Advanced modeling tools for 10 TeV wakefield colliders

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Accelerator Technology & Applied Physics Division

EAAC2025

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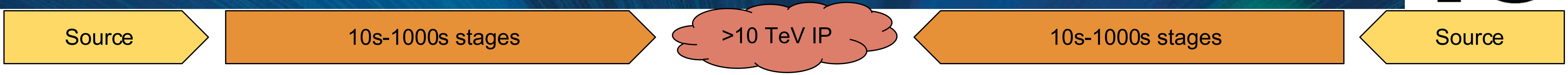
La Biodola Bay, Isola d'Elba, Italy

BERKELEY LAB
ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline



- **Collider design studies**
  - The *10 TeV Design Initiative* for a 10 TeV pCM wakefiled collider
    - The Simulations/Computing/AI Working (SCAI) Group
- **The Collaboration for Advanced Modeling of Particle Accelerators (CAMPA)**
  - Standardized data & tools: openPMD, PICMI, LASY, PALS, GeSt-api
- **Toward multi-modal AI-ready data sources & models**
- **Summary**

Ongoing high-gradient wakefield collider studies

ALEGRO
Advanced LinEar collider study GROup

Collider Design Studies - Challenges

HALHF (Since 2023)	ALiVE (Since 2024)	10 TeV (Since 2025)
HALHF **H**ybrid, **A**symmetric, **L**inear **H**iggs **F**actory	**ALiVE** **A Lin**ear accelerator for **V**ery high **E**nergies	**10 TeV** Design Initiative for a **10 TeV** pCM Wakefield Collider
Challenges: High repetition rate plasma operation and cooling, Staging, Production and acceleration of polarized beams, BDS design,… **10-15 years of R&D**	**Challenges:** High power synchrotron, Proton Bunch Compression, Plasma Source Development, Positron Acceleration, Energy Transfer Efficiency, Beam Quality Preservation,…	**Chosen design constraints:** • $E_{z,avg}$ > 500 MeV/m • $\mathcal{L}/P_{tot}$ > 10^{32} $cm^{-2}s^{-1}$ MW^{-1}
ESPP Input #57: HALHF: a hybrid, asymmetric, linear Higgs factory using plasma- and RF-based acceleration (link)	**ESPP Input #210: Proton-Driven Plasma Wakefield Acceleration for Future HEP Colliders (link)**	**ESPP Input #98: Design Initiative for a 10 TeV pCM Wakefield Collider (link)**

European Strategy for Particle Physics

23.06.2025 High-Gradient Wakefield Accelerators, ESPP Symposium Venice 2025 9 / 15

10 TeV Wakefield Collider Design Study

The Design Study aims to produce a unified, self-consistent concept for a 10 TeV parton-center-of-mass (pCM) collider based on wakefield accelerator (WFA) technology.

The Study is Initiated by the 2023 US P5 Report, but it is a **global** undertaking.

- We collaborate with on-going design efforts, including ALEGRO, HALHF, ALIVE, and XCC and contribute to the LC Vision program.

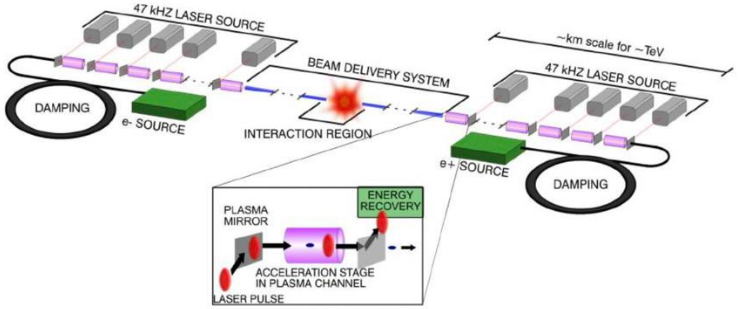
This is an HEP-wide **community** effort. The study requires input from:

- HEP Theorists
- Detector Physicists
- Accelerator Physicists
- Advanced Accelerator Research

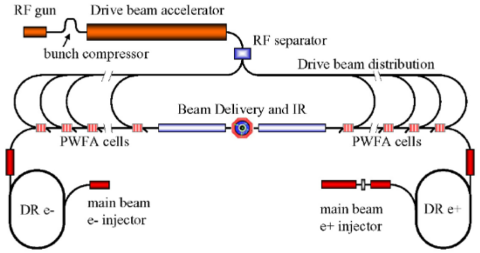
Working Groups: includes “Simulations/Computing/AI” (SCAI)

Several options:

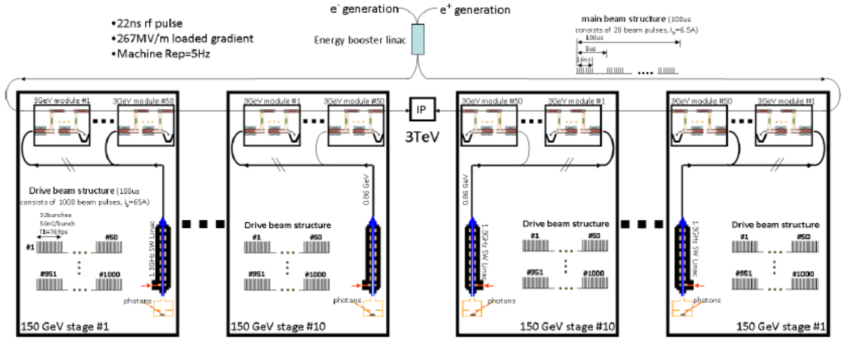
LWFA



PWFA



SWFA



- System integration and optimization
- Beam sources (incl. damping rings)
- Drivers
  - Laser
  - Beams - SWFA
  - Beams - PWFA
- Linacs
  - LWFA
  - SWFA
  - PWFA
- Beam delivery system
- Beam-beam interactions
- Beam diagnostics
- Machine-detector interface
- HEP detector
- HEP physics case
- Environmental impact
- **Simulations/computing/AI**

This talk

Green = Broader accelerator community
Orange/blue/purple = AAC specific
Red = HEP and broader community

Most of the design work requires simulations!

➔ We are limited by what we can compute…

…the SCAI is the limit!

(adapted from) R. lehe & M. Thevenet, Kick-off meeting for the simulation WG for a 10TeV wakefield-based collider, July 25, 2024

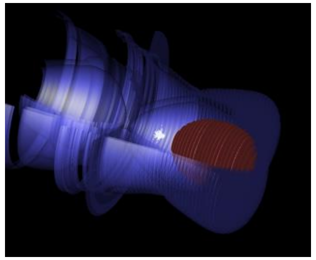
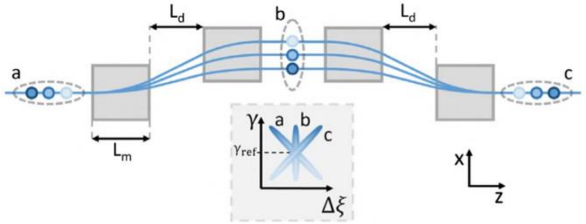
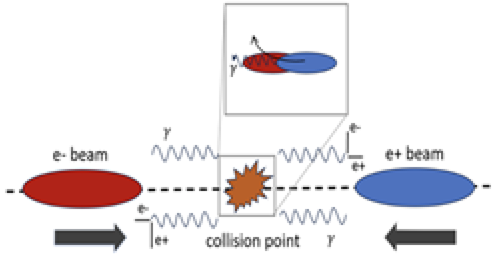
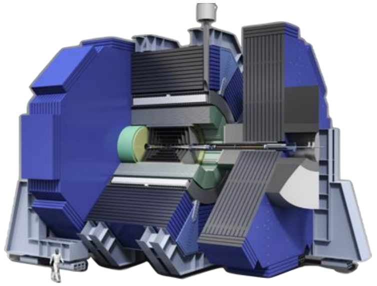
Next Steps

- Pre-CDR's are critical
  - Simulation tools are fantastic … use them
  - Quantify stability and tolerances
  - Detail the R&D and necessary steps
  - What test facilities are needed and be clear about purpose and goals

Simulations are key to address many AAC-based collider challenges

- Demonstrate capabilities with applications
  - FEL's are excellent but injectors and other applications are also great
- Engage the community
  - Convey the enthusiasm but don't oversell

Simulation tools cover a wide range of codes

Accelerator stages	Beam dynamics/transport	Interaction point	(Detectors)
			
E.g., QPAD, HiPACE++, Inf&rno, QuickPIC, Wake-T, LCODE, TurboWAVE, FBPIC, WarpX, OSIRIS, Smilei, VLPL, Epoch, …	E.g., ImpactX, Elegant, XSuite, BMAD, Wake-T, …	E.g., Guinea-Pig, CAIN, WarpX, Osiris, VLPL …	E.g., DDSim, DD4HEP, …

+ "Systems code" for design, optimization & costs (e.g., ABEL)

Axel Huebl, "Modelization of Plasma Accelerators in the Exascale Era", EAAC25, Thursday @11:30AM

Needs

- More codes: **not really**
- Better codes & algorithms; more physics; benchmarking: **always!**
- More & better documentation; examples: **definitely!**
- More integration & interoperability; workflows: **definitely!**

(adapted from) R. lehe & M. Thevenet, Kick-off meeting for the simulation WG for a 10TeV wakefield-based collider, July 25, 2024

SCAI WG can leverage & help coordinate efforts

- New website with samples input scripts for various codes
- Coordination with, e.g.:
  - Codes developers to provide examples, participate to benchmarking, add physics, …
  - CAMPA: openPMD, PICMI, LASY, PALS, GeSt_api
  - HElmholtz Laser Plasma Metadata Initiative (HELPMI)
  - HALHF: ABEL
  - ALiVE
  - …
- Coordinate simulation efforts to address 10TeV collider questions/challenges

SCAI WG Website is being developed

Simulation Guide

latest

Search docs

CONTENTS:

/ Simulation Guide for the 10 TeV Wakefield Collider Design Study — View page source

Simulation Guide for the 10 TeV Wakefield Collider Design Study

This documentation provides material to get started with simulation work for the 10 TeV Wakefield Collider Design Study.

It summarizes the capabilities of some of the relevant codes for these simulations and provides a few examples of how to use them.

Contents:

If you encounter any issues with this documentation, please report them on our GitHub Issues page.

https://10tev-simulation-guide.readthedocs.io

Next

/ Example Simulation Scripts / Single-stage simulations — View page source

Single-stage simulations

This section contains example scripts for single-stage simulations.

- Single-stage laser-driven acceleration in cylindrical geometry (using Wake-T)
- Single-stage laser-driven acceleration in full 3D (using HiPACE++)
- Single-stage beam-driven acceleration in quasi-3D cylindrical geometry (using QPAD)

Previous — Next

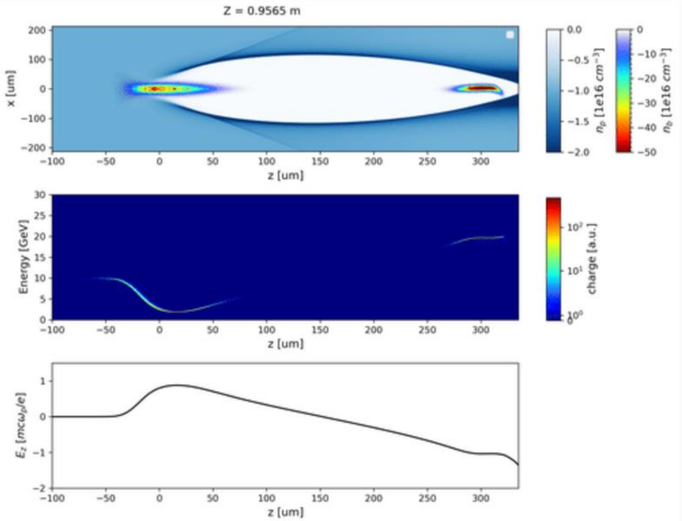
Warning

Make sure to modify the path to your qpad executable in the above script.

```
path_to_exe = ''   # <---- specify path to executable here
```

Visualization and postprocessing

Here's a gif showing the output of this simulation.



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Simulation Guide

latest

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CONTENTS:

Example Simulation Scripts / Beam-beam simulations at the interaction point

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Beam-beam simulations at the interaction point

This section contains example scripts for simulations of beam-beam crossing at the interaction point using WarpX and Guinea-Pig. As an arbitrary choice, we selected the C^3 collider parameters at 125 GeV.

Overview

This simulates the collision between a beam of electrons and a beam of positrons traveling at 125 GeV. As usual, x, y, z are the horizontal, vertical, and longitudinal coordinates, respectively. The beams are initialized such that their centroids are $4\sigma_z$ away from interaction point.

Beamstrahlung and coherent pair production (though not actually important for these beam parameters) are activated. Note that incoherent processes are not enabled in either WarpX and Guinea-Pig. We will add them in future versions of this example.

WarpX

Resources

Some useful WarpX's links if you get stuck or want to know more:

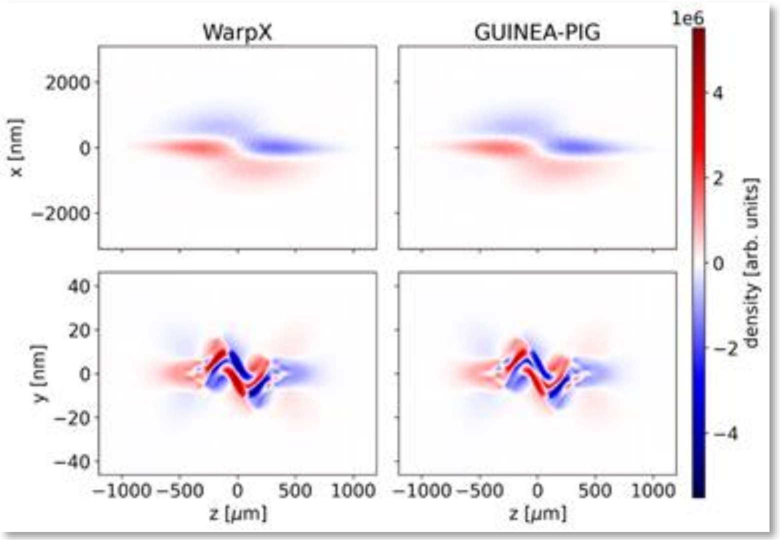
- GitHub repository
- ReadTheDocs documentation
- Beam-beam tutorial

Build

WarpX is open-source and available on GitHub. You can install WarpX in several different ways (for

Generate a video of the colliding beams

```
!mkdir -p "plots"

gp_dir = "gp"
wx_dir = "wx"

path=os.path.join(wx_dir, 'diags/trajs')
series = OpenPMDTimeSeries(path)

v0 = n0 * np.sqrt(sigmax * sigmay) * 0.05
extent_zx = [gridz[0]/micro, gridz[-1]/micro, gridx[0]/nano, gridx[-1]/nano]
extent_zy = [gridz[0]/micro, gridz[-1]/micro, gridy[0]/nano, gridy[-1]/nano]

plt.rcParams.update({'font.size': 16})

# loop through the timesteps
for n in iterations:

    # prepare canvas
    fig, ax = plt.subplots(ncols=2, nrows=2, figsize=(16,12), dpi=300, sharex='col', share

    H_zx, H_zy = one_step_gp(n, gp_dir)
    im=ax[0][0].imshow(H_zx, extent=extent_zx, cmap='seismic', origin='lower', interpolati
    im=ax[1][0].imshow(H_zy, extent=extent_zy, cmap='seismic', origin='lower', interpolati
    ax[0][0].set_title("Guinea-Pig")
```



Collaboration for Advanced Modeling of Particle Accelerators

Fermilab SLAC NATIONAL ACCELERATOR LABORATORY
CAMPA
BERKELEY LAB UCLA
Argonne NATIONAL LABORATORY OAK RIDGE National Laboratory

Team (lead) BERKELEY LAB

PIC algorithms & WarpX Code, Plasma Modeling

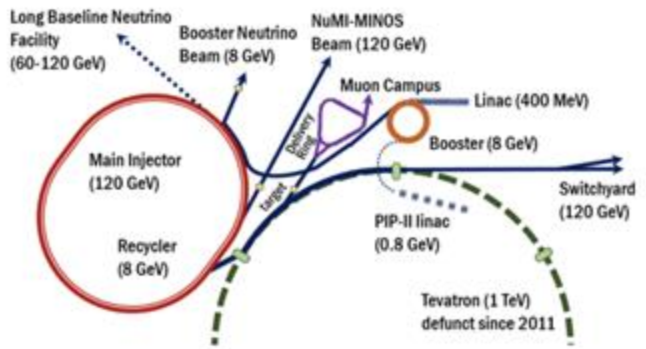
AMReX, Solvers

Conventional/Plasma Accelerator Modeling

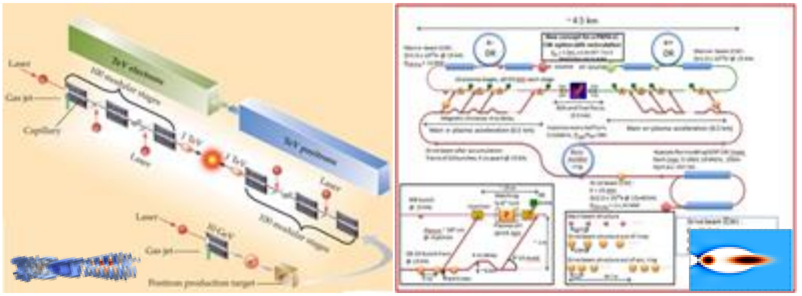
AI/ML, Optimization Data I/Os

Science thrusts (aligned w/ 2023 P5)

a) Fermilab complex: PIP-II+booster.



b) **design of plasma-based colliders.**



2023 P5

- Modeling tools for **beam intensity, quality, control** and **prediction Grand Challenges**
- Support **Fermilab complex (PIP-II, IOTA, …)**
- Support R&D & designs of **Higgs factory & 10 TeV CoM colliders (RF, plasma or muons)**
- Support key cyberinfrastructure components such as **shared tools & a sustained R&D effort in computing**…
- **Adapt** software & computing systems to **emerging hardware**
- **Leverage AI/AML** for accelerator modeling & collider design
- Foster development of **standards & workflows**

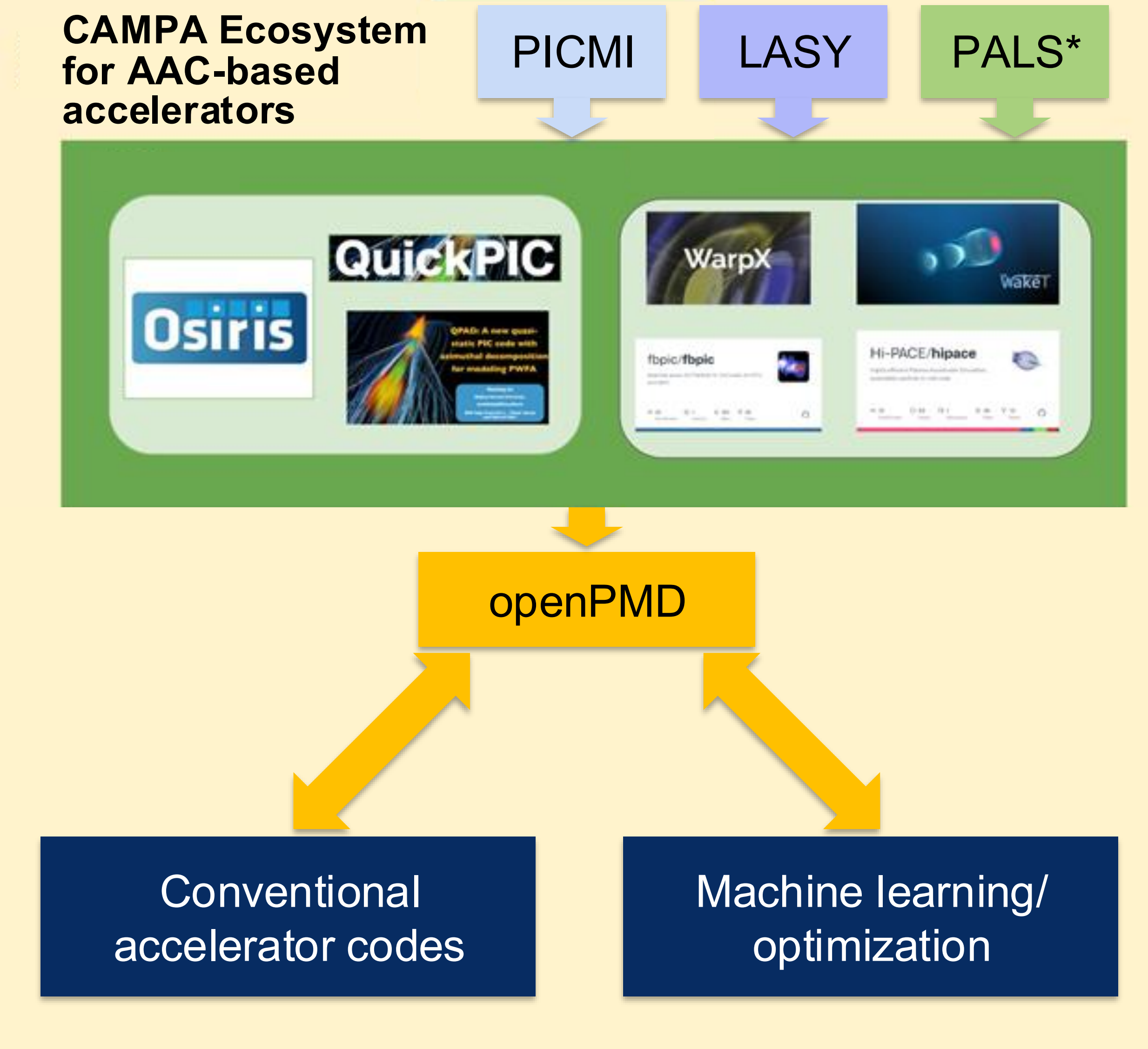
Particle-in-cell Modeling Interface (PICMI) & open Particle-Mesh Data (openPMD) standards

Conventions for input and output (I/O)

- **Particle-in-Cell Modeling Interface (PICMI) standard** for naming and structuring of Particle-In-Cell input decks in Python.
- **open particle-mesh data standard (openPMD)** for metadata and naming conventions of scattered (e.g., particles) and mesh-based (structured & unstructured) data, with support for ADIOS & HDF5 data format (other data formats possible).

Status

- openPMD is quite **mature and supported by many codes** within & beyond CAMPA
- PICMI is **being developed and supported by multiple codes** within CAMPA

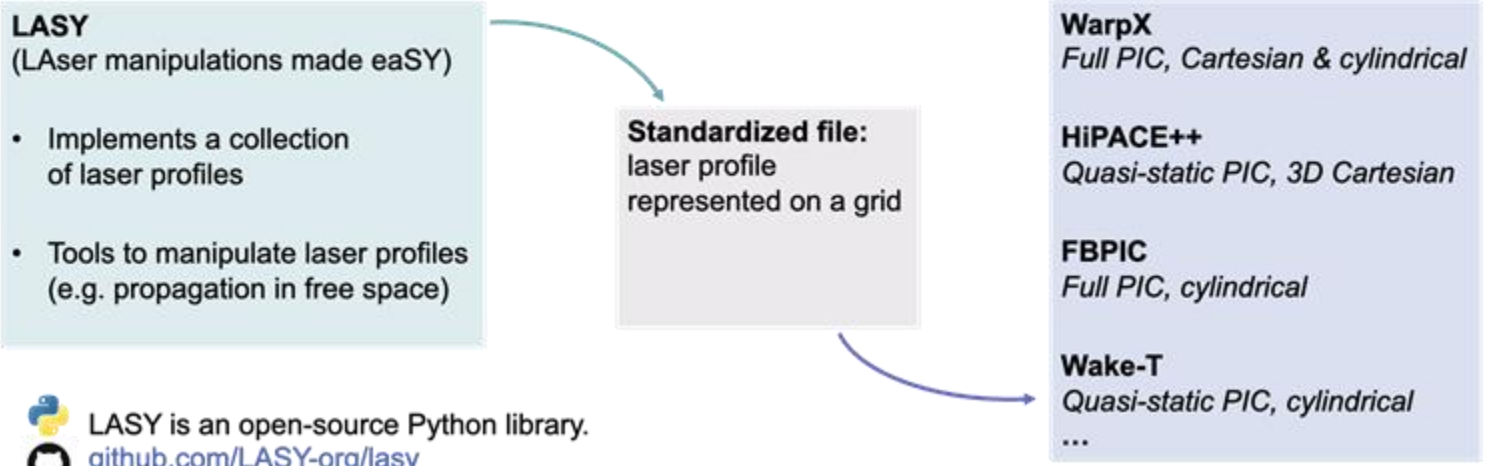


*in development

LASY: LAser manipulations made eaSY

- simple Python implementation allows **rapid addition of new laser profiles**
- w/ **advanced laser manipulation tools**, including calculation of propagation through complex optical elements
- leveraged by several projects requiring modeling of **sophisticated and/or experimentally realistic laser pulses**

All the codes listed below can read files produced by LASY



LASY is an open-source Python library.
github.com/LASY-org/lasy

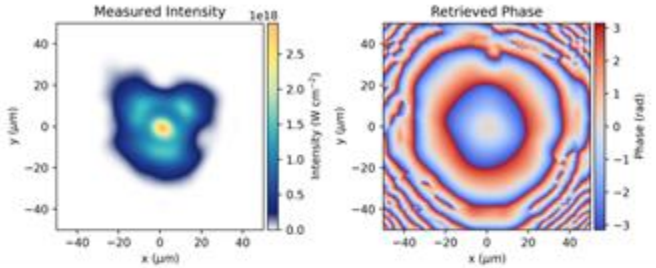
current contributors DESY. BERKELEY LAB loa cea

Rob Shalloo, "LASY: LAsers manipulations made eaSY", EAAC25, Today @19:00.

LASY supports many types of laser profiles, including:

Profile with orbital angular momentum

Profile defined by experimental measurements



[1]M. Thévenet, et al, "LASY: LAser manipulations made eaSY", Proc. EAAC 2023 https://arxiv.org/abs/2403.12191.

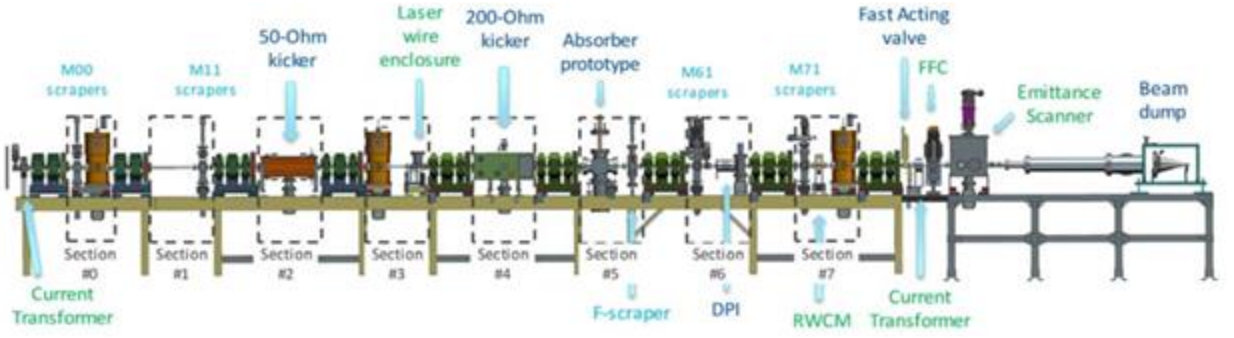
New, open Particle Accelerator Lattice Standard (PALS)

- Accelerator community currently uses different file formats for the **accelerator lattice description**
- PALS[1] is a standard for **sharing lattice description** across simulation codes, experiments, etc
- **Facilitates global collaboration** on increasingly complex accelerator projects
- Enables creation of **standardized datasets for AI/ML training**

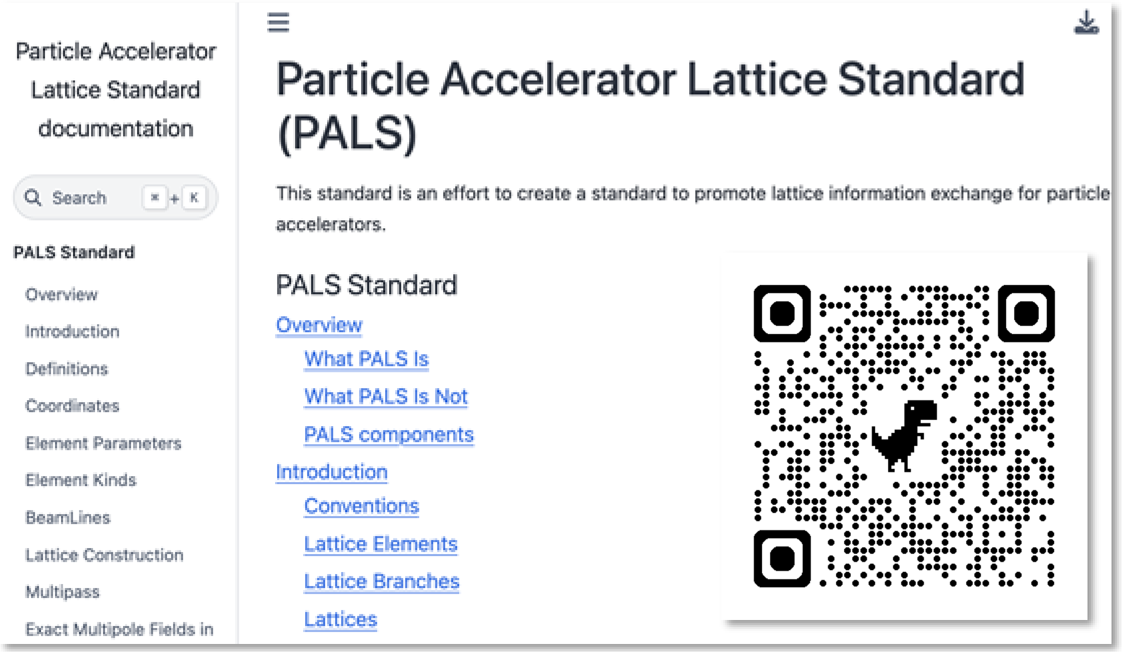
  ➔ Key to initiatives such as the upcoming **“American Science Cloud”**

- Weekly meetings w/ partakers from LBNL, Cornell U., ANL, FNAL, SLAC, BNL, ORNL, JLAB, MSU, MIT, Radiasoft, Xelera Research, CERN, GSI, DESY, ESRF, …

Join the fun! david.sagan@cornell.edu, jlvay@lbl.gov



github.com/campa-consortium/pals

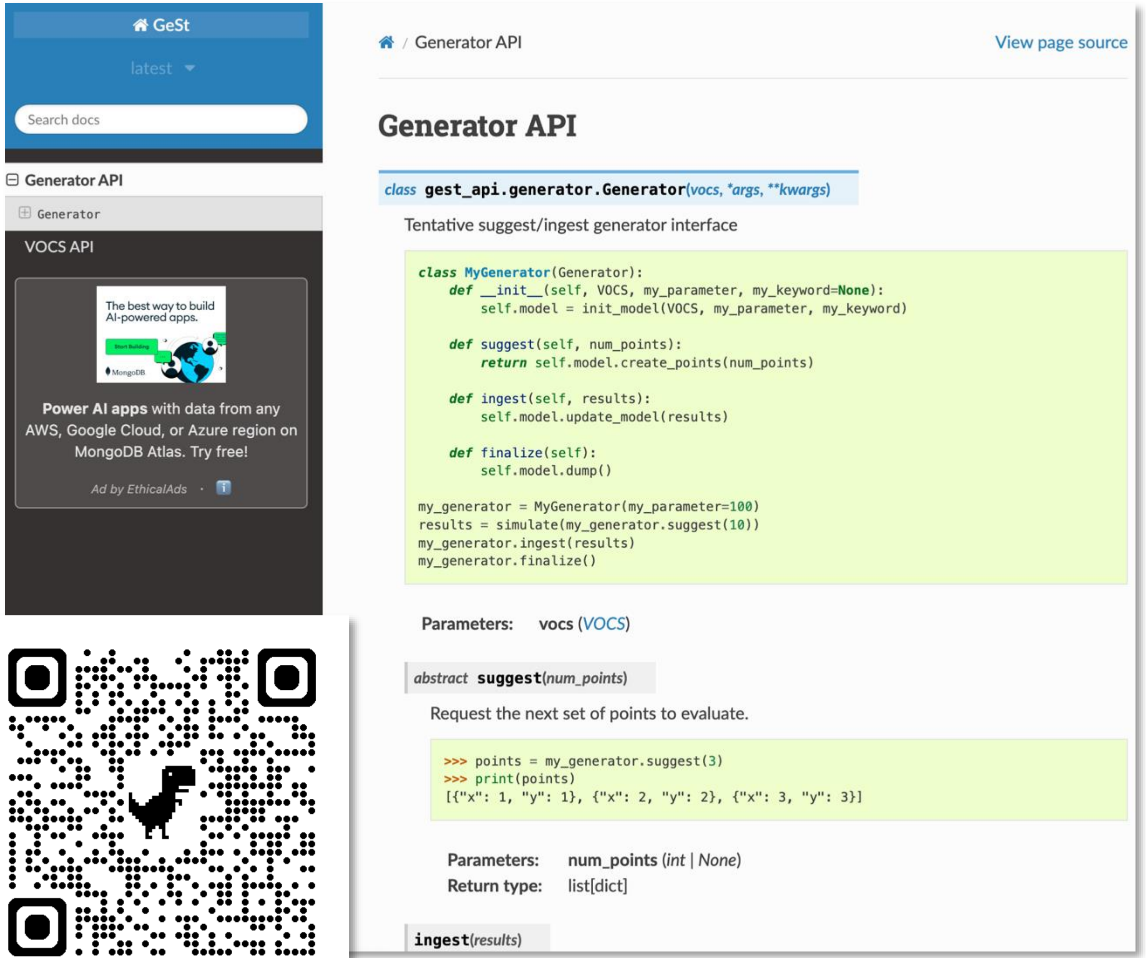


[1]Mitchell et al, "A Community Effort Toward a Particle Accelerator Lattice Standard (PALS)," in Proc. NAPAC2025, TUP004, Sacramento, CA, 2025.

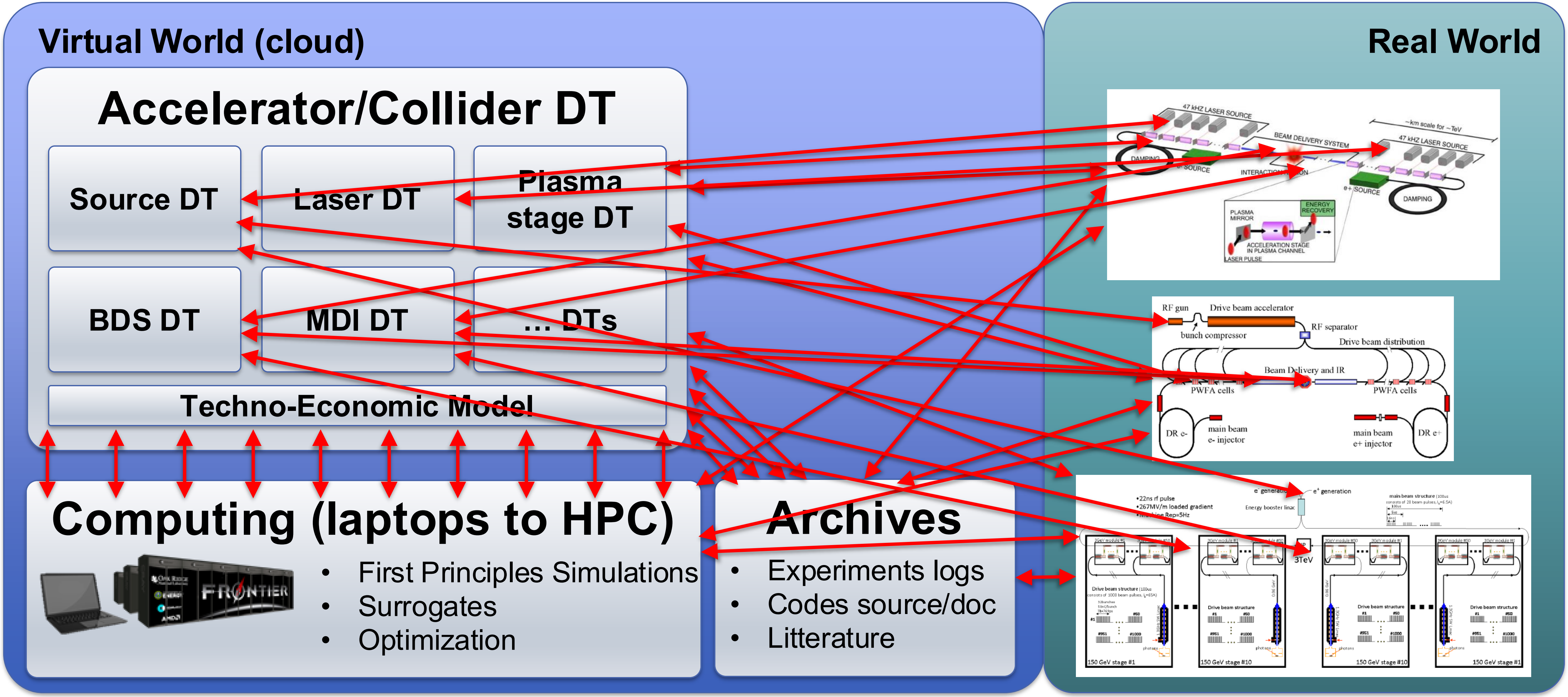
Generator Standard (GeSt-api) for optimization studies

- **Simulation-based design optimization** is an important workflow when designing accelerators
- Efficient optimizers (e.g., TurBO, APOSMM, etc.) have been implemented in **separate** optimization frameworks (e.g., Xopt, libensemble, optimas, …) and have **different** interfaces
- A **standardized interface** is now being implemented in the above frameworks to foster **interoperability**

github.com/campa-consortium/generator_standard



Coordination & standardization will enable multi-modal (incl. multiple facilities) AI-ready data sources & models



Coordination & standardization will enable multi-modal (incl. multiple facilities) AI-ready data sources & models

Virtual World (cloud)

Accelerator/Collider DT

Source DT	Laser DT	Plasma stage DT
BDS DT	MDI DT	… DTs

Techno-Economic Model

Data

AI Readiness
- Standardization
- Labeling
- Normalization
- Versioning

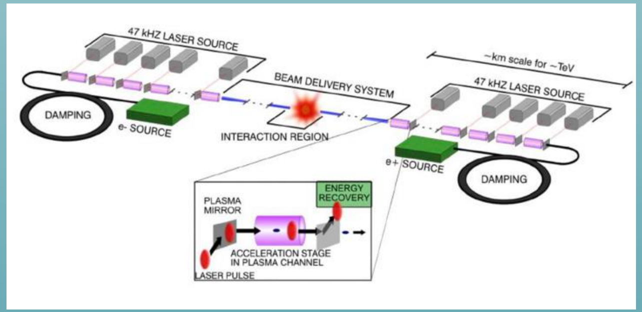
Computing (laptops to HPC)

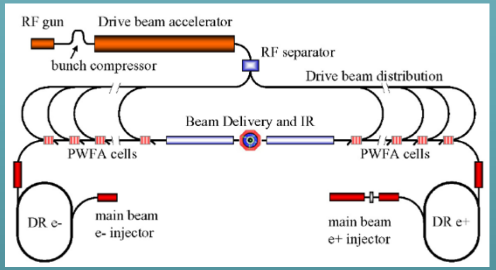
- First Principles Simulations
- Surrogates
- Optimization

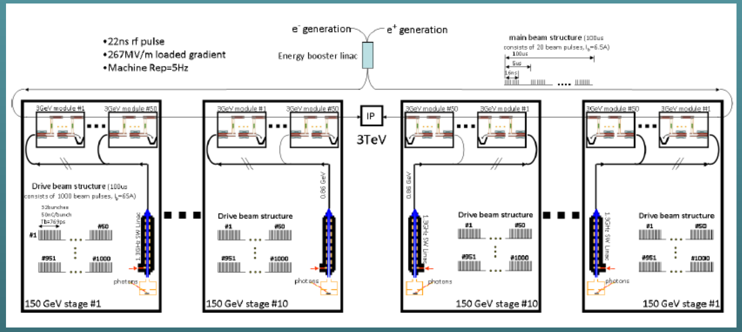
Archives

- Experiments logs
- Codes source/doc
- Litterature

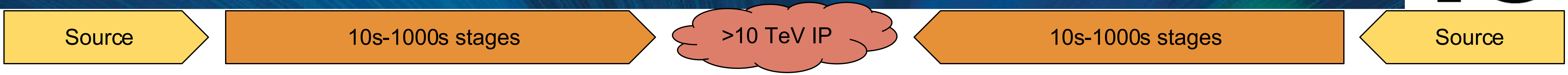
Real World







Summary



- **Collider design studies** based on AAC tech are ongoing
- ***10 TeV Design Initiative*** includes a Simulations/Computing/AI Working (SCAI) Group
- **Many simulation tools** exist and continue to be improved
  - ➔ see **A. Huebl plenary talk** tomorrow
- Increasing efforts to develop standardized data and tools
  - ➔ From ***nice to have*** to ***must have*** for multi-modal AI-ready data sources/models
- All these require a **community effort**: look for community workshops to come to organize the community and develop these standardized data & tools

Let's avoid to develop N new standards & workflows!

Looking forward to work with all of you!

Thank you!

Questions?

jlvay@lbl.gov