Getting a Kick out of Xenon

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Oxford, May 2018

Spoiler Alert

We haven't found Dark Matter yet

Xenon-based experiments are probing our most popular models

Creative new ideas cut across theory and experiment, bring discovery science back to universities

Possible Dark Matter Masses

80 orders of magnitude

10^{-21}eV μeV meV eV MeV GeV TeV M_{Planck} M_{solar}

wavelength doesn't fit in galaxies

excluded by gravitational lensing

Possible Dark Matter Masses

80 orders of magnitude

10^{-21}eV μeV meV eV MeV GeV TeV M_{Planck} M_{solar}

1/year

optical

bosonic / field | fermionic / particle | astro

Axions WIMPs

axion-like particles thermal relics

Possible Dark Matter Masses

80 orders of magnitude

10^{-21}eV μeV meV eV MeV GeV TeV M_{Planck} M_{solar}

1/year optical

bosonic / field | fermionic / particle | astro

Eöt-Wash
MAGIS
CASPEr
DMRadio
ABRACADABRA
ADMX
HAYSTAC

NEWS-G XENON10 XMASS
CRESST-II Sabre XENON100
CRESST-III COSINE LUX
DAMIC LBECA PandaX DarkSide-50
SENSEI PICO XENON1T Deap3600
SF-He SuperCDMS XENONnT LZ DarkSide-20k
GaAs/Al_2O_3 Gen3/DARWIN Argo

Gaia

Available Mass Space

Dark Matter only has
80 orders of magnitude
to hide

WIMP Direct Detection 101

- coherent scattering

$$\frac{\lambda_{\mathrm{deBroglie}}}{2\pi} = \frac{\hbar}{p} = \frac{\hbar c}{mc^2\, v/c} \sim \frac{197\,\mathrm{MeV\ fm}}{100\,\mathrm{GeV}\ 10^{-3}} \approx \mathrm{fm} \approx r_{\mathrm{nucleus}}$$

- rate prefers high-A (high-J) targets

$$N = n_{\mathrm{target}}\,\Phi\,\sigma_{\chi,N}\,A^2 \qquad \text{or } \propto \sigma_{\chi,N}\,J(J+1)$$

- recoil spectrum: falling exponential at low energies

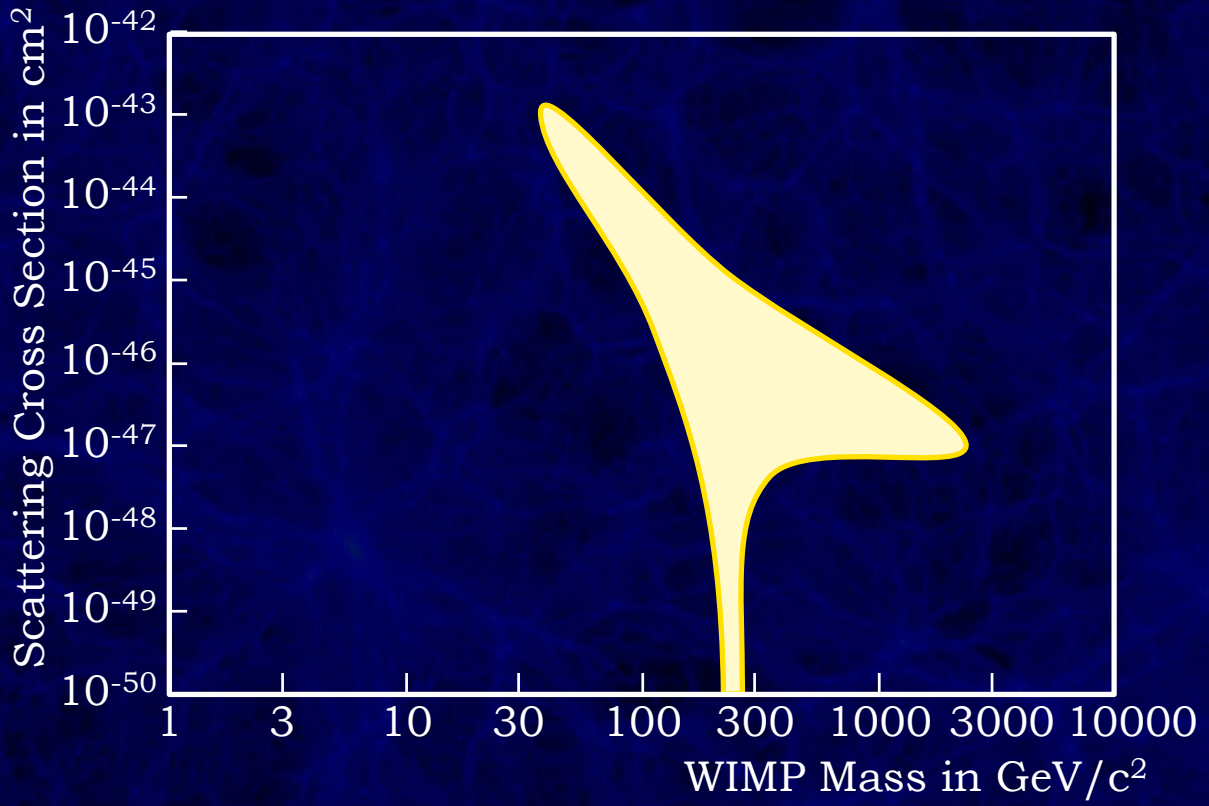
$$E_{\mathrm{r,max}} \sim \frac{p_\chi^2}{2m_{\mathrm{N}}} \sim \frac{\left(100\,\mathrm{GeV/c^2} \times 10^{-3}\mathrm{c}\right)^2}{2 \times 100\,\mathrm{GeV/c^2}} = 50\,\mathrm{keV}$$

WIMP Detection: Target

Plot Cross Section versus WIMP mass

fill with your own prior

e.g. Z-mediation through a box, or Higgs-mediated, or Z-mediation at 10^{-10} abundance



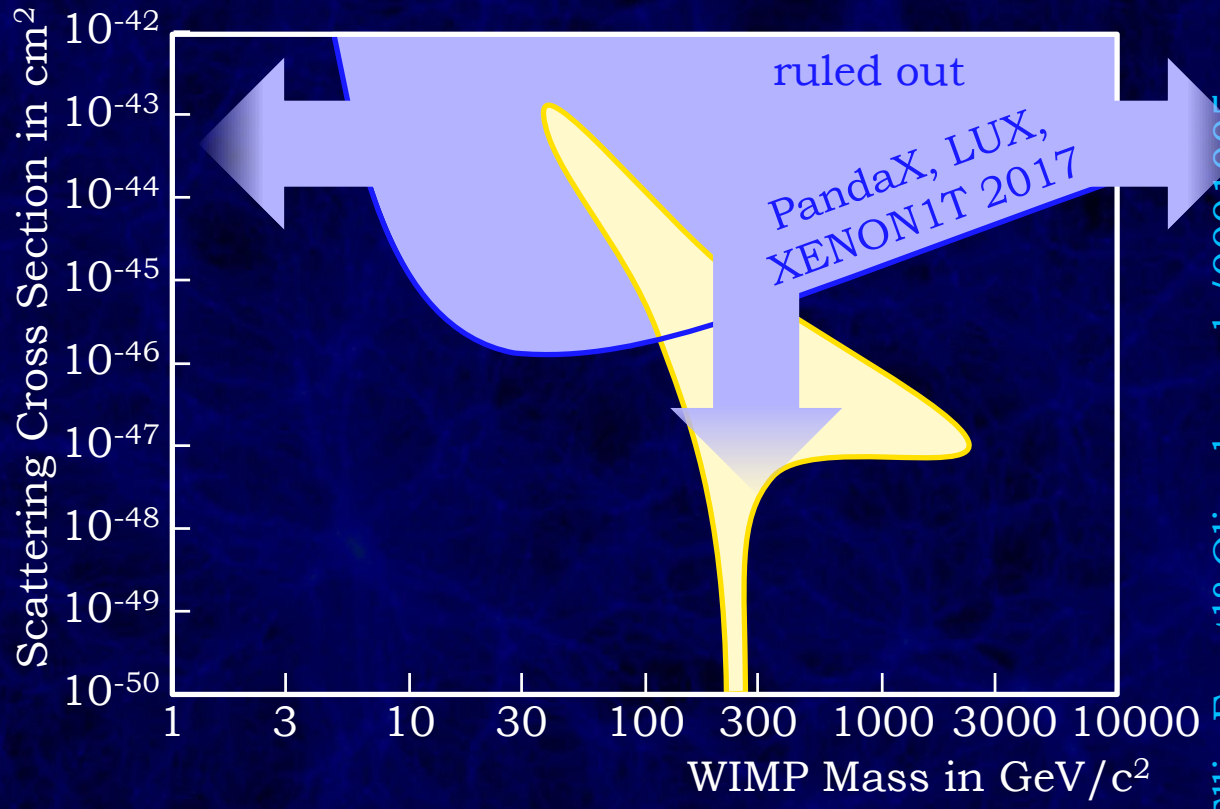
Ellis,Ferstl&Olive hep-ph/0001005

WIMP Detection: Status

Best limits all from xenon experiments

Low masses: fight threshold

High masses: number density decreases as mass density is fixed



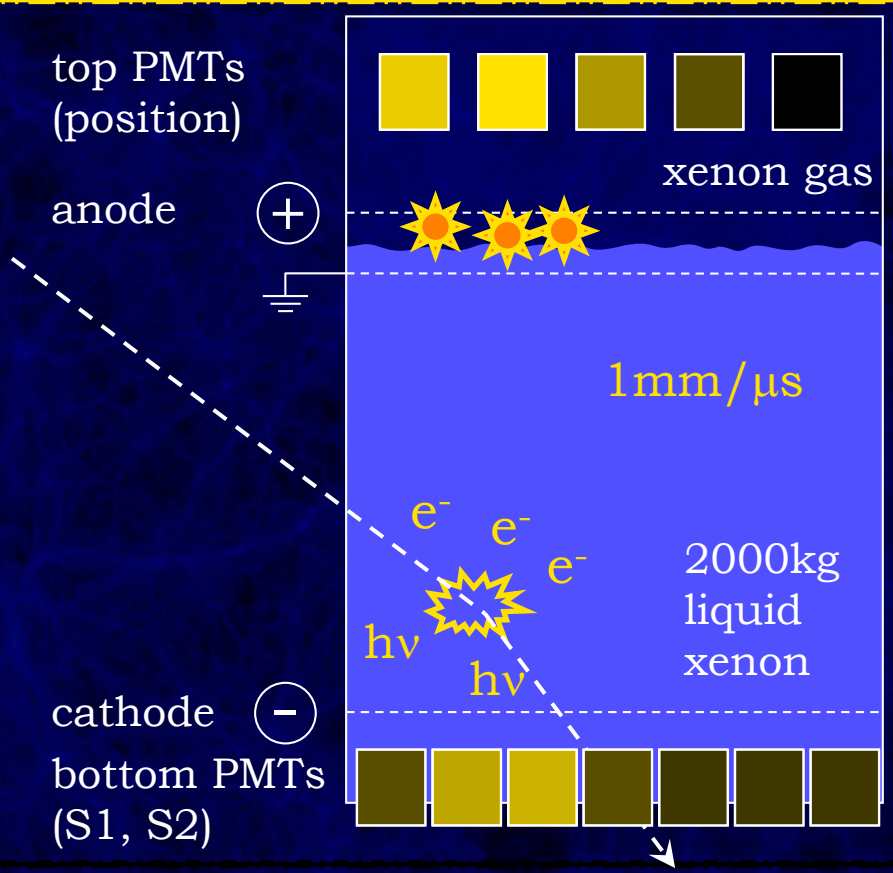
Ellis,Ferstl&Olive hep-ph/0001005

WIMP Detection

Simple non-relativistic scattering

Push deeper, lighter, and heavier

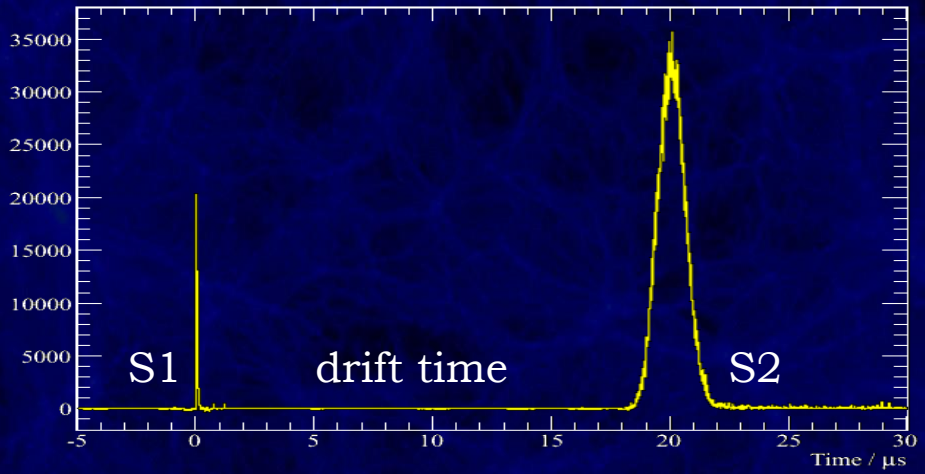
Dual-Phase TPC: e.g. XENON1T



3D position information

S2 hit pattern: $\delta r < 2\,\mathrm{cm}$

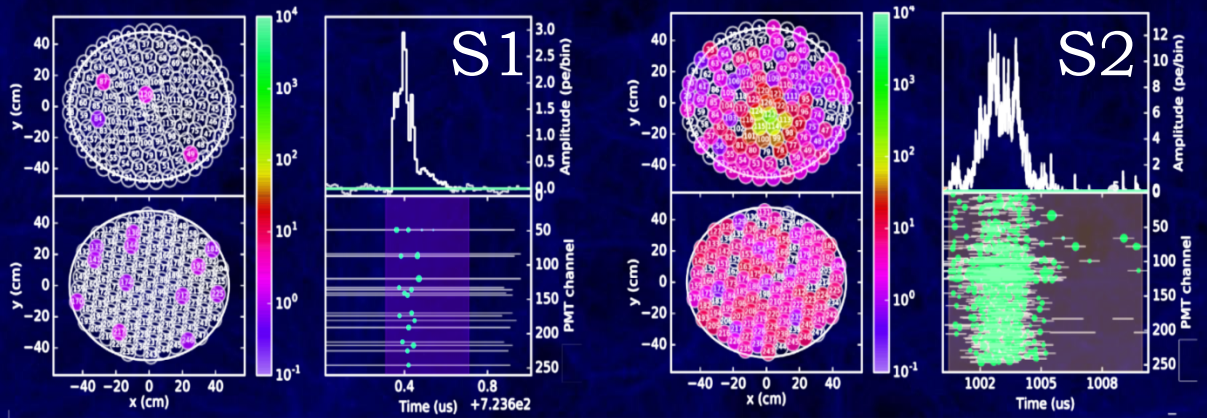
drift time: $\delta z < 500\,\mu\mathrm{m}$

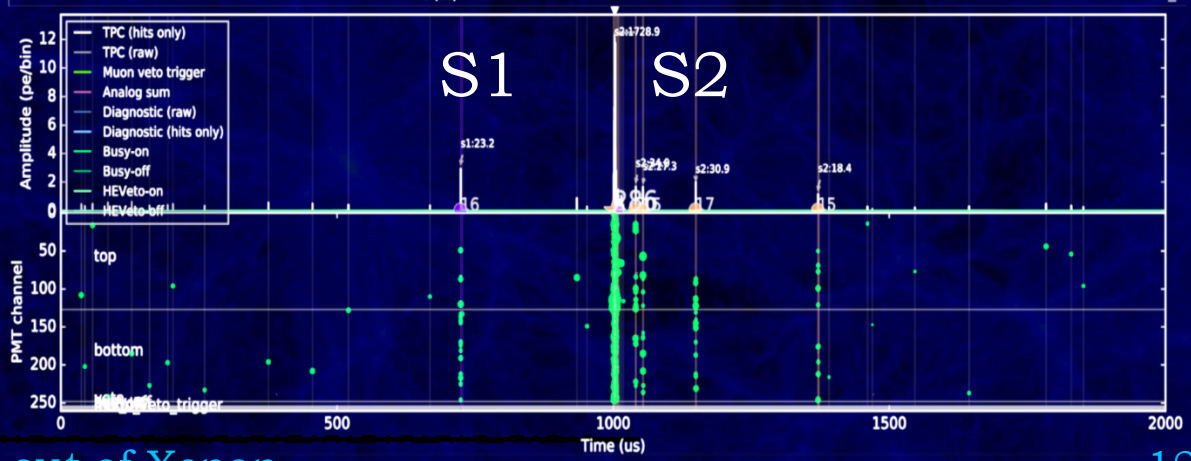


The Secret of Success

Redundant event information: can fight detector artefacts

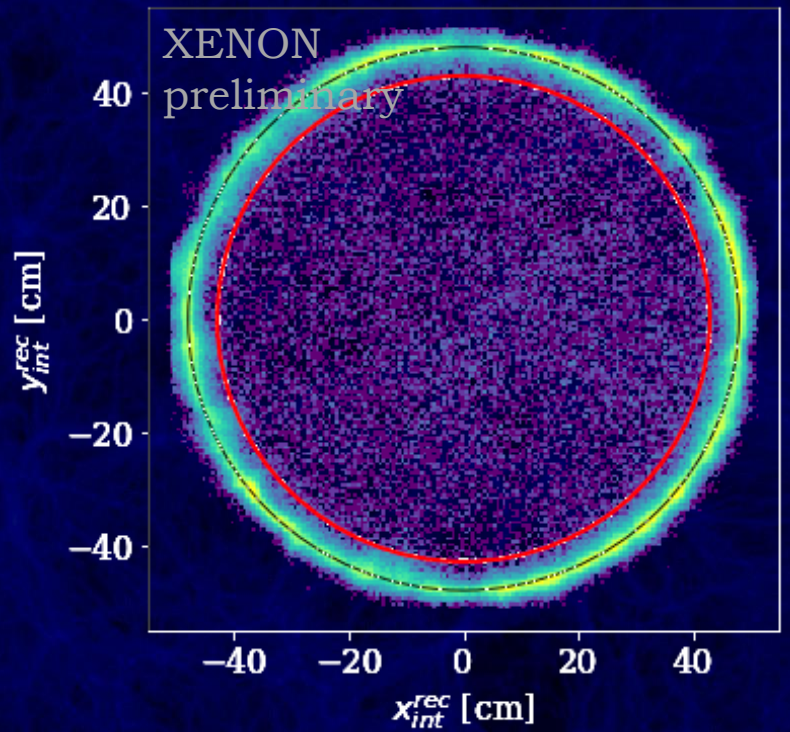
(collect ~2.5MB per event)

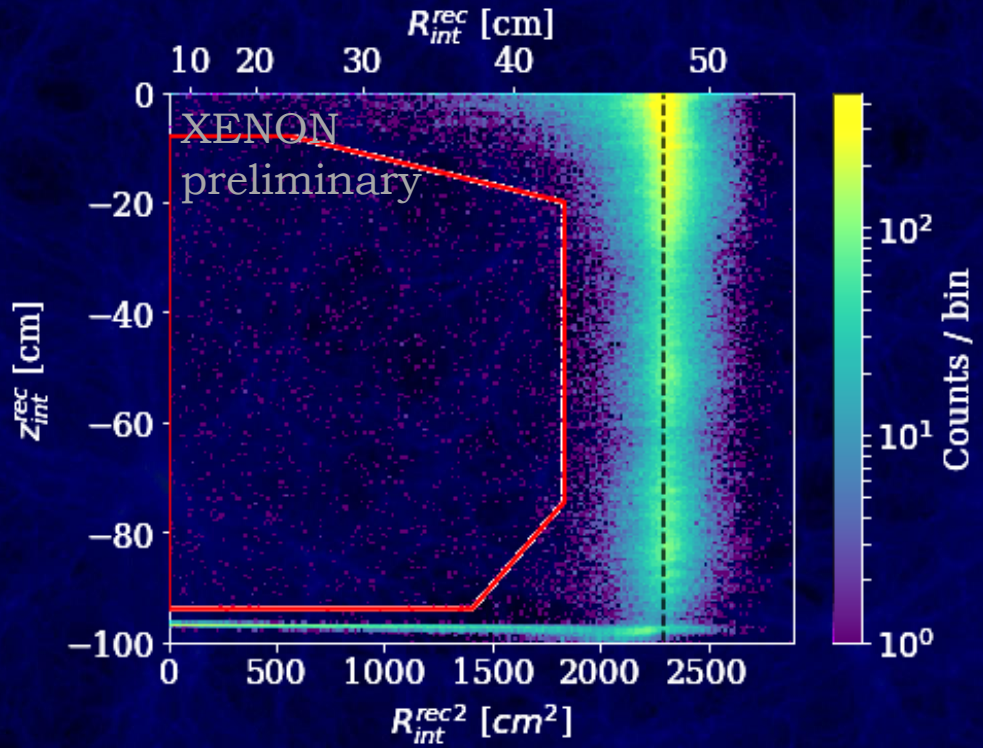




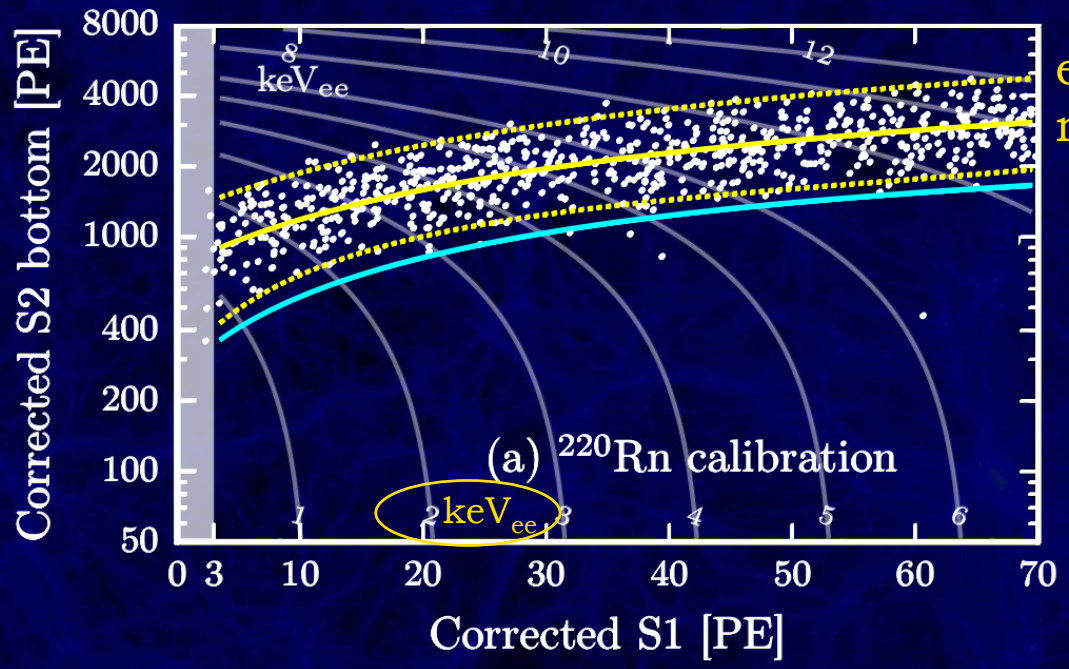
Self-Shielding in Xenon

Reduce background with exp(-diameter/λ_γ)

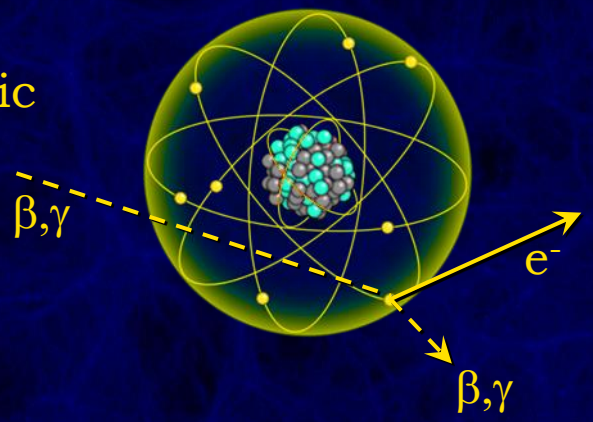




ER/NR Discrimination

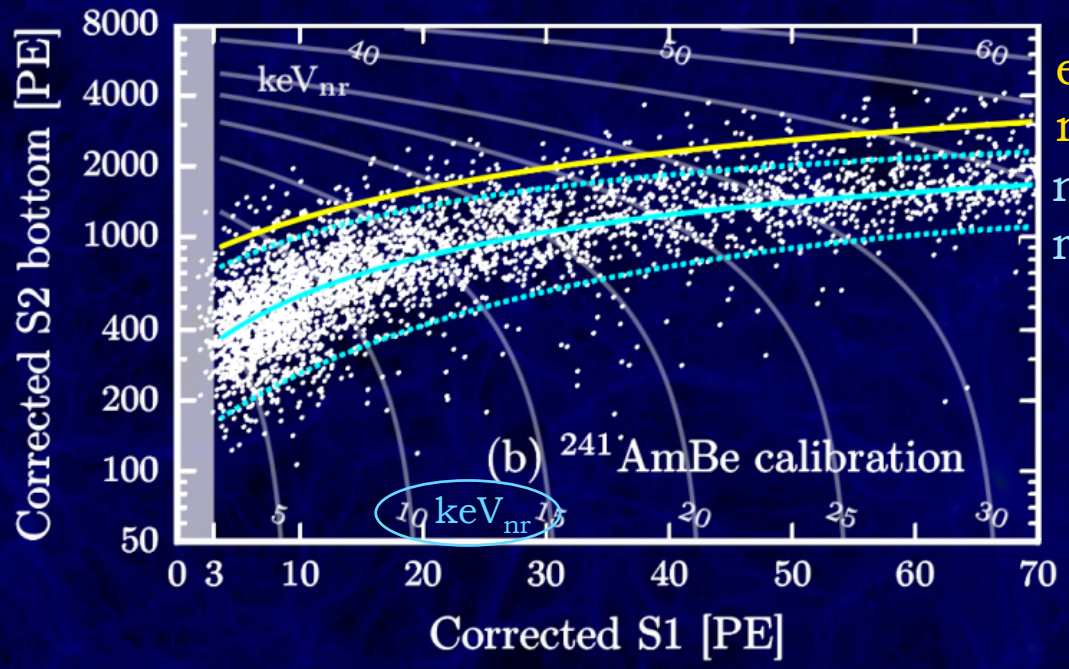


electronic recoils



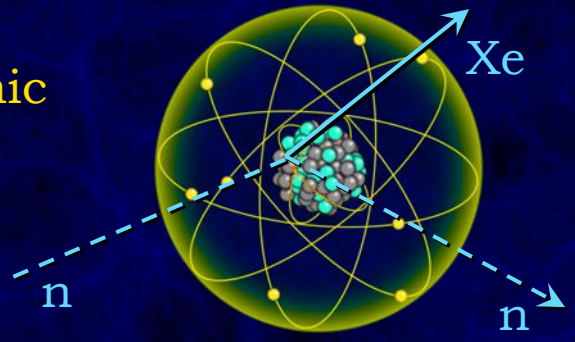
XENON 1705.06655

ER/NR Discrimination



electronic recoils

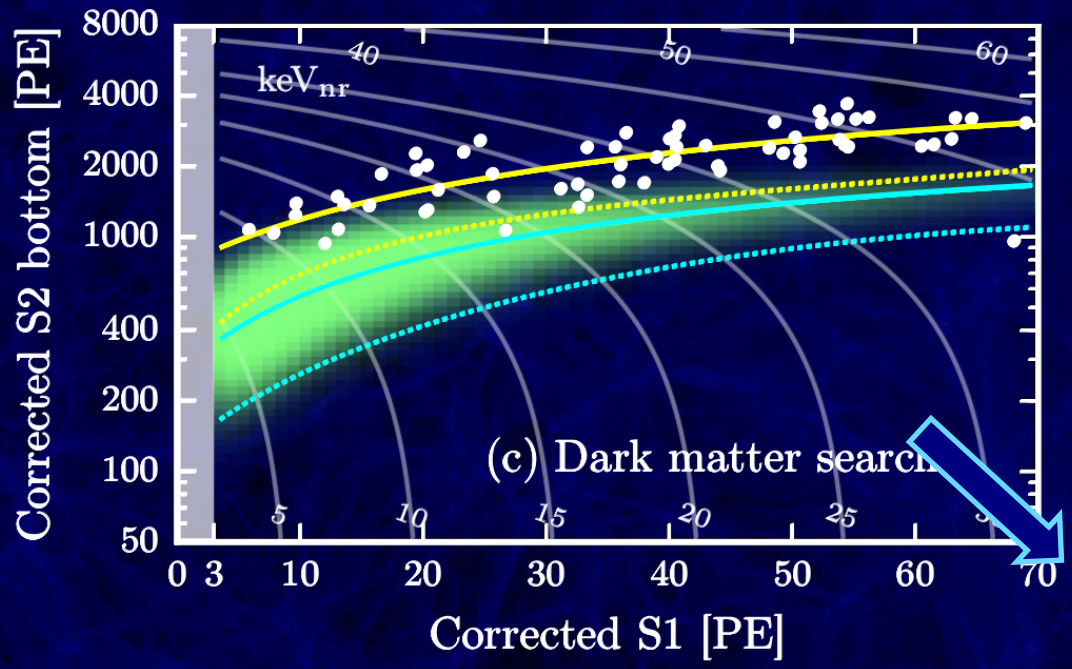
nuclear recoils



XENON 1705.06655

Dark Matter Search

First science data, 34 live days:

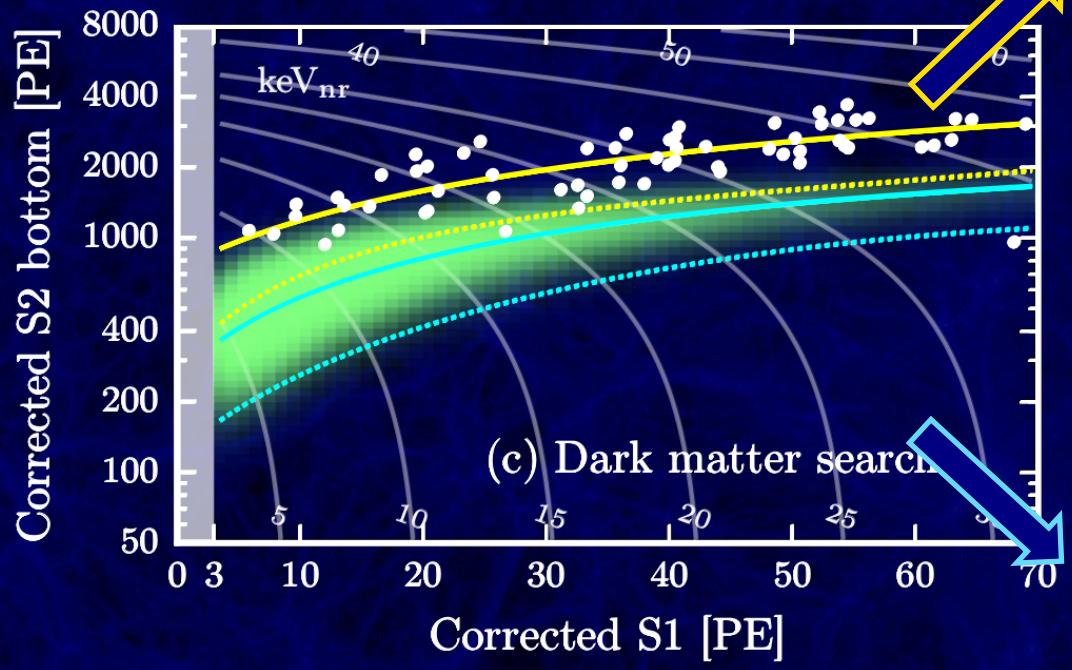


- WIMPs, SI & SD!
- iDM and other EFT
- GeV DM

XENON 1705.06655

Ample Science from "Background"

First science data, 34 live days:



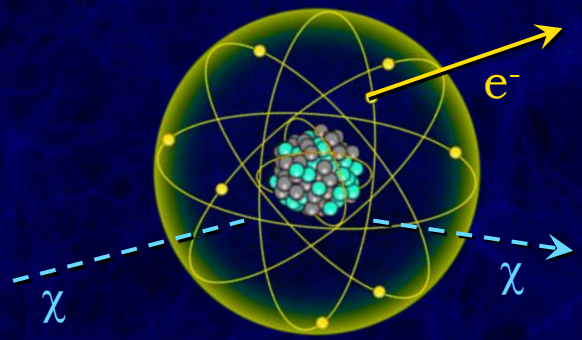
- leptophilic/axial-vector WIMPs, MeV DM
- Migdal & Bremsstrahlung
- inelastic scatter, miDM
- ALPs, dark photons, SuperWIMPs, solar axions, luminous DM, mirror DM
- sterile ν
- DEC on ^{124}Xe

- WIMPs, SI & SD!
- iDM and other EFT
- GeV DM

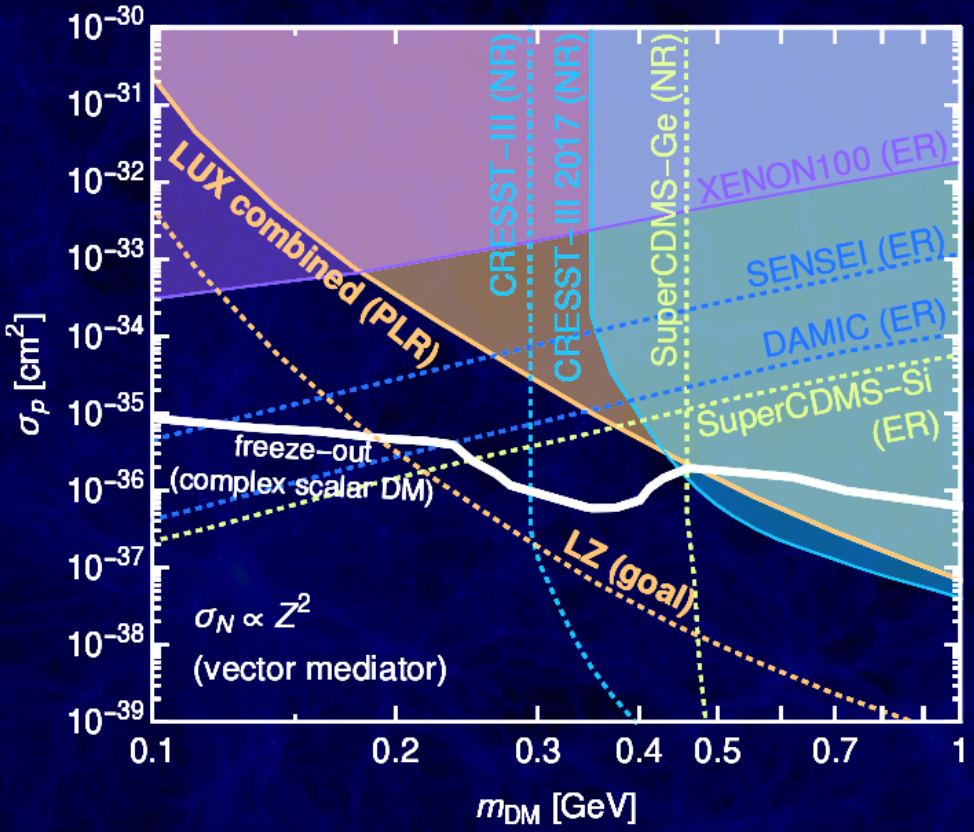
too many XENON100 references to list here

Migdal Effect

Scatter inelastically off entire atom



Eject Auger electron at higher energy, at expense of lower rate



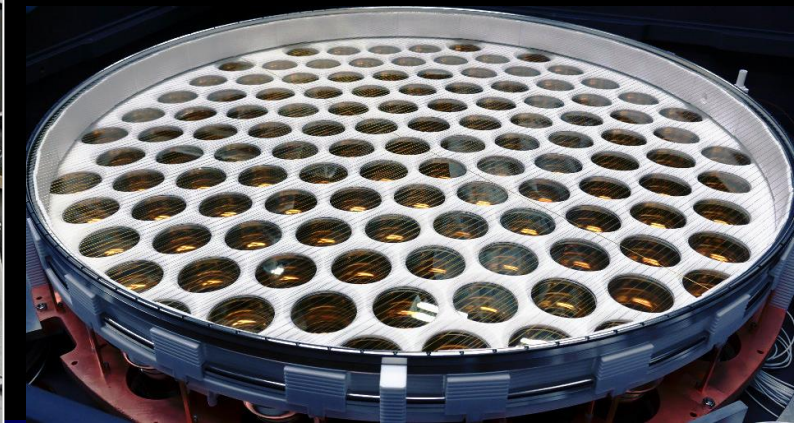
Dolan, Kahlhöfer, McCabe 1711.09906

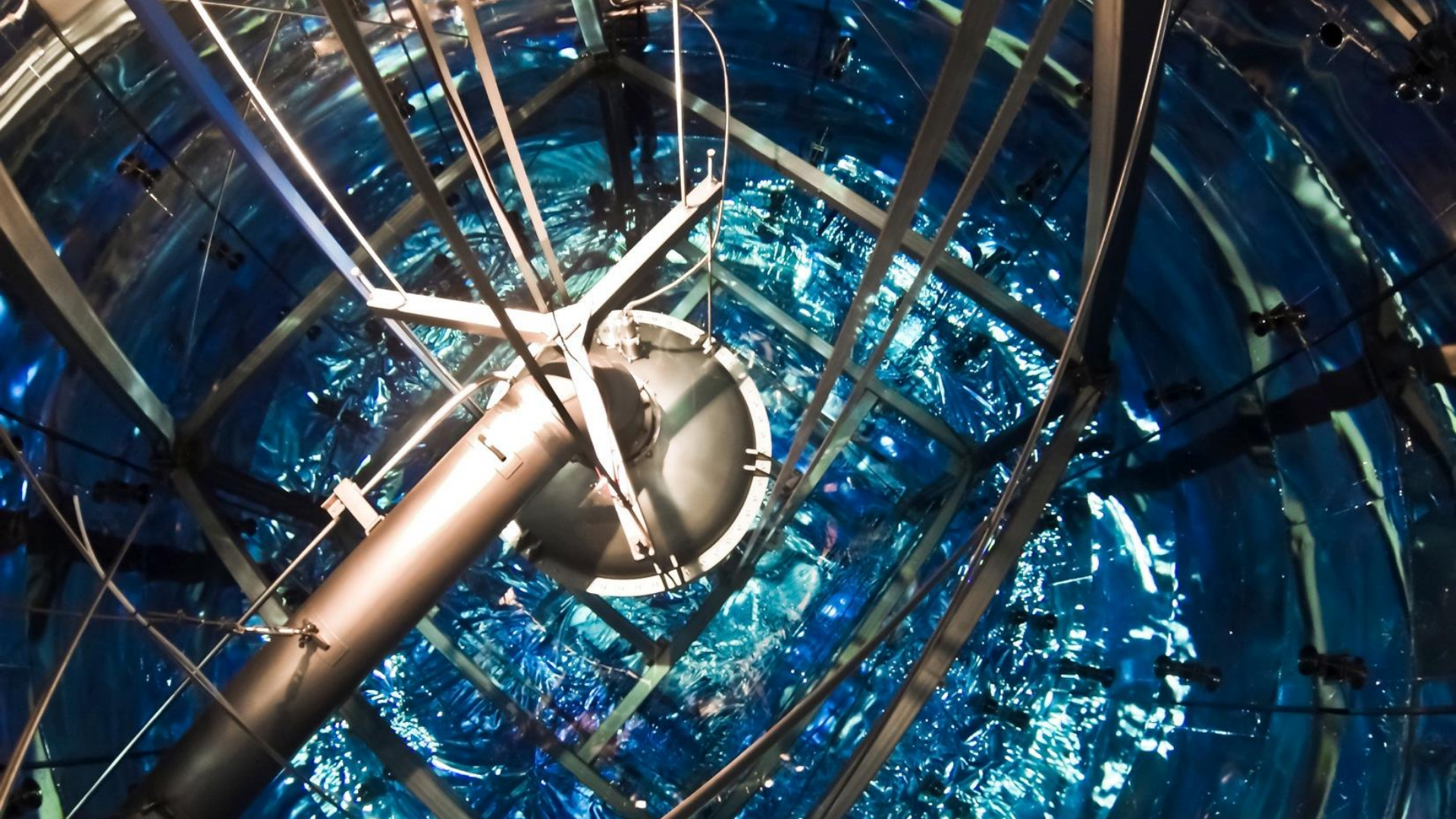
Liquid TPCs

Technology of choice for WIMPs: monolithic, scalable, cheap, redundant event information


i.N.F.N.
solo autorizzati


XENON
XENON
enlightening





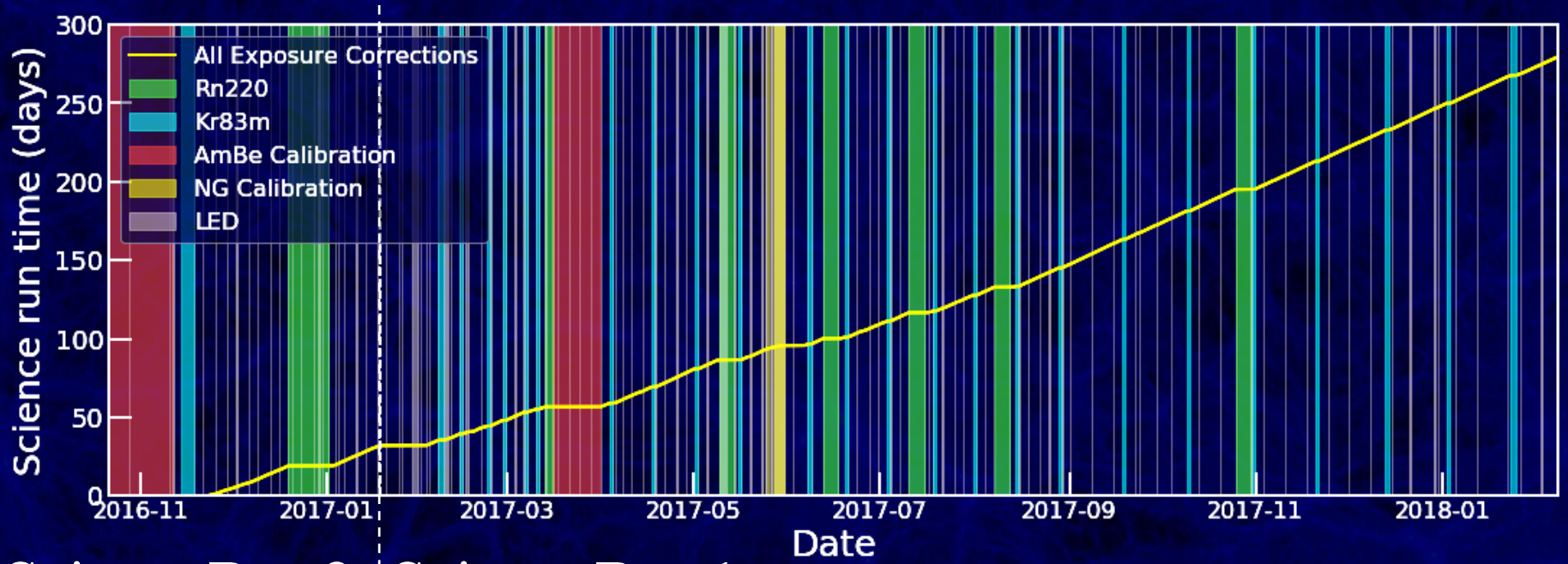
XENON1T

Uhm…

We can take pretty pictures too?

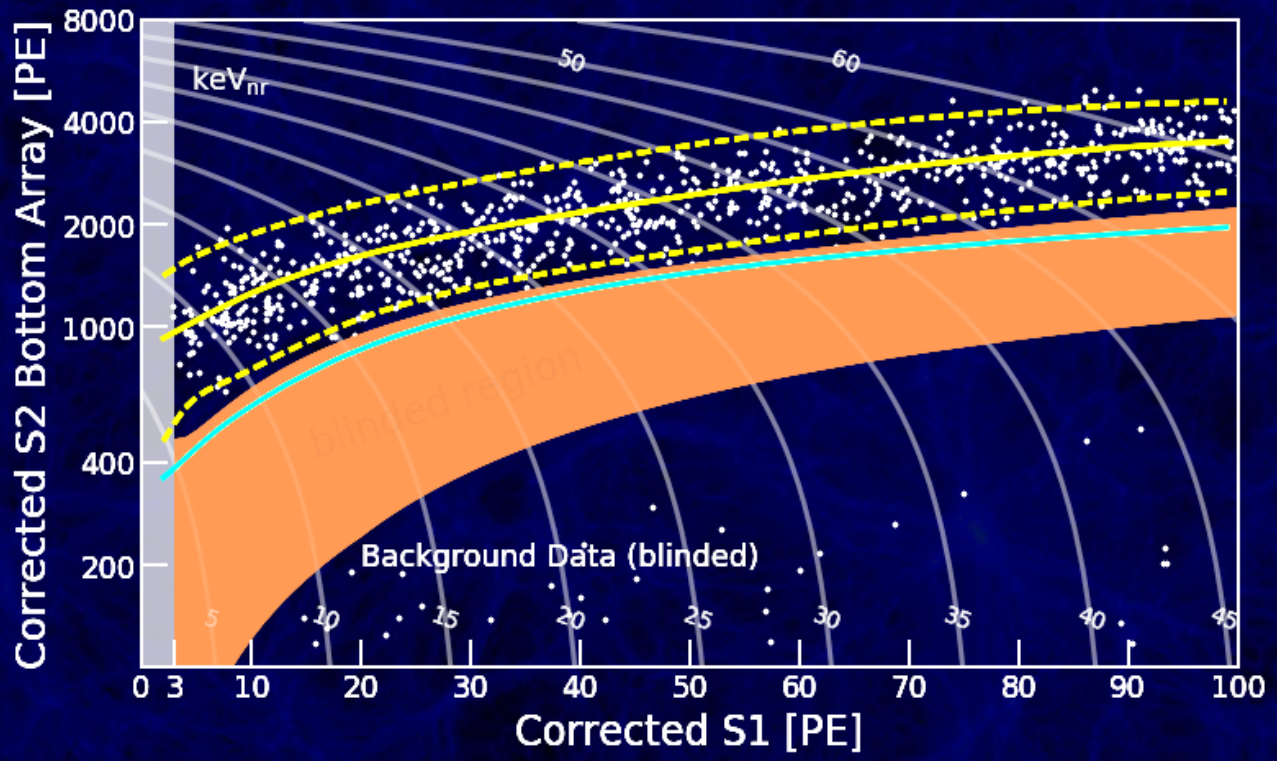
Excellent Data Taking & Stability

279 live days of dark matter data on tape:



ScienceRun0 | ScienceRun1

XENON1T Science Run 1

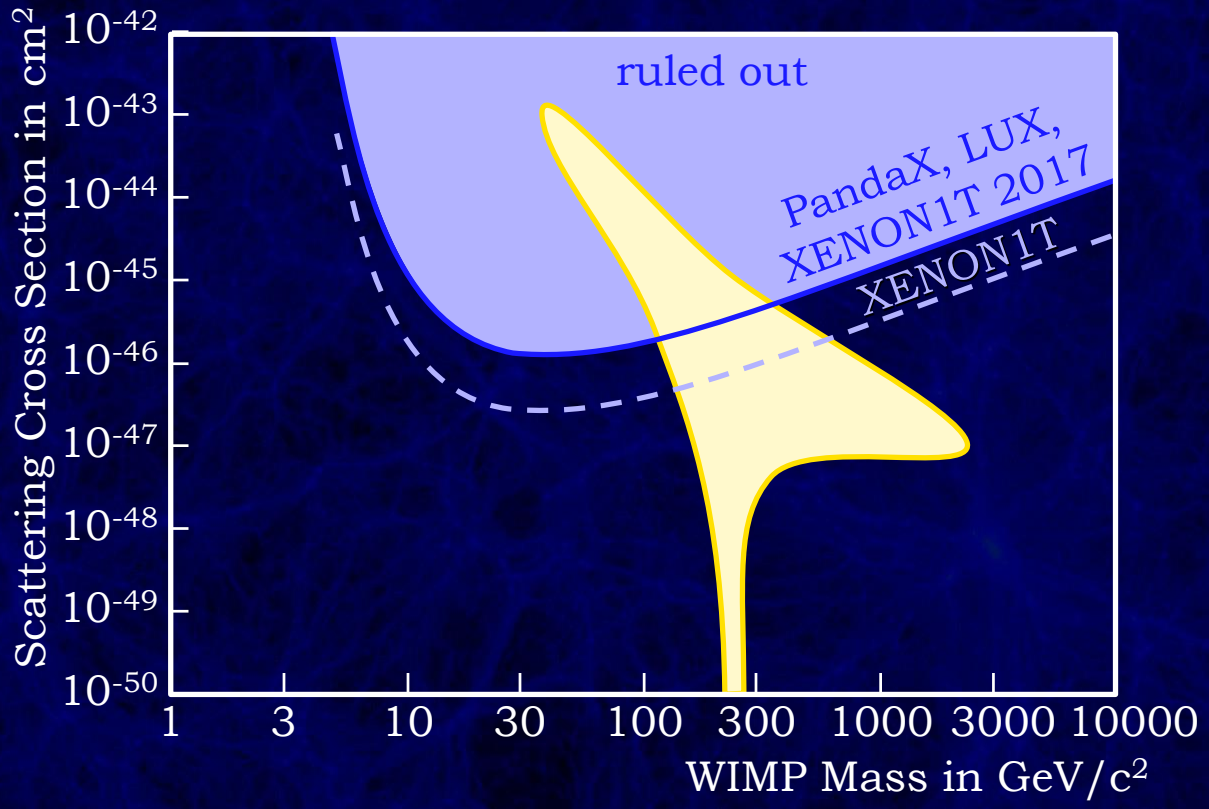


recently unblinded

unsalted last week

public this month

Very Near Future



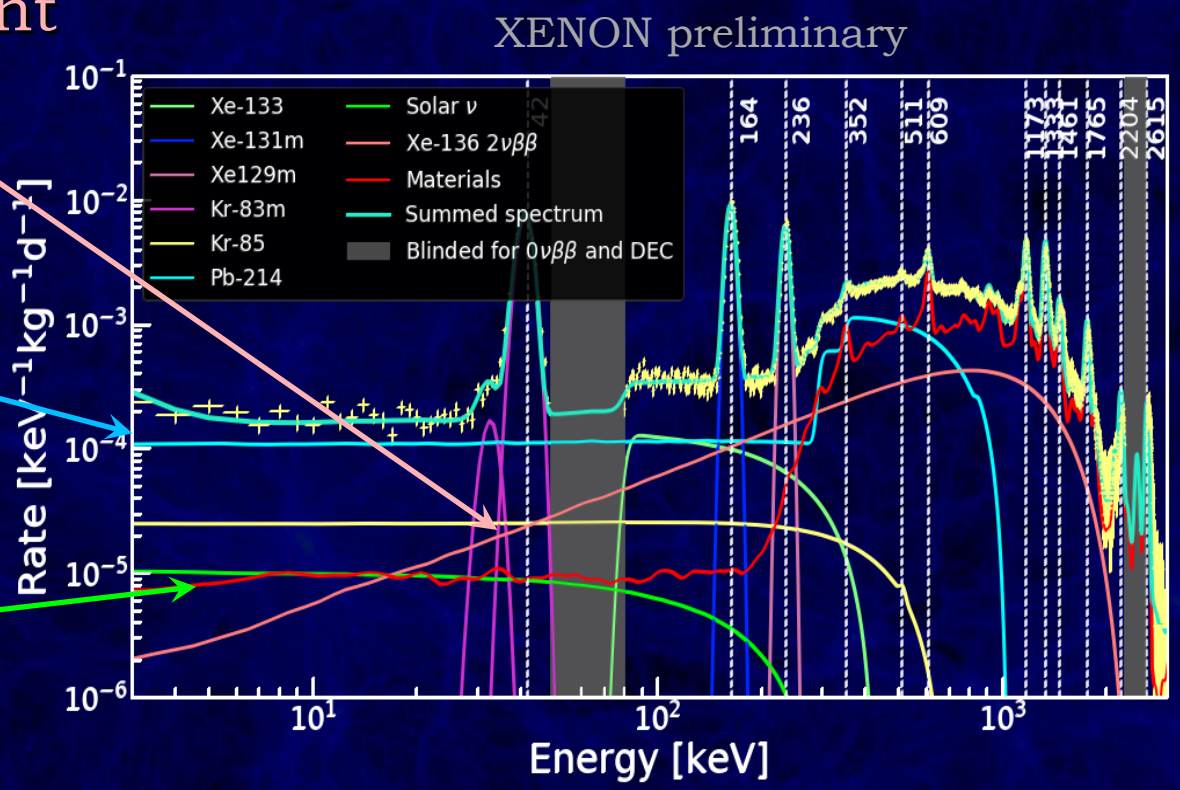
XENON1T with improved sensitivity soon

XENON1T Background Spectrum

overall, 2ν2β important ($t_{1/2}$~10^{21} years!)

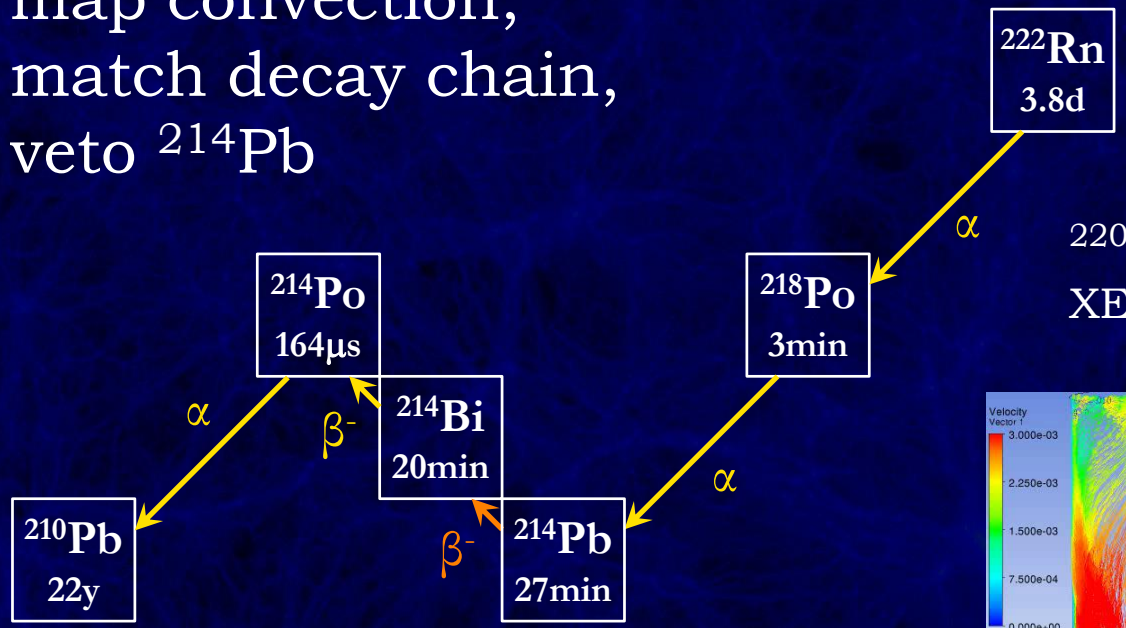
^{222}Rn a technological challenge

some sensitivity at low energies to pp solar ν

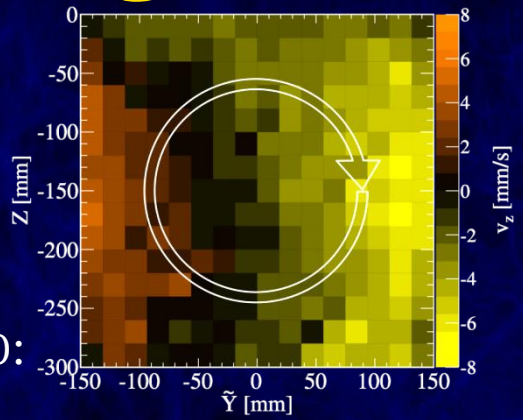


Veto Dominant ^{222}Rn Background

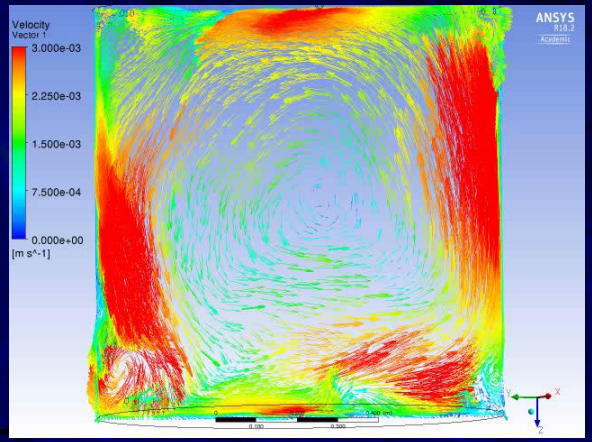
map convection,
match decay chain,
veto ^{214}Pb



^{220}Rn in XENON100:



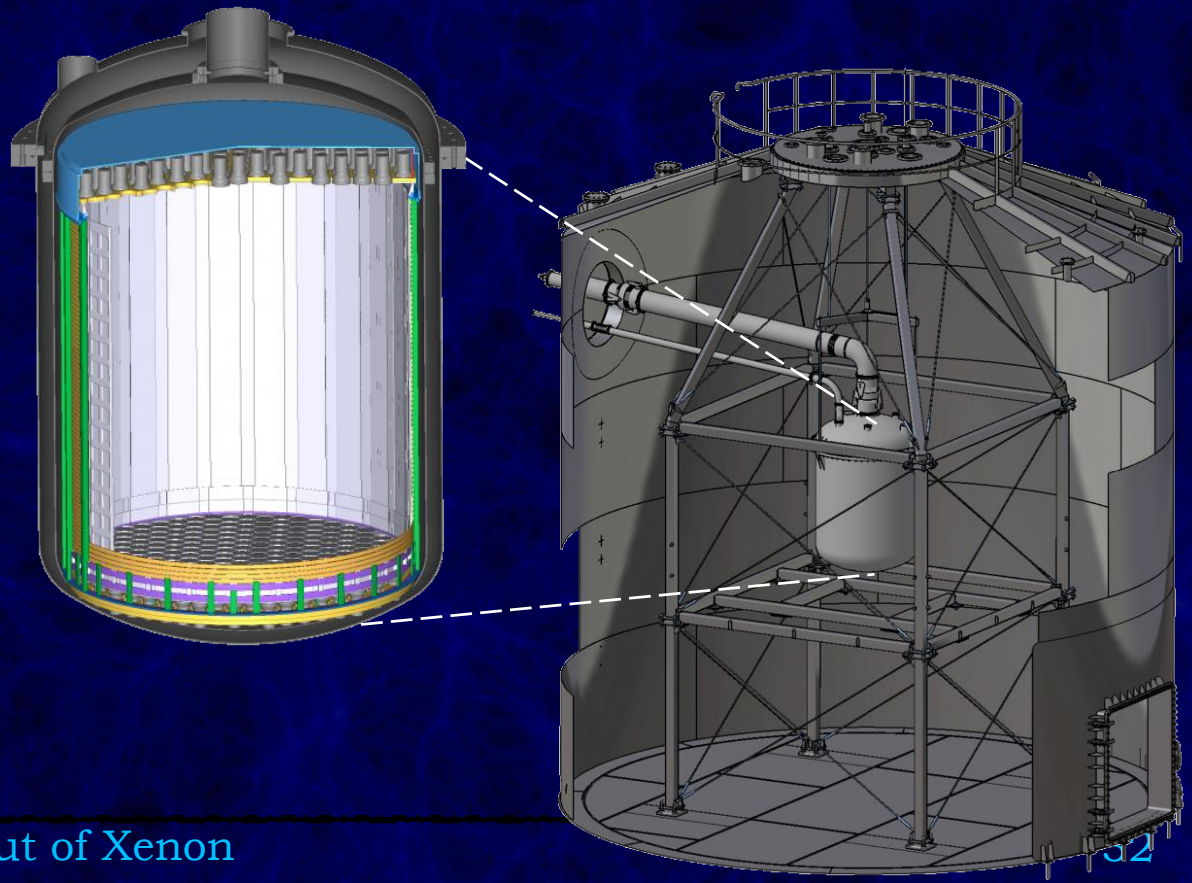
XENON 1611.03585



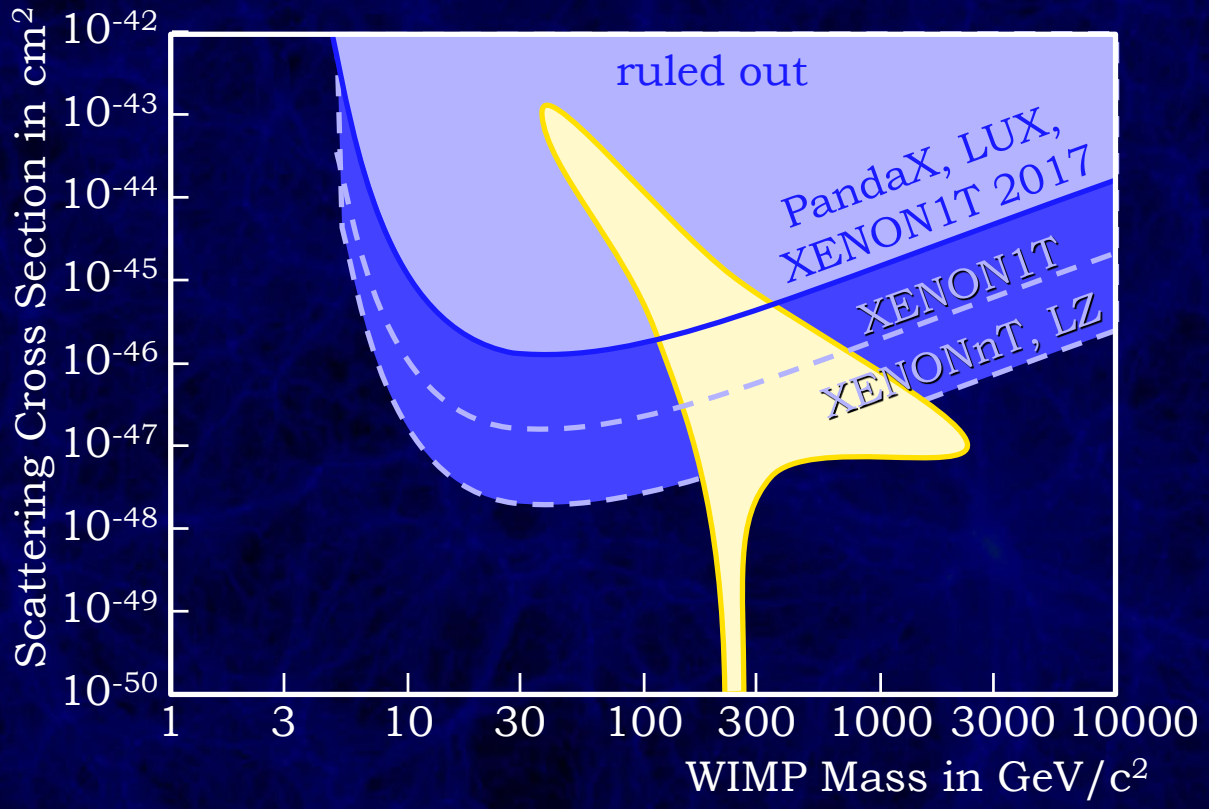
XENON1T Simulation

Upgrade: XENONnT

- Rapid upgrade:
  8t total
  6t active
  4t fiducial
  start 2019
- Re-use most sub-systems
- Xenon in hand, PMTs tested, fixing design



Near Future



XENONnT and LZ start 2019

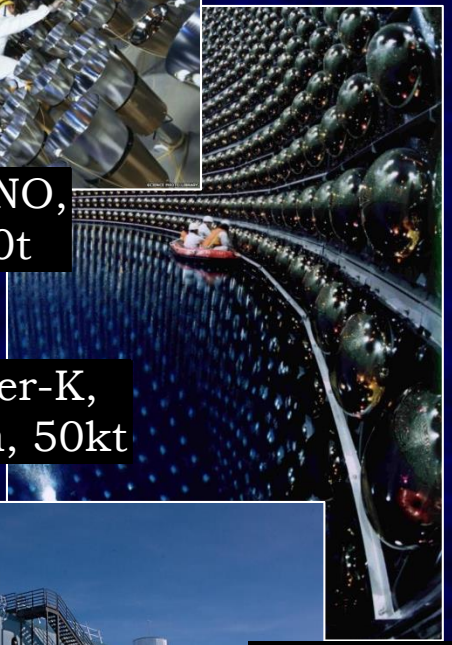
XENON1T and Beyond

Results from 1 year with 1300kg coming anytime now

Starting 2019, XENONnT & LZ dig another order of magnitude deeper

Seriously, Neutrinos!

BOREXINO,
17m, 280t



Super-K,
40m, 50kt

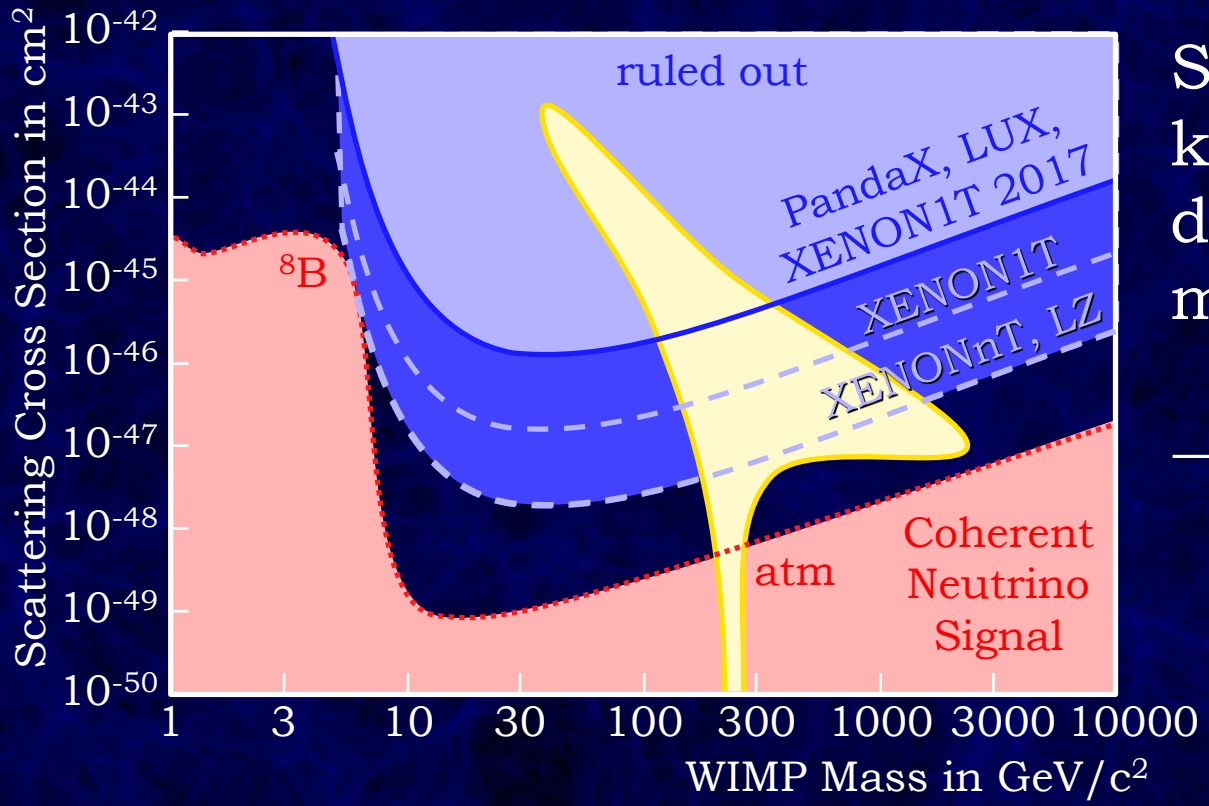
IceCube,
1km^3, 1Gt

low (keV) energies: coherent neutrino-nucleus scattering

$\sigma \propto A^2$

XENON1T,
1m^3, 2t

Neutrino-Nucleus Scattering



Simple scattering kinematics: degenerate in momentum

→ put on same plot

Billard, Strigari, Figueroa-Feliciano 1307.5458

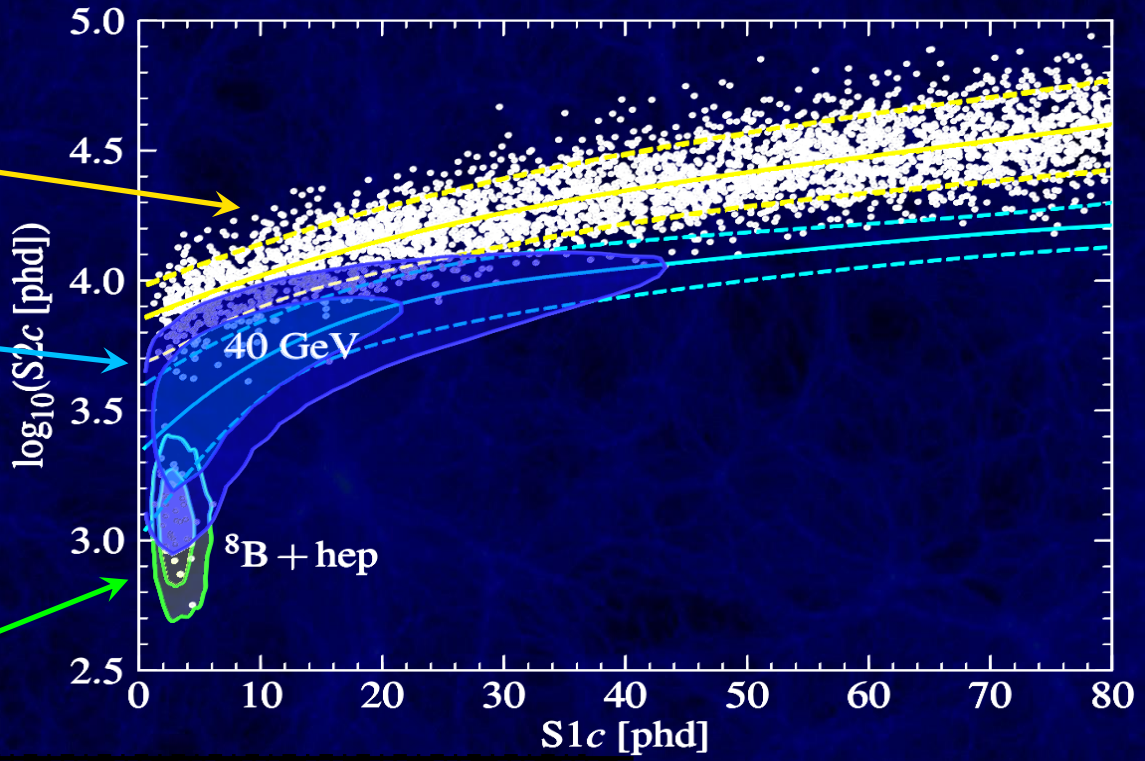
Solar ^{8}B neutrinos ~2023

simulation: 1000 days LZ

electronic recoil background

dark matter nuclear recoils

~36 ^{8}B solar neutrino nuclear recoils



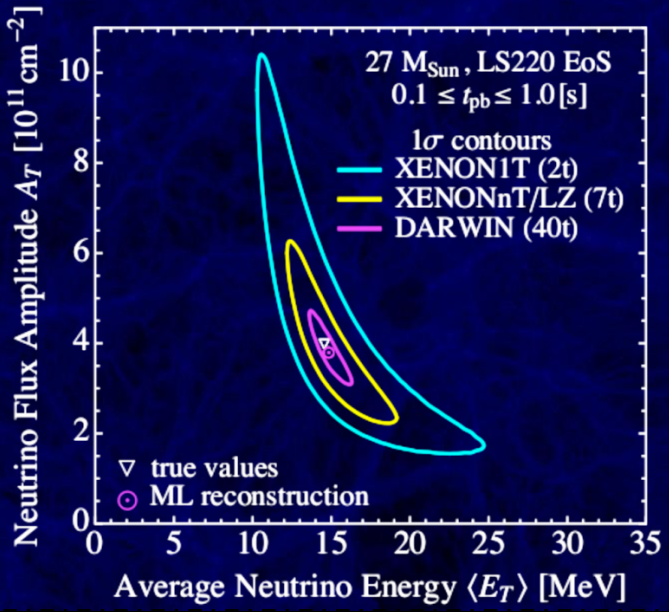
LZ/Dobson UCLA 2018

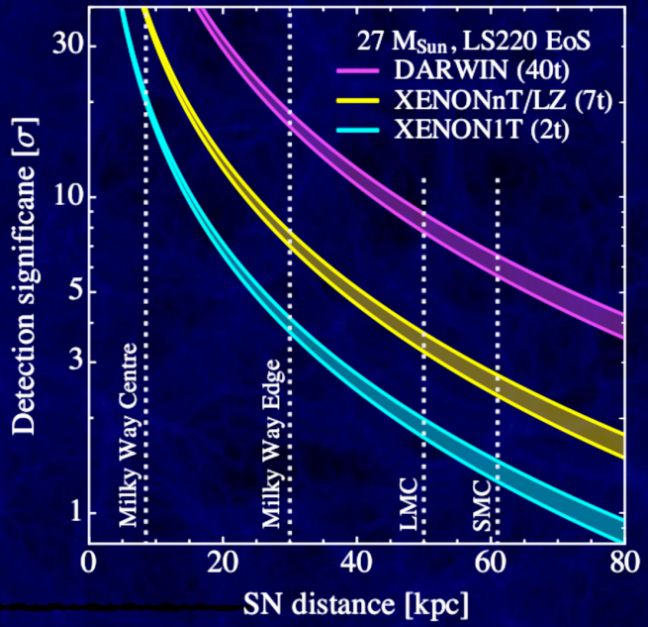
Supernova Neutrinos

few second burst $\nu_x + N \rightarrow \nu_x + N$

flavor-independent: complementary information

XENON1T sensitive across entire Milky Way:

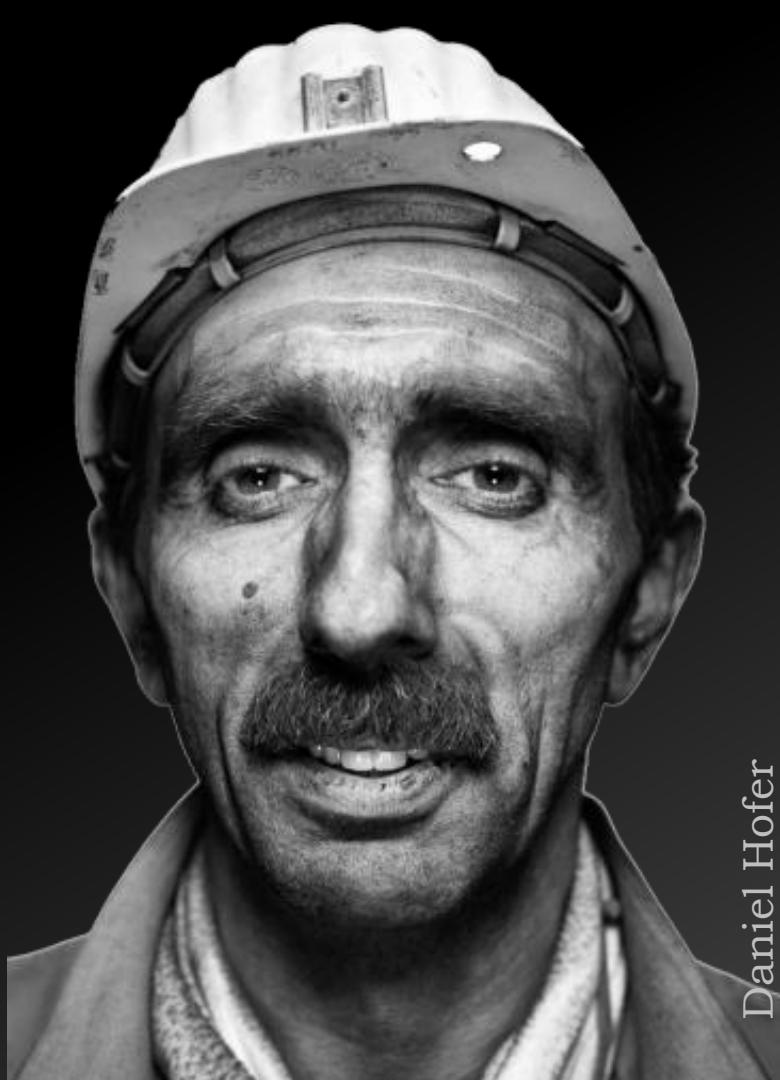




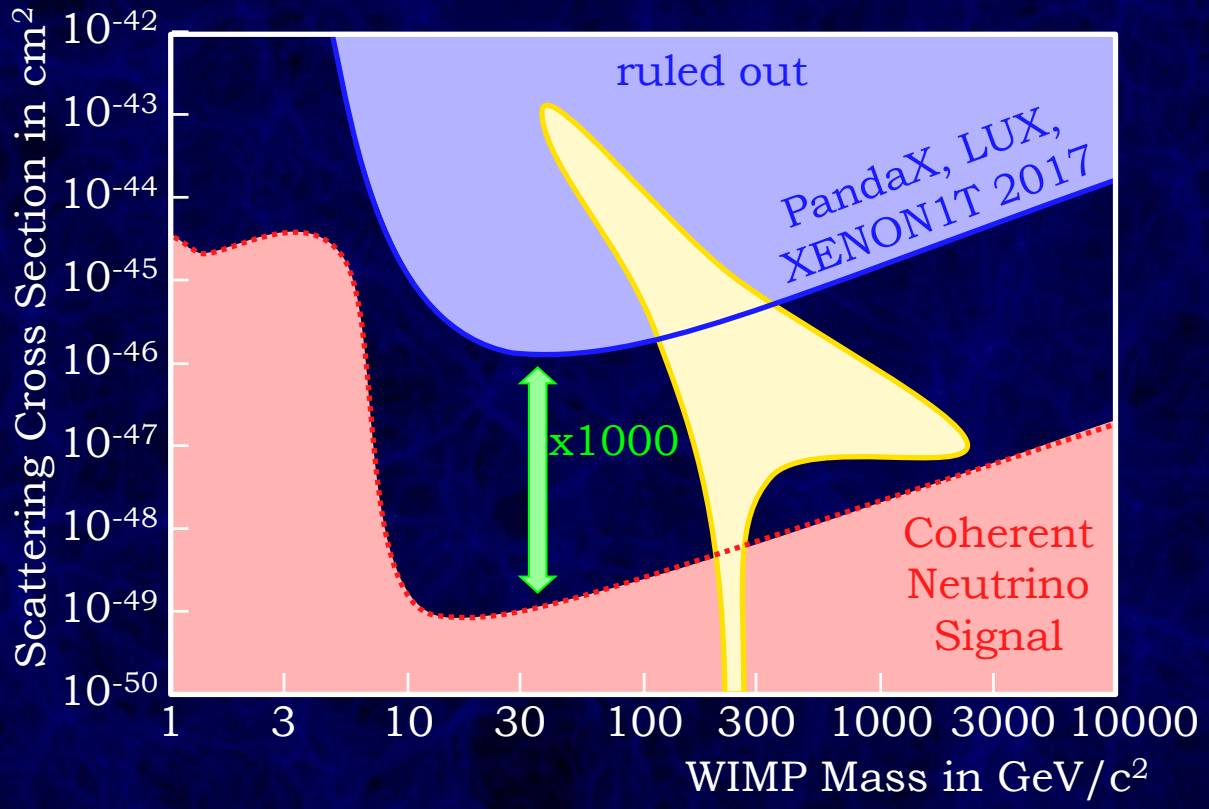
Rafael+ 1606.09243

Measuring Neutrinos

Direct dark matter experiments
become sensitive
to solar and supernova neutrinos

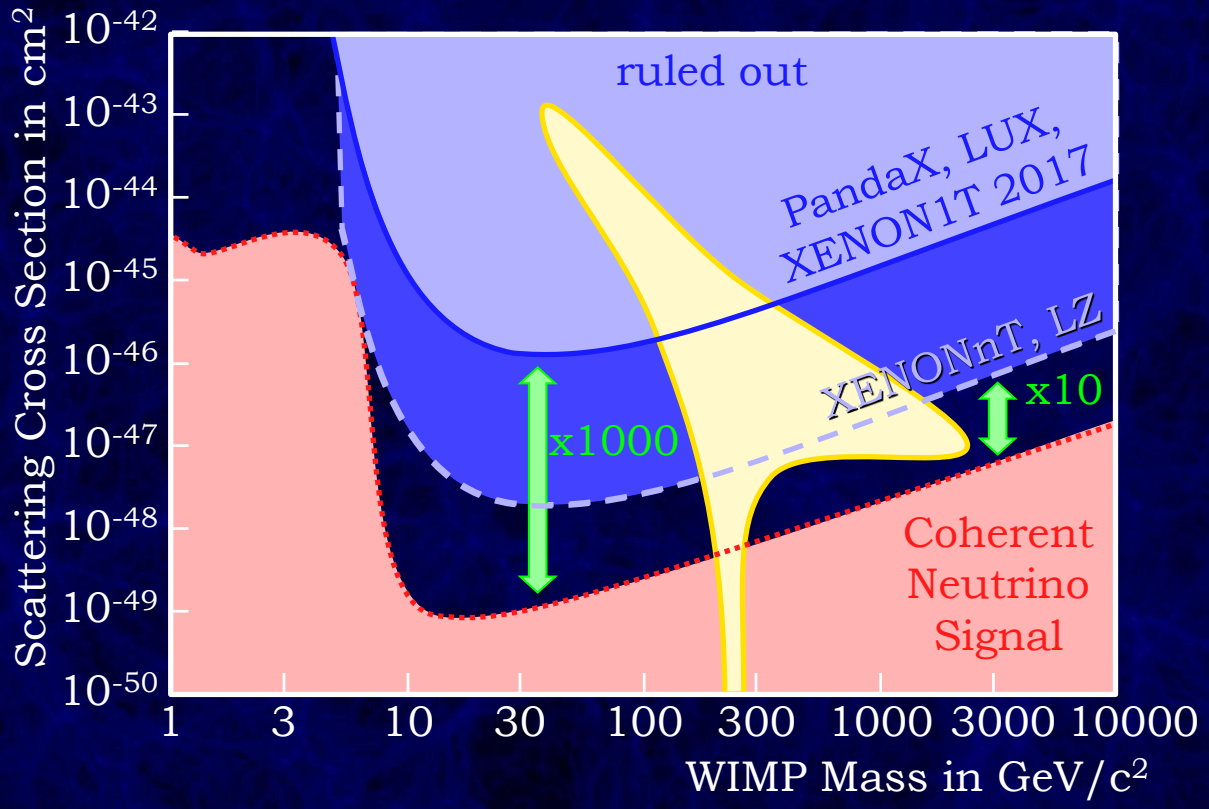


Direct Detection: Status



neutrino floor far, far away

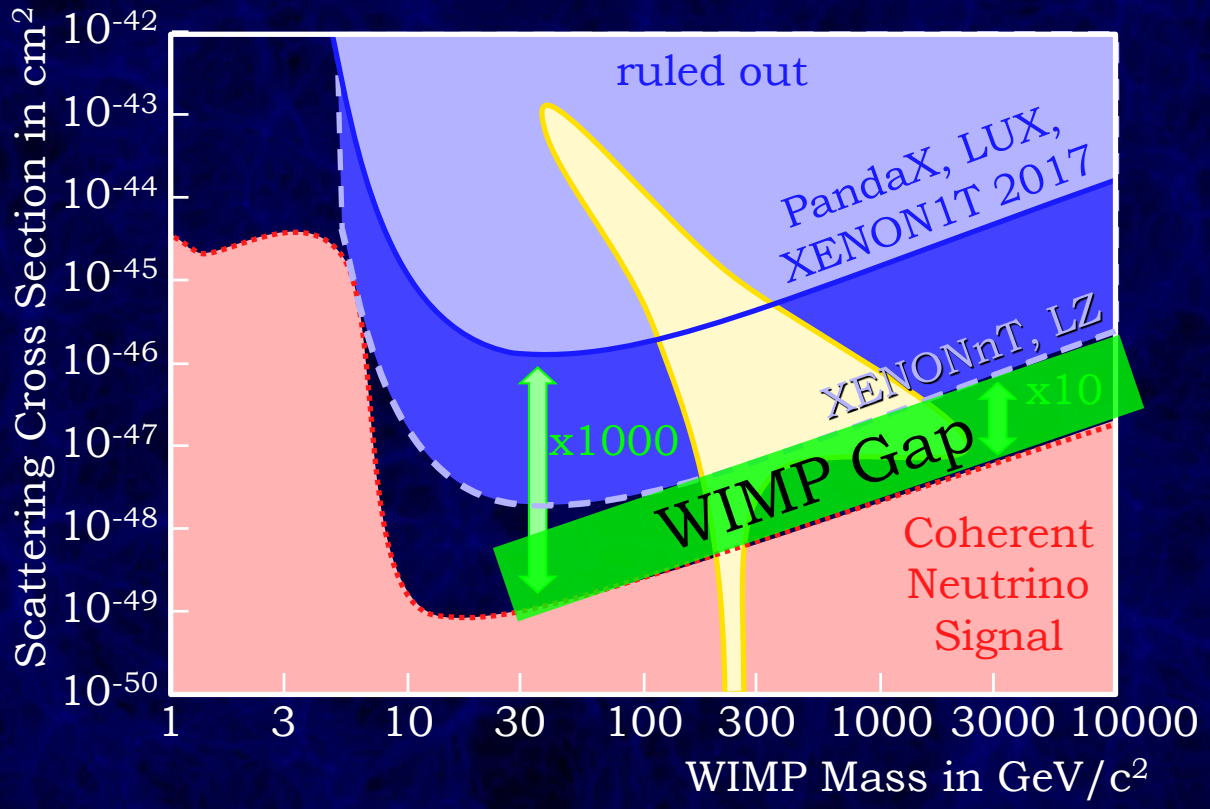
Direct Detection: Outlook



neutrino floor far, far away

strong program to improve factor 100

Require Generation-3 Detectors



neutrino floor far, far away

strong program to improve factor 100

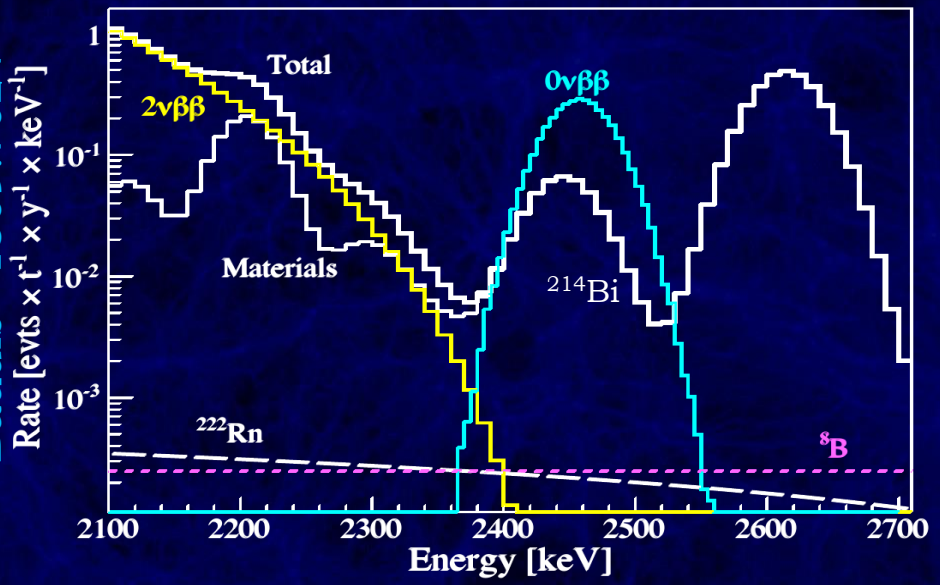
current program leaves a WIMP gap

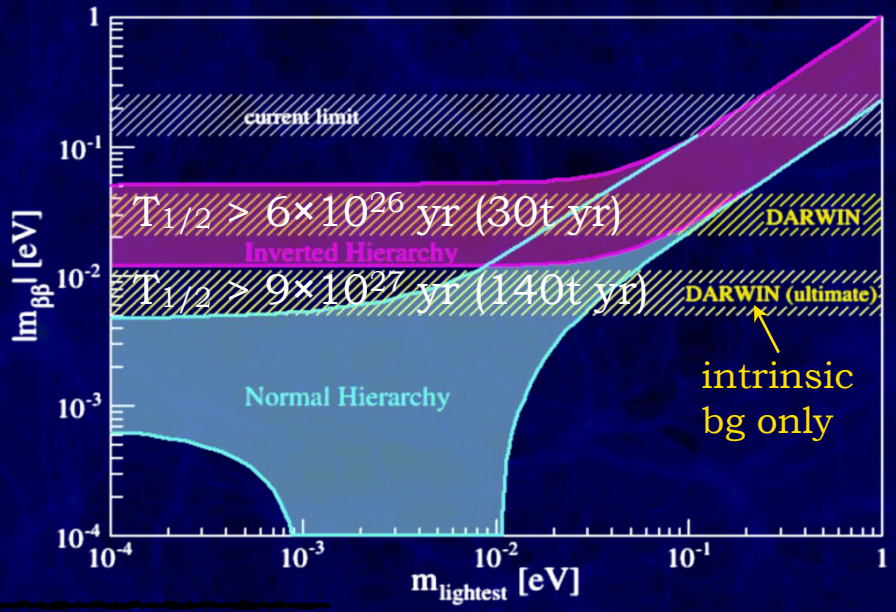
^{136}Xe 0ν2β With ^{nat}Xe Target

$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba} + 2e^-$ (abundance 8.9%)

Requires large dynamic range of detector

Baudis+ 1309.7024





DARWIN 1606.07001

Physics with 60t LXe

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
- 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

- $2\nu\beta\beta$ decay of ^{136}Xe
- $0\nu\beta\beta$ decay of ^{136}Xe
- double-EC on ^{124}Xe

Other:

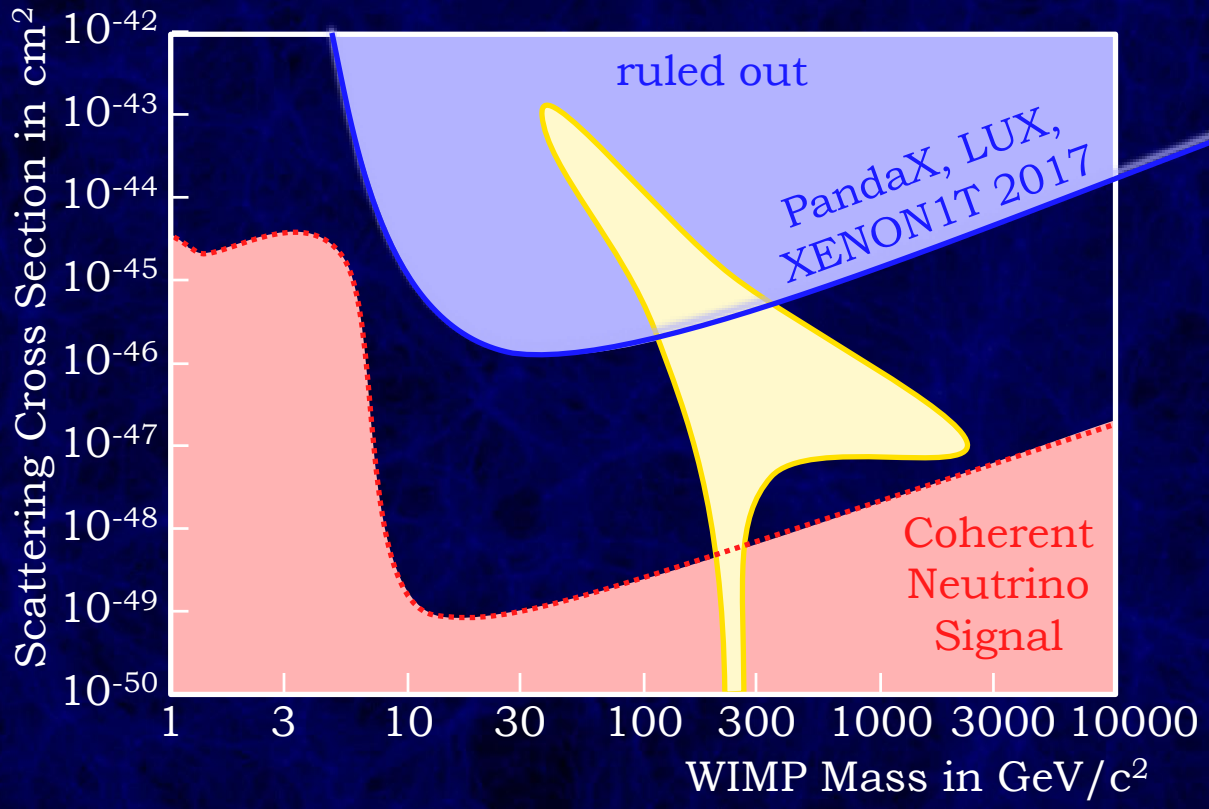
- solar axions
- fractionally charged particles

Not There Yet

Signal from atmospheric neutrinos far, far away

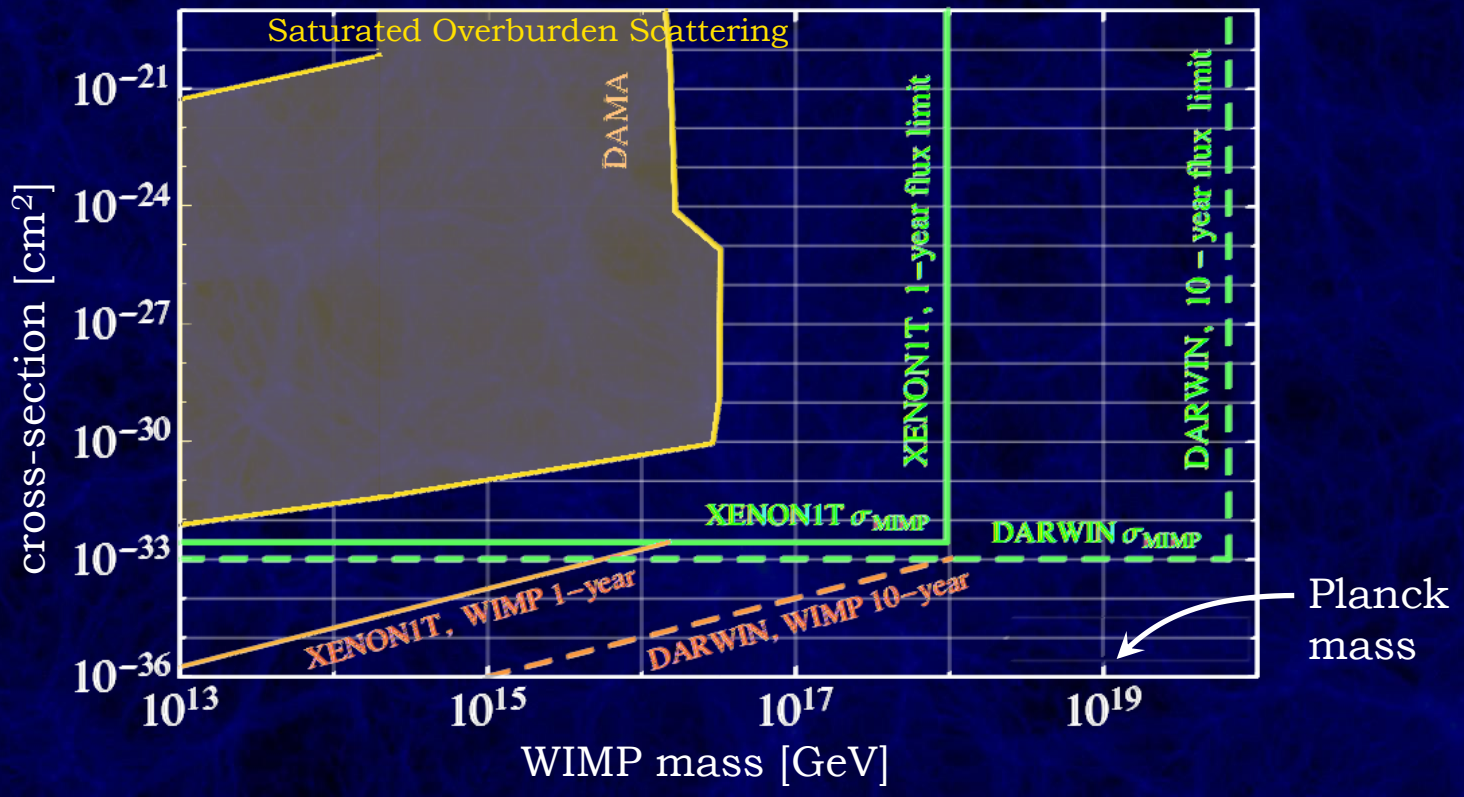
Need Generation-3 experiments to cover WIMP space

Extrapolating to High Masses



Which assumption breaks down?

Direct Detection at High Mass



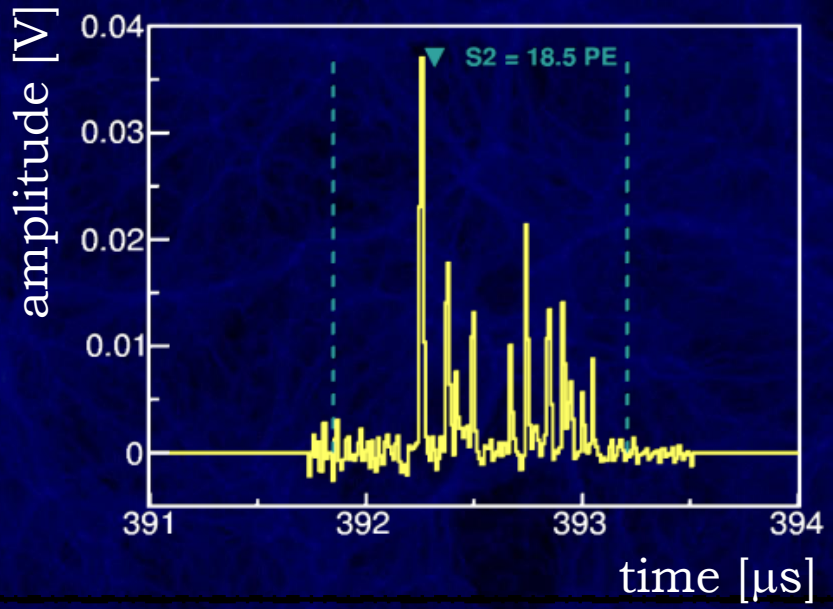
Joe, Ben, Rafael & Nirmal 1803.08044

Probing Planck Mass

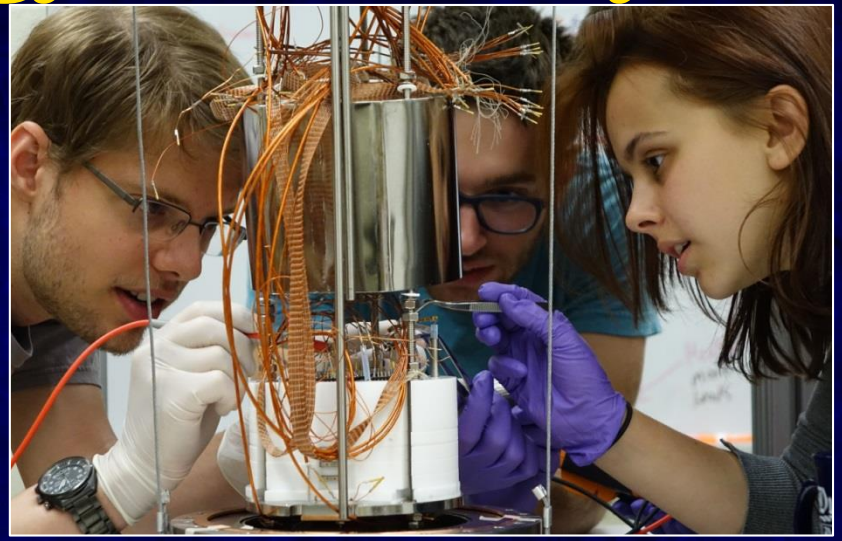
Generation-3 experiment can do it.
Neutrino experiments too.

Extreme Low-Energy Sensitivity

Detect even individual electrons liberated anywhere in 2000kg of Xenon:



XENON100 1311.1088

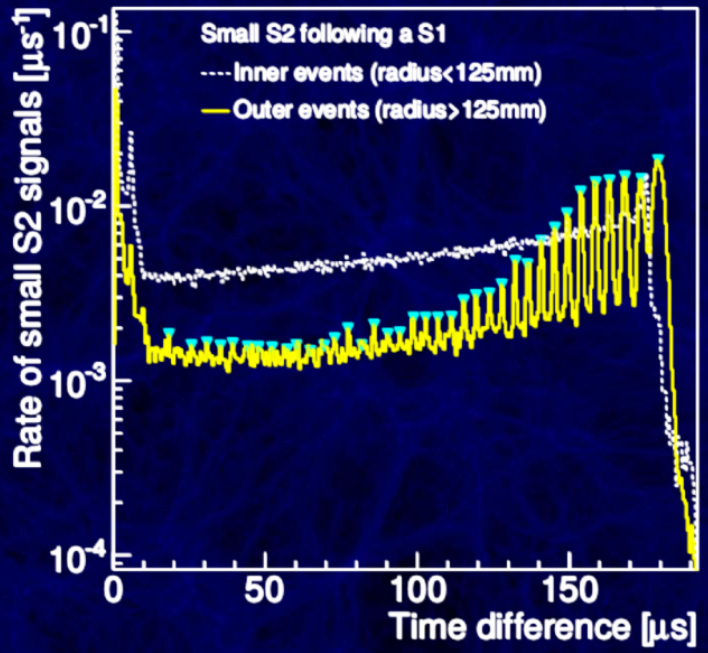


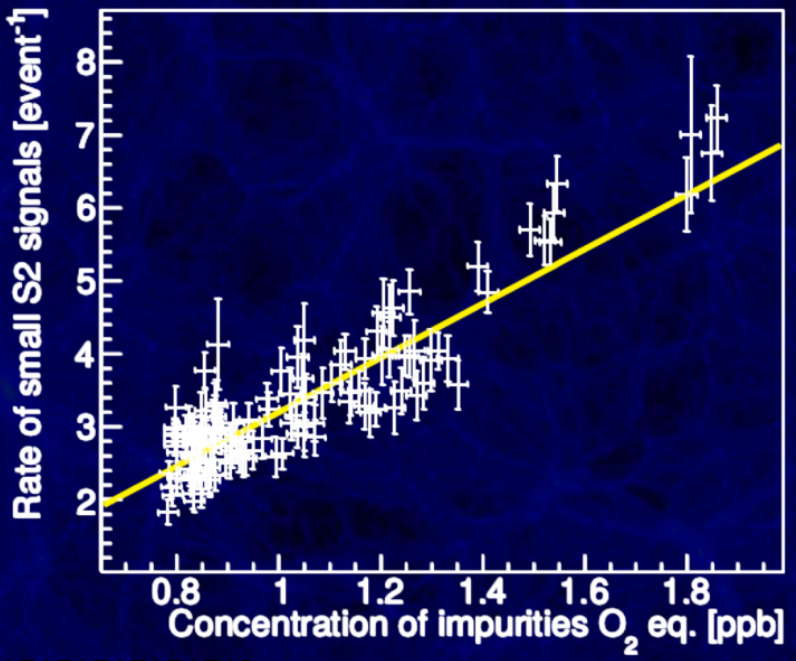
Build dedicated detector to tackle backgrounds and probe Dark Matter

Backgrounds: Photoionization

Xenon light 175nm=7eV

- Photoionizes metals & impurities



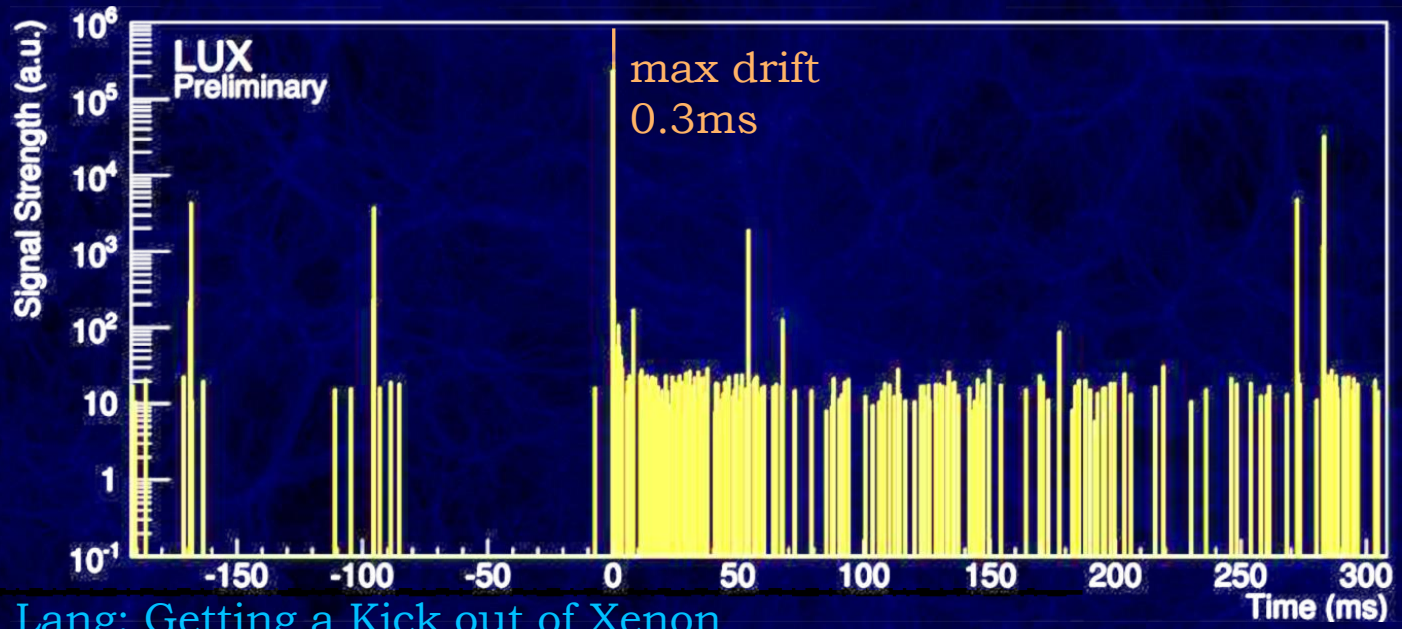


XENON100 1311.1088

Backgrounds: Extraction

Xenon light 175nm=7eV

- Photoionizes metals & impurities
- Delayed extraction:



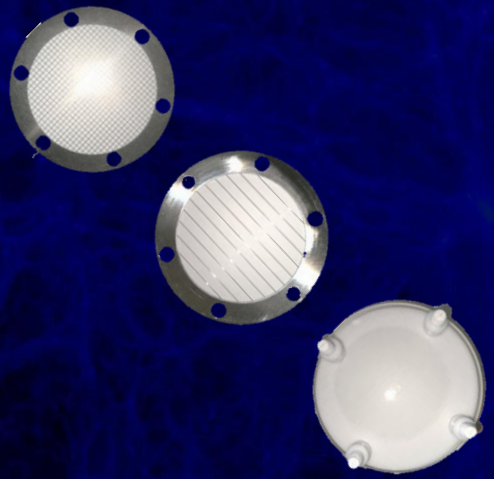
P.Sorensen 1702.04805

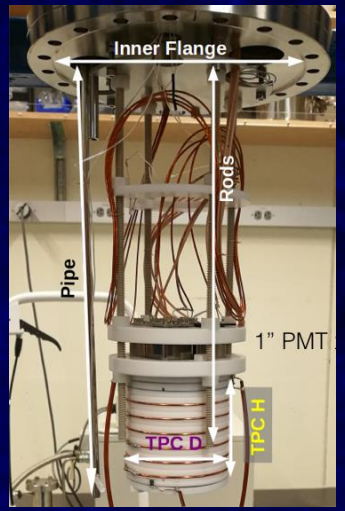
Jingke Xu/LUX, APS Meeting 2016

LBECA Project

A.Bernstein, J.Xu, P.Sorensen, K.Ni,
R.Essig, M.Fernandez-Serra, Rafael

- Critical Xe expertise, multiple R&D setups
- Understand & reduce single e⁻
- Build dedicated search

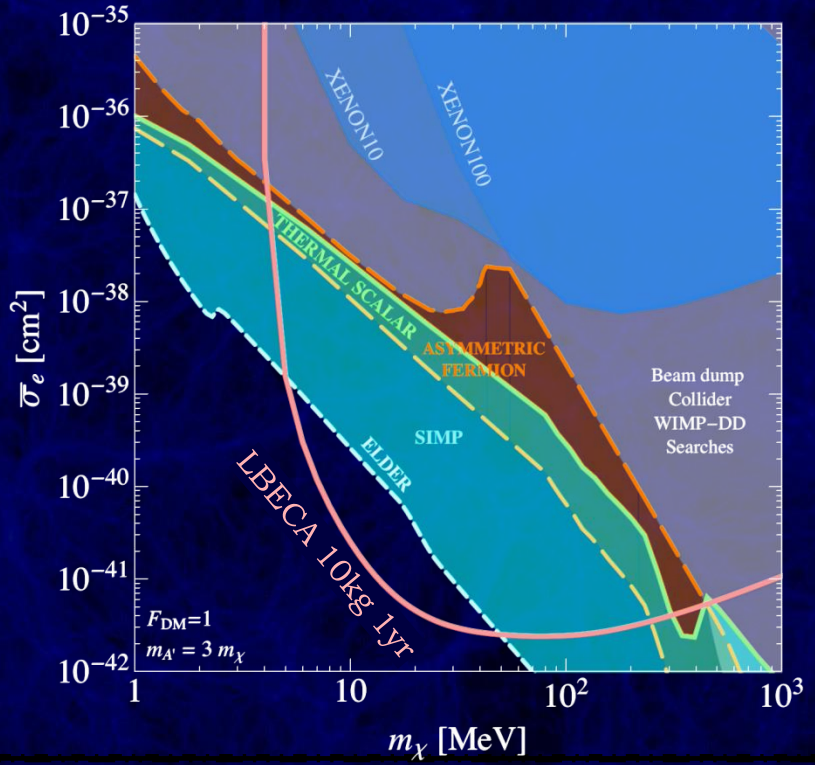


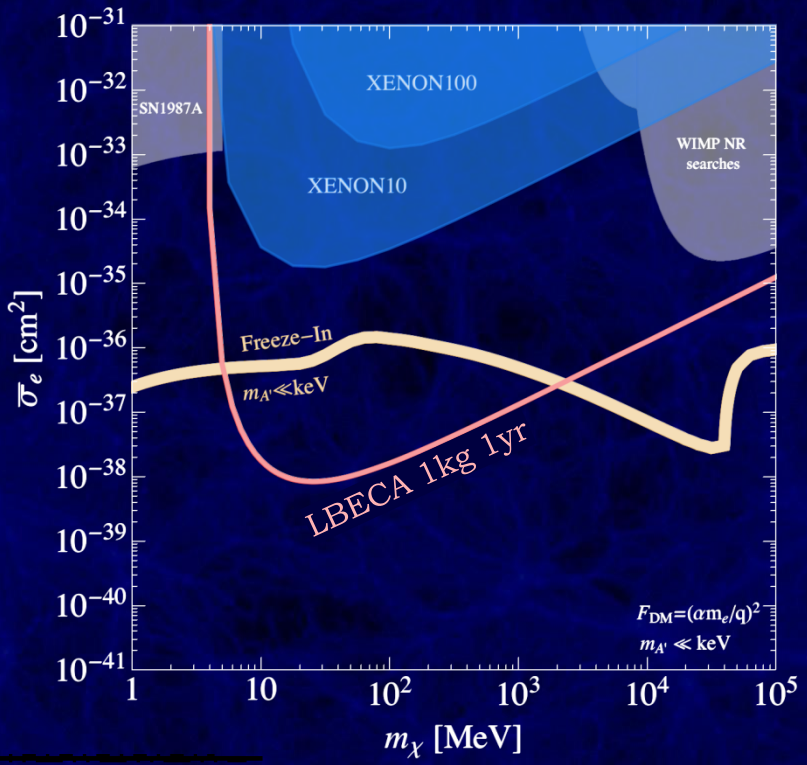


LBECA Project

A.Bernstein, J.Xu, P.Sorensen, K.Ni, R.Essig, M.Fernandez-Serra, Rafael

Swiftly build dedicated, conventional xenon detector:





LBECA

Promising for fast results
even below 10MeV

Bringing discovery-level science
back to the universities

Much more than just a WIMP search

Dark Matter

- spin-independent WIMPs ▷
- EFT couplings and inelastic WIMPs ▷ ▷
- GeV and MeV WIMPs ("S2-only") ▷ ▷
- Magnetic Inelastic WIMPs ▷
- inelastic scattering ▷
- axial-vector coupling ▷
- Mirror & luminous DM ▷
- Axion-like particles ▷
- SuperWIMPs
- Dark photons ▷ ▷
- annual modulation searches ▷

Astrophysics

- solar pp ν ▷
- normalization of ^{8}B solar rate ▷
- galactic supernovae ▷

Double-Beta

- 2ν and 0ν decay of ^{136}Xe ▷
- double-EC on ^{124}Xe ▷

Particle Physics

- coherent neutrino-nucleus scattering ▷
- neutrino oscillations ▷
- sterile neutrinos ▷
- solar axions ▷
- fractionally charged particles ▷

Liquid Noble Physics

- light and charge yield
- properties of xenon
- radioactivity assays
- particle interaction modeling
- technology R&D for other applications

Conclusions

- Liquid Xe TPCs became versatile science machines
- Generation-3 detectors required to cover WIMPs
- Ample opportunities for creative phenomenology and impactful involvement in experiment