Astroparticle Physics with a Generation-3 Liquid Xenon Detector

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Physics with Gen-3 LXe TPC

Dark Matter:
- spin-independent WIMPs
- spin-dependent WIMPs
- EFT couplings and inelastic WIMPs
- GeV and MeV WIMPs (“S2-only”)
- Planck mass dark matter
- Migdal & Bremsstrahlung searches
- Annual modulation searches
- Magnetic Inelastic WIMPs
- inelastic scattering
- axial-vector coupling
- Leptophilic models
- Mirror & luminous DM
- Axion-like particles
- SuperWIMPs
- Dark photons

Neutrinos:
- solar pp neutrinos
- coherent neutrino-nucleus scattering
- $^8$B solar neutrinos
- Galactic supernovae
- neutrino oscillations
- sterile neutrinos
- neutrino magnetic moment
- CNO neutrinos
- $0\nu\beta\beta$ decay of $^{136}$Xe
- $2\nu\beta\beta$ decay of $^{136}$Xe
- double-EC on $^{124}$Xe

Other:
- solar axions
- fractionally charged particles
Coherent Elastic Scattering

For both WIMPs & solar/supernova ν:

\[ \frac{\lambda_{\text{deBroglie}}}{2\pi} = \frac{\hbar}{p} \sim \frac{197 \text{ MeV fm}}{100 \text{ GeV} \times 10^{-3}c} \sim \frac{197 \text{ MeV fm}}{10 \text{ MeV}} > r_{\text{nucleus}} \]

→ interact with entire nucleus: \( \sigma \propto A^2 \)

Recoil is degenerate in transferred momentum \( p \)

→ at some points in parameter space get both WIMPs and neutrinos: “neutrino floor”

(not really a floor)
Best limits all from LXe experiments

Priors include Z-mediation through a box, Z’- or Higgs-mediation, Z-mediation at $10^{-10}$ abundance
Strong Program Going Forward

Start next year to probe another 2 orders of magnitude

Scattering Cross Section in cm$^2$

WIMP Mass in GeV/c$^2$

ruled out

PandaX, LUX, XENON1T 2018

XENONnT, LZ

Ellis, Ferstl & Olive hep-ph/0001005

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Dark Matter and CEνNS

Simple scattering kinematics: degenerate in momentum

Heavy WIMP, $\nu \sim 10^{-3}c$

Coherent Neutrino-Nucleus Scattering: light $\nu$, $\nu \sim c$

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Neutrino Floor is far, far away

Current program leaves a WIMP gap

Atmospheric neutrinos require generation-3 experiment
Generation-3

- Goal: probe WIMPs down to the atmospheric floor: need to measure atmospheric ν CEνNS

- Scale-up LXe TPC technology

- Start after LZ & XENONnT, ~2026

- 8M€ R&D funding, on roadmaps, collaborations and expressions of interest, whitepaper in prep
Xe: Spin-Dependent Sensitivity

Half of Xe isotopes carry spin!

PICO is better for proton coupling

In general, Xe is great EFT target
Many other interesting channels

Axion-Like Particles:

Sub-GeV WIMPs:

Dark Photons:

Leptophilic models:
Collider Complementarity

Probe less mediator mass but to higher WIMP masses.

How high can we go?
Probe DM Flux Beyond Planck Mass

- Kinematics only depend on reduced mass

- Direct detection becomes flux limited only at

  \[ m_{\chi}^{\text{max}} \sim 10^{19} \ \text{GeV} \left( \frac{A}{\text{m}^2} \right) \left( \frac{T}{10\text{yr}} \right) \]

  \[ m_{\text{Planck}} \]

  → Generation-3 experiment will probe up to & beyond Planck-scale, using dedicated multi-scatter search

  Bramante, Broerman, Rafael & Raj 1803.08044; also 1812.09325

- Still need to work out exact interpretation of results

  Digman, Cappiello, Beacom, Hirata & Peter 1907.10618
Dominant ER Background

Elastic scattering, mostly from pp solar neutrinos

- Measure $\sin^2 \theta_W$ to a few percent
- Measure flux to refine solar models
Add $\mu_\nu$ or A’

Modifies $\nu$ elastic scattering

- Magnetic dipole moment of neutrino $\mu_\nu \sim 10^{-12} \mu_B$
- Additional U(1)’ vector bosons A’

$\nu_e + e^- \rightarrow \nu_e + e^-$

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Heavy Sterile Neutrinos

Modified predictions for neutrino elastic scattering:
 enhace coherent rates below some threshold

generation-3

$\nu_s + e^- \rightarrow \nu_s + e^-$
Solar $^8$B CEνNS ~2023

here: simulation of 1000 days LZ

- electronic recoil background
- dark matter nuclear recoils
- $\sim 36$ $^8$B solar neutrino nuclear recoils

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Solar Metallicity with $^8$B CEνNS

It’s hard, but get e.g. 90 events/t/year above 1keV$_{\text{nr}}$

BOREXINO: 7% measurement using CC & spectral fit:

Decisive measurement using generation-3 experiment

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<100MeV Atmospheric Neutrinos

measure \text{atm} \nu \text{ signal to get rate & spectrum}
unmeasured \nu \text{ energy range}

\nu_{\mu,e} + \bar{N} \rightarrow \nu_{\mu,e} + \bar{N}

need \sim 1000 t \text{ years}:

-25\% / +25\%
sys. on flux, preliminary
Supernova Neutrinos

flavor-independent:
complementary measurement

$\nu + N \rightarrow \nu + N$

Supernova Neutrinos

flavor-independent: $\nu \rightarrow \nu$
complementary measurement $A \rightarrow A$

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$^{136}\text{Xe}$ $0\nu 2\beta$ with $\text{nat}^{136}\text{Xe}$ Target

abundance 8.9%: Don’t need (expensive) enrichment

updated simulations in progress @Zurich&Freiburg
CNO Neutrinos in 60t Xenon

$\nu_e + e^- \rightarrow \nu_e + e^-$

136Xe hurts, i.e. use depleted target

CNO detection significance

${\nu_e + e^- \rightarrow \nu_e + e^-}$

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Conclusions

Dark Matter
- Dark photons
- Axion-like particles
- Planck mass

WIMPs
- Spin-independent
- Spin-dependent
- Sub-GeV

Sun
- Solar pp neutrinos
- Solar Boron-8 neutrinos

Supernova
- Supernova neutrinos
- Multi-messenger

Big Bang
- Neutrinoless double beta decay
- Double electron capture

Cosmic Rays
- Atmospheric neutrinos