Status of GERDA, LEGEND and BAT

Oliver Schulz

MAX-PLANCK-GESELLSCHAFT

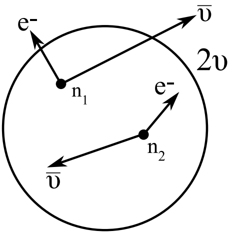
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

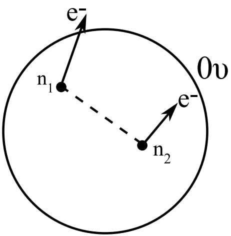
oschulz@mpp.mpg.de

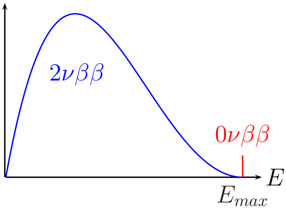
MPP Project Review, December 14, 2020

$0\nu\beta\beta$ Decay, very short recap

- Single β decay not allowed for some isotopes, only double β decay
- Also $0\nu\beta\beta$ decay, due to Majorana-ν ($\nu = \bar{\nu}$)?







$$\left(T_{1/2}^{0\nu}\right)^{-1} = G(Q,Z)\,|M_{\mathrm{nucl}}|^2\,\langle m_{ee}\rangle^2$$

- Discovery of $0\nu\beta\beta$ decay would
  - Imply lepton-number violation
  - Tell us about nature of ν (Majorana component?)
  - Give information about absolute Neutrino mass / hierarchy?

Low-Background Challenge

- Expected $0\nu\beta\beta$ decay half lives very long ($\geq 10^{26}$ years):
  [Agostini et al., Phys. Rev. D 96, 053001 (2017)],
  [Caldwell et al., Phys. Rev. D 96, 073001 (2017)]
- Ideal experiment (almost) background-free:
  < 1 counts within 1 FWHM of $Q_{\beta\beta}$ up to design exposure
- Need
  - underground location
  - excellent shielding
  - radio-pure materials
  - good energy resolution
  - high source mass
- For sensitivity 10^{28} yr:
  need < 1 event per 10 years per ton of detector

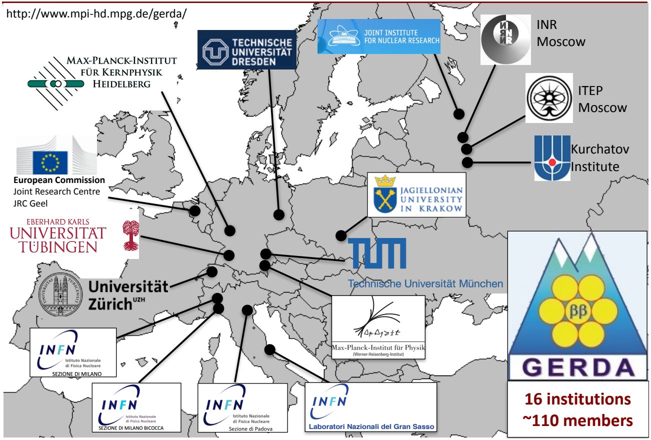
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

The GERDA Experiment

- Search for $0\nu\beta\beta$ decay in $^{76}\mathrm{Ge}$ at $Q_{\beta\beta} = 2039$ keV
- Array of isotopically enriched HPGe detectors, suspended in liquid argon
- Ultra-low background setup, located underground at LNGS (1400 m rock overburden, 3500 m water equivalent)
- Phase I from 2011 to 2013
- Phase II: Increased target mass (BEGe detectors), lower background, active LAr veto, from 2015 to 2019
- Current status: Transfer of infrastructure to ...
- ... successor: LEGEND-200

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

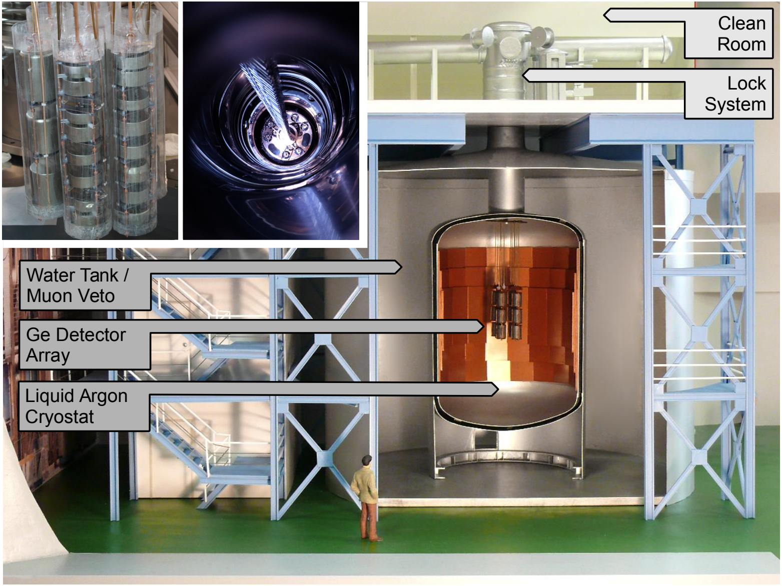
The GERDA Collaboration



- MPP GERDA Group: B. Majorovits (group leader), F. Fischer, L. Manzanillas, O. Schulz, A. Zsigmond

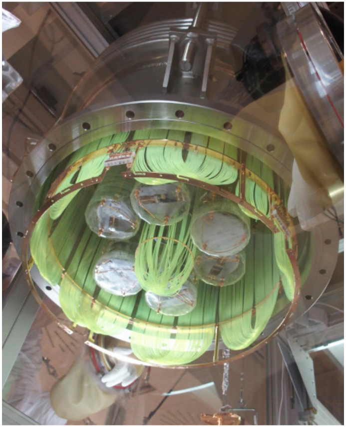
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

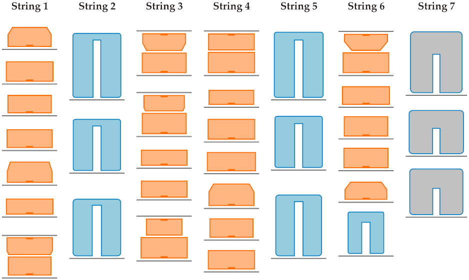
GERDA (and future LEGEND-200) Setup



...ax-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Final GERDA Phase-II Detector Array



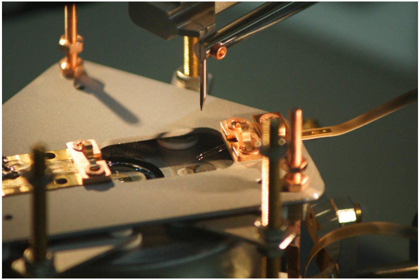


- 7 string, 40 detectors in total:
  - 7 enriched coax-type (15.8 kg)
  - 30 enriched BEGe-type (20 kg)
  - 4 enriched IC-type (9.5 kg)
- Array enclosed by LAr veto

[arXiv:1711.01452]

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Radiopure Detector Surroundings

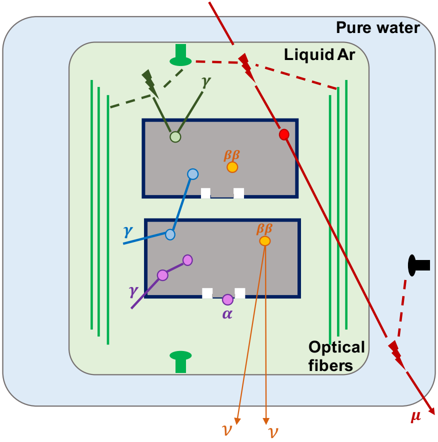


- Lightweight detector holders, built from monocrystalline silicon and OFC copper
- Detectors contacted by wire-bonding
- Holders connected to form strings

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

Background Reduction Strategy

$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume



Pulse shape discrimination (PSD) for multi-site and surface α events

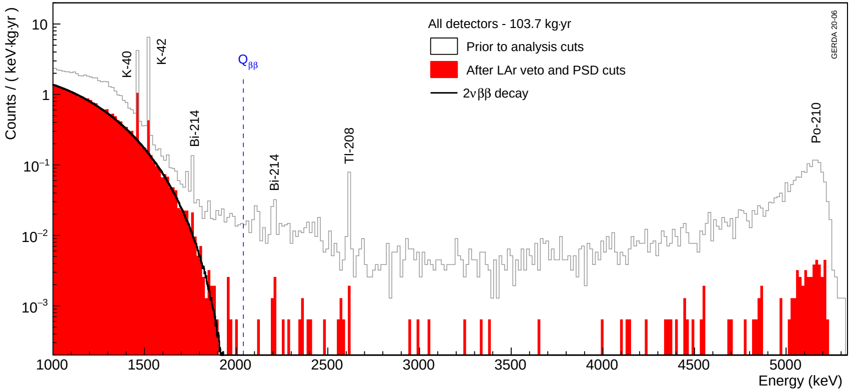
Ge detector anti-coincidence

LAr veto based on Ar scintillation light read by fibers and PMT

Muon veto based on Cherenkov light and plastic scintillator

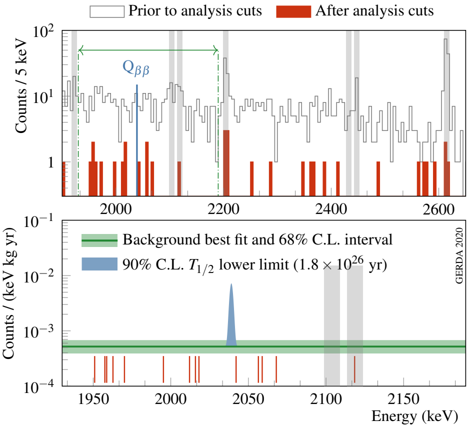
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

GERDA Background Reduction Efficiency



- After LAr veto and PSD, unprecedented low background in ROI: $\approx 5 \times 10^{-4}$ cts/(keV$\cdot$ kg$\cdot$ yr)

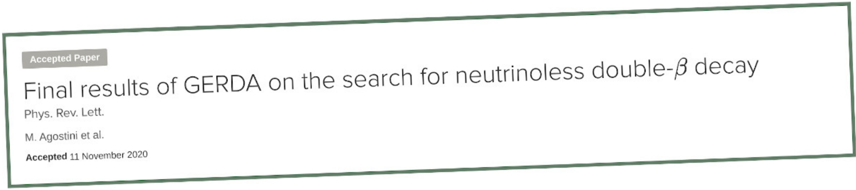
Final GERDA Result



Phase I plus Phase II:

- Total exposure: 127.2 kg yr
- $T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ yr (Frequentist)
- $T^{0\nu}_{1/2} > 1.4 \times 10^{26}$ yr (Bayesian, using BAT.jl)

(all limits: 90% CL/CI)


Accepted Paper

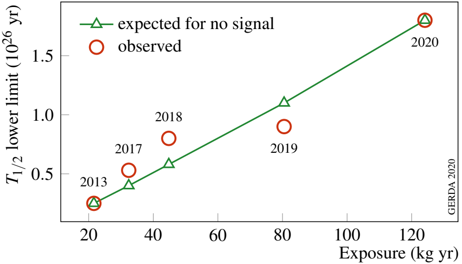
Final results of GERDA on the search for neutrinoless double-β decay

Phys. Rev. Lett.

M. Agostini et al.

Accepted 11 November 2020

GERDA Summary



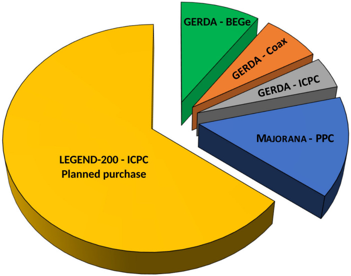
- 2013: PRL 111 (2013) 12, 122503
- 2017: Nature 544 (2017) 47
- 2018: PRL 120 (2018) 13, 132503
- 2019: Science 365 (2019) 144
- 2020: PRL, release imminent

(all limits: 90% CL/CI)

- Total exposure 127.2 kg yr
- World-record low background: $\approx 5 \times 10^{-4}$ cts/(keV$\cdot$ kg$\cdot$ yr)
- Limit on $0\nu\beta\beta$: $T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ yr
- Surpassed design goals
- Time for the next step in the story … LEGEND-200

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

Changes from GERDA to LEGEND-200



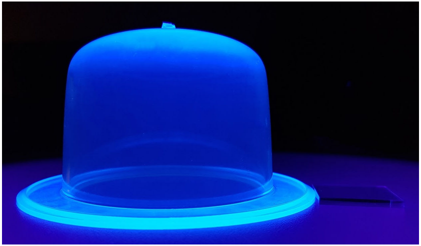
- Increased detector mass: GERDA + MAJORANA + new
- ROI background target: < 0.6 cts/(FWHM t yr)
- Use ultra-pure electroformed copper
- Low-mass electronics frontend on detector holders
- New lock system and cables
- Detector holders made from PEN (led by MPP)

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

LEGEND-200 Status of Preparations

- Fully funded
- Have most of enriched Ge already in hand
- Detector production and characterization underway
  goal 140 ICPC detectors, first detectors delivered
- LNGS infrastructure transferred, water tank drained
- Cryostat, lock and cleanroom modifications under way
- Post-GERDA-tests finished: Feb. to August 2020, max 17 detectors (Majorana PPC and L200 ICPC, 15 operational), yielded valuable insights
- Intense MC simulation campaign ongoing
- New analysis software stacks in Python and Julia (complementary)
- With luck, might be able to start (partial) operation in late 2021

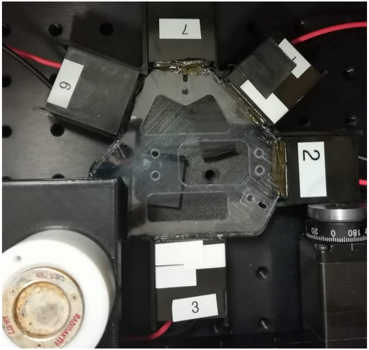
New technology: Scintillating PEN



- Polyethylene Naphthalate (PEN) is both a scintillator and wavelength-shifter, emits blue light (around 450 nm)
- Mechanically strong and cryo-compatible
- Injection molding allows (almost) arbitrary shape
- Good radiopurity plus self-vetoing
- LEGEND-200: Detector holders made from PEN replace GERDA silicon plates
- LEGEND-1000: Detector encapsulation in PEN?
- Concept of PEN in LEGEND originated at and led by MPP

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

PEN in LEGEND-200 and at MPP



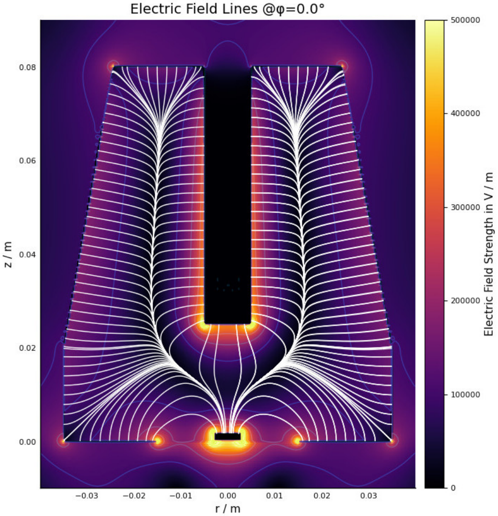
- PEN detector holders successfully deployed in post-GERDA-tests
- Detailed scans of test holders at MPP, crucial for accurate L-200 simulation
- MPP coordinates PEN holder production

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

HPGe Detector Simulation

- LEGEND goals require ultra low background and advanced PSD, confidence in results will depend on quality of detector simulation
- Novel HPGe detector simulation framework SolidStateDetectors.jl (SSD), developed at MPP, written in Julia
- Uses multi-threading and SIMD parallelization
- Takes detector environment into account, supports arbitrary detector geometries and segmented contacts
- Ongoing developments: GPU support, charge diffusion, self-repulsion, advanced visualization

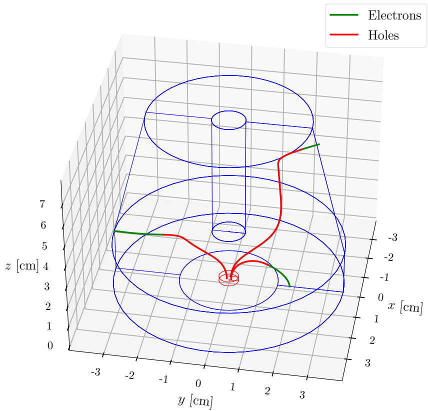
SSD Detector Field Calculation



- Only free 3D package that can simulate environment beyond detector boundaries

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

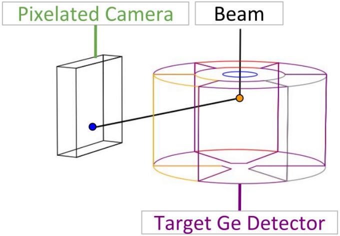
SSD Charge Drift Simulation



- 3D electron and hole charge drift simulation
- Modular design, can study different drift models
- HPGe detectors are complex beasts - how to check if we're right?

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

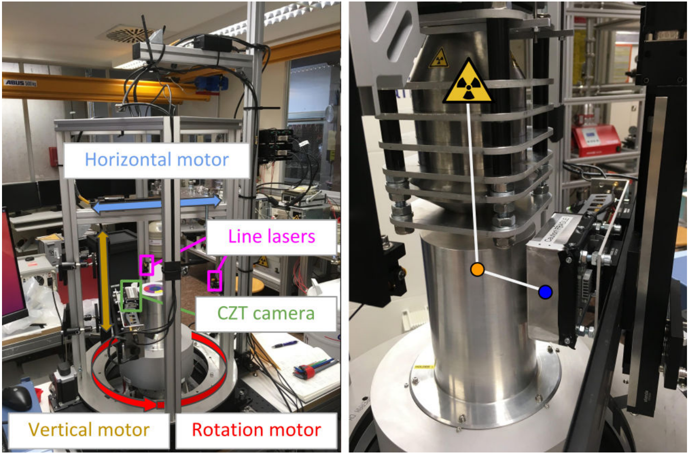
Detector Compton Scanning at MPP



- Want to measure detector signals with known interaction point
- Common approach: Strong collimated γ-source, 90° Compton scattering with collimator, very low efficiency
- MPP compton scanner uses pixelated CdZnTe detector as Compton camera as sensor, no collimator
- Not limited to 90° scattering, increased efficiency

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

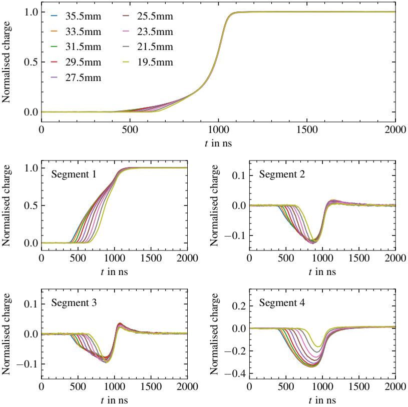
Detector Compton Scanning at MPP

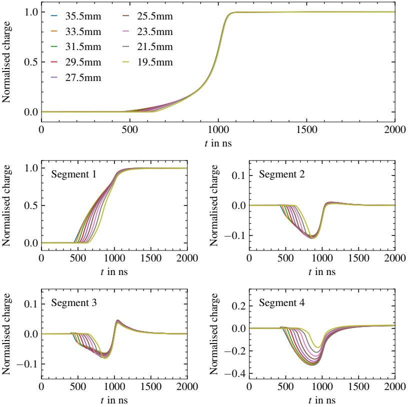


- 740 MBq Cs-137 Source, collimated to 1 mm over 100 mm, 2-3 kHz event rate in detector
- Motorized rotary and linear stages for automated scanning

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Compton Scanning and SSD Simulation

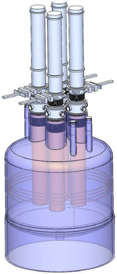


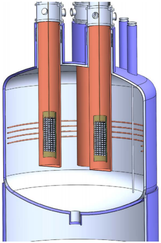


- Starting to achieve very good match between Compton Scanner data (left) and SSD simulation (right)
- Gives us access to charge carrier mobilities, crystal axes effects, drift temperature dependence, and detector bulk impurity density

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

LEGEND-1000





- Aim: 10 ton-years exposure with 1 ton detector mass to reach 10^{28} year limit, < 0.1 cts/(FWHM t yr) in ROI
- Baseline design: 4 arrays (payloads) in reentrant tubes filled with depleted Ar
- DOE portfolio discussion April 2021 (LEGEND, NEXO, CUPID)
- Host lab: Several options (e.g. SNOLAB or CJPL) but politics will play a role
- MPP involvement: PEN encapsulation and PEN vessels for payloads with frozen Argon
- Larger MPP commitments depend on future structural decisions at MPP

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

LEGEND Summary

- LEGEND-200 fully funded, detector production and installation preparations under way
- Important contributions from MPP: PEN technology, detector studies, Julia software including (SSD)
- LEGEND-1000 pCDR close to final
- LEGEND at MPP:
    - MPP Project lead: I. Abt,
      also LEGEND institute-board and speakers-buerau chair
    - Ge detectors and simulation:
      C. Gooch, F. Hagemann, L. Hauertmann, X. Liu, O. Schulz,
      M. Schuster, A. Zsigmond, D. Hervas (guest for a year)
    - PEN L200/R&D:
      F. Fischer, M. Guitart, B. Majorovits, L. Manzanillas,
      O. Schulz
    - We thank the workshops for all their support!

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

The Bayesian Analysis Toolkit (BAT)

- Software package for Bayesian inference
- Typical tasks: Given a set of data and prior knowledge
  - estimate parameters
  - compare models (Bayes factors)

  according to Bayes theorem

$$P(\vec{\lambda}|\vec{D}) = \frac{P(\vec{D}|\vec{\lambda})P_0(\vec{\lambda})}{\int P(\vec{D}|\vec{\lambda})P_0(\vec{\lambda})\, d\vec{\lambda}}$$

- Functionalities
  - Posterior space exploration via Markov chain Monte-Carlo (MCMC)
  - Integration of non-normalized posterior (i.e. evidence calculation)
  - User-friendly plotting and reporting

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

BAT.jl, the new BAT

- Original: BAT-C++, developed at MPP
- Very successful over the years, > 250 citations (INSPIRE)

  [Caldwell et al., DOI: 10.1016/j.cpc.2009.06.026 (2009).]

  - Written in C++, based on CERN ROOT
  - Proven in many real-life use cases
  - Wide user base, esp. in high-energy, nuclear and astro-physics
- By now reached flexibility limit of original software design
- Started complete re-design in 2017
- Successor: BAT.jl, written in Julia. Team:
  - MPP (A. Caldwell): O. Schulz (project lead), V. Hafych, S. Hayashi, L. Shtembari
  - TU-Dortmund (K. Kröninger): C. Grunwald, S. Lacagnina
  - ORIGINS ODSL: F. Capel, P. Eller, J. Knollmüller

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

Design goals for new version of BAT

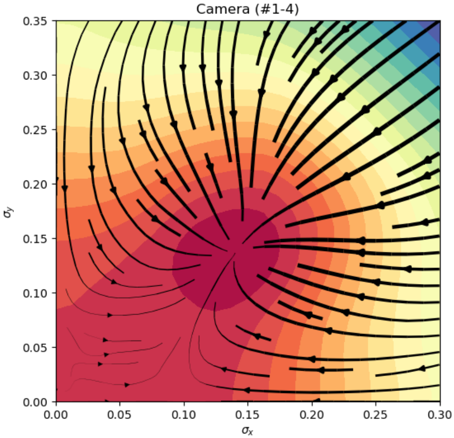
- Core philosophy: User provides likelihood
  (typically expensive, high data volumes, etc.)
  BAT does the rest
- Easy to use with defaults, but allow for detailed fine-tuning
- Multiple MCMC algorithms
  (BAT-C++ only supports Metropolis-Hastings)
- Deep support for parallel operation:
  - Parallelize both likelihood and MCMC chains
  - Local (multiple threads) plus distributed (compute clusters)
- Auto-differentiation for mode-finding, HMC, etc.
- Choice of programming language?

BAT.jl Features

- MCMC samlpling via Metropolis-Hastings, Hamiltonian Monte Carlo, Sobol and importance sampling
- New ARP sample weighting scheme
- Posterior integration with novel AHMI algorithm (Caldwell et. al, MPP) and Cuba (T. Hahn, MPP)
- Automatic space transformations cast target density into space suitable for algorithm
- Julia brings auto-differentiation, excellent package management and unmatched code composability via multiple dispatch (and much more)
- Released BAT.jl version 2.0 last night.
- https://github.com/BAT/BAT.jl

[arXiv:2008.03132]

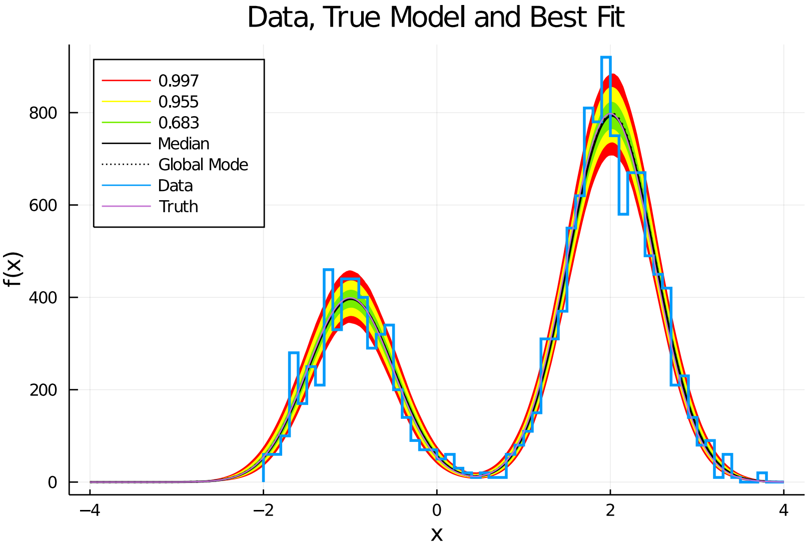
Auto-Differentiation in Julia



Julia powerful enough to auto-diff (almost) arbitrary code.
Example above: Complex posterior for AWAKE, likelihood uses image processing and lookup tables.

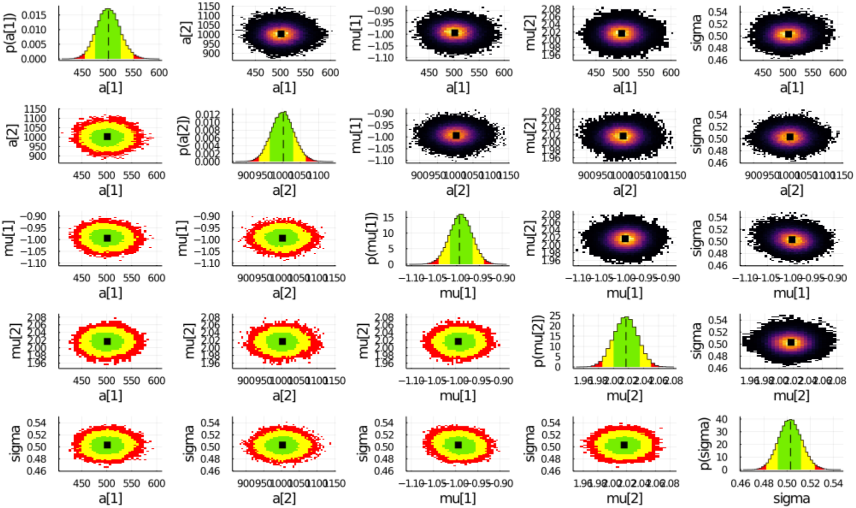
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Simple BAT.jl example: Histogram Fit



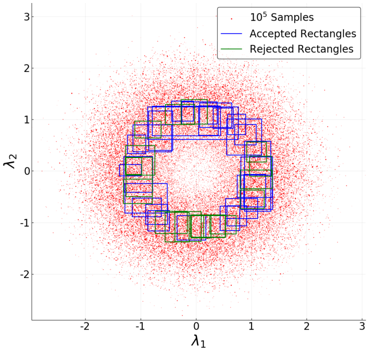
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

BAT.jl plotting: Posterior projections



Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Adapive Harmonic Mean Integration (AHMI)



- Computes posterior integral/evidence from samples via harmonic mean [Int.J.Mod.Phys.A 35 (2020) 24, 1950142]
- Operates in hyper-rectangles with limited posterior variance to control integral variance

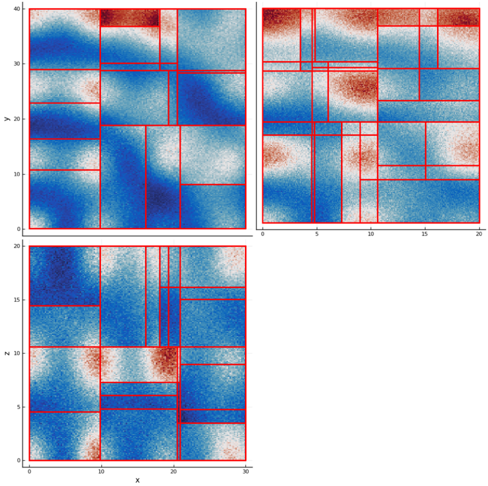
Parameter space partitioning (Experimental)

- MCMC expensive, need maximum parallelization
- Parallelization potential of likelihood often limited
- Increasing number of chains doesn't help (burn-in cost)
- New concept: partition parameter space
  run separate set of chains in each subspace
- Rationale: posterior in small subspaces simpler,
  fast burn-in
- Challenge: find good partitioning for given posterior,
  work in progress

[arXiv:2008.03098]

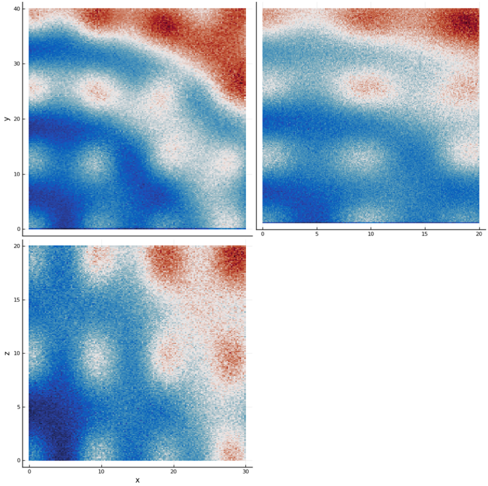
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Parameter Space Partitioning, Raw



- Subspaces contains unequal probability mass: can't just stitch MCMC results together

Parameter Space Partitioning, Reweight



- Solution: Use AHMI to integrate posterior in each subspace, then reweight by integral

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

BAT Summary

- BAT concept:
  user brings domain knowledge and likelihood,
  BAT provides robust sampling, integration and visualization
- Current BAT (C++) is a success story,
  but flexibility limit reached
- Just released BAT.jl (Julia) v2.0,
  focus on ease of use, parallelization and modern algorithms
- Future improvements: Lot's of ideas, also interesting
  computing/numerical technology on the horizon

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)