Title: Turning Back Time on Space

Speakers: Farnik Nikakhtar

Series: Cosmology & Gravitation

Date: April 23, 2024 - 11:00 AM

URL: https://pirsa.org/24040109

Abstract: One big question in the physics of large-scale structures is how we can trace back the evolution of cosmic structures and reconstruct the initial density field. The universe we observe today is dotted with galaxy clusters separated by vast voids, in sharp contrast to its initial state, which was nearly uniform with only minor density fluctuations. The evolution from this early uniformity to today's complex structure of galaxies is a profound transformation, with many intermediate processes still unexplained. This talk focuses on this transformation, aiming to reconstruct both the initial density and the displacement fields of galaxies observed in spectroscopic surveys. I will discuss new reconstruction algorithms that depend weakly, if at all, on a cosmological model. These algorithms have paved the way for new astrophysical achievements in several directions, such as: Baryon Acoustic Oscillations (BAO) analysis, morphological analysis of proto-halos, and kinematic Sunyaev-Zel'dovich (kSZ) effect.

Zoom link

Turning Back Time on Space

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In collaboration with:

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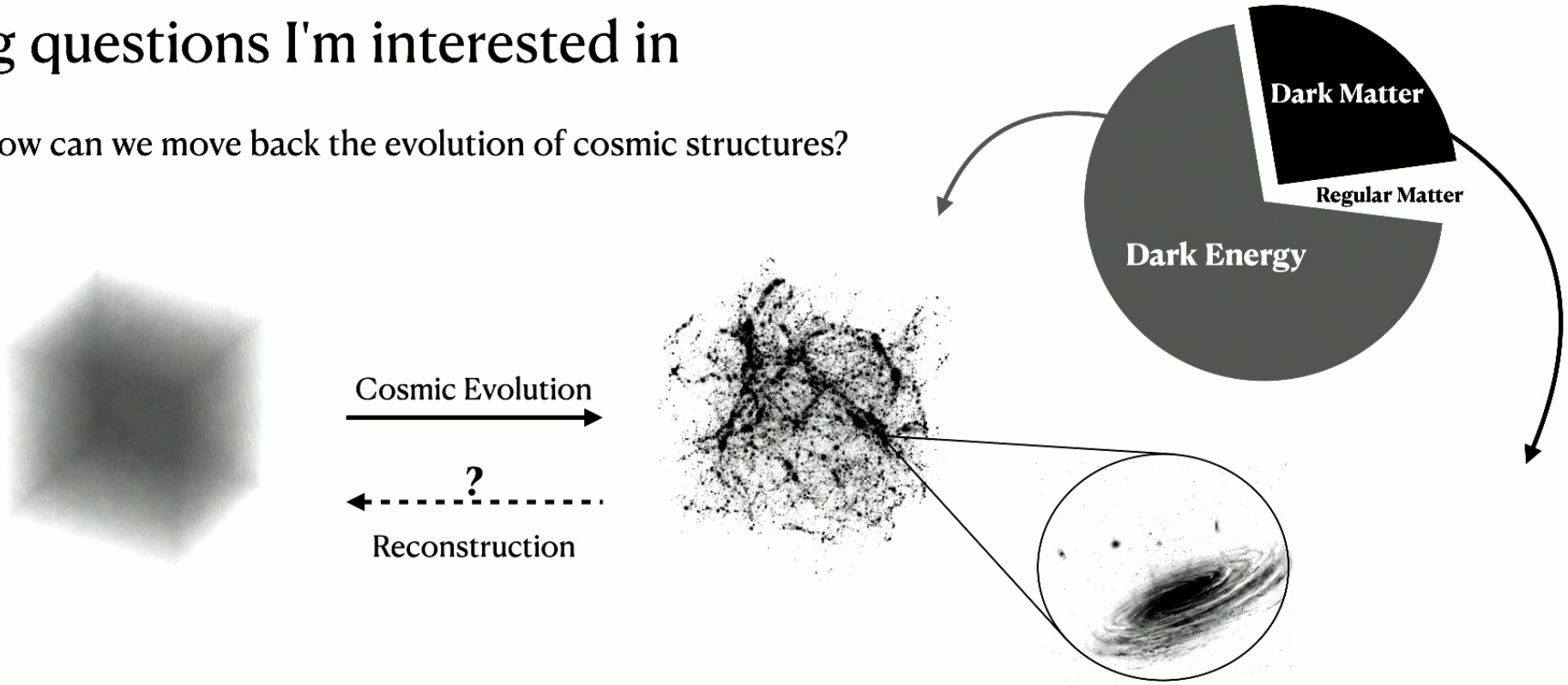
Bruno Levy (Inria)
Navya Uberoi (Yale)

Interstellar, Christopher Nolan (2014)

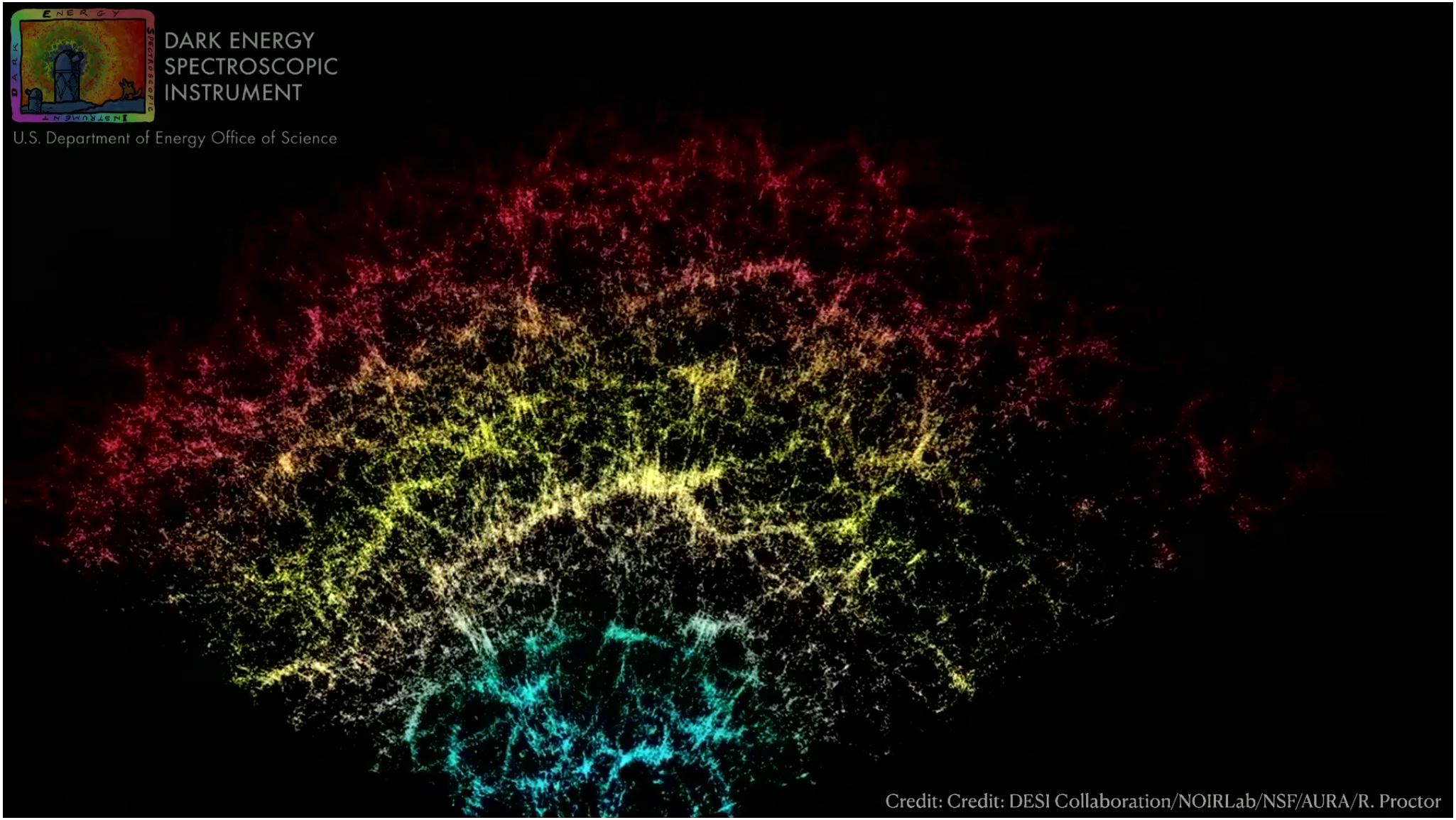
Perimeter Institute, Cosmology Seminar
April 23, 2024

Big questions I'm interested in

- How can we move back the evolution of cosmic structures?



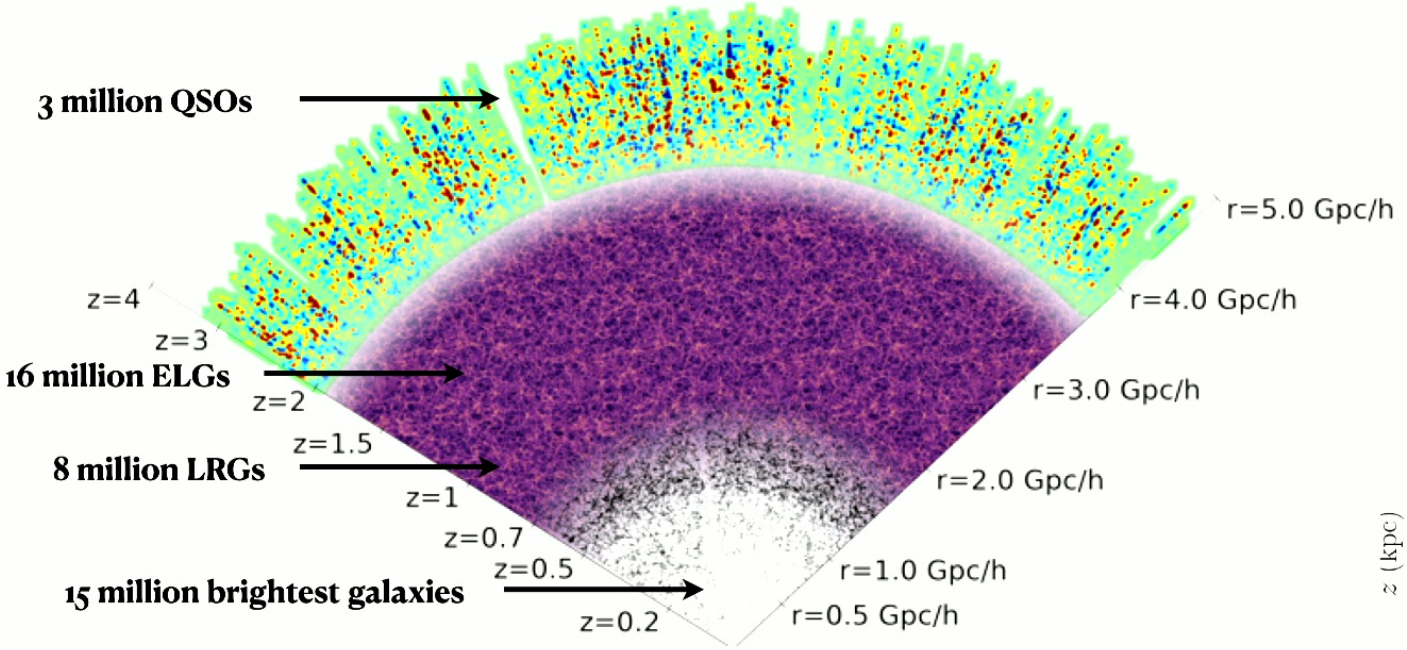
- How can we quantify out-of-equilibrium characteristics of galactic systems?


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT
U.S. Department of Energy Office of Science
Credit: Credit: DESI Collaboration/NOIRLab/NSF/AURA/R. Proctor

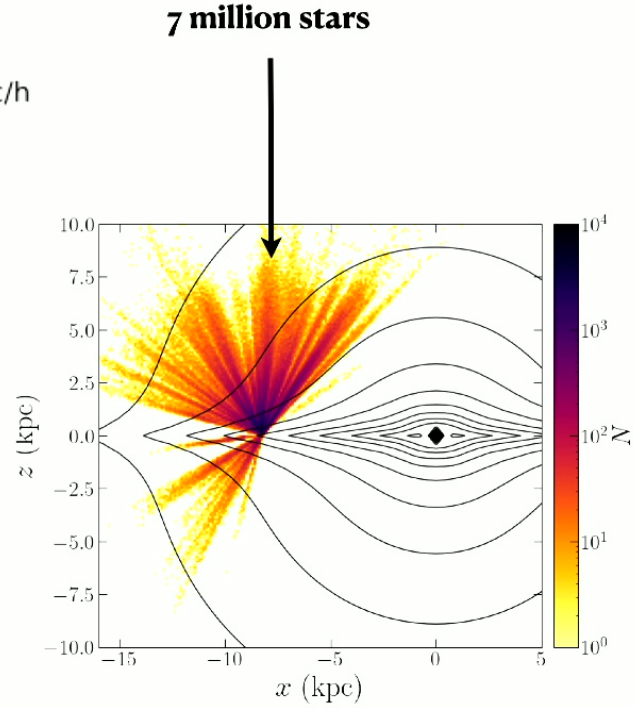
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI will be the largest 3D map of the universe this decade!



Credit: D. Schlegel (LBNL)



Turning Back Time on Space or how can we move back the evolution of cosmic structures?

A simple "biased" view of reconstruction

Initial position

Evolved position $\vec{X} = \vec{q} + \vec{S}$ Displacement

$$\vec{X}_2 - \vec{X}_1 = \vec{q}_2 - \vec{q}_1 + \vec{S}_2 - \vec{S}_1$$

$$\underbrace{\vec{X}_{12}}_{\text{data}} = \underbrace{\vec{q}_{12}}_{\text{signal}} + \underbrace{\vec{S}_{12}}_{\text{noise}}$$

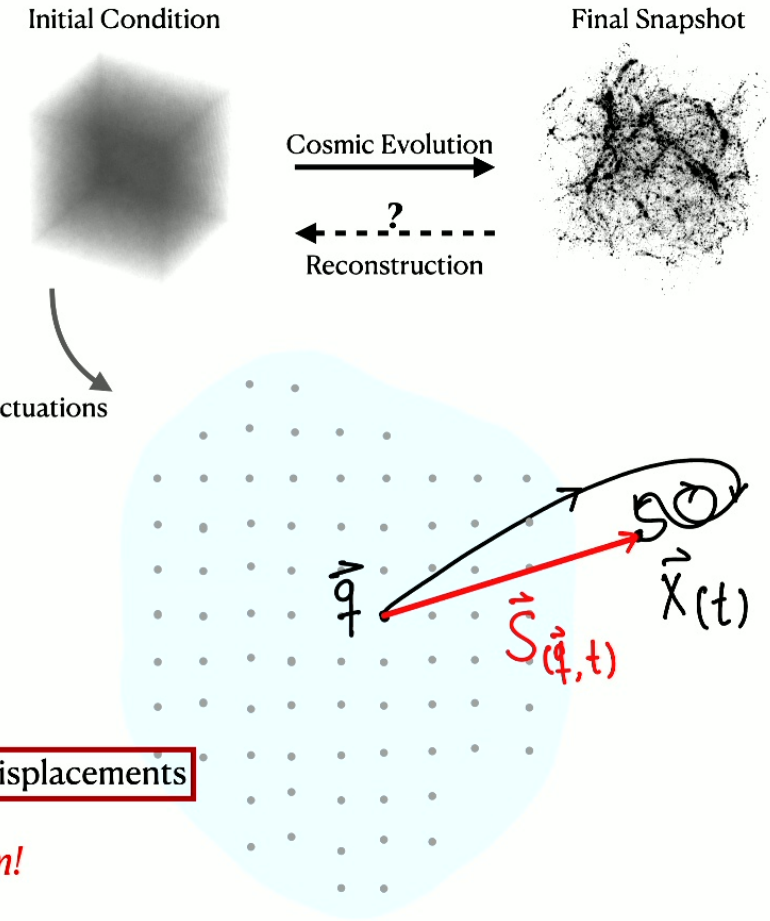
$$\mathcal{P}(\text{data}) = \int d(\text{signal})\, \mathcal{P}(\text{signal})\, \mathcal{P}(\text{noise} = \text{data} - \text{signal} \,|\, \text{signal})$$

Histogram of pair separations today =

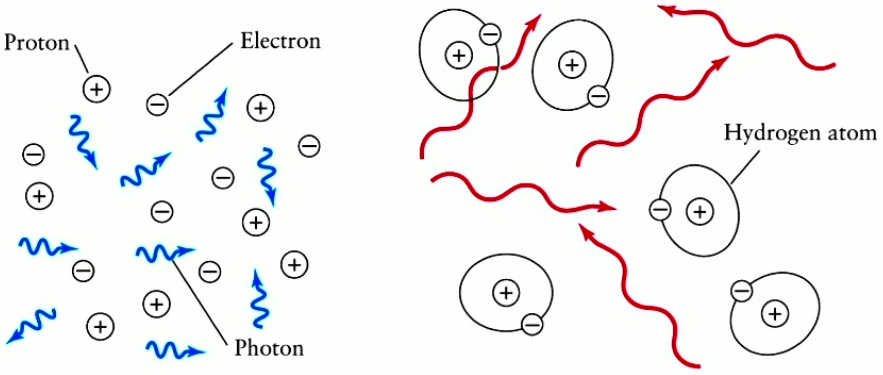
Convolution of initial pair separation histogram with distribution of pairwise displacements

Reconstruction of ~~pair separations~~ is a deconvolution problem!

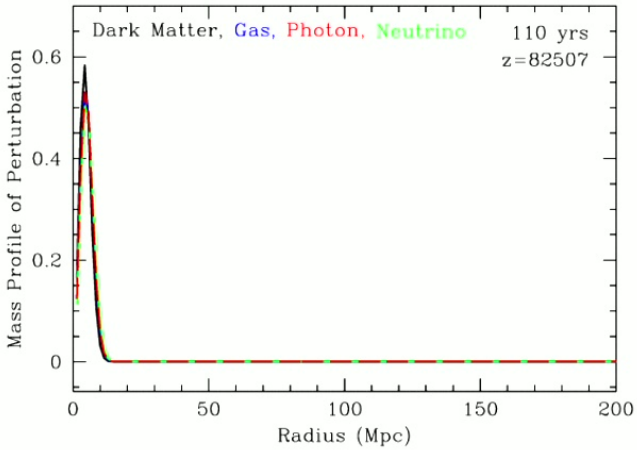
2-point correlation function



Baryon Acoustic Oscillations from Soup to Nuts



Recombination & Decoupling (last scattering)



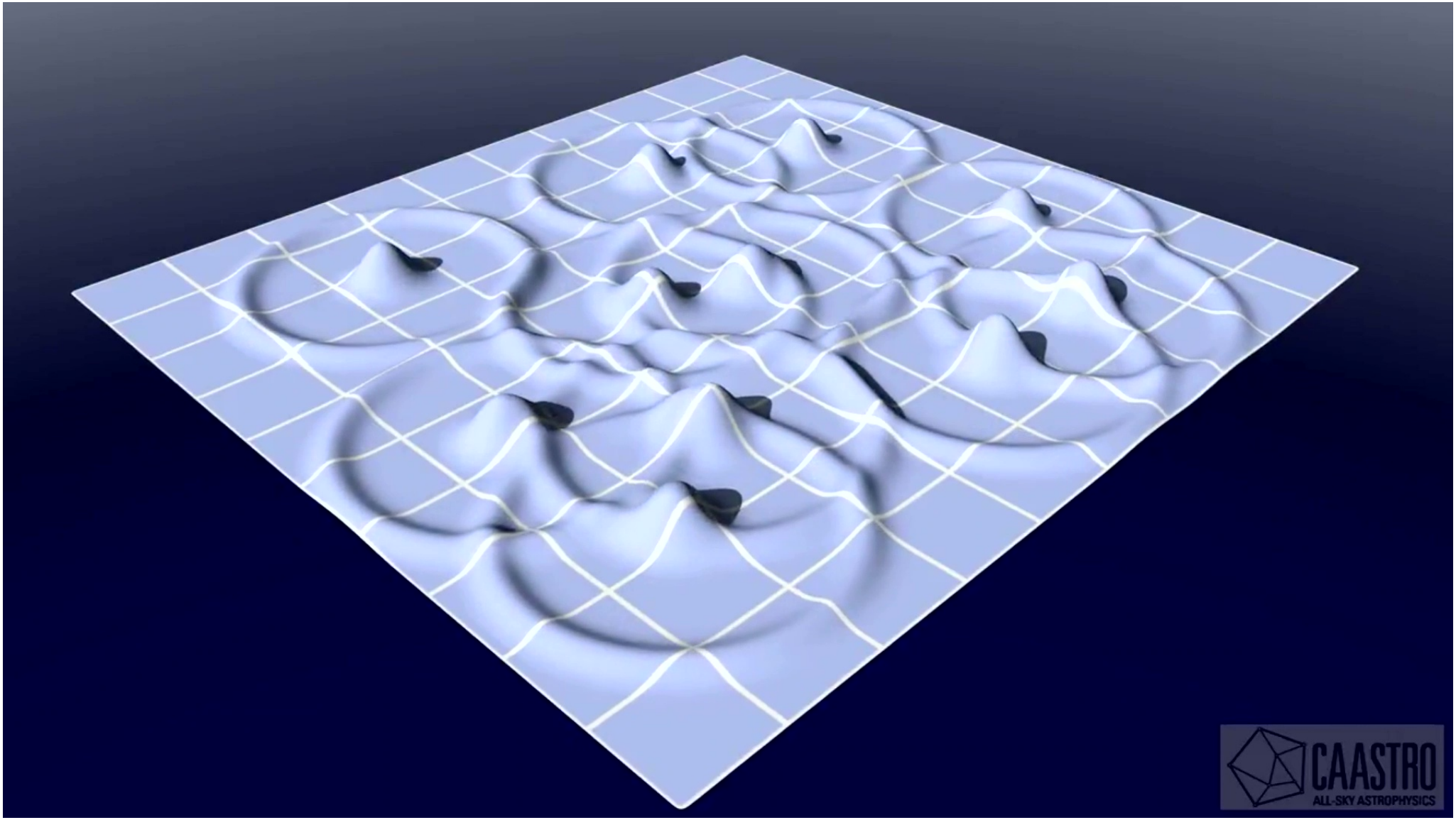
Credit: D. Eisenstein (Harvard)

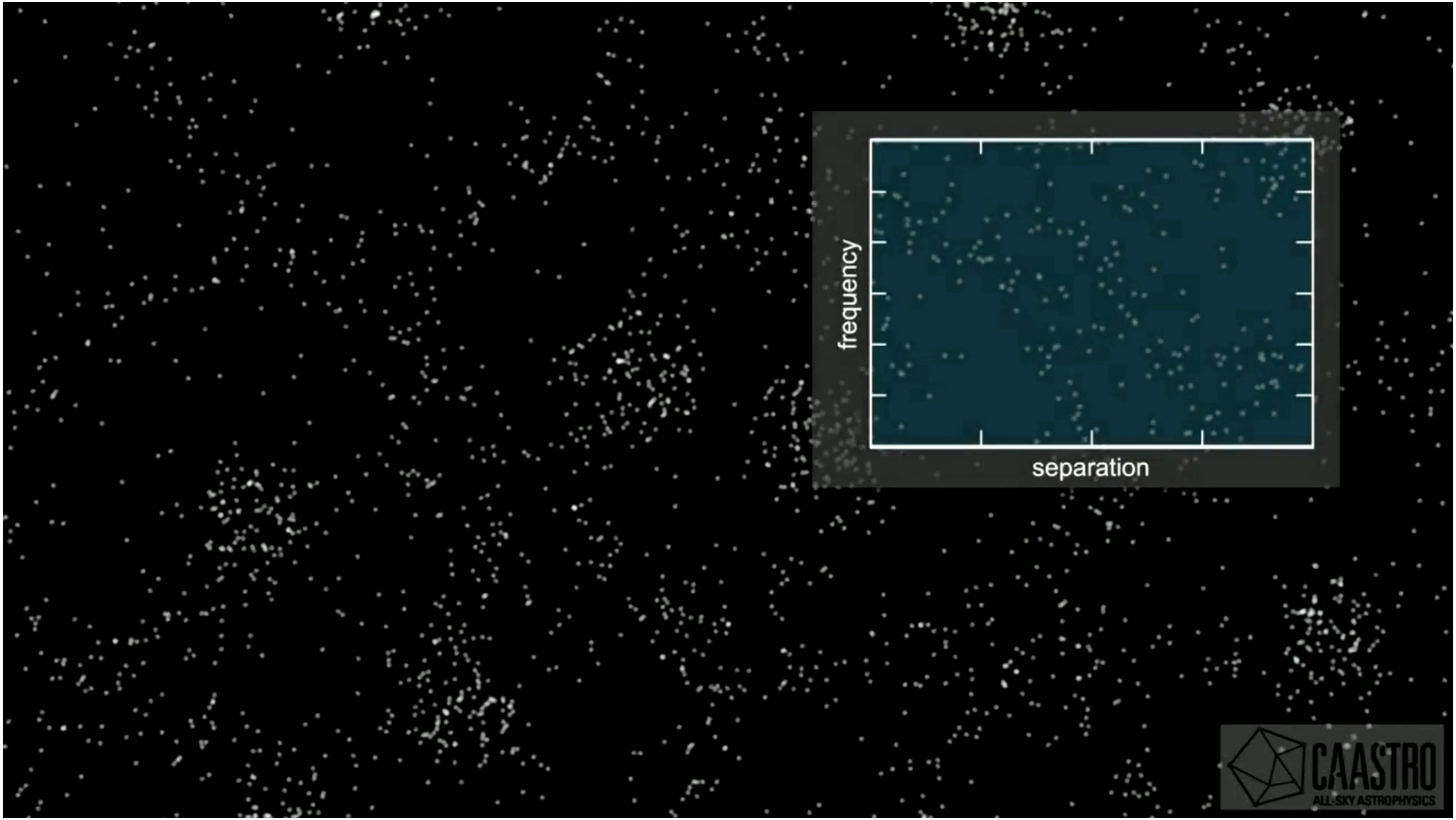
Photons "drag" baryons for ~400,000 years

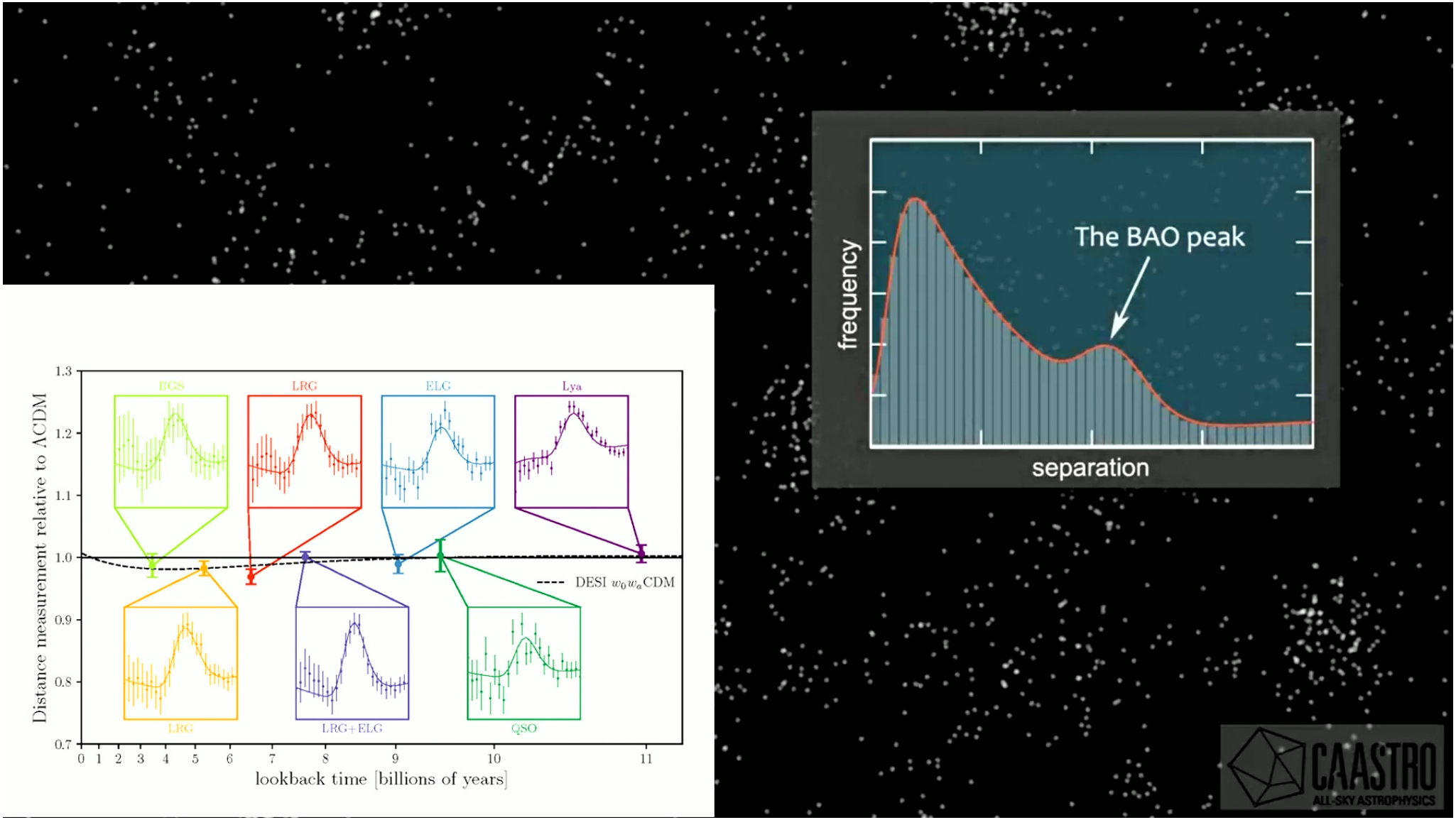
at speed ~ $\frac{c}{\sqrt{3}}\left[\frac{3}{4}\frac{\bar{\rho}_{\rm b}(z)}{\bar{\rho}_{\gamma}(z)}+1\right]^{-1/2}$

$v\,\Delta t$ ~ 300,000 light years ~ 100,000 pc ~ 100 kpc (set by $\Omega_m h^2$, $\Omega_b h^2$)

Expansion of Universe since then stretches this to (3000/2.725) × 100 kpc ~ 100 Mpc


CAASTRO
ALL-SKY ASTROPHYSICS


frequency
separation
CAASTRO
ALL-SKY ASTROPHYSICS

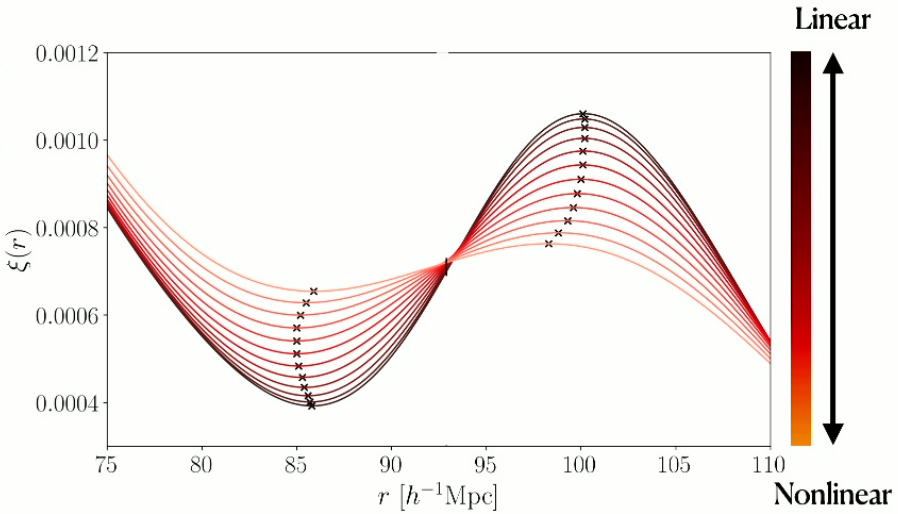

frequency
The BAO peak
separation
BGS
LRG
ELG
Lya
LRG
LRG+ELG
QSO
DESI w_0w_aCDM
Distance measurement relative to ΛCDM
lookback time [billions of years]
CAASTRO
ALL-SKY ASTROPHYSICS

Reconstruction of 2-point correlation function

2PCF of today = Convolution of initial 2PCF with a displacement kernel

$$\xi_{\rm NL}(s) = \int_0^\infty \frac{dr}{\Sigma} \chi_3\left(\frac{r}{\Sigma}|\frac{s}{\Sigma}\right) \xi_{\rm L}(r)$$

smoothing scale/growth of structures



Laguerre Reconstruction: **Nikakhtar** et al. (2021a, 2021b, 2022)

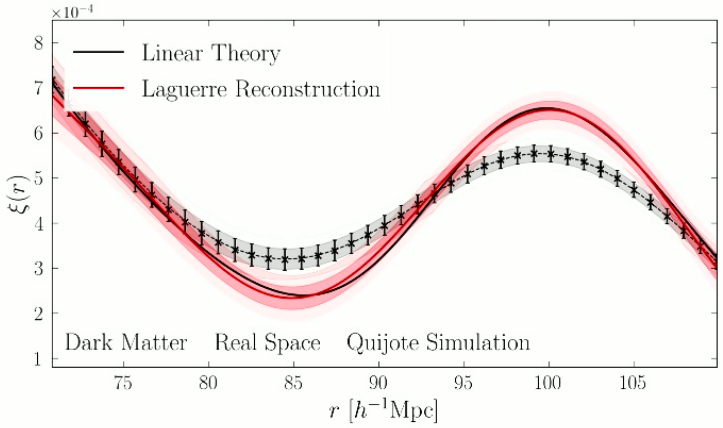
If we assume: $\xi_{\rm L}(r) = \sum_{k=0}^{n} a_k r^k$

$$\xi_{\rm NL}(s) = \sum_{k=0}^{n} c_k \mu_k(x)$$ moments of the kernel

(For specialists: Easy to include mode-coupling)

Navya Uberoi (Yale)

Uberoi, **Nikakhtar**, Padmanabhan et al. (2024 in prep.)



How to reconstruct the full field ?

(not only its 2-point statistics)

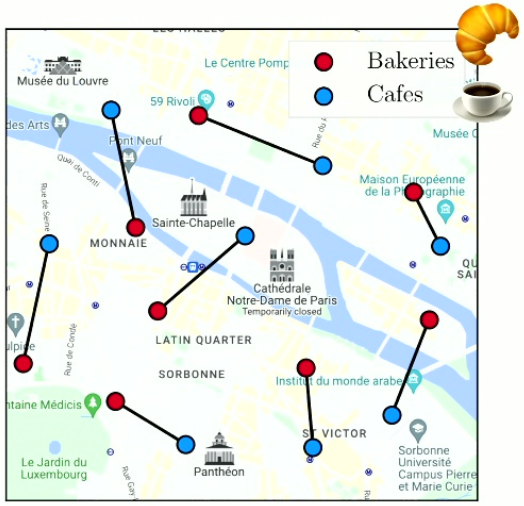
Turning Back Time on Space or how can we move back the evolution of cosmic structures?

Optimal Transport Theory

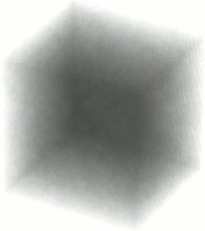
Gaspard Monge
(1746 — 1818)

Leonid Kantorovich
(1912 – 1986)

Yann Brenier
Polar factorization theorem
1991



Initial Condition



Cosmic Evolution

?

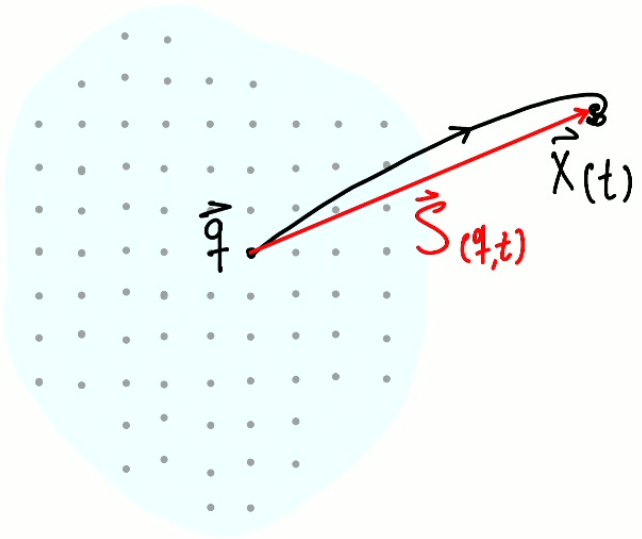
Reconstruction

Final Snapshot

OT: How to map a distribution into another one while preserving weights and minimizing the effort ?

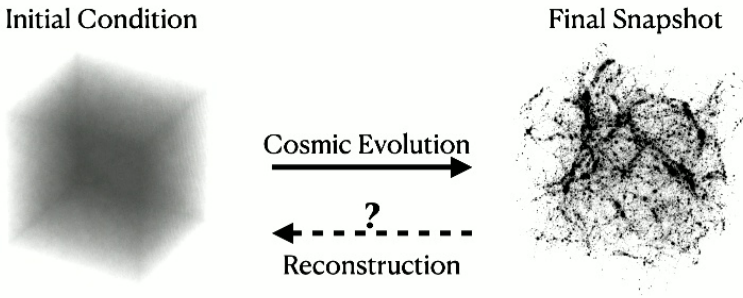
Conservation law

Minimum action principle



Minimum action principle subject to conservation law!

Turning Back Time on Space or how can we move back the evolution of cosmic structures?



Optimal Transport Theory (Assignment Problem)

Mass Conservation

$$\rho_{\rm fin}(\mathbf{x})\mathrm{d}^3\mathbf{x} = \rho_{\rm ini}(\mathbf{q})\mathrm{d}^3\mathbf{q}$$

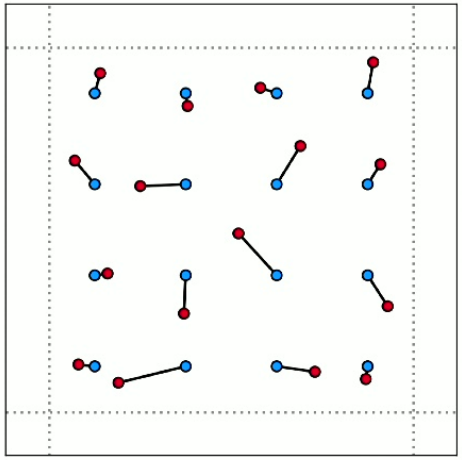
$$\mathbf{q} = \mathbf{x} + \nabla\Theta(\mathbf{x})$$

$$\frac{\rho_{\rm fin}(\mathbf{x})}{\bar{\rho}} = \left|\frac{\mathrm{d}^3\mathbf{q}}{\mathrm{d}^3\mathbf{x}}\right| = \det\left(\frac{\partial q^i}{\partial x^j}\right) = \det[1 + \partial_i\partial_j\Theta(\mathbf{x})]$$

Monge–Ampère equation

Yann Brenier

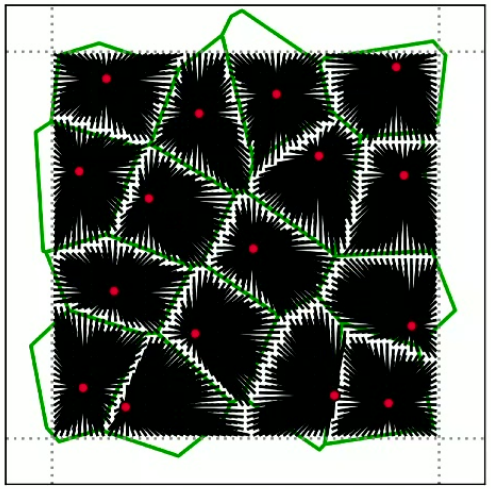
Brenier 1991: *Solving MA is equivalent to the solution of OT with quadratic cost (existence and uniqueness)*



Frisch et al. (2002)
Brenier et al. (2003)

Semi-Discrete Optimal Transport

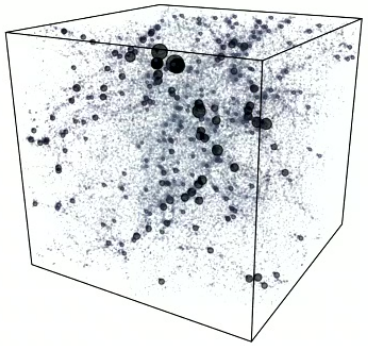
Mostly everything gets worse before it gets better!



Partition space into Laguerre cells

(power diagram / modified Voronoi diagram)

Observed Field



Nikakhtar et al. PRL 129, 251101 (2022)

Optimal Transport Reconstruction

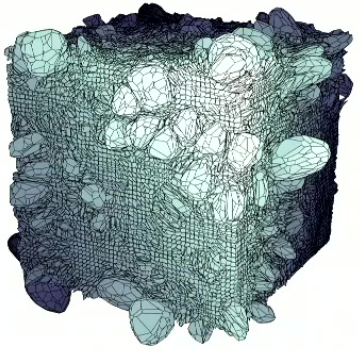
$$\underbrace{V_i^{\psi}}_{\substack{\text{Reconstructed}\\ \text{Patches}}} = \left\{ \mathbf{q} \;\middle|\; \underbrace{\frac{1}{2}|\mathbf{x}_i - \mathbf{q}|^2}_{\text{Kinetic}} - \underbrace{\psi_i}_{\text{Potential}} < \frac{1}{2}|\mathbf{x}_j - \mathbf{q}|^2 - \psi_j,\ \forall j \neq i \right\}$$

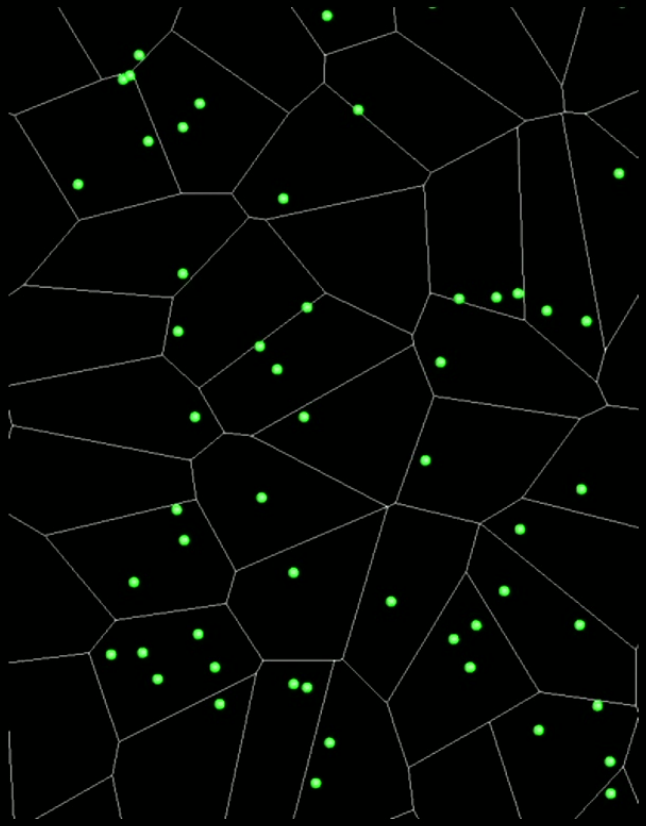
Geometrical Optimization in Mathematics

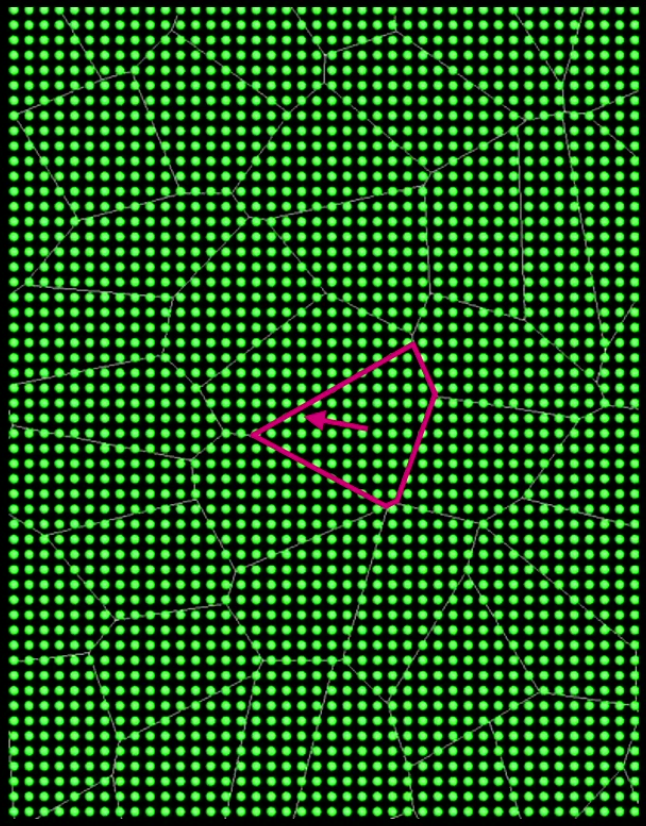
$\equiv$

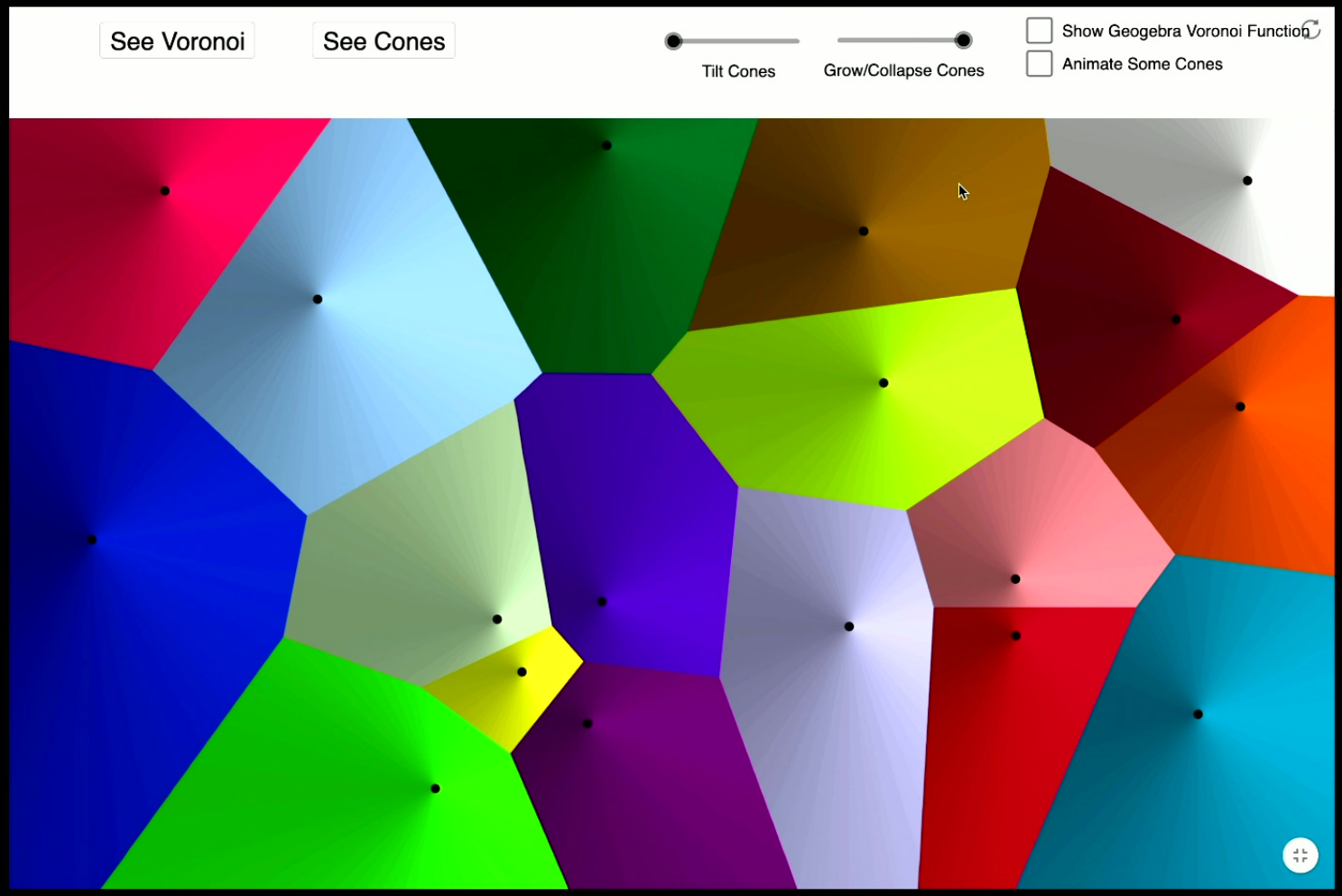
Action Minimization in Physics

Reconstructed Field

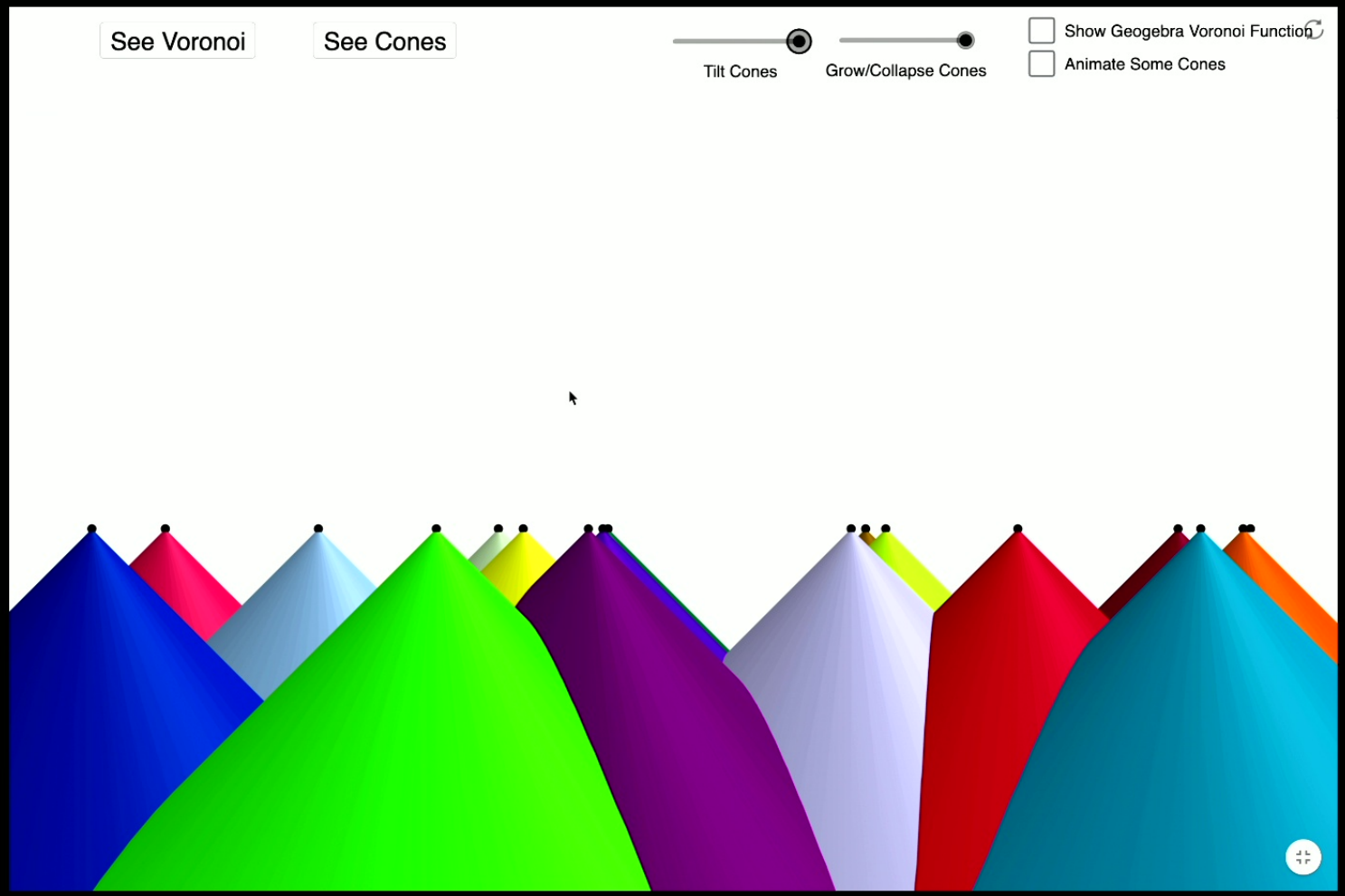








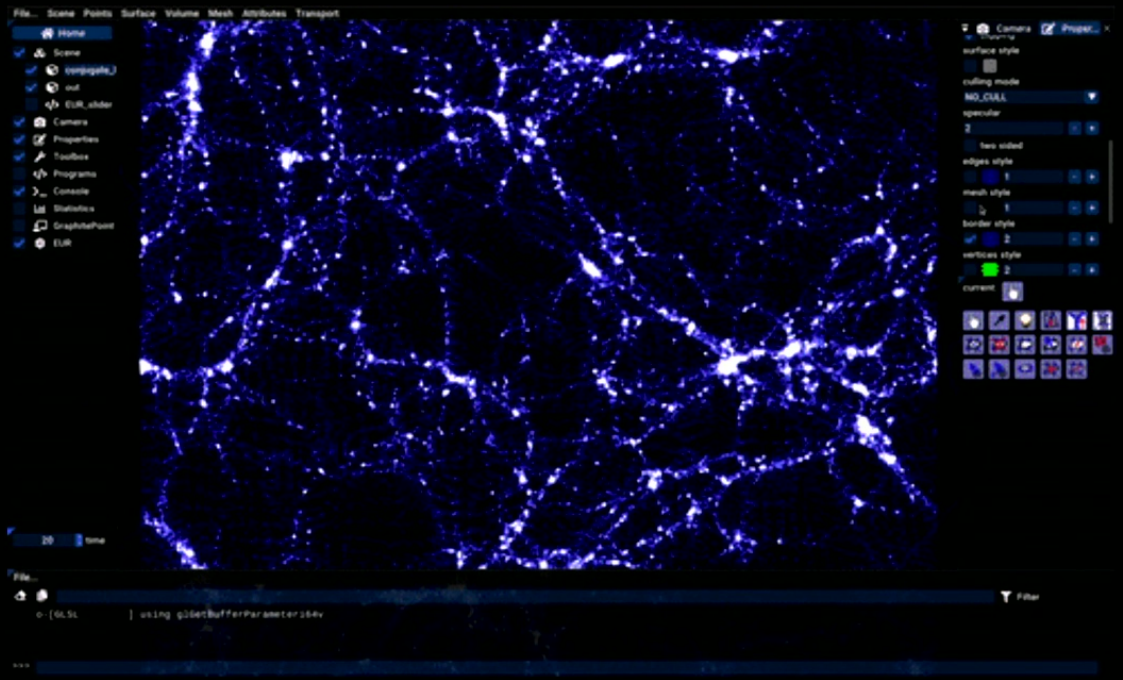
Credit: Tom Walsh (ophysics.com)



Credit: Tom Walsh (ophysics.com)

Geogram: programming library with geometric algorithms

https://github.com/BrunoLevy/geogram



Bruno Levy (Inria-Paris)

Farnik Nikakhtar April 23, 2024 Yale University

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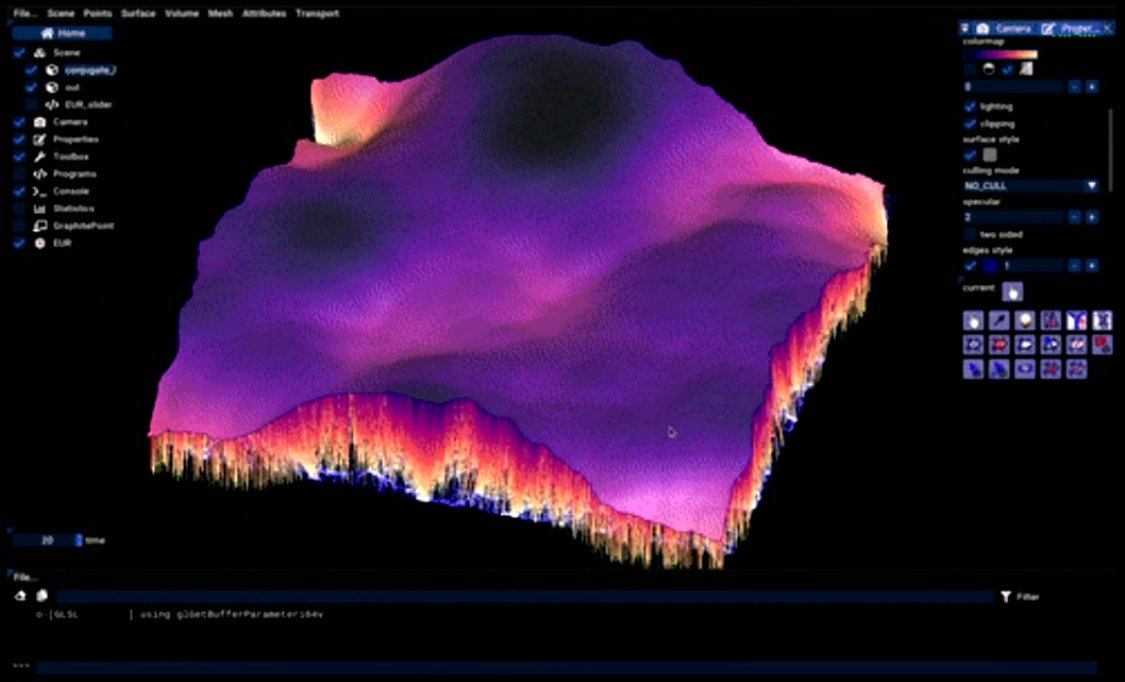
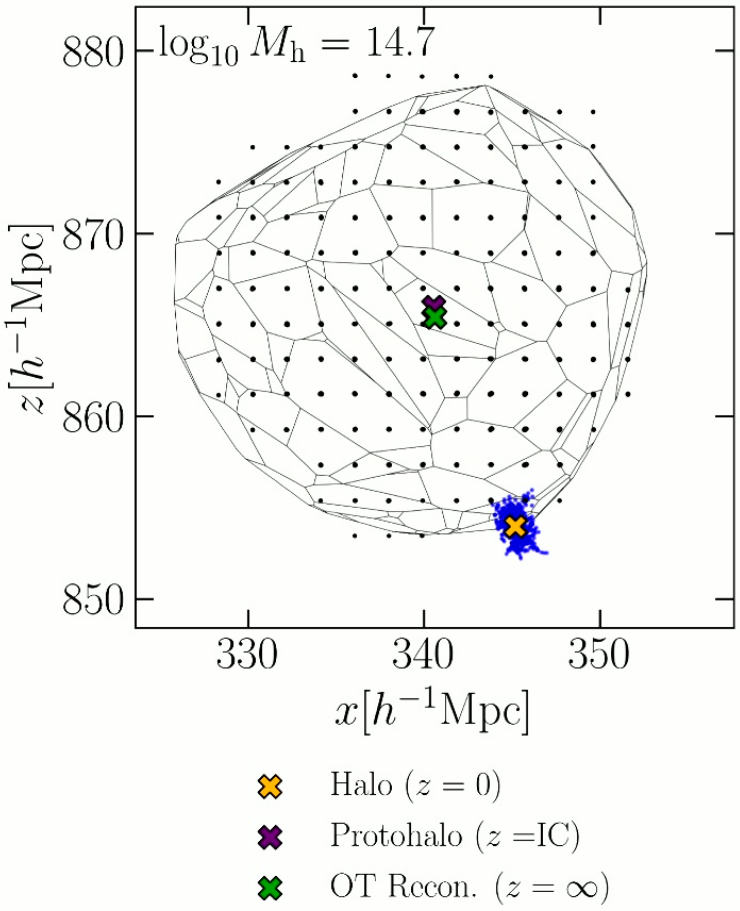
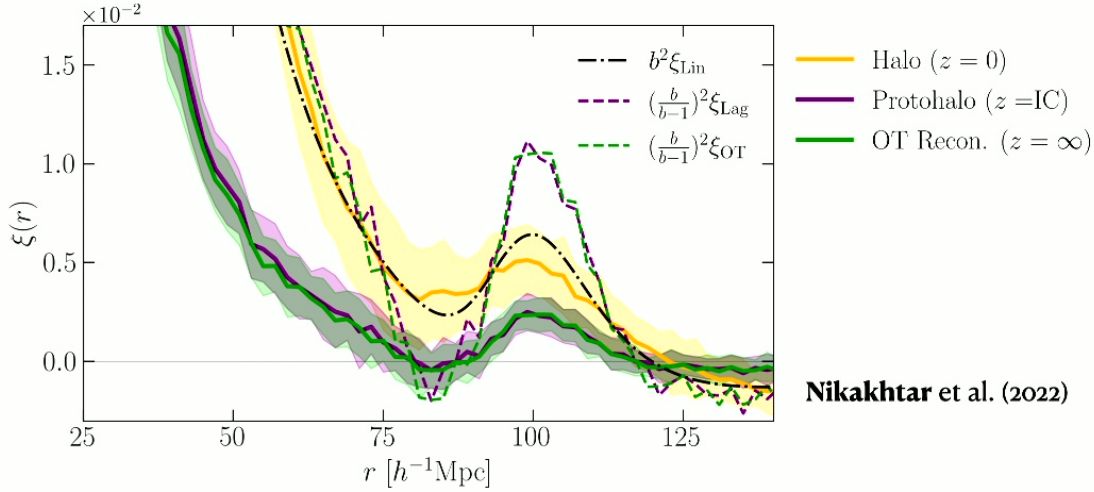


Bruno Levy (Inria-Paris)

Farnik Nikakhtar April 23, 2024 Yale University

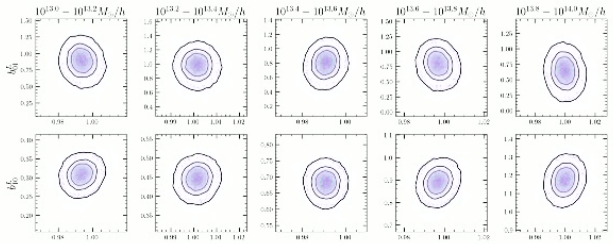
Reconstructing Protohalo Positions + Shapes





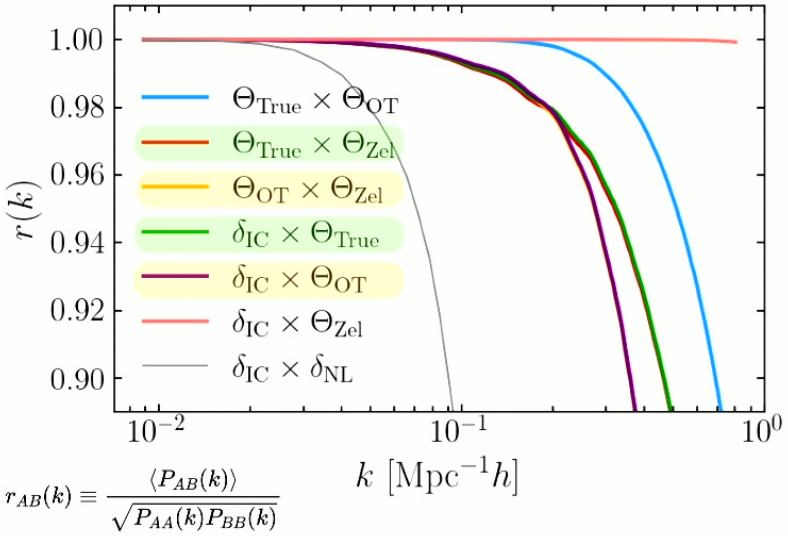
Nikakhtar et al. (2022)

Sasha Gaines (Yale)



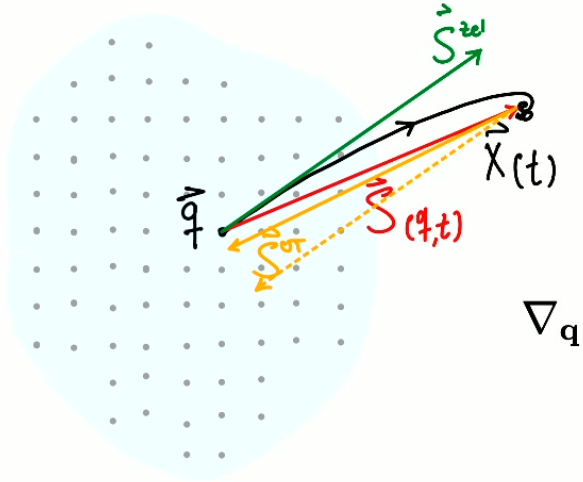
Gaines, **Nikakhtar**, Padmanabhan, Sheth (2024 in prep.)

Displacement Field Analysis

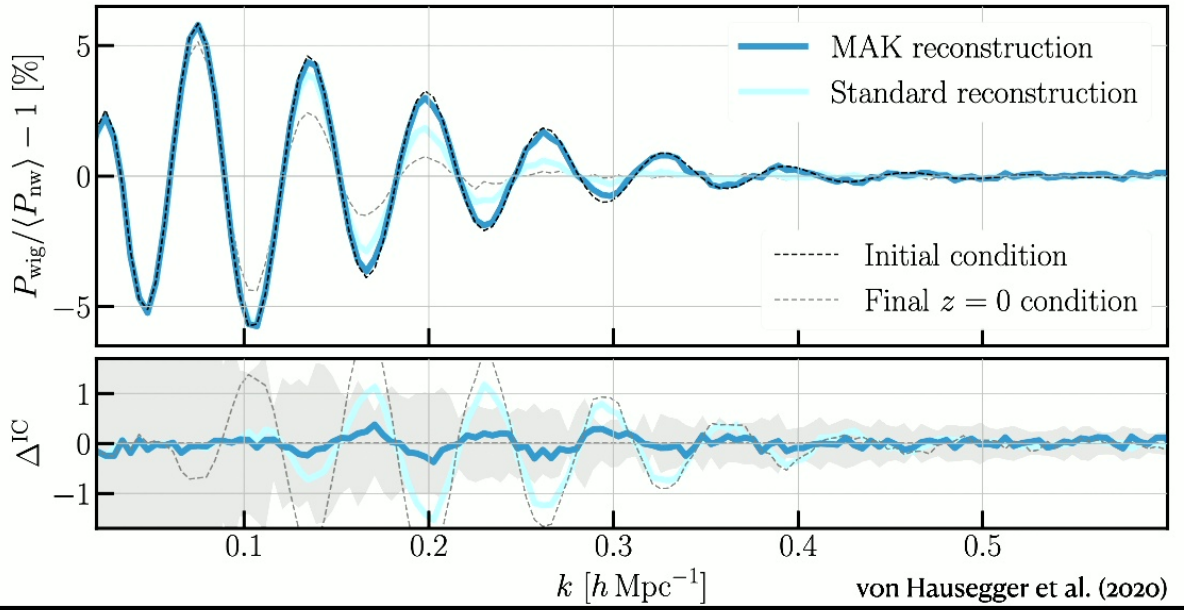


$$r_{AB}(k) \equiv \frac{\langle P_{AB}(k) \rangle}{\sqrt{P_{AA}(k) P_{BB}(k)}}$$

Nikakhtar et al. (2024)

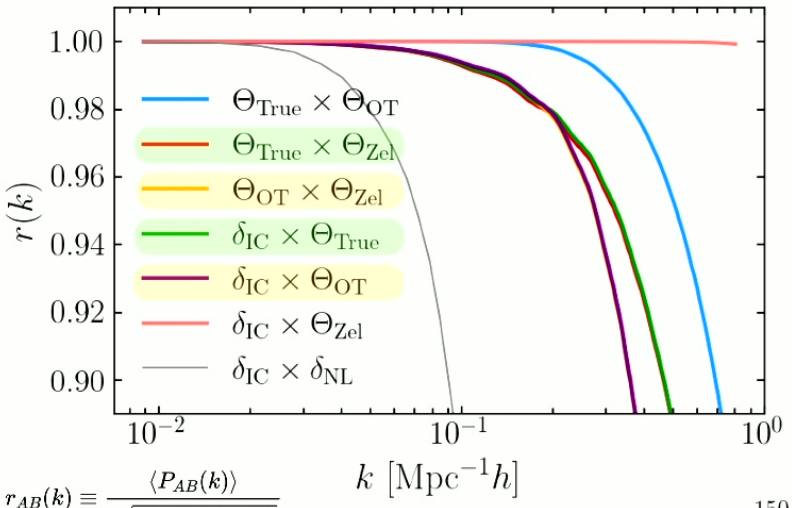


$$\nabla_{\mathbf{q}} \cdot \mathbf{S}^{\rm Zel} = -\delta_{\rm init}$$



von Hausegger et al. (2020)

Displacement Field Analysis



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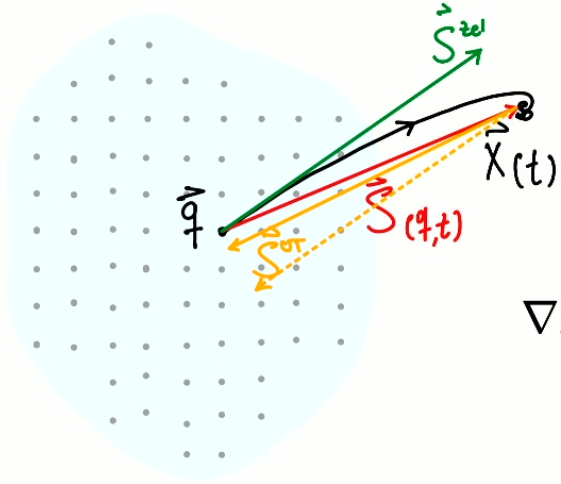
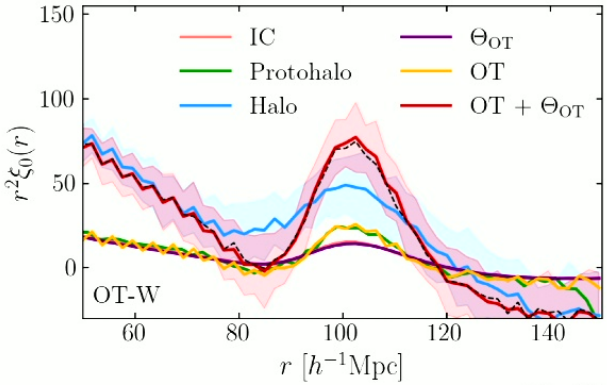
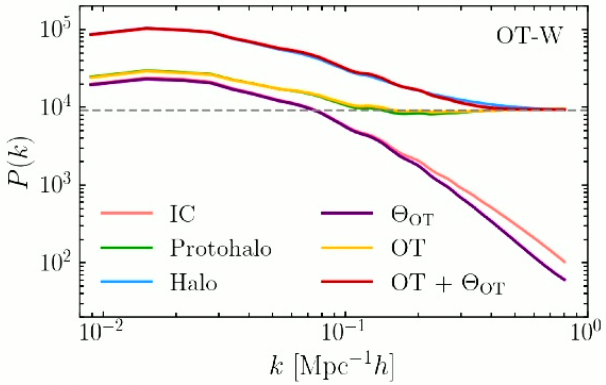


$$\nabla_{\mathbf{q}} \cdot \mathbf{S}^{\rm Zel} = -\delta_{\rm init}$$

Reconstruction of biased tracers:

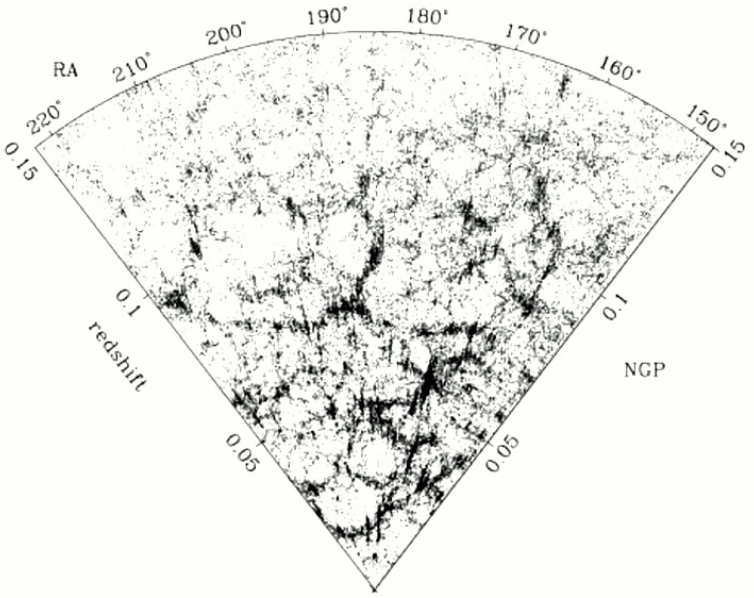
$$\delta_{\rm OT(protohalo)} + \Theta_{\rm OT}$$





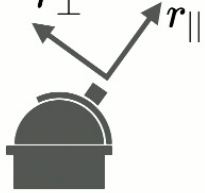
Nikakhtar et al. (2024)

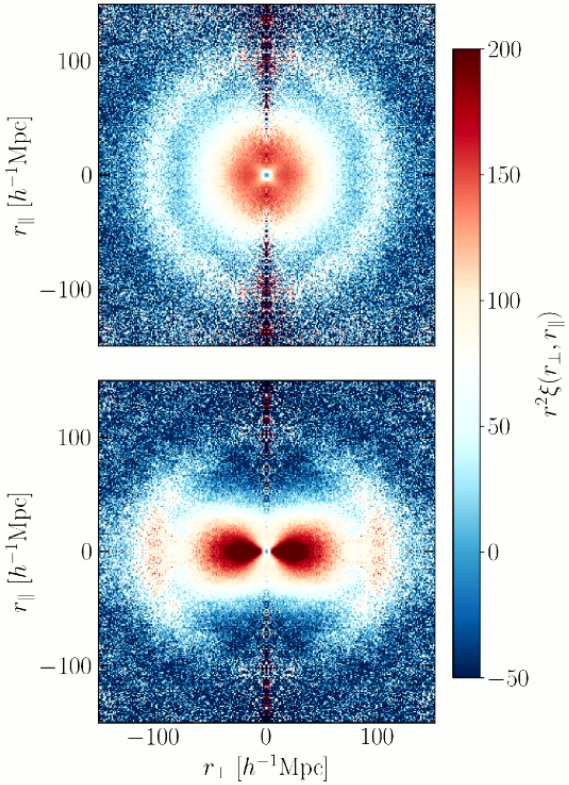
Redshift Space Distortions & Anisotropic OT



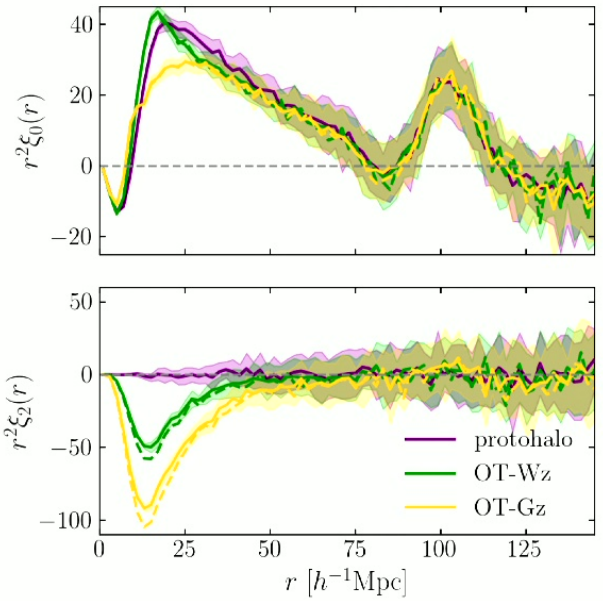
Eke et al. (2003)

$$z_{\rm obs} = z_{\rm true} + \frac{v_{\rm pec}}{c}$$





$$\xi_{(r_{||},\, r_\perp)} = \xi_0(s)\mathcal{L}_0(\mu) + \xi_2(s)\mathcal{L}_2(\mu) + \xi_4(s)\mathcal{L}_4(\mu)$$



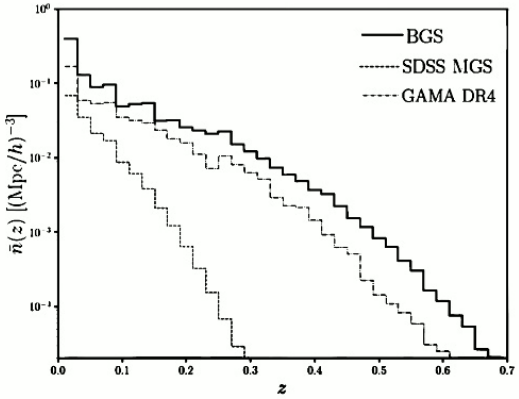
Nikakhtar et al. (2023)

OT Reconstruction on DESI Bright Galaxy Survey

15 million galaxies at $z < 0.6$ in the **dark energy dominated epoch**

magnitude limited sample to $r < 19.5$, fainter sample to $r < 20.175$ **over 14,000 deg^2 footprint**

2 magnitude deeper than SDSS main survey

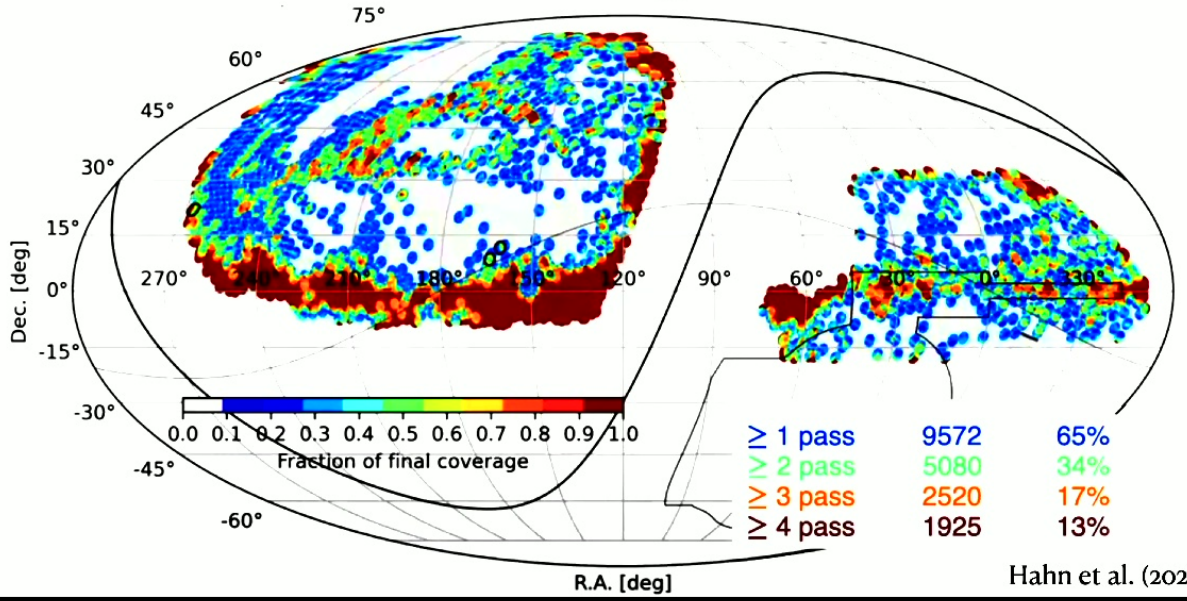


high density sample

more than **an order of magnitude** larger

than previous surveys

in its 1st year, BGS is >33% complete



Hahn et al. (2022)

What else can we learn from reconstructed density & displacement?

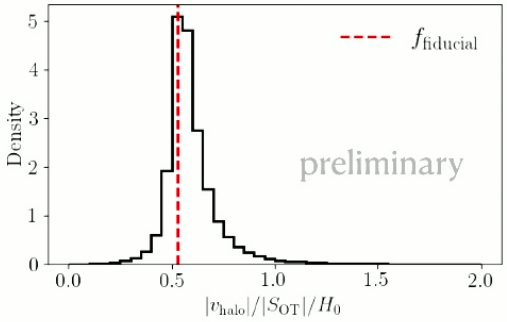
Future Research Avenues

Peculiar Velocity Surveys

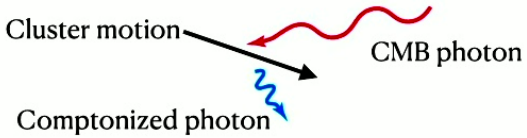
Tully-Fisher / Fundamental Plane relations

$$\boldsymbol{v}^{\rm rec} = afH\,\mathbf{S}^{\rm rec}$$

Growth rate of structures



Baryonic feedback with the kSZ effect

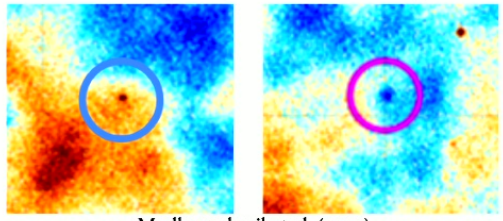


$$\frac{\delta T_{\rm kSZ}(\hat{\boldsymbol{n}})}{T_{\rm CMB}} = -\tau_{\rm gal}\left(\frac{v_{e,r}}{c}\right)$$

Optical depth
integral of gas density along LOS

Electron/halo velocity

cluster moving away cluster moving inward



Madhavacheril et al. (2020)

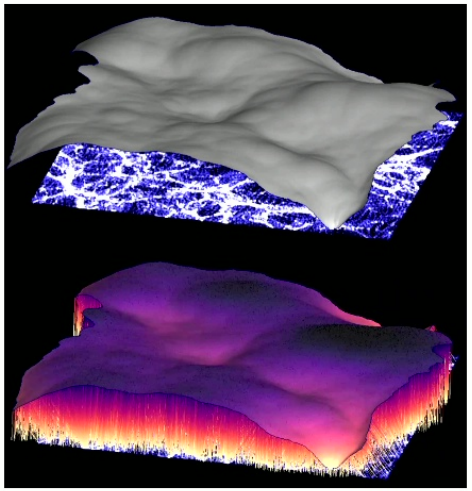
DESI x ACT

Accurate straight-line-evolved sims

$$\mathbf{q} = \mathbf{x} + \nabla\Theta_{\rm OT}(\mathbf{x}) \qquad \mathbf{x} = \mathbf{q} + \nabla\Phi_{\rm OT}(\mathbf{q})$$

$$\Theta_{\rm OT}(\mathbf{x}) = \max_{\mathbf{q}}\ \mathbf{x}\cdot\mathbf{q} - \Phi_{\rm OT}(\mathbf{q})$$

$$\Phi_{\rm OT}(\mathbf{q}) = \max_{\mathbf{x}}\ \mathbf{x}\cdot\mathbf{q} - \Theta_{\rm OT}(\mathbf{x})$$

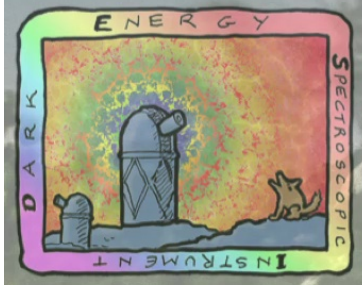


Summary

DESI: Exciting Data Ahead for both *Galaxy Clustering & Milky Way Studies*

Reconstruction is interesting: if we reconstruct the *initial density & displacement* fields, we can understand several other things: BAO scale, growth rate, baryon distribution, ...

Optimal Transport theory is not merely a tool — in our language, we can consider it as: *Minimum action principle subject to conservation law!*



DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Thank you!

For more details:

- Uberoi, **FN**, Padmanabhan et al. (2024 in prep.)
- Gaines, **FN**, Padmanabhan, Sheth (2024 in prep.)
- **FN**, N Padmanabhan, R Sheth, B Lévy, R Mohayaee; PRD submitted, 2024
- **FN**, N Padmanabhan, R Sheth, B Lévy, R Mohayaee; PRD, 108 (8), 083534
- **FN**, RK Sheth, B Lévy, R Mohayaee; PRL, 129 (25), 251101
- **FN**, RK Sheth, I Zehavi; PRD 105 (4), 043536
- **FN**, RK Sheth, I Zehavi; PRD 104 (6), 063504
- **FN**, RK Sheth, I Zehavi; PRD 104, 043530