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Using the peculiar velocities of galaxies to test cosmology and particle physics

Rencontres du Vietnam 2023: Windows on the Universe

By *Abbé Whitford*, 2nd year PhD student, supervised by Professor Tamara Davis, Dr Cullan Howlett

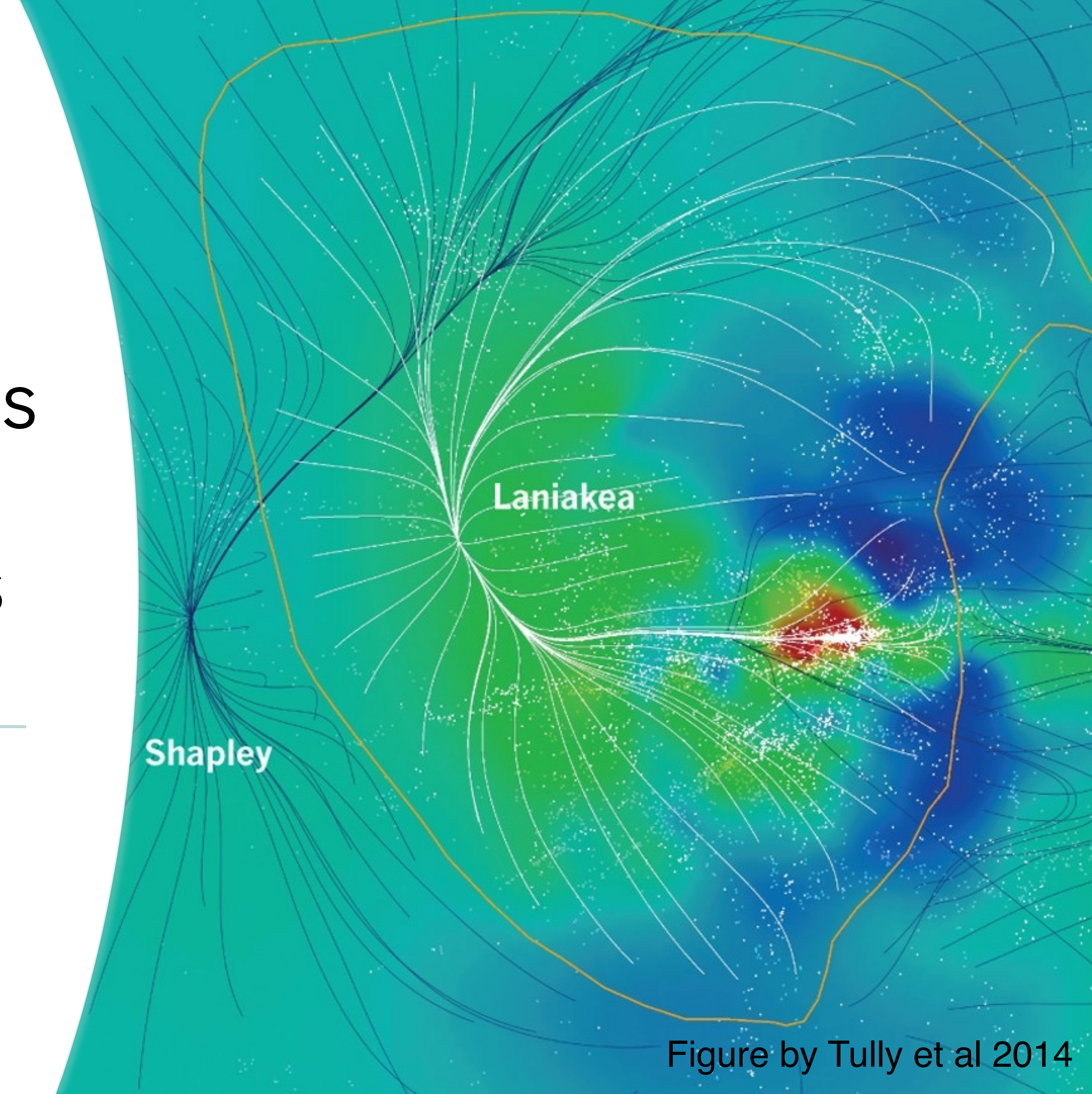
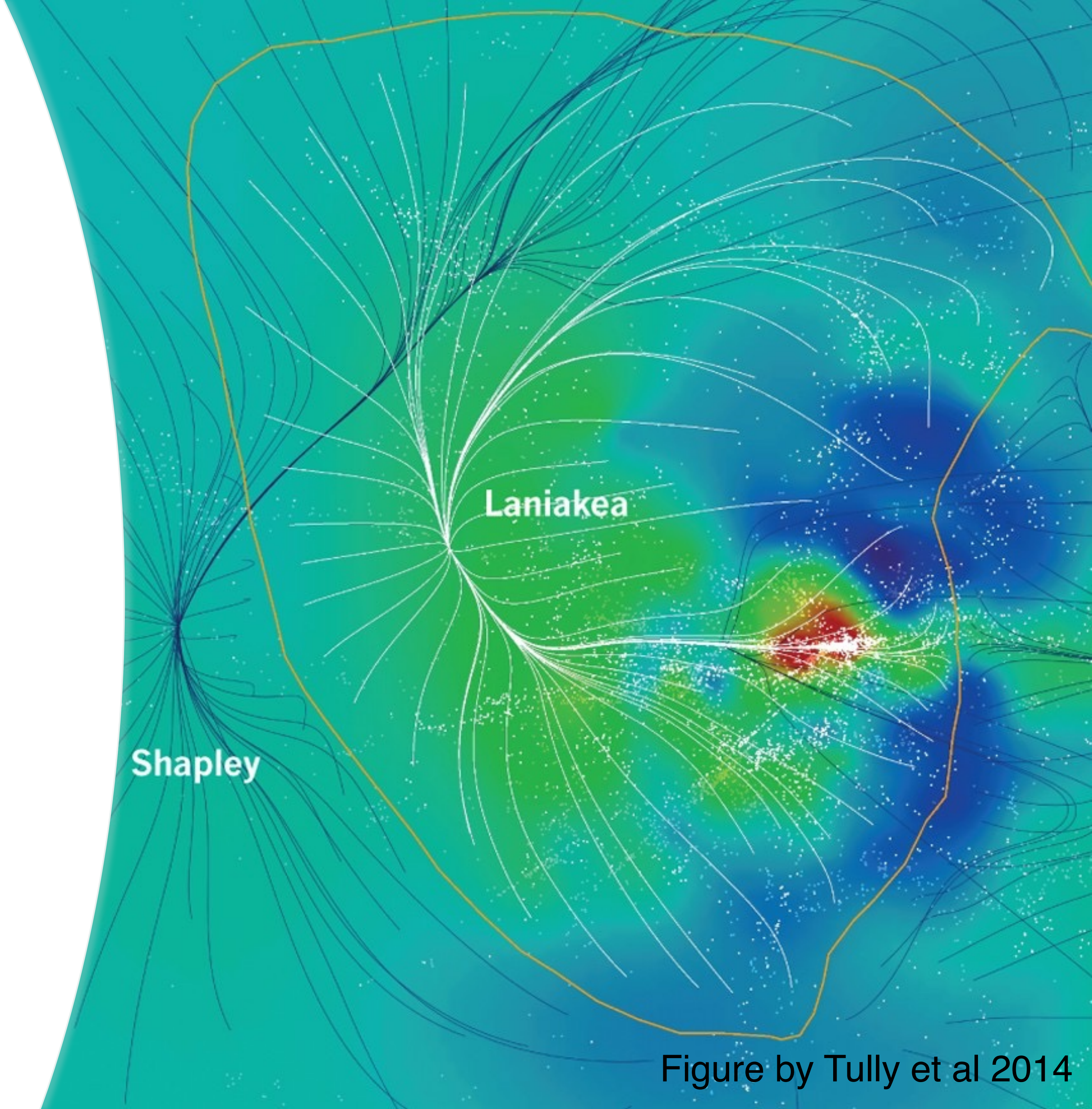


Figure by Tully et al 2014

- Introduction to peculiar velocities + applications



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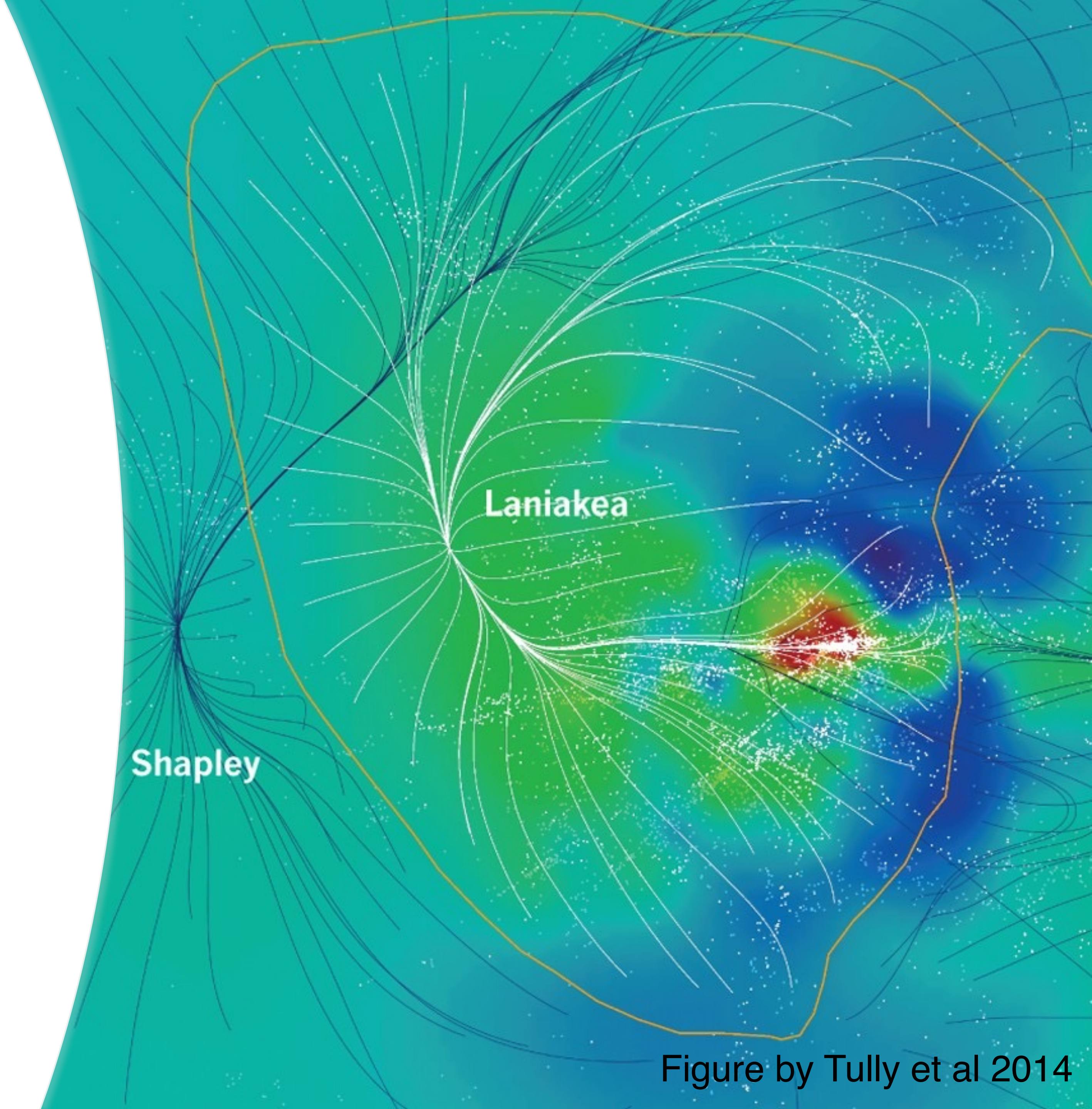

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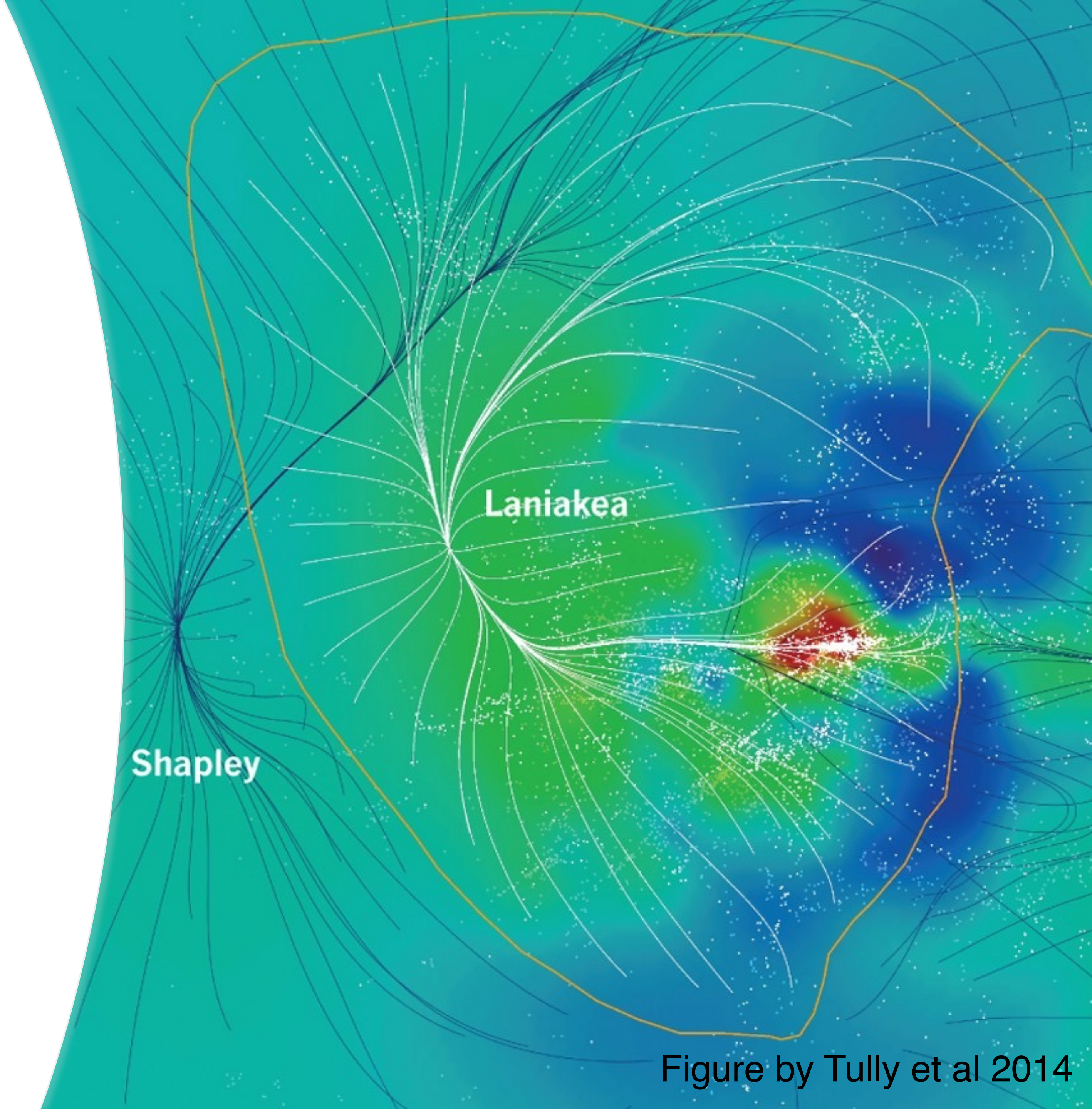

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What are peculiar velocities? $v_{\mathrm{total}} = v_{\mathrm{rec}} + v_{\mathrm{pec}}$

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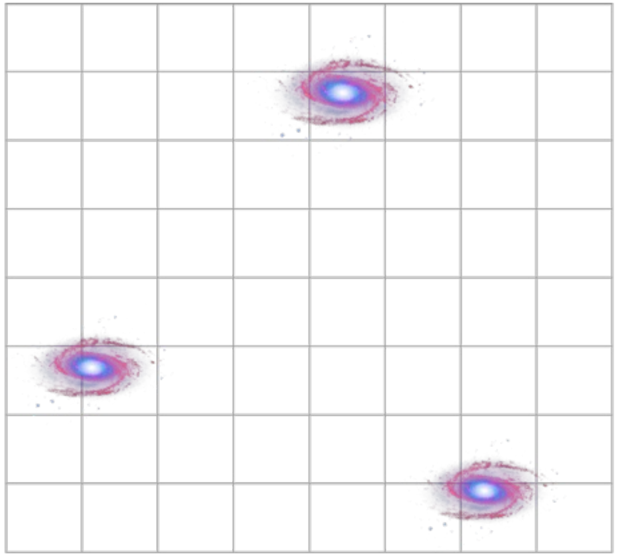
Expansion of space
→ recession velocity



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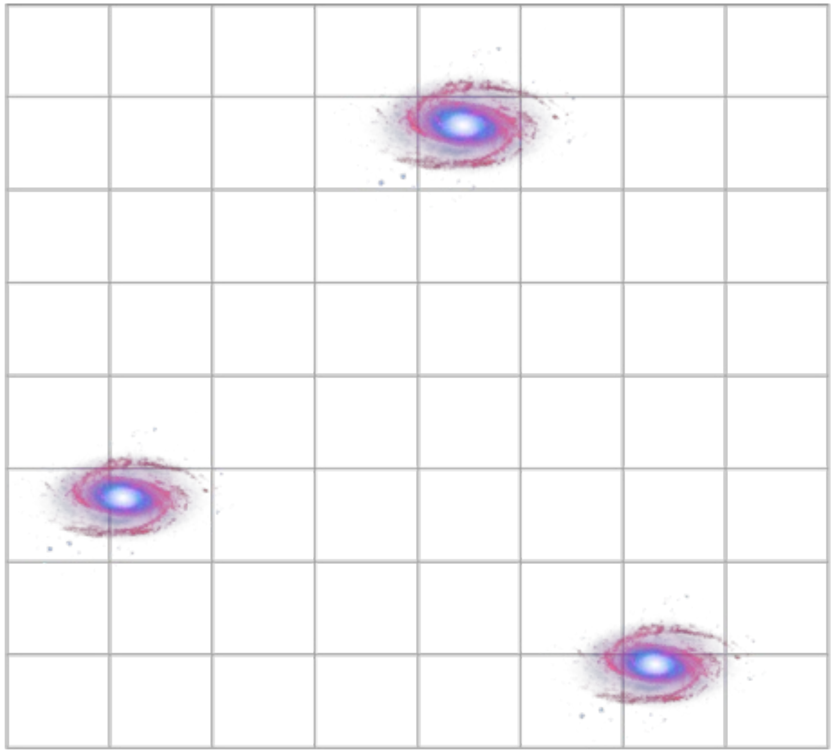

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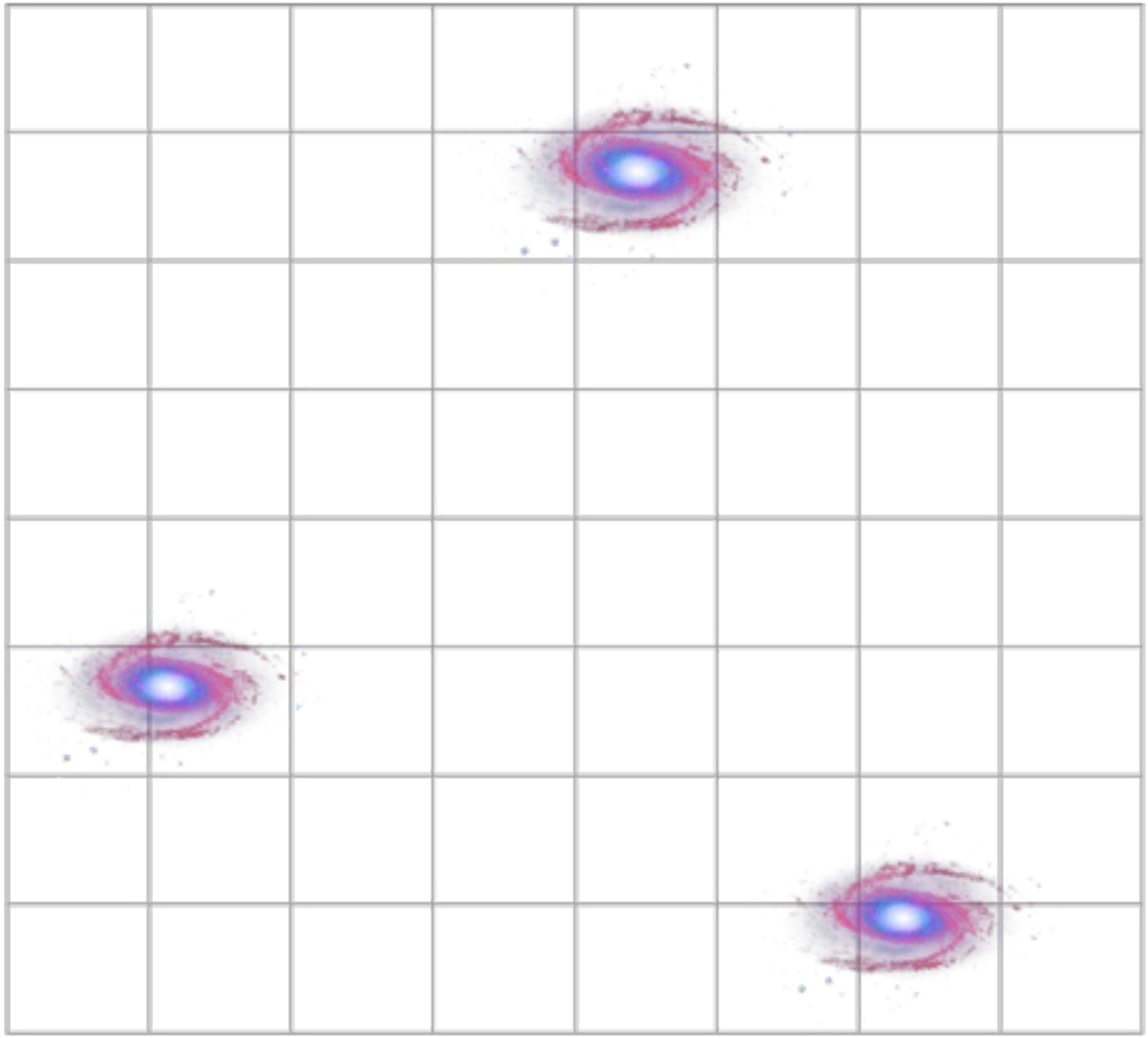

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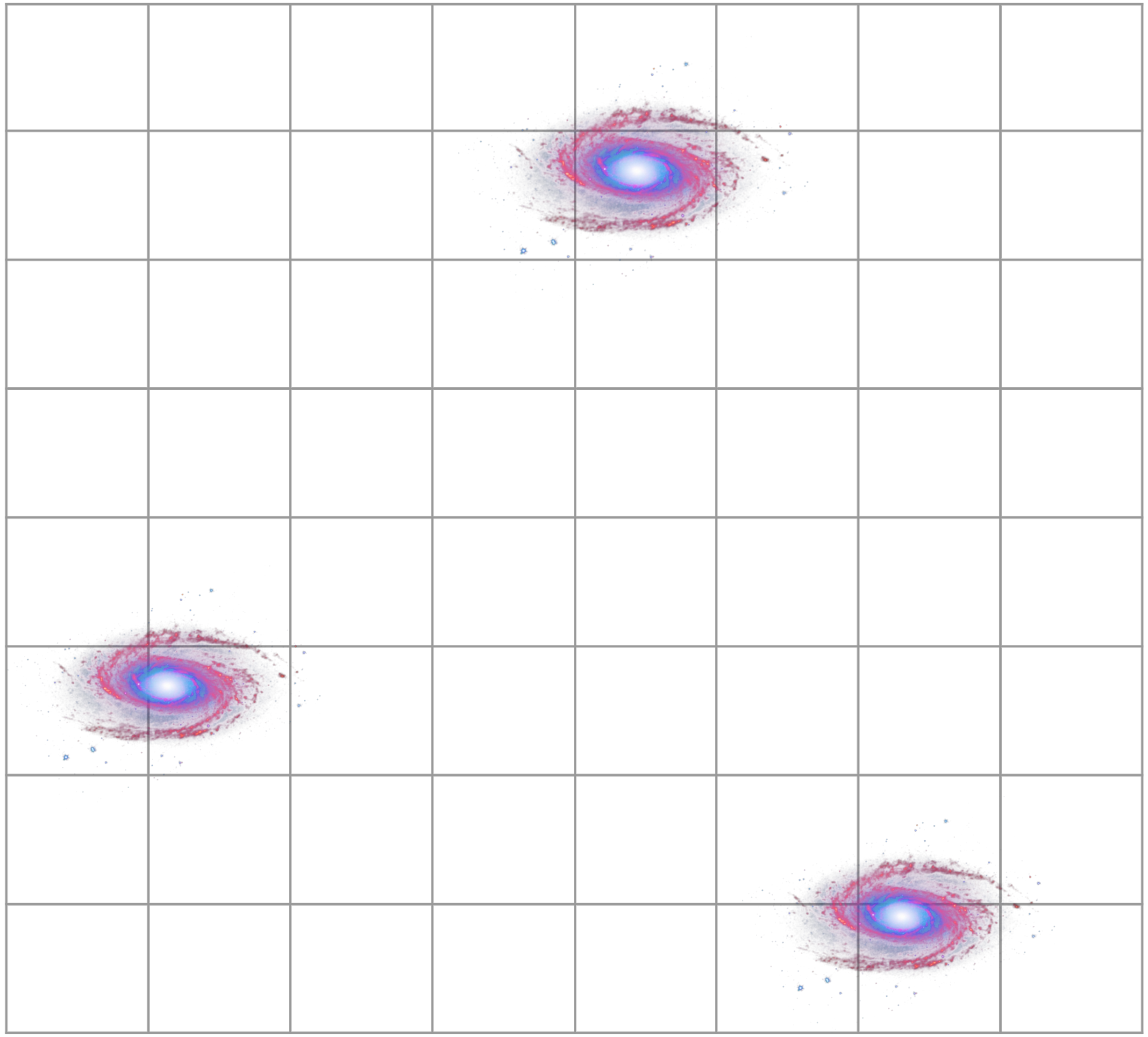

gravitational interaction → peculiar velocity

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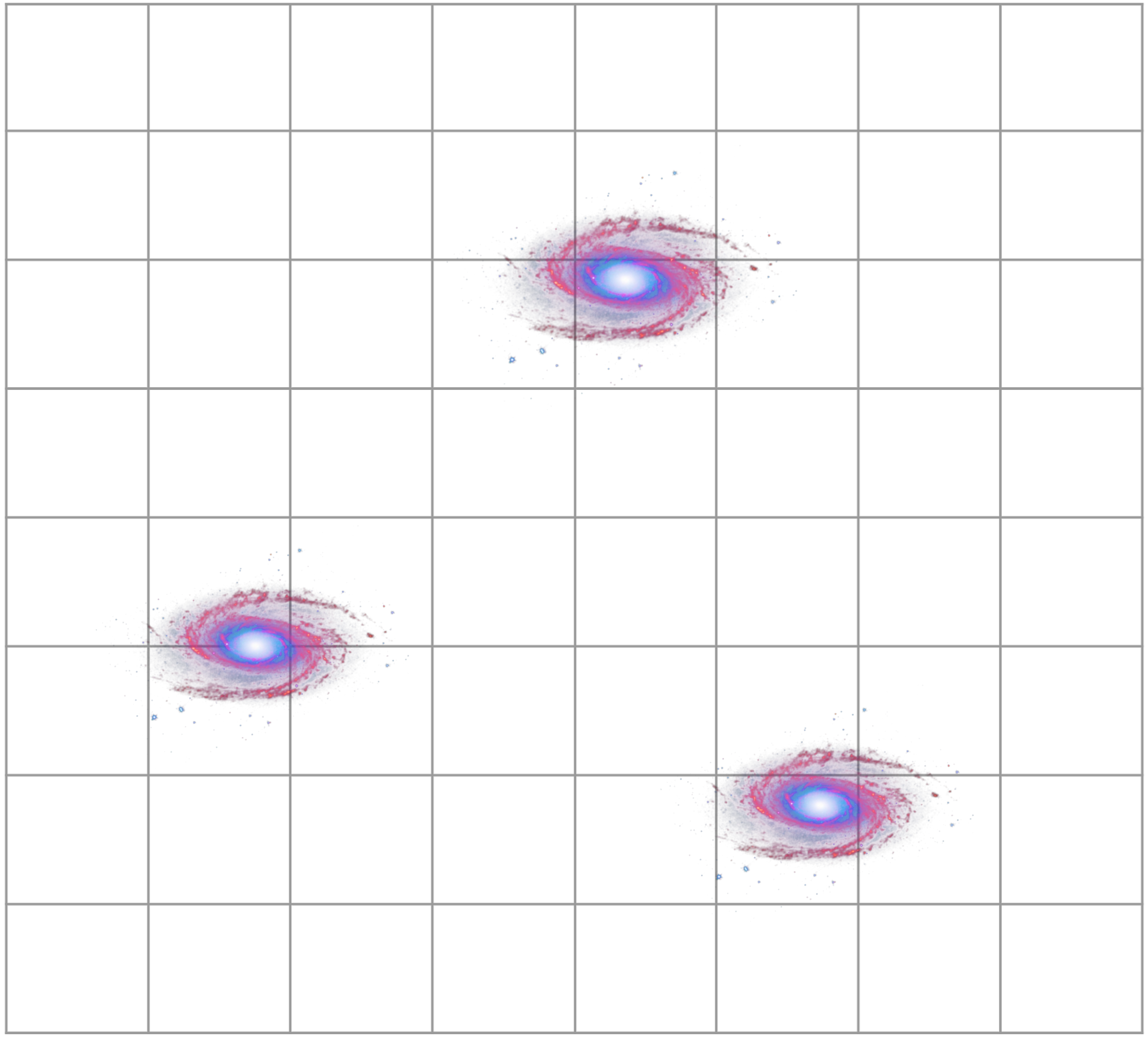

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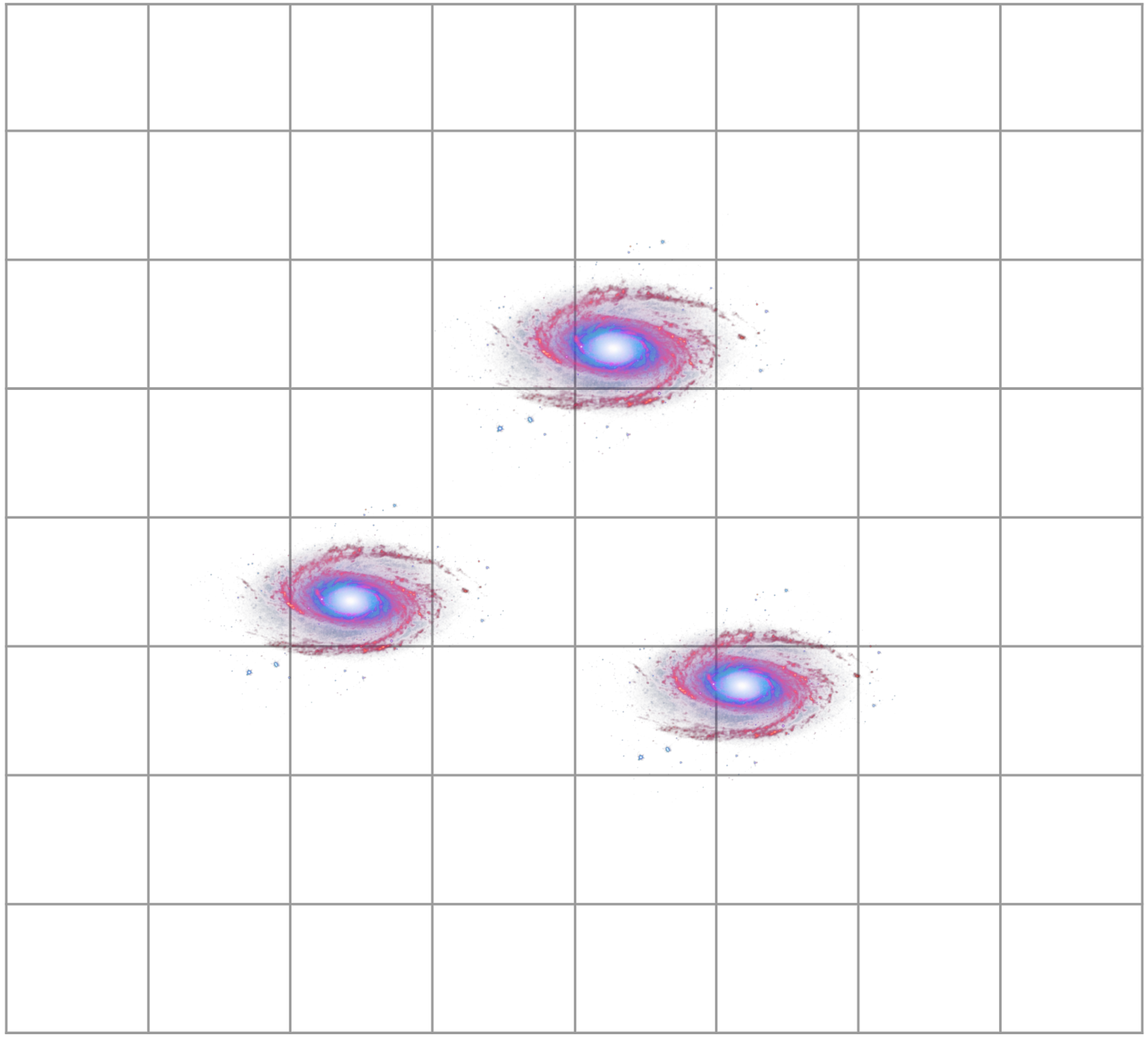


gravitational interaction → peculiar velocity

Peculiar velocities: applications for testing cosmology + particle physics

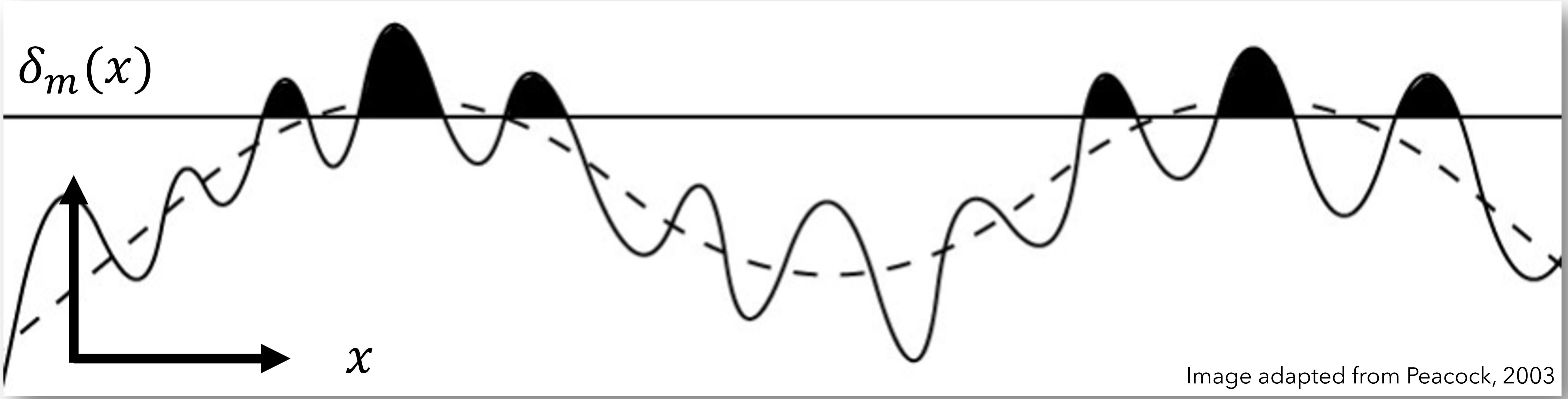


Image adapted from Peacock, 2003

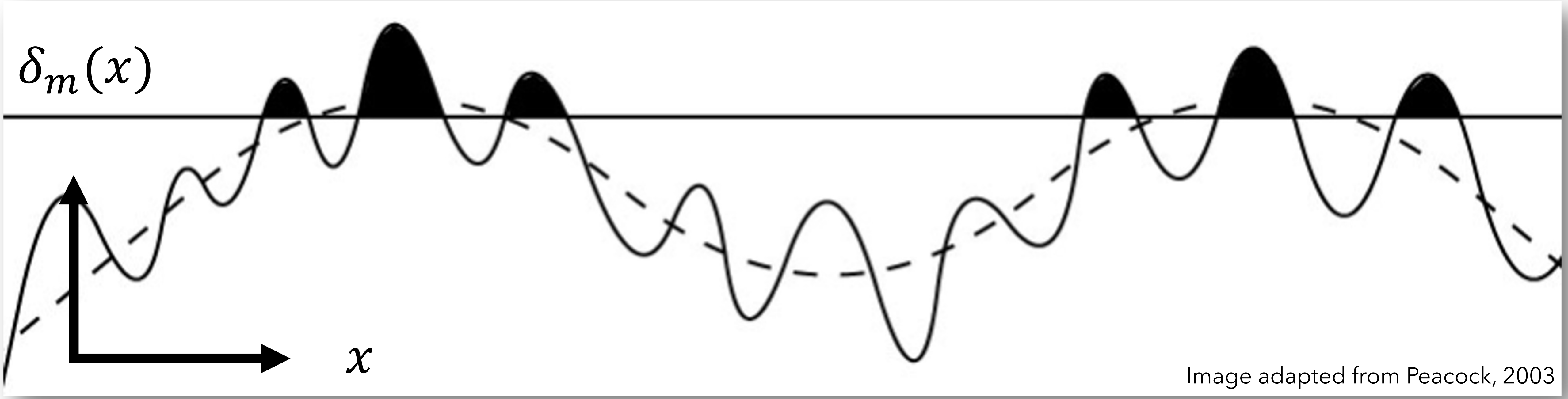
Peculiar velocities: applications for testing cosmology + particle physics

galaxy bias factor

$$\delta_g(r) \approx b_g \delta_m(r)$$

density field of galaxies

density field of matter



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Peculiar velocities: applications for testing cosmology + particle physics

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$$\delta_g(r) \approx b_g \delta_m(r)$$

density field of galaxies

density field of matter

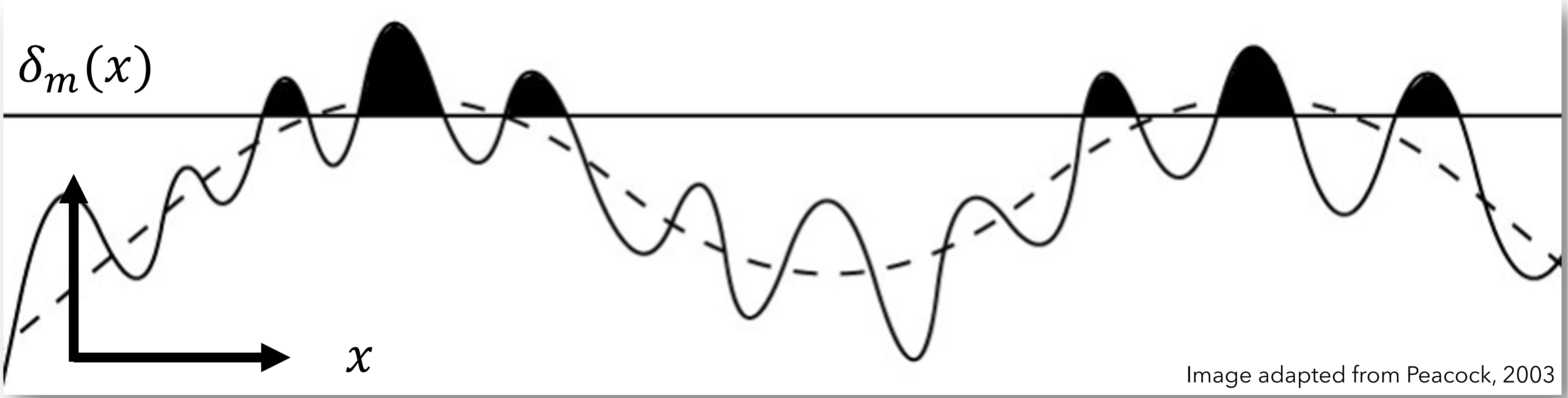
growth rate of structure

$$\nabla \cdot u(r) = -a\, H(a) f(a) \delta_m(r)$$

observed peculiar velocity field

expansion of space

density field of matter



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Peculiar velocities: applications for testing cosmology + particle physics

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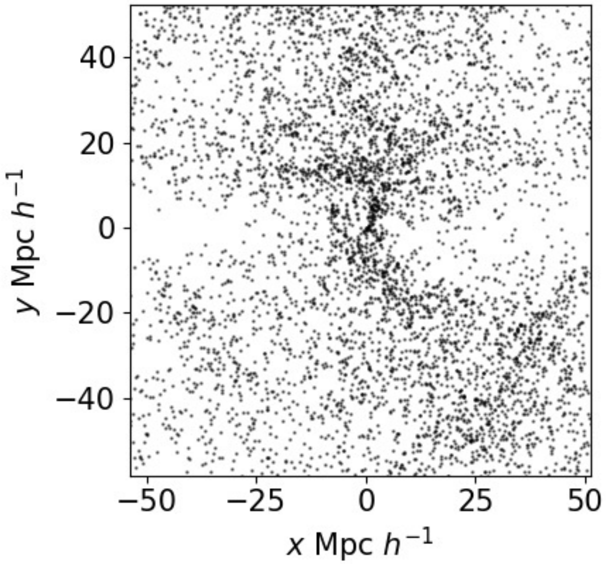

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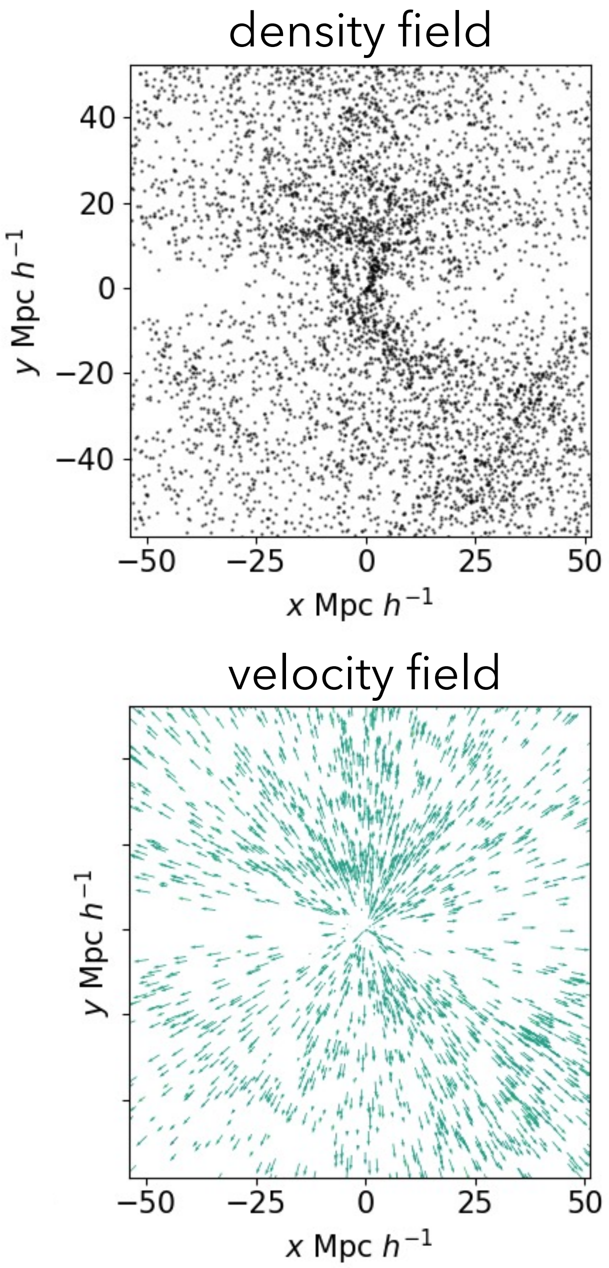

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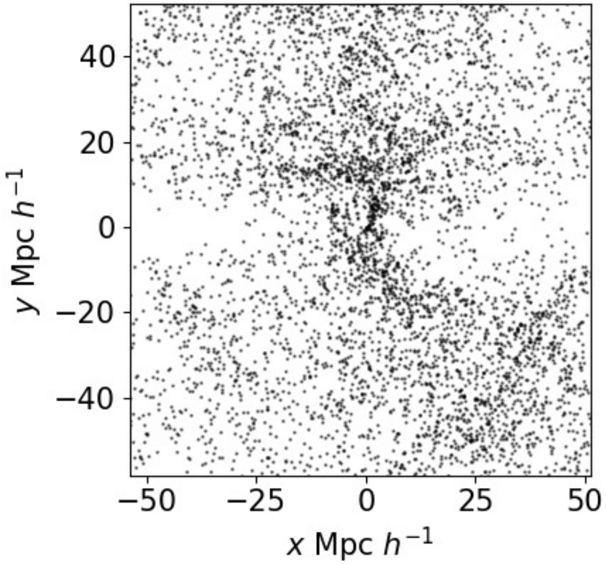
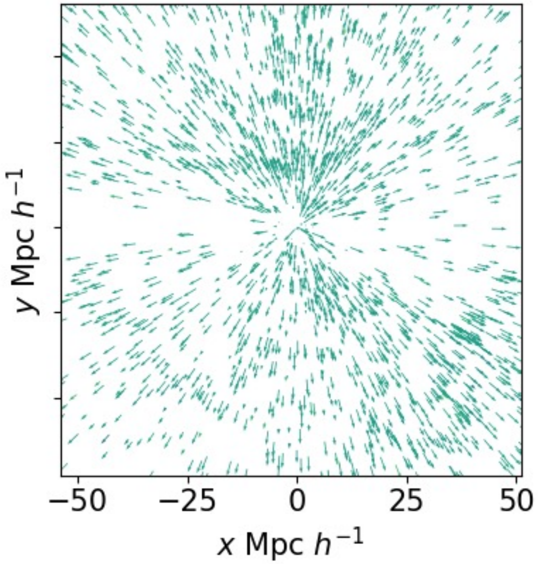
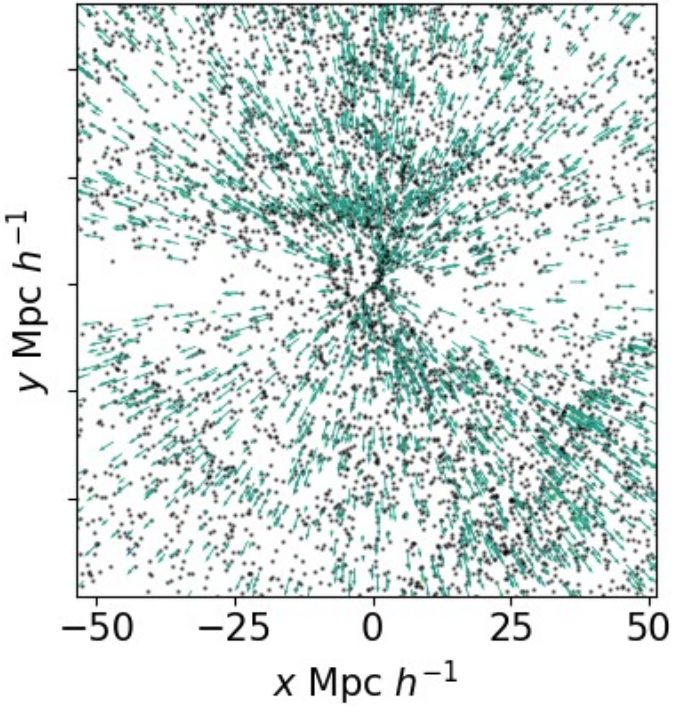


velocity field





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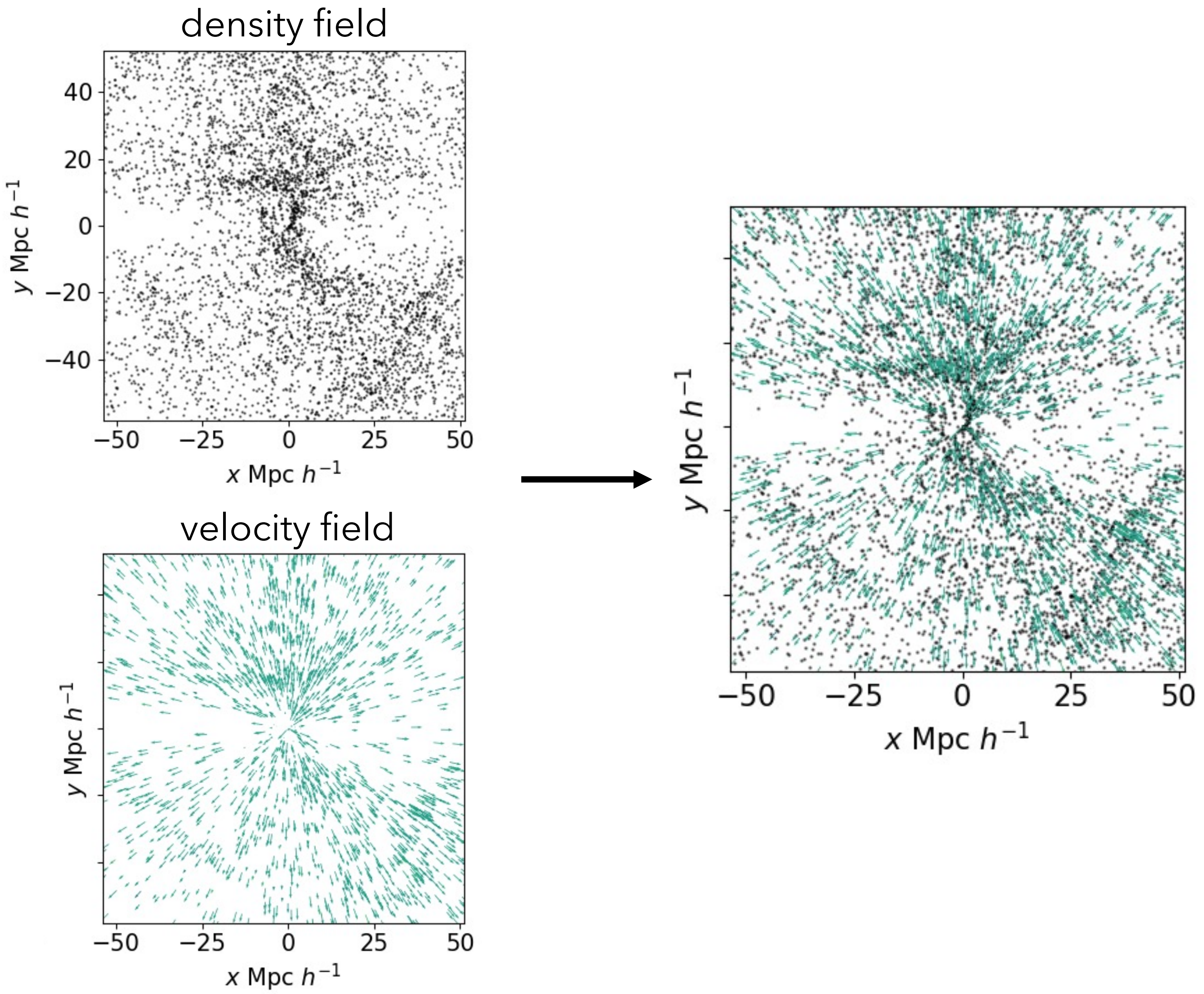


Literature:

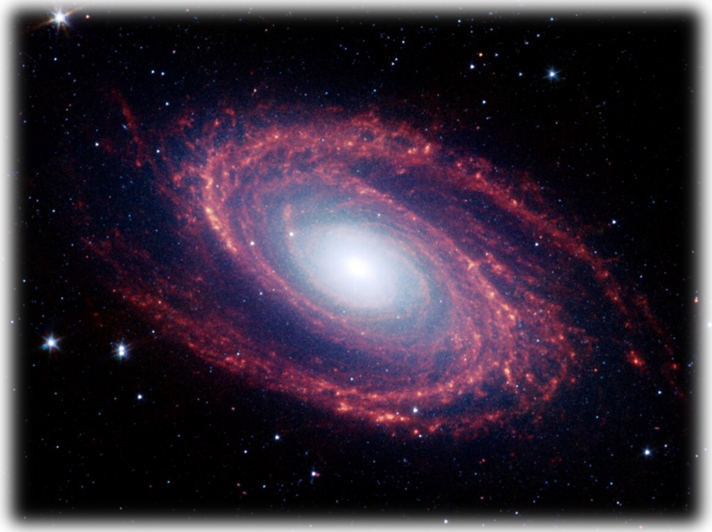
Peculiar velocity field as an unbiased tracer – Burkey and Taylor, 2004, Zheng et al 2015

Growth rate of structure forecasts/ constraints – Koda et al 2014, Howlett et al 2017a, 2017b, Qin et al 2019, Yan Lai et al 2022

Forecasts, neutrino mass constraints - Whitford et al 2022

Bulk flow measurements – Watkins et al 2009, Scrimgeour et al 2016 , Qin et al 2018, 2019, 2021, Howlett et al 2022, Watkins et al 2023, Whitford et al 2023 + many many more!

How are peculiar velocities measured?



Tully-Fisher relation
(Tully and Fisher, 1977)

Image from Spitzer Space telescope

- uses empirical relation between **rotation speed** and **luminosity**

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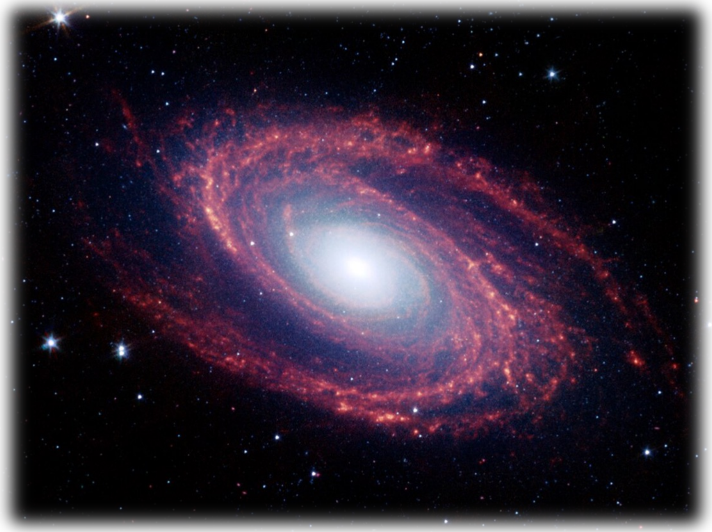

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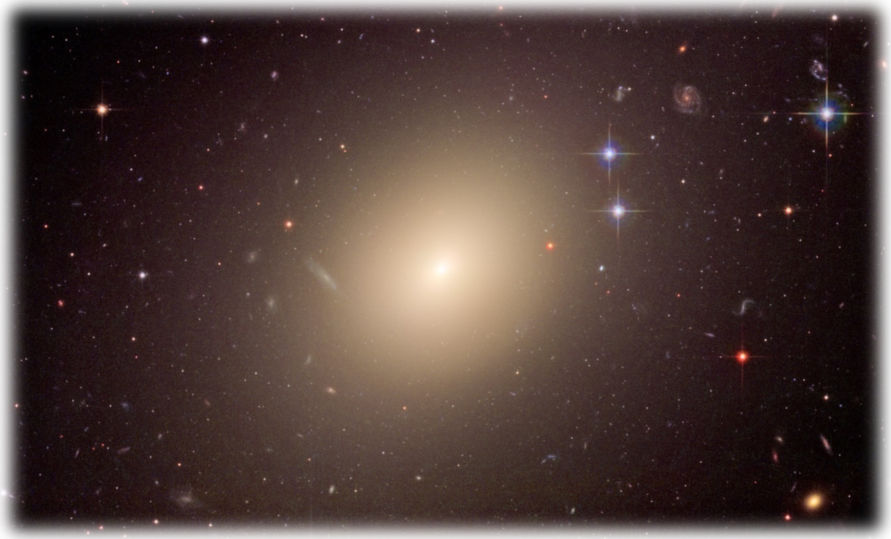

Fundamental Plane
(Djorgovski, S., & Davis, M. ,1987)

Image from HST

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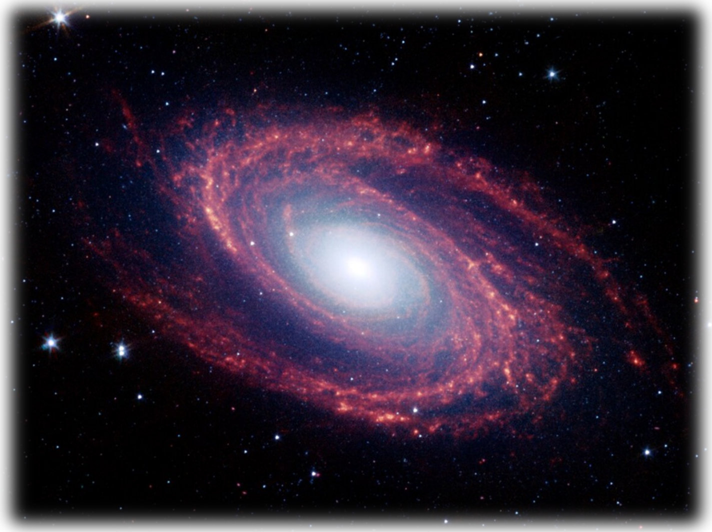

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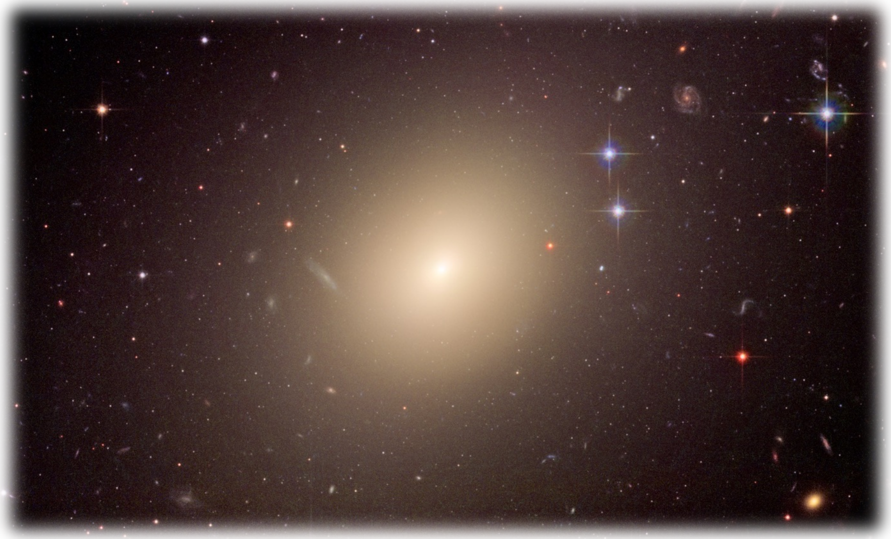

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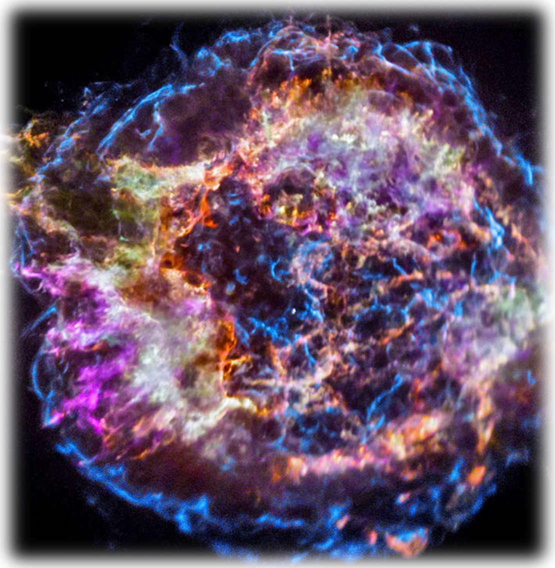


Type Ia Supernovae
(Phillips, 1993)

Image from NASA

- Standard candles
- **time for light curve to fade** allows **luminosity** to be measured

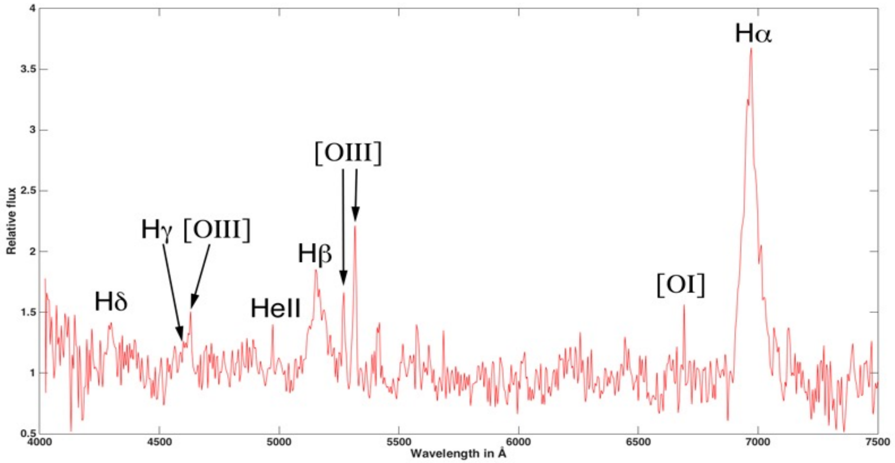
How are peculiar velocities measured?

$$(1 + z_{\text{obs}}) = (1 + z_{\text{rec}})(1 + z_{\text{pec}})$$

Spectroscopy/photometry

distance measurements

isolate the radial peculiar velocity



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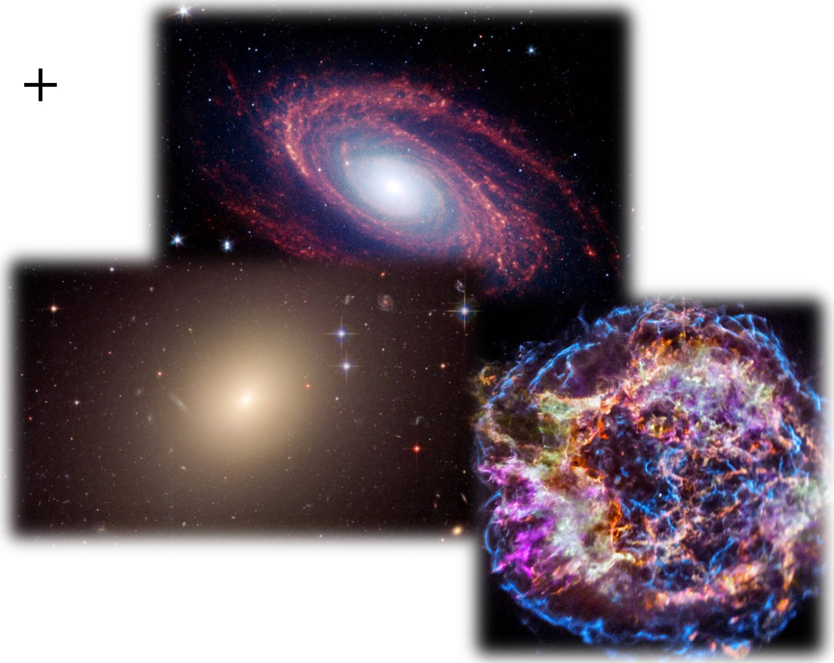

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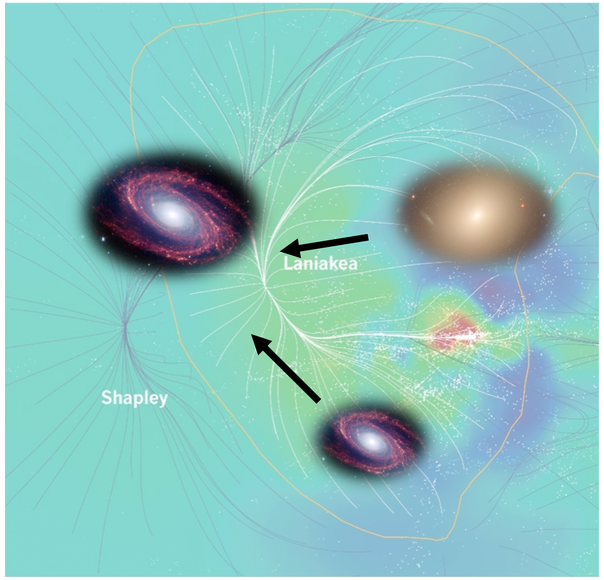
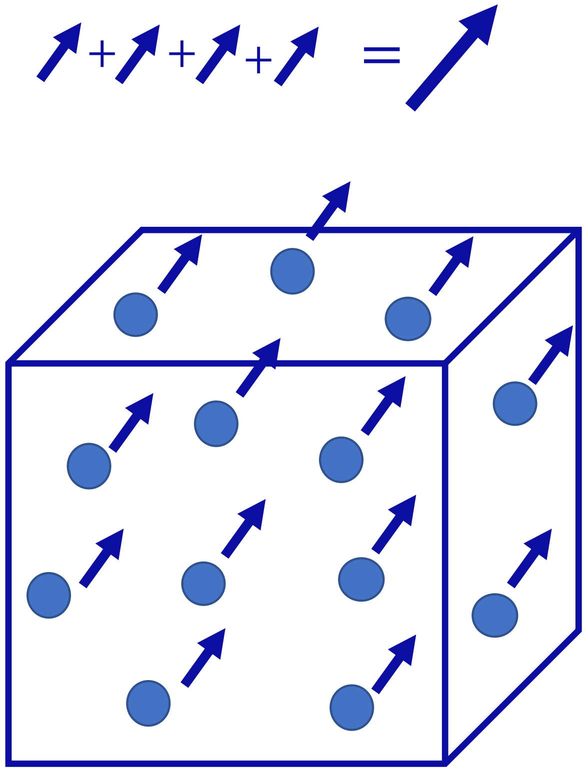
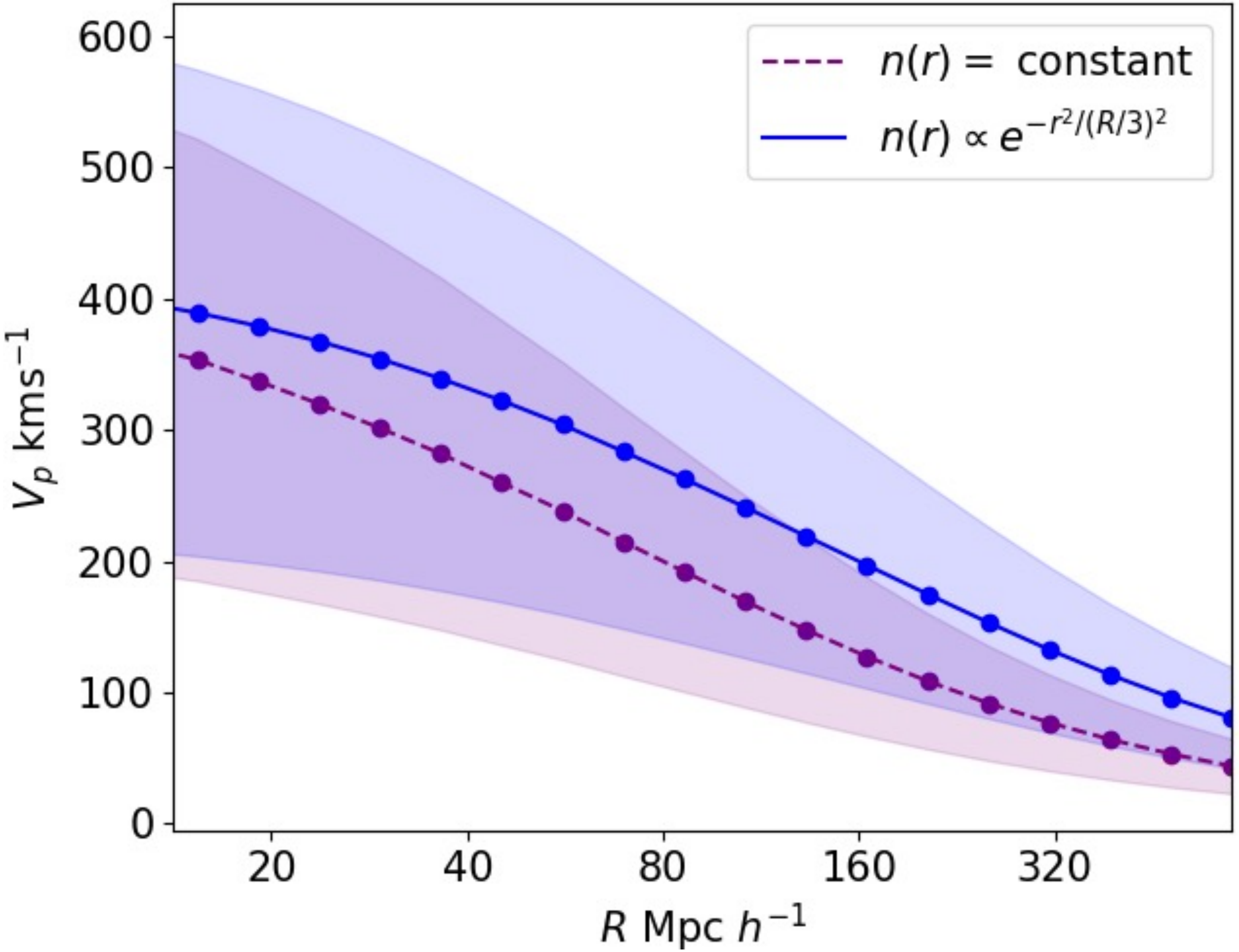


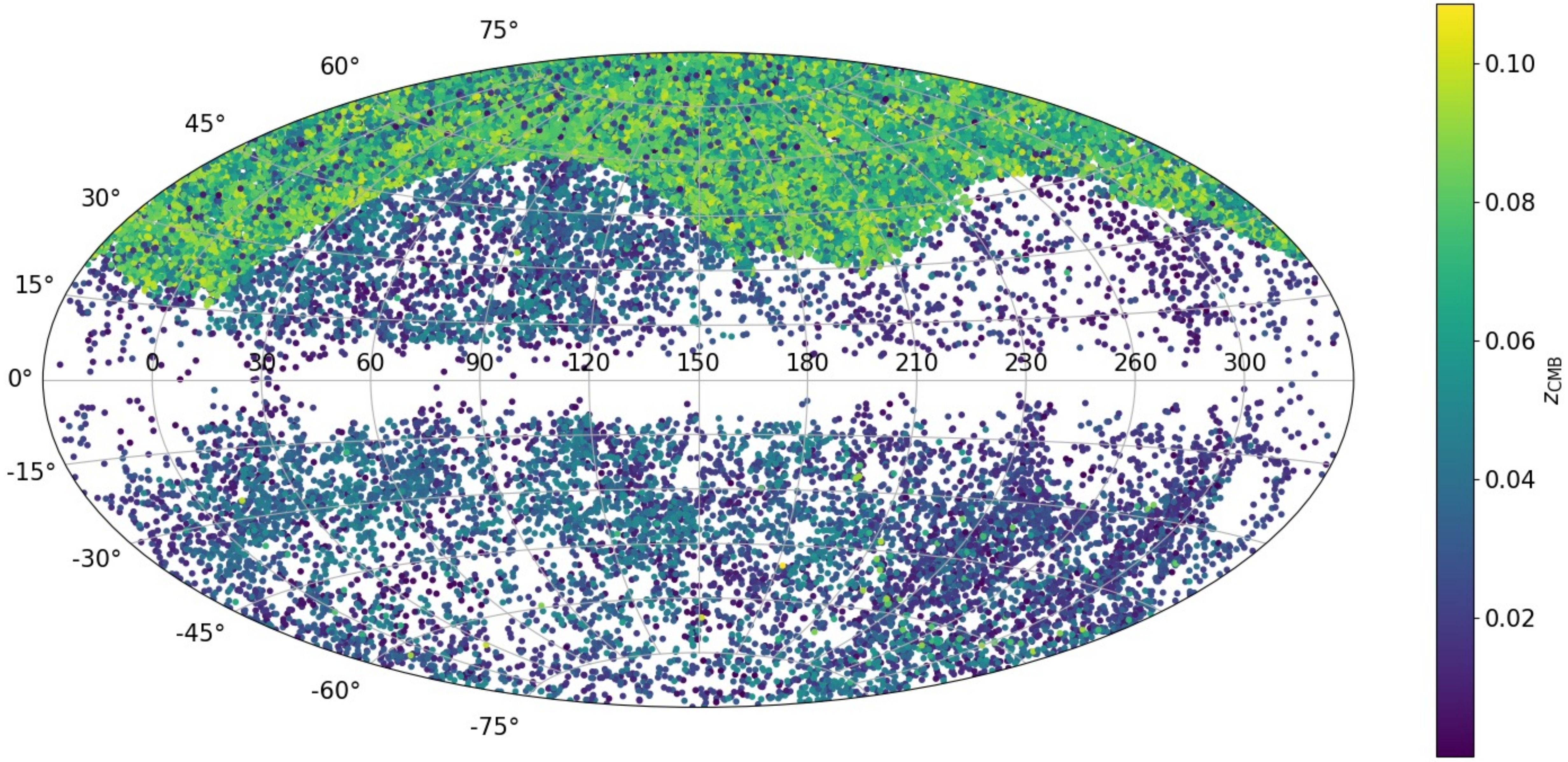
Using the bulk flow for testing cosmology

$$\boldsymbol{B} = \frac{1}{V}\int_V d^3r' \, \boldsymbol{v}(\boldsymbol{r}')$$

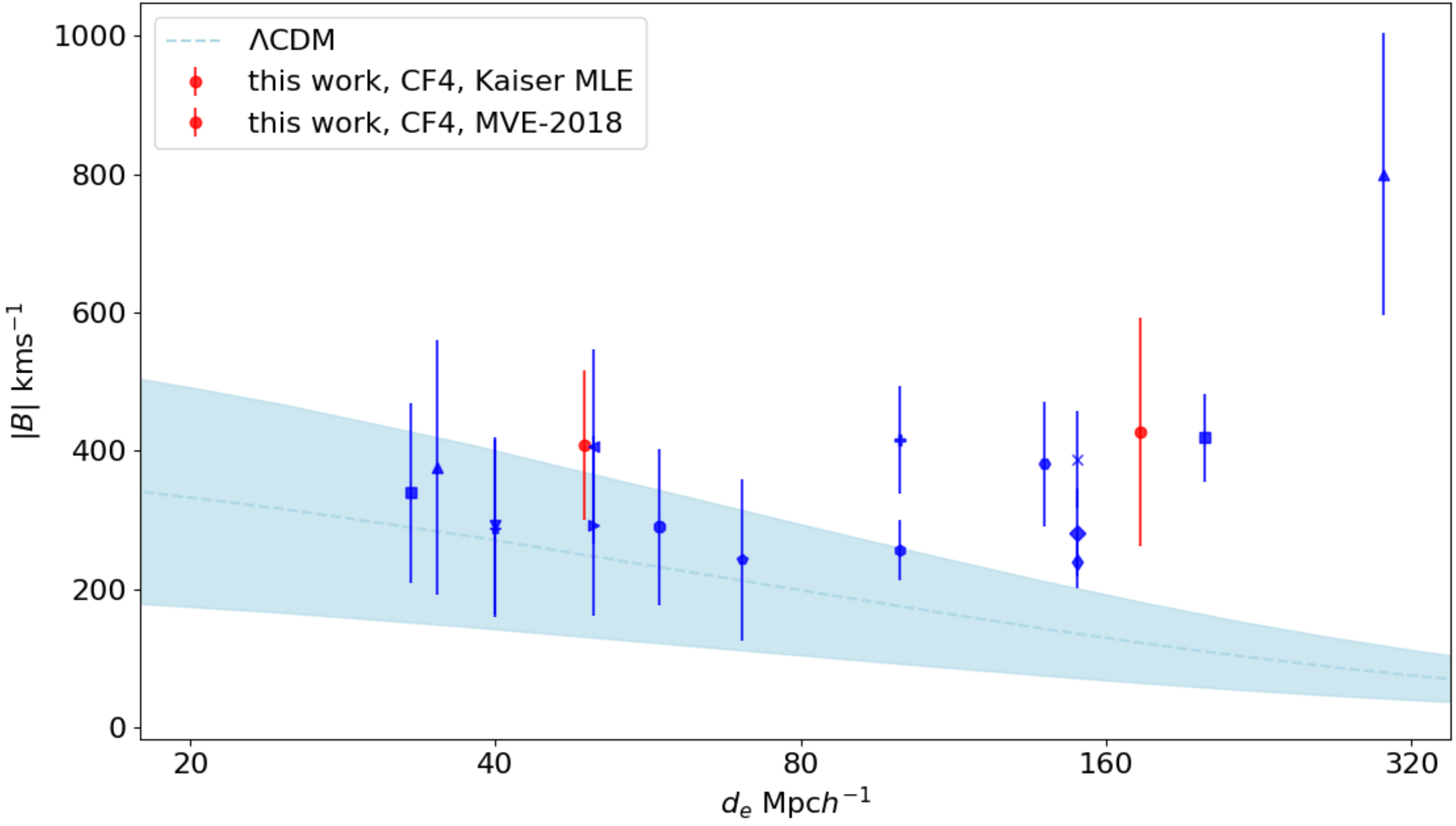




CosmicFlows-4, largest compilation of peculiar velocities to date, by Tully et al 2023



Measurement with CosmicFlows-4 data



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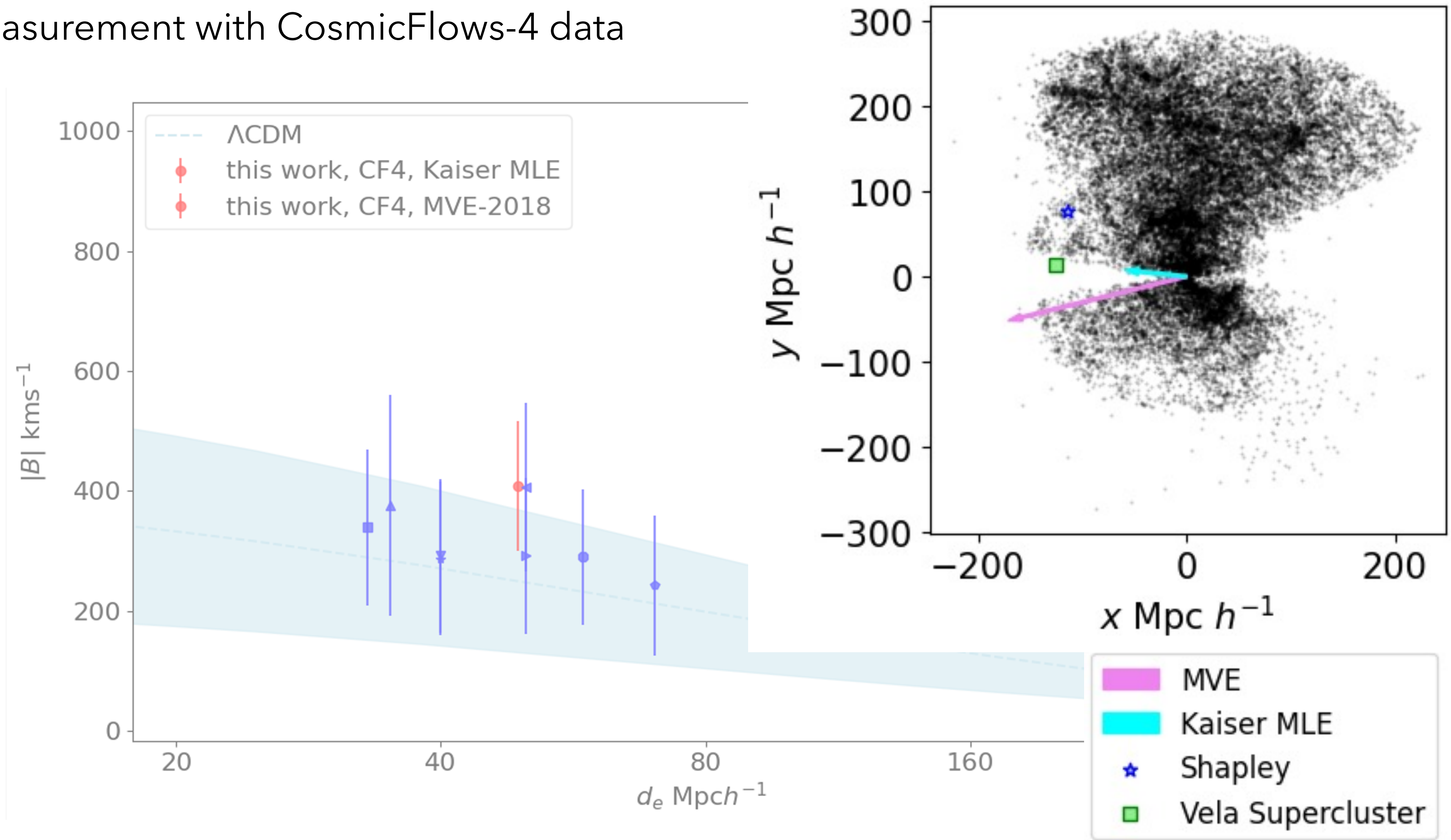
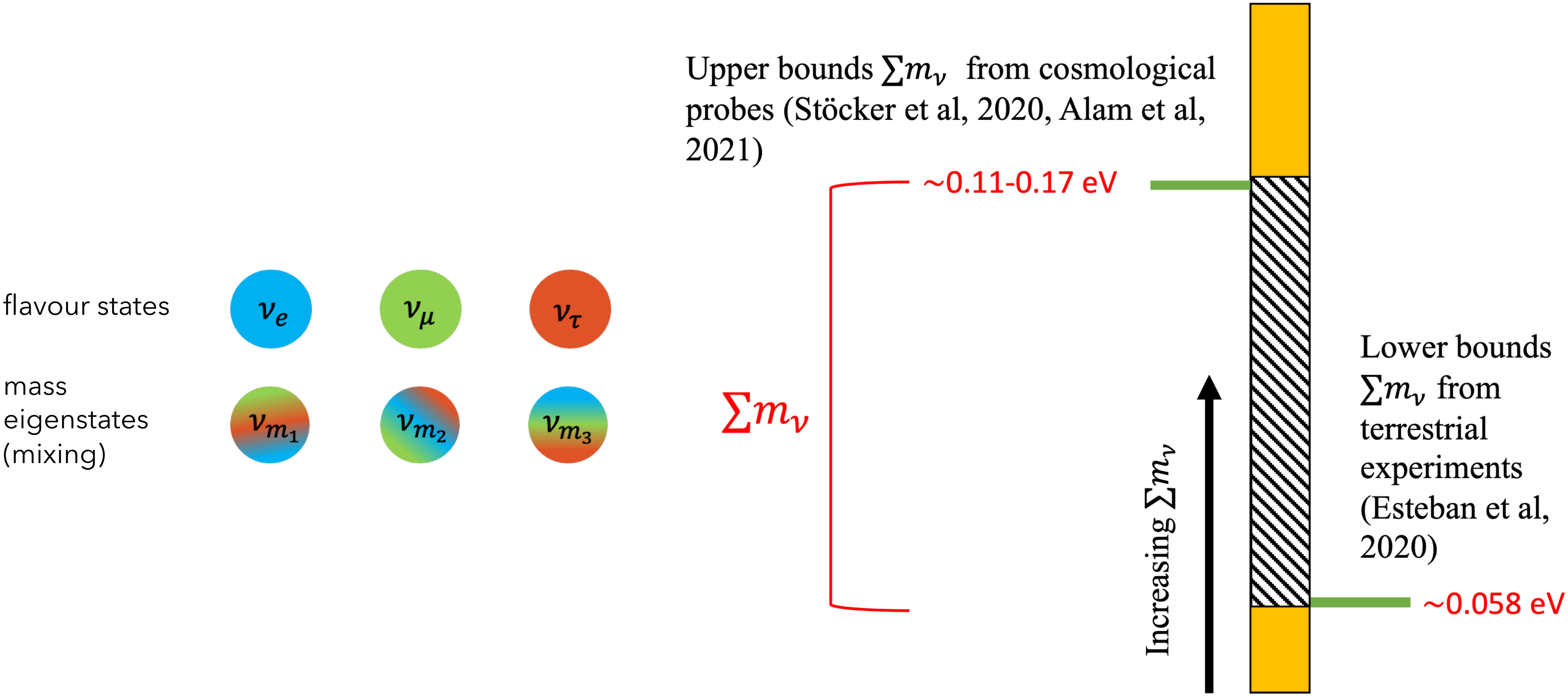


Overview of neutrinos in cosmology

(see more detail in Lesgourges and Pastor, 2012)



Overview of neutrinos in cosmology
(see more detail in Lesgourges and Pastor, 2012)

Oscillation experiments (Fuduka et al, 1998) give mass splittings Δm^2.

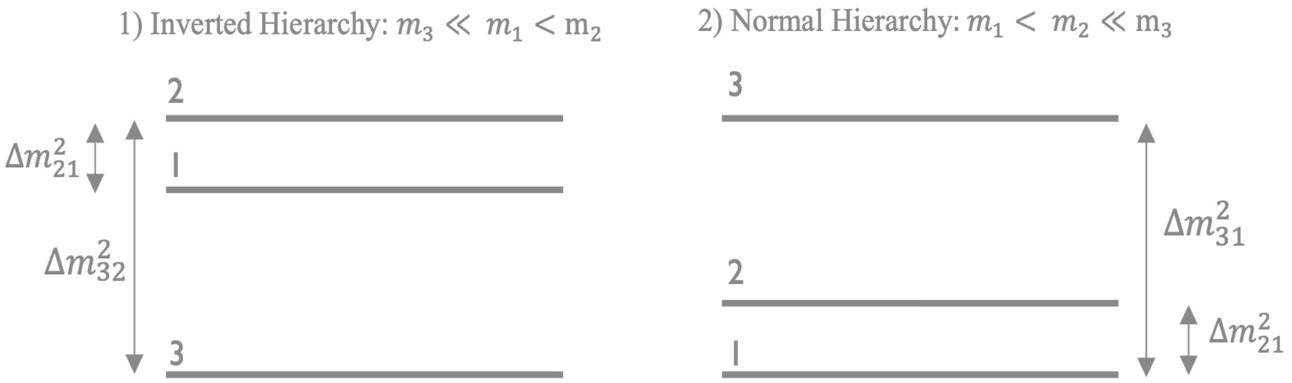
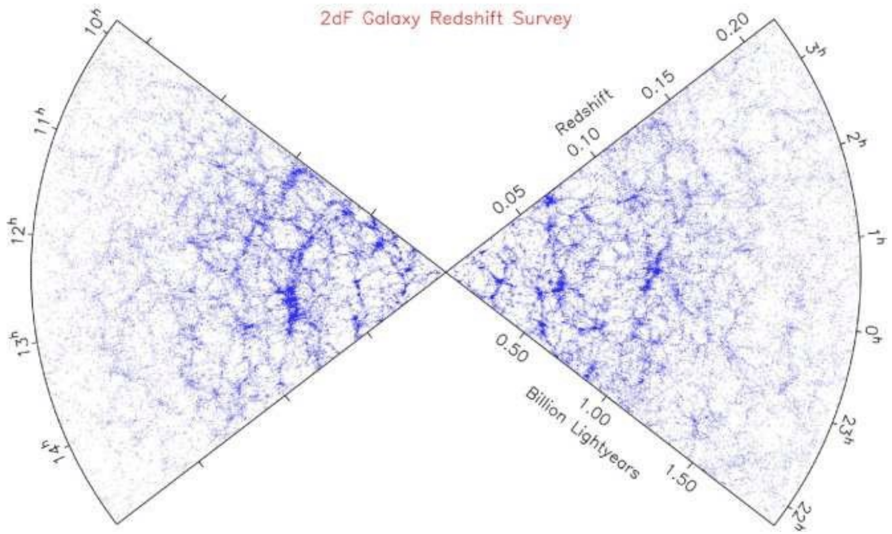


Figure inspired by Figure 1 in Lesgourgues and Pastor (2006)

+ cosmological probes give an upper bound to $\sum M_\nu$ (Image: Colless, 2003)



$$\sum m_\nu = \begin{cases} m_1 + \sqrt{m_1^2 + \Delta m_{21}^2} + \sqrt{m_1^2 + \Delta m_{31}^2} & \text{(Normal hierarchy)} \\ m_3 + \sqrt{m_3^2 + \Delta m_{32}^2 - \Delta m_{21}^2} + \sqrt{m_3^2 + \Delta m_{32}^2} & \text{(Inverted hierarchy)} \end{cases}$$

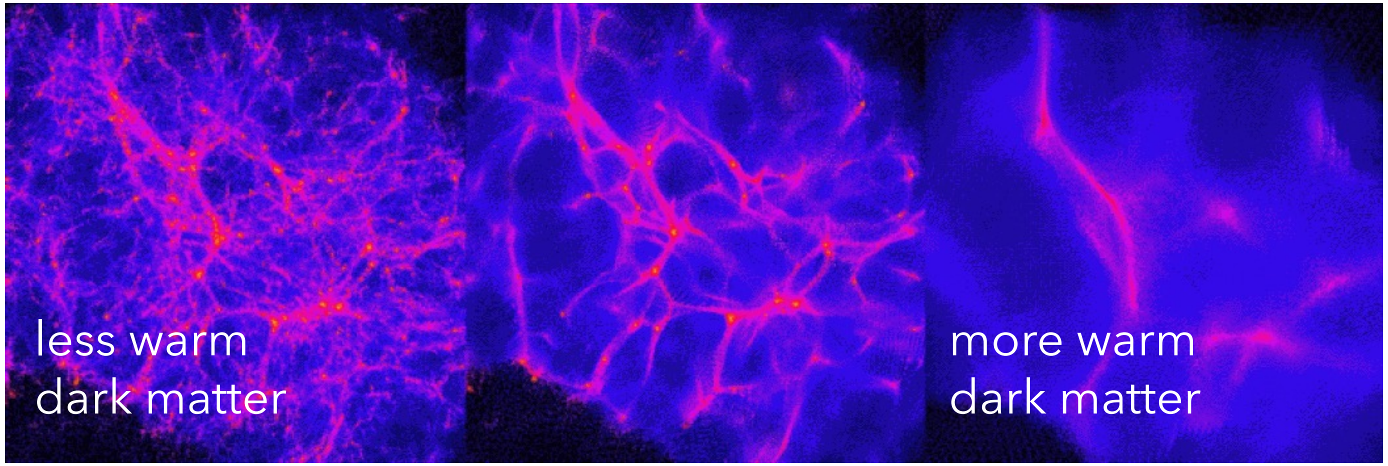
Overview of neutrinos in cosmology
(see more detail in Lesgourges and Pastor, 2012)

Massive neutrinos affect Large Scale Structure by:

1) Alters expansion rate of the Universe (signal can be measured in galaxy distribution and Cosmic Microwave Background)

$$a_{eq} = \frac{\Omega_r}{\Omega_m}$$

2) suppressing the growth of Large-Scale Structure in the Universe.



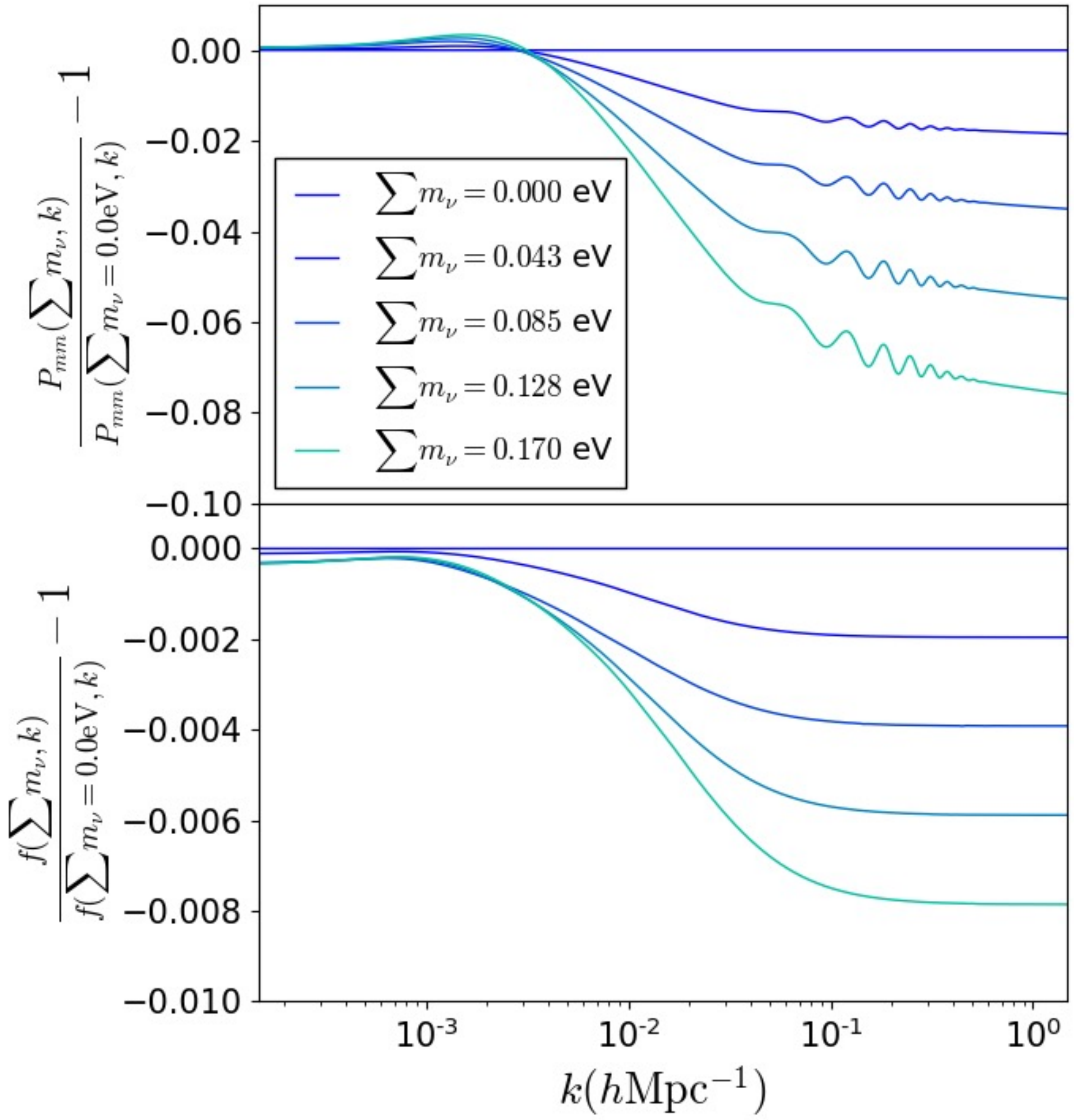


Image: Simulation, University of Zurich

Neutrino mass constraints with peculiar velocities

Aim to answer: can we use peculiar velocities to improve neutrino mass constraints?

Fisher information forecasts:

$$F = -\langle \frac{d^2 \mathcal{L}}{dx^2} \rangle$$

Generalizing to multiple variables.. $x_i = [x_1, x_2, \ldots . x_n]$

$$F_{ij} = -\langle \frac{d^2 \mathcal{L}}{dx_i dx_j} \rangle$$

The inverse of the Fisher matrix F_{ij} gives the best possible covariance C_{ij} matrix for our set of parameters x_i (Cramér-Rao bound).

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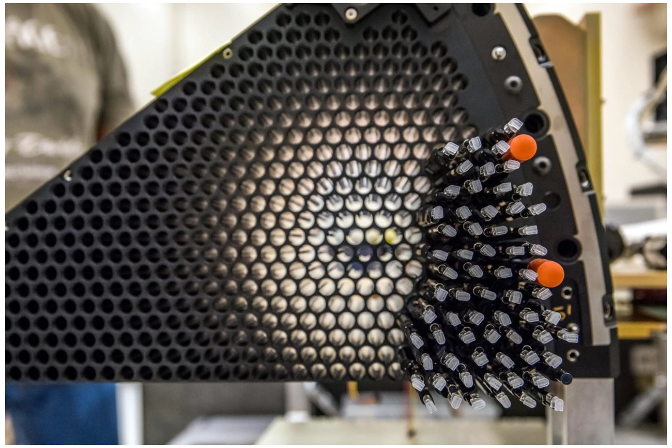
Forecasting for:

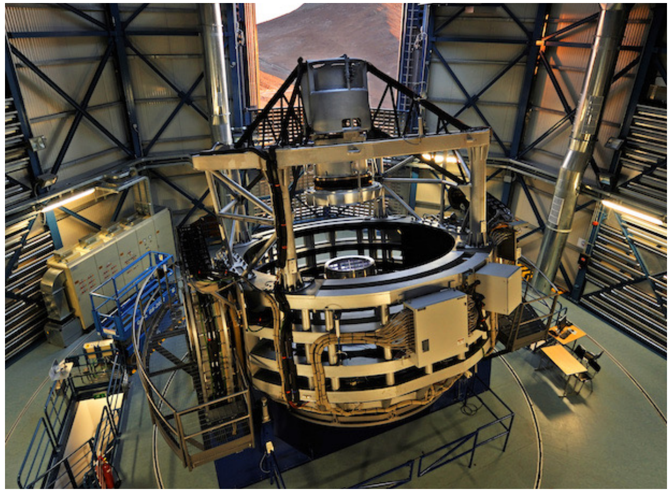
Legacy Survey of Space and Time (LSST)
Image: Rubin Obs/NSF/AURA

WALLABY on CSIRO ASKAP telescope
Image: CSIRO

Dark Energy Spectroscopic Instrument (DESI)
Image: Marilyn Chung / LBNL



4-metre multi-object spectroscopic telescope (4MOST) Image: G. Hüdepohl



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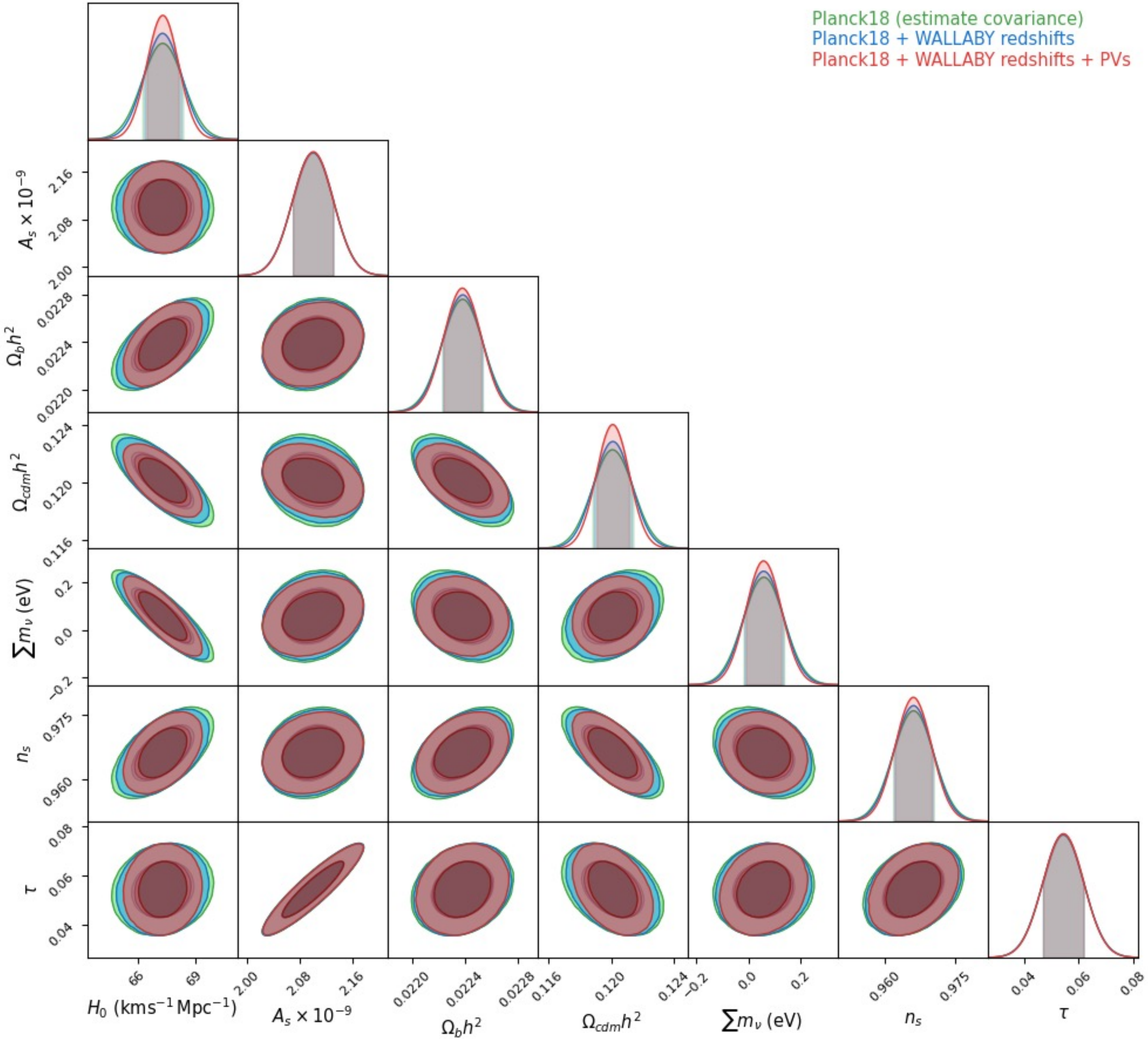
Results: Yes *

- ➢ Constraints improve by ~ 10% for low redshift survey data + *Planck* data
- ➢ High redshift survey + *Planck* data: negligible improvement



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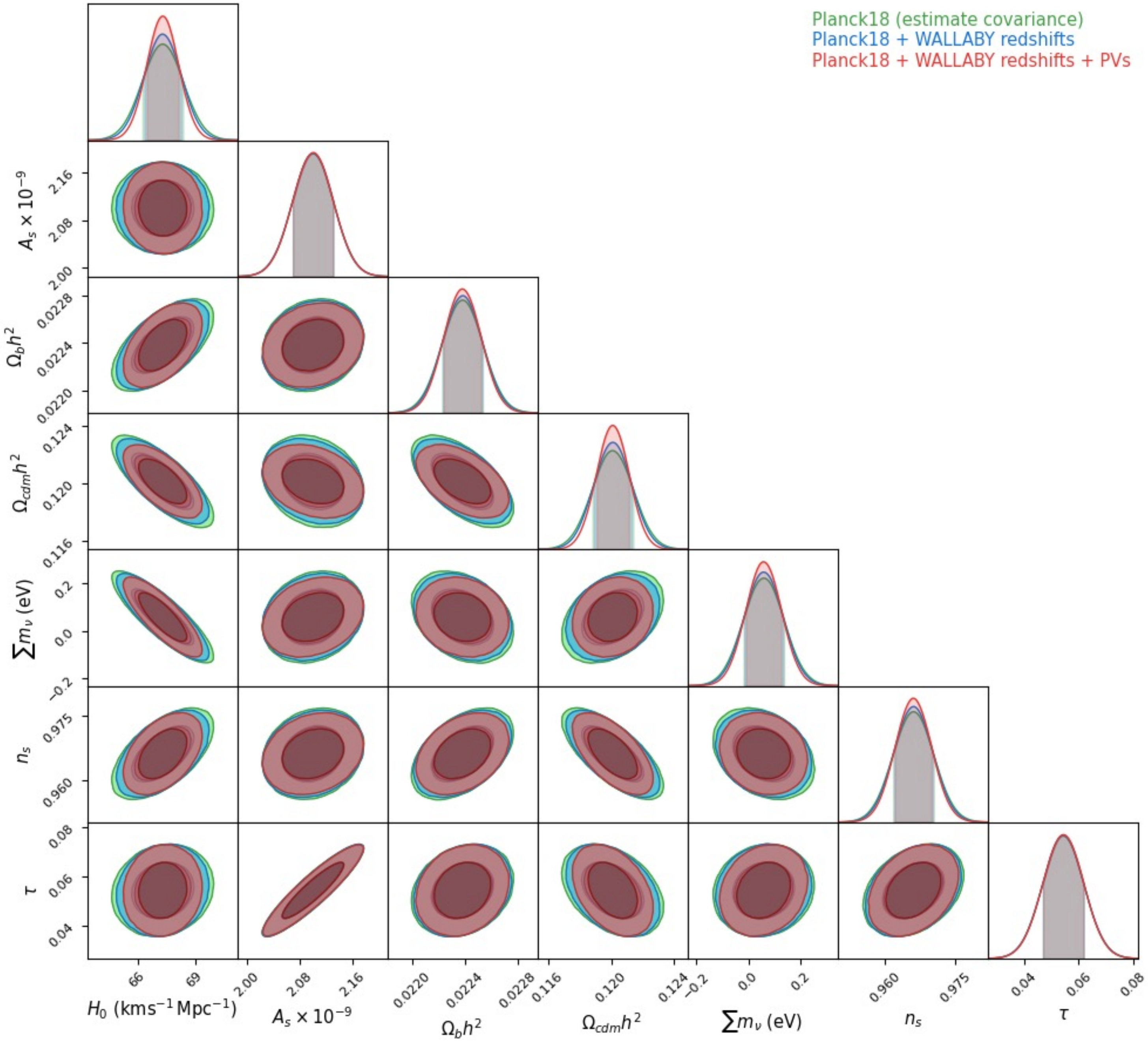

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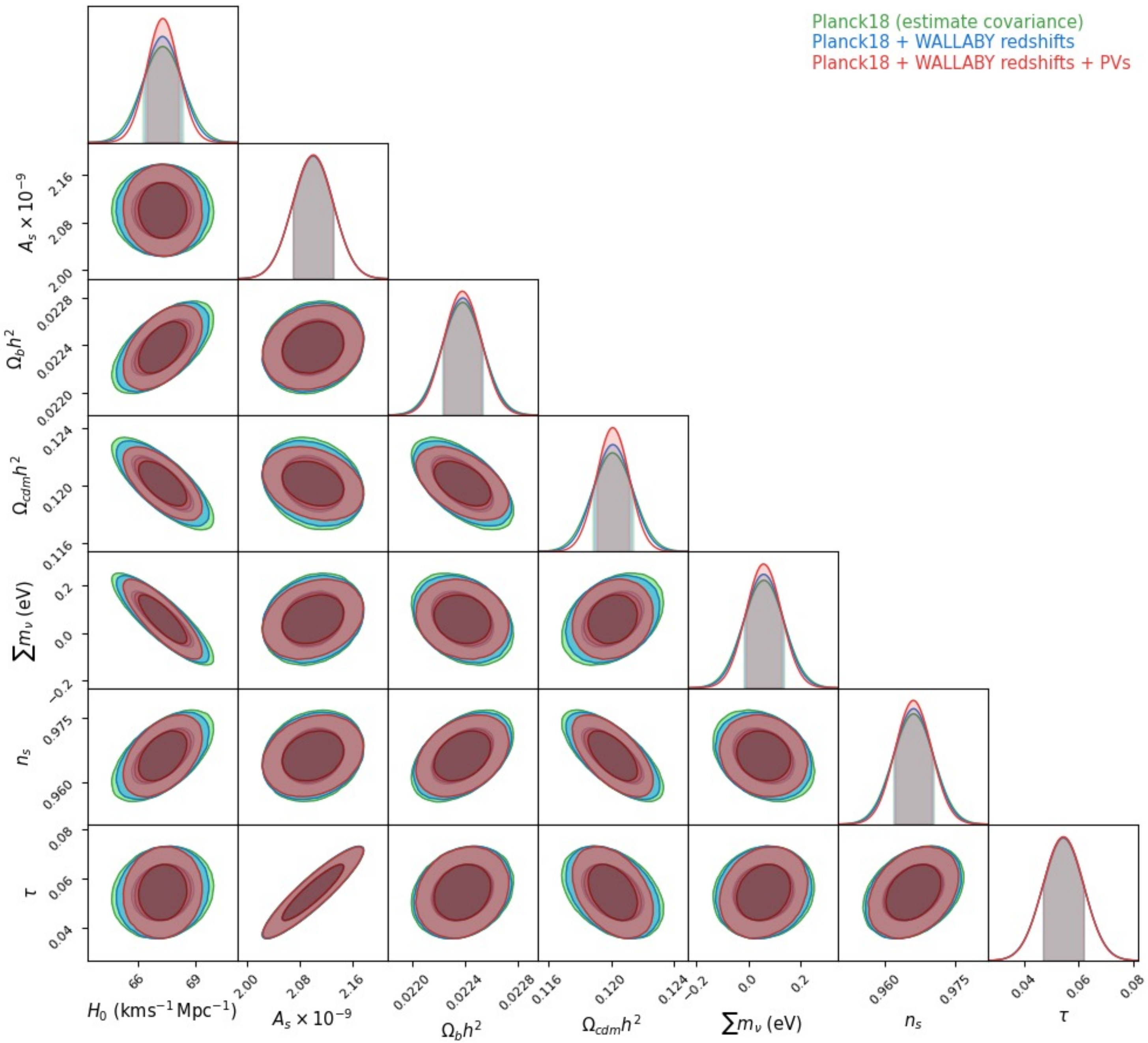
- High redshift surveys (without *Planck*): ~ 15-17% improvement (greater than 50% when $N_{\rm eff}$ is free)
- The best constraint we obtained from surveys without *Planck* was $\sigma_{\sum m_\nu} = 0.139$ eV
- **future:** constraints that don't depend on *Planck?*



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Summary:

- Peculiar motions:
  - contain info on Universe's matter distribution
  - can be used to test cosmology e.g., bulk flow
  - measured bulk flow from CosmicFlows-4 in tension with ΛCDM model
  - can potentially be used to help constrain neutrino mass in future

Bulk flow measurement preprint: arXiv: **2306.11269**

Forecasts for neutrino mass constraint paper: arXiv: **2112.10302**