KICP CELEBRATION 20 YEARS CHICAGO - 2024

KICP

20TH ANNIVERSARY CELEBRATION

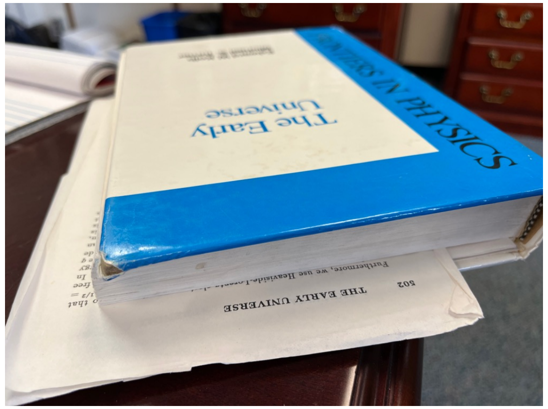
COSMOLOGY PAST, PRESENT, AND FUTURE

JUNE 6-8, 2024 • CHICAGO

Breaking a Model by Making a Map

Scott Dodelson, Alan Junzhe Zhou, …

KICP@20: The Compelling Idea



Age old questions:

-- What is stuff made of?

-- What is out there? How did we get here?

We have two advantages over people in the past (who were no less smart than us):

1. Data

2. Answering the second of these ***requires*** an answer to the first. Answering the second may help us understand the first.

People at UC/Fermilab from 1985-2000 helped birth this idea

By 2000, a fiducial model had been established

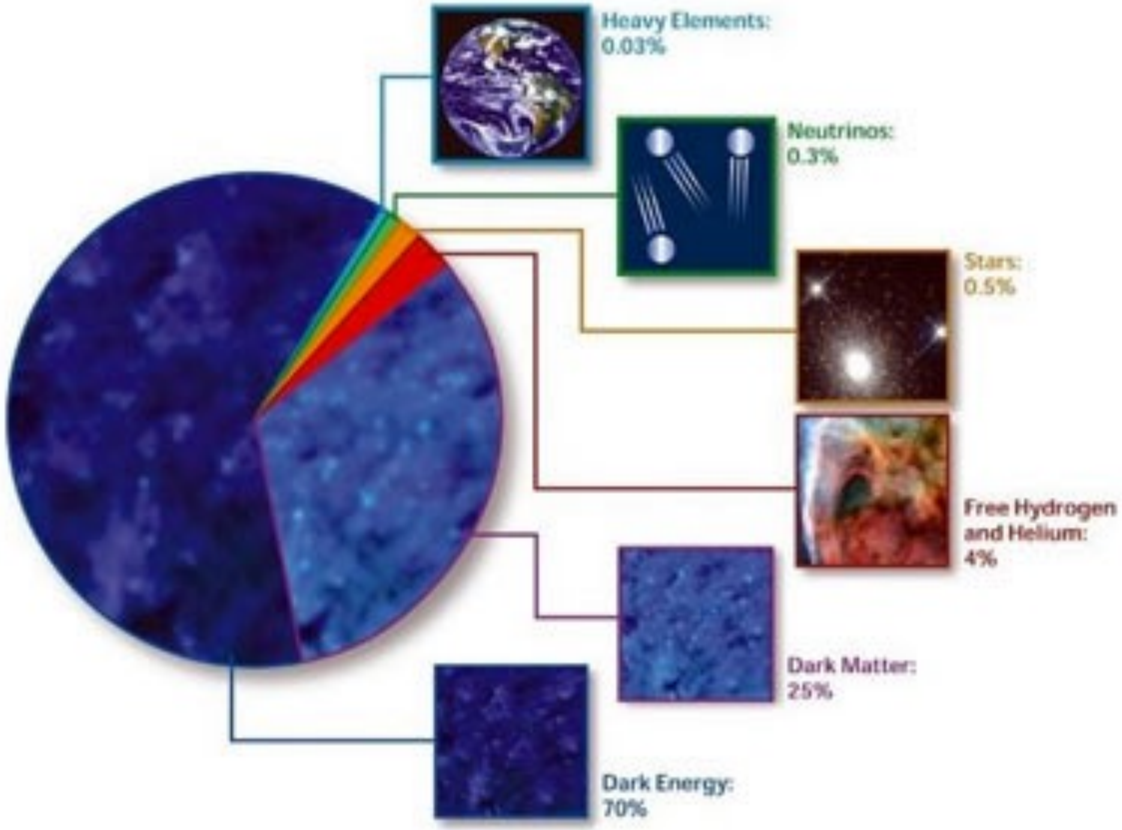
ARTICLE

Cold Dark Matter

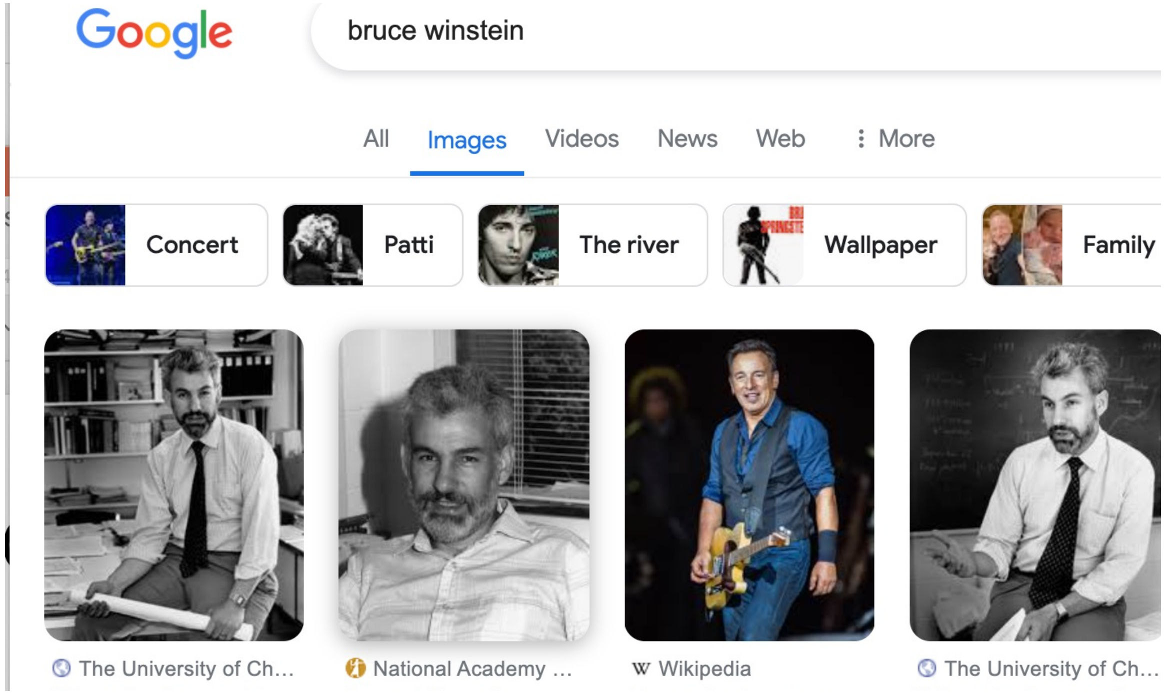
Science 1996

Scott Dodelson, Evalyn I. Gates, Michael S. Turner

These above considerations, with the possible exception of the preliminary determination of q_0, favor ΛCDM (44). Most



Center for Cosmological Physics: 2001



arXiv > astro-ph > arXiv:astro-ph/0111606

Astrophysics

[Submitted on 30 Nov 2001 (v1), last revised 17 May 2002 (this version, v3)]

Mass Reconstruction with CMB Polarization

Wayne Hu (CfCP, U. Chicago), Takemi Okamoto (U. Chicago)

Weak gravitational lensing by the intervening large-scale structure of the Universe induces high-order correlations in the cosmic microwave background (CMB) temperature and polarization fields. We construct minimum variance estimators of the intervening mass distribution out of the six quadratic combinations of the temperature and polarization fields. Polarization begins to assist in the reconstruction when E-mode mapping becomes possible on degree-scale fields, i.e. for an experiment with a noise level of ~40 uK-arcmin and beam of ~7', similar to the Planck experiment; surpasses the temperature reconstruction at ~26 uK-arcmin and 4'; yet continues to improve the reconstruction until the lensing B-modes are mapped to l ~ 2000 at ~0.3 uK-arcmin and 3'. Ultimately, the correlation between the E and B modes can provide a high signal-to-noise mass map out to multipoles of L ~ 1000, extending the range of temperature-based estimators by nearly an order of magnitude. We outline four applications of mass reconstruction: measurement of the linear power spectrum in projection to the cosmic variance limit out to L ~ 1000 (or wavenumbers 0.002 < k < 0.2 i h/Mpc), cross-correlation with cosmic shear surveys to probe the evolution of structure tomographically, cross-correlation of the mass and temperature maps to probe the dark energy, and the separation of lensing and gravitational wave B-modes.

arXiv > astro-ph > arXiv:astro-ph/0209478

Astrophysics

[Submitted on 23 Sep 2002]

Detection of Polarization in the Cosmic Microwave Background using DASI

J. Kovac (1), E. M. Leitch (1), C. Pryke (1)J. E. Carlstrom (1), N. W. Halverson (2)W. L. Holzapfel (2) ((1) University of Chicago, (2) UC Berkeley)

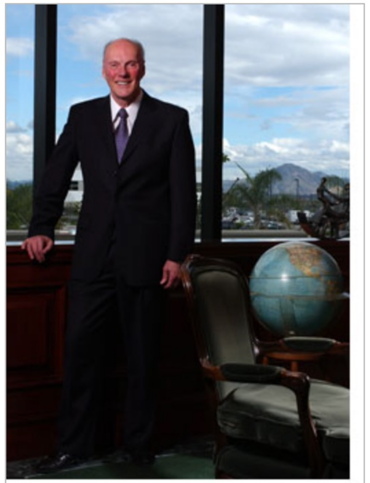
We report the detection of polarized anisotropy in the Cosmic Microwave Background radiation with the Degree Angular Scale Interferometer (DASI), located at the Amundsen-Scott South Pole rese station. Observations in all four Stokes parameters were obtained within two 3.4 FWHM fields separated by one hour in Right Ascension. The fields were selected from the subset of fields observed DASI in 2000 in which no point sources were detected and are located in regions of low Galactic synchrotron and dust emission. The temperature angular power spectrum is consistent with previou measurements and its measured frequency spectral index is -0.01 (-0.16 -- 0.14 at 68% confidence), where 0 corresponds to a 2.73 K Planck spectrum. The power spectrum of the detected polari is consistent with theoretical predictions based on the interpretation of CMB anisotropy as arising from primordial scalar adiabatic fluctuations. Specifically, E-mode polarization is detected at high confidence (4.9 sigma). Assuming a shape for the power spectrum consistent with previous temperature measurements, the level found for the E-mode polarization is 0.80 (0.56 -- 1.10), where th predicted level given previous temperature data is 0.9 -- 1.1. At 95% confidence, an upper limit of 0.59 is set to the level of B-mode polarization with the same shape and normalization as the E-n spectrum. The TE correlation of the temperature and E-mode polarization is detected at 95% confidence, and also found to be consistent with predictions. These results provide strong validation o underlying theoretical framework for the origin of CMB anisotropy and lend confidence to the values of the cosmological parameters that have been derived from CMB measurements.

Early Success led to KICP

Kavli Foundation Grant

March 10, 2004

Steve Koppes
University of Chicago News Office



Fred Kavli, Kavli Foundation Chairman
Photo credit: Mr. Dan Dry

The University of Chicago will devote $7.5 million in donations from Fred Kavli and the Kavli Foundation of Oxnard, Calif., to studying some of the most puzzling scientific questions about the origin and evolution of the universe and the laws that govern it.

The funds will make permanent the Center for Cosmological Physics, established in 2001 by the National Science Foundation. The center will be renamed the Kavli Institute for Cosmological Physics. The new institute is one of seven being established by Kavli around the country and in Europe on brain science, nanoscience and cosmology.

"My goal in establishing these institutes is to support research at the frontiers of science," said Kavli Foundation Chairman Fred Kavli. "I feel that it is especially important to pursue the most far-reaching opportunities and challenges and to seek answers to the most fundamental unanswered questions."

Kavli said he selected the three areas of emphasis because they provide the greatest opportunity for major scientific breakthroughs. "We selected the University of Chicago primarily because of its research strengths in experimental and theoretical cosmology. The presence of an interactive group of outstanding researchers supported by an NSF Physics Frontier Center was also a factor."

The University of Chicago is proud to have the Kavli name associated with its rich tradition of research in physics, astronomy and astrophysics, said University President Don Michael Randel. "This tradition includes our alumnus Edwin Hubble, who discovered 75 years ago that the universe is expanding. With the generous support of Fred Kavli and the Kavli Foundation, our scientists aim to make equally startling discoveries in the years ahead."

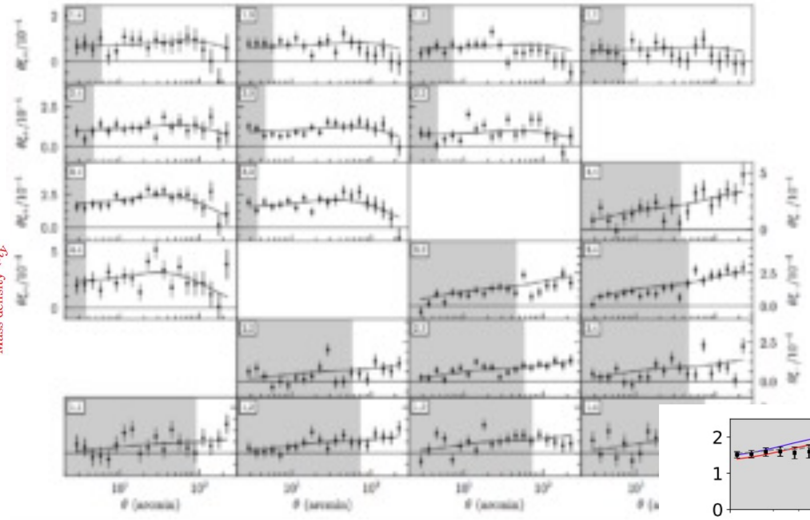
More than 90 scientists and students at the new Kavli Institute carry out research that fuses cosmology with particle physics. Of particular interest to the institute's researchers are the following questions: why is the universe expanding at an accelerating rate, did the universe begin in a burst of expansion called inflation, and did a single unified force influence the beginning of the universe?

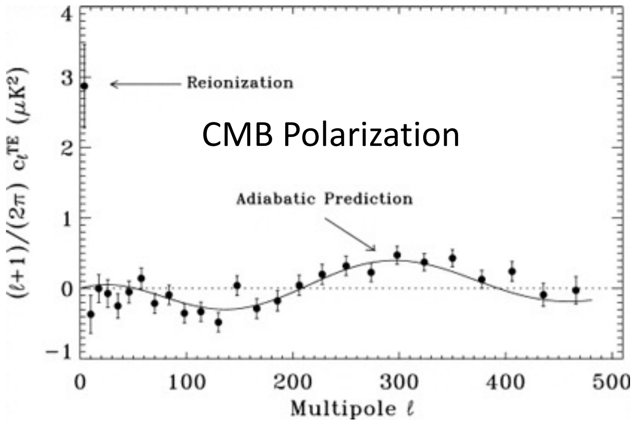
The interdisciplinary work pioneered by David Schramm at the University of Chicago from 1974 until his death in 1997 has established that there are deep and profound connections between the very small quarks and the very

My perspective: Fred Kavli was a pioneer in scientific philanthropy. The Kavli Foundation has been ***carefully impactful.***

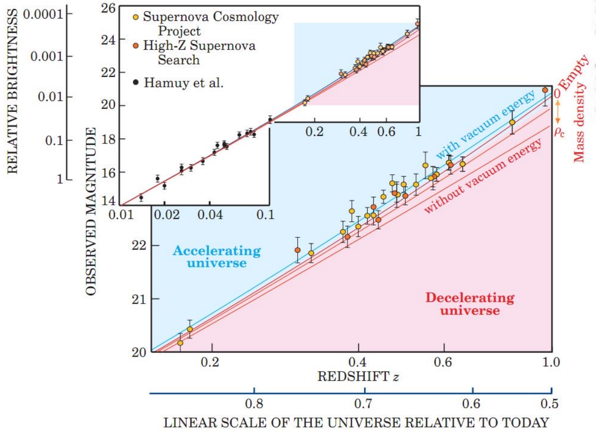
Today, almost all observations support LCDM

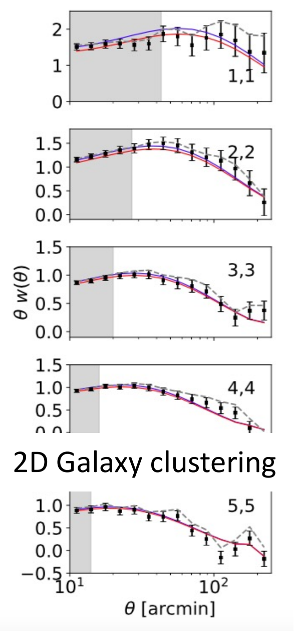
Gravitational Lensing

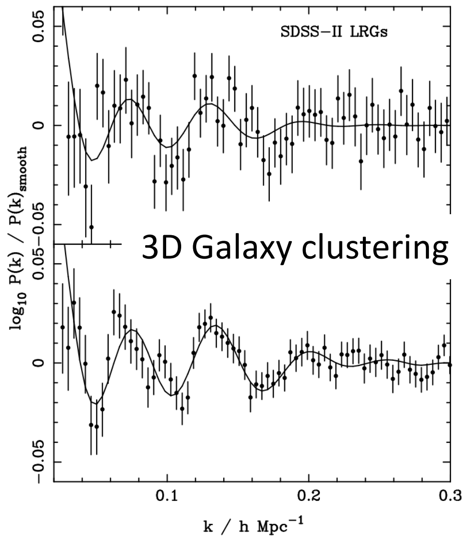


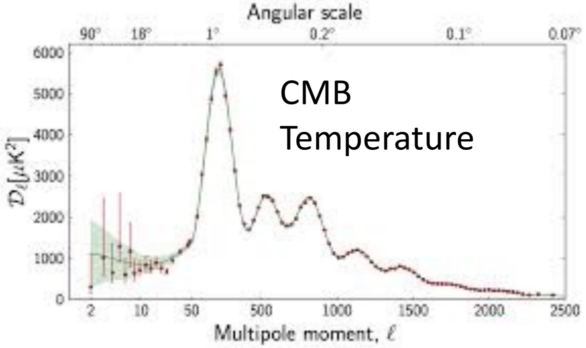


Supernova



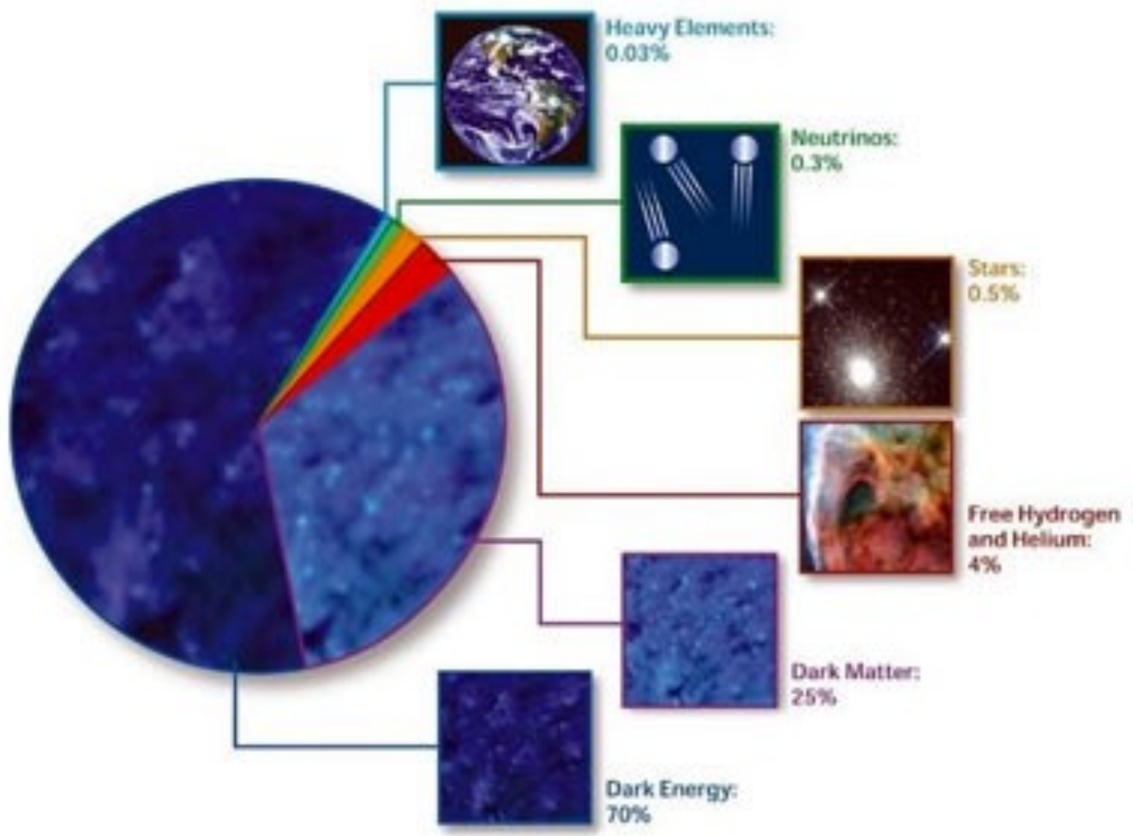






However, the model is built on shaky assumptions …

- Need to *invent* a new field (**inflaton**) at very high energies to solve some basic problems and seed structure
- Need to *invent* a new type of matter, beyond known leptons, quarks, and bosons: **dark matter**
- Need to *specify* the **cosmological constant Λ**, a back-of-the-envelope calculation for which is 128 orders of magnitude too large



We will hear how KICP alum are voting with their feet to chart the course of the coming decades

My perspective

Two possible approaches: search for evidence of the model (detect dark matter or inflationary B-modes) or *try to break the model*.

Best way to break the model: Test the 0-parameter CMB-informed LCDM predictions for growth of structure using surveys.

Challenge: Extract maximal (nonlinear modes) robust (systematic errors < very small statistical errors) information from galaxy surveys

Field Level Inference (done "with" Alan Zhou)

- Data is signal plus noise; assuming the noise is Gaussian leads to the likelihood, the probability of getting the data given the signal
- If the signal is drawn from a Gaussian distribution (e.g., the CMB temperature or the density field on large scales), we can implement a prior on signal at all pixels on the sky and on the cosmological parameters (which typically determine the variance of the signal).

$$-2\ln\mathcal{L} = \left[d - \sum_\alpha s^\alpha\right] [\mathbb{C}^n]^{-1} \left[d - \sum_\beta s^\beta\right]$$

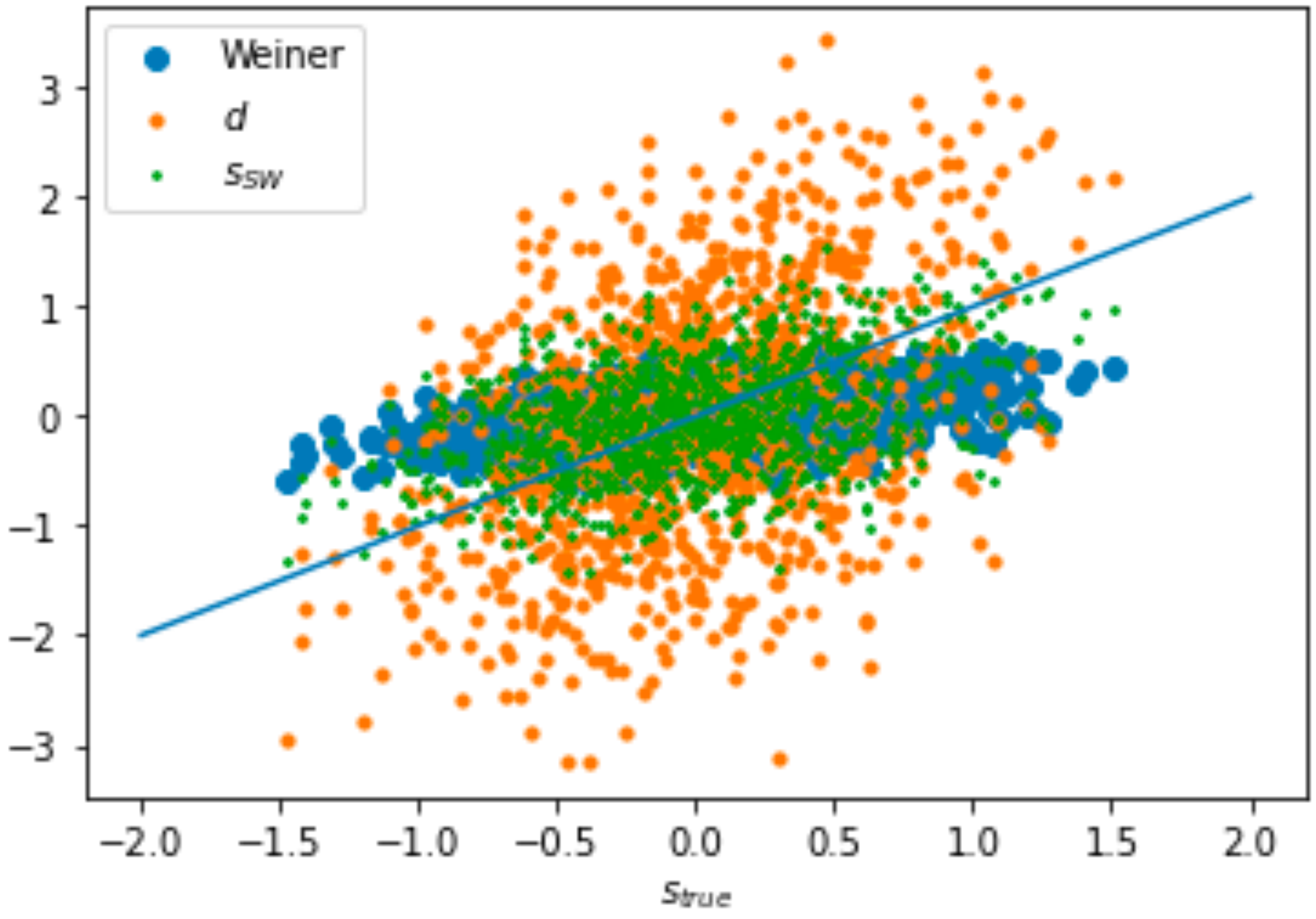
$$-2\ln p = -2\ln\mathcal{L} + \sum_{\alpha\beta} s^\alpha \left(\mathbb{C}^{-1}(\theta)\right)^{\alpha\beta} s^\beta + \ln\det\mathbb{C}(\theta) - 2\ \ln\mathrm{prior}(\theta)$$

Field Level Inference

- Think of the signal in every pixel as a set of parameters.
- The maximum of the posterior is then the Weiner filter:

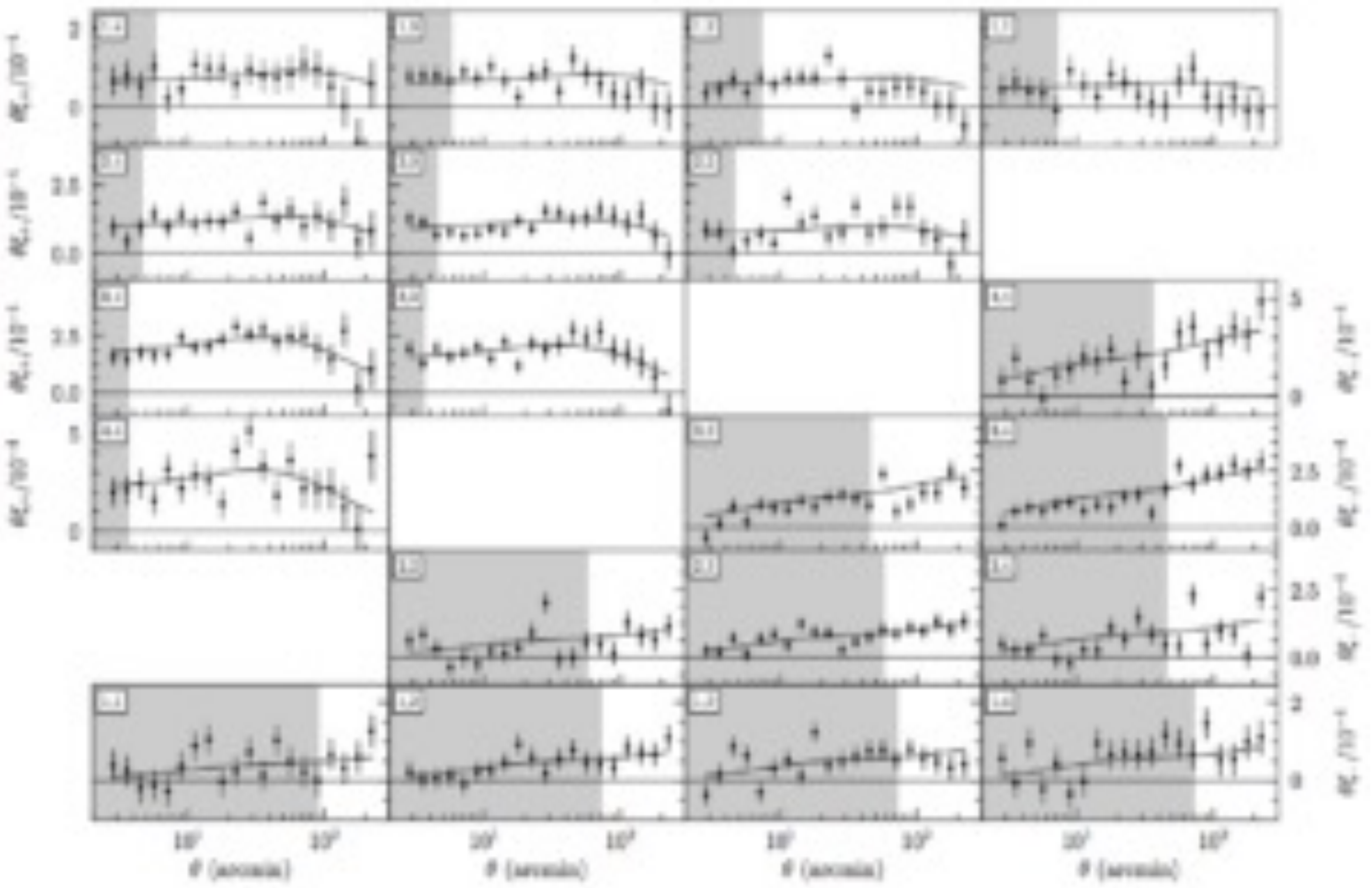
$$s = \frac{C^s}{C^s + C^N} \mathrm{d}$$

- The power spectrum of the Weiner-filtered map (the Maximum of the Posterior) is suppressed by the ratio of the signal to noise.



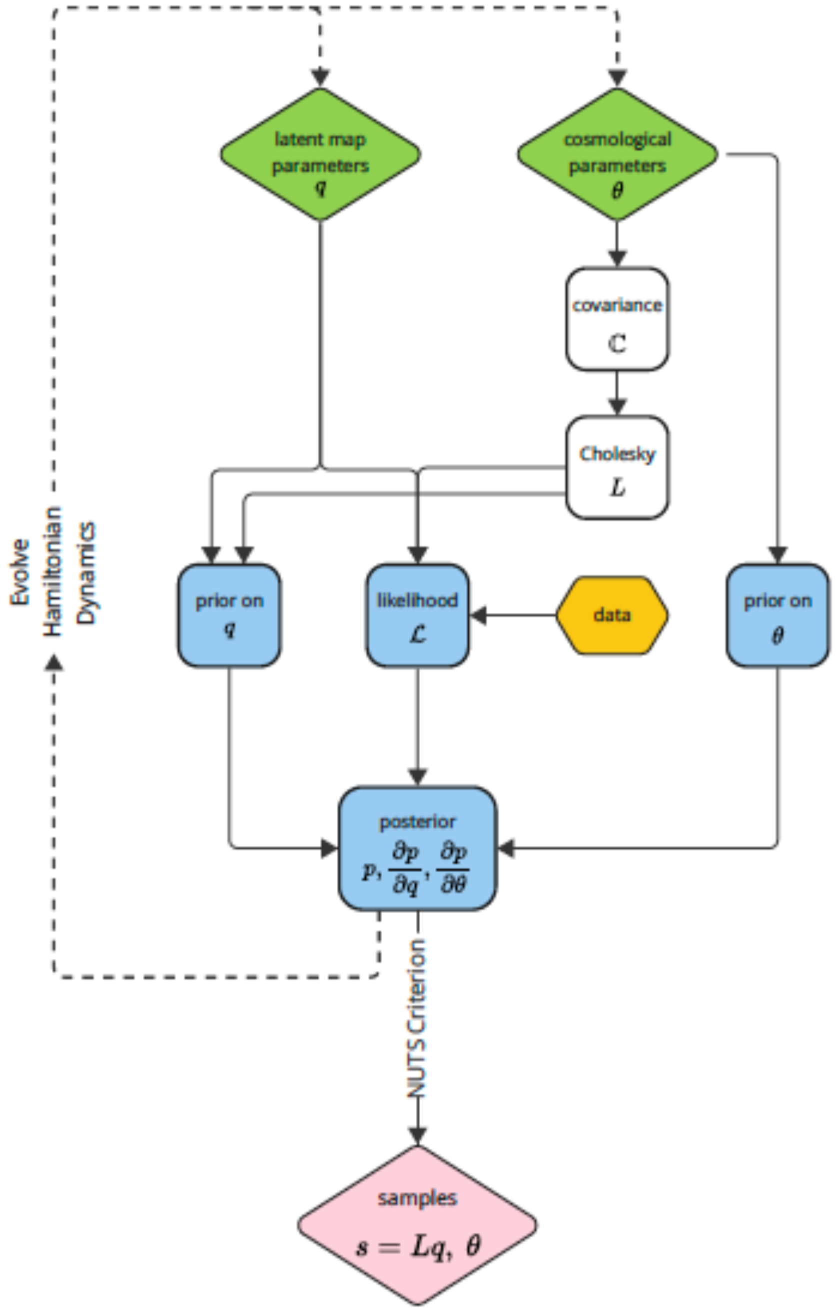
It doesn’t matter

Cosmology is typically done by (implicitly) analytically integrating over the (millions of) signal parameters and obtaining a posterior for the remaining cosmological parameters in terms of the two-point functions



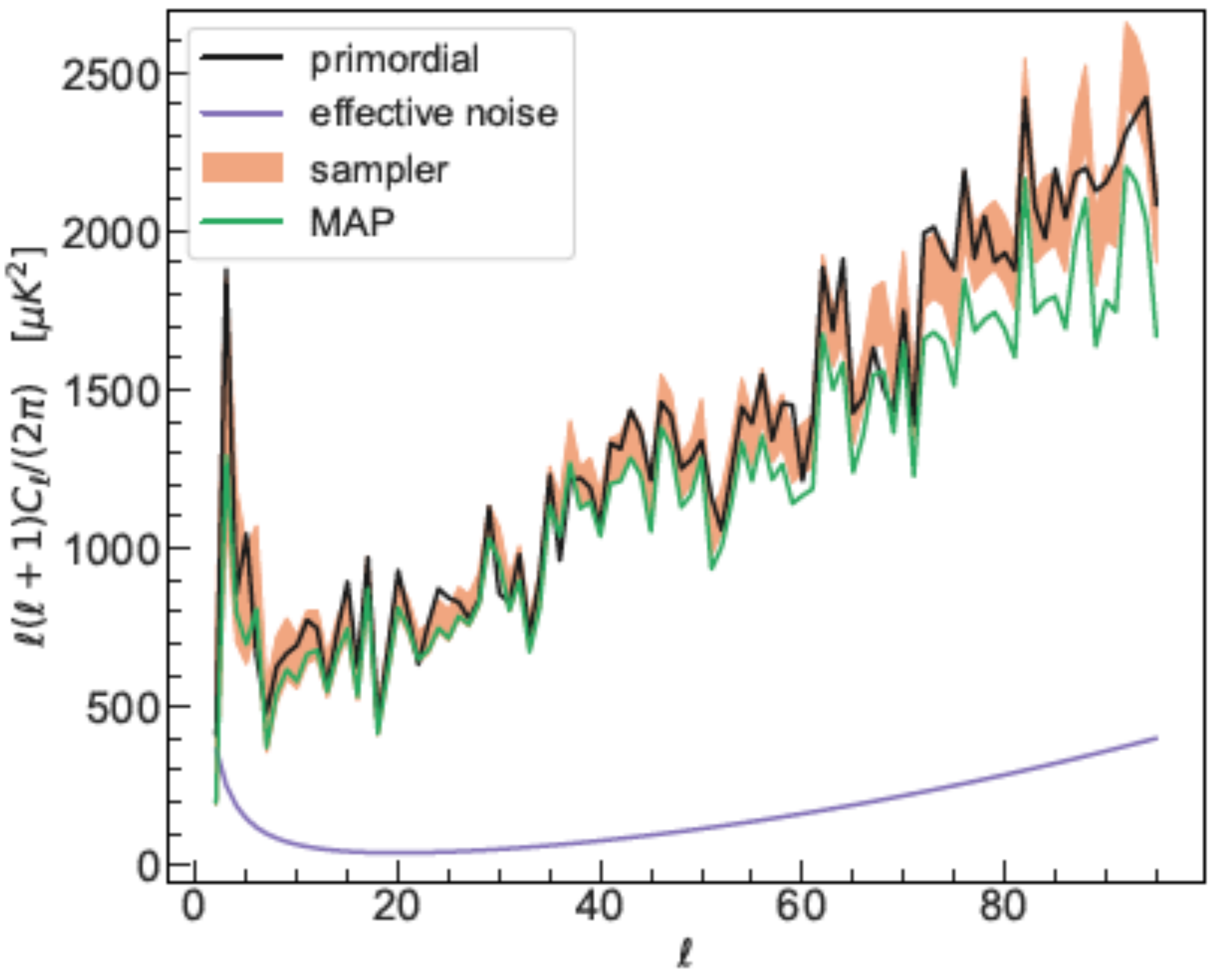
Field Level Inference

- FLI varies the signal parameters at the same time as the cosmological parameters are varied.
- Instead of 6 cosmological parameters, vary $6+10^6$ parameters (with the last million being the values of the signal (overdensity, convergence, …) in every pixel
- It turns out to be feasible ;)



Field Level Inference

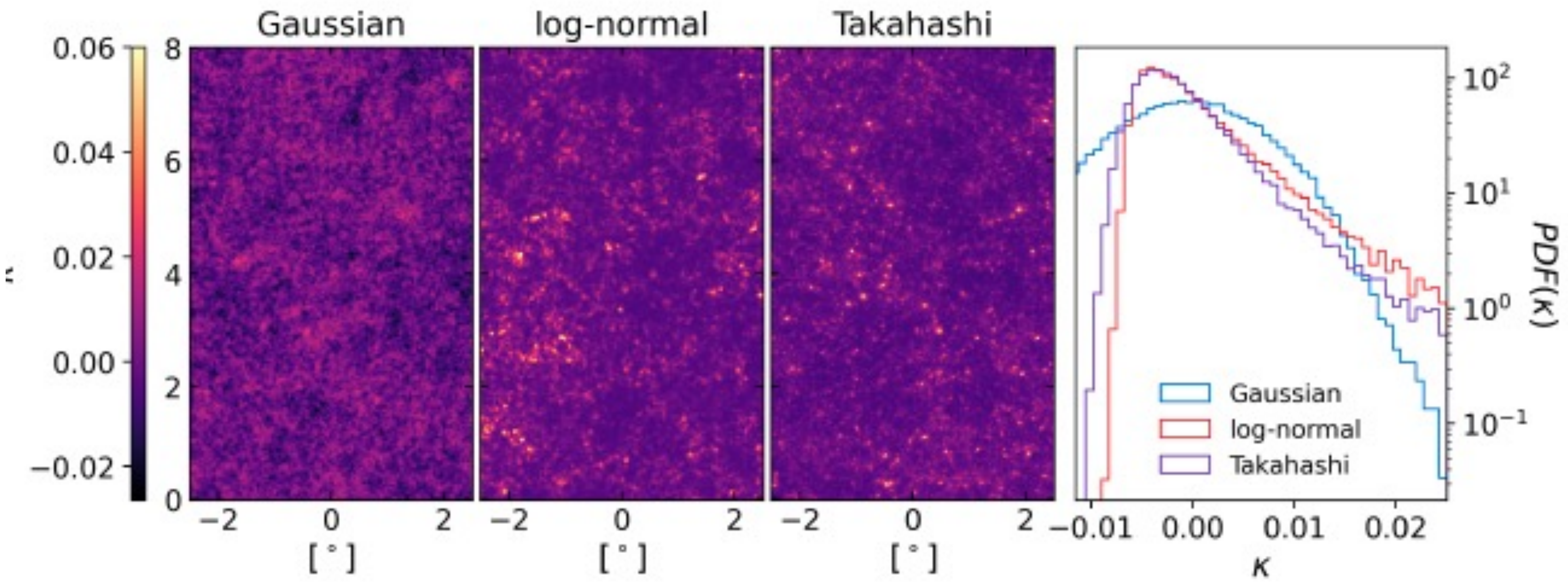
- Several advantages even in the Gaussian case where the analytic integration gets the right constraints.
- Each sample yields a map and a set of cosmological parameters.
- The distribution of the power spectrum yields the correct mean.



So What? (with Xiangchong Li, Mandelbaum)

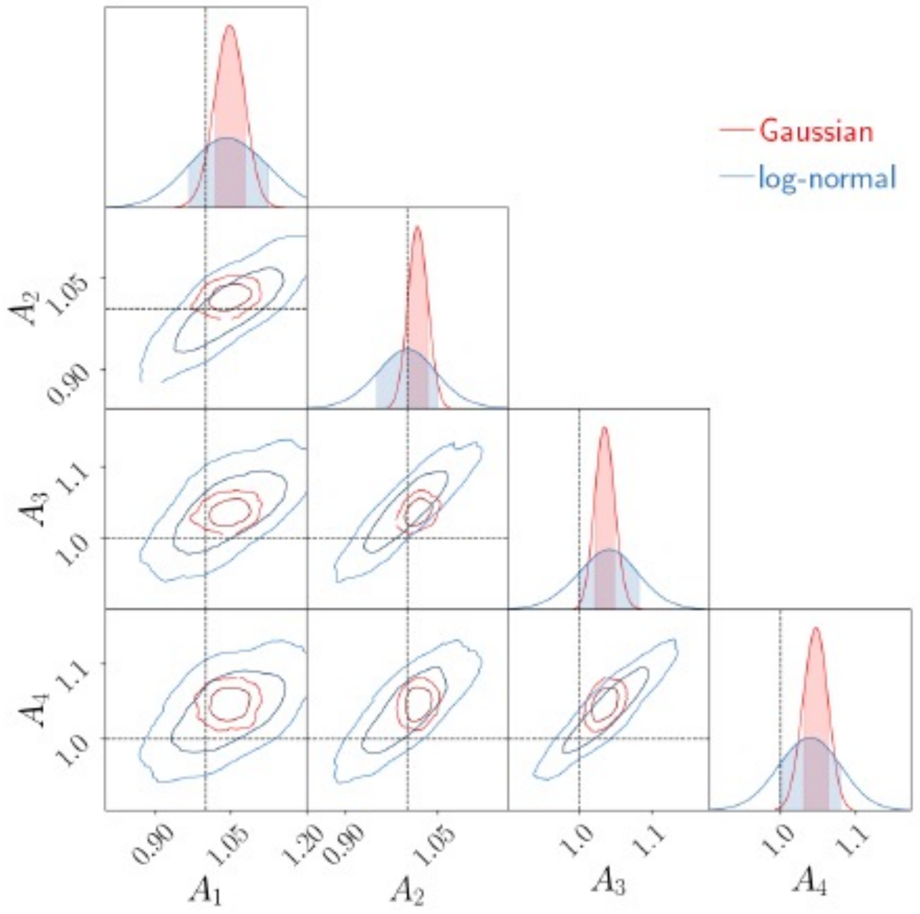
If the prior on s is Gaussian, we don't need to sample millions of parameters to get the right answer

If s is not drawn from a Gaussian (and it's not if we're interested in extracting science from nonlinear scales), what can you do?



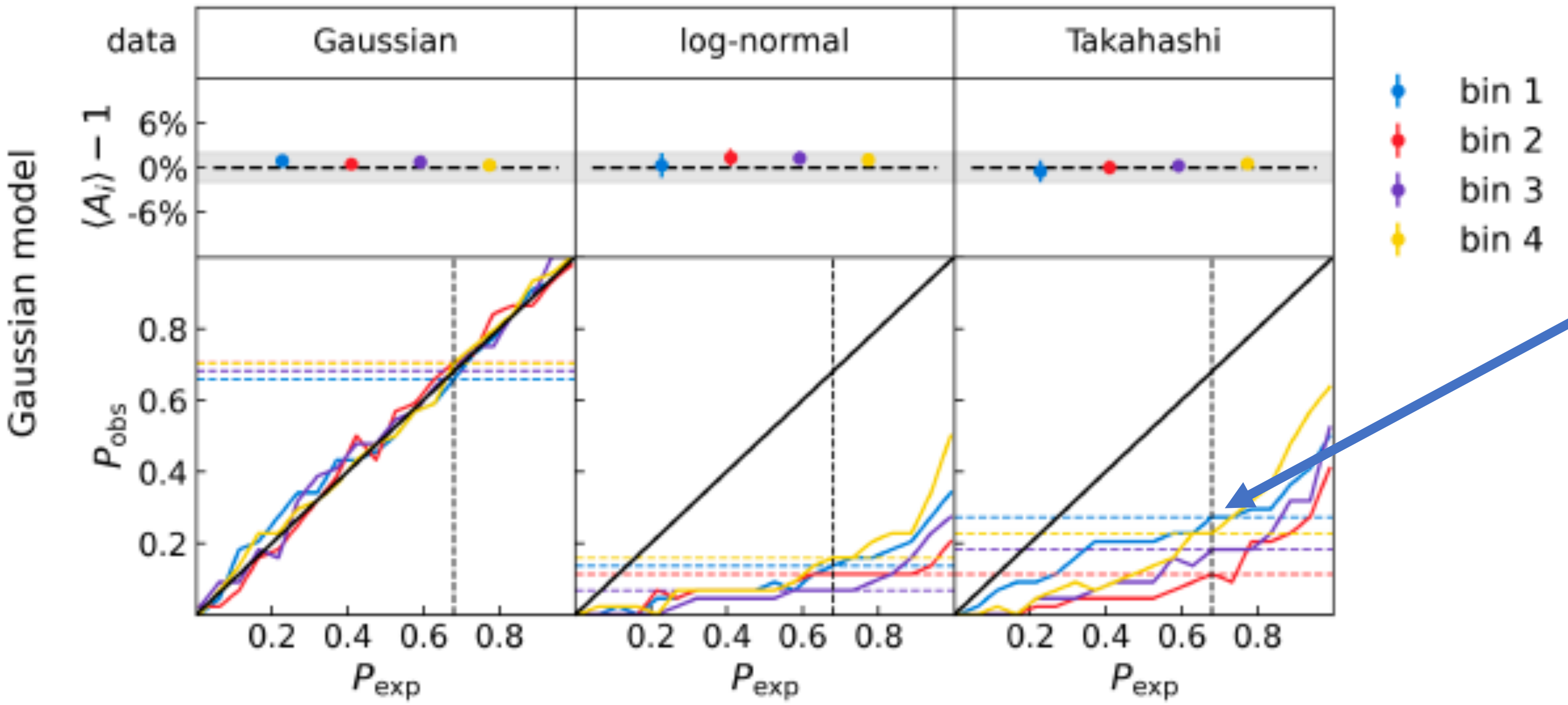
Try different priors on weak lensing simulations with 4 tomographic bins

Gaussian prior seems to be ok (this is one 40 square degree patch) and has smaller error bars than the lognormal prior, which is presumably more realistic



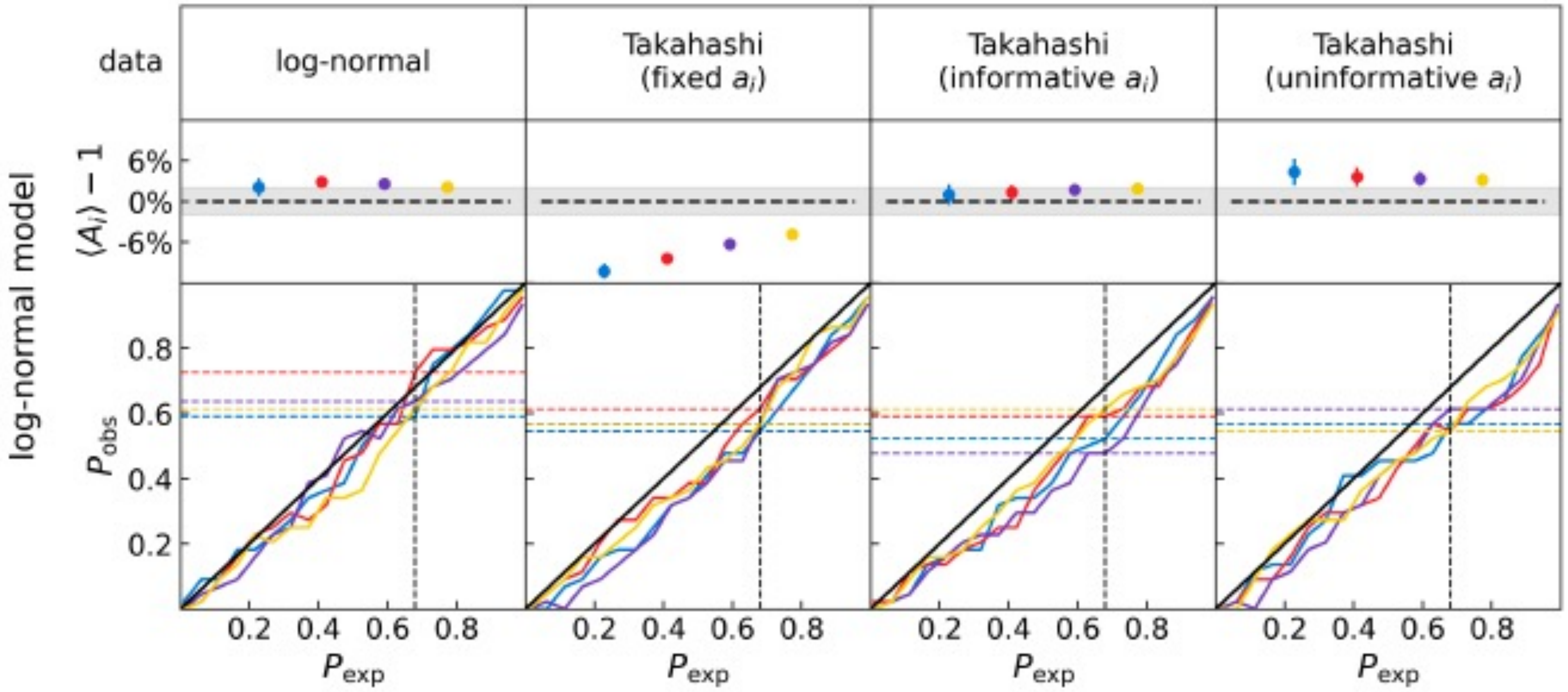
A's are the amplitude of the power spectrum in each bin

Try a Gaussian Prior on 100 sims to accumulate statistics on the bias and the noise bias



The Gaussian prior is unbiased (the mean A's are correct) but under-predicts the errors on realistic sims

Lognormal Prior on 100 sims



Mean can be biased unless care is taken with parameters of PDF. Error bars are correct … but larger than when Gaussian model is used

Next step: Analyze HSC weak lensing data using gaussian prior but calibrating the error bars

There is a better way (with Yin Li, Mandelbaum, Zhang, Li, Fabbian)

Instead of taking the signal values in each pixel to be the late time over-density:

- Choose these parameters to be the overdensities at very early time (when they really are drawn from a gaussian distribution)
- Evolve deterministically until today to compare with observations

$$-2\ln p = -\,2\ln \mathcal{L} + \sum_{\alpha\beta} s^\alpha \left(\mathbb{C}^{-1}(\theta)\right)^{\alpha\beta} s^\beta$$
$$+ \ln\det \mathbb{C}(\theta) - 2\ \ln \mathrm{prior}(\theta)$$

Combine N-Body Code with Super-Resolution Simulations with Ray Tracing …

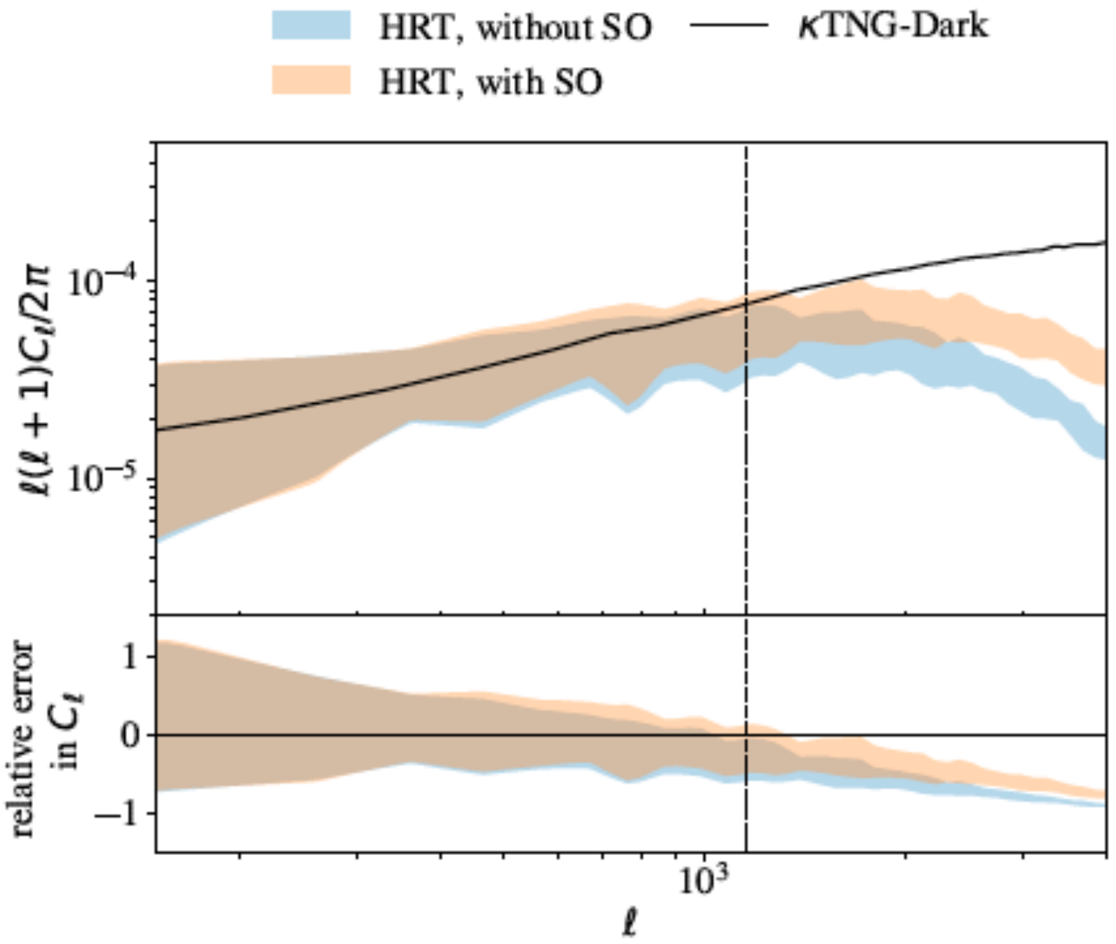
Algorithm 1 Reverse-time co-evolution of dark matter and a single ray

procedure RAYTRACING($\mathcal{P}_{\mathrm{P}}, \mathcal{P}_{\mathrm{DM}}, n_g$)
  $A \leftarrow \mathbb{I}_{2\times 2}, B \leftarrow \mathbb{O}_{2\times 2}$
  $[\kappa, \gamma_1, \gamma_2, \omega] \leftarrow \mathbf{0}$
  $z \leftarrow 0$
  while $z \leq z_{\max}$ **do** ▷ ray-trace backward in time to $z_{\max}$
    $\boldsymbol{\nabla}_{\perp}\Phi \leftarrow \mathcal{P}_{\mathrm{DM}}$
    $\mathcal{P}_{\mathrm{DM}} \leftarrow$ `nbody_reverse_step`($\mathcal{P}_{\mathrm{DM}}, \boldsymbol{\nabla}_{\perp}\Phi$) ▷ Evolve dark matter backward [8];
reuse $\boldsymbol{\nabla}_{\perp}\Phi$
    $\mathcal{P}_{\mathrm{P}} \leftarrow$ `kick`($\mathcal{P}_{\mathrm{P}}, \boldsymbol{\nabla}_{\perp}\Phi$) ▷ Eq. (2.5); reuse $\boldsymbol{\nabla}_{\perp}\Phi$
    $B \leftarrow$ `iterate_B`($\mathcal{P}_{\mathrm{P}}, A, B, \boldsymbol{\nabla}_{\perp}\Phi$) ▷ Eq. (4.8); reuse $\boldsymbol{\nabla}_{\perp}\Phi$
    $\mathcal{P}_{\mathrm{P}} \leftarrow$ `drift`($\mathcal{P}_{\mathrm{P}}$) ▷ Eq. (2.6)
    $A \leftarrow$ `iterate_A`($\mathcal{P}_{\mathrm{P}}, A, B$) ▷ Eq. (4.9)
    $\mathcal{P}_{\mathrm{P}} \leftarrow$ `kick`($\mathcal{P}_{\mathrm{P}}, \boldsymbol{\nabla}_{\perp}\Phi$) ▷ Eq. (2.7); reuse $\boldsymbol{\nabla}_{\perp}\Phi$
    $B \leftarrow$ `iterate_B`($\mathcal{P}_{\mathrm{P}}, A, B, \boldsymbol{\nabla}_{\perp}\Phi$) ▷ Eq. (4.10); reuse $\boldsymbol{\nabla}_{\perp}\Phi$
    $\kappa, \gamma_1, \gamma_2, \omega \leftarrow$ `observe`($A, n_g, \kappa, \gamma_1, \gamma_2, \omega$) ▷ Eqs. (4.4) and (4.12)
    $z \leftarrow z + \Delta z$
  end while
  return $\kappa, \gamma_1, \gamma_2, \omega$
end procedure

Run N-Body forward and then ray trace light and matter backwards in time … differentiably!

pmwd: https://github.com/eelregit/pmwd

Combine N-Body Code with Super-Resolution Simulations with Ray Tracing …



Important because Beyond Born effects [captured by this algorithm] impact higher order functions/nonlinear shear

Tour de Force: but computational requirements on LSST area immense

We have plans but are left with questions

- Can FLI be implemented on large sky survey data?
- Can it include both galaxy surveys and CMB data?
- How can baryons be included?
- How much better will FLI be than standard 2-point analyses?
- Will FLI replace standard analyses?
- Are there alternatives that learn the posterior?

KICP@20: The challenges are formidable but the stakes are high (we are trying to figure out the universe) and talented young people are interested.