Dark Matter sensitivity of neutrino detectors

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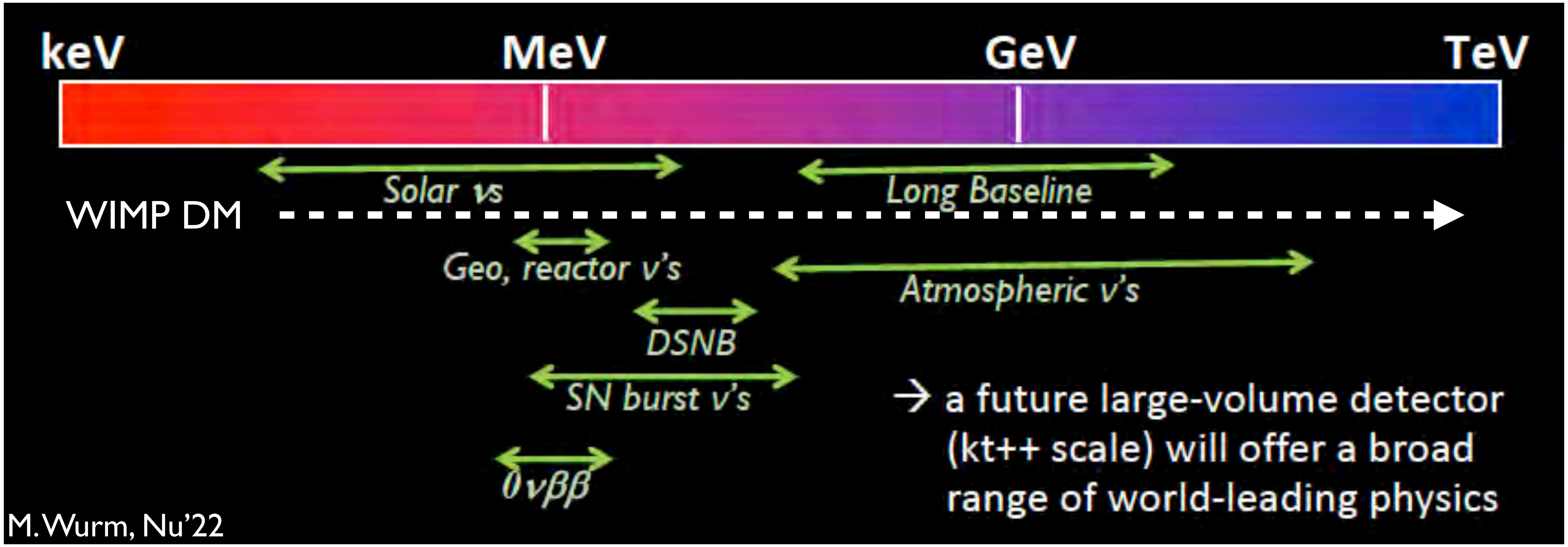
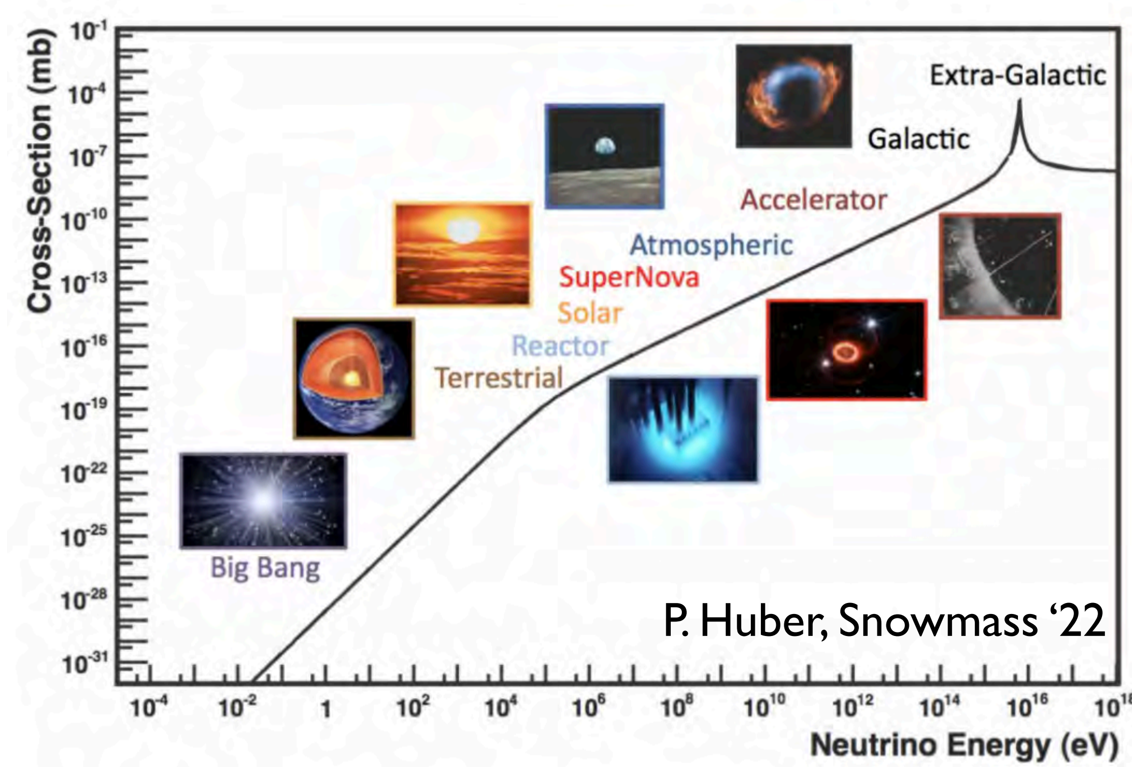
DMNet, MPIK
14th Sept, 2022

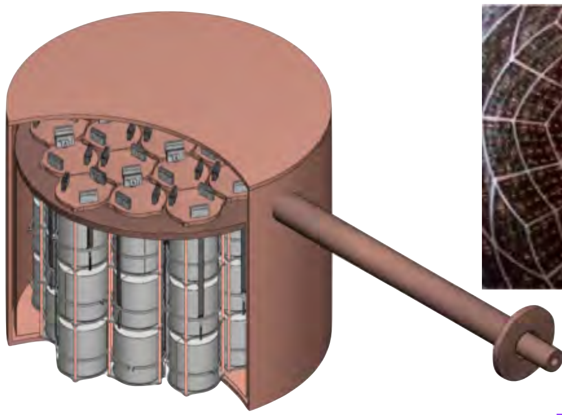
Broad physics program

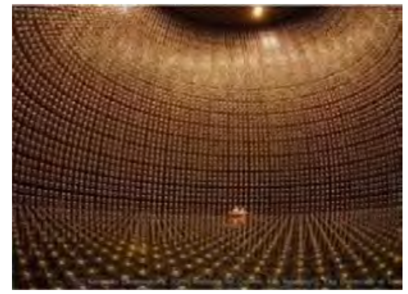
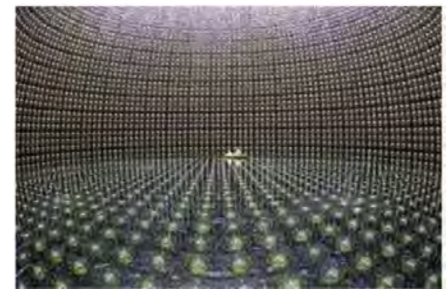
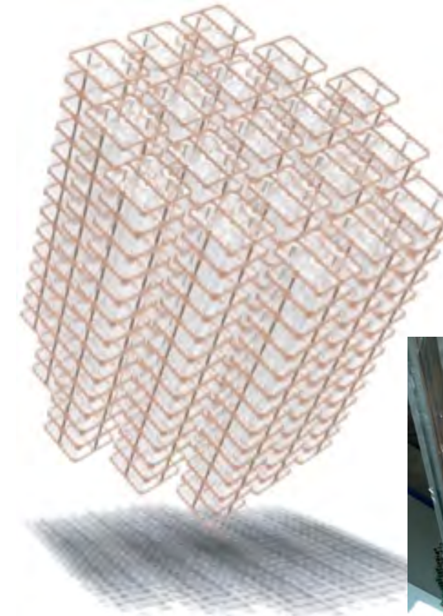
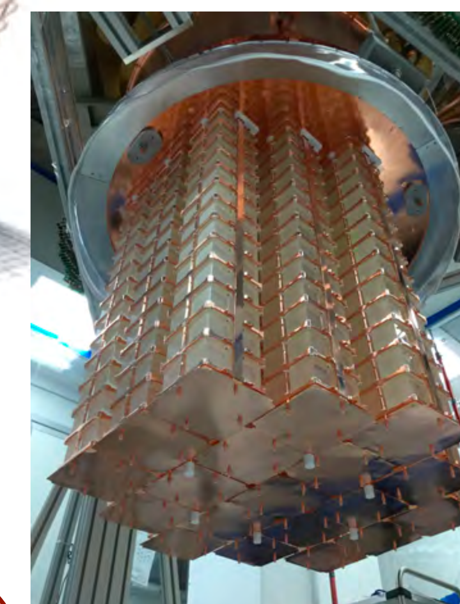


- Low energy threshold (but not as low as for nuclear recoils!)
- High detection efficiency
- Large exposure
- Directionality
- Broad detection range



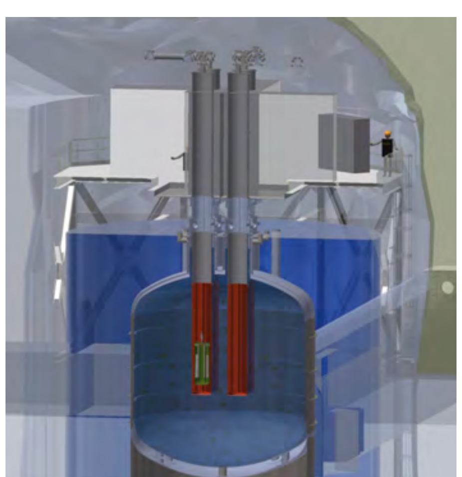
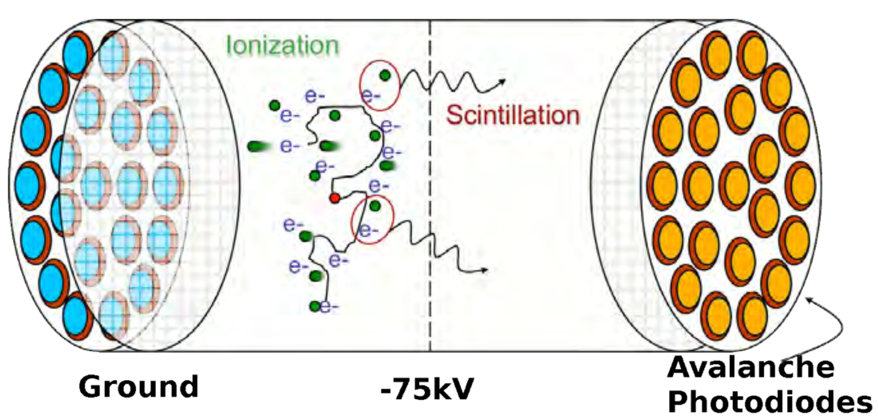
Neutrino detection technology

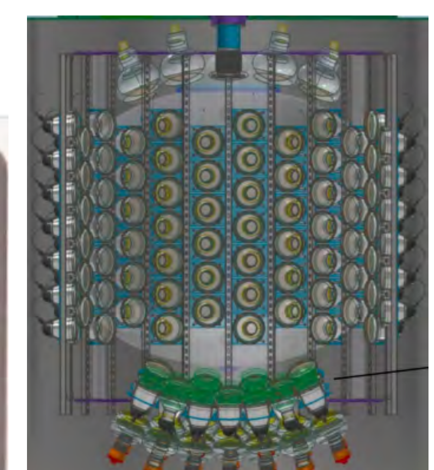
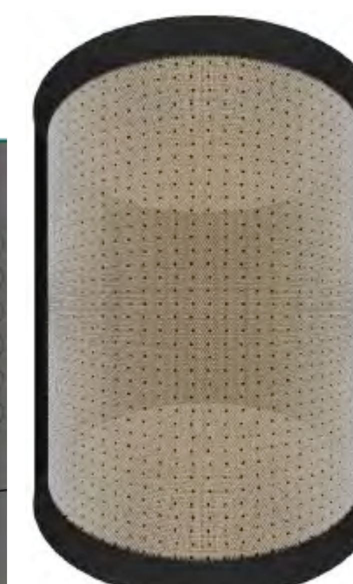


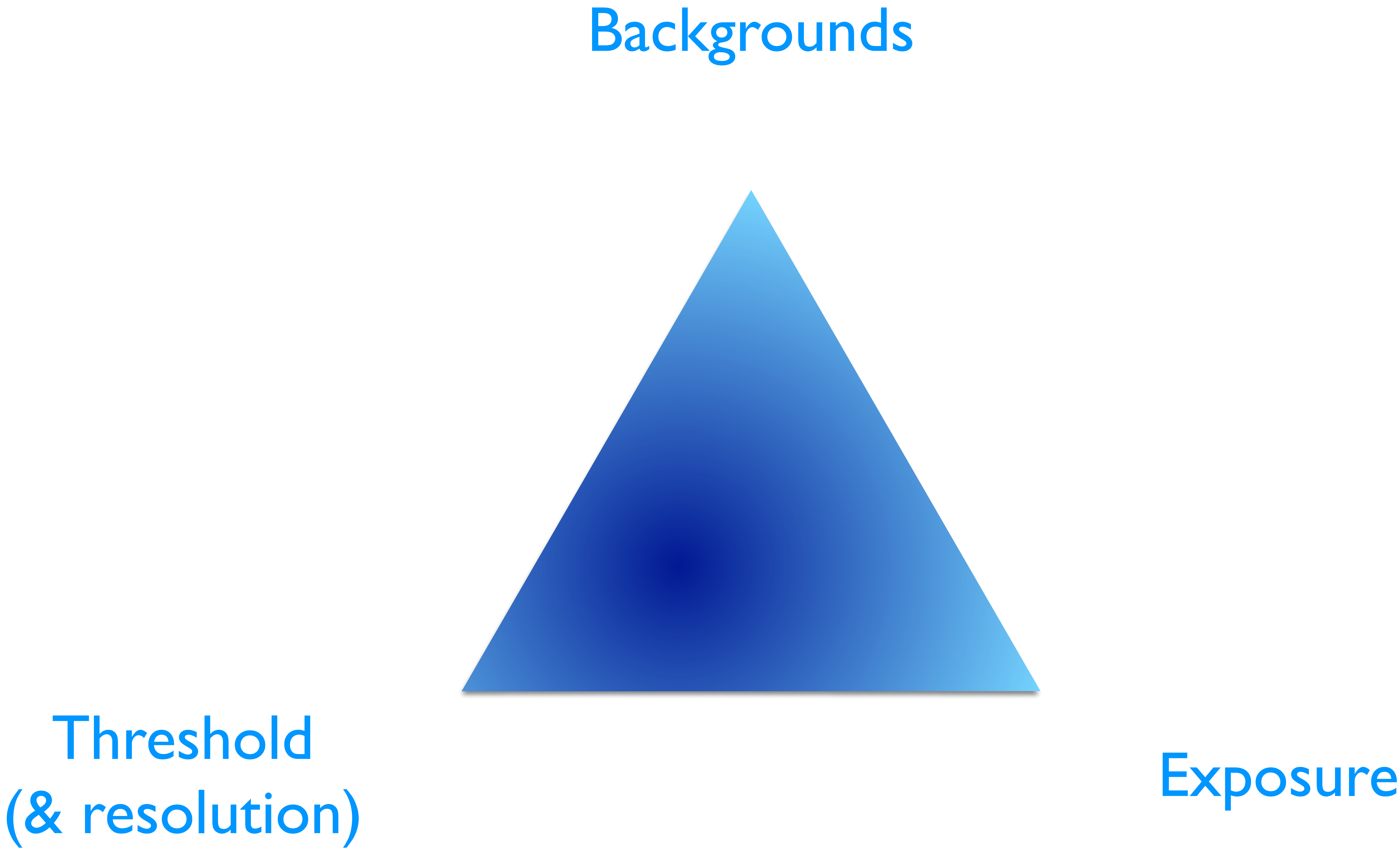

- Ultra-pure Ge
- High resolution bolometry
- Noble liquid / gas TPCs: LAr, LXr, GXe (S+I)
- Water Cherenkov
- Organic liquid scintillator / "Hybrid" detection (S+Ch)

✳ *Sample of approaches relevant for this topic*

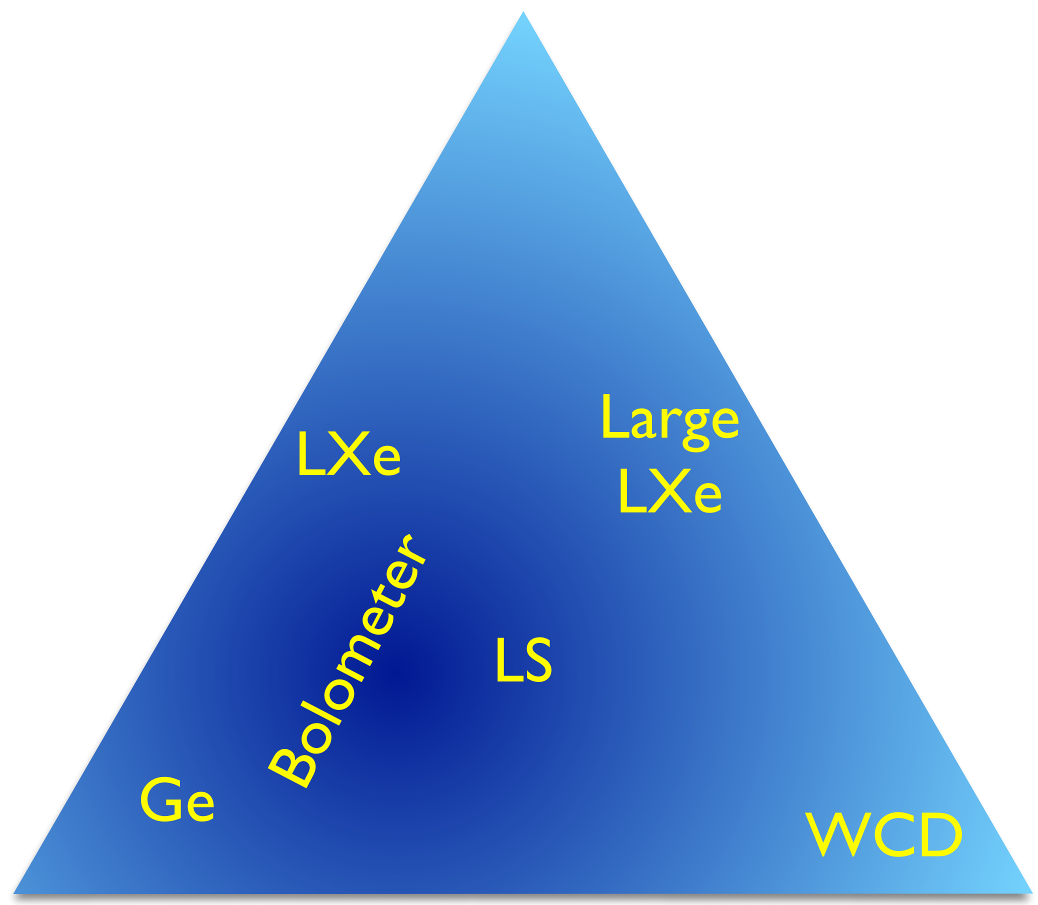




Detector technology



Detector technology

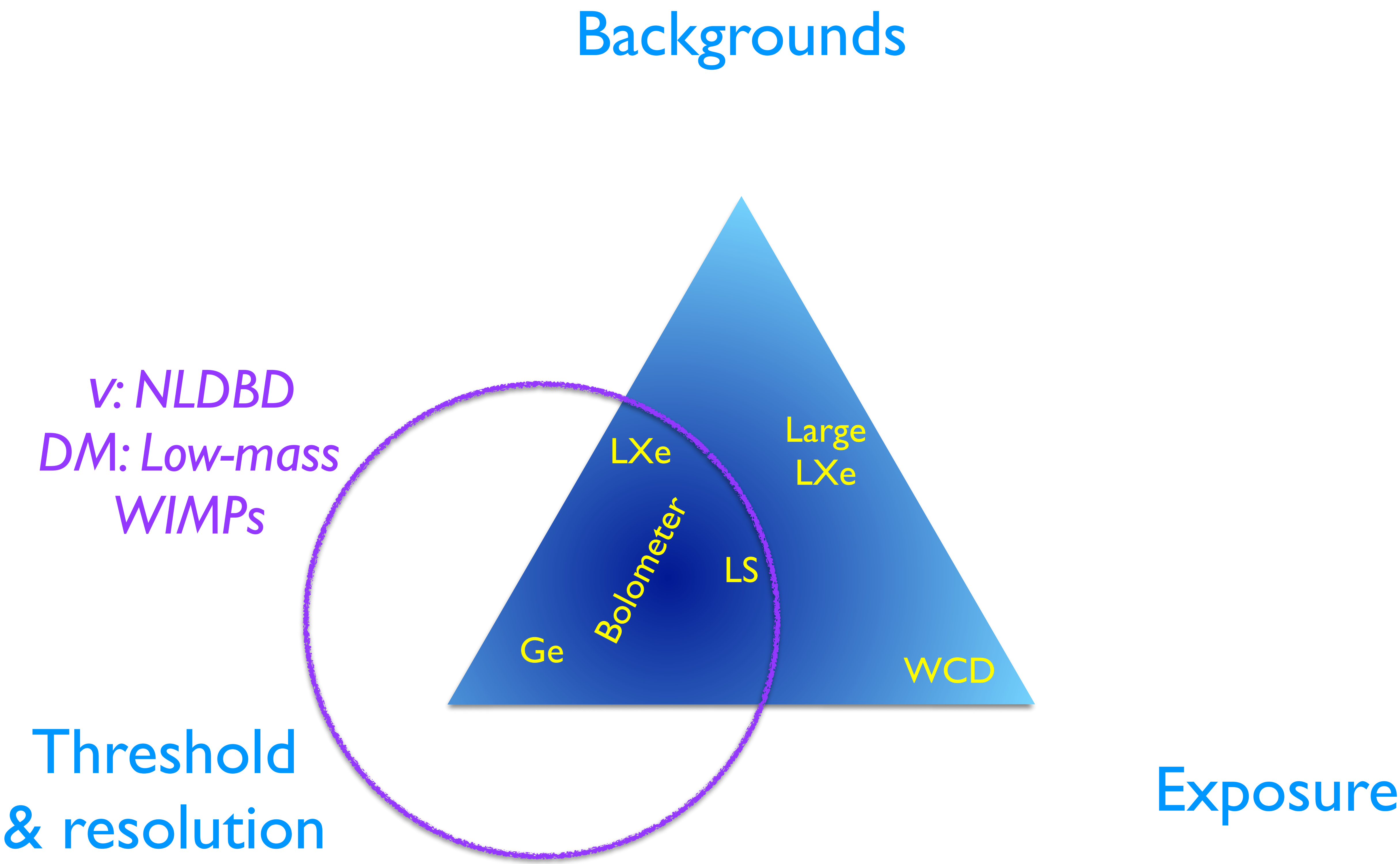
Backgrounds



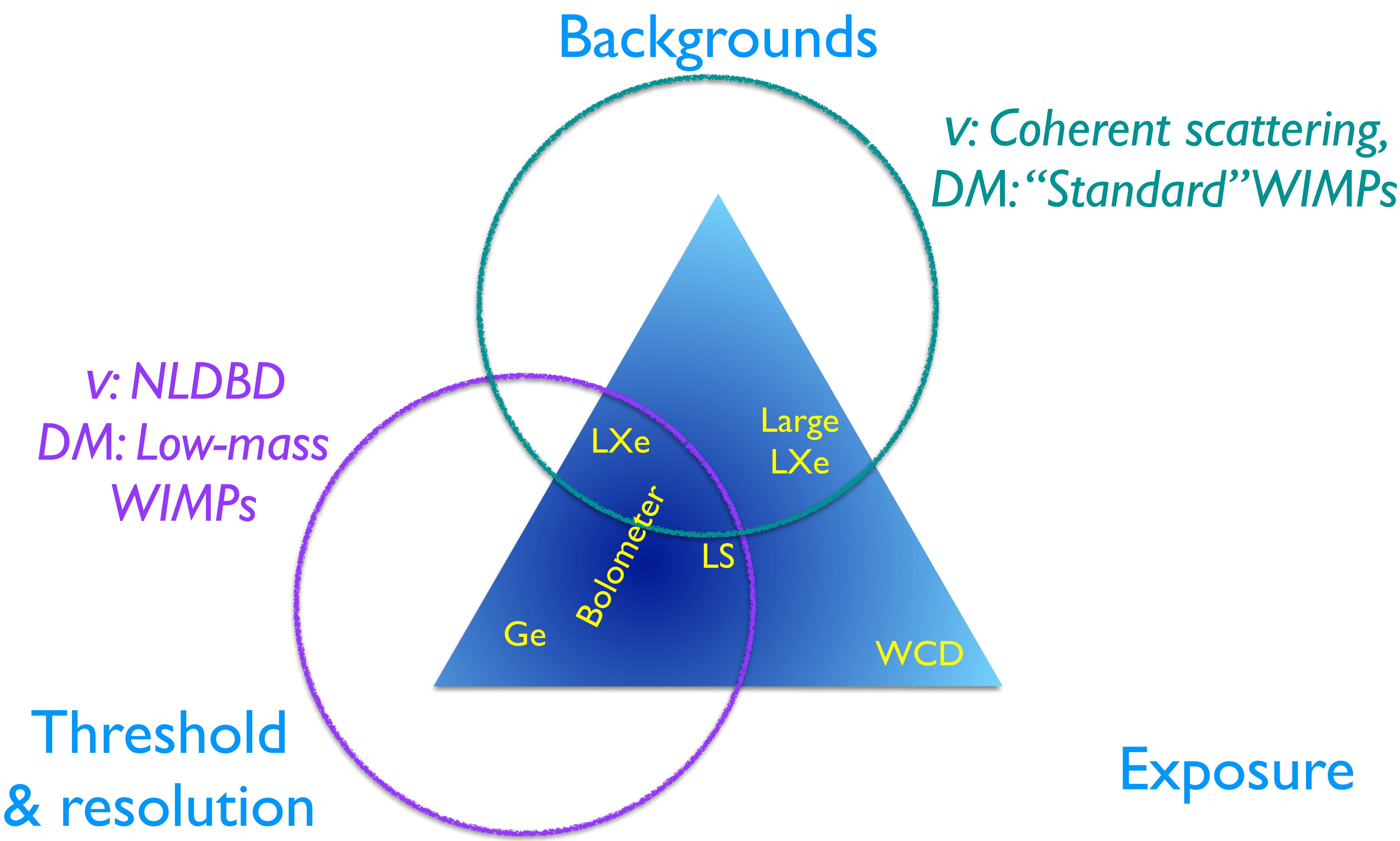
Threshold & resolution

Exposure

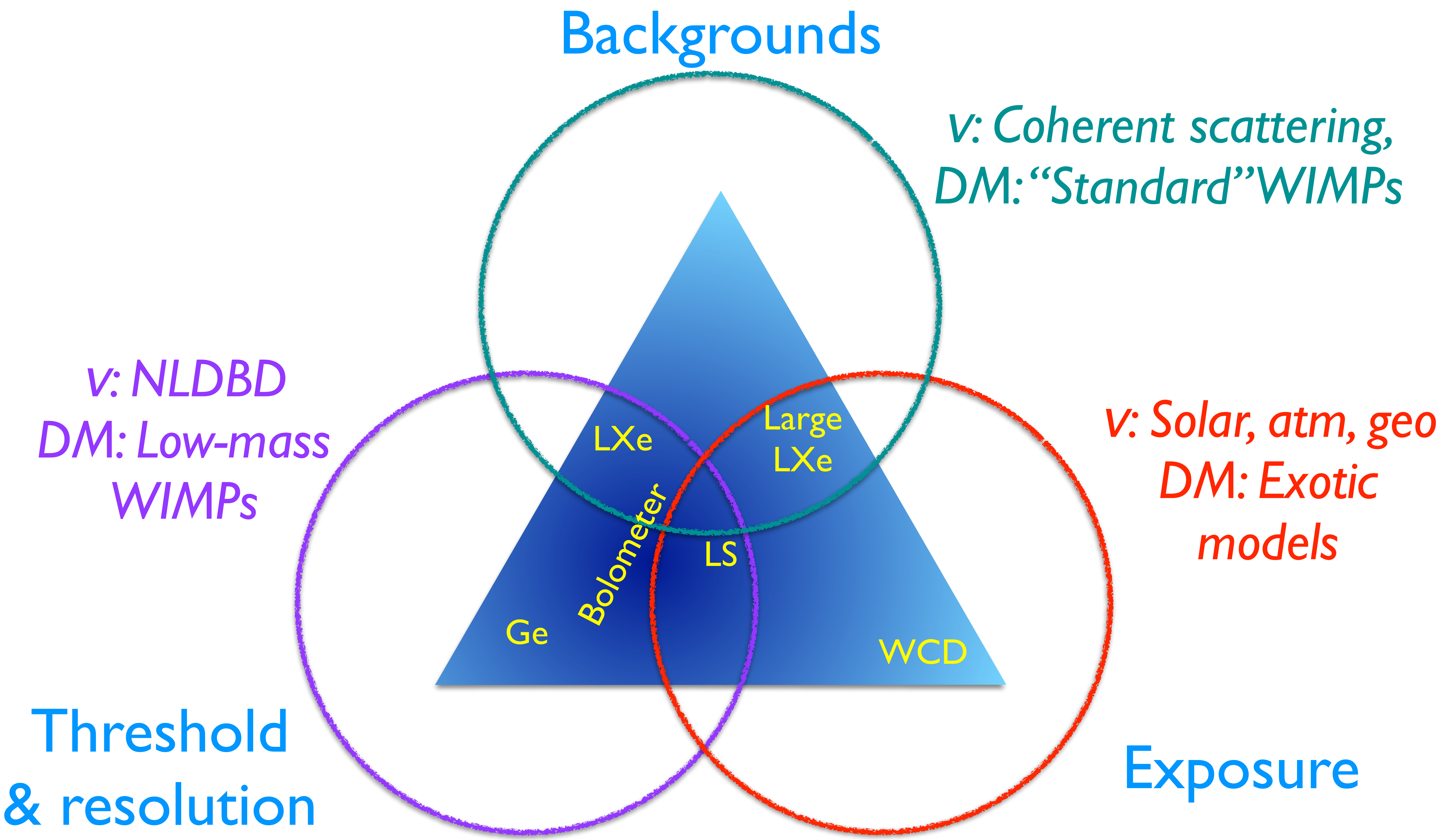
Detector technology



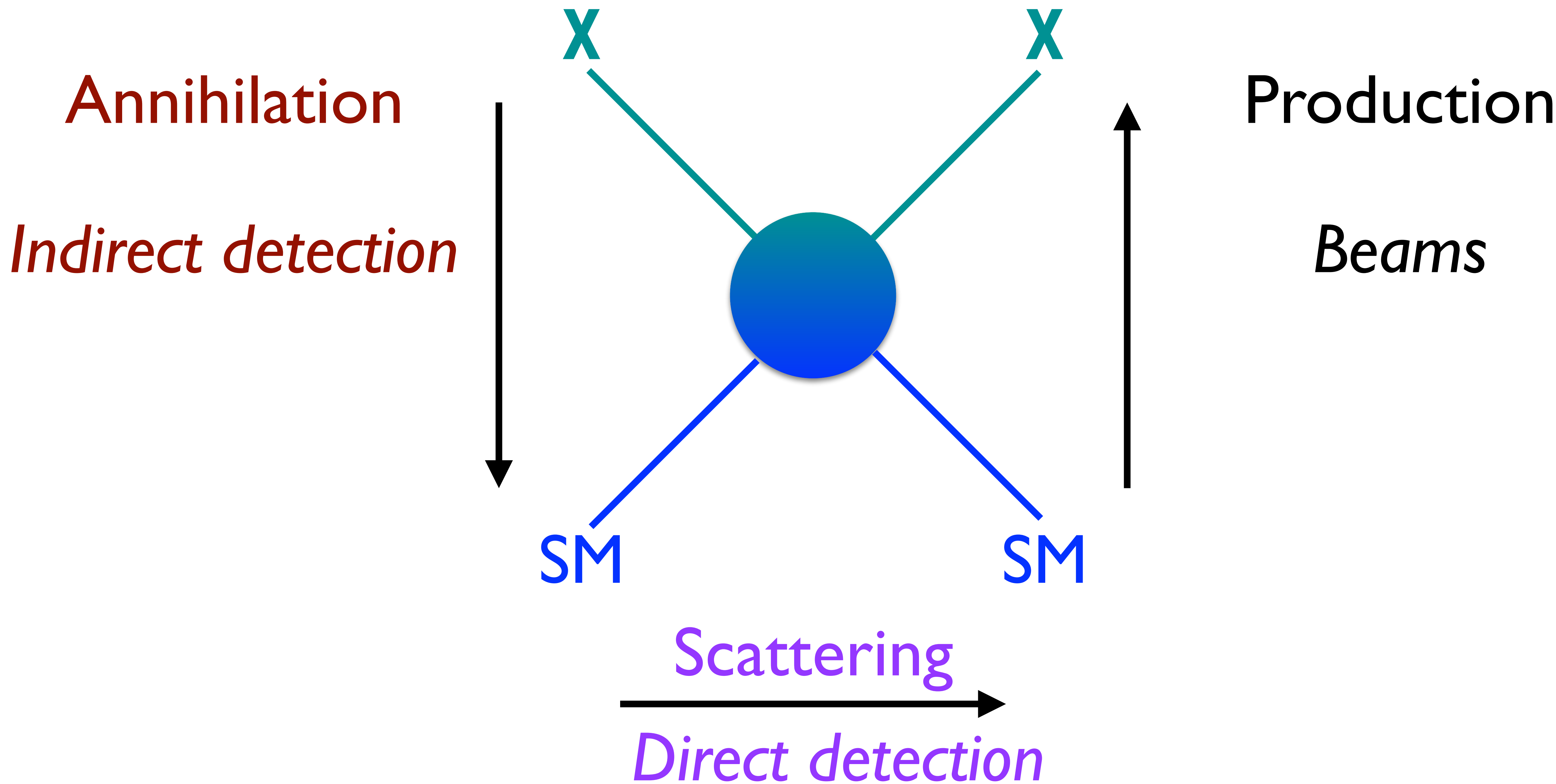
Detector technology



Detector technology



Detection processes

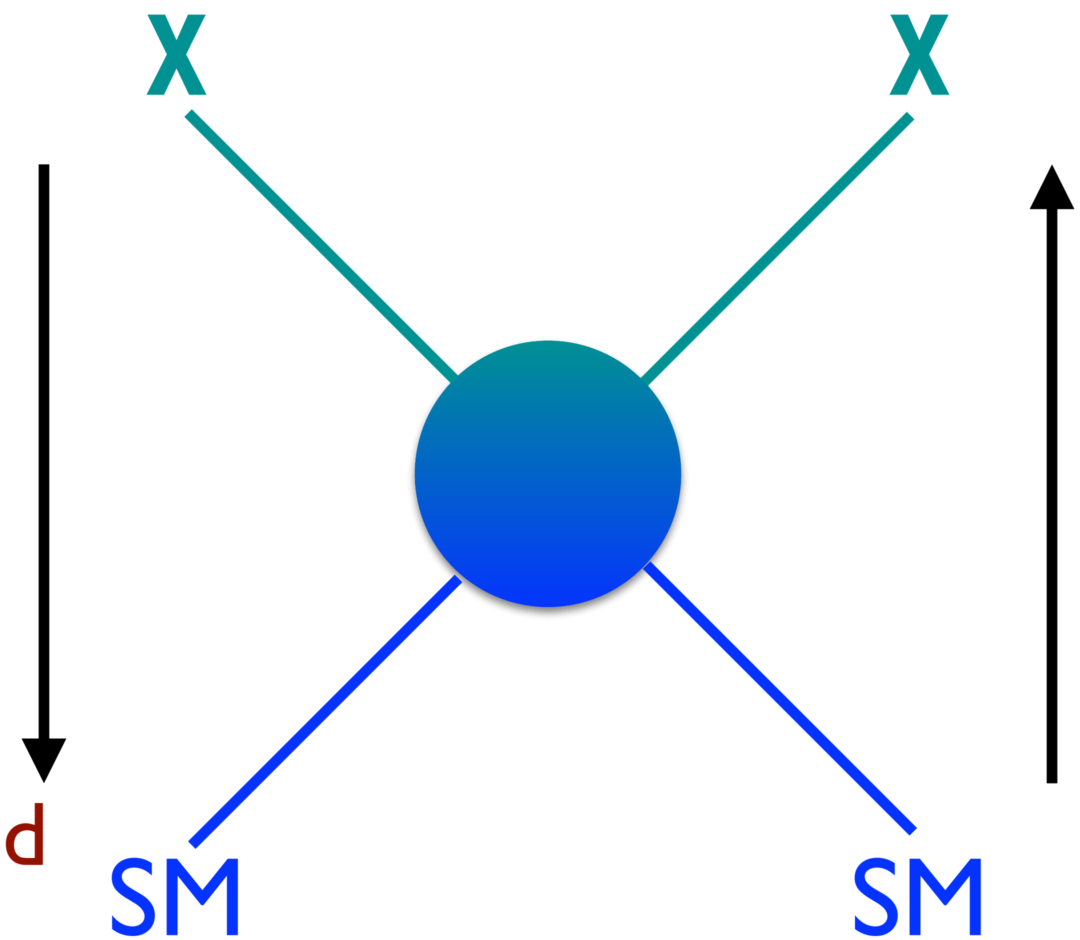


Detection processes

Annihilation

Indirect detection

Directionality
Exposure
Low / well-understood background
=> large WCD / LS detectors



Production

Beams

Scattering

Direct detection

Detection processes

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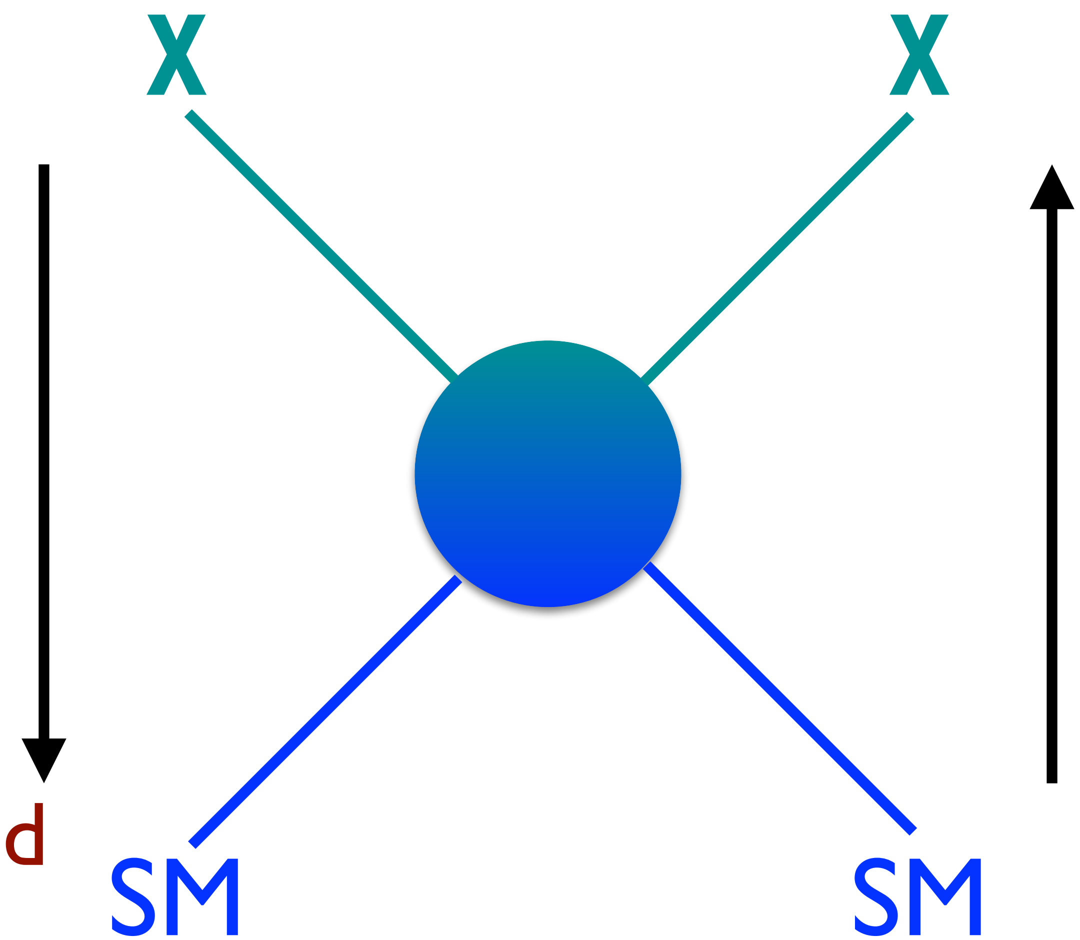

Production

Beams

Scattering

Direct detection

Threshold, (exposure, low bkg)

=> ν detectors have niche sensitivity to "exotic" models

Detection processes

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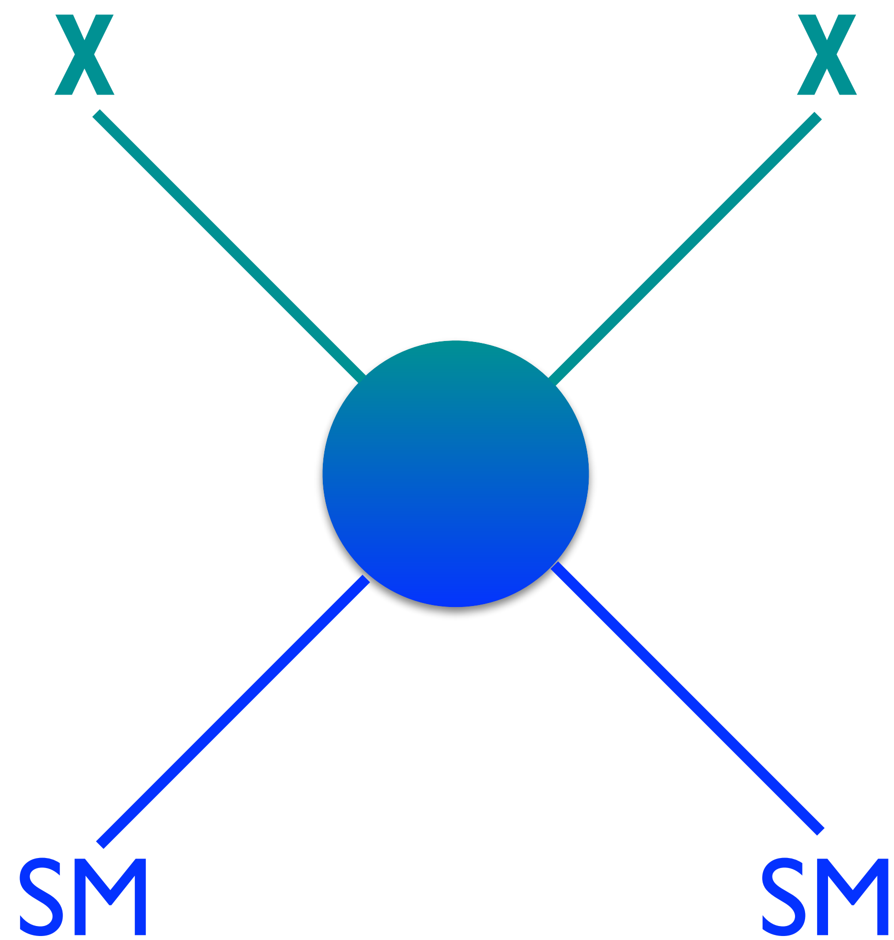


Production

Beams

Missing energy
Beam-correlated delayed events

Scattering

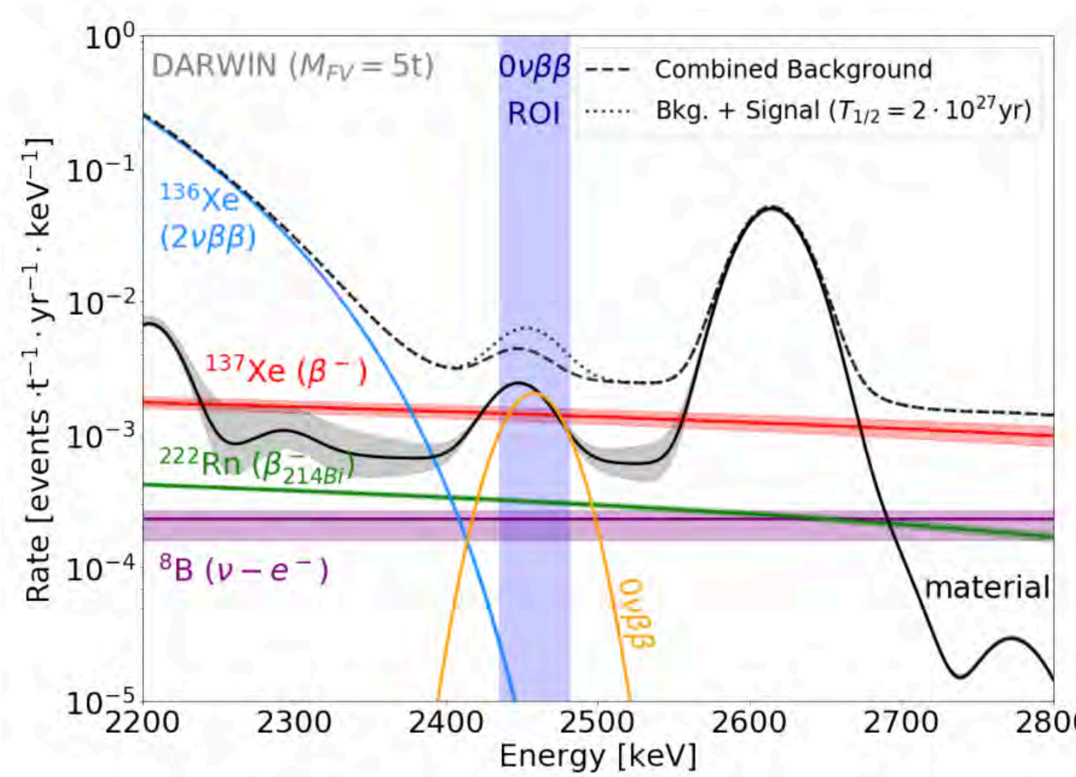
Direct detection

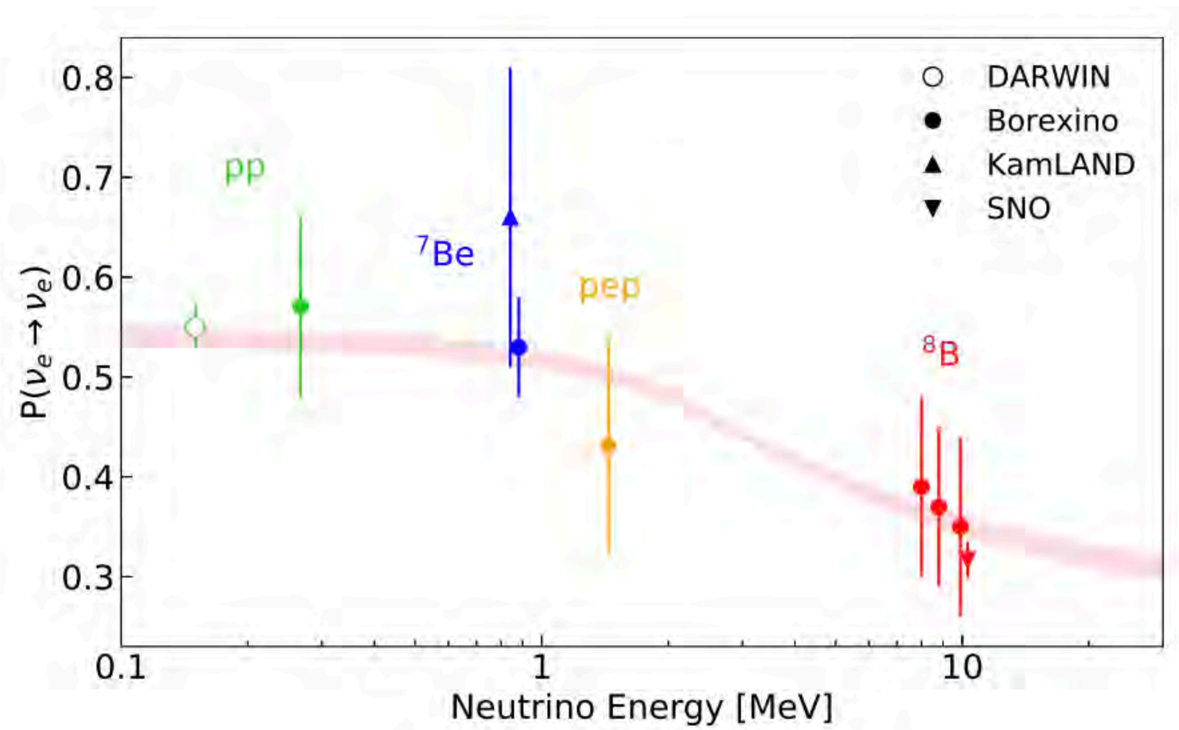
Threshold, (exposure, low bkg)

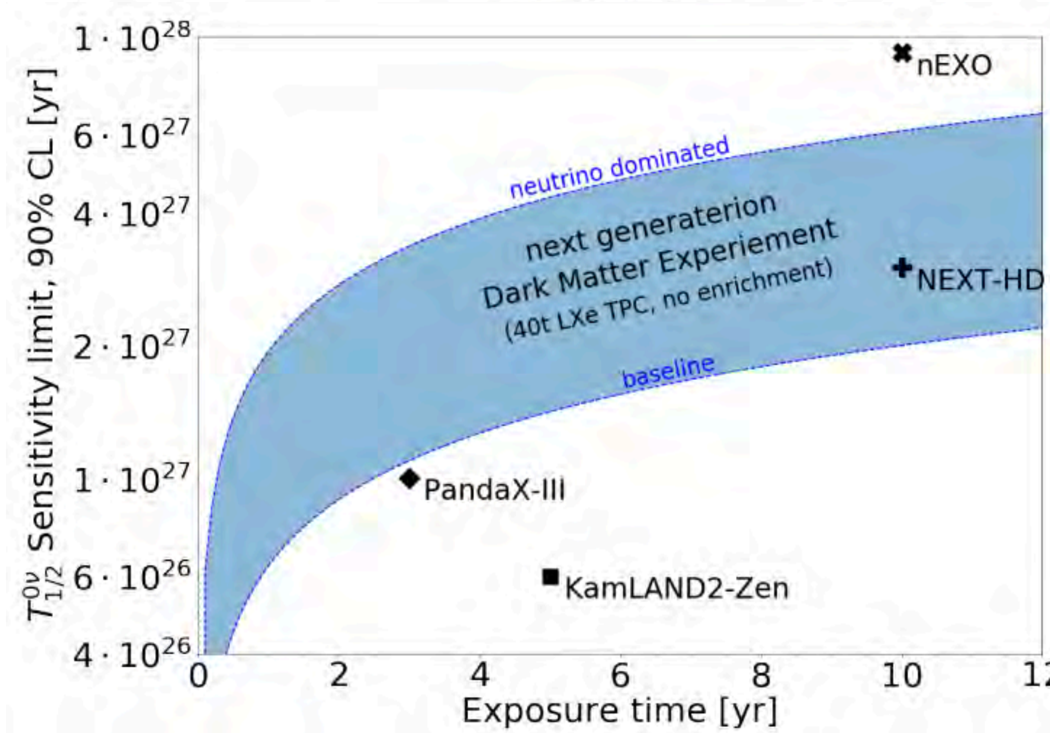
=> ν detectors have niche sensitivity to "exotic" models

Complement: ν in DM detectors

- DARWIN / next-gen LXe detector
- 40-ton LXe TPC
- Low threshold, low background
- Unique observatory for rare events and precision measurements







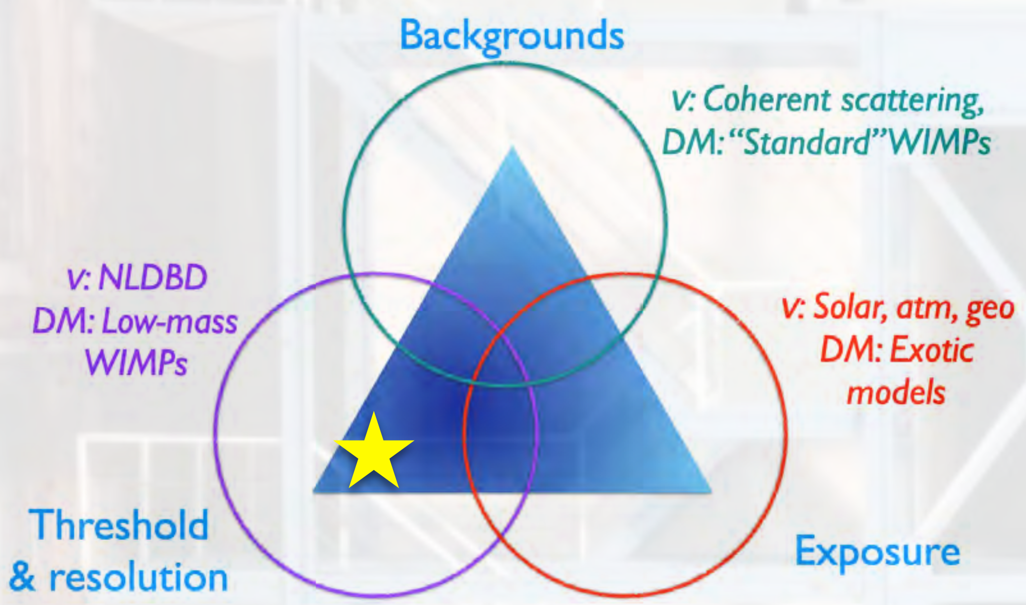
https://arxiv.org/pdf/2203.02309.pdf

(Subset of) DM Models

- "Standard" WIMP hypothesis - dominated by DD DM experiments
- Boosted DM: upscattered by CRe, DSNB-ν, blazars…
- Axions, produced in dense, massive regions e.g. solar axions
- Indirect searches e.g. ν produced from DM annihilation
- Plus many other interesting ideas

- Neutrino experiments offer a niche for certain models:
  - Large exposure
  - Optimized performance in somewhat higher energy regime
  - Ultra-low background & precision background model
  - Directional sensitivity

Ge detectors

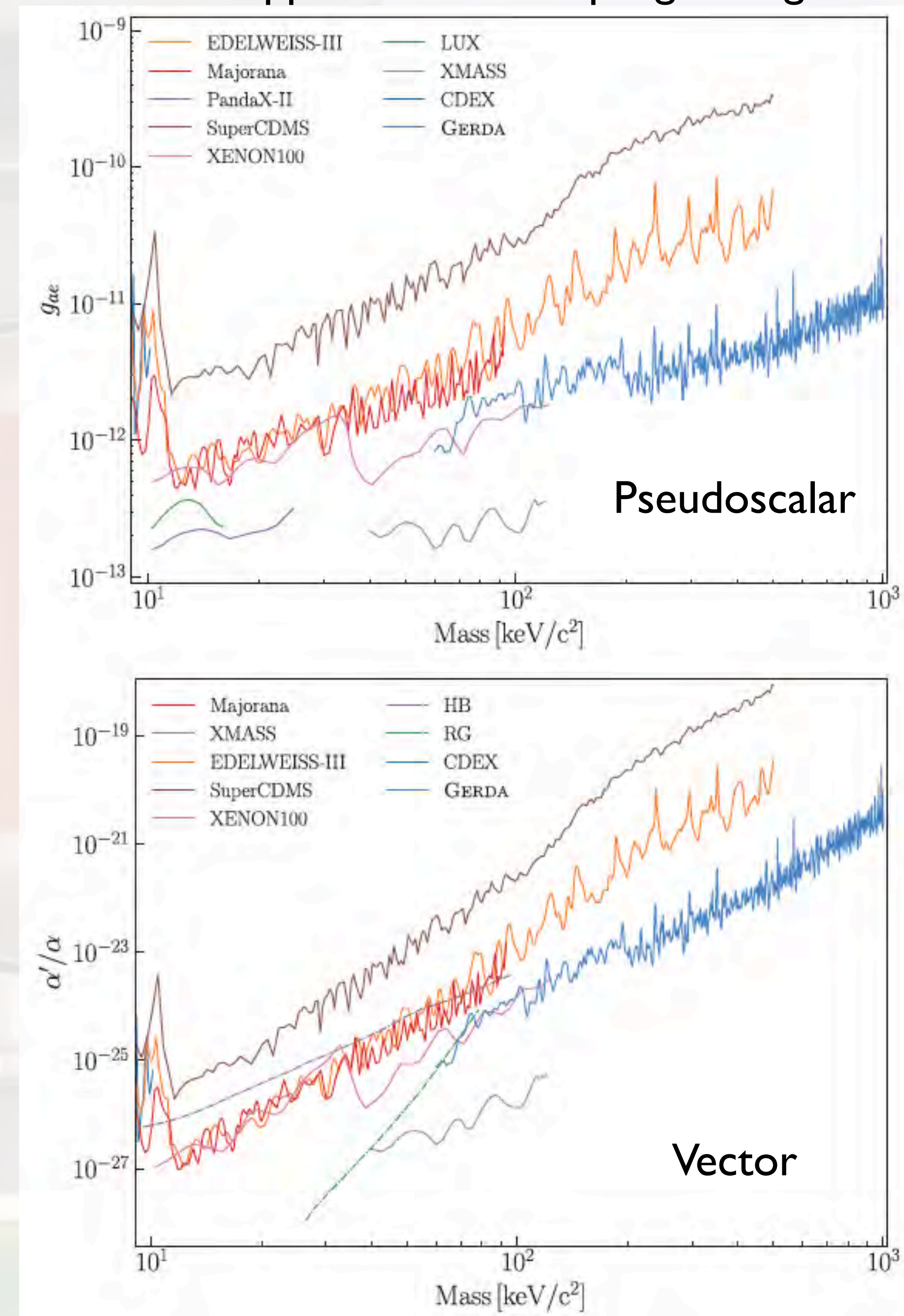


- HPGe enriched to 87% 76Ge
- LNGS (INFN), Italy
- ~3keV energy resolution
- Ultra-low radiogenic bkg
- High exposure

SuperWIMPs at GERDA

- Bosonic super weakly interacting massive particles
- keV-scale, ultra weak coupling to SM
- ALP / dark photon absorption
- Energy transfer to e- => full absn peak in spectrum
- Search range: 60keV - 1MeV
- Reject coincidence interactions; instrumental effects

90% CI upper limit on coupling strength



PRL 125, 011801 (2020)

SuperWIMPs at GERDA

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- New results from Xe-nT

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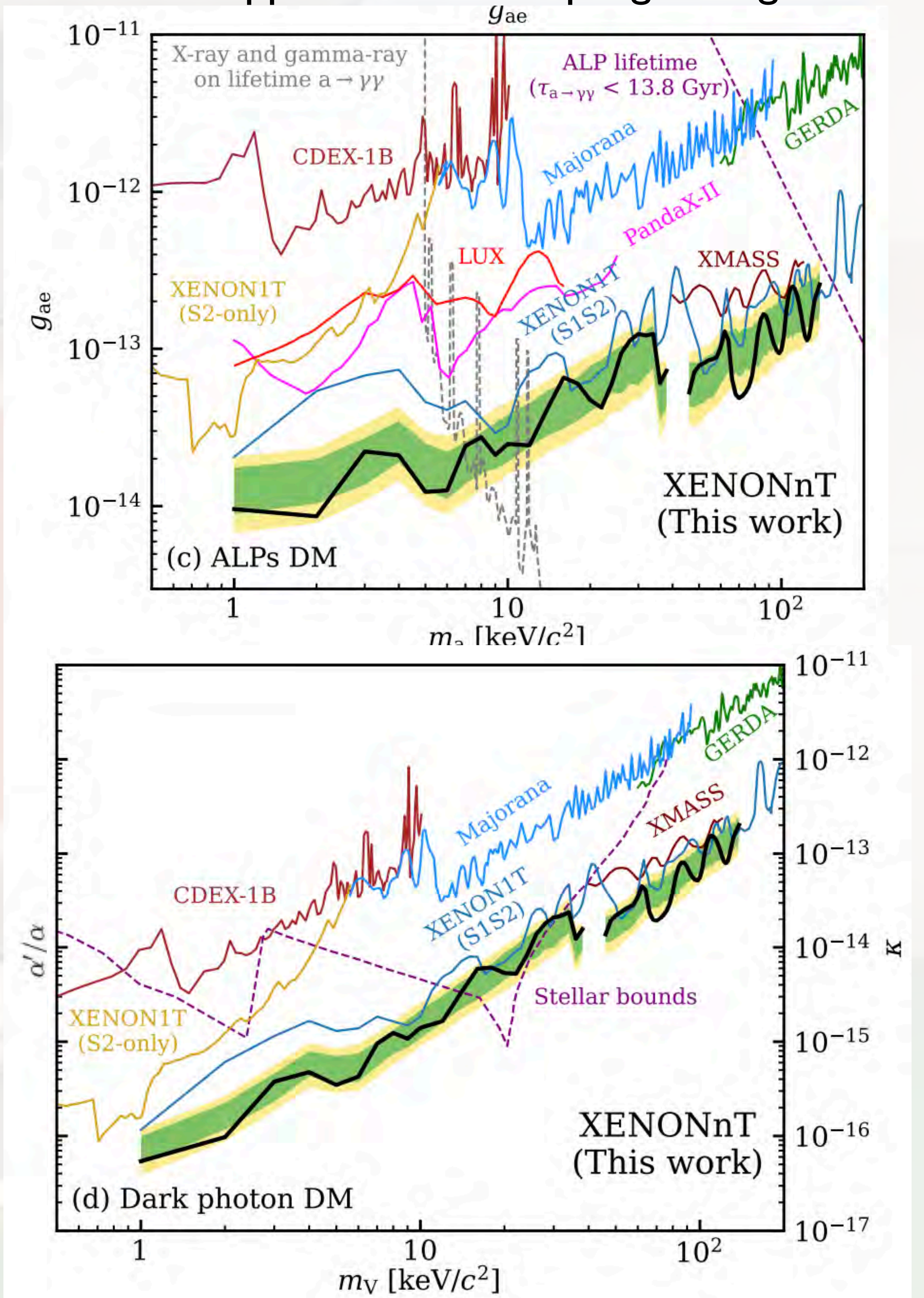
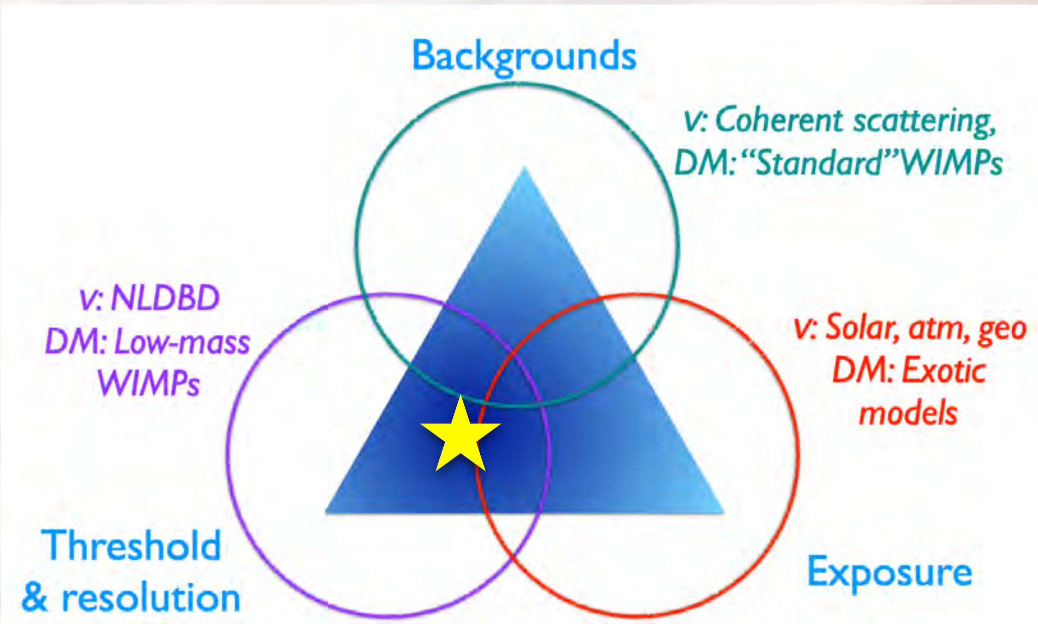
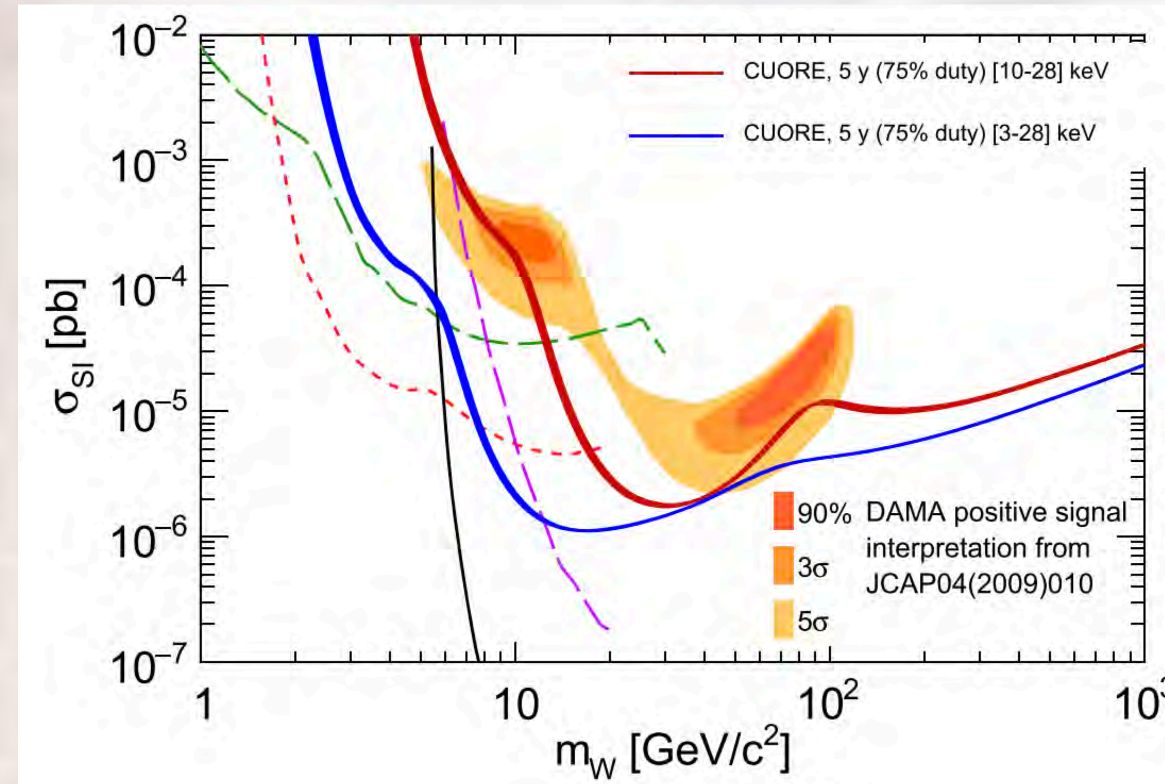


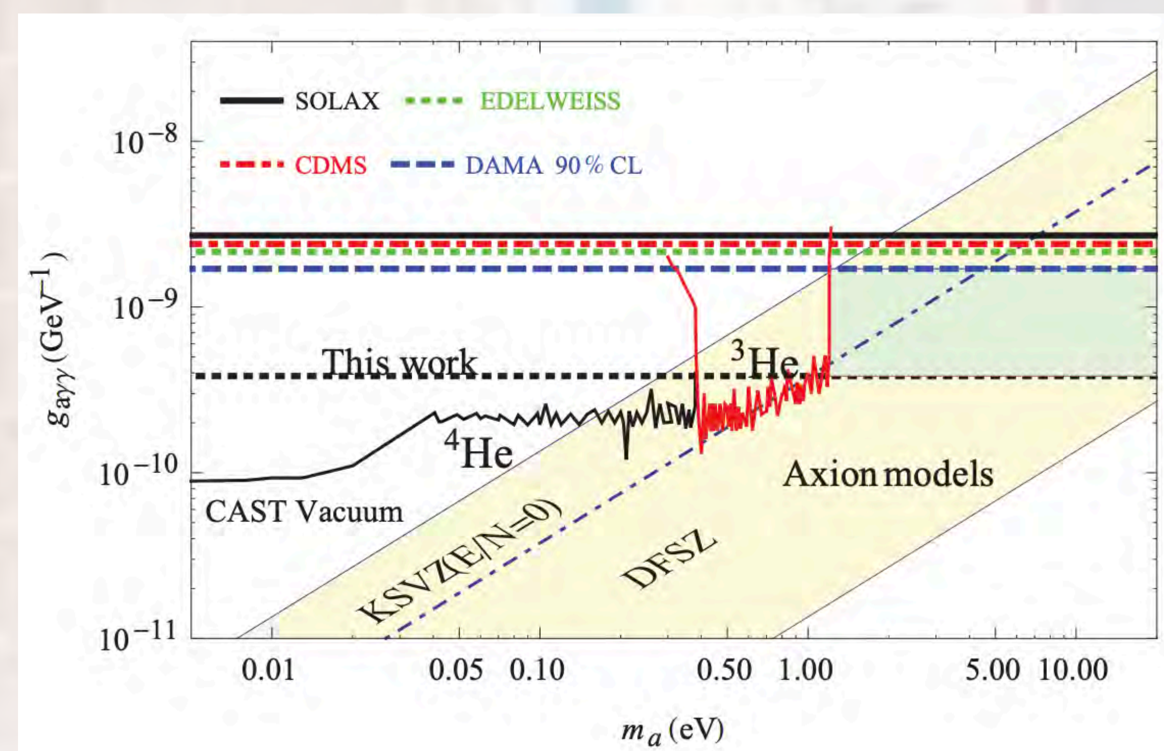
PRL 125, 011801 (2020); arXiv:2207.11330

Bolometers



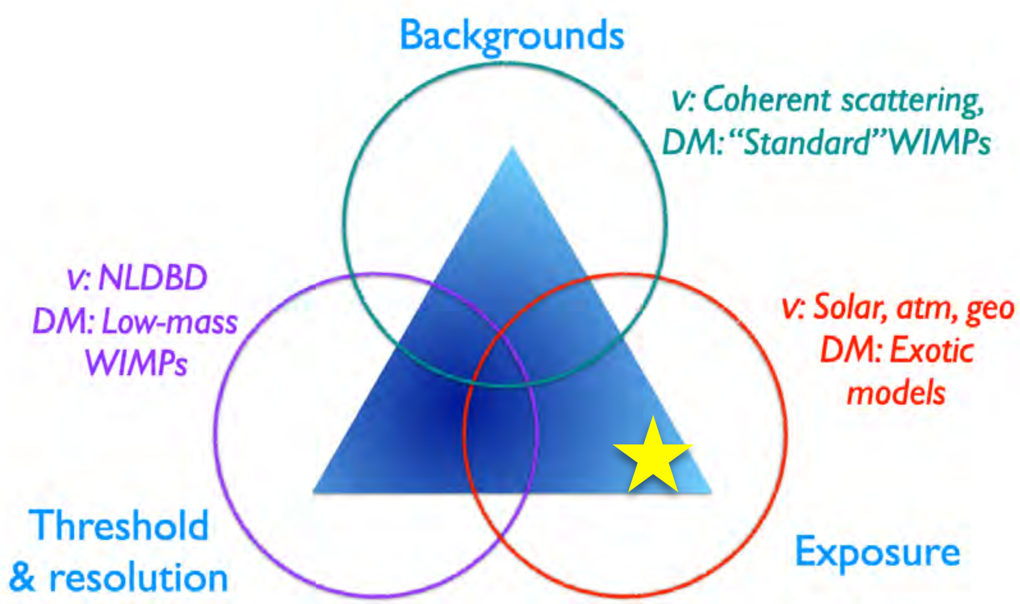


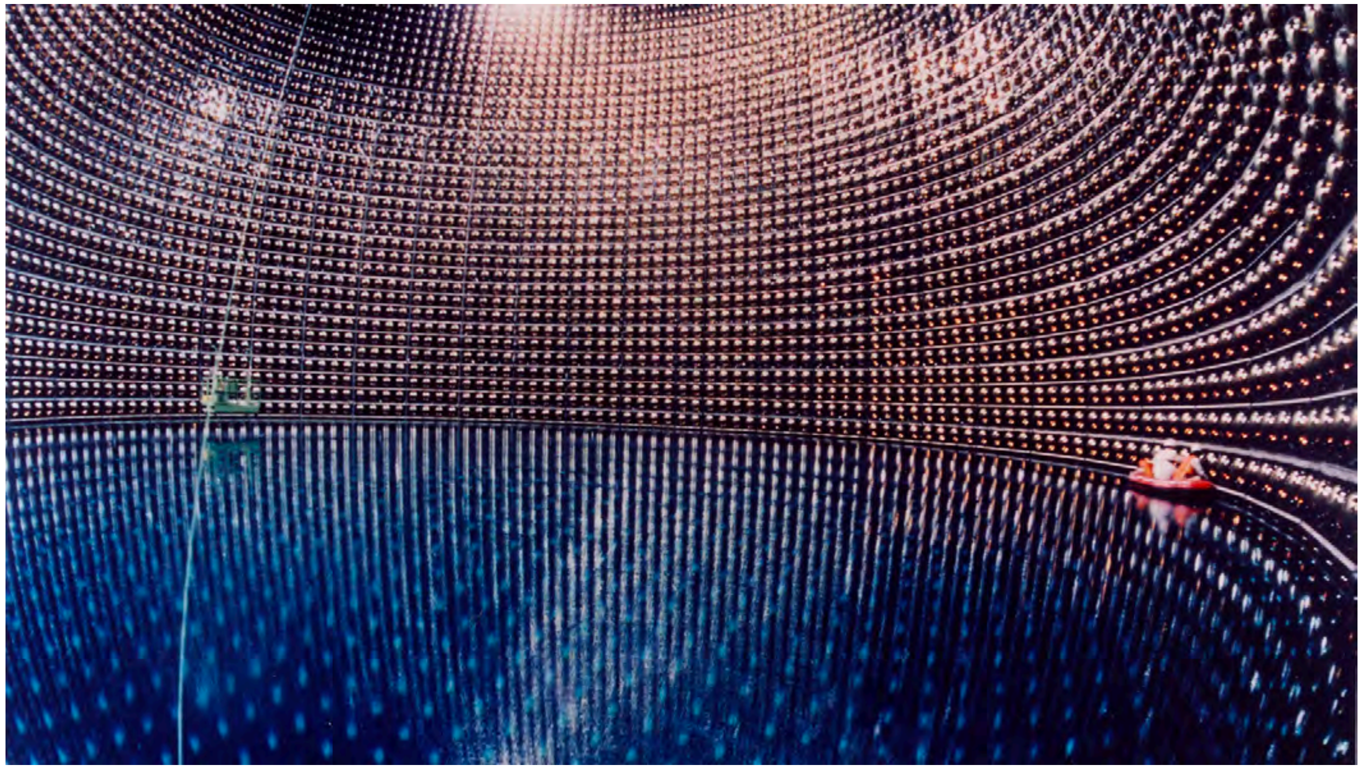
- CUORE: 742 kg TeO2
- LNGS (INFN), Italy
- ~5keV energy resolution (2.5MeV)
- Ultra-low radiogenic bkg
- Largest exposure of solid state DBD
- Requires 10keV threshold



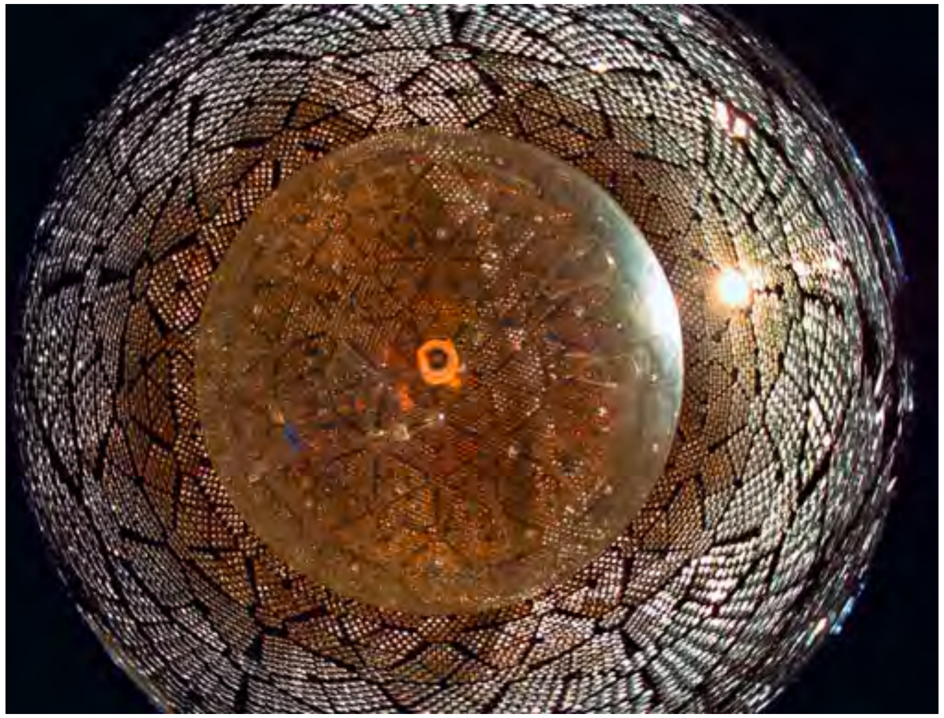
Eur. Phys. J. C (2017) 77:857, JCAP10(2015)065

WCD detectors



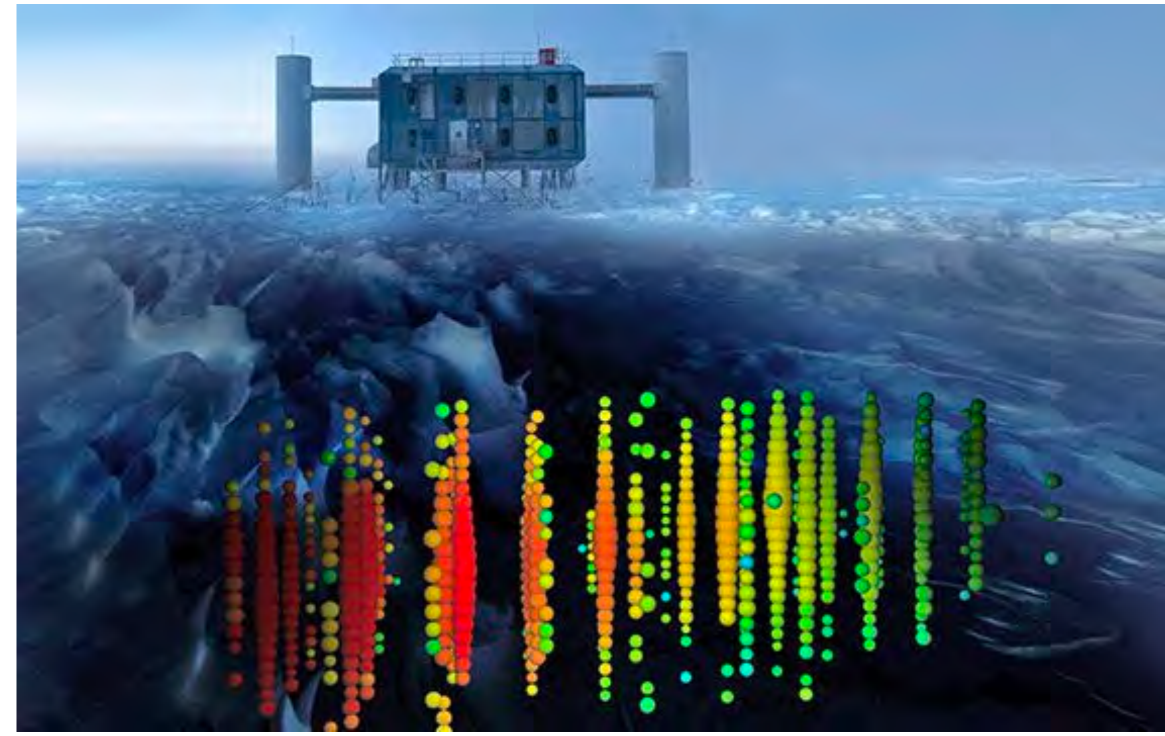


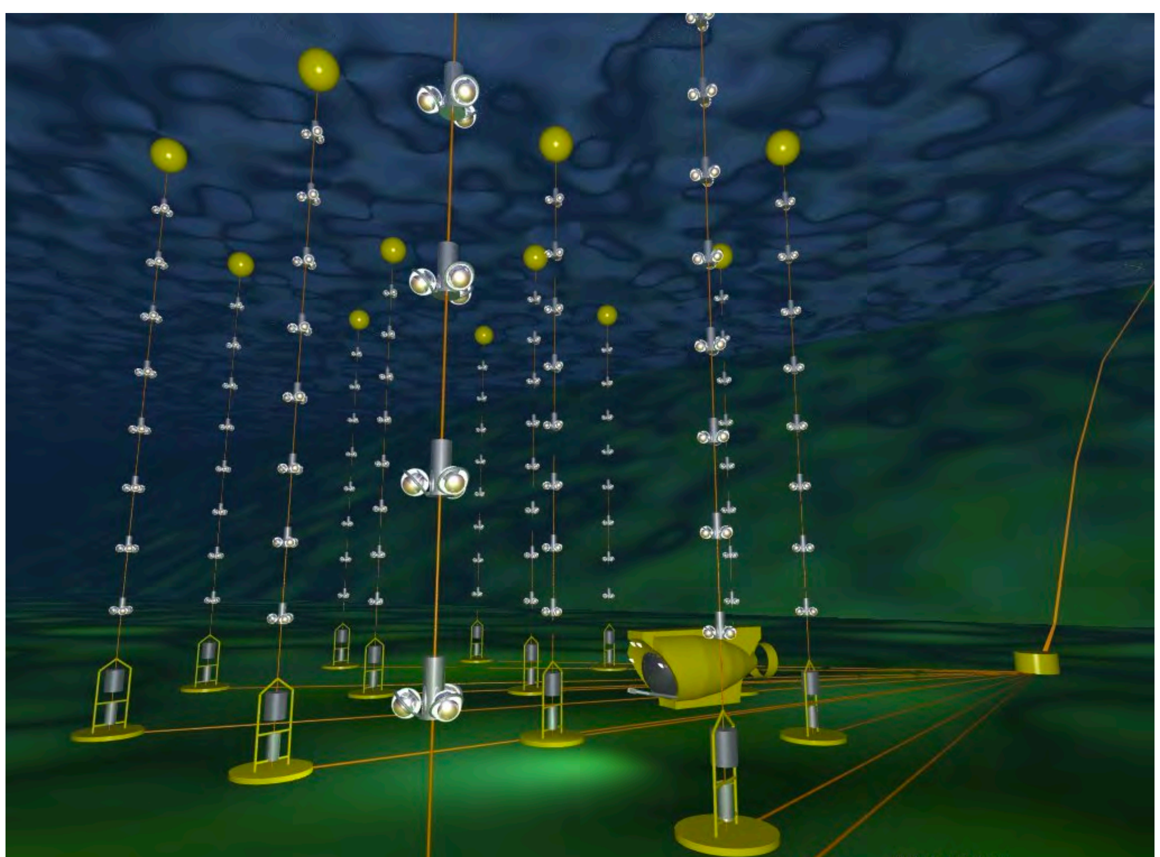
- Very large exposure
  (161.9 kt-yr from SK-iv alone)
- Cherenkov ring imaging: particle ID
- n tagging: remove atmospheric ν bkg
- Directional sensitivity

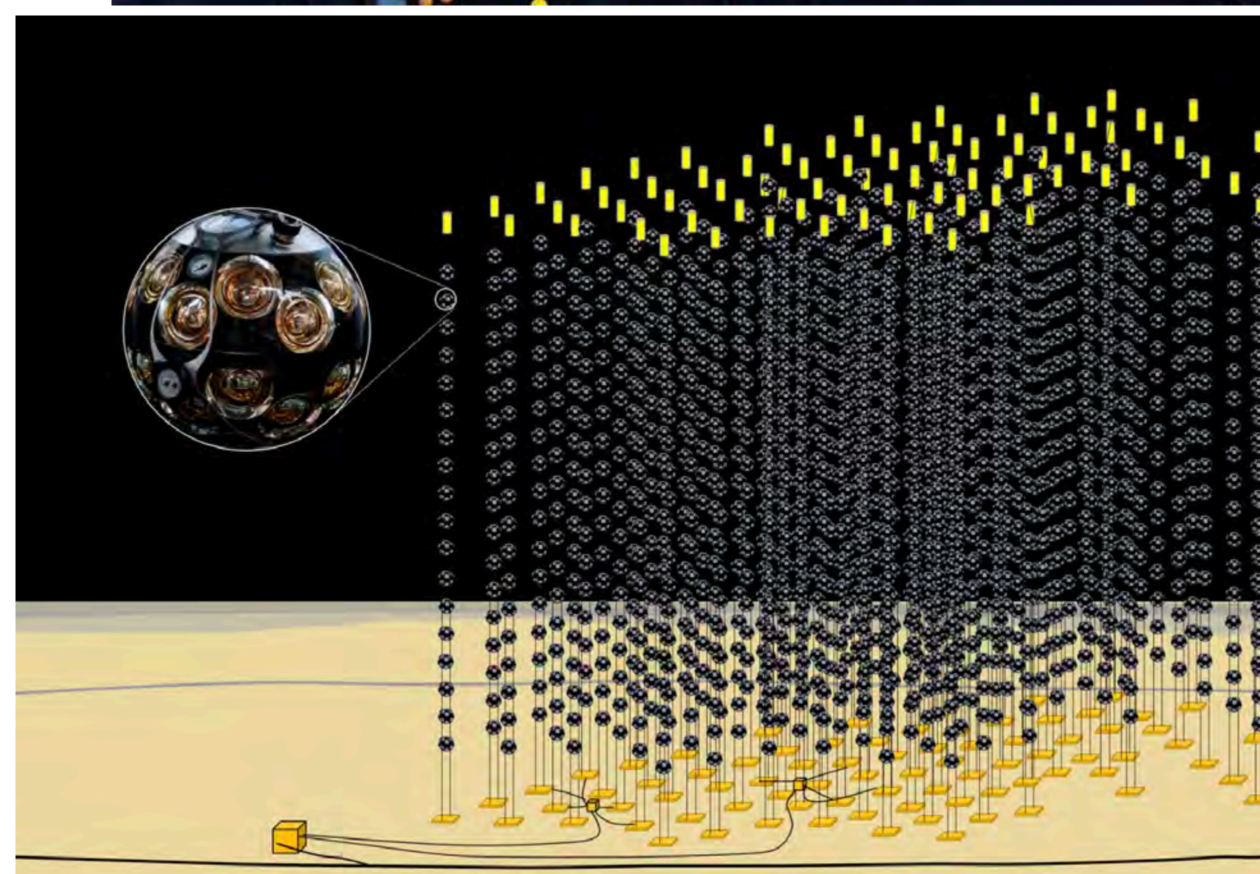


Neutrino telescopes

- IceCube: cubic-km, 2.5km depth, 5k PMTs + dense "DeepCore" area
- ANTARES: 2.5km, Med. Sea, 900 PMTs
- KM3Net: MTon scale, 10ks PMTs
- See tomorrow's talk



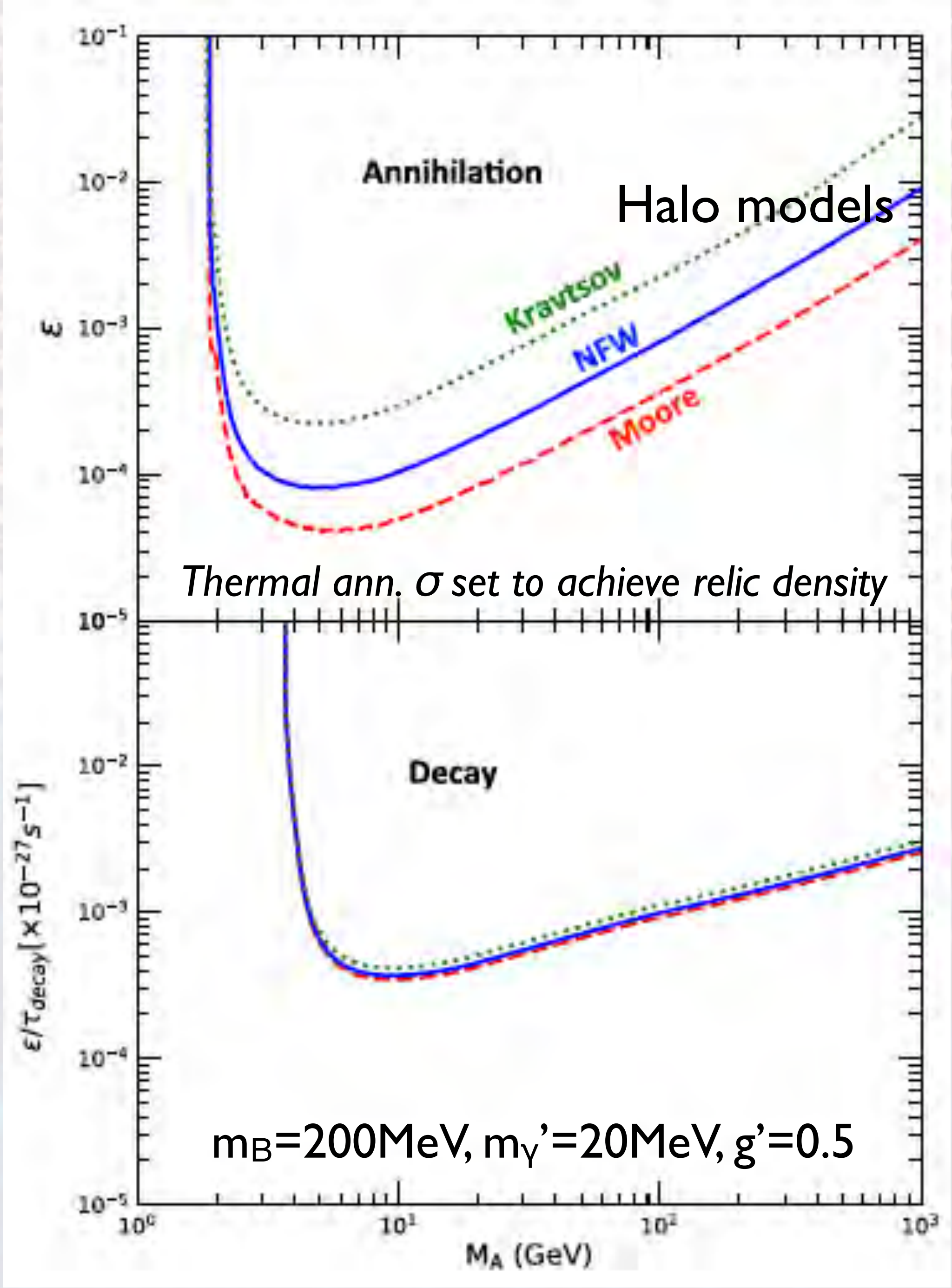




Direct search: BDM at SK

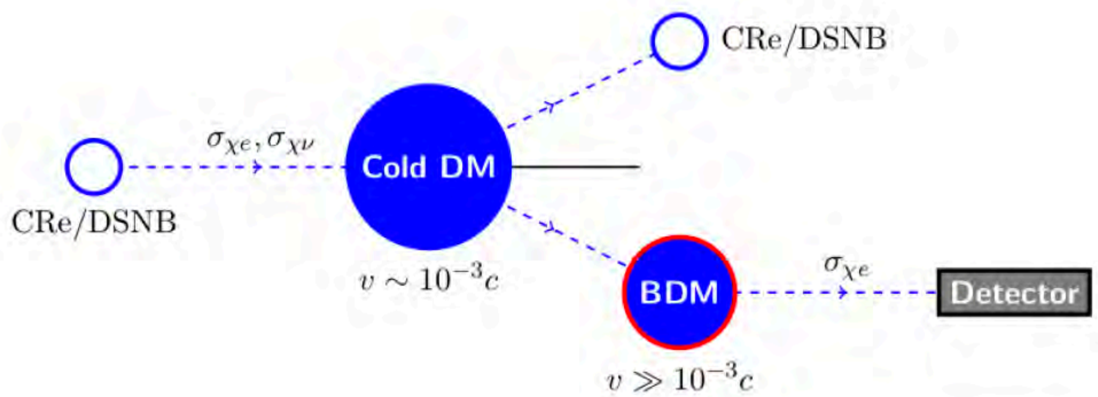
- Model-independent search for BDM from Sun / Galactic centre
- Consider scattered e- 100MeV - 1TeV
- Candidates: single high-E electron, no signs of nuclear interaction (decay e-, n)
- Look for directions consistent with Sun / Galactic Centre
- Use off-angular regions & MC to define atmospheric ν bkg
- Consistent with current limits: only BDM couples to SM; or SD $\sigma_{\chi N}$

Model interpretation — cold Ψ_A, BDM Ψ_B couples to SM via γ'
ε: coupling of γ'-e / γ-e

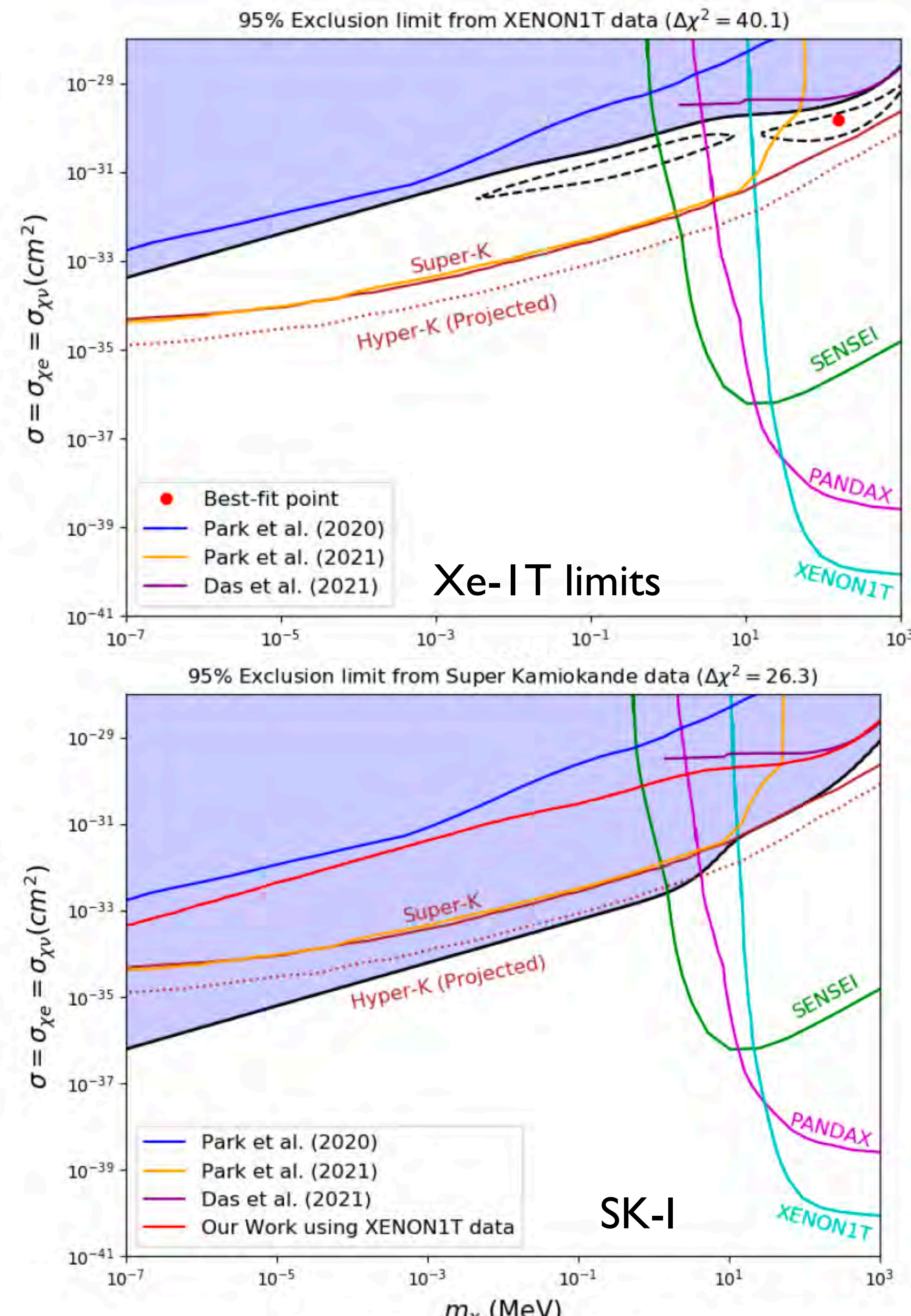


PRL 120 (2018) 221301

DM-ν/e scattering



- BDM: boosted to higher E by interaction with CRe *and* DSNB-ν
- Data from Xe-1T: few-keV e- recoils and SK-I: few-MeV e- recoils
- Look for consistency with Xe1T excess
- "Recovers" parameter space ruled out by DD experiments
- Can also consider blazar-boosted DM

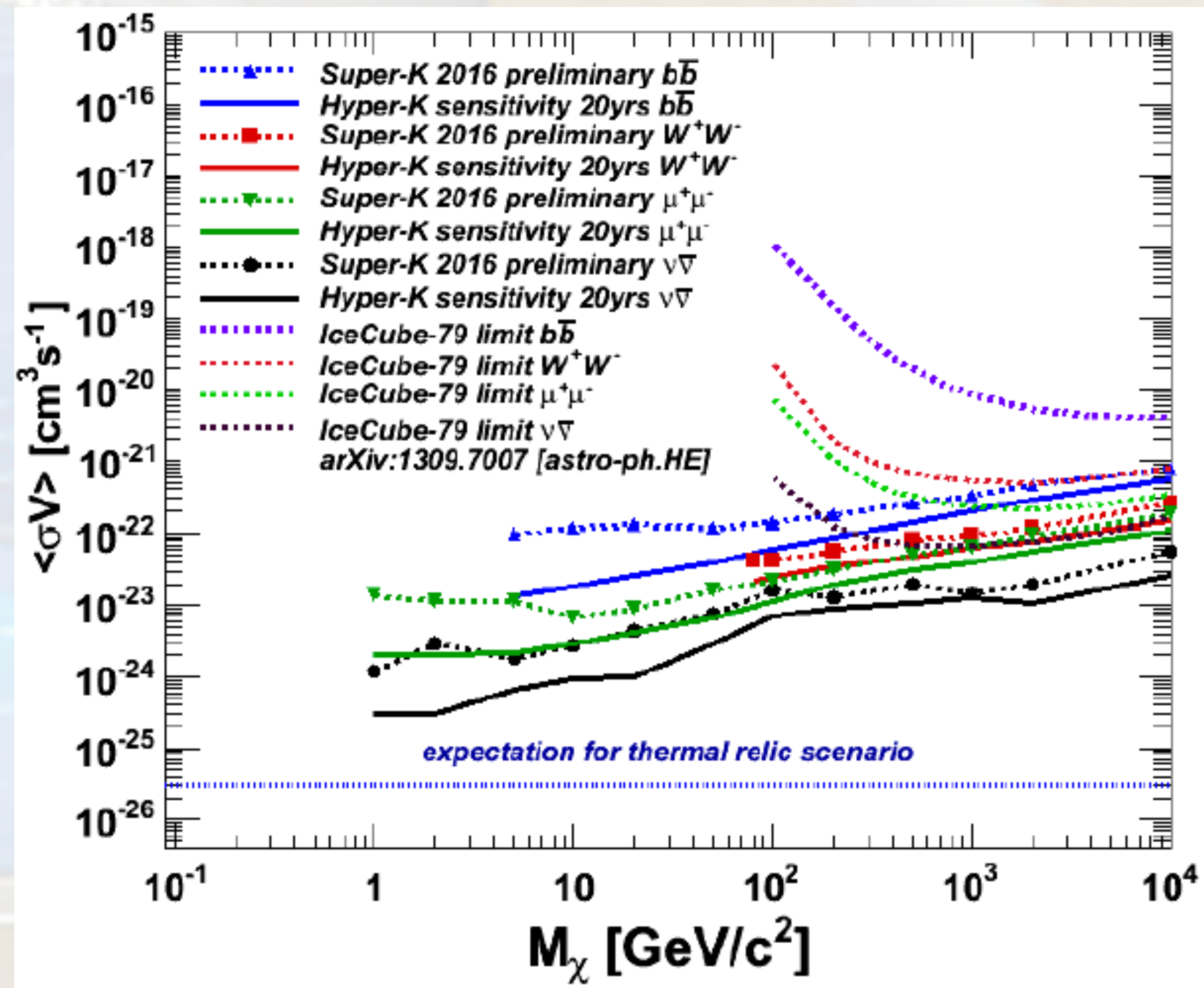


Phys. Rev. D 105, 103029 (2022); JCAP 07 (2022) 013

Indirect searches at SK/HK

- Search for excess of νs due to annihilations in the Sun, Earth, and Galactic halo
- $\chi\chi$ -> $\nu\bar{\nu}$ / $b\bar{b}$ / μ+μ- / W+W-
- Full MC: atm ν bkg & WIMP signal
- Look for excess above bkg in E x θ
- Data-driven check using on- /off-source directional analysis
- Signal should appear in all channels
- Hyper-Kamiokande: ~250 kton WCD, 40% coverage

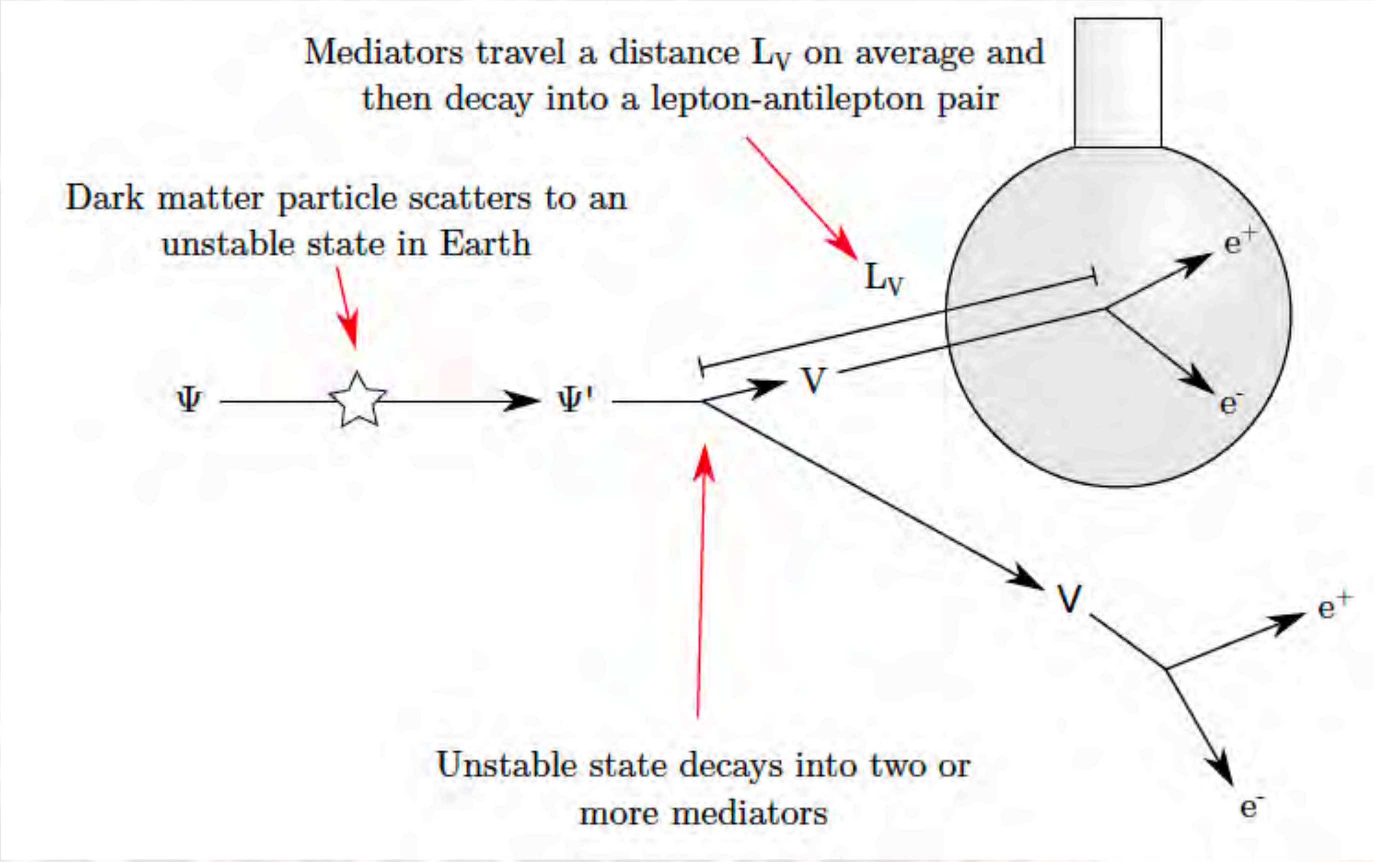
Upper limit (90%) on DM self annihilation crosssection $\langle\sigma_A V\rangle$

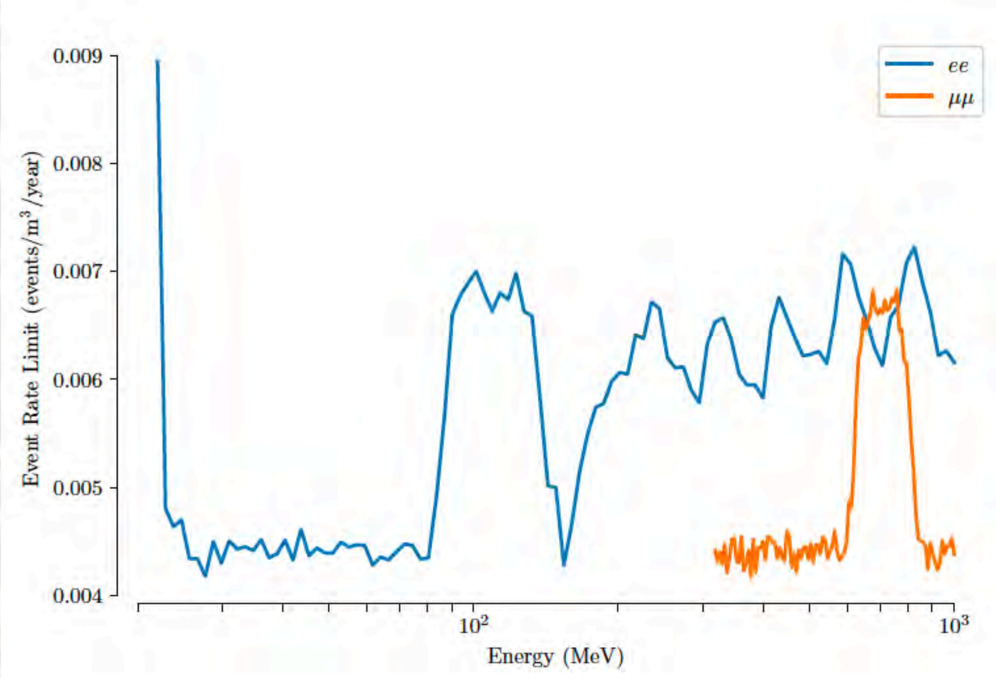


Phys. Rev. D 102, 072002; Phys. Rev. Lett. 114, 141301 (2015); Hyper-K CDR, arXiv:1805.04163

Self-destructing DM at SNO

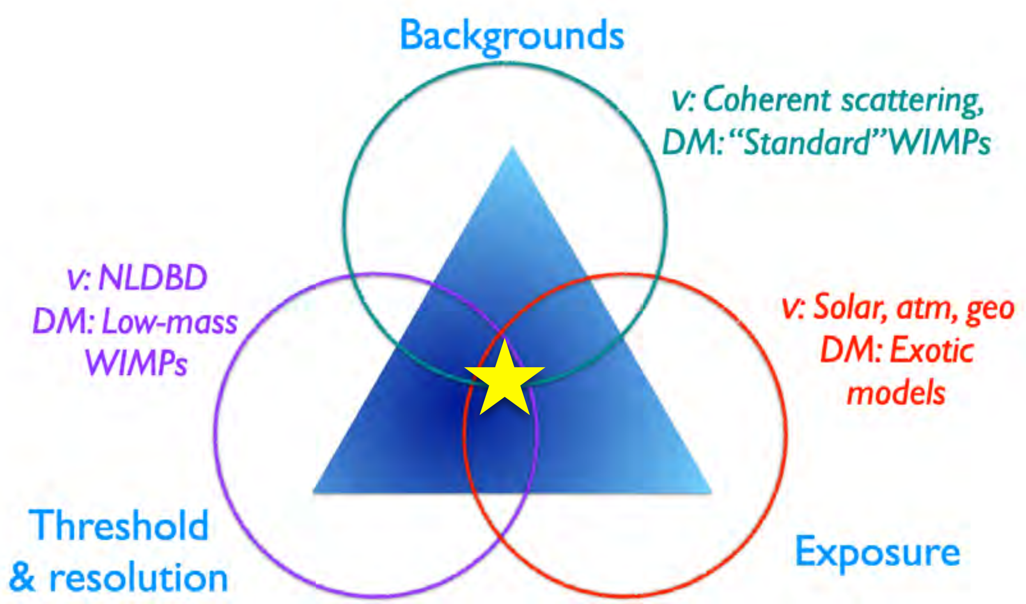
- DM bound state, Ψ, transitions to short-lived state, Ψ', after interaction with matter.
- Ψ' -> dark photons -> leptons
- Signature: 1+ high-E lepton pairs with fixed invariant mass
- Visible in WCDs (large mass, PID)
- SNO: null hypothesis test, e-/e+ search, μ-/μ+ search
- Consistent with atmospheric ν bkg
- 90% CL limit on SDDM rate

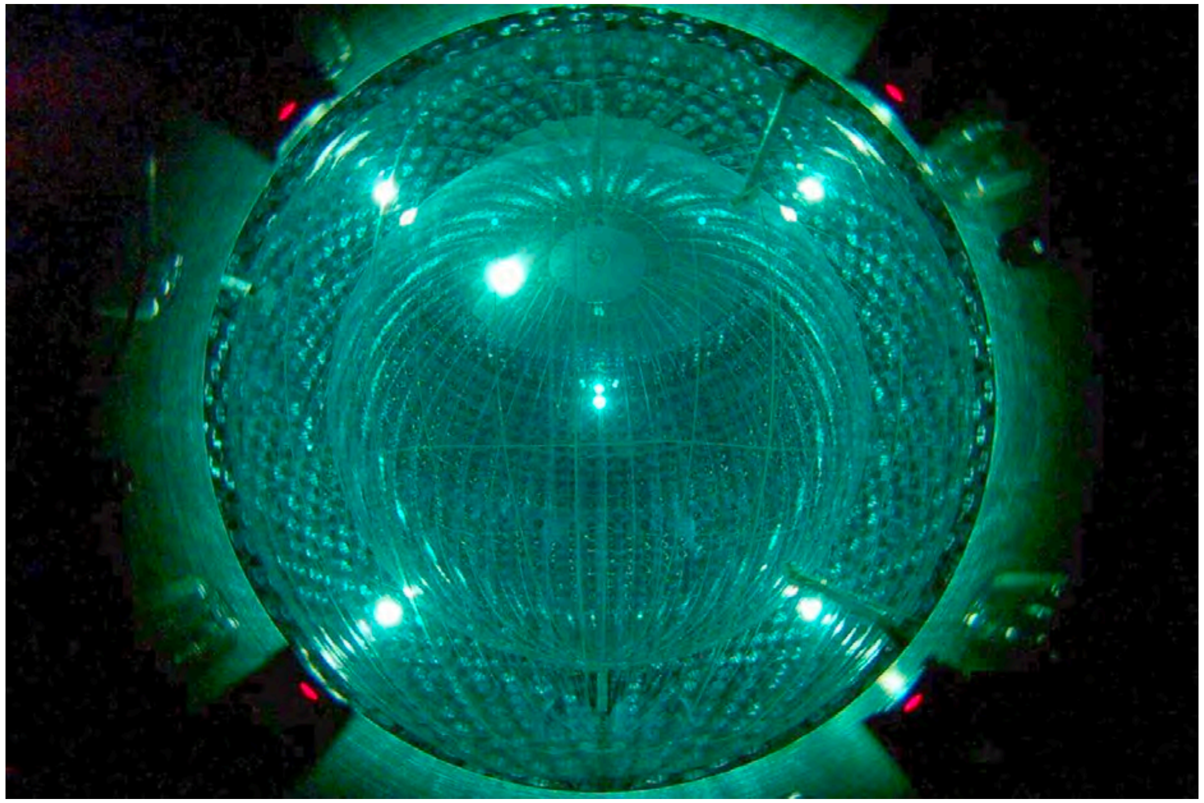




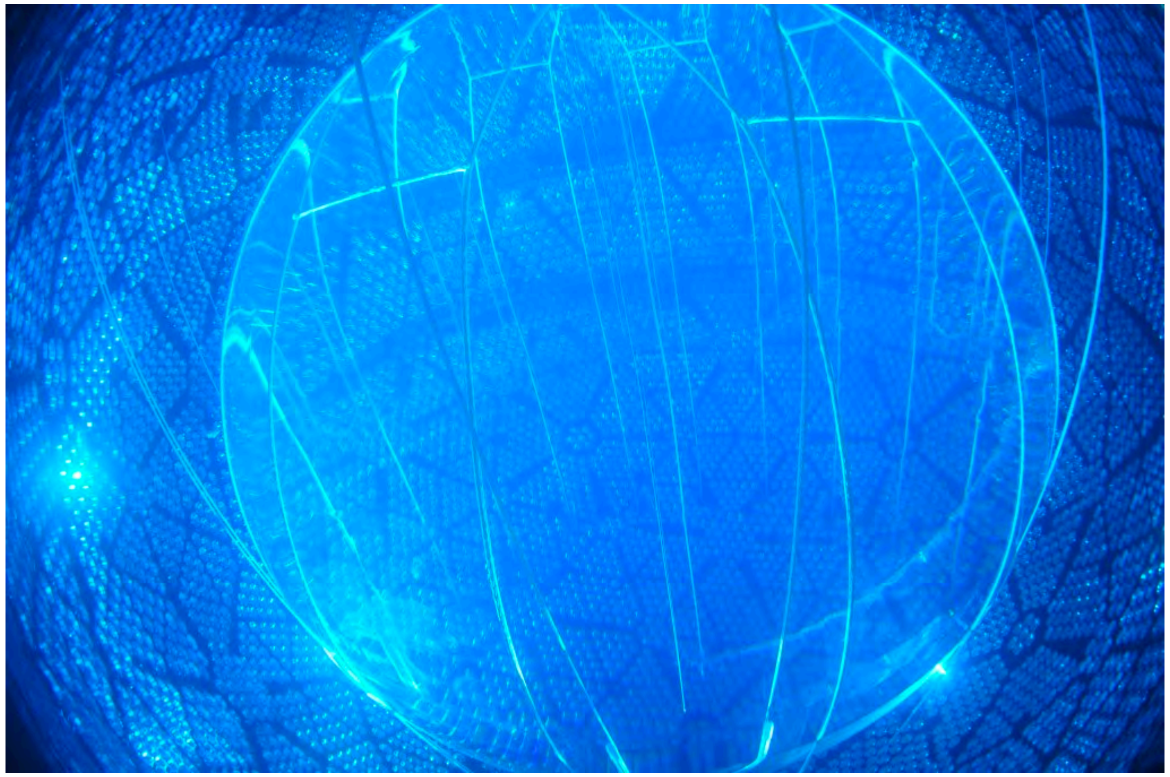
A. LaTorre thesis, U. Chicago; publication under prep.

LS detectors



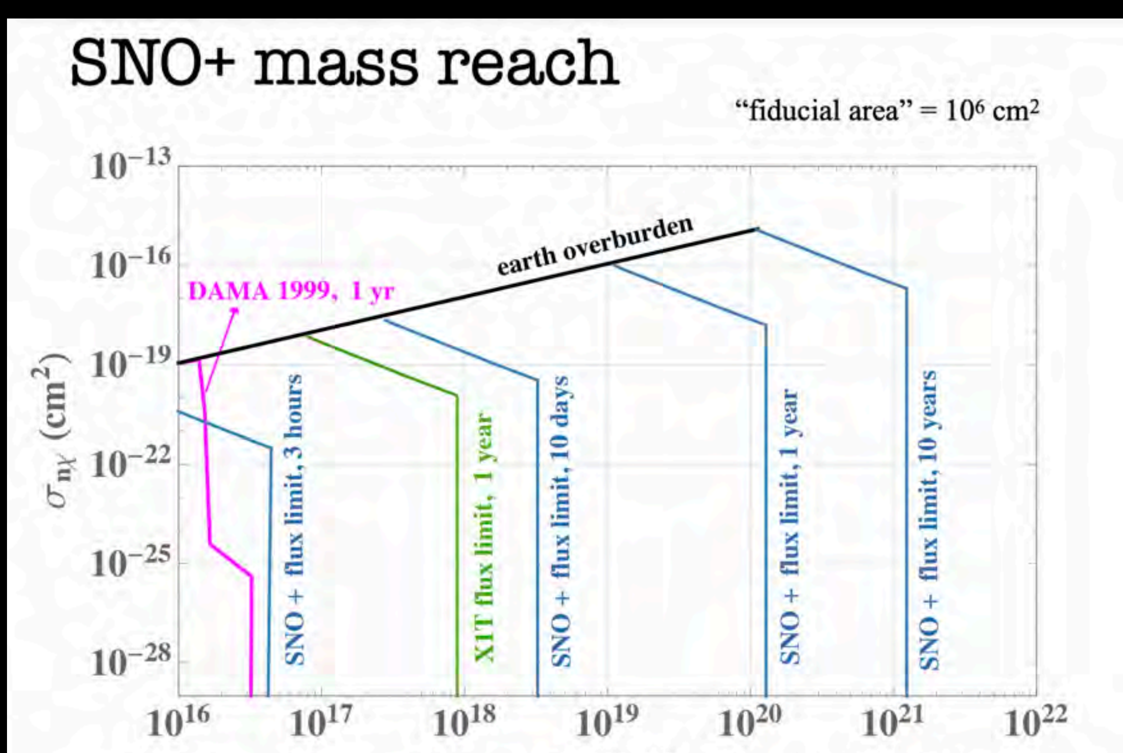


- Large exposure
- With improved resolution, threshold
- Particle ID from scintillation profile
- Sub-Cherenkov threshold sensitivity
- Ultra-low background

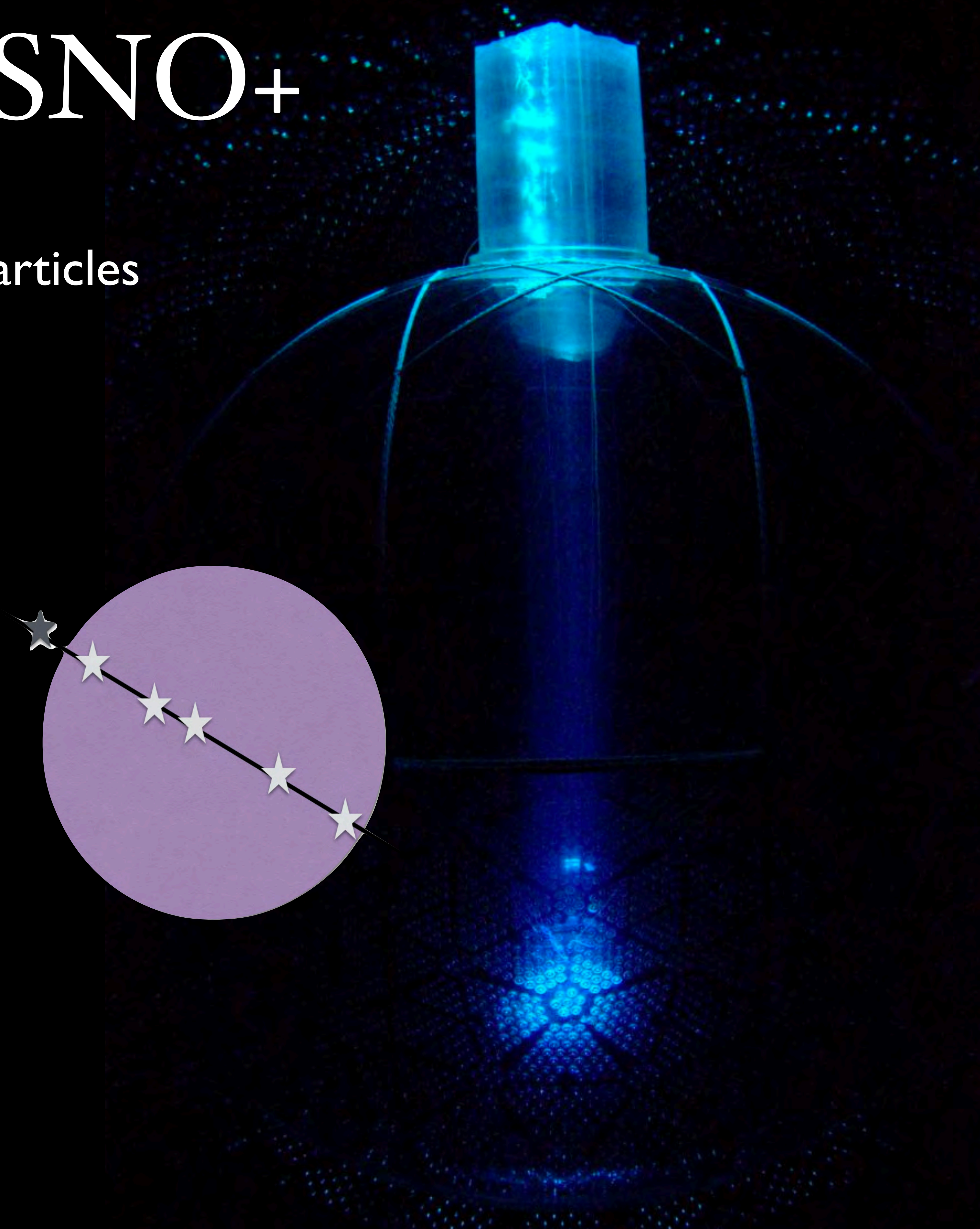


MIMPs at SNO+

- Multiply-Interacting Massive Particles
- Detector transit time ~ 10 µs
- Requirements:
  - Large detector
  - Low threshold
  - Non-Cherenkov signature



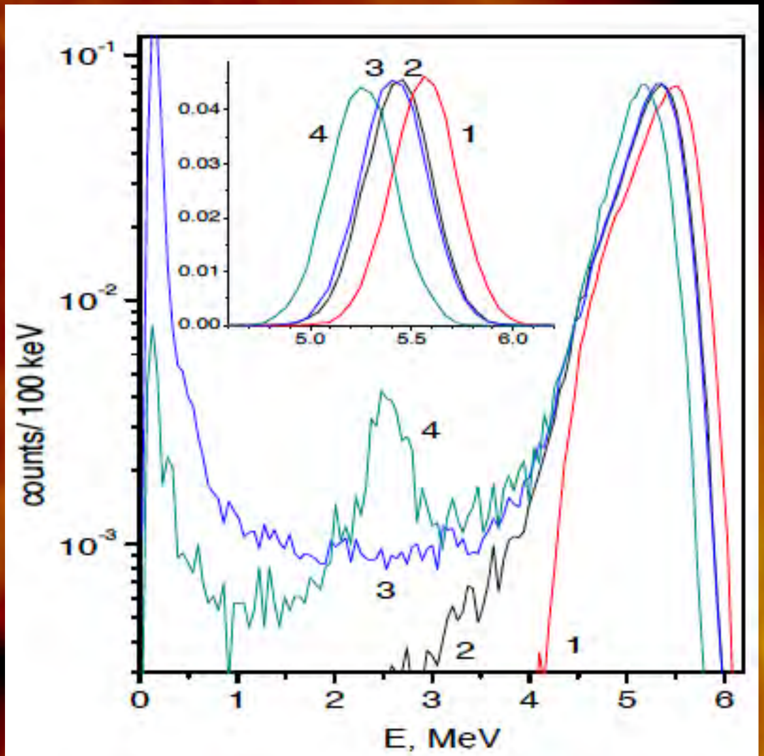
First experiment to reach Planck mass!

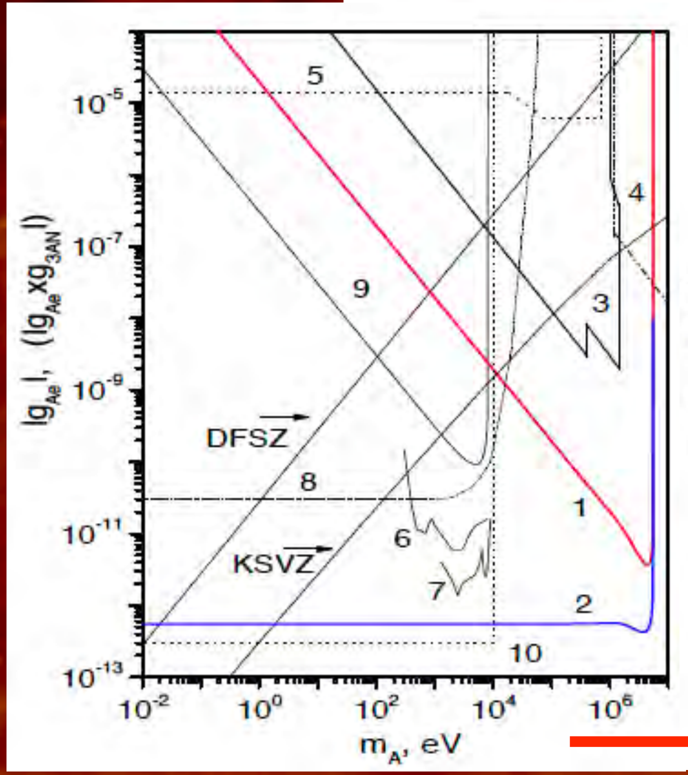


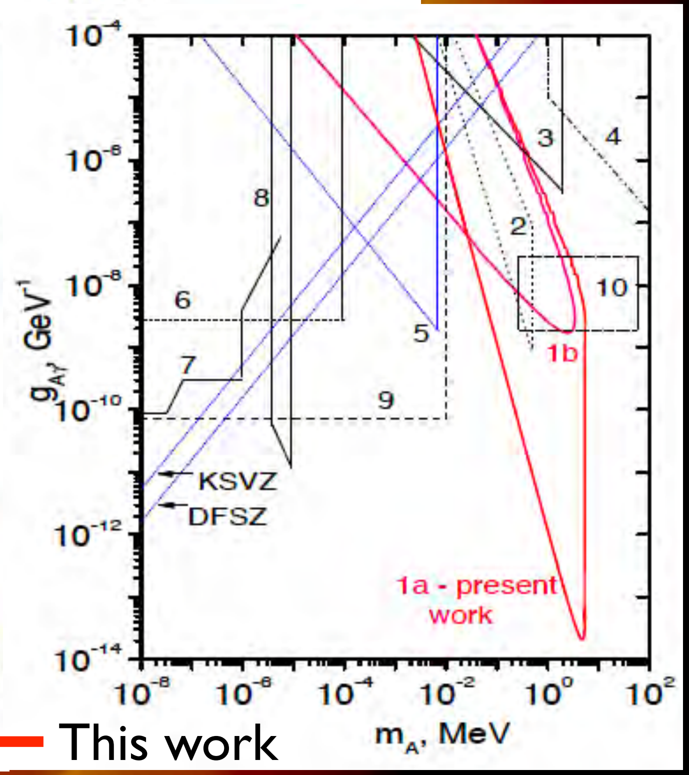
Phys. Rev. D 99, 083010 (2019); Phys. Rev. D 98, 083516 (2018)

Solar axions at Borexino

- ALPs can be produced in the Sun via e.g. γ-axion conversion
- Borexino: 278t high-light yield, ultra-pure liquid scintillator detector
- Astonishing record of solar neutrino measurements (full spectroscopy of pp-chain, first detection of CNO cycle ν)
- Search for 5.5-MeV peak from solar axions produced in p+d->3He+γ
- Full MC of response (quenching effects)
- Limits on couplings to e,γ,N





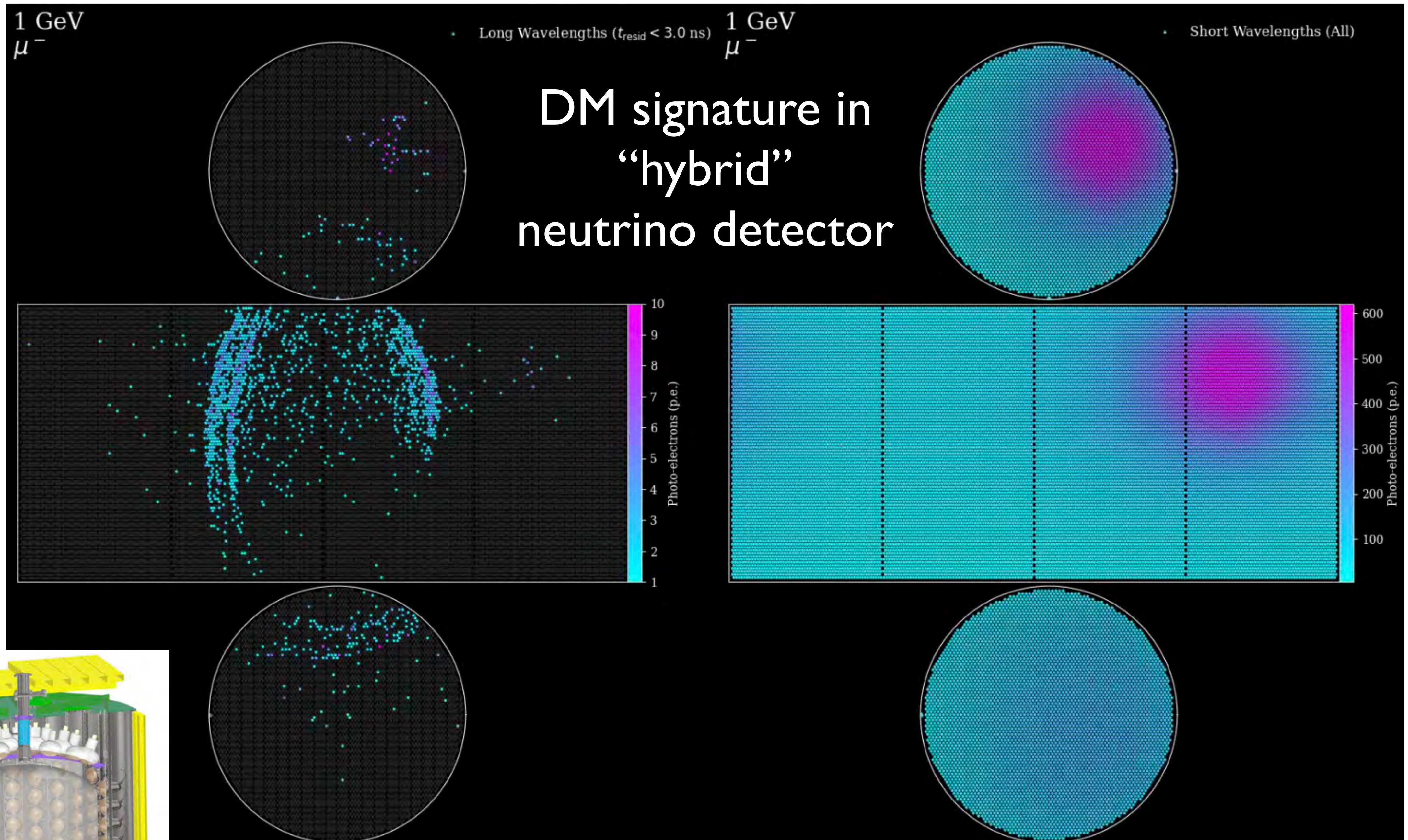


PRD **85**, 092003 (2012)

Next-generation prospects

- Ton-scale NLDBD experiments
  - LEGEND-200/1000: next-gen HPGe detector, LAr veto
  - CUPID: Li_2MoO_4 scintillating bolometers with PID
  - nEXO: LXe TPC
- DUNE: 20-40 kton LAr TPC + GeV-scale ν beam from FNAL
  - Light DM detection: NC-like interactions with e-/N in ND
  - BDM: cosmogenic
  - Indirect: annihilation in the solar core
- HyperK: see yesterday's talk

The future



DM signature in
"hybrid"
neutrino detector

Eos: 4-ton technology demonstrator

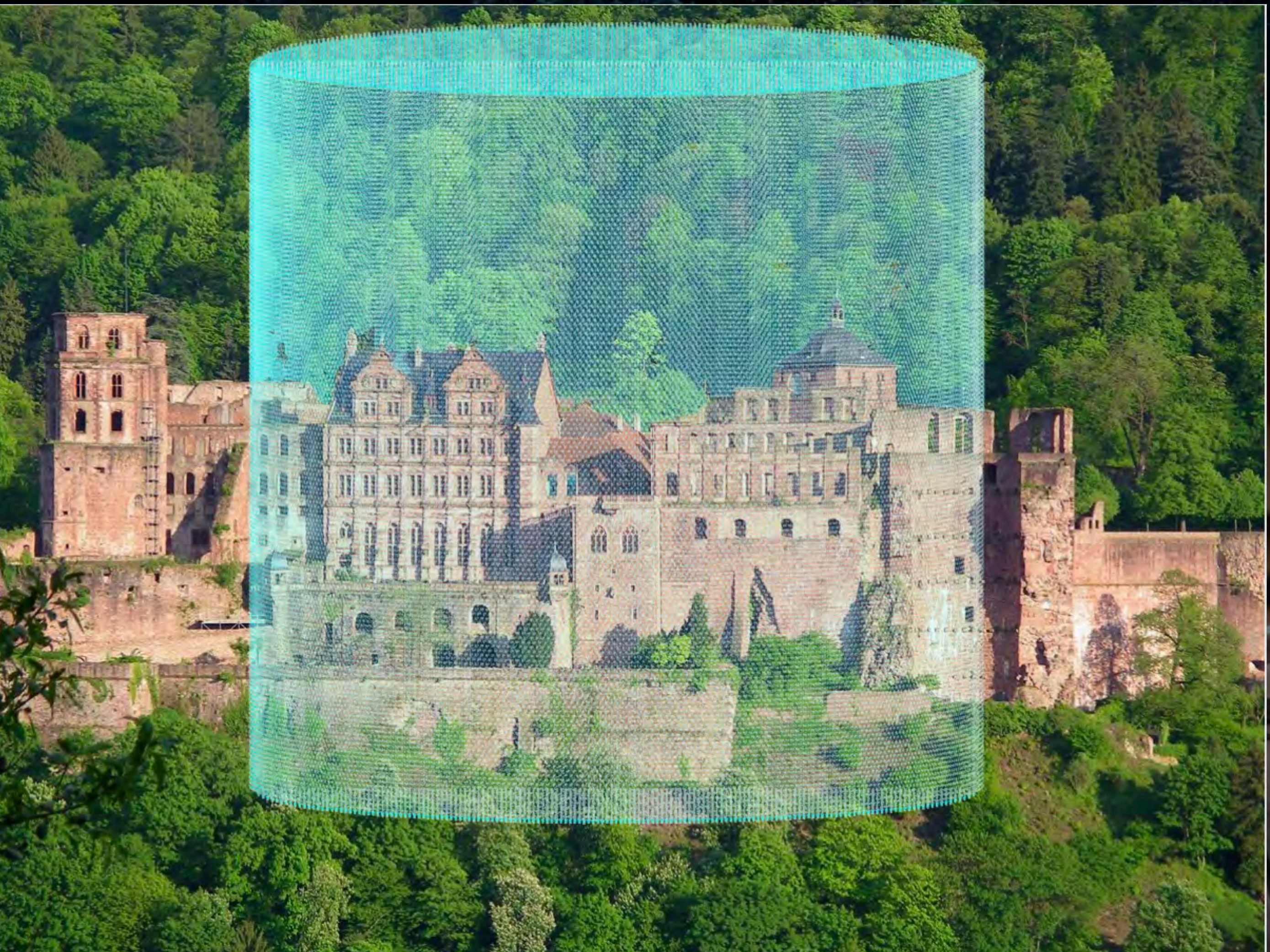
DM in ν detectors

Target of opportunity

Summary

- Neutrino detectors occupy a particular niche in DM detection
- These detectors offer sensitivity to both direct and indirect DM signatures
- As we scale up, overlap in programs increases
- The future program will leverage multi-purpose, next-generation, precision detectors
- A robust program in dark matter will be a broad program, bringing together expertise from different technologies and different energy regimes

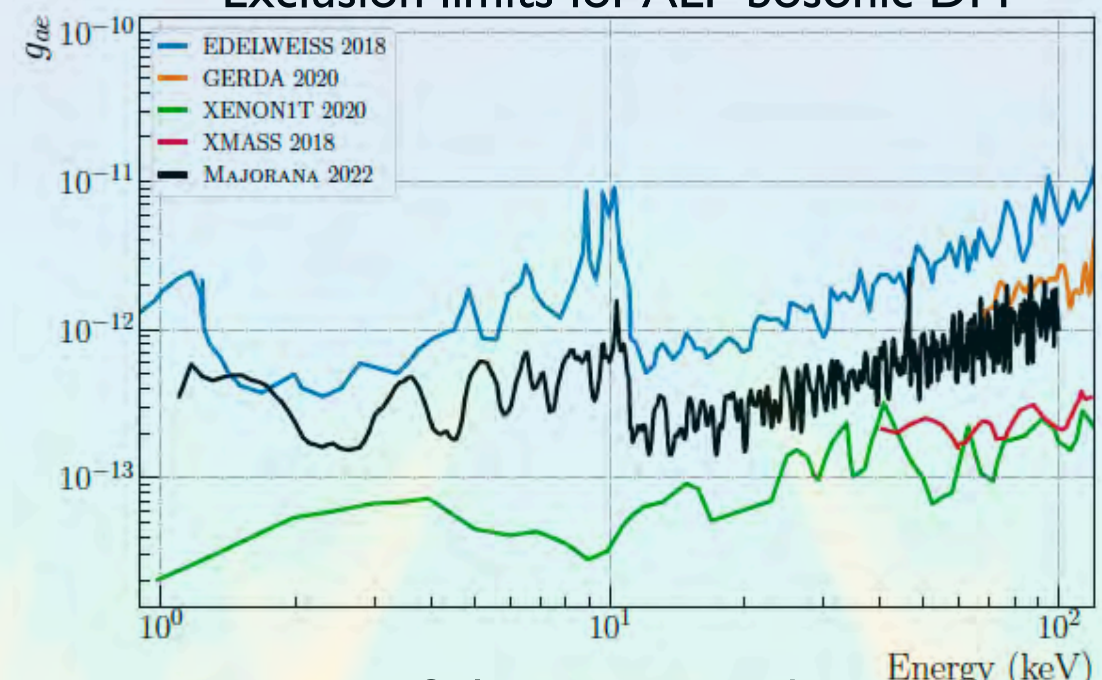
Thank you!



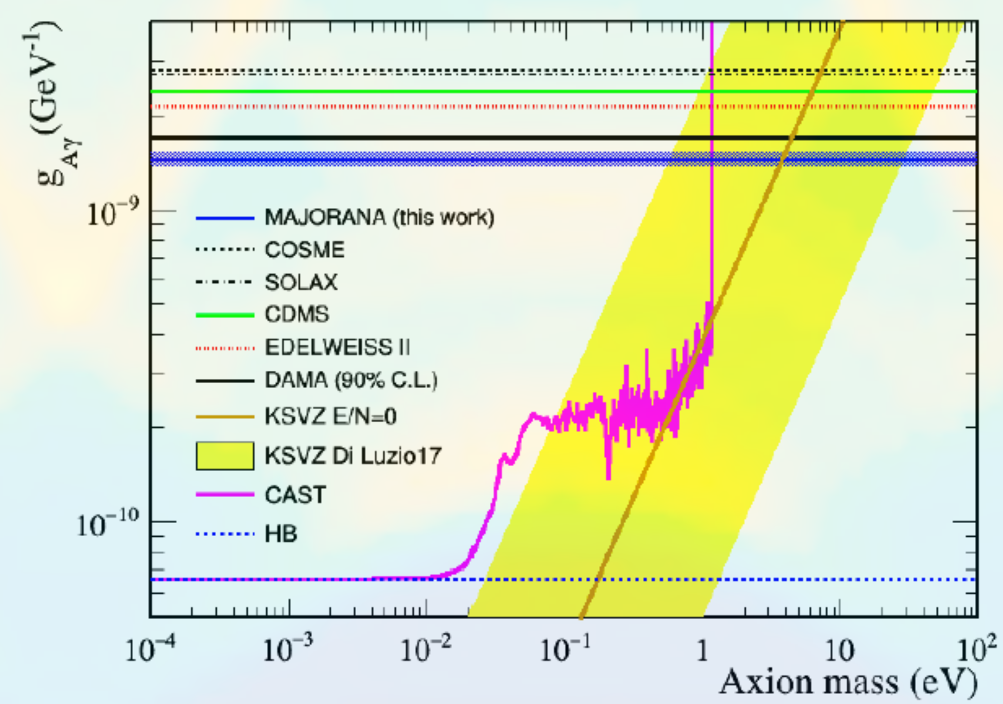
Exotic DM at MJD

- Sensitivity to sub-GeV DM, ALP, dark photons, keV-scale vs
- Majorana: 29.7kg HPGe at SURF, USA
- 37.5 kg-yr exposure
- Search for a peak in the range 1-100keV
- Polynomial bkg continuum + γ lines
- Consider a range of exotic DM models

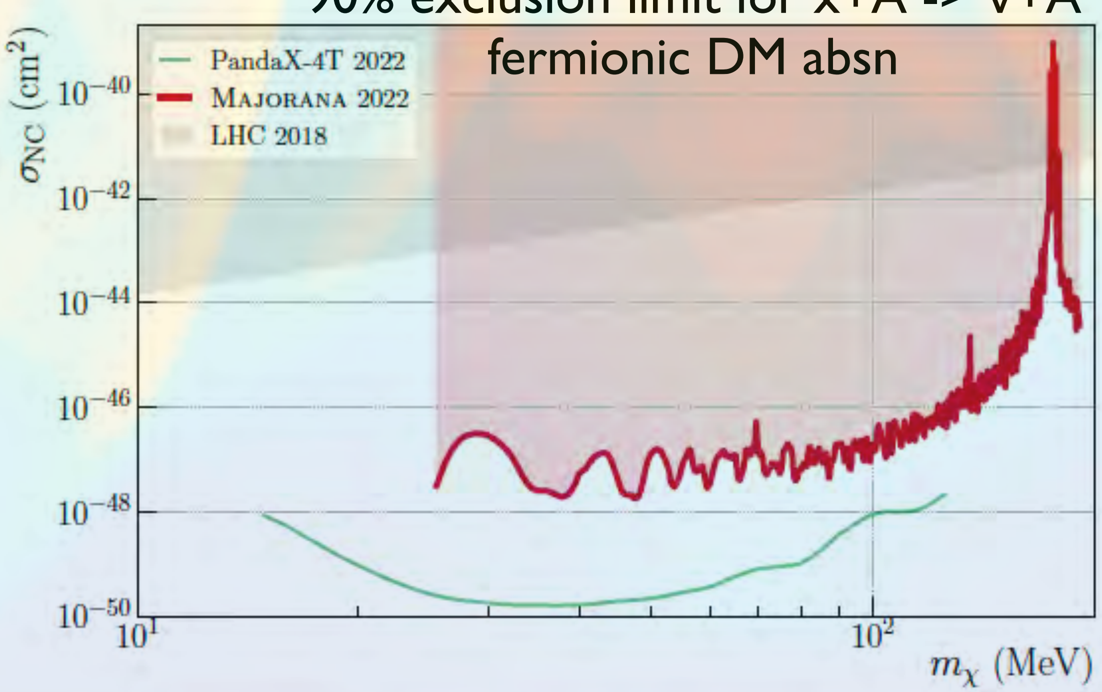
Exclusion limits for ALP bosonic DM



Solar axion search



90% exclusion limit for x+A -> ν+A fermionic DM absn



arXiv: 2206.10638; arXiv:2206.05789

XeIT / SK constraints

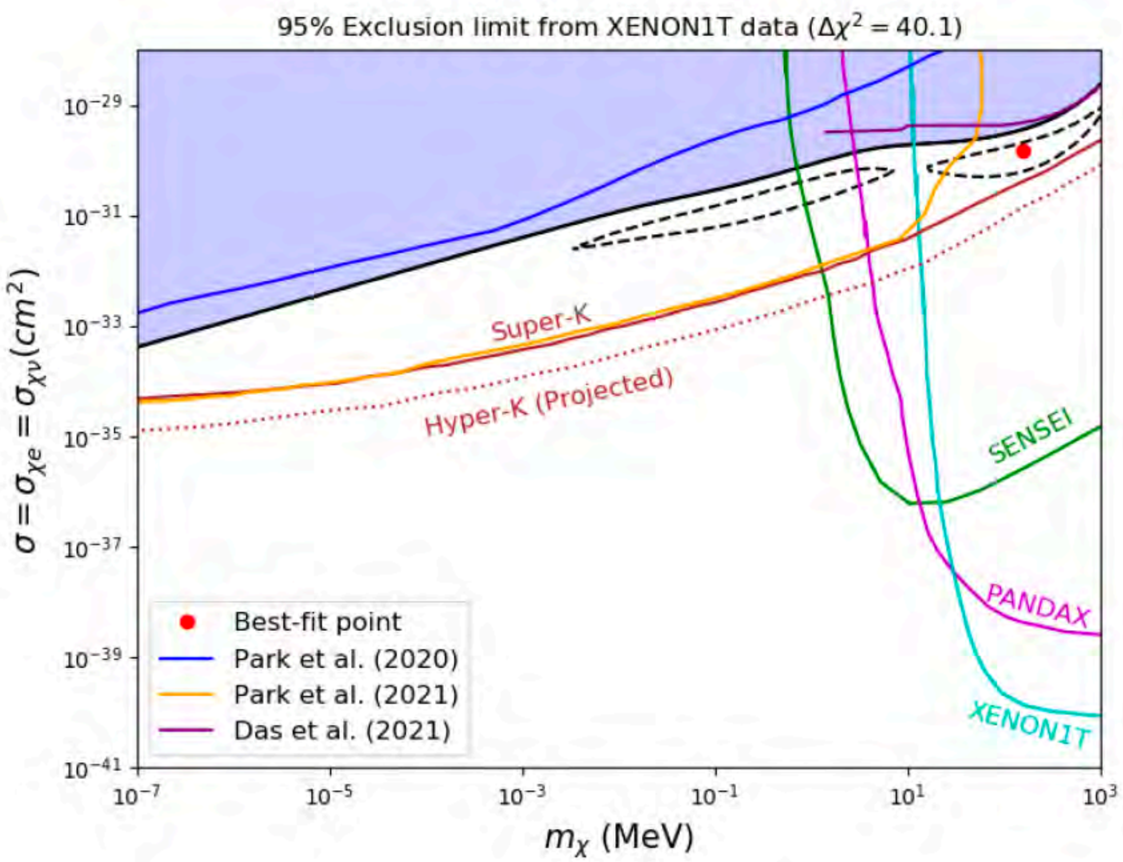


FIG. 9. Exclusion region in the $(m_\chi\,, \sigma_{\chi\nu} = \sigma_{\chi e})$ plane derived from the XENON1T data at the 95% confidence level for DM boosted by both CRe and DSNB, corresponding to $A \neq 0$ and $B \neq 0$ in Eq. (15). For all points inside the dashed line $\Delta\chi^2 < 0$ and the best fit point (156 MeV, $1.5 \times 10^{-30}\text{cm}^2$) marked with red point correspond to $\Delta\chi^2 = -3.1$. The constraints from other experiments on light cold DM such as SENSEI [68], PANDAX II [69], XENON1T [70], along with the constraints based on the results from Ref. [44] for CRe BDM, Ref. [49] for stellar neutrino BDM and Ref. [50] for DSNB BDM, derived from XENON1T data, are shown for comparison. We also give the results from Ref. [41] for CRe boosted DM derived from Super-K (also Hyper-K projection) data.

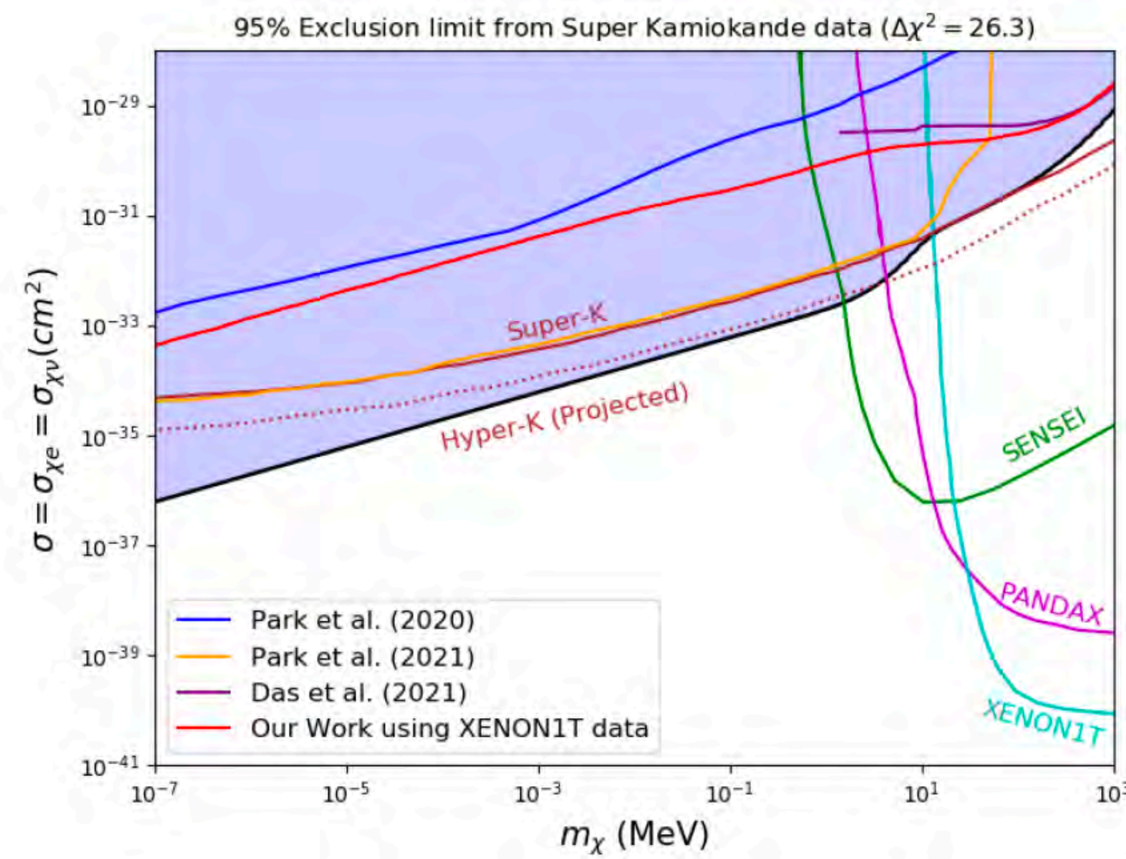


FIG. 14. Exclusion region in the $(m_\chi\,, \sigma_{\chi\nu} = \sigma_{\chi e})$ plane derived from the SK I data at the 95% confidence level for DM boosted by both CRe and DSNB, corresponding to $A \neq 0$ and $B \neq 0$ in Eq. (15). The constraints from other experiments on light cold DM such as SENSEI [68], PANDAX II [69], XENON1T [70], along with the constraints based on the results from Ref. [44] for CRe BDM, Ref. [49] for stellar neutrino BDM and Ref. [50] for DSNB BDM, derived from XENON1T data, are shown for comparison. We also give the results from Ref. [41] for CRe boosted DM derived from Super-K (also Hyper-K projection) data.

BBDM at SK

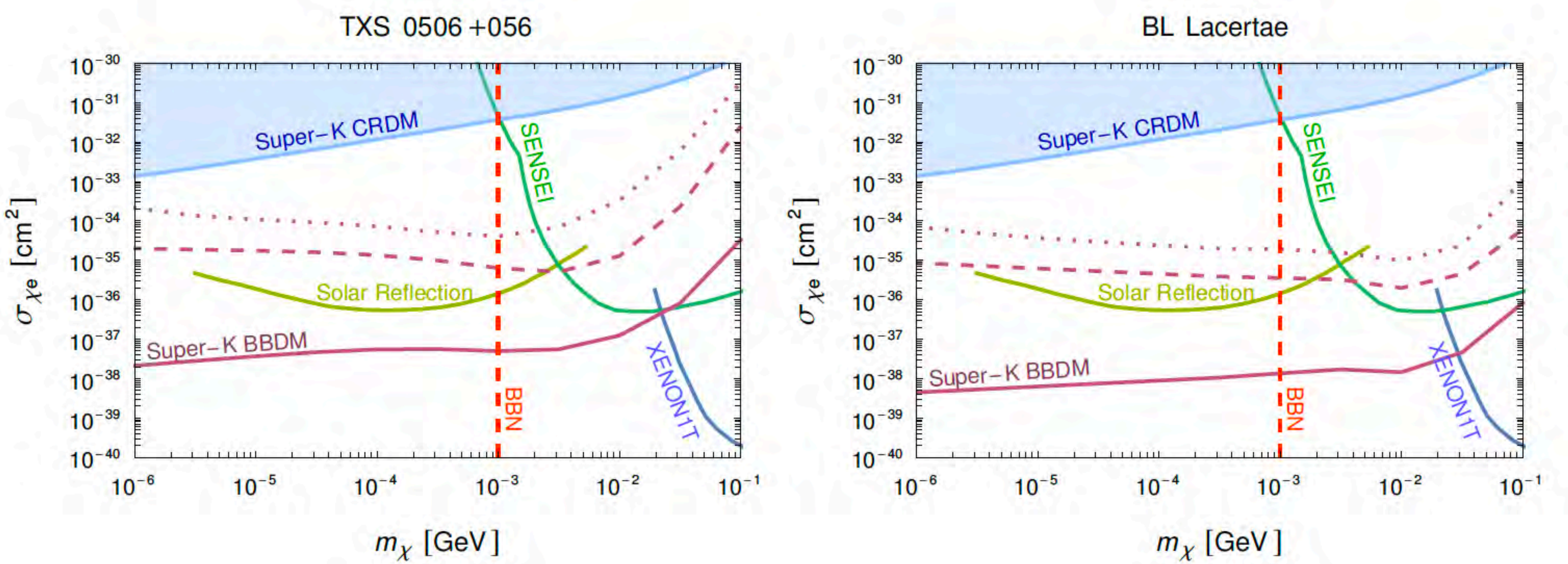
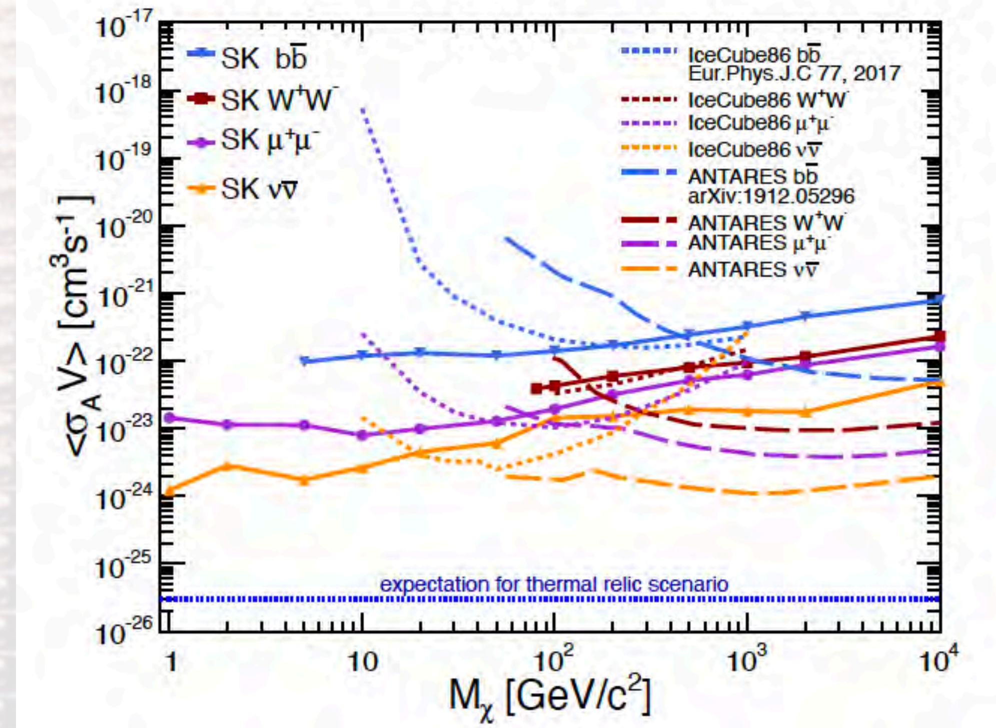


Figure 4. The constraints on DM-electron scattering cross section imposed by Super-K [13]. The left panel is for TXS 0506+056, while the right panel for BL Lacertae. The solid, dashed, and dotted purple lines correspond to BMP1, BMP2, and BMP3, respectively. For comparison, the constrains from CRDM [14, 15], XENON1T [6], SENSEI [59], Solar Reflection [58], and BBN [56, 57] are included.

JCAP 07 (2022) 013

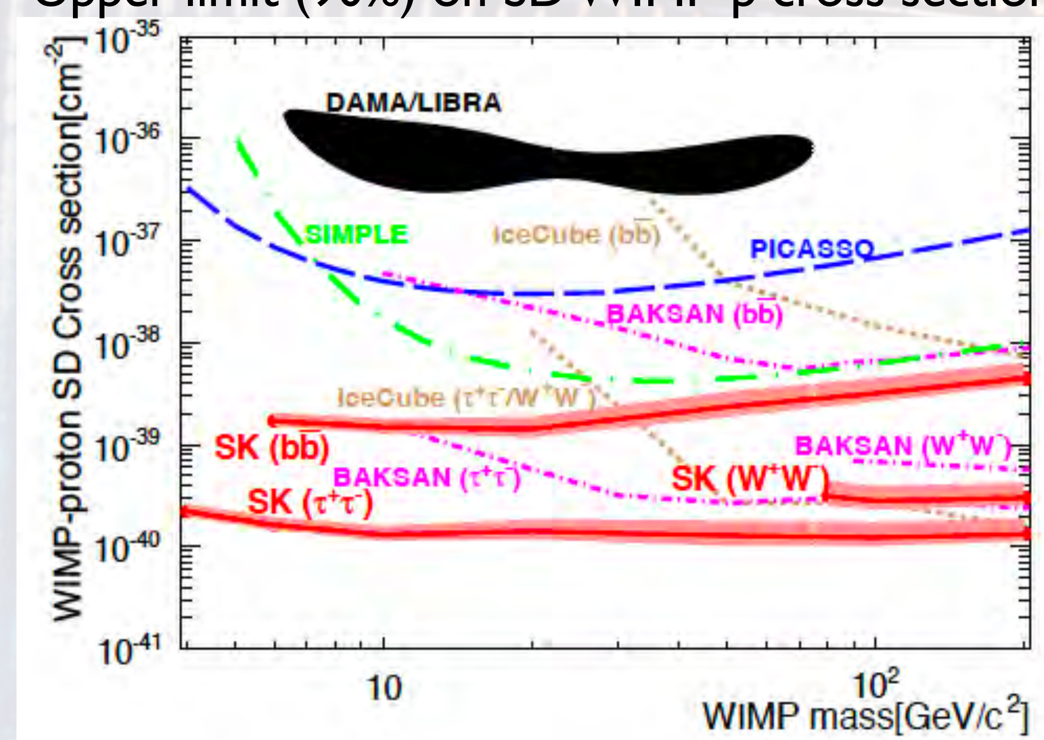
Indirect searches at SK

Upper limit (90%) on DM self annihilation x-section <σ_AV>



- Search for an excess of νs due to annihilations in the Sun, Earth, and Galactic halo
- χχ -> νν / bb / μ+μ- / W+W-
- Full MC of atm ν bkg and WIMP signal
- Look for excess above bkg in E x θ
- Data-driven check using on- /off-source directional analysis
- Signal should appear in all channels
- Solar annihilation: convert 90% upper limit on ν flux from DM annihilation into upper limit on WIMP-N σ

Upper limit (90%) on SD WIMP-p cross section



Phys. Rev. D 102, 072002, Phys. Rev. Lett. 114, 141301 (2015)

Indirect SK results

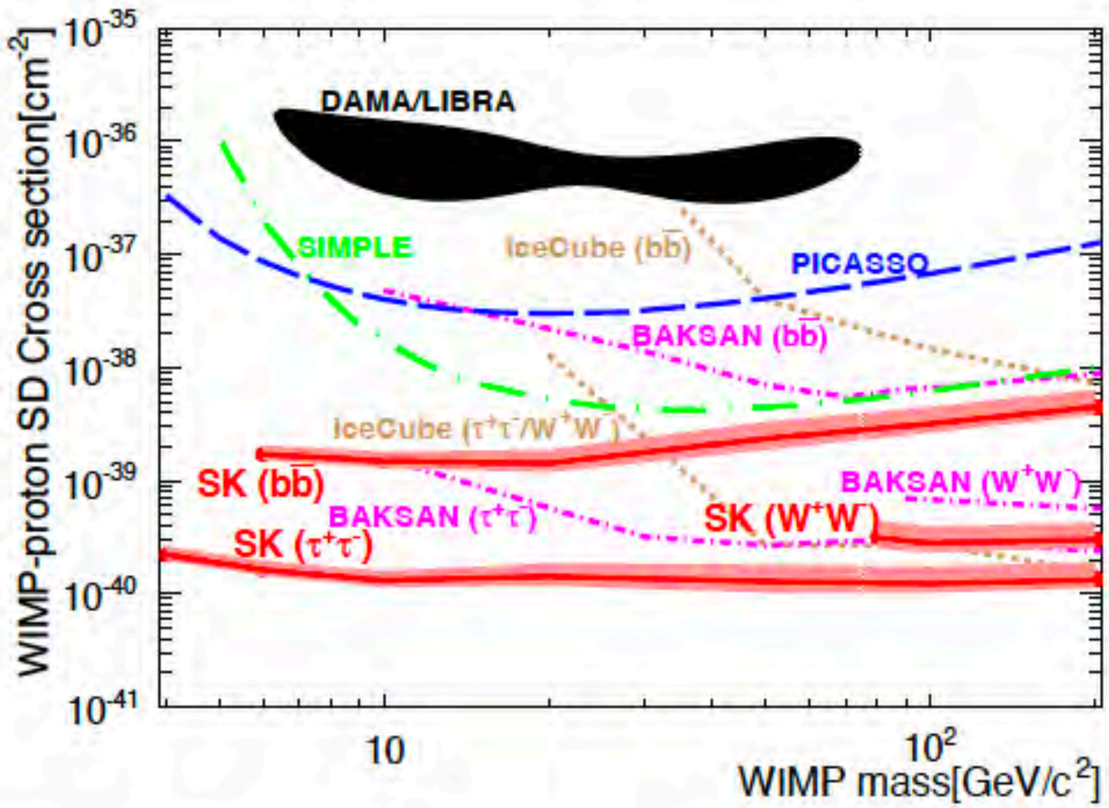


FIG. 3. 90% C. L. upper limits on SD WIMP-proton cross section calculated at DarkSUSY [30] default are shown in red solid with uncertainty bands to take account uncertainties in the capture rate for the $b\bar{b}$, W^+W^- and $\tau^+\tau^-$ channels from top to the bottom. Also shown are limits from other experiments: IceCube [9] in brown dashed: $b\bar{b}$ (top) / W^+W^- or $\tau^+\tau^-$ (bottom); BAKSAN [10] in pink dot-dashed: $b\bar{b}$ (top) / W^+W^- (middle) / $\tau^+\tau^-$ (bottom); PICASSO [31] (blue long-dashed); SIMPLE [32] (green long dot-dashed). The black shaded region is the 3σ C.L. signal claimed by DAMA/LIBRA [12, 33].

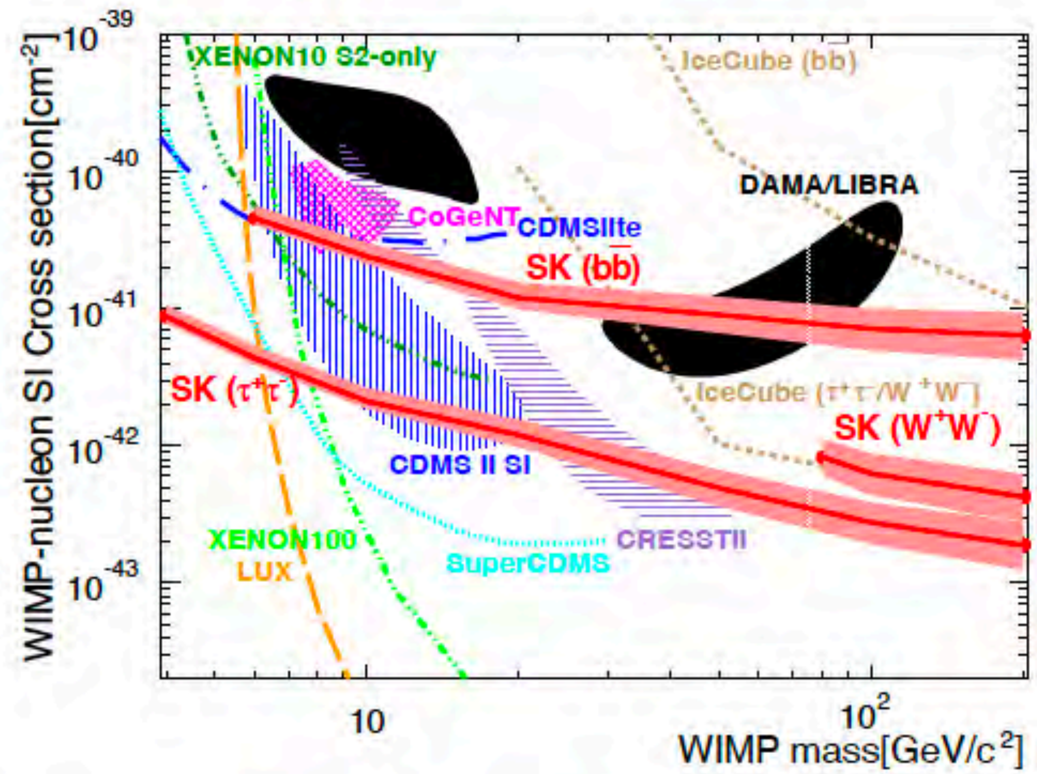


FIG. 4. 90% C. L. upper limits on the SI WIMP-nucleon cross section (plotting scheme is the same as Fig.3). Also shown are event excesses or annual modulation signals reported by other experiments: DAMA/LIBRA (black shaded regions, 3σ C.L.); CoGeNT [13] (magenta diagonally cross-hatched region, 90% C.L.); CRESSTII [14] (violet horizontally-shaded regions, 2σ C.L.); CDMS II Si [15] (blue vertically-shaded region, 90% C.L.); and limits: IceCube [9] in brown dashed: $b\bar{b}$ (top) / W^+W^- or $\tau^+\tau^-$ (bottom); SuperCDMS [34] (cyan dotted); CDMSlite [35] (blue long dot-dashed); XENON10 S2-only [36] (dark green dash triple dot); XENON100 [37] (green dash double dot); LUX [38] (orange long-dashed).

Bx results

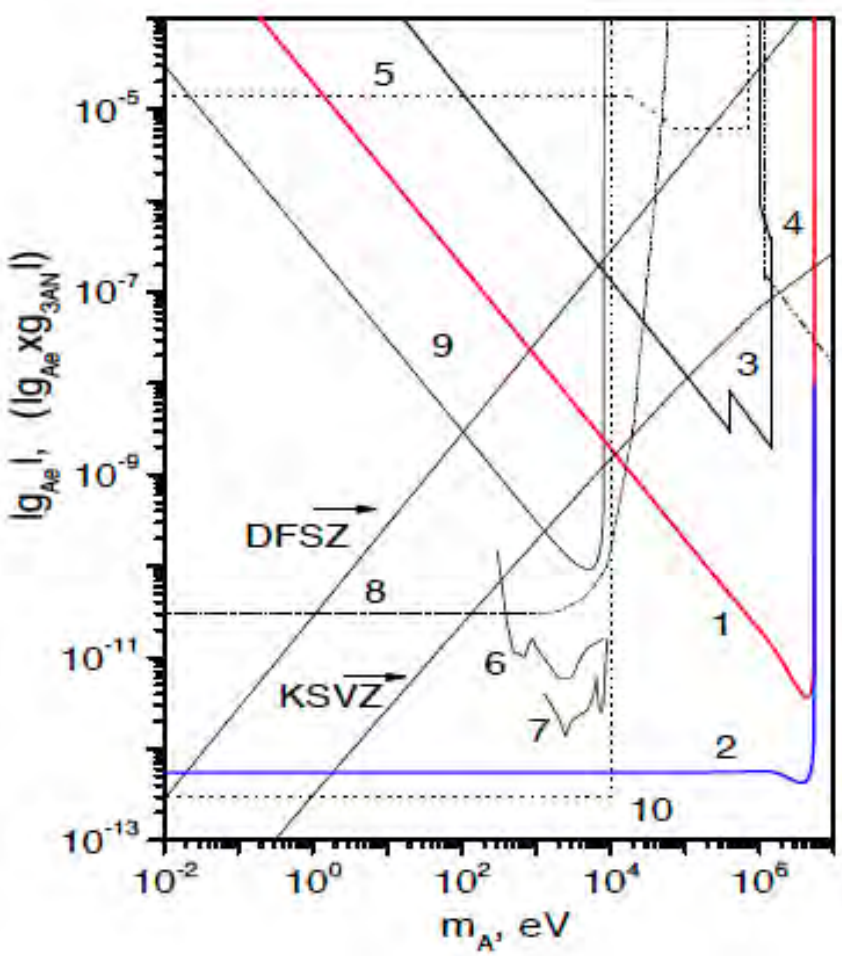


FIG. 6. The limits on the g_{Ae} coupling constant obtained by 1- present work, 2 - present work for $|g_{Ae} \times g_{3AN}|$, 3- reactor [39, 40] and solar experiments [15, 25], 4- beam dump experiments [41, 42], 5- ortho-positronium decay [43], 6- CoGeNT [44], 7- CDMS [45], 8- solar axion luminosity [47], 9-resonance absorption [46], 10- read giant [48]. The excluded values are located above the corresponding lines. The relations between g_{Ae} and m_A for KSVZ- and DFSZ-models are shown also.

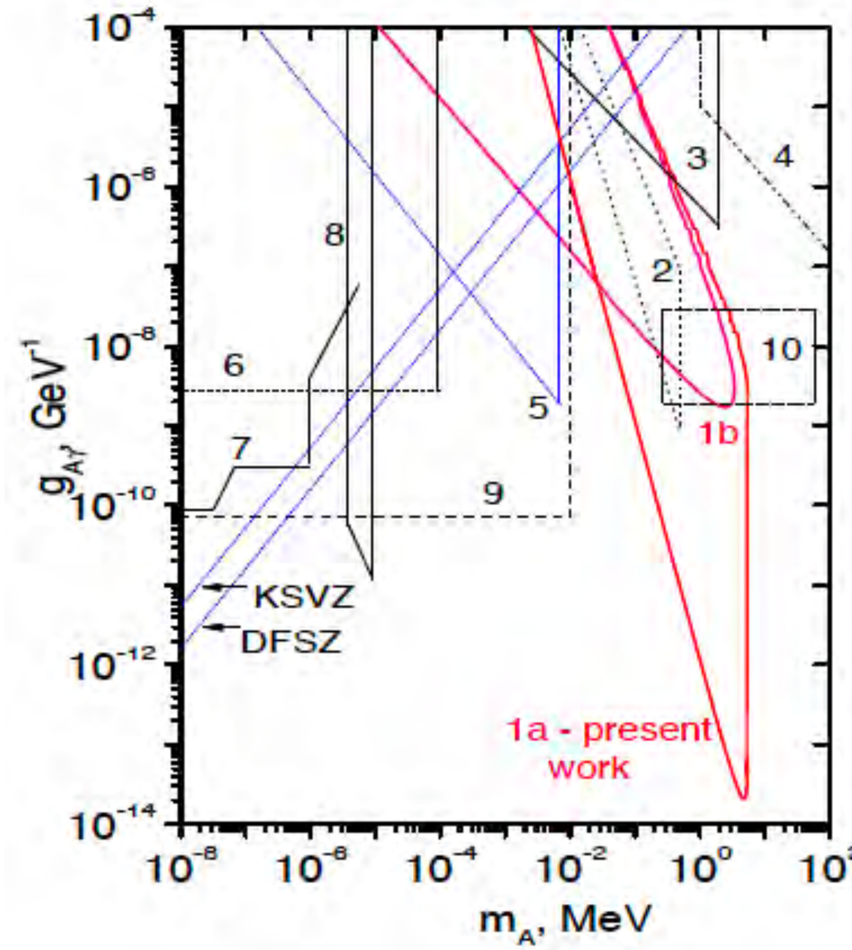


FIG. 7. The limits on $g_{A\gamma}$ obtained by 1- present work (a - $A \to 2\gamma$, b - PC, areas of excluded values are located inside contour), 2 - CTF [15], 3- reactor experiment [40], 4- beam dump experiments [41, 42], 5- resonant absorption [49], 6- solar axions conversion in crystals - [50–52], 7- CAST and Tokyo helioscope [53–55], 8-telescopes [56–58], 9- HB Stars [48], 10- expectation region from heavy axion models [10–12].

Dark photon allowed space

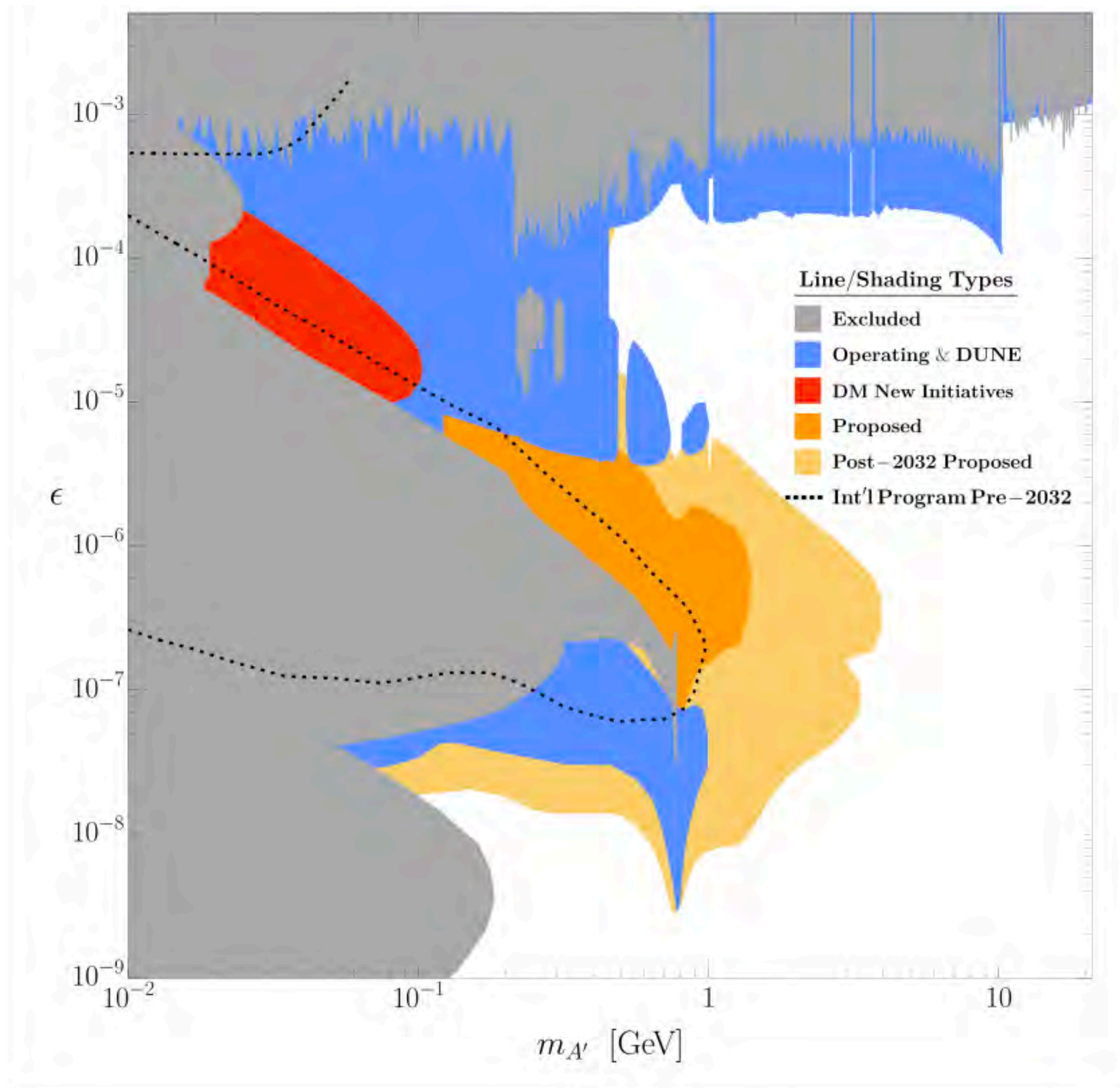
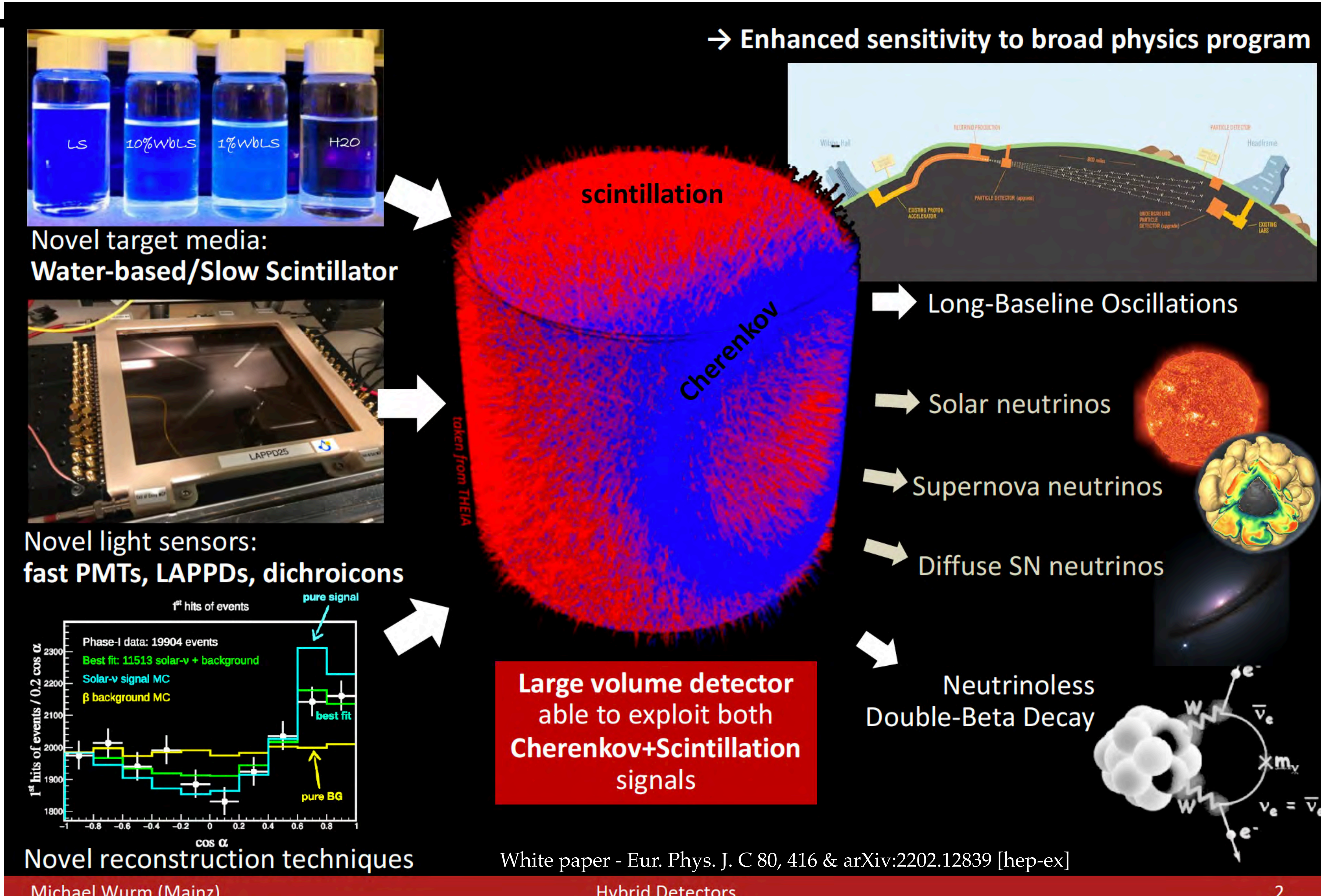


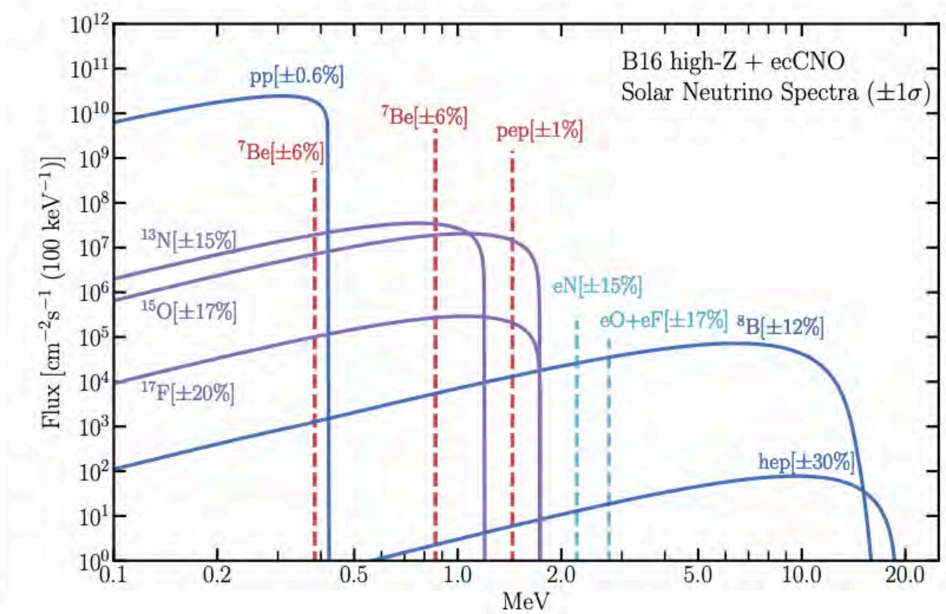
Figure 3. *Visible dark-photon parameter space (compatible with secluded thermal DM) [4]: Near-term and future opportunities to search for visibly decaying dark photons interacting through the vector portal displayed in the dark photon mass ($m_{A'}$) – kinetic mixing (ϵ) parameter space. Constraints from past experiments (gray regions) and projected sensitivities from operating and fully funded experiments and DUNE (blue regions), the DMNI-supported experiments (red region), and other proposed near-term (pre-2032) experiments based in the US and/or with strong US leadership (orange region) are shown. Primarily international projects are shown as a dashed line. Proposed experiments that are farther into the future are shown in light yellow. See Fig. 12 for a more detailed version of this figure showing individual experiments color-coded by experimental approach, highlighting one aspect of the complementarity between different facilities/experiments. Collectively, these experiments are poised to cover large regions of open dark photon parameter space.*

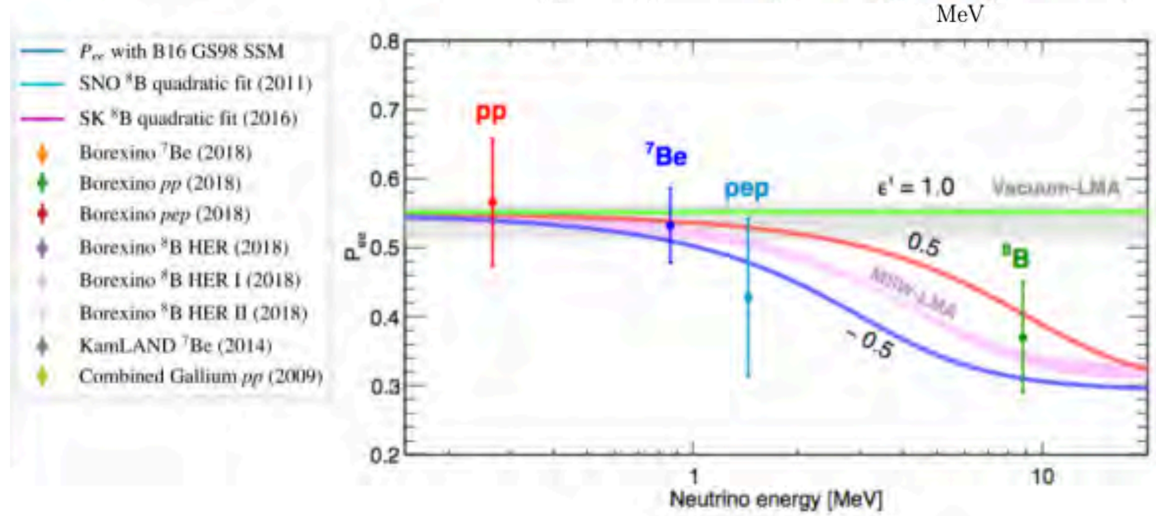
Hybrid neutrino detection

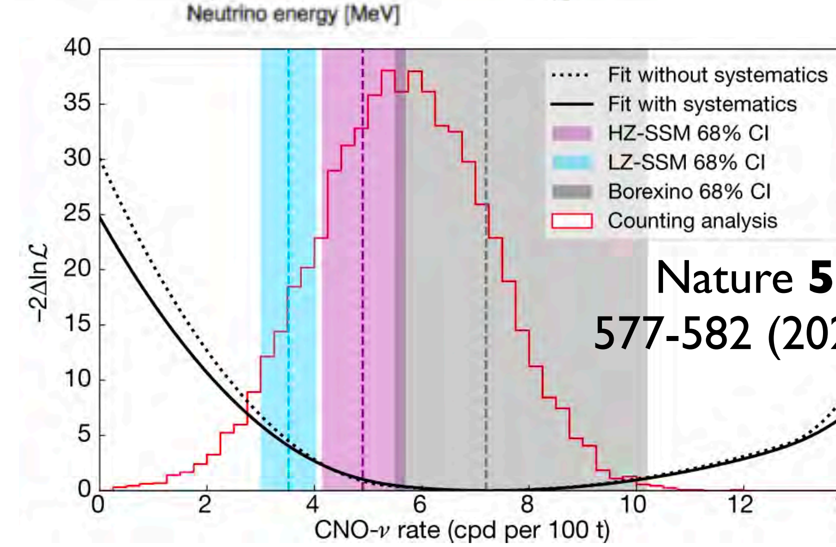


Beyond the Solar Neutrino Problem

- Fluxes
  - hep: last unobserved flux
  - CNO: solar metallicity
  - 8B, 7Be: T, environmental factors
  - pp: luminosity constraint
- Oscillation parameters / spectrum
  - Day/night effect
  - Δm^2_{12} (mild tension)
  - NSIs, sterile



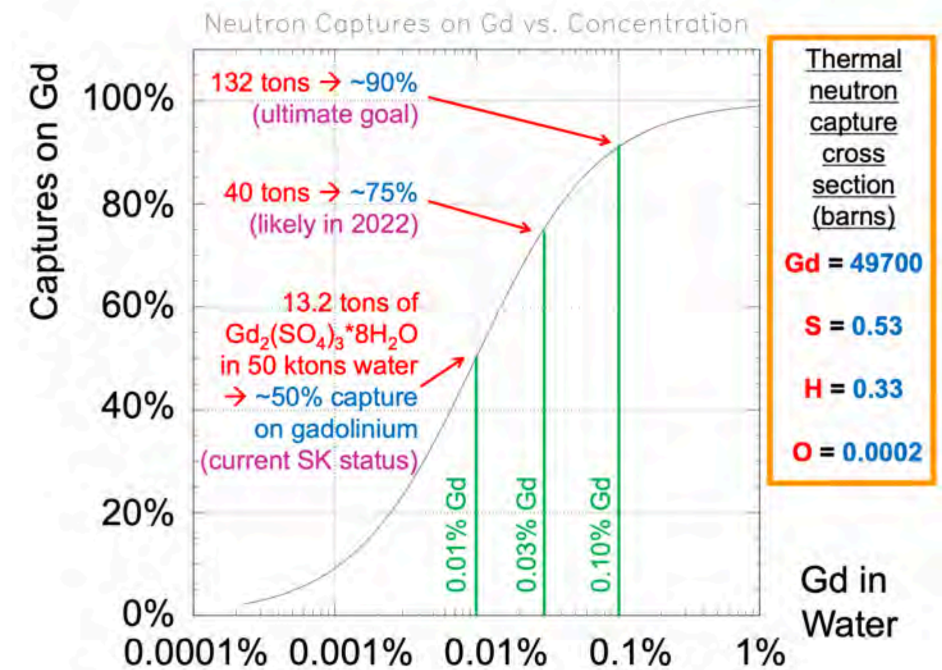




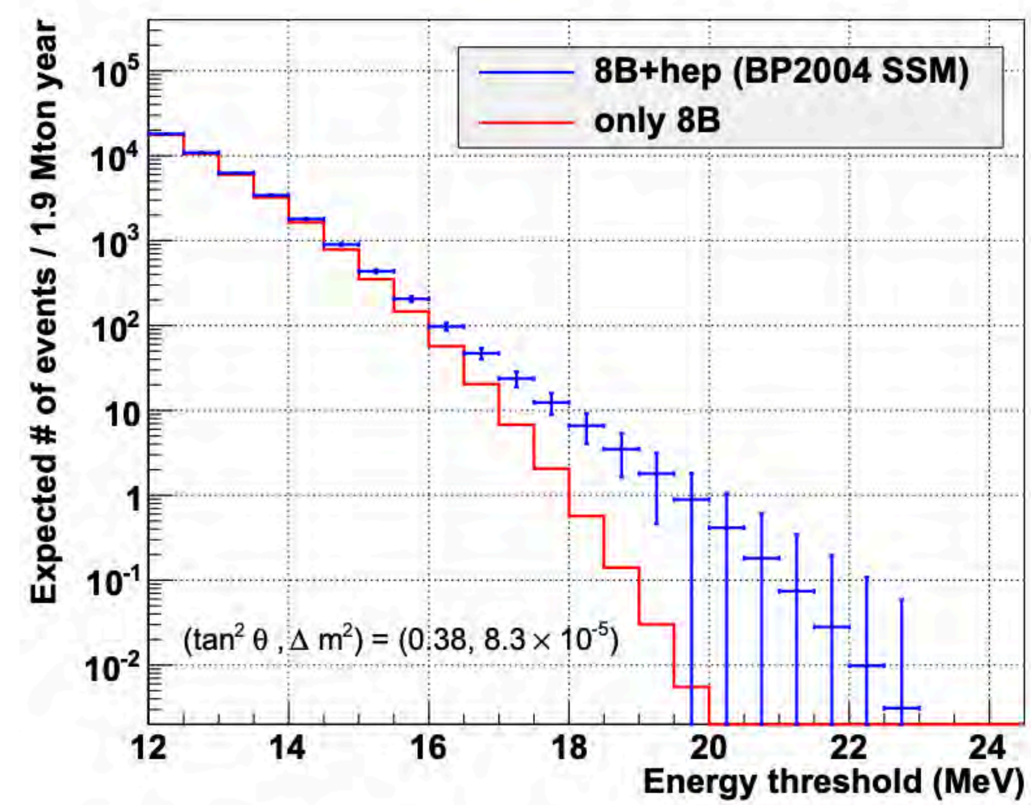
Nature **587** 577-582 (2020)

Super-/Hyper-Kamiokande (+Gd)

- **Super-K**: first large detector ever to be filled with Gd-H2O (0.021% $Gd_2(SO_4)_3$ ~0.01% Gd)
- Enhance neutron capture efficiency
- Transparency observed to be as good as H2O phase
- Next phase (0.03%Gd) should allow the first detection of DSNB
- Ongoing measurements of low-energy solar ν



- **Hyper-K**: >200 kton, 40% coverage
- 4 (8)σ sensitivity to day/night effect in 10 years for values currently predicted by reactor (solar) experiments
- 8B spectrum (ES)
- hep neutrino observation

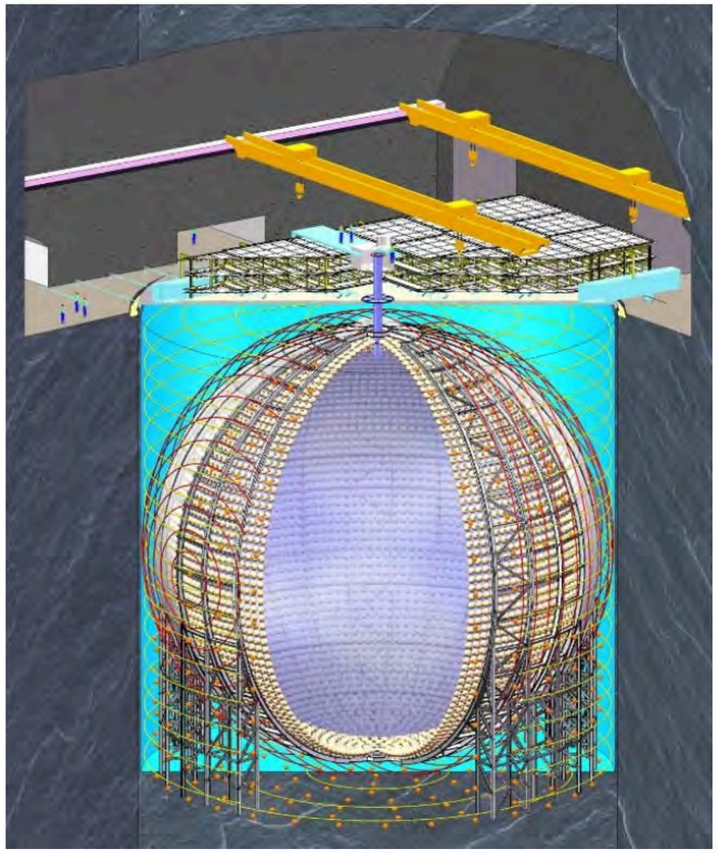


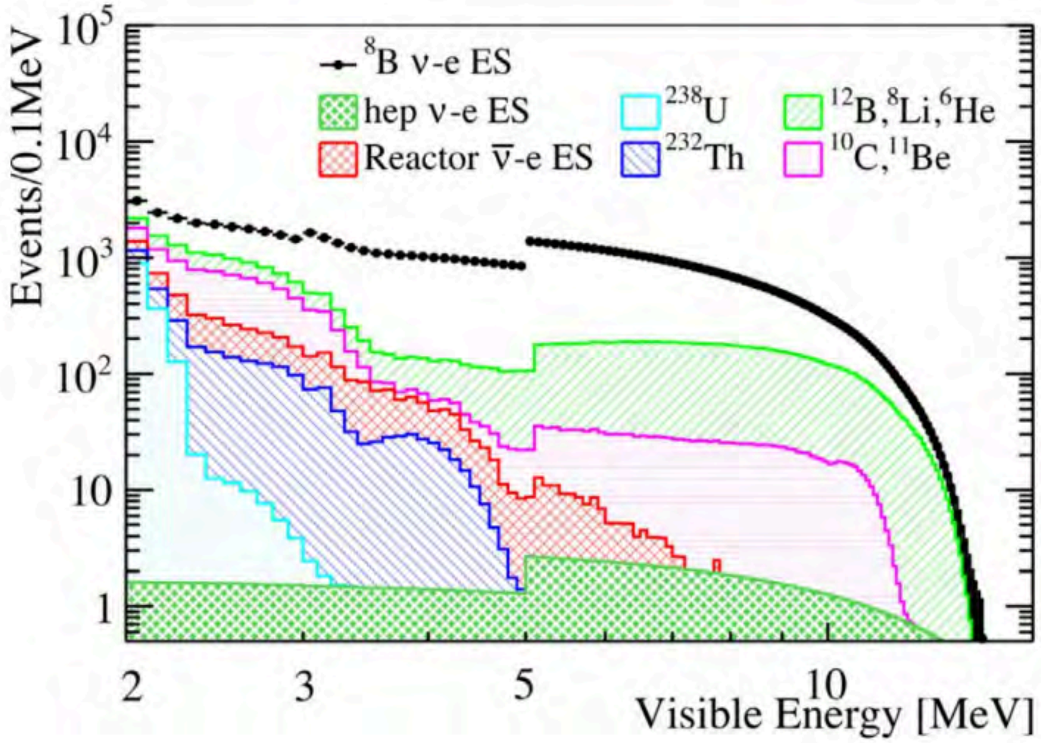
https://arxiv.org/pdf/2109.00360.pdf; M. Vagins Supernova and Early Universe Workshop

https://arxiv.org/abs/1805.04163

JUNO

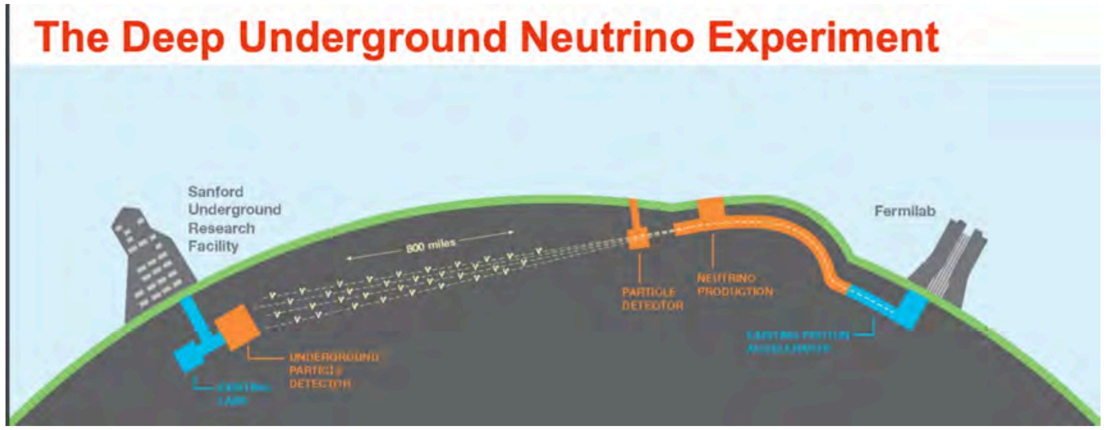
- 20 kton, 3% / MeV resolution
- 0.7 km overburden (Guangdong, China)
- Due to complete construction this year
- Will be the largest LS to-date, with world-leading sensitivity to several oscillation parameters and physics searches
- 2-MeV t/h:
  sensitivity to probe transition region via low-energy ^{8}B ν
- 2-3σ sensitivity to day/night
- Precision measurement of ΔM^2_{21}

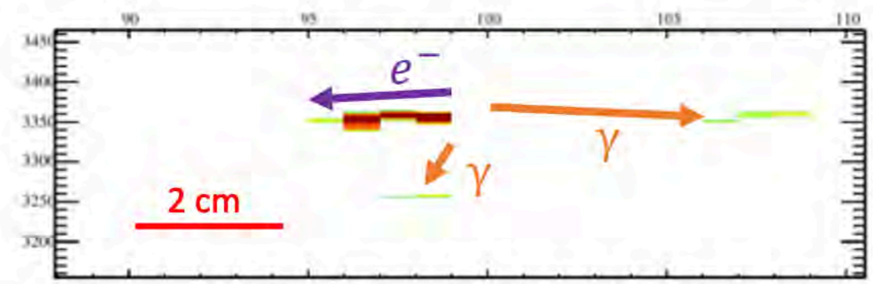




Prog.Part.Nucl.Phys. 123 (2022) 103927

LAr: DUNE



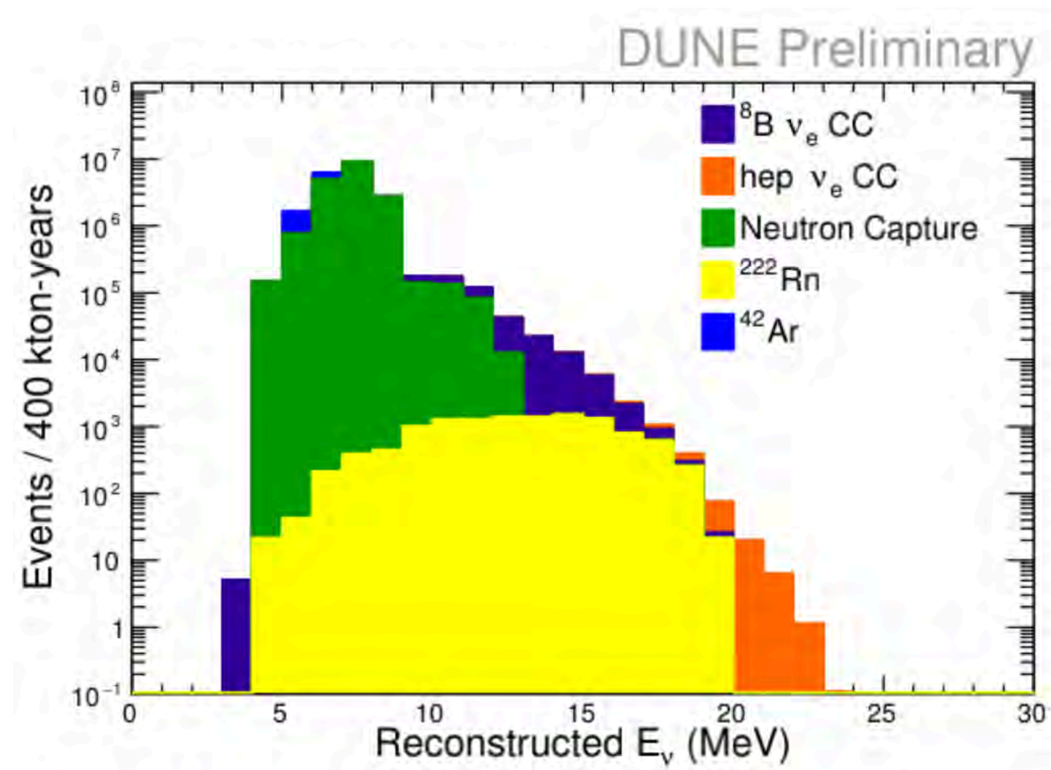


$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

CC dominates signal
~10MeV e + γ cascade

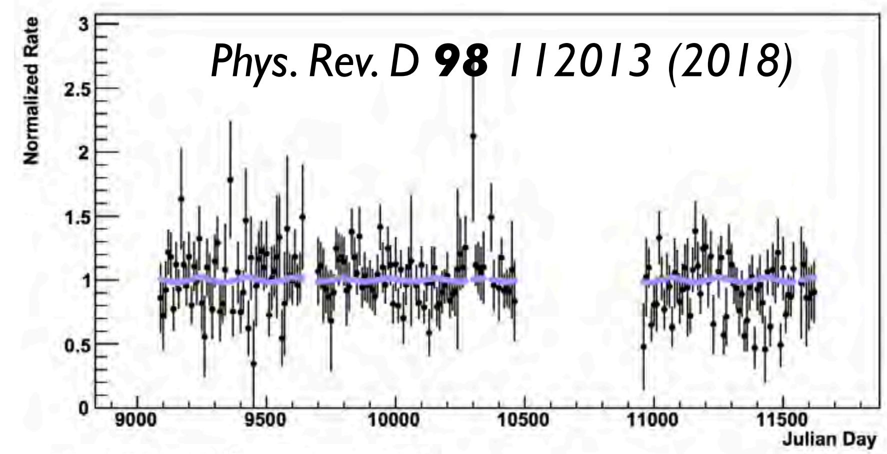
Bkg	Rate
^{40}Ar(n,γ)	44 / t-yr
^{36}Ar(n,γ)	0.62 / t-yr
^{40}Ar(α,γ)	0.051 / t-yr

- Offers CC on Ar, good for precision spectral measurement (day/night);
- Limited by threshold and background
- Novel ideas to leverage phase II upgrades
  - UG-Ar,
  - pixelated detectors,
  - novel readout,
  - Xe doping
  - Hybrid detection (Theia-25)

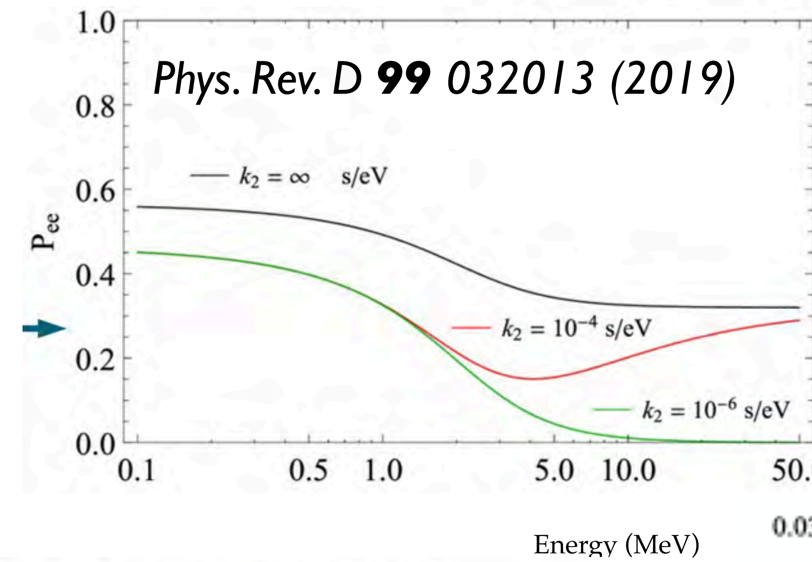


Sudbury Neutrino Observatory

- Search for Lorentz violating effects (preferred direction)
- New / improved constraints on 38 / 16 model parameters



- Search for neutrino decay
- Energy-dependent disappearance
- New limit on lifetime
  k_2 (= τ_2/m_2) > 1.92 x 10-3 s/eV (90% CL)



- Search for hep & DSNB neutrinos
- Final undetected solar ν flux
- Probe "glow" from past core-collapse SNe

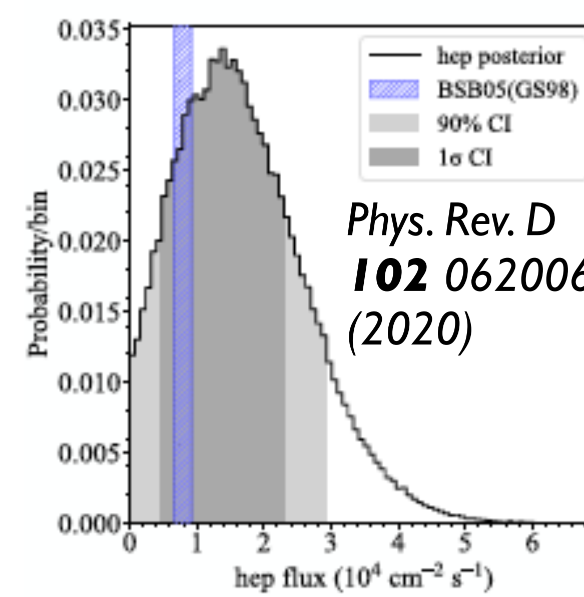
Bayesian one-sided 90% CI:

$\Phi_{DSNB}^{*} < 19$ cm^{-2} s^{-1} ($22.9 < E_\nu < 36.9$ MeV)

(*sensitivity ~ 30 cm^{-2} s^{-1})

Bayesian 90% CI:

$\Phi_{hep} < 30 \times 10^3$ cm^{-2} s^{-1}



- Measurements of n production from μ and atm ν

Phys. Rev. D ***99*** *112007 (2019), Phys. Rev. D* ***100*** *112005 (2019)*

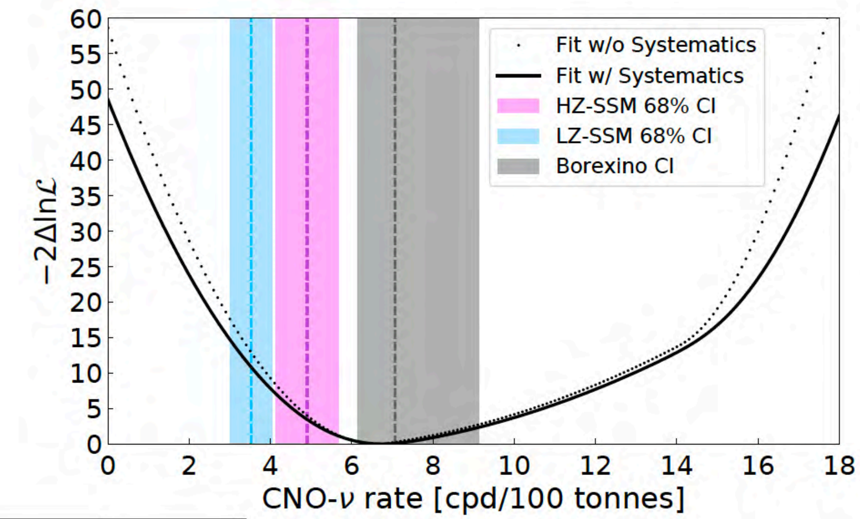
SNO+ status

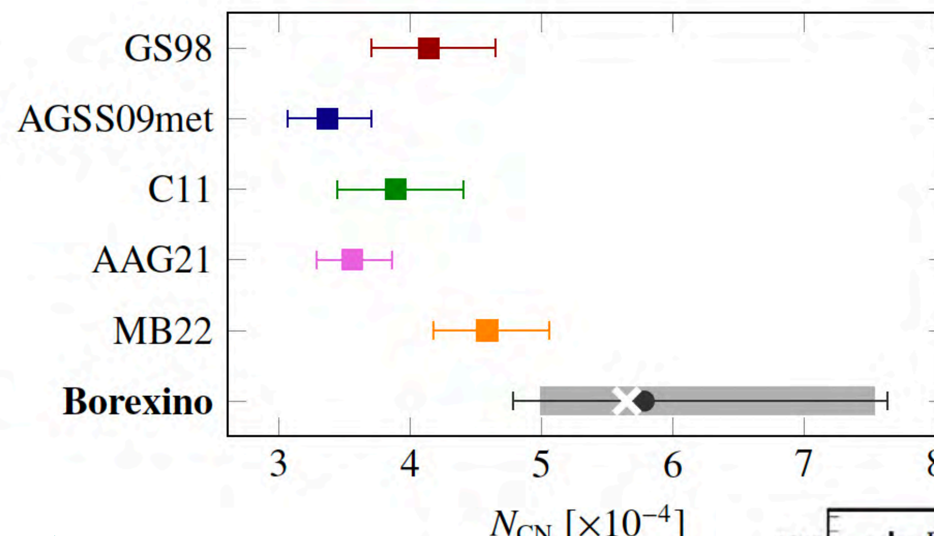
- Completed data taking with water
- LS fill complete, end of March, 2021 (780kg LAB+PPO)
- PPO fill complete: 2.2 g/L
- Largest, deepest operating LS detector
- Ultra-low background
- NLDBD target backgrounds achieved!
- Broad ongoing physics program

Related work:
Phys. Rev. D 105, 112012 (2022)
JINST 16 P10021 (2021)
JINST 16 P08059 (2021)
JINST 16 P05009 (2021)
Phys. Rev. C 102, 014002 (2020)
Phys. Rev. D 99, 032008 (2019)
Phys. Rev. D 99, 012012 (2019)

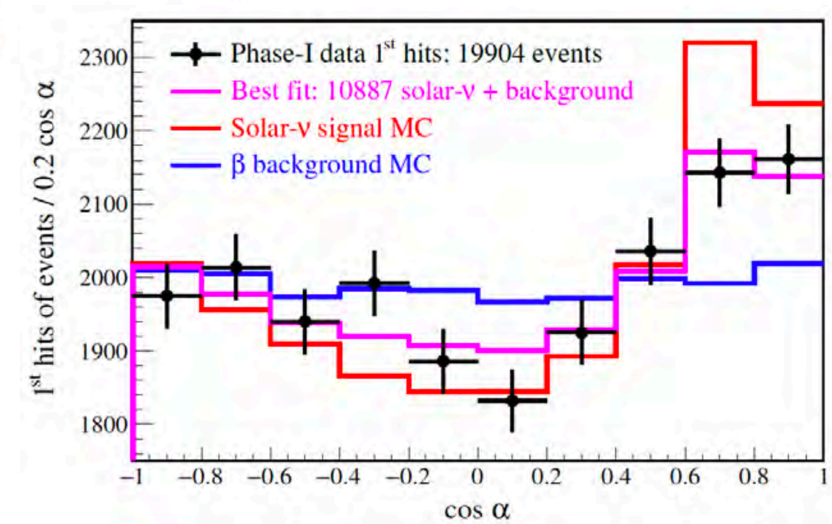
Borexino

- First measurement of CNO ν flux!
  - ^{232}Th and ^{238}U ~ 10^{-19}g/g; ^{210}Bi events ≤11.5 ± 1.3 cpd/100t
  - CNO flux: $6.6\ ^{+2}_{-0.9} \times 10^{8}$ cm^{-2}s^{-1} (7σ)
  - First evaluation of C, N solar abundance using ν
  - 2σ tension with low-metallicity measurements
  - Global fit (8B, 7Be) allows to disfavour B16-AGSS09met (vs B16-GS98) at 3.1σ





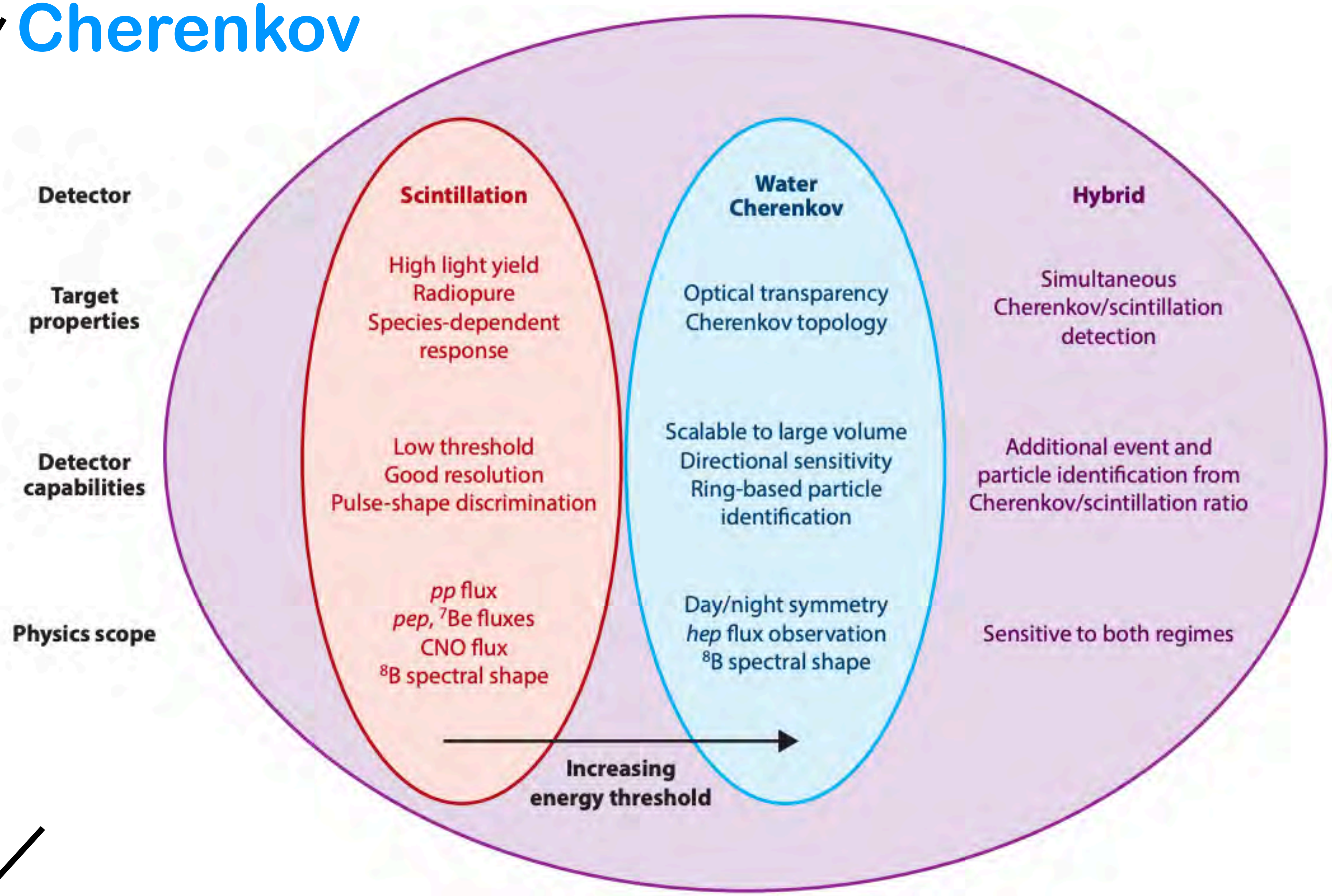
- Integrated directionality at Borexino:
  - consider earliest photons in the event
  - take angle between early photons and solar direction
  - 6σ angular excess caused by Cherenkov photons
- Measurement of primarily 7Be ν demonstrates first directional detection of sub-MeV neutrinos



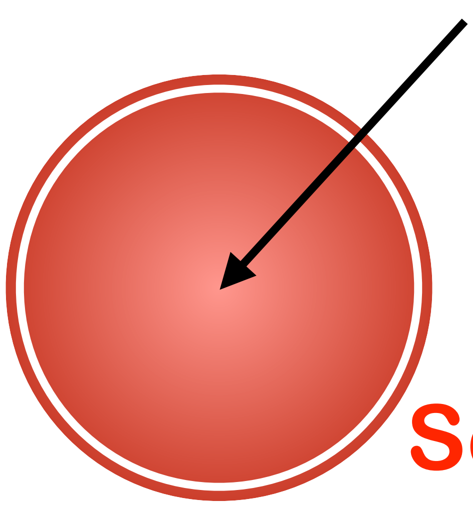
Nature 587, pages 577–582 (2020), Phys.Rev.Lett. 128 (2022) 9, 091803, Phys.Rev.D 105 (2022) 5, 052002; PRD 105.052002, PRL 128 (2022) 9, 091803

Hybrid Detectors

Cherenkov



Improved background rejection for precision ν measurements



Scintillation

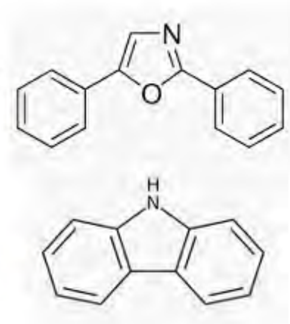
Builds on core (Wb)LS development at BNL (Yeh et al.)

Detector development

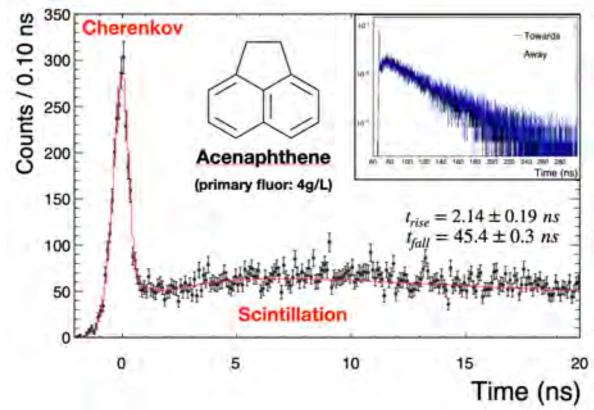
Engineering WbLS properties: Bourret (LBNL)

Example:
slowing down decay time

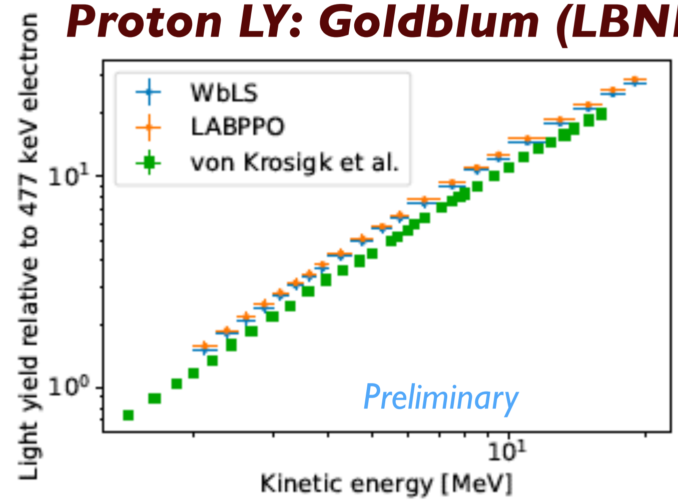
- Standard PPO → 2ns
- New carbazole → 15ns



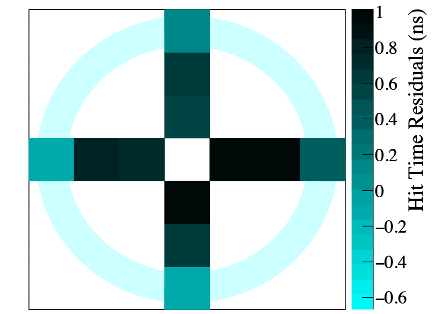
Slow LS: Oxford, Mainz

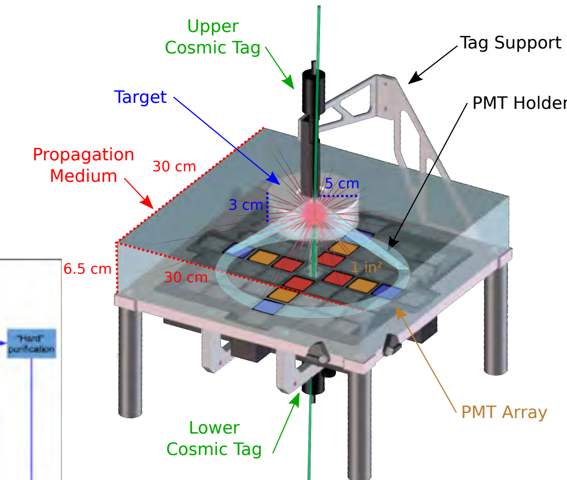


Proton LY: Goldblum (LBNL)



CHESS detector: LBNL



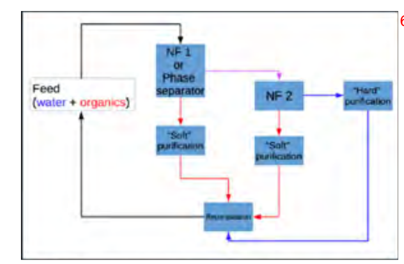


Extensive international effort in Germany (Mainz, Munich), UK, China

Additional work on: slow LS, alternative fluors, alternative surfactants

Scattering & attenuation: UC Davis, UC Berkeley+LLNL

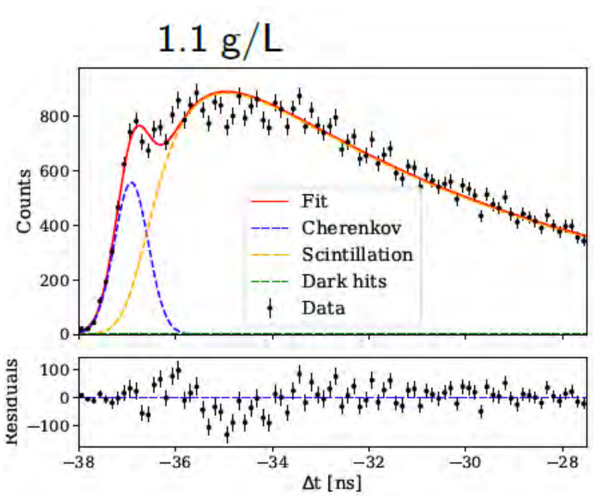
Nanofiltration: UC Davis



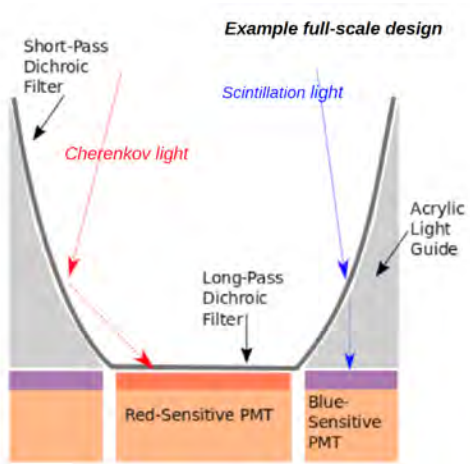
Preliminary design for a two-staged nanofiltration concept for large scale WbLS purification.

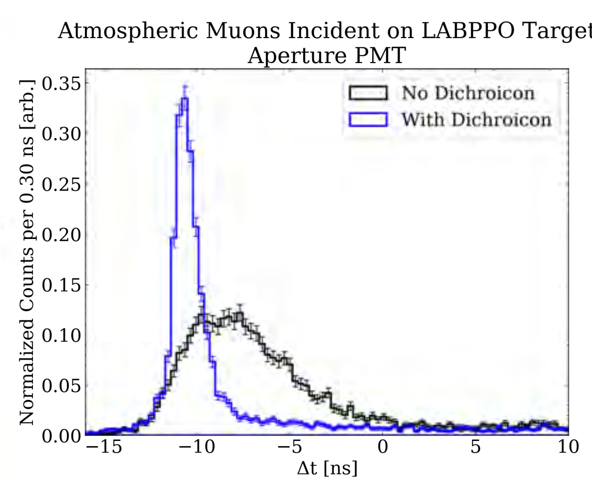
NIMA 889 69 (2018); JINST 14 T05001 (2019); Phys. Rev. D 105 (7) 2022; Phys. Rev. C 95 055801 (2017); Eur. Phys. Jour. C 80 867 (2020); Mat. Adv. 1 71 (2020); Eur. Phys. Jour. C 82 169 (2022); NIMA 947, 162604 (2019); arXiv:1902.06912; JINST13 P07005 (2018); JINST9 P06012 (2014); NIMA 943 162420 (2019); Eur. Phys. Jour. C 77 811 (2017); arxiv:1908.03564; arXiv:1502.01132; arXiv:1707.08222; NIMA 972 164106 (2020); Astropart. Phys. 109 33 (2019); NIMA 852 15 (2017); NIMA 712 162 (2013); Phys. Rev. D 97 052006 (2018); JINST14 1 (2019); Phys. Rev. D 101 072002 (2020); arXiv:2006.00173

LAPPDs: ANNIE, CHESS

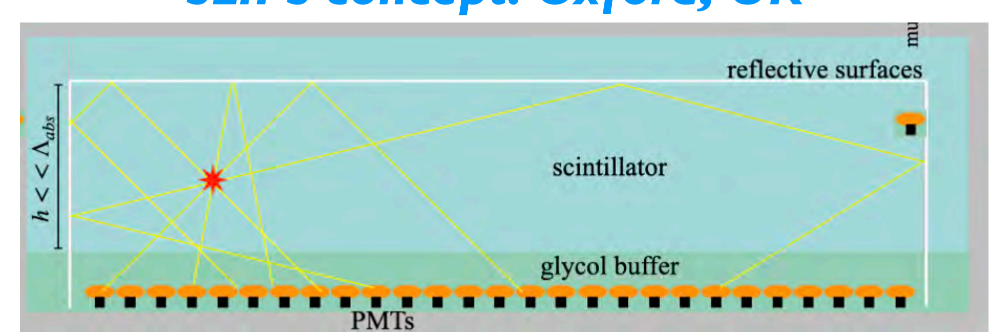


Dichroicon: Penn, CHESS



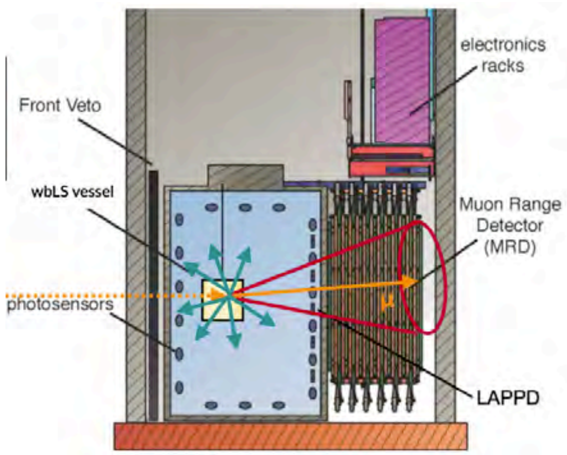


SLIPS concept: Oxford, UK



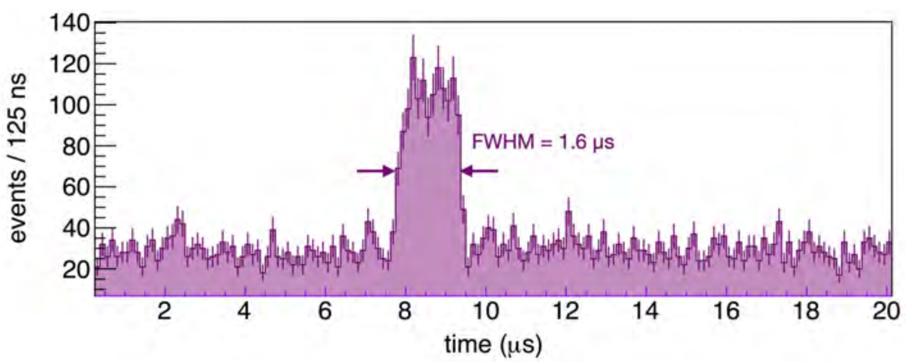
Prototypes

ANNIE: WbLS in a ν beam



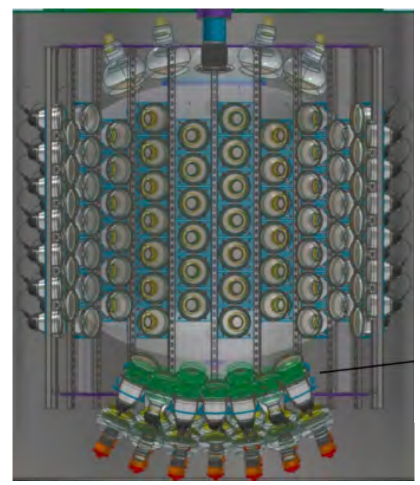
365 kg WbLS + LAPPDs
Ch/S separation
High- and low-energy events

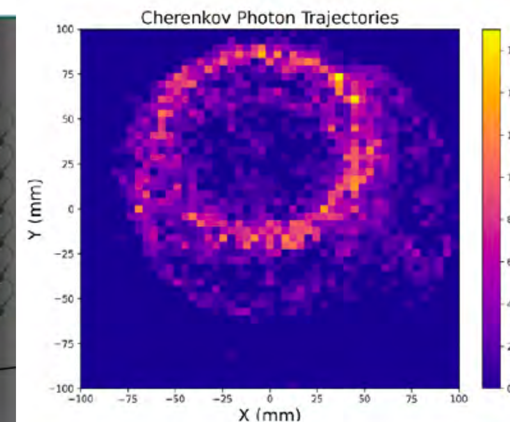
First neutrinos detected with an LAPPD!



NuDot:
LS + isotope for 2vbb event reconstruction
Ton scale
Highly intstrumented

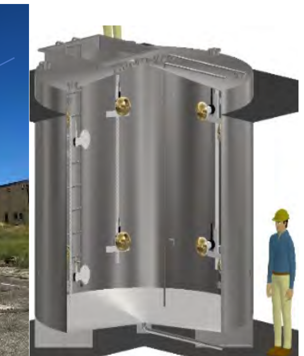
Eos: Low-energy event reconstruction and model validation





- 4-ton target mass
- 200 8-" PMTs
- Dichroicon deployment for spectral sorting
- Vertex, energy, direction, PID

BNL: 1- and 30-ton



- First ton-scale deployment
- Optical transparency in an operating detector
- Optical stability over time
- Recirculation of WbLS (nanofiltration)