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Review of experiment likelihood frameworks: SO

Cosmo Forward

A critical review of current and future routes to cosmological results.

Ian Harrison

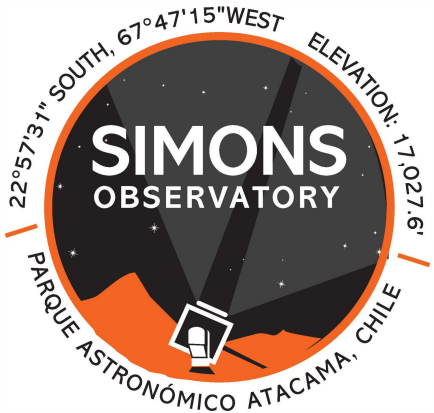
CARDIFF UNIVERSITY

PRIFYSGOL CAERDYDD

erc

European Research Council

Established by the European Commission



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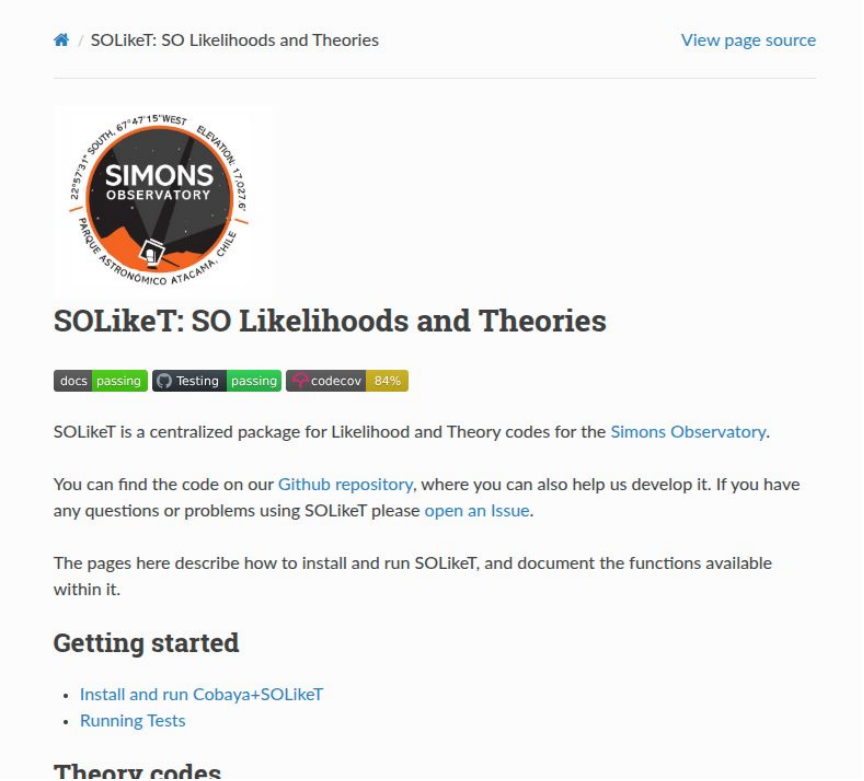
SO and its Likelihoods and Theorys [sic]

- Will describe the Likelihood and Theory framework for the SO-LAT
  - SOLikeT
- What is SOLikeT and what is it not?
- What can it do currently?

- Try to ask some motivating questions for cross-experiment combinations
- Say some things about a FAIR utopia



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Deliverable Projects

- See 2018 and 2025 SO-LAT Goals and Forecast papers:

2018

Table 9
Summary of SO key science goals[a]

	Parameter	SO-Baseline[b] (no syst)	**SO-Baseline**[c]	SO-Goal[d]	Current[e]	Method	Sec.
Primordial perturbations	r	0.0024	**0.003**	0.002	0.03	BB + ext delens	3.4
	$e^{-2\tau}\mathcal{P}(k = 0.2/\mathrm{Mpc})$	0.4%	**0.5%**	0.4%	3%	$TT/TE/EE$	4.2
	$f_{\mathrm{NL}}^{\mathrm{local}}$	1.8	**3**	1	5	$\kappa\kappa$ × LSST-LSS + 3-pt	5.3
		1	**2**	1		kSZ + LSST-LSS	7.5
Relativistic species	N_{eff}	0.055	**0.07**	0.05	0.2	$TT/TE/EE + \kappa\kappa$	4.1
Neutrino mass	Σm_ν	0.033	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO	5.2
		0.035	**0.04**	0.03		tSZ-N × LSST-WL	7.1
		0.036	**0.05**	0.04		tSZ-Y + DESI-BAO	7.2
Deviations from Λ	$\sigma_8(z = 1 - 2)$	1.2%	**2%**	1%	7%	$\kappa\kappa$ + LSST-LSS	5.3
		1.2%	**2%**	1%		tSZ-N × LSST-WL	7.1
	H_0 (ΛCDM)	0.3	**0.4**	0.3	0.5	$TT/TE/EE + \kappa\kappa$	4.3
Galaxy evolution	η_{feedback}	2%	**3%**	2%	50-100%	kSZ + tSZ + DESI	7.3
	p_{nt}	6%	**8%**	5%	50-100%	kSZ + tSZ + DESI	7.3
Reionization	Δz	0.4	**0.6**	0.3	1.4	TT (kSZ)	7.6

- Initial Science Operations (ISO) list of opt-in and opt-out papers being formed
- Year 1 list of opt-in and opt-out papers being formed

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Deliverable Projects

- See 2018 and 2025 SO-LAT Goals and Forecast papers:

Table 9

Table 2. Summary of Enhanced Science Goals from SO LAT Survey[a]

	Current[b]	**SO 2025–2034**	Using Rubin, DESI, or *Euclid*	Reference
Primordial perturbations				
n_s	0.004	0.002	-	Shandera et al. (2019)
$e^{-2\tau}\mathcal{P}(k = 0.2\,\mathrm{Mpc}^{-1})$	3%	0.4%	-	Slosar et al. (2019b)
$f_{\mathrm{NL}}^{\mathrm{local}}$	5	1	✓	Meerburg et al. (2019)
Relativistic species				
N_{eff}	0.2	0.045	-	Green et al. (2019)
Neutrino mass[c]				
$\sum m_\nu$ (eV, $\sigma(\tau) = 0.01$)	0.1	0.03	✓	Dvorkin et al. (2019)
$\sum m_\nu$ (eV, $\sigma(\tau) = 0.002$)		0.015	✓	
Accelerated expansion				
$\sigma_8(z = 1 - 2)$	7%	1%	✓	Slosar et al. (2019a)
Galaxy evolution				
η_{feedback}	50–100%	2%	✓	Battaglia et al. (2019)
p_{nt}	50–100%	4%	✓	Battaglia et al. (2019)
Reionization				
Δz	1.4	0.3	-	Alvarez et al. (2019)
τ	0.007	0.0035	-	Alvarez et al. (2019)
Cluster catalog	4000	33,000	✓	
AGN catalog	2000	96,000	-	

2025

- Initial Sc being formed
- Year 1 li

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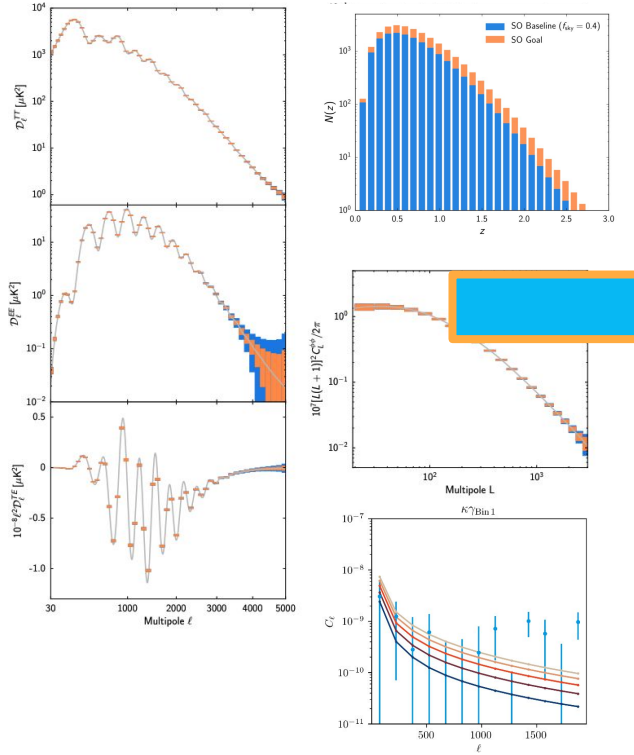
SOLikeT Goals

(LAT) Data Vector(s)
(+ covariance matrices)
+ other AWG knowledge



LT AWG

Ingest data vectors

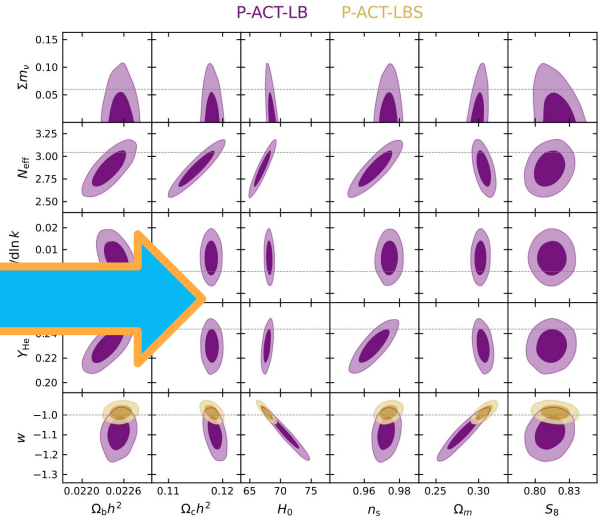
Calculate
theory curves
(LT.2; Harrison, Lague)

Combine with
systematics models

Compare them
in a likelihood
(LT.1; Galloni, Jense)

Generate samples
from the posterior
(LT.3; Kou)

Cosmological
Model Constraints



ACT-DR6
Calabrese & Hill et al 2025

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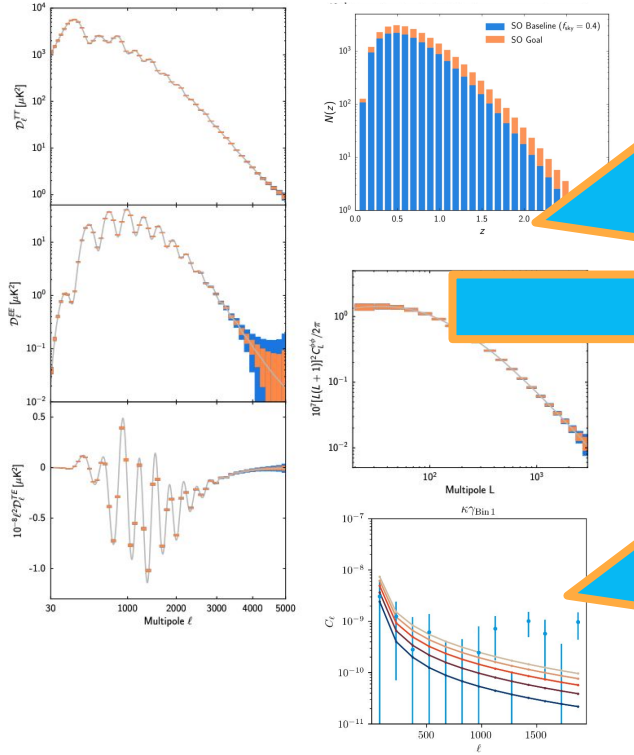
SOLikeT Goals

(LAT) Data Vector(s)
(+ covariance matrices)
+ other AWG knowledge



LT AW

Ingest da

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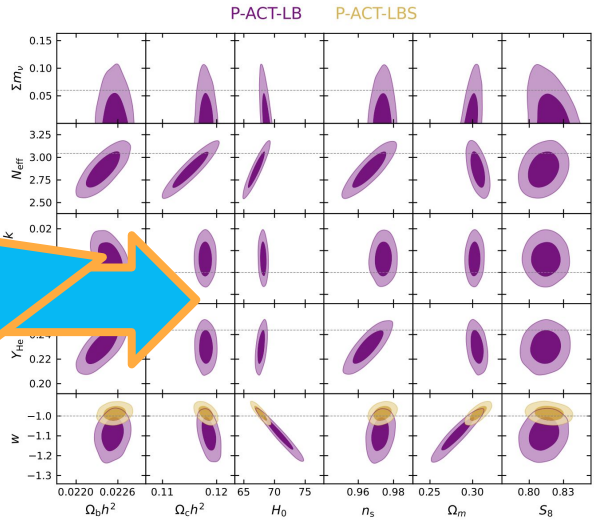
, Kou)

Make this as easy and efficient as possible when data vectors arrive

Make our results FAIR for ourselves and external community

Cosmological Model Constraints



ACT-DR6
[Calabrese & Hill et al 2025]

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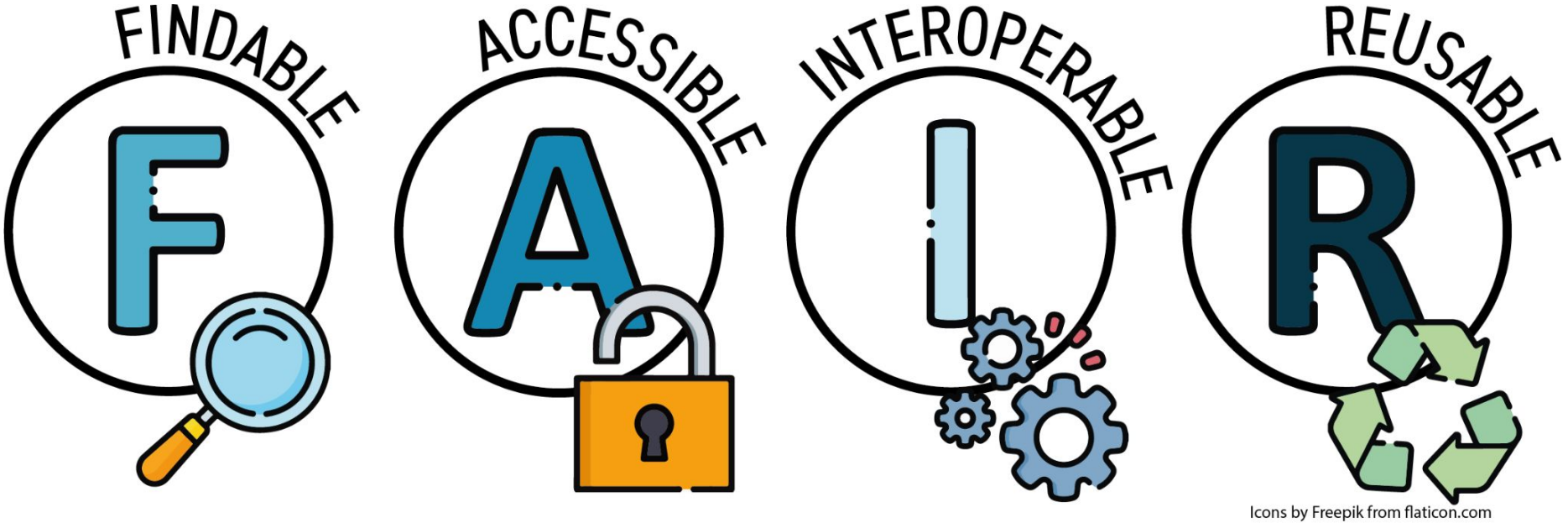

Data

Code

Publications

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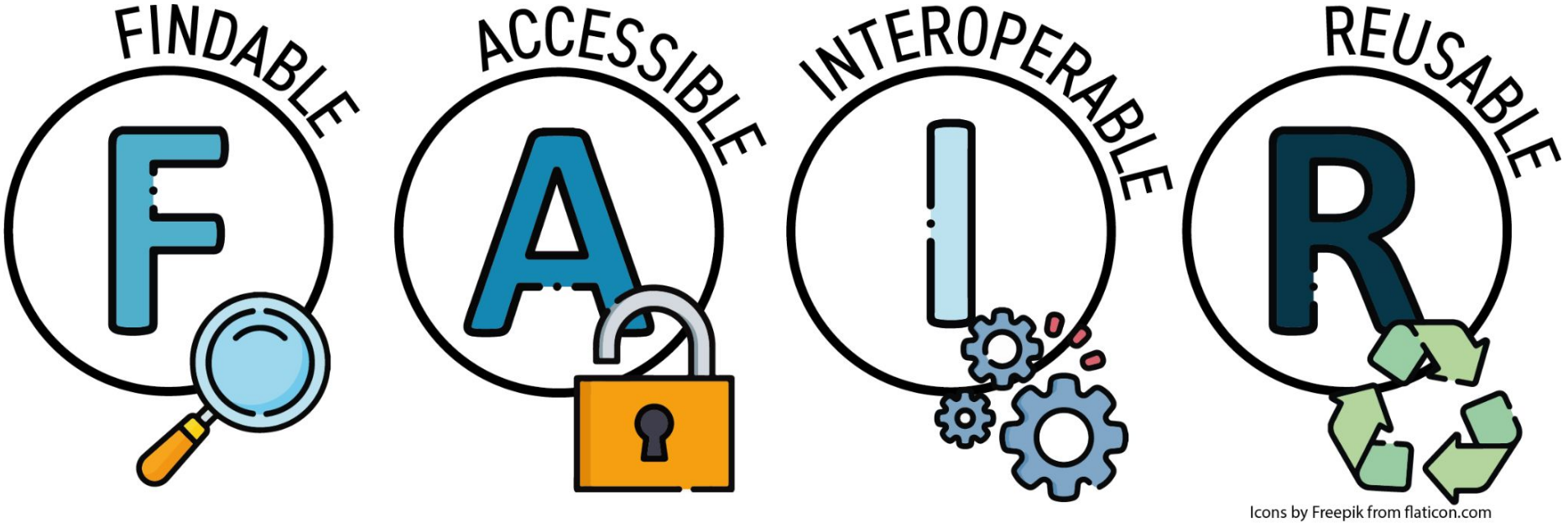
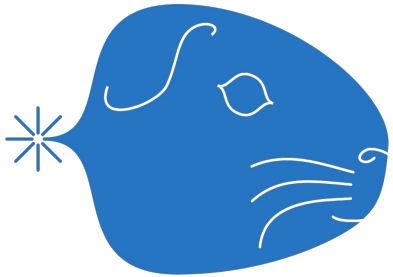


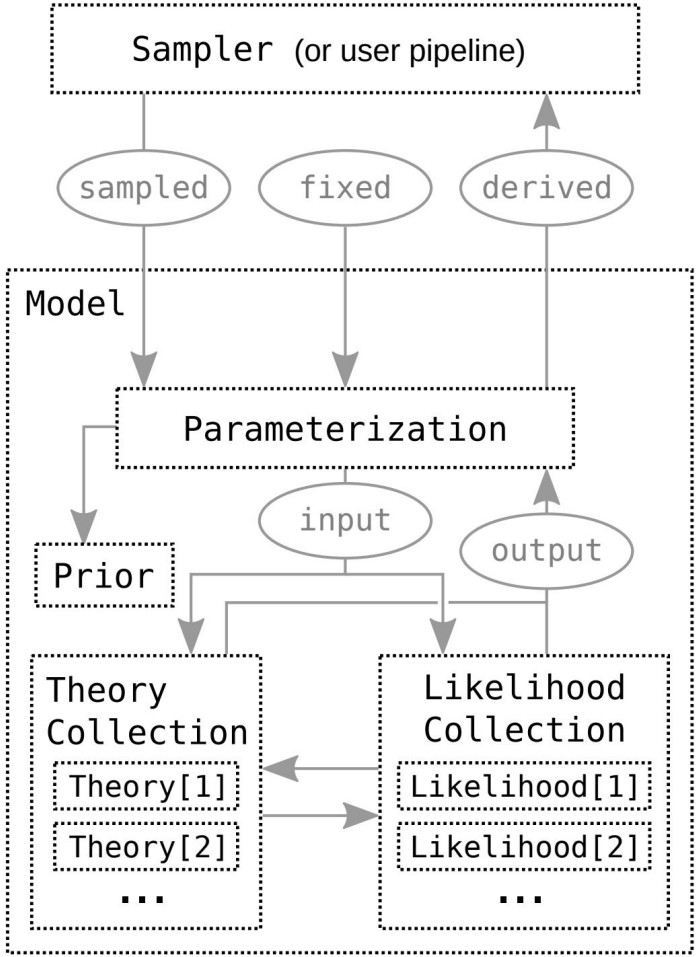
Pipelines / Workflow

Data | **Code** | **Publications**

What is SOLikeT?

- SOLikeT builds on Cobaya
- Cobaya: framework for sampling and statistical modelling
  - From the cosmology community
  - other comparable frameworks are available: CosmoSIS, MontePython

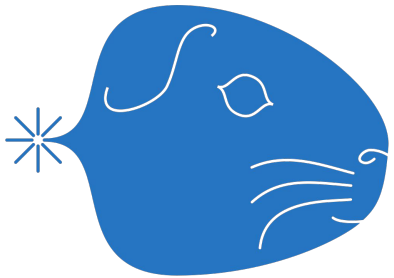




What is SOLikeT?

$$\sum_{ij} \left(F(\vec{\theta})_i - d_i\right) \boldsymbol{C}_{ij}^{-1} \left(F(\vec{\theta})_i - d_i\right)$$

- Cobaya has many modules making Theory predictions and for calculating Likelihoods for cosmological data sets
  - Theorys calculate predicted data vector $F(\boldsymbol{\theta})$ at a set of parameters
    - e.g. CAMB
  - Likelihood scores this against some observed data vector, normalised by errors (Covariance Matrix)
    - e.g. Gaussian, Poisson
  - Sampler makes educated choices for which parameter values to calculate at to efficiently estimate posterior and summary statistics



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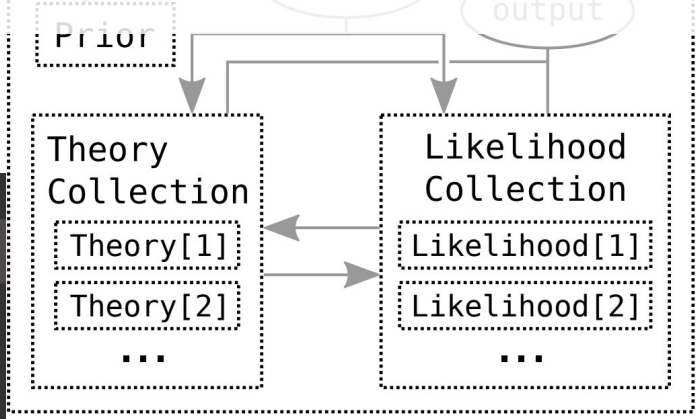
What is SOLikeT?

- SOLikeT is a set of Cobaya Theory and Likelihood modules specifically designed for Simons Observatory



THEORY CODES

- Core Cosmology Library (CCL) Calculator
- Cosmopower (Boltzmann Emulator)
- Bandpass (CMB)
- Foreground (CMB)
- Bias (Galaxy Bias)
- HaloModel (Halo Model Non-Linear Power Spectrum)

LIKELIHOOD CODES

- MFLike (Primary CMB)
- Lensing (CMB Lensing)
- Clusters (Galaxy Clusters)
- XCorr (Cross-correlation)
- CrossCorrelation

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Framework Steps

1. Sampling
   - Choosing the model parameters to map the posterior
2. Theory calculation
   - Making a data prediction with the model
3. Likelihood calculation
   - Scoring the prediction against the data

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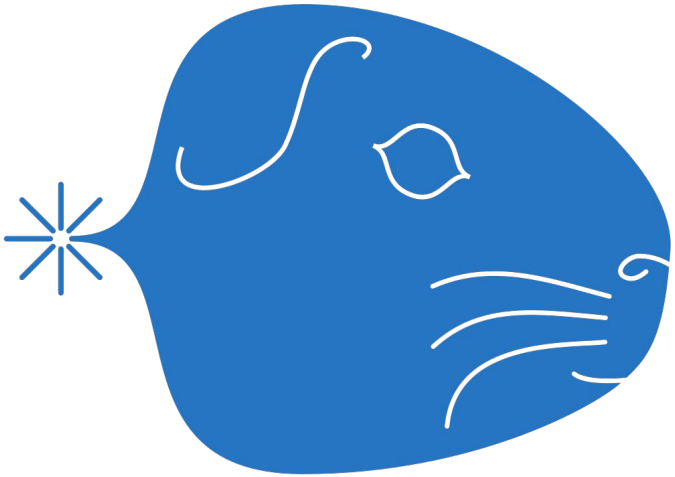
Framework Steps

1. Sampling
    - Taken care of by Cobaya
        - CosmoMC-style MCMC
        - Polychord



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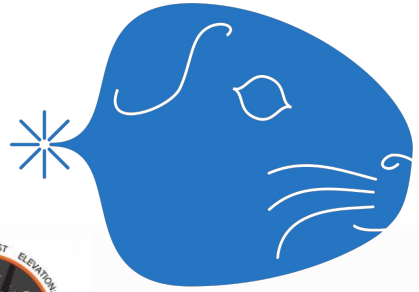
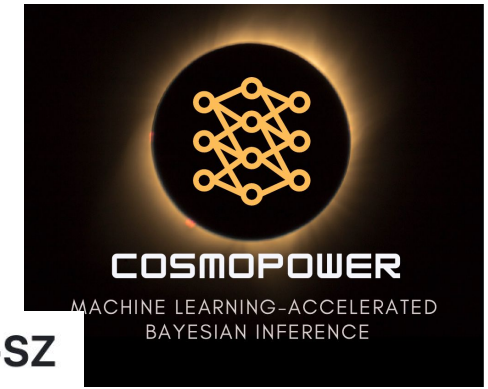
Framework Steps

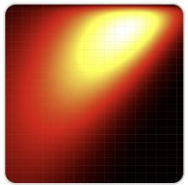


1. Sampling
   - Taken care of by Cobaya
     - CosmoMC-style MCMC
     - Polychord
2. Theory Calculation
   - Existing cobaya modules
     - camb, class
   - SOLikeT: SO specific cobaya modules
     - CCL calculator mode wrapper (Limber integration for tracers)
     - Linear bias, pyhalomodel (intended as templates)
     - ***CosmoPower**** for Cl and P(k)
   - Other SO-managed python modules
     - fgspectra (cross-frequency CMB foregrounds)
     - ***class_sz**** (Bolliet+)

SIMONS OBSERVATORY

SOLikeT: SO Likelihoods and Theories





CLASS-SZ

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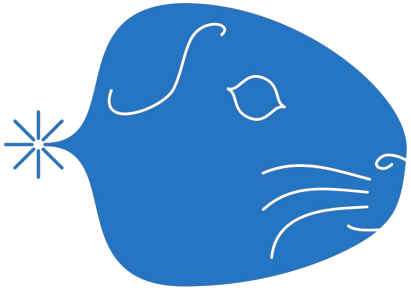
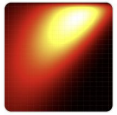
Framework Steps



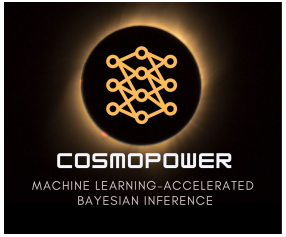
1. Sampling
   - Taken care of by Cobaya
2. Theory Calculation
   - Existing cobaya modules
   - SOLikeT: SO specific cobaya modules
   - Other SO-managed python modules
3. Likelihood Calculation
   - Existing cobaya likelihoods…
   - SOLikeT: SO specific cobaya likelihoods
     - CMB Lensing
     - CMB Lensing x Shear (include WL nuisance), x Galaxies
   - Other SO-managed cobaya likelihoods
     - cosmocnc (Cluster number counts, Inigo Zubledia+)
     - LAT_MFLike (Multifrequency Primary CMB TTTEEE, including bandpass and foregrounds, Louis, Garrido, Giardiello++)
     - lat_cmbonly (Hidde Jense)

SIMONS OBSERVATORY

SOLikeT: SO Likelihoods and Theories



CLASS-SZ



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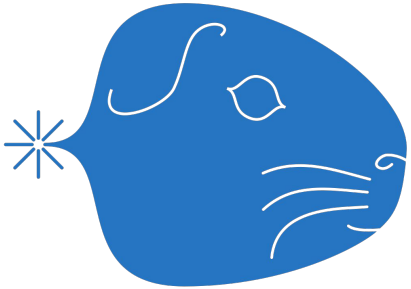

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Framework management

- Cobaya (sampling, some theory calculations, some likelihoods) managed off-project by people who are in SO (Antony Lewis+)
- Multi-probe SOLikeT managed by SO LT Analysis Working Group (AWG)
  - Constructing joint framework from individual probe likelihoods
  - Considering cross-covariances (see Kou & Lewis 2025)
  - Evaluating accuracy requirements
  - Developed in an open repo
- Single-probe likelihoods and theorys managed by individual SO AWG
- Data repository in HIPPO/SOPO (Josh Borrow)

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Framework Packaging

- Public repos in simonsobs github org
- Trying to package and version control things properly!
  - https://packaging-guide.openastronomy.org/en/latest/index.html for packaging guidance
  - …or speak to Giacomo Galloni!
- Currently v0.3.2 is on PyPI
  - Requires all dependencies also on pypi
- Unit test suite
  - Currently 84% coverage
  - Multi-platform (ubuntu, macos, windows)
- Tutorial notebooks (Giacomo, Matteo Forconi)

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Framework validation and requirements

- Have been producing multi-probe ‘smooth theory’ forecast (Martina)
  - …demonstrating cobaya grid run functionality for easily setting up and running multiple runs over combinations of samplers, parameters and theories (Raphael Kou)

- Accuracy requirements not formally specified in great detail (yet)
- Building on ACT DR6 Primary CMB exercise from Boris, Kristen, Colin++ (Sunny Desai, Matteo Forconi)
  - Baseline (very) slow high-accuracy Theory run
  - Data-level differences
  - Likelihood slices
  - Stability of Fisher information
  - Stability of profile likelihoods
  - Stability of contours

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Expected external combinations

- With reference to 2018/25 Goals and Forecasts
  - BAO
    - Likelihood from cobaya
  - WL
    - Likelihood within SOLikeT?
  - Photometric galaxy density
    - Likelihood within SOLikeT?
  - WL cluster mass calibration
    - Within cosmocnc
  - Cluster redshifts
    - Within cosmocnc

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Exchange of likelihoods

- How do we send SO to Rubin / Euclid?
  - Foreground marginalised / CMB-only likelihood
    - How many nuisance parameters?
  - Spectra?
  - Maps?
- How do we use Rubin / Euclid in SO?
  - Nuisance marginalised / cosmology-only likelihoods?
    - Penalty? Identify set of models where this is no penalty?

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In an ideal world… its DoIs all the way down 🐢

- Posterior estimate in a *paper*[v] links to a *chain*[v] via a DoI
- The chain's metadata links to a sacc *data file*[v] via a DoI
- The sacc file's metadata links to *workflow*[v](s) via a DoI
- The workflow's metadata links to *code*[v](s) via a DoI
  - …and input data / maps with DoIs which have in their metadata workflows which… etcetera

- …the chain's metadata also links to an inference *workflow*[v] via (...you get the picture)
- The inference workflow's metadata links to *code*[v](s)

- Workflows are packaged (as much as possible) with an *execution environment*[v] in which they run

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Many of these repositories exist at some level

- Papers: arXiv
- Data files / chains: zenodo / SOPO
- Workflows: show your work / maneage
- Code: github / pypi / Software Heritage
- Execution envs: containers / maneage (full software stacks from POSIX tools!)

- As do frameworks for metadata / FAIRness validation (e.g. F-UJI)

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Summary

- SOLikeT will deliver multi-probe cosmology posteriors from SO-LAT data
- SOLikeT is a set of SO-specific cobaya modules
  - …and links to other SO-managed cobaya and python modulus
- SOLikeT contains *some initial* infrastructure for cross-correlations, but way forward requires collaboration
- SOLikeT has some clear areas for tidying up
  - Better integration with CosmoPower
  - Better integration with class_sz (i.e. for halo model)
  - Better integration with CCL (e.g. HEFT for cross-correlations)
- SO inference workflows will be as FAIR as we have resources to make them…

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Avenues for Extensions

- Write a cobaya likelihood
  - you have new data
- Write a cobaya theory
  - you have a new fundamental theory
  - you have a new systematics model
- Train a cosmopower emulator
  - you have a new fundamental theory
  - you have a new systematics model
- Re-compute a covmat
  - you have a new fundamental theory
- Re-run a chain
  - you disagree with our prior
  - you want to use less / more data with the same model

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In my unrealistic utopian world what could we deliver?

- A DoI for the whole pipeline per posterior estimate (chain)
  - Maps
  - Masks
  - Spectra
  - Covariances
  - Configuration files
  - Full software stack built from only POSIX tools (only joking… kind of…)
- A versioned release of SOLikeT with a DoI for the baseline chain
  - Library of Cobaya Theories and Likelihoods in our repo
  - …what about Likelihoods from outside our repo? Want tagged versions of those
- A complete set of maps
- A complete set of masks
- A single sacc file with all our probes and one covariance
  - Baseline + variations?
- Configuration files for each pipeline version
  - Which *nest as much as they can*

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Which probes?

Probe	SO	DESC	*Euclid*
Primary CMB	✅ cutting-edge		
CMB Lensing	✅ cutting-edge		
Cluster counts	✅ cutting-edge		
Galaxy density	✅ toy		
Galaxy lensing	✅ toy		
…			

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Which ‘data’ formats?

Element	SO	DESC	*Euclid*
Sacc	✅		
Cosmopower Cell	✅		
Cosmopower Pk	✅ish (Hidde’s version, classy_sz)		
…			

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Which theory models?

Model	SO	DESC	*Euclid*
LCDM+ CMB Cell	✅ camb/class		
LCDM+ linear P(k)	✅ camb/class		
LCDM non-linear P(k) FastPT			
…			
LCDM Halo Model classy_sz	✅ish		
BaryonForge			
…			