Hunting dark matter and more with XENON

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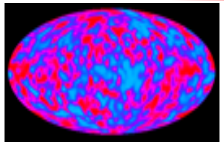
What are we looking for?



radiation: 0.005%

chemical elements:
(not H & He) 0.025%

stars:0.8%

H &He: gas 4%

ν_e, ν_μ, ν_τ

neutrinos = CνB: 0.17%

black holes: PBH or LBH

?

dark matter: 26.8%
one component/cocktail?

?

dark energy: 68.3%

Gravity		Particles	
Modified GR	**BHs**	**BSM physics motivated ←→ SM problems**	**Models with correct abundance**
MOND simple one scale modification → fails... **Other** is the EP fundamental or effective?	**today's BHs** a suitable population (mass, number) of primordial black holes	- neutrinos - WIMPs: ...neutralino ...other - axions - sterile ν's - ...	- WIMPs - dark photons - ALPs - other new particles
		thermal production (WIMP miracle, ...) non-thermal (decay, out-of-equilibrium, ...)	

→ **theory: both phenomenological & formal**

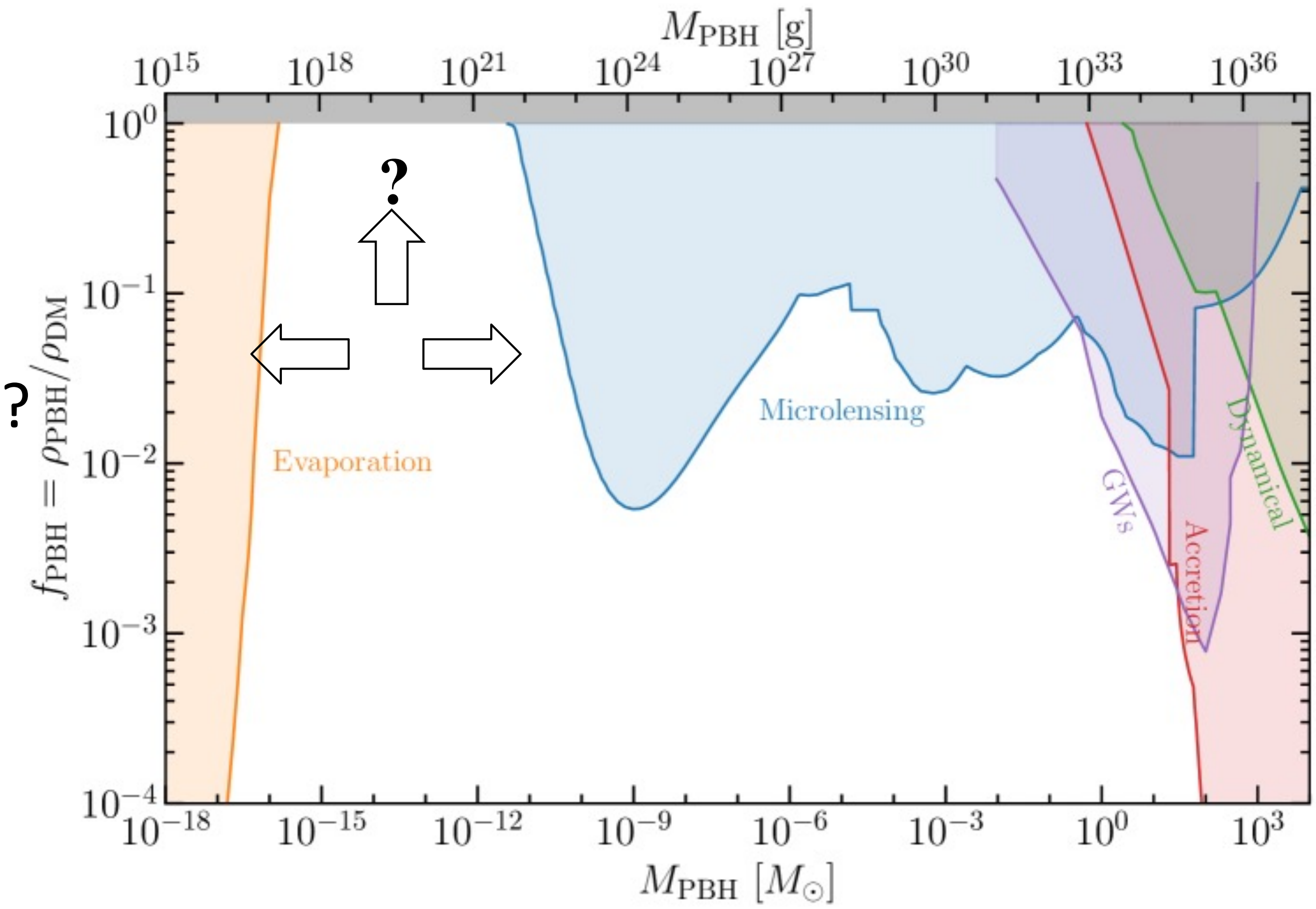
i) potential solutions ii) preferred candidates iii) exclusions

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

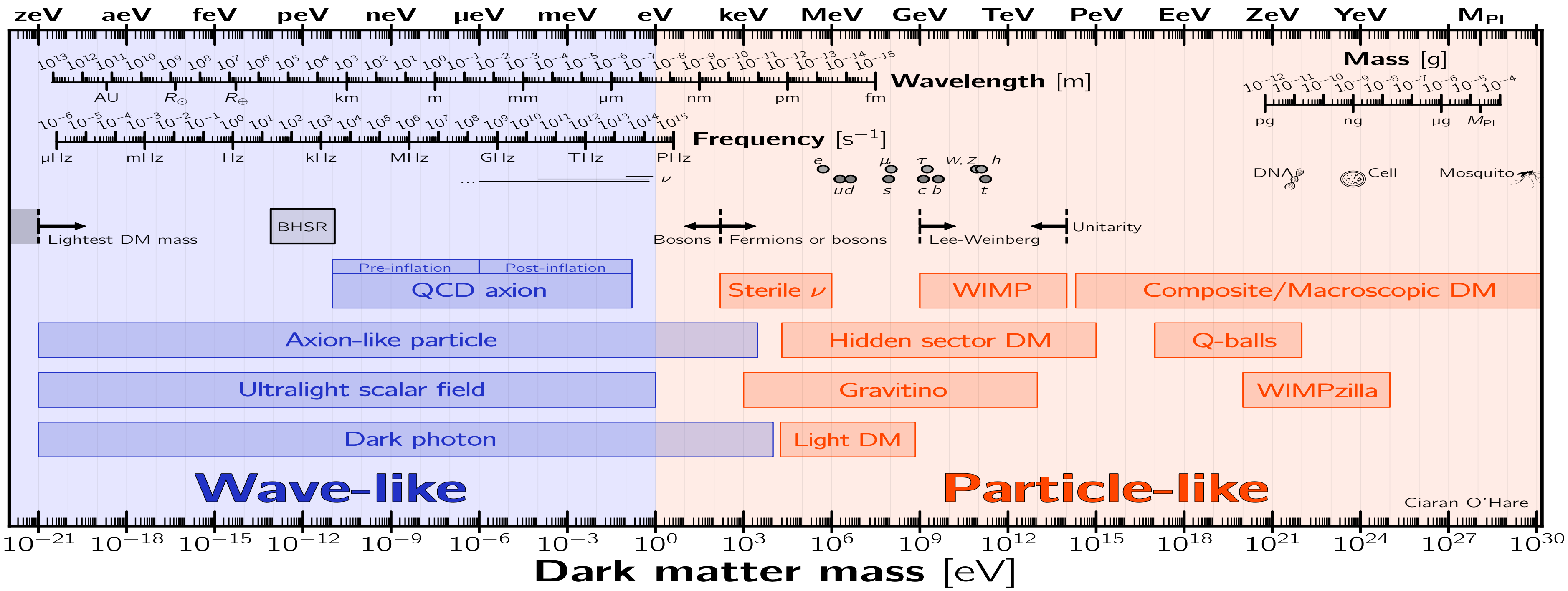
➔ which masses?
➔ evolution
➔ under/over density?

➔ 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?**

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

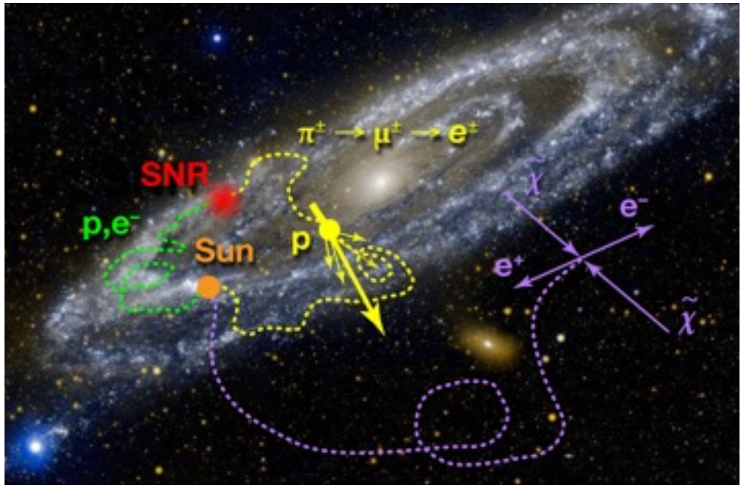
→ motivated by other facts / problems / realizability / ...

WIMPs, axions, sterile neutrinos, ...

(Heavy) Particle-Like DM Hunting

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

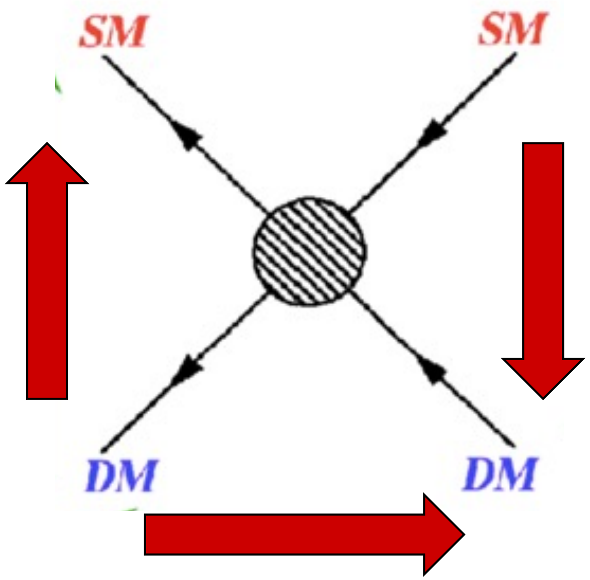
indirect detection



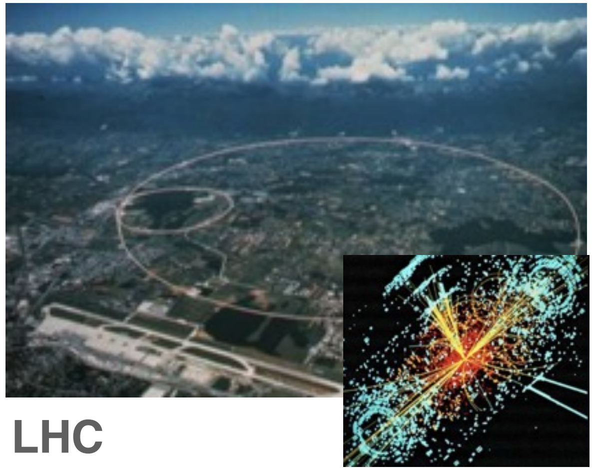
FERMI, PAMELA, AMS, HESS, IceCube, CTA, HAWC…

astronnomical uncertainties...

→ signal without doubt DM?



colliders



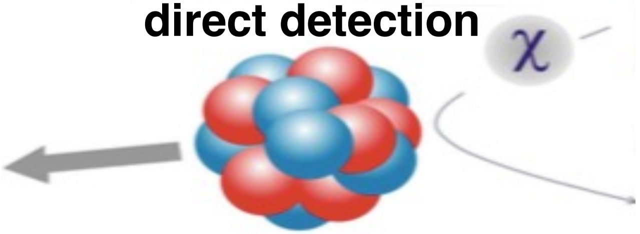
LHC

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

So far nothing seen…

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

direct detection



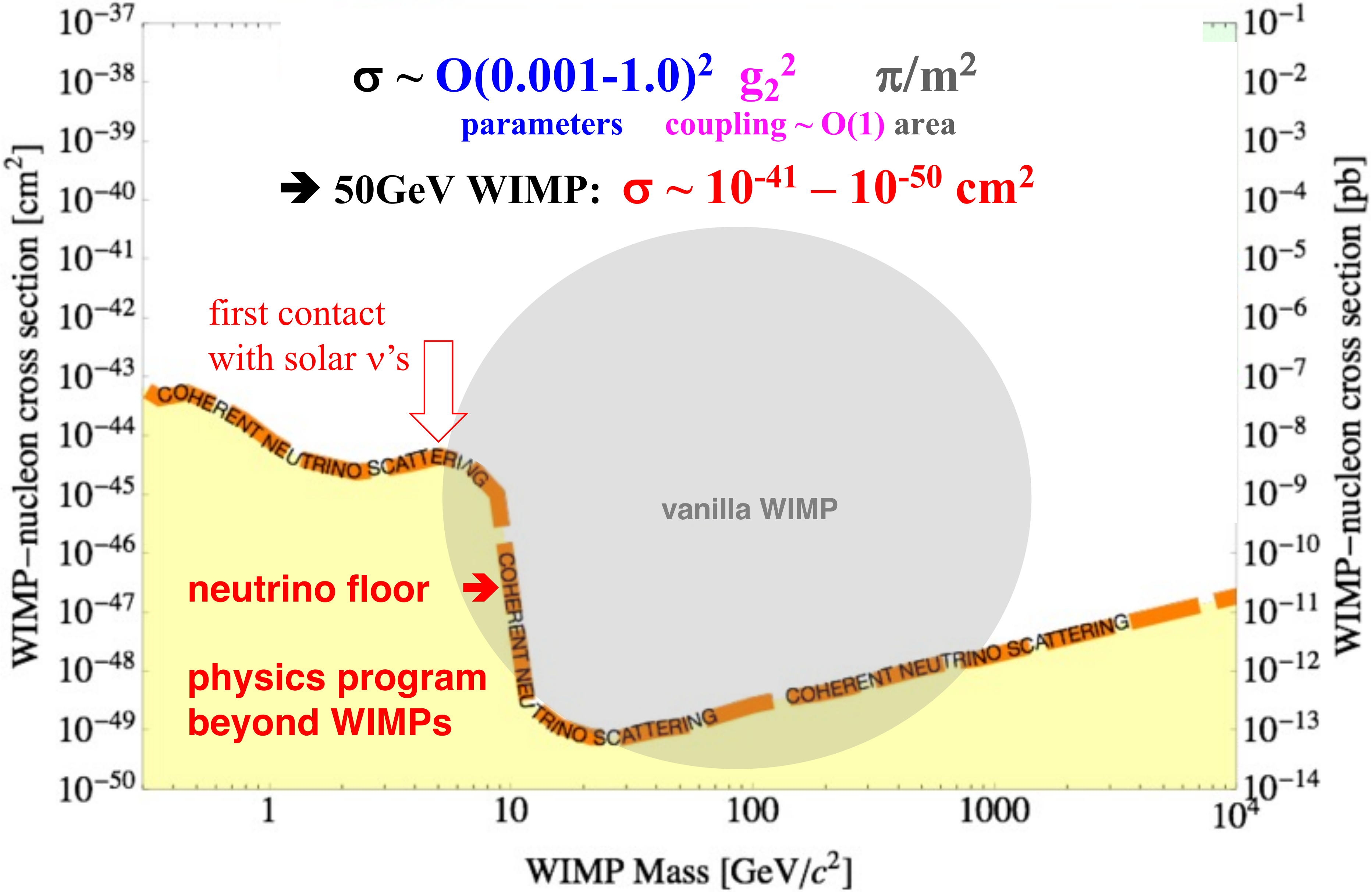
WIMP wind : ~232km/s from Cygnus

- → modelling
- → rare event backgrounds

→ direct detection!

WIMPs: The Vanilla Territory

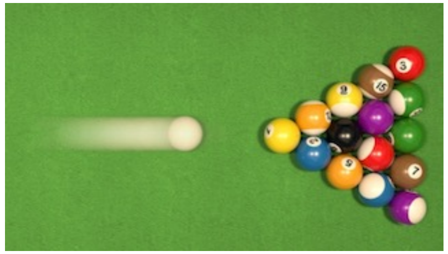
“size” of a particle: $\pi\lambda^2 = \pi/m^2$ ➔ σ = area ✖ coupling



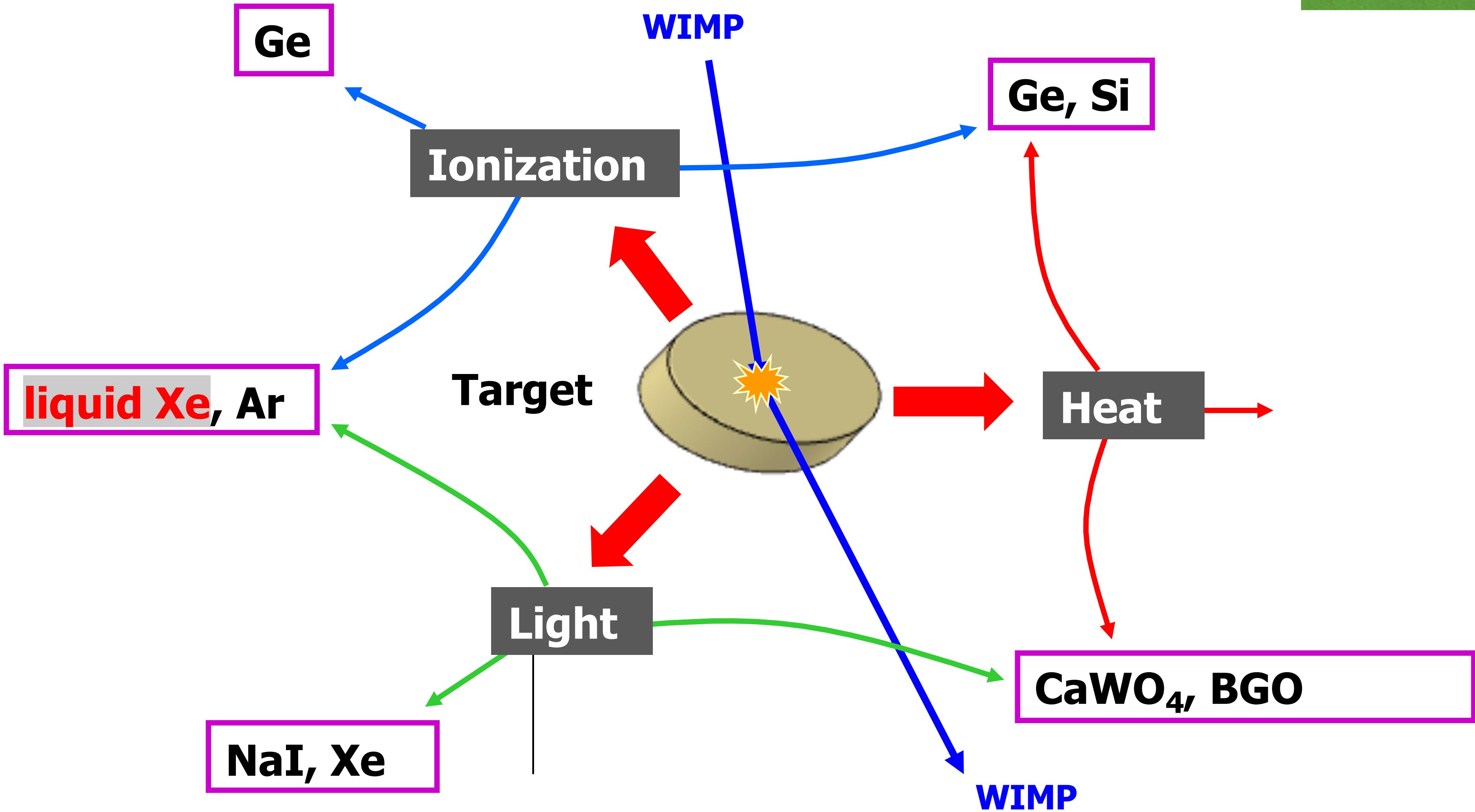
Direct Detection Techniques

- **Directly see what the Universe is made of**

~billard with invisible balls...



➔ **WIMP wind scatters on target atoms ➔signal**



➔ **challenge: increase signal and reduce background**

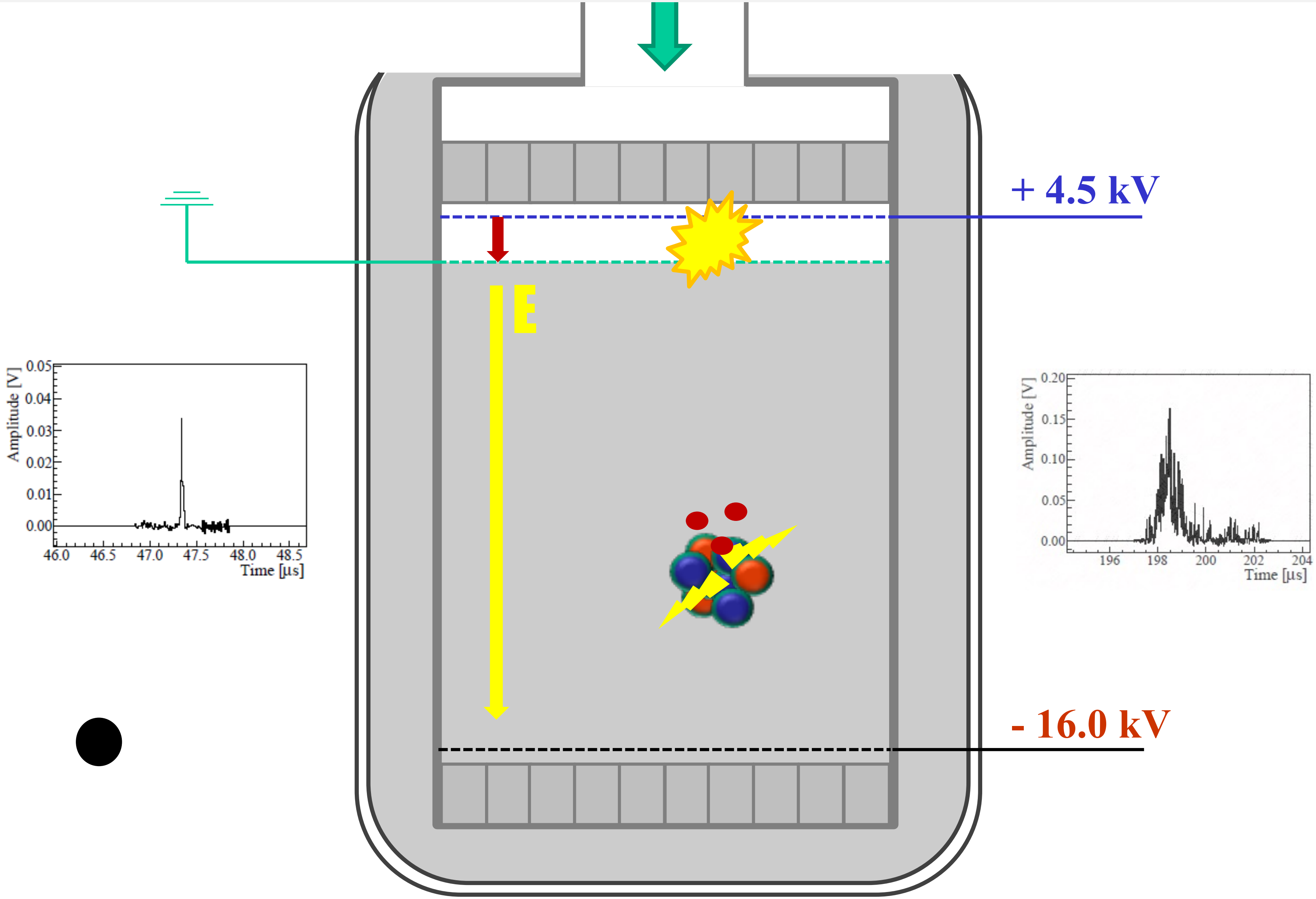
The XENON Collaboration

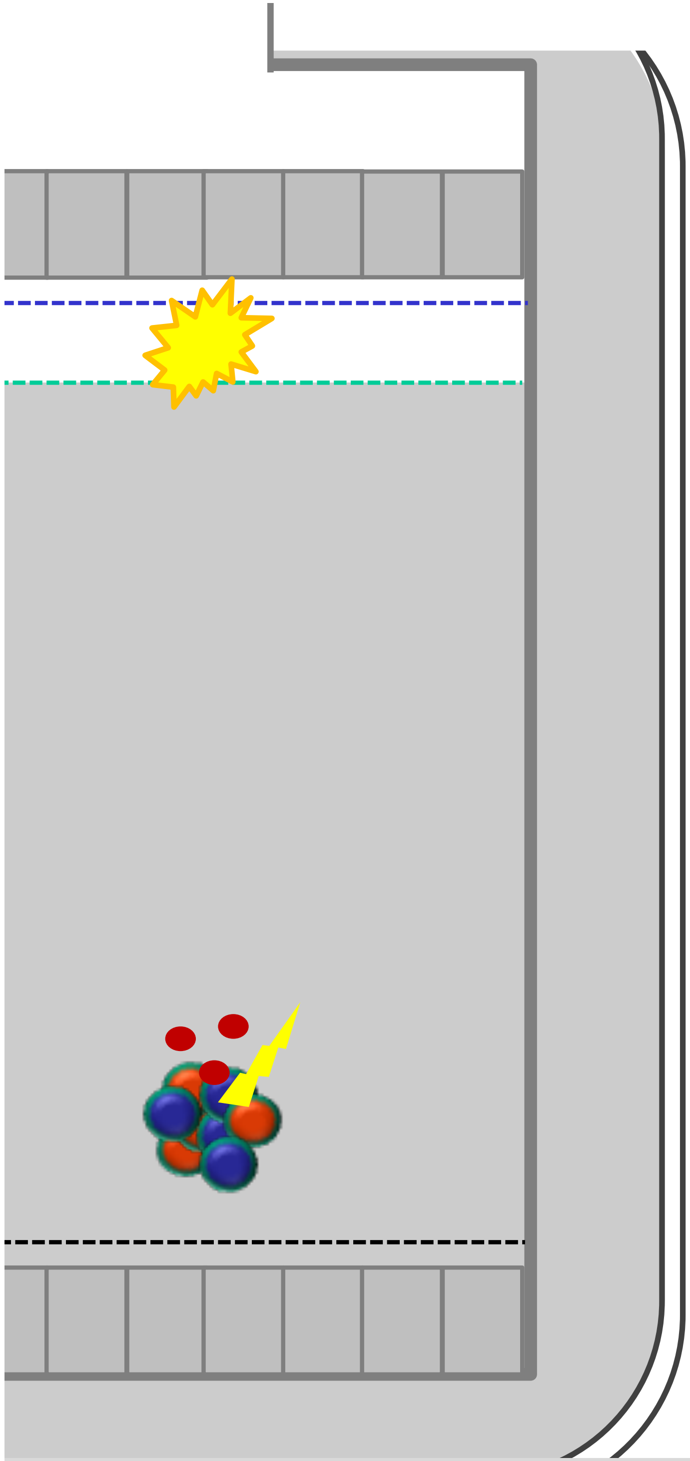
200+ members, 29 institutes, 12 countries

Very strong roles ←→ essential German contributions:

- Co-spokesperson, CB Chair, Analysis Coordinator, Several task group leaders

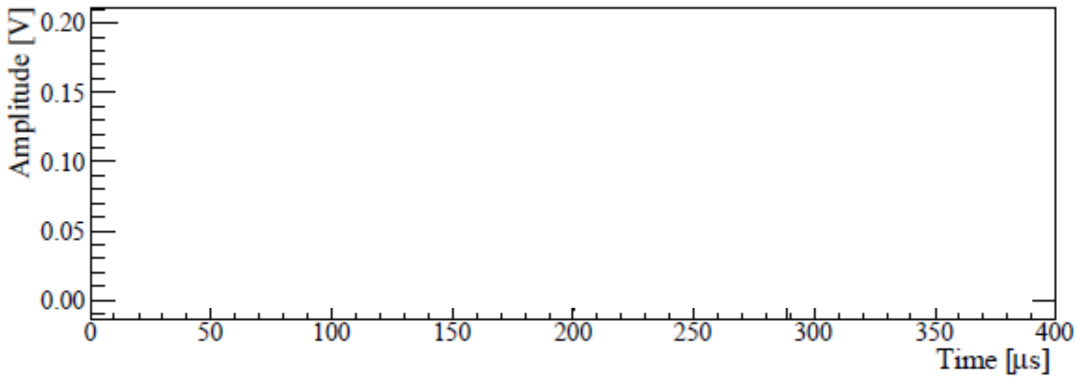
Powerful Device: Dual Phase LXe TPC





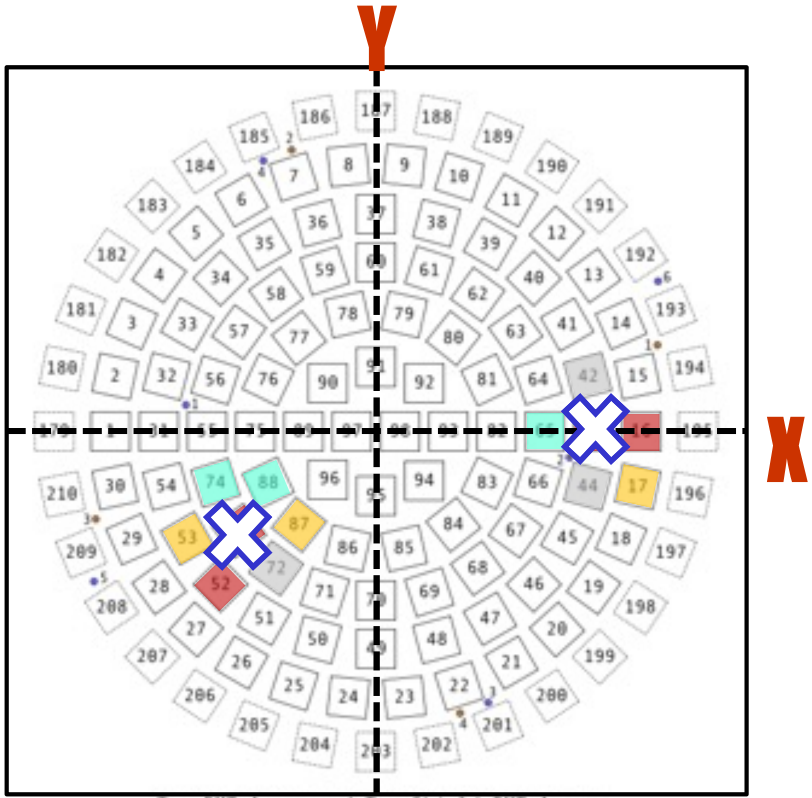
Rec

Slow motion

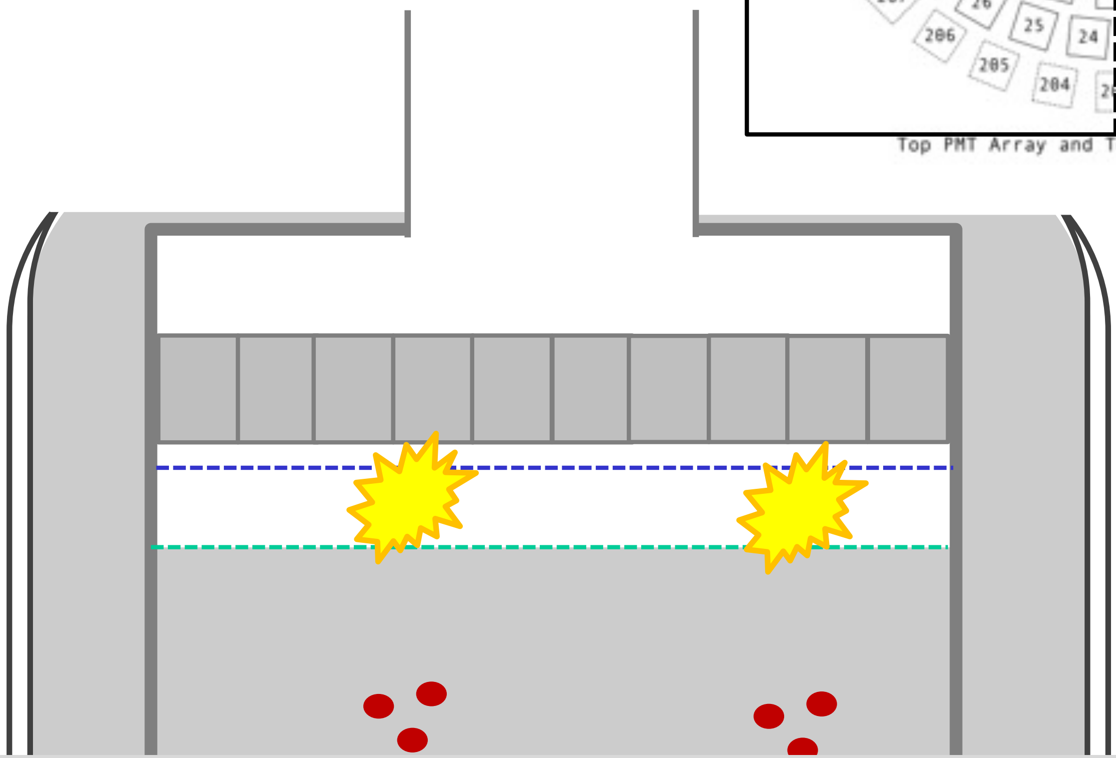


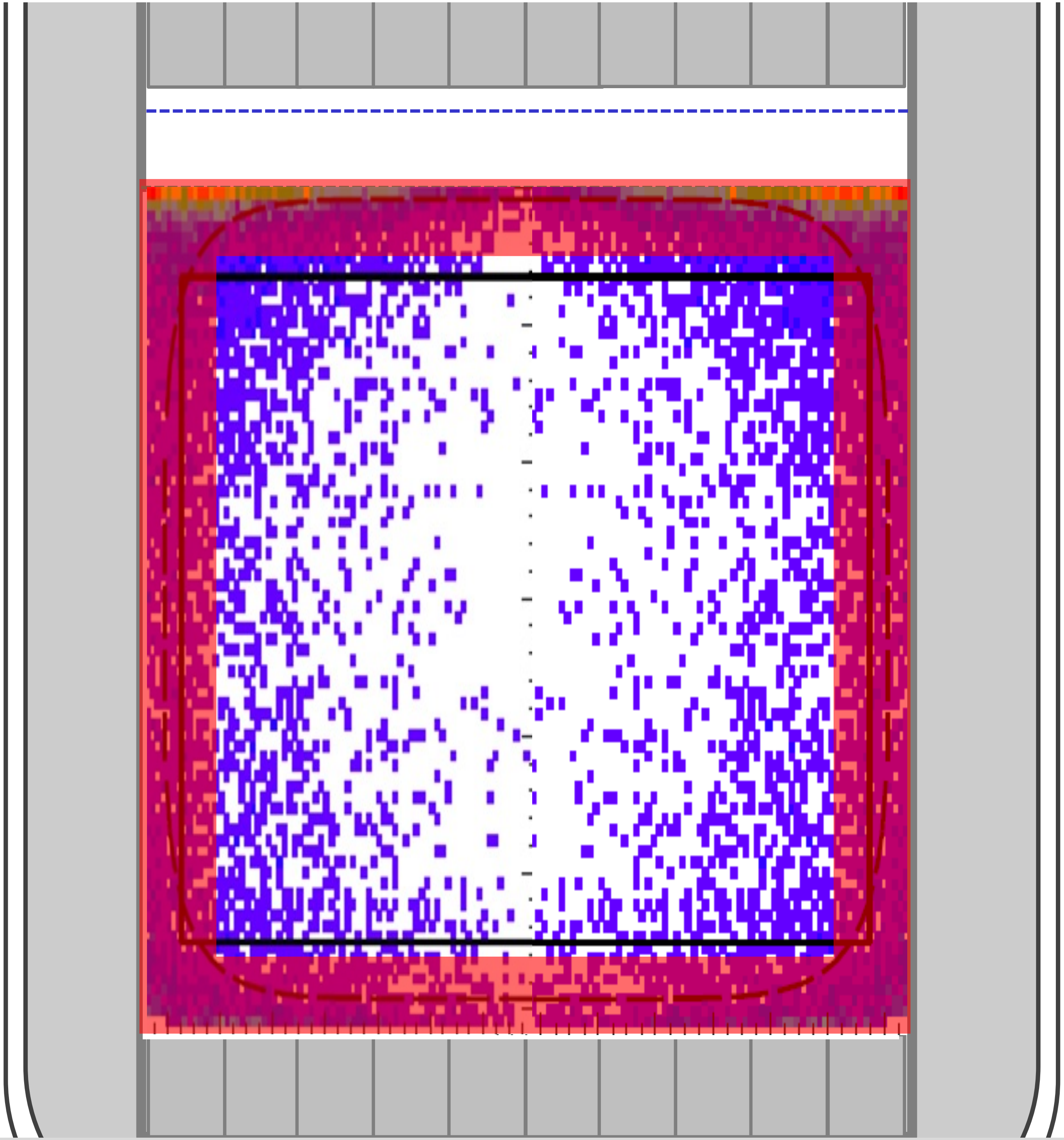
$$z(dt) = vDrift \cdot dt$$

$$vDrift \approx 1{,}74\ mm/\mu s$$



Top PMT Array and Top Shield PMT Array





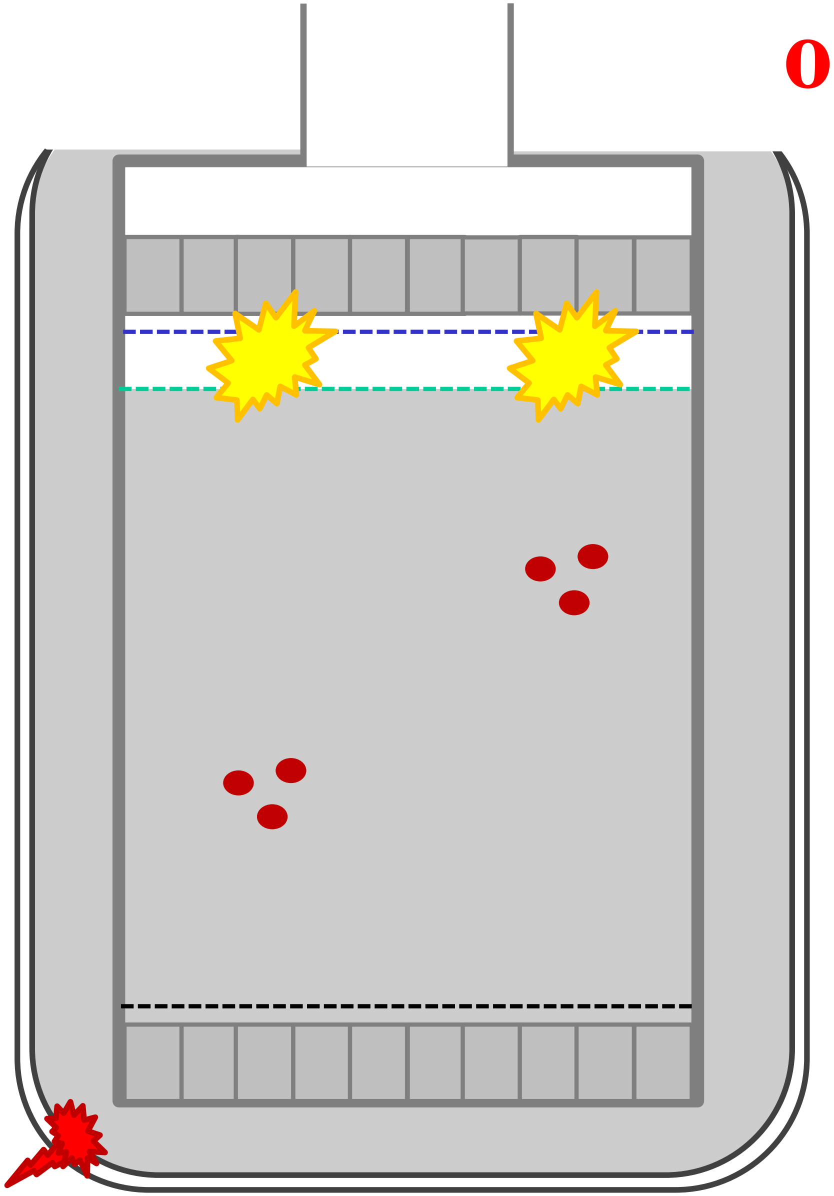
- **reconstruct x,y,z**

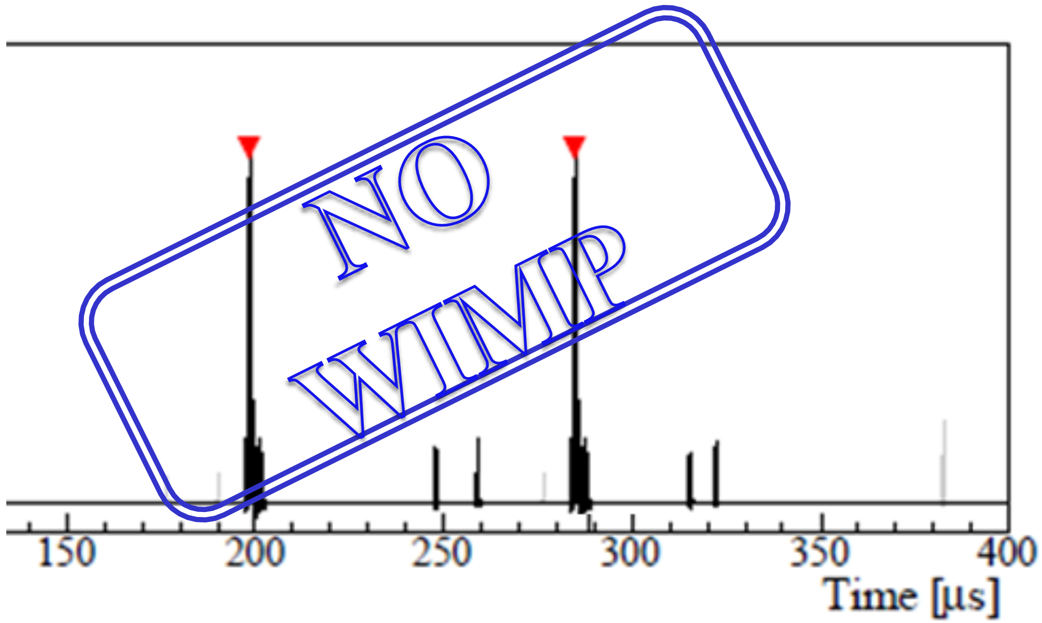
Next:
- **fiducialization**

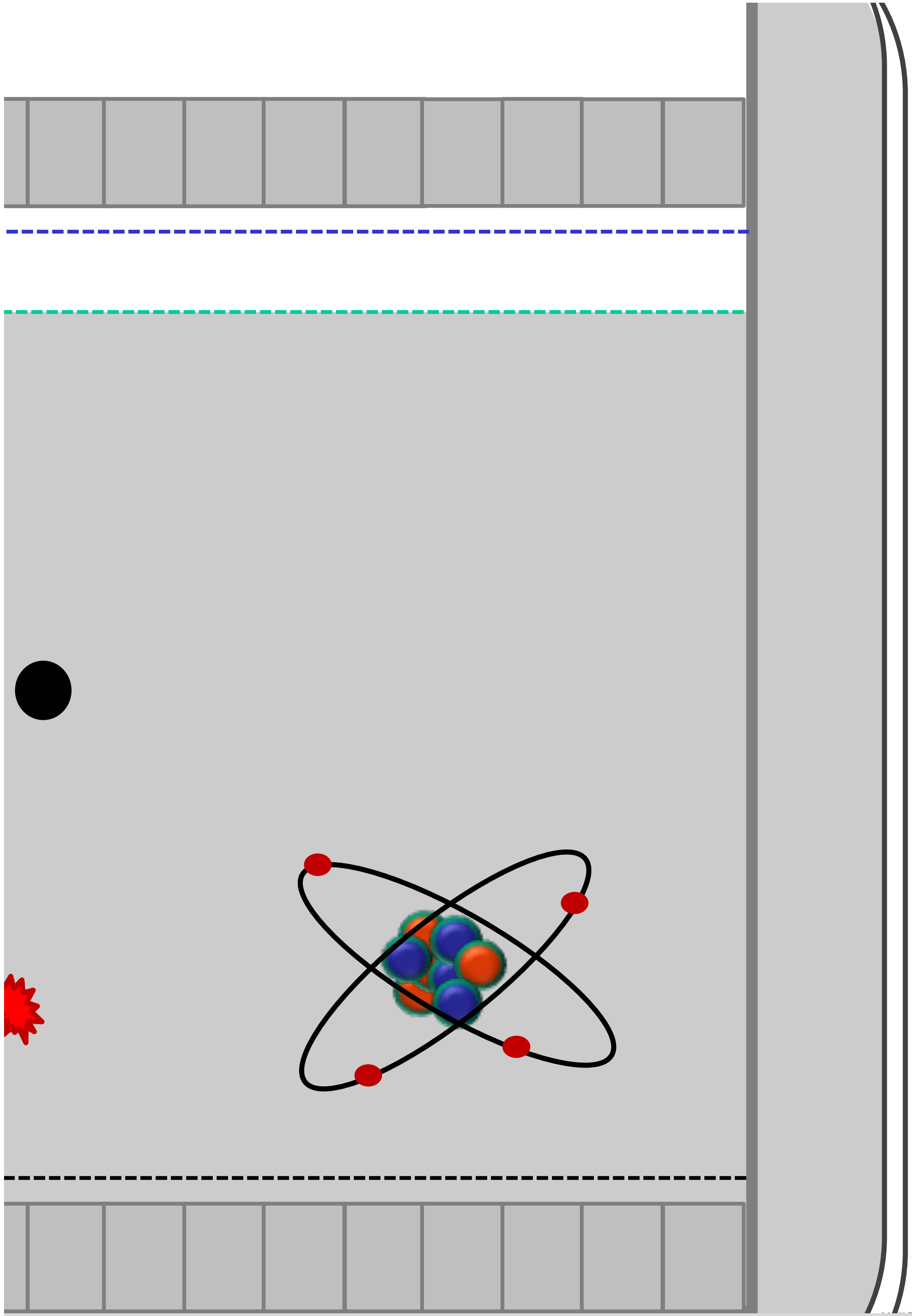
fixed before unblinding
→ optimal S/B
→ use bg knowledge

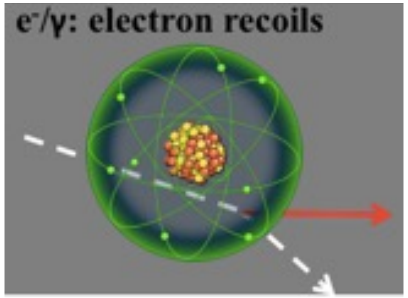
- **remove bg events**

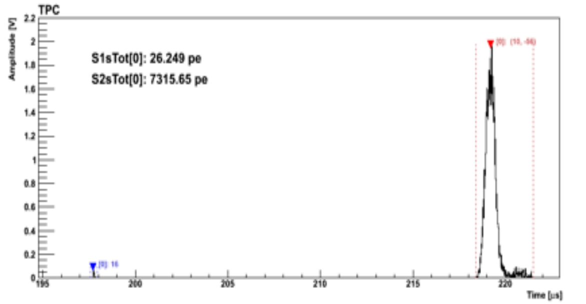
A WIMP scatters only once (if at all)

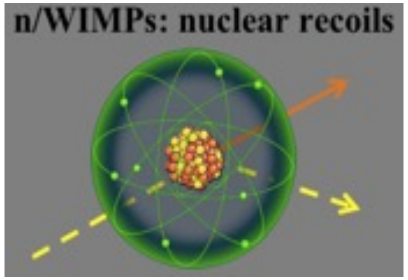


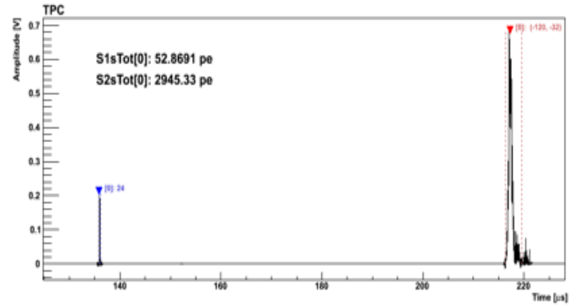








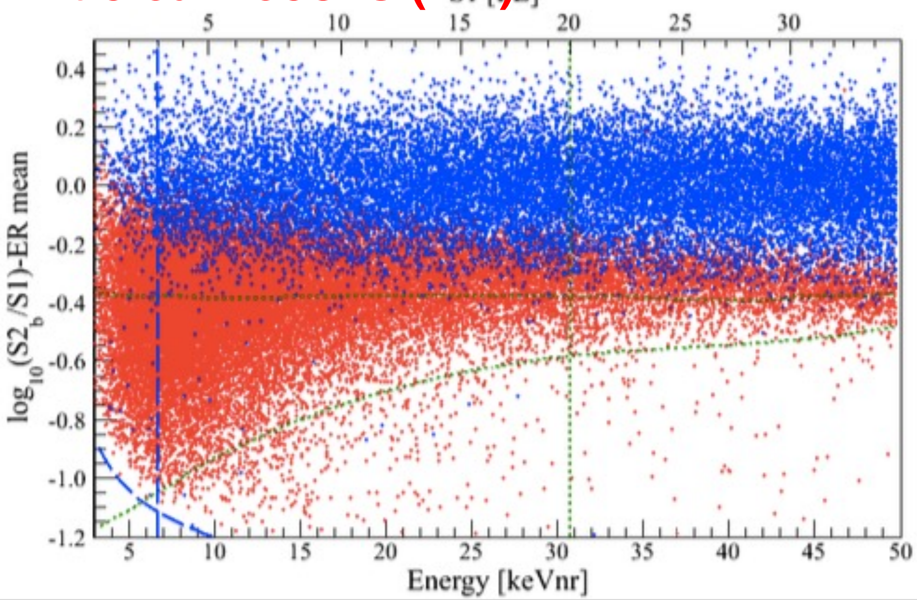




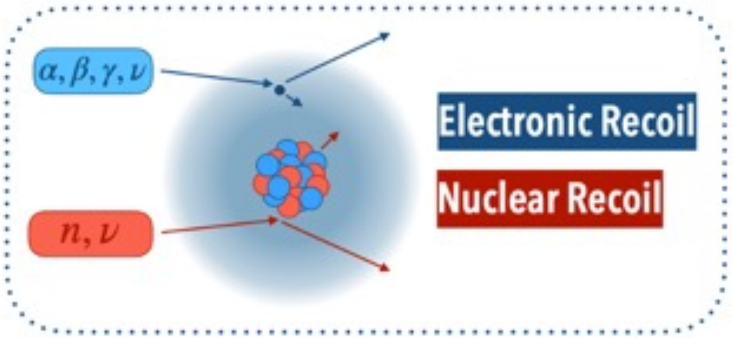
➔ **S2/S1 discrimination of ER / NR**

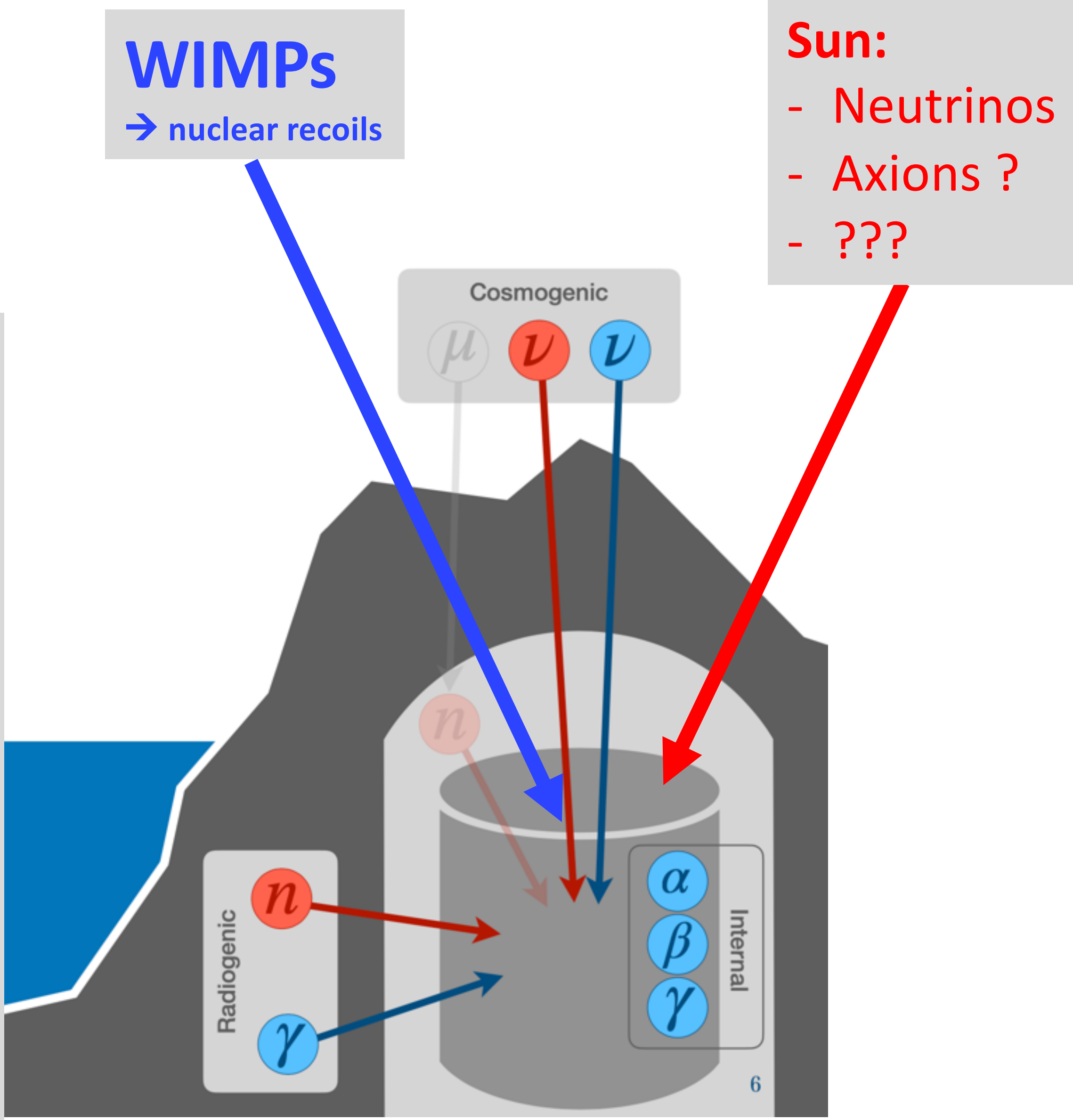
electronic recoils (ER)

nuclear recoils (NR)



Backgrounds





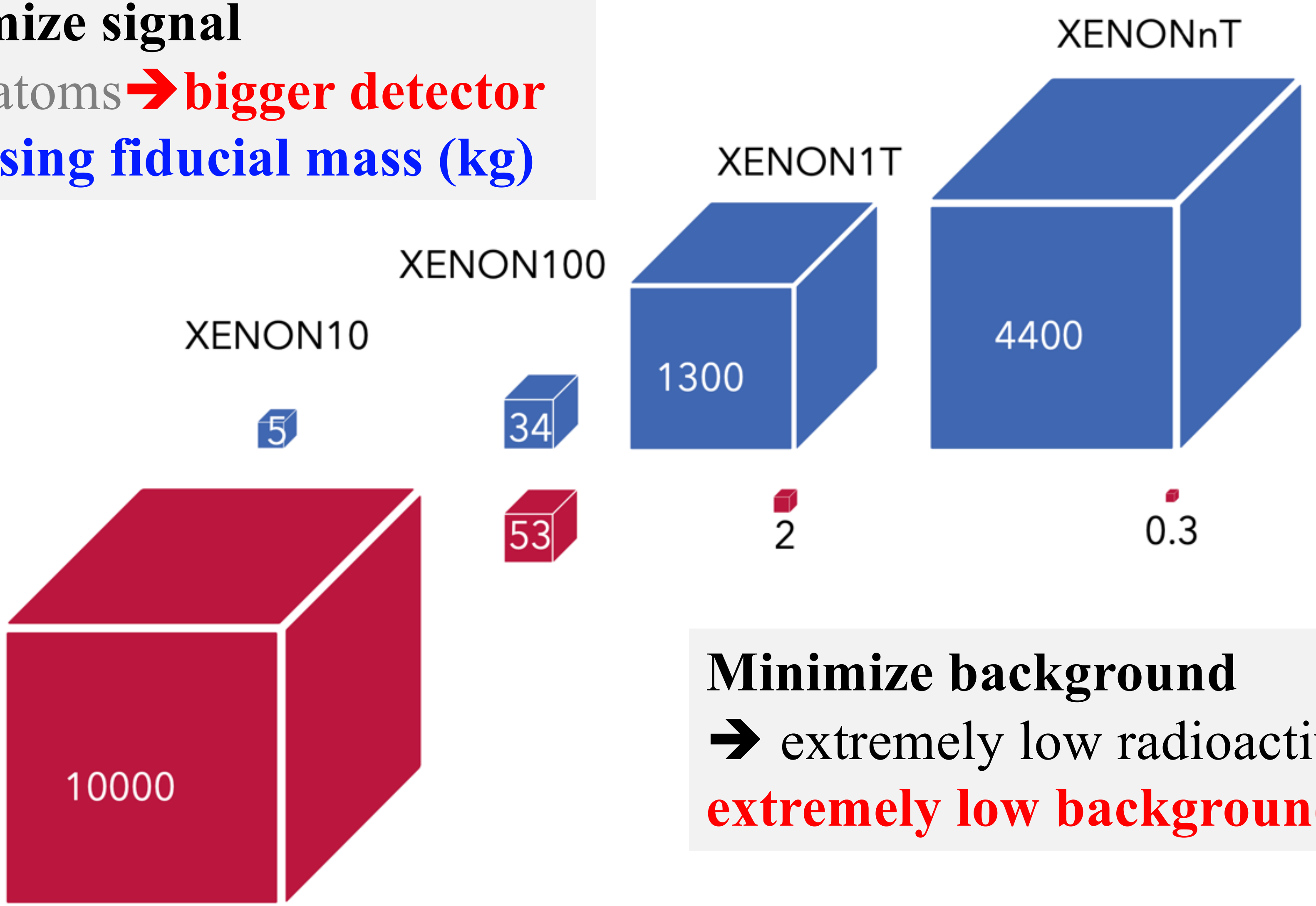
Background reduction

➔ extremely challenging:

- material selection
- screening (γ, Rn, …)
- graded shielding
  - go deeply underground
  - veto systems
  - water
- cryogenic distillation
- pulse shape analysis
- …

Evolution: Detector Mass and Background

Maximize signal
many atoms ➔ **bigger detector**
increasing fiducial mass (kg)



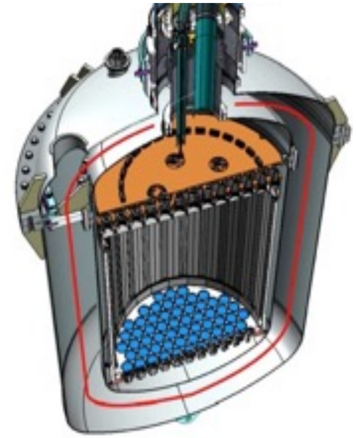
Minimize background
➔ extremely low radioactivity
extremely low backgrounds

~ normal environment

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

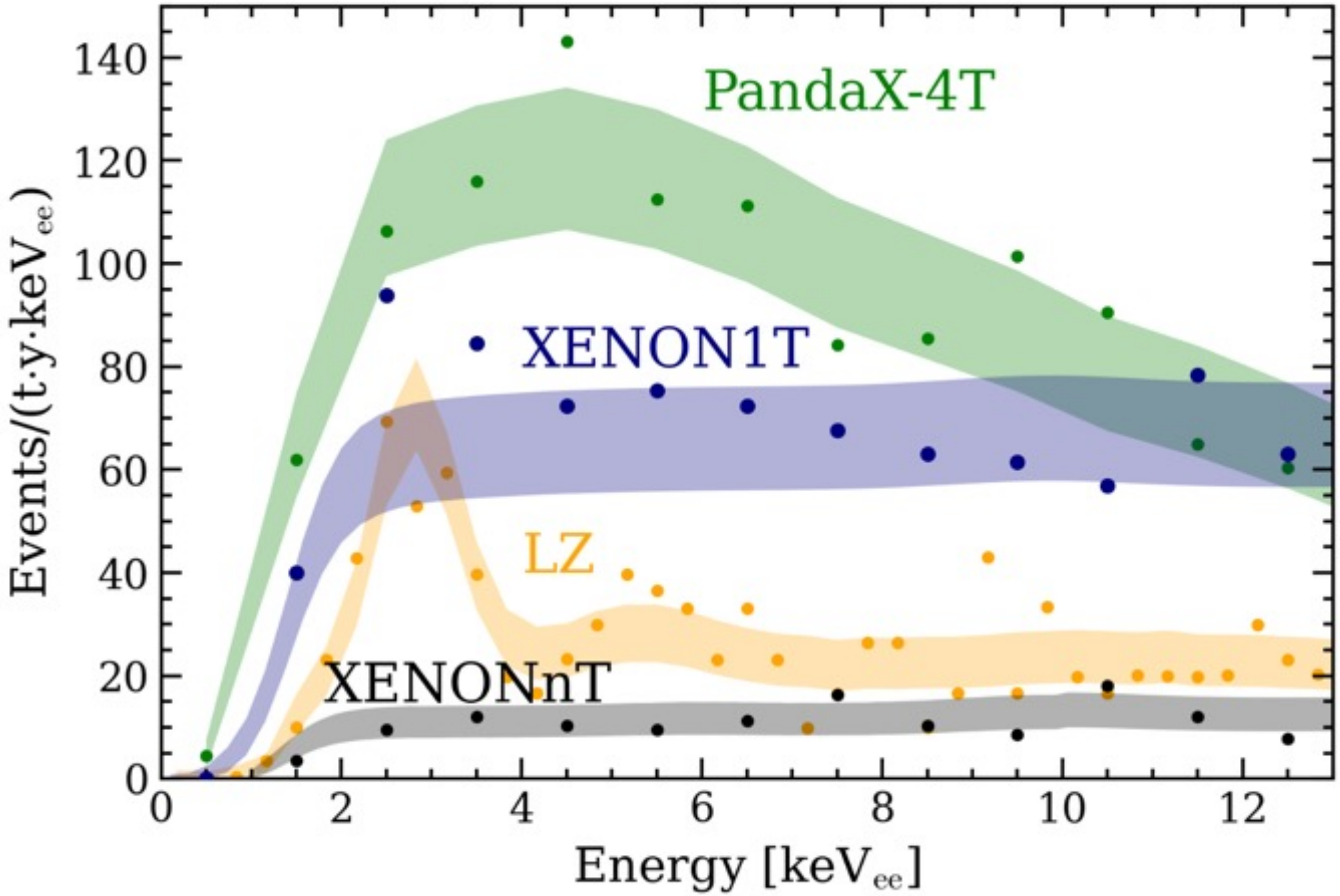
The XENON Dark Matter Program

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

XENONnT @ LNGS

Achieved Background Conditions



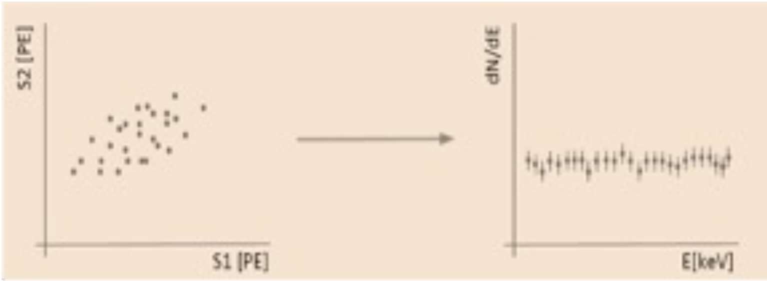
Achieved ultra low ER background ~16 events/(t × y × keV)

XENON1T and XENONnT results obtained **with blind analysis**

blind analysis is very important to avoid biases and mis-interpretation

Results: Electronic Recoils

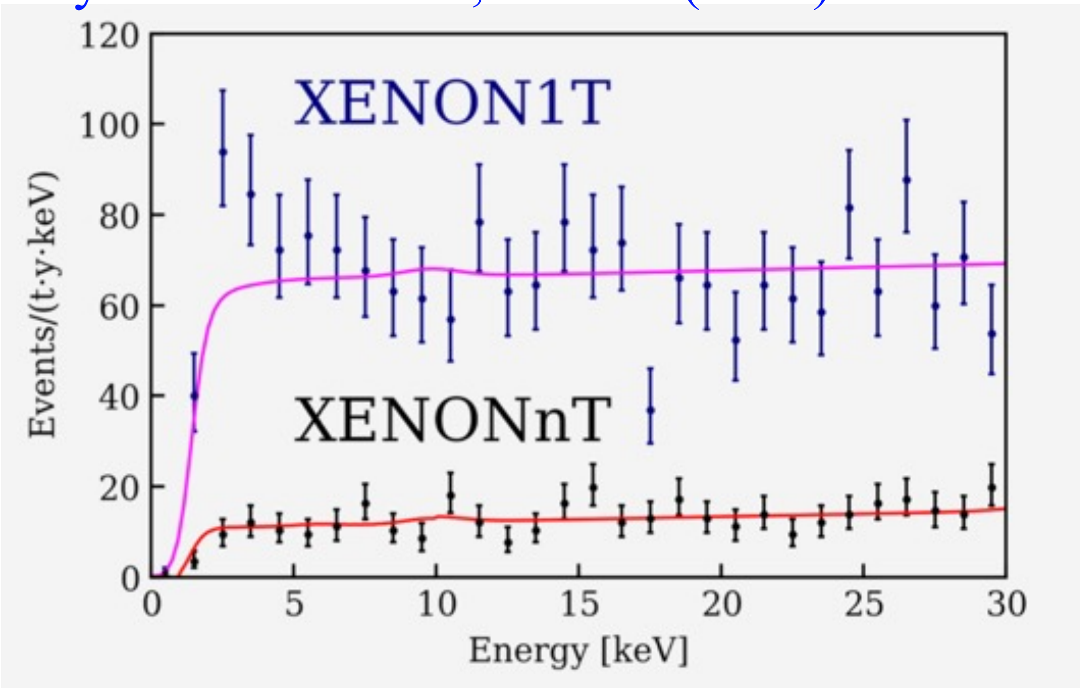
XENON1T: Electronic recoils energy reconstructed from S1 and S2 ➔ excess
Phys. Rev. D 102, 072004 (2020)

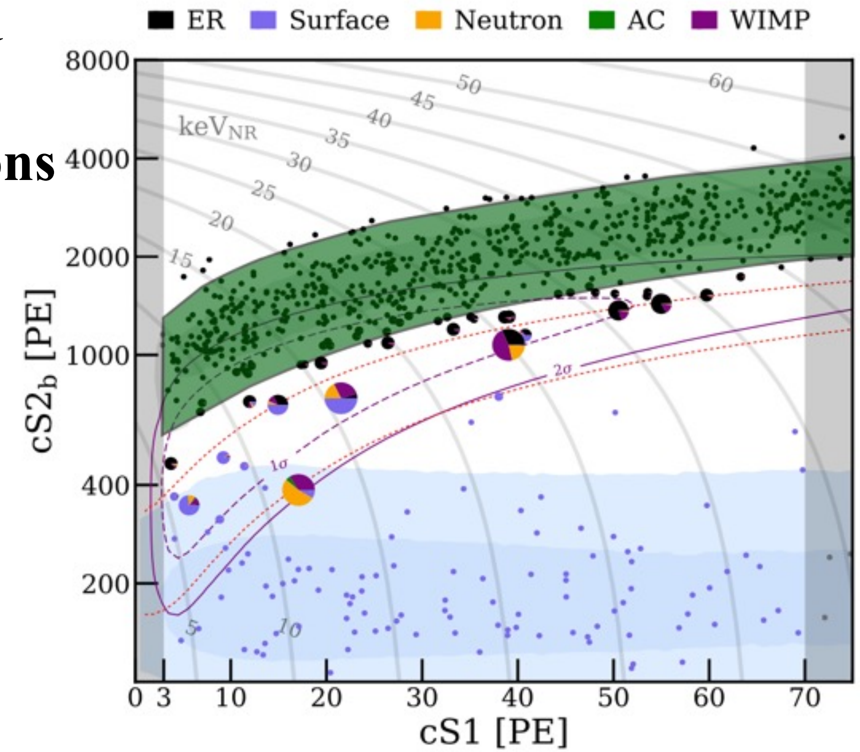


XENONnT: Unprecedented low background

15.8 ± 1.3 events / (t·y·keV)

No longer excess ➔ **excludes BSM explanations**
Phys. Rev. Lett. 129, 161805 (2022)





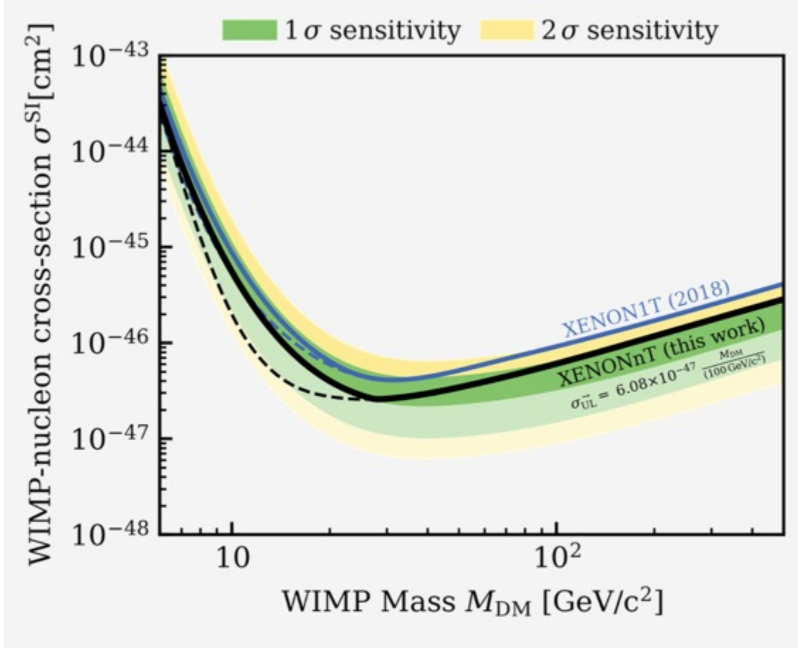
Limit on SI WIMP-Nucleon Cross Section

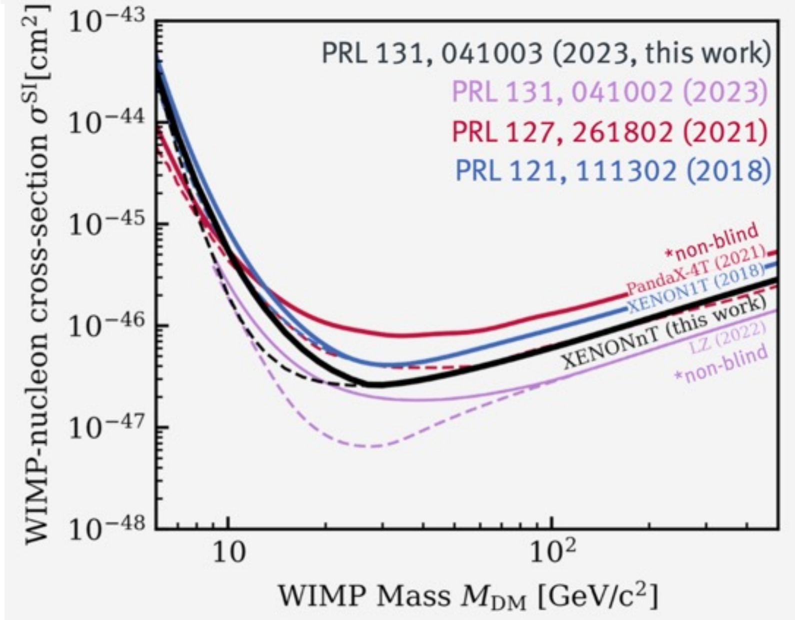
Results

- Limit: **2.6 · 10^{-47} cm^{2}** @WIMP mass 28 GeV
- Factor 1.6 improvement w.r.t. XENON1T
- **Phys. Rev. Lett. 131, 041003 (2023)**

Limit Setting

- Unbinned maximum likelihood
- Power constraint limits (PCL) to avoid spurious exclusion limits
- Only exclude the parameter space that the detector is sensitive to.
- Conservative choice at median of sensitivity band
- Differences needs to be discussed within the community

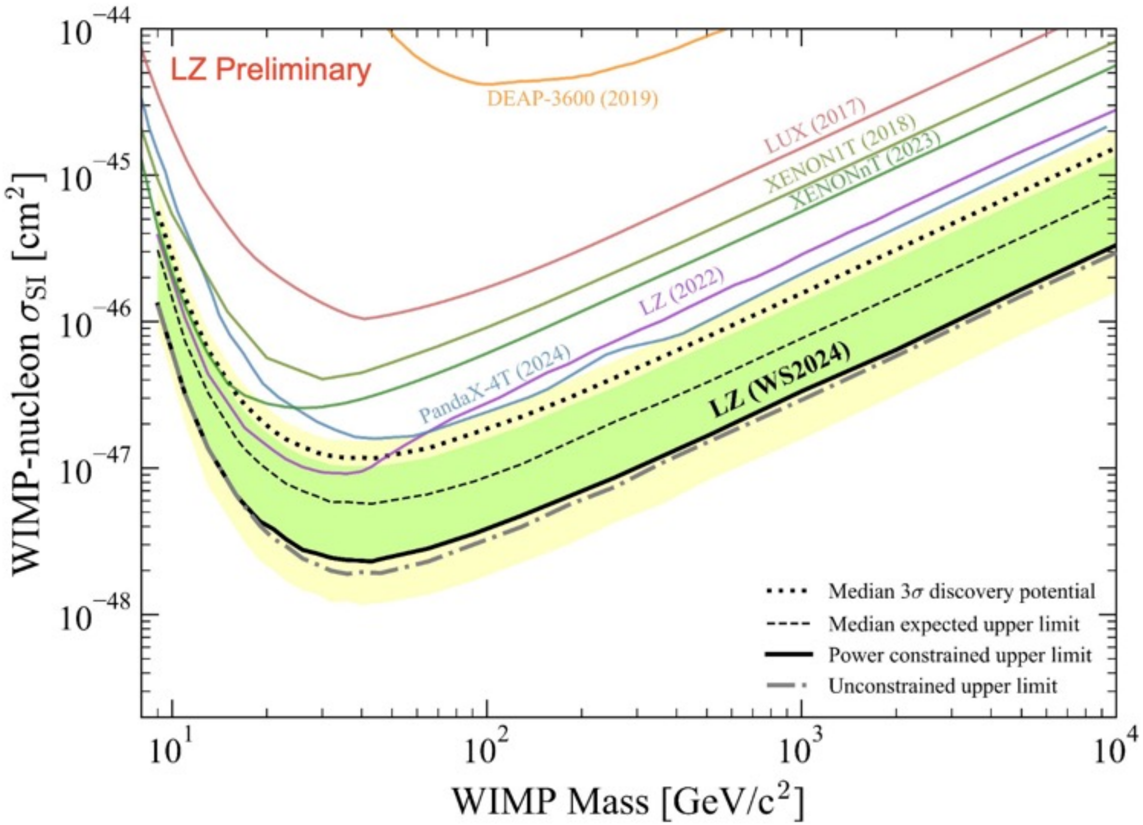




Recent Result from LZ

S. Haselschwardt, TeVPA 2024, August 26, 2024

- Frequentist, 2-sided profile likelihood ratio test statistic
- Upper limit is power constrained @ -1σ sensitivity band per DM conventions: *EPJC* **81** 907 (2021)
- Under fluctuation results from observed arrangement of accidental events in WIMP region
- **WS2024-only min cross section: σ_{SI}= 2.3 x 10^{-48} cm^2 @ 43 GeV/c^2**



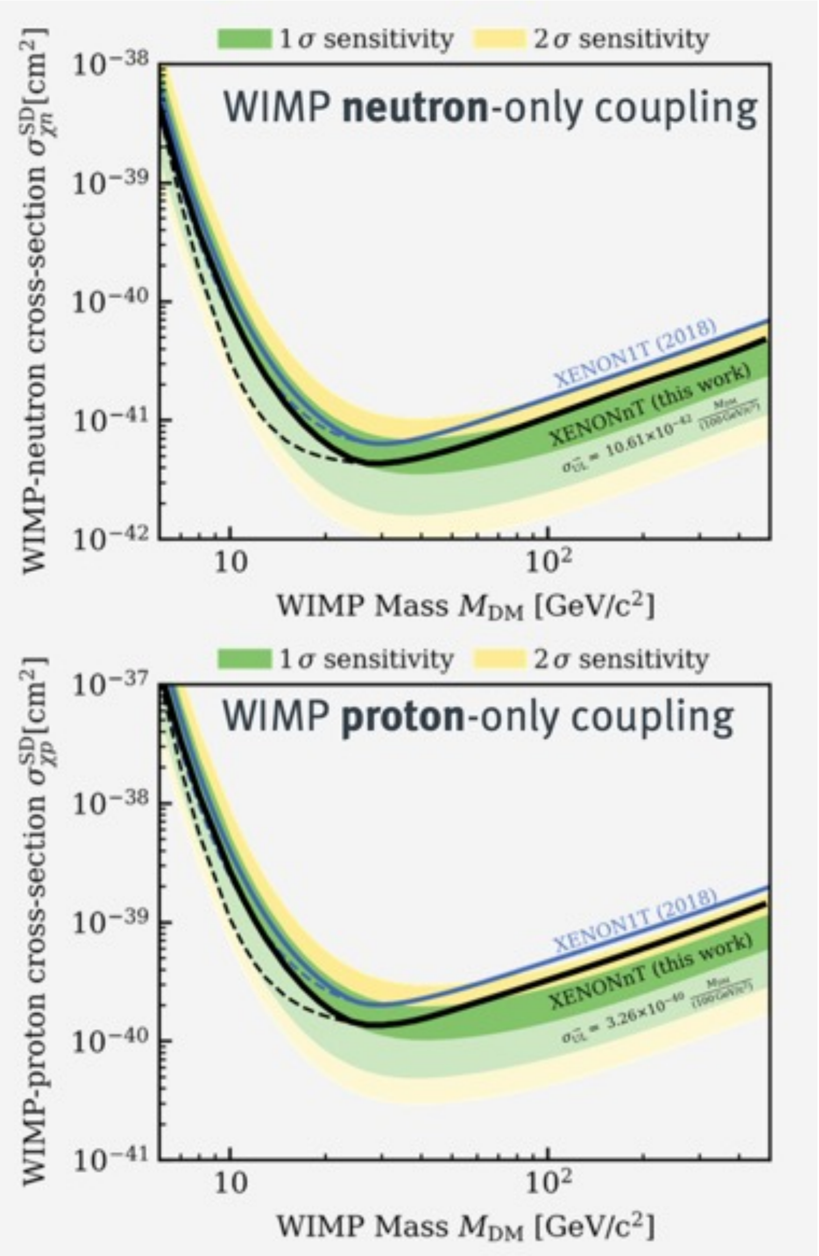
➔ ...wait and see (soon) results from on-going analysis of SR2 of XENONnT

Limit on SD WIMP-Nucleon Cross Section

Phys. Rev. Lett. 131, 041003 (2023)

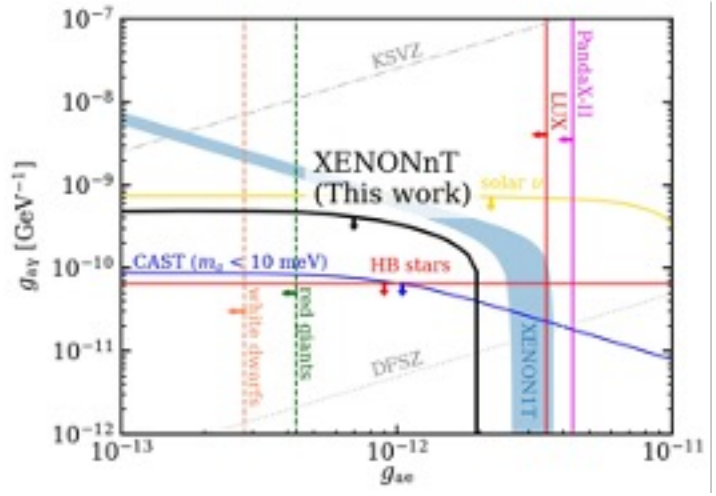
Limit Setting

- Unbinned maximum likelihood
- Power constraint limits (PCL) to avoid spurious exclusion limits
- Only exclude the parameter space that the detector is sensitive to.
- Conservative choice at median of sensitivity band
- Comparison needs discussions within the community



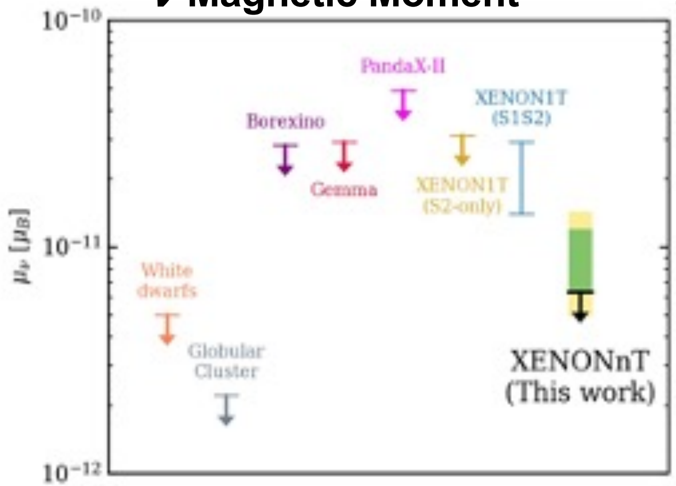
XENONnT Limits on New Physics

Solar Axions



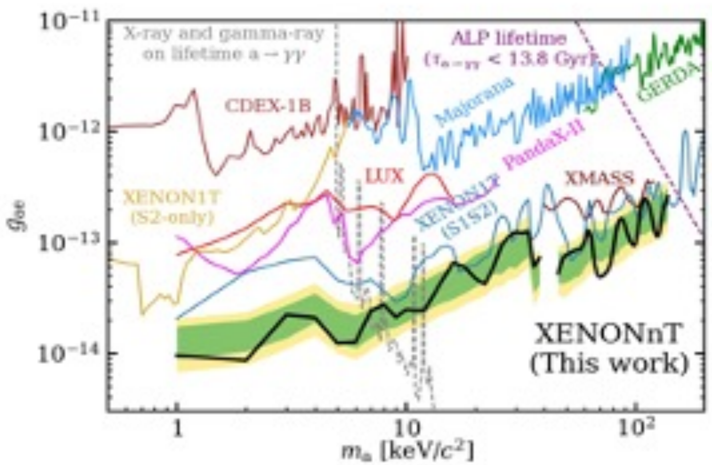
Limit on 14.4 keV peak for ^{57}Fe solar axions is < 20 events/(t*y)

ν Magnetic Moment

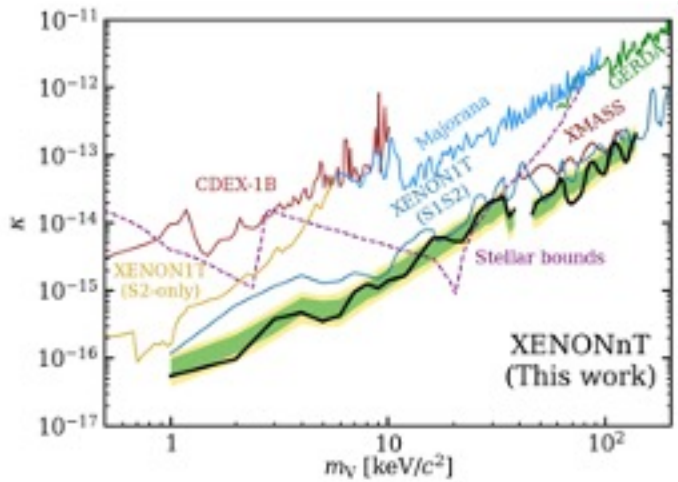


μ_ν < 6.3 10^{-12} μ_B, most stringent DD imit

Axion-like particles



Dark Photon

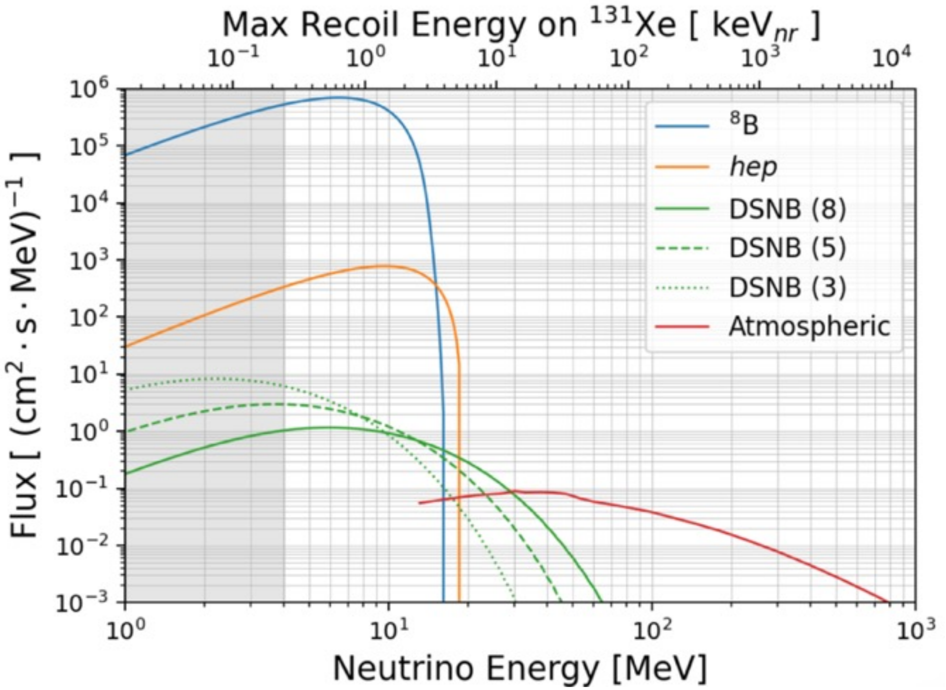


Phys.Rev.Lett. 129 (2022) 16, 161805

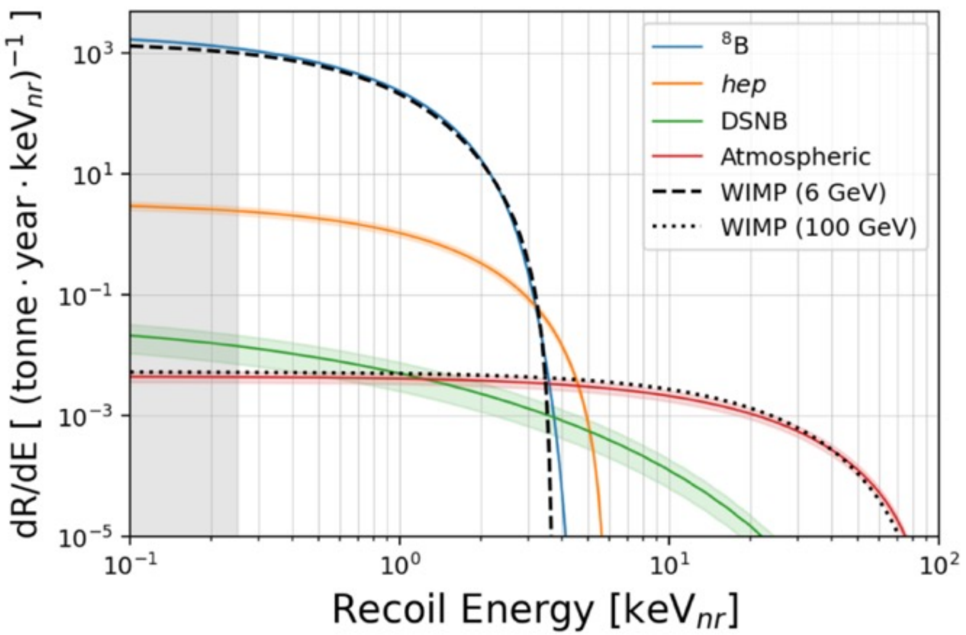
Nuclear Recoils from solar Neutrinos: CEvNS

CEvNS: Coherent Elastic Neutrino Nucleus Scattering

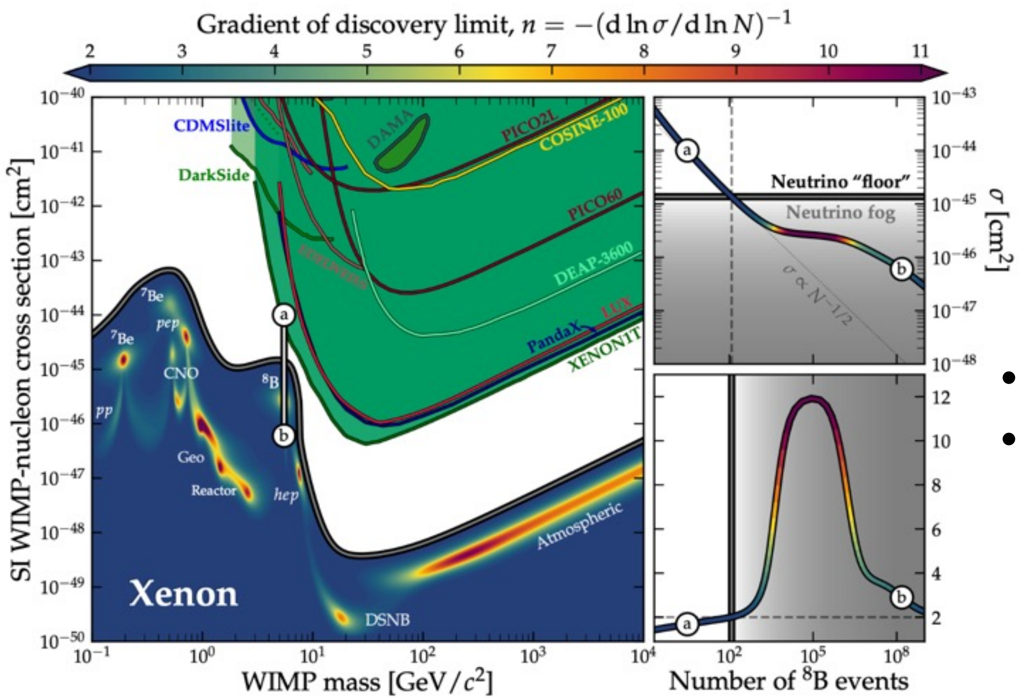
→ large flux - predominantly ^8B
→ (relatively) large x-section:
$\sigma \propto N^2 \simeq 6000$



Phys. Rev. D 108, 022007



→ low momentum transfer
→ small recoil energies
→ mimics nuclear recoil signals from WIMPs
→ ν's can become dominant BG



O'Hare, Phys. Rev. Lett. 127, 251802

➔ entering the solar neutrino signal

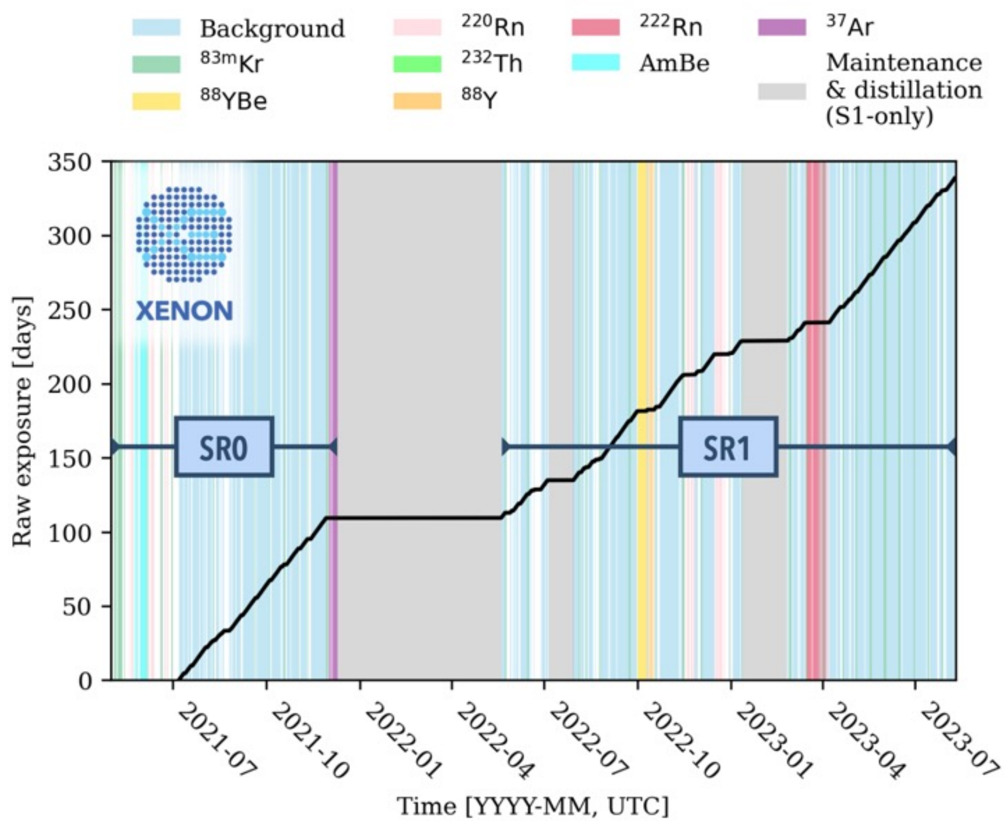
- **background for WIMP search @ca. 6 GeV**
- **signal of low energy CEvNS & solar ^{8}B ν's**

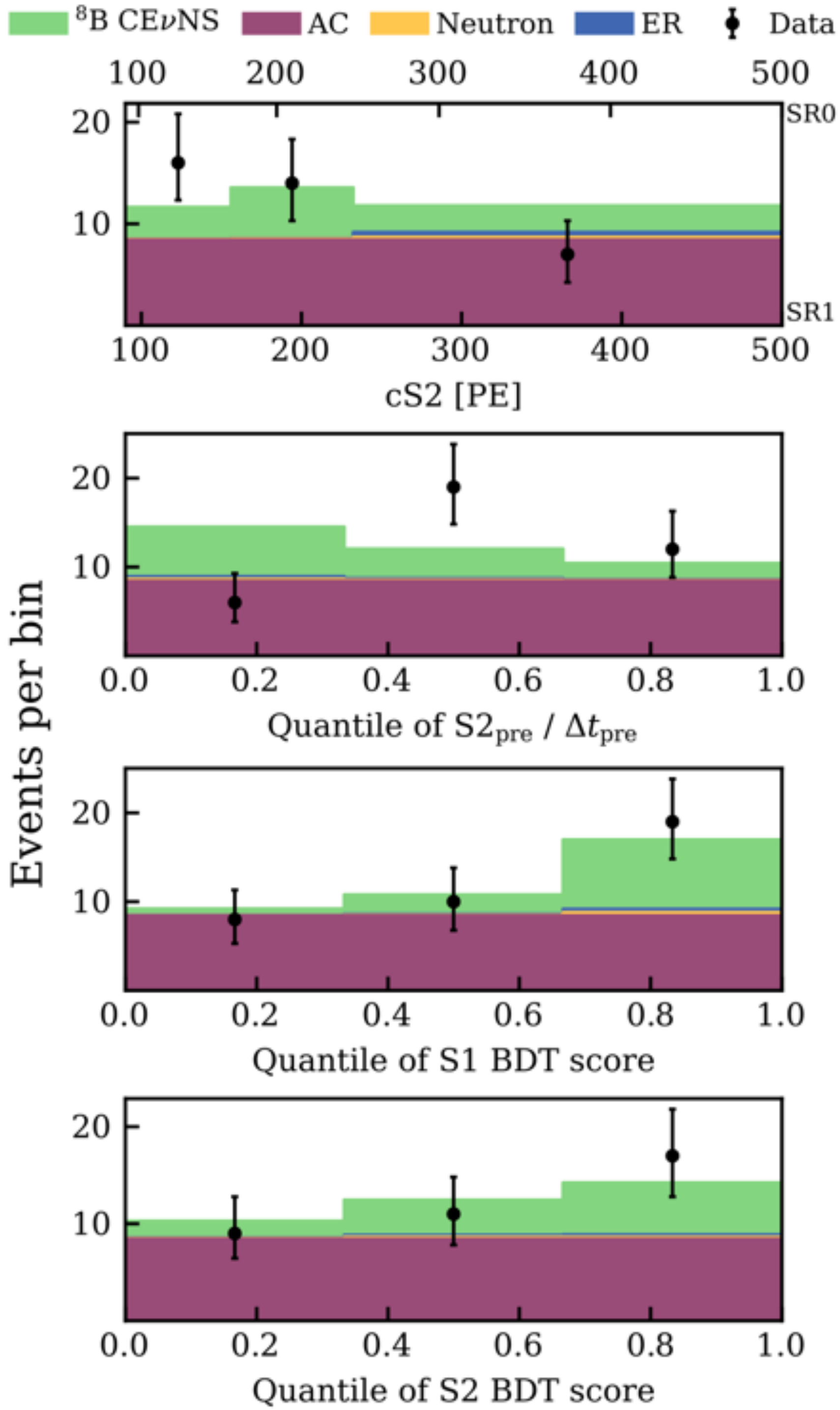
combine first science runs (SR0,SR1)

➔ 108.0 d (SR0) + 208.5 d (SR1)

- fiducial mass: ~4 t
- exposure: 3.5 t x yr
- good stability of the detector

➔ perform a blind analysis





🡐 best-fit signal, background and data in the projected analysis dimensions, summing SR0+SR1

Component	Expectation	Best-fit
AC (SR0)	7.5 ± 0.7	7.4 ± 0.7
AC (SR1)	17.8 ± 1.0	17.9 ± 1.0
ER	0.7 ± 0.7	$0.5^{+0.7}_{-0.6}$
Neutron	$0.5^{+0.2}_{-0.3}$	0.5 ± 0.3
Total background	$26.4^{+1.4}_{-1.3}$	26.3 ± 1.4
^{8}B	$11.9^{+4.5}_{-4.2}$	$10.7^{+3.7}_{-4.2}$

Observed: 37 events → 2.73 σ

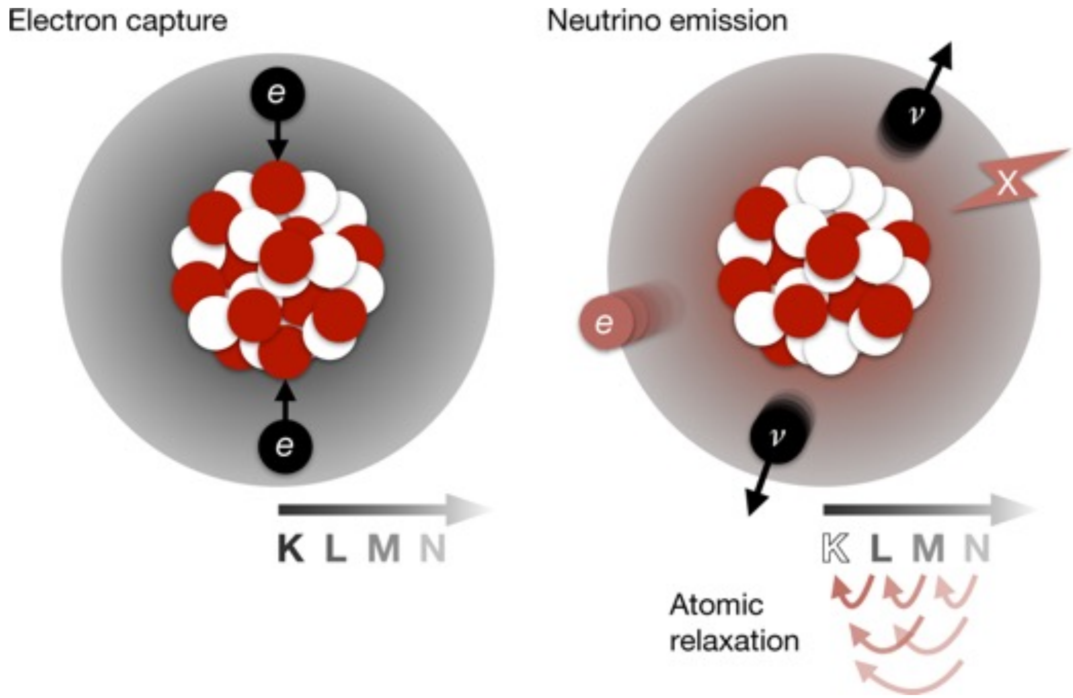
→ ^{8}B neutrinos measured before (SNO)

→ more: SR2 – being analyzed...

→ WIMP Limits @ ca. 6GeV....

arXiv: 2408.02877, to appear in PRL

Double Electron Capture of ^{124}Xe



Second order weak effekt

T = $1.8 \pm 0.5_{stat} \pm 0.1_{sys} \times 10^{22}\ yr$

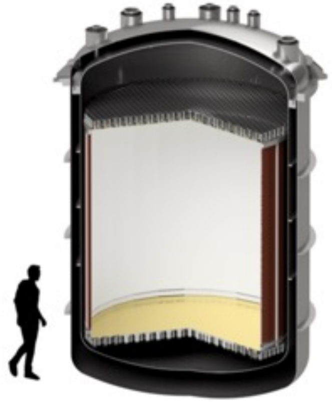
No rejection significane: 4.4σ

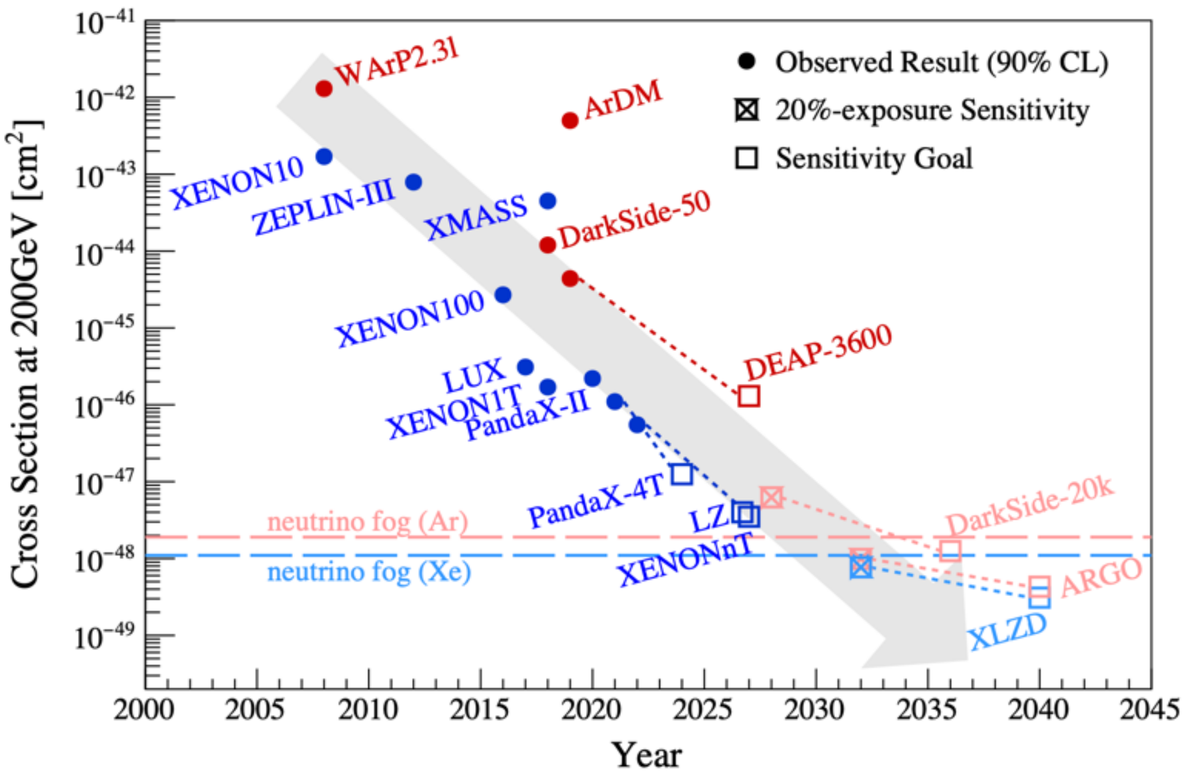
➔ **about one trillion times the age of the Universe**

➔ **longest half-life ever measured directly**

Nature 568 (2019) 7753, 532-535

Future: DARWIN → XLZD





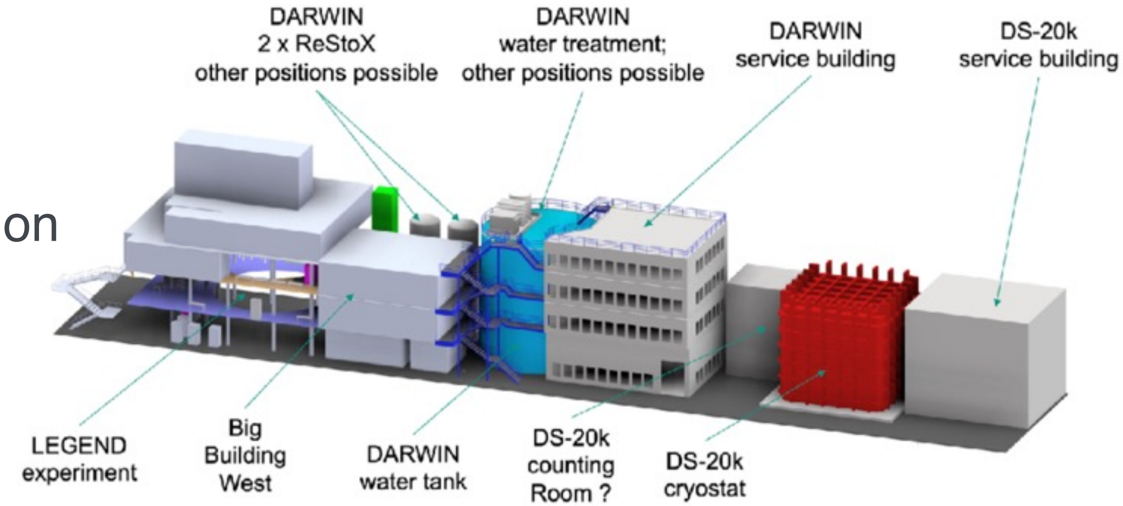
mass: 75 t Lxe (60t)
drift length ca. 300 cm

XLZD = merger:
XENON, LZ, DARWIN
8 German institutions:
KIT, MPIK, Freiburg,
Mainz, Münster, Heidelberg,
Darmstadt, Dresden

Ongoing R&D

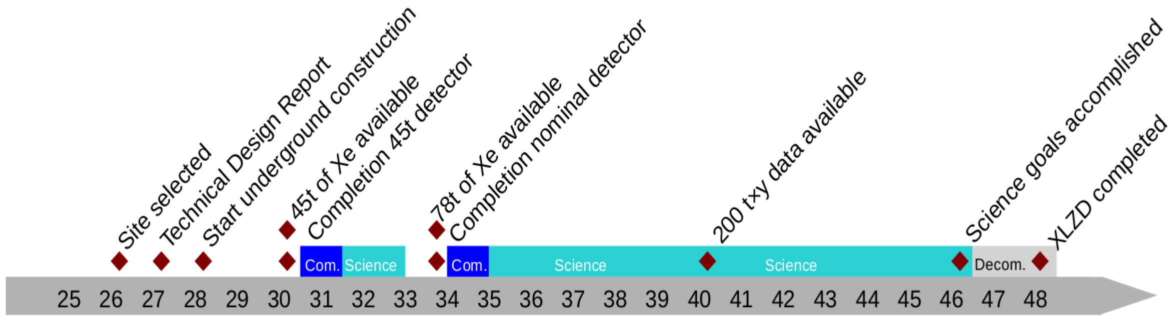
TPC scaling:
- Xenoscope (drift length)
- Pancake (wide grids)
- PMTS and other photosensors
- HV and grids
- alternative designs
- ...

Background mitigation:
- distillation
- improved γ and Rn screening
- coating for reduced Rn emanation
- ...



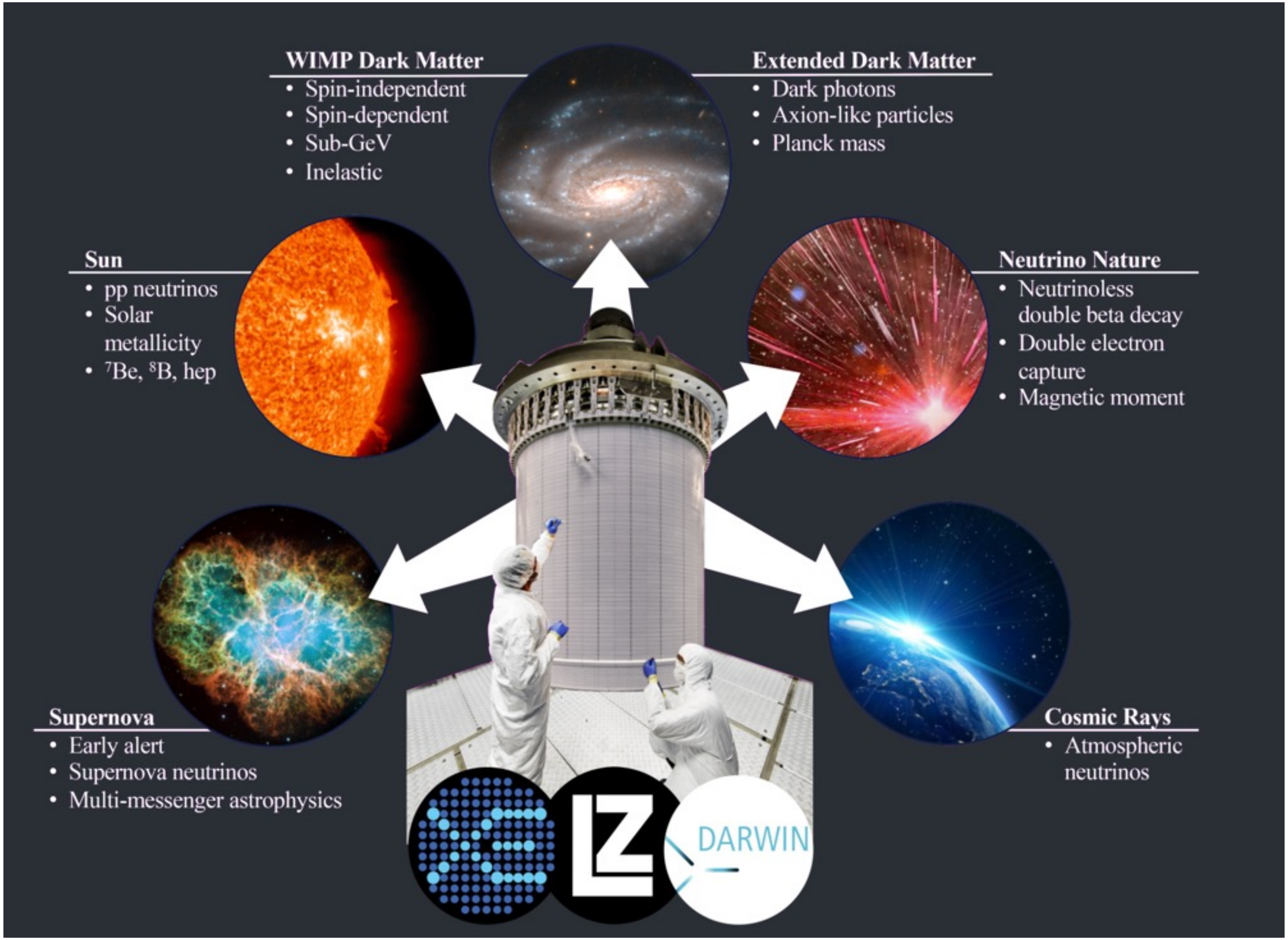
Proposed DARWIN-10/20 t demonstrator at LNGS-Hall B
(given funding)

Possible XLZD locations: LNGS, Boulby, SURF, Kamioka, SNOLAB



XLZD: An Observatory for Rare Physics

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



CEνNS: The simple Picture

Z-exchange of ν with nucleus

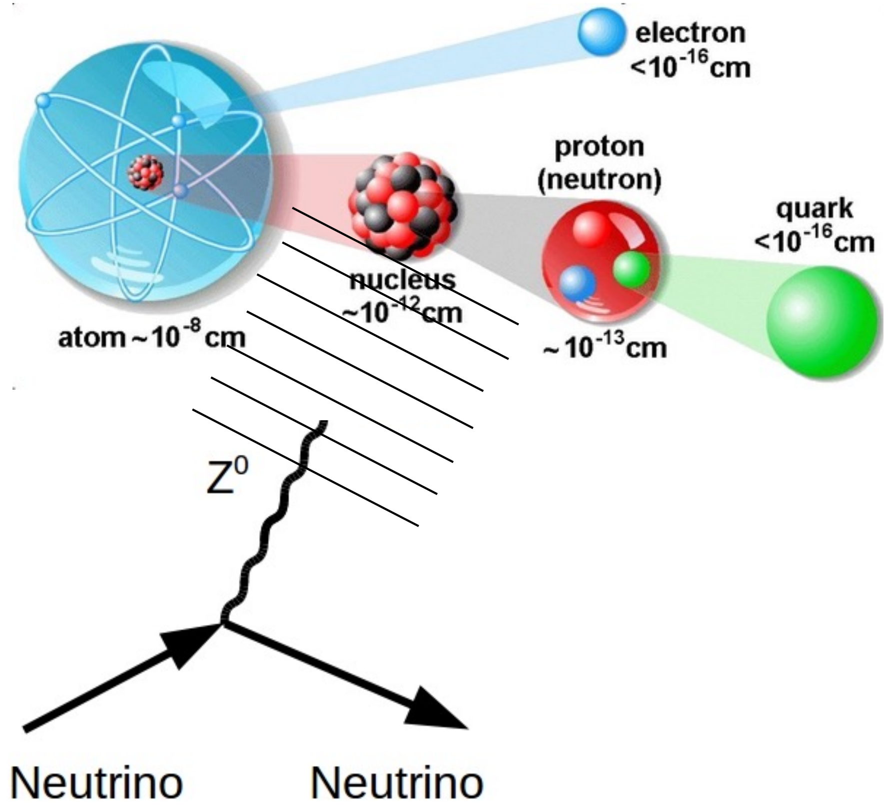
$$Q_w = N - (1 - 4\sin^2\theta_w)Z \quad \sim N$$

➔ sees mostly neutrons

momentum ←→ wavelength

Very low momentum

➔ **nucleus recoils as a whole**



Coherence length ~ 1/E ➔ E_ν below O(50) MeV

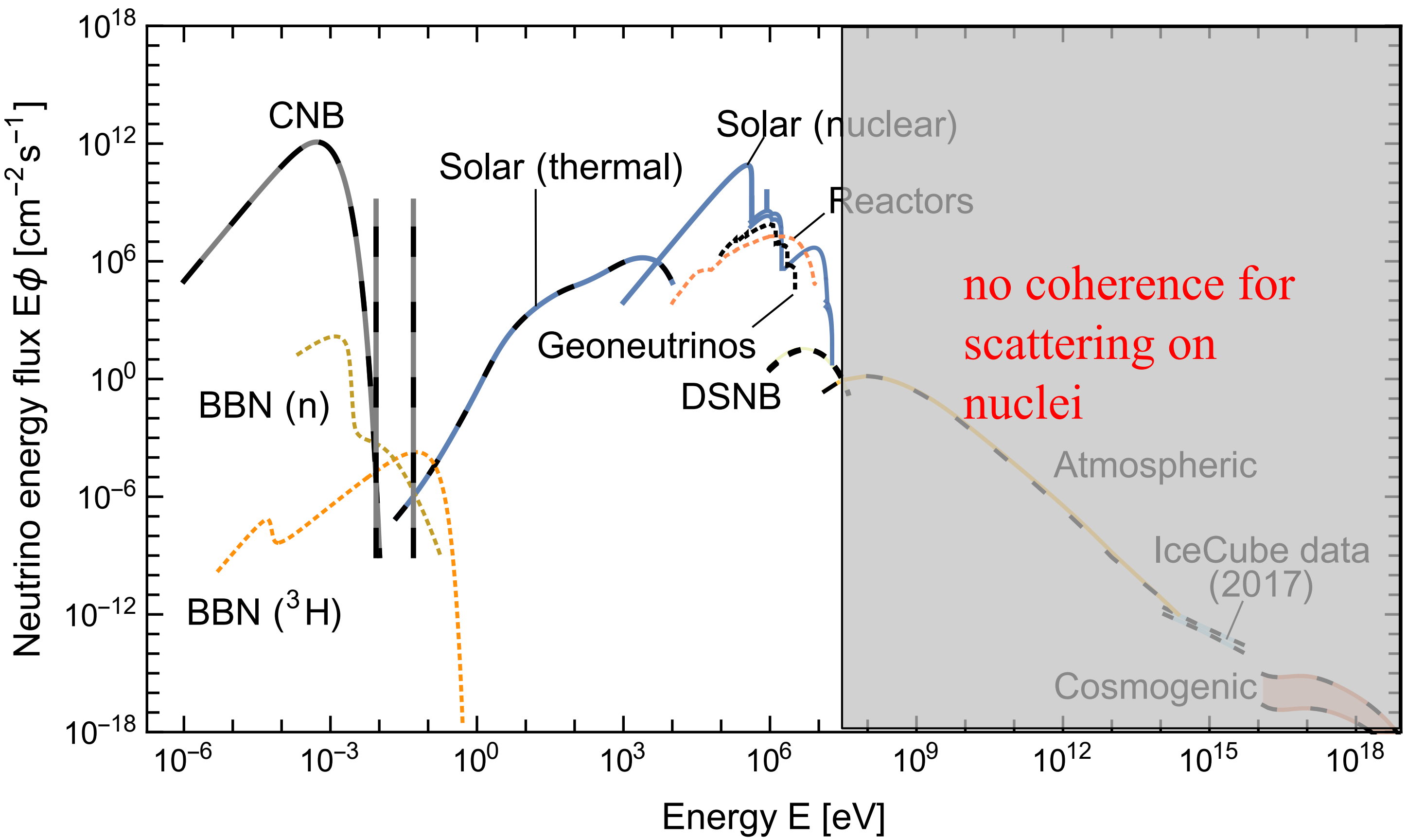
→ low energy E_ν ←→ lower cross sections ➔ very high flux!

$$\frac{d\sigma(E_\nu, T)}{dT} = \frac{G_f^2}{4\pi} Q_w^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2) \sim \mathbf{N^2}$$

N $\simeq$ 40 ➔ N^2 = 1600 ➔ detector mass 10t ➔ few kg

Sources: Flux ⊗ Energy

Vitagliano, Tamborra, Raffelt, Rev.Mod.Phys. 92 (2020) 45006



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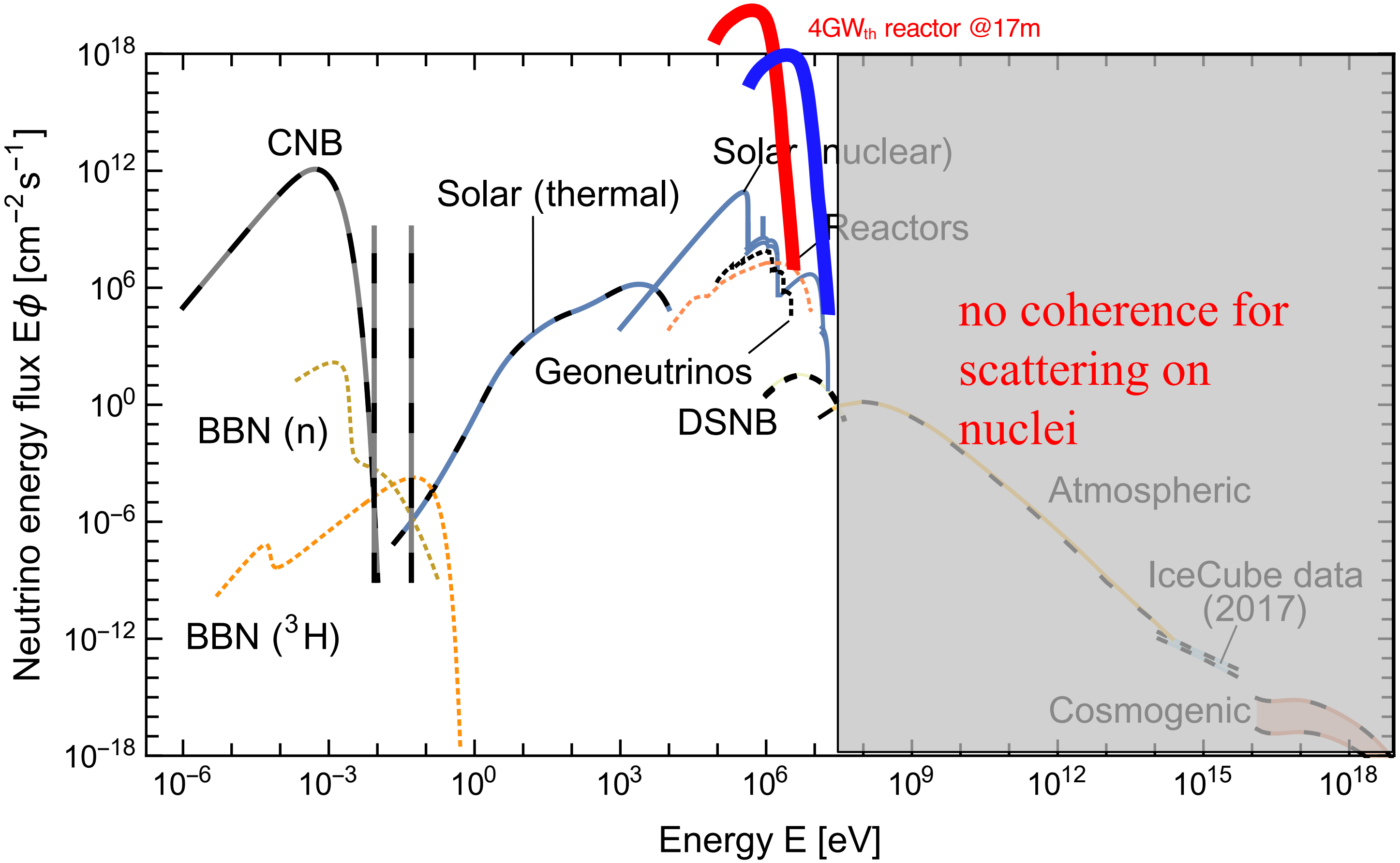
➔ **include: close to a nuclear power reactor, stopped π-beam, or a supernova**



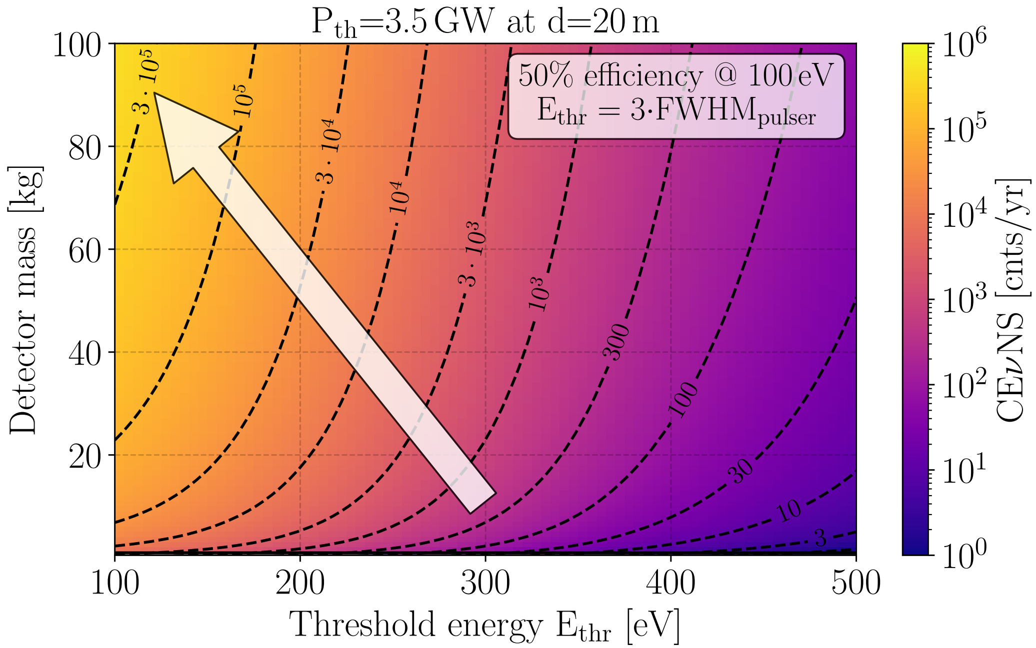
➔ event rates: ⊗ detector size ←➔ G3 dark matter detectors

➔ and in all cases: backgrounds...

The Potential of CEνNS & Combinations

Foreseeable high statistics CEνNS future:

- next generation dark matter detectors like DARWIN/XLZD
- next generation beam measurements of CEνNS:
  - COHERENT (neutrinos from π-DAR ➔ bigger detectors)
  - GanESS project @ESS (~8.5 × 10^{22} /flavour /year➔ ⊗9.2 @SNS
- future high statistics reactor neutrino experiments
  example: Upscaling of CONUS from 4kg → 100kg germanium
  100 eV threshold achieved
  → detector mass!



What is CEvNS good for?

High statistics CEvNS experiments touch many interesting topics:

- Large cross sections → small neutrino detectors → faster progress, applications
- Clean SM predictions for cross sections → BSM sensitivity
- Sensitivity to neutrino magnetic moment and $\langle r_\nu^2 \rangle$ → BSM sensitivity
- Possibility to measure $\sin^2\theta_W$ at low energies → BSM sensitivity
- Masurements of neutron formfactors (nuclear structure) → unique
- Nuclear reactor monitoring (non-proliferation) → applications
- Precision flavor-independent neutrino flux measurements for oscillation experiments → synergy with other experiments
- Sterile neutrino searches → BSM
- Energy transport in supernovae → important for next SN
- SN neutrino detection → SNEWS, pointing, ...
- Input for dark matter direct detection (neutrino floor) → solar neutrinos
- dark matter physics → BSM

Conclusions

Dark Matter is a very active and diverse field

- New particles or gravitational effects or both?
- Both sides contribute already a bit (neutrinos, black holes)
- Many theoretical options.... (GR, particle like, wave like, ...)
- Complimentary detection methods:
  LHC, Indirect Detection and **Direct Detection** and various other...

- **Direct Detection with XENONnT:**
- orders of magnitude ←→ scaling of TPC and background
- presented latest limits
- more on WIMPs to come very soon from SR2...

- **Future: Continue to further up-scale a powerful technology**
  - XENON, LZ, DARWIN → merging into XLZD
  - excellent potential: DM, CEνNS, solar ν's, supernovas, 0νββ, ...