Statistical inference with a frequentist framework: Flamedisx

Project 18

Students: D'Antonio M., Kůs P., Meloni P.
Supervisors: Biondi R., Ferella A. D., Ferrari C.

Table of Contents

Table of Contents

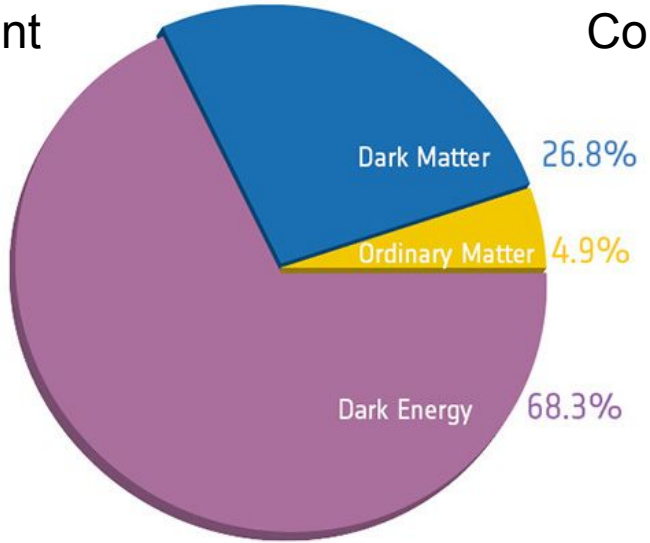
Dark matter problem

Standard model of cosmology:

ΛCDM

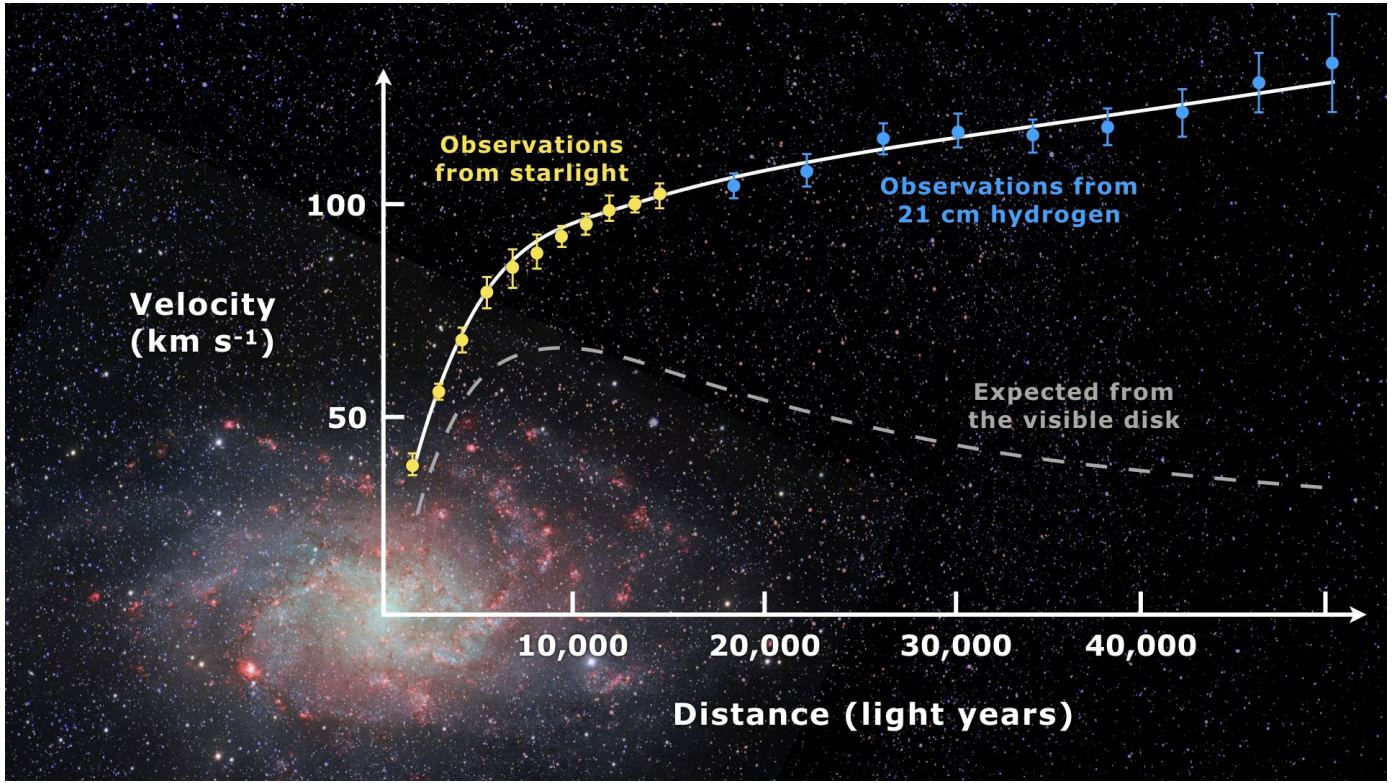
Cosmological constant

Cold dark matter



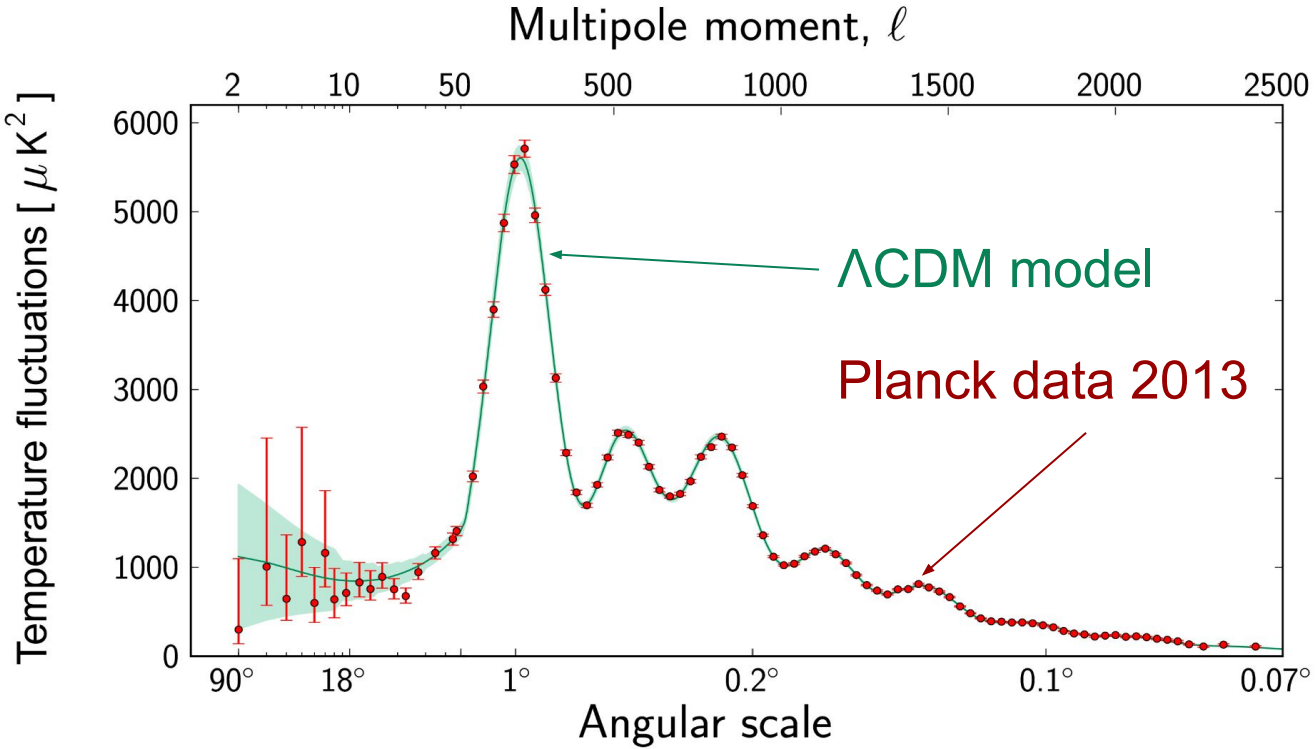
Not this time…

Evidence of dark matter (ex.1)



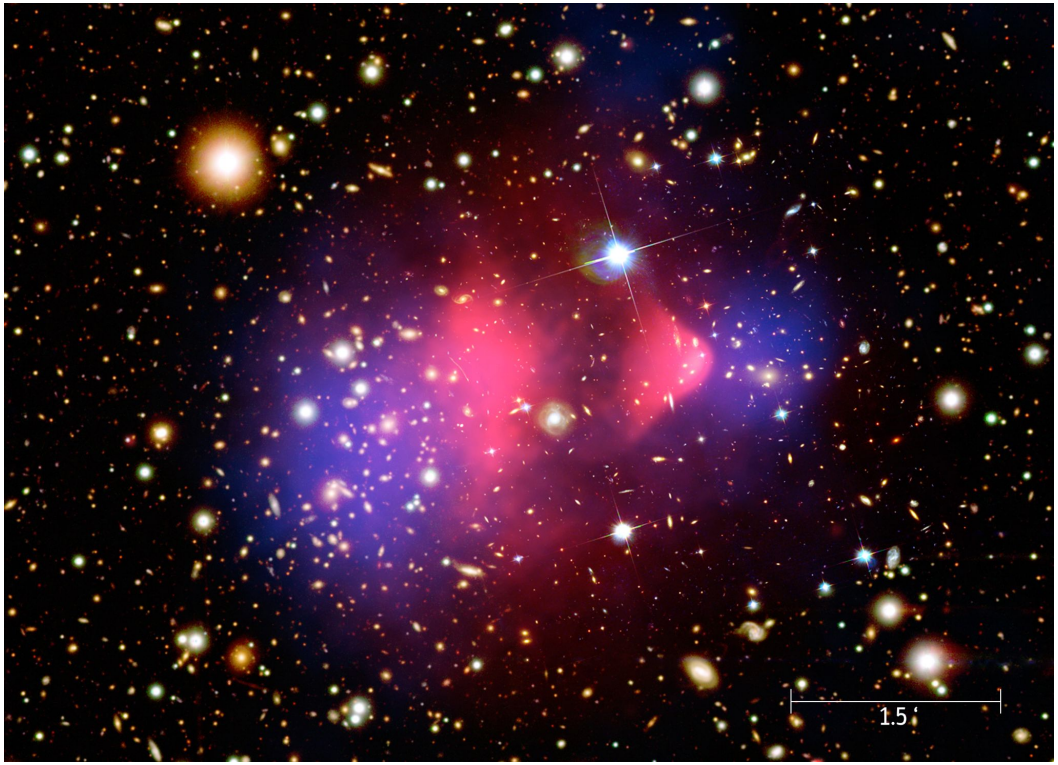
Rotation curves of galaxies

Evidence of dark matter (ex.2)



The power spectrum of temperature fluctuations in CMB

Evidence of dark matter (ex.3)

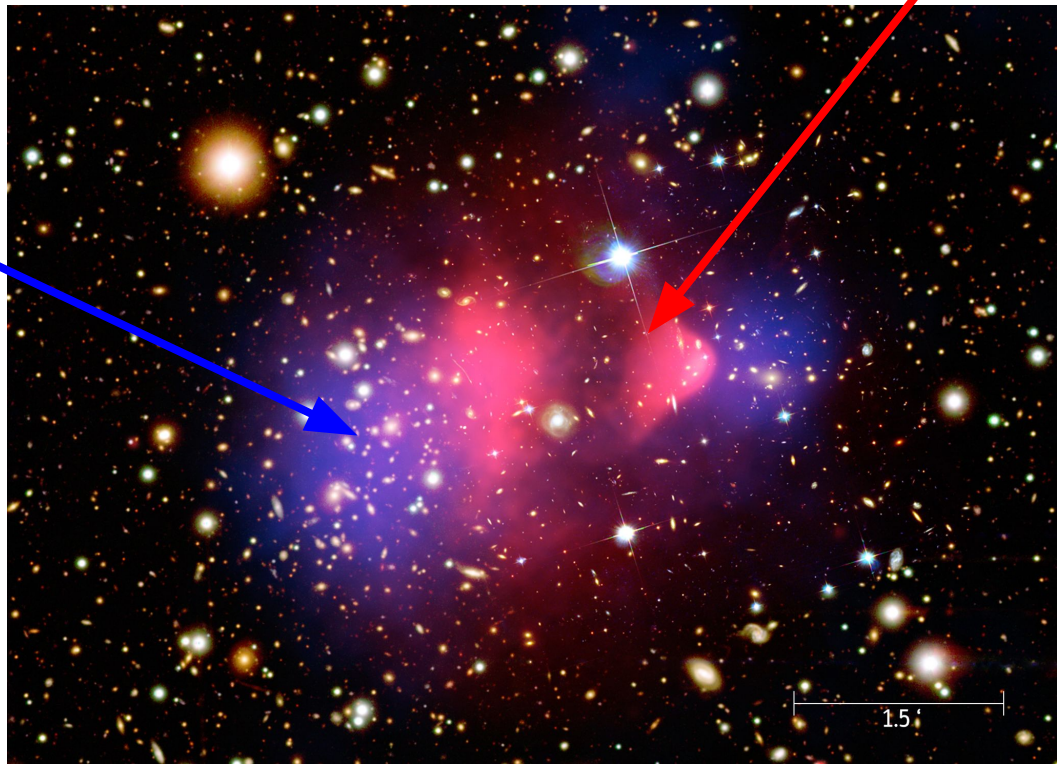


Bullet cluster

Evidence of dark matter (ex.3)

X-ray image
(~ visible galaxy)

matter distribution
from grav. lensing

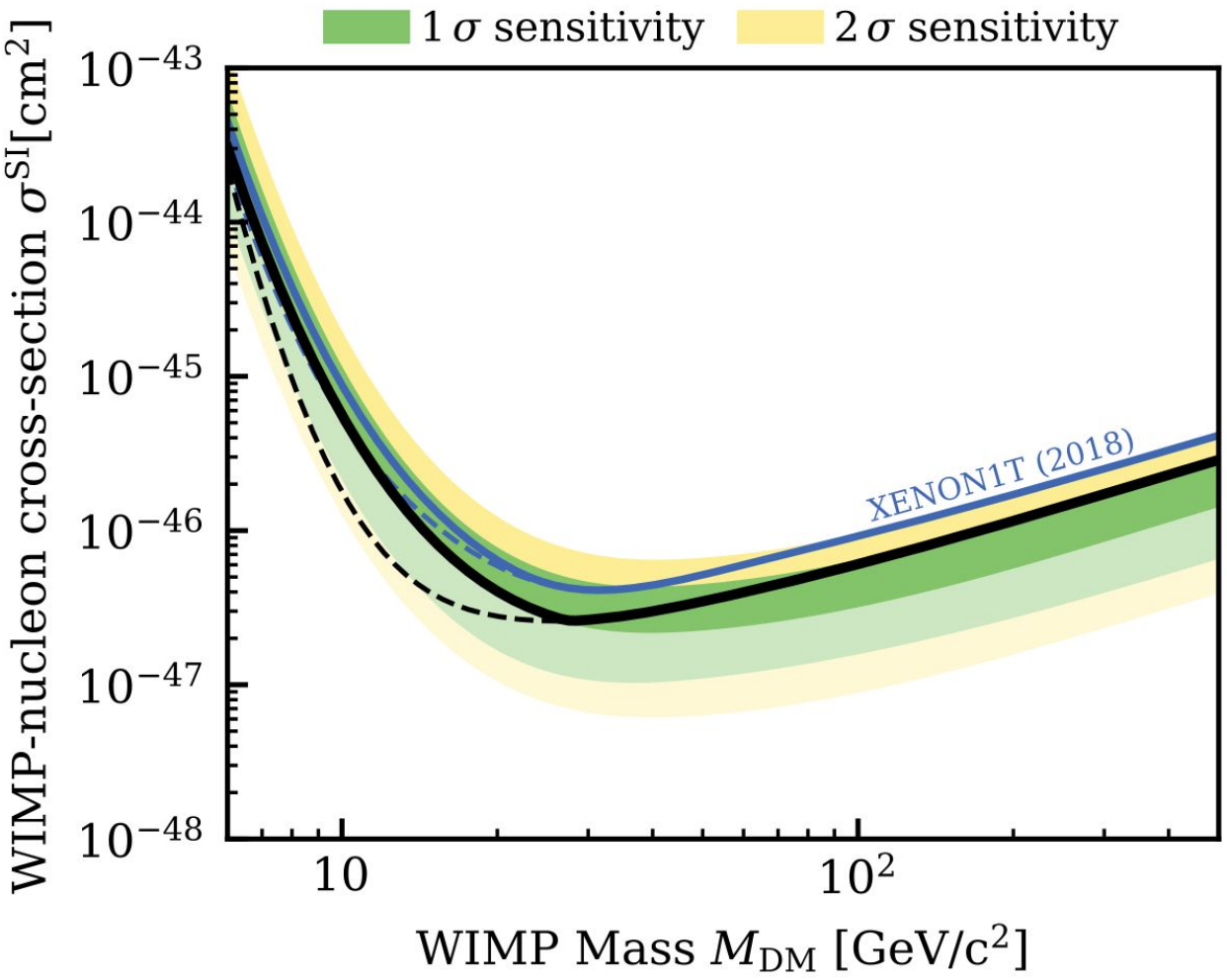


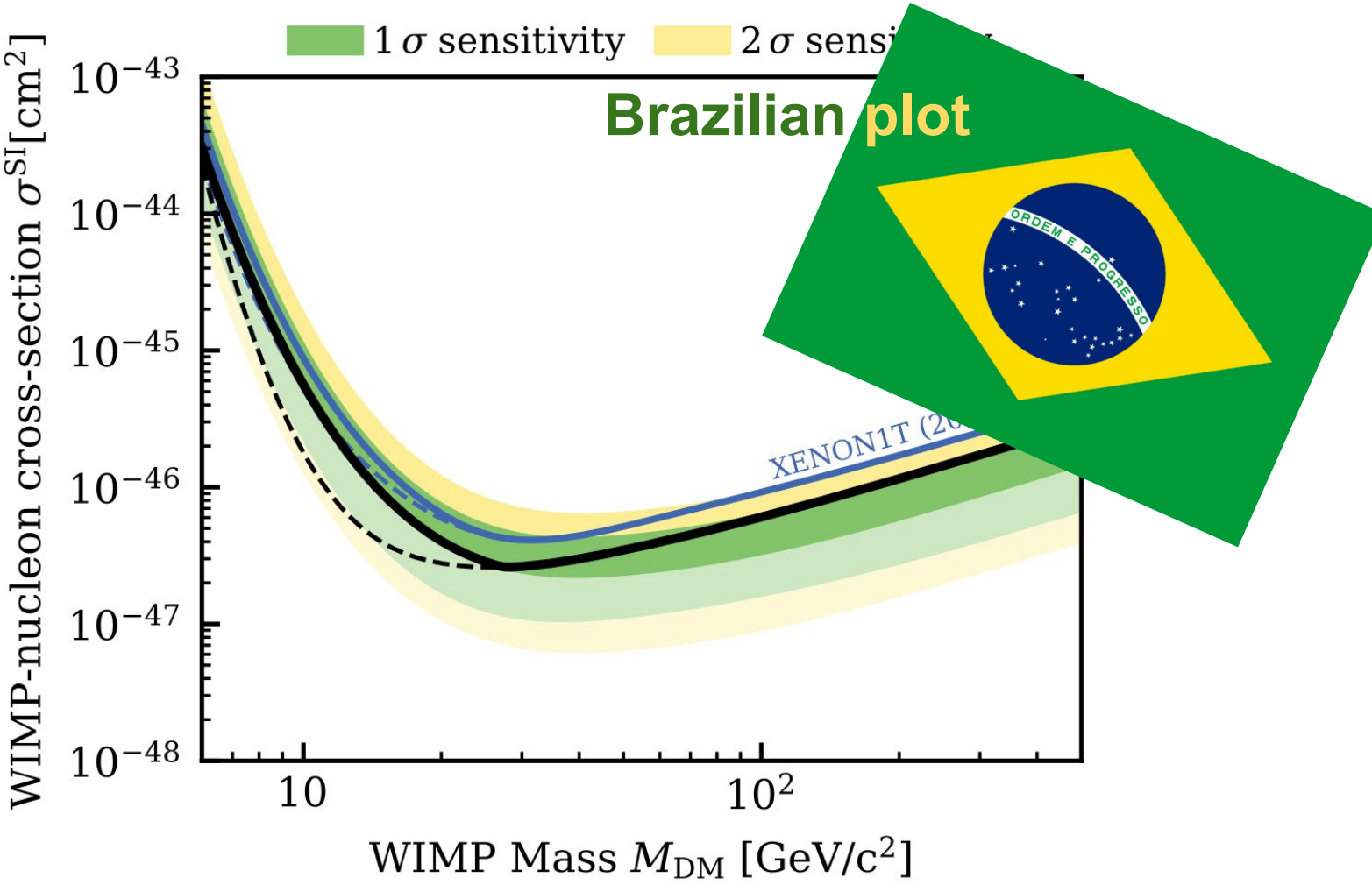
Bullet cluster

Table of Contents

XENONnT experiment

- particles: WIMP
- interaction: direct
- interaction rate: rare
- target: Liquid Xenon
- predecessor: XENON1T


1 σ sensitivity
2 σ sensitivity
XENON1T (2018)
WIMP-nucleon cross-section $\sigma^{SI}[cm^2]$
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10
10^2
WIMP Mass M_{DM} [GeV/c^2]


1 σ sensitivity
2 σ sensi
Brazilian plot
ORDEM E PROGRESSO
XENON1T (20
WIMP-nucleon cross-section $\sigma^{SI}[cm^2]$
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10
10^2
WIMP Mass M_{DM} [GeV/c^2]

XENONnT experiment

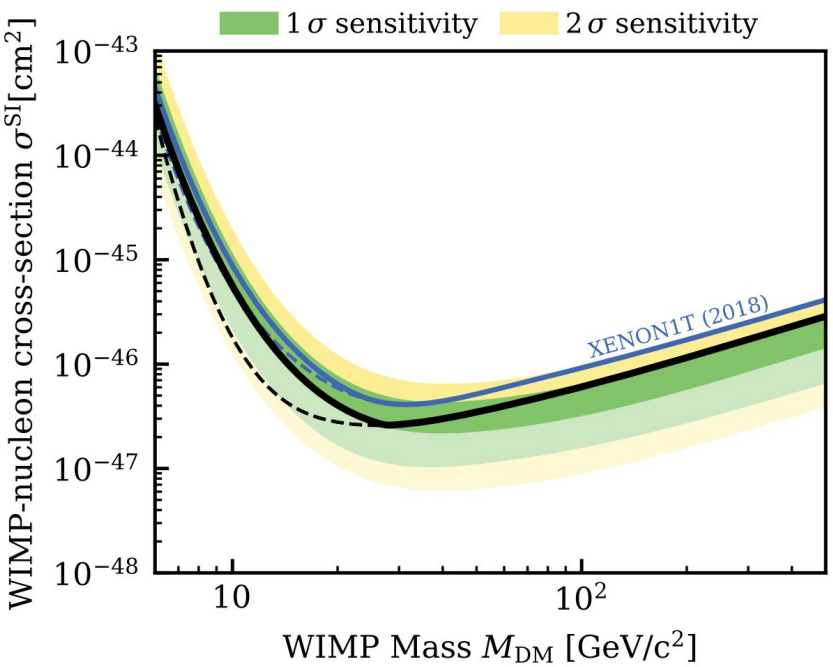
- particles: WIMP
- interaction: direct
- interaction rate: rare
- target: Liquid Xenon
- predecessor: XENON1T

SPOILER:

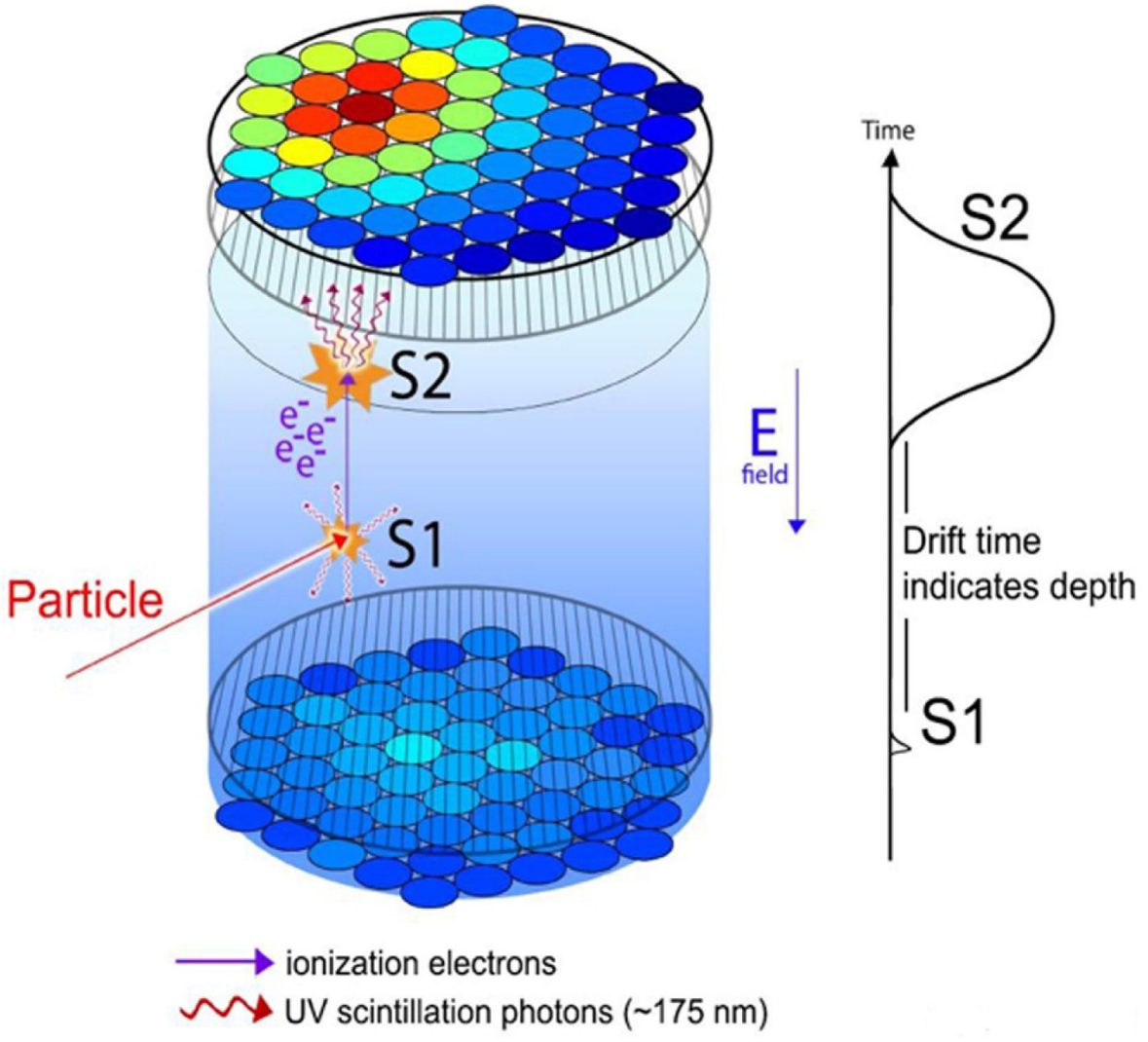
We will construct sensitivity graphs

σ vs m_{WIMP}

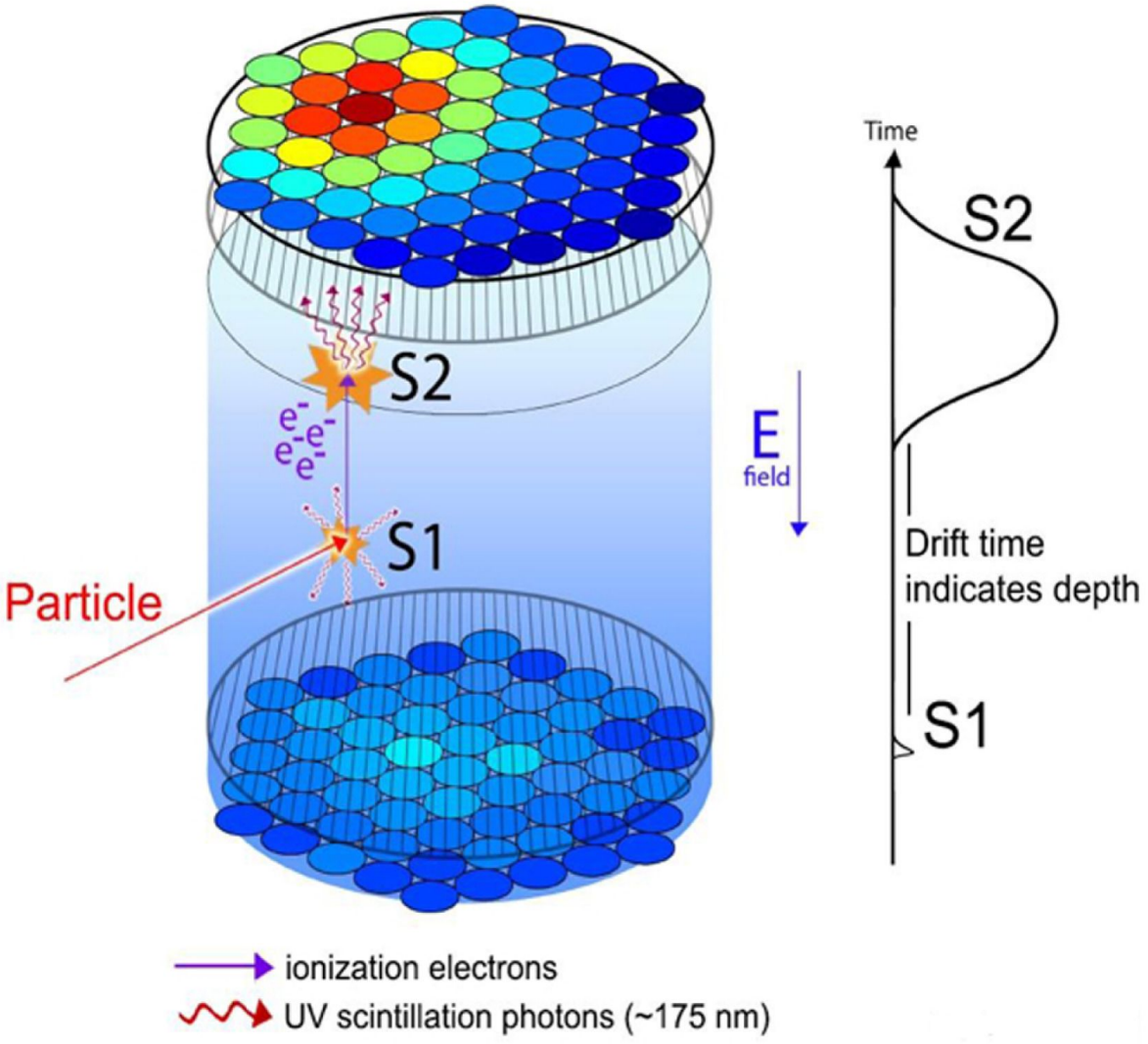
ourselves (hands-on activity)!




Xe
XENON
Matter Project

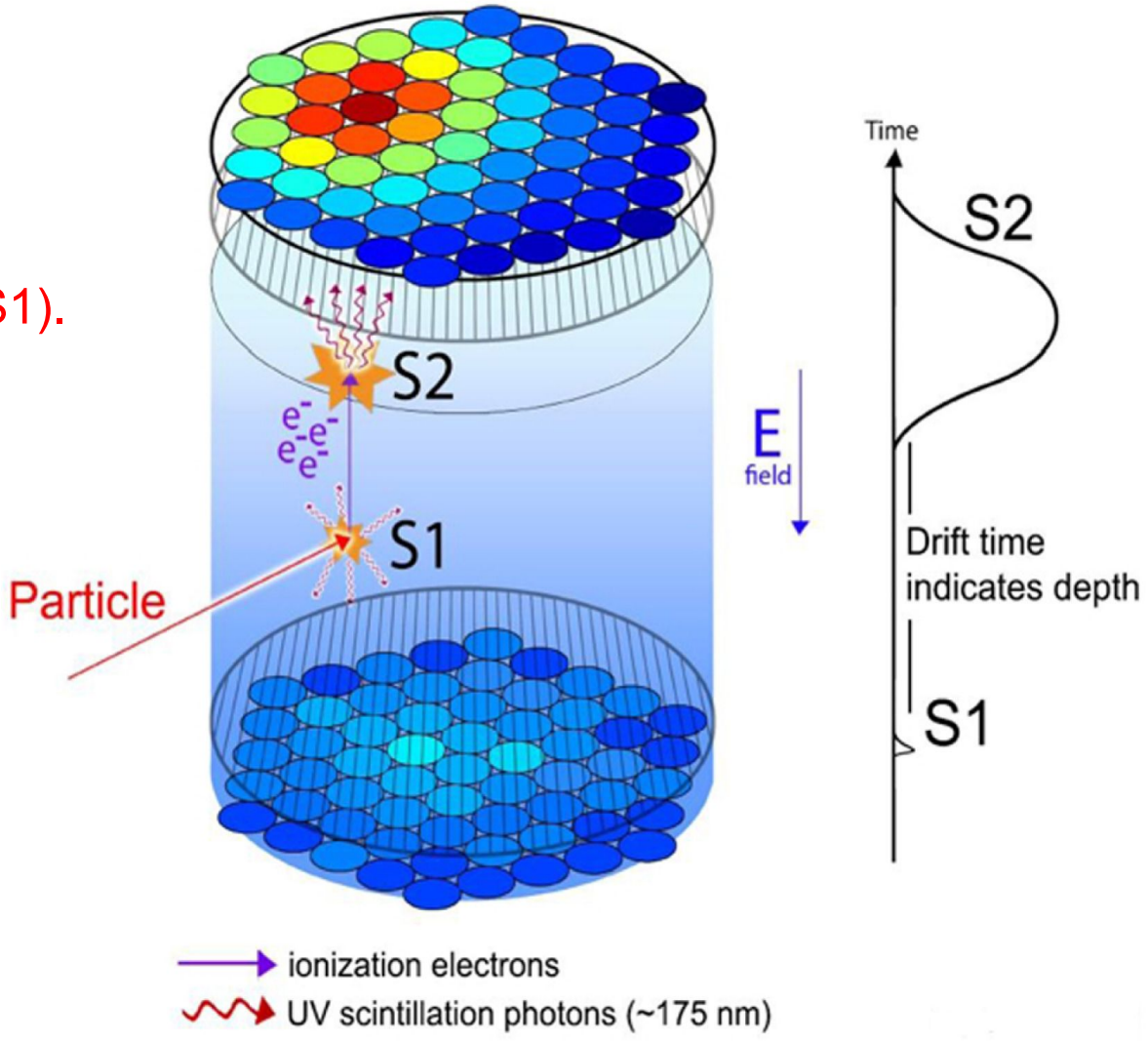

S2
e-
e-
e-
e-
S1
Particle
E
field
Time
S2
Drift time
indicates depth
S1
ionization electrons
UV scintillation photons (~175 nm)

1) WIMP interacts with nuclei.



1) WIMP interacts with nuclei.

2) Scintillation, UV photons (S1).



1) WIMP interacts with nuclei.

2) Scintillation, UV photons (S1).

3) Ionization, drifting, amplification and scintillation (S2).

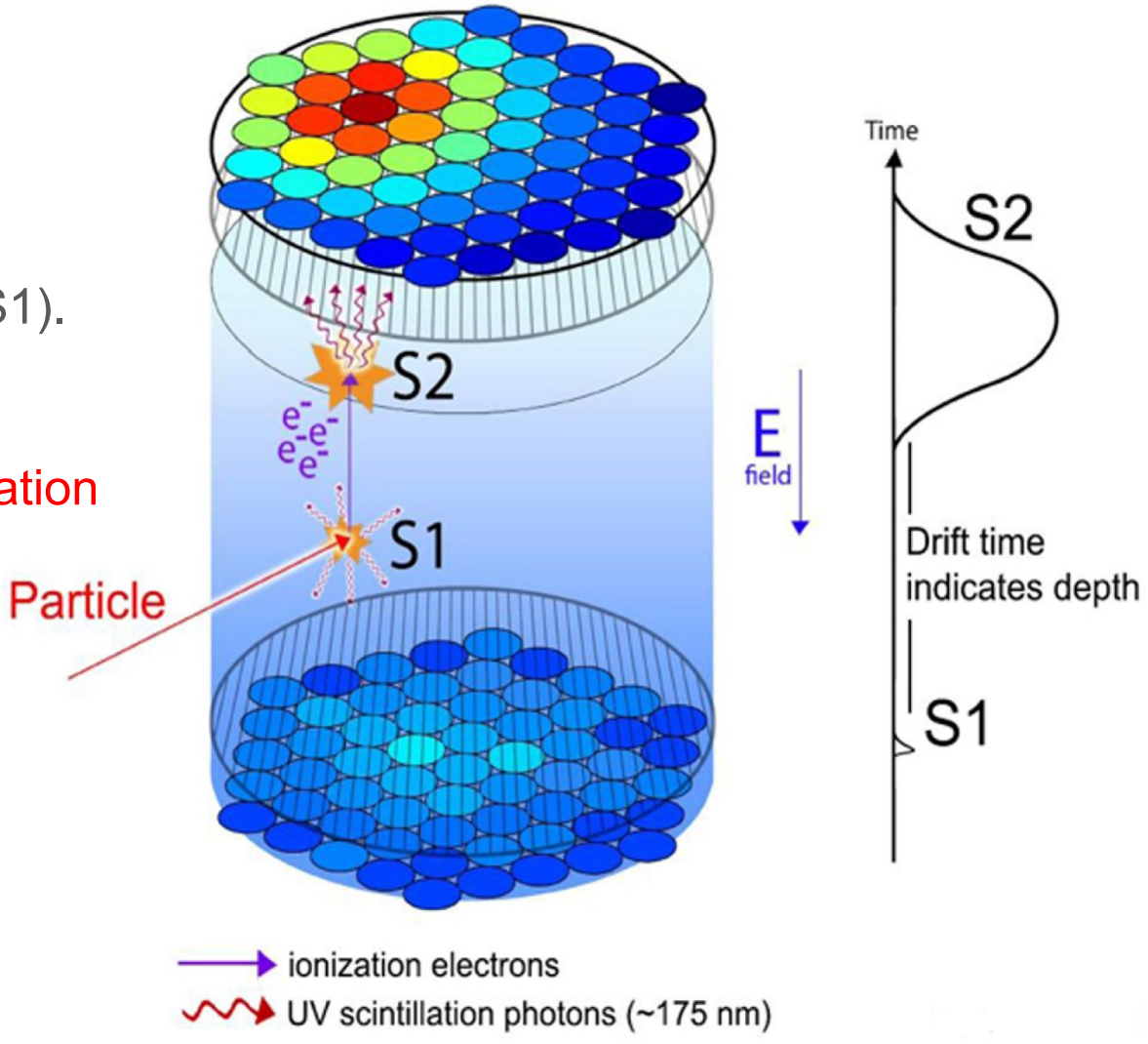


Table of Contents

flamedisx

latest

Search docs

CONTENTS:

- Flamedisx tutorial
  - 0. Setup
  - 1. Simulation
  - 2. Inference
  - 3. Modelling
  - 4. Modelling 2
  - 5. Why bother with high-dimensional likelihoods?
- WIMP limit example
- Spatially varying rate demo
- Customizing the flamedisx model

API REFERENCE

- flamedisx package

Read the Docs v: latest

» Flamedisx tutorial

Edit on GitHub

Flamedisx tutorial

Flamedisx is a package for inference on Liquid Xenon TPC data. This tutorial assumes you are familiar with these detectors, and we will not attempt to explain jargon like S1, S2, etc.

0. Setup

To run this notebook, you have two options:

1. Install flamedisx locally with `pip install flamedisx` in a fresh environment. This should install all necessary dependencies (in particular, tensorflow 2).
2. Use Google's colaboratory, so you do not have to install anything and can use a GPU. Follow the steps below:

- Open the notebook in colab using https://colab.research.google.com/github/FlamTeam/flamedisx-notebooks/blob/master/Tutorial.ipynb.
- Run just the cell below (starting with `!wget -nc ...`)
- Restart the runtime (Runtime -> Restart runtime).
- (Optional: make sure you are using a GPU, using Runtime -> Change runtime type)
- Run the notebook.

https://github.com/FlamTeam/flamedisx

flamedisx

latest

Search docs

CONTENTS:

- Flamedisx tutorial
  - 0. Setup
  - 1. Simulation
  - 2. Inference
  - 3. Modelling
  - 4. Modelling 2
  - 5. Why bother with high-dimensional likelihoods?
- WIMP limit example
- Spatially varying rate demo
- Customizing the flamedisx model

API REFERENCE

- flamedisx package

Read the Docs v: latest

» Flamedisx tutorial

Edit on GitHub

Flamedisx tutorial

Flamedisx is a package for inference on Liquid Xenon TPC data. This tutorial assumes you are familiar with these detectors, and we will not attempt to explain jargon like S1, S2, etc.

0. Setup

To run this notebook, you have two options:

1. Install flamedisx locally with `pip install flamedisx` in a fresh environment. This should install all necessary dependencies (in particular, tensorflow 2).
2. Use Google's colaboratory, so you do not have to install anything and can use a GPU. Follow the steps below:

- Open the notebook in colab using https://colab.research.google.com/github/FlamTeam/flamedisx-notebooks/blob/master/Tutorial.ipynb.
- Run just the cell below (starting with `!wget -nc ...`)
- Restart the runtime (Runtime -> Restart runtime).
- (Optional: make sure you are using a GPU, using Runtime -> Change runtime type)
- Run the notebook.

FD enhances sensitivity by replacing template fitting with TensorFlow computations and expanding the dimensions in the likelihood.

Table of Contents

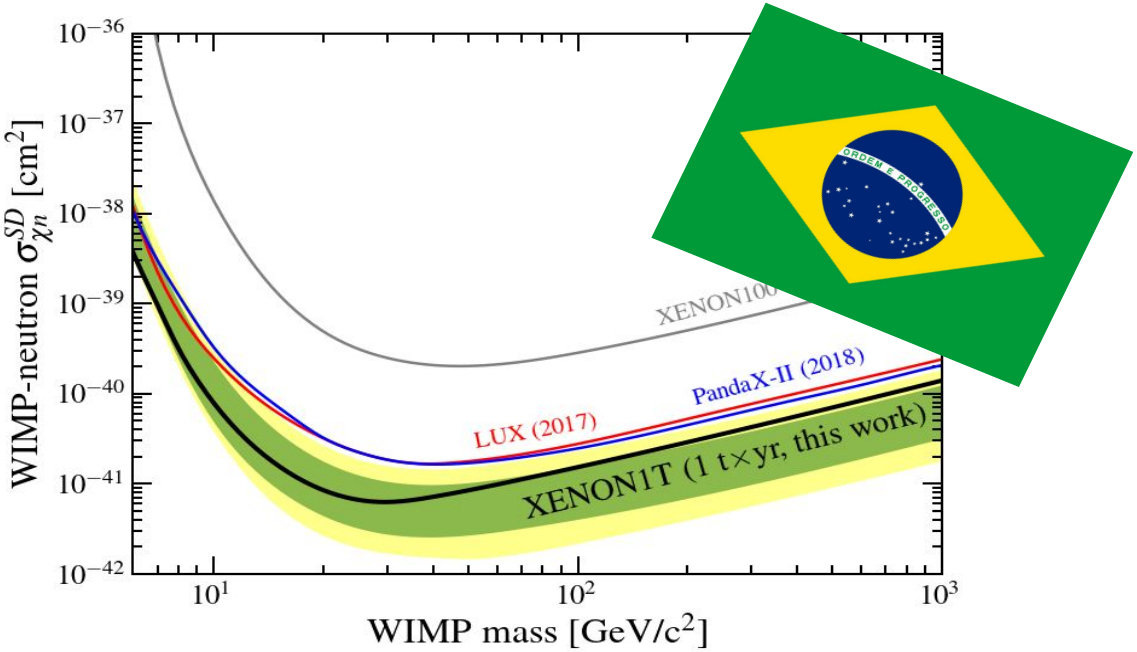
Flamedisx: Hands-on activity

Tasks:

Construct σ vs m_{WIMP} (sensitivity) plot
for simulated data and different background models

Tasks:

Construct σ vs m_{WIMP} (sensitivity) plot
for simulated data and different background models



Tasks:

Construct σ vs m_{WIMP} (sensitivity) plot
for simulated data and different background models

Background models:

- **Electronic recoil (ER) - a photon scatters off electron**
- **Nucleonic recoil (NR) - a neutron scatters off nucleon**

Tasks:

Construct σ vs m_{WIMP} (sensitivity) plot
for simulated data and different background models

Background models:

- **Electronic recoil (ER) - a photon scatters off electron**
- **Nucleonic recoil (NR) - a neutron scatters off nucleon**

Energy spectrum: Flat, Monochromatic, Gaussian, Exponential

Tasks:

Construct σ vs m_{WIMP} (sensitivity) plot
for simulated data and different background models

Background models:

- **Electronic recoil (ER) - a photon scatters off electron**
- **Nucleonic recoil (NR) - a neutron scatters off nucleon**

Energy spectrum: Flat, Monochromatic, Gaussian, Exponential

N.B.: WIMP – NR only

Tasks:

for s

models

Backgroun

Electron

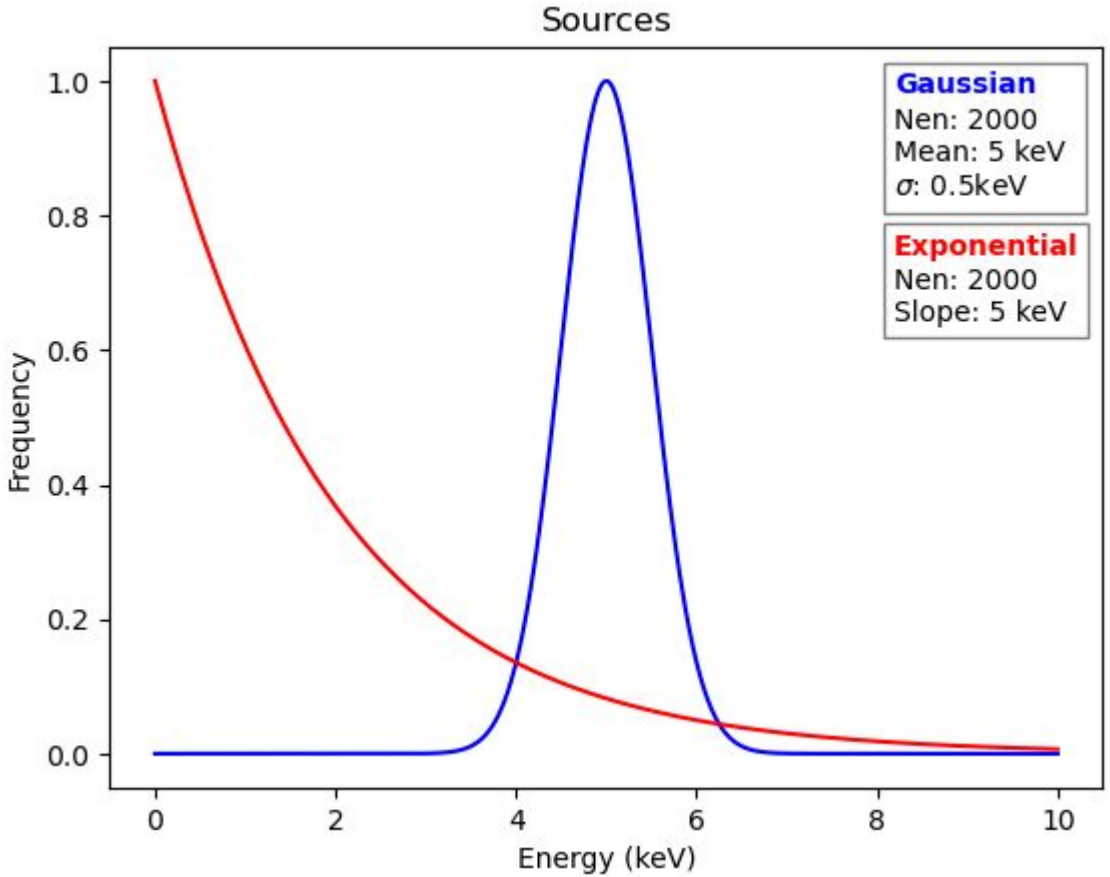
tron

Nucleon

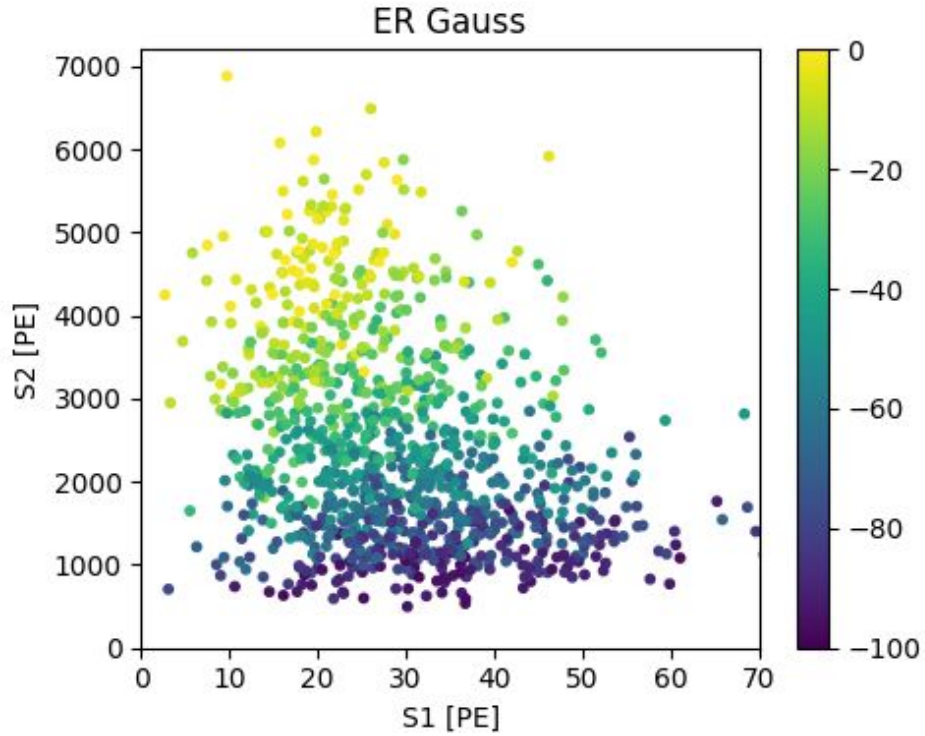
cleon

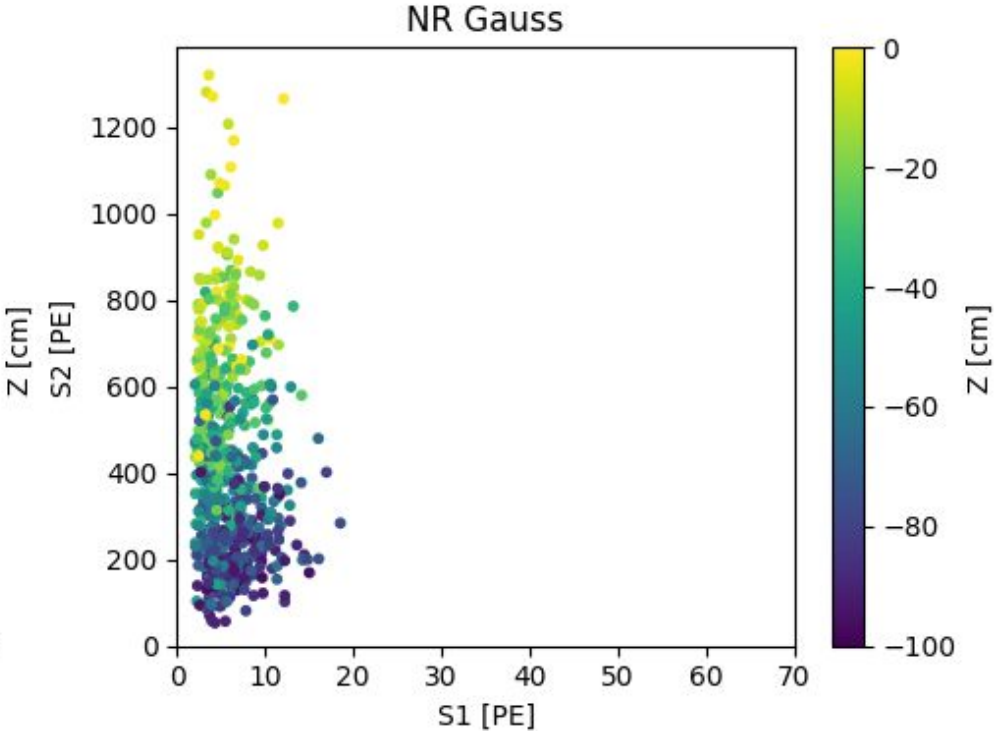
Energy spe

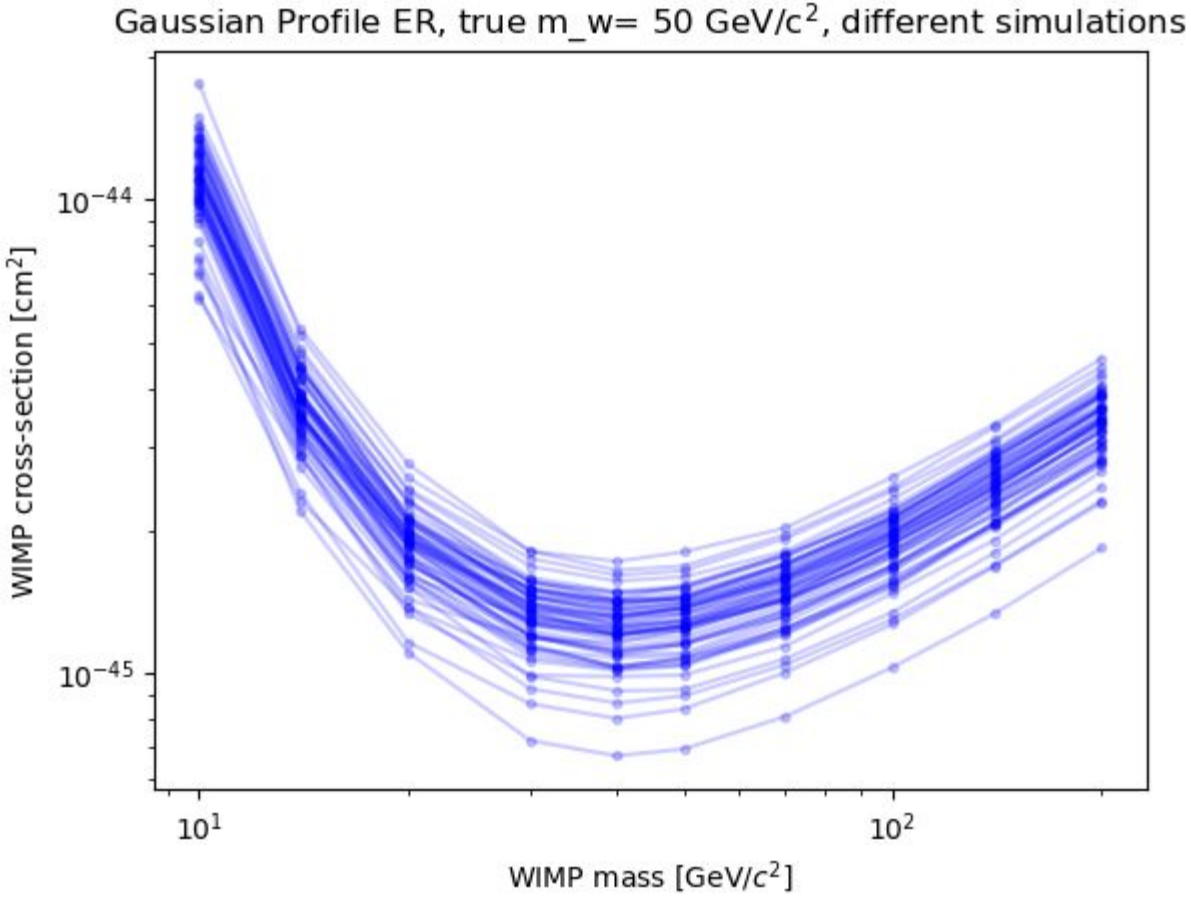
xponential

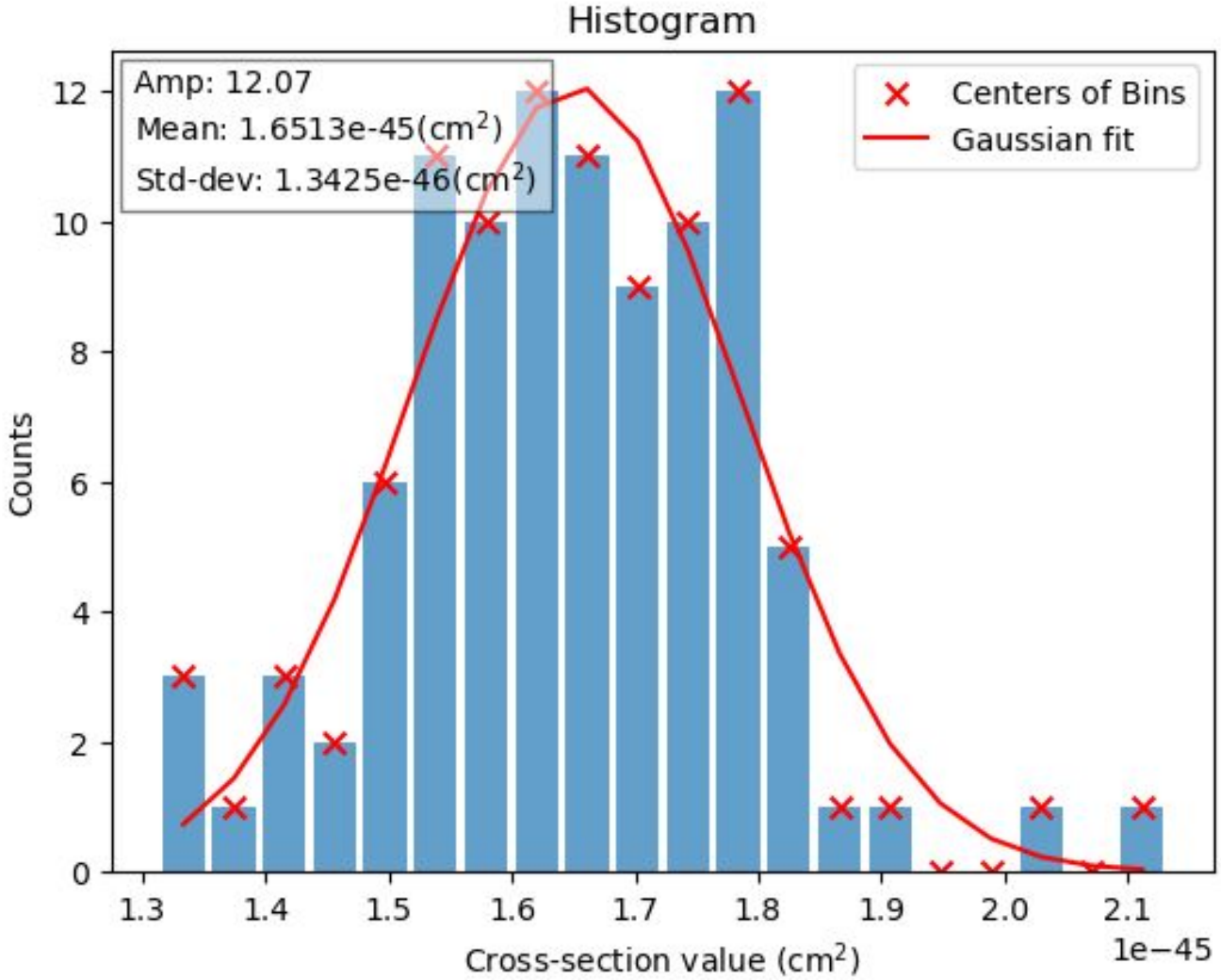


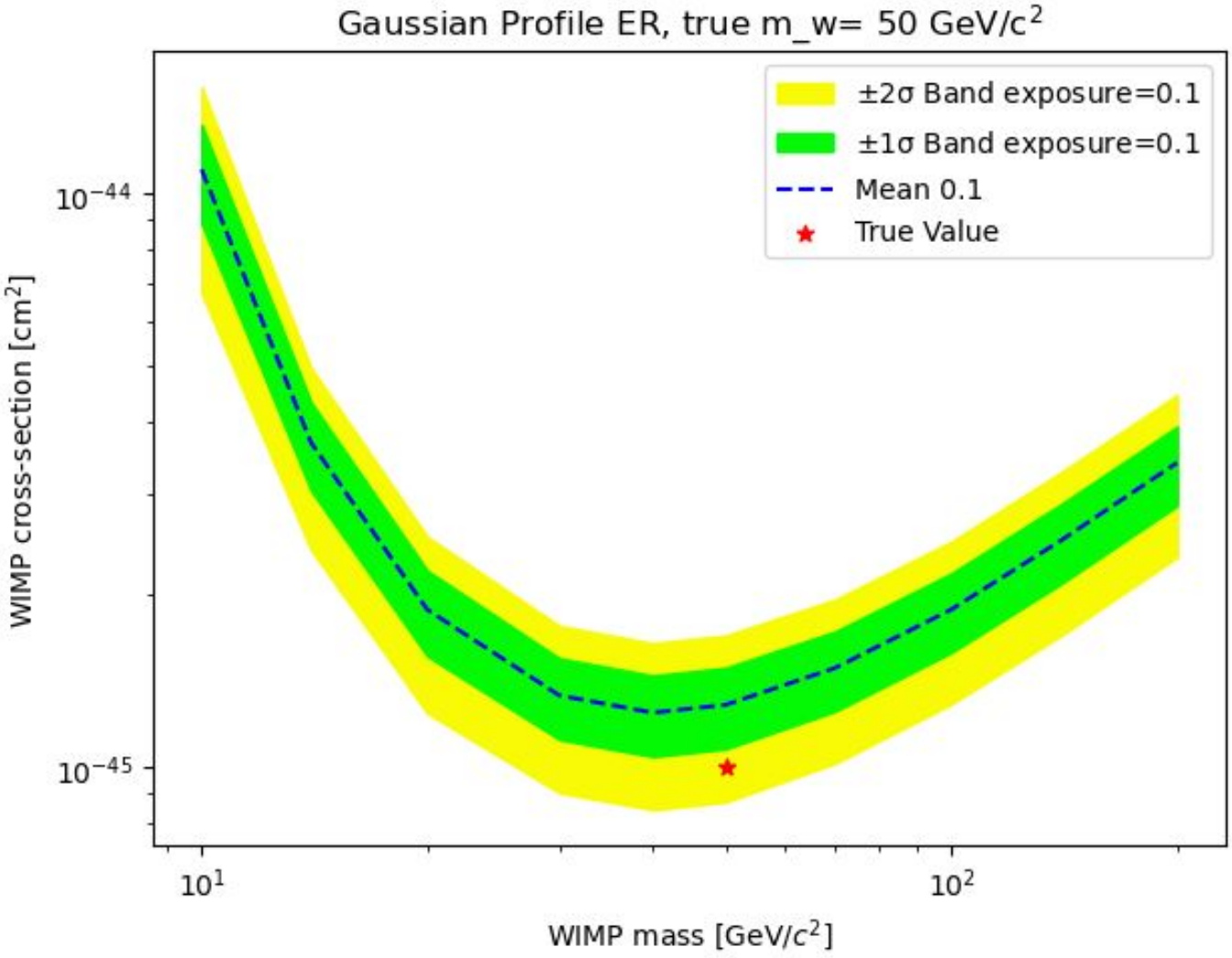
N.B.: WIMP

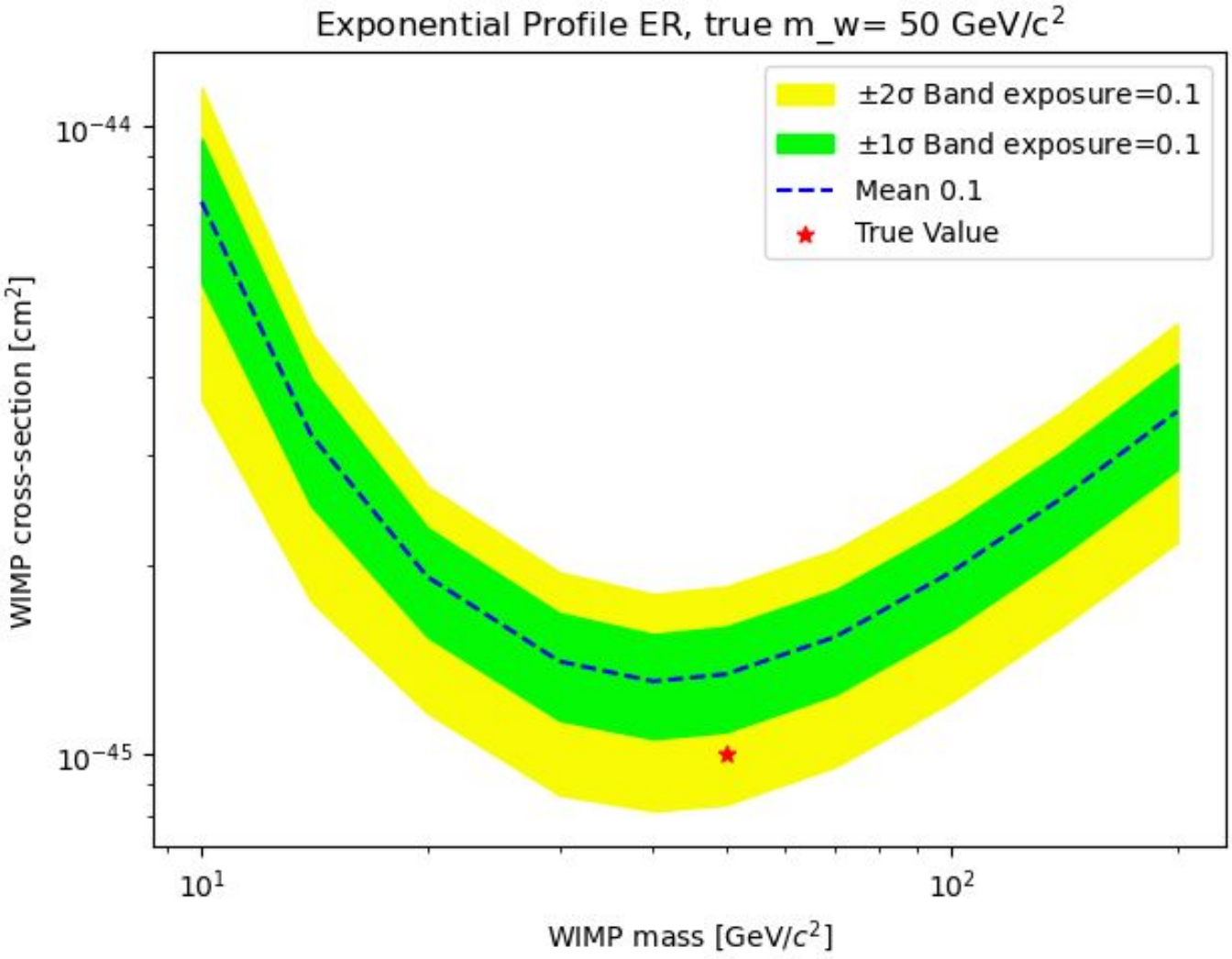

ER Gauss
S2 [PE]
S1 [PE]
Z [cm]
0
1000
2000
3000
4000
5000
6000
7000
0
10
20
30
40
50
60
70
0
−20
−40
−60
−80
−100

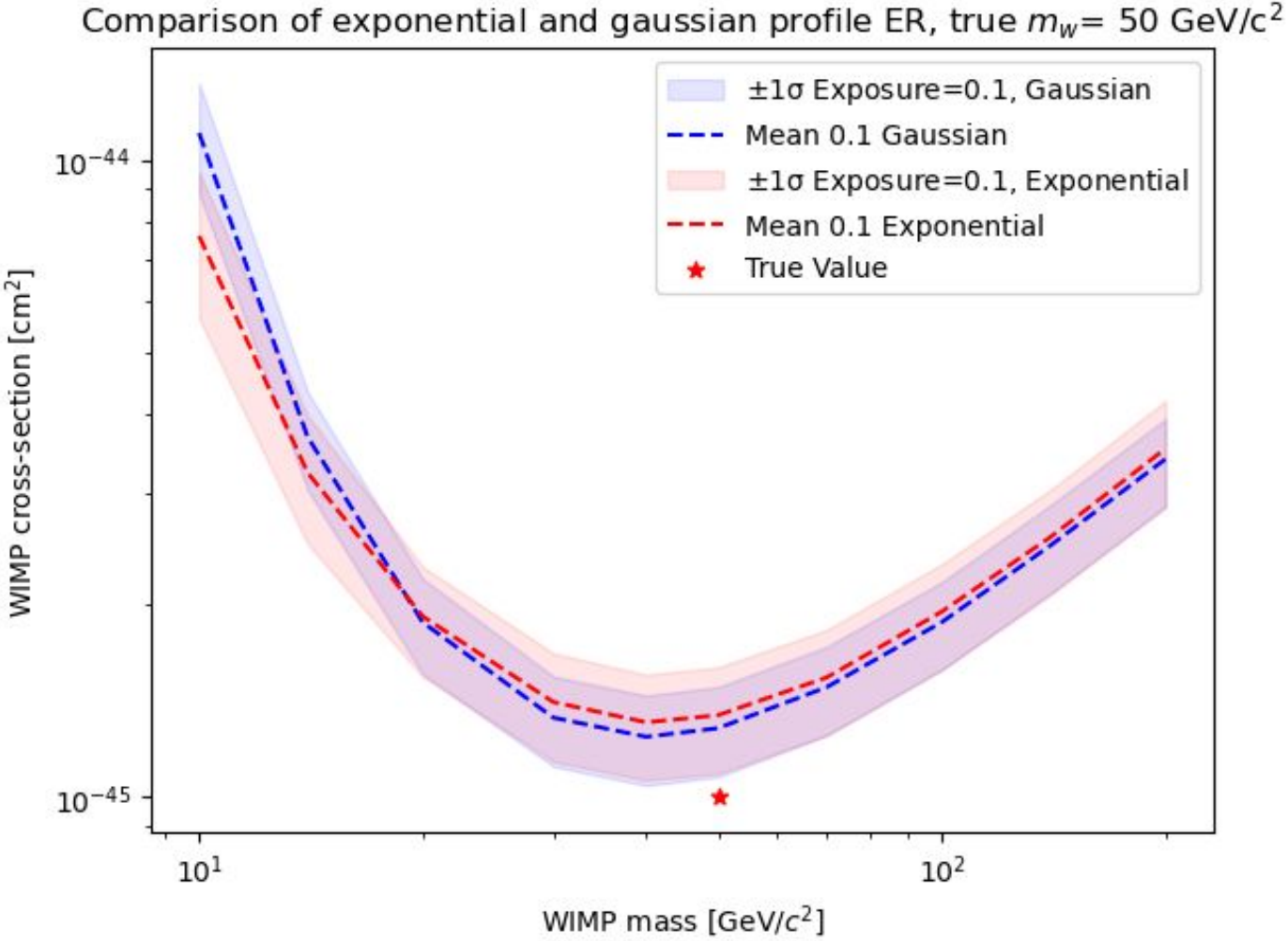

NR Gauss
S2 [PE]
S1 [PE]
Z [cm]
0
200
400
600
800
1000
1200
0
10
20
30
40
50
60
70
0
−20
−40
−60
−80
−100

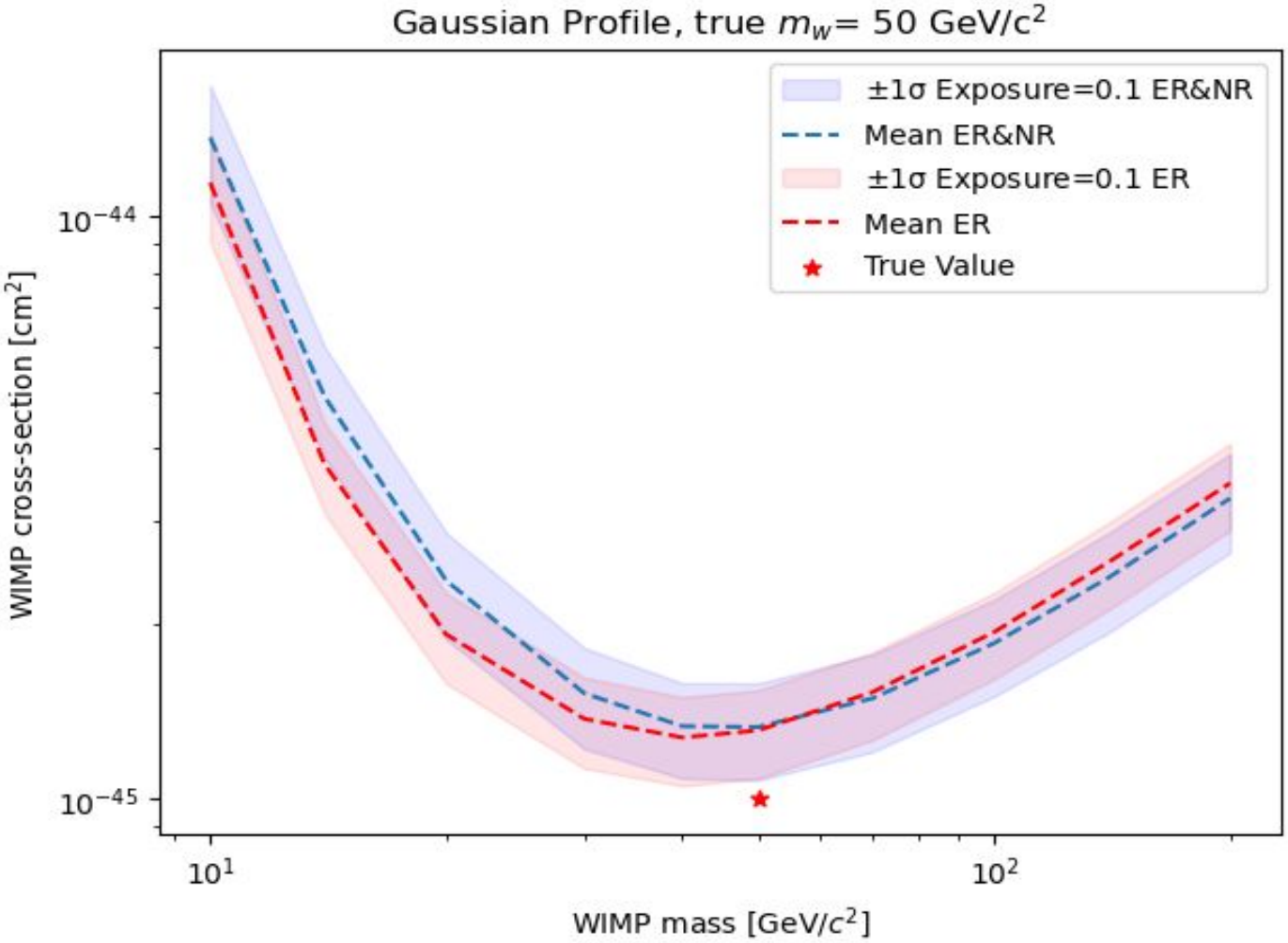

Gaussian Profile ER, true m_w= 50 GeV/c^2, different simulations
WIMP cross-section [cm^2]
10^{-44}
10^{-45}
10^1
10^2
WIMP mass [GeV/c^2]


Histogram
Amp: 12.07
Mean: 1.6513e-45(cm^2)
Std-dev: 1.3425e-46(cm^2)
Centers of Bins
Gaussian fit
Counts
0
2
4
6
8
10
12
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
Cross-section value (cm^2)
1e−45


Gaussian Profile ER, true m_w= 50 GeV/c^2
±2σ Band exposure=0.1
±1σ Band exposure=0.1
Mean 0.1
True Value
10^{-44}
10^{-45}
WIMP cross-section [cm^2]
10^1
10^2
WIMP mass [GeV/c^2]


Exponential Profile ER, true m_w= 50 GeV/c^2
±2σ Band exposure=0.1
±1σ Band exposure=0.1
Mean 0.1
True Value
10^{-44}
10^{-45}
WIMP cross-section [cm^2]
10^1
10^2
WIMP mass [GeV/c^2]


Comparison of exponential and gaussian profile ER, true m_w= 50 GeV/c^2
±1σ Exposure=0.1, Gaussian
Mean 0.1 Gaussian
±1σ Exposure=0.1, Exponential
Mean 0.1 Exponential
True Value
10^{-44}
10^{-45}
WIMP cross-section [cm^2]
10^1
10^2
WIMP mass [GeV/c^2]


Gaussian Profile, true m_w= 50 GeV/c^2
±1σ Exposure=0.1 ER&NR
Mean ER&NR
±1σ Exposure=0.1 ER
Mean ER
True Value
10^{-44}
10^{-45}
WIMP cross-section [cm^2]
10^1
10^2
WIMP mass [GeV/c^2]

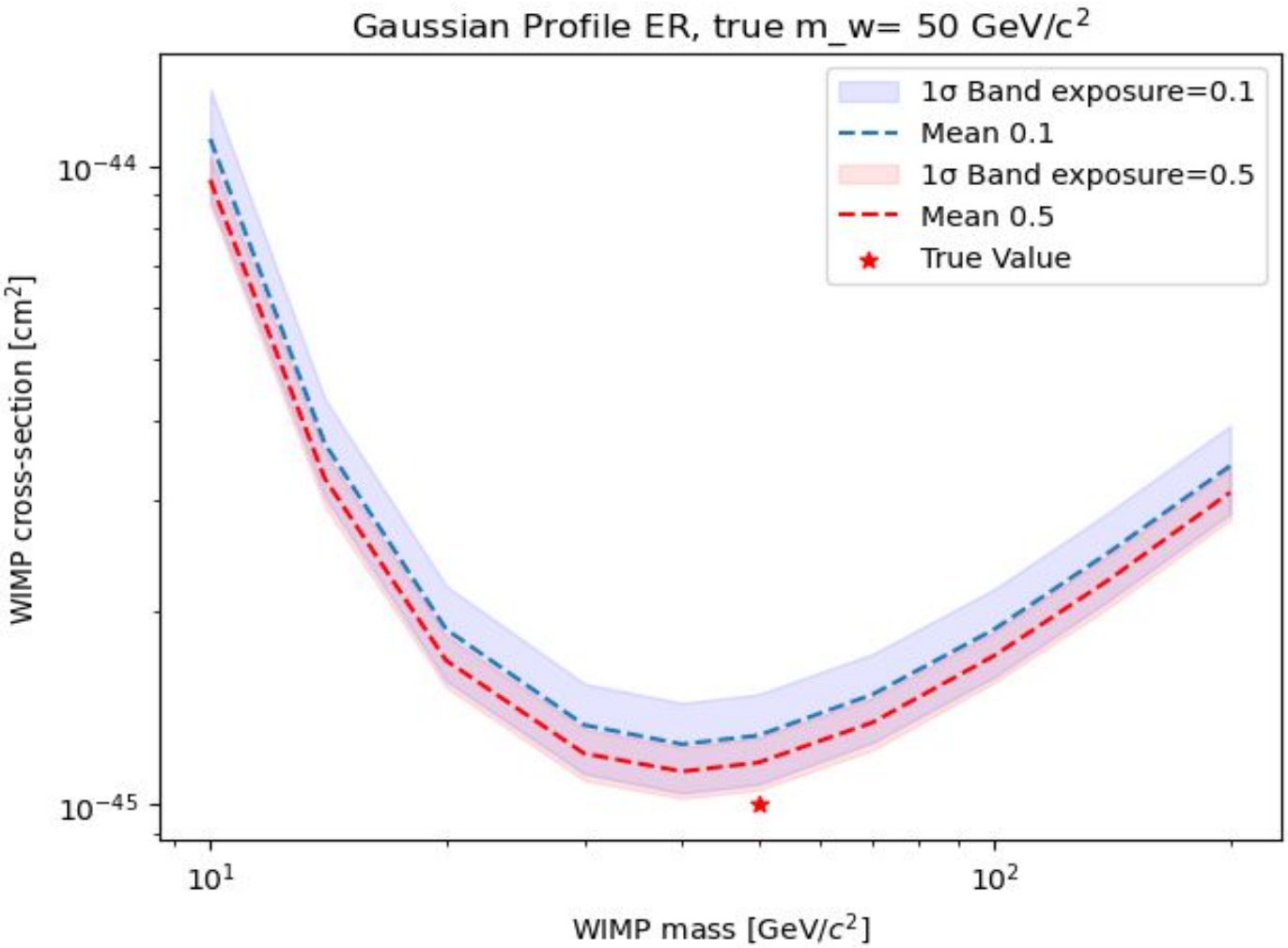

Gaussian Profile ER, true m_w= 50 GeV/c^2
1σ Band exposure=0.1
Mean 0.1
1σ Band exposure=0.5
Mean 0.5
True Value
10^{-44}
10^{-45}
WIMP cross-section [cm^2]
10^1
10^2
WIMP mass [GeV/c^2]

Table of Contents

Correct typo in blocks.rst #329

Open **pietro14** wants to merge 1 commit into `FlamTeam:main` from `pietro14:main`

Conversation 1 | Commits 1 | Checks 1 | Files changed 1

pietro14 commented 3 days ago • edited

Correct typo in blocks.rst

Correct typo in blocks.rst — Verified — 2a8804e

JelleAalbers approved these changes 3 days ago — View reviewed changes

JelleAalbers left a comment — Member

Well spotted, thanks! For reference, the original attribute is here:

flamedisx/flamedisx/lxe_blocks/energy_spectrum.py
Line 179 in `b54a5a4`

```
179     rates_vs_energy = tf.ones(1000, dtype=fd.float_type())
```

1

Summary

1. We understood the basics of Flamedisx.
2. We constructed the sensitivity plot σ vs m_{WIMP} for different background models (ER, NR, different spectra).
3. We found a typo in code.
4. We didn’t find dark matter.

Thank you!

Pietro, Marco, Pavel

Backup Slides

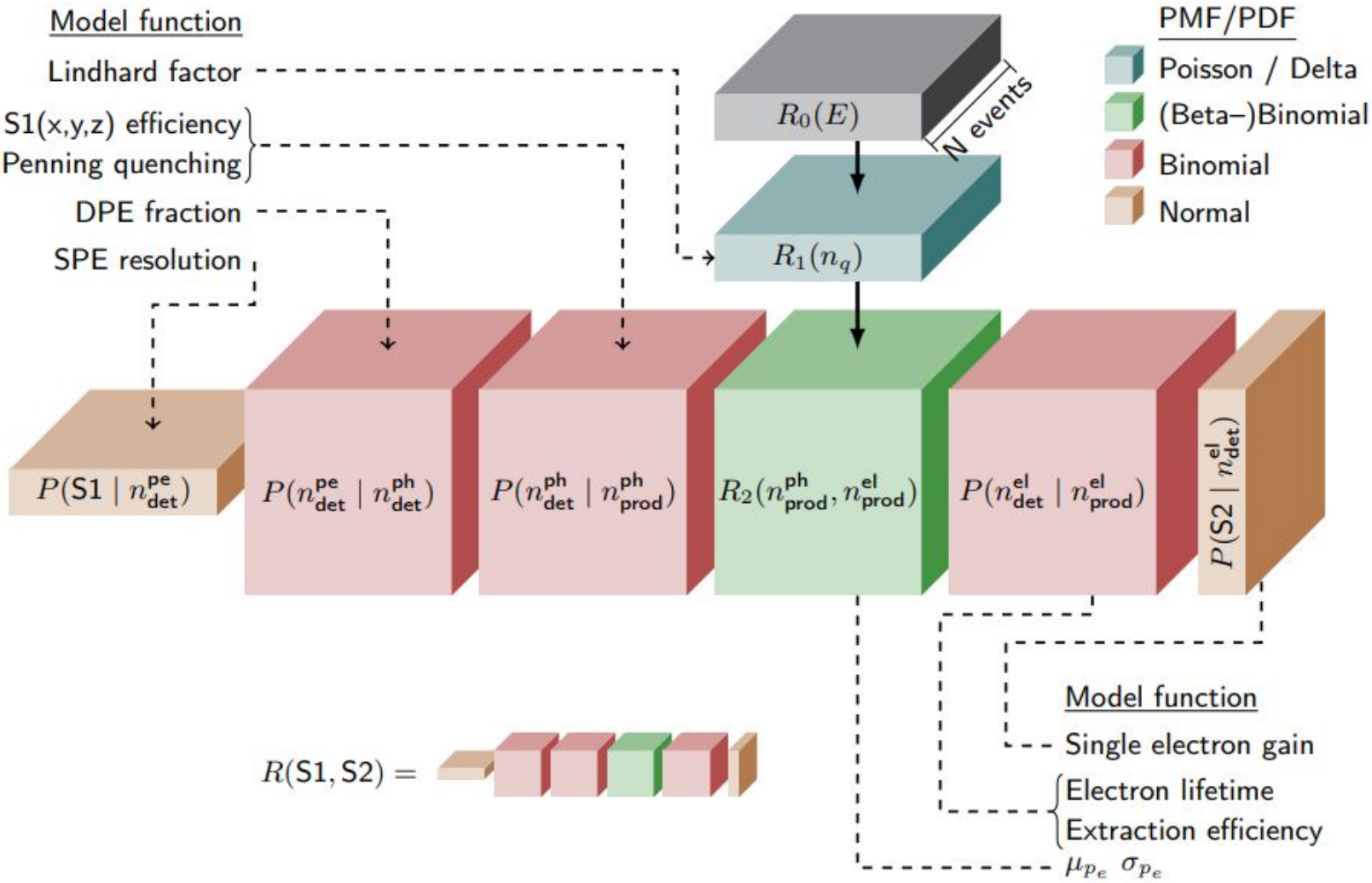
Flamedisx

Fast likelihood analysis in more dimensions for xenon TPCs.

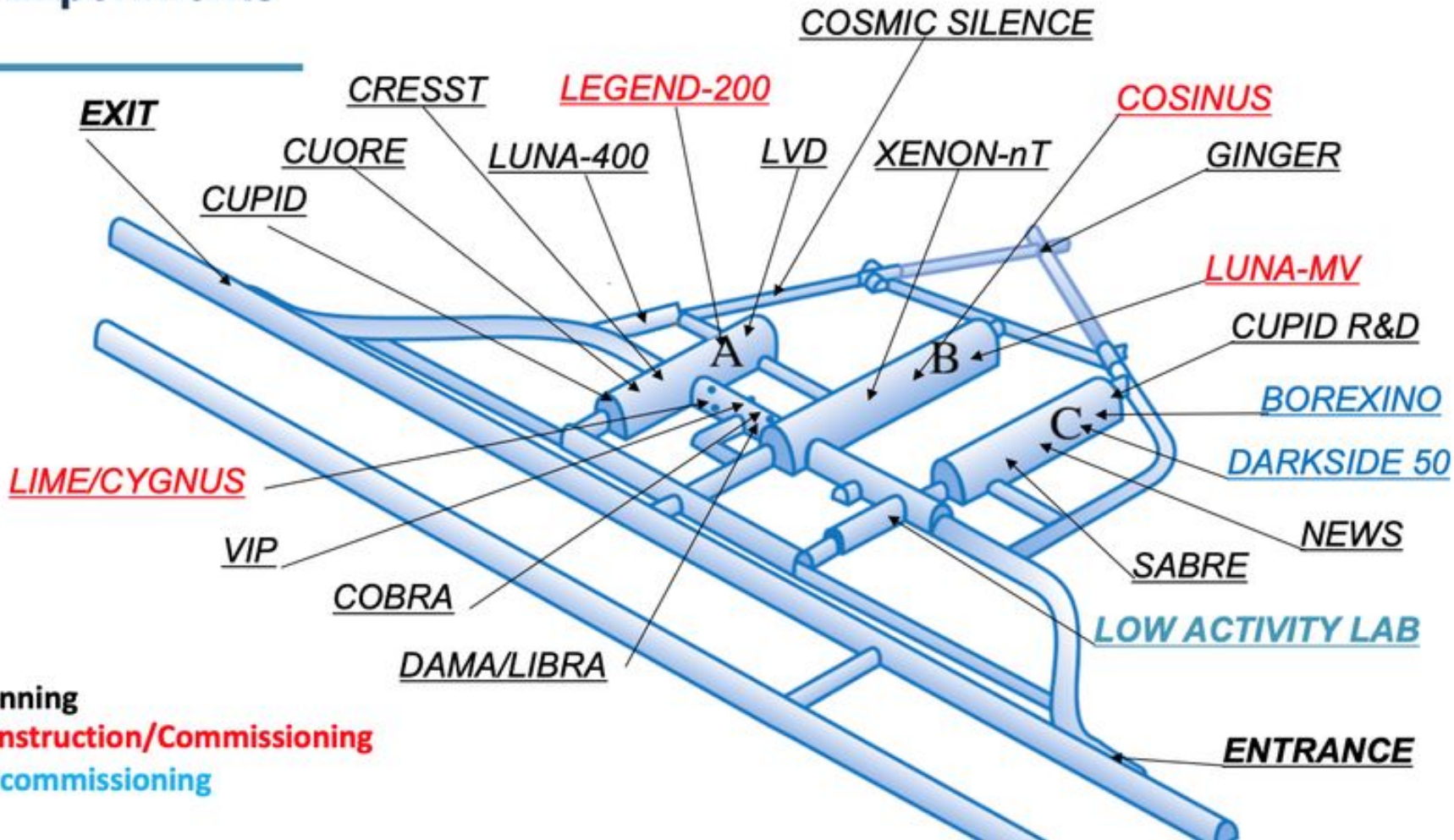
Flamedisx aims to increase the practical number of dimensions and parameters in likelihoods for liquid-xenon (LXe) detectors, which are leading the field of direct dark matter detection.

Traditionally, particle physicists compute signal and background models by filling histogram 'templates' with high-statistics Monte Carlo (MC) simulations. However, the LXe model can also be computed with a series of (large) matrix multiplications, equivalent to the integral approximated by the MC simulation. Using TensorFlow makes this computation differentiable and GPU-scalable, so it can be used practically for fitting and statistical inference.

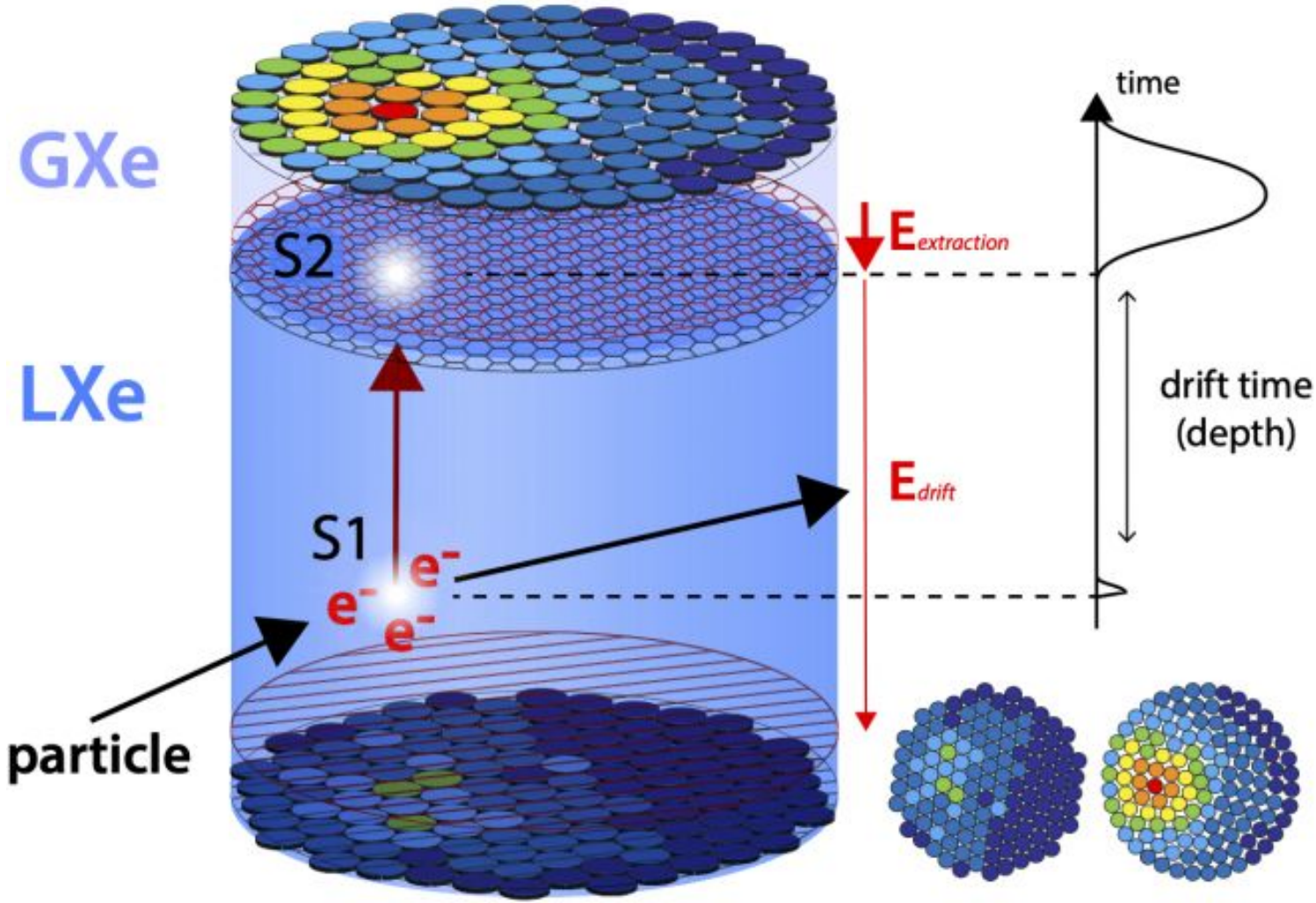
The result is a better sensitivity, since the likelihood can use all observables, and more robust fits, because using simultaneous correlated nuisance parameters no longer requires challenging interpolation and template morphing.


Model function
Lindhard factor
S1(x,y,z) efficiency
Penning quenching
DPE fraction
SPE resolution
$R_0(E)$
N events
$R_1(n_q)$
PMF/PDF
Poisson / Delta
(Beta–)Binomial
Binomial
Normal
$P(\mathrm{S1} \mid n_{\mathrm{det}}^{\mathrm{pe}})$
$P(n_{\mathrm{det}}^{\mathrm{pe}} \mid n_{\mathrm{det}}^{\mathrm{ph}})$
$P(n_{\mathrm{det}}^{\mathrm{ph}} \mid n_{\mathrm{prod}}^{\mathrm{ph}})$
$R_2(n_{\mathrm{prod}}^{\mathrm{ph}}, n_{\mathrm{prod}}^{\mathrm{el}})$
$P(n_{\mathrm{det}}^{\mathrm{el}} \mid n_{\mathrm{prod}}^{\mathrm{el}})$
$P(\mathrm{S2} \mid n_{\mathrm{det}}^{\mathrm{el}})$
$R(\mathrm{S1}, \mathrm{S2}) =$
Model function
Single electron gain
Electron lifetime
Extraction efficiency
μ_{p_e} σ_{p_e}

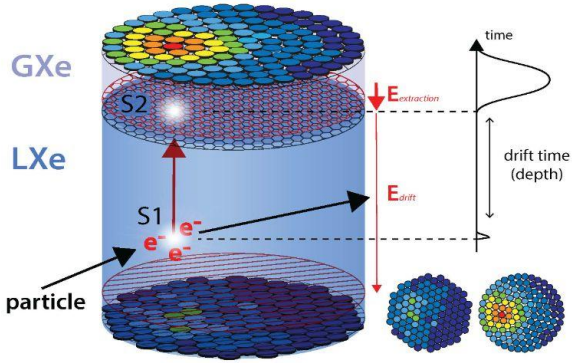
LNGS Experiments

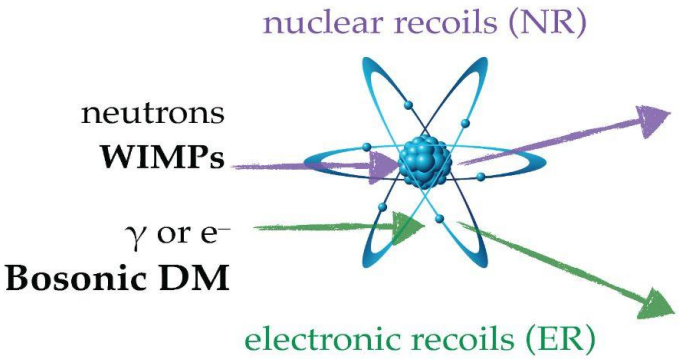


- Running
- Construction/Commissioning
- Decommissioning


GXe
LXe
S2
S1
e-
e-
e-
particle
E extraction
E drift
time
drift time
(depth)

XENON1T: not just for WIMPs



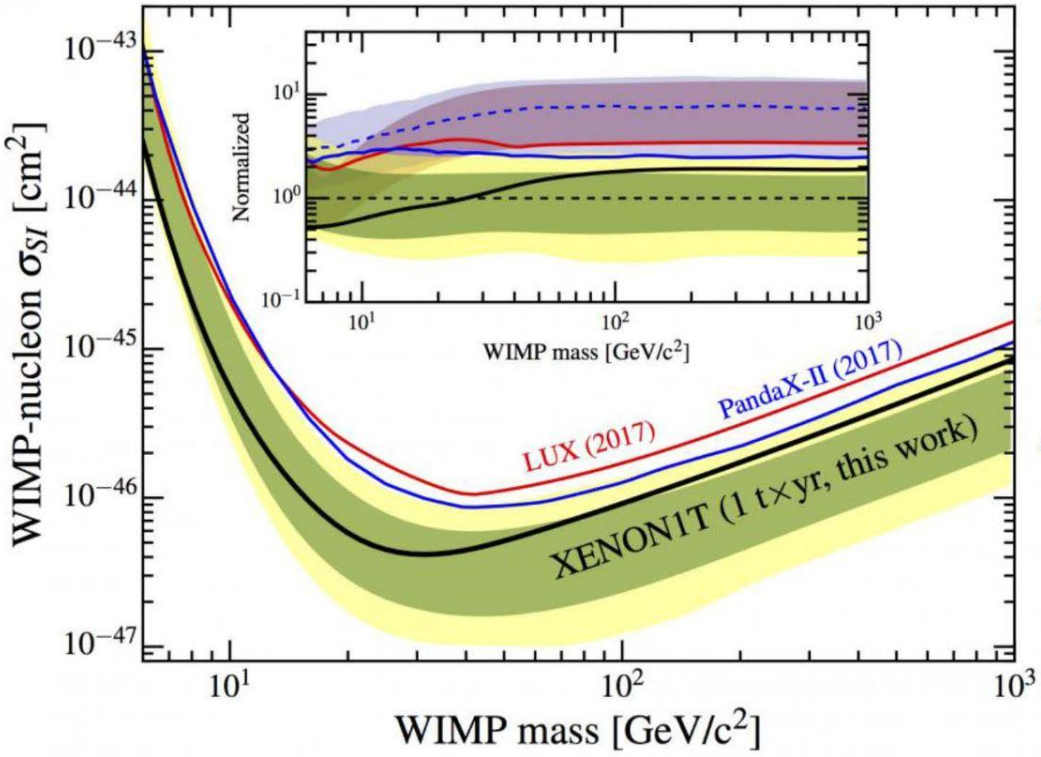


WIMPs scatter **… Low-mass, bosonic dark matter is absorbed!**

Super-weakly interacting + early thermal decoupling: keV-scale cold DM satisfies both relic abundance and galactic small-scale structure

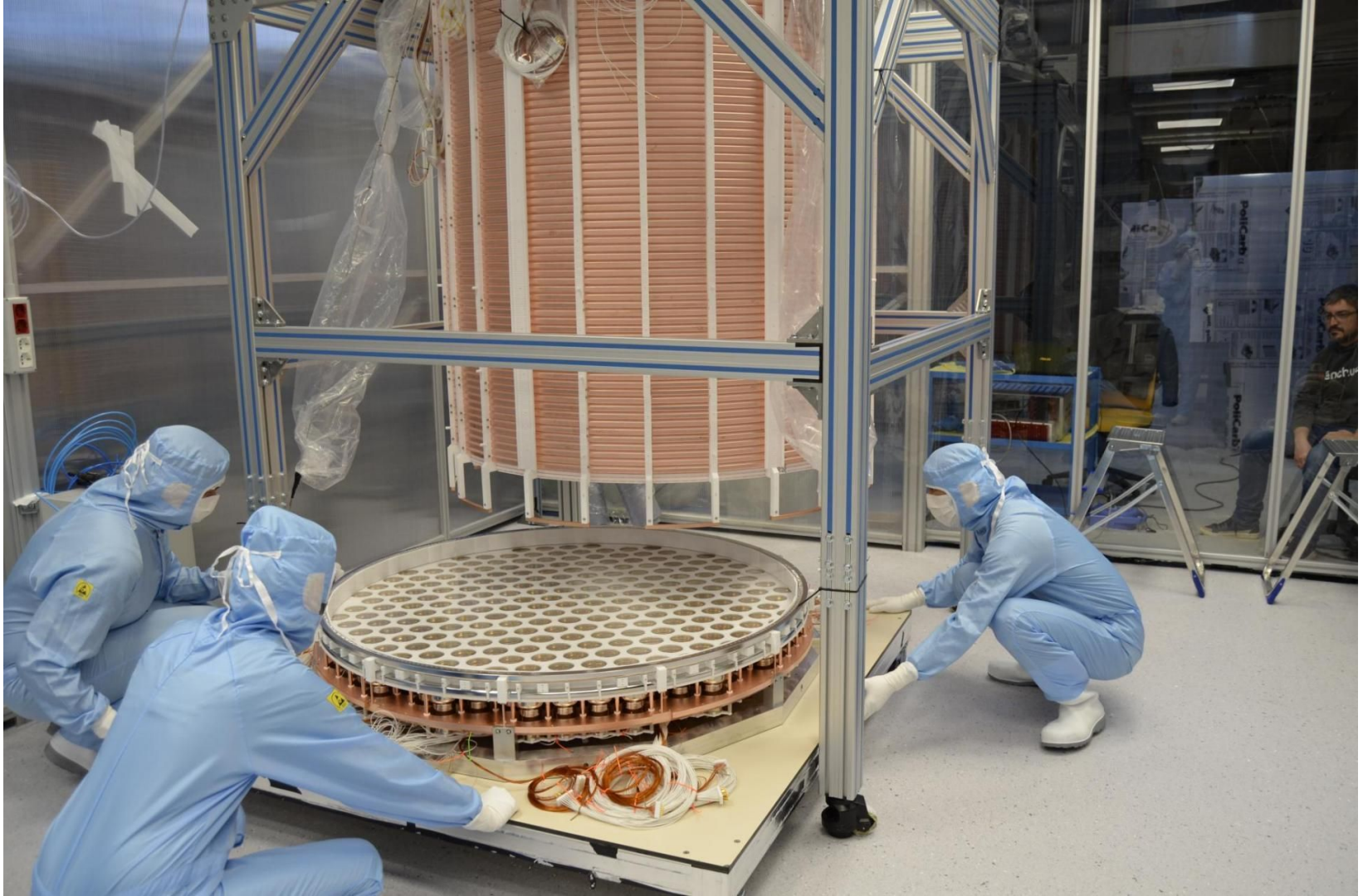
XENON1T can probe other well-motivated DM candidates with masses down to ~few keV

Spin-Independent WIMP interaction



1. **World best constraint on WIMP Dark Matter.** Most stringent exclusion limits (@ 90% CL) for WIMPs > 6 GeV/c^2;
2. **×7 improved sensitivity** compare to previous experiments (LUX, PANDAX-II);
3. **Upper limit:** $\sigma_{SI} < 4.1 \times 10^{-47}$ cm^2 @ 30 GeV/c^2.

Phys. Rev. Lett. 121, 111302



Show the source functions and say that they have these type of source, a flat one from radon and some peaks from argon

Argon - 2.8 keV, extra background. The sensitivity can be better if it is in the underground