New cosmological tests for fundamental physics

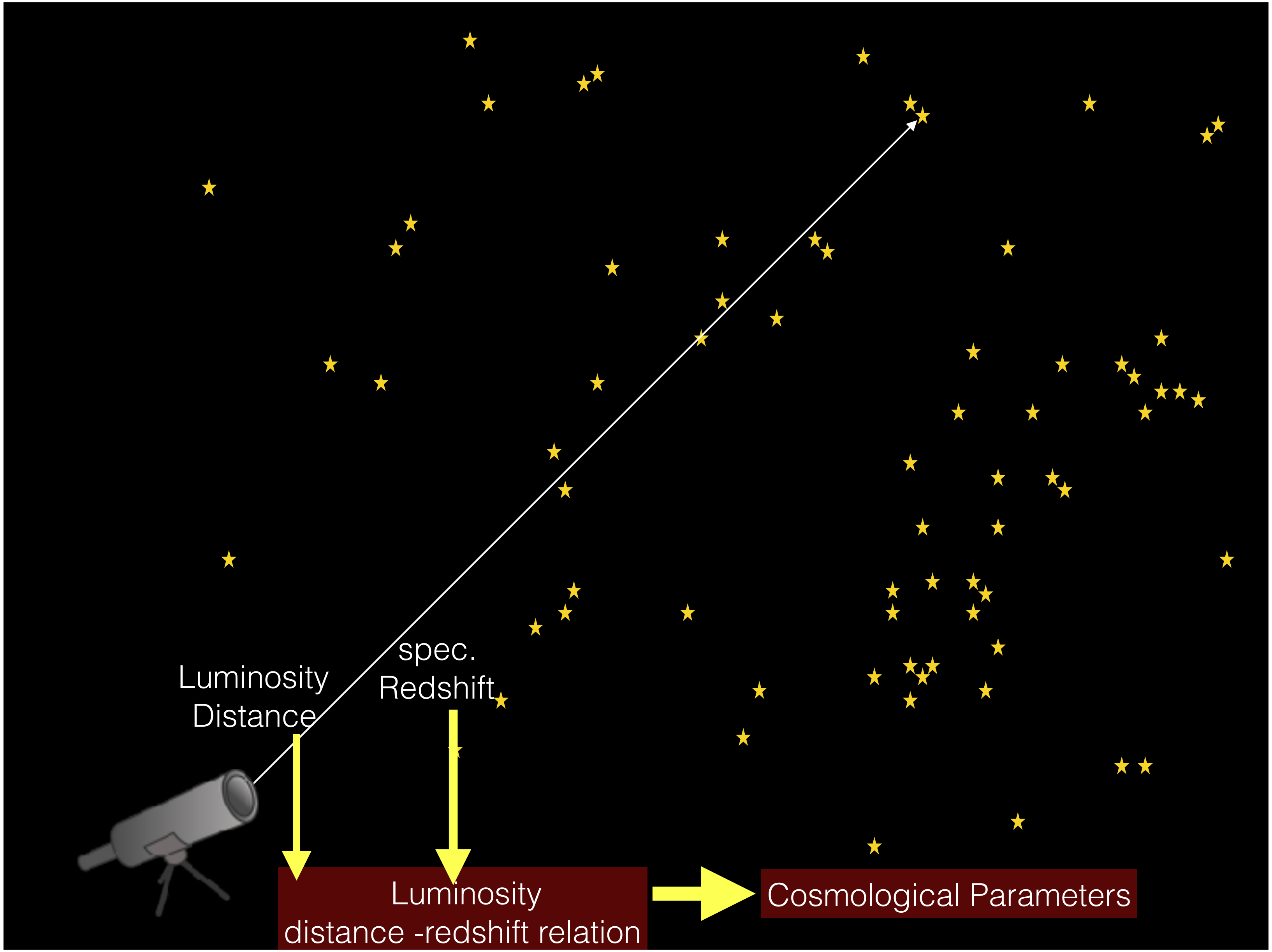
Benjamin Wandelt

with Suvodip Mukherjee, Doogesh Kodi Ramanah, Justin Alsing, Tom Charnock, Guilhem Lavaux, Stephen Feeney…

Cosmology 101

- Chapter 1: Homogeneous and isotropic universe
  - 1.1 FLRW metric
  - 1.2 RW equation
  - …
- Chapter 2: Classical cosmological tests
  - 2.1 Luminosity-distance redshift test

    "Observe an object's luminosity distance and redshift and plot them against each other"


Luminosity
Distance
spec.
Redshift
Luminosity
distance -redshift relation
Cosmological Parameters

Cosmology 101

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    "Observe an object's luminosity distance and redshift and plot them against each other"

    But there are no objects in a homogeneous and isotropic universe!

    Clearly need to consider *structure*.

A new way to think about the luminosity distance redshift test

- Consider two types of tracers
  - A luminosity distance tracer *sn*
  - A redshift tracer *g*
- Let's write down the simplest possible model for their densities:
  - Gaussian pdf

$$-2\mathcal{L}_{\mathrm{full}}(\boldsymbol{\delta}_g, \boldsymbol{\delta}_{sn}|\boldsymbol{\theta}) = \begin{pmatrix} \boldsymbol{\delta}_g \\ \boldsymbol{\delta}_{sn} \end{pmatrix}^T \boldsymbol{\Xi}^{-1} \begin{pmatrix} \boldsymbol{\delta}_g \\ \boldsymbol{\delta}_{sn} \end{pmatrix} + \ln|\boldsymbol{\Xi}|$$

A new way to think about the luminosity distance redshift test

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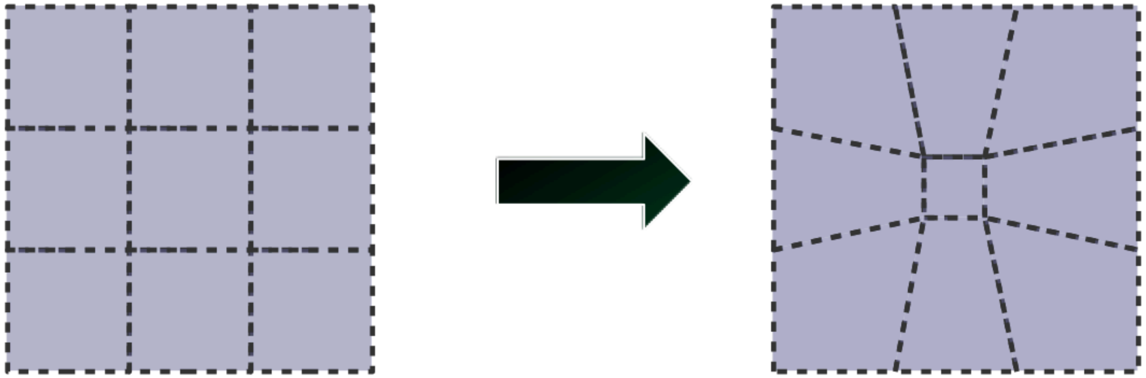
Assume both cluster and are mapped from comoving coordinates into luminosity distance and redshift space. Then

$$\boldsymbol{\Xi}(\boldsymbol{\theta}) = \begin{pmatrix} \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-g}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \\ \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}^T_{\text{g-sn}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{sn-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \end{pmatrix}$$

What are the ***Z*** and ***D***?

The transformation matrix *Z*



Comoving coordinates

$$\vec{x}$$

Scaled redshift coordinates

$$\vec{\mathfrak{z}}_i = \frac{c}{H_0} z_i \hat{u}_i$$

D is the analogous transformation to distance space.

A new way to think about the luminosity distance redshift test

$$-2\mathcal{L}_{\rm full}(\boldsymbol{\delta}_g, \boldsymbol{\delta}_{sn}|\boldsymbol{\theta}) = \begin{pmatrix} \boldsymbol{\delta}_g \\ \boldsymbol{\delta}_{sn} \end{pmatrix}^T \boldsymbol{\Xi}^{-1} \begin{pmatrix} \boldsymbol{\delta}_g \\ \boldsymbol{\delta}_{sn} \end{pmatrix} + \ln|\boldsymbol{\Xi}|$$

Assume both cluster and are mapped from comoving coordinates into luminosity distance and redshift space. Then

Global generalization of Alcock Paczynski test

A new multi-tracer Global AP test!

$$\boldsymbol{\Xi}(\boldsymbol{\theta}) = \begin{pmatrix} \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-g}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \\ \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}^T_{\text{g-sn}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{sn-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \end{pmatrix}$$

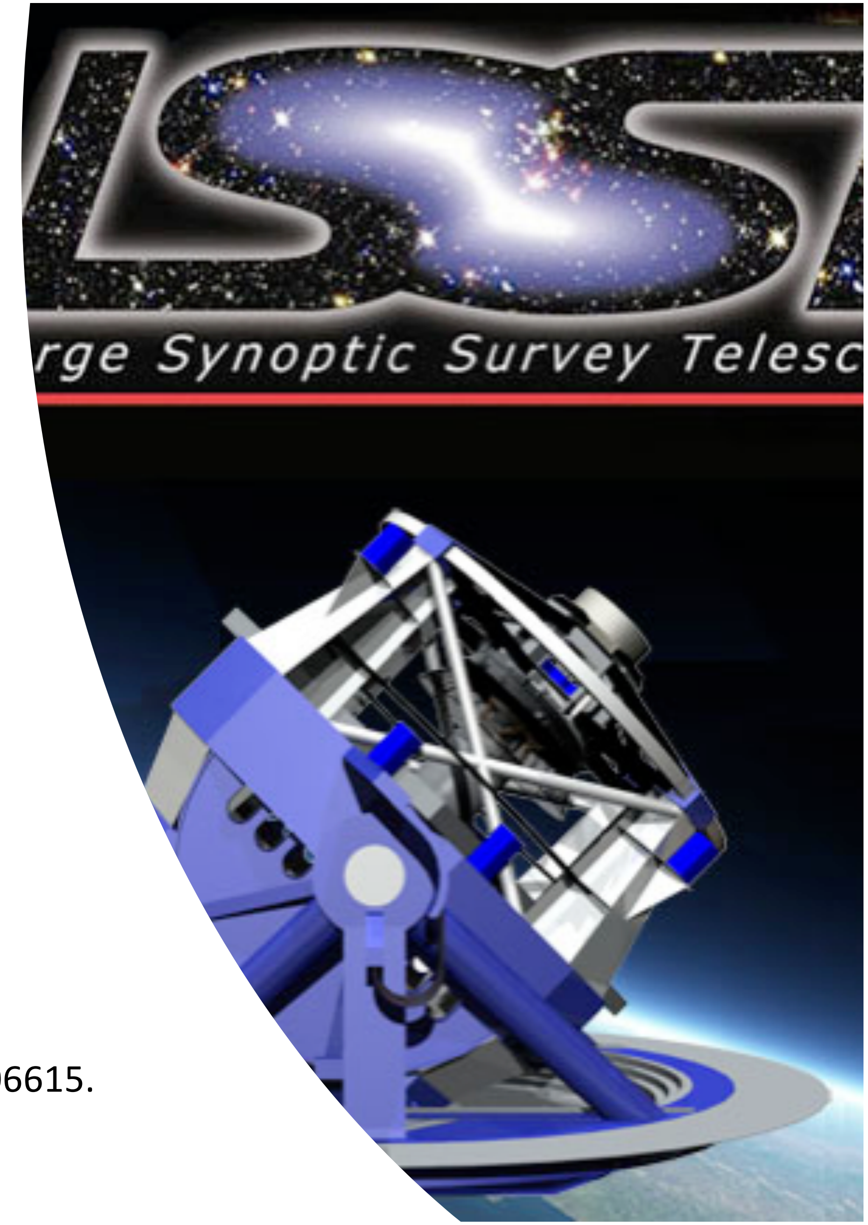
A new Global AP-test in D_L-space

The luminosity distance-redshift test is a cross-correlation Alcock-Paczynski test!

$$\boldsymbol{\Xi}(\boldsymbol{\theta}) = \begin{pmatrix} \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-g}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \\ \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}^T_{\text{g-sn}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{sn-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \end{pmatrix}$$

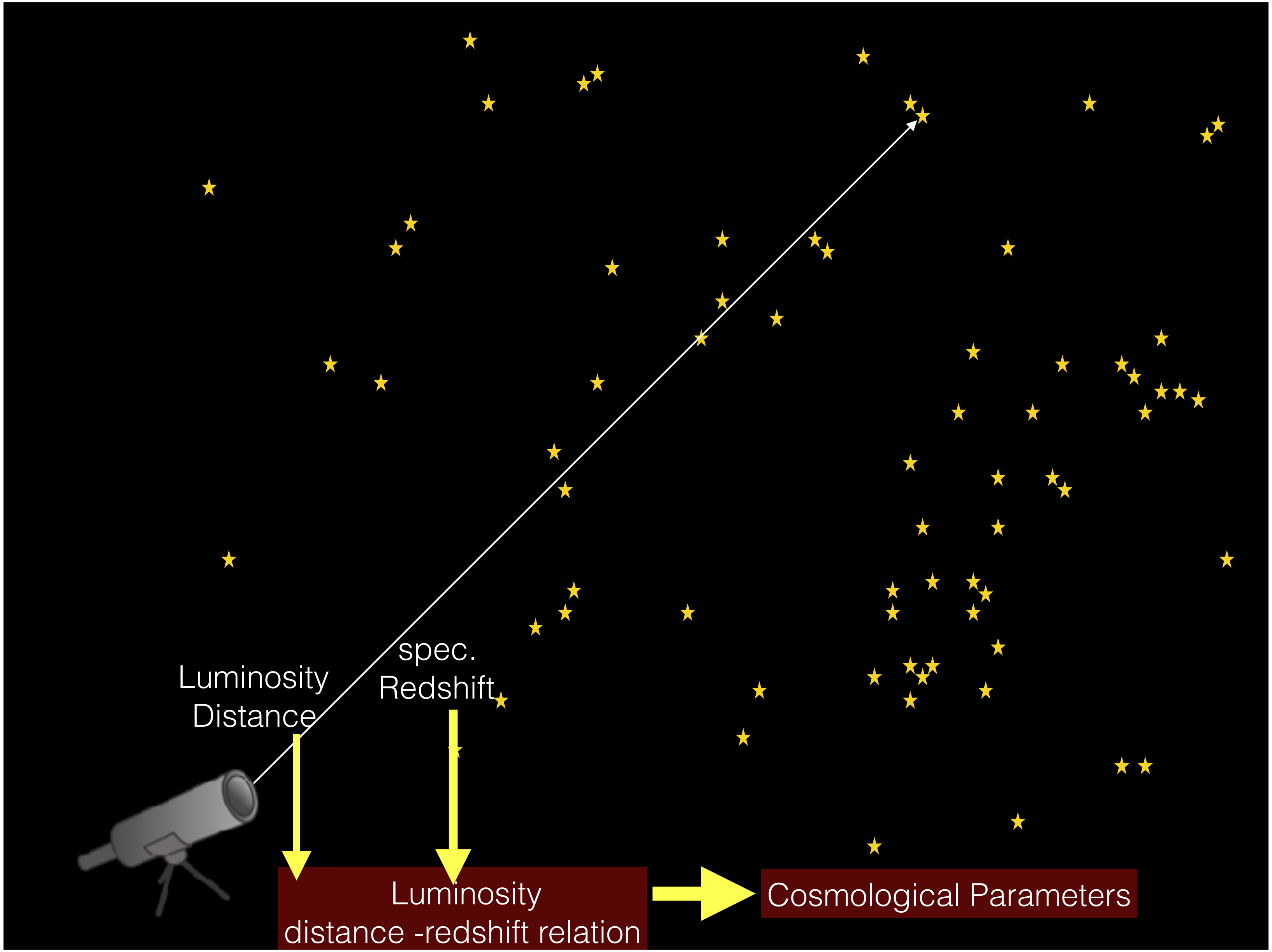
- The D_L-z test is part of a multi-tracer AP test – involves sum over all pairs of distance and redshift tracers.
- If we force the covariance to be diagonal then we get a single sum with those objects that trace both D_L and z. But galaxies are clustered so we can use all pairs -> can get better performance than with the classical test!
- *Can exploit this to solve a major problem in SN cosmology for the next decade*

Next-decade supernova cosmology



- Upcoming surveys will have tens of thousands of supernovae
- Far too many to follow all of them up spectroscopically!
- Photometric information leads to type contamination and photo-z systematics.

S. Mukherjee & B. Wandelt, arXiv: 1808:06615.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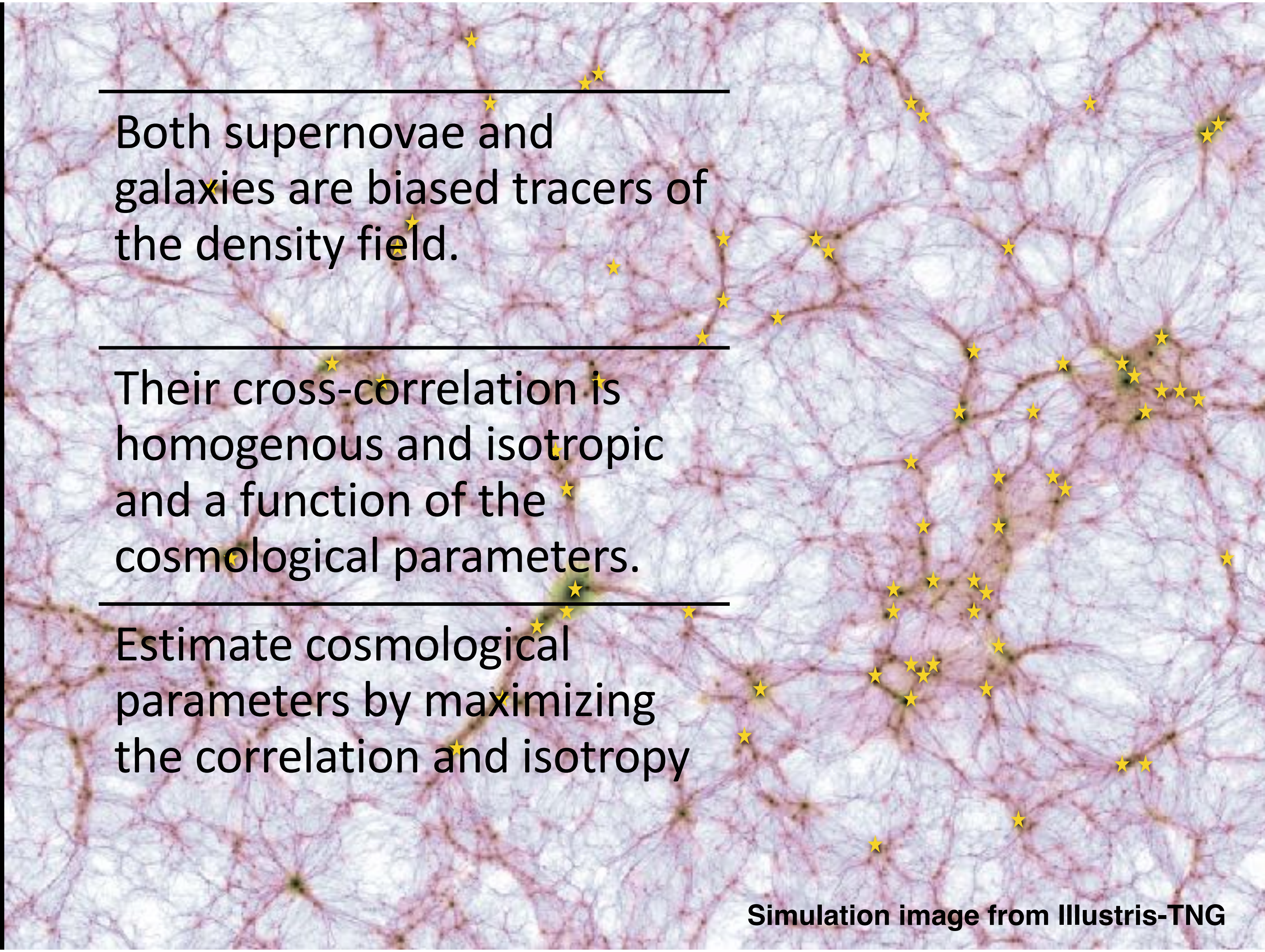
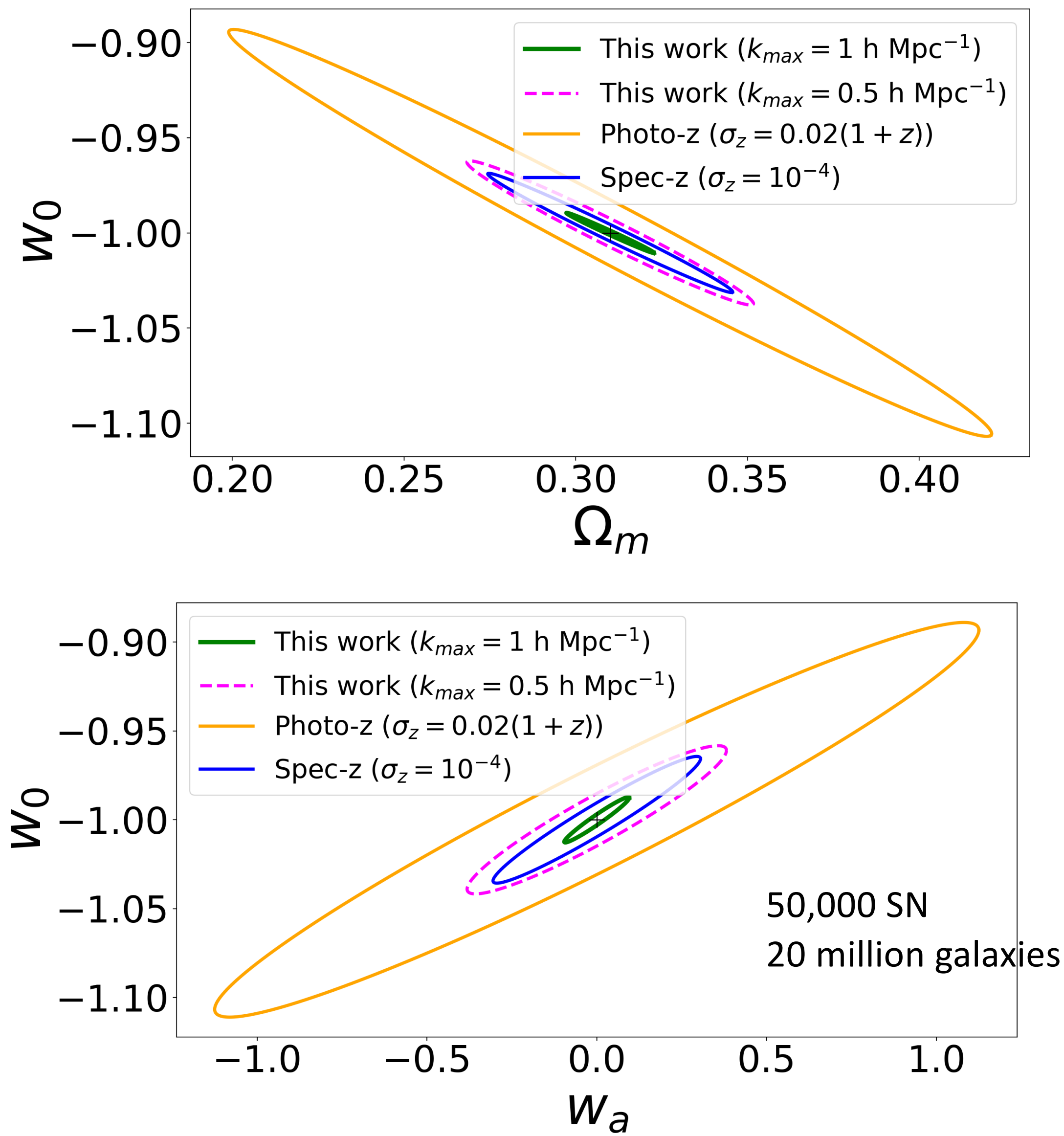

Both supernovae and galaxies are biased tracers of the density field.
Their cross-correlation is homogenous and isotropic and a function of the cosmological parameters.
Estimate cosmological parameters by maximizing the correlation and isotropy
Simulation image from Illustris-TNG

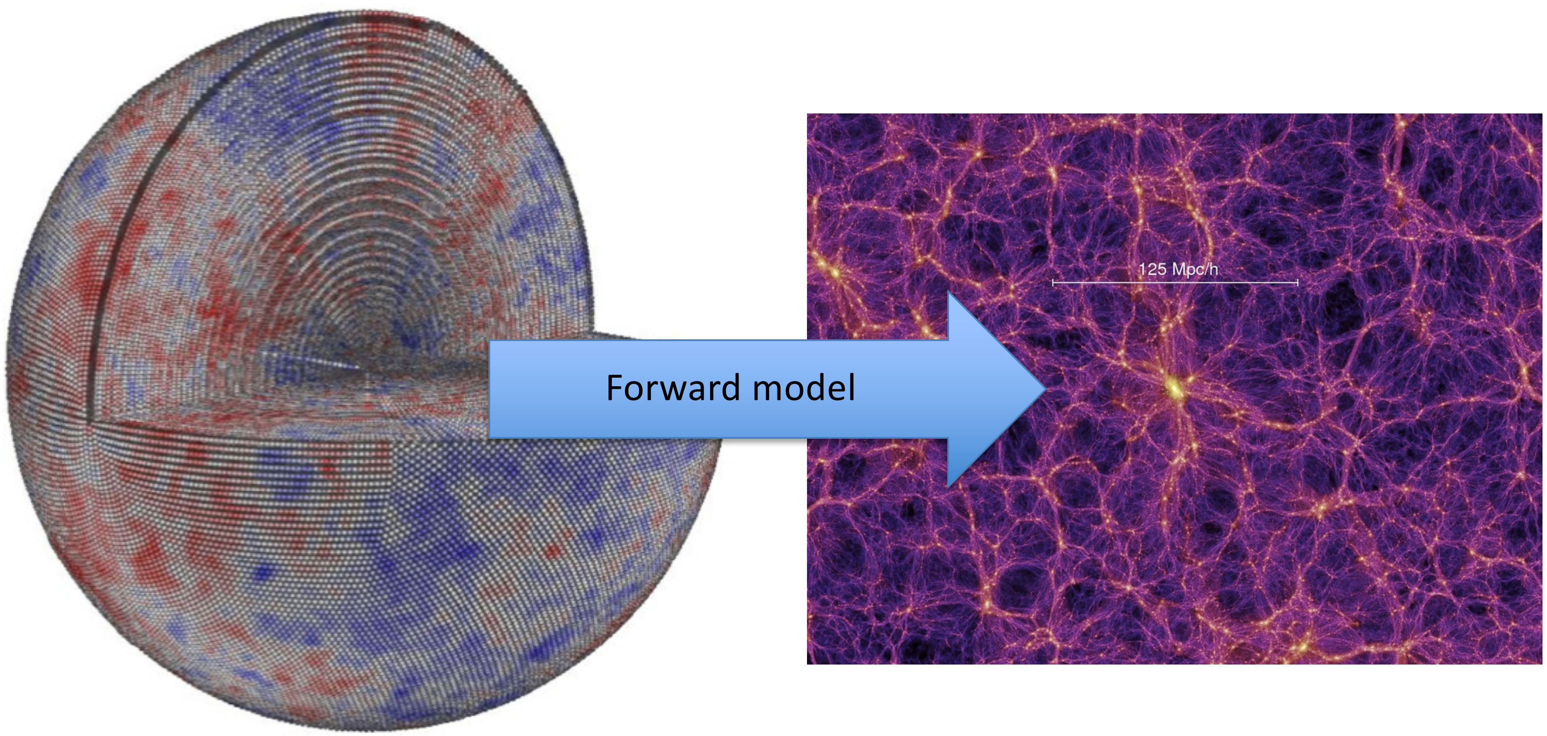
Luminosity distance–redshift test using SN-galaxy cross correlations

- Robust to type contamination
- Insensitive to photo-z systematics
- *Suppression of cosmic variance comes from multi-tracer approach, as expected for background test!*

S. Mukherjee and B. Wandelt, arXiv: 1808:06615 .



Full forward model modeling of LSS



Initial conditions of the universe

The universe today

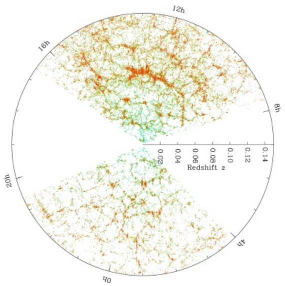
A fully generative *probabilistic* model of galaxy surveys with O(10^7) parameters

BORG: *Bayesian Origin Reconstruction from Galaxies*

- Gaussian prior + **Gravity** + likelihood for galaxies

  (includes survey model, bias model, automatic noise level calibration, selection function, mask, …)

- Hamiltonian Markov Chain Monte Carlo in O(10^7)-D



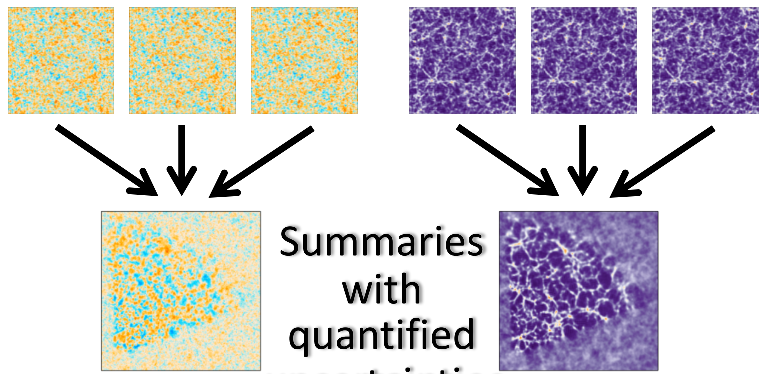
Observations

(galaxy catalog + meta-data: selection functions, completeness…)

→ BORG →

E.g. inferred dark matter densities

z=100 z=0



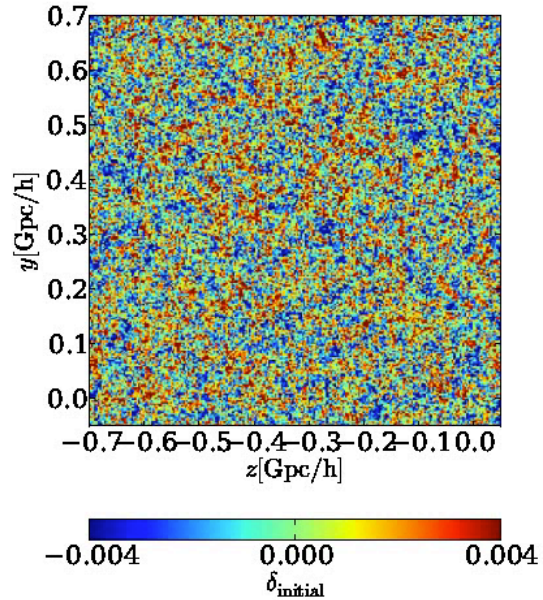
Summaries with quantified uncertainties

Jasche & Wandelt 2013, arXiv:1203.3639

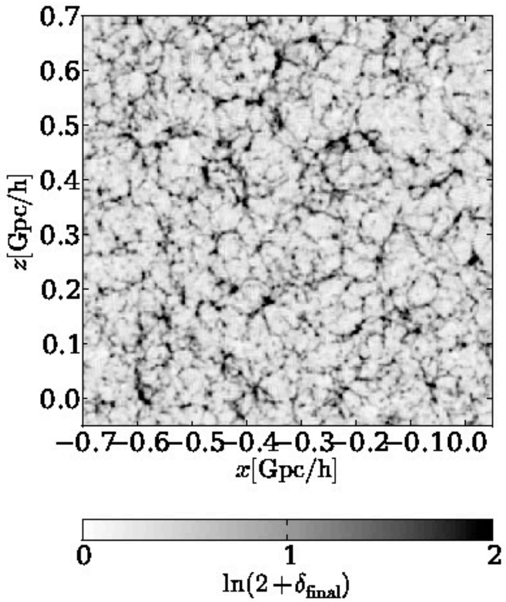
Jasche, Leclercq & Wandelt 2015, arXiv:1409.6308

Lavaux & Jasche 2017

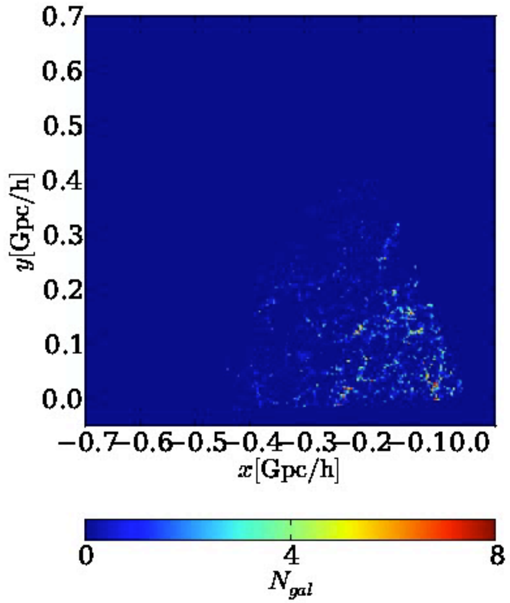
Bayesian LSS sampling with BORG – the movie



Initial conditions



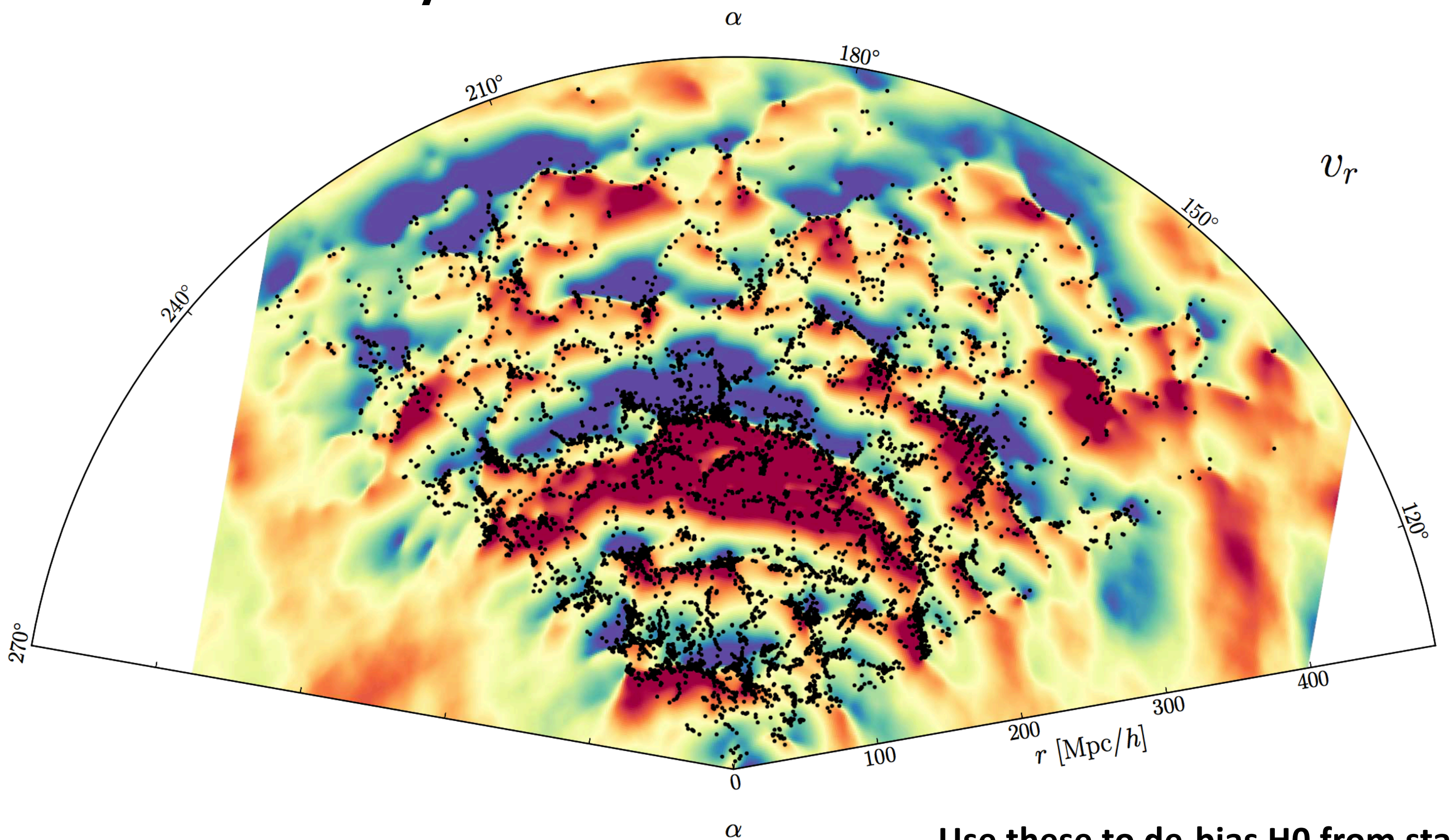
Final conditions



Observations

Jasche, Leclercq & Wandelt 2014, arXiv:1409.6308

Example Bayesian LCDM predictions: dynamical velocities



Leclercq et al. 2017

Use these to de-bias H0 from standard sirens!
Mukherjee et al arXiv:1909.08627

How to do cosmology with BORG?

- Tons of statistical power! How to make robust?
- Want to decouple bias model from cosmological parameters
- Do (generalized, global) "Alcock-Paczynski:" *only keeping parameter dependence in coordinate mapping*

Alcock Paczynski test

$$\boldsymbol{\Xi}(\boldsymbol{\theta}) = \begin{pmatrix} \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-g}}\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{Z}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \\ \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{g-sn}}^T\boldsymbol{Z}(\boldsymbol{\theta}) & \boldsymbol{D}^T(\boldsymbol{\theta})\boldsymbol{\xi}_{\text{sn-sn}}\boldsymbol{D}(\boldsymbol{\theta}) \end{pmatrix}$$

AP test with all moments of the density field

Coordinate Transformation

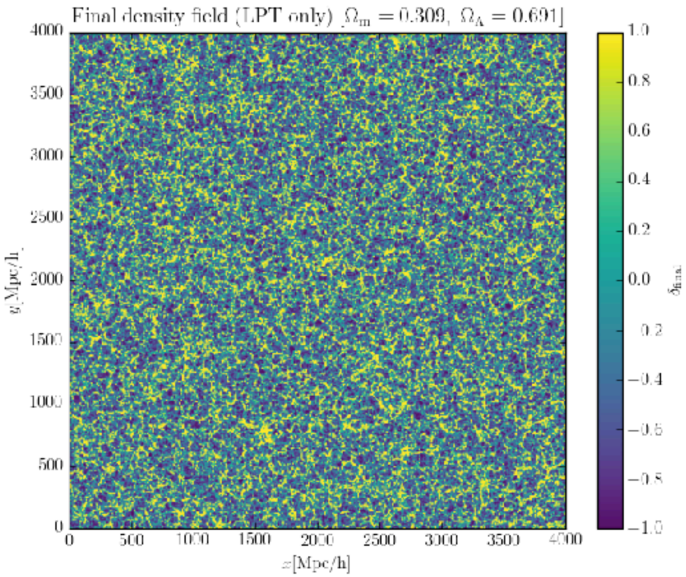
(Alcock & Paczyński 1979)

$$(z, \vec{u}) \quad \xleftrightarrow{\{\Omega_m, \Omega_\Lambda, \Omega_k, \omega, H_0\}} \quad (d, \vec{u})$$

Redshift space — **Comoving space**

- Distortions due to assumption of incorrect cosmological parameters
- Structure: **Spherical → Ellipsoidal**
- Statistical distribution: **Isotropic → Anisotropic**

comoving space



Doogesh Kodi Ramanah et al., arXiv 1808.07496

$$d = \int_{z_1}^{z_2} \frac{1}{cH(z)}$$

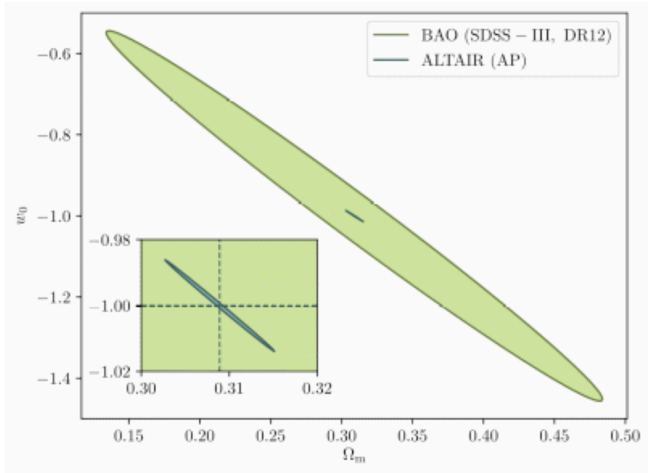
$$H(z) = H_0(\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda)^{\frac{1}{2}}$$

High precision inferences

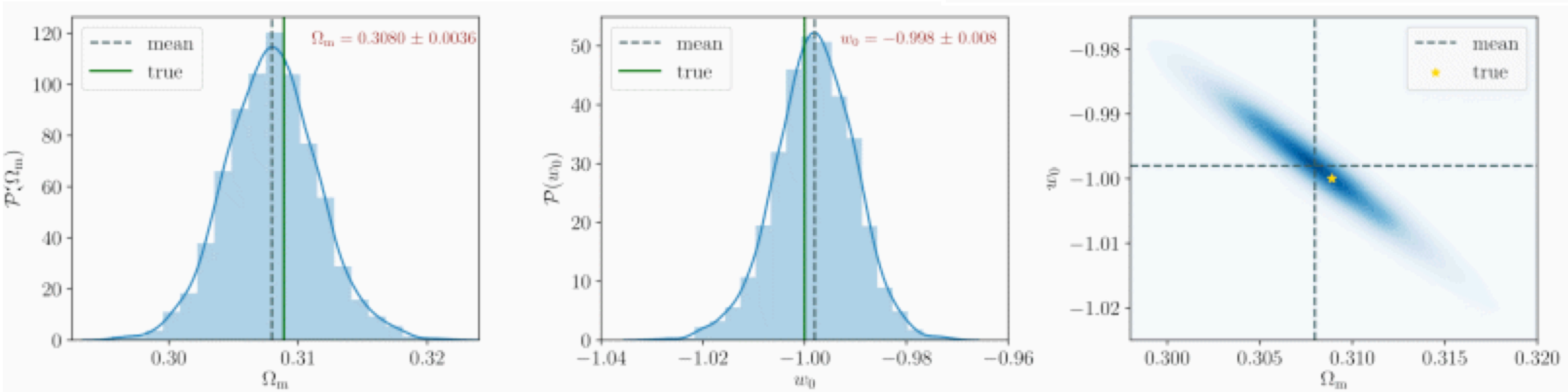
- Probing deep redshift range; geometric distortion due to cosmic expansion is highly informative

$$\{\Omega_\mathrm{m} = 0.3080 \pm 0.0036, \;\; w_0 = -0.998 \pm 0.008\}$$

Comparison to standard BAO constraints

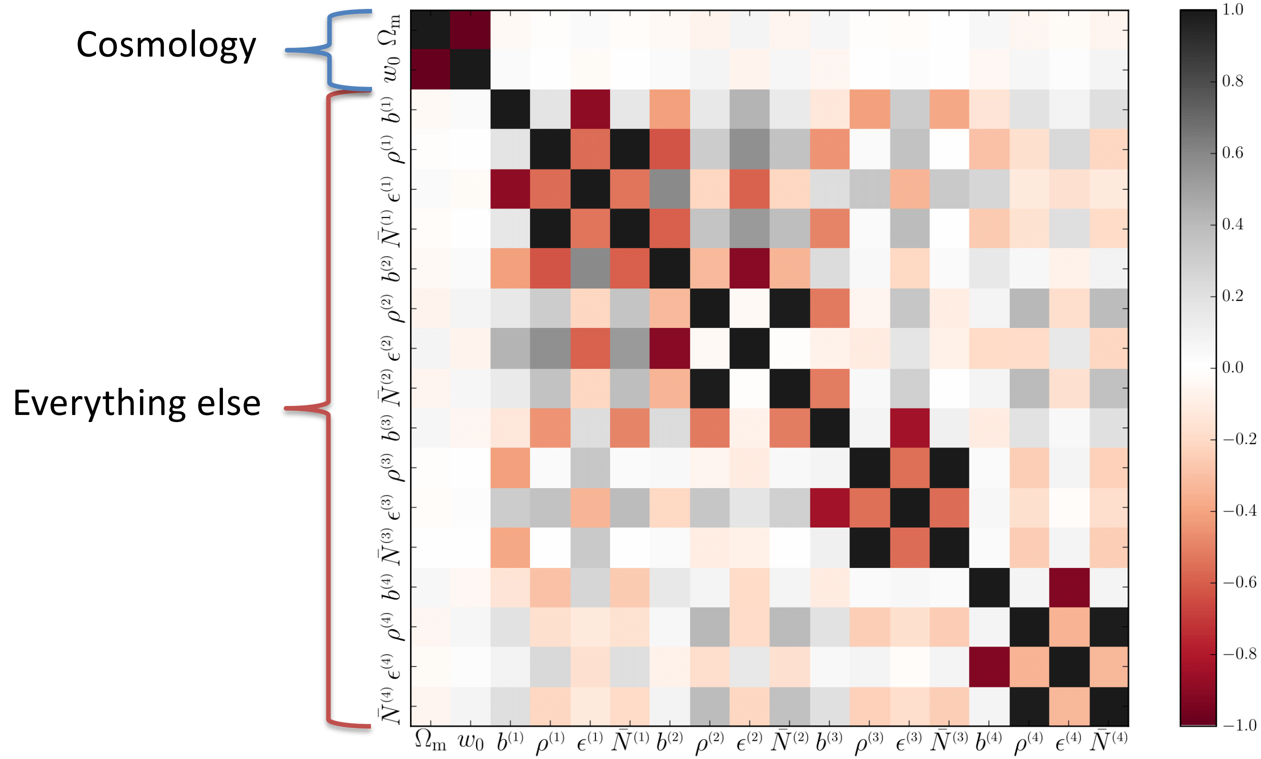


Marginal & joint posteriors



Doogesh Kodi Ramanah et al., arXiv 1808.07496

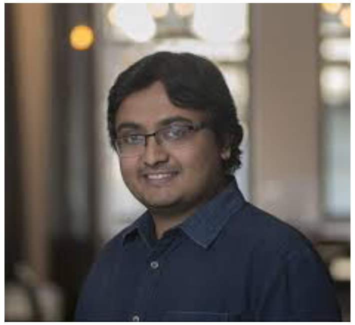
Inferred cosmology is robust to bias and model misspecification



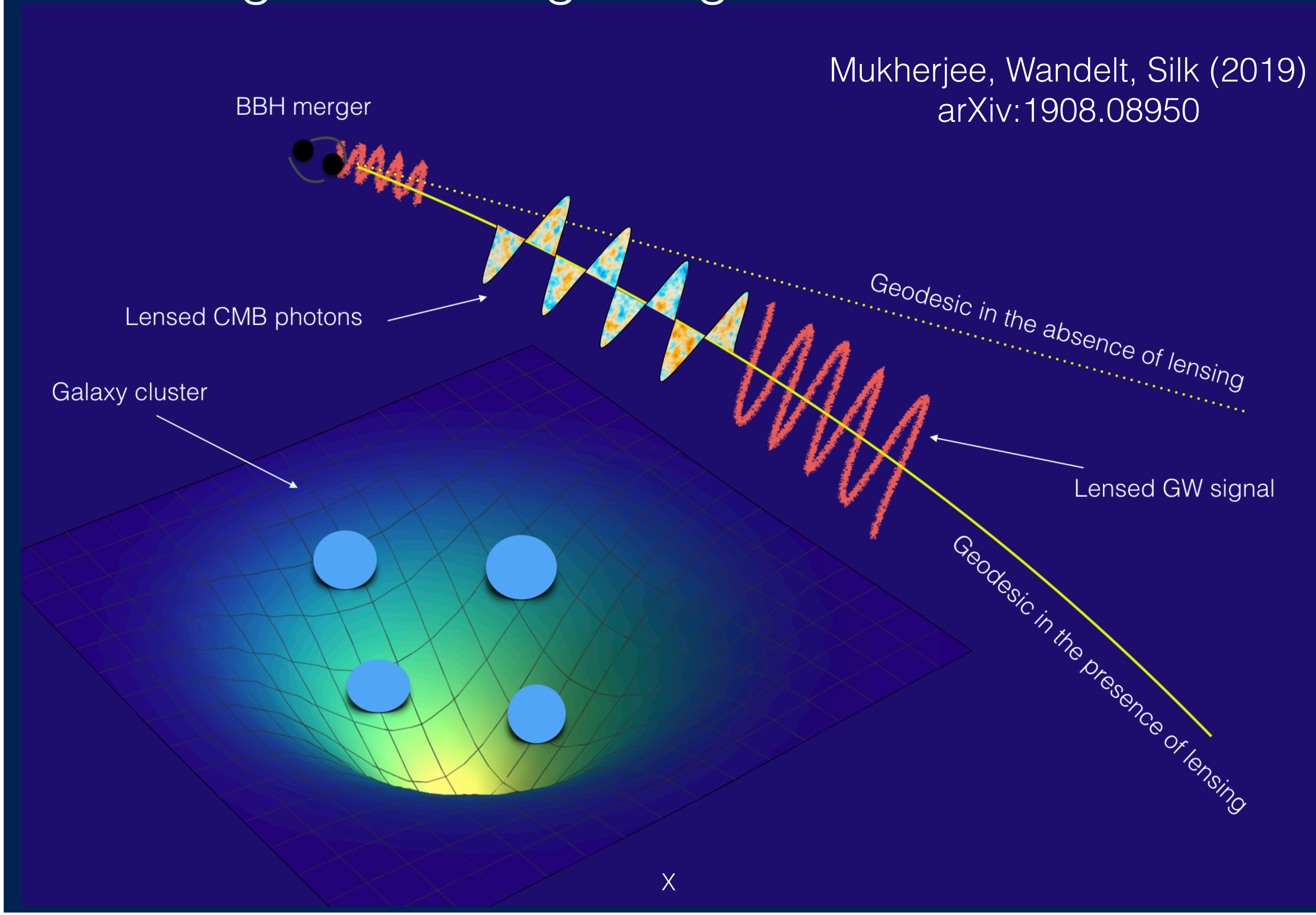
Doogesh Kodi Ramanah et al., arXiv 1808.07496

Testing gravity with gravitational wave lensing

with Suvodip Mukherjee, Joe Silk



Probing GW lensing using CMB-GW correlation



Effects on the gravitational waves signal

$$\tilde{\nu} = \nu\left(1 - \left(\Phi|_e^r - (\vec{n}.\vec{v})|_e^r - \int_{\lambda_e}^{\lambda_r} \partial_\eta(\Psi + \Phi) d\lambda'\right)\right),$$

$$\tilde{h}(\tilde{\nu}, \hat{n}) = h(\tilde{\nu}, \hat{n})[1 + \kappa_{gw}(\hat{n})],$$

$$\kappa_{gw}(\hat{n}) = \int_0^{z_s} dz \frac{3}{2} \frac{\Omega_m H_0^2 (1+z)\chi(z)}{cH(z)} \int_z^\infty dz' \frac{dn_{gw}(z')}{dz'} \frac{(\chi(z_s) - \chi(z'))}{(\chi(z_s))} \delta(\chi(z)\hat{n}, z).$$

Measuring the lensing signal from GW sources

Mukherjee, Wandelt, Silk (2019)
arXiv:1908.08950

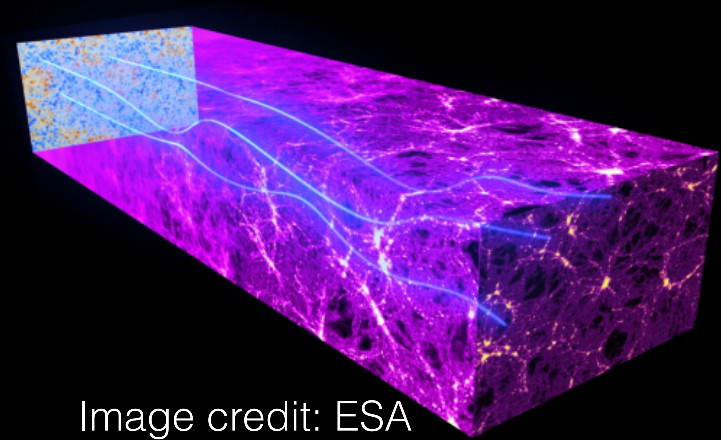
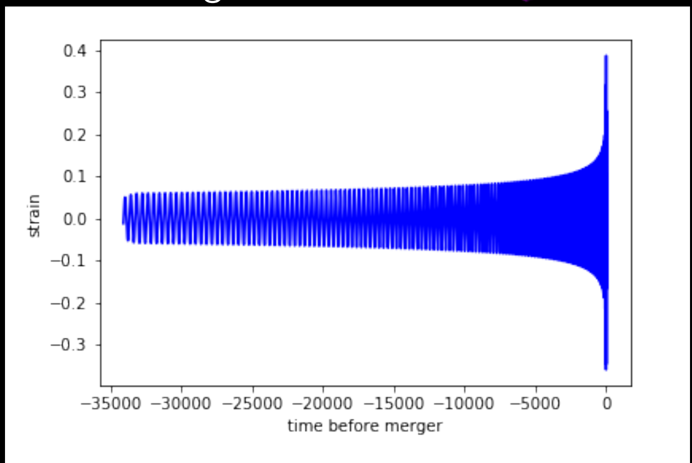
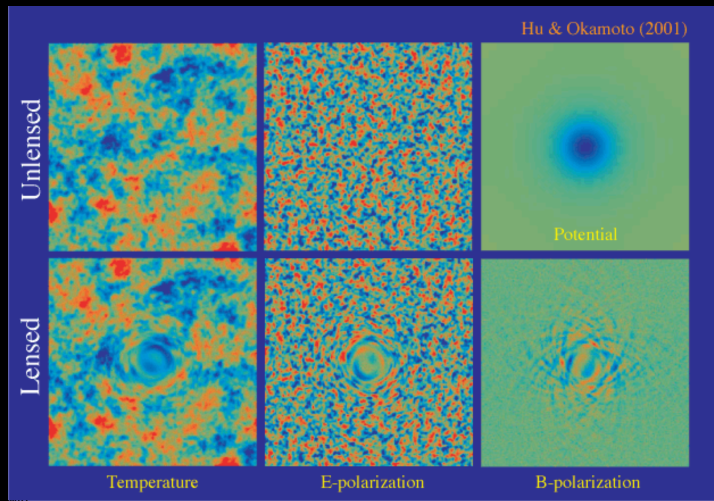


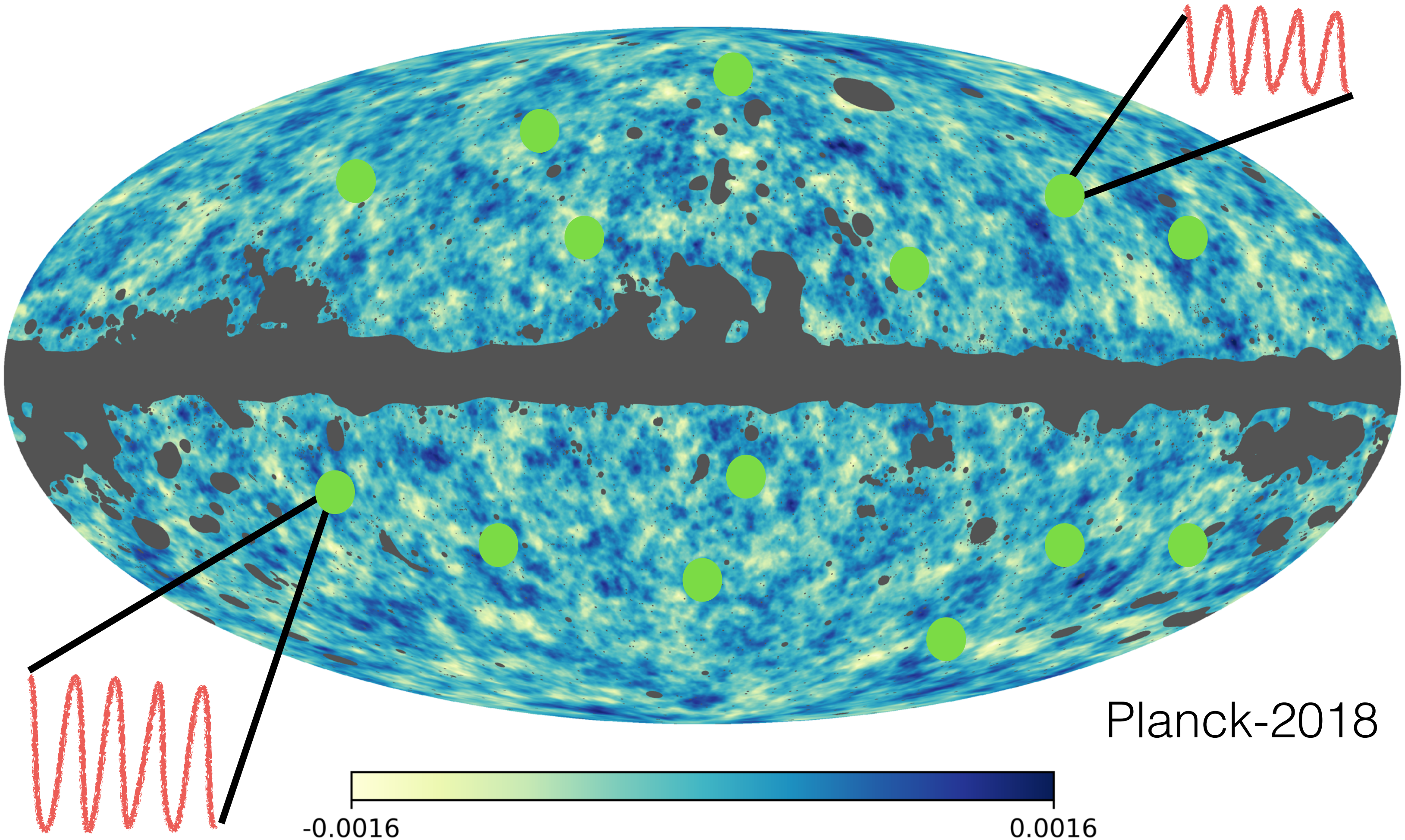
Image credit: ESA



X

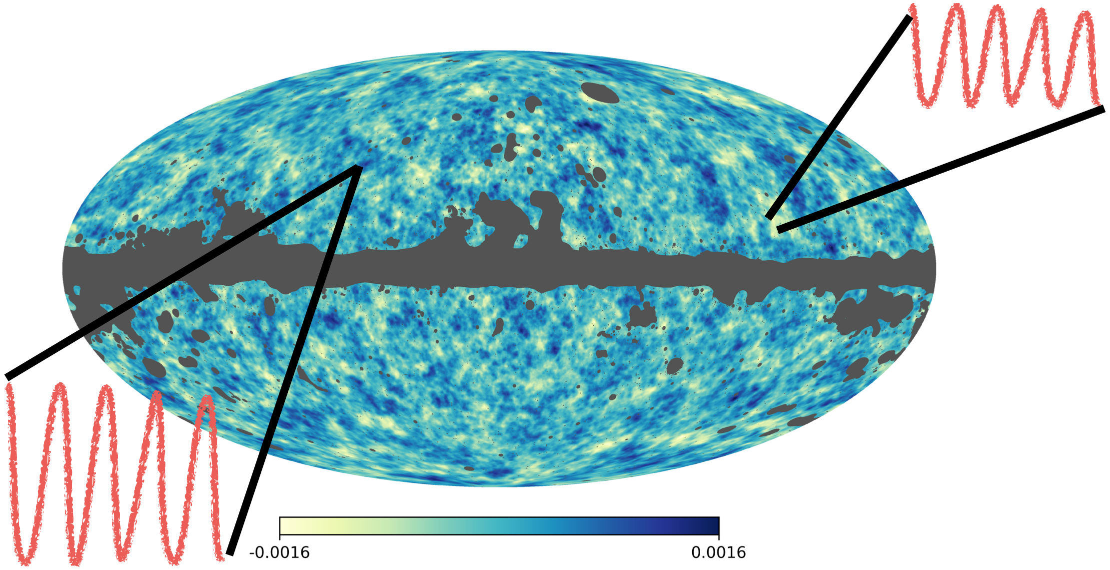


X Image credit: Hu and Okamoto

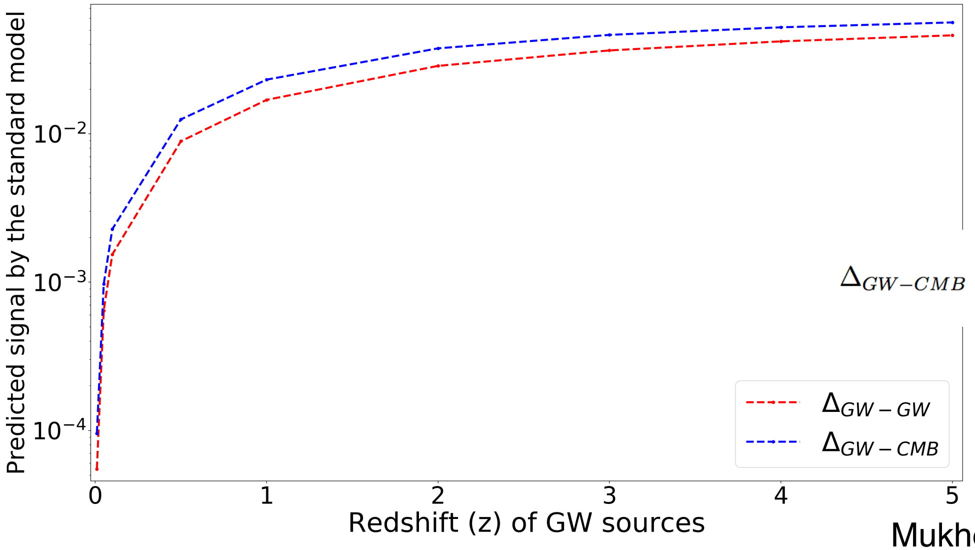

Planck-2018
-0.0016
0.0016

Estimator of the signal

$$\hat{\mathcal{E}}^{\kappa_{gw}\kappa_{cmb}} \equiv \frac{1}{4\pi}\int d^2\hat{n}\,\hat{\mathcal{D}}_L(\hat{n})\hat{\kappa}_{\rm CMB}(\hat{n}')$$
$$= \frac{1}{4\pi}\int d^2\hat{n}\,\epsilon(\hat{n})\hat{\kappa}_{\rm CMB}(\hat{n}') + \frac{1}{4\pi}\int d^2\hat{n}\,\hat{\kappa}_{gw}(\hat{n})\hat{\kappa}_{\rm CMB}(\hat{n}').$$



Prediction from Standard Model



$$\Delta_{GW-CMB} \equiv \sum_l [(2l+1) C_l^{\kappa_{gw}\kappa_{cmb}}/4\pi]^{1/2}$$

Mukherjee, Wandelt, Silk

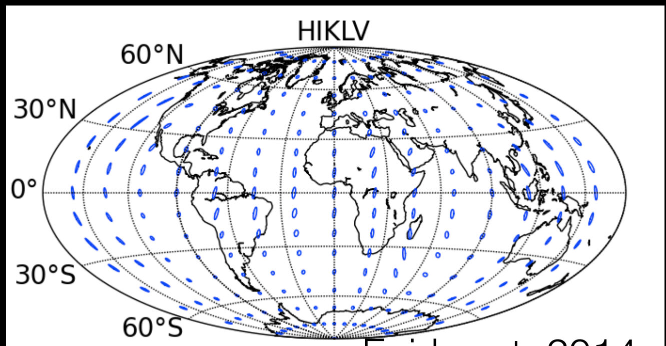
$$\kappa_{CMB}(\hat{n}) = \int_0^{z_s} dz \frac{3}{2} \frac{\Omega_m H_0^2 (1+z)\chi(z)}{cH(z)} \left[\frac{(\chi(z_s) - \chi(z))}{(\chi(z_s))} \delta(\chi(z)\hat{n}, z) \right],$$

$$\kappa_{gw}(\hat{n}) = \int_0^{z_s} dz \frac{3}{2} \frac{\Omega_m H_0^2 (1+z)\chi(z)}{cH(z)} \int_z^{\infty} dz' \frac{dn_{gw}(z')}{dz'} \frac{(\chi(z_s) - \chi(z'))}{(\chi(z_s))} \delta(\chi(z)\hat{n}, z).$$

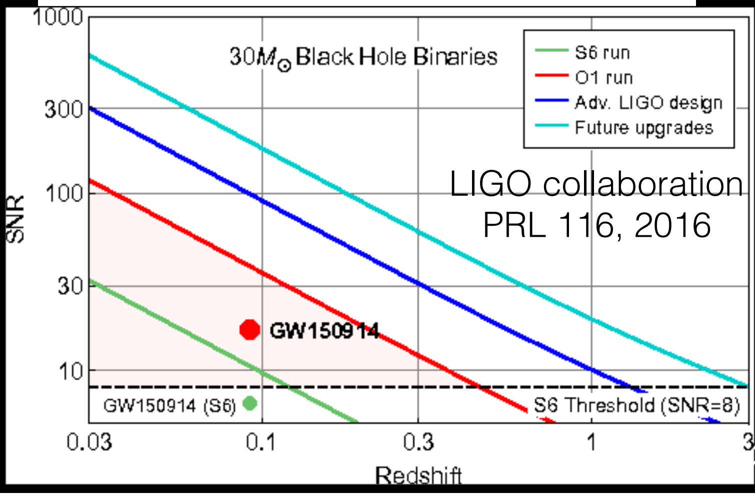
$$C_l^{\kappa_{gw}\kappa_{cmb}} = \int \frac{dz}{\chi^2} \frac{H(z)}{c} \left[W_{gw}(\chi(z)) W_{cmb}(\chi(z)) \times P_\delta((l+1/2)/\chi(z)) \right]$$

Redshift reach of future GW experiments

LIGO

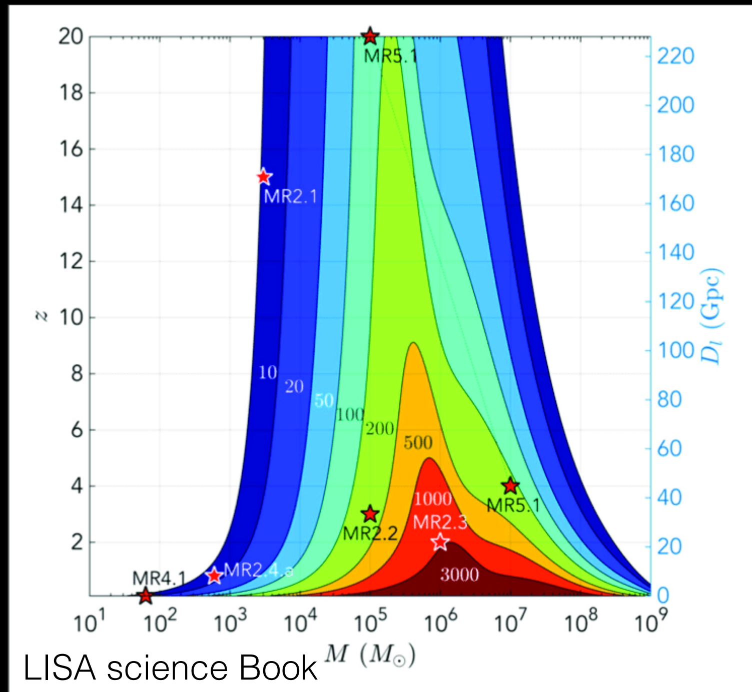


Fairhurst, 2014



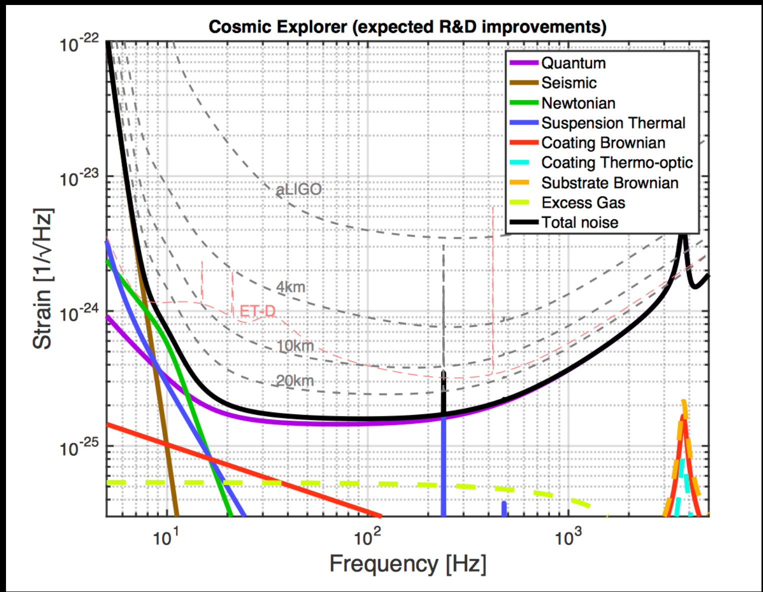
LIGO collaboration PRL 116, 2016

LISA



LISA science Book

Multi-frequency window



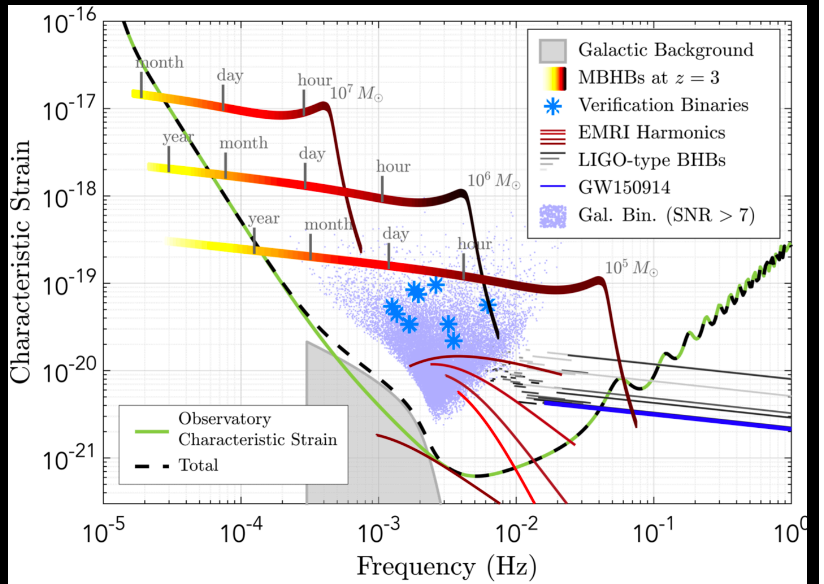
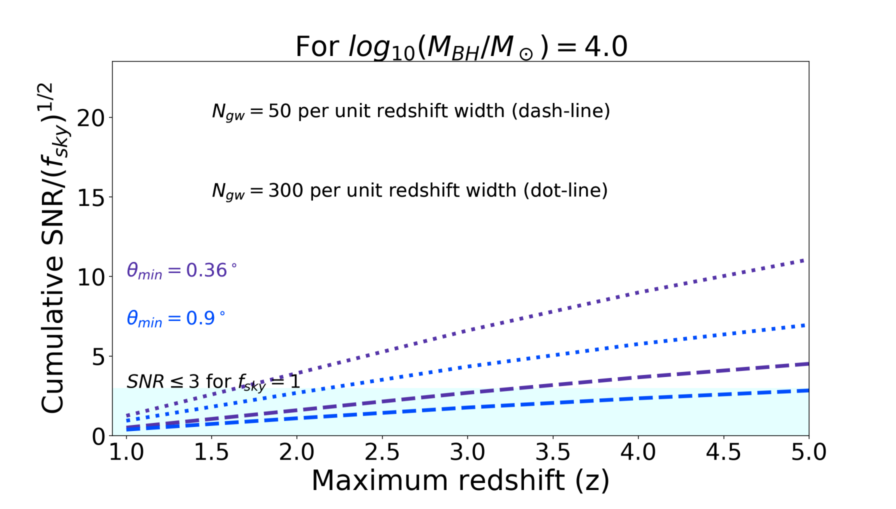


Image: LIGO collaboration
1607.08697

Image: LISA Science Proposal

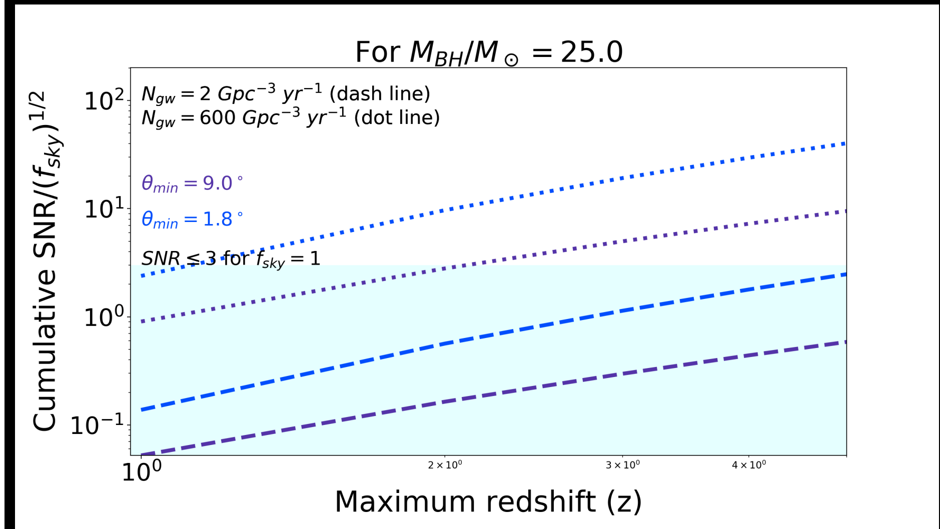
Discovery space



Mukherjee, Wandelt, Silk (2019)

arXiv:1908.08950

LISA



aLIGO+Virgo+Kagra+LIGO-India
and from Cosmic Explorer at
high redshift

Testing gravity

- Concordant trajectory between electromagnetic waves and gravitational waves
- Measurement of the lensing signal from GW events
- Delensing of GW strain
- A probe to the theories of extra dimensions of spacetime

$$h \propto \frac{1}{d_L\left[1+\left(\frac{d_L}{R_c}\right)^{n(D-4)/2}\right]^{1/n}},$$

(Deffayet & Menou 2007, LIGO-VIRGO Coll. (2018))

- A probe to the alternative theories of gravity

$$h''_{ij} + (2+\nu)\mathcal{H}h'_{ij} + (c_T^2 k^2 + a^2\mu^2)h_{ij} = a^2\Gamma\gamma_{ij}$$

Constraints from the BNS event

Nearer term prospects from GW - galaxy lensing X-correlation:

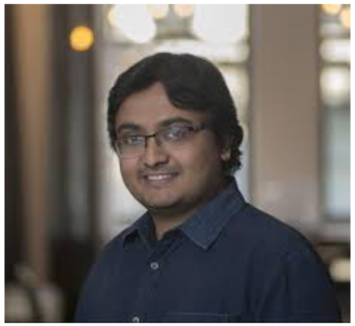
Mukherjee, BDW & Silk

arXiv:1908.08951

X

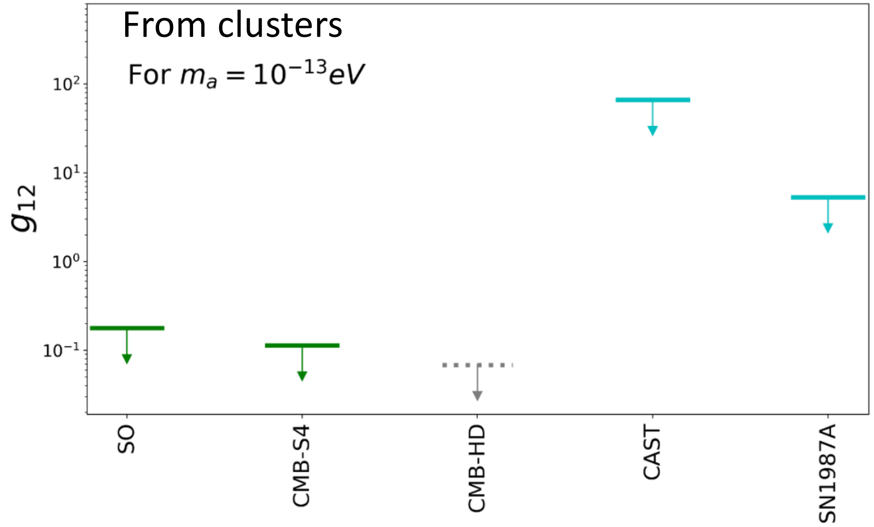
New science target: Axion physics with CMB polarization experiments

with Suvodip Mukherjee, Rishi Khatri, David Spergel



Photons convert to axions in magnetic field

- Resonance conversion of CMB photons to axions in magnetic fields produce a distinctive polarized spectral distortion
- Highly efficient process in magnetic fields of our galaxy or of clusters
- Promises to be a world-leading probe of light axion-like particles!



Mukherjee, Khatri & Wandelt (2018), arXiv:1801.09701 (also voids!)

Mukherjee, Spergel, Khatri & Wandelt, arXiv: 1908.07534

Summary

- A new perspective on classical cosmological tests generalize the AP test, solve a major problem in Supernova cosmology, and produce more powerful cross-correlation tests of dark energy
- Applying this to non-linear galaxy surveys unlocks billions of modes of large scale structure data to test the expansion history
- A new test of gravity with the GW– CMB cross bispectrum
- Next gen CMB polarization experiments are fantastic probes of light axions!

To reproduce the results in the IMNN paper the code version used is archived on zenodo

https://doi.org/10.5281/zenodo.1175196

The most current development version is on github:

IMNN:

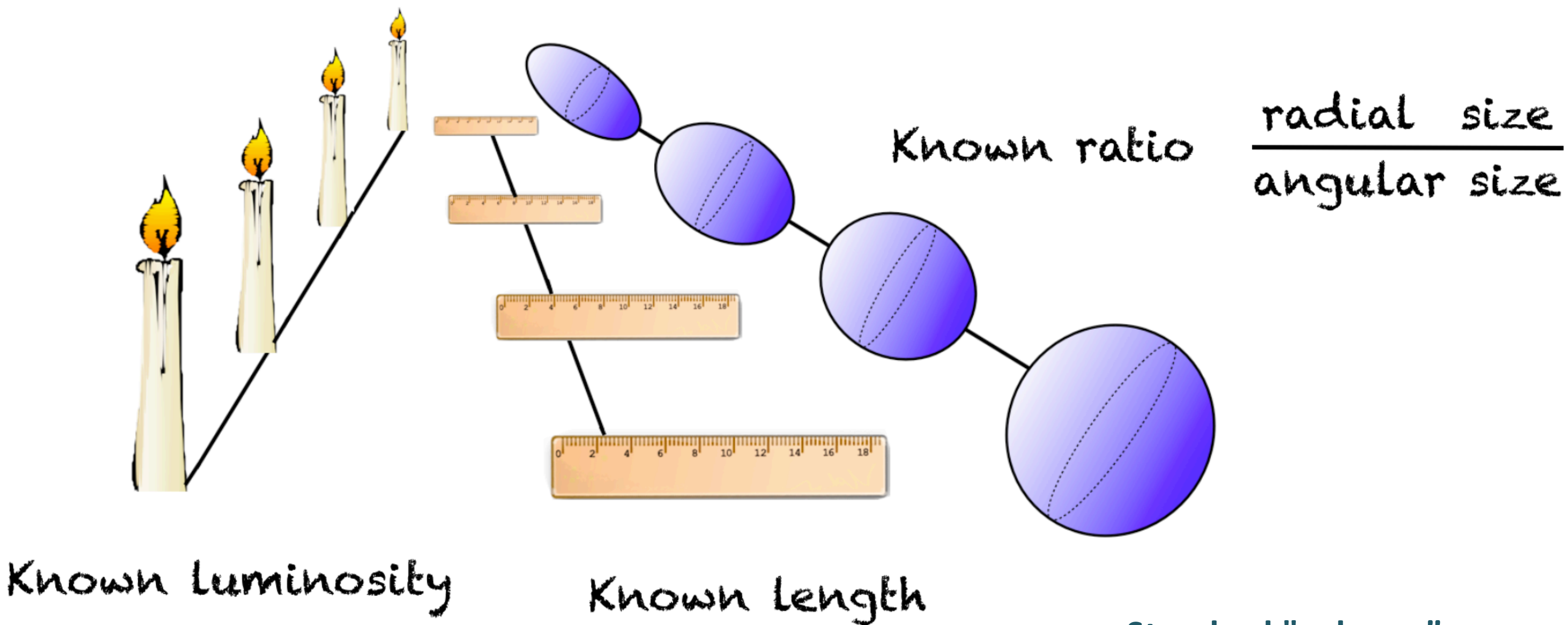
https://github.com/tomcharnock/IMNN

DELFI:

https://github.com/justinalsing/pydelfi

Benjamin Wandelt

Cosmography with the Alcock-Pazcynski test



Standard "candles"

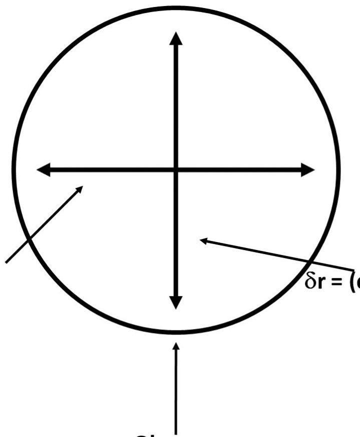
Standard "rulers"

Standard "spheres" – e.g. isotropic correlation function

Alcock-Paczynski test

Perform *Alcock-Paczynski test* to constrain cosmological parameters:

- Angular separation $\delta r_\perp = D_A(z)\,\delta\Theta$
- Radial separation $\delta r_\parallel = cH^{-1}(z)\,\delta z$



ANGULAR DIAMETER DISTANCE & HUBBLE RATE

$$D_A(z) = c\int_0^z H^{-1}(z')\,\mathrm{d}z' \quad , \quad H(z) = H_0\sqrt{\Omega_\mathrm{m}(1+z)^3 + \Omega_\Lambda}$$

Any deviation from the fiducial cosmology causes geometric distortions. ⇒ Determine ellipticity ε via

$$\varepsilon = \frac{\delta r_\parallel}{\delta r_\perp} = \frac{D_A^\mathrm{true}(z)H^\mathrm{true}(z)}{D_A^\mathrm{fid}(z)H^\mathrm{fid}(z)}$$