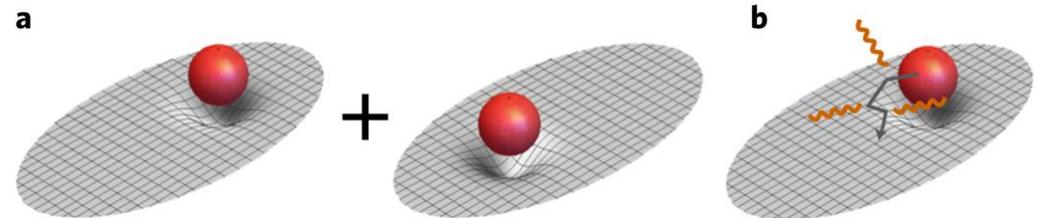# Wave Function Collapse Models

- Internal mechanism causing the collapse of the wave function at the transition from the microscopic to the macroscopic scale

- **Experimentally falsifiable**

  - Continuous Spontaneous Localization (CSL) model
  - Diósi-Penrose (DP) model

- Predict that particles undergo **a random motion**

→ Continuous **X-ray emission by charged particles**

Schrödinger dynamics

Collapse dynamics

$$
\begin{aligned}
\mathrm{d}\,|\psi_t\rangle = \Big[&-\frac{i}{\hbar}\hat{H}\,\mathrm{d}t + \sqrt{\alpha}\int \mathrm{d}^3\mathbf{x}\left(\hat{M}(\mathbf{x}) - \langle\hat{M}(\mathbf{x})\rangle_t\right)\mathrm{d}W_t(\mathbf{x}) \\
&-\frac{\alpha}{2}\int \mathrm{d}^3\mathbf{x}\,\mathrm{d}^3\mathbf{y}\,\mathcal{D}(\mathbf{x}-\mathbf{y})\prod_{\mathbf{q}=\mathbf{x},\mathbf{y}}\left(\hat{M}(\mathbf{q}) - \langle\hat{M}(\mathbf{q})\rangle_t\right)\mathrm{d}t\Big]|\psi_t\rangle
\end{aligned}
$$

a   +   b

Gravity induced collapse in DP model

Donadi et al., *Nat. Phys.* 17 (2021), 74–78
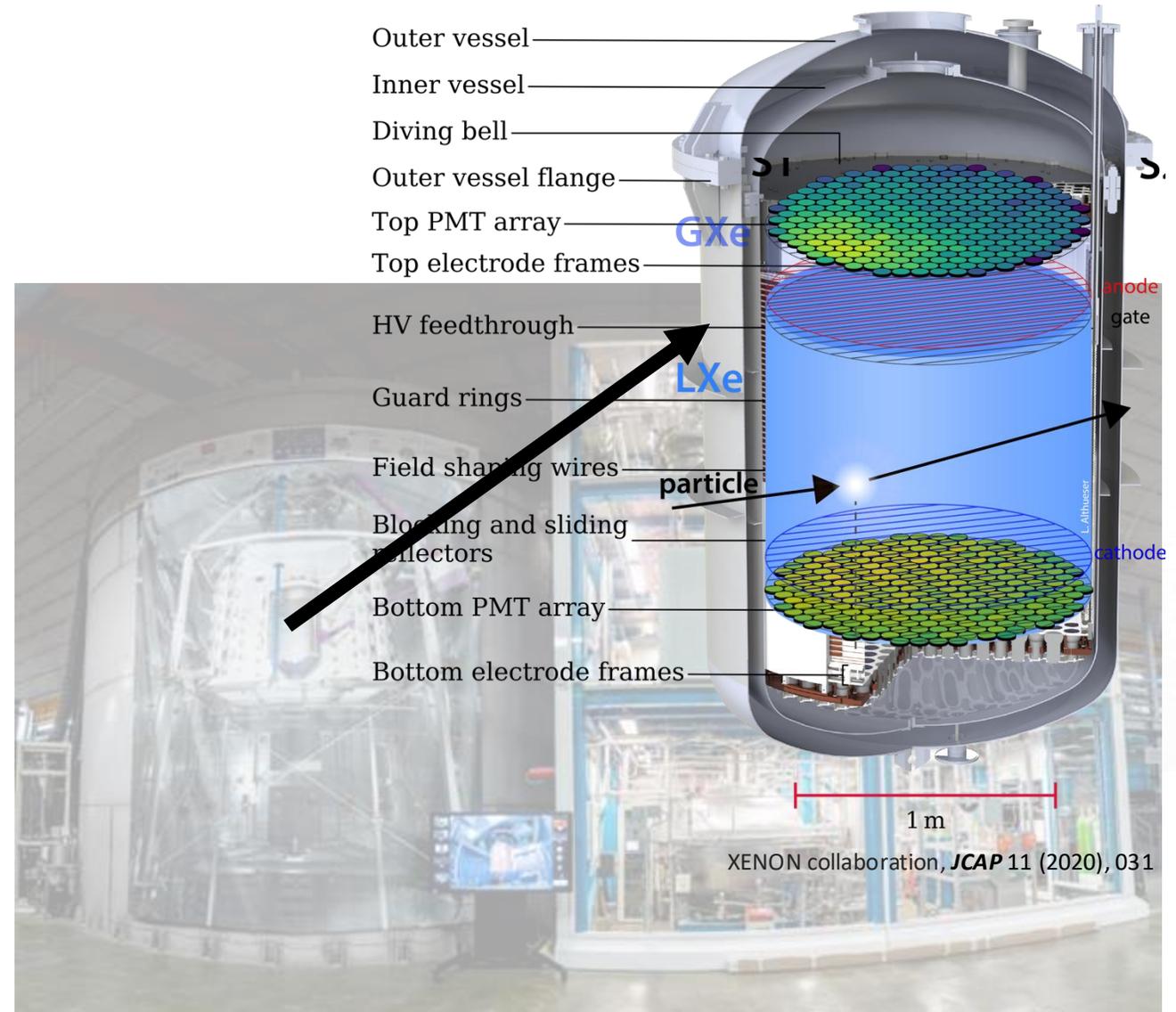
XENONnT Experiment

- Large xenon target of **5.9 t**

- Energy threshold of **1 keV**

- Low background

- 1.3 m x 1.5 m dual-phase Time Projection Chamber (TPC)

XENON collaboration
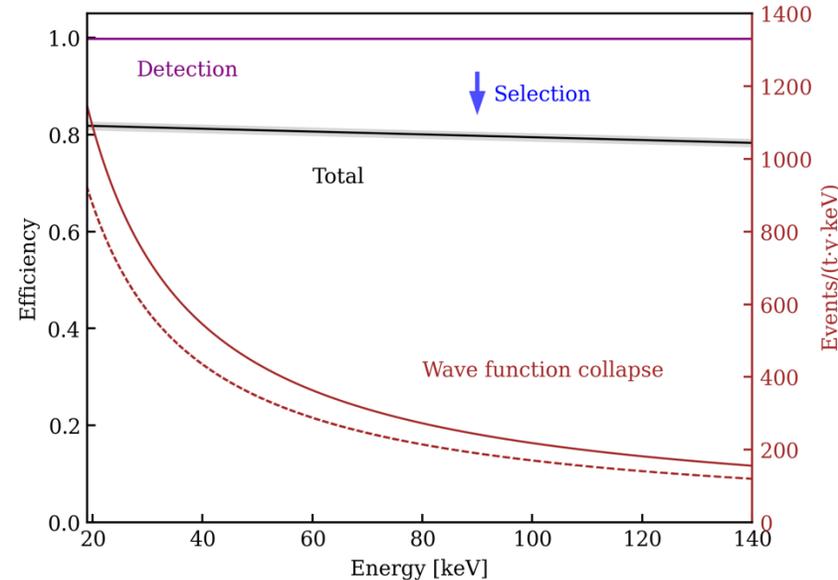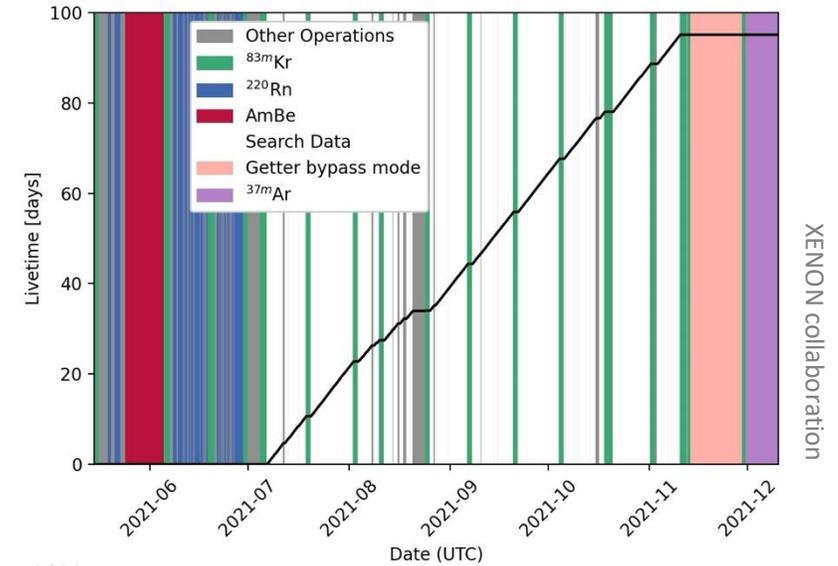
XENONnT Experiment

- Large xenon target of **5.9 t**

- Energy threshold of **1 keV**

- Low background

- 1.3 m x 1.5 m dual-phase Time Projection Chamber (TPC)

Outer vessel
Inner vessel
Diving bell
Outer vessel flange
Top PMT array
Top electrode frames
HV feedthrough
Guard rings
Field shaping wires
Blocking and sliding reflectors
Bottom PMT array
Bottom electrode frames

GXe
LXe
anode
gate
particle
cathode

1 m

XENON collaboration, *JCAP* 11 (2020), 031

Universität
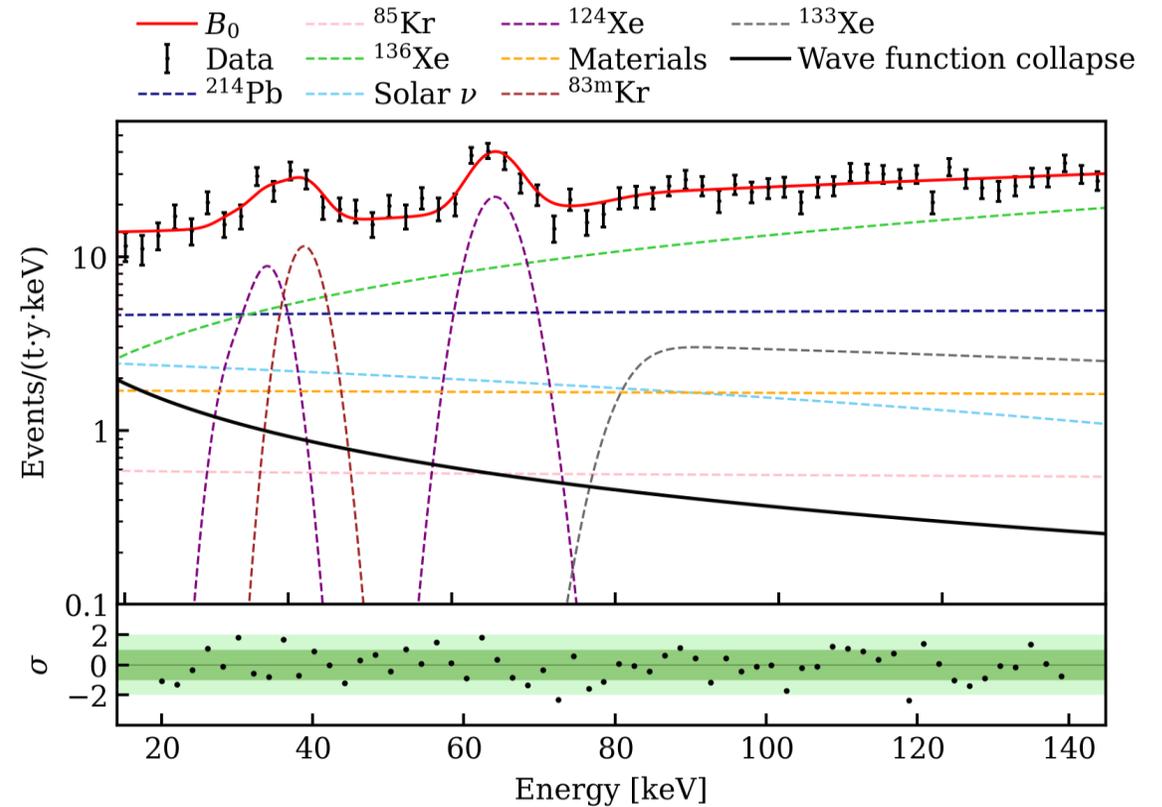Zürich

Signal Search in XENONnT Data

- Low-energy electronic recoil data from the first XENONnT science run

- **3335** observed electronic recoil events in **1.16 tonne-years of exposure**

- Implement **1/E signal** of CSL and DP wave function collapse models into analysis framework
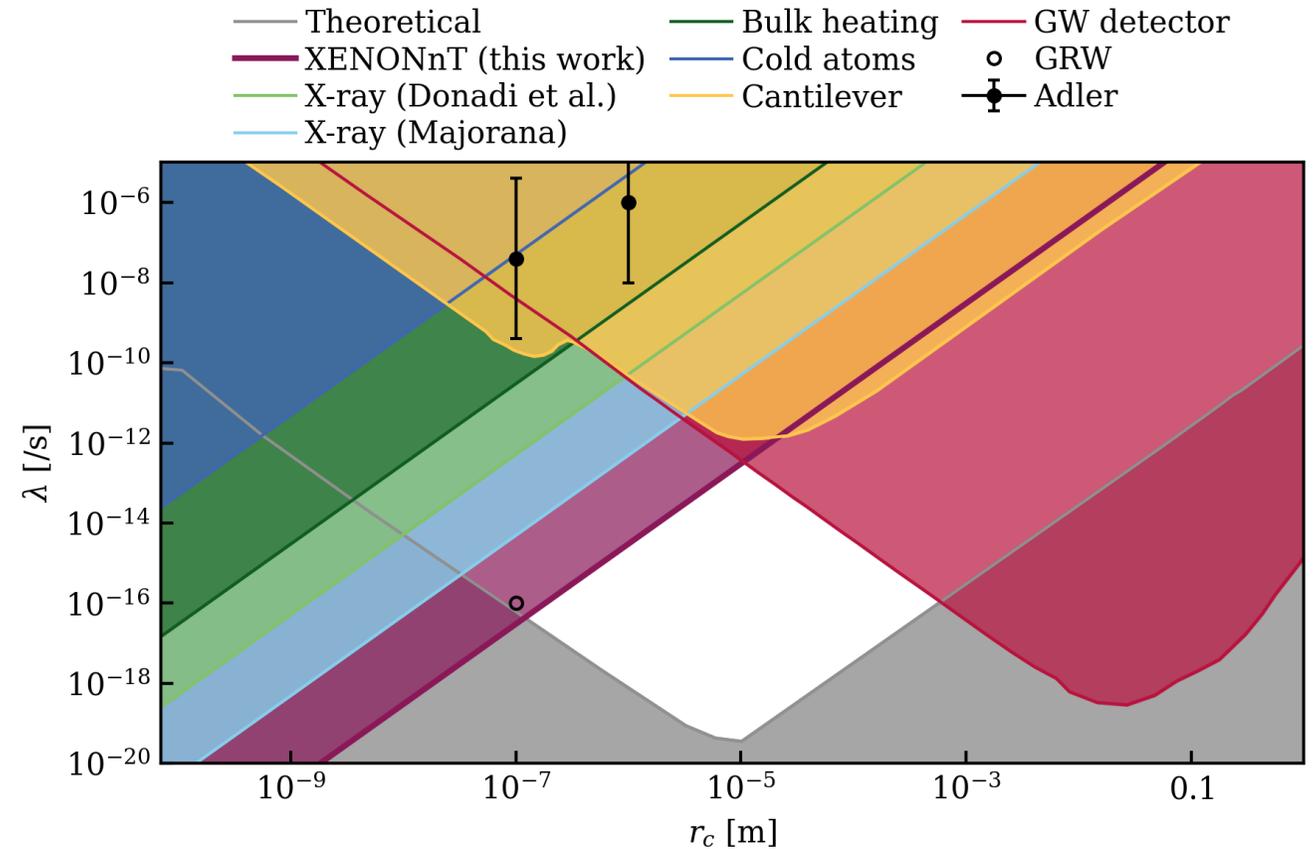
Results

- No significant signal is observed with a significance of 0.73 σ for H_1 compared to B_0 in the region (19, 140) keV

- Allows to set upper limit on number of signal events
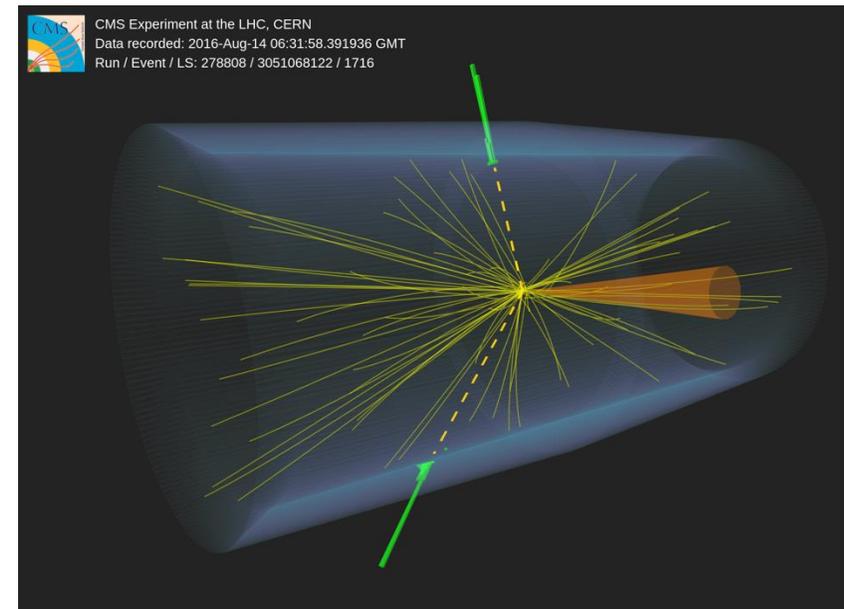
Upper limit at 95% C.L.
268 events / (tonne-year)

New exclusion limits

- Upper limit on number of events can be converted into limits on phenomenological parameters

- First results from a liquid xenon TPC that set the strongest upper bounds on the CSL model for $r_c < 10^{-5}$ m and the strongest bounds on the DP model to date

From Gran Sasso to Point 5

- Searching for the Higgs coupling to charm quarks with the CMS Experiment

- Higgs production in association with a charm quark (H+c)
  - In the diphoton decay channel of the Higgs

Summary

- Measurement problem leads to the introduction of wave function collapse models that predict x-ray emission by matter

- XENONnT provides and excellent opportunity to search for x-ray emission from wave function collapse

- First results from a liquid xenon TPC that set the strongest upper bounds on the CSL model for $r_c < 10^{-5}$ m and the strongest bounds on the DP model to date.

Backup

The measurement problem of quantum mechanics

- Unresolved discrepancy between the dynamics of a quantum system before and during a measurement

- If quantum mechanics is a complete theory, then macroscopic objects like a measurement apparatus should also obey the Schrödinger equation

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left|\text{🐱}\right\rangle + \frac{1}{\sqrt{2}}\left|\text{🐭}\right\rangle$$

Well-defined outcomes

Superposition principle

Schrödinger Evolution	$\neq$ Measurement
Linear	Non-linear
Deterministic	Stochastic

Born rule:
Repeated measurements of the same initial quantum state yield outcomes distributed according to $|\psi|^2$

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Continuous Spontaneous Localization (CSL) Model

Schrödinger dynamics

Collapse dynamics

$$\mathrm{d}\,|\psi_t\rangle = \left[-\frac{i}{\hbar}\hat{H}\,\mathrm{d}t + \sqrt{\alpha}\int \mathrm{d}^3\mathbf{x}\left(\hat{M}(\mathbf{x}) - \langle\hat{M}(\mathbf{x})\rangle_t\right)\mathrm{d}W_t(\mathbf{x}) \right.$$
$$\left. -\frac{\alpha}{2}\int \mathrm{d}^3\mathbf{x}\,\mathrm{d}^3\mathbf{y}\,\mathcal{D}(\mathbf{x}-\mathbf{y})\prod_{\mathbf{q}=\mathbf{x},\mathbf{y}}\left(\hat{M}(\mathbf{q}) - \langle\hat{M}(\mathbf{q})\rangle_t\right)\mathrm{d}t \right]|\psi_t\rangle$$

Stochastic noise field

$$w_t(x) = dW_t(x)/dt$$

Collapse strength

$$\alpha_{\mathrm{CSL}} = \frac{\lambda}{m_0^2}$$

Correlation function $\mathcal{D}(\mathbf{x}-\mathbf{y}) = \exp\left(-|\mathbf{x}-\mathbf{y}|^2/4r_{\mathrm{C}}^2\right)$

- A randomly fluctuating field (noise) couples with the mass density operator $\widehat{M}(x)$, inducing the collapse of the wave function

- Idealized white noise model
  - Noise field of physical origin must have non-flat frequency spectrum (colored) with a cutoff frequency

2 free parameters
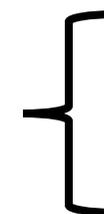
Collapse rate $\lambda\,[\mathrm{s}^{-1}]$

Correlation length $r_c\,[\mathrm{m}]$

Diósi-Penrose (DP) Model

Donadi et al., *Nat. Phys.* 17 (2021), 74–78

- Gravity-related collapse model

- Superposition of different spacetimes causes collapse of wave function

- Regularization parameter R_0 gives particles a finite size. Penrose suggested to set R_0 equal to the spatial width of the wave function. However, this is ruled out experimentally.

→Parameter-free version of model ruled out:

1 free parameter: $R_0 \ [\mathrm{m}]$

Correlation function $\mathcal{D}_{\mathrm{DP}}(\mathbf{x} - \mathbf{y}) = \dfrac{1}{|\mathbf{x} - \mathbf{y}|}$

Collapse strength $\alpha_{\mathrm{DP}} = \dfrac{G}{\hbar}$ → Gravitational constant

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New exclusion limits

- Upper limit on number of events can be converted into limits on phenomenological parameters

For the CSL model:

$$\frac{\lambda}{r_c{}^2} < 3.03 \times 10^{-3} \; s^{-1}m^{-2} \text{ at } 95\%$$
C.L

- Strongest upper bound on the CSL model for $r_c < 10^{-5}$ m

For the DP model:

$$R_0 > 1.4 \times 10^{-9} \; \text{m at } 95\% \text{ C.L}$$

- Strongest lower bound on the DP model

Experimental tests

- Search for collapse-induced random motion:
  - **X-ray emission by matter**
  - Cold atoms
  - Bulk heating
  - Cantilever
  - Gravitational waves

- Interferometric experiments:
  - Matter-wave interference of large molecules

Test of superposition principle

X-ray emission by matter:

Particles continuously interact with the noise field and **undergo a random motion** → Charged particles emit radiation in the x-ray regime

Requirements:
- **Low background**
- **Energy threshold at the keV scale**
- **Large mass**

→ Direct detection dark matter and neutrinoless double-beta decay experiments

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