Next-generation astrophysical inference across the interdisciplinary frontier

Will Handley
<wh260@cam.ac.uk>

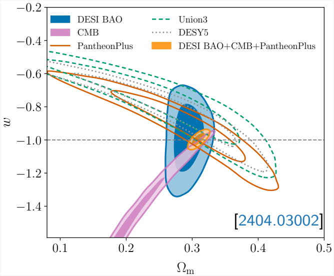
Royal Society University Research Fellow
Astrophysics Group, Cavendish Laboratory, University of Cambridge
Kavli Institute for Cosmology, Cambridge
Gonville & Caius College
willhandley.co.uk/talks

29th April 2024

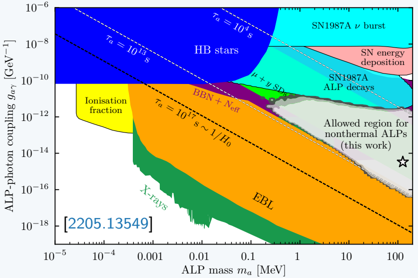
The future of astronomy is interdisciplinary

- Across astronomy, combining data and disciplines will be the key to the next breakthroughs.

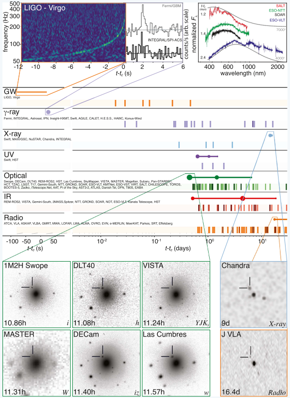
CMB+BAO



HEP+Astro



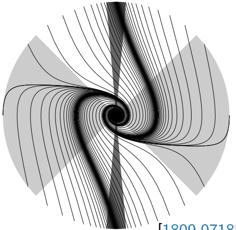
GW170817 [1710.05833]



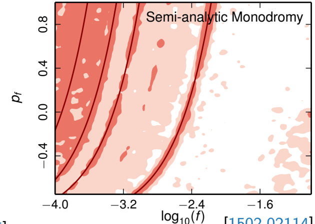
- We have spent the last 5 years hair-splitting "parkable" tensions.
- The next 25 years of data confront the real tensions in our understanding of the Universe.
- I aim to show how my research programme is preparing us for this interdisciplinary challenge.

Planck: Inflation & primordial power spectrum

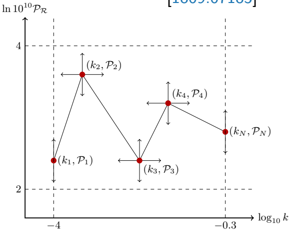
- Began theoretical PhD in 2012 investigating initial conditions for inflation.
- Joined Planck inflation team, working on Bayesian model fitting alongside theory.
- Found I enjoyed the observation & inference as much as the theory.
- `FlexKnots` were used to reconstruct the primordial power spectrum, inflationary potential & reionisation history (now used by Fialkov group) [1908.00906].
- `PolyChord` developed for model comparison, particularly axion monodromy.
  - Now used widely within cosmology (DES, DESI, CMB) and beyond (exoplanets, GW, galaxies, 21cm, . . .) [`ADS`]

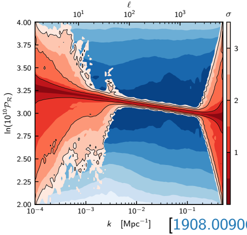


[1809.07185]



[1502.02114]





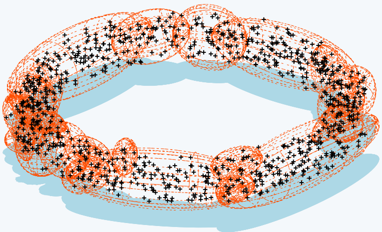
[1908.00906]

Analytic innovation: from MultiNest to PolyChord

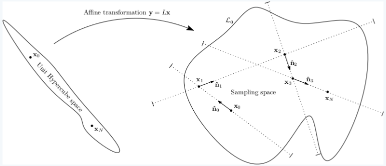
- MultiNest [0809.3437] was the leading Bayesian numerical model comparison tool in 2013.
  - A general purpose & performant implementation of John Skilling's nested sampling meta-algorithm.
  - Remains the leader of the pack in $n \sim \mathcal{O}(10)$ parameter fits.
  - Careful testing in *Planck* showed that it couldn't handle the many fast-slow nuisance parameters needed for systematics .
- I analytically developed and numerically implemented PolyChord, which has polynomial scaling efficiency $f_{\mathrm{PC}} \sim \frac{1}{n}$ with model parameters (c.f. exponential $f_{\mathrm{MN}} \sim e^{-n/n_0}$).
- Exemplifies theoretical innovation & numerical implementation driven by astrophysical challenges.

PolyChord inspired a new generation of nested samplers (dynesty, UltraNest, nessai. . .), but remains the state of the art in high-dimensional model comparison.

MultiNest [0809.3437]



PolyChord [1506.00171]



Aside: theoretical work

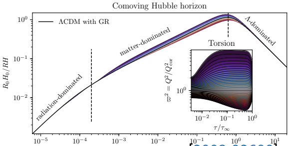
This talk will focus on my interdisciplinary work, but I have theoretical interests in:

- Quantum fields in curved spacetime (Mary Letey, Zak Shumaylov, Fruzsina Agocs)
- Poincaré Gauge Theory (Sinah Legner, Will Barker)
- Future conformal boundary/CPT universes (Metha Prathaban, Wei-Ning Deng)
- Curved finite inflation (Lukas Hergt)

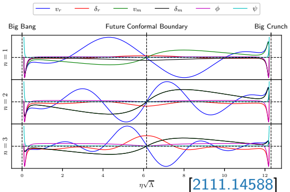
energy tensor (5). Inserting the mode function (26) into (32) and taking the coincidence limit, one finds:

$$\langle 0|T_{00}(x)|0\rangle_{\text{ren}} = \frac{1}{2}\int \frac{d^3k}{(2\pi)^3 a^2}(\chi_{\mathbf{k}}' - \frac{a'}{a}\chi_{\mathbf{k}})(\chi_{\mathbf{k}}^{*\prime} - \frac{a'}{a}\chi_{\mathbf{k}}^*) + \left(k^2 + m^2a^2\right)\chi_{\mathbf{k}}\chi_{\mathbf{k}}^* + \tilde{T}, \quad (34)$$

where $\tilde{T}$ signifies the plethora of additional terms arising from the renormalisation process that have no dependence on the variables $\mathcal{X}$. Minimising this with respect [1607.04148]



[2003.02690]

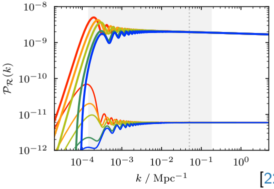


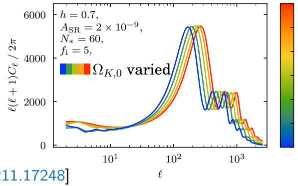
[2111.14588]

Substituting Eq. (24) into the above, and integrating by parts one more time returns the unusual action

$$\frac{1}{2}\int d^4x\sqrt{|c|}a^3\frac{\dot\phi^2}{H^2}\left\{\frac{1}{a^2}\mathcal{R}\mathcal{D}^2\mathcal{R} + \left(\dot{\mathcal{R}} - \frac{K}{a^2}\frac{\mathcal{R}}{H}\right)\frac{\mathcal{D}^2}{\mathcal{D}^2 - K\mathcal{E}}\left(\dot{\mathcal{R}} - \frac{K}{a^2}\frac{\mathcal{R}}{H}\right)\right\}. \quad (26)$$

[1907.08524]





[2211.17248]

Interdisciplinary work to date

- CMB cosmology
- Cosmological tension quantification
- **21cm cosmology**
- Radio Instrumentation
- **Gravitational waves**
- **Exoplanets**
- **Particle physics**
- Theory of machine learning
- Nested sampling theory
- Atomistic chemistry
- **Industrial applications**
- ...

50 minutes is not enough time to cover a decade's publishing.

arxiv.org/a/handley_w_1.html

Will showcase a targeted subset.

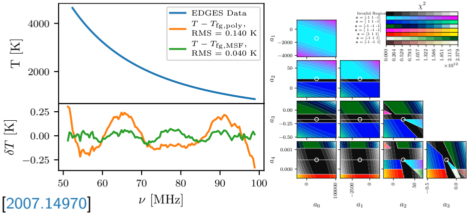
Harry Bevins

PhD→KICC fellow

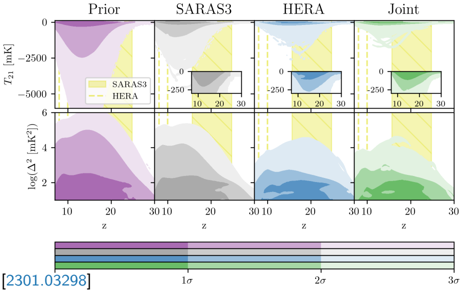
Transferring interdisciplinary ideas into 21cm cosmology with Anastasia Fialkov & Eloy de Lera Acedo.

- `maxsmooth` [2007.14970]
  - quadratic programming choice arose from quantitative finance consultancy work
- `FlexKnots`
  - importing ideas from inflationary reconstruction into reionisation [2310.05608](Heimersheim) & ionospheric reconstruction [2311.14537](Shen).
- `margarine` [2205.12841] [2207.11457]
  - combination of ideas from interdisciplinary fields (emulators, nested sampling, marginal density estimation)

These techniques are now widely used beyond the Cambridge 21cm community.



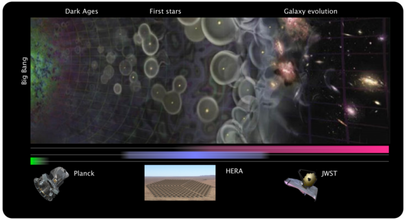
[2007.14970]

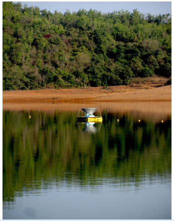


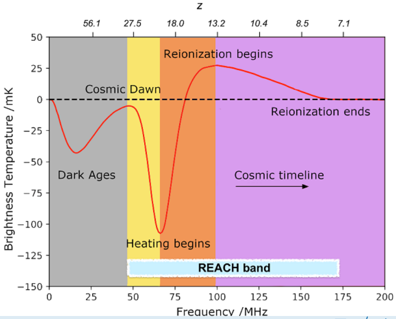
[2301.03298]

REACH: Global 21cm cosmology [2210.07409]

- Imaging the universal dark ages using CMB backlight.
- 21cm hyperfine line emission from neutral hydrogen.
- Global experiments measure monopole across frequency.
- Challenge: science hidden in foregrounds $\sim 10^4 \times$signal.
- Lead data analysis team (REACH first light in January)
- Nested sampling woven in from the ground up (calibrator, beam modelling, signal fitting, likelihood selection).
- All treated as parameterised model comparison problems.







Gravitational waves

Metha Prathaban
PhD

- Nested sampling has been used in GW since the beginning [GW150914]
- Work with Alvin Chua & Chris Moore on transdimensional sampling for EMRI [1803.10210]
- Recent work with Metha Prathaban showing new chain-based approaches for improving precision [2404.16428]

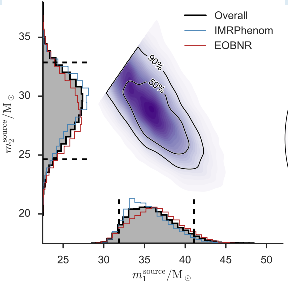
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **478,** 28–40 (2018) doi:10.1093/mnras/sty1079
Advance Access publication 2018 April 28

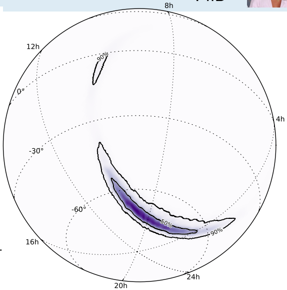
Towards a framework for testing general relativity with extreme-mass-ratio-inspiral observations

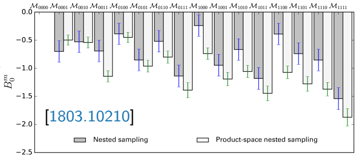
A. J. K. Chua,[1,2★] S. Hee,[3,4] W. J. Handley,[3,4,5] E. Higson,[3,4] C. J. Moore,[6,7] J. R. Gair,[8] M. P. Hobson[3] and A. N. Lasenby[3,4]

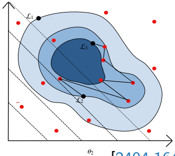
Costless correction of chain based nested sampling parameter estimation in gravitational wave data and beyond

Metha Prathaban[1,2,3★] and Will Handley[1,2,4†]









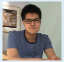
[2404.16428]

- Discussed use of `margarine` [2207.11457] as alternative to GW hierarchical modelling at inaugural data science discussion group

Exoplanets

Namu Kroupa

PhD



- Exoplanet science requires solution of subtle inference problems
  - Inference from RV data [1806.00518]
  - Survey challenges [2007.07278]
  - Stellar activity [2102.03387]
- Gaussian processes+Nested Sampling for transit astronomy [2311.04153]
- Potential for further collaboration with Madhu's group who are seeking beyond `MultiNest` solutions as their problems scale in dimensionality
- Ongoing cross-disciplinary theoretical chemistry work may be useful in Paul Rimmer's group.

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **528**, 1232–1248 (2024) https://doi.org/10.1093/mnras/stae087

Advance Access publication 2024 January 12

Kernel-, mean-, and noise-marginalized Gaussian processes for exoplanet transits and H_0 inference

Namu Kroupa,[1,2,3★] David Yallup,[1,2] Will Handley [1,2] and Michael Hobson[1]

The HARPS search for southern extra-solar planets – XLV. Two Neptune mass planets orbiting HD 13808: a study of stellar activity modelling's impact on planet detection

E. Ahrer [1,2★] D. Queloz,[1,3] V. M. Rajpaul [1] D. Ségransan,[3] F. Bouchy,[3] R. Hall [1] W. Handley [1,4] C. Lovis,[3] M. Mayor,[3] A. Mortier [1,4] F. Pepe,[3] S. Thompson,[1] S. Udry[3] and N. Unger [3]

Global analysis of the TRAPPIST Ultra-Cool Dwarf Transit Survey

F. Lienhard [1★] D. Queloz,[1] M. Gillon,[2] A. Burdanov [3,4] L. Delrez [1,2,5] E. Ducrot,[2] W. Handley,[1] E. Jehin,[5] C. A. Murray [1] A. H. M. J. Triaud [6] E. Gillen [1‡] A. Mortier [1] and B. V. Rackham [3,7†]

On the Feasibility of Intense Radial Velocity Surveys for Earth-Twin Discoveries

Richard D. Hall,[1★] Samantha J. Thompson,[1] Will Handley[1,2] and Didier Queloz[1,3]

GAMBIT

Interdisciplinary case studies

- GAMBIT is an interdisciplinary community and software framework.
- Like `CosmoMC`/`Cobaya`/`Bilby`, an organiser of data, likelihoods & theory, including:
  - Collider data (e.g. LHC)
  - Direct detections (e.g. XENON1T)
  - Cosmology (`MontePython`)
  - Astrophysics (e.g. Bullet Cluster, Supernovae)
  - Pulsar timing
  - … & much more
- `GravBit` and `LowEnergyBit` arising from GAMBIT@KICC workshop

GAMBIT: sub-GeV Dark matter constraints

Interdisciplinary case studies

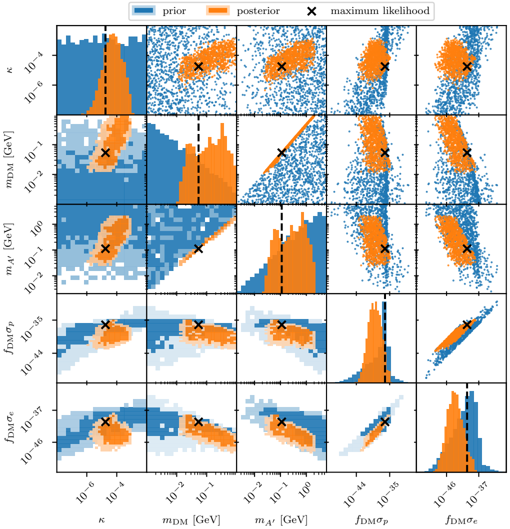
- Physical model of sub-GeV thermal dark matter with a dark photon mediator A:

$$\mathcal{L}_{\text{int}} = -\frac{1}{2}m_{A'}^2 A'^{\mu} A'_{\mu} - \frac{1}{4}A'^{\mu\nu}A'_{\mu\nu} - \kappa e A'^{\mu}\sum_f q_f \bar{f}\gamma_\mu f \,,$$

- Constrain using cosmological, astrophysical, accelerator & direct detection data.
- Bayesian Model comparison of Fermion ψ vs scalar Φ models (scalar preferred).

$$\mathcal{L}_\psi = \bar{\psi}(i\partial\!\!\!/ - m_{\text{DM}})\psi + g_{\text{DM}}A'^{\mu}\bar{\psi}\gamma_\mu\psi \,,$$

$$\mathcal{L}_\Phi = |\partial_\mu\Phi|^2 - m_{\text{DM}}^2|\Phi|^2 - g_{\text{DM}}^2 A'_\mu A'^{\mu}|\Phi|^2 + i g_{\text{DM}} A'^{\mu}\left[\Phi^*(\partial_\mu\Phi) - (\partial_\mu\Phi^*)\Phi\right] \,,$$

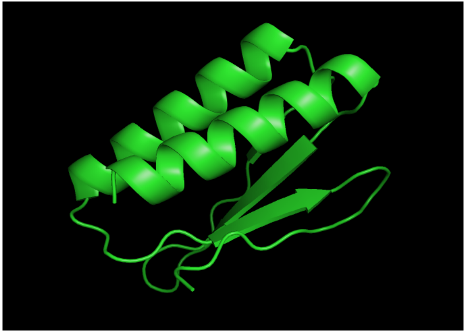


PolyChord Ltd: interdisciplinary R&D spinout

Interdisciplinary case studies

Catherine Watkinson
Senior Data Scientist

- Techniques have been spun-out (PolyChord Ltd) to:
- Protein folding
  - Navigating free energy surface.
  - Computing misfolds.
  - Thermal motion.
- Nuclear fusion reactor optimisation
  - multi-objective.
  - uncertainty propagation.
- Telecoms & DSTL research (MIDAS)
  - Optimising placement of transmitters/sensors.
  - Maximum information data acquisition strategies.



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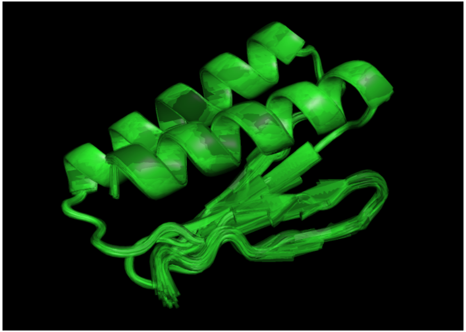

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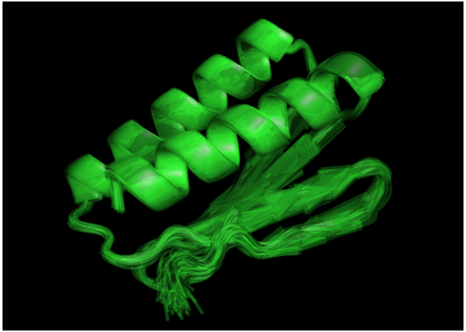

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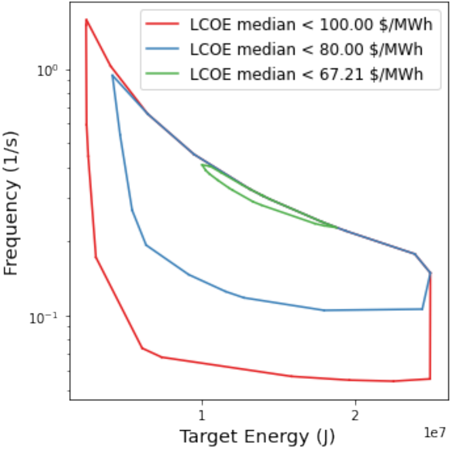

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PhD → Data Scientist

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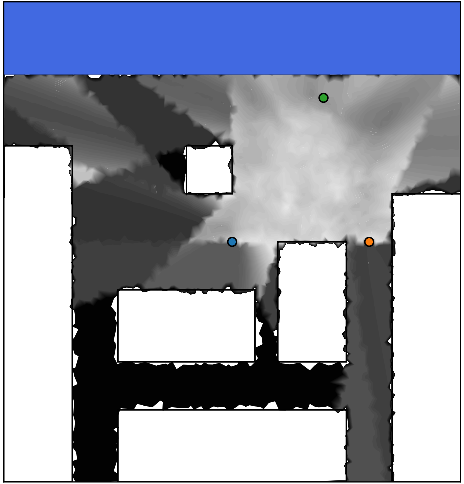

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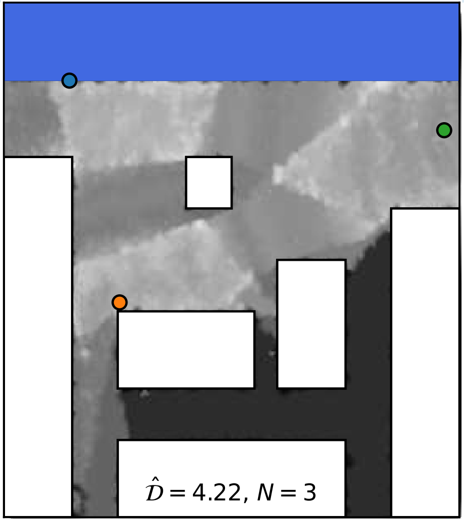

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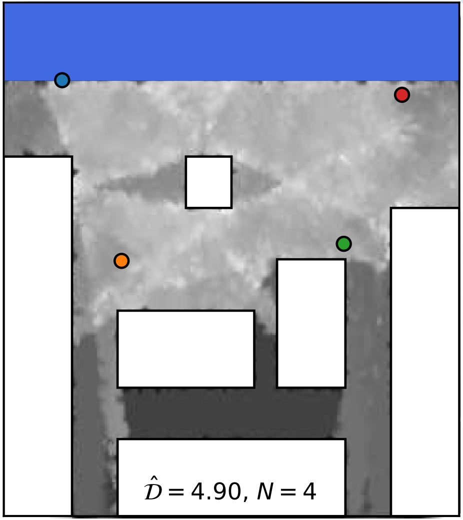

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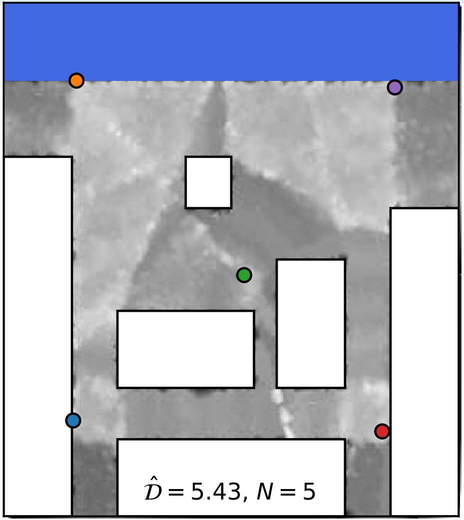
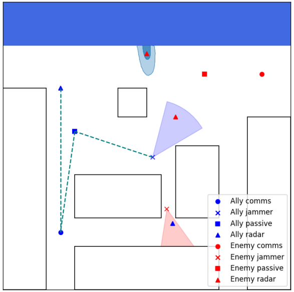


DSTL: Bayesian OODA loops

Interdisciplinary case studies

- Work through Isaac Newton Institute with Defence Science & Technology Laboratory.
- Quantification of "OODA" loop concept from litigation, business, law enforcement, management and military strategy



- Two-way research interaction between government and academia.
- techniques now being used in REACH antenna design [2309.06942]

Observe
Collect data $\boldsymbol{D}$ about system $\boldsymbol{\theta}$ using strategy $\boldsymbol{s}$.

Orient
Update knowledge from prior $\pi(\boldsymbol{\theta})$ to posterior $\mathcal{P}(\boldsymbol{\theta}|\boldsymbol{D})$.

MIDAS

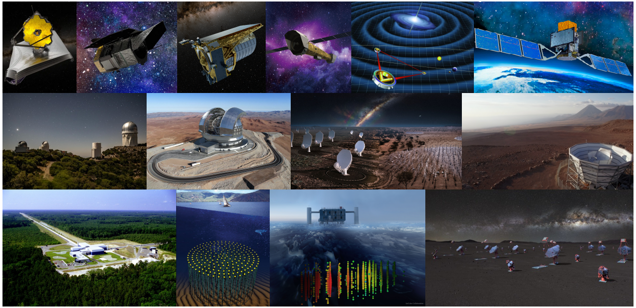
Decide
choose strategy $\boldsymbol{s}$ using information $\hat{\mathcal{D}}_{\mathrm{KL}}(\boldsymbol{s}|\mathcal{P})$.

Act
Execute strategy $\boldsymbol{s}$
Replace prior π with posterior $\mathcal{P}$

Beginning the golden age of astronomy data

- Over our research lifetimes we will see next-generation data rates across the electromagnetic spectrum & beyond:

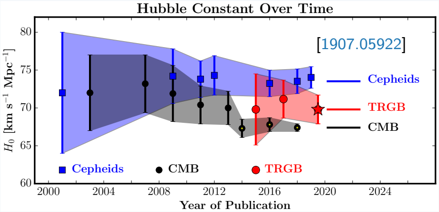
Radio	SKA *et al*
Micro	SO/CMB-S4/LiteBIRD
IR	JWST, Roman
Optical	Euclid, DESI, Rubin, EELT
X-ray	Athena
Gamma-ray	e-ASTROGAM
Gravitational	LIGO/LVK^{+}/LISA
Particle	CTA, IceCube, KM3NeT



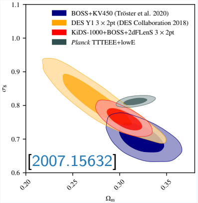
- This ever-increasing statistical weight will mean true accuracy demands rigorous attention to systematics.
- This applies to all of cosmology, astrophysics, particle physics and beyond.

Tensions in cosmology

Hubble

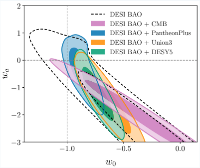


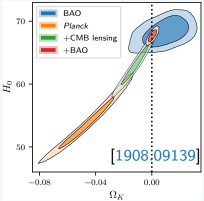
Weak lensing



other $w_0/\Omega_K/\nu$?

[2404.03002]





- Tensions have been appearing in cosmology over the last five years.
- Though their significance may be debatable, they have revealed a gap in the armour of modern data analysis.
- Likelihood-based methods have to assume a fiducial cosmology.
- This will cast greater doubt on the robustness of our conclusions from stage 4 surveys and beyond.

DESI BAO paper: [2404.03000]

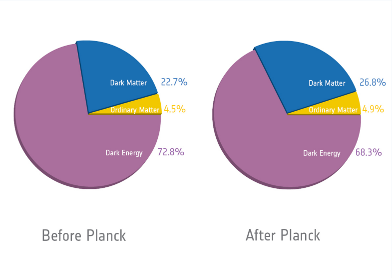
5.4 Systematics due to the assumption of the fiducial cosmology

In this subsection, we summarize the impact of using a wrong fiducial cosmology in the BAO analysis, which were extensively studied in [51].

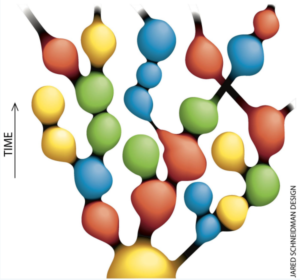
The choice of reference cosmology comes into play at three different stages. First, we assume a set of cosmological parameters when converting redshift measurements into distances; we term this the **grid cosmology**. The difference between the grid and true cosmologies causes a distortion of the BAO scale along and across the line of sight [10], which is quantified by the parameters $q_{\parallel} = H_{\rm grid}(z)/H_{\rm true}(z)$ and $q_{\perp} = D_{\rm true}(z)/D_{\rm grid}(z)$ respectively. Without the three-dimensional standard ruler like BAO, this effect is somewhat degenerate with the redshift-space distortions, but with a sufficiently large data set, such as we have with DESI, and with the BAO feature it is possible to distinguish between the two [145, 146]. Second, a **template cosmology** is chosen in order to compute the linear power spectrum, which is then used to create the model power spectrum for the fitting ($P_{\rm nw}$ and P_w in Eq. (4.1)). The effect of fixing the template is interpreted as an additional isotropic rescaling of the distances by a factor of $r_d^{\rm tem}/r_d^{\rm true}$. Lastly, the values for the linear bias b_1 and the growth rate $f(z)$ input into the reconstruction algorithm are cosmology dependent, affecting the estimation of the displacement field. The separate effect of both the template and the values assumed for reconstruction have been comprehensibly studied in the past [147–150], as well as the joint effect of consistently changing the reference cosmology in the whole pipeline [114], while the separate effect of the grid is less explored [151]. Potential systematic shifts of the order of a few tenths of a percent in the alpha values have been reported in the most extreme scenarios.

The real tensions in the room

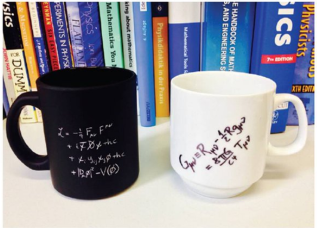
Dark tension



Initial conditions



Quantum gravity



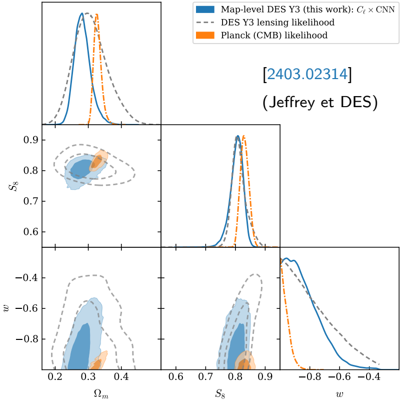
- These are existential questions that don't go away if ΛCDM is phenomenologically correct...
- ...and if it is, we will need an interdisciplinary approach that goes far beyond cosmology (using astronomy, collider & experimental physics).
- The GW redshift frontier, time domain astronomy & 21cm SKA will be the key tools for challenging our astronomical understanding.

The future: simulation-based inference

Kilian Scheutwinkel
PhD

- Traditional Likelihood-based inference (LBI) requires knowledge of the likelihood $P(D|\theta)$
  - For the CMB, it is possible to compute Probability(Sky|ΛCDM) [with caveats]
  - For almost everybody else (different models, more evolved systems), the likelihood is approximate
- Simulation-based inference learns the likelihood from physical simulations $\theta \to D$.

- Can extract nonlinear information from data.
- Do not need to assume a fiducial model, since data covariance is implicit in simulations.
- Users do not need to know advanced statistics
  - For this reason alone, it will come to dominate the next generation $\Rightarrow$ imperative to build a principled understanding!
- My interest has been in understanding how essential machine learning is by building analytics `github.com/handley-lab/lsbi`
- Have also made progress on the first simulation-based nested sampler `PolySwyft` (presenting at EuCAIFCon)



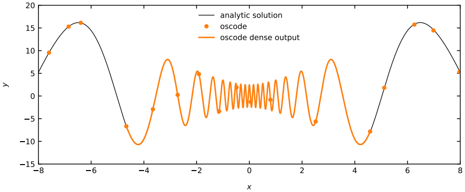
[2403.02314]
(Jeffrey et DES)

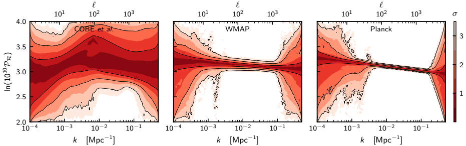
ERC grant: COSMOTENSION

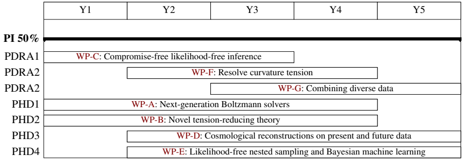
willhandley.co.uk/ERC.pdf

Resolving cosmological tensions with diverse data, novel theories and Bayesian machine learning

- ERC starting grant $\Rightarrow$ UKRI Frontier, commencing October 2024.
- Funds 3 PDRAs and 4 PhDs over 5 years.
- Research programme centered around combining novel theories of gravity, Boltzmann solvers [1906.01421], reconstruction [1908.00906], nested sampling & simulation-based inference (née LFI).
- Aims to disentangle cosmological tensions H_0, σ_8, Ω_K with next-generation data analysis techniques.







Conclusions

github.com/handley-lab

- The astronomy challenges of our generation are interdisciplinary.
- Interdisciplinary approaches are two-way streets for innovation.
- Simulation-based inference represents the frontier of how we will all be doing data analysis.
- Our research programme at the interface between theory, observation and inference is well-placed to explore the interdisciplinary frontier.