Searching for Dark Matter with XENON1T

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IFIRSE Seminar
February 2021

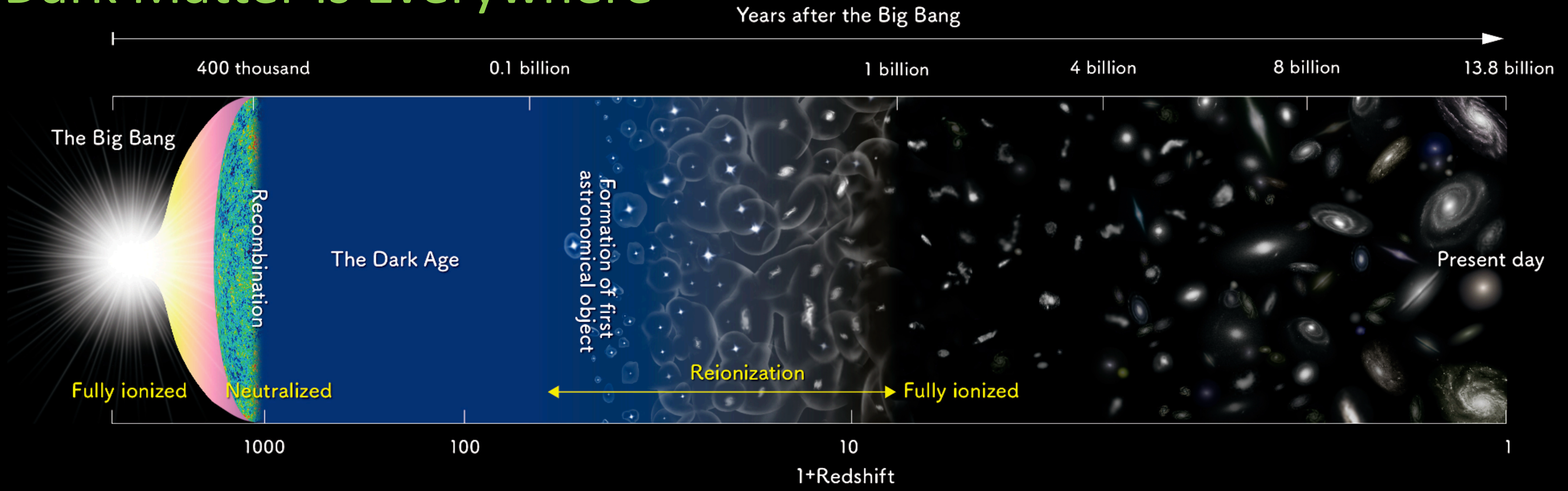
ArXiv:2006.09721

Guiding Questions

- What do we know about Dark Matter?
- What is the XENON1T Dark Matter Detector?
- What have we learned from XENON1T?
- What’s next?

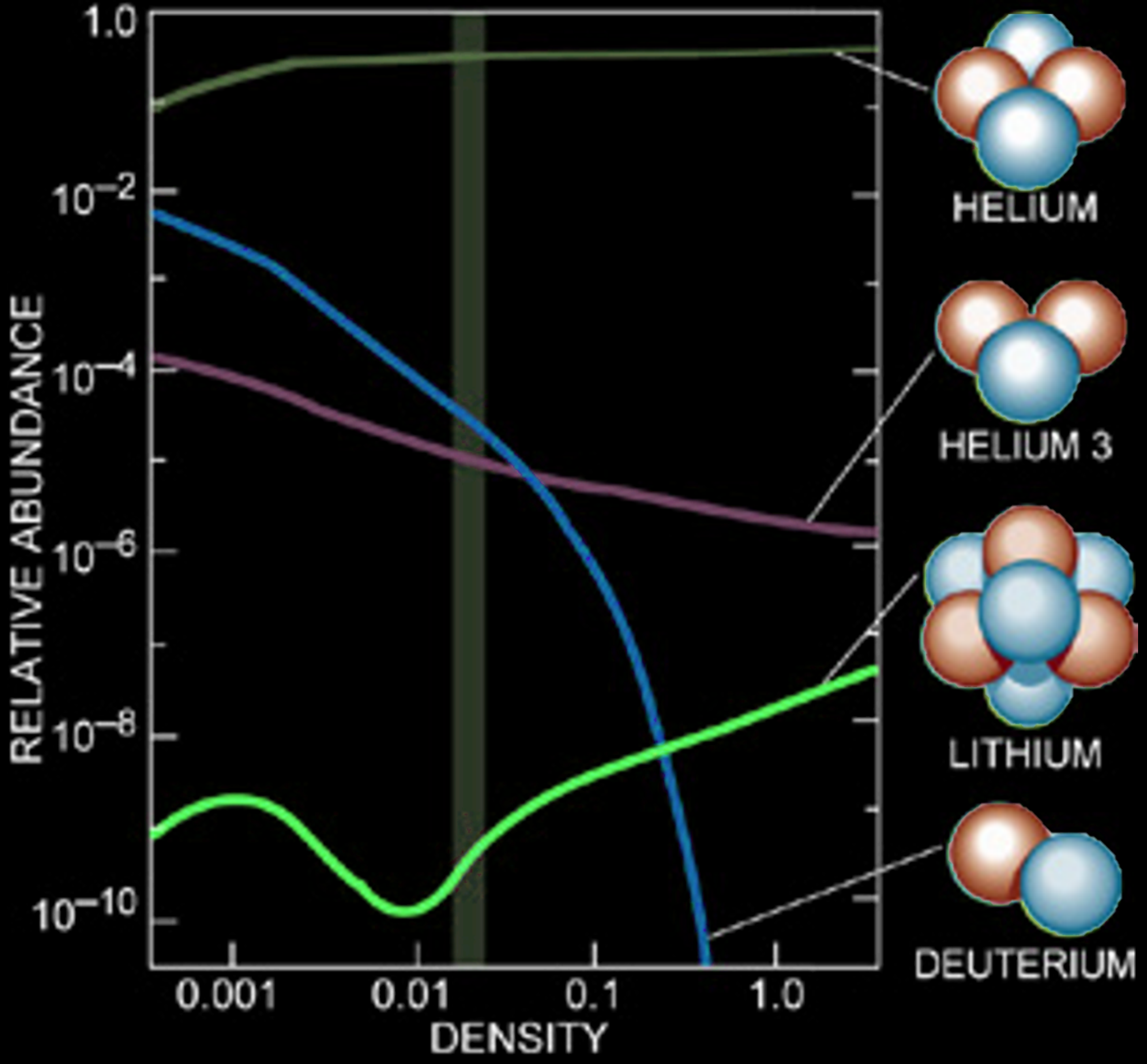
Volanski, Tomer. “Dark Matter; Theory and Practice.” Phenomenology Symposium 2018.

Dark Matter is Everywhere



The evolution of the Universe indicates that it is shaped by invisible matter uncoupled (or very weakly coupled) to normal matter. Our current best model is the ΛCDM Model.

The relative abundance of light atoms formed after the Big Bang via nucleosynthesis indicates that only a few percent of matter is in atoms.

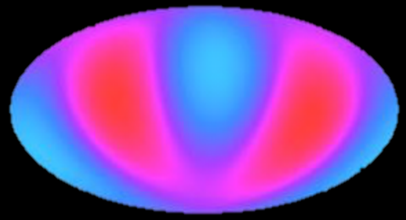


http://w.astro.berkeley.edu/~mwhite/darkmatter/altbbn.jpg

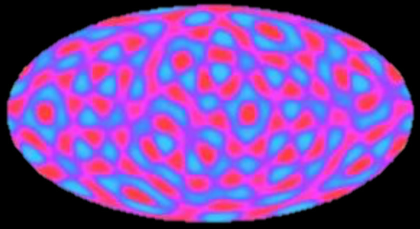
CMB Fluctuations

https://wiki.cosmos.esa.int/planckpla2015/images/thumb/2/2f/A15_TT.png/800px-A15_TT.png

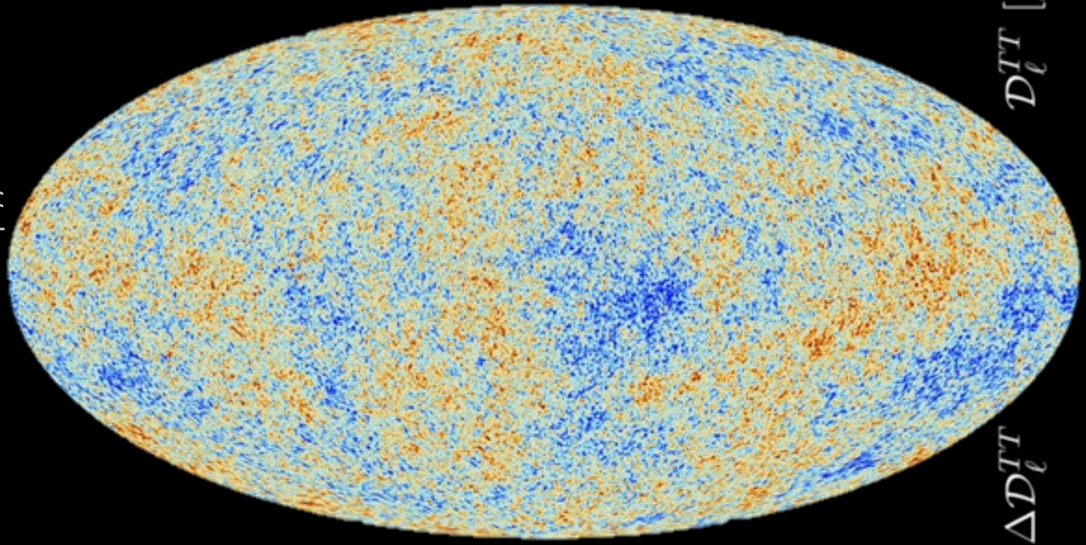
http://www.astro.ucla.edu/~wright/CMB-DT.html



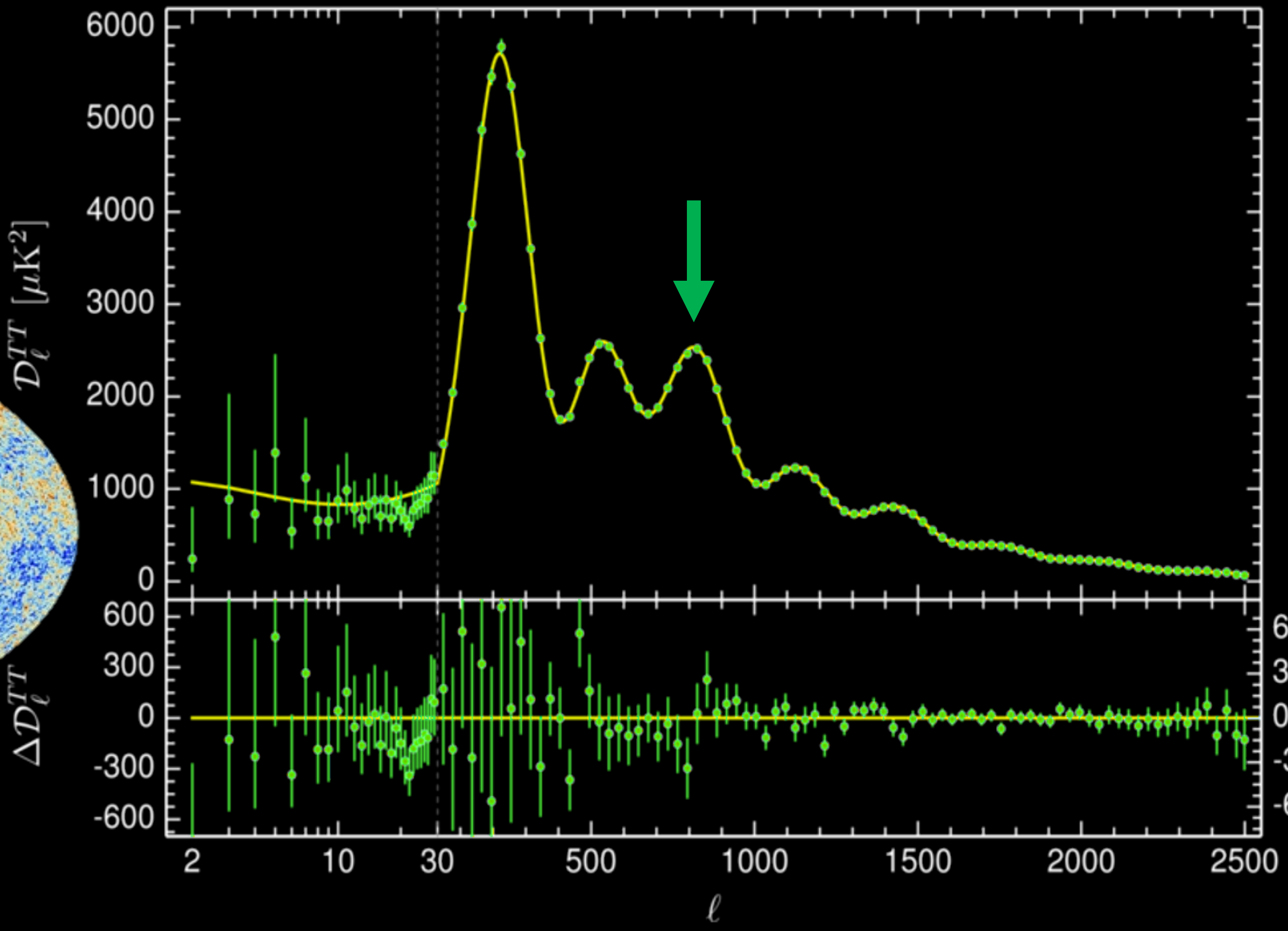
$\ell = 2$



$\ell = 16$

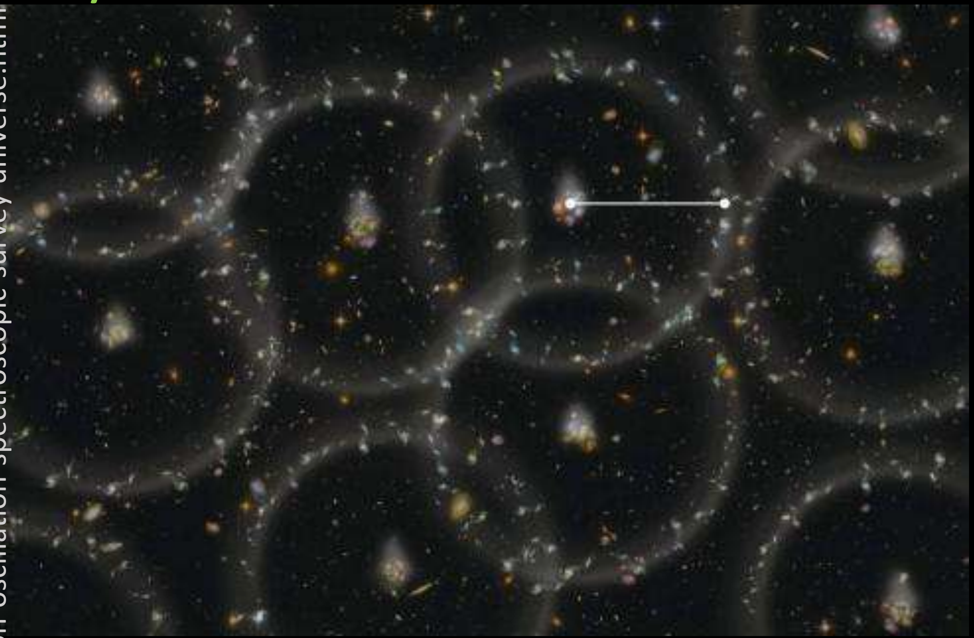


European Space Agency, Planck Collaboration



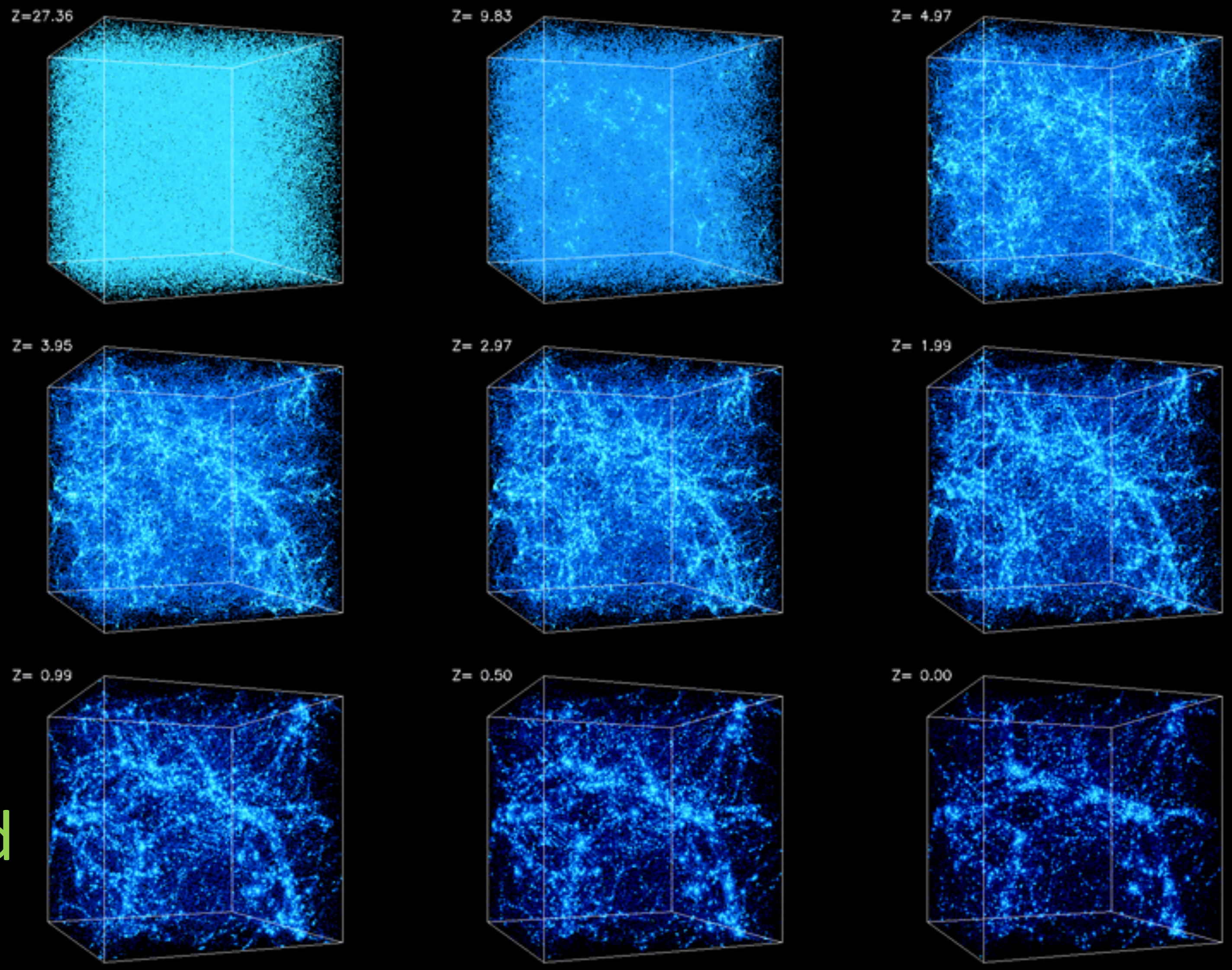
Temperature anisotropies in the Cosmic Microwave Background indicate baryon acoustic oscillations and a significant amount of matter that cannot interact electromagnetically.

Baryon Acoustic Oscillations and Structure Formation



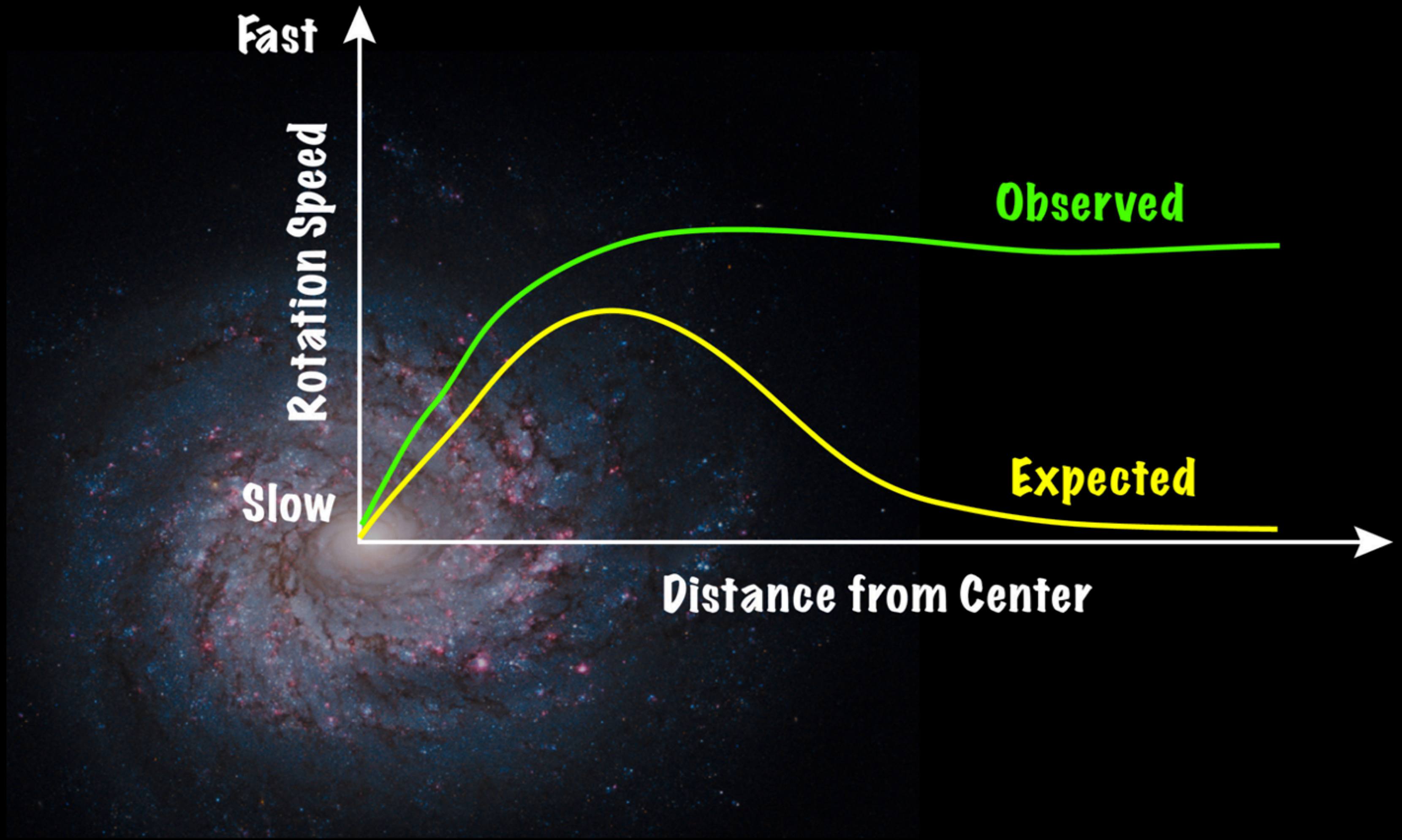
https://phys.org/news/2014-01-baryon-oscillation-spectroscopic-survey-universe.html

http://cosmicweb.uchicago.edu/filaments.html



Echos of the CMB baryonic acoustic oscillations persist through time, observable in structure formation controlled by the distribution of dark matter.

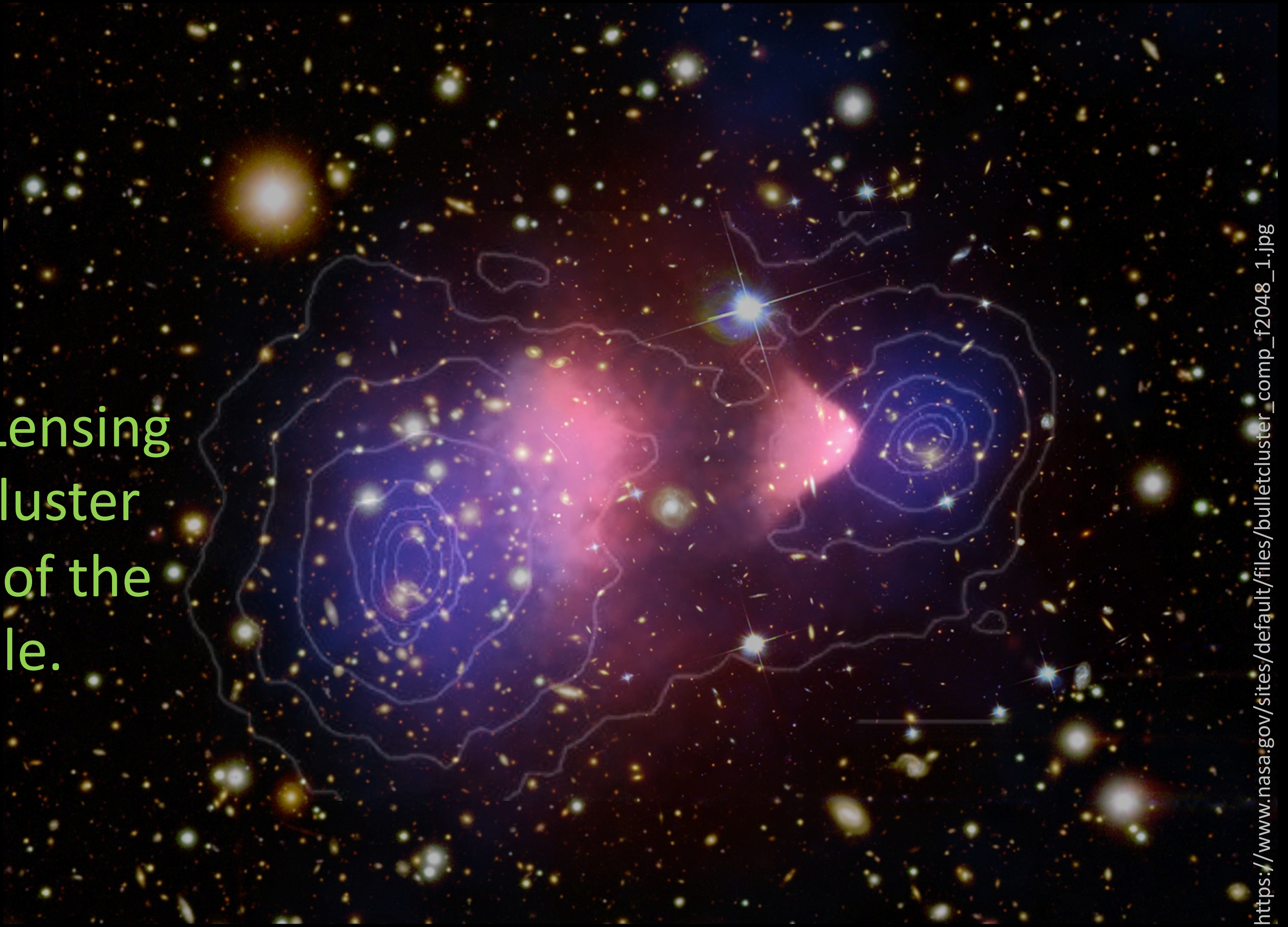
Rotation Curves of Galaxies



https://resonance.is/wp-content/uploads/galaxyrotationcurve.jpg

The mass in a galaxy determines the velocities of orbiting matter.

Observed velocities indicate significantly more mass than observations see.

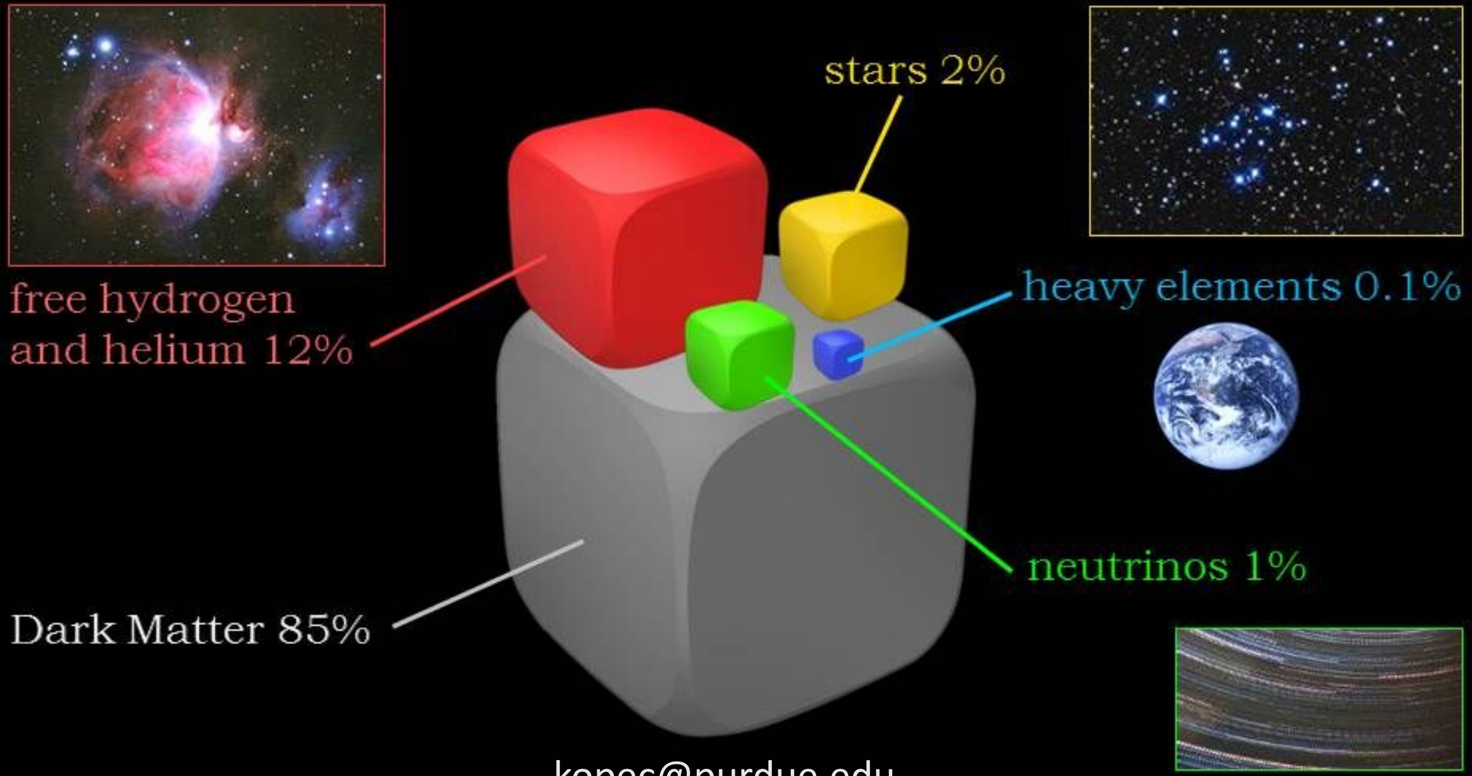


Weak Gravitational Lensing around the bullet cluster indicates that most of the mass is not visible.

https://www.nasa.gov/sites/default/files/bulletcluster_comp_f2048_1.jpg

Summary of Dark Matter

- Very stable
- Non-relativistic
- Accounts for ~85% of the Universe’s Mass and ~25% of the Energy
- No (or weak) coupling to regular baryonic matter beyond Gravity
- ~90 orders of magnitude to search: 10^{-21} to 10^{66} eV.



The XENON Collaboration

Columbia | KIT | Nikhef | Muenster | Stockholm | Mainz | MPIK, Heidelberg | Freiburg | Zurich

Chicago

UCSD

Rice

Purdue

Tsinghua

Tokyo

Nagoya

Kobe

Subatech | Coimbra | LPNHE | Torino | Bologna | L'Aquila | LNGS | Napoli | Weizmann | NYUAD

Last Collaboration Meeting in person, December 2019

Last Collaboration Meeting during COVID, December 2020

The XENON Experiments to Date

XENON10
2.4 kg×yr
15cm
10^{-43}

XENON100
81 kg×yr
30cm
10^{-45}

XENON1T
1 t×yr
1m
10^{-47}

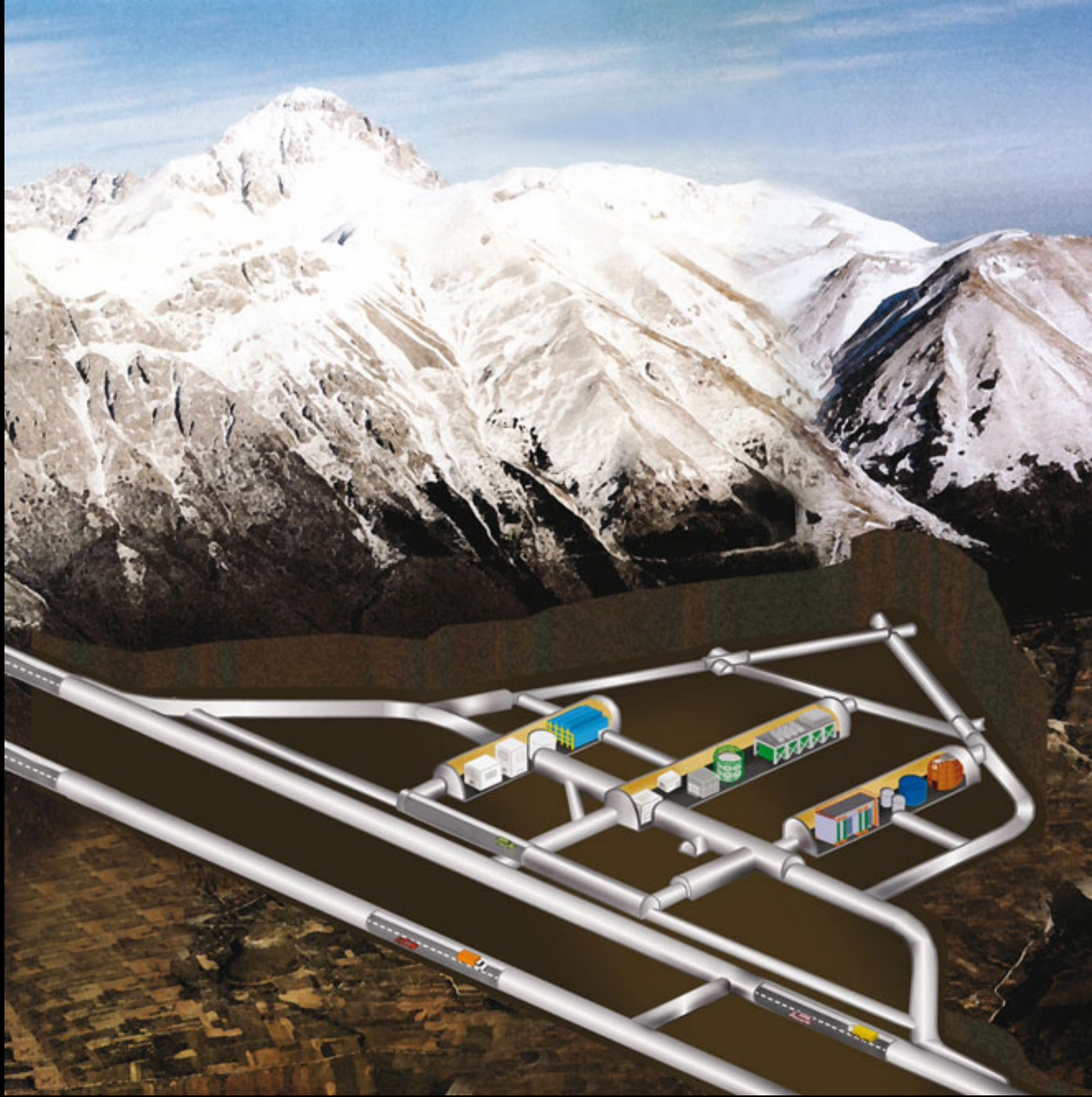
XENONnT
20 t×yr
1.5m
10^{-48}

Deep Under a Mountain in Italy

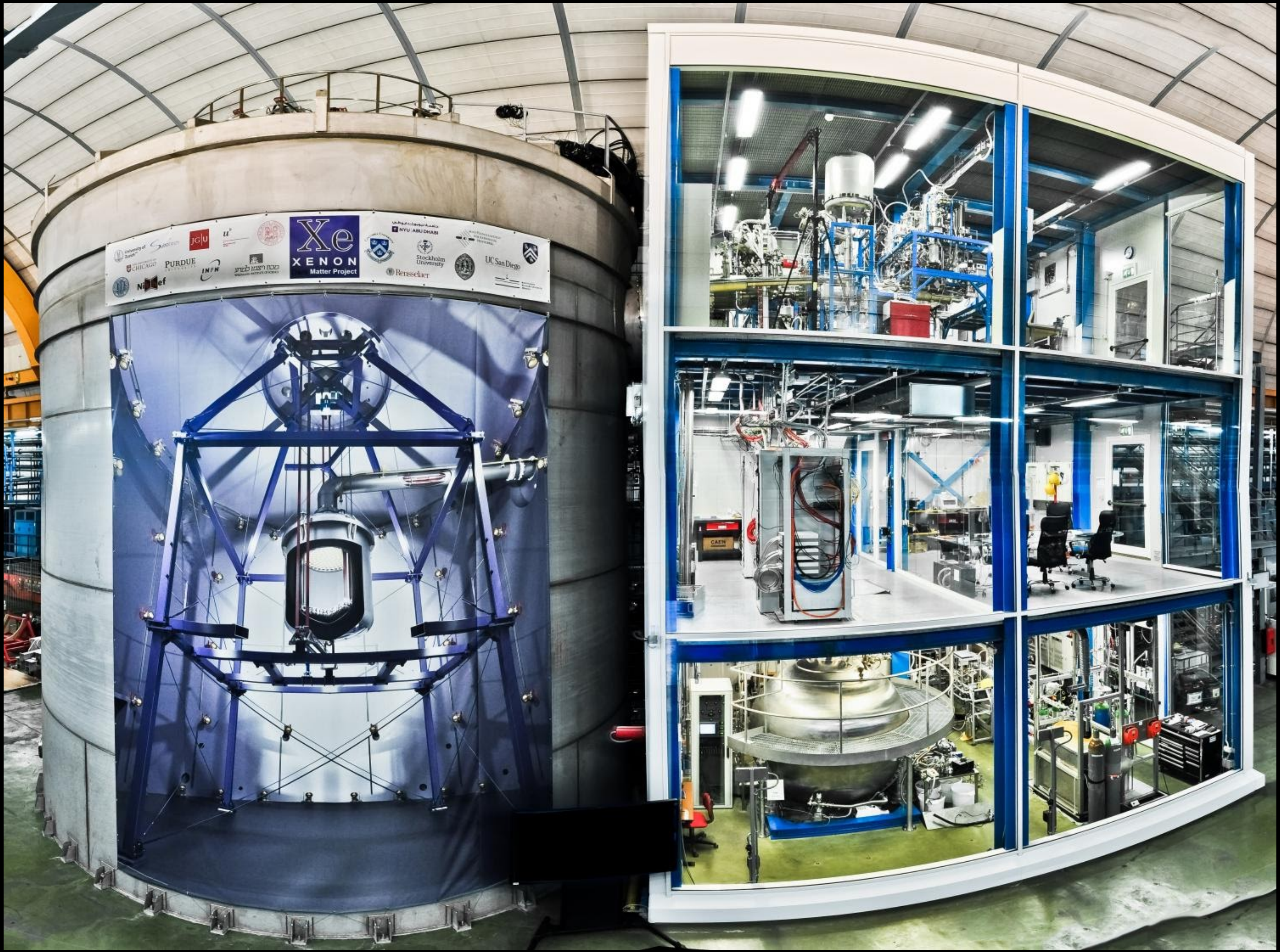
LNGS – Hall B

1.5 km Rock overburden

3.6 km water equivalent



Water
Cherenkov
Muon Veto

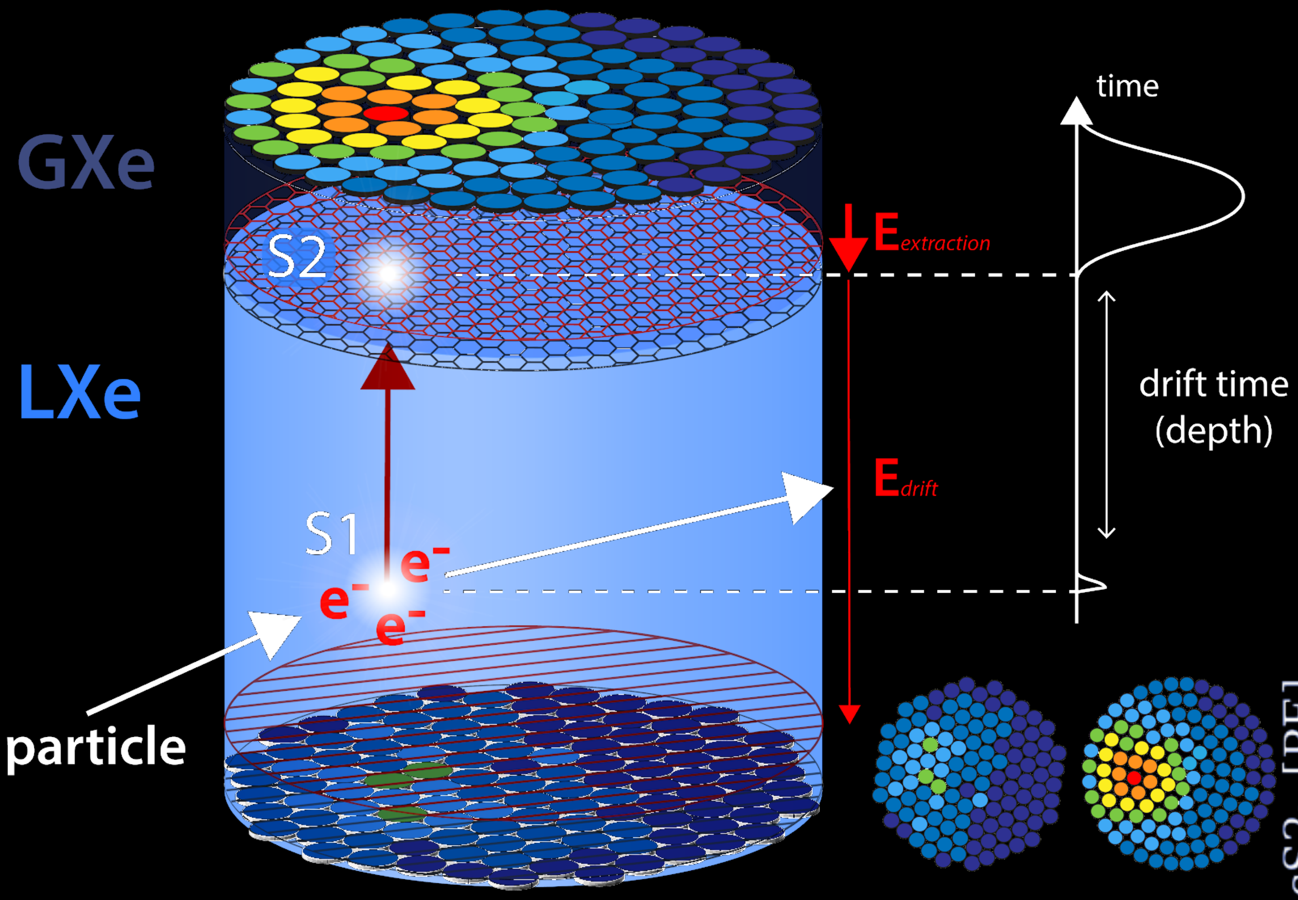


Purification &
Operations

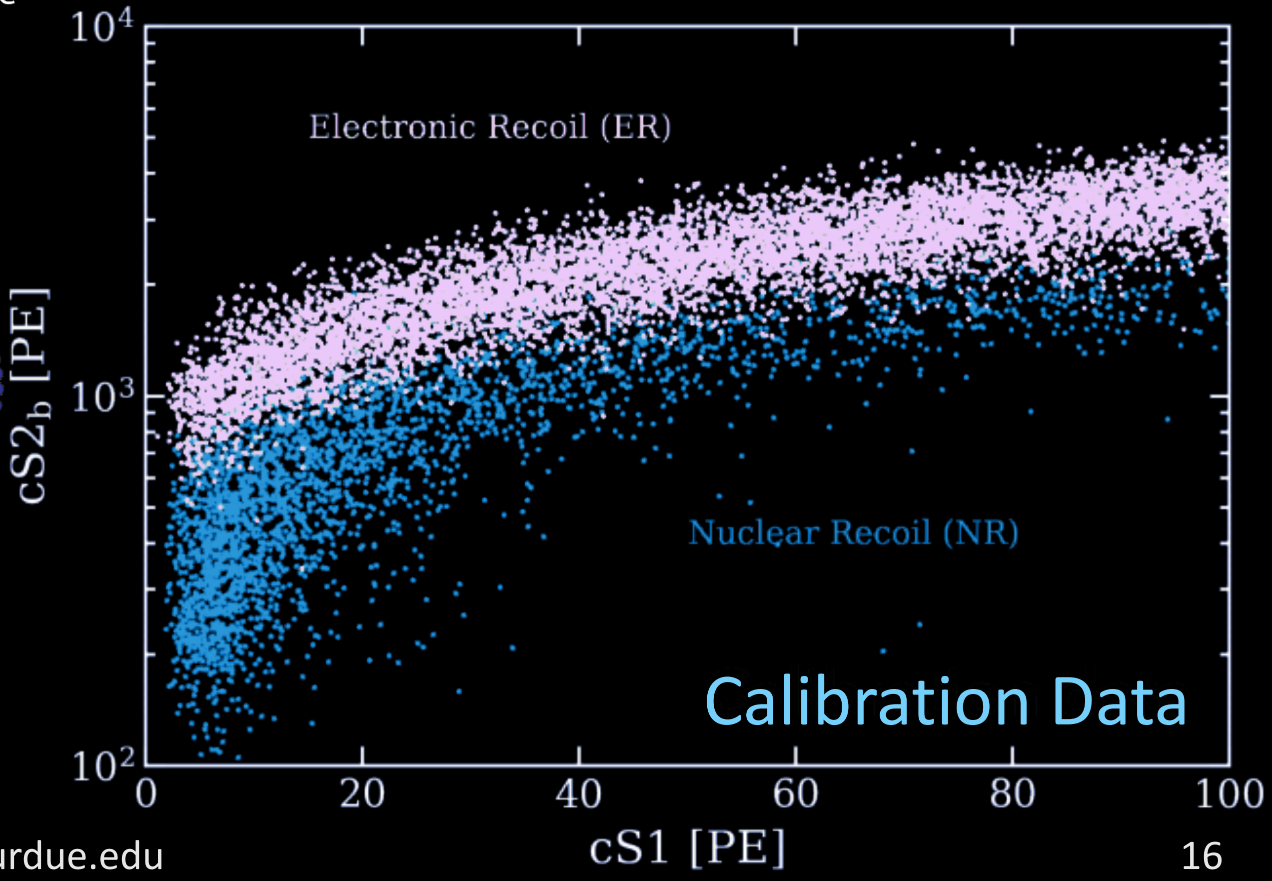
DAQ &
Shifter Room

Xenon
Storage

A Time Projection Chamber (TPC)



Interaction gives prompt scintillation (S1) and drifting electrons that later proportionally scintillate in the gas (S2).



The relative sizes of an S1 to its S2 can differentiate Nuclear and Electronic Recoils.

Why Xenon?

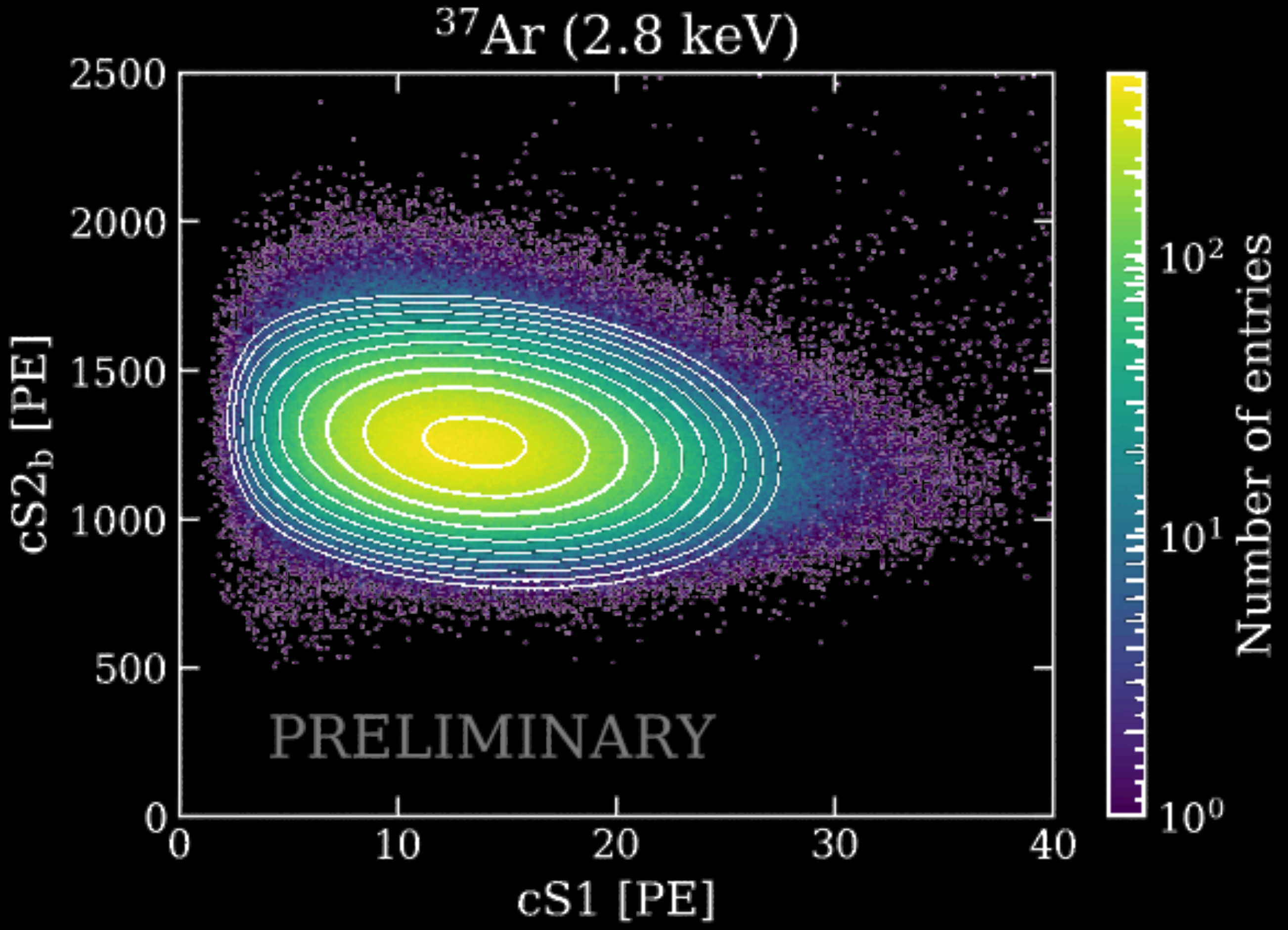
- 130 GeV nucleus → 100 GeV WIMP → easy kinematics
- Stable → low background
- Self-shielding → fiducial volume with low outgassing contamination
- Noble element → non-reactive and easy to purify with a getter
- 172nm Scintillator → a good wavelength for photosensors
- Liquid temperatures -100℃ → easy "cryogenics"

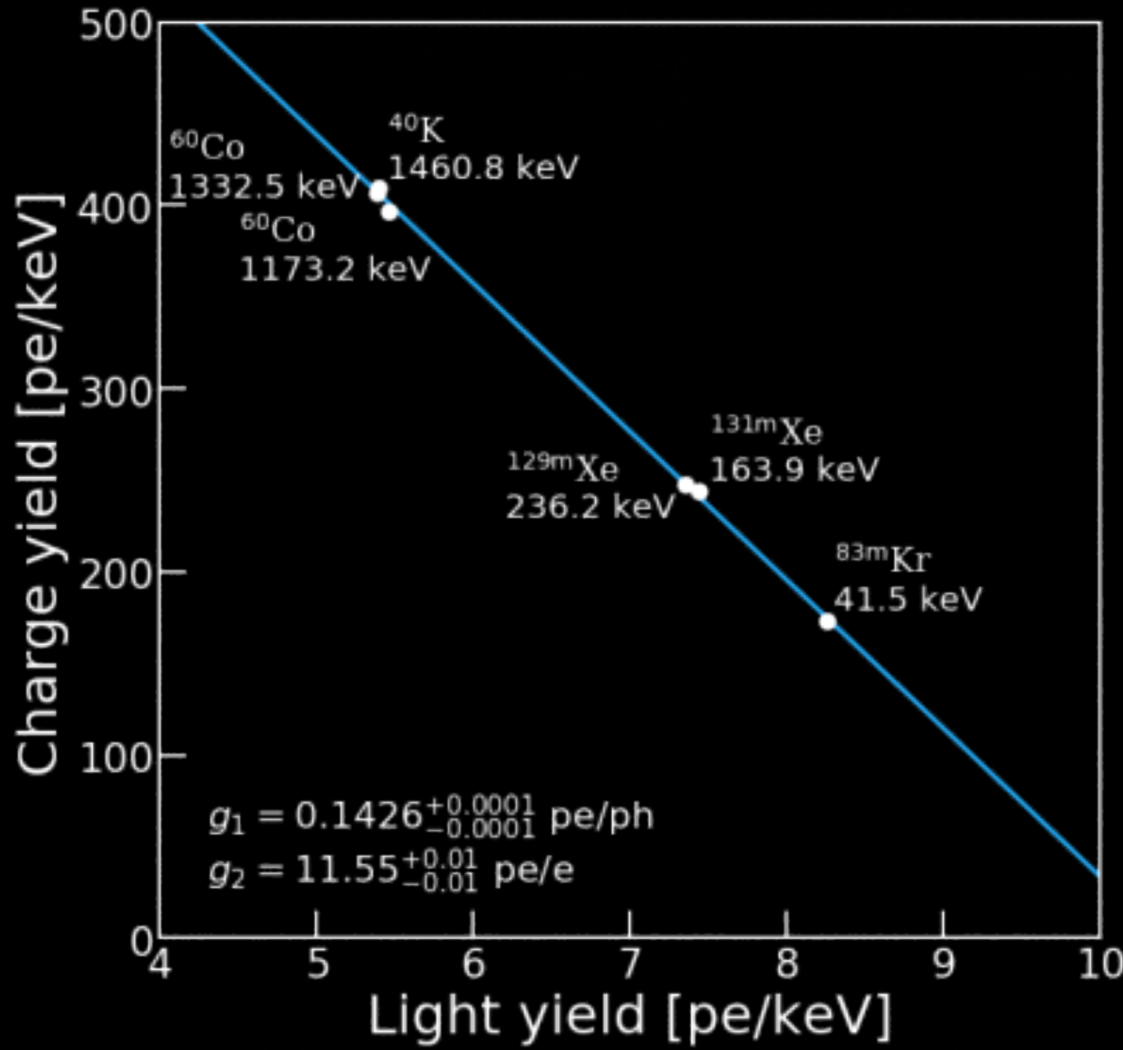
Why a dual phase TPC?

- Gas gap for proportional scintillation → single ionization electron threshold *(technically)*
- Efficient S2 measurement → NR/ER Discrimination and better Energy Resolution
- Bright S2s → Good (x,y) position reconstruction

Energy Calibration

$$E = W\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$





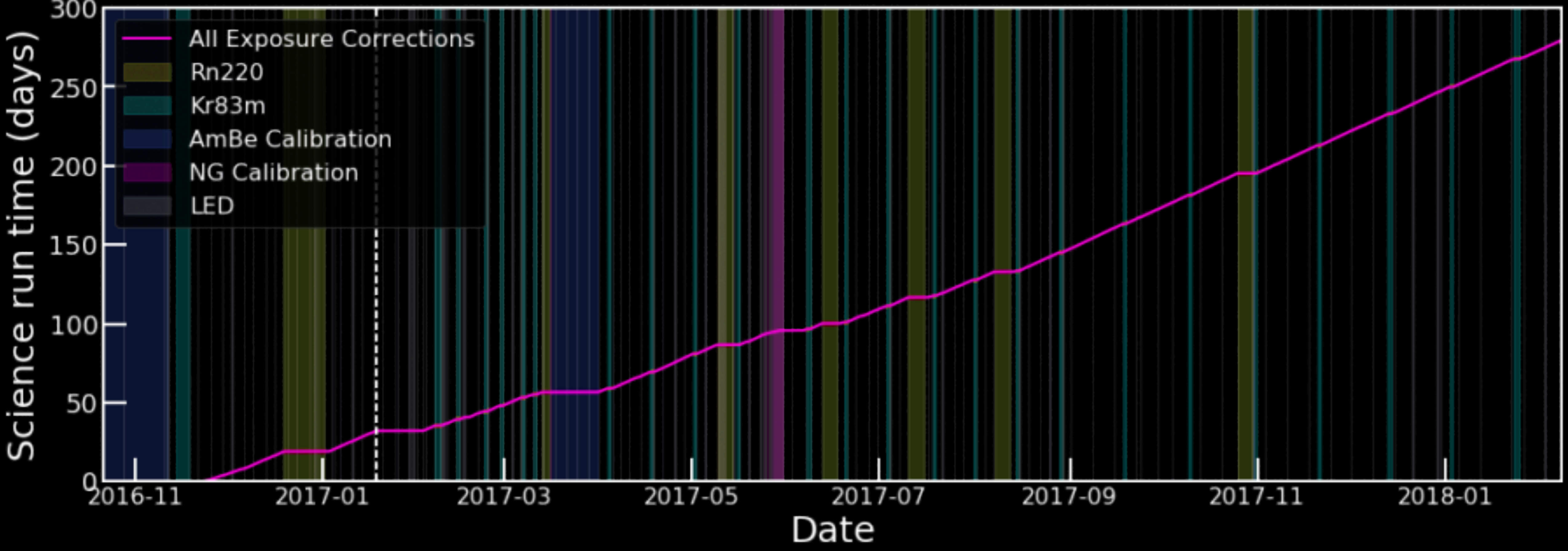
A Prolific Experiment

XENON1T produced a wealth of Science data:

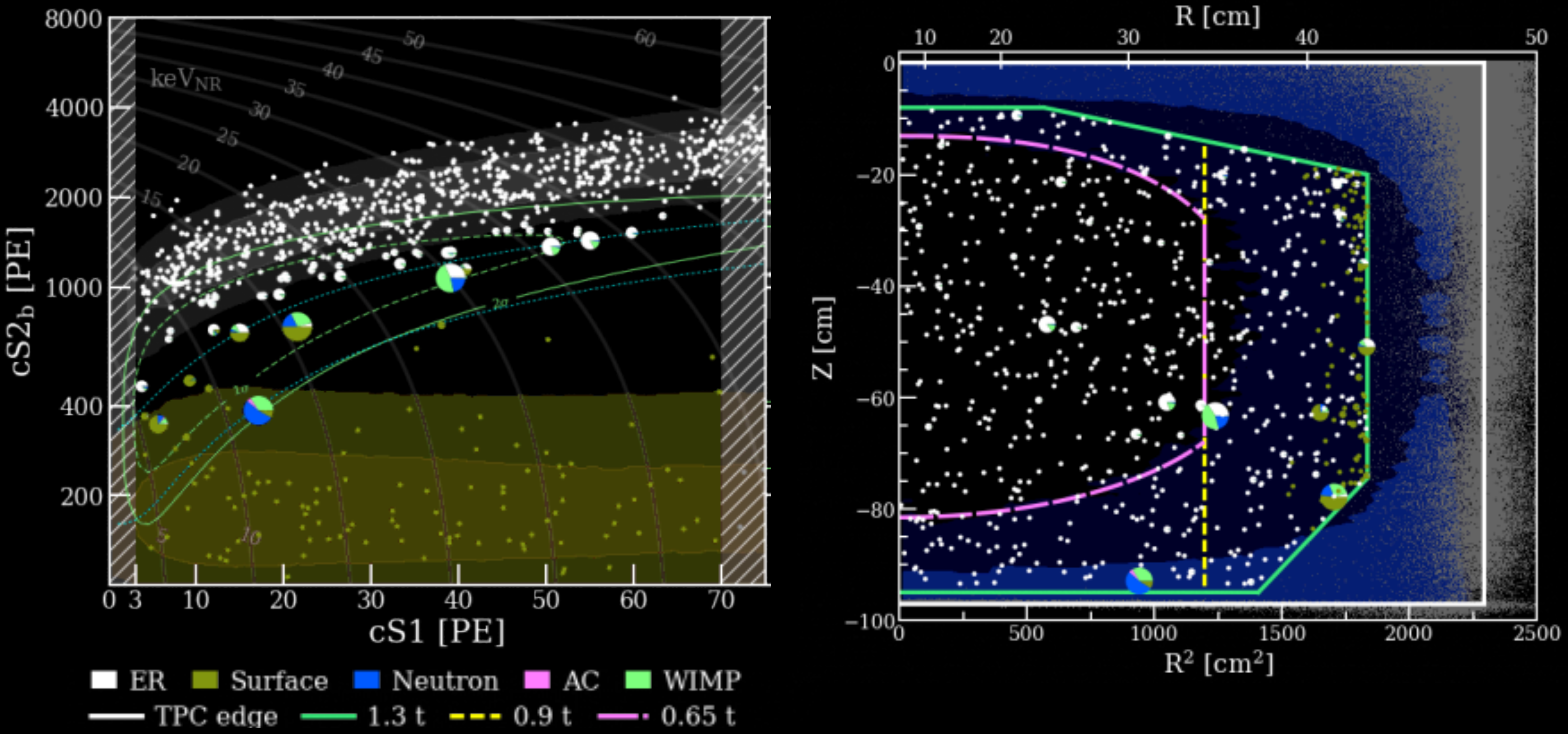
1705.06655 - First Dark Matter Search Results from the XENON1T Experiment
1805.12562 - Dark Matter Search Results from a One Tonne×Year Exposure of XENON1T
1811.12482 - First results on the scalar WIMP-pion coupling, using the XENON1T experiment
1902.03234 - Constraining the Spin-Dependent WIMP-Nucleon Cross Sections with XENON1T
1904.11002 - First observation of two-neutrino double electron capture in 124Xe with XENON1T
1907.11485 - Light Dark Matter Search with Ionization Signals in XENON1T
1907.12771 - Search for Light Dark Matter Interactions Enhanced by the Migdal effect or Bremsstrahlung in XENON1T
2006.09721 - **Excess Electronic Recoil Events in XENON1T**
2011.10431 - Search for inelastic scattering of WIMP dark matter in XENON1T
2012.02846 - Search for coherent elastic scattering of solar 8B neutrinos in the XENON1T dark matter experiment

Data - 279 Live Days

|--------SR0--------|------------------------------------SR1--|



Spin-Independent WIMP Search Results



ArXiv: 1805.12562

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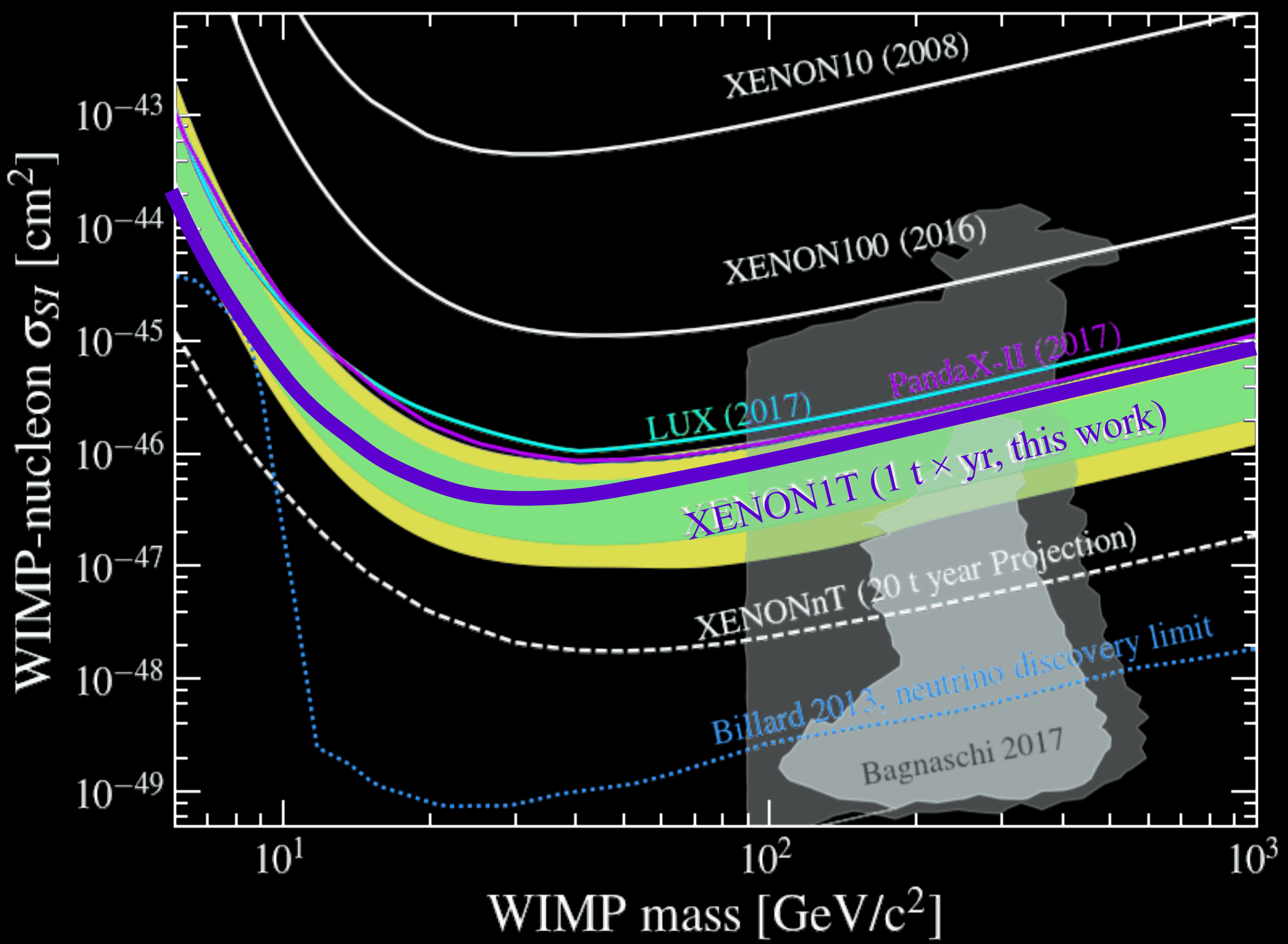
Spin-Independent WIMP Search Results



1.3 tonne fiducial mass

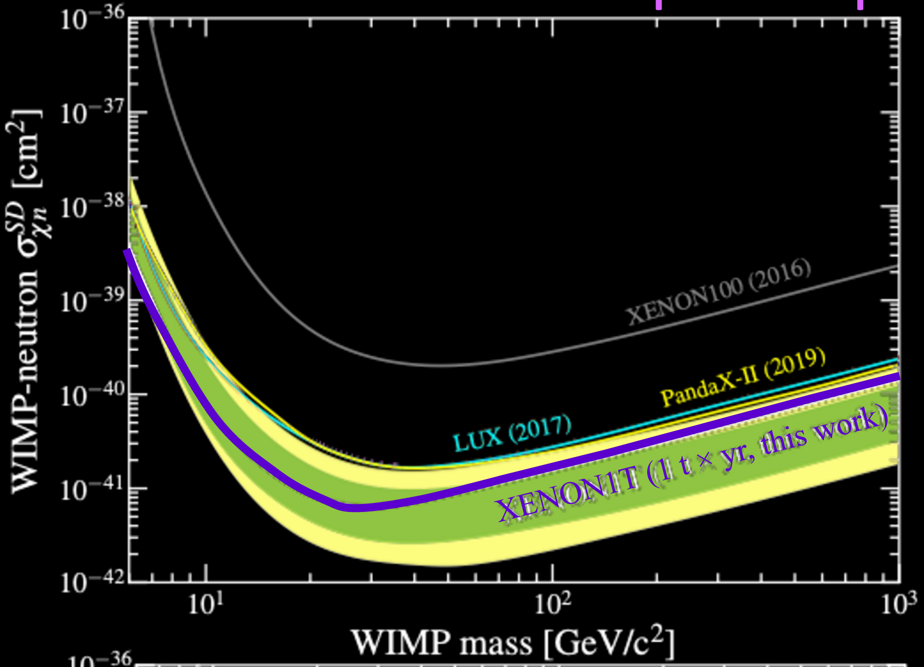
World-leading cross-section:

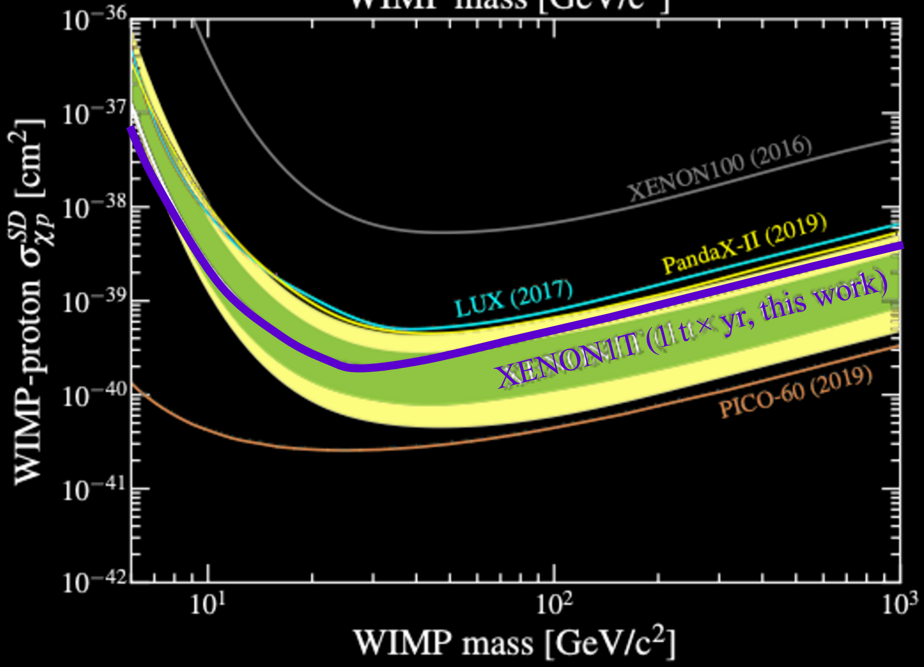
4.1×10^{-47} cm^2 at 30 GeV/c2

ArXiv: 1805.12562

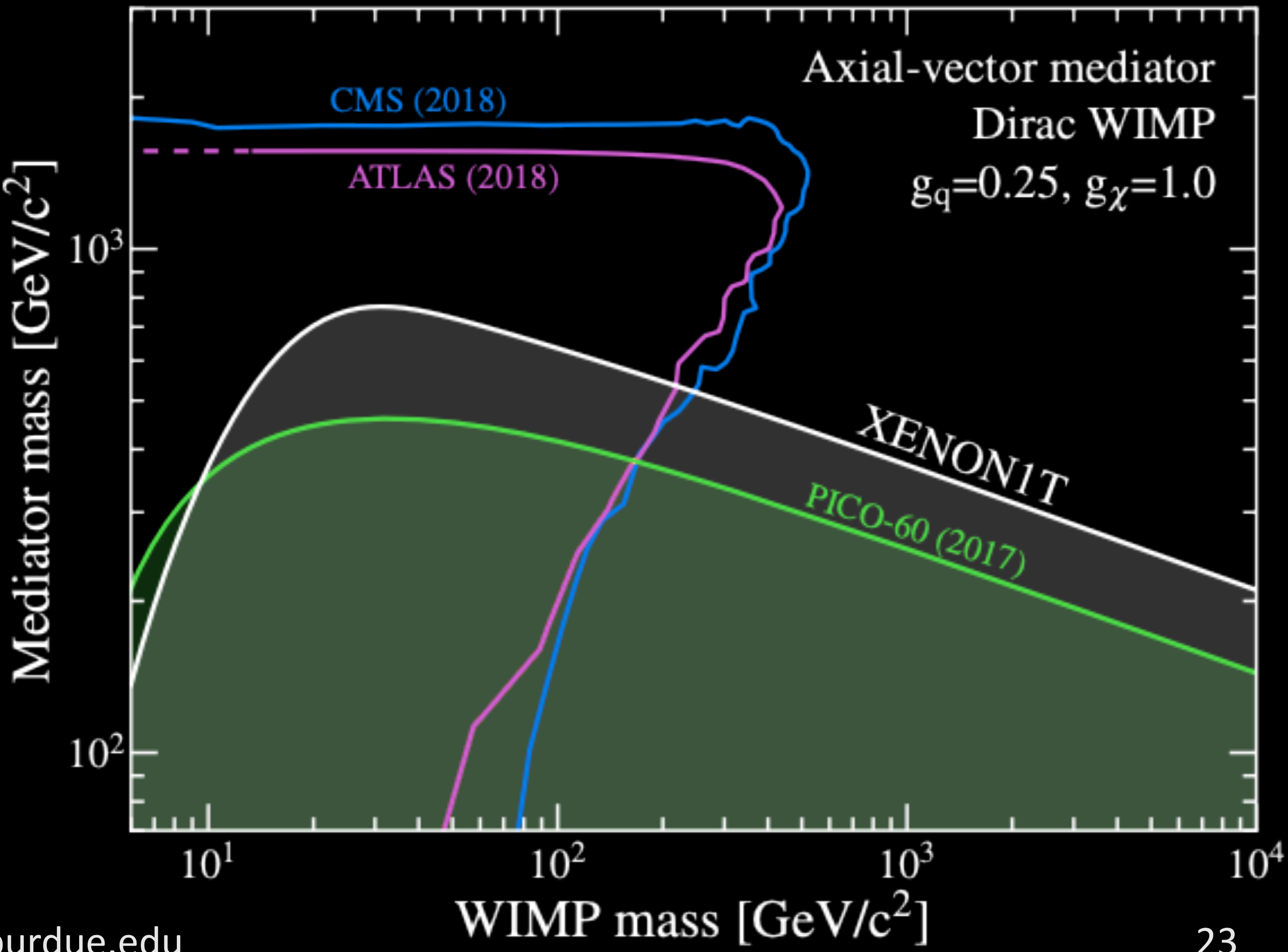
ArXiv: 1902.03234

Spin-Dependent WIMP Search Results





Decent for WIMP-neutron, better at higher masses than the LHC.



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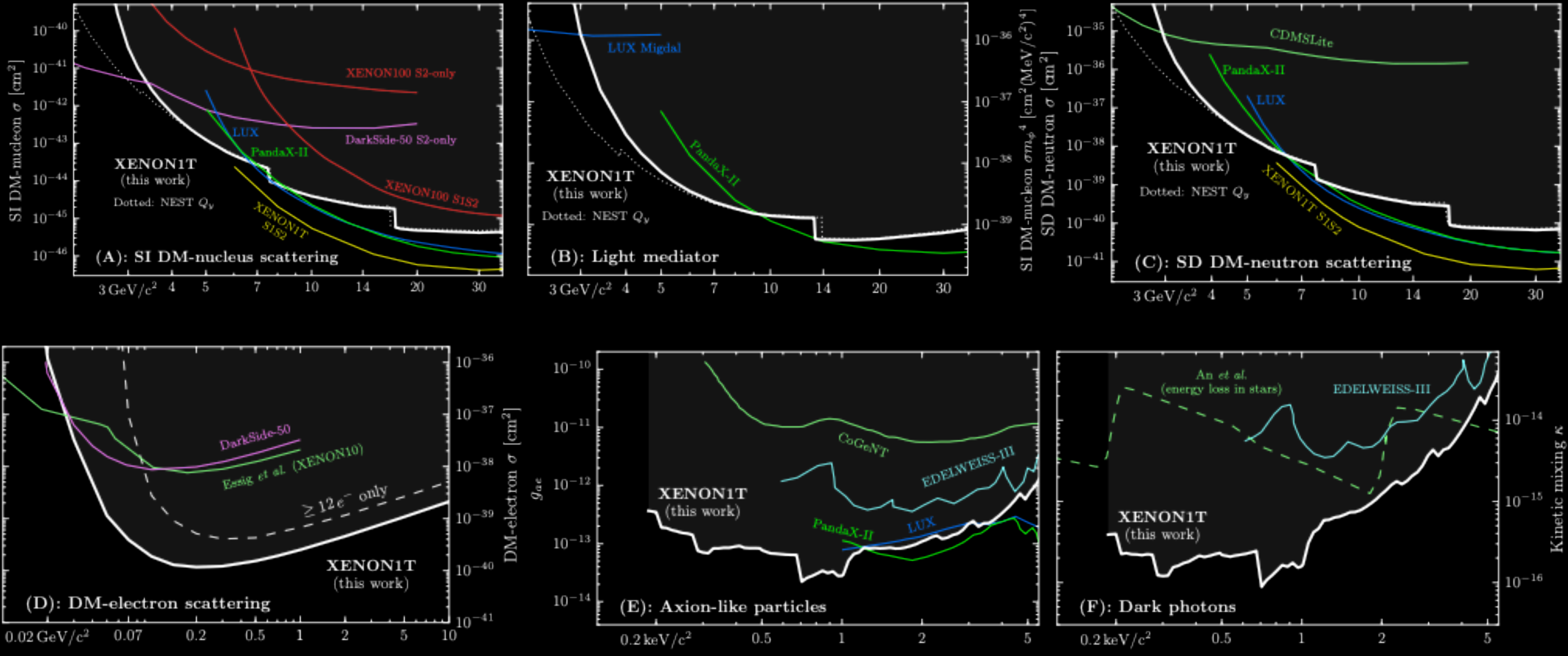
Light Dark Matter Search Results



ArXiv: 1907.11485

kopec@purdue.edu

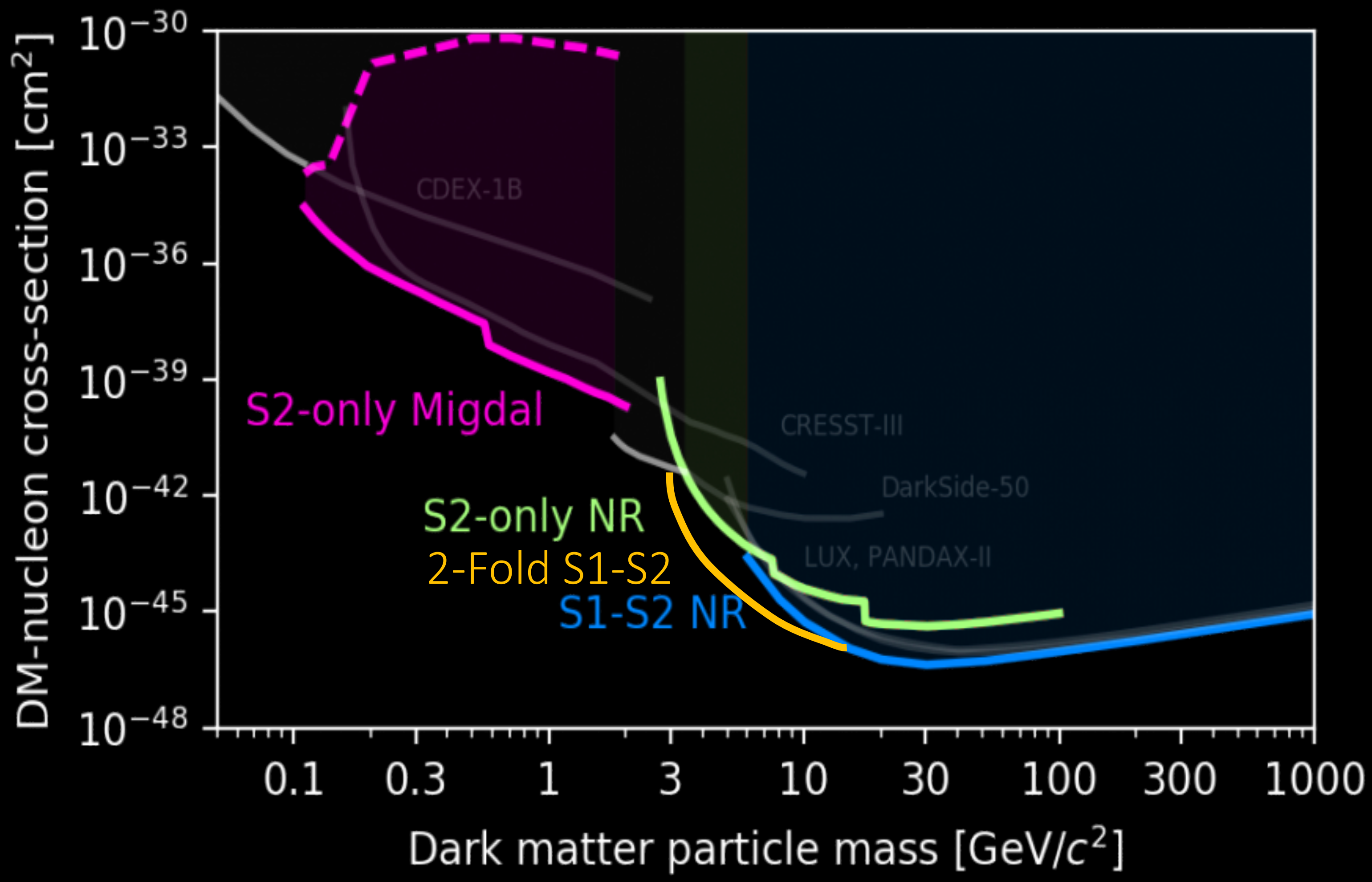
Light Dark Matter Search Results

ArXiv: 1907.12771

ArXiv: 1907.11485

ArXiv: 2012.02846

ArXiv: 1805.12562



The lowest background S2 rates achieved in a Lxe TPC ~mHz for S2s ≳100PE

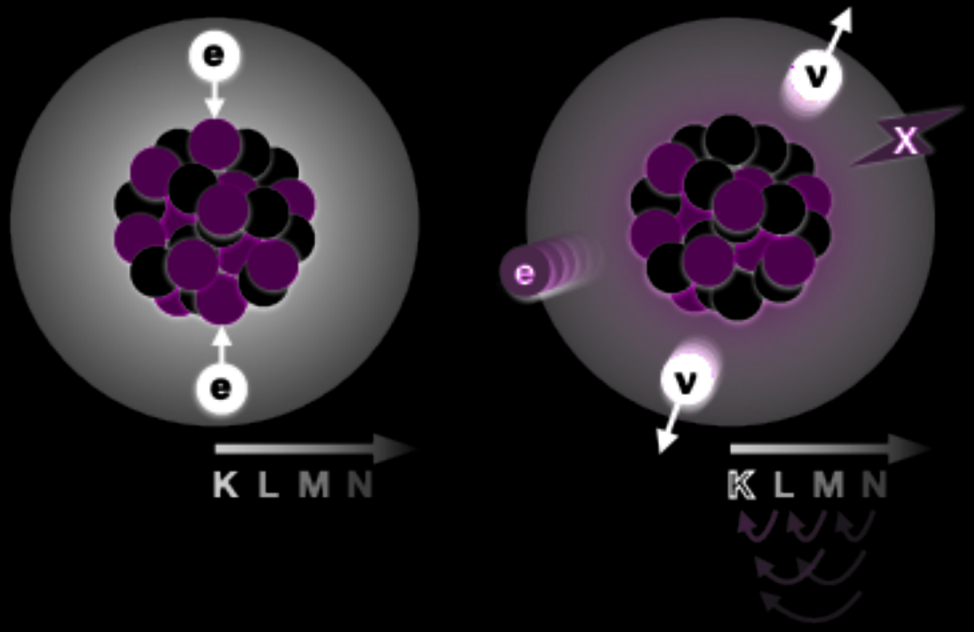
Rarest Decay Process Directly Measured!

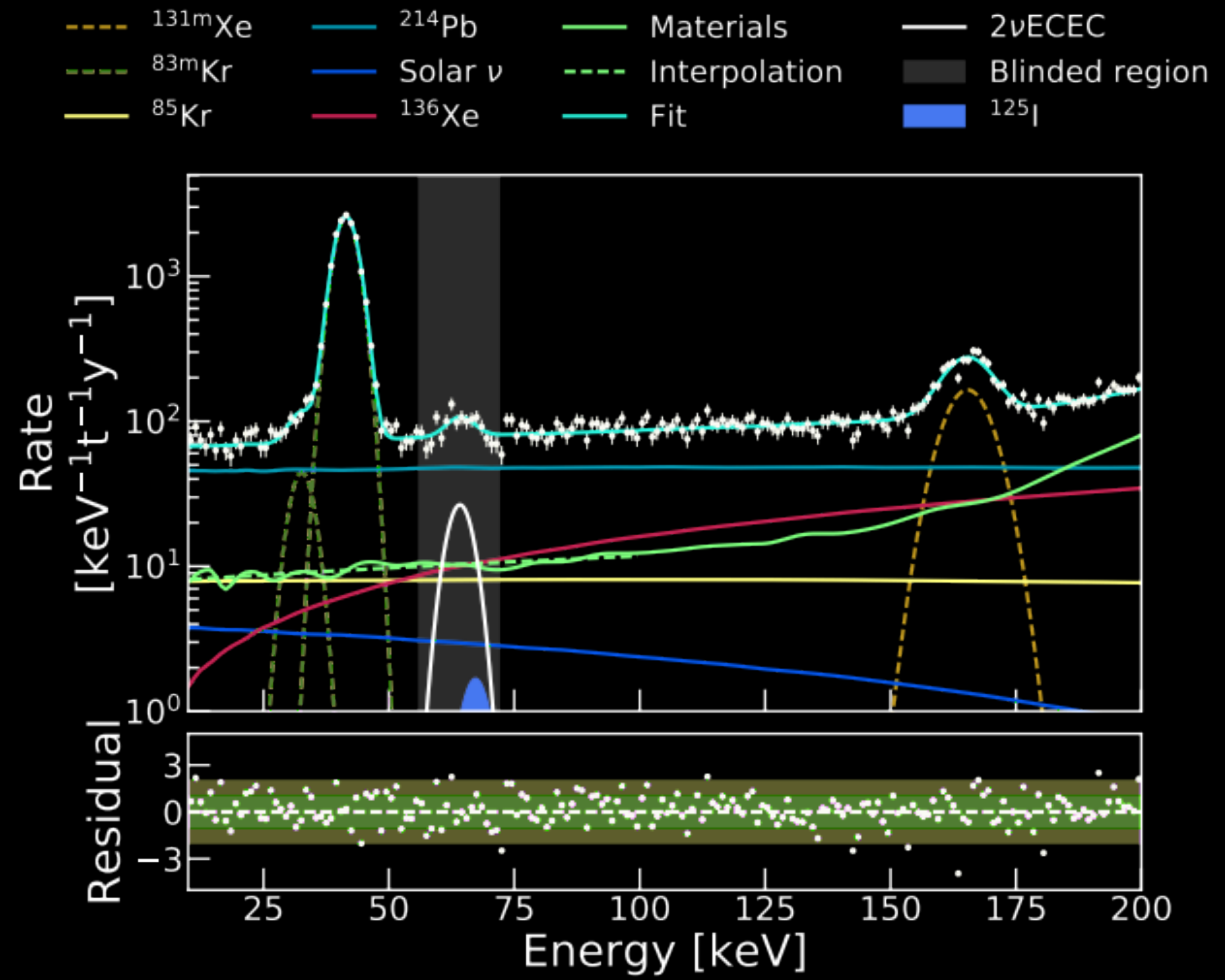
2-Neutrino Double Electron Capture

$^{124}Xe \rightarrow {}^{124}Te$

$T^{2\nu ECEC}_{1/2} = (1.8 \pm 0.5_{stat} \pm 0.1_{sys}) \times 10^{22}$ y

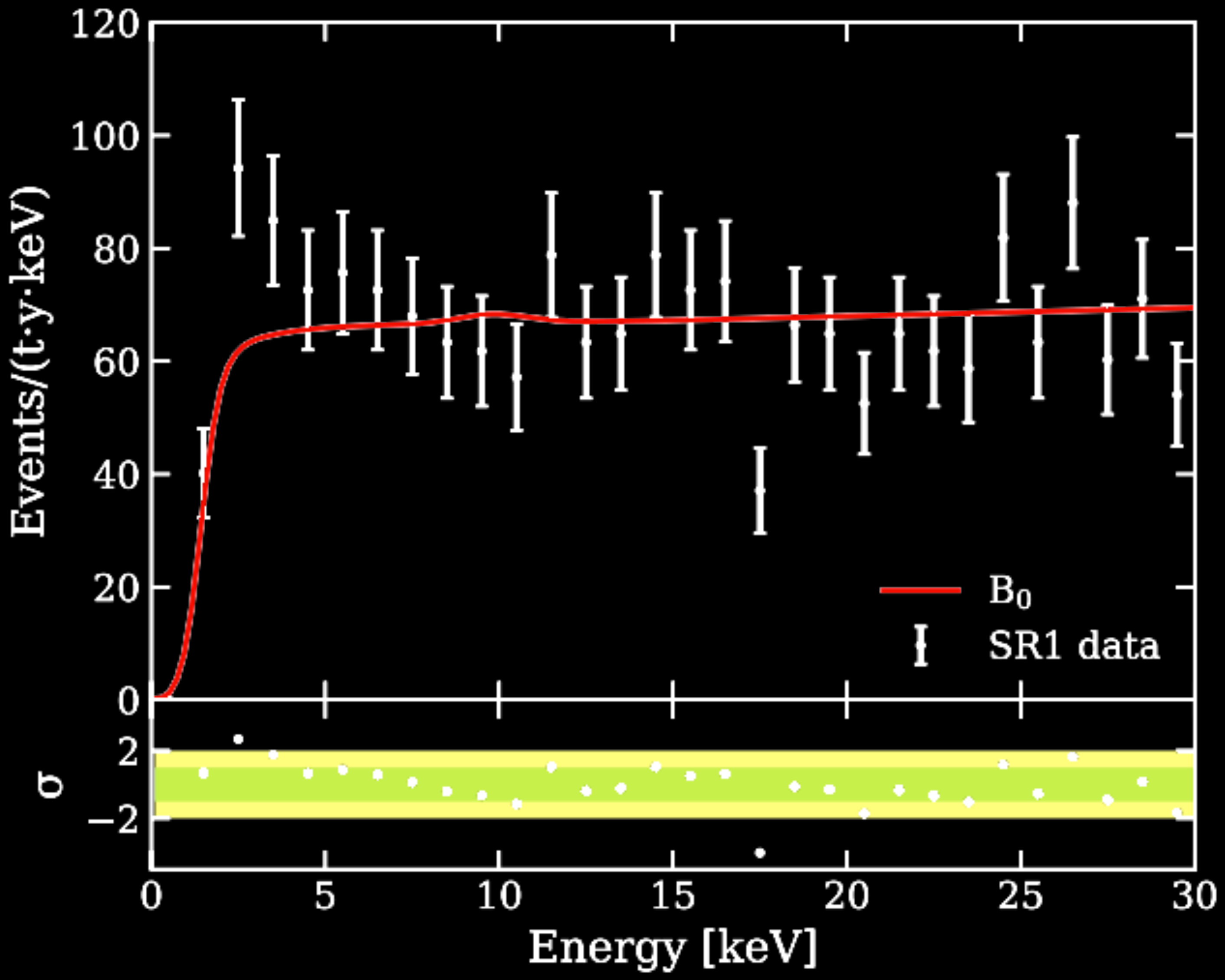
(The Universe is only 10^{10} y old…)





ArXiv: 1904.11002

Electronic Recoil Excess!

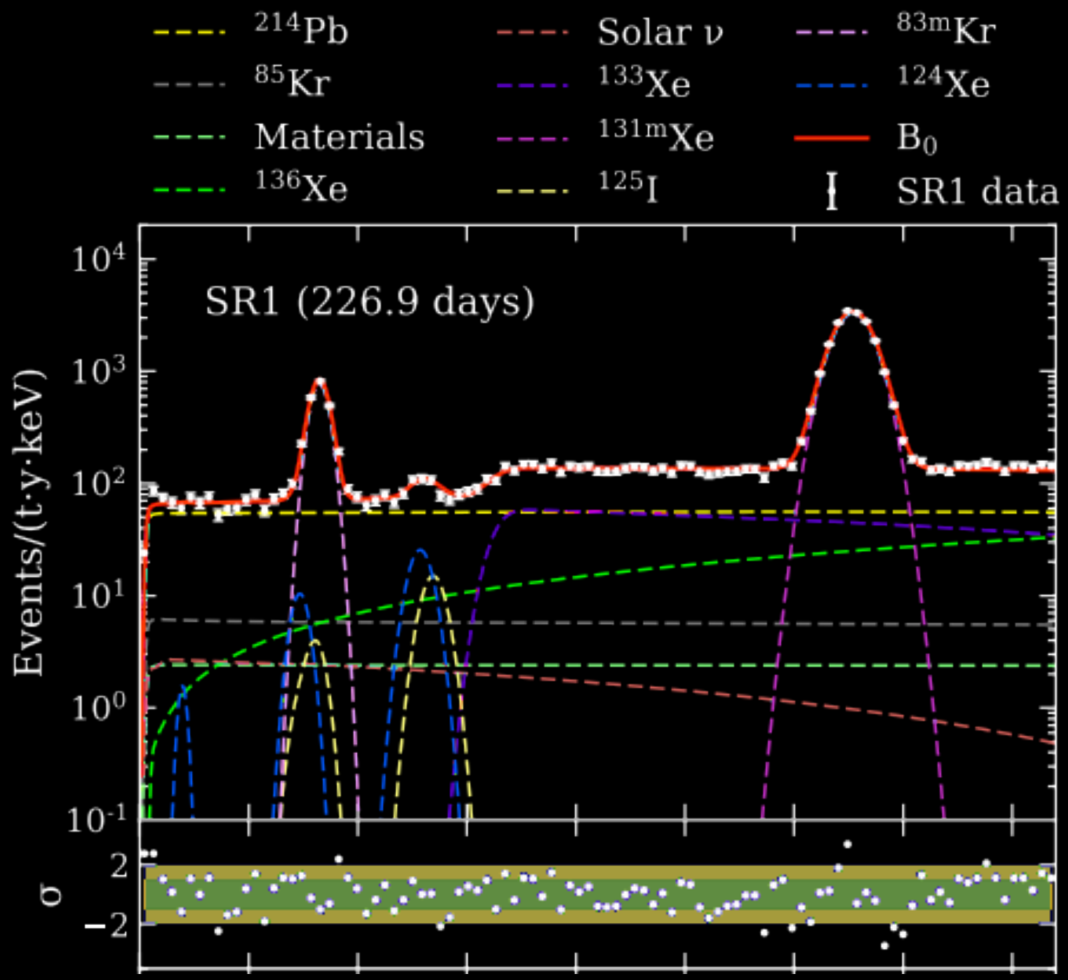


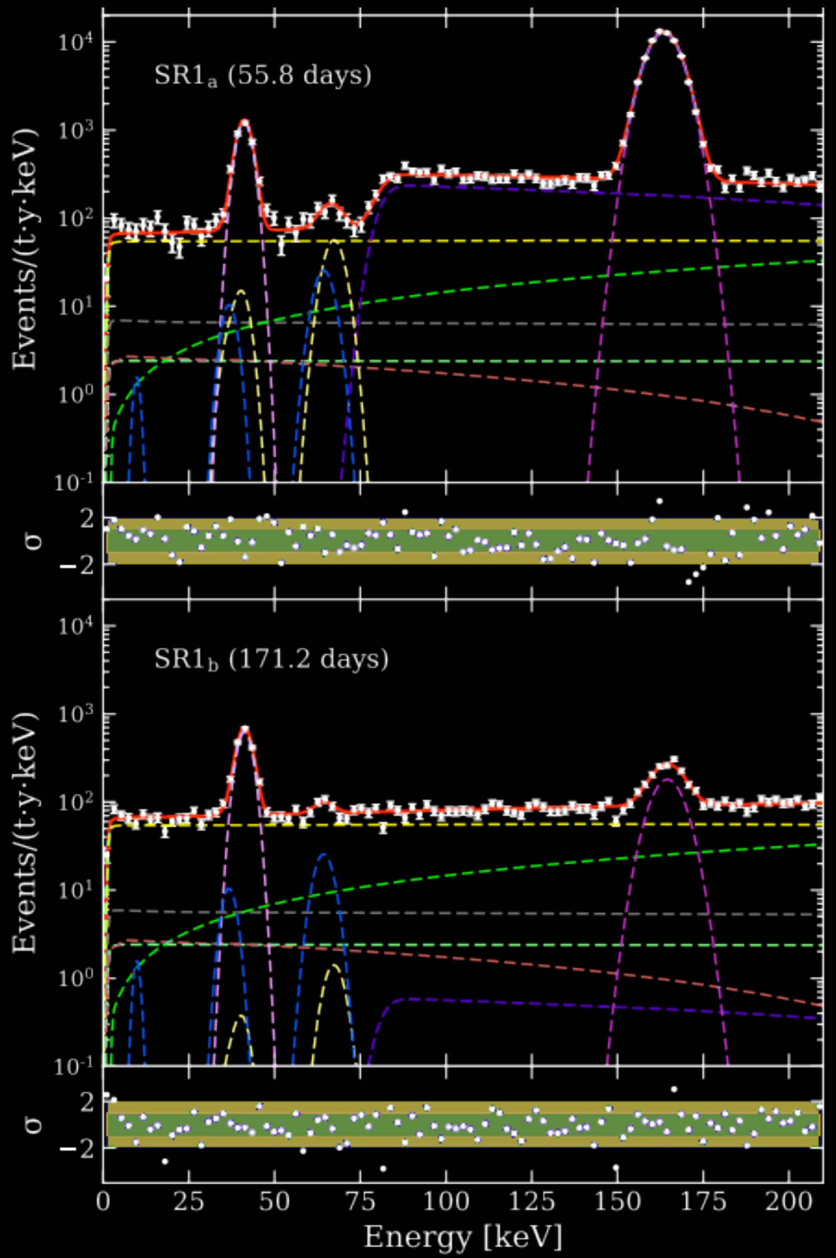
1-7 keV ERs

285 events observed
232 events expected
(53 excess events)

3.3σ excess

Models: Background (B_0)

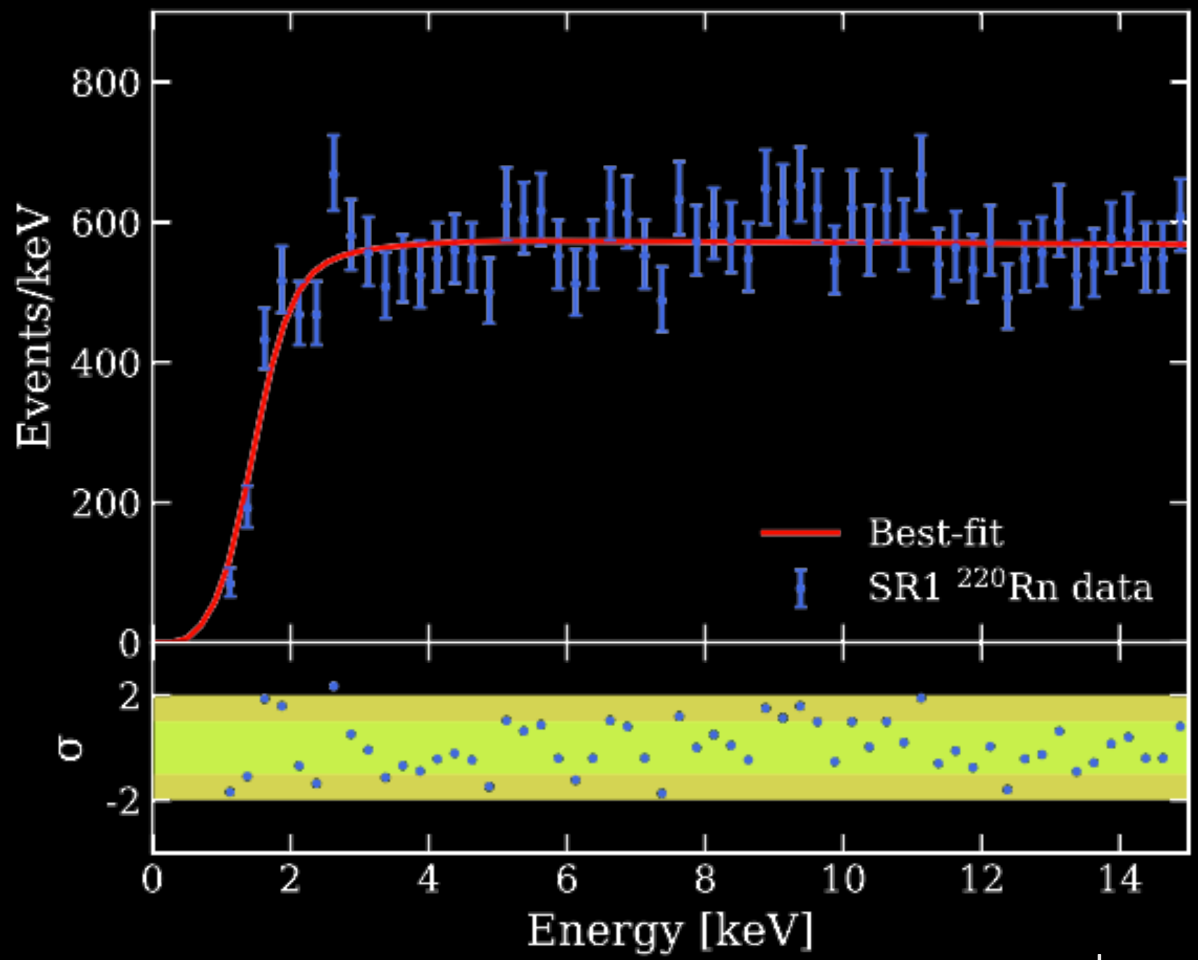


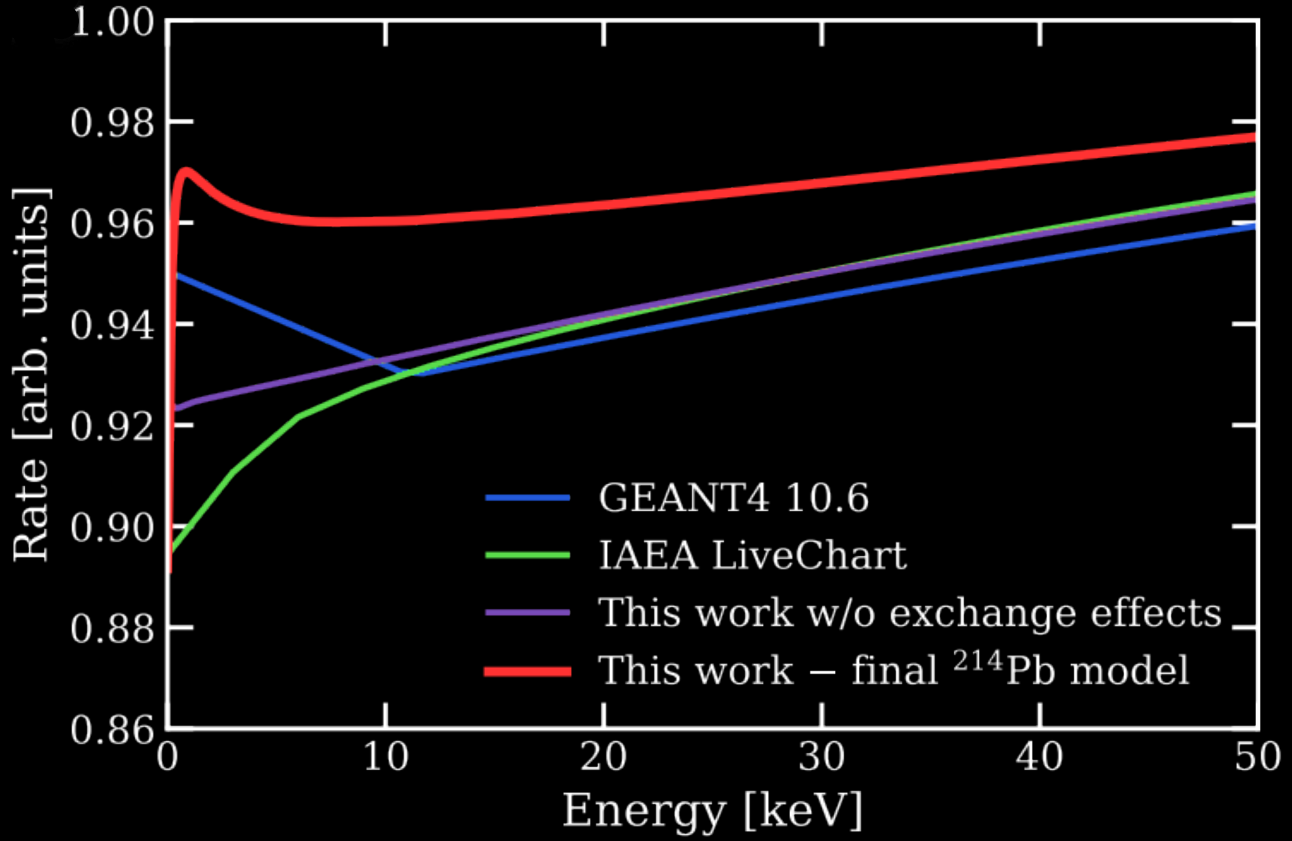


Days after Neutron Calibrations show higher neutron-activated backgrounds: ^{125}I, ^{133}Xe, and ^{131m}Xe

Models: Background ^{214}Pb

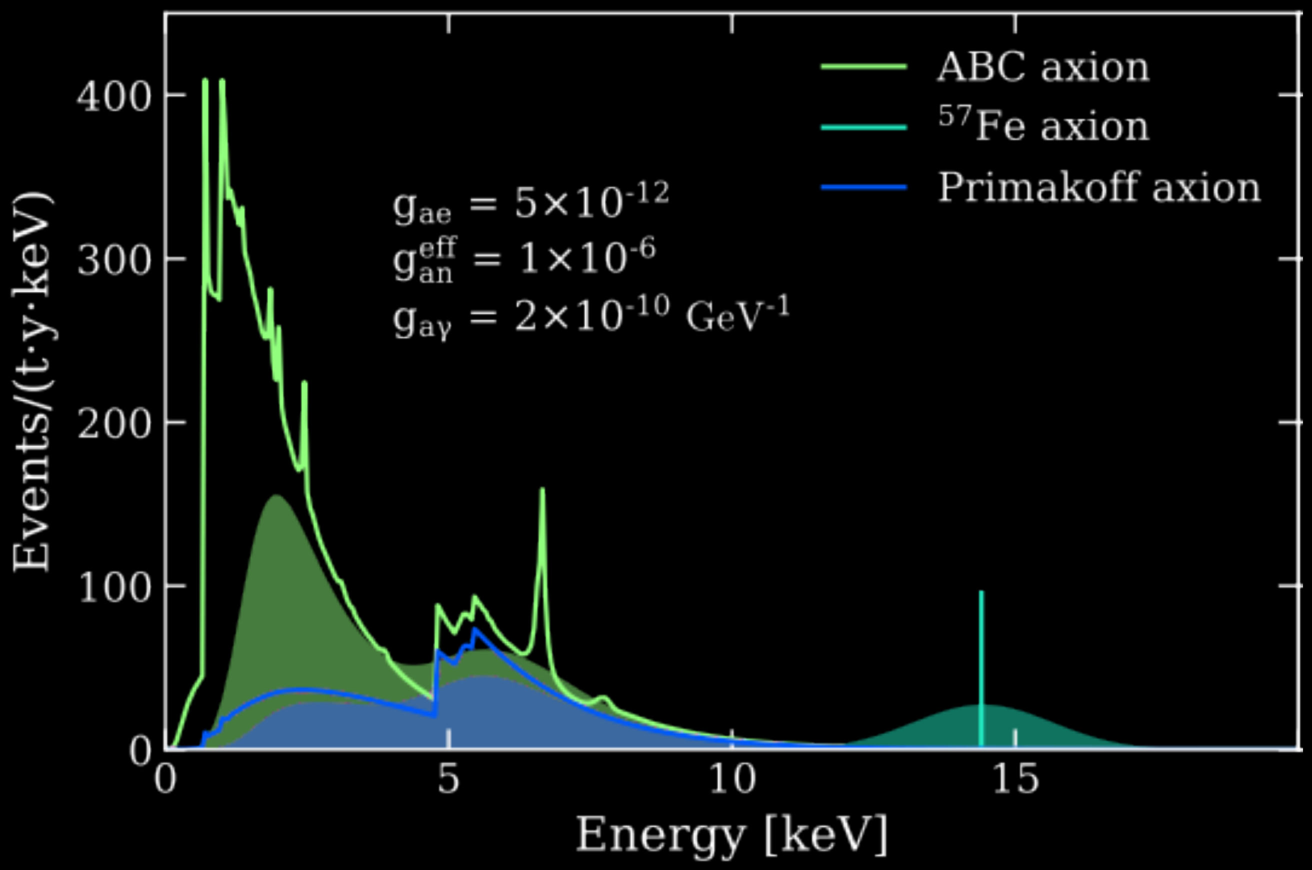
^{220}Rn Calibration gives us ^{212}Pb events in the correct energy range





At low energies, the effects of Atomic Shielding and Exchange Effects are important, so we needed a better ^{214}Pb beta decay model

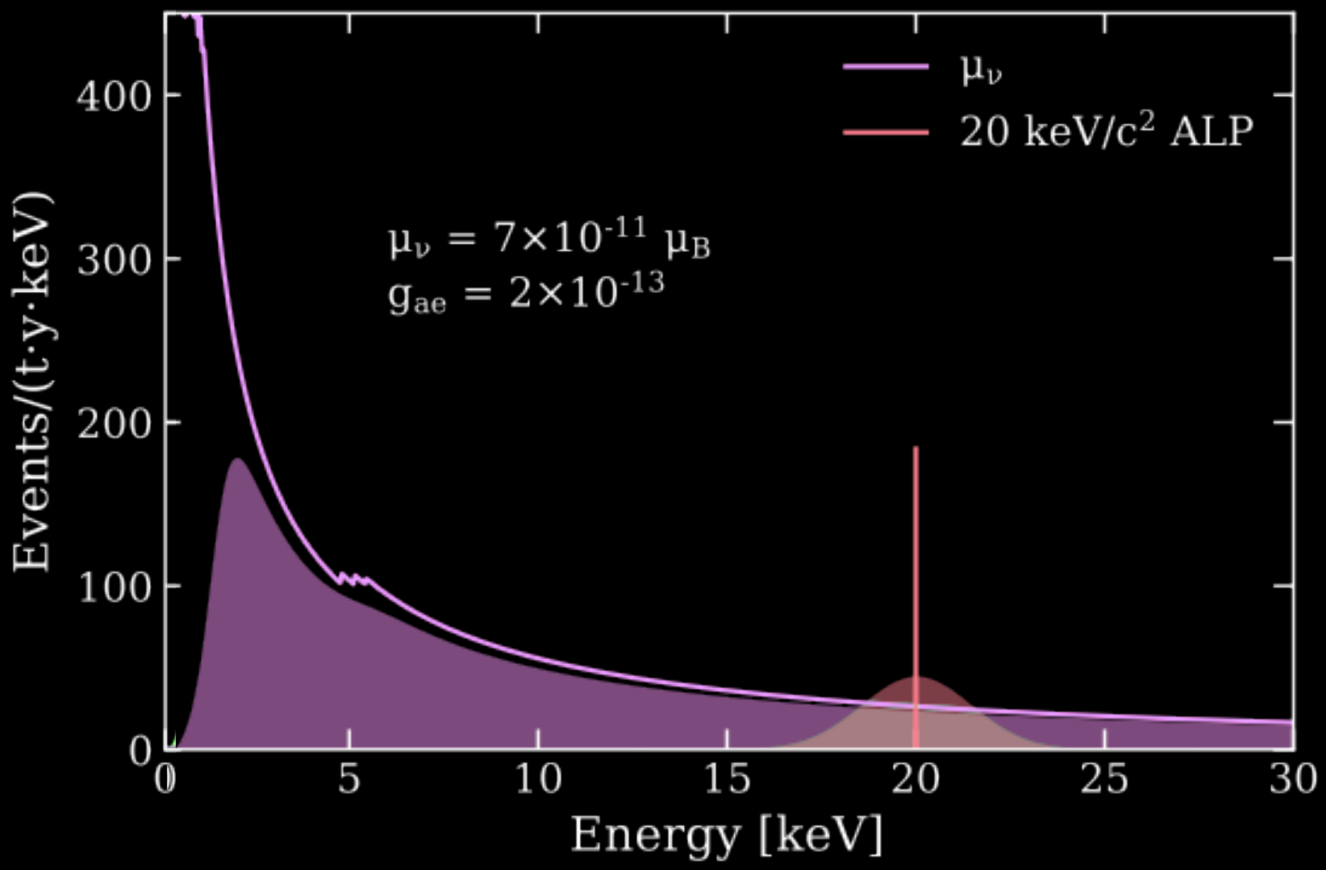
Models: Solar Axions



Three production methods based on axion-matter couplings:

- ABC = **A**tomic Recombination and de-excitation, **B**remsstrahlung, and **C**ompton interactions. Axion-electron coupling
- Fe-57 = monoenergetic (14.4 kV) nuclear transition. Axion-nucleon coupling
- Primakoff Conversion = photons and axions oscillate. Axion-photon coupling

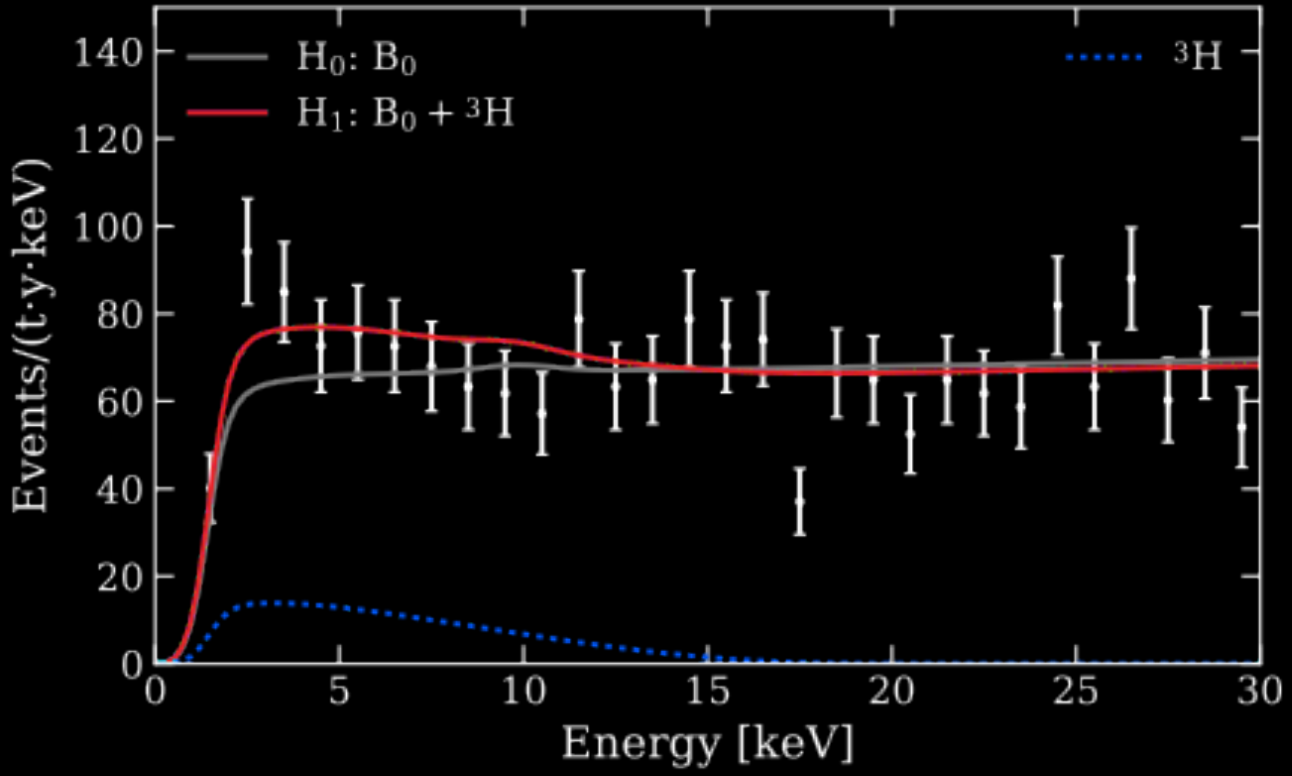
Models: Neutrino Magnetic Moment and Light Dark Matter



A Neutrino Magnetic moment would lead to an enhanced neutrino-electron interaction cross-section

A single light dark matter candidate (Axion-like particle) would produce a monoenergetic signature in the detector.

Results: Tritium?

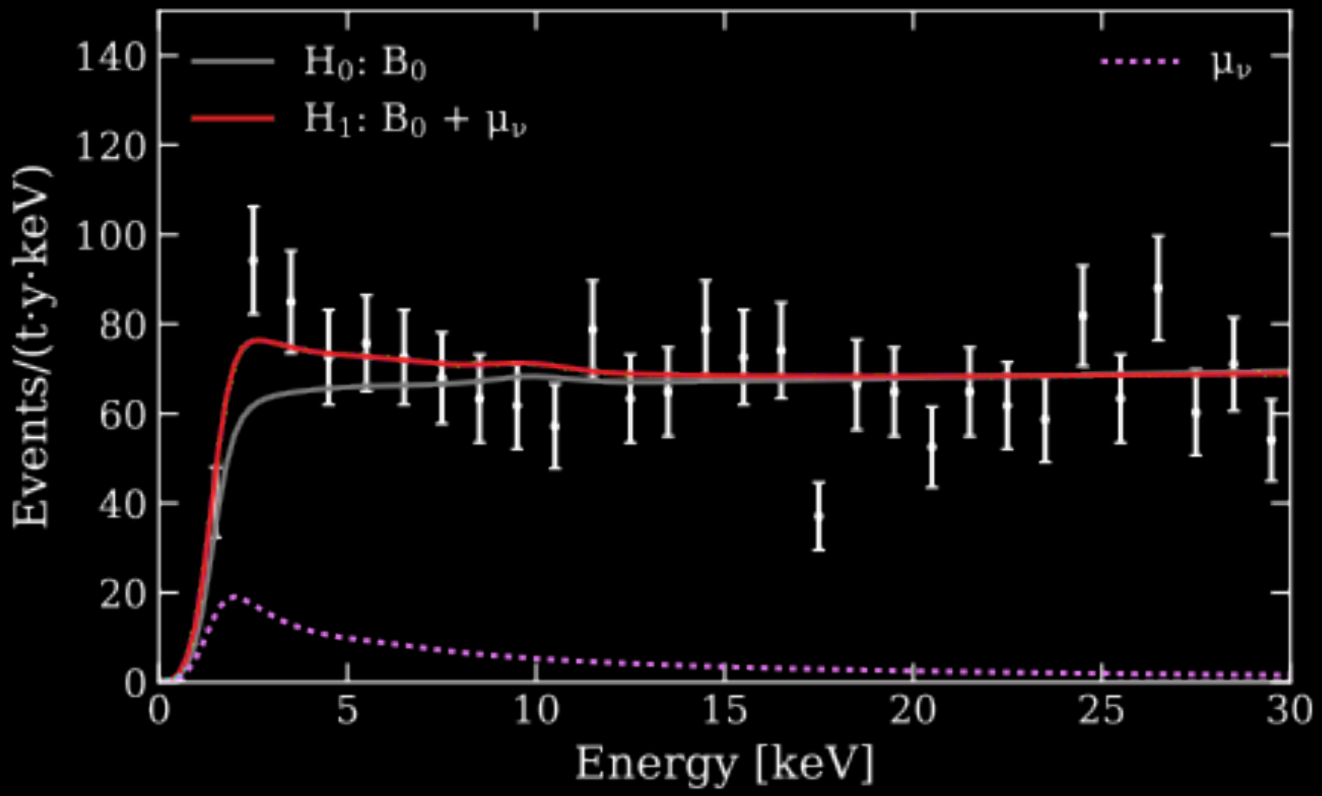


Did we forget a background component?

Hydrogen is everywhere, and therefore tritium is too, at least according to its natural abundance.

This model is preferred to B_0 by 3.2σ.

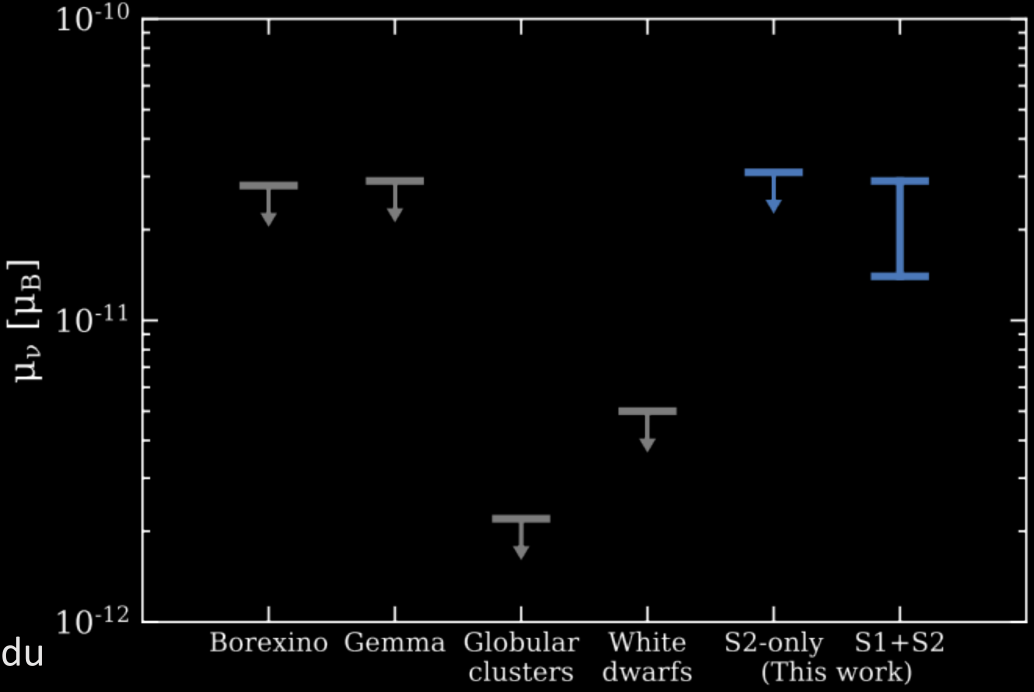
Results: Neutrino Magnetic Moment?



Do neutrinos have a magnetic moment?

$\mu_\nu \in (1.4, 2.9) \times 10^{-11}\ \mu_B$

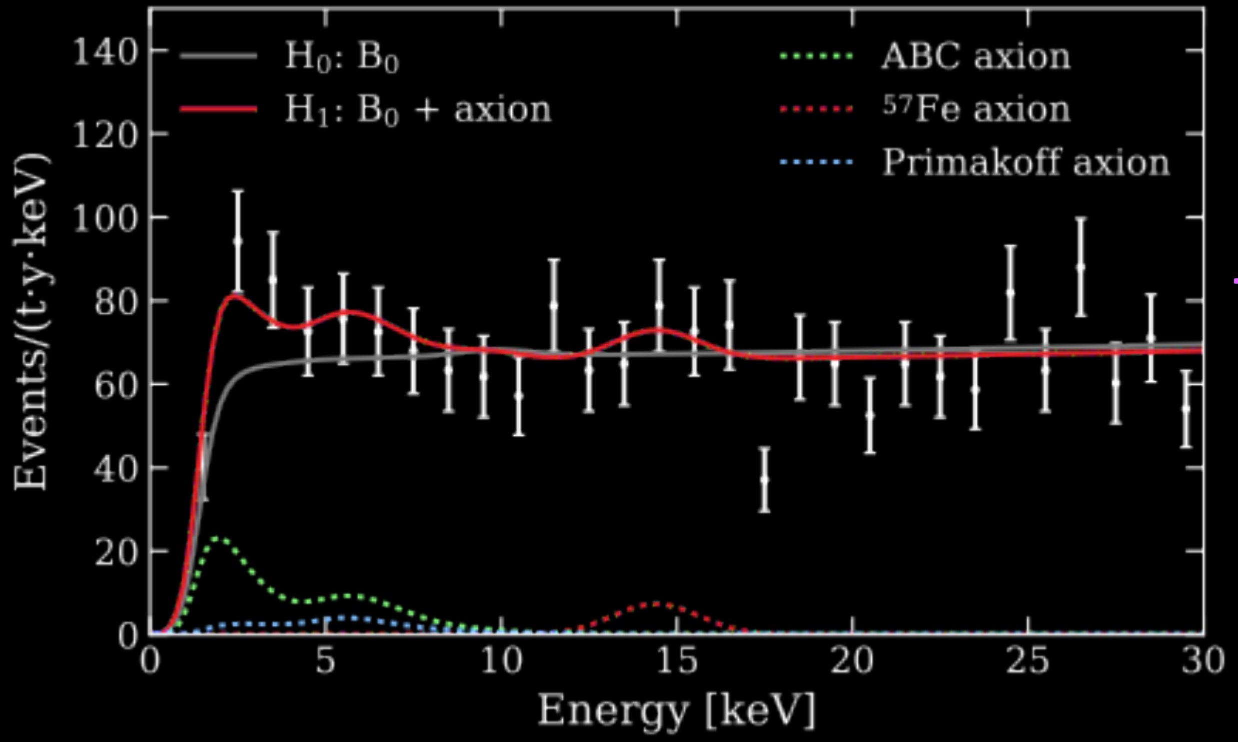
That number is in contention with other measurement…



This model is preferred to B_0 by 3.2σ

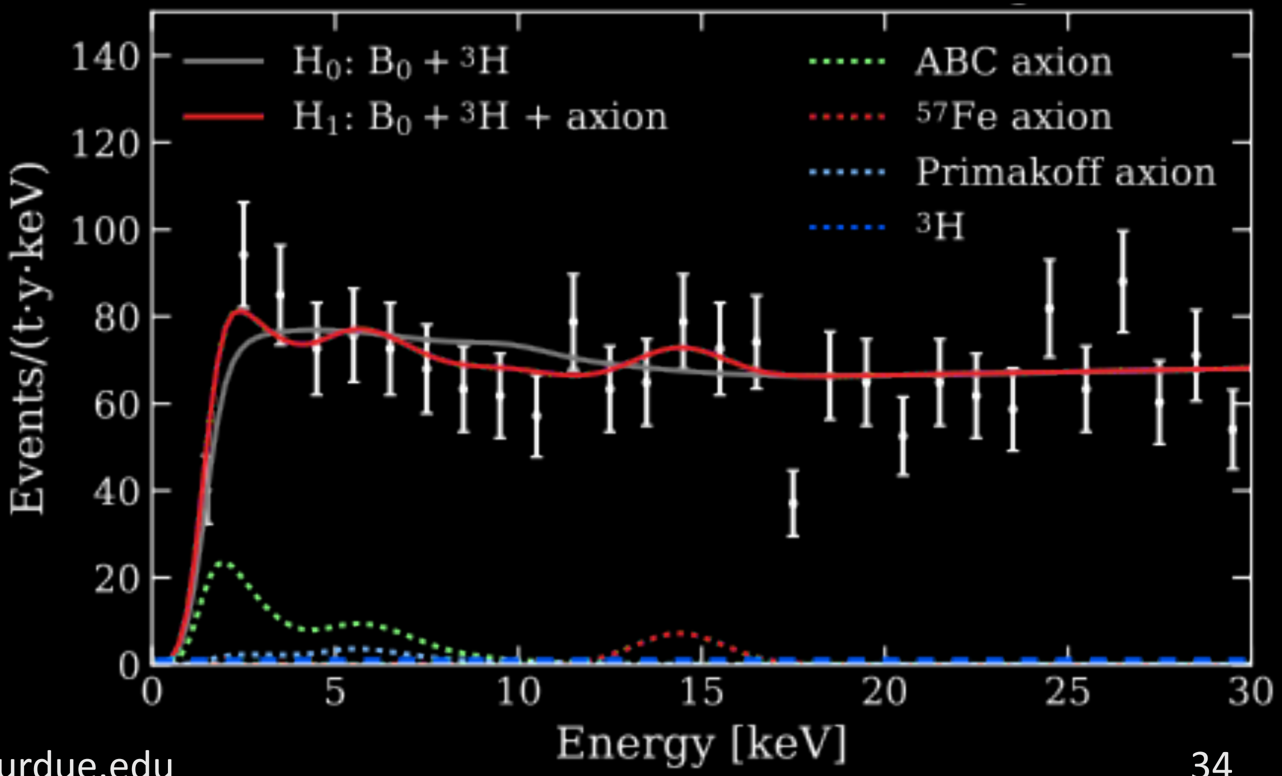
(This model is preferred to the B_0+^{3}H by only 0.9σ.)

Results: Solar Axions?



Have we found solar axions?

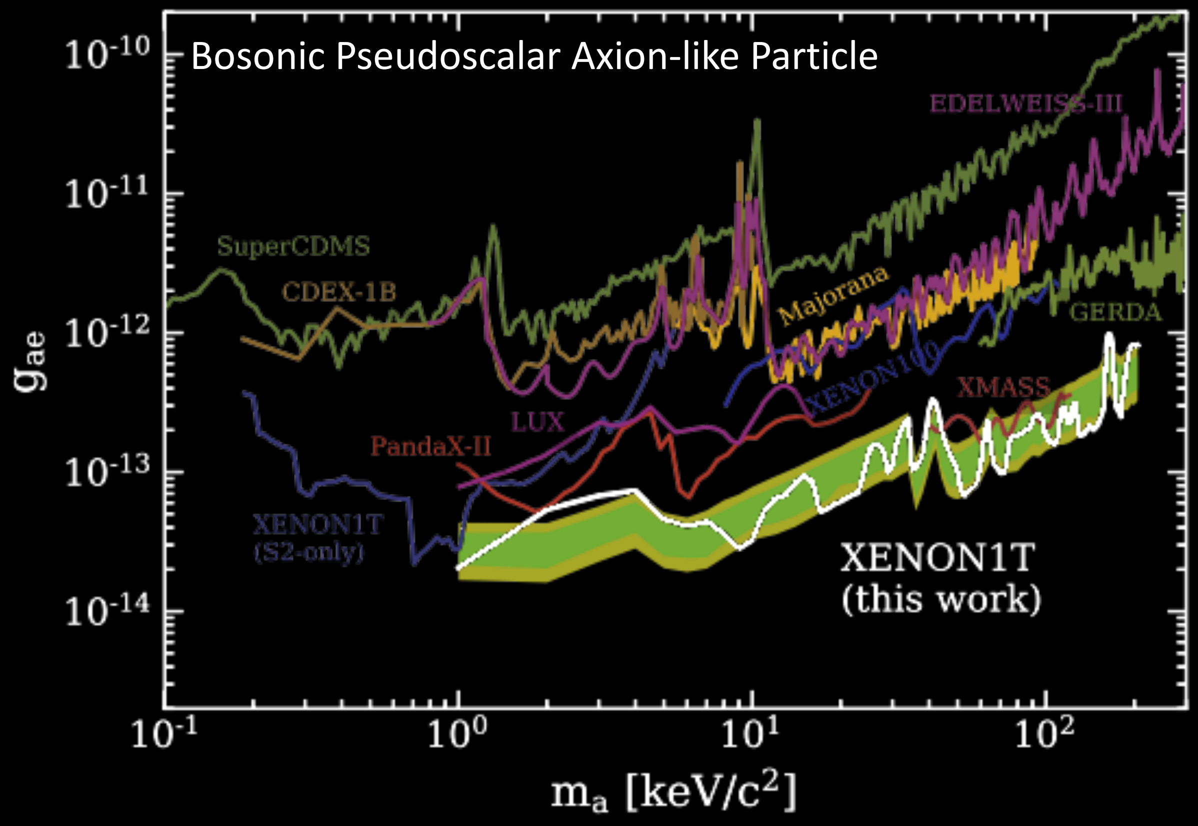
This model is preferred to B_0 by 3.5σ

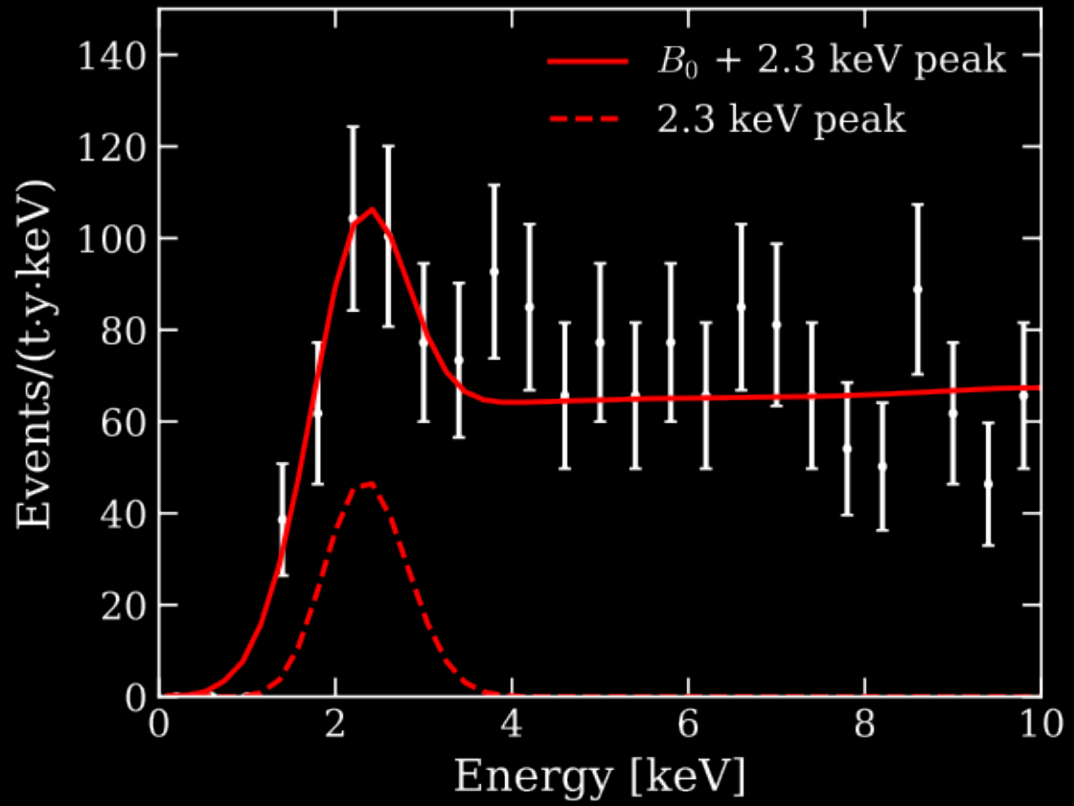


This model is preferred to the B_0+^{3}H by 2.0σ

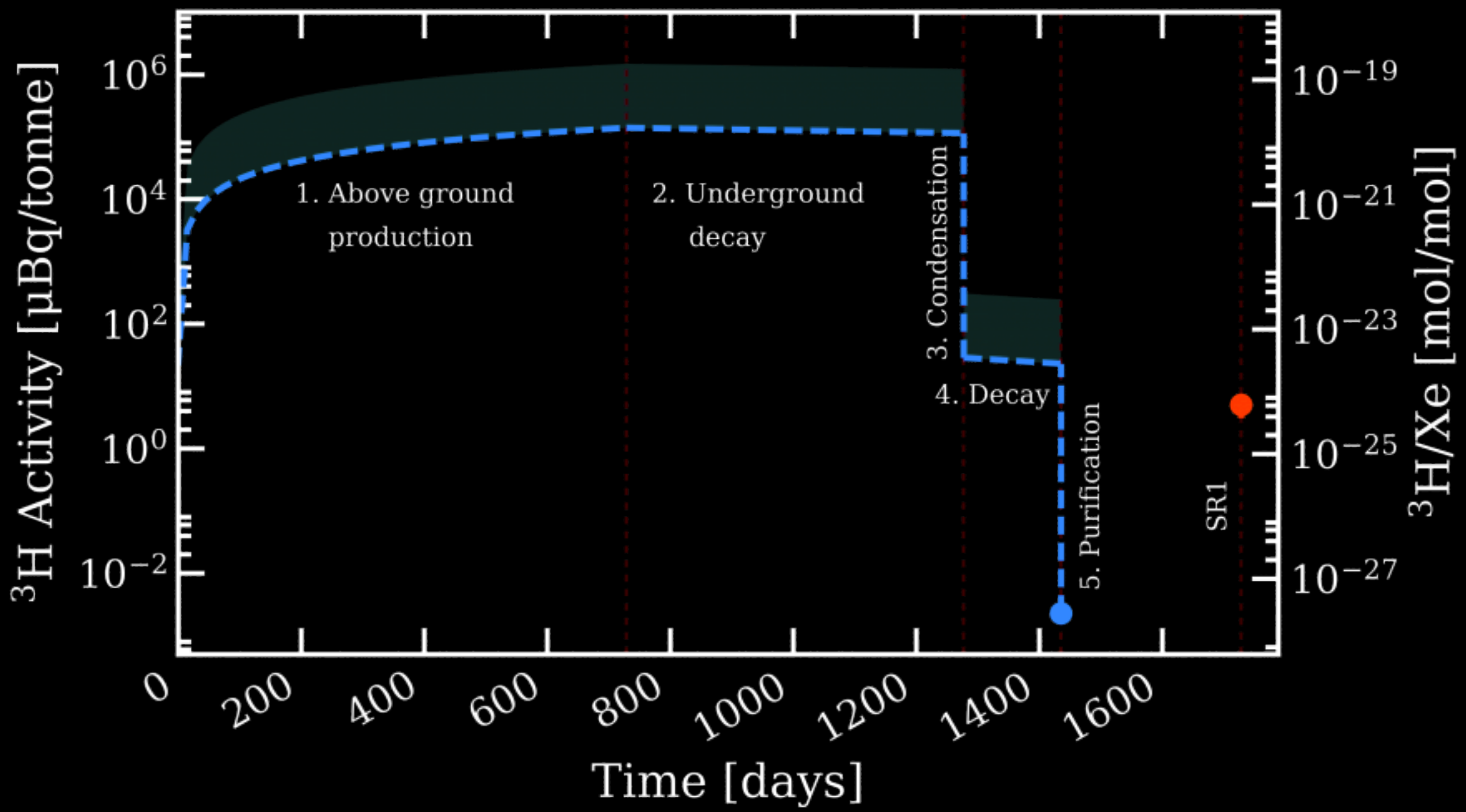
Results: Dark Matter?

Have we found a monoenergetic peak from dark matter?
The significance of an excess at 2.3keV is 3.0σ.





Tritium? Unlikely, but not excluded…



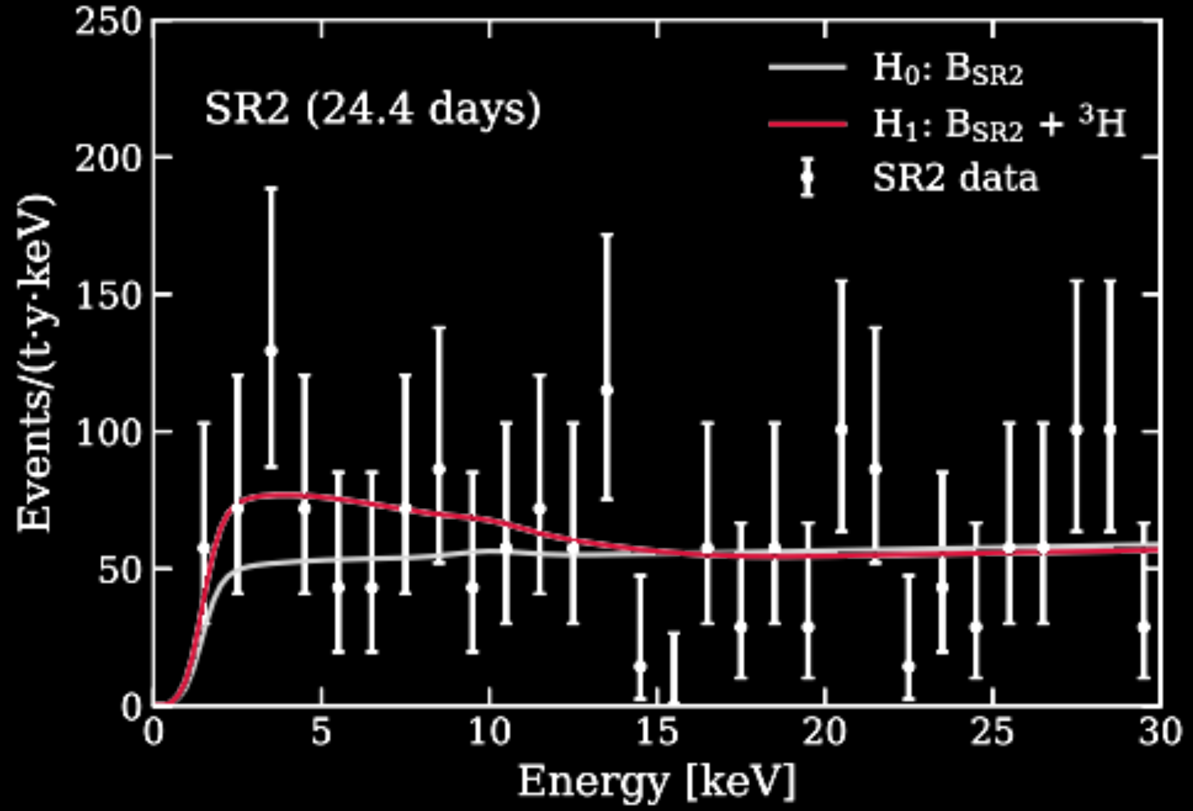
$(6.2 \pm 2.0) \times 10^{-25}$ mol ^{3}H per mol Xe

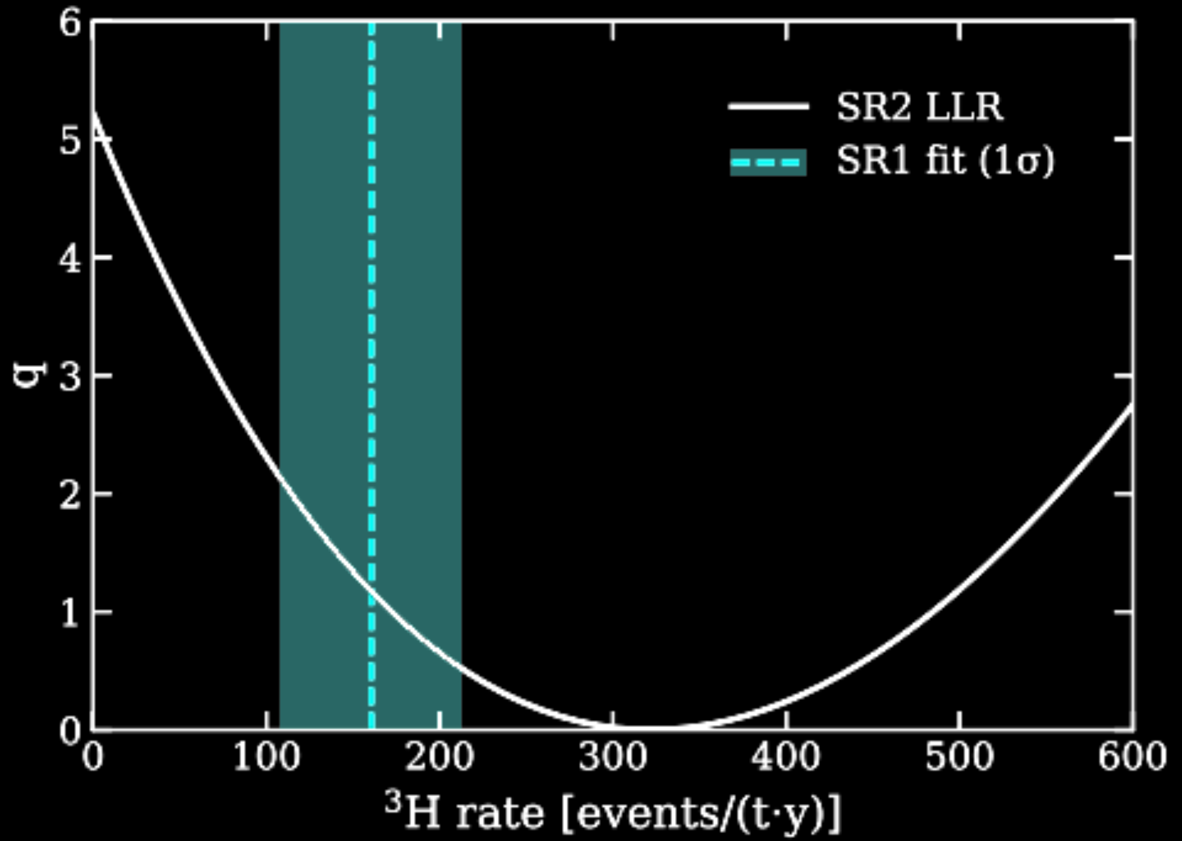
It cannot all be tritiated water: our light collection efficiency is too good for that much water.

So, hydrogen gas?

The concentration is much higher than we expect from Cosmic Ray Activation

Tritium? Unlikely, but not excluded…





We also checked with SR2. We would not have expected the ^{3}H to increase.

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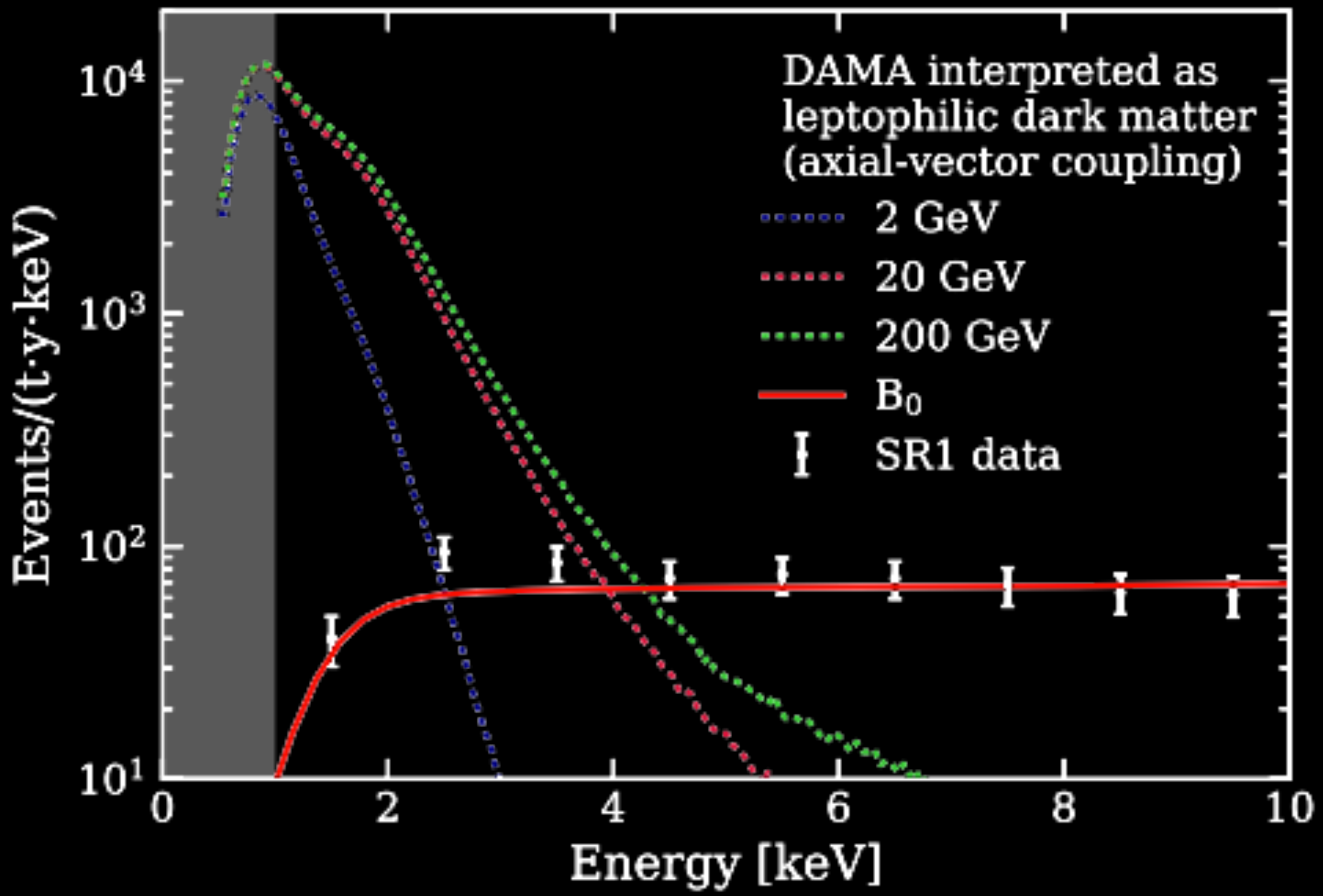
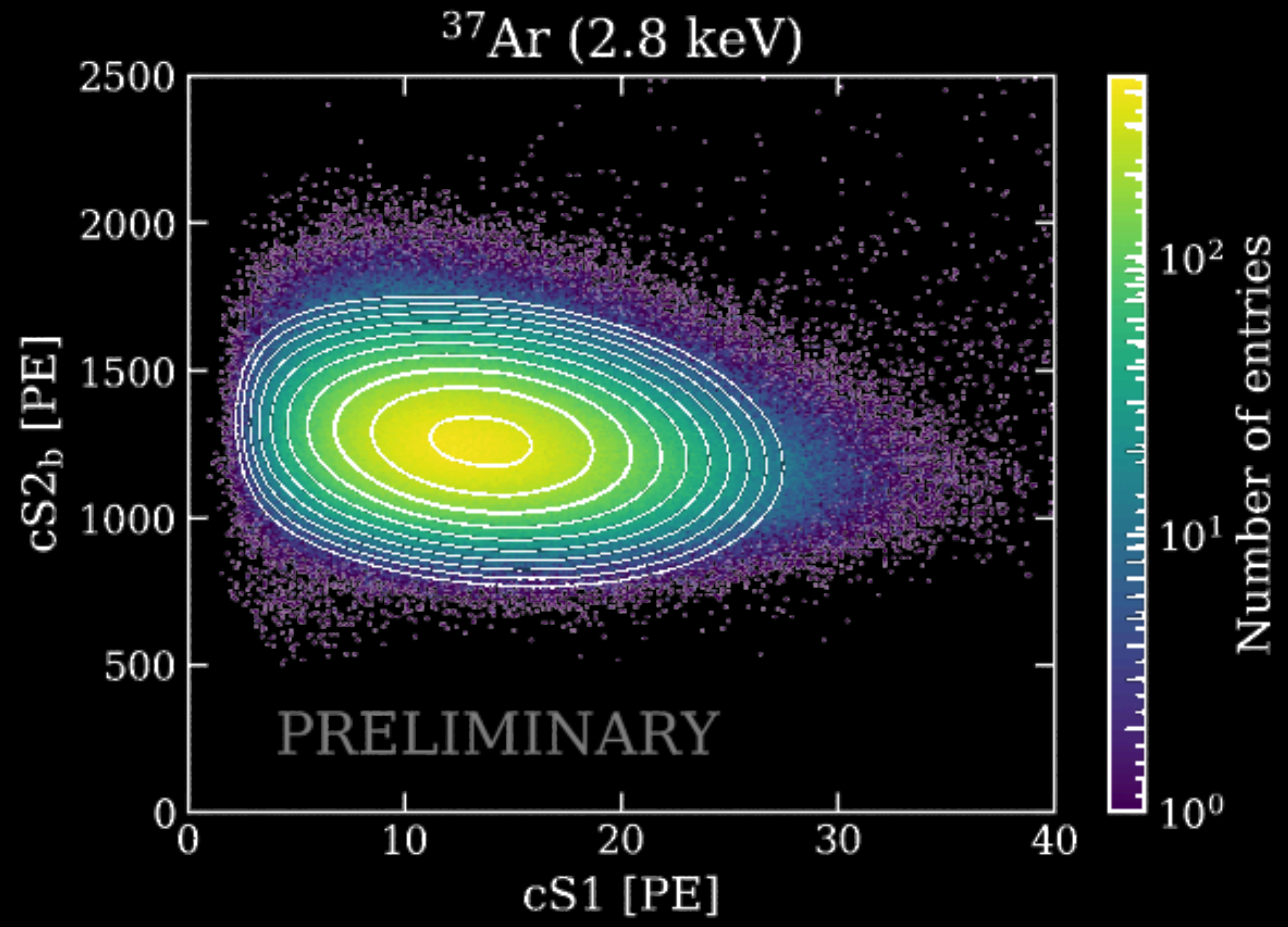
What about DAMA's signal?



Their signal would be enormous for us, even accounting for detector efficiency, so it is probably not that.

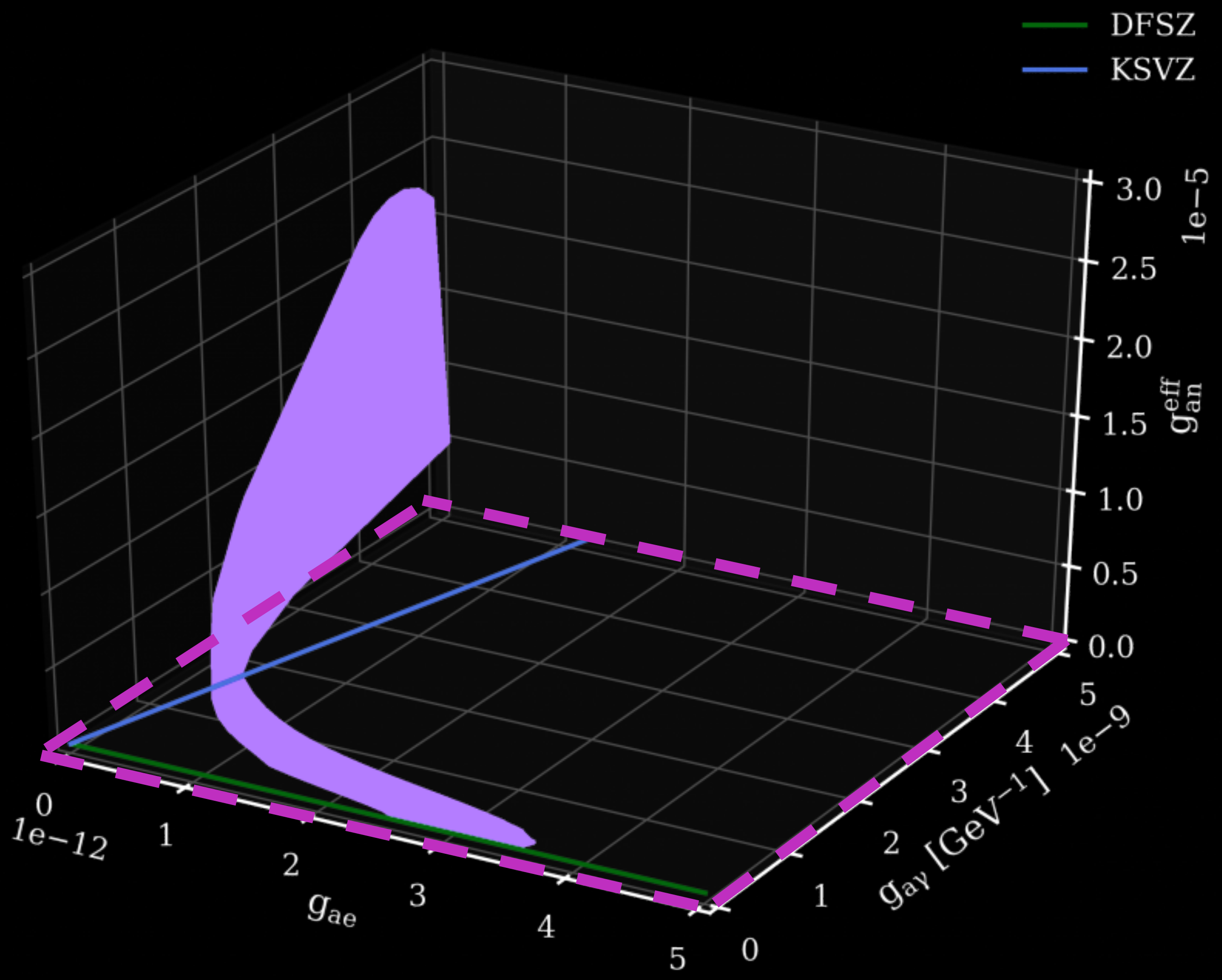
What about ^{37}Ar?



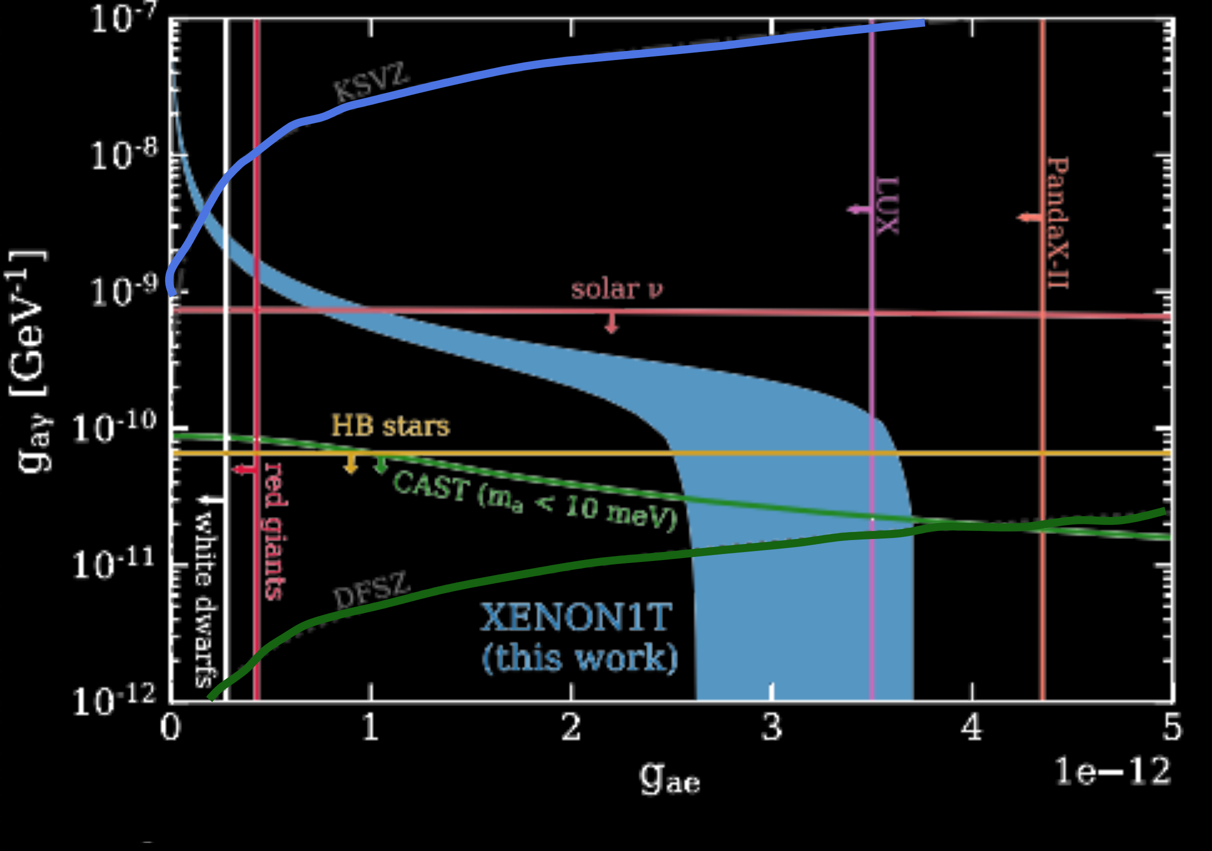
We *know* that we see ^{37}Ar at 2.8keV, while the excess appears to be a monoenergetic peak at 2.3keV.

Our ^{37}Ar rate is negligible.

If it is Solar Axions… what are the allowed couplings?



Couplings to light and electrons



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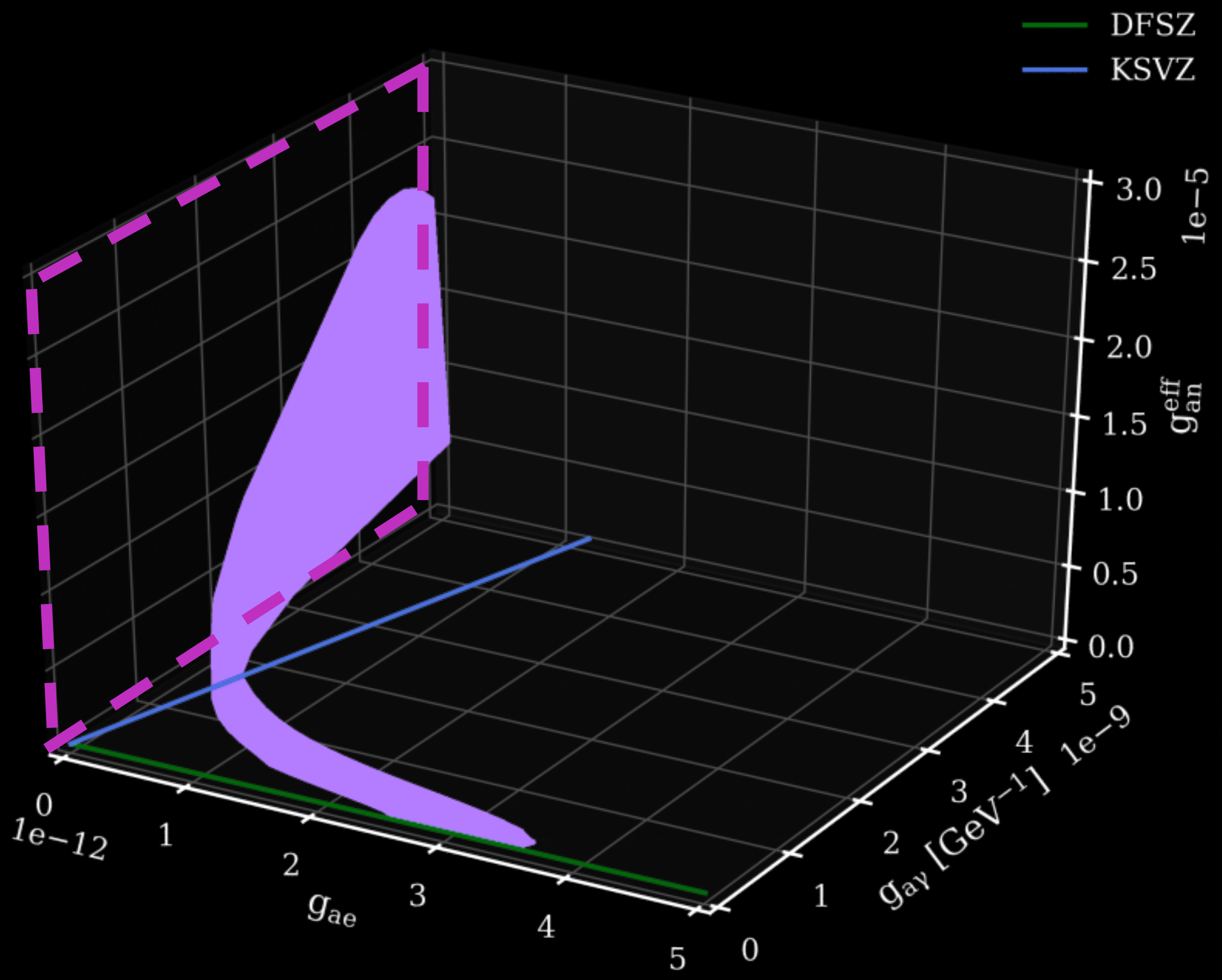
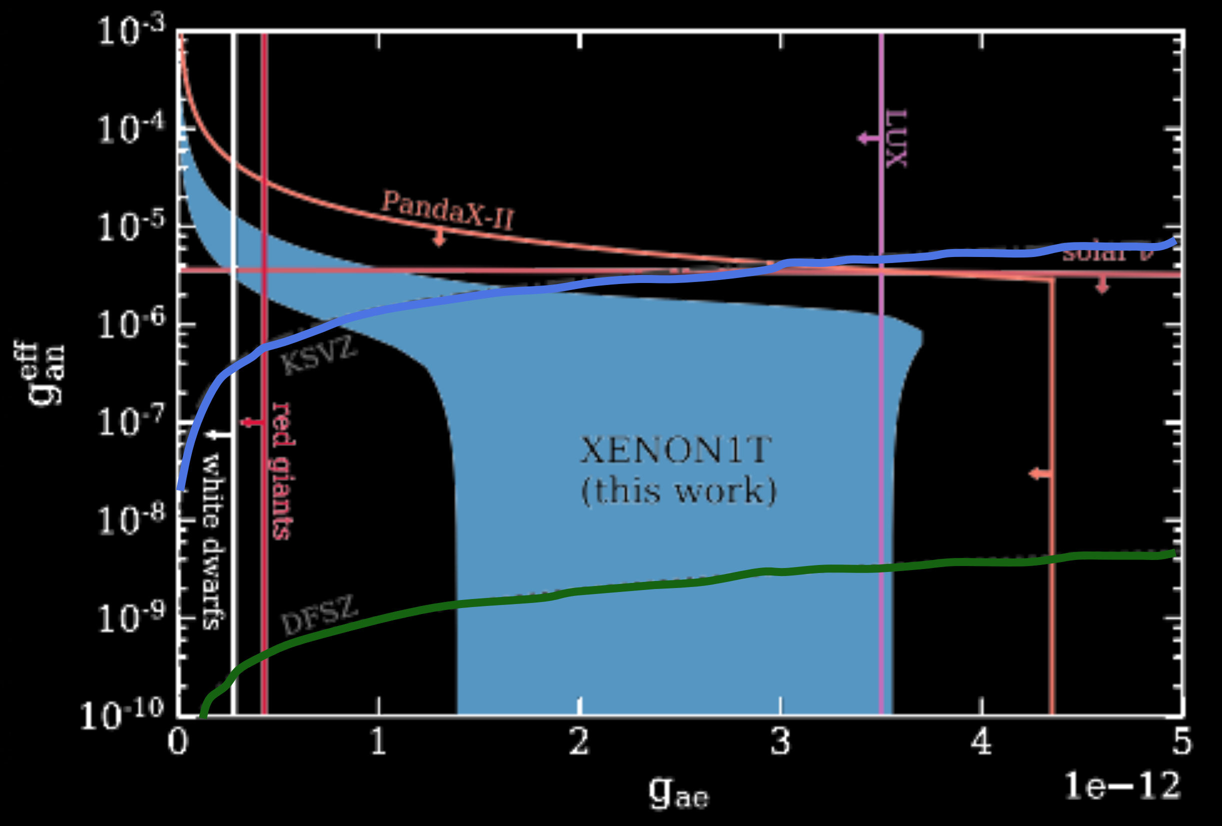
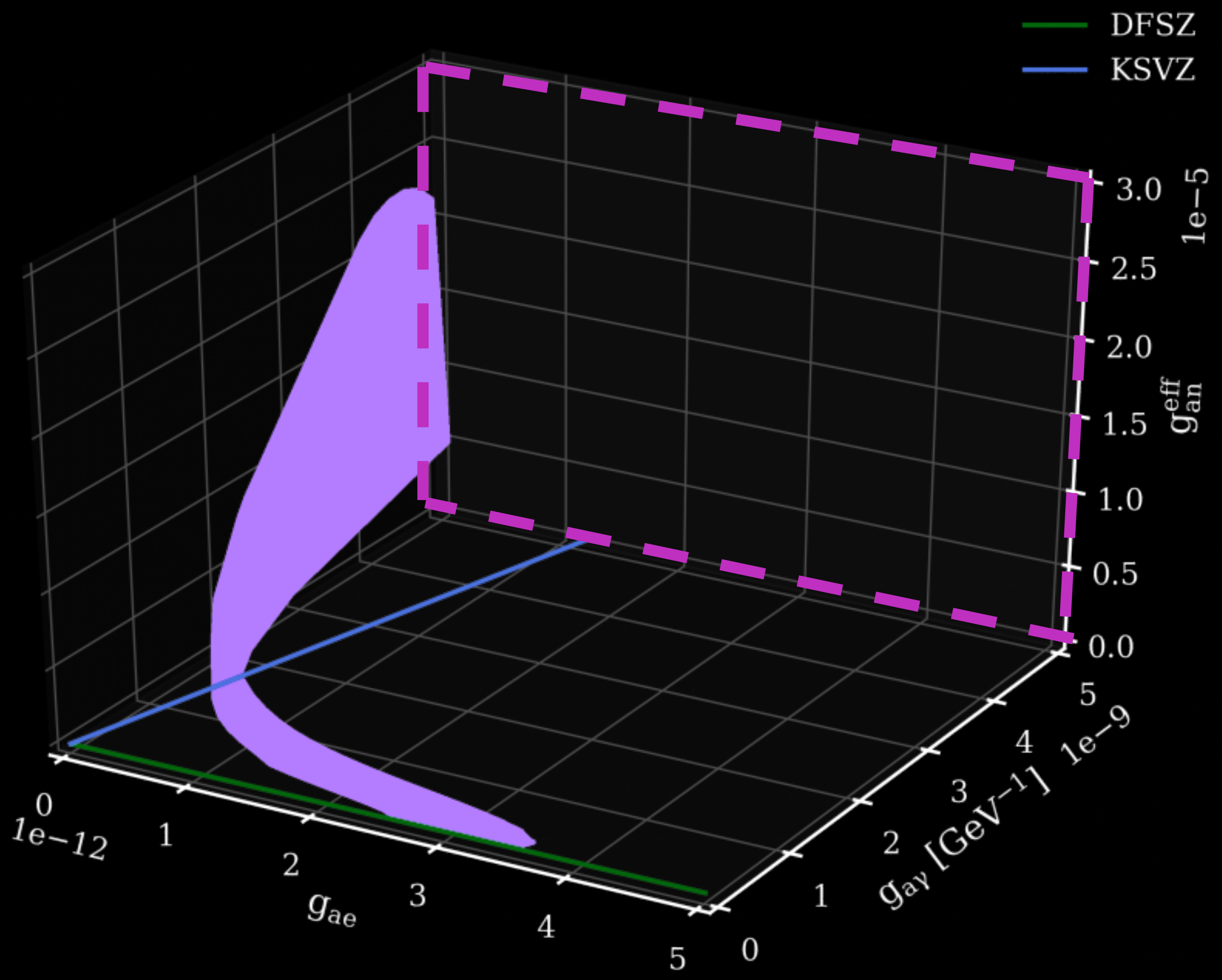


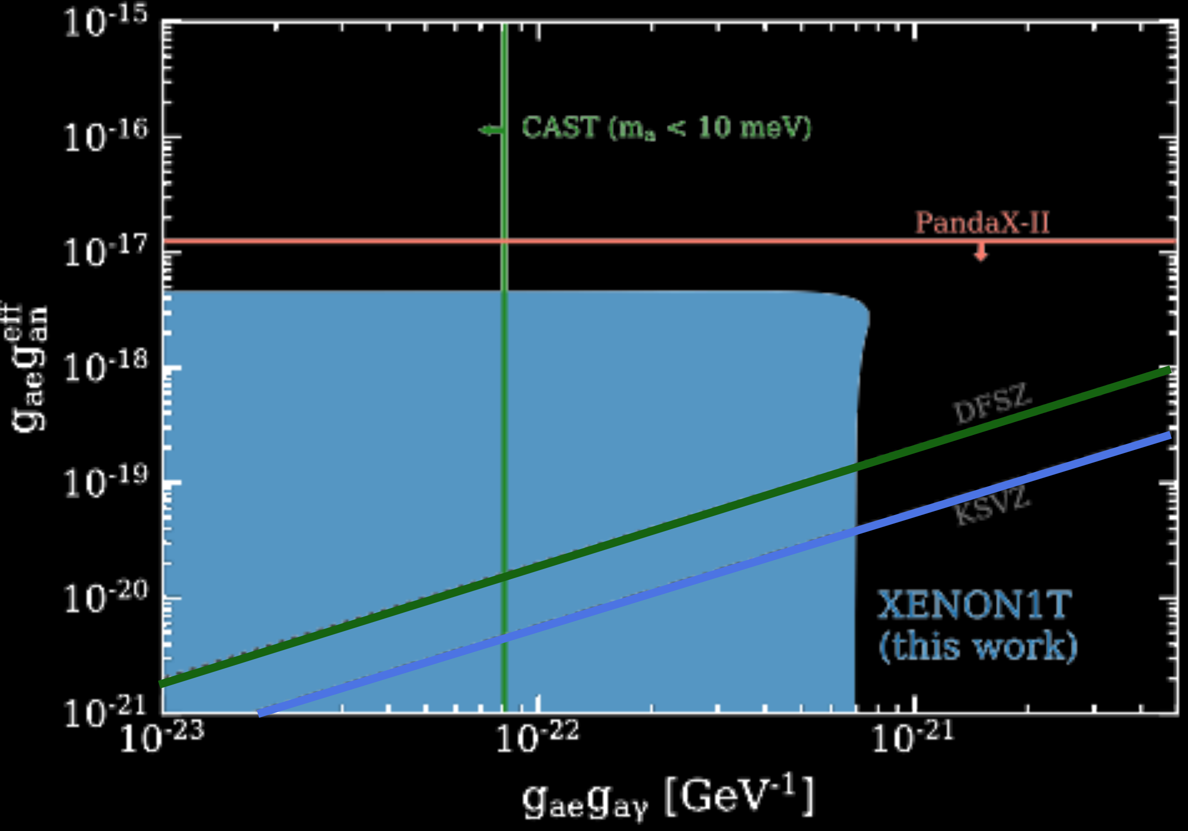
Couplings to nucleons and electrons



If it is Solar Axions… what are the allowed couplings?

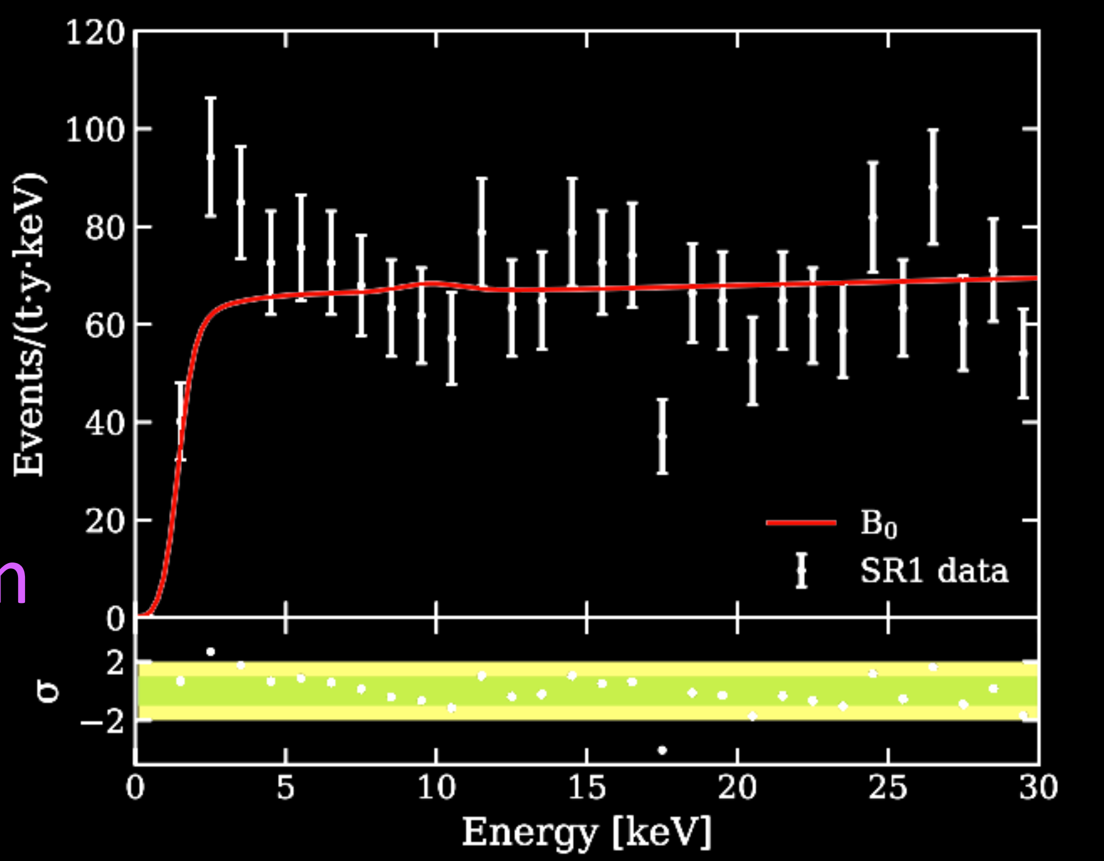


Couplings to nucleons and photons



What else could it be?

- Solar Axions are the best model we've tried, but our measurement of the couplings does not necessarily agree with previous limits
- A monoenergetic peak at 2.3keV is more promising than a beta spectrum
- We cannot rule out tritium



What's next? XENONnT!

Could match XENON1T's statistics in 3-4 months of data taking.

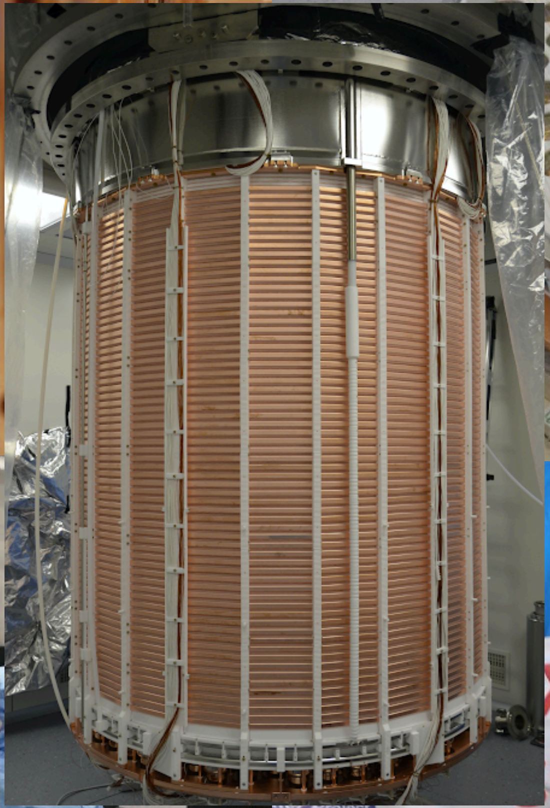
6 tonne active volume

~500 PMTs

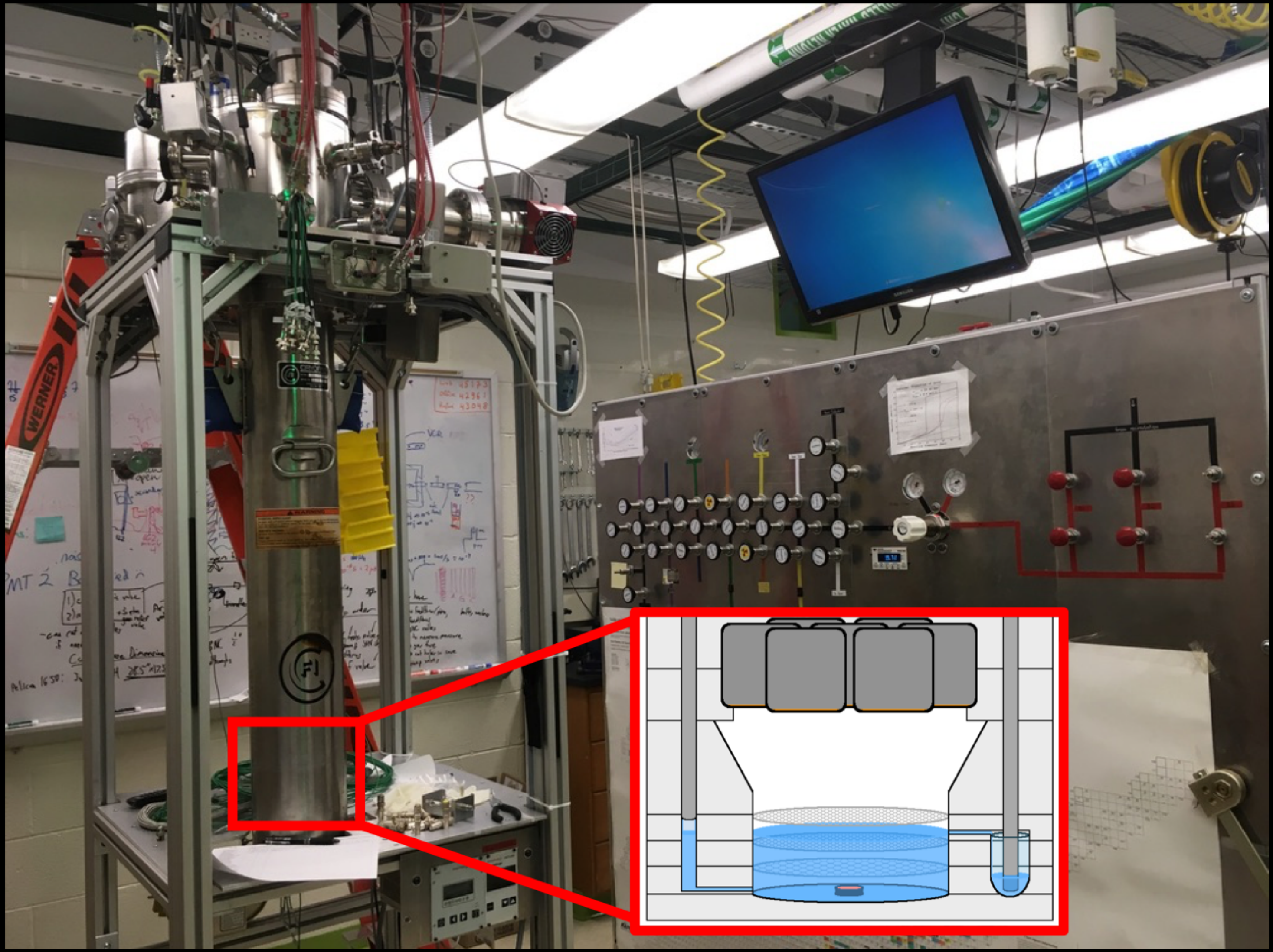
Aggressive ^{222}Rn reduction measures and improved purification

Currently under commissioning!

XENONnT



What's next? Improving Low Energy Sensitivity



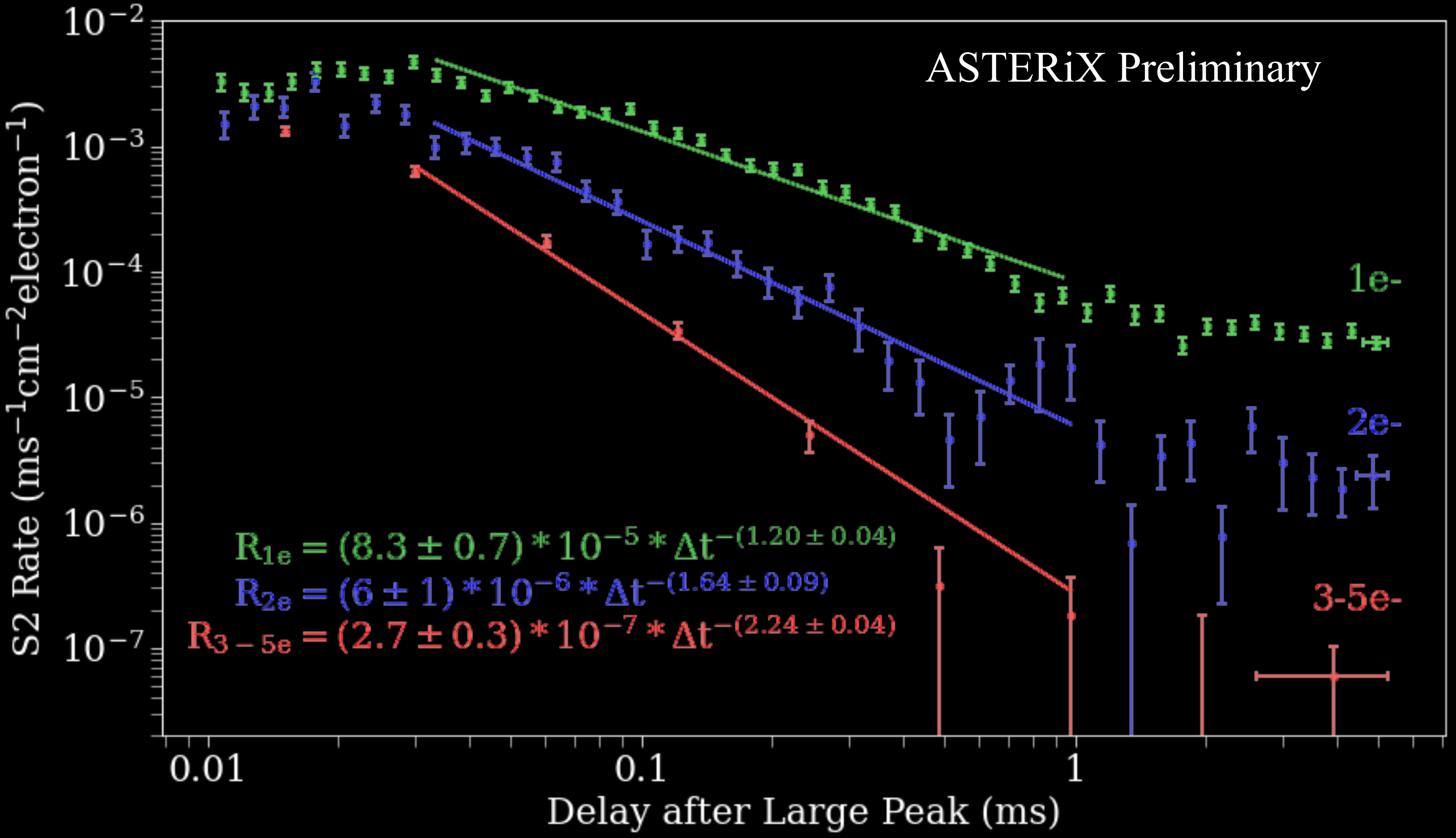
Studying Background S2 Rates

R&D at Purdue

A Small **T**PC for **E**xperimental **R**esearch **i**n **X**enon (ASTERiX)

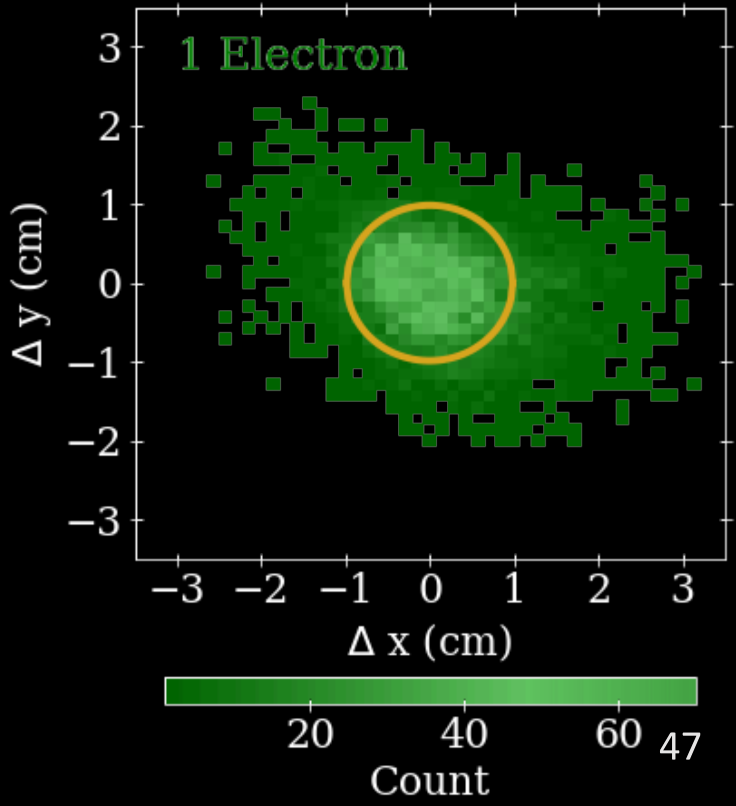
kopec@purdue.edu

Reducing Background S2 Rates



Small S2s (< $5e^-$) are correlated in time and position with larger (> $100e^-$) S2s.

Hard to suppress but can be vetoed.



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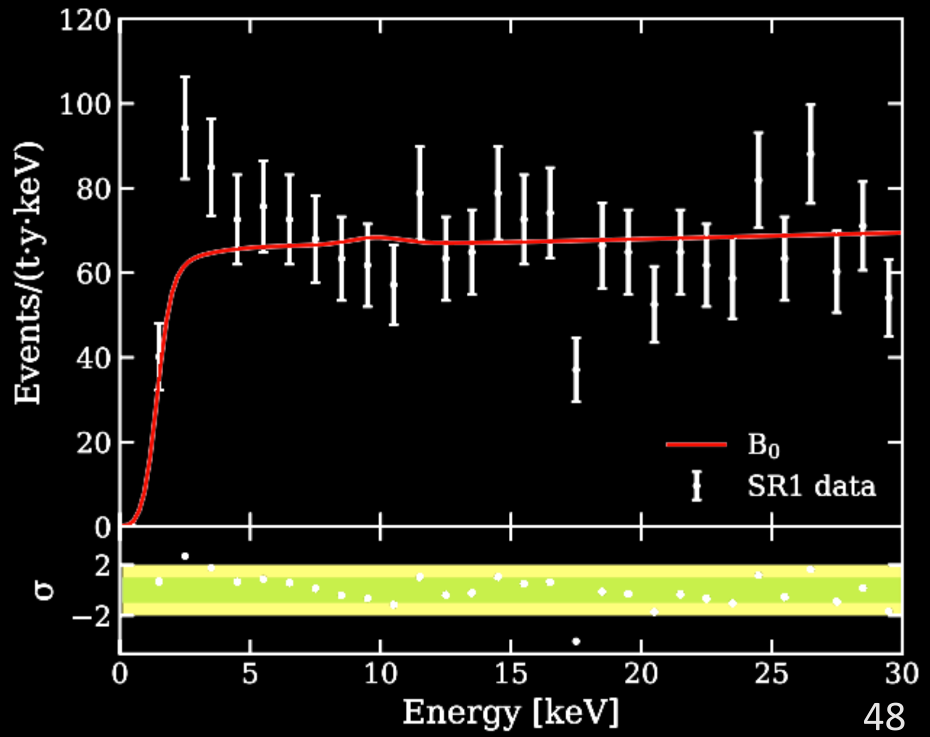
Thank you for your attention!
To summarize:

Most of the Universe's mass is apparently non-interactive invisible matter.

The XENON1T Experiment is a Liquid Xenon Time Projection Chamber

XENON1T made abundant contributions to constraining Dark Matter models, and observed a 3.3σ excess in Electronic Recoils

XENONnT is under commissioning, with a goal to quickly probe this excess and have the lowest background contamination yet.



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