WG1 “Science and Sensitivity”

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XLZD Collaboration Meeting, LNGS June 30 - July 2 2025

The WG1 was in pre-collaboration times charged with:

1. **Study main science drivers** for the phased approach defining sensitivity and discovery potential metrics, and how they are affected by **design and performance choices for detector**
2. **Develop and maintain MC code** including documentation, software infrastructure, interface with data tools

Our main design drivers are: standard WIMPs, 0νββ

Currently, the vast majority of WG1 personpower is working within the requirements taskforce on the top level detector requirements -> See following talks.

We have to design a detector that does what it should

But we should not neglect other channels and studies

Funding proposals, strategy processes, need up-to date sensitivity projections

Keep up with latest developments on ‘physics background’ (i.e. cosmic neutrino) rates and rate uncertainties

Keep up with theory developments/new models for signal and background

Speak the right language (MSSM out, portals in)

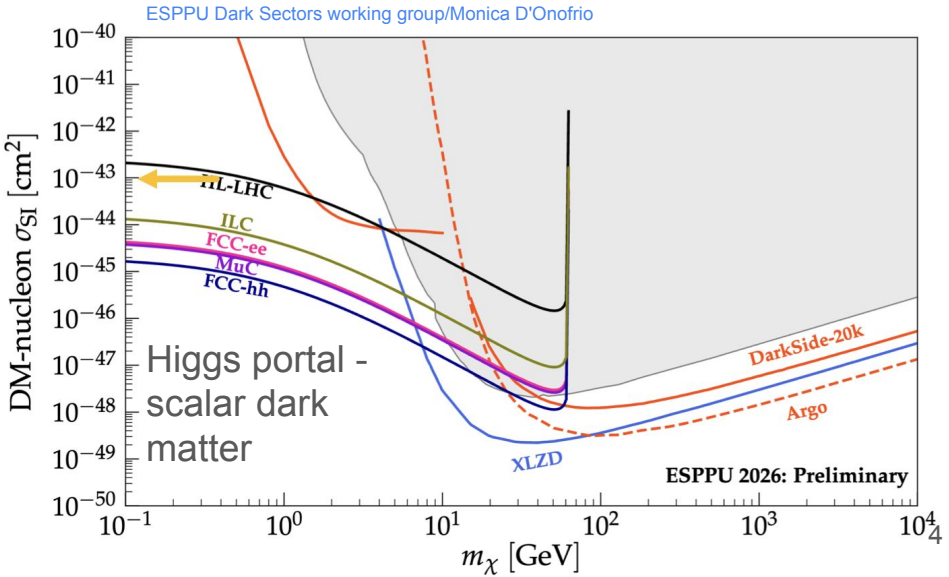
And convince the community that the effort is worth it

ESPPU (European Strategy for Particle Physics Update) science prep team requested further inputs (i.e. sensitivity curves)

"Non standard" EFT coupling operators (we usually use 'SI' and 'SD' couplings) that better compare to collider sensitivity projections.

Alternate DM models to cover all the portals (Higgs portal, vector portal (dark photons), axion portal/ALPs)

In general: We should make an effort to show complementarity between LXe TPCs and experiments at colliders.



Workflow: from model to sensitivity

Source models for signal and backgrounds

Recoil energy spectra

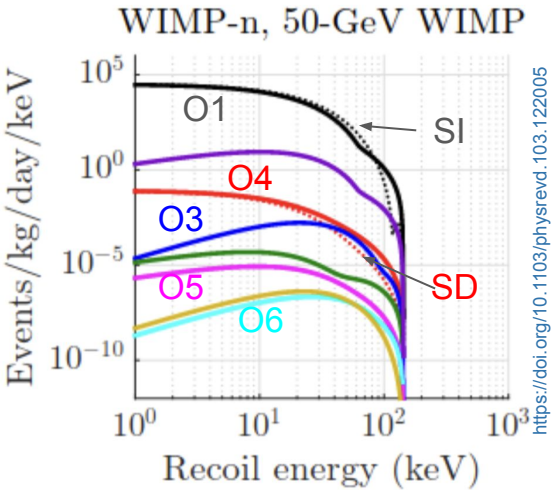
S1, S2, [x, y, z], t

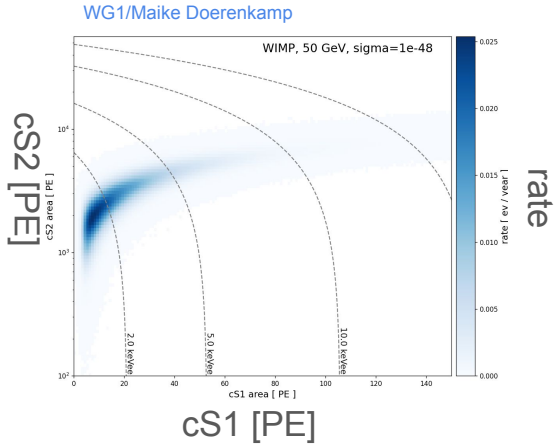
Sensitivity curves

Calculation or GEANT4

Calculation or NEST or full MC/GEANT4

Inference tools



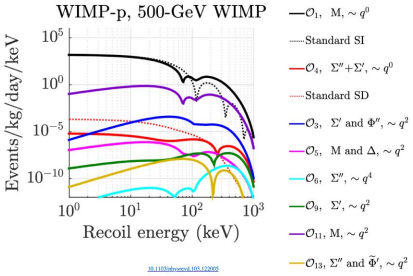


We **know how** to generate recoil spectra for all known particle sources that will or could interact in the detector.

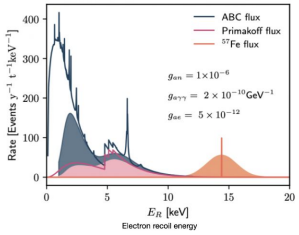
ER

NR

WIMPs



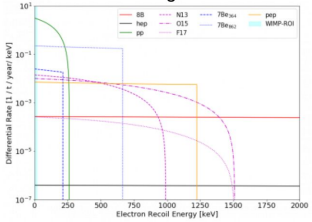
Axions



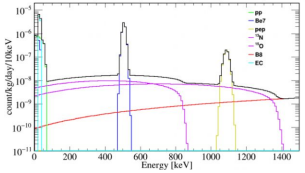
Neutrino cross section uncertainties!

Neutrinos

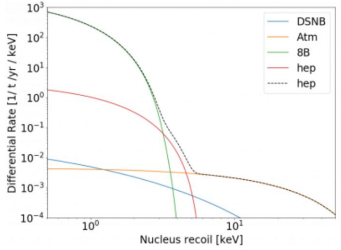
Electron scattering



Neutrino capture (energy of prompt electron)



CEvNS

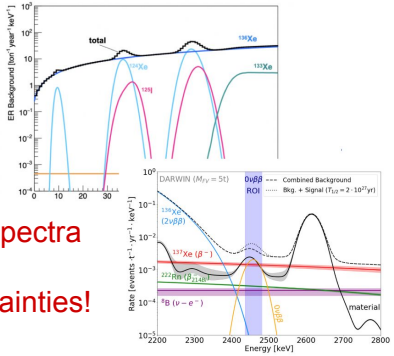


ER

NR

Electrons

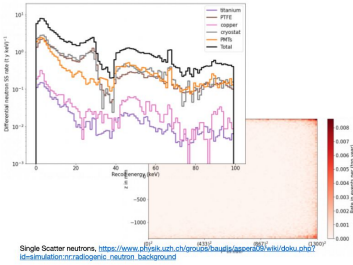
Xe isotopes



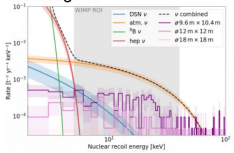
Beta spectra shape uncertainties!

Neutrons

Radiogenic

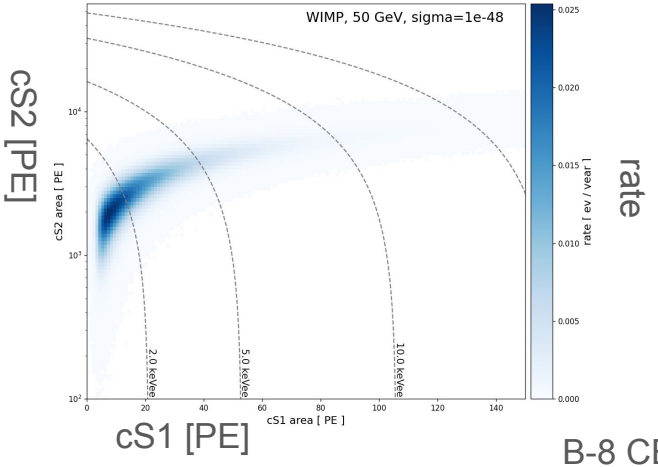


Cosmogenic



We **also know how to model detector response.**

50 GeV WIMP

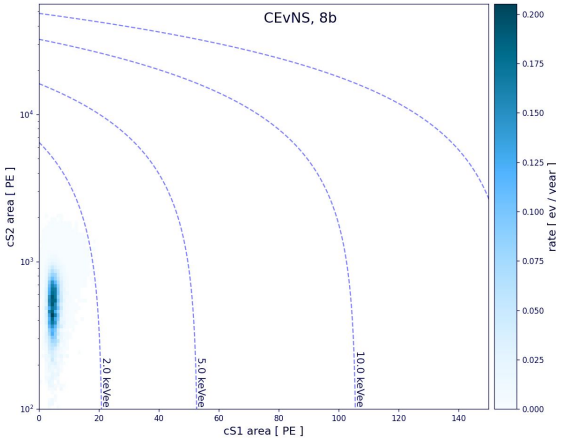


cS2 [PE]

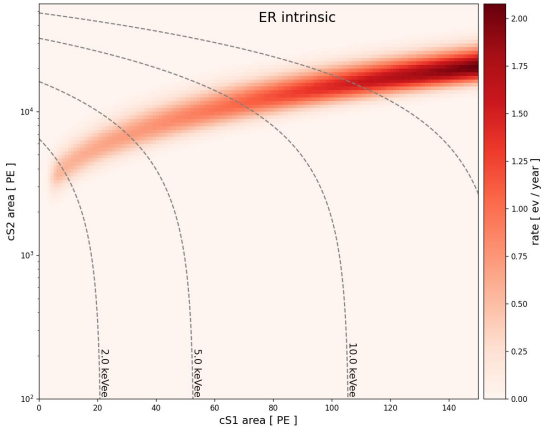
cS1 [PE]

rate

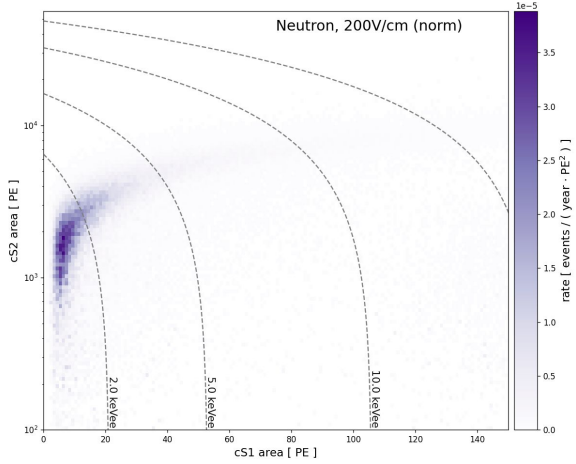
B-8 CEvNS



ER intrinsic



Neutrons



We **do not yet know how** to predict instrumental backgrounds - accidental coincidences, lone-S2's etc. and these are not currently included in any projections

-> More in talk on AC backgrounds tomorrow

We know how to do all the steps and have tools to do each step, but not in a consistent **framework** that allows efficient turn-around of studies with varying detector parameters.

See slide 2 of yesterday's contribution "Engineering framework"
Speaker: Joe O'Dell

- XLZD is **significantly bigger** than any previous dark matter detectors
- We are combining many hardware contributions from different institutes across many different countries (much **wider collaboration** than previous collaborations)

*Note: An Engineering framework is a **structured approach**, methodology, or set of principles that guide the **design, analysis, or development of mechanical systems and components**. It provides a systematic way to address engineering challenges, ensuring **consistency** and **efficiency**.*

-> The same goes for software

Software strategy - kitbashing existing code into a coherent framework optimized for detector design studies

Individual pieces of code that do one thing well but don't use the same conventions or architecture as the rest

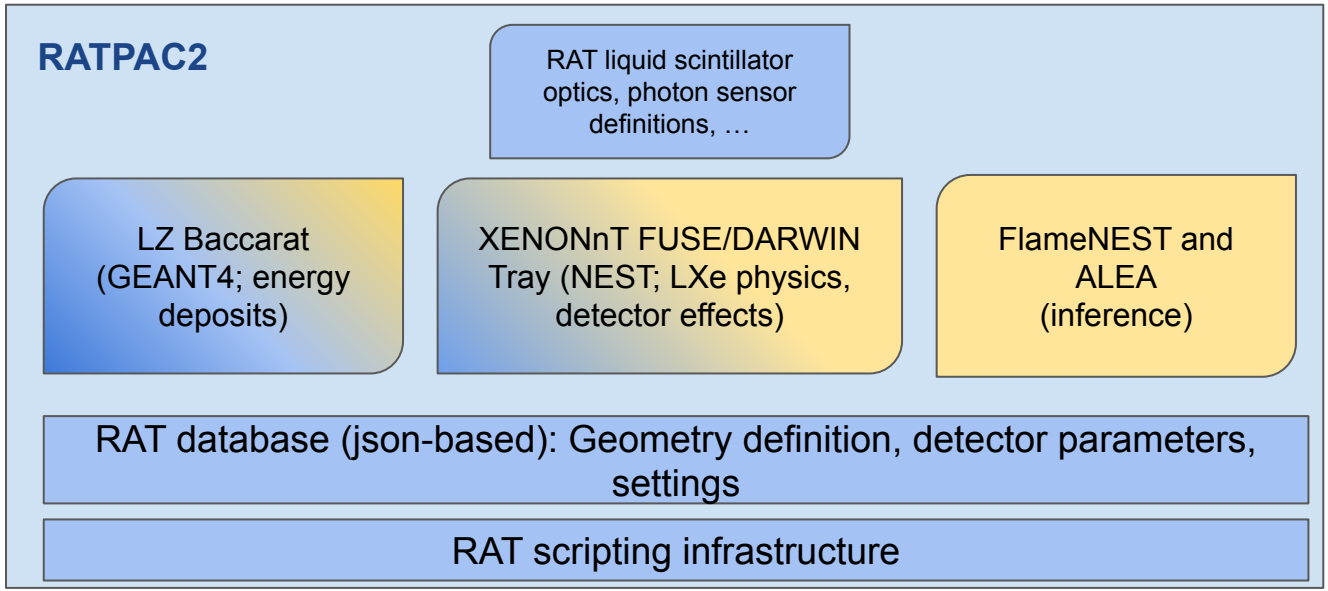
Code from running experiments optimized for one specific detector configuration; difficult to run for many different configurations

Tools rumored to exist, lost on old computers, abandoned git repositories, …

https://www.reddit.com/r/lego/comments/l09i7y/any_advice_for_finishing_this_halfassembled_and/

Software strategy - merging disparate software tools with existing framework optimized for fast turn-around with many different detector configurations: XLZD-RAT

XLZD-RAT will combine existing LZ, XENON and DARWIN Simulation packages with the geometry and settings management in RATPAC, and thus make them usable through a **common interface optimized for fast turn-around on detector design studies, above and beyond just sensitivity curves.**



Software taskforce within WG1

Add your name if you want to join!
https://docs.google.com/spreadsheets/d/1KIkHmpyhn27fF2D1gmYGp7jznP6z_0DbKoPBFP1SckY/edit?usp=sharing

Tasks	Main team	Senior advisors
XLZD TPC and OD Detector Geometry Simulation and Integration within RAT: TPC light collection efficiency, UK detector drawing (OD+TPC) integration into RAT	Theresa F	
	Sally S	
	Luke K	
	Owen	
	Lorentzo	
	Sam (Jinkoo) Kang	Kim
	Samantha C	Sally
	Sean	
	Steve	
	Sam W	
	Alberto	
	Ryan	
Detector physics, Signal Simulation and Integration within RAT (focus on TRAY and aspects of FUSE, e.g. DER response)	Antoine C	Jelle A
	Maike D	Kim Palladino/Nick
	Samantha C	Diego
	Qin	
	Andre S. (FUSE	
Inference tools (FLAMENEST) Integration within RAT		Jelle A
	Rob	Maike
	Lorentzo	
RATPAC2 management and integration, (Wb)LS properties and modeling, performance verification & detector design optimisation	Chris T, Gabriel & team	

Tops and Tips

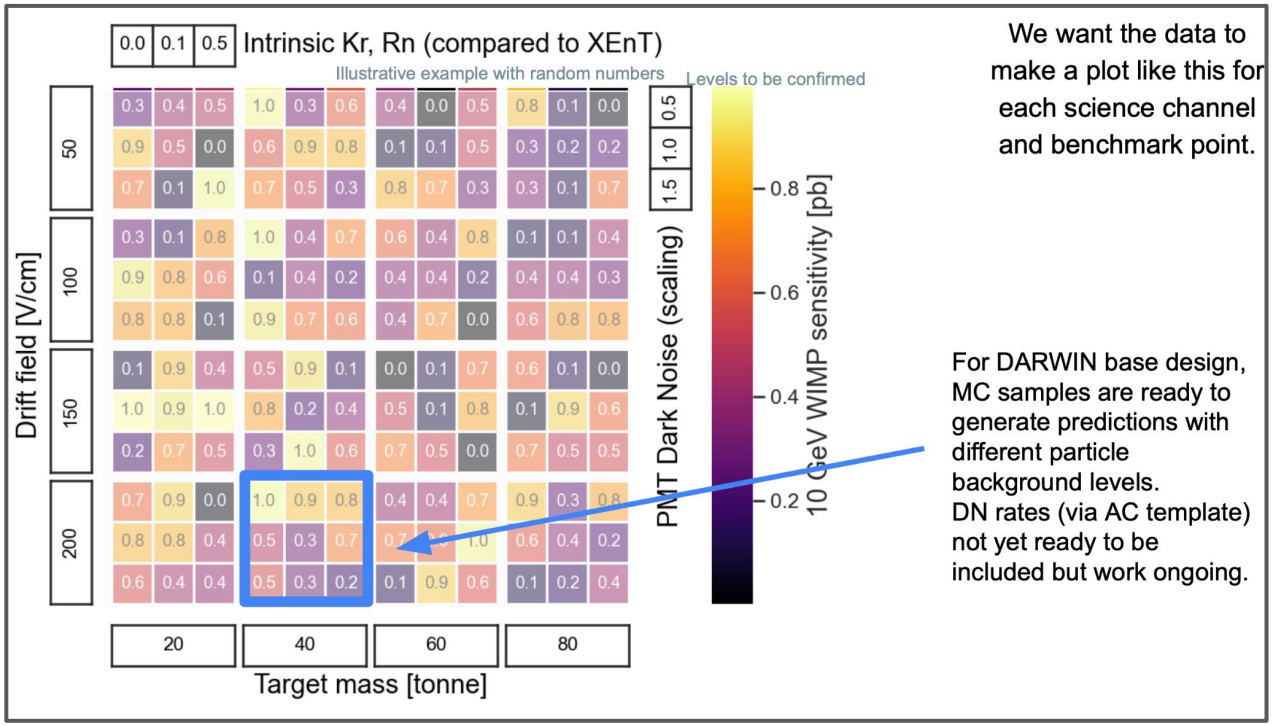
+ Common computing infrastructure at KIT! Computing project for general access tokens for all collaboration members.

- Access to a common GIT repo/access to software is not smooth/timely and blocks people from efficiently getting things done
- Need closer collaboration between different teams within XLZD
- Despite many names signed up for tasks, personpower is the limiting factor, with most people contributing a tiny amount of their time to XLZD/WG1.

And now for some actual science and sensitivity in the following talks …

.. with finally some actual results from the studies we started planning in 2022

Slide from “Science groups (ER, NR, 0vbb) work plan” discussed Nov 2022:



https://www.amazon.com/dp/B0CKTW4TTL?tag=bf-courtneylynch-20&ascsubtag=7884984%2C7%2C47%2Cd%2C0%2C0%2C0%2C1396%3A1%3B900%3A2%3B974%3A3%3B1338%3A1%2C63587335%2C0%2C0%2Cgoogle&btn_ref=srctok-ae07577f61ac6933&th=1

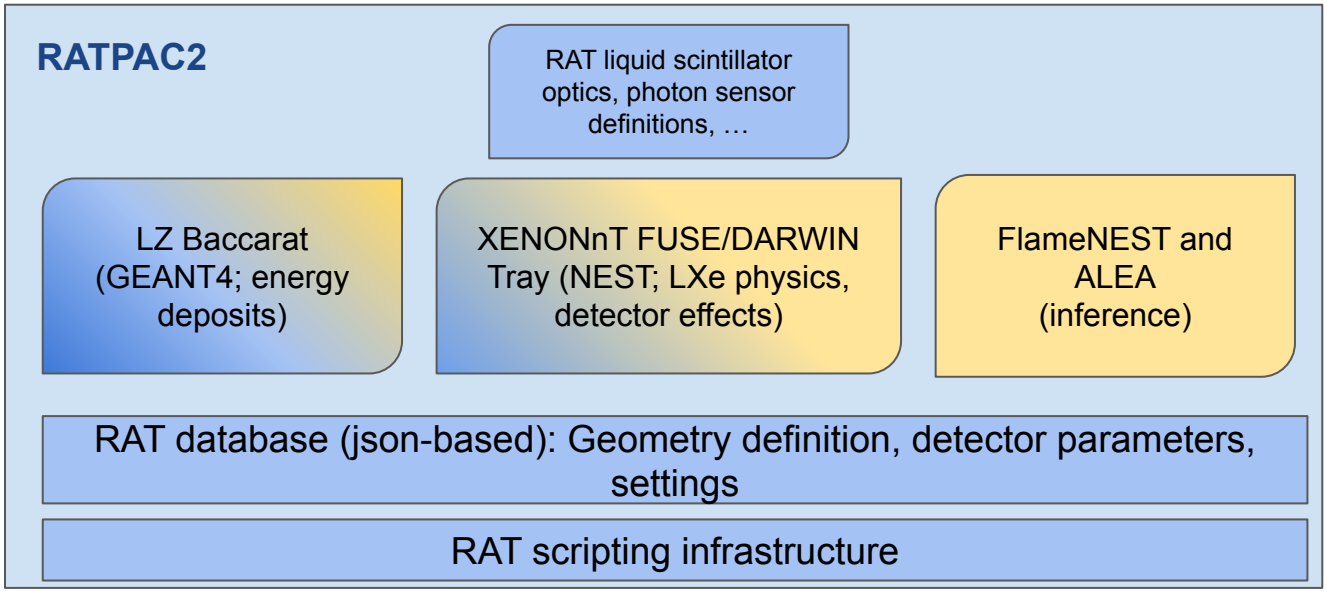
Backup

Software strategy - merging disparate software tools with existing tool optimized for fast turn-around with many different detector configurations: XLZD-RAT

Reuse as much existing code and expertise as possible

Keep all code in a common format, with common inputs and outputs to avoid duplication of work, and to make sure each part of the chain reads the very same detector configuration.

Enable multiple types of simulation studies from the same base framework; generate waveforms if you want, or skip detector physics altogether and just run inference with calculated PDFs.



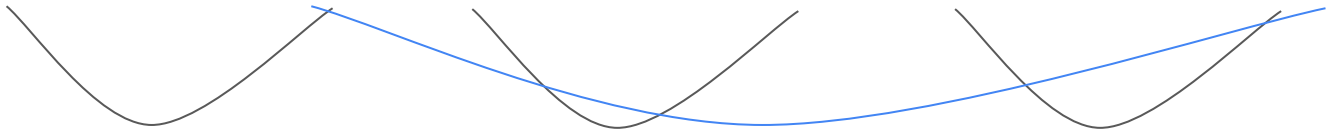
Workflow: from model to sensitivity, current status

Source models for signal and backgrounds

Recoil energy spectra

S1, S2, [x, y, z], t

Sensitivity curves



Calculation or Geant4

BACCARAT

DARWIN-G4

Calculation or NEST or full MC/Geant4

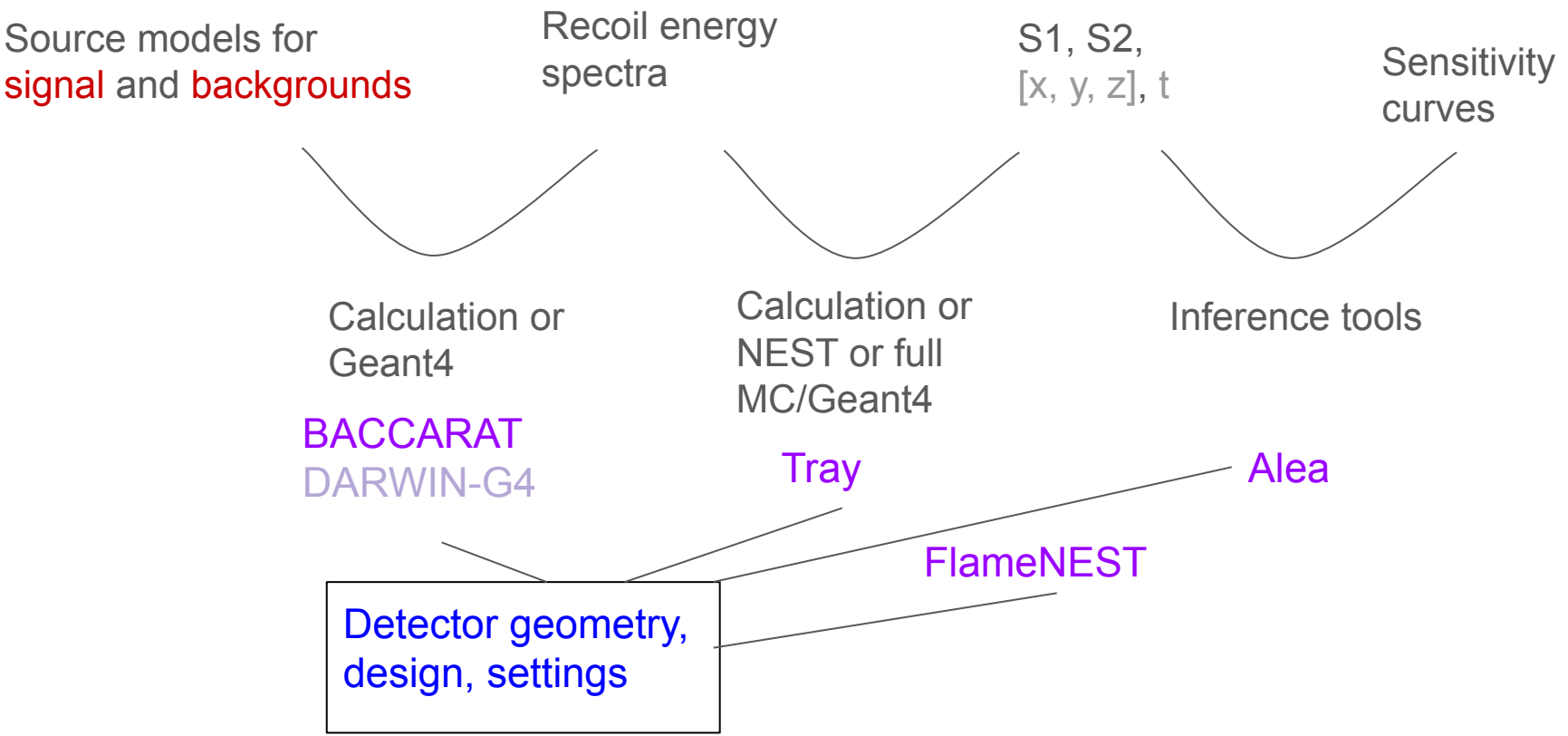
Tray

FlameNEST

Inference tools

Alea

Workflow: from model to sensitivity, current status



The need for an updated software paradigm

The current paradigm was meant as an interim solution for XLZD, to be overhauled asap.

Worst case: ~ 7 background PDFs and ~3 signal PDFs have to be generated per detector design choice, using consistent inputs. Several in-between results (effective detector parameters) have to be matched to support workflows that don’t do full MC - LCE maps/g1, g2, ER/NR separation, …)

We have no chance of keeping results consistent and reproducible if we work in separate, organically arising codebases.

We should use solutions based on lessons learned from previous experiments of XLZD size and scope (and wider than just XENON and LZ experience), where appropriate.

Workflow: from model to sensitivity - future

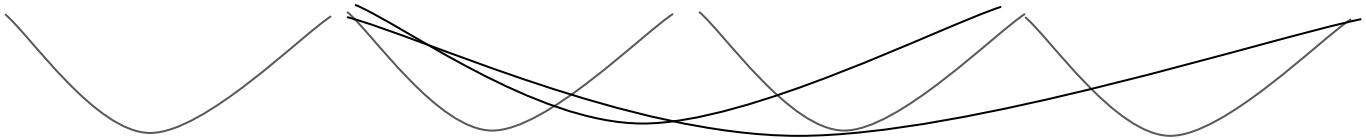
Source models for signal and backgrounds

Recoil energy spectra

PMT waveforms

S1, S2, [x, y, z], t

Sensitivity curves



Integrated software framework

- Physics models
- Geant4
- NEST
- Digital signal processing
- Non-particle background model
- Inference

- Geometry files
- Database
- Run environment/scripting - ‘recipe’ or ‘makefile’ for generating a specific curve