Flamedisx

Fast Likelihood Analysis in MorE DImensionS for Xenon TPCs

On behalf of the **FlamTeam**

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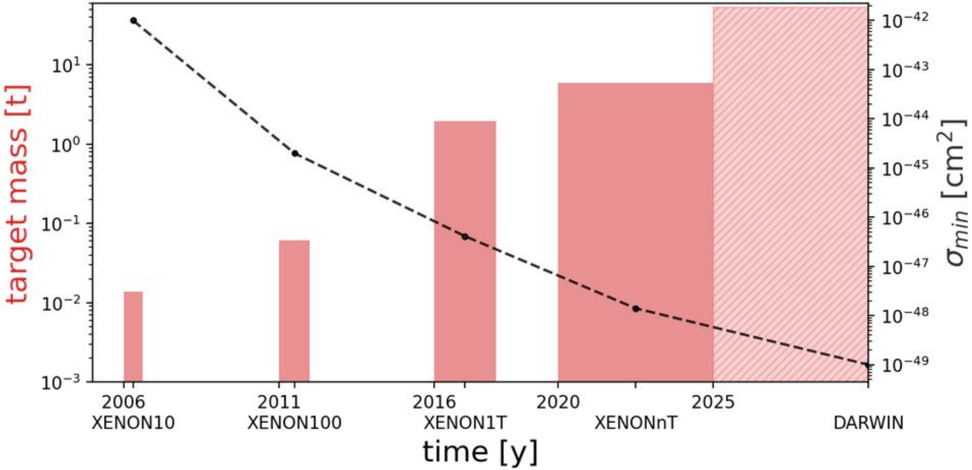
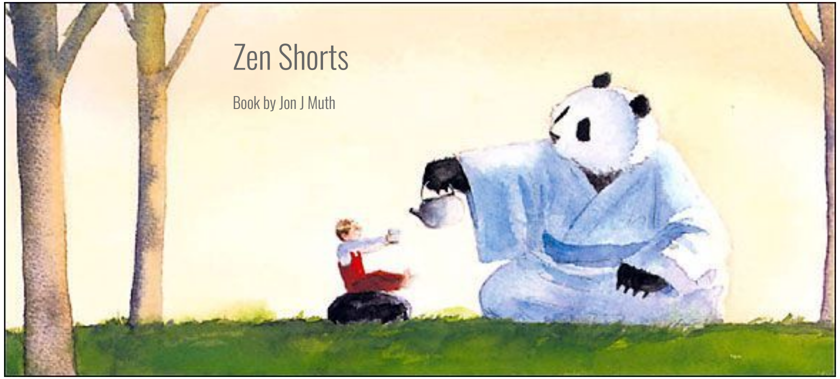
Cecilia Ferrari - GSSI/INFN

A zen exercise to be practiced with patience

Nowadays **consolidated techniques** allow the **target mass** and the experimental **life-time** to scale up.



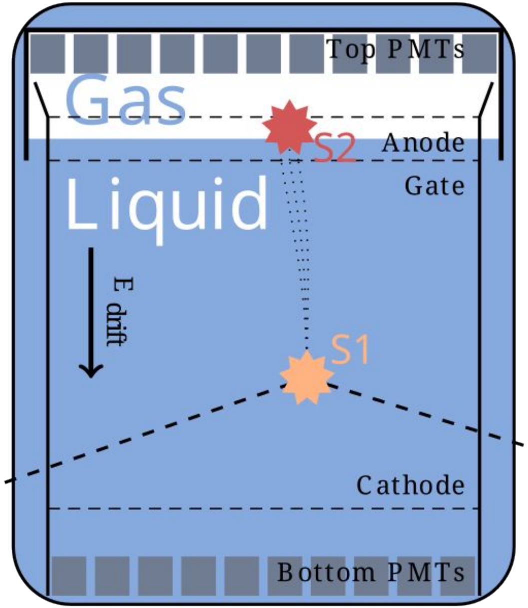


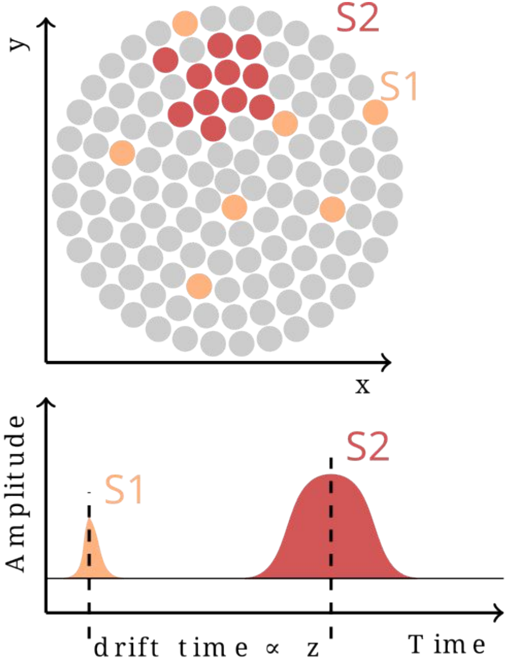
How can we deal with possible detector instabilities?
Is there a way to reach the desired discovery potential **faster**?

In this talk:

- Xenon TPCs for direct dark matter searches
- Two different analysis strategies for Xenon TPCs
- Implementation of LXe emission model
- Why should we care about multidimensional analysis?

Xenon TPCs for direct dark matter searches



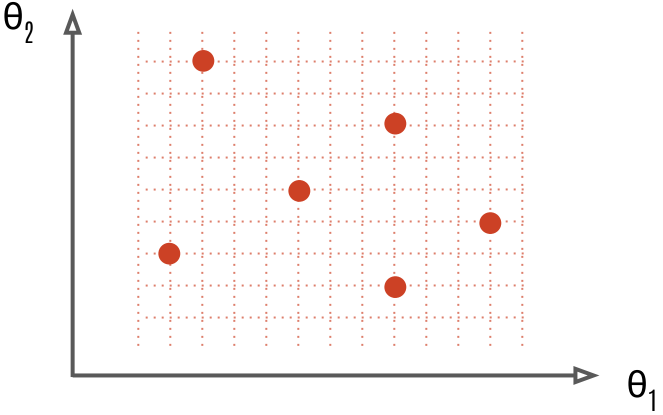


- Particles scattering off xenon target generate **S1** and **S2** signals
- **x-y** and **z** identified by S2 top PMTs pattern and S1 S2 time delay
- S1 and S2 can be corrected into **cS1 cS2** to absorb eventual detector x,y,z,t dependence

Two different analysis strategies for Xenon TPCs

Parameter Inference with Monte–Carlo Simulations

- Pre-compute cS1 cS2 **templates** with large MC simulations at strategic points in the parameter space
- Run optimizer in the parameter space and get differential rates with **template morphing**

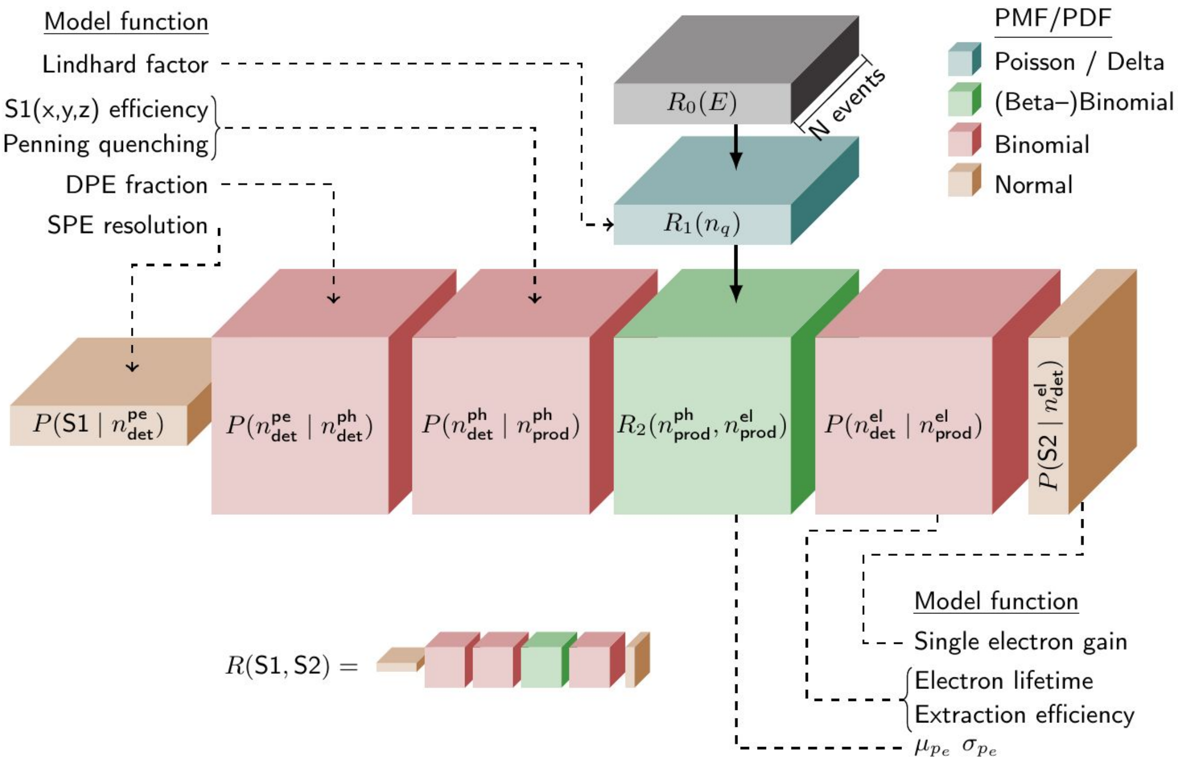


Parameter Inference by Explicit Likelihood - Flamedisx

- Compute **differential rate** (R(s)) for each event (s) given the **LXe emission model**, implemented using **matrix multiplications**

$$L = \text{Poisson}(N_{\text{tot}}|\mu) \prod_i^{\text{events}} \sum_j^{\text{sources}} \frac{R^j(\boldsymbol{s}_i)}{\mu}$$

Implementation of LXe emission model



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

$P(\mathrm{S1} \mid n^{\mathrm{pe}}_{\mathrm{det}})$ $P(n^{\mathrm{pe}}_{\mathrm{det}} \mid n^{\mathrm{ph}}_{\mathrm{det}})$ $P(n^{\mathrm{ph}}_{\mathrm{det}} \mid n^{\mathrm{ph}}_{\mathrm{prod}})$ $R_2(n^{\mathrm{ph}}_{\mathrm{prod}}, n^{\mathrm{el}}_{\mathrm{prod}})$ $P(n^{\mathrm{el}}_{\mathrm{det}} \mid n^{\mathrm{el}}_{\mathrm{prod}})$ $P(\mathrm{S2} \mid n^{\mathrm{el}}_{\mathrm{det}})$

$R(\mathrm{S1}, \mathrm{S2}) =$

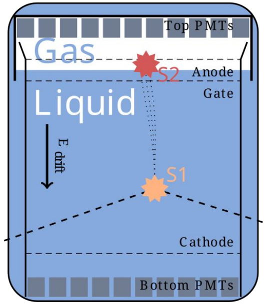
Model function

Single electron gain

Electron lifetime

Extraction efficiency

μ_{pe} σ_{pe}



Notice that in this case the full event information is exploited (S1,S2,x,y,z,t)

* If interested in the emission model in the NEST fashion look at DOI: 10.1088/1748-0221/17/08/p08012

DOI: 10.1103/PhysRevD.102.072010

Why should we care about 6D analysis?

Increased **statistics** by

Extending the fiducial volume

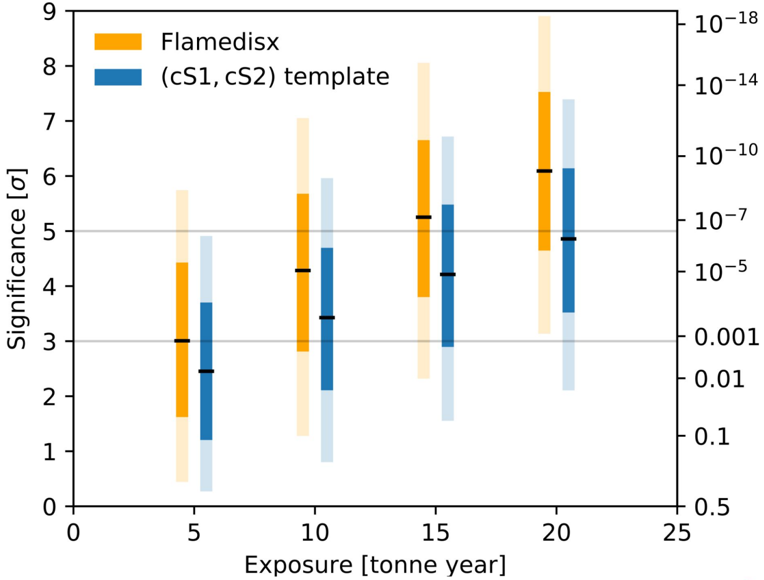
- Model spatial-dependent backgrounds (e.g. TPC surface background)
- Include detector inhomogeneities

Extending the temporal exposure

- Model temporal-dependent signals (e.g. annual modulation)
- Model temporal-dependent backgrounds (e.g. neutron activated backgrounds due to calibration runs)
- Include detector instabilities

Increased **discovery potential** with

improved background discrimination



Same results can be achieved with a 6D template, but..

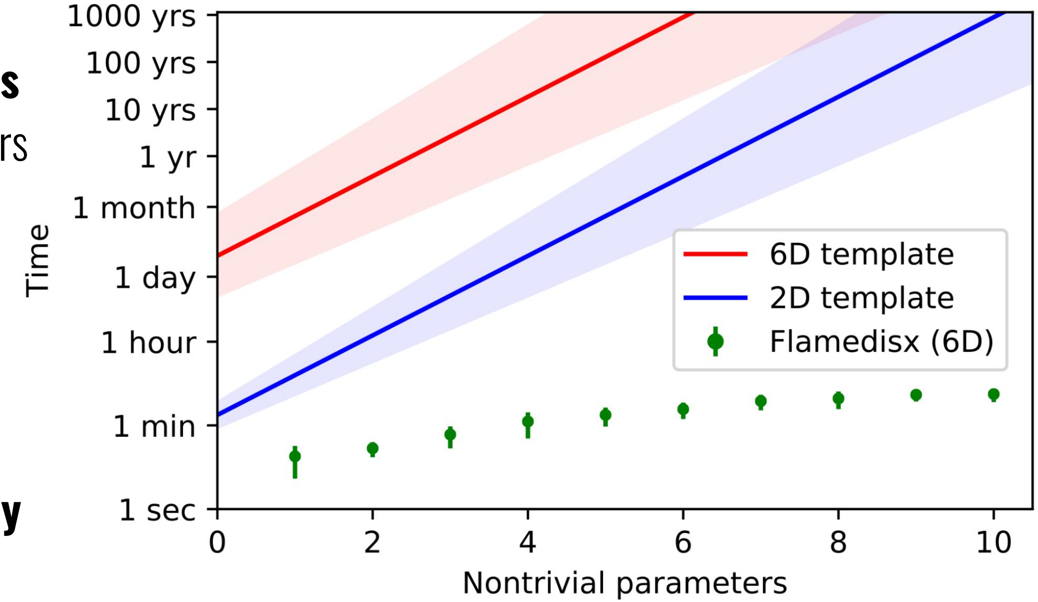
Additional advantages

- **Explicit likelihood** approach (for xenon TPCs) requires **small computational costs** also for a large number of nontrivial parameters

Moreover

- More parameters allows **better modeling**
- **Propagation of errors** is granted also for correlated nuisance parameters
- Extra dimensions provides **better sensitivity**

Template approach in **6D** is **unfeasible**

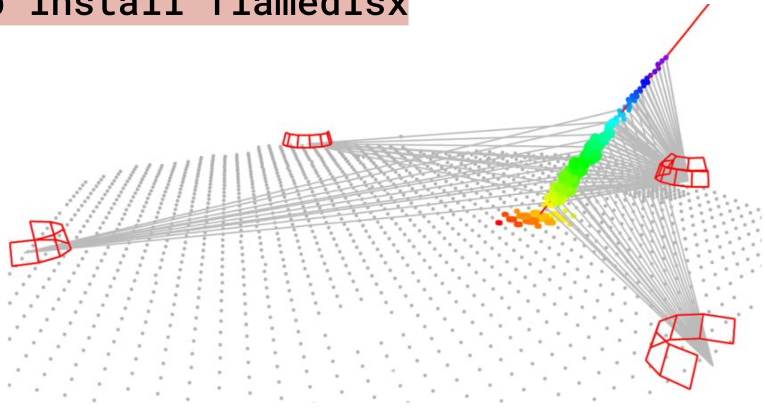


Flamedisx for LXe TPCs can **deal** with **detector instabilites**/inhomogeneities and **reach** the **desired sensitivity faster**

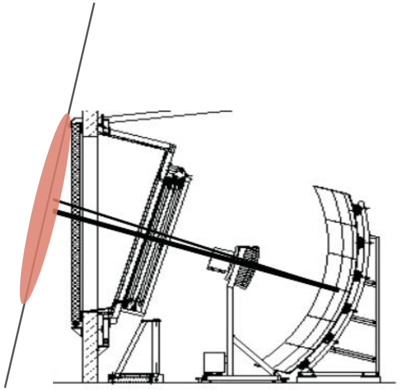
Is it true also for your experiment?

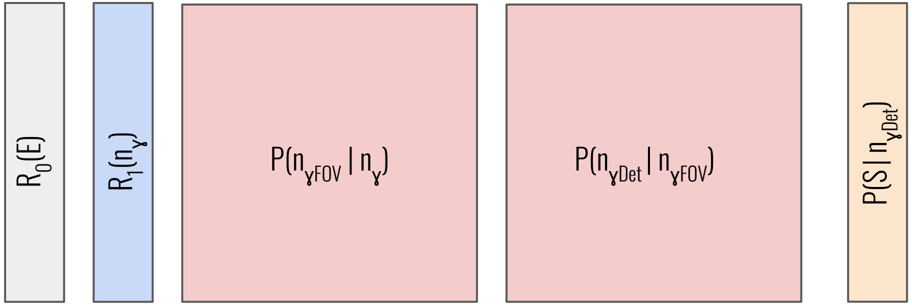
Install flamedisx and build your experiment blocks!

```
pip install flamedisx
```



- **Pierre Auger** experiment detect EAS **fluorescence** light
- In this case the signal (S) seen by the fluorescence detectors depends both on **geometrical acceptance** and **atmospheric conditions**





$R_0(E)$

$R_1(n_\gamma)$

$P(n_{\gamma FOV} | n_\gamma)$

$P(n_{\gamma Det} | n_{\gamma FOV})$

$P(S | n_{\gamma Det})$

Thank you for your attention

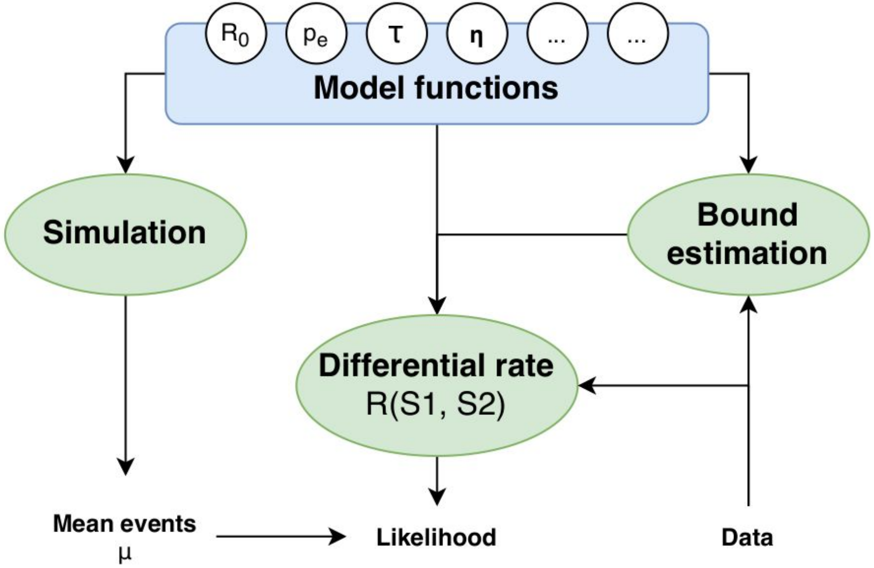
Implementation of LXe emission model

Parameter	**What is it?**	**Which block?**
Lindhard	Describes energy loss as heat for NR	Quanta generation
Q_y	Recombination probability	Quanta splitting
Δr	Recombination probability fluctuation	Quanta splitting
S1(x,y,z)	S1 relative light yield	Detect photons
Reconstruction efficiency	S1 reconstruction efficiency	Detect photons
Penning q	Penning quenching	Detect photons
g1	Average S1 size per detected photoelectron	Detect photons
DPE fraction	Probability of double photoelectron emission	Double photoelectron
SPE resolution	Single Photoelectron resolution	Make S1
Electron lifetime	Average time an electron survives in liquid xenon before getting absorbed by impurities	Detect electrons
Extraction efficiency	Fraction of ionizing electrons that get extracted into gaseous xenon at the liquid-gas interface	Detect electrons
Single electron gain	Average S2 size per detected ionizing electron	Make S2

Flamedisx fitting workflow

Recombination fluctuation model, DPE model, etc.

1 round of MC required to estimate mu

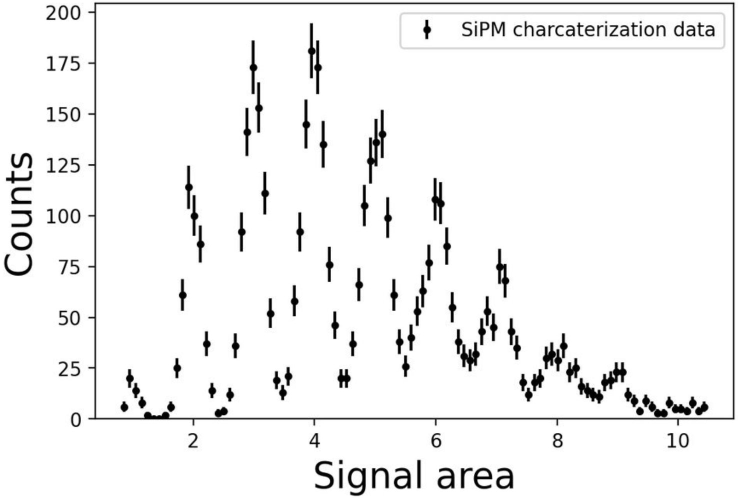


Number of electrons produced, photons produced, etc. to sum over

Maximise (log)likelihood to solve for rate multipliers (number of ER, NR, WIMPs, etc) and nuisance parameters (g1, SE gain, etc)

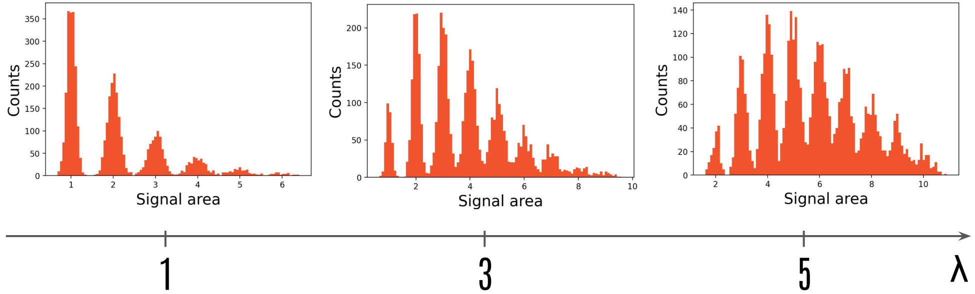
Two different analysis strategies

SiPM with no noise triggered by an external LED



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

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



- Probability density computation though **templates**

$$\begin{aligned} P(s) &= \sum_n P(s|n)P(n) \\ &= \sum_n \text{Gauss}(s-n, 0.1\sqrt{n})\text{Poisson}(n|\lambda) \end{aligned}$$

- Probability density computation though **explicit likelihood**

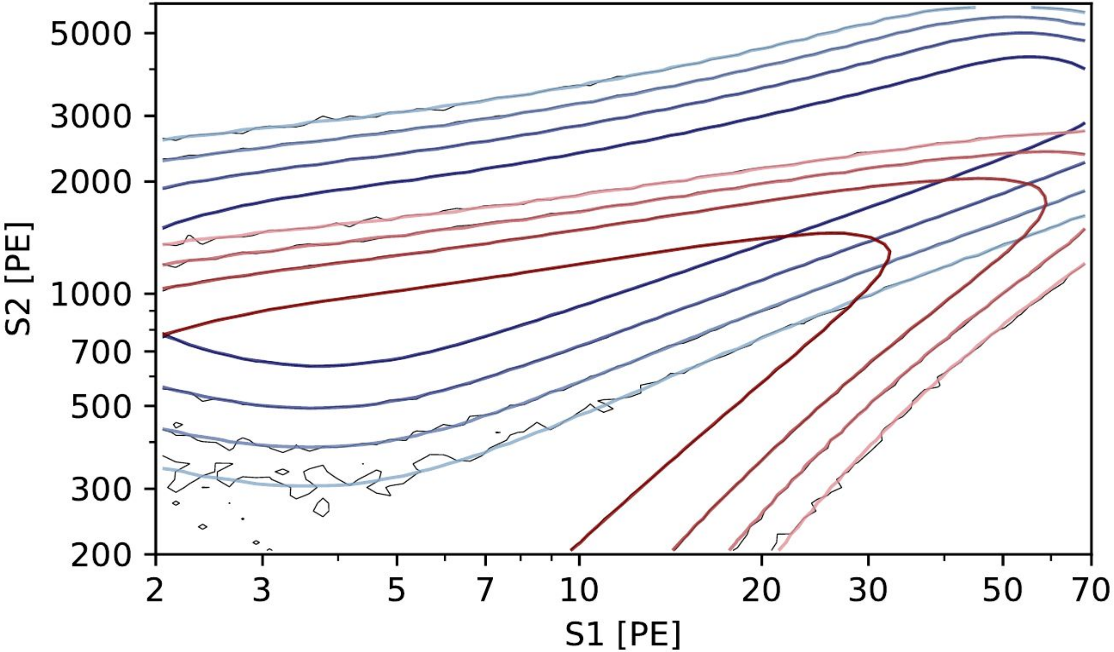
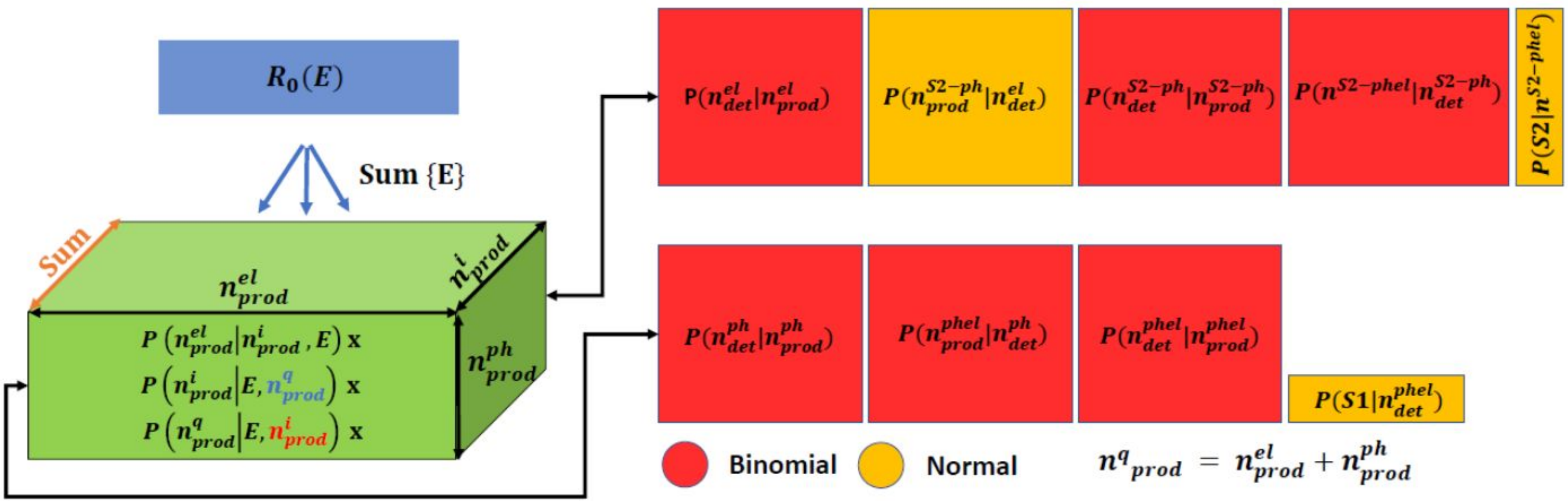


Figure 4. Contours in (S1, S2) enclosing, from bright to faint colors, 90%, 99%, 99.9%, and 99.99% of events with the highest differential rates, for a $0 - 10\,\mathrm{keV}$ flat ER source (blue) and a $30\,\mathrm{GeV/c^2}$ WIMP (red), at a single event position and time. The colored contours show the result from FLAMEDISX; thin black lines show the result from a template with 10^8 simulated events, described further in the text.

Implementation of LXe emission model in NEST fashion



Pre-Quanta

$R_0(E)$

Sum {E}

Sum

n^{el}_{prod}

n^{i}_{prod}

n^{ph}_{prod}

$P\left(n^{el}_{prod}|n^{i}_{prod}, E\right)$ x

$P\left(n^{i}_{prod}|E, n^{q}_{prod}\right)$ x

$P\left(n^{q}_{prod}|E, n^{i}_{prod}\right)$ x

Post-Quanta

$P(n^{el}_{det}|n^{el}_{prod})$

$P(n^{S2-ph}_{prod}|n^{el}_{det})$

$P(n^{S2-ph}_{det}|n^{S2-ph}_{prod})$

$P(n^{S2-phel}|n^{S2-ph}_{det})$

$P(S2|n^{S2-phel})$

$P(n^{ph}_{det}|n^{ph}_{prod})$

$P(n^{phel}_{prod}|n^{ph}_{det})$

$P(n^{phel}_{det}|n^{phel}_{prod})$

$P(S1|n^{phel}_{det})$

🔴 Binomial 🟡 Normal

$n^{q}{}_{prod} = n^{el}_{prod} + n^{ph}_{prod}$