Constraining cosmology with transverse velocity and CMB cross-correlations

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University of Edinburgh

YC, J. Peacock, A. de Graaff, S. Alam, 2025, arXiv: 2504.02525

GGI workshop: Exploring New Frontiers in Cosmology
Galileo Galilei Institute, Firenze
23/07/2026

Why peculiar velocities

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$$\boldsymbol{v_k} = -\mathrm{i}\frac{afH}{b_g}\frac{\boldsymbol{k}}{k^2}\delta_{\boldsymbol{k}}$$

Line-of-sight peculiar velocities

$$s = r + v_z/aH$$

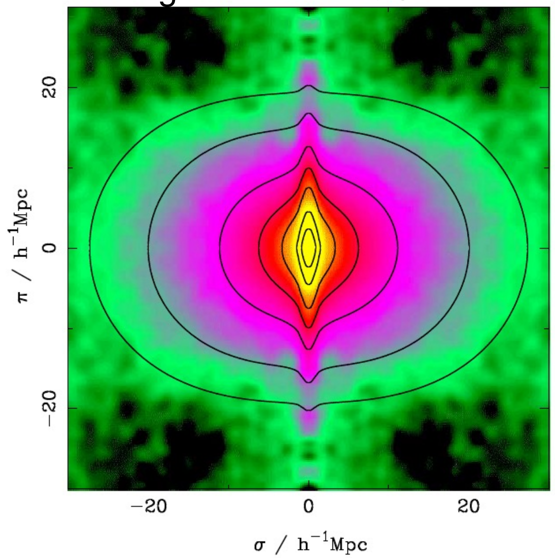
Peculiar velocity surveys e.g.
CosmicFlow4

Distance indicators e.g.,
TF relation, standard candles

Line-of-sight peculiar velocities

$$s = r + v_z/aH$$

Image credit: 2dFGS team



Peculiar velocity surveys e.g. CosmicFlow4

Distance indicators e.g., TF relation, standard candles

$$1 + \xi^s(s_\perp, s_\parallel) = \int [1 + \xi(r)]\, \mathcal{P}(v_\parallel, \mathbf{r})\mathrm{d}v_\parallel.$$

Redshift-space distortions

Line-of-sight peculiar velocities

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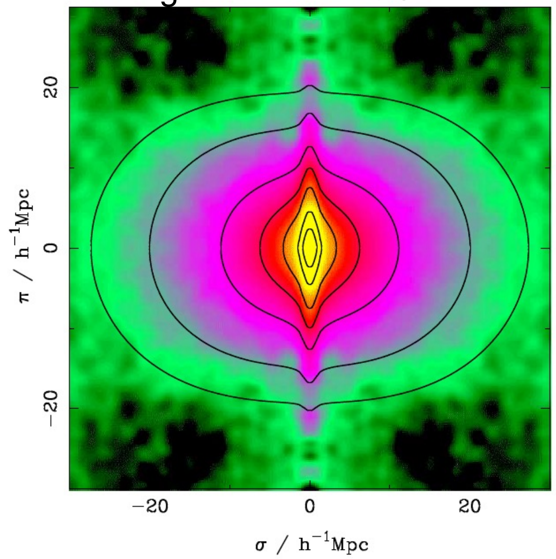

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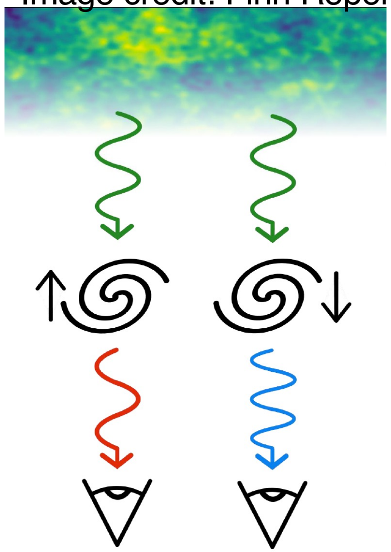
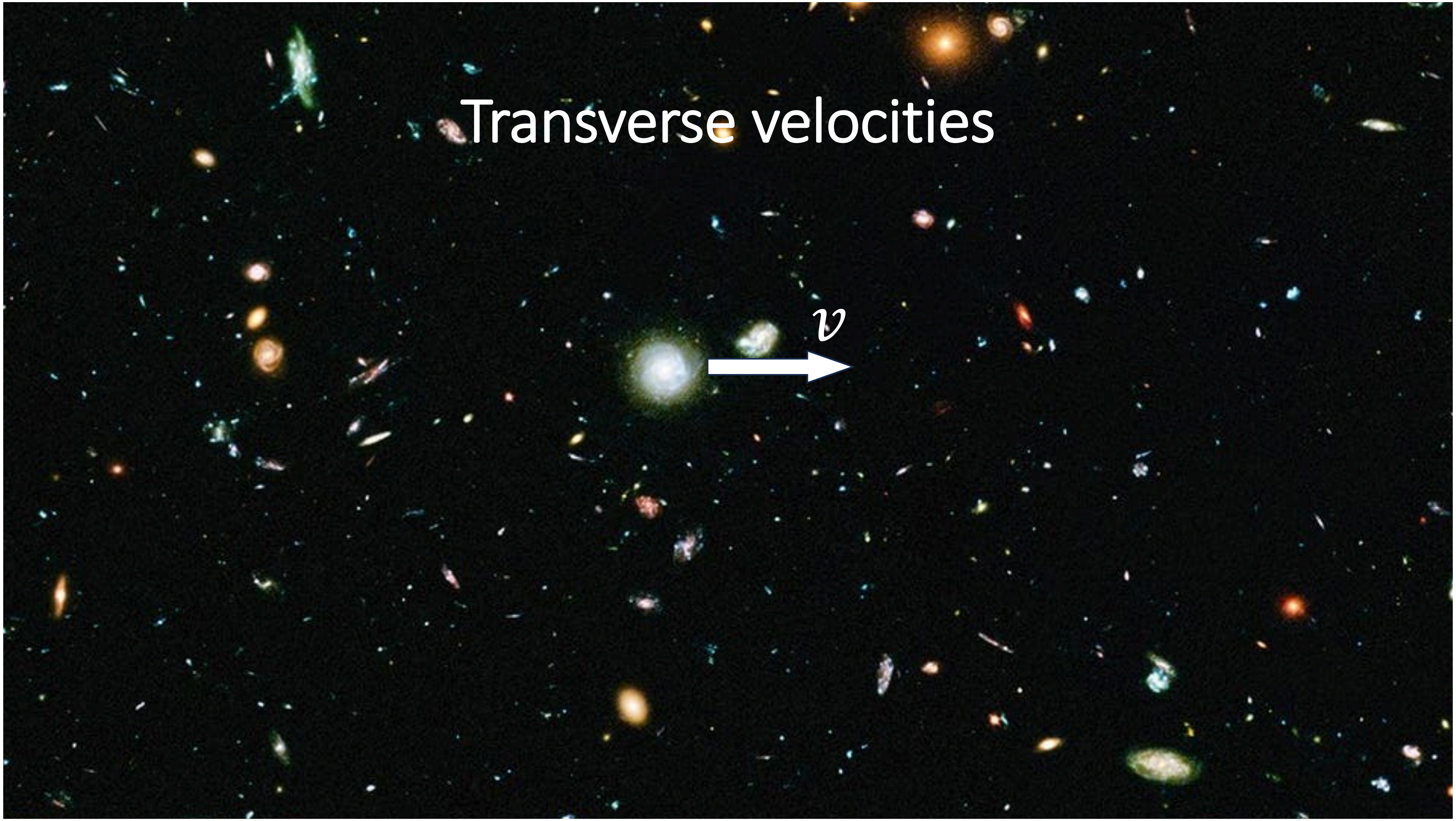
Redshift-space distortions

Image credit: Finn Roper



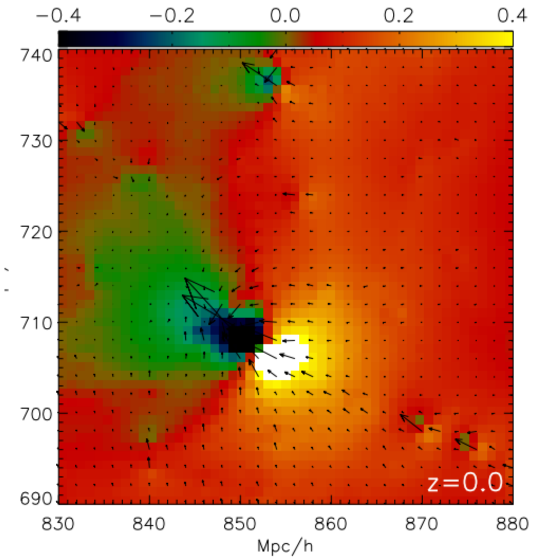
$$\frac{\Delta T_{\mathrm{kSZ}}}{T_{\mathrm{CMB}}} = -\sigma_T \int \mathrm{d}l\, n_e(\mathbf{r}) \frac{\hat{\mathbf{r}} \cdot \mathbf{v}_e(\mathbf{r})}{c}$$

Kinetic Sunyaev Zeldovich effect


Transverse velocities
v

Transverse velocities

Moving lens effect



Birkinshaw & Gull 1983Natur.302..315B
Cai et al. 2010MNRAS.407..201C
Hotinli et al., 2022JCAP...10..026H & arXiv: 2605.18938

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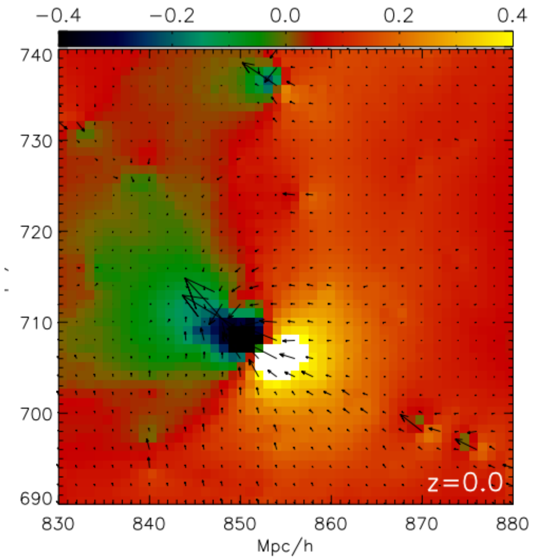

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Polarised kinetic Sunyaev Zeldovich effect

$$T_0 = T_r[1 - \beta\mu_0 + \beta^2(\mu_0^2 - 1/3) + \ldots].$$

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Gon & Khatri, 2023JCAP...11..072G

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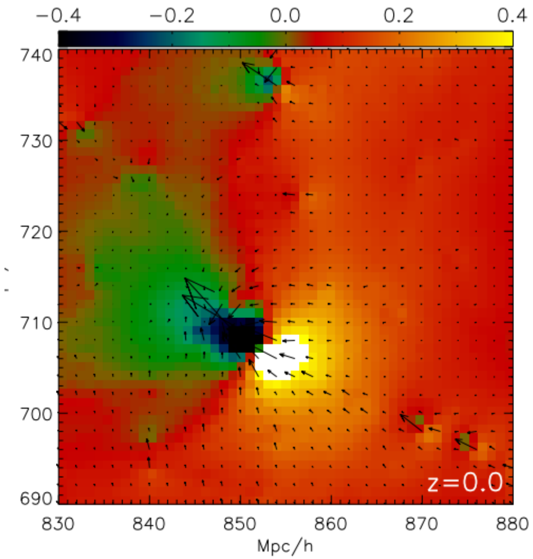

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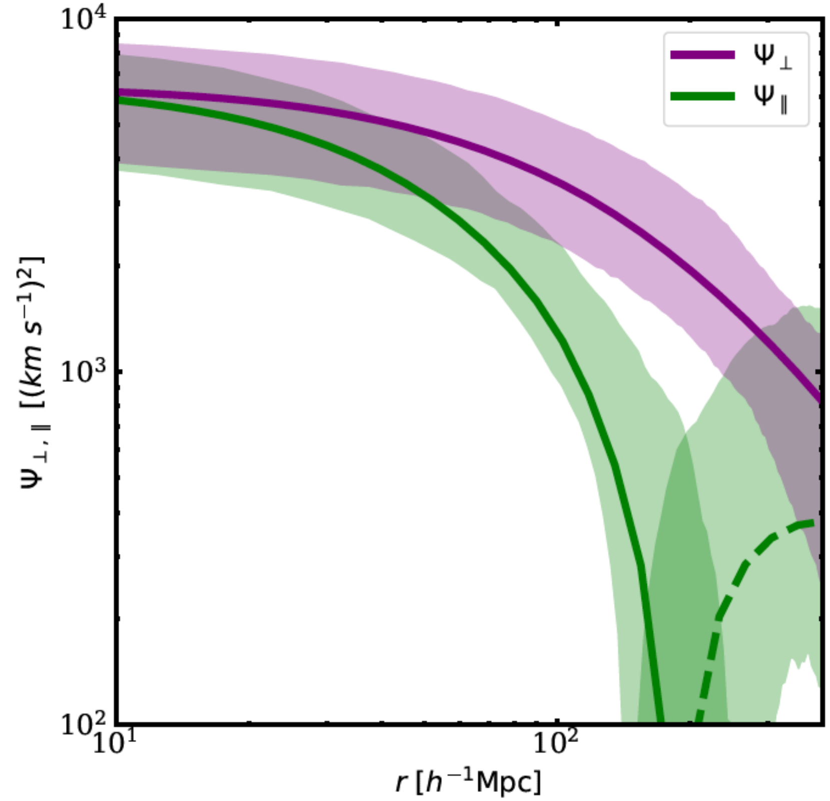
Transverse Doppler redshift

$$\propto v^2/c$$

Kaiser, 2013MNRAS.435.1278K
Zhao et al,. 2013PhRvD..88d3013Z
Cai et al. 2017MNRAS.468.1981C

Correlation functions of velocities



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ON THE PATTERN OF PERTURBATIONS OF THE HUBBLE FLOW

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$$\langle v_i v_j' \rangle \equiv \Psi_{ij} = \Psi_\perp(r)\,\delta_{ij} + [\Psi_\parallel(r) - \Psi_\perp(r)]\,r_i r_j / r^2,$$

$$\Psi(r) = a^2 H(z)^2 f_g^2(z) \int \Delta^2(k,z)\,k^{-2}\,d\ln k\,K(kr),$$

$$\begin{aligned} K_\perp(x) &= [\sin(x) - x\cos(x)]/x^3; \\ K_\parallel(x) &= \sin(x)/x - 2[\sin(x) - x\cos(x)]/x^3. \end{aligned}$$

Conditional velocity field

Conditional velocity field

v(0) along the x-axis, we have:

$$\langle \mathbf{v} \rangle = |\mathbf{v}(\mathbf{0})| \, \frac{1}{r^2} \begin{bmatrix} \psi_{\perp} y^2 + \psi_{||} x^2 \\ (\psi_{||} - \psi_{\perp}) \, xy \end{bmatrix}$$

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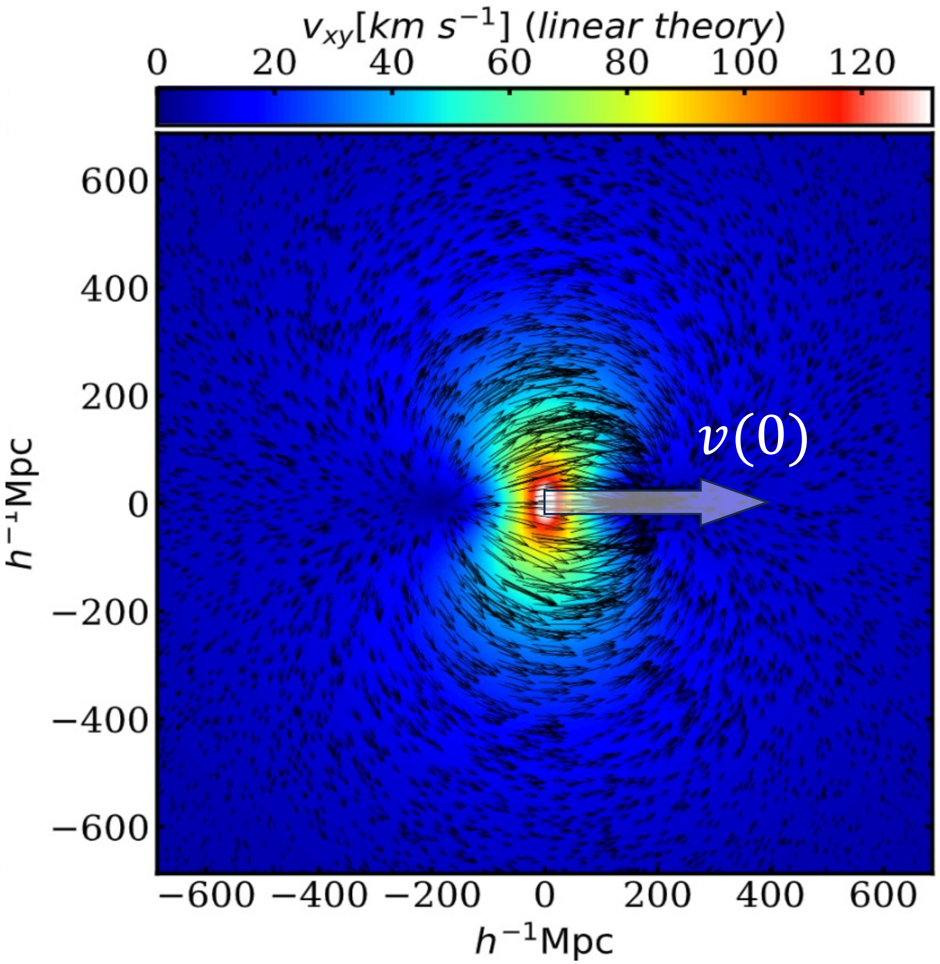
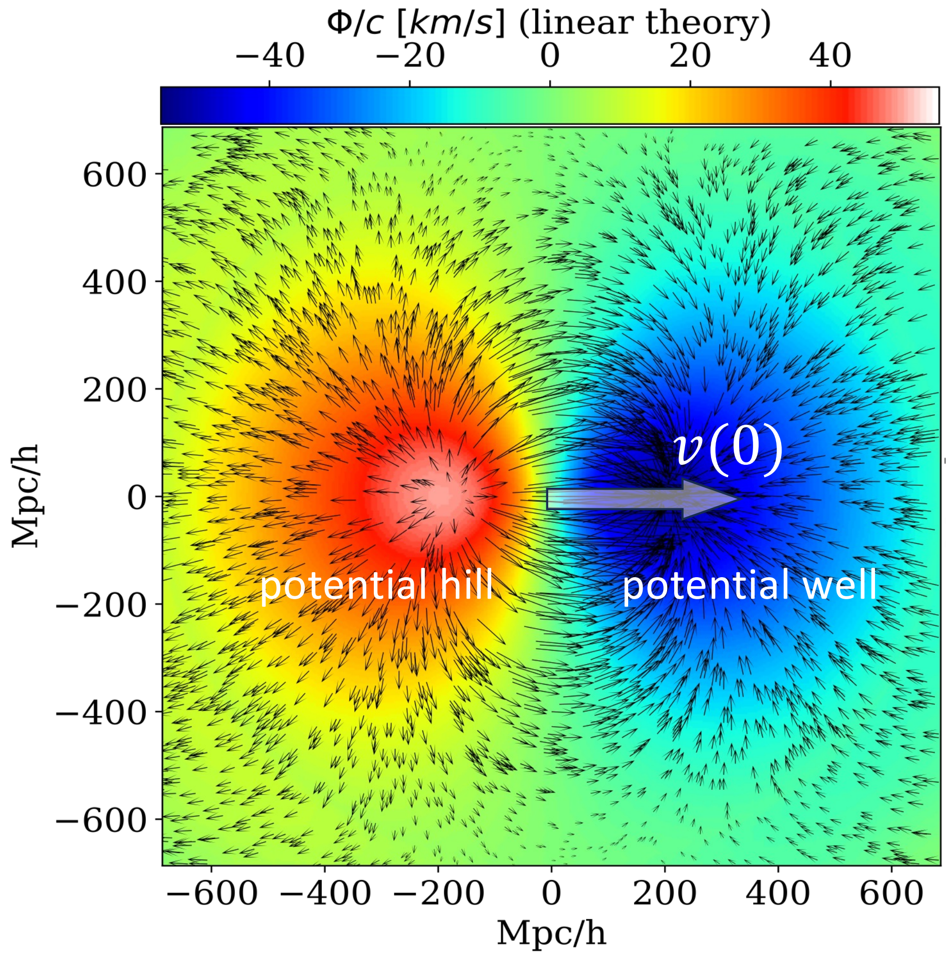
$\boxed{\text{Oriented stacked velocity field}}$

Velocity at the origin defines a preferred direction



Velocity points at the dipole of potential



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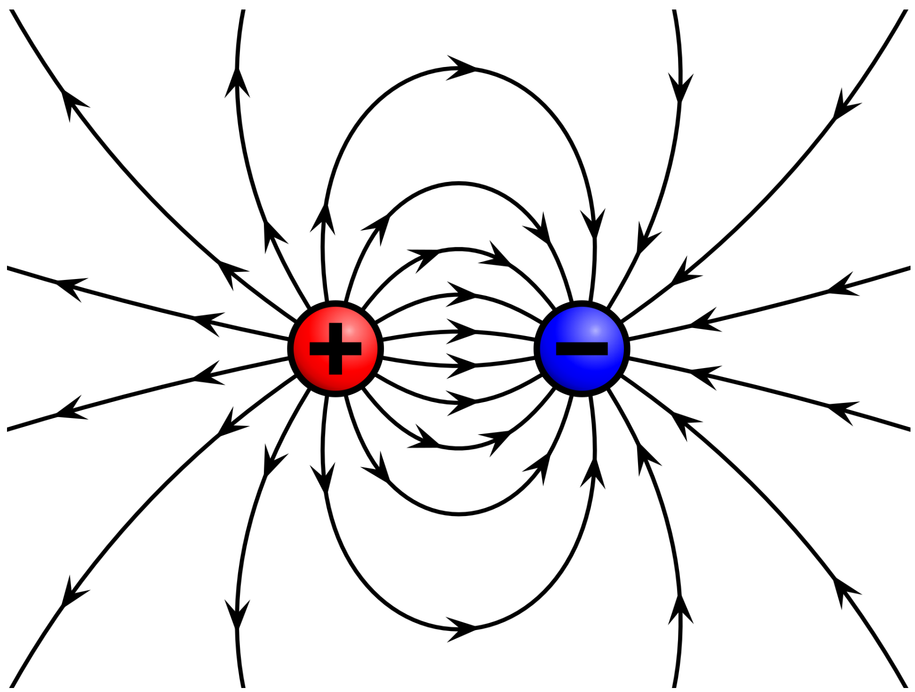
Potential dipole resembles electric dipole



Conditional potential field

v(0) along the x-axis, we have:

$$< \Phi | v > \quad \propto \quad \cos\theta \; C_{\Phi v}$$

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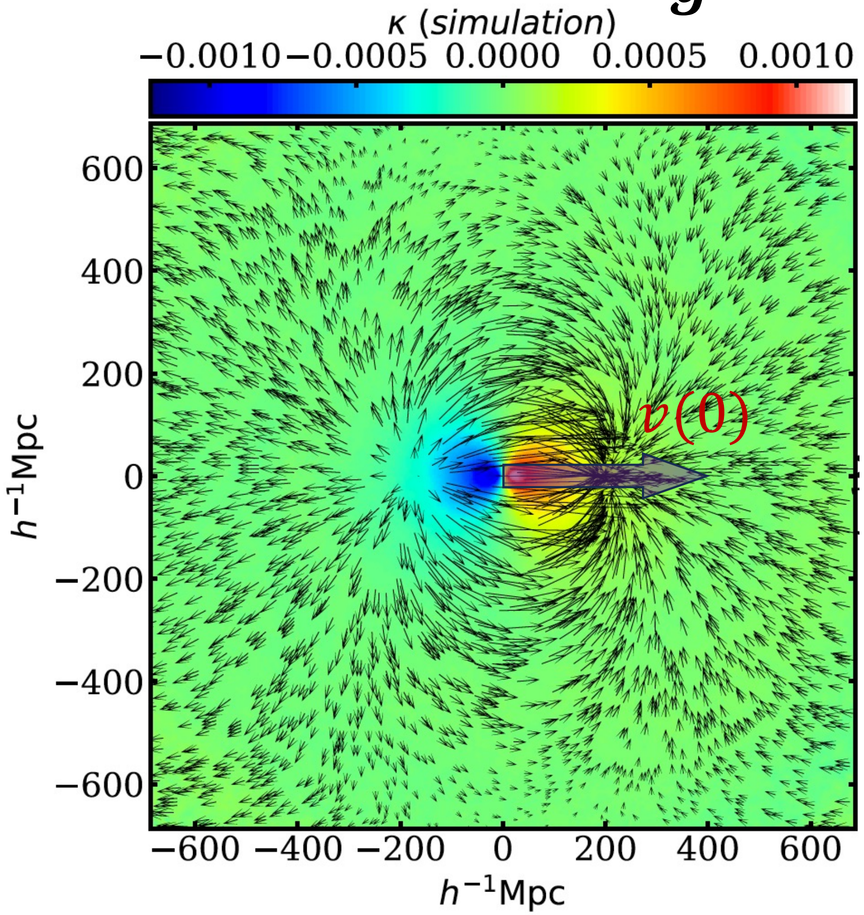
$$< \delta_m|v > \quad \propto \quad \cos\theta \; C_{\delta_m v}$$

...

$\boldsymbol{v}$-$\boldsymbol{\kappa}$ correlation, $\boldsymbol{v}$-$\boldsymbol{\delta_g}$ correlation



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Velocities X CMB

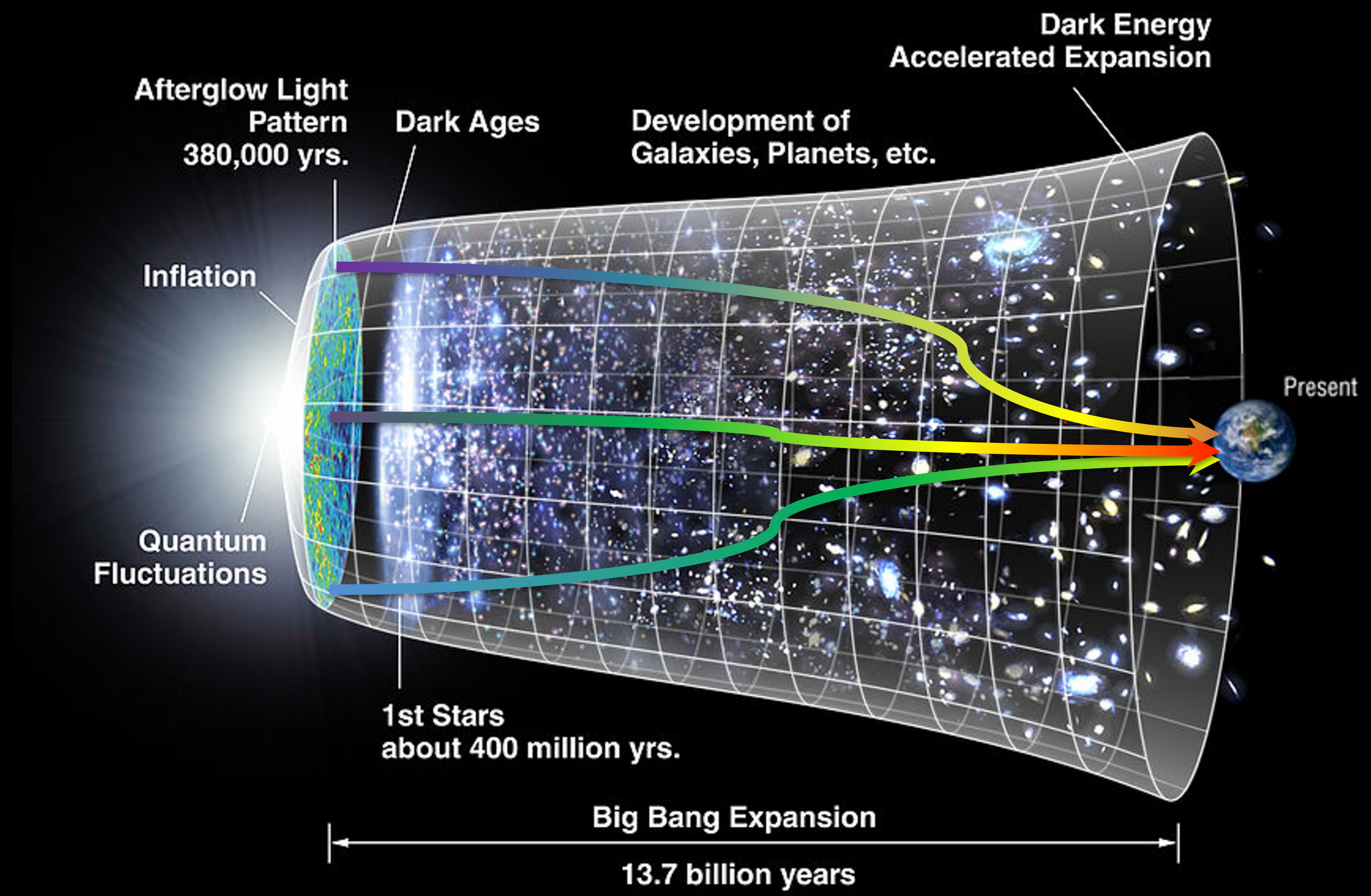

Image credit: NASA WMAP team

$\boxed{\text{Galaxy field } \delta_g}$

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$\boxed{\text{Velocity reconstruction}}$

$$\boldsymbol{v}_{\boldsymbol{k}} = -\mathrm{i}\frac{afH}{b_g}\frac{\boldsymbol{k}}{k^2}\delta_{\boldsymbol{k}}$$

Galaxy field δ_g

Velocity reconstruction

$$\boldsymbol{v}_{\boldsymbol{k}} = -\mathrm{i}\frac{afH}{b_g}\frac{\boldsymbol{k}}{k^2}\delta_{\boldsymbol{k}}$$

Oriented stacking with $[T_{CMB}, \kappa, \delta_g]$ using v

Traditional observables

Galaxy-X correlations:

- ISW monopole: $\boldsymbol{\delta_g}$-$\boldsymbol{ISW}$ $\langle \boldsymbol{\delta_g T} \rangle$
- CMB lensing monopole:. $\boldsymbol{\delta_g}$-$\boldsymbol{\kappa}$
- Galaxy number density monopole: $\boldsymbol{\delta_g}$-$\boldsymbol{\delta_g}$

New observables

Velocity-X correlations:

- ISW dipole: $\boldsymbol{v}$-$\boldsymbol{ISW}$ $\langle \boldsymbol{vT} \rangle$
- CMB lensing dipole: $\boldsymbol{v}$-$\boldsymbol{\kappa}$
- Galaxy number density dipole: $\boldsymbol{v}$-$\boldsymbol{\delta_g}$

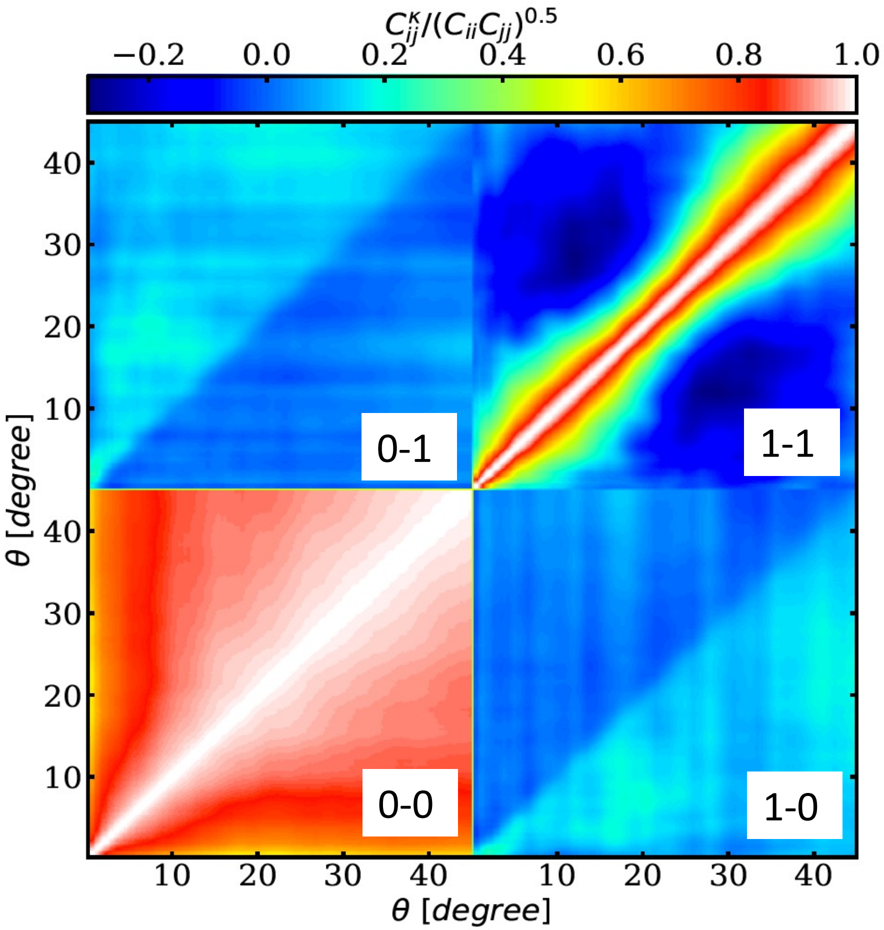
A signal independent of galaxy bias

$$< \delta_m | v > \;\propto\; \cos\theta \; C_{\delta_m v} / \sigma_v$$

$$C_{\delta_m v} = \; aHf \int k^{-1} \; \Delta^2(k) j_1(kx) d \ln k$$

$$\sigma_v^2 = \; (aHf)^2 \int k^{-2} \; \frac{\Delta^2(k)}{3} d \ln k$$

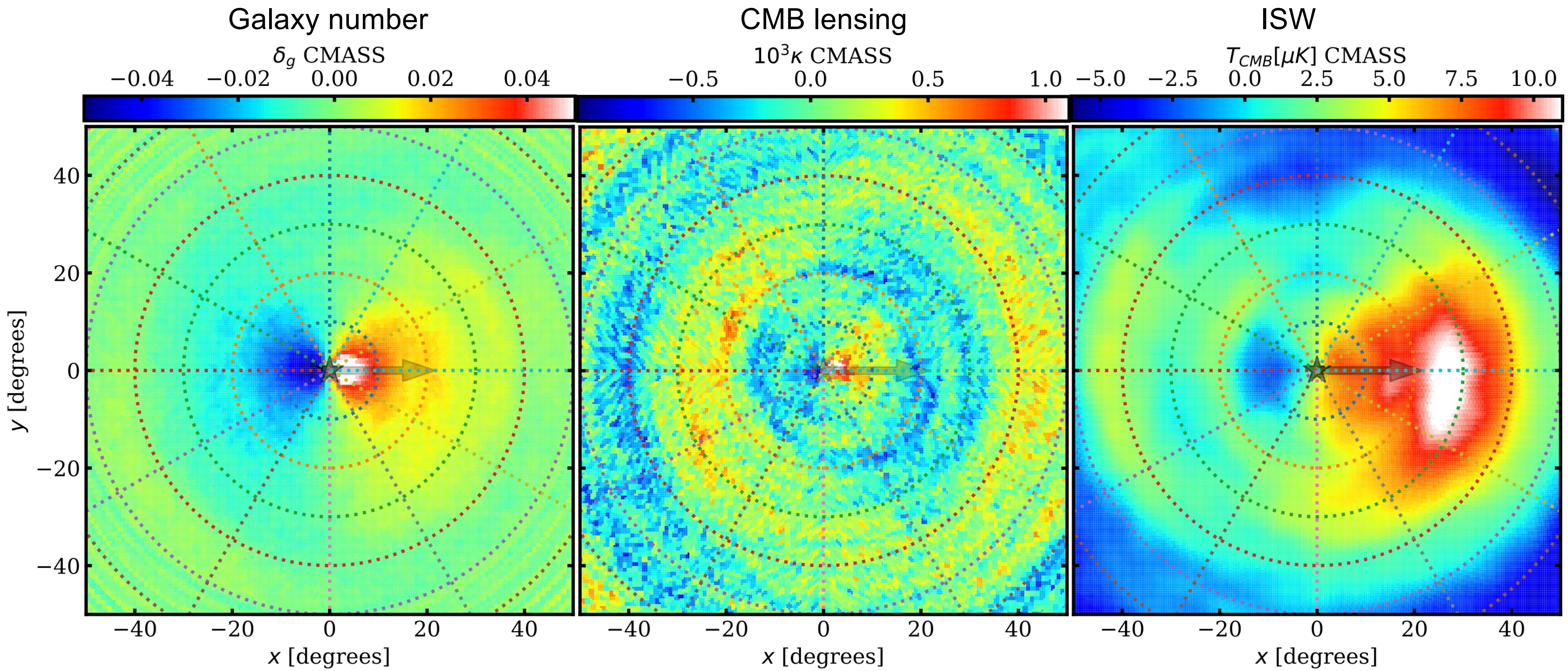
Monopole and dipole are independent



Detections with

SDSS-BOSS x Planck

Oriented stacking



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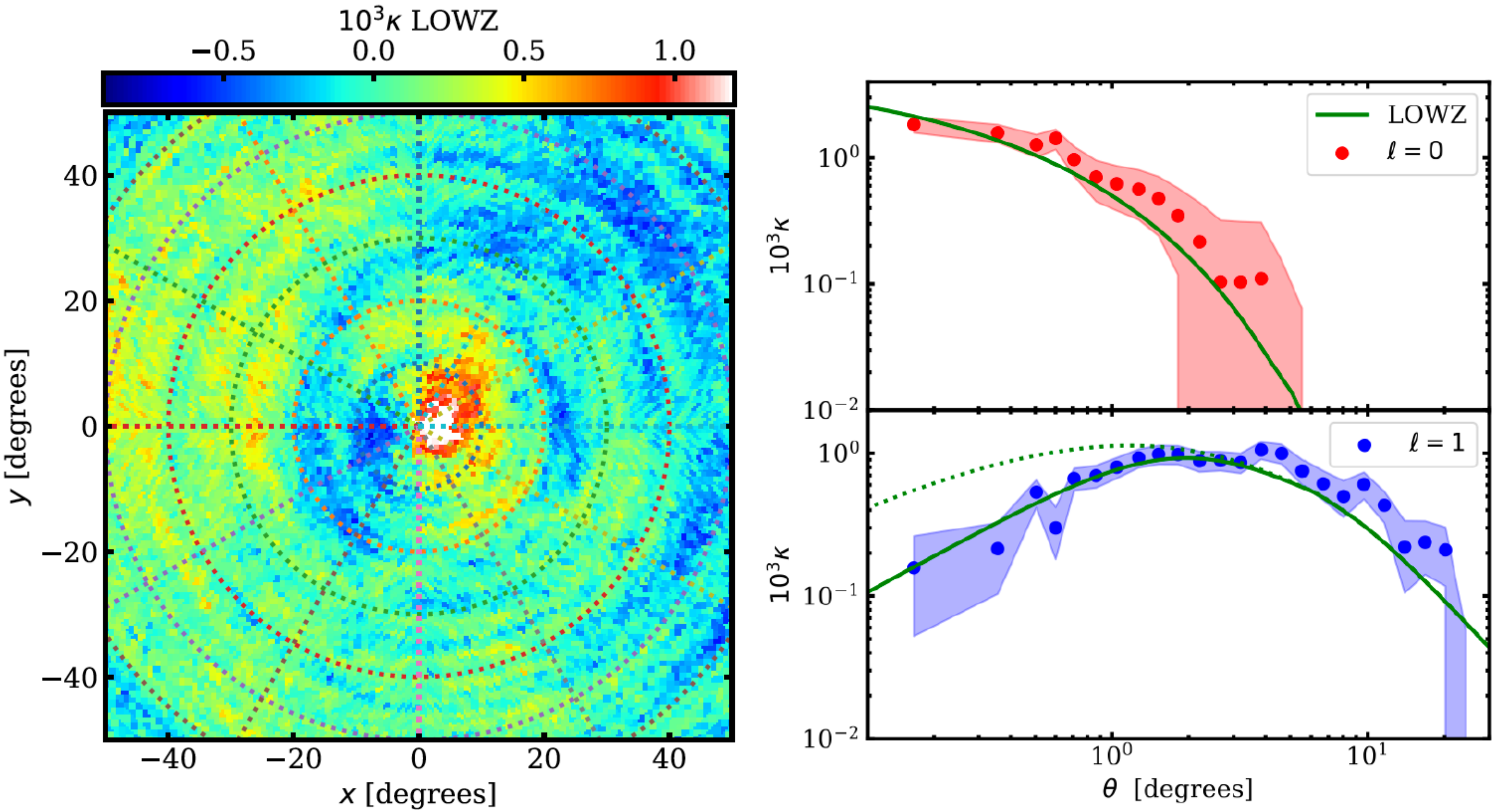

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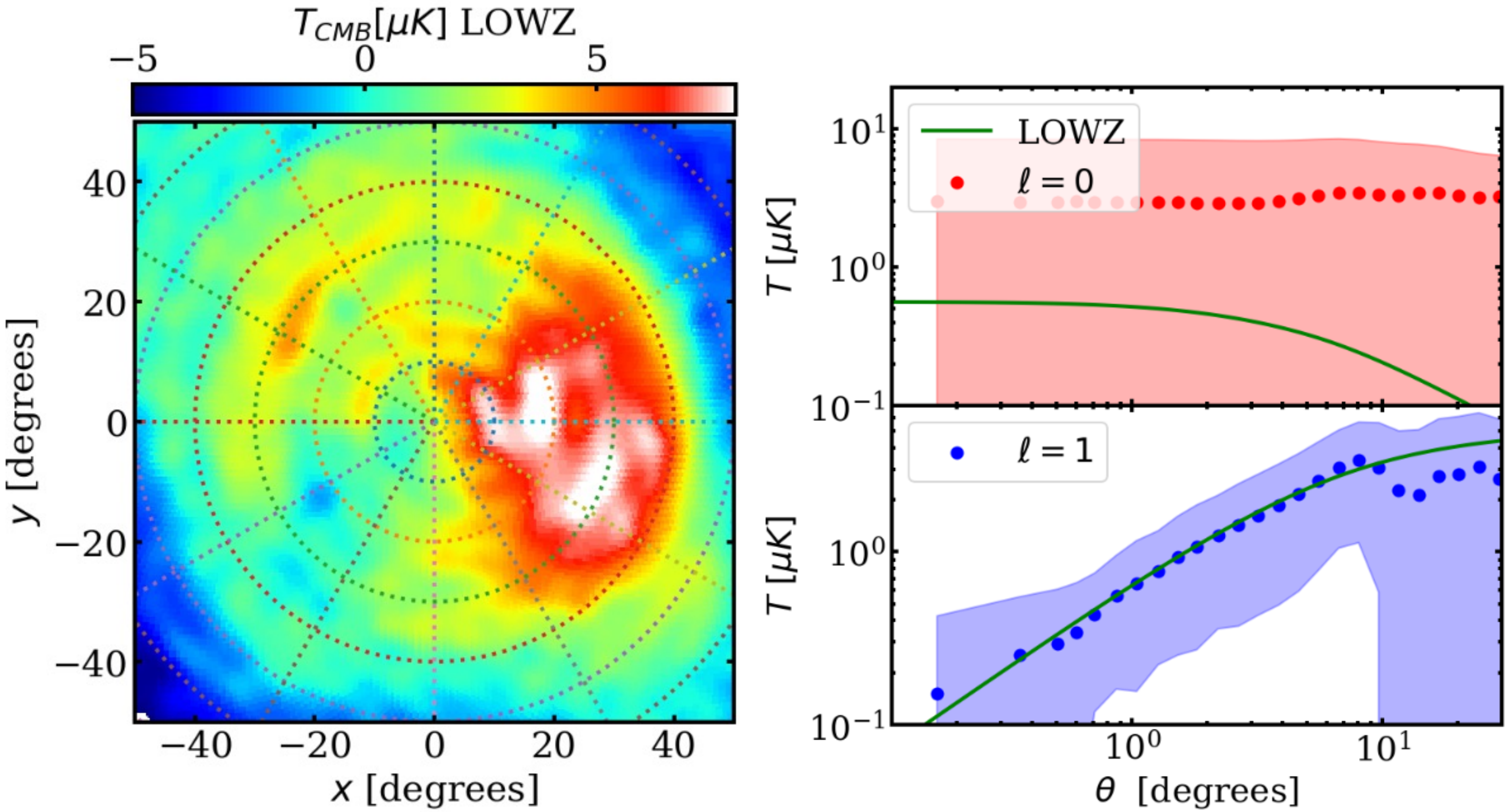

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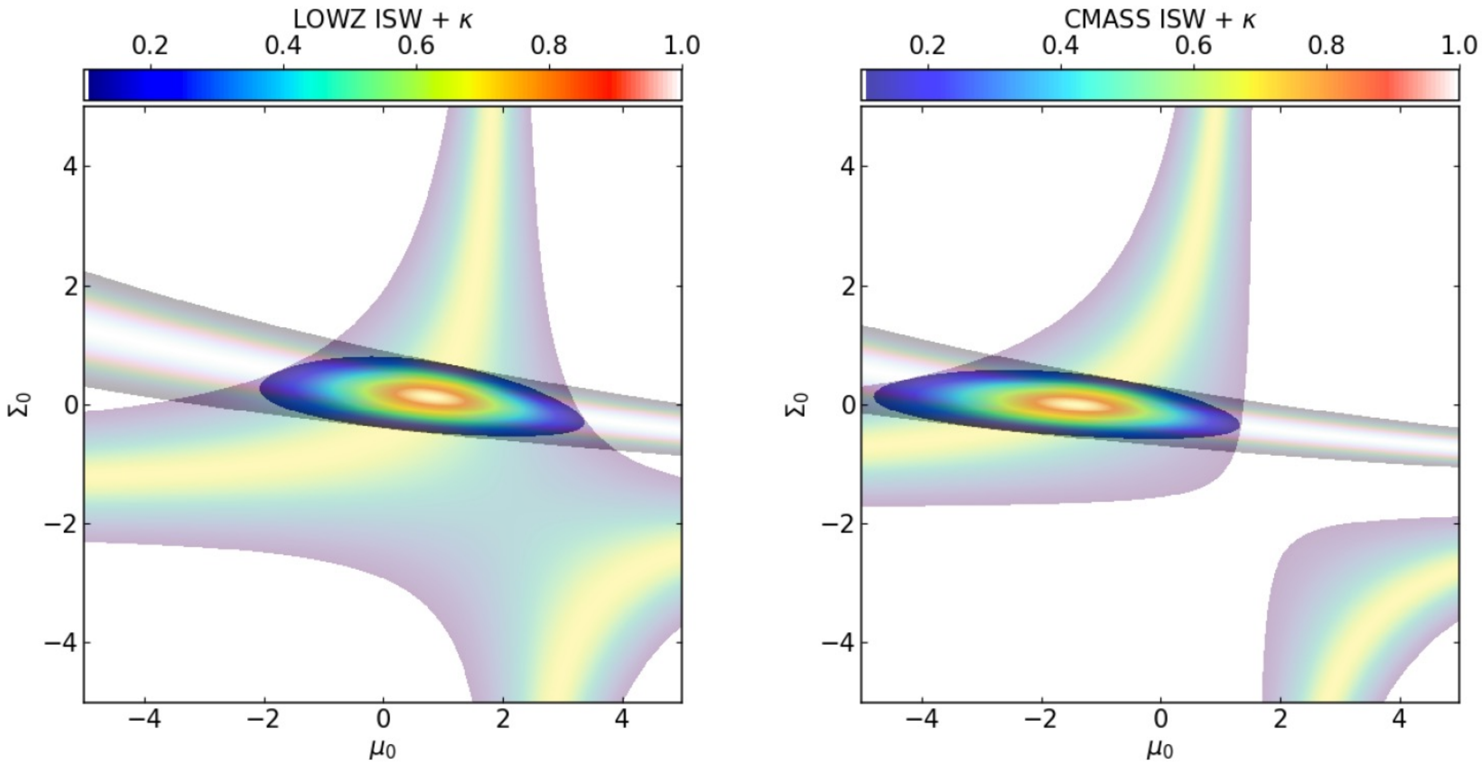
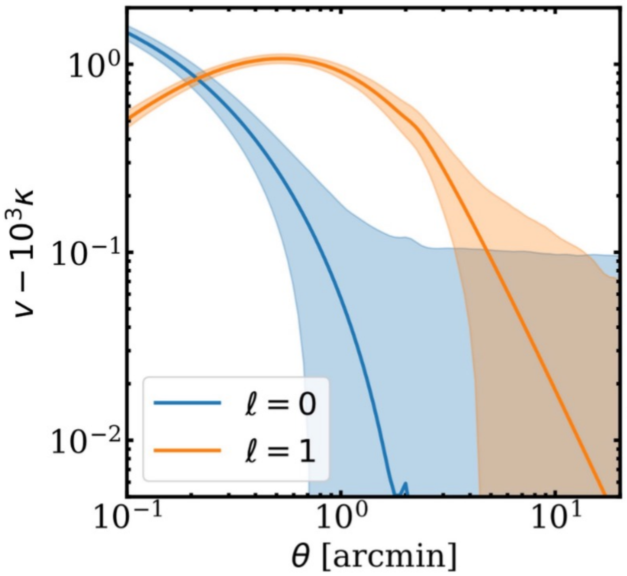
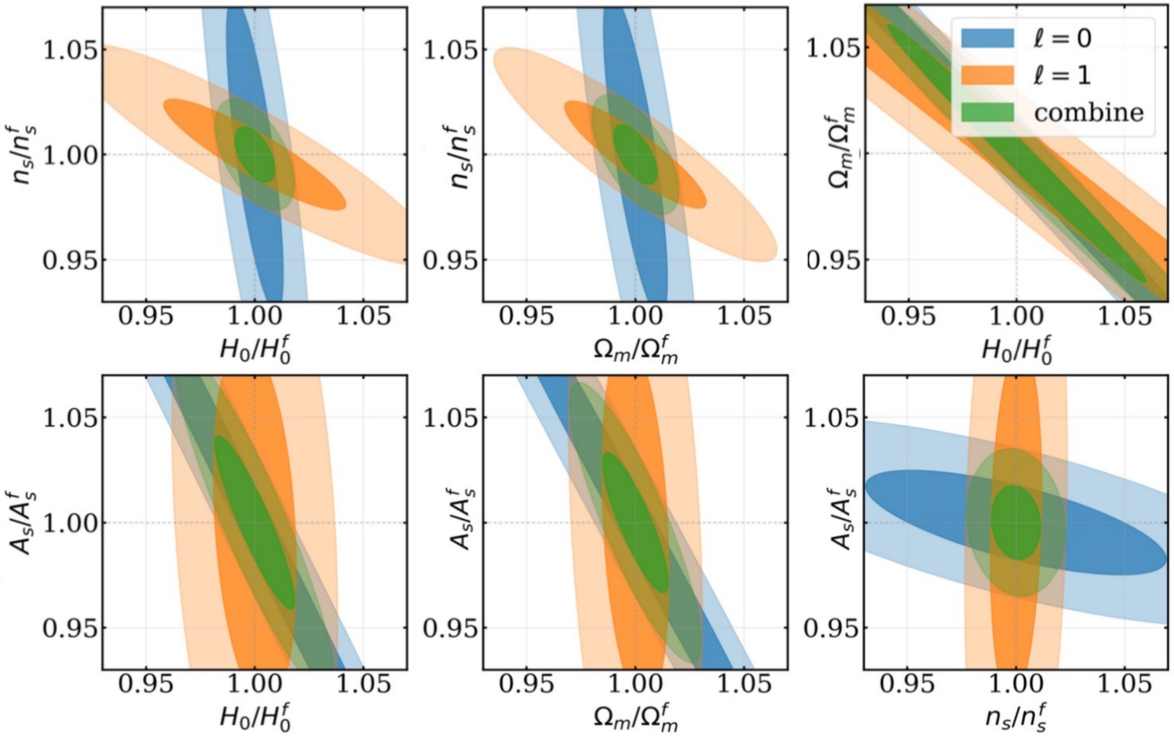
Constraints on modified gravity



$$\Psi = (1+\mu)\,\Psi_{\rm GR}$$
$$\Psi + \Phi = (1+\Sigma)\,[\Psi+\Phi]_{\rm GR}$$

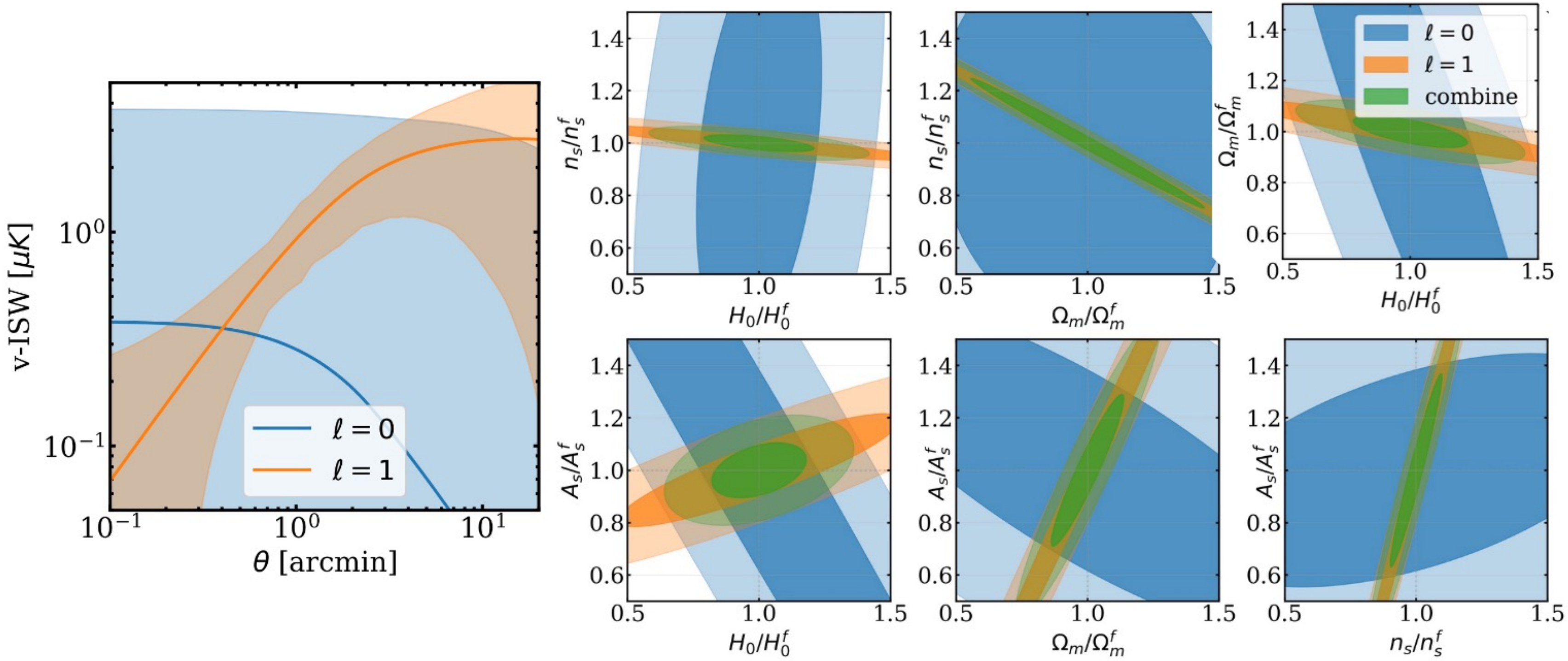
Expected constraints on cosmology





YC++ in prep.

Expected constraints on cosmology



YC++ in prep.

Summary

- Gpc-scale dipoles of velocities resemble electric dipoles
- Gravitational imprints on the CMB --- ISW & lensing
- Detections of both with galaxies x CMB
- Dipoles of cross-correlations are
    independent from monopoles
    free from galaxy bias
- Independent constraints on cosmology & gravity