B+ :
Inflationary gravitational waves and more

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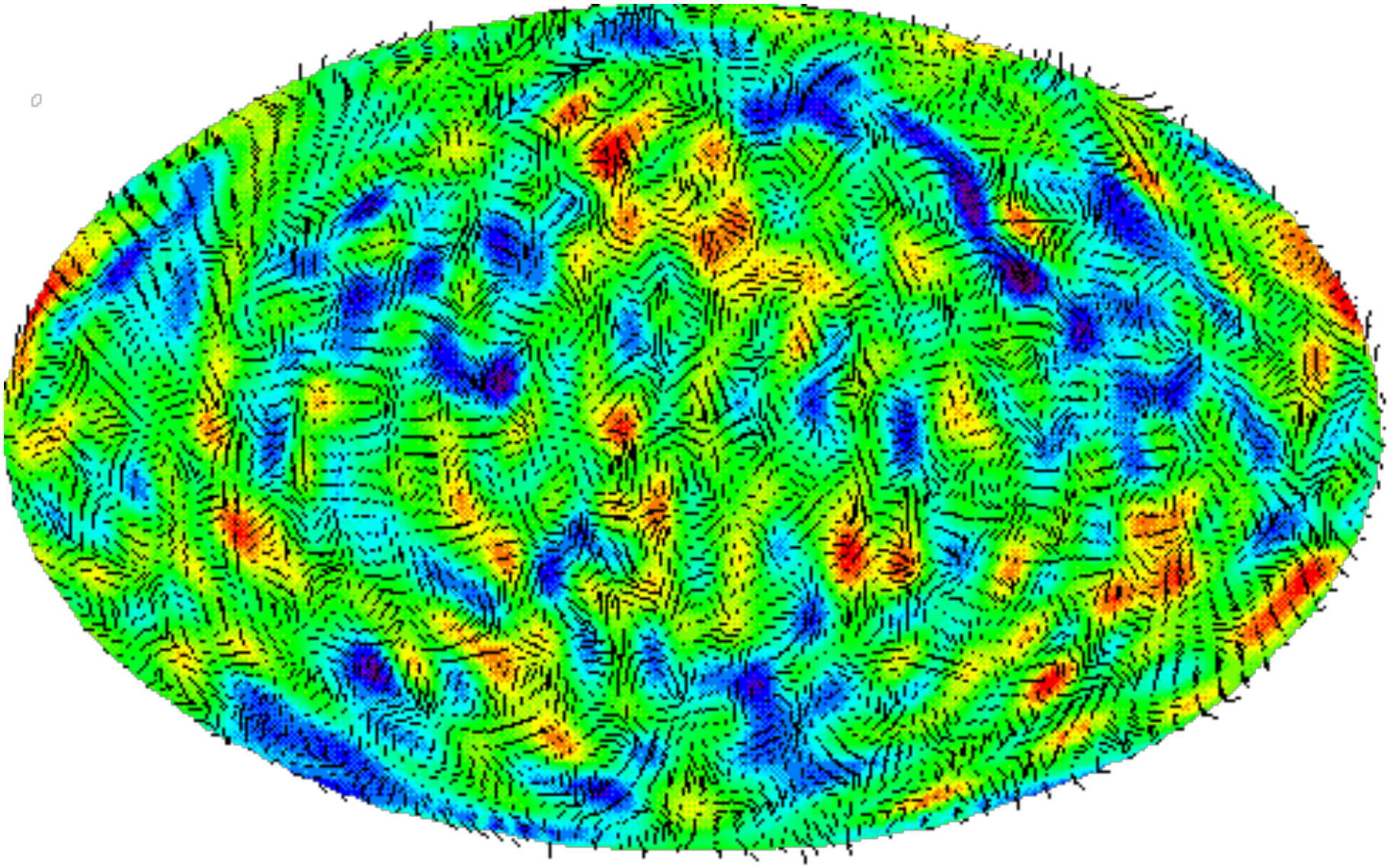
COSPAR

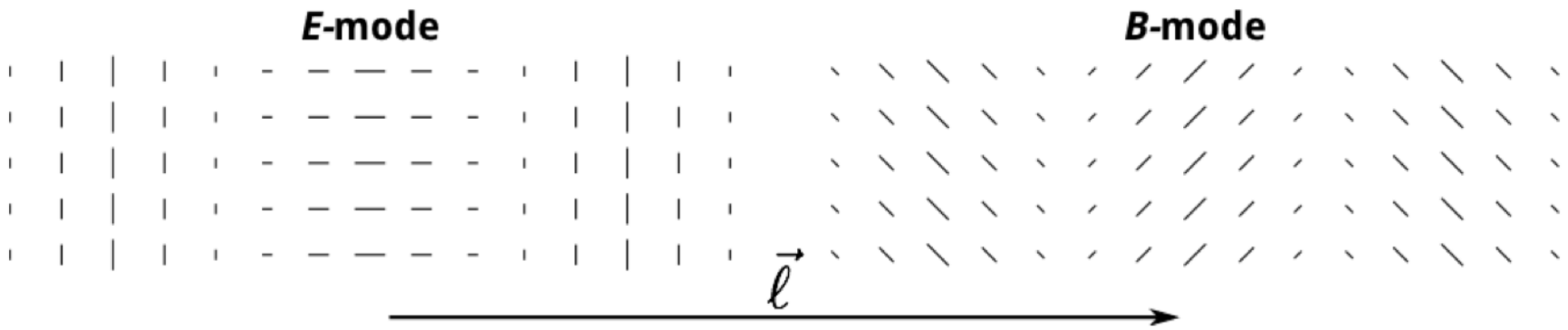
”The quest for B modes from inflationary gravitational waves,” MK and Kovetz, ARAA 54, 227 (2016), arXiv:1510.06042

Outline

- E and B modes
- Inflationary gravitational waves
- Cosmic birefringence and chiral GWs
- Dust polarization and ISM physics
- 3D generalization: clustering fossils
- Total angular momentum waves



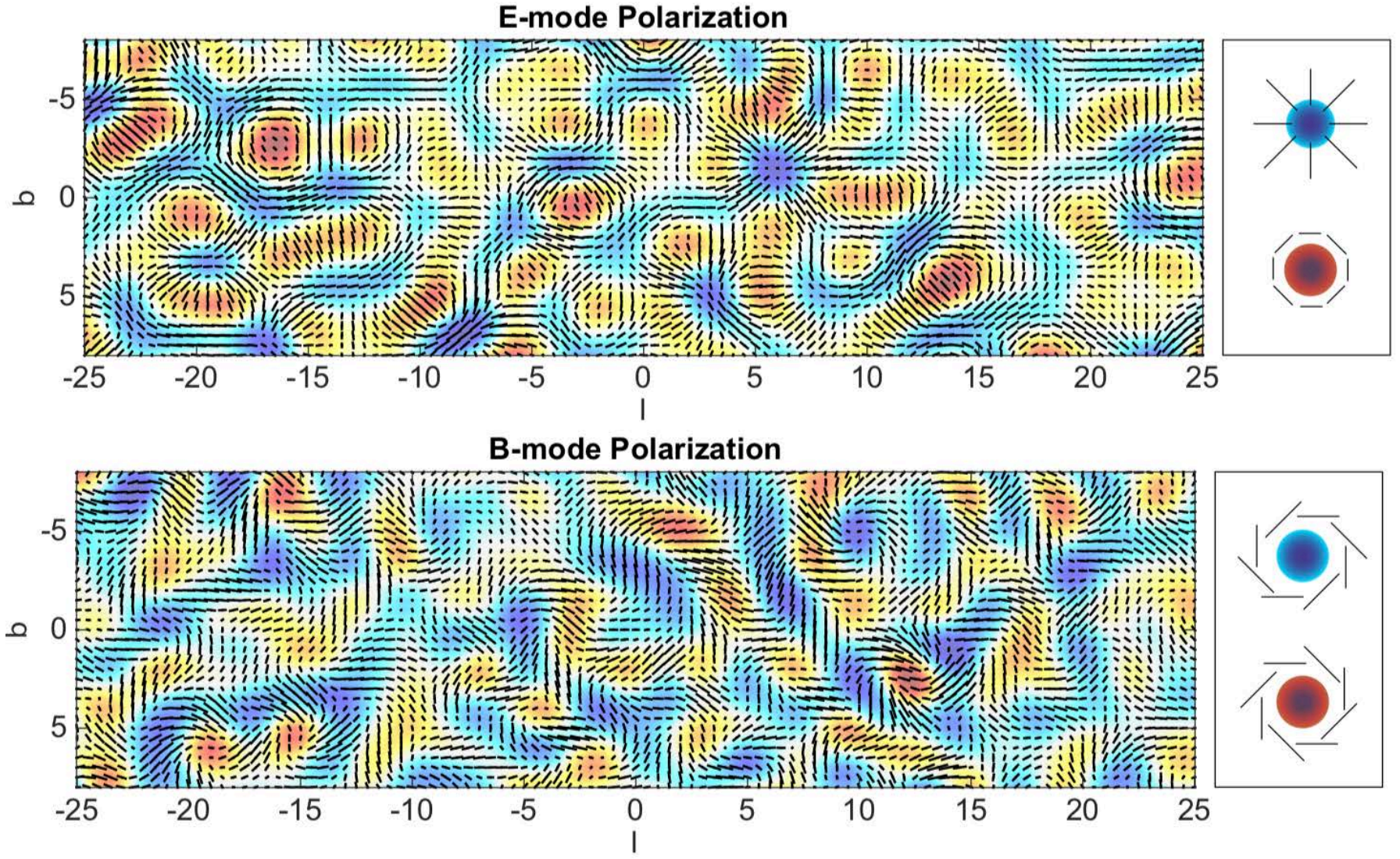
Caldwell, MK, Wadley 1999


E-mode
B-mode
$\vec{\ell}$

$$\mathcal{P}_{ab}(\hat{n}) = \frac{1}{\sqrt{2}} \begin{pmatrix} Q(\hat{n}) & U(\hat{n}) \sin\theta \\ U(\hat{n}) \sin\theta & -Q(\hat{n}) \sin^2\theta \end{pmatrix}$$

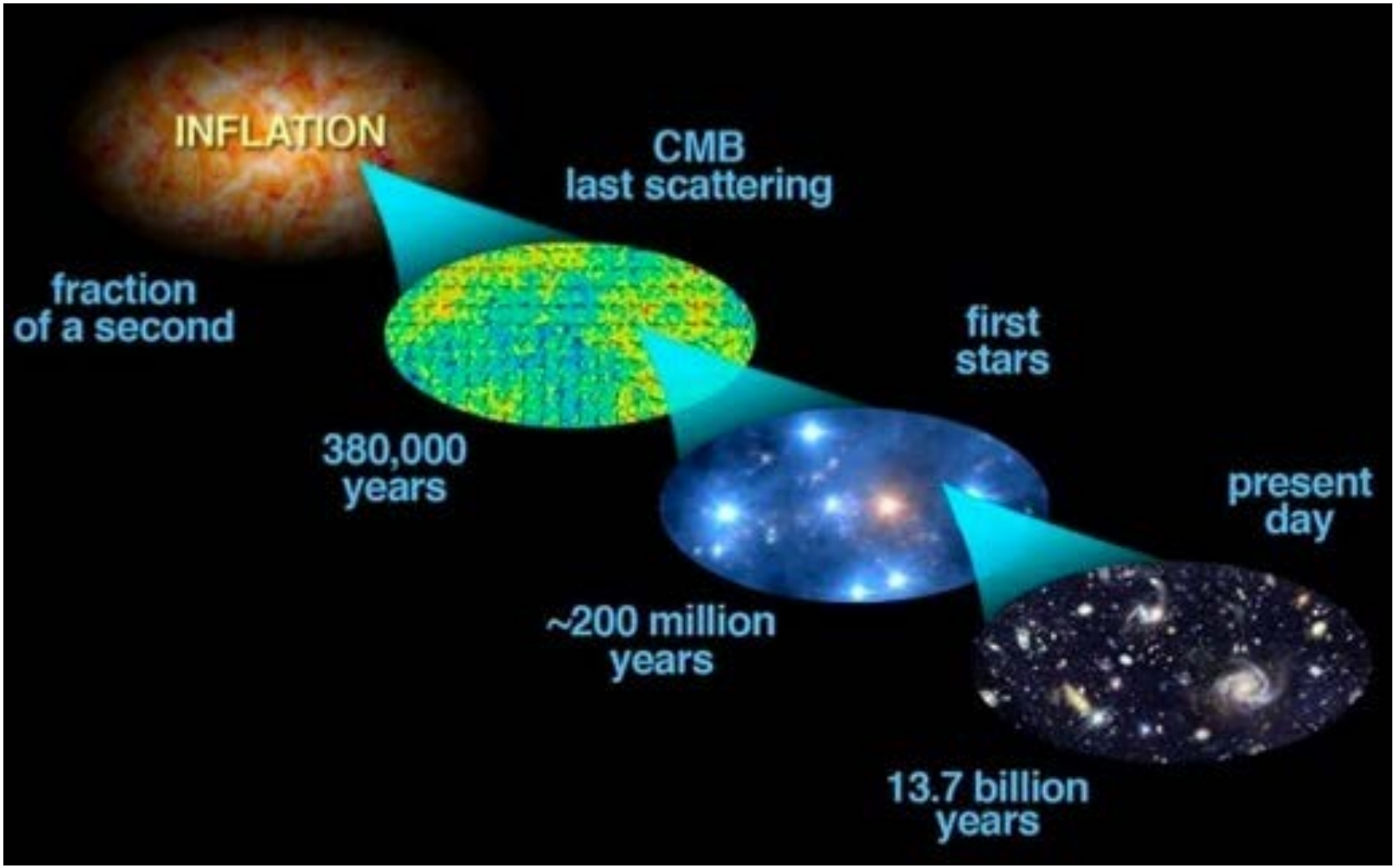
$$\mathcal{P}_{ab}(\hat{n}) = T_0 \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} \left[a^{\rm E}_{\ell m} Y^{\rm E}_{(\ell m)ab}(\hat{n}) + a^{\rm B}_{\ell m} Y^{\rm B}_{(\ell m)ab}(\hat{n}) \right]$$

MK, Kosowsky, Stebbins 1997; Zaldarriaga & Seljak 1997

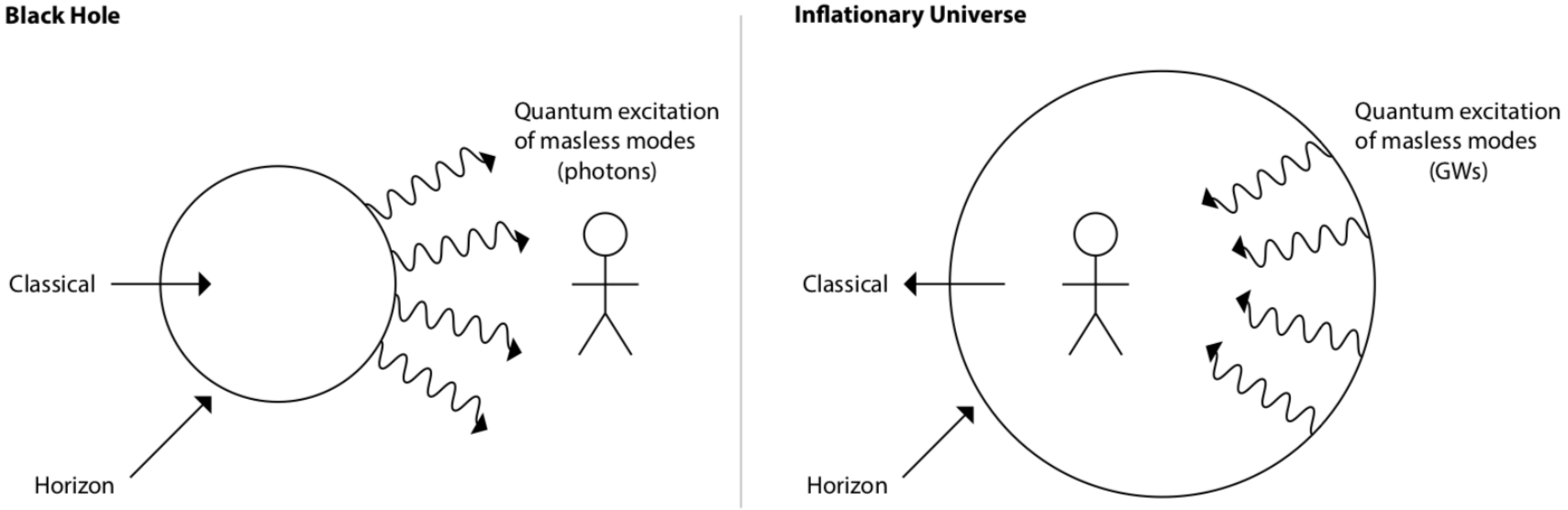


MK & Kovetz, ARAA 2016

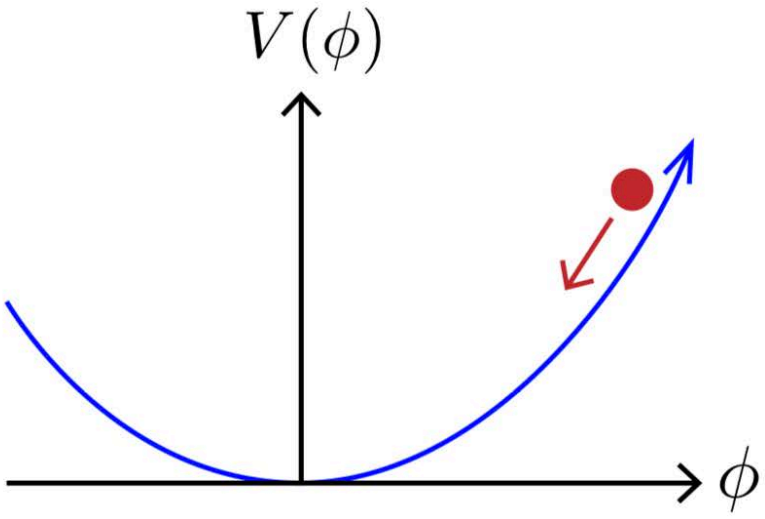
CMB → Inflation

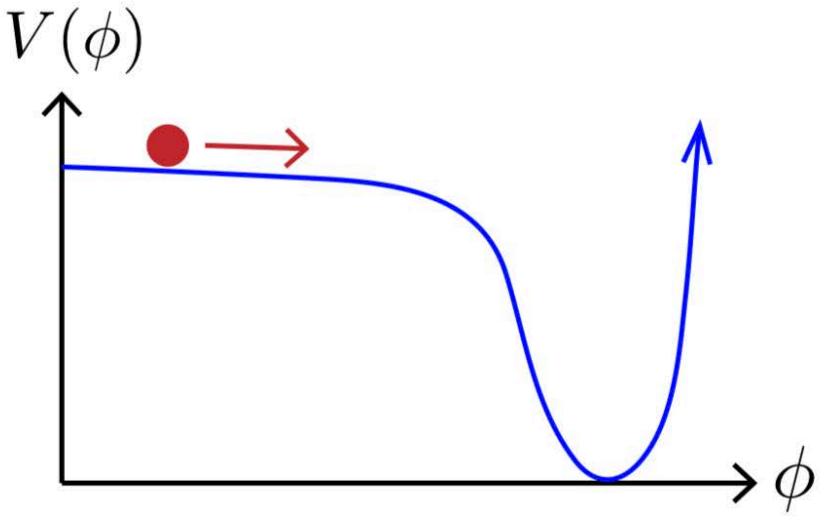


Black-hole analogy



MK & Kovetz, ARAA 2016

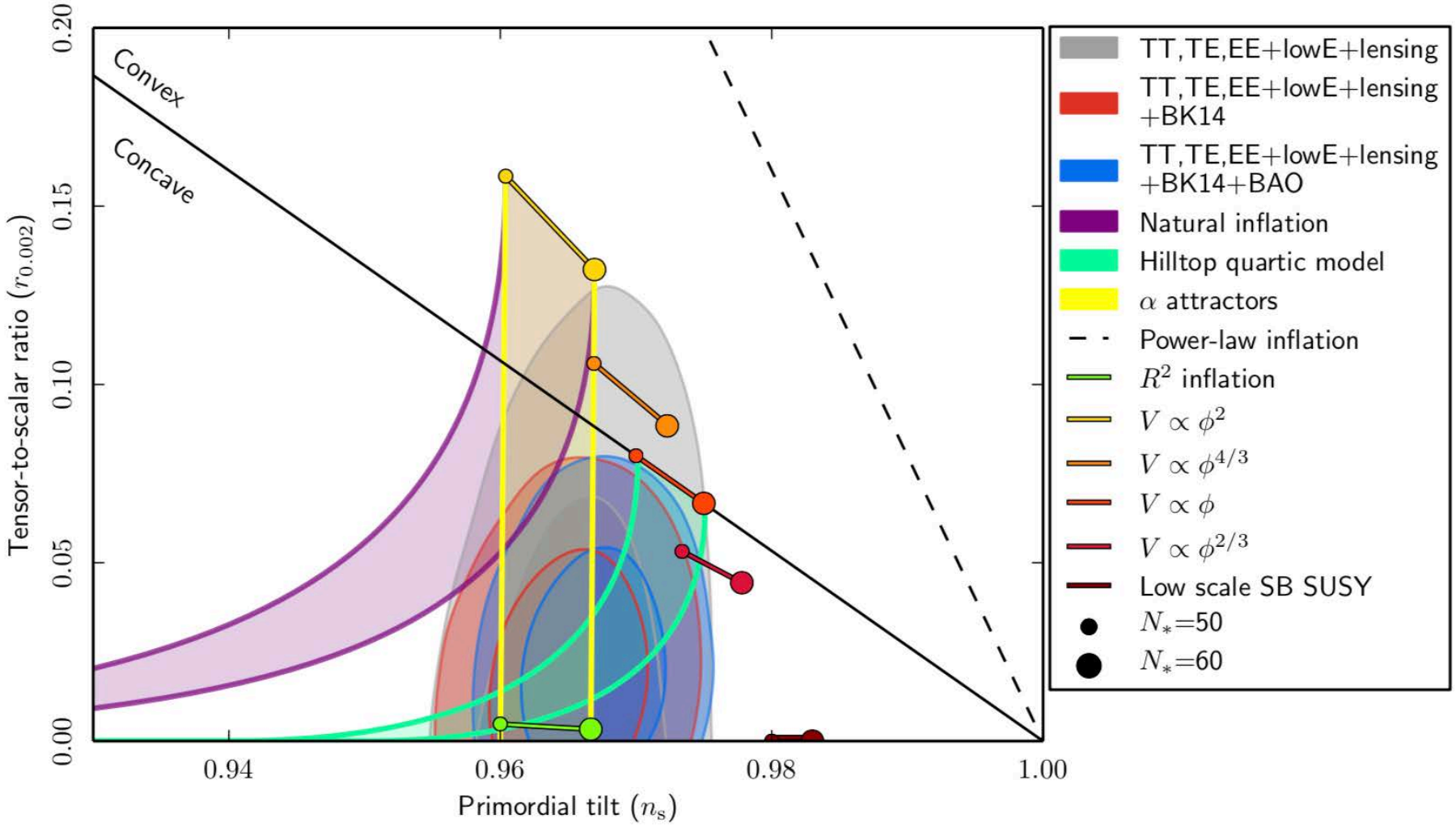

$V(\phi)$
ϕ


$V(\phi)$
ϕ

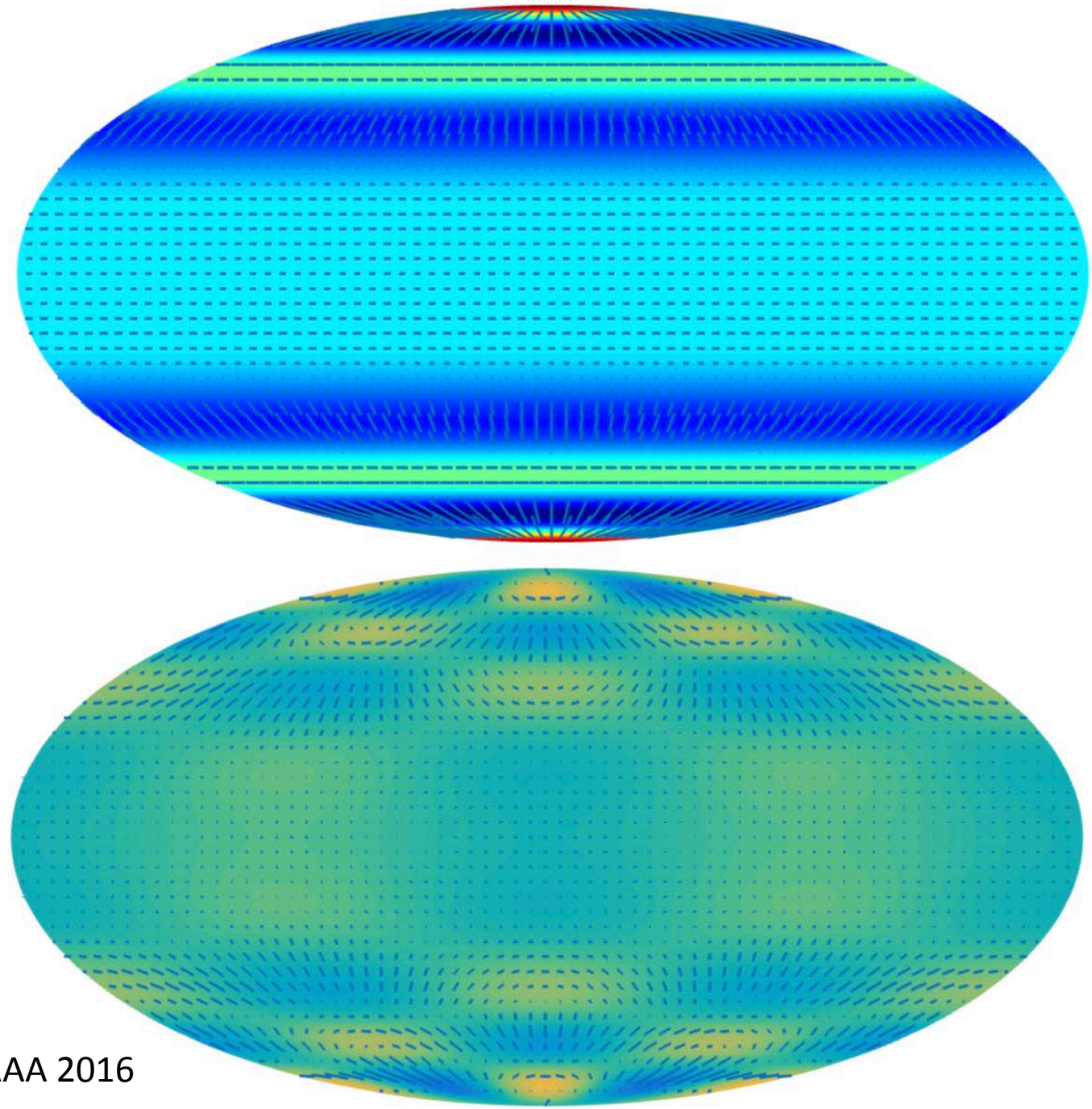
$$\Delta^2_{\mathcal{R}}(k) \equiv \frac{k^3}{2\pi^2}\left\langle |\mathcal{R}|^2 \right\rangle = \frac{1}{8\pi^2}\frac{H^2}{{M_{\rm Pl}}^2\epsilon} \simeq \frac{1}{24\pi^2}\frac{V}{{M_{\rm Pl}}^4\epsilon}$$

$$n_s(k) - 1 \equiv \frac{d\ln\Delta^2_{\mathcal{R}}(k)}{d\ln k}$$

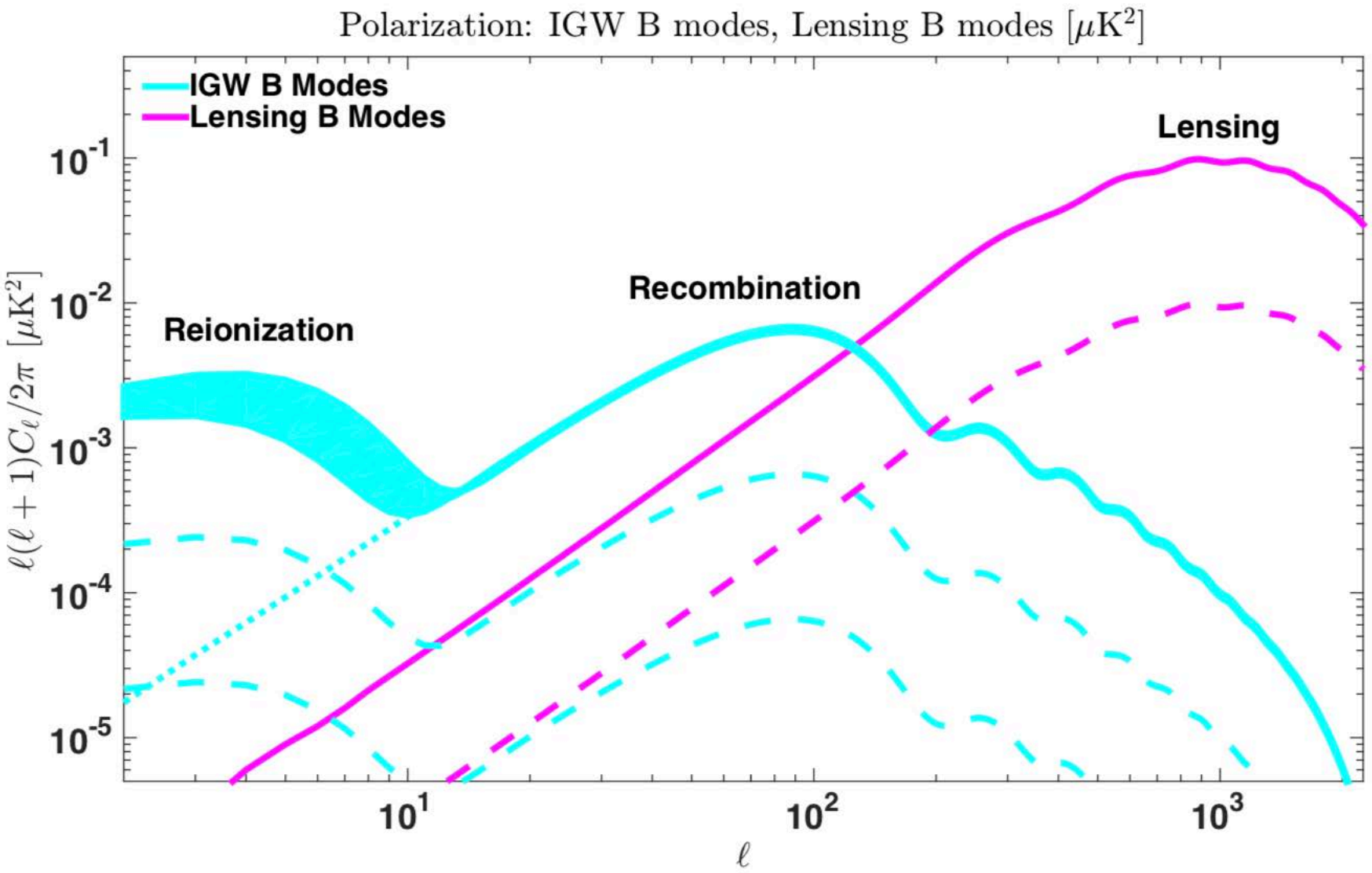
$$r \equiv \frac{\Delta^2_h}{\Delta^2_{\mathcal{R}}} = 16\epsilon \simeq 0.1\left(\frac{V}{[2\times 10^{16}\ {\rm GeV}]^4}\right)$$


Convex
Concave
Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.94
0.96
0.98
1.00
TT,TE,EE+lowE+lensing
TT,TE,EE+lowE+lensing +BK14
TT,TE,EE+lowE+lensing +BK14+BAO
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
R^2 inflation
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
Low scale SB SUSY
N_*=50
N_*=60

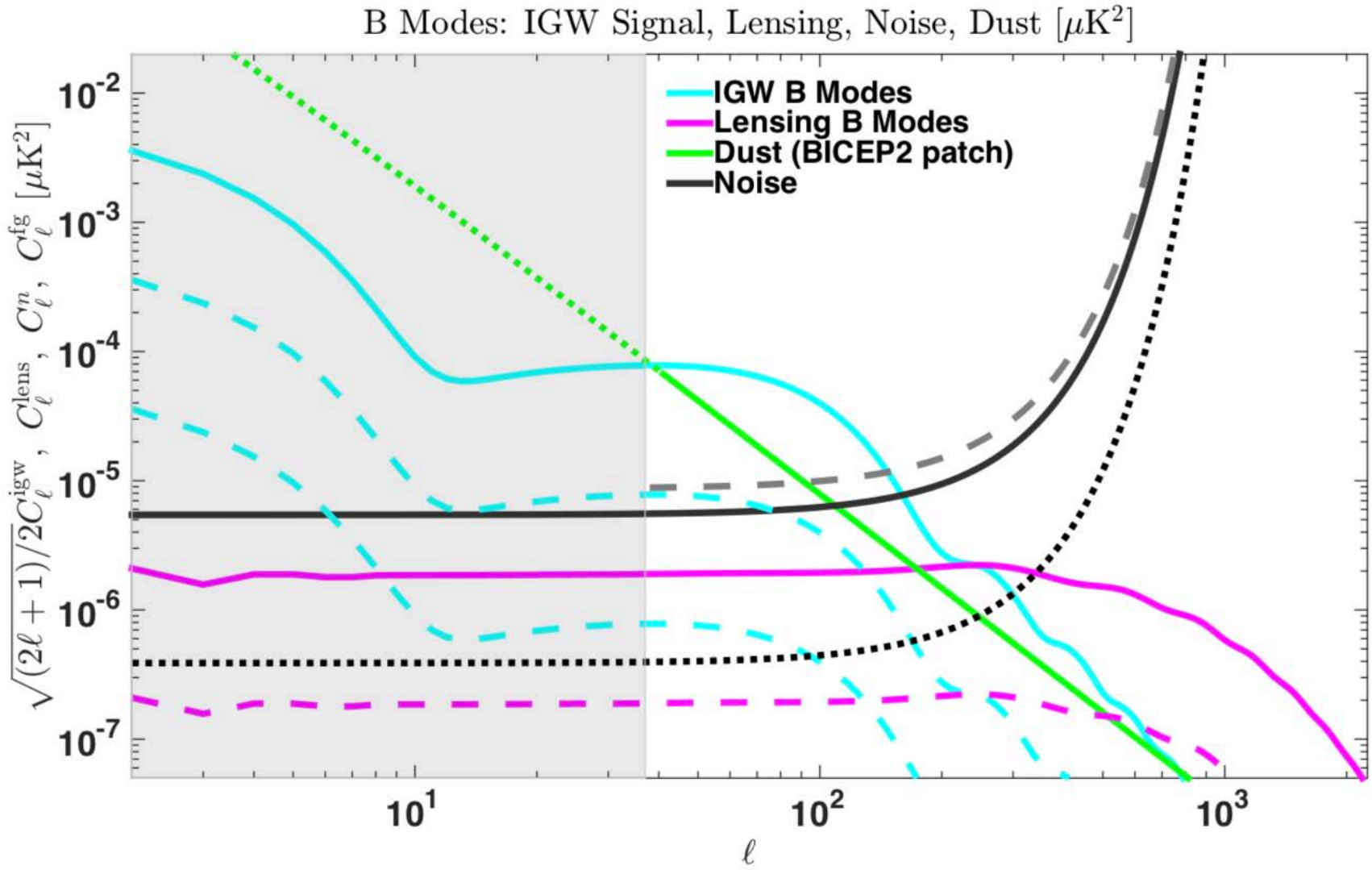
Planck 2018



MK & Kovetz, ARAA 2016



MK & Kovetz, ARAA 2016



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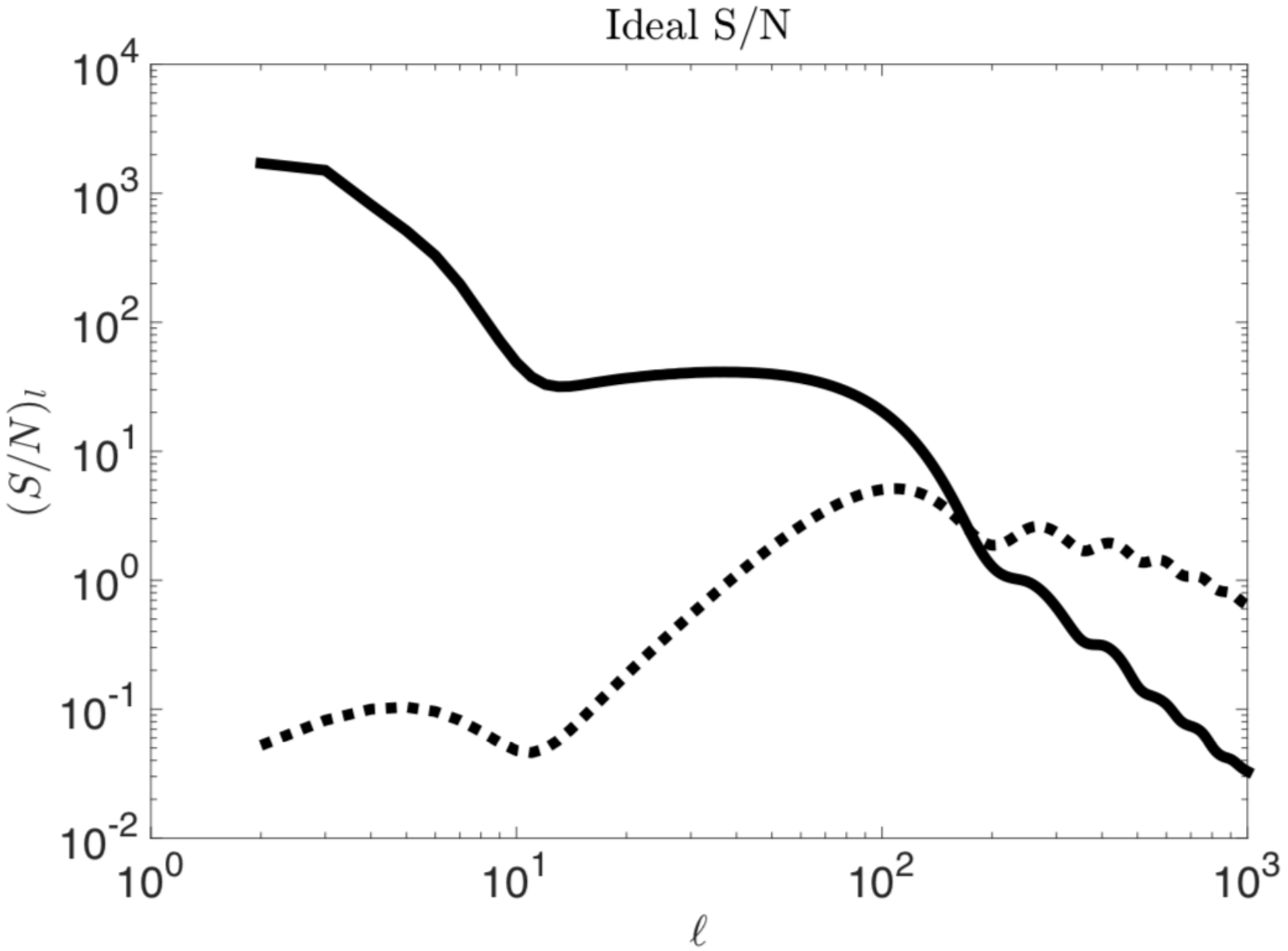
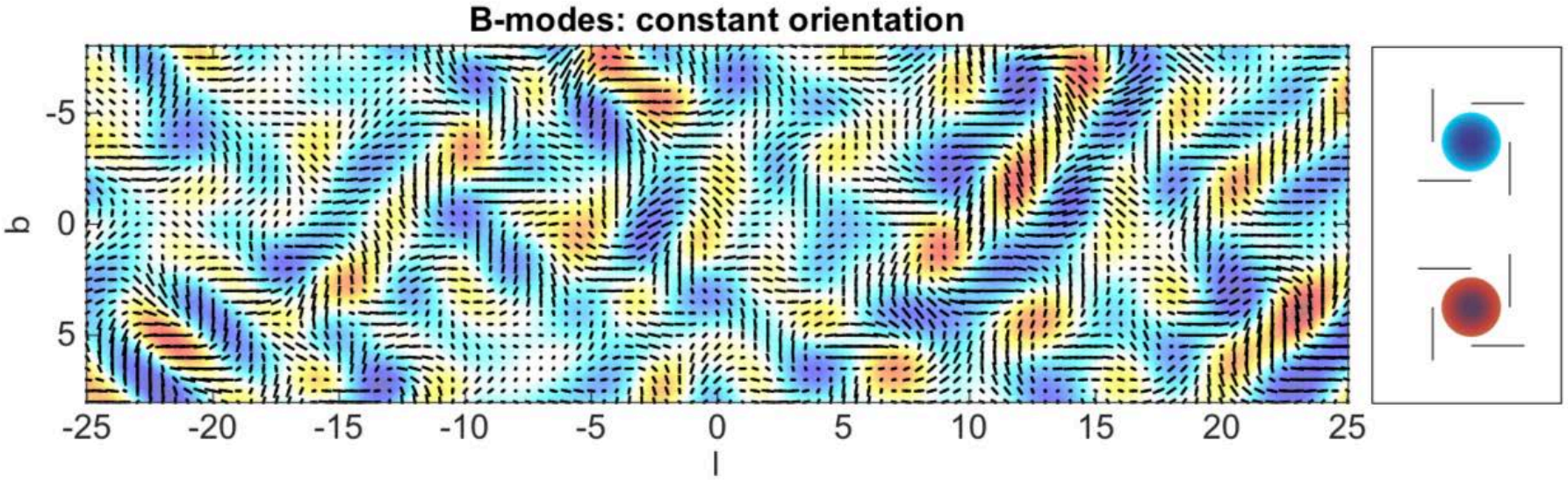


MK & Kovetz, ARAA 2016

Mitigating dust contamination with local departures from statistical isotropy

(MK&Kovetz, PRL, 2014, arXiv:1408.4125)



Discussed further by Huffenberger & Rotti, arXiv:1604.08946,
and more recently elaborated and verified by Philcox, Sherwin, & van Engelen , arXiv:1805.09177)

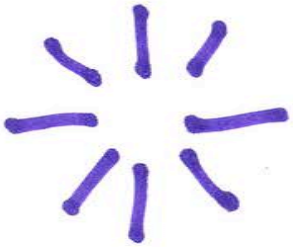
Cosmic birefringence (should be called "cosmic optical rotation")

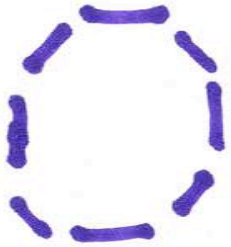
Interaction of light with dark energy might rotate linear polarization as light propagates through Universe (Carroll, Field, Jackiw 1998)

Rotation induces EB cross-correlation (Lue, Wang, MK 1999; MK, PRL 2009; Gluscevic,MK,Cooray, 2009; Yadav, Biswas, Su & Zaldarriaga, 2009)

Will also rotate linear polarization of extragalactic radio sources (MK 2010)

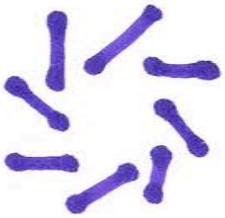
E modes

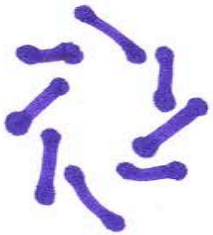




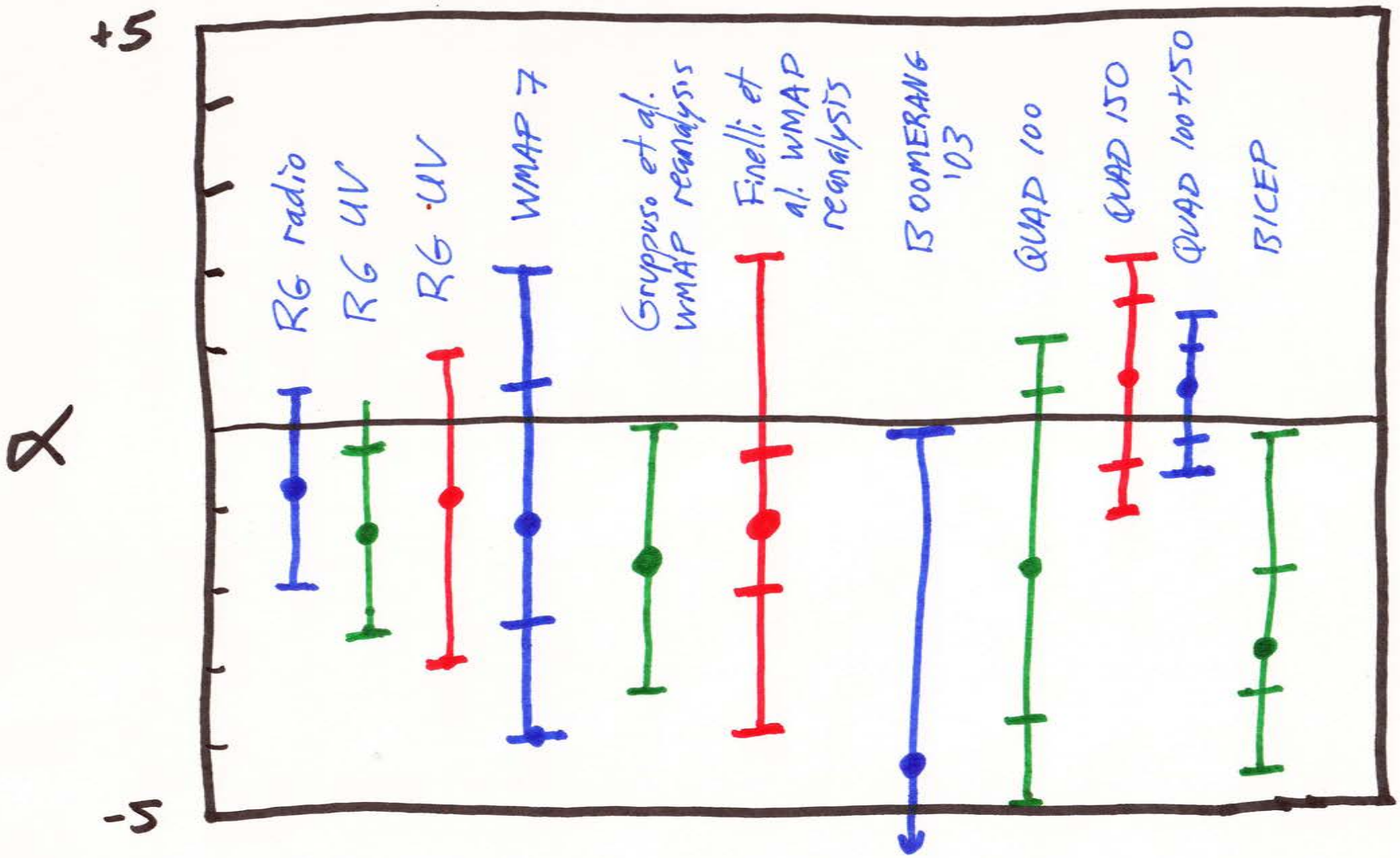
No handedness

B modes





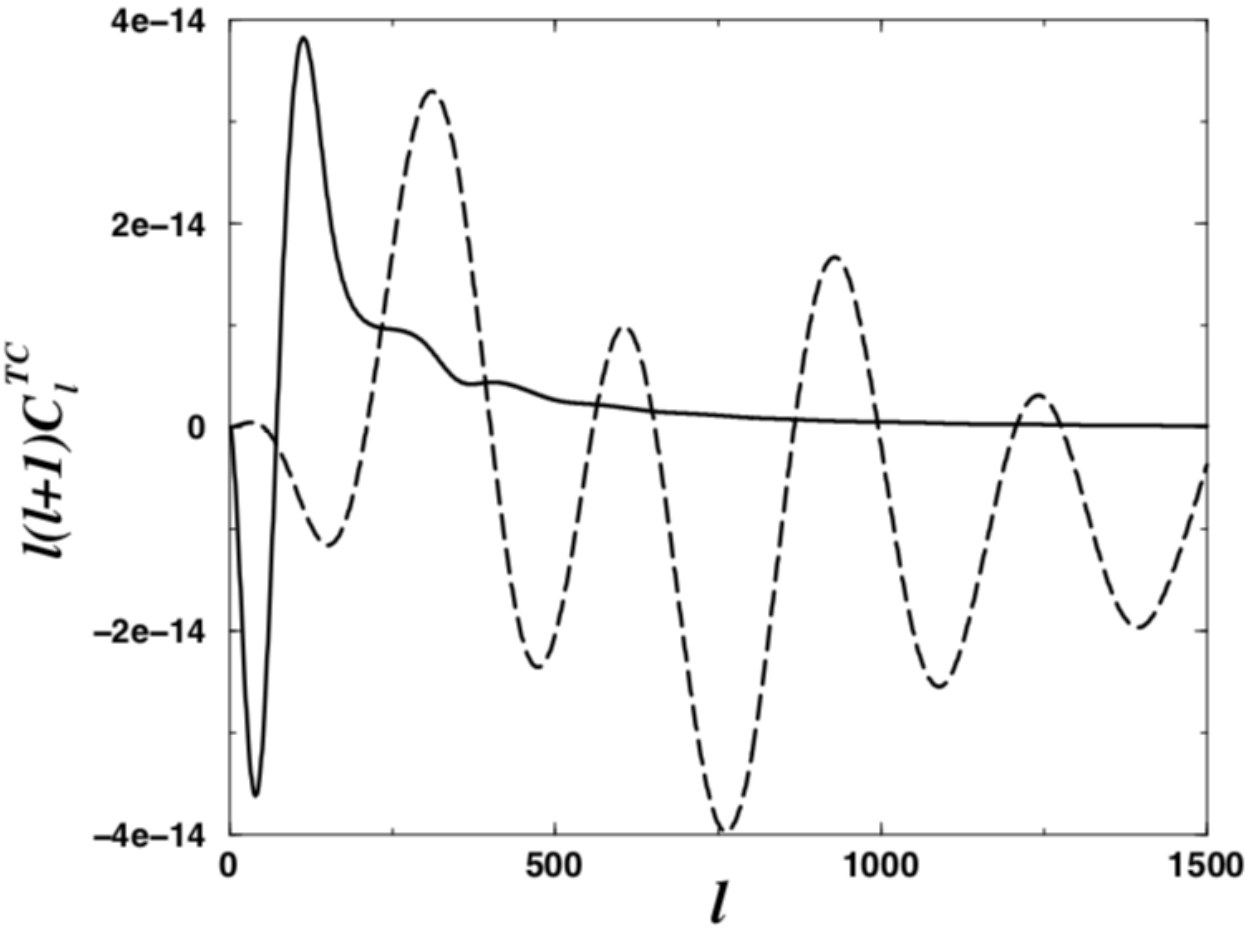
Handedness



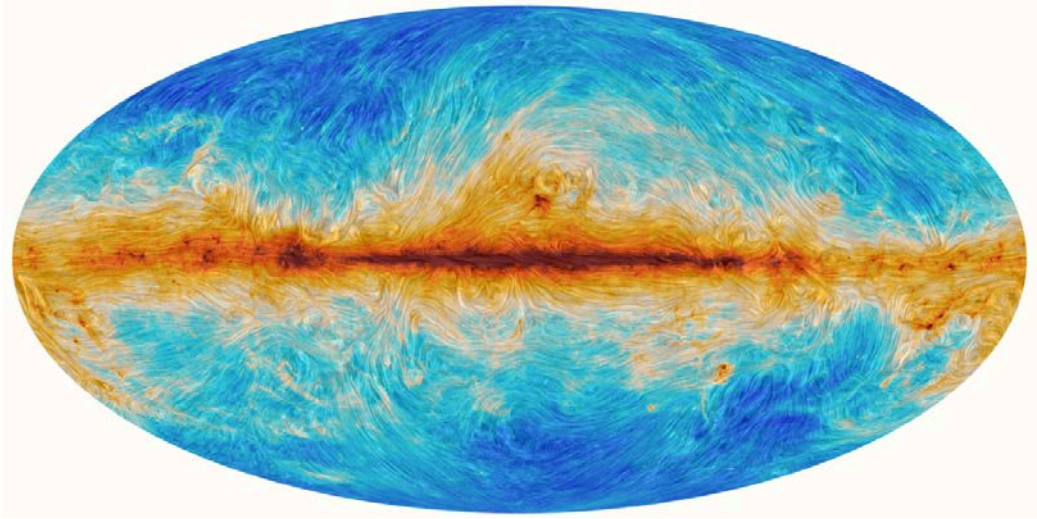
Cartoon of measurements

Asymmetry between left- and right-handed GWs

(Lue, Wang, MK 1999; Gluscevic,MK, 2010)



Dust-polarization maps and interstellar turbulence



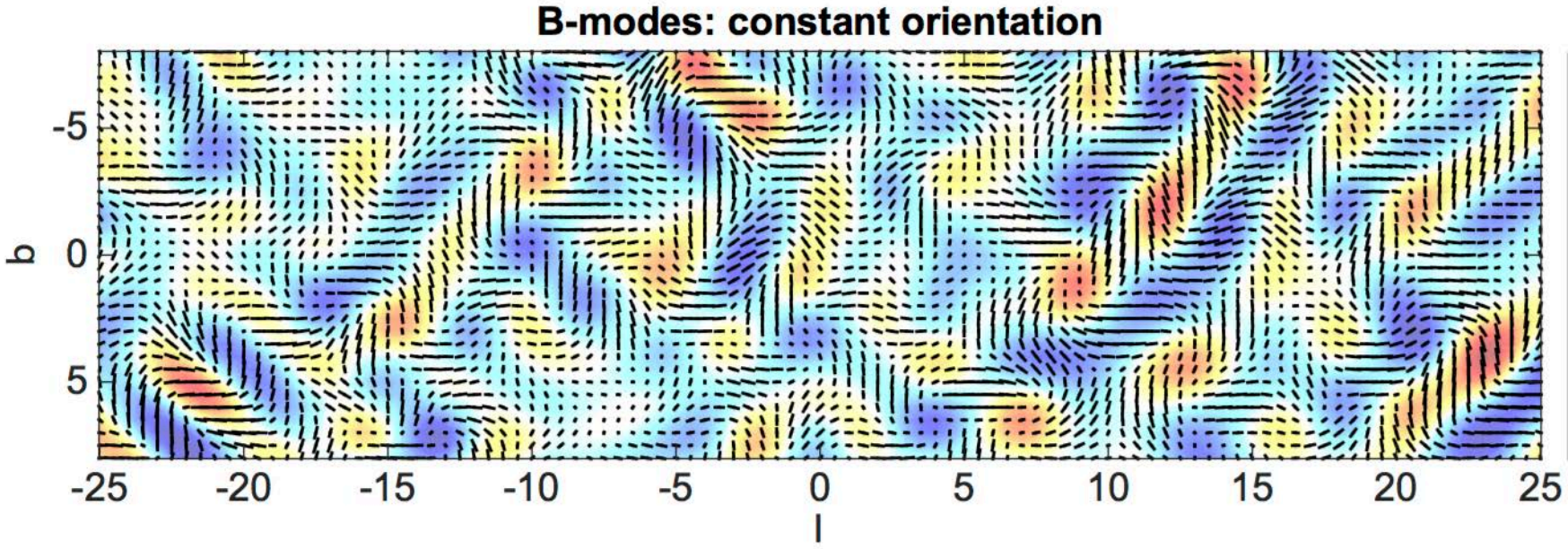
(Caldwell, Hirata, & MK, arXiv:1608.08138)

Pre-Planck dust expectation:

$$C_\ell^{\rm BB} = C_\ell^{\rm EE}$$

(e.g., Zaldarriaga 2001; O'Dea et al. 2012; Delabrouille et al. 2013; Kovetz&MK 2014)

- E.g., from random polarization field
- Or if dust is randomly distributed in uniform magnetic field


B-modes: constant orientation
b
-5
0
5
-25
-20
-15
-10
-5
0
5
10
15
20
25
l

What Planck finds!

$$C_\ell^{\mathrm{EE}} \simeq 2C_\ell^{\mathrm{BB}}$$

Another fun fact

- TE (temperature-polarization) cross-correlation is measured by Planck and found to be *positive*

Dust polarization is a diagnostic for MHD fluctuations in ISM

(Caldwell, Hirata, MK, arXiv:1608.08138)

B-field/dust-density fluctuations in ISM decomposed into slow/fast/Alfven waves

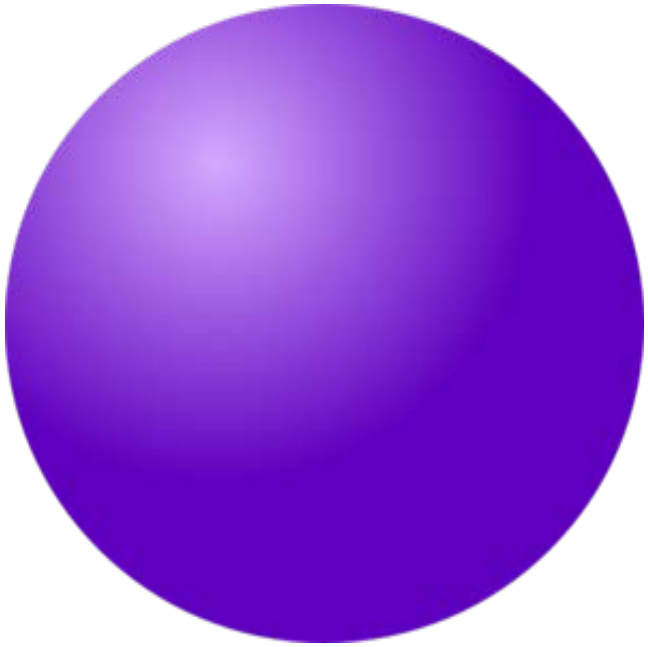
Each such wave has an imprint on the observed E/B/T pattern

P.S. We inferred from E/B/T and power spectral indexes that CMB polarization pattern does not arise from MHD turbulence, but ISM/MHD experts disagree

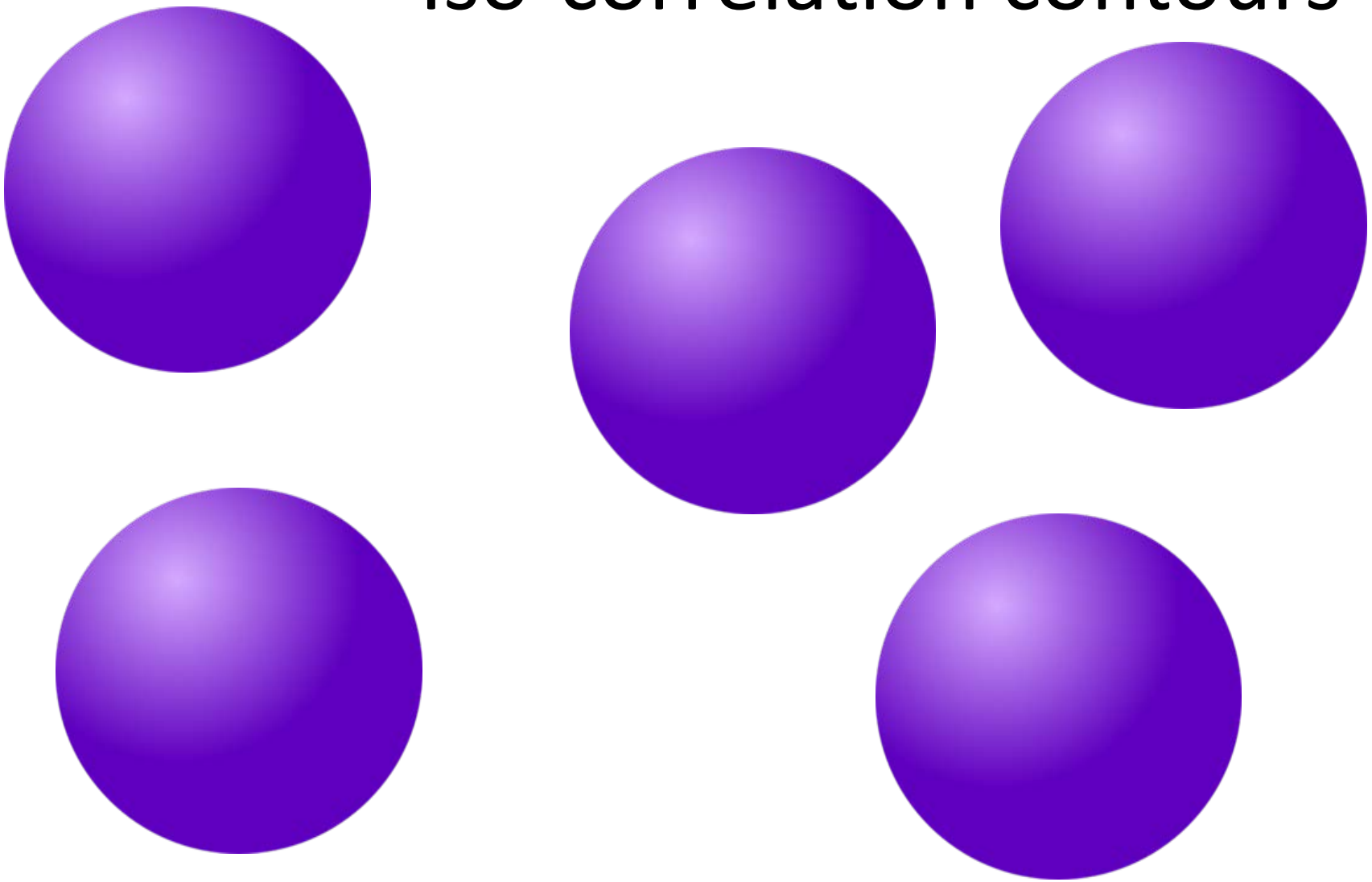
3D generalization: galaxy-galaxy cross-correlation
(Jeong&MK 2012)

- Spatial variation (e.g., from lensing, redshift-space distortions, non-gaussianity, exotic primordial physics) of the 2-pt galaxy autocorrelation function is a spin-2 field in 3D

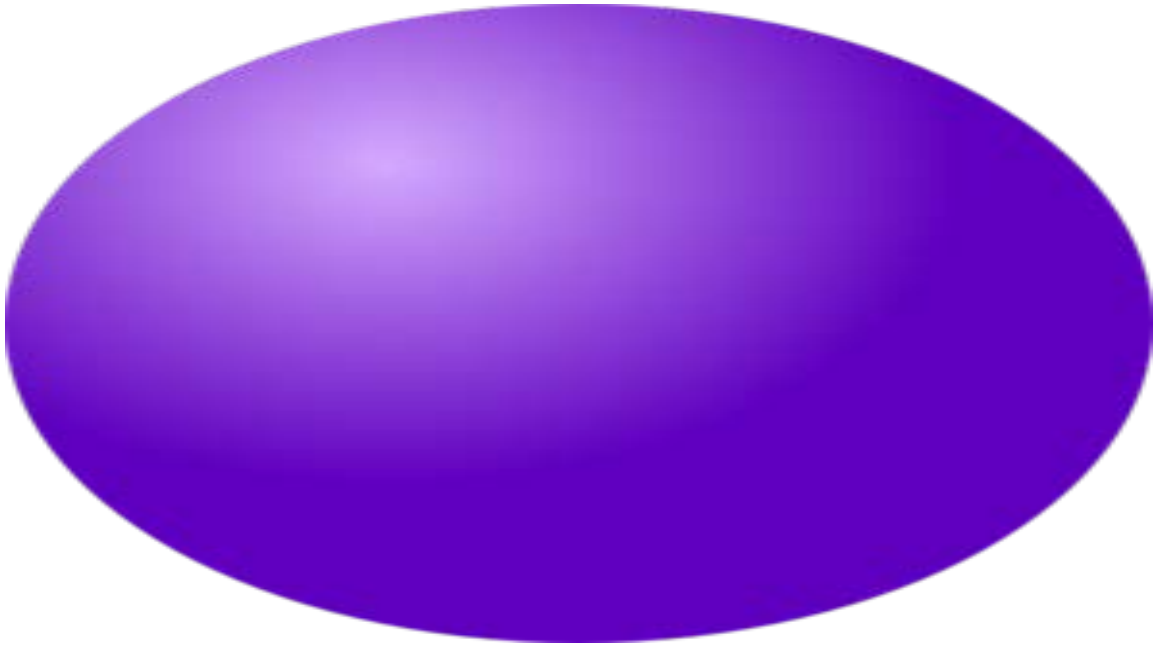
Iso-correlation contours



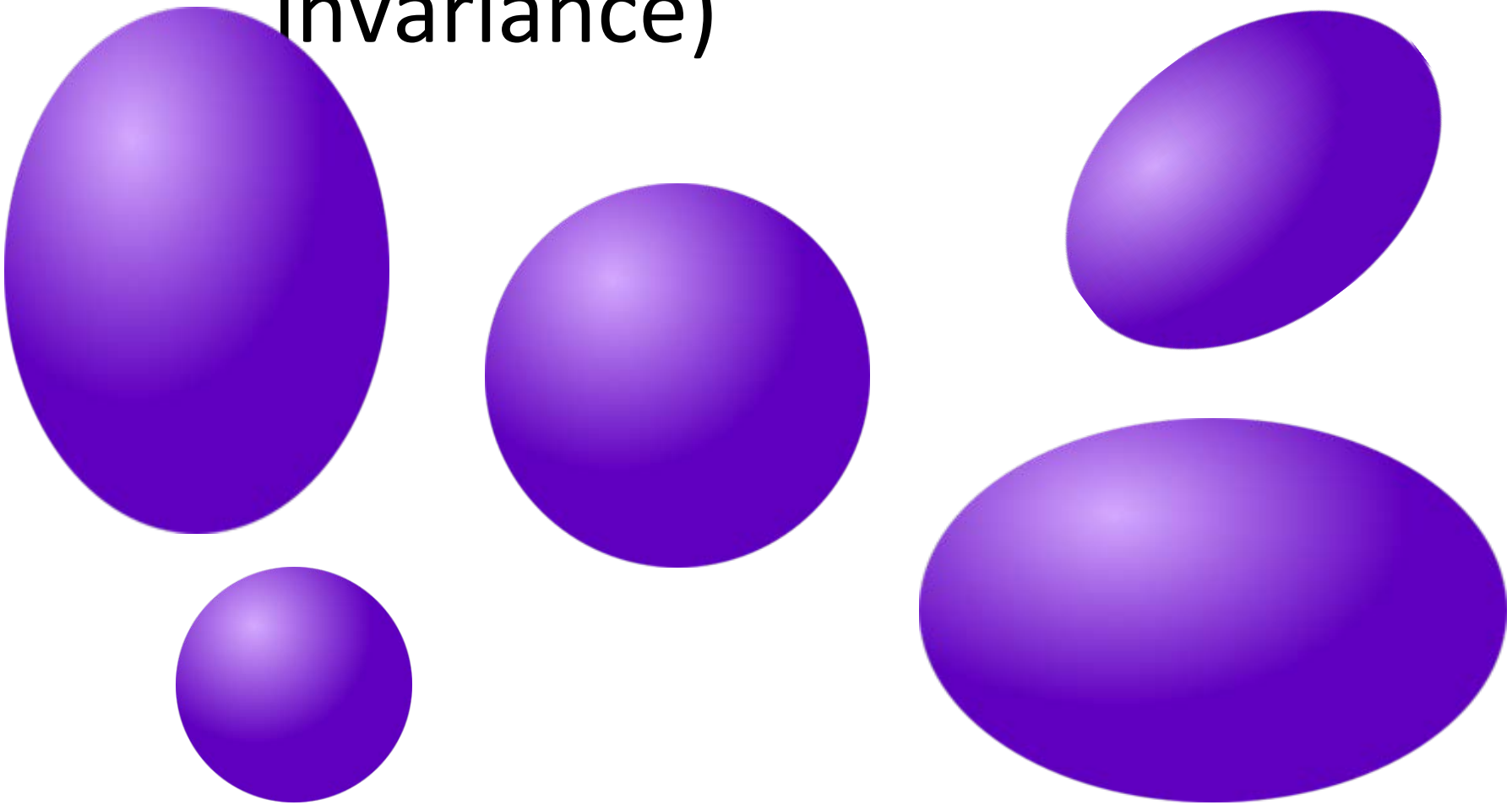
Iso-correlation contours

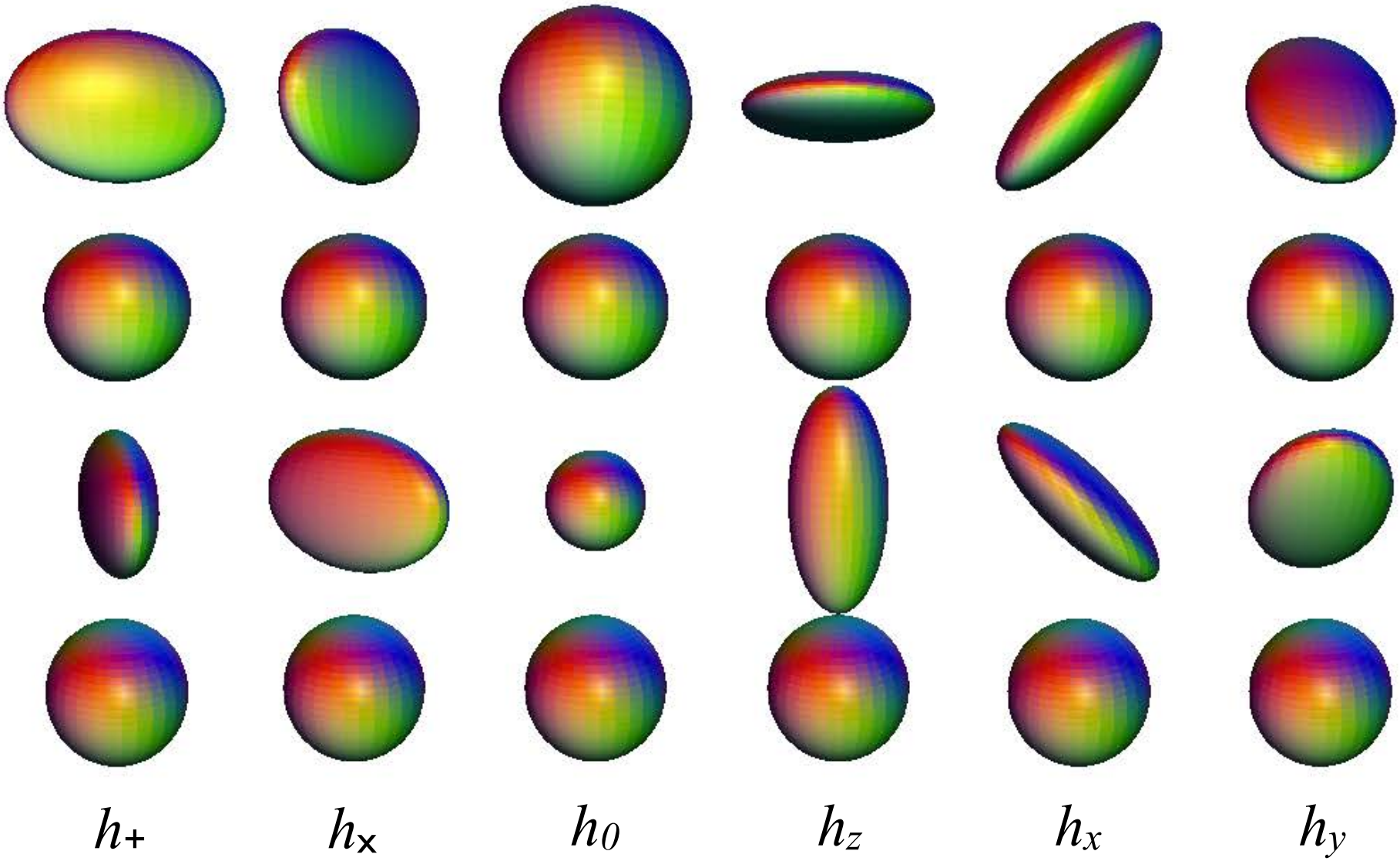


But departure from statistical isotropy (rotational invariance) is conceivable



As is departure from statistical homogeneity (translational invariance)




h_+
$h_\times$
h_0
h_z
h_x
h_y

3D in spherical basis: Total angular momentum waves (Dai, Jeong, MK 1209.0761)

- Five tensor bases: ”TB”, “TE”, “VE”, “VB”, “L”
- Projection onto spherical sky introduced ab initio
- Many conceptual/calculational advantages; e.g.,
  - Weak lensing (1209.0761)
  - Angular three-point functions (Dai, Jeong, MK, 1211.6110)
  - Circular polarization (MK, 1804.06412)
  - Stochastic GWS and astrometry (Qin, Boddy, MK, Dai, in prep)

Recap

- Search for B modes from inflationary gravitational waves well under way
- B modes useful for other exotic physics and for ISM
- Analogous geometric decompositions may be powerful tools elsewhere