Weeding out the WIMPs

Liquid Xenon TPCs and the Direct Detection of Dark Matter

Daniel Coderre
Albert Einstein Center for Fundamental Physics, University of Bern
June 2015, Krakow

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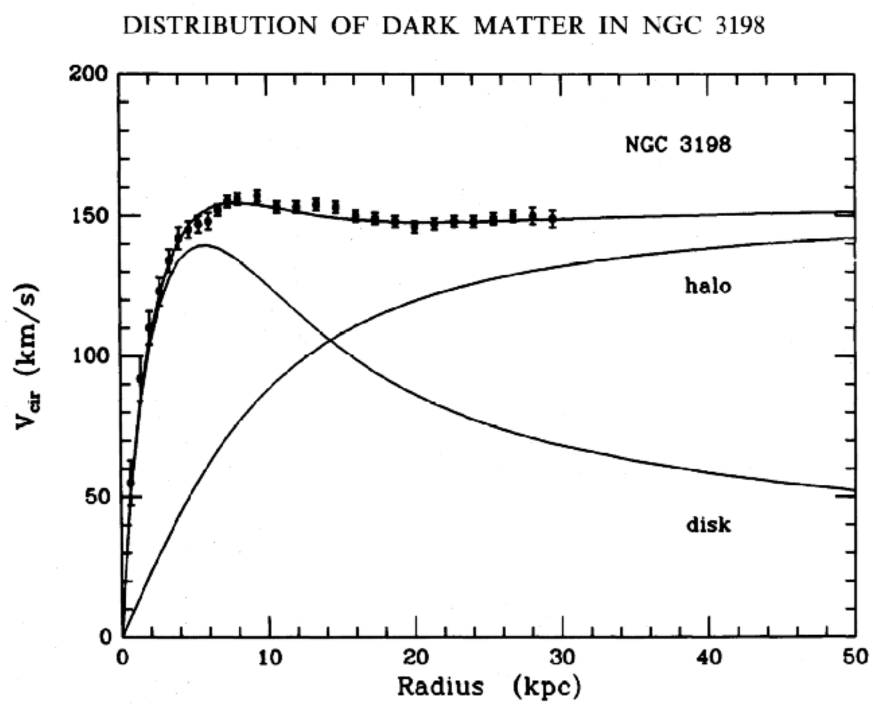
FOR FUNDAMENTAL PHYSICS

Q: How do we know dark matter is a thing?

A: Astronomy and Cosmology

Galaxies rotate… but not like we would expect

- We can **predict** the mass of a galaxy by measuring the light it emits
- We can **measure** how fast a galaxy rotates via doppler shift
- We see a **large discrepancy!**
- **About ⅔ of the mass of the galaxy is not visible!**
- Adding a dark matter halo allows us to describe the measurements
  - **($\rho \propto 1/r^2$)**

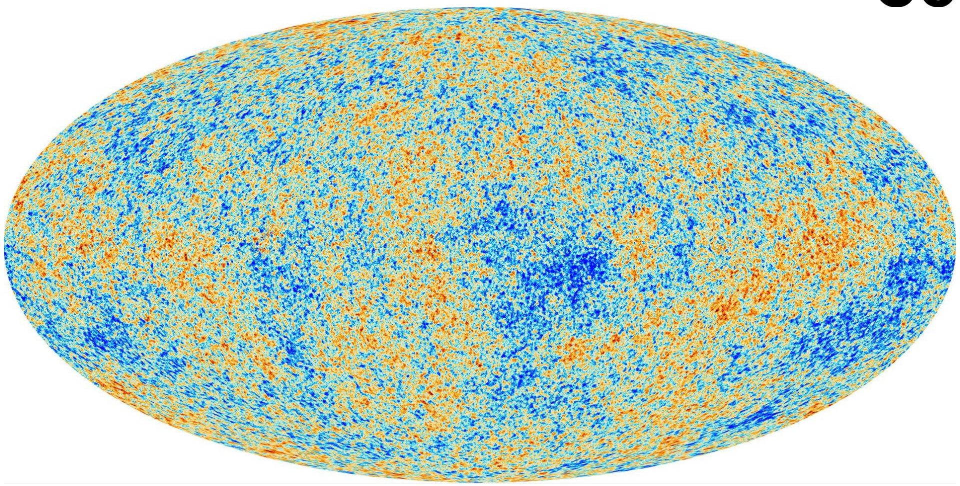


Gravitational lensing measurements

- Movements of clusters of galaxies indicate various amounts of dark matter in different galaxies

- Bullet cluster → a collision of two galaxy clusters shows a clear separation of the hot gas (pink, x-rays measured) and dark matter (purple, measured via lensing)

Cosmic microwave background



- Quantify anisotropy of CMB measurements
- Large amounts of dark matter required to reproduce observed distribution
- Newest Plank measurement: 26.8% of the universe is dark matter

arXiv:1502.01582 [astro-ph.CO]

There are many theoretical dark matter candidates, but we will focus here on WIMPs

"WIMP miracle"

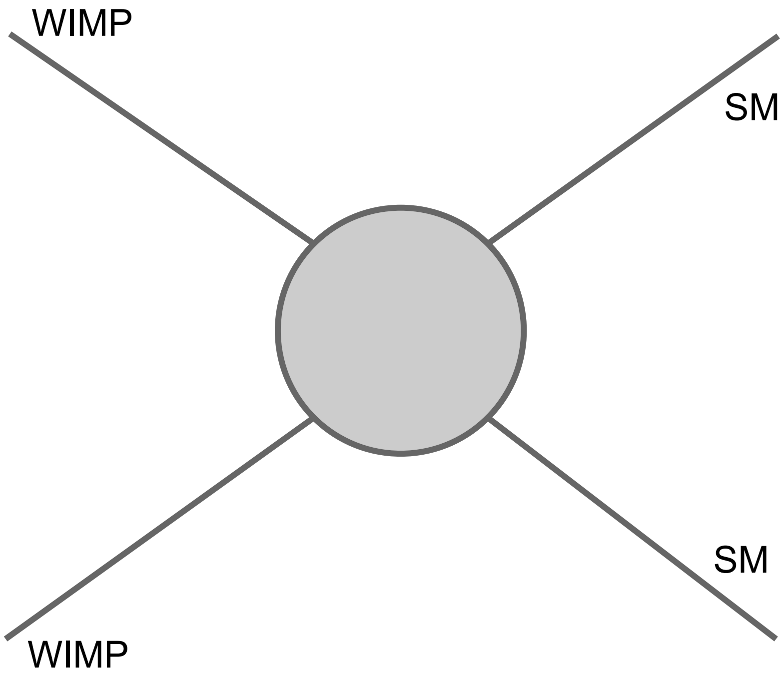
Assuming thermal production, the observed dark matter density is roughly reproduced by assuming a ~100 GeV particle with weak-scale interactions

Properties of our WIMP

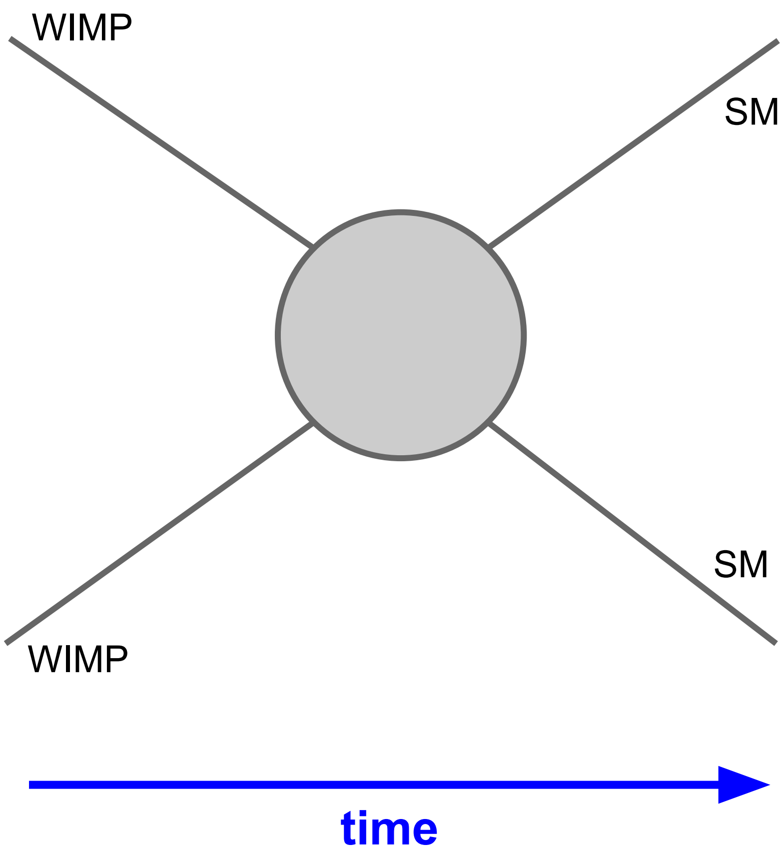
- Mass in 10-1000 GeV range
- Weak-scale interaction cross section with matter
- Exist in our solar system with a flux of about ~ $10^7/m_\chi$ GeV/cm^{-2}

Finding Dark Matter

Requirement: WIMPs must interact with matter! Otherwise it's hopeless anyway.



Finding Dark Matter

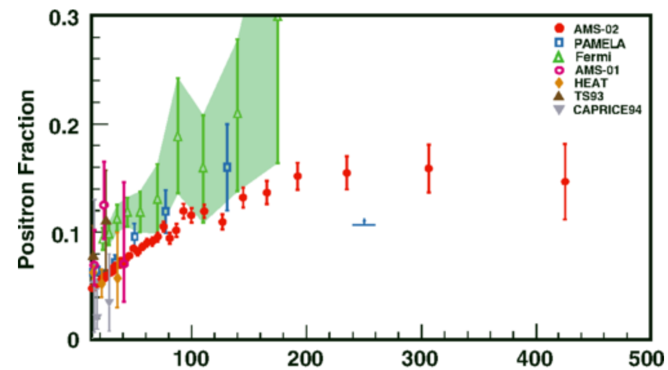


Indirect detection

Assumption
WIMPs can interact and produce SM particles

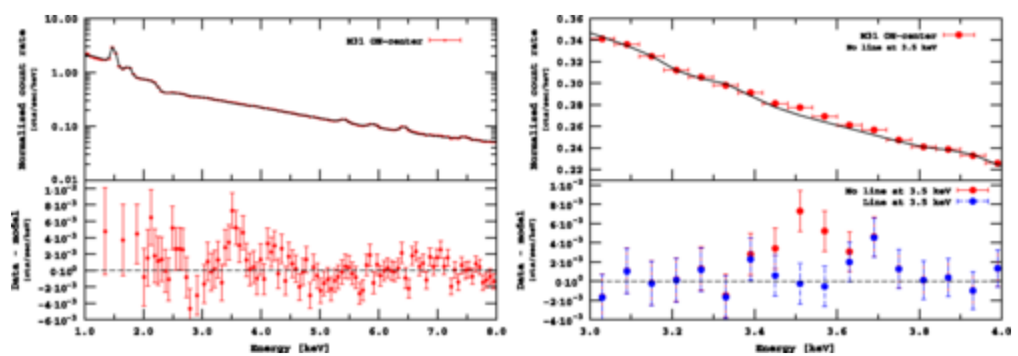
Where to look
Space! From ground or satellite-based observatories

Examples: AMS positron fraction



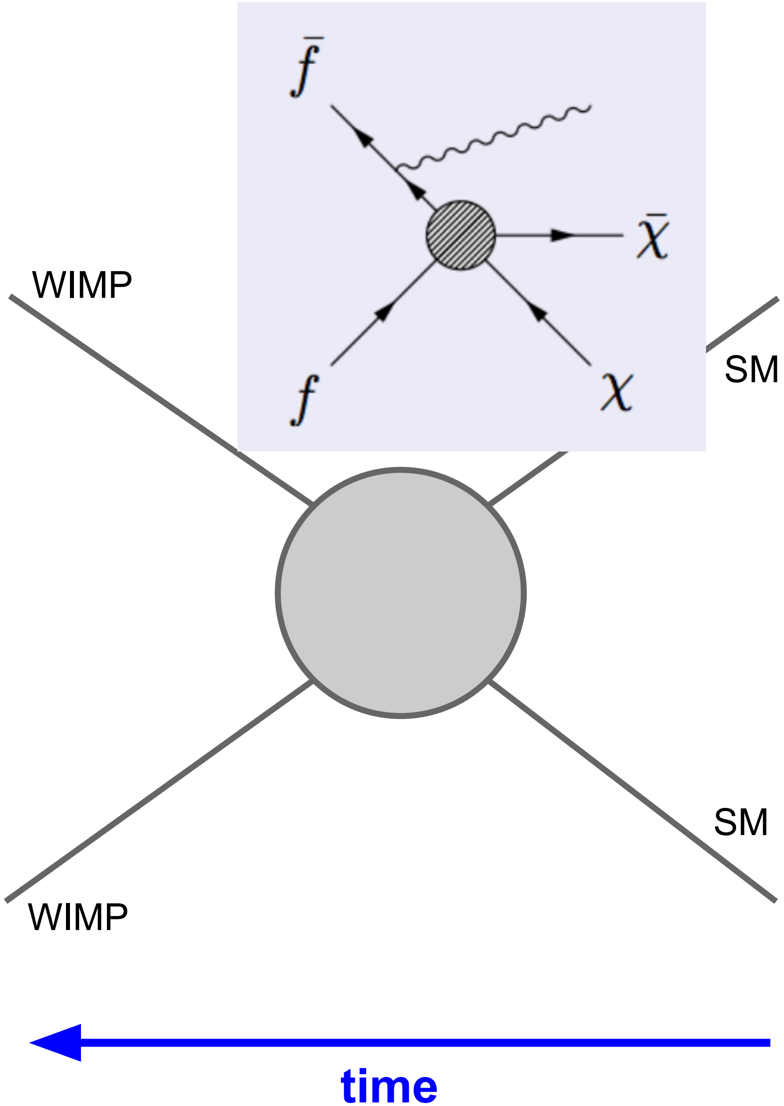
Phys. Rev. Lett. 113, 121101

Sterile neutrino interpretation of XMM-Newton data



Phys. Rev. Lett. 113, 251301

Finding Dark Matter

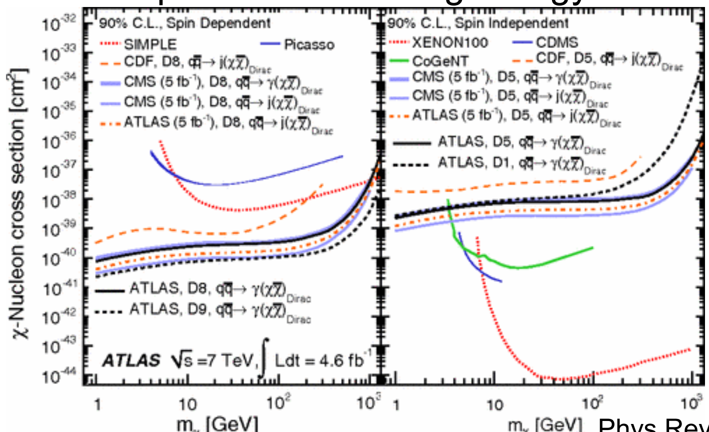


Dark Matter Production

Assumption
SM particles can interact and produce WIMPs

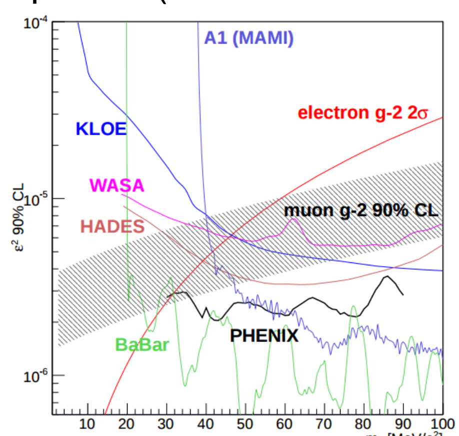
Where to look
Accelerators.

Examples: LHC missing energy searches



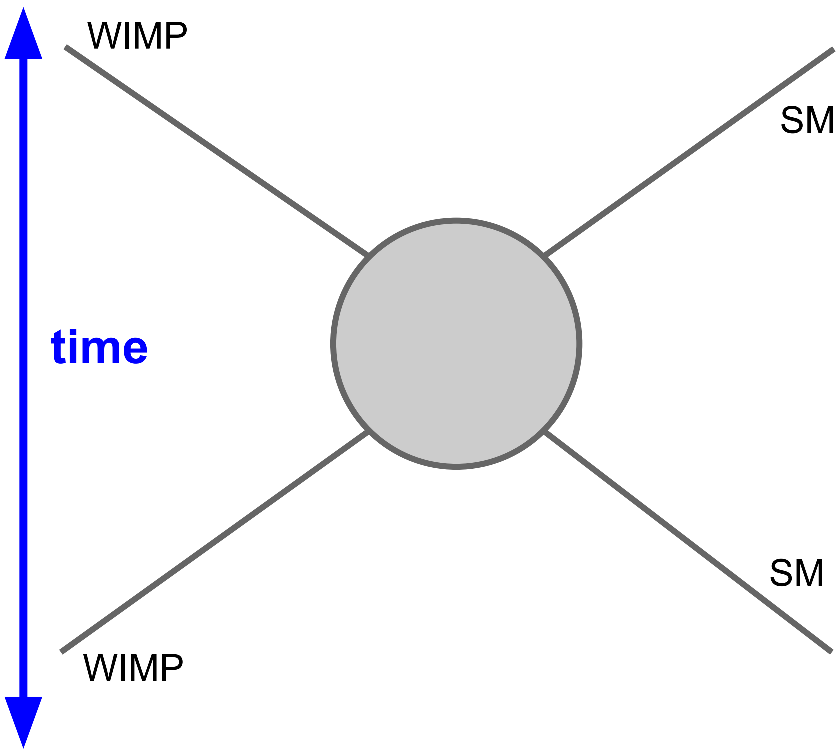
Phys.Rev.Lett.110,&011802(2013)

Dark photon (not a WIMP but also accelerators)



PhysRevC.91.031901
(PHENIX)

Finding Dark Matter



Direct Detection

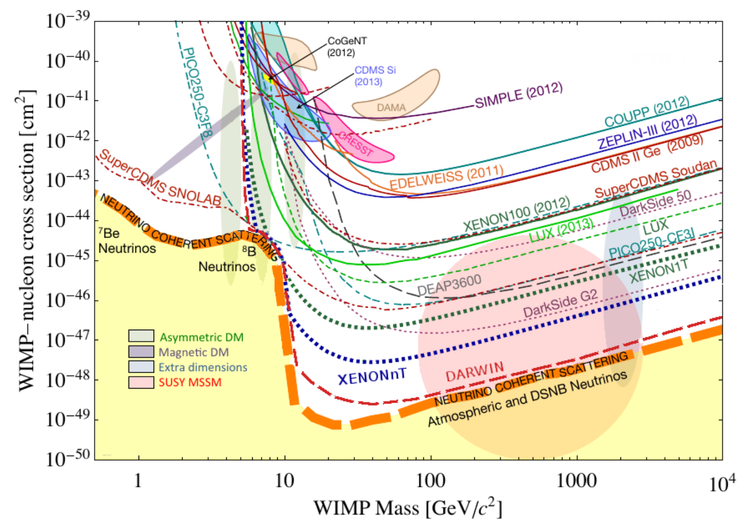
Assumption

The earth is floating through a cloud of WIMPs

Where to look

Earth based detectors. Carefully designed and shielded to remove as much background as possible.

Examples: See next slide, there are many!



Direct Detection

Various measurement methods boil down to the same idea:

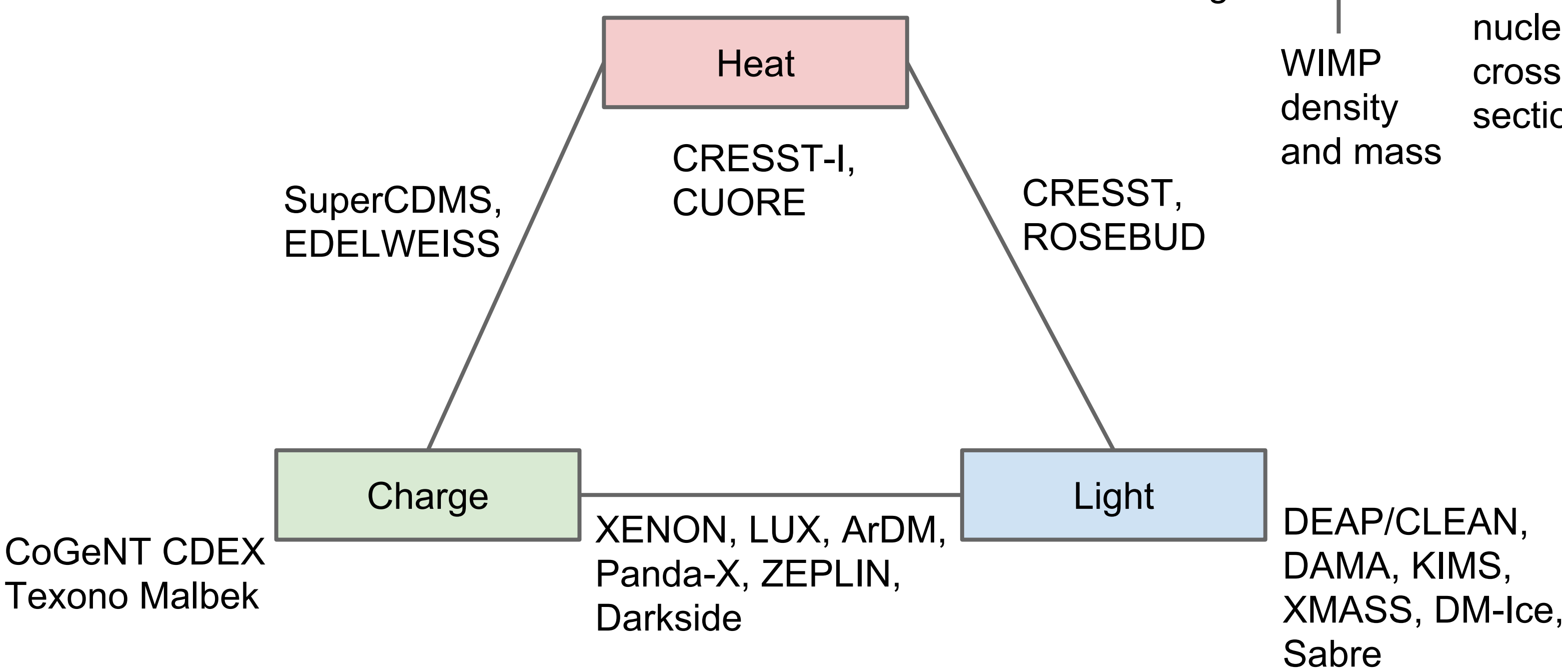
- Build an ultra-sensitive detector
- Put it in a low background environment
- Perform a long exposure and count any unexpected events
    - Our events:
        - Single scatter
        - Nuclear recoil
        - Very low energy → (~10 keV!)

$$\Gamma \propto N * (\rho_X / m_X) * \sigma_{X\text{-}N}$$

Target

WIMP density and mass

WIMP nucleon cross section



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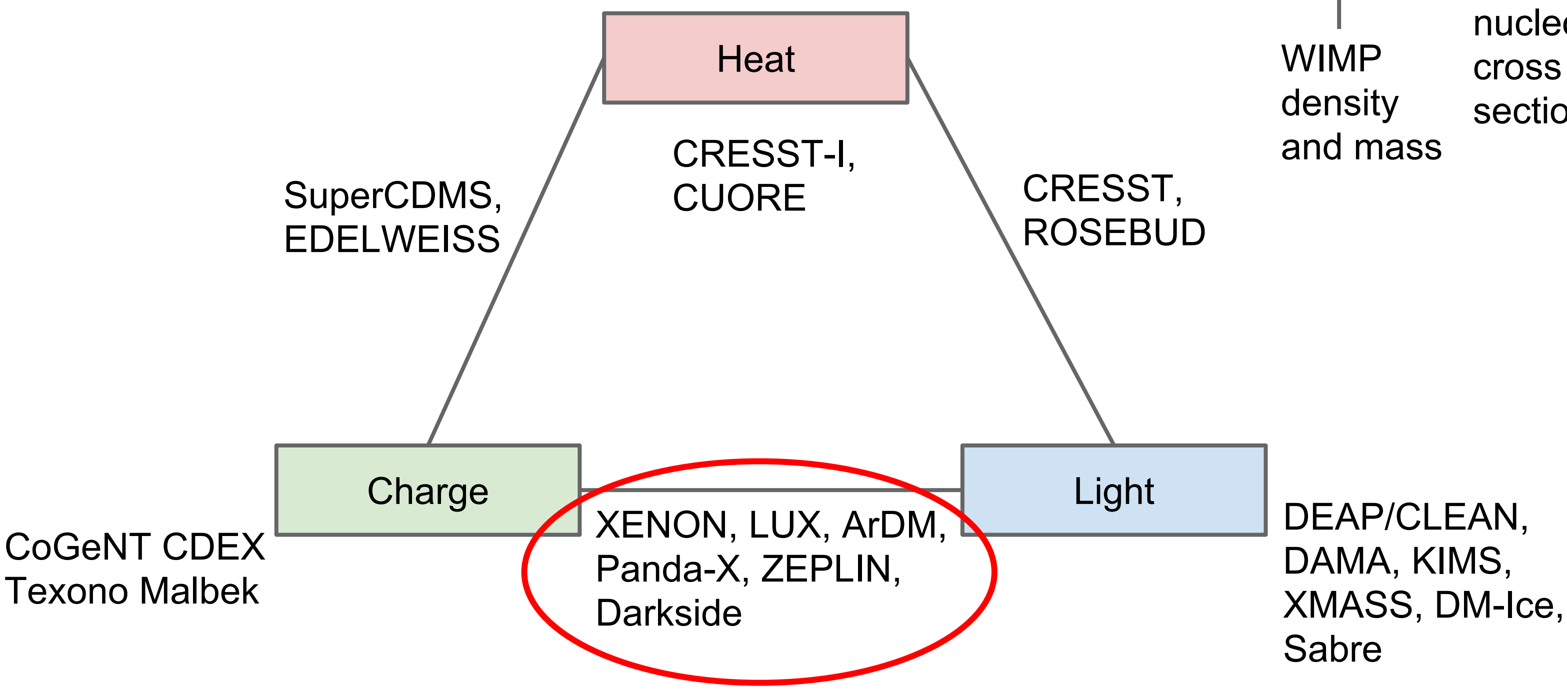
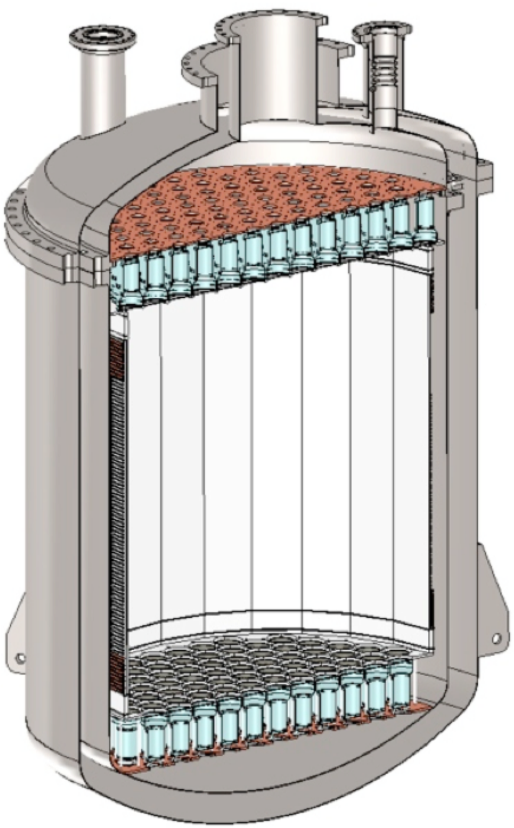
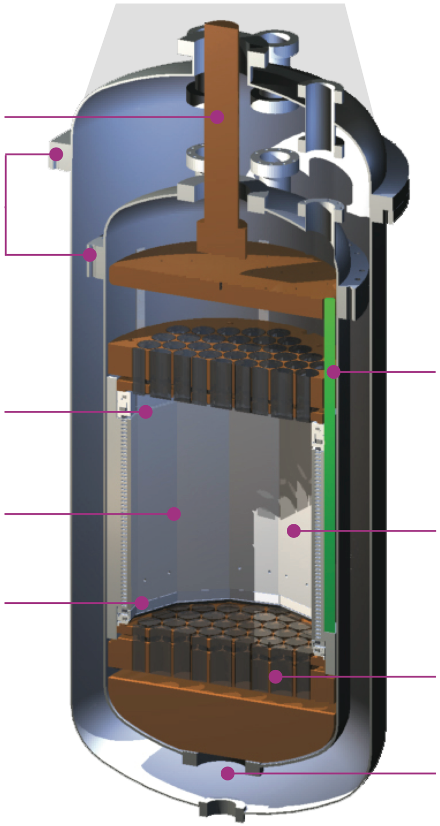


Liquid xenon TPCs

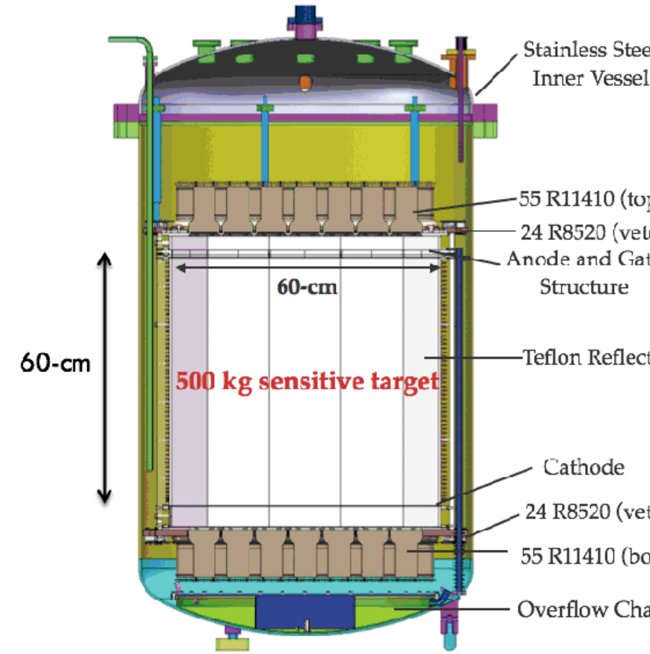
Examples: NOT to scale (but very roughly)!



XENON1T, LNGS (2015)



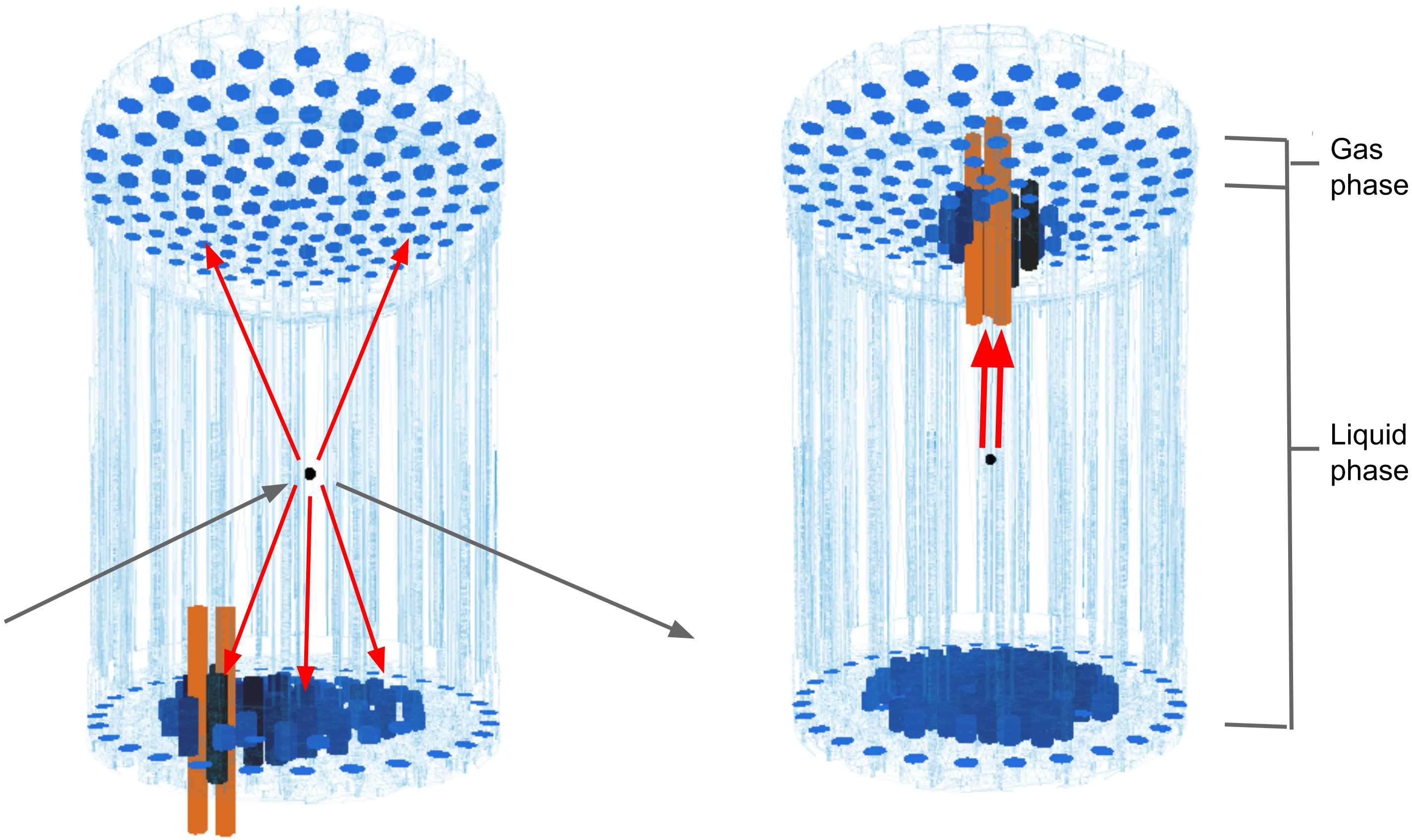
LUX, SURF (running)



PandaX stage 2, China (2015)

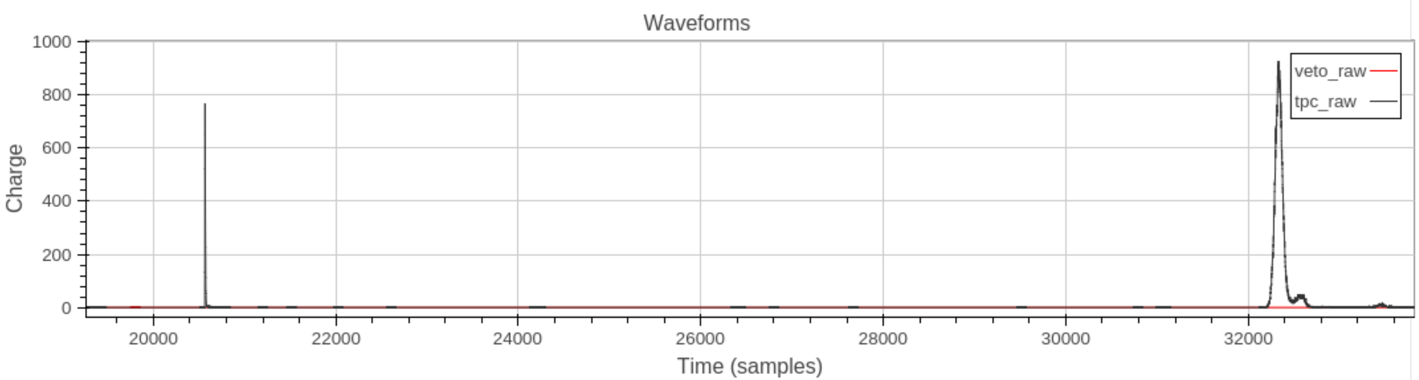
Lots of competitors, but all have the same basic design...

Liquid xenon TPCs



S1 (light)

S2 (electrons → light)



Energy

Determined by amplitude of charge and light signal

Collision type

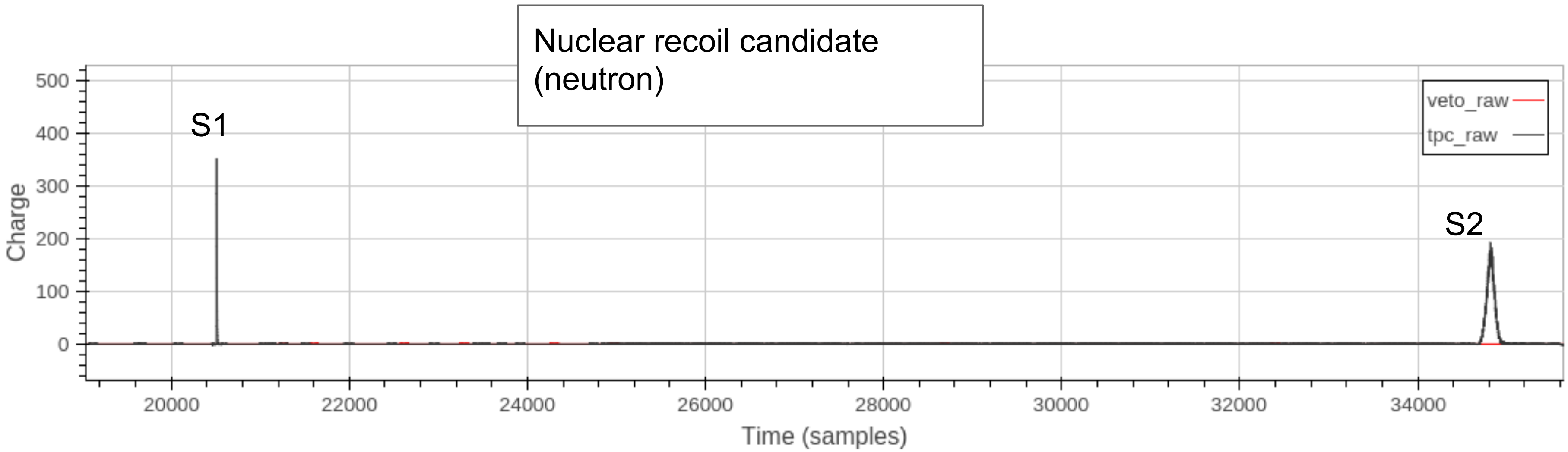
Determined by proportion of charge and light signal (next slide)

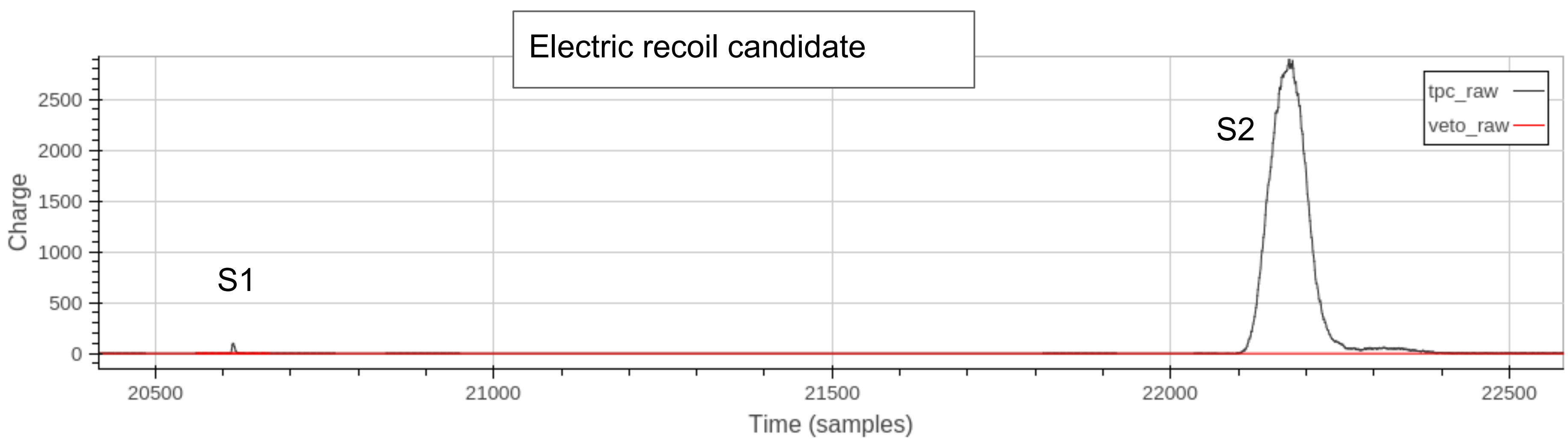
Position

x,y determined by localization of ionization signal on top array

z determined by time difference between S1 and S2

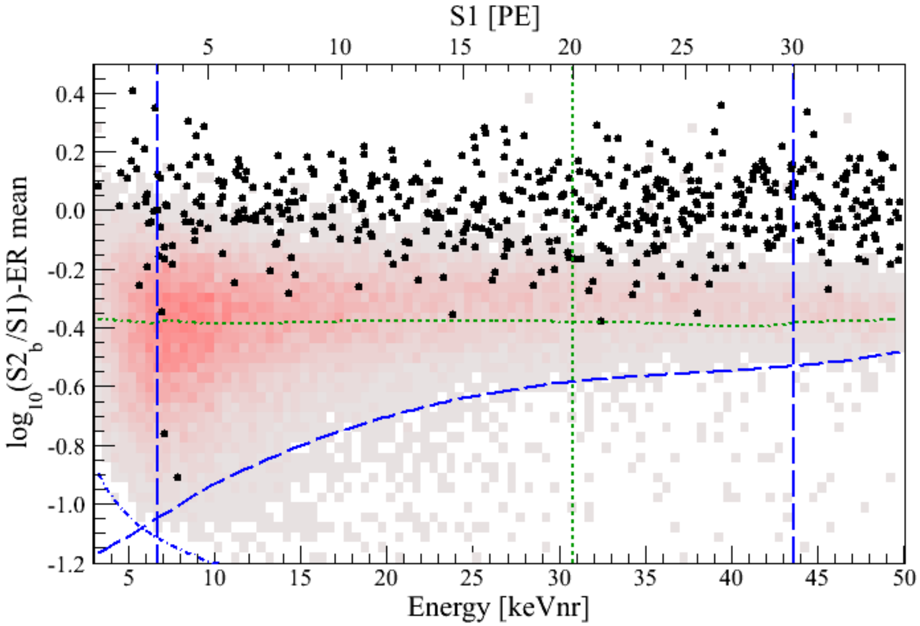
ER/NR Discrimination





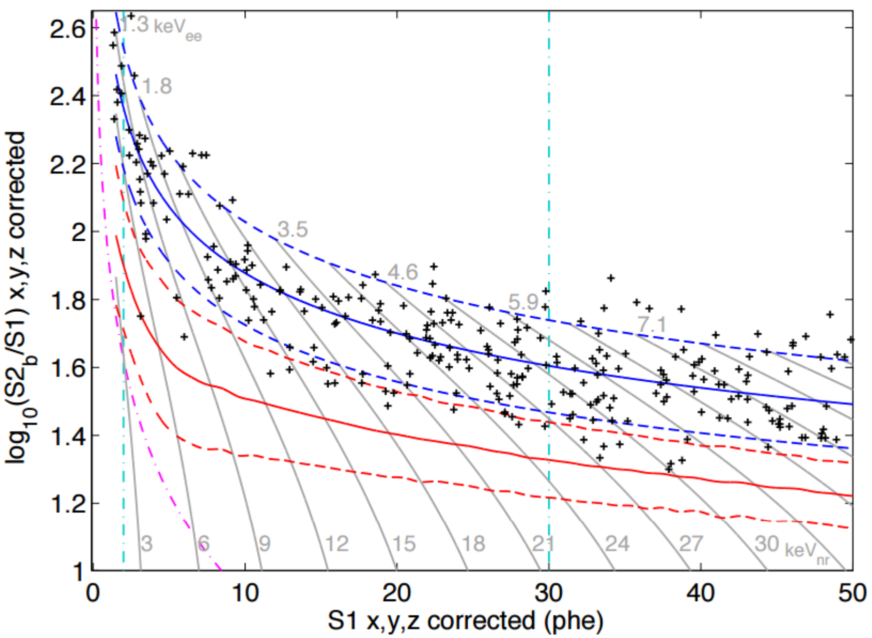
Ratio of scintillation and ionization signals

XENON100



Phys. Rev. Lett. **109**, 181301

LUX



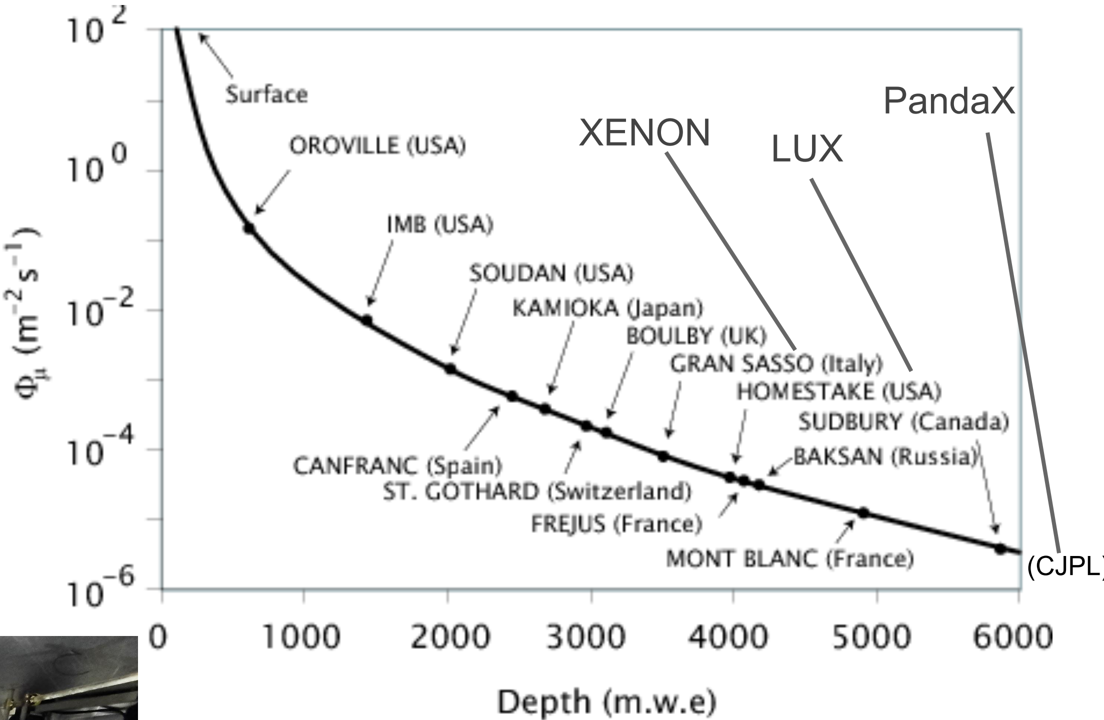
Phys. Rev. Lett. **112**, 091303.

- **In both cases remaining backgrounds after analysis comes from electric recoils**
- **No significant nuclear recoil backgrounds remain, thus null results**

Background Reduction - Muons

Put the experiment underground

- **Orders of magnitude (>10^6) reduction of flux compared to surface**



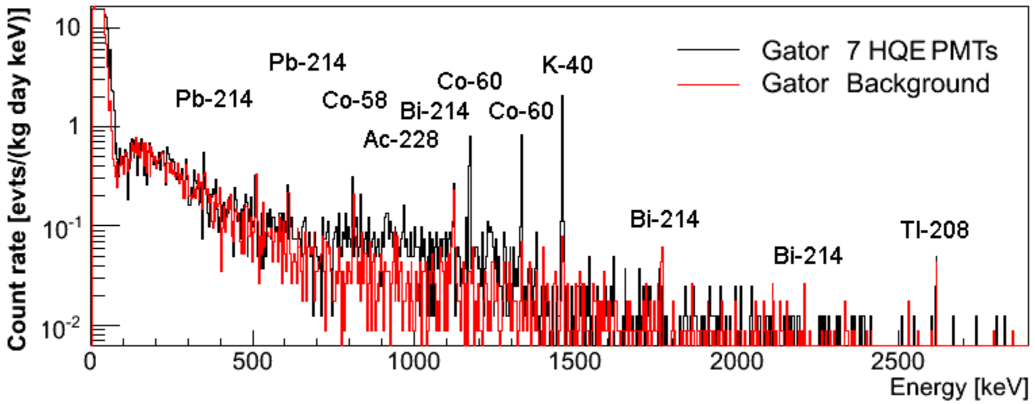
Active shielding from muon-induced neutrons

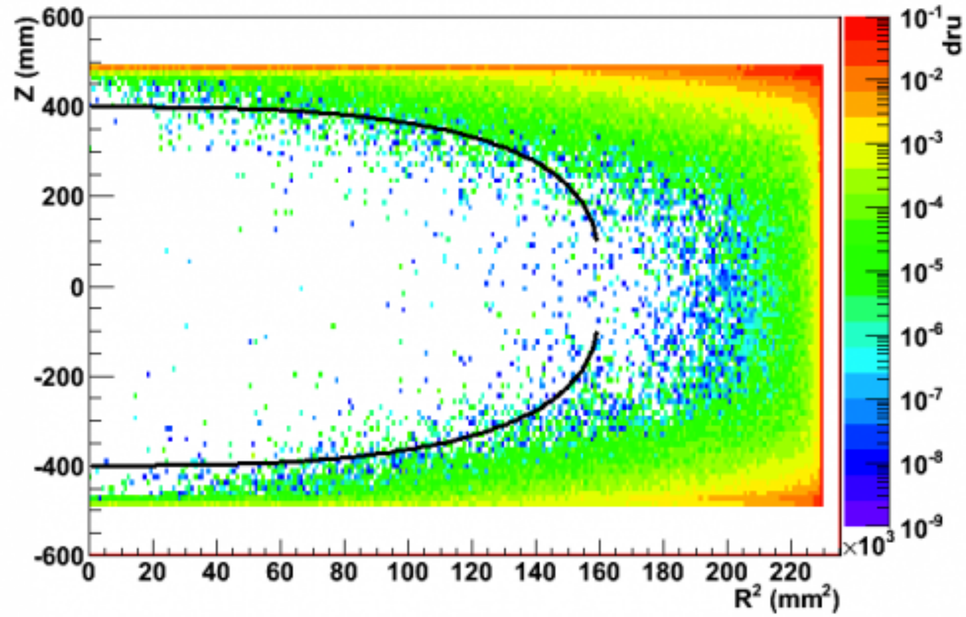
- **Active Cherenkov water shields reduce expected muon-induced background to zero, even for ton-scale experiments**

Background Reduction - Materials/Environment

Material Screening

- **All materials are screened for radioactivity using HPGe detectors and mass spectrometry**
- **Only the cleanest materials are chosen, material budgets are minimized**



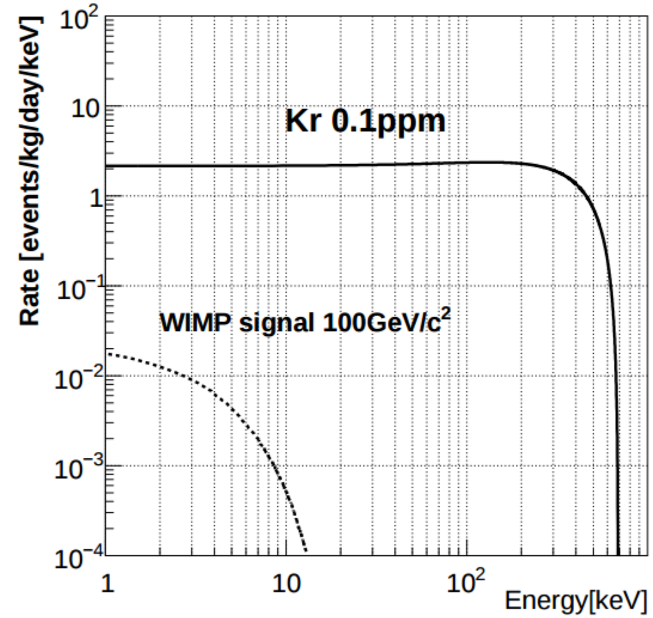


Fiducial volume

- **Xenon is an excellent shield**
- **Outer layers of xenon block external radiation from the physical materials and environment**
- **Inner volume of xenon chosen for analysis, optimized with calibration data**

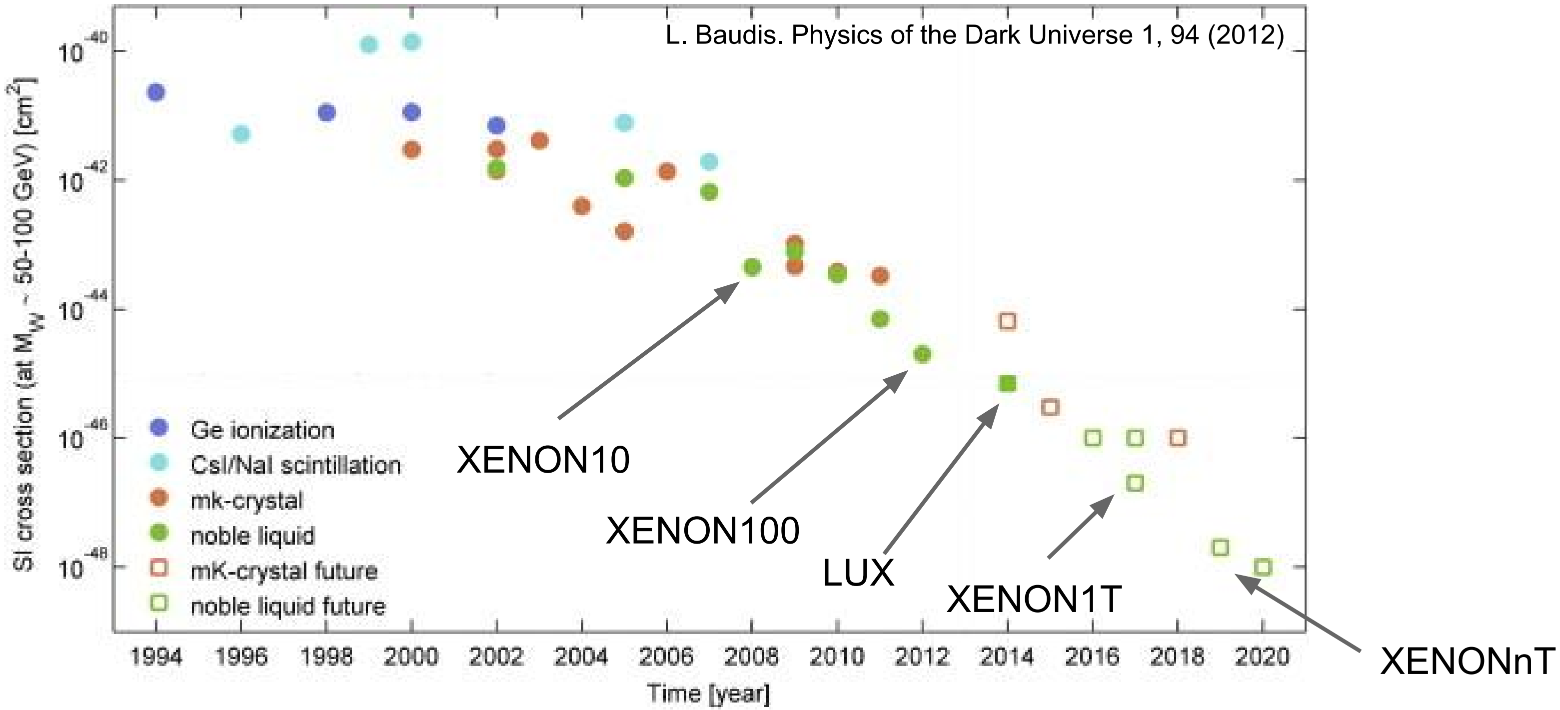
Background Reduction - ^{85}Kr, ^{219}Rn, ^{220}Rn, ^{222}Rn

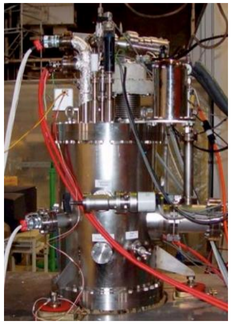
- ^{85}Kr artificially produced (bomb tests, power plants), found in air
- ^{85}Kr/Kr ~ 10^{-11}
- Commercial xenon contains krypton at ppm or ppb level
- Rn present in all of our materials
  - Kept low by screening
  - Will require constant distillation for future experiments



- Cryogenic distillation to take advantage of different boiling points of Xe and Kr
  - Done at XENON1T and XMASS
- ^{85}Kr levels down to ppq level have been attained for XENON1T S.Lindemann, H.Simgen, Eur.Phys.J.C (2014) 2746.
  - About 2 orders of magnitude improvement to previous experiments

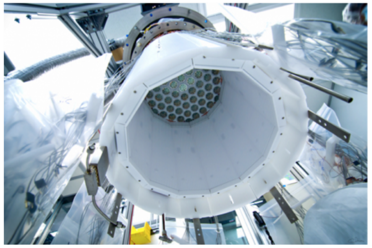
Direct Detection Timeline



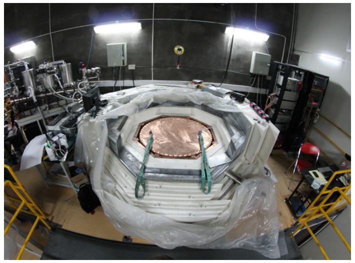


XENON10
Time: Until 2007
xenon: 14kg
Fiducial: 5.4kg
Limit: ~10^{-43}

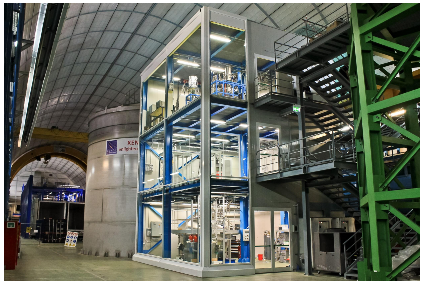
XENON100
Time: Since 2008
xenon: 161kg
Fiducial: 48kg
Limit: ~10^{-45}



LUX
Time: Since 2013
xenon: 370kg
Fiducial: 118kg
Limit: ~10^{-46}

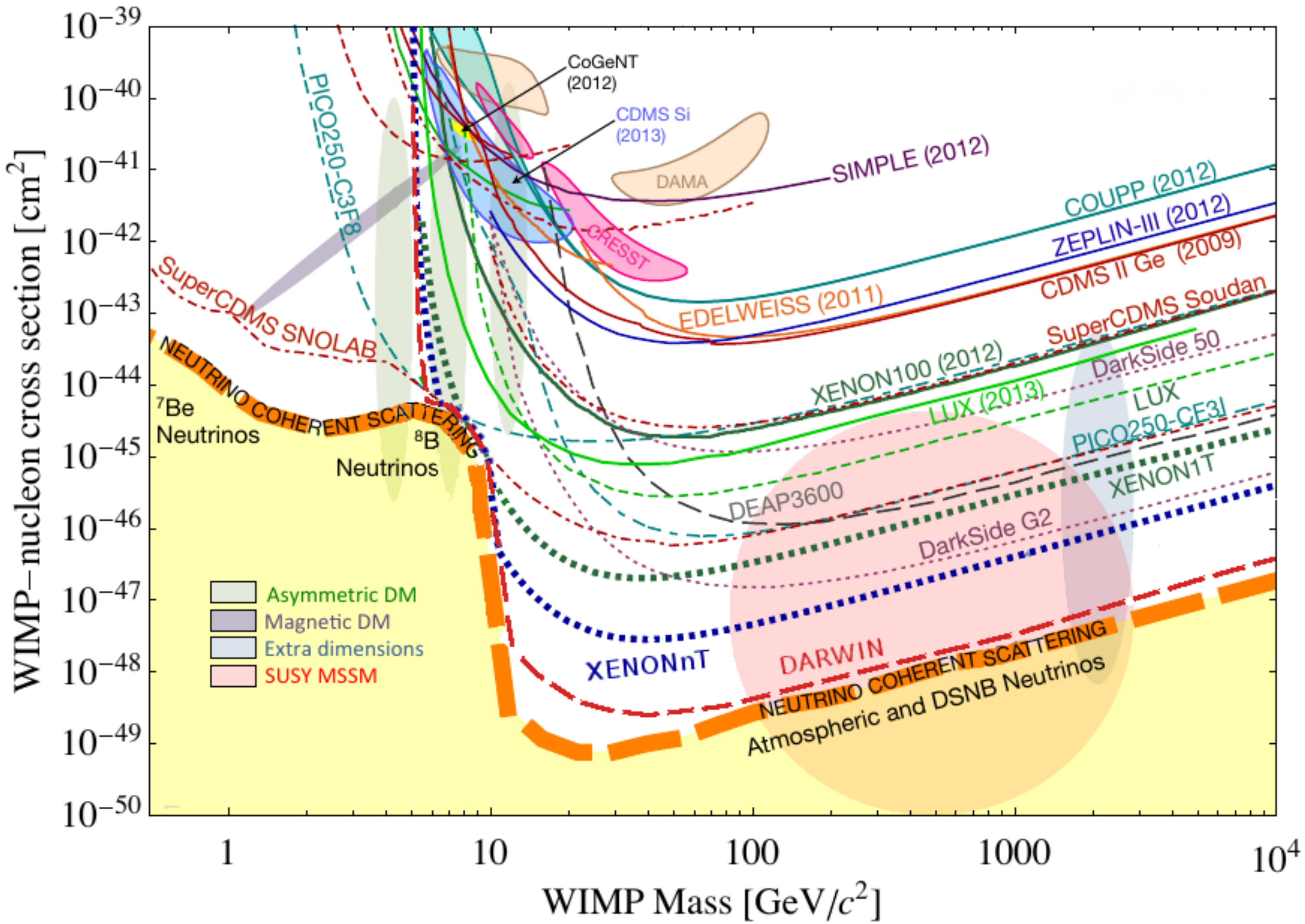


PandaX
Time: Since
xenon: 120kg
Fiducial: 37kg
Limit: ~10^{-44}



XENON1T - 3t
Pandax - >1t
XENONnT - 7t
LZ - 7t
DARWIN - ~30t
...

State of the Art



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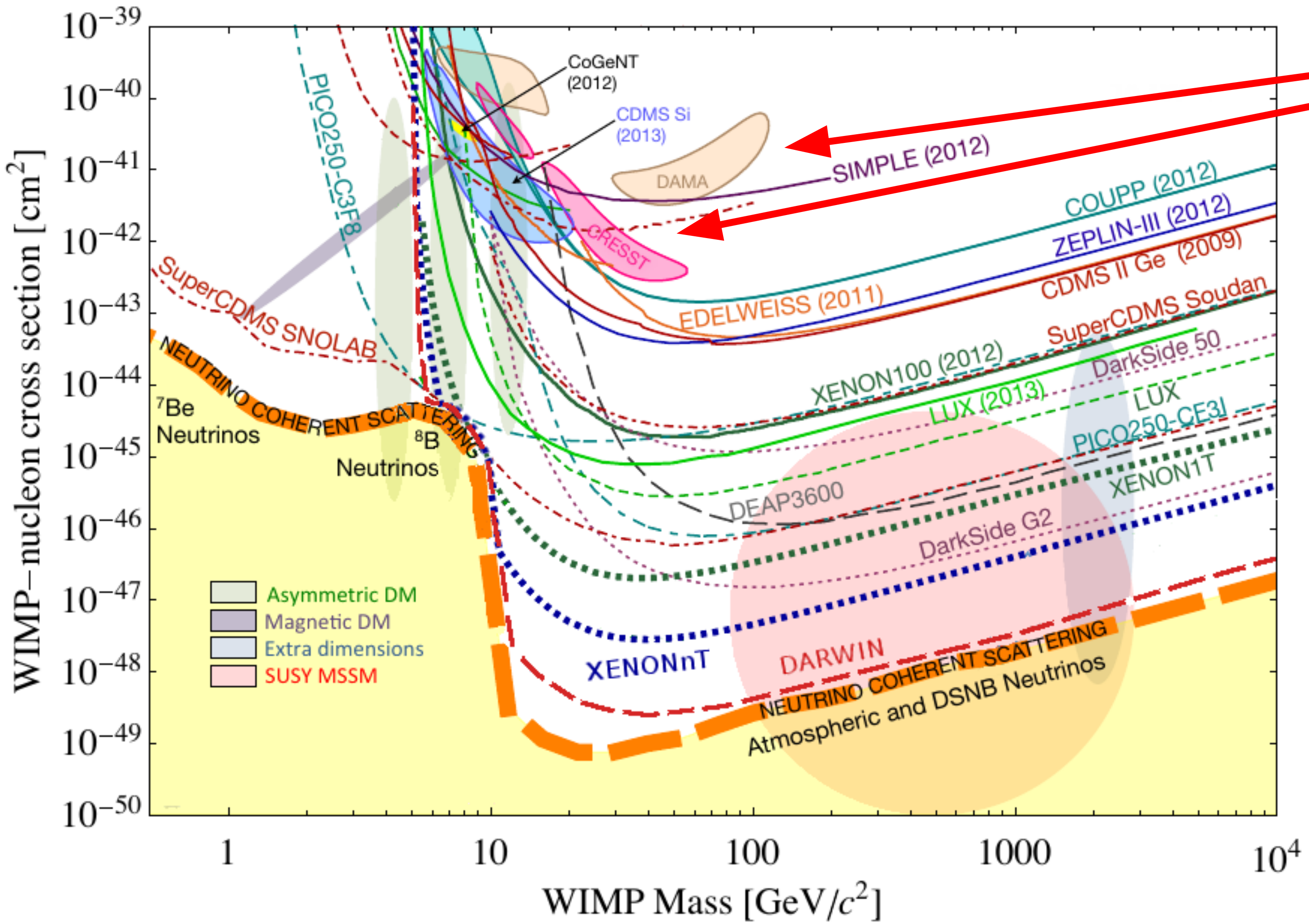
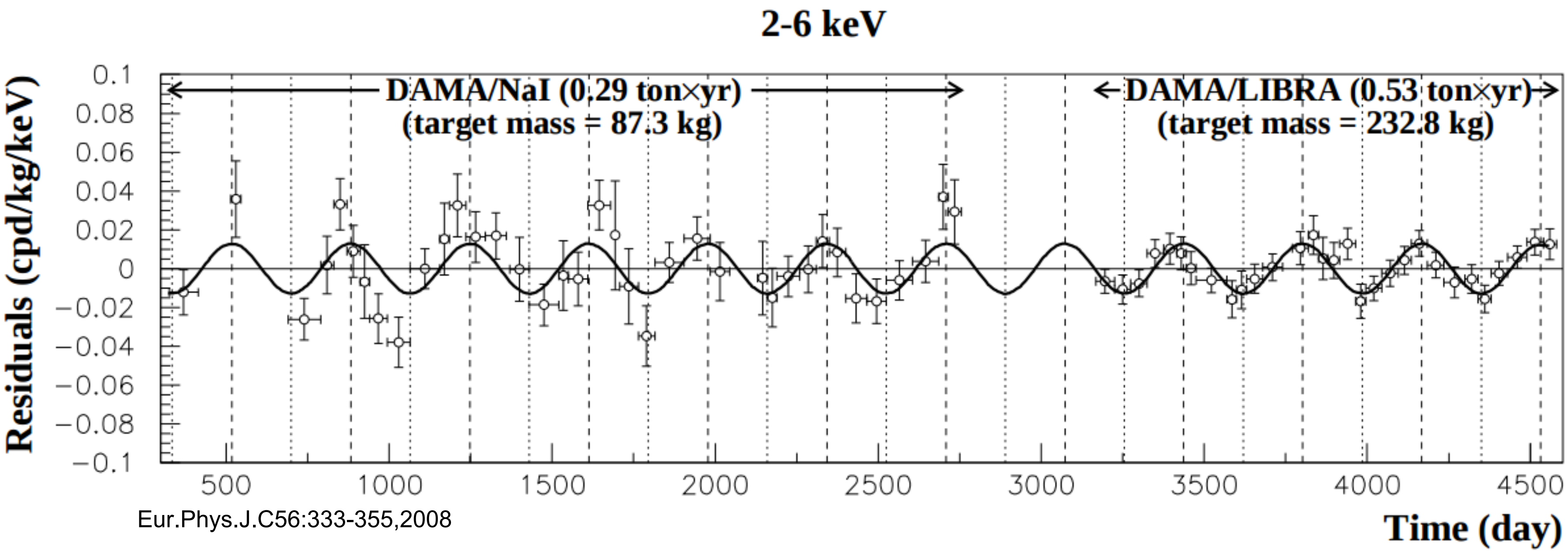
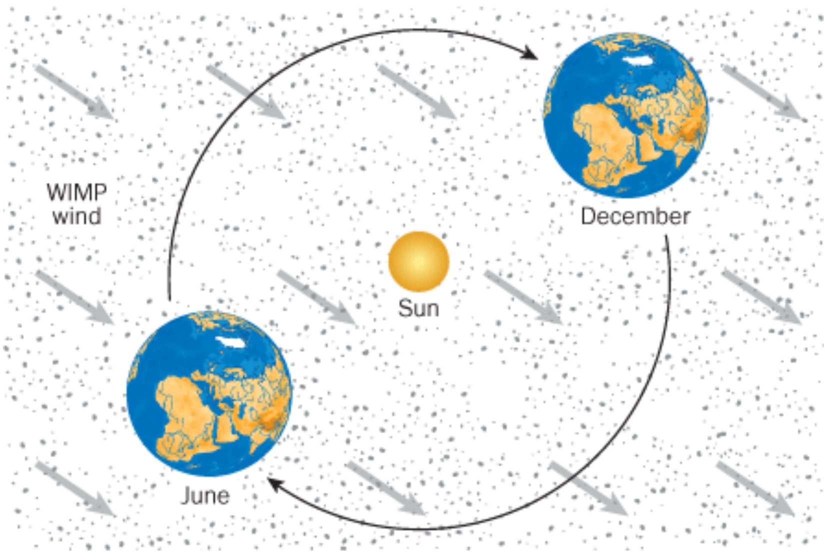


What's are the islands?

Annual Modulations



Eur.Phys.J.C56:333-355,2008



Most significant claim → DAMA

- The solar system is moving through the dark matter cloud surrounding the galaxy (“WIMP wind”)
- Depending on the time of year the earth is moving more or less into the wind
- We then expect an enhancement in summer and a lower rate in winter
- DAMA has measured this to high significance

Other detections?

- CDMS-Si 3 events in signal region for silicon detectors only.
  - Excluded by Ge data from CDMS, but Si signal remains

- COGENT 1.9-sigma excess in low-mass spectrum and 2.2-sigma modulation signal
  - High backgrounds, various interpretations exclude dark matter entirely

- CRESST ~25 event excess EUR PHYS J C Volume 72, Number 4 (2012)
  - Ruled out by new measurements by the CRESST collaboration with updated detector technology EUR PHYS J C Volume 74, Number 12 (2014) ,astro-ph/1407.3146

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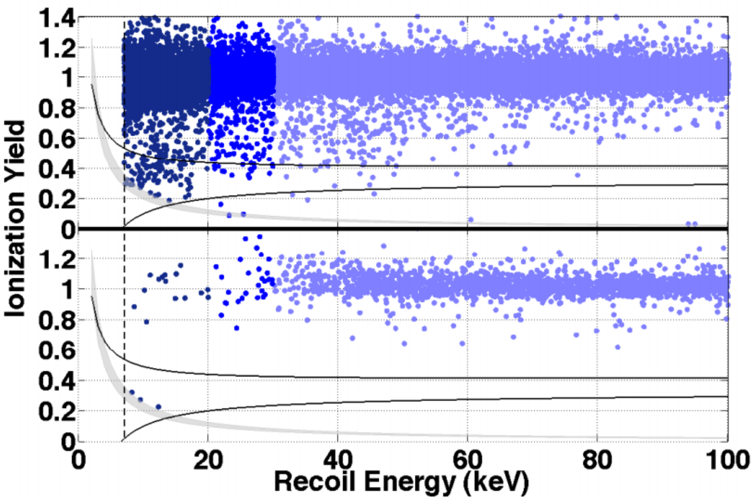
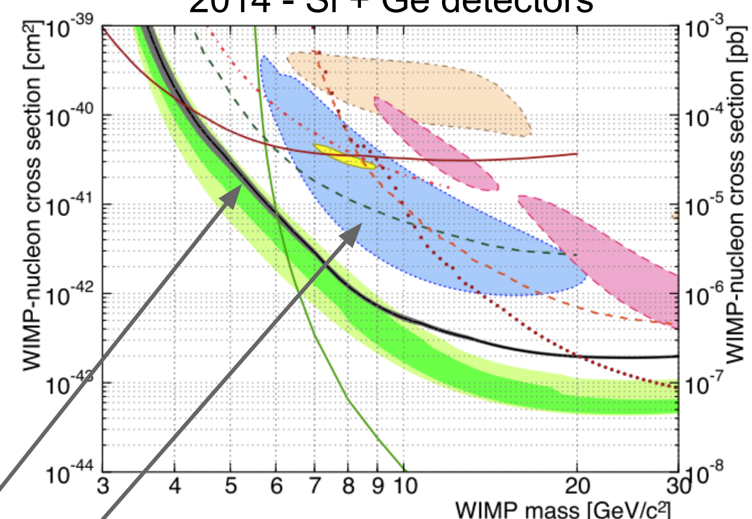
2013 - Si detectors



arXiv:1304.4279 [hep-ex]

2014 - Si + Ge detectors



Phys. Rev. Lett. 112, 241302 (2014)

2014 limit

2013 signal region

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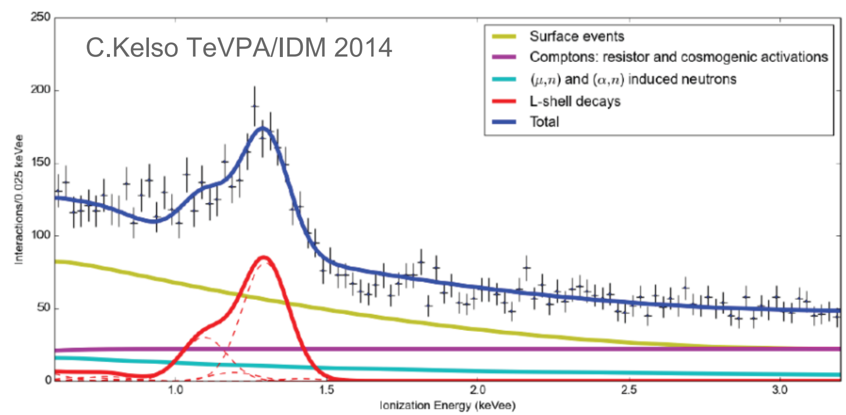
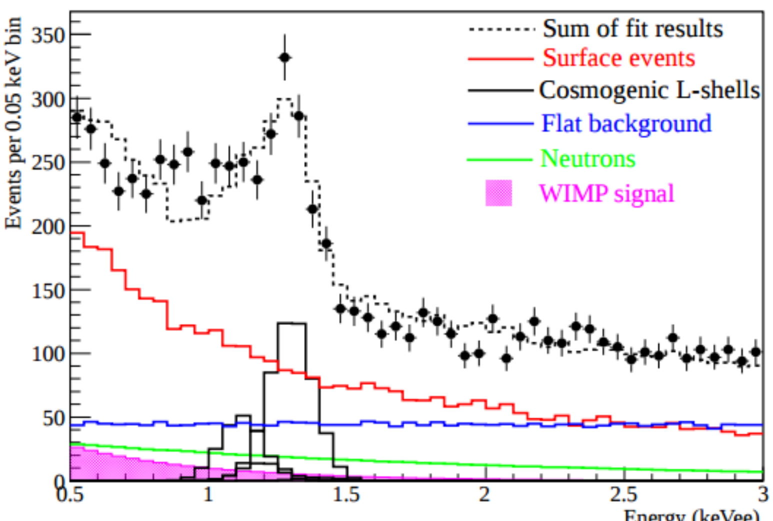
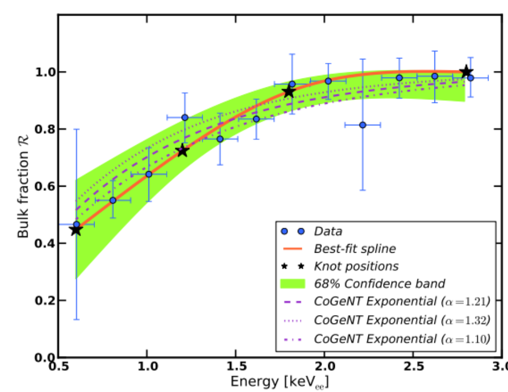




arXiv:1401.6234 [astro-ph.CO]

J.Davis et al. JCAP08(2014)014



Also see: arXiv:1401.3295 [astro-ph.CO]

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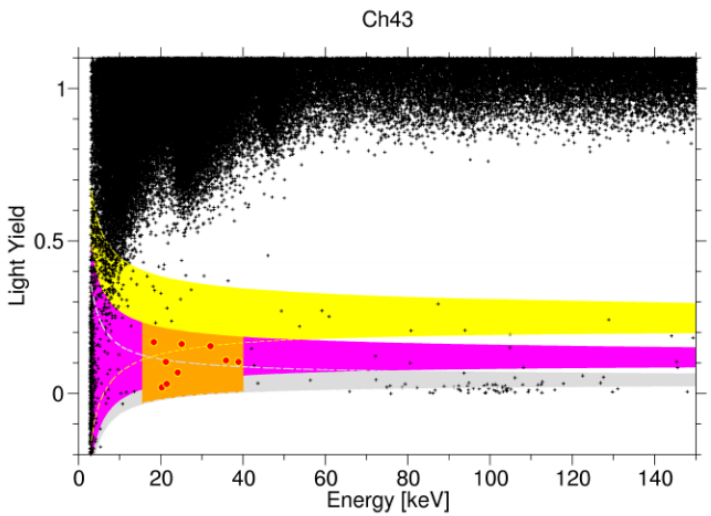
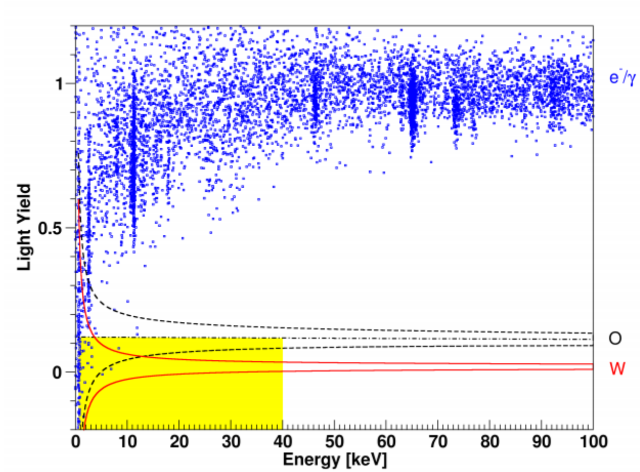
2012



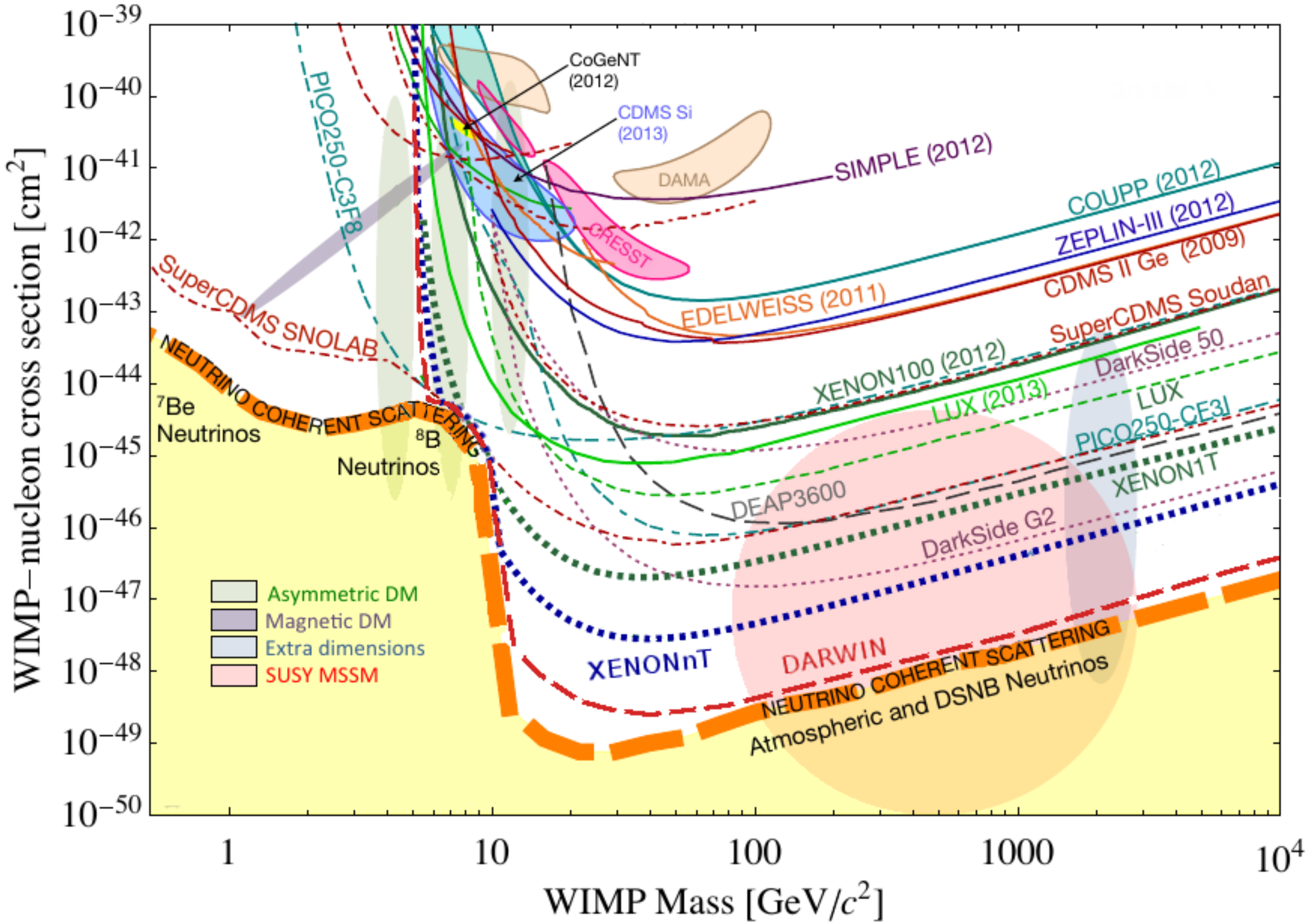
10.1140/epjc/s10052-012-1971-8

2014

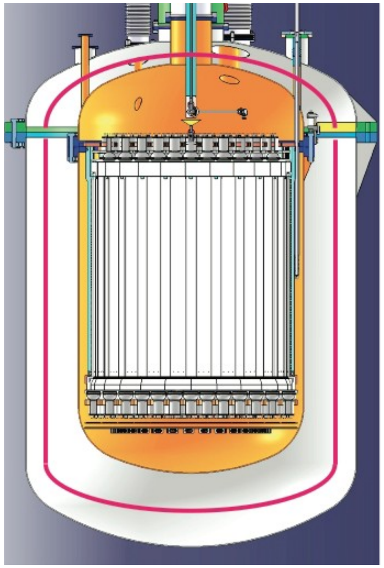


EUR PHYS J C Volume 74, Number 12 (2014)

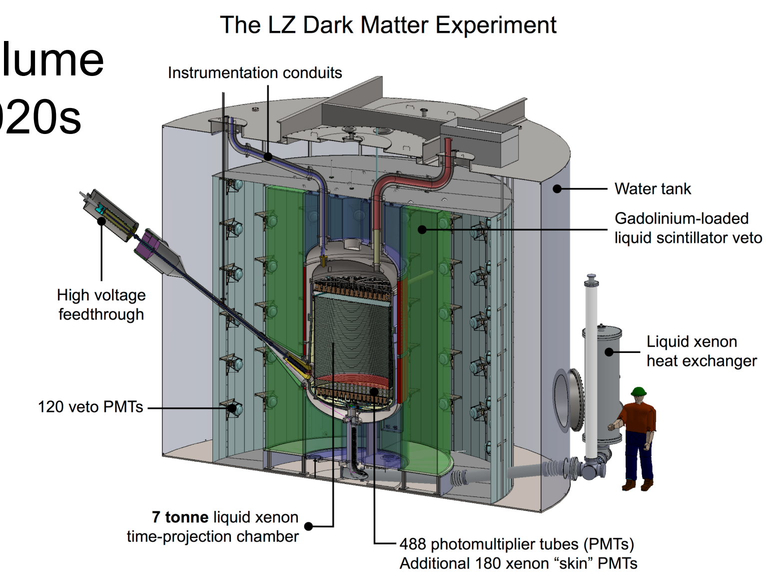
State of the Art



Where to go from here?



- **Short term** → XENON1T experiment
  - Starting in a few months
- **Longer term**
  - XENONnT (LNGS)
    - 7 tons target volume
    - Direct update to XENON1T using same facility
  - LUX-ZEPLIN (SURF, USA)
    - Staged approach, 7 ton target volume
    - Target data-taking starting 2018
  - DARWIN
    - Next evolution from XENONnT (probable location LNGS)
    - 30 ton target volume
    - Time frame ~2020s

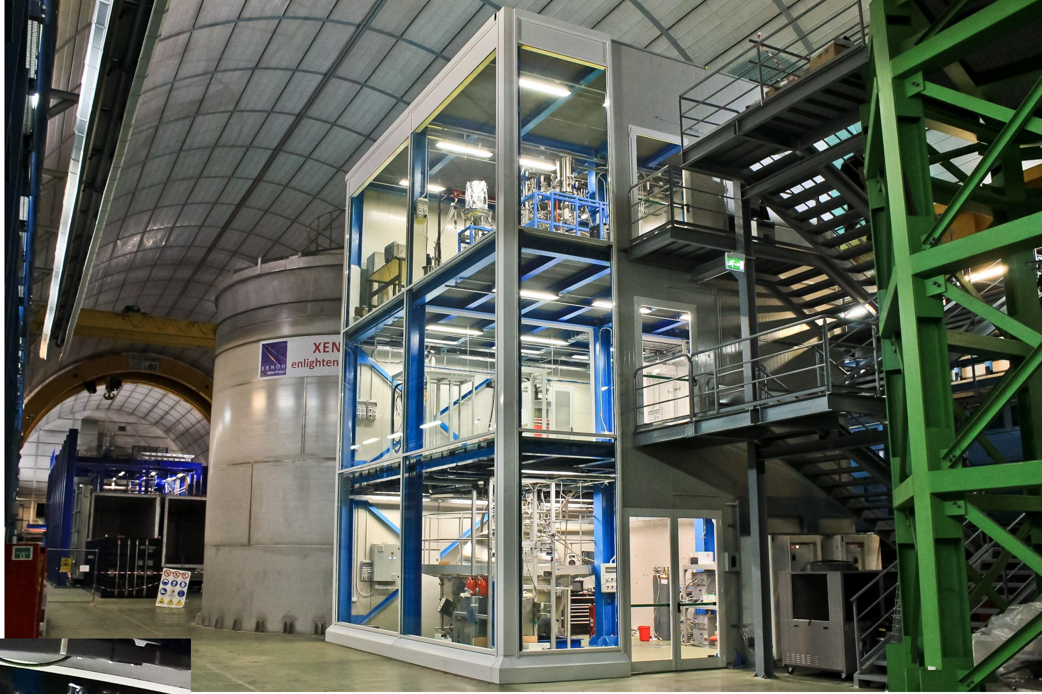


Outlook

- Liquid xenon TPCs are a competitive tool in the search for dark matter

- Data from multiple LXe TPCs excludes recently reported low-mass WIMP signals by several orders of magnitude

- Ton-scale LXe TPCs begin operation this year with XENON1T and continue in the next several years with XENONnT, LZ, and DARWIN



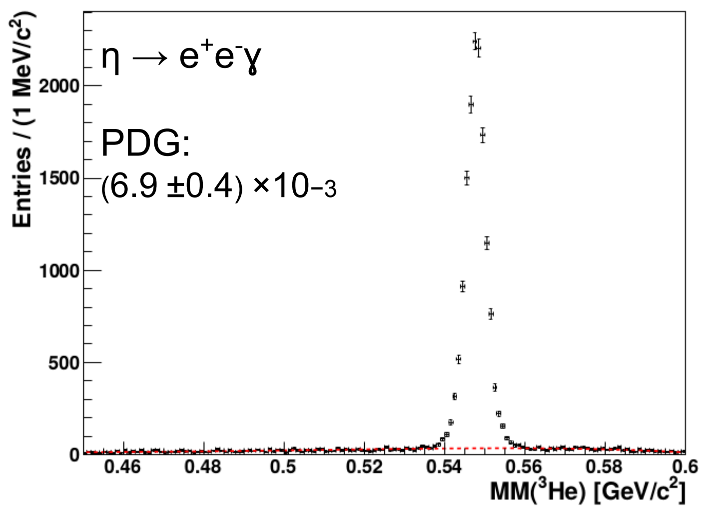
Advertisement - η decays with WASA-at-COSY

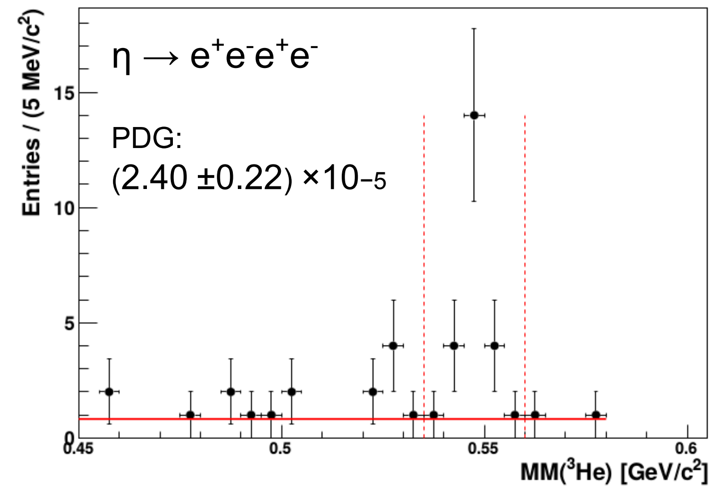
- We measure the branching ratios of four charged η decays
- Data is from 12 weeks running in $pd \to {}^3He\,\eta$
- A total of 3×10^7 η mesons exist in the dataset

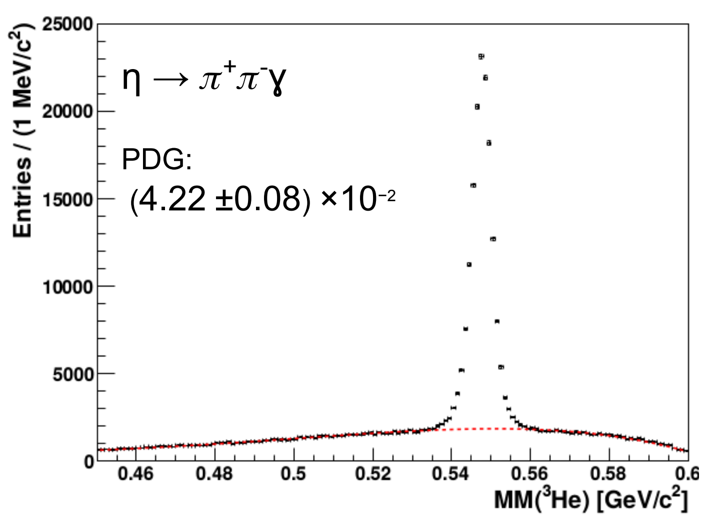
▼**Neutral modes**				
Γ_1	$\eta \to$ neutral modes	$(7.212 \pm .034) \times 10^{-1}$	S=1.2	
Γ_2	$\eta \to 2\gamma$	$(3.941 \pm .020) \times 10^{-1}$	S=1.1	274
Γ_3	$\eta \to 3\pi^0$	$(3.268 \pm .023) \times 10^{-1}$	S=1.1	179
Γ_4	$\eta \to \pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	S=1.1	257
Γ_5	$\eta \to 2\pi^0 2\gamma$	<1.2E-3	CL=90%	238
Γ_6	$\eta \to 4\gamma$	<2.8E-4	CL=90%	274
Γ_7	$\eta \to$ invisible	<1.0E-4	CL=90%	
▼**Charged modes**				
Γ_8	$\eta \to$ charged modes	$(2.810 \pm .034) \times 10^{-1}$		
Γ_9	$\eta \to \pi^+\pi^-\pi^0$	$(2.292 \pm .028) \times 10^{-1}$	S=1.2	174
Γ_{10}	$\eta \to \pi^+\pi^-\gamma$	$(4.22 \pm 0.08) \times 10^{-2}$	S=1.1	236
Γ_{11}	$\eta \to e^+e^-\gamma$	$(6.9 \pm 0.4) \times 10^{-3}$	S=1.3	274
Γ_{12}	$\eta \to \mu^+\mu^-\gamma$	$(3.1 \pm 0.4) \times 10^{-4}$	S=1.0	253
Γ_{13}	$\eta \to e^+e^-$	<5.6E-6	CL=90%	274
Γ_{14}	$\eta \to \mu^+\mu^-$	$(5.8 \pm 0.8) \times 10^{-6}$		253
Γ_{15}	$\eta \to 2e^+ 2e^-$	$(2.40 \pm 0.22) \times 10^{-5}$		274
Γ_{16}	$\eta \to \pi^+\pi^- e^+ e^- (\gamma)$	$(2.68 \pm 0.11) \times 10^{-4}$		235
Γ_{17}	$\eta \to e^+e^-\mu^+\mu^-$	<1.6E-4	CL=90%	253
Γ_{18}	$\eta \to 2\mu^+ 2\mu^-$	<3.6E-4	CL=90%	161
Γ_{19}	$\eta \to \mu^+\mu^-\pi^+\pi^-$	<3.6E-4	CL=90%	113
Γ_{20}	$\eta \to \pi^+ e^- \overline{\nu}_e$ + c.c.	<1.7E-4	CL=90%	256
Γ_{21}	$\eta \to \pi^+\pi^- 2\gamma$	<2.1E-3		236
Γ_{22}	$\eta \to \pi^+\pi^-\pi^0\gamma$	<5E-4	CL=90%	174
Γ_{23}	$\eta \to \pi^0\mu^+\mu^-\gamma$	<3E-6	CL=90%	210

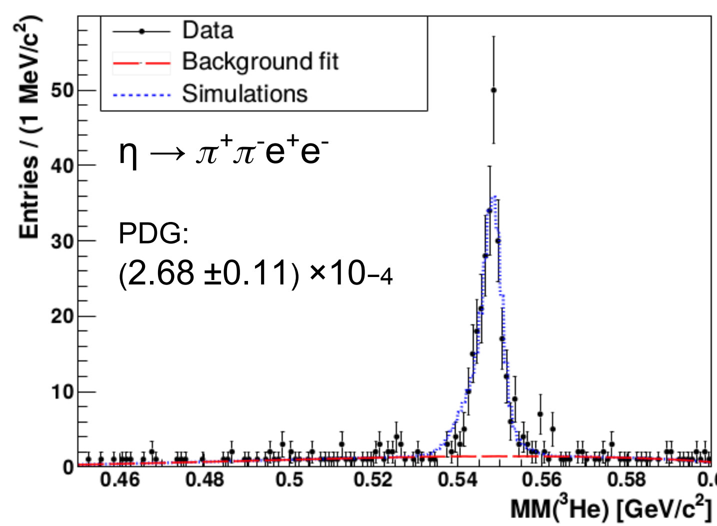
Advertisement - η decays with WASA-at-COSY

- Common analysis steps were used for all channels
- Clean samples are extracted and normalized to $\eta \to \pi^+\pi^-\pi^0$
- Competitive statistics are available in all channels





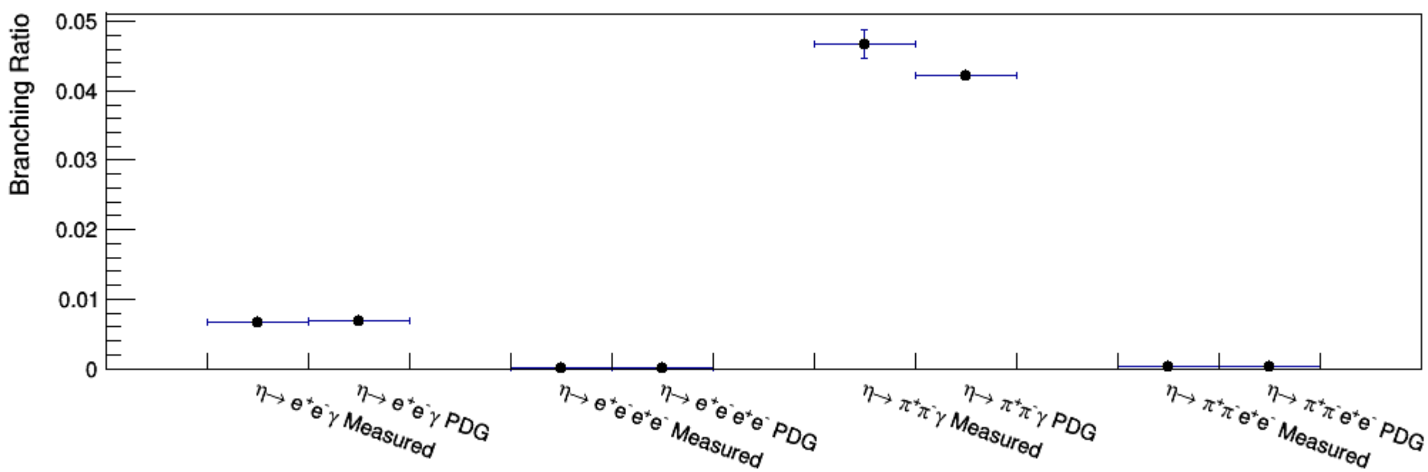




Advertisement - η decays with WASA-at-COSY

- Branching ratios in agreement with PDG
- Slight discrepancy in $\eta \to \pi^+\pi^-\gamma$ compared to KLOE result
- A larger dataset exists in proton-proton reactions and is under analysis
- Keep an eye out for the proton-deuteron paper in the coming month

Channel	Statistics Collected (signal)
$\eta \to e^+e^-\gamma$	(14,040 ± 120)
$\eta \to e^+e^-e^+e^-$	(18.4 ± 4.9)
$\eta \to \pi^+\pi^-\gamma$	(139, 760 ± 430)
$\eta \to \pi^+\pi^-e^+e^-$	(251 ± 17)



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