

# Next-generation astrophysical inference across the interdisciplinary frontier

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Kavli Institute for Cosmology, Cambridge  
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29<sup>th</sup> April 2024



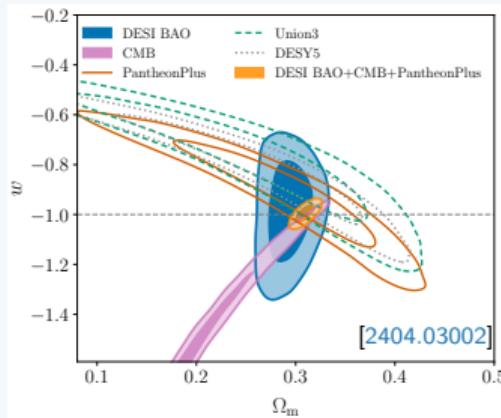
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CAMBRIDGE



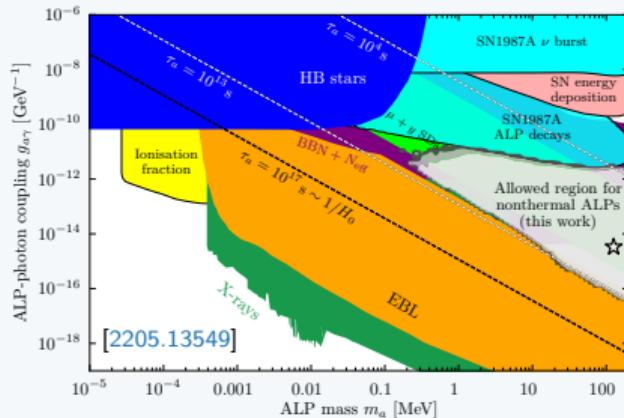
# The future of astronomy is interdisciplinary

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

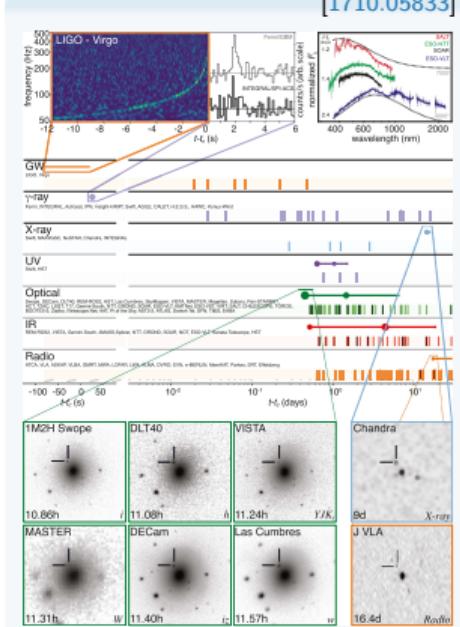
## CMB+BAO



## HEP+Astro



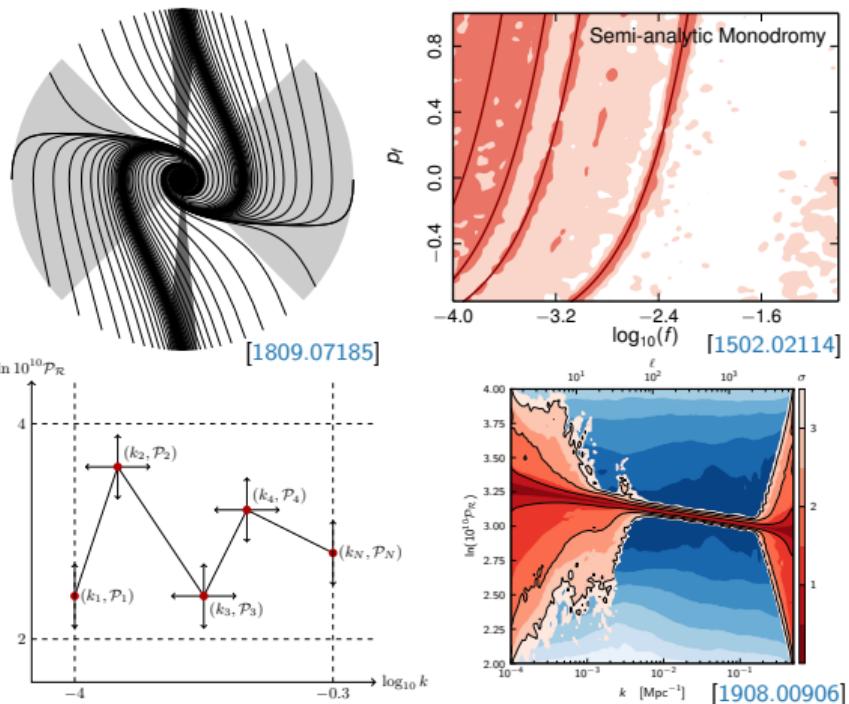
## GW170817



- ▶ 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]

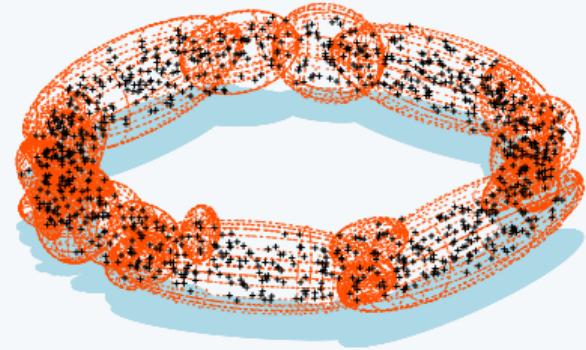


# Analytic innovation: from MultiNest to PolyChord

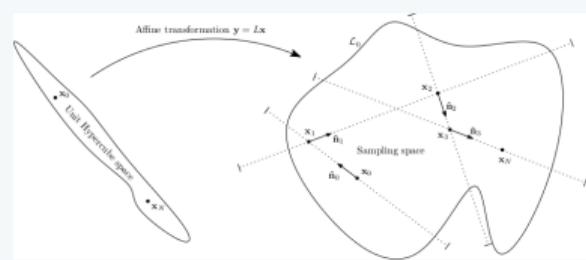
- ▶ MultiNest [0809.3437] was the leading Bayesian numerical model comparison tool in 2013.
  - ▶ A general purpose & performant implementation of John Skilling's nested sampling meta-algorithm.
  - ▶ Remains the leader of the pack in  $n \sim \mathcal{O}(10)$  parameter fits.
  - ▶ Careful testing in *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  $f_{\text{PC}} \sim \frac{1}{n}$  with model parameters (c.f. exponential  $f_{\text{MN}} \sim e^{-n/n_0}$ ).
- ▶ 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)

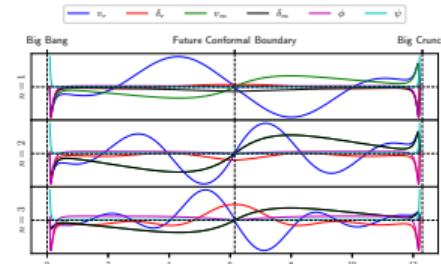
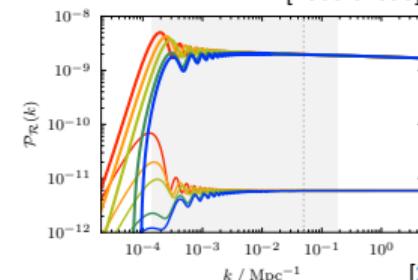
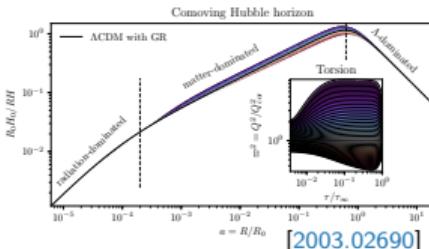


energy tensor (5). Inserting the mode function (26) into (32) and taking the coincidence limit, one finds:

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

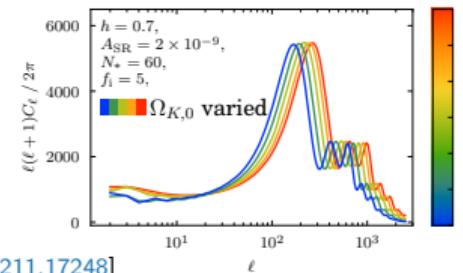
where  $\tilde{T}$  signifies the plethora of additional terms arising from the renormalisation process that have no dependence on the variables  $\mathcal{X}$ . Minimising this with respect

[1607.04148]



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

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



# 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](http://arxiv.org/a/handley_w_1.html)

Will showcase a targeted subset.

# 21cm cosmology

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

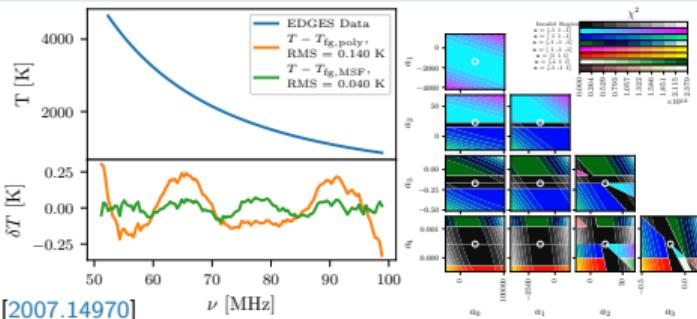
- ▶ **maxsmooth** [2007.14970]
  - ▶ quadratic programming choice arose from quantitative finance consultancy work
- ▶ **FlexKnots**
  - ▶ importing ideas from inflationary reconstruction into reionisation [2310.05608](Heimersheim) & ionospheric reconstruction [2311.14537](Shen).
- ▶ **margarine** [2205.12841] [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.

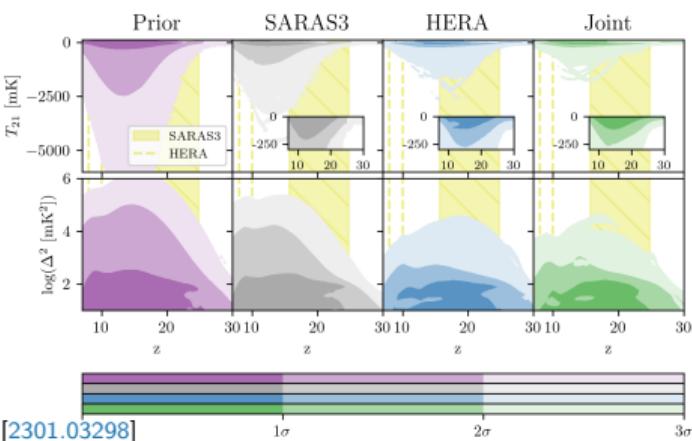
Harry Bevins



PhD→KICC fellow



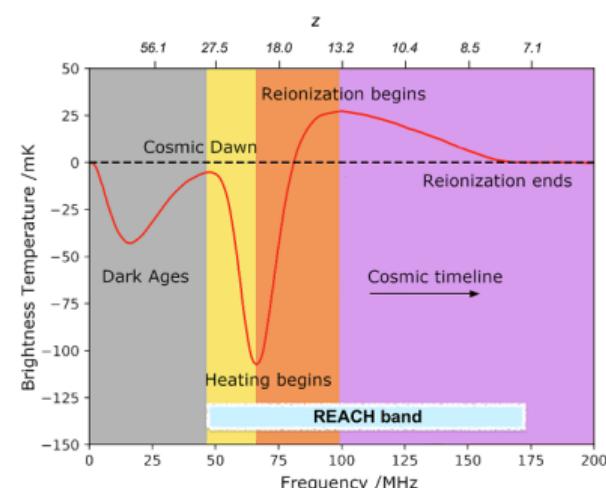
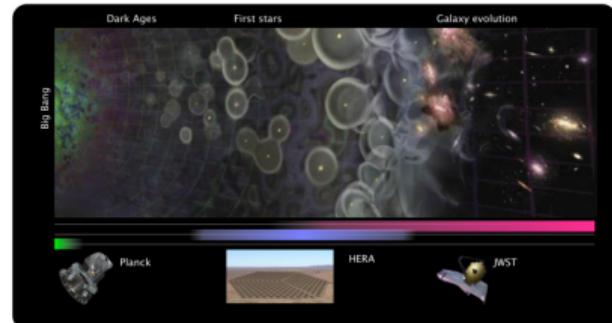
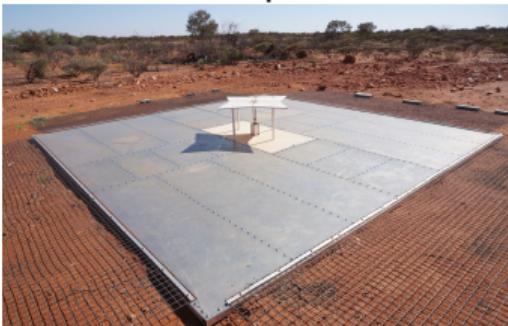
[2007.14970]



[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)

Advance Access publication 2018 April 28



doi:10.1093/mnras/sty1079

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

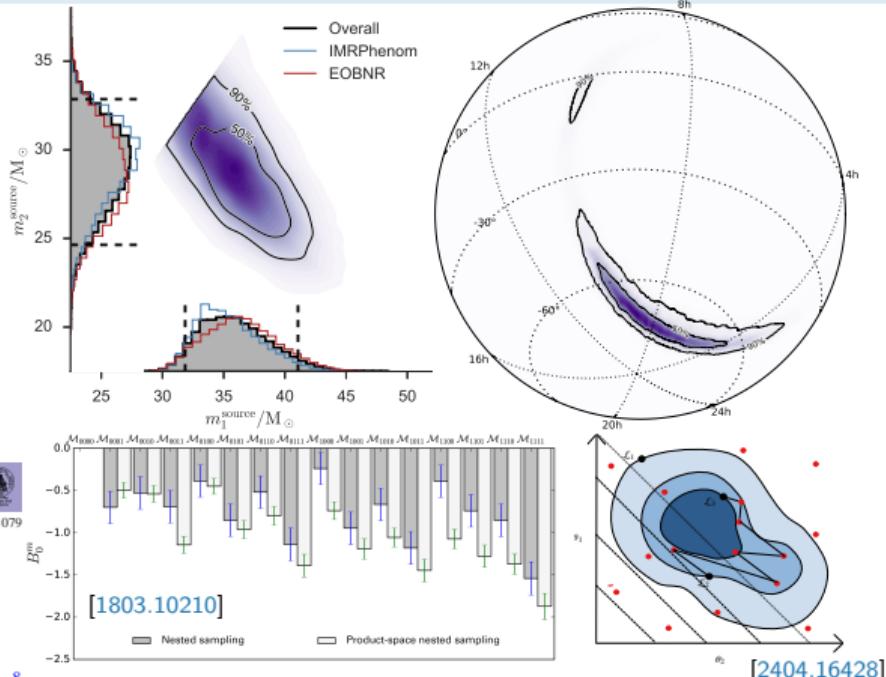
A. J. K. Chua,<sup>1,2\*</sup> S. Hee,<sup>3,4</sup> W. J. Handley,<sup>3,4,5</sup> E. Higson,<sup>3,4</sup> C. J. Moore,<sup>6,7</sup> J. R. Gair,<sup>8</sup> M. P. Hobson<sup>3</sup> and A. N. Lasenby<sup>3,4</sup>

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

Metha Prathaban<sup>1,2,3\*</sup> and Will Handley<sup>1,2,4†</sup>

<wh260@cam.ac.uk>

willhandley.co.uk/talks



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



- ▶ 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.

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

Namu Kroupa,<sup>1,2,3\*</sup> David Yallup,<sup>1,2</sup> Will Handley<sup>3</sup> and Michael Hobson<sup>1</sup>

## 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<sup>1,2</sup>, D. Queloz,<sup>1,3</sup> V. M. Rajpaul<sup>1</sup>, D. Ségransan,<sup>3</sup> F. Bouchy,<sup>3</sup> R. Hall<sup>1</sup>, W. Handley<sup>1,4</sup>, C. Lovis,<sup>3</sup> M. Mayor,<sup>3</sup> A. Mortier<sup>1,4</sup>, F. Pepe,<sup>3</sup> S. Thompson,<sup>1</sup> S. Udry<sup>3</sup> and N. Unger<sup>1,3</sup>

## Global analysis of the TRAPPIST Ultra-Cool Dwarf Transit Survey

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

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

Richard D. Hall,<sup>1</sup>\*, Samantha J. Thompson,<sup>1</sup> Will Handley<sup>1,2</sup> and Didier Queloz<sup>1,3</sup>

# 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

Felix Kahlhoefer et al

GAMBIT cosmo/DM working group



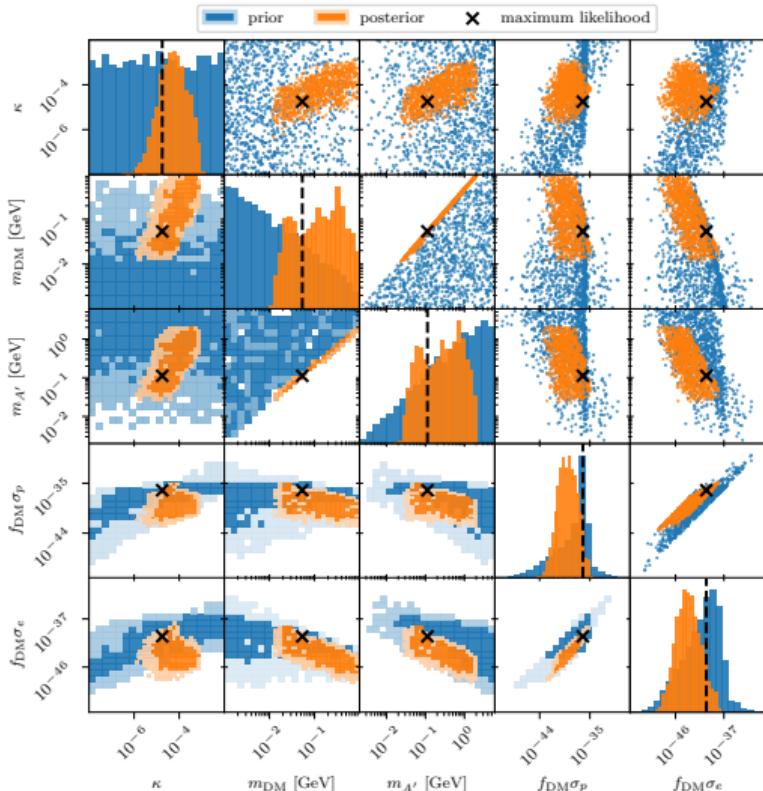
- ▶ Physical model of sub-GeV thermal dark matter with a dark photon mediator  $A$ :

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

- ▶ Constrain using cosmological, astrophysical, accelerator & direct detection data.
- ▶ Bayesian Model comparison of Fermion  $\psi$  vs scalar  $\Phi$  models (scalar preferred).

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

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



# PolyChord Ltd: interdisciplinary R&D spinout

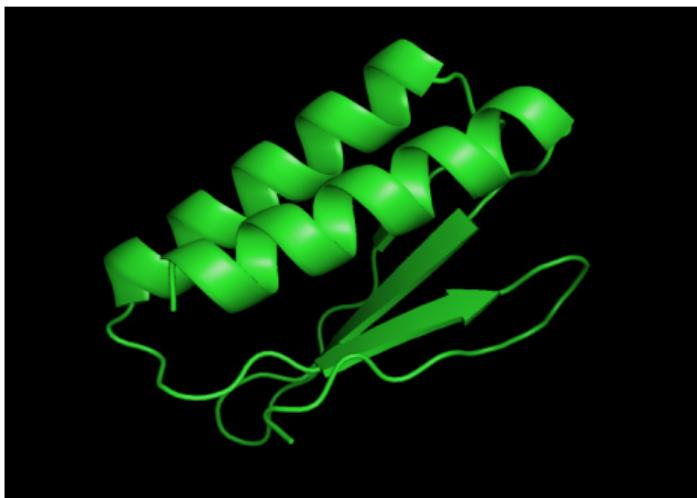
## Interdisciplinary case studies

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.



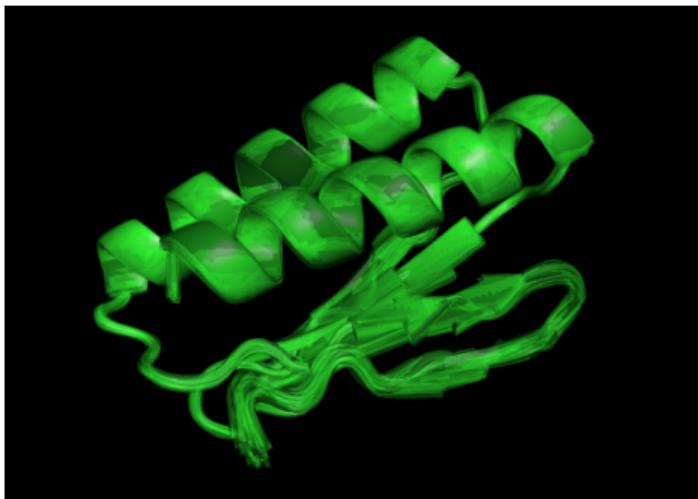
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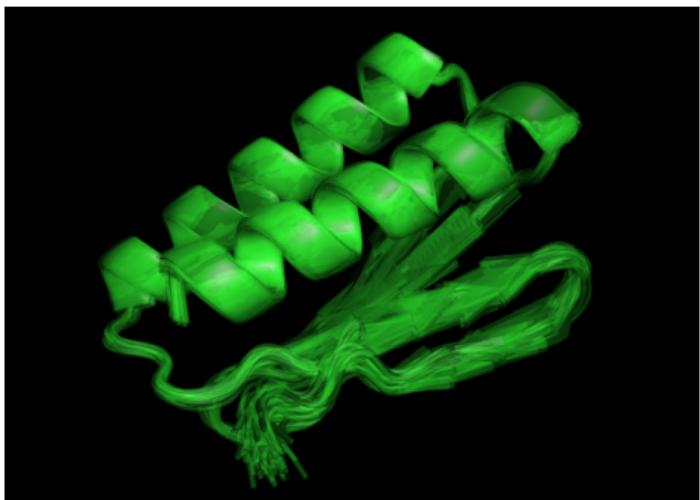
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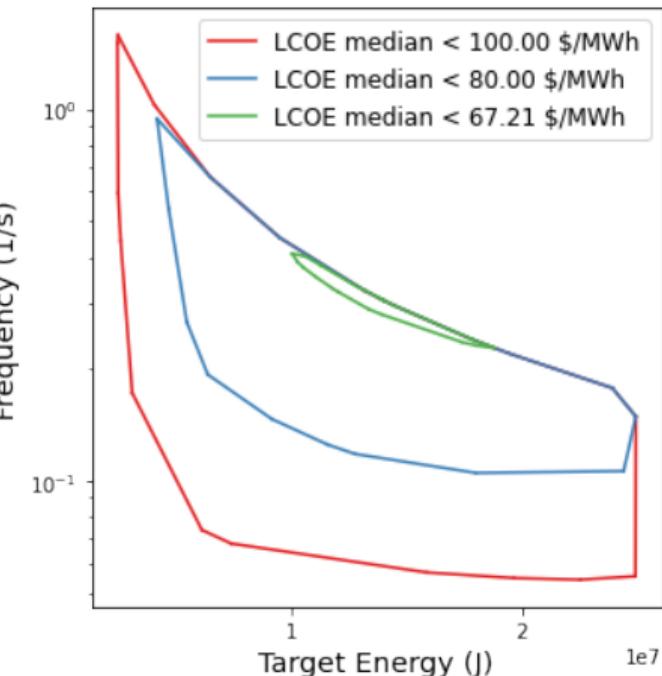
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Senior Data Scientist



# PolyChord Ltd: interdisciplinary R&D spinout

## Interdisciplinary case studies

Thomas Mcaloone

PhD → Data Scientist



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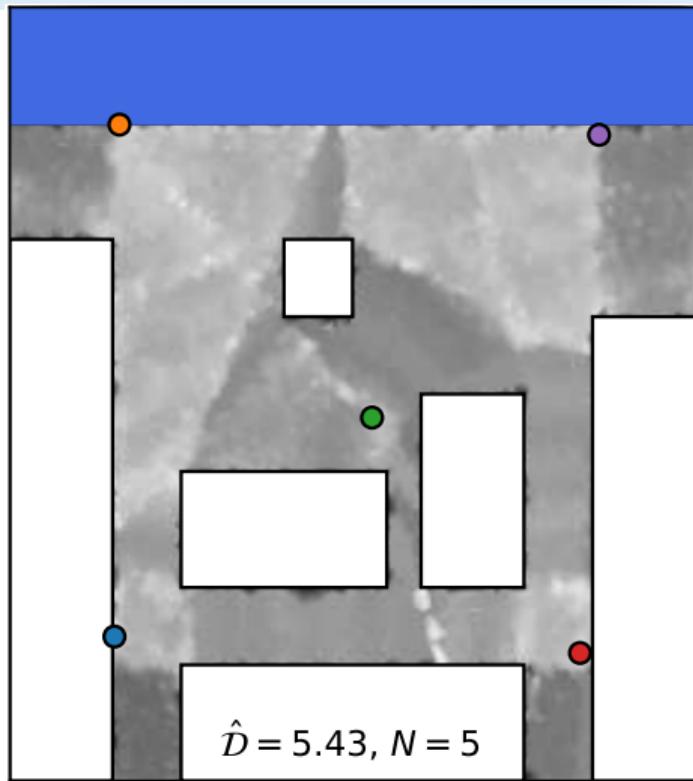
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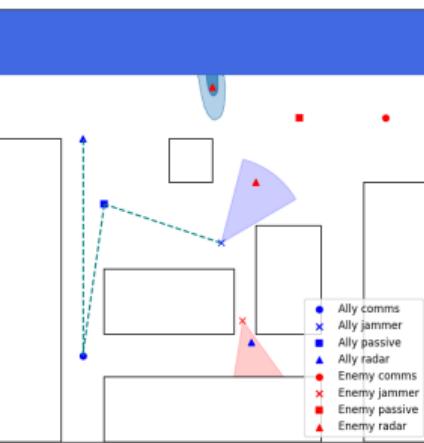
PhD → Data Scientist



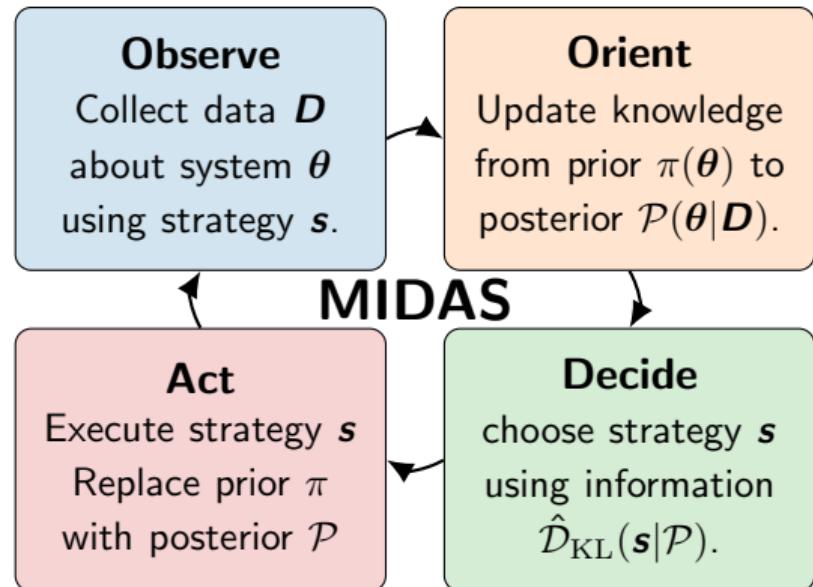
# DSTL: Bayesian OODA loops

## 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]



# 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

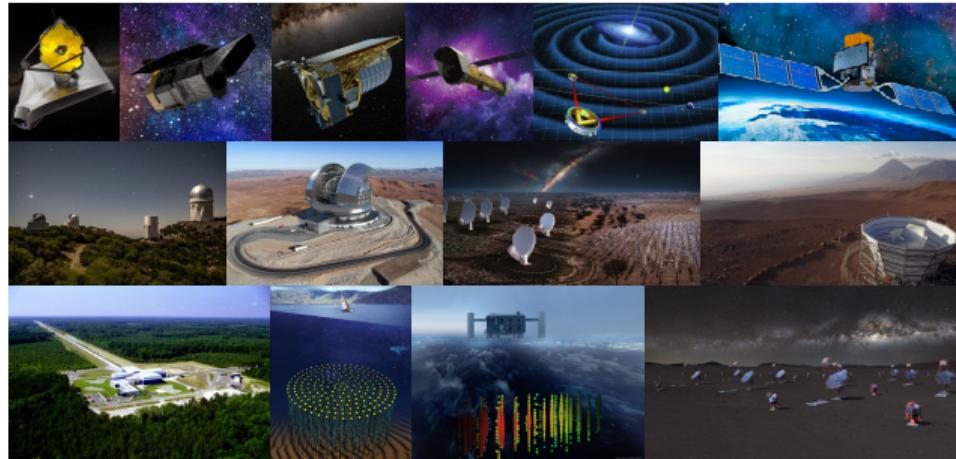
Optical Euclid, DESI, Rubin, EELT

X-ray Athena

Gamma-ray e-ASTROGAM

Gravitational LIGO/LVK<sup>+</sup>/LISA

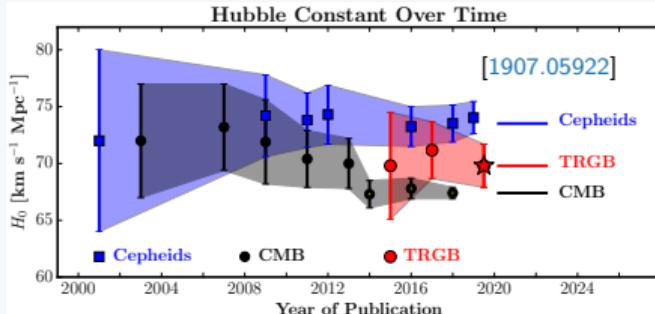
Particle CTA, IceCube, KM3NeT



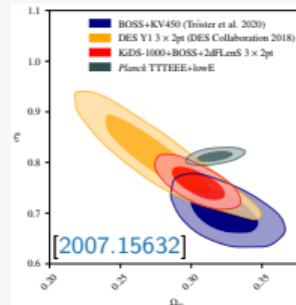
- ▶ This ever-increasing statistical weight will mean true accuracy demands rigorous attention to systematics.
- ▶ This applies to all of cosmology, astrophysics, particle physics and beyond.

# Tensions in cosmology

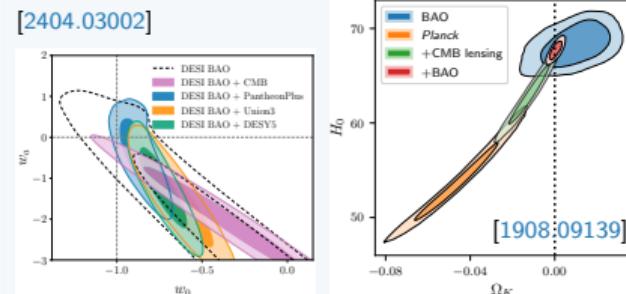
## Hubble



## Weak lensing



## other $w_0/\Omega_K/\nu?$



- ▶ 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]

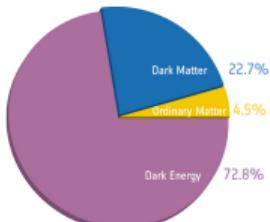
### 5.4 Systematics due to the assumption of the fiducial cosmology

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

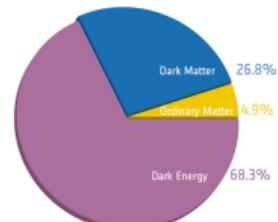
The choice of reference cosmology comes into play at three different stages. First, we assume a set of cosmological parameters when converting redshift measurements into distances, we term this the *grid cosmology*. The difference between the grid and true cosmology causes a distortion of the BAO scale along and across the line of sight [10], which is quantified by the parameters  $\eta_1 = H_{\text{grid}}(z)/H_{\text{true}}(z)$  and  $\eta_2 = D_{\text{grid}}(z)/D_{\text{true}}(z)$  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 ( $P_{\text{fit}}$  and  $P_{\text{c}}$  in Eq. (4.1)). The effect of fixing the template is interpreted as an additional isotropic rescaling of the distances by a factor of  $\eta_{\text{true}}^{\text{non-lin}}/\eta_{\text{grid}}^{\text{non-lin}}$ . 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 comprehensively 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

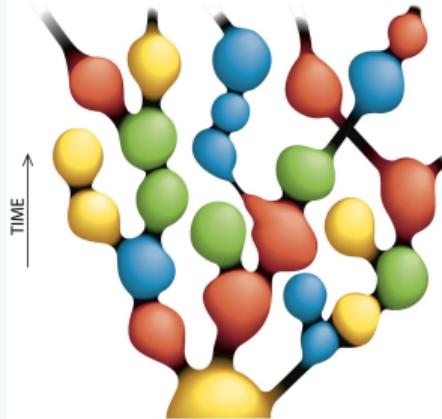


Before Planck

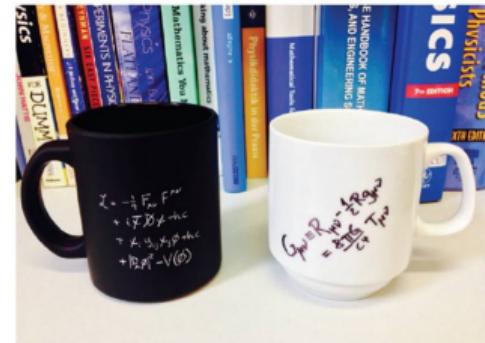


After Planck

## Initial conditions



## Quantum gravity



- ▶ These are existential questions that don't go away if  $\Lambda$ CDM 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.

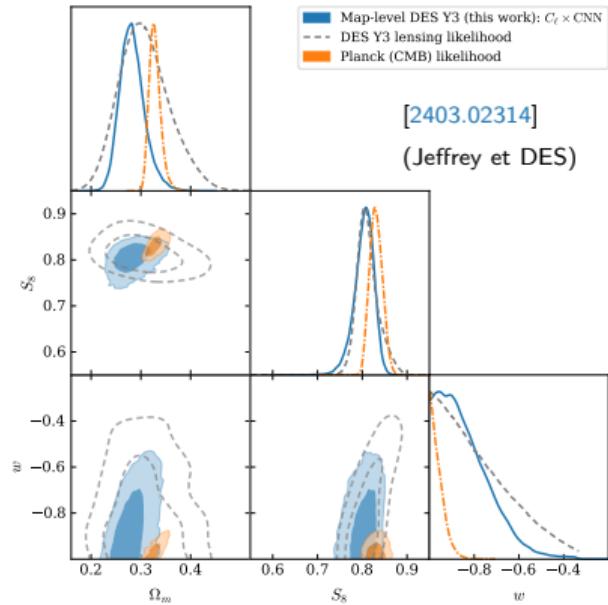
# The future: simulation-based inference

Kilian Scheutwinkel

PhD



- ▶ Traditional Likelihood-based inference (LBI) requires knowledge of the likelihood  $P(D|\theta)$ 
  - ▶ For the CMB, it is possible to compute  $\text{Probability}(\text{Sky}|\Lambda\text{CDM})$  [with caveats]
  - ▶ For almost everybody else (different models, more evolved systems), the likelihood is approximate
- ▶ Simulation-based inference learns the likelihood from physical simulations  $\theta \rightarrow D$ .
- ▶ 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/lsvbi](https://github.com/handley-lab/lsvbi)
- ▶ Have also made progress on the first simulation-based nested sampler PolySwyft (presenting at EuCAIFCon)

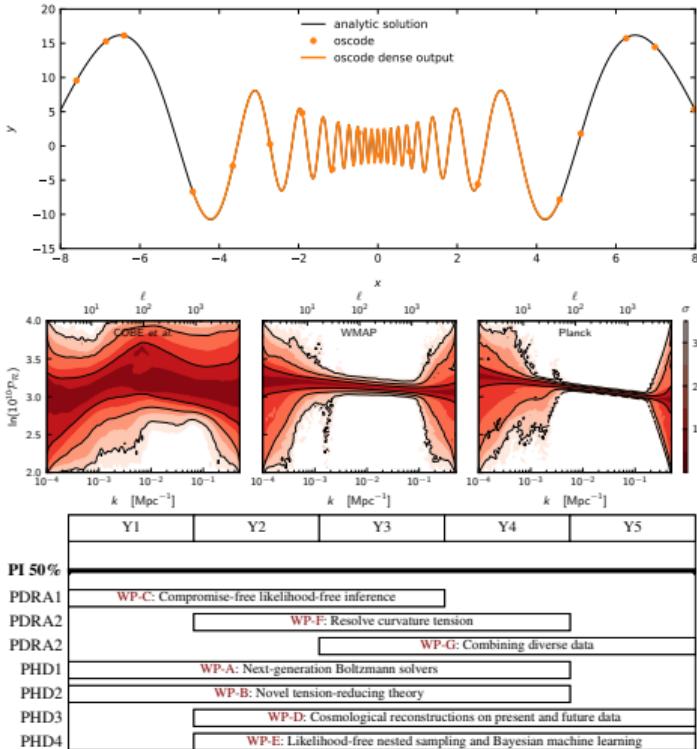


# ERC grant: COSMOTENSION

[willhandley.co.uk/ERC.pdf](http://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  $H_0$ ,  $\sigma_8$ ,  $\Omega_K$  with next-generation data analysis techniques.



# Conclusions

[github.com/handley-lab](https://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.

