Flamedisx

Fast likelihood analysis in more dimensions for xenon TPCs

Pueh Leng Tan

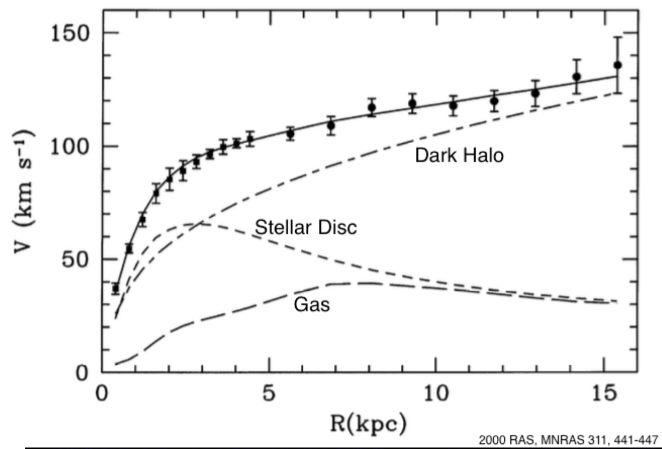
Partikeldagarna 2020, 25 November 2020

on behalf of Jelle Aalbers, Bart Plessers, Cristian Antochi, Jan Conrad

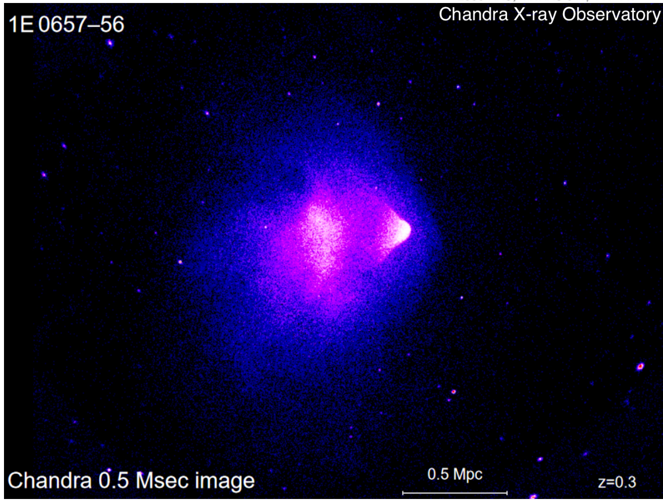
Stockholm University

Dark Matter

- Makes up 26.4% (Planck 2018) of the universe
- Experimental hints
  - Rotational curve of galaxies
  - Gravitational lensing
  - CMB
  - Formation and evolution of galaxies
- Theoretical motivations
  - WIMPs
  - QCD Axions, Axion-like Particles
  - Sterile neutrinos
- Alternatives to dark matter
  - Modified gravity



2000 RAS, MNRAS 311, 441-447



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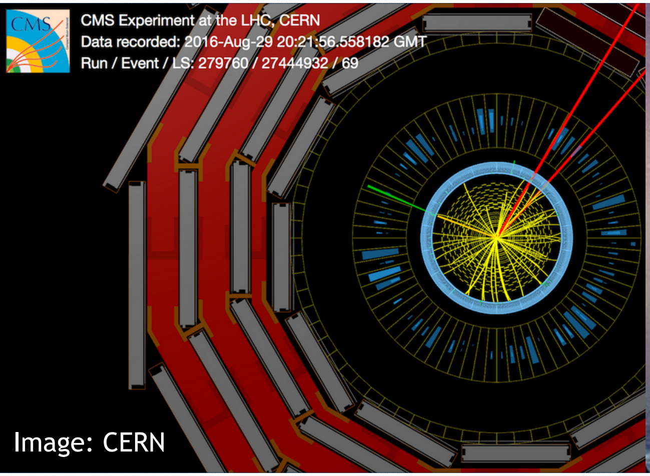
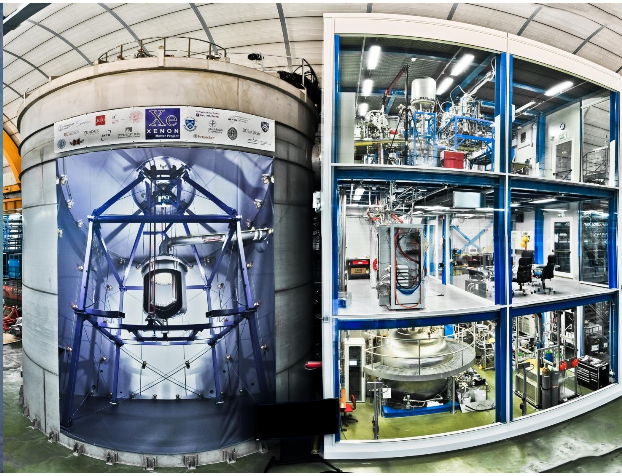
Dark Matter Searches





- Make it
  - Accelerators
  - Missing transverse momentum
- Break it
  - Telescopes
  - Annihilation
  - Indirect search
- Shake it
  - Nuclear recoils
  - Direct search

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XENON experiment

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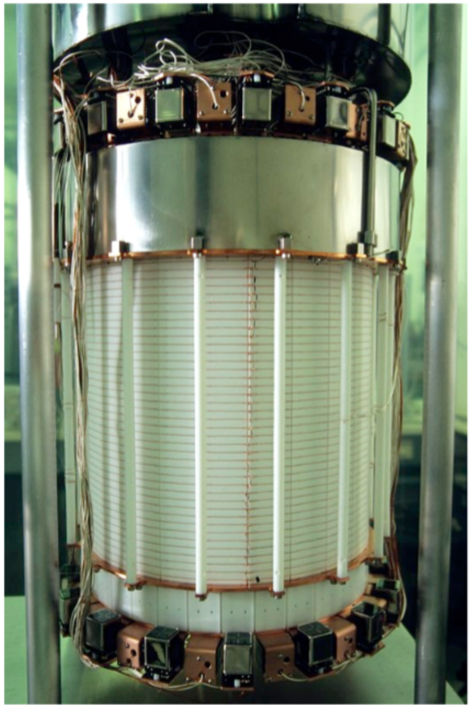

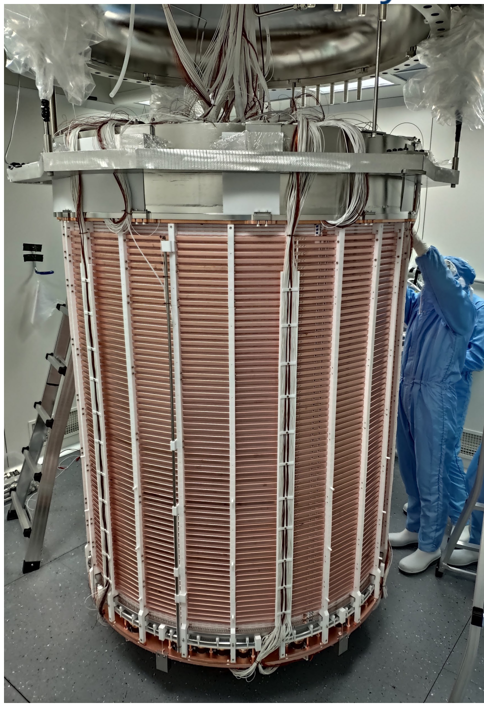

XENON10
2005-2007
25 kg LXe
σ_{SI}~9x10^{-44} cm^2
at 100 GeV/c^2 (2007)
PRL 100 (2008) 021303

XENON100
2009-2016
161 kg LXe
σ_{SI}~10^{-45} cm^2
at 50 GeV/c^2 (2016)
PRD 94 (2016) 122001

XENON1T
2016-2018
3.2 t LXe
σ_{SI}~4x10^{-47} cm^2
at 30 GeV/c^2 (2018)
PRL 121 (2018) 111302

XENONnT
2020-2025
8.4 t LXe
σ_{SI}~2x10^{-48} cm^2
at 50 GeV/c^2 (20 tyr)
JCAP 2020(11), 031-031

Liquid xenon TPCs

- Interactions
  - Nuclear Recoil (NR)
  - Electronic Recoil (ER)
- Dual-phase TPC
  - S1 generated in liquid xenon
  - S2 generated in gaseous xenon
- Discrimination in S2, S1 space

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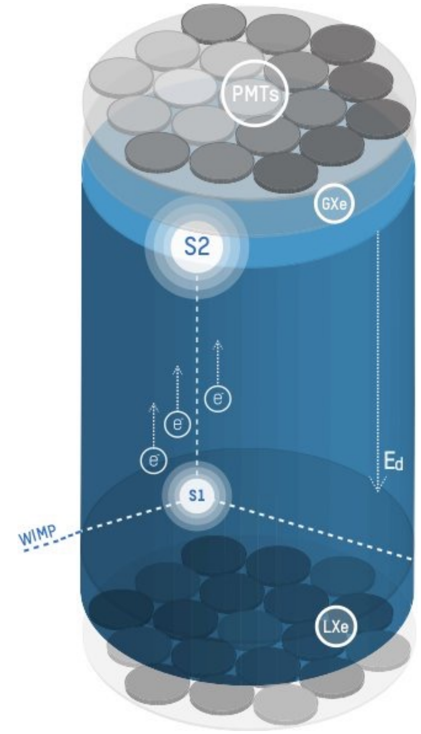

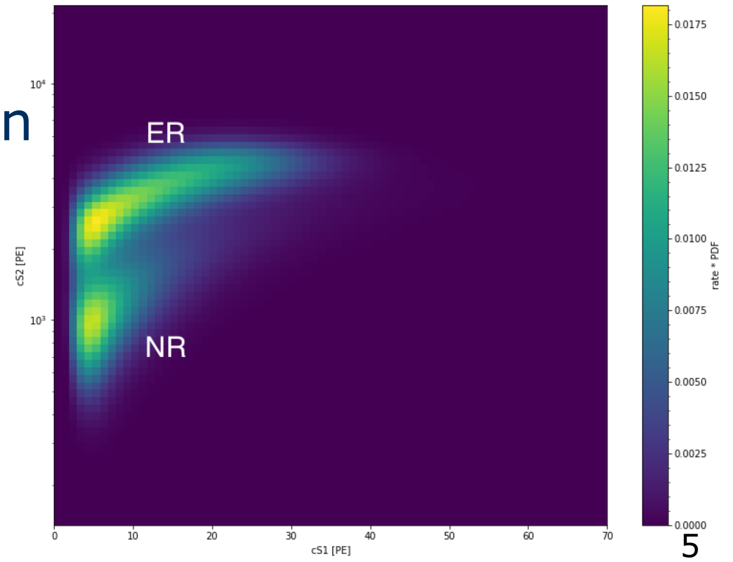

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Signal/Background discrimination

Traditional

- Templates

$$N \sim \text{Poisson}(\lambda),$$

$$S \sim \text{Gauss}(\mu = N, \sigma = 0.1\sqrt{N})$$

- Monte Carlo
- 2-dimensional

Flamedisx

- Explicit profile likelihoods

$$P(s) = \sum_n P(s|n)P(n)$$

$$= \sum_n \text{Gauss}(s - n, 0.1\sqrt{n})\text{Poisson}(n|\lambda)$$

- Summation as tensor multiplication
  - TF backbone
  - Autodiff gives gradient and hessian wrt nuisance parameters
- Higher dimensions

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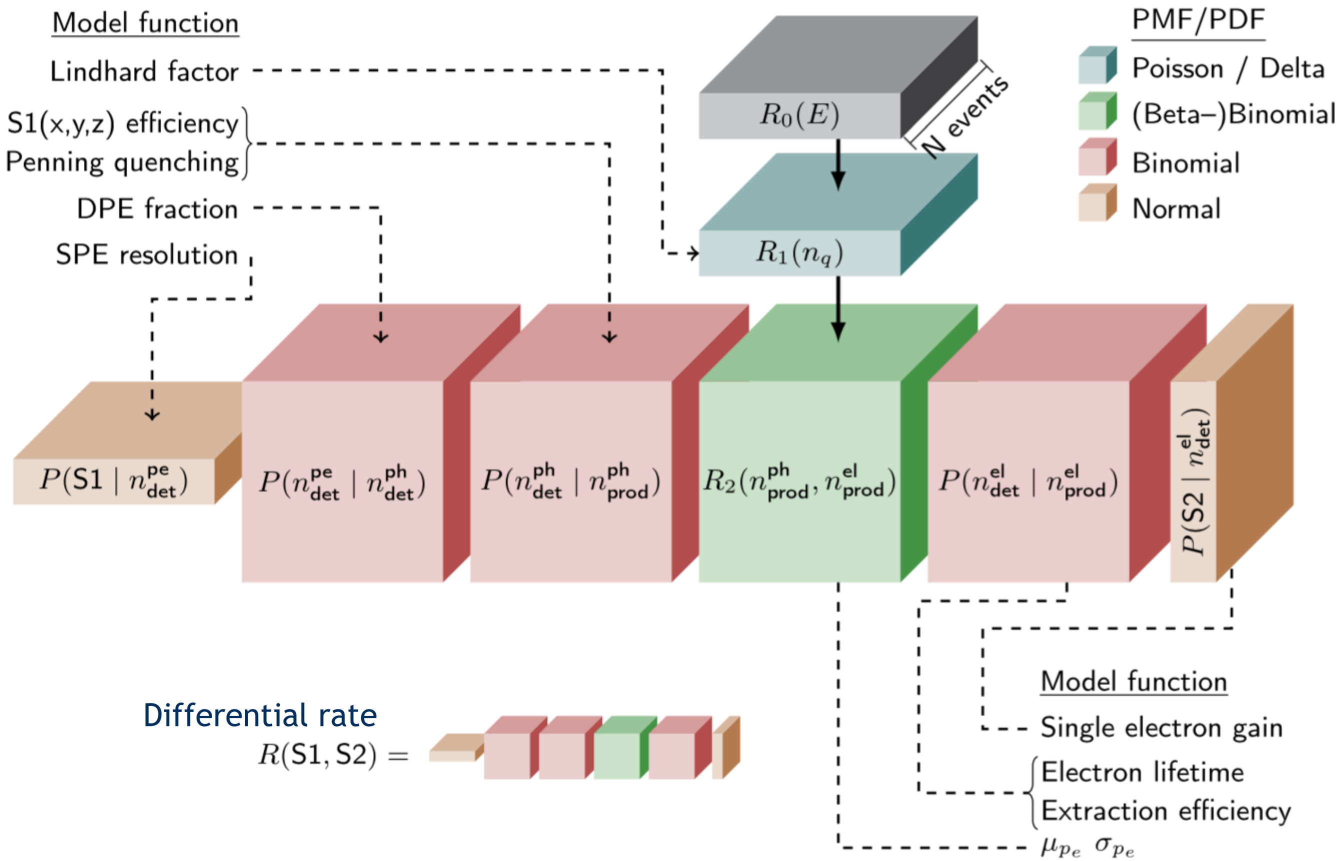
Implementation of LXe Emission Model



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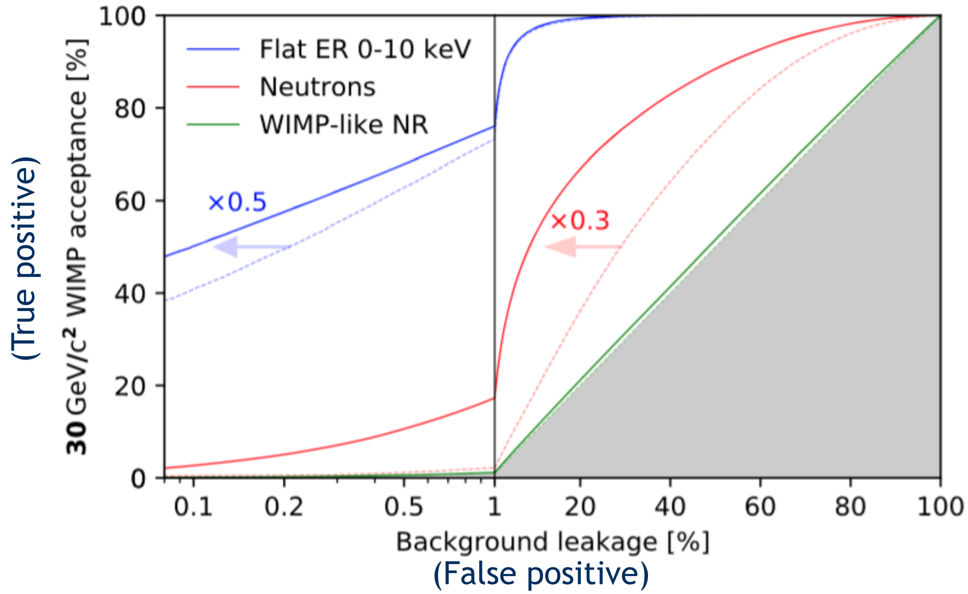
Result 1: Better discrimination

- Testing different backgrounds
    - Homogeneous ER
    - Wall neutrons (NR)
    - WIMP-like NR with no annual modulation
- Better discrimination for wall neutrons
    - Made use of spatial information
- Better discrimination for flat ER
    - Made use of z information
- Negligible improvement for WIMP-like NR
    - Time component does not contribute much

ROC curves



Flamedisx in darker line
2D template method in fainter line

5t fiducial volume
1.5 drift length
electron lifetime 500μs

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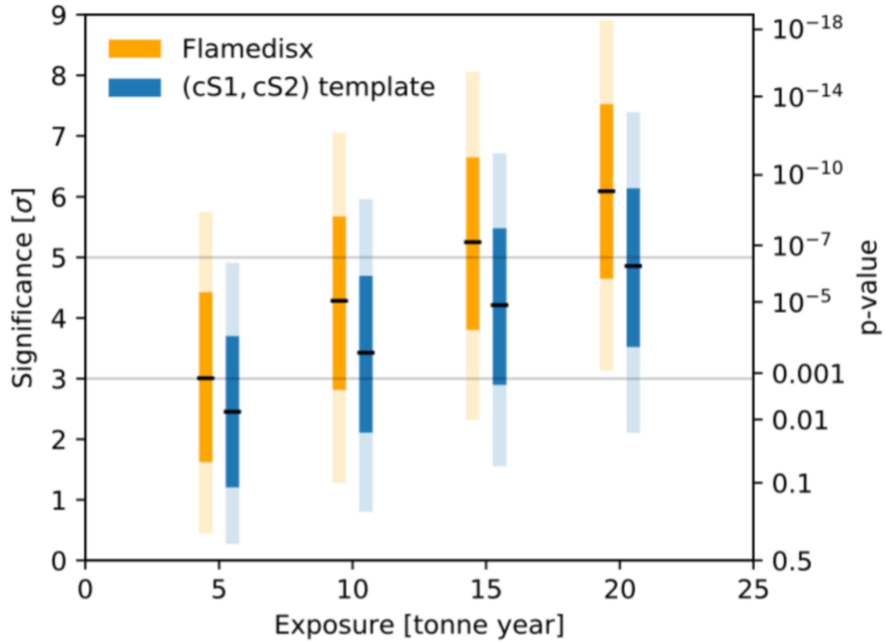
Result 2: Less exposure required

- Discovery significances from profile likelihood test statistic

- Improved background discrimination means less exposure required
  - Saves 1 year of data taking for detector with 5 t fiducial volume



1σ, 2σ asymptotic discovery bands for a 200 GeV/c^2 WIMP with $\sigma = 2\times10^{-47}$ cm^2 computed from 1×10^5 MC datasets.

WIMP rate of ~1.4 events/tonne yr,
Flat ER background of 75 events/tonne yr,
Radiogenic NR background of ~0.04 events/tonne yr.

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Summary

- Explicit profile likelihood with higher dim
- Information from more dimensions gives better background discrimination
- Less exposure required
- Publications
  - PRD 102, 072010 (2020), arXiv 2003.12483
- Codes available
  - https://github.com/FlamTeam/flamedisx
  - https://pypi.org/project/flamedisx/

pip install flamedisx

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Putting in the last PMT!

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Liquid xenon purification system

Backup Slides

Nature of Dark Matter

CERN website. Image from G. Bertone and T. M. P. Tait

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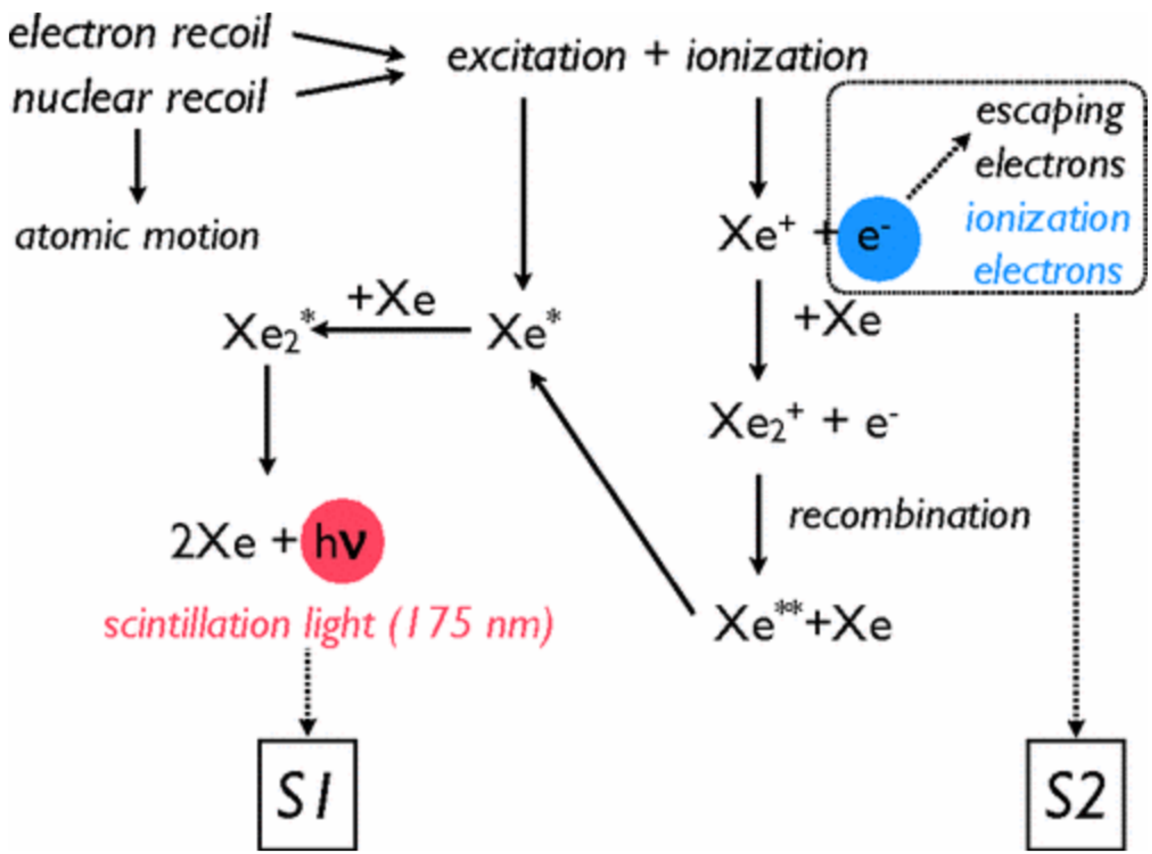
Liquid xenon signal production



PRC 81 (2010) 025808

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Signal Correction

S1 photon detection efficiency highest at the bottom of the TPC
S2 electron detection efficiency lowest at the bottom of the TPC

$$\mathrm{cS1}(\mathrm{S1}, x, y, z, t) = \mathrm{S1}\,\frac{g_1}{G_1(x, y, z, t)},$$

$$\mathrm{cS2}(\mathrm{S2}, x, y, z, t) = \mathrm{S2}\,\frac{g_2}{G_2(x, y, z, t)}.$$

G_1: Mean expected signal size (PE) per released photon at interaction site

G_2: Mean expected signal size (PE) per released electron at interaction site

$$g_1 = \frac{1}{V\delta T}\int dx dy dz dt G_1(x, y, z, t),$$

$$g_2 = \frac{1}{A\delta T}\int dx dy dt G_2(x, y, z = 0, t),$$

cS1=S1 inside fiducial volume
cS2 = S2 at liquid-gas interface

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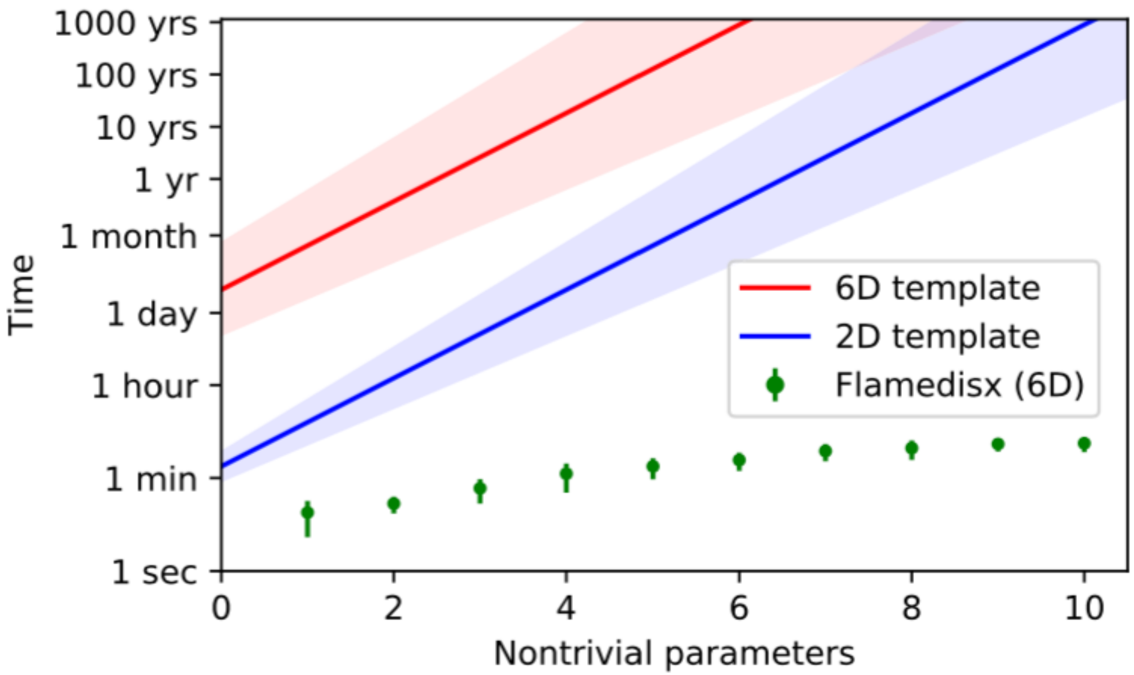
Computational Speed



Templates: Time required to compute template
Flamedisx: Mean duration of fitting ER model to ER calibration data set with 1000 events

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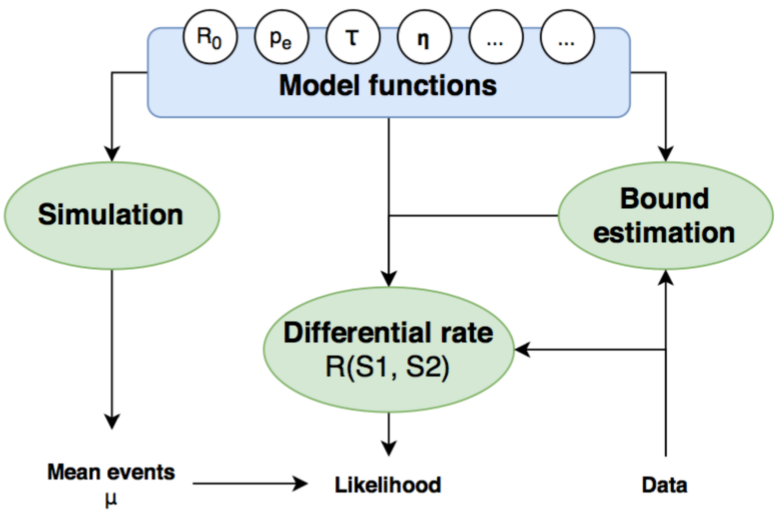
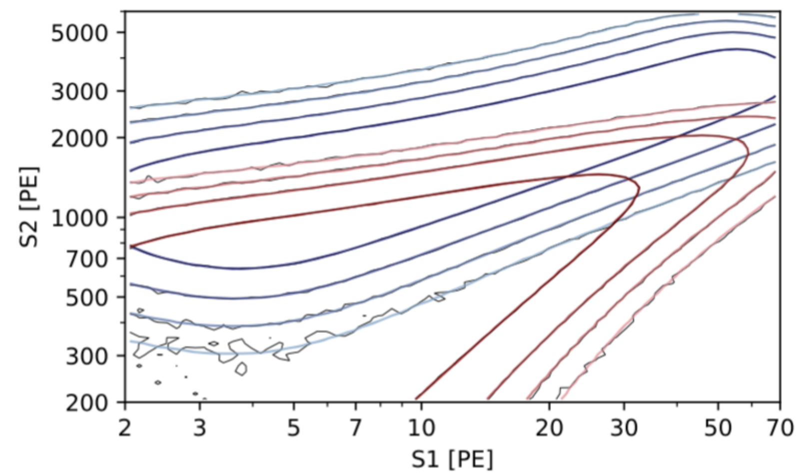
Code structure verification



Flamedisx code structure. Model functions used for both simulating events and calculating differential rate required for likelihood construction.

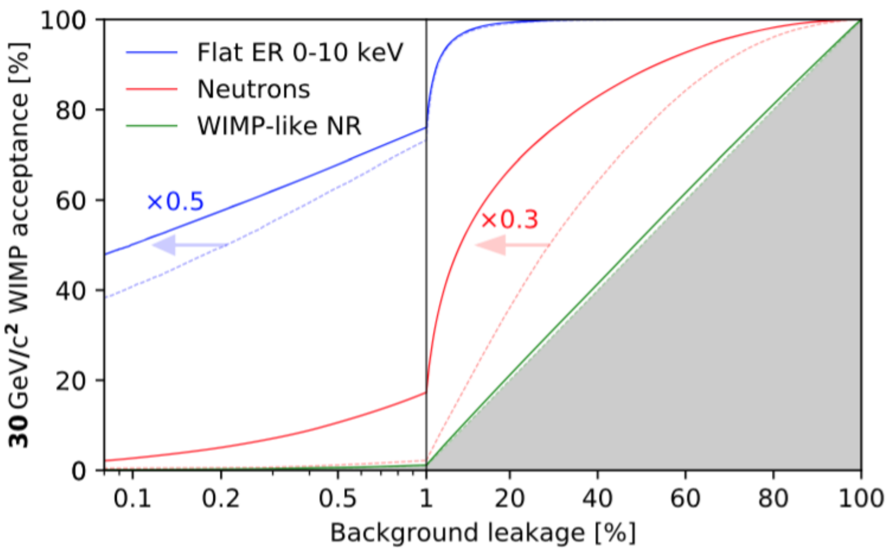


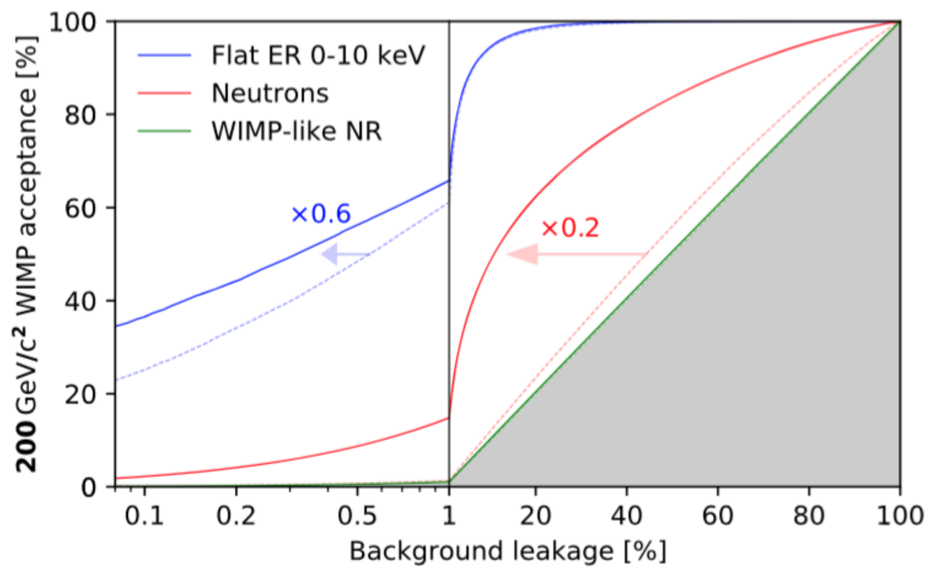
2D template constructed from Flamedisx simulated events in black. Differential rates computed from Flamedisx model functions in colour.

ER in blue, NR in red.

Fits to data required to check correctness of model functions

ROC curves for different WIMP mass





Flamedisx offers greater discrimination improvements for higher WIMP masses

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Profile Likelihood test statistic

Best fit of nuisance parameters, $\boldsymbol{\theta}$, conditional on no WIMP

$$t_0 = -2\log\frac{L(\sigma = 0, \hat{\hat{\theta}})}{L(\hat{\sigma}, \hat{\theta})}$$

Likelihood at global best fit

Asymptotically distributed as

$\frac{1}{2}\delta(0) + \chi^2_{\nu=1}$

Asymptoticity verified.

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Axions?
WIMP?
f(R)?
Thank you