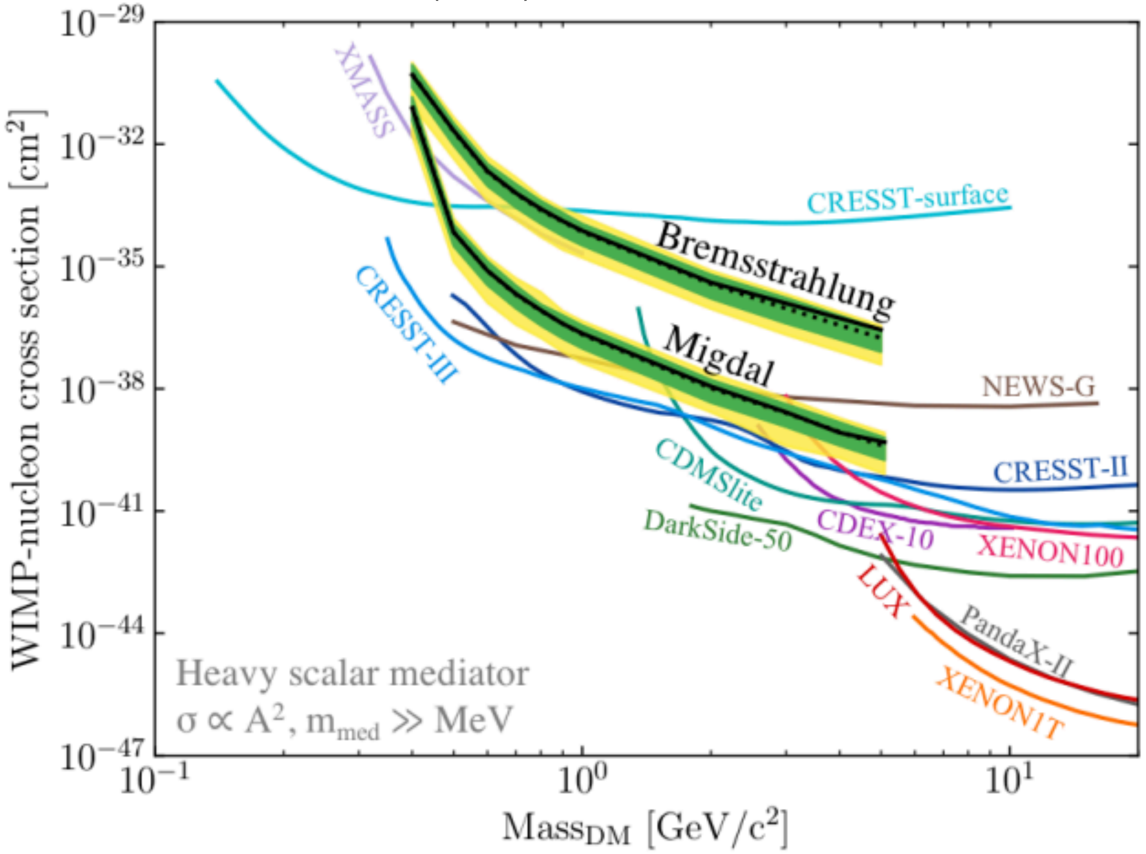

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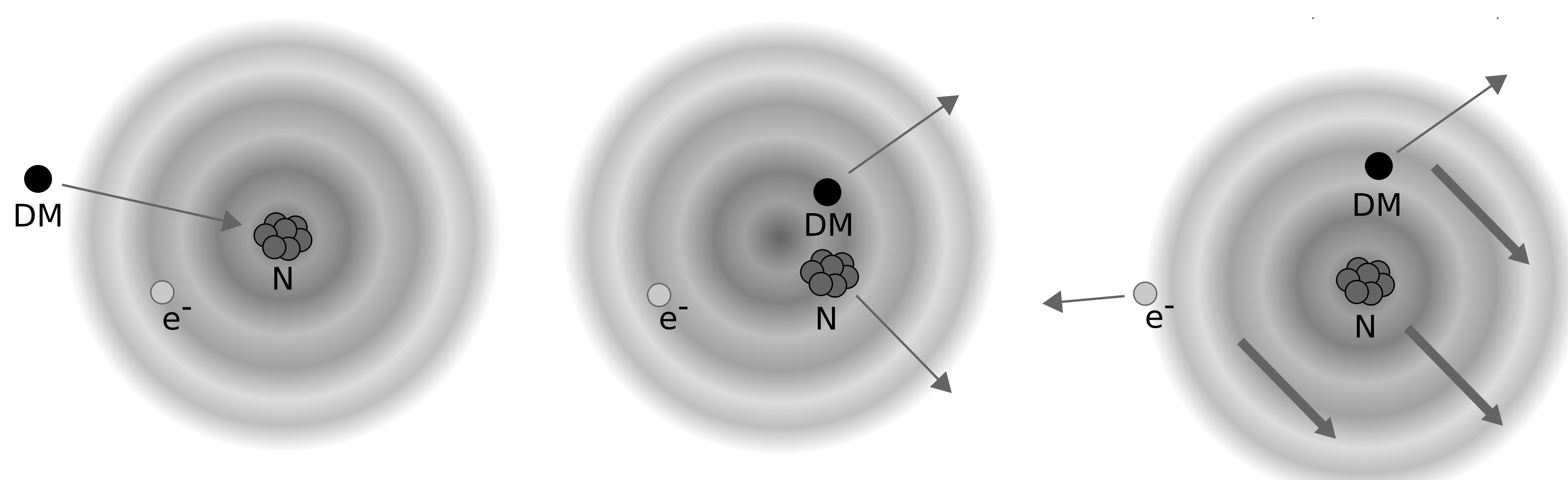

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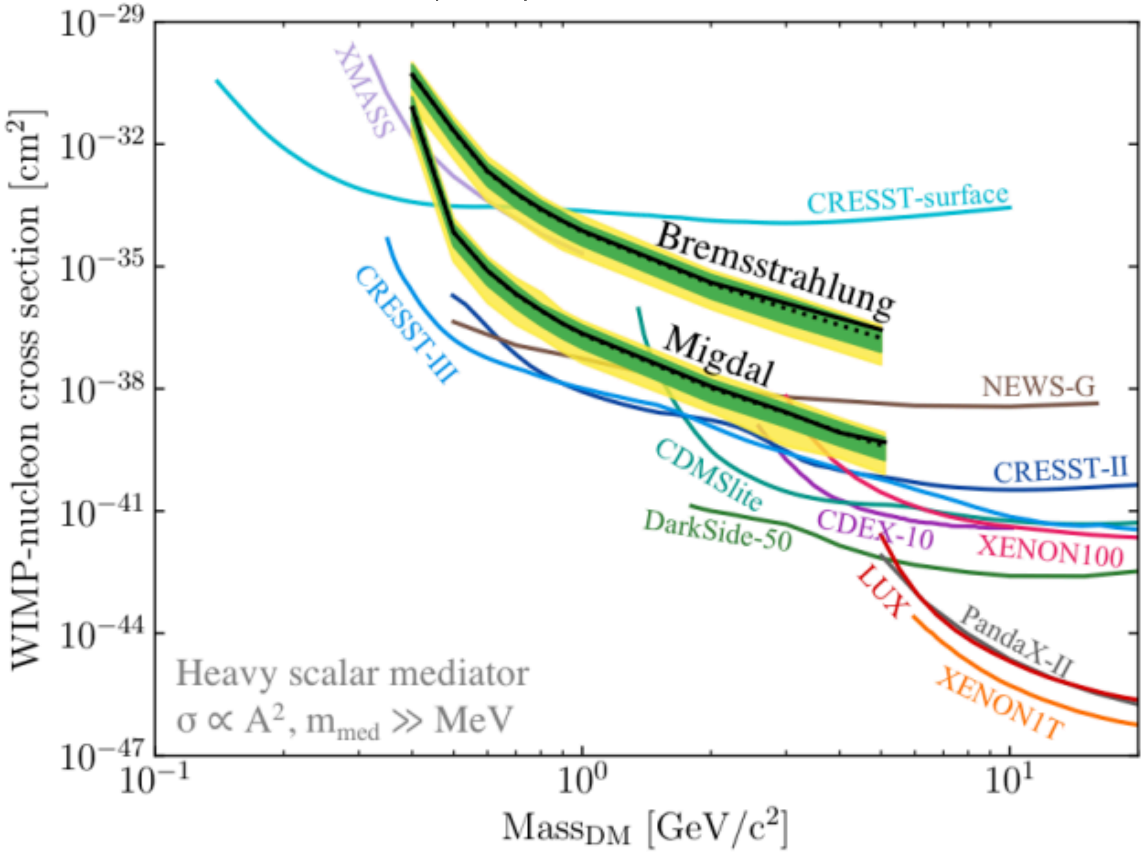

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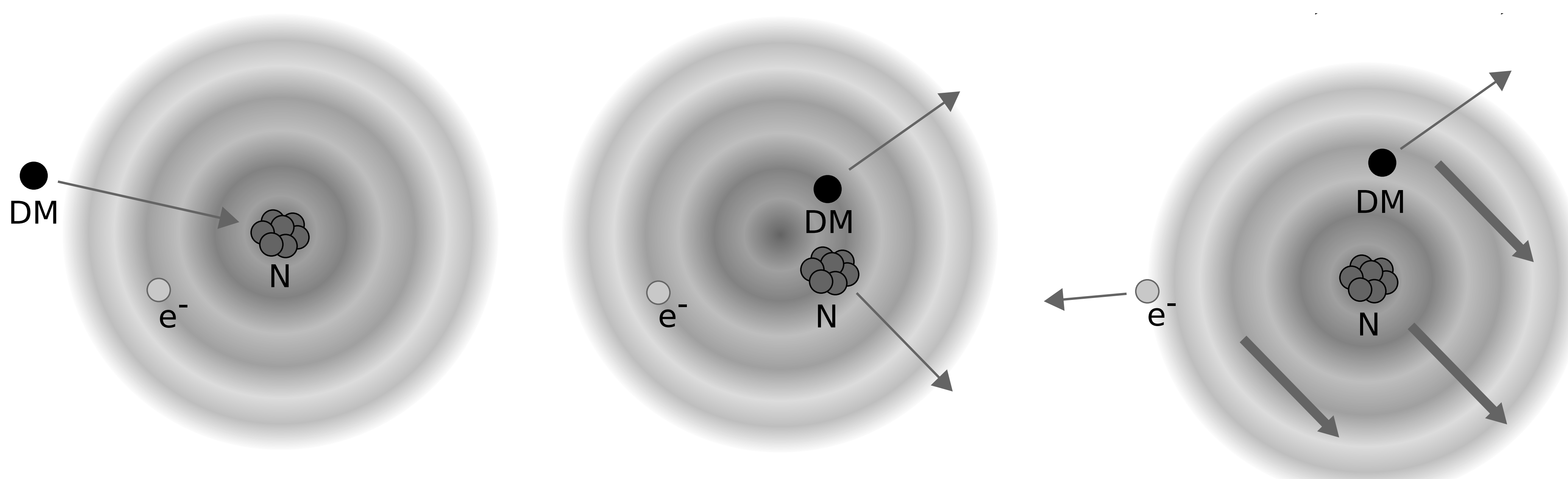

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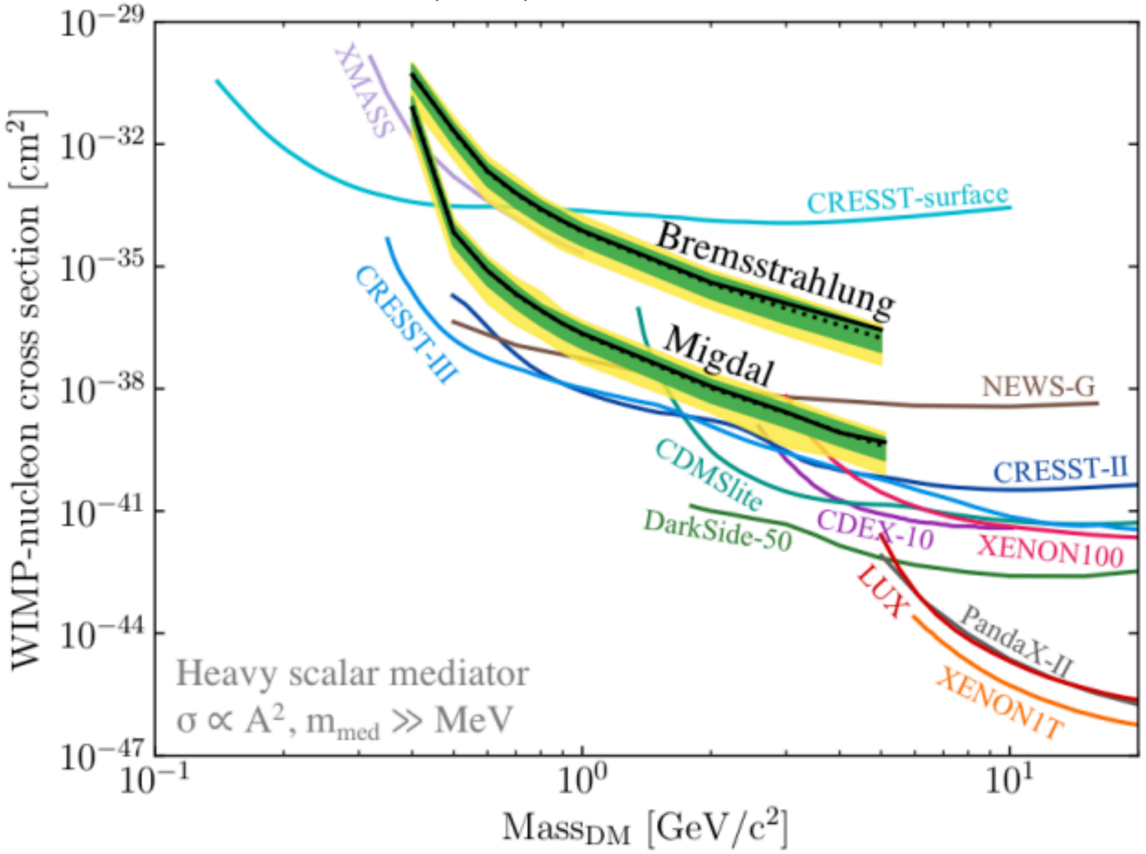

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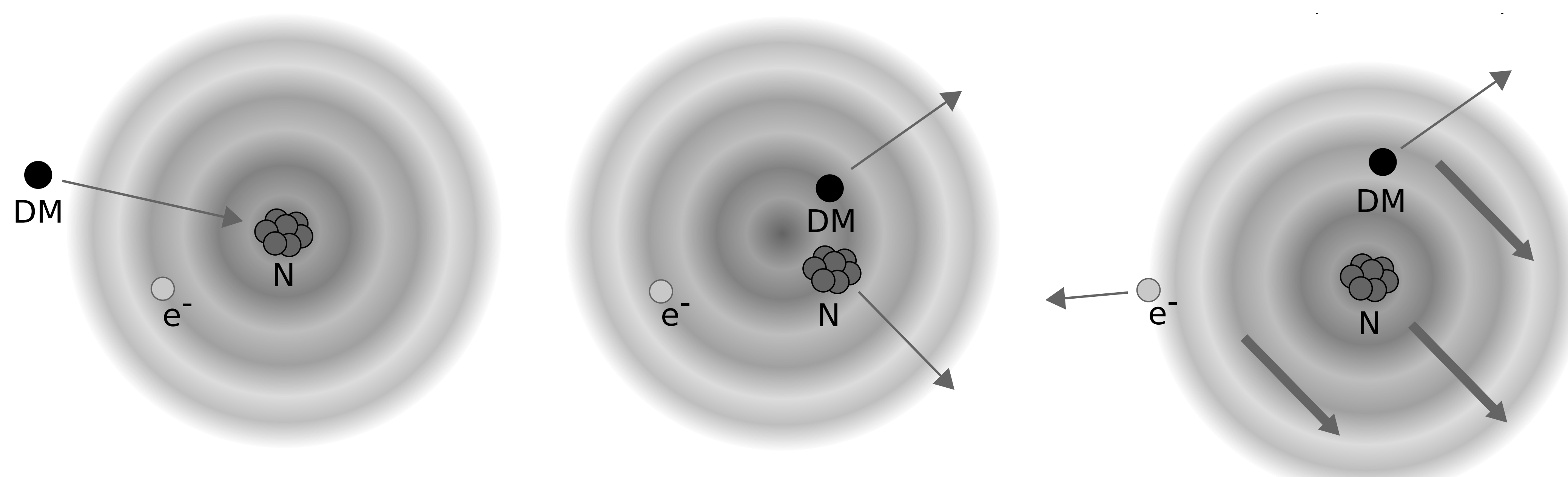
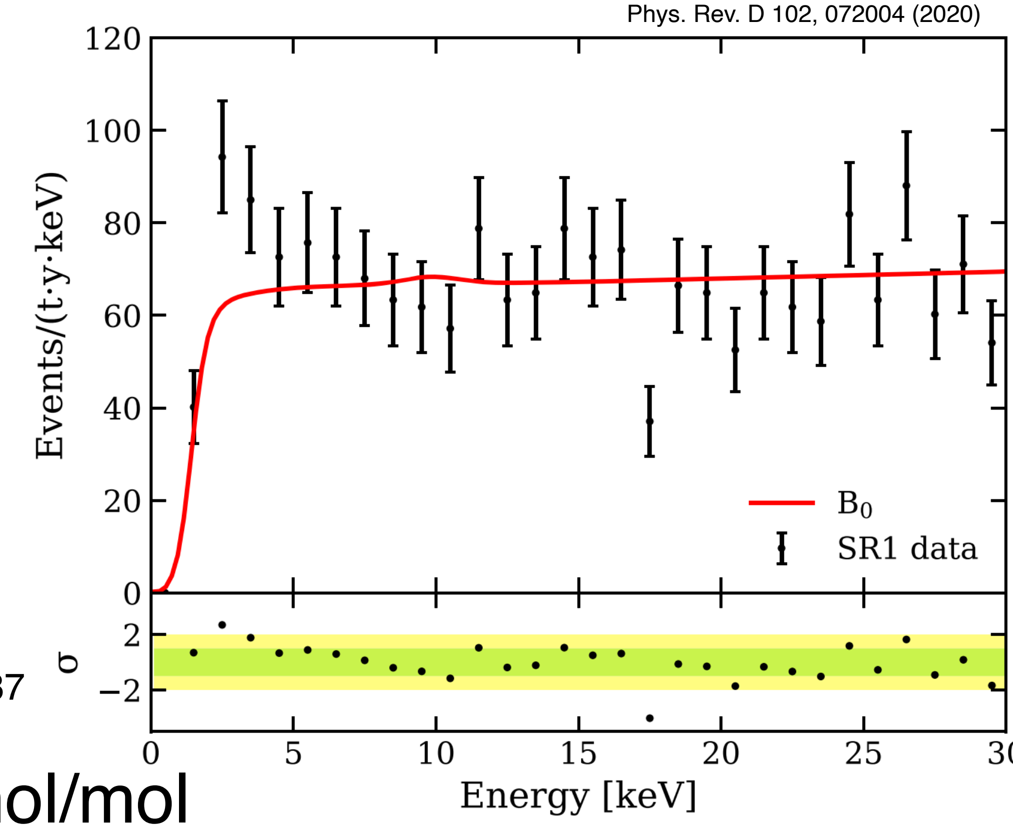
MIGDAL
Migdal In Galactic Dark mAtter expLoration

See talk by I. Katsioulas



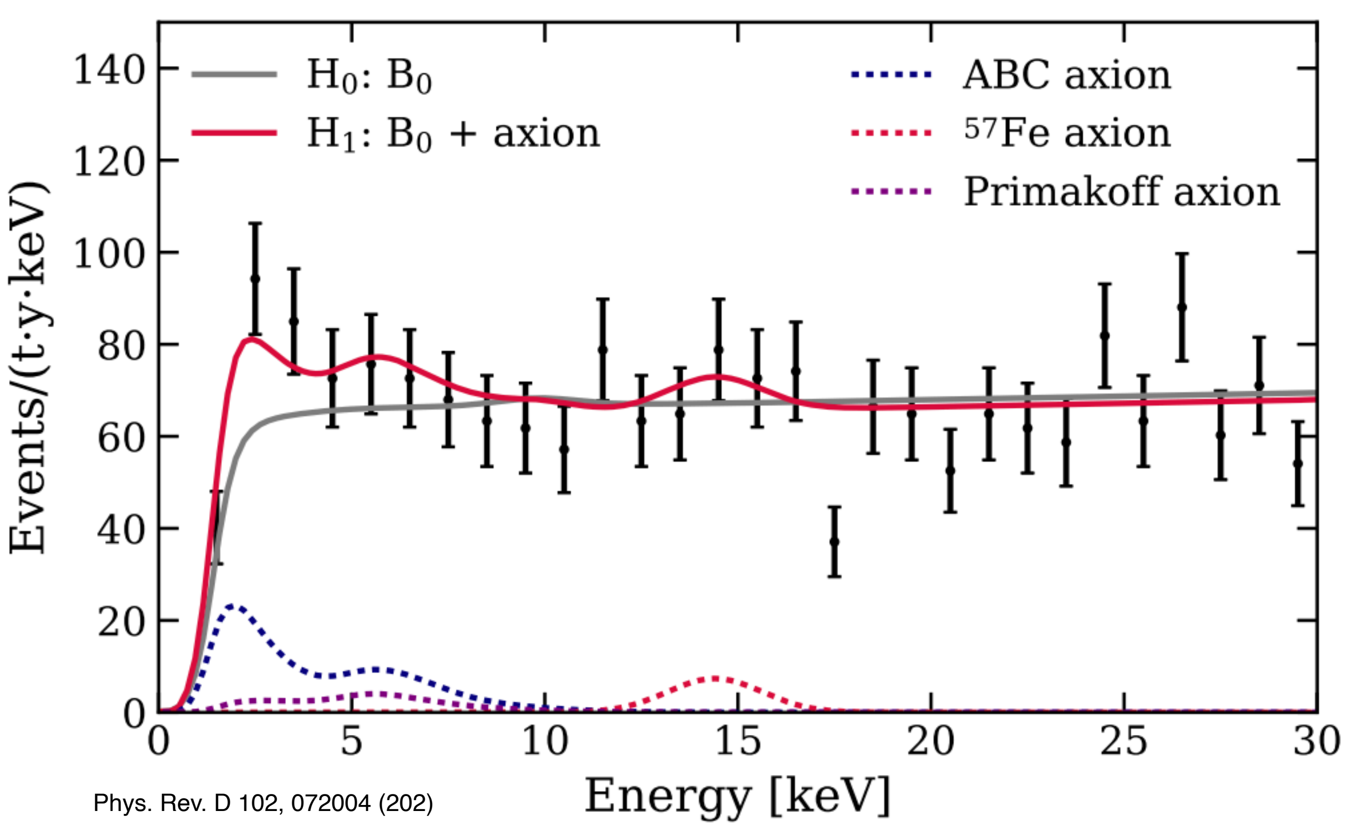
Xenon1T: Electronic recoil excess

Phys. Rev. D 102, 072004 (2020)

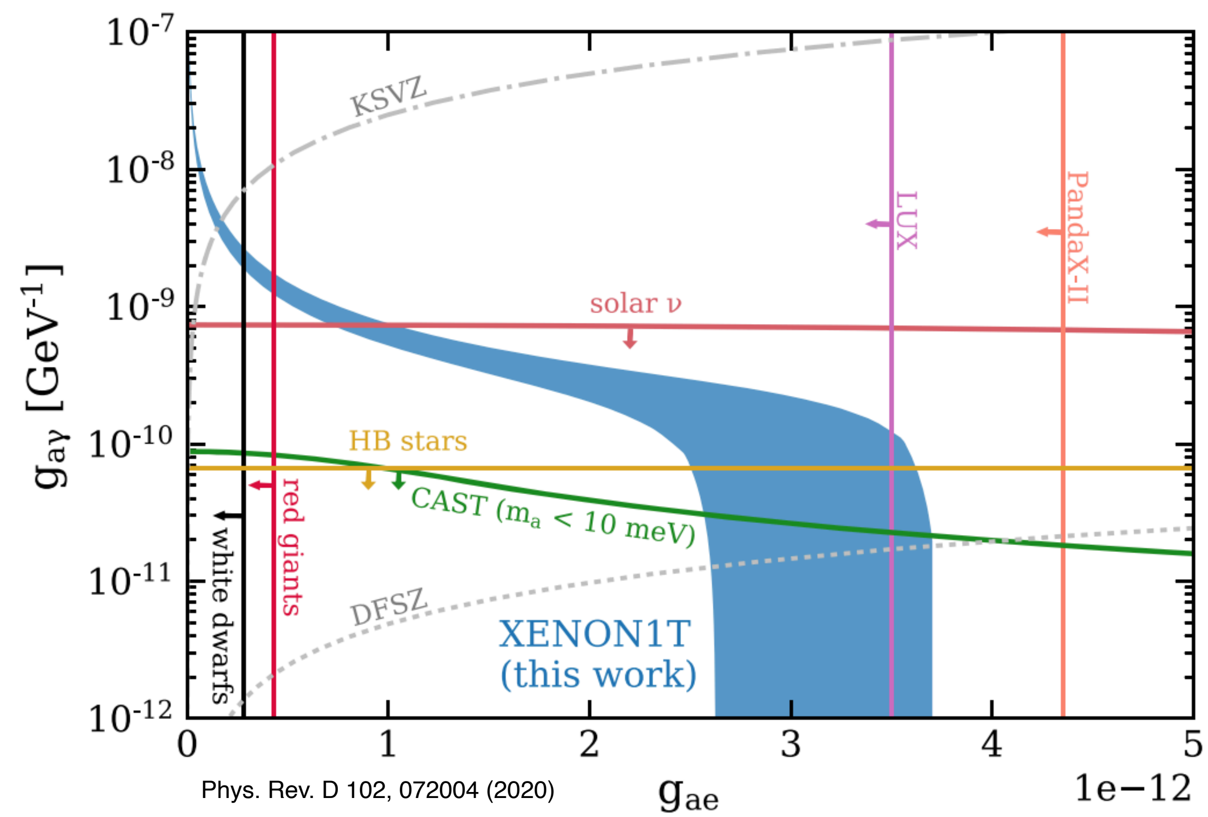


- **Excess observed between (1,7) keV**
  - 285 observed events
  - (232±15) events expected from background
- **Origin of excess unclear**
  - Tritium, solar axions, ALPs, dark photons,… ?
  - Solar axion favoured over B-only at 3.4σ
    - But discrepancy with stellar cooling constraints
  - ^{3}H favoured over B-only at 3.2σ
    - Indicating ^{3}H/Xe concentration of (6.2±2)x10^{-25} mol/mol

arXiv:2006.12487

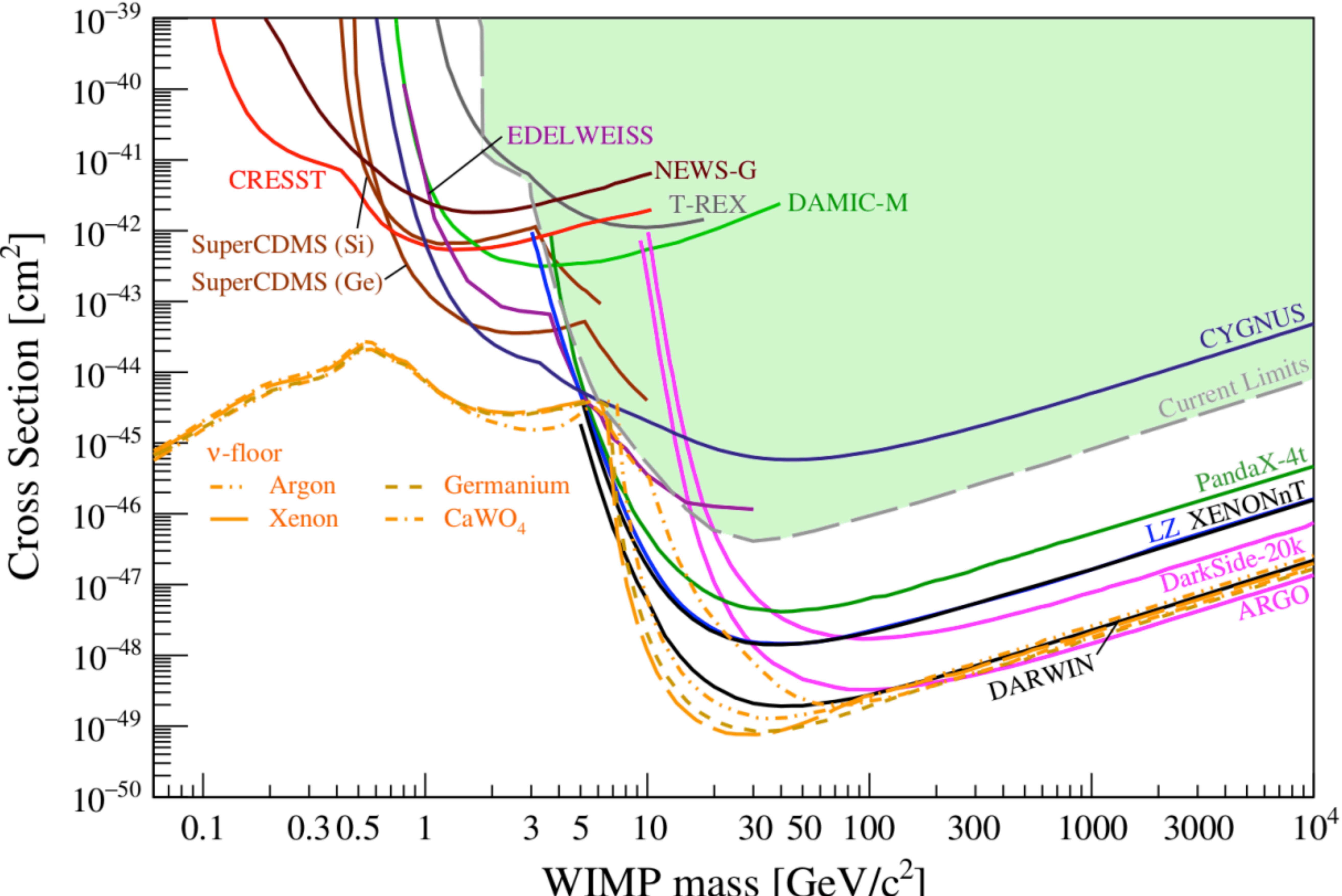


Phys. Rev. D 102, 072004 (202)



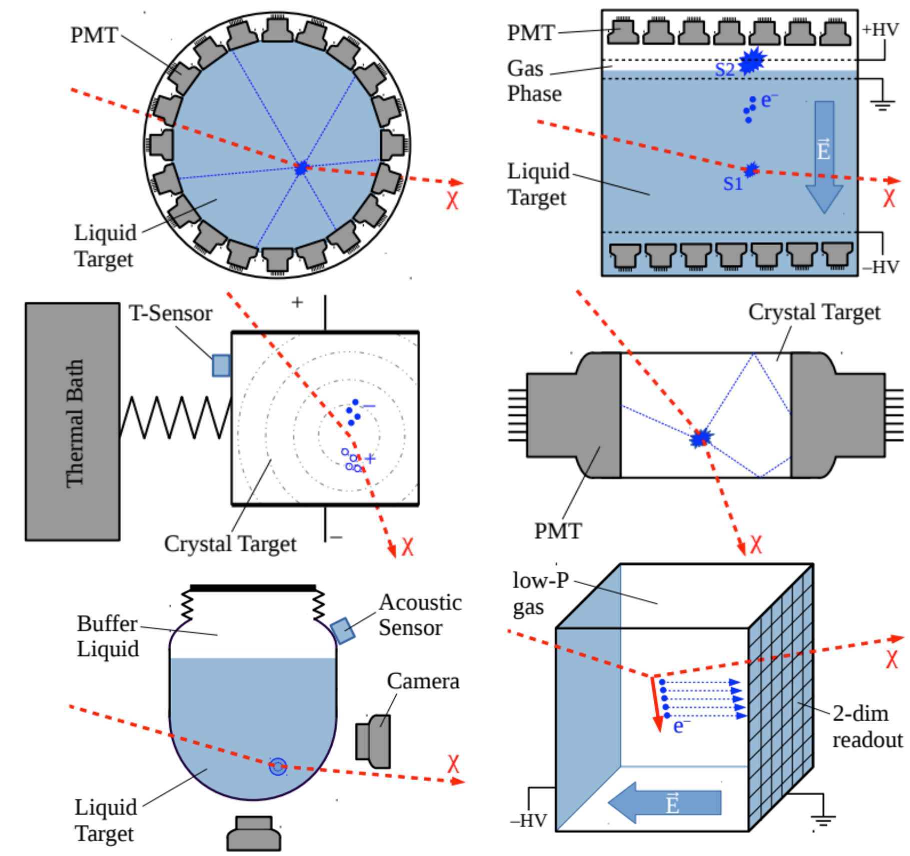
Phys. Rev. D 102, 072004 (2020)

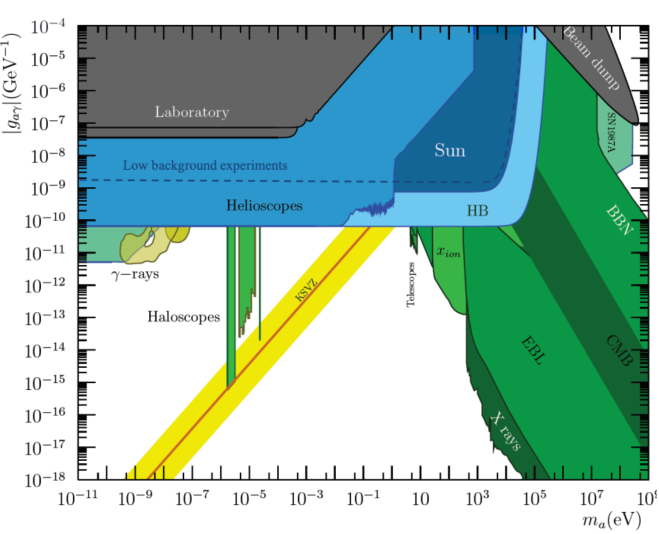
Prospects for Direct Detection searches

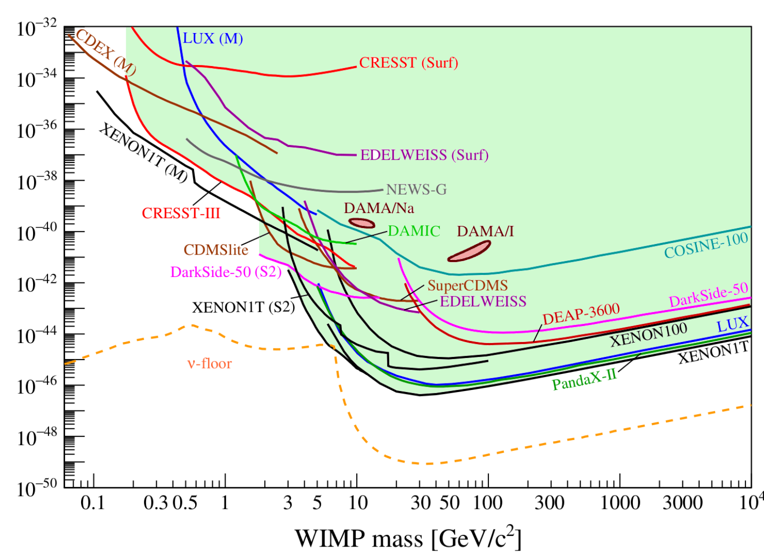


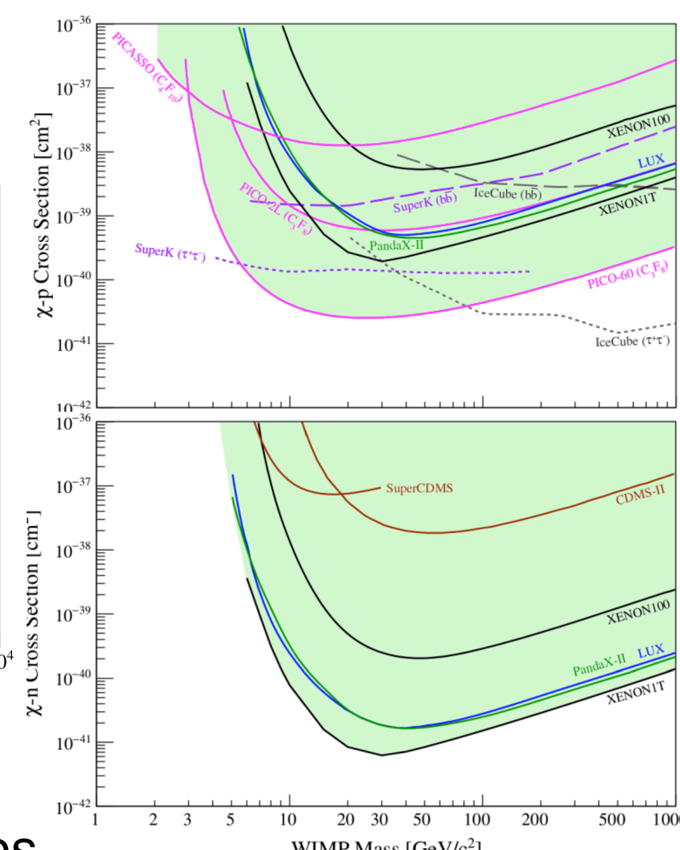
Summary

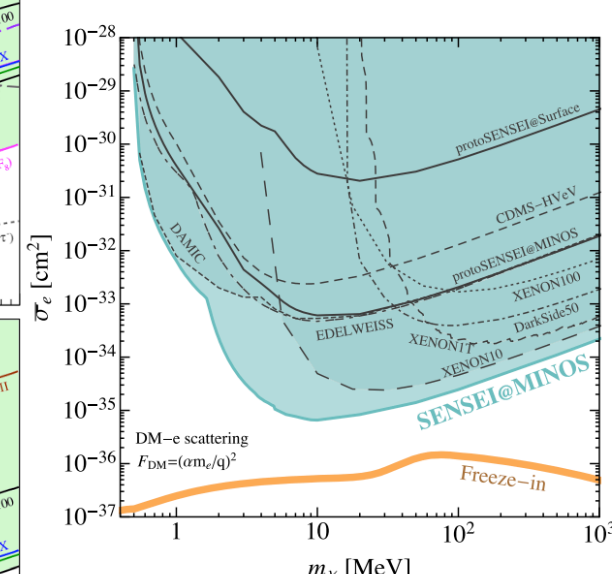
- **Particle nature of Dark Matter is unknown!**
  - Sub-GeV mass range is uncharted territory
- **Experimental challenges**
  - lower energy threshold
  - reduce/understand backgrounds
  - increase target masses
- **A wide variety of complementary approaches**
  - New ideas appearing continuously
  - Large variance in collaboration size/cost
  - Eventually sensitivity could reach neutrino floor









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