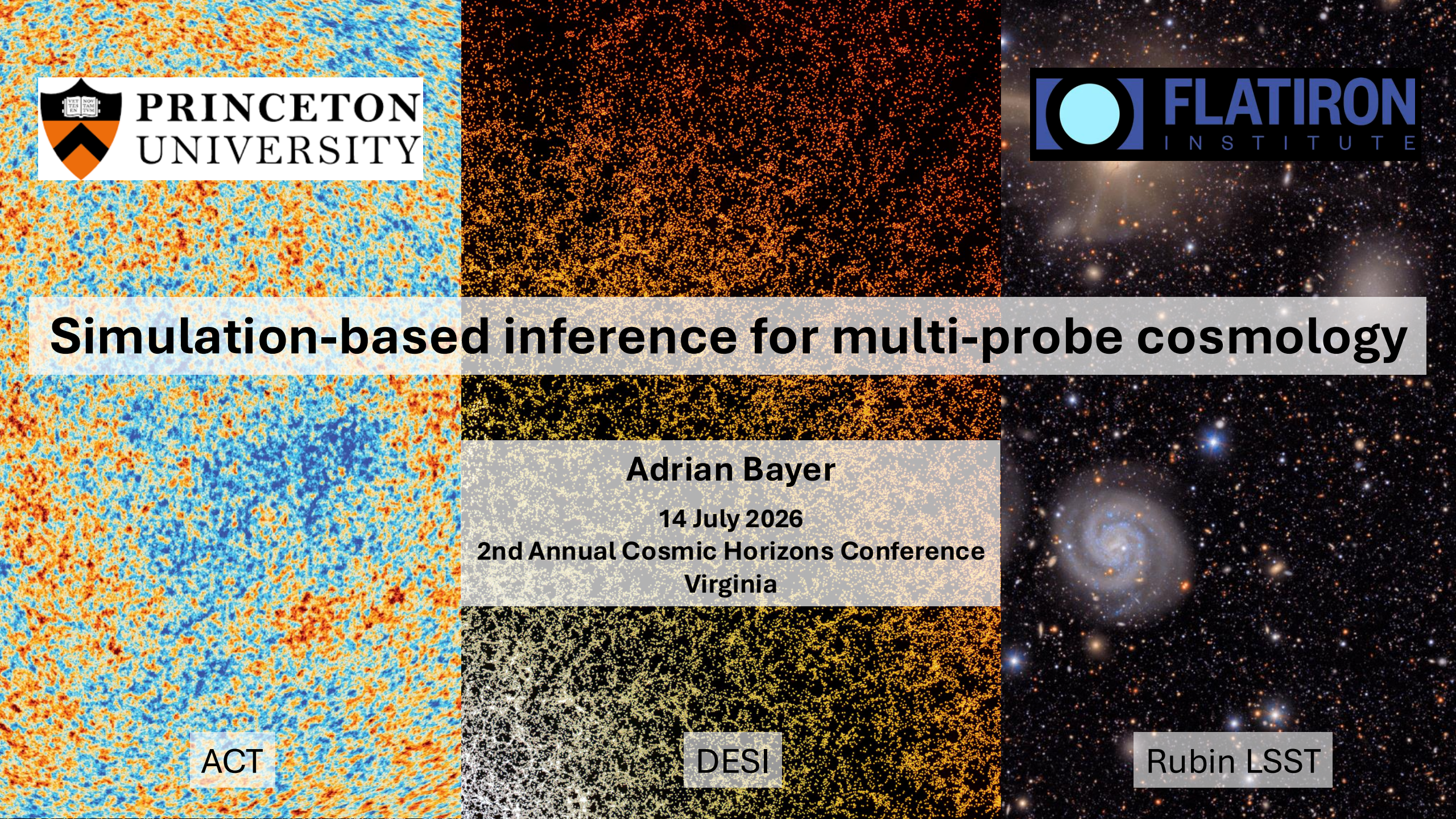


Simulation-based inference for multi-probe cosmology

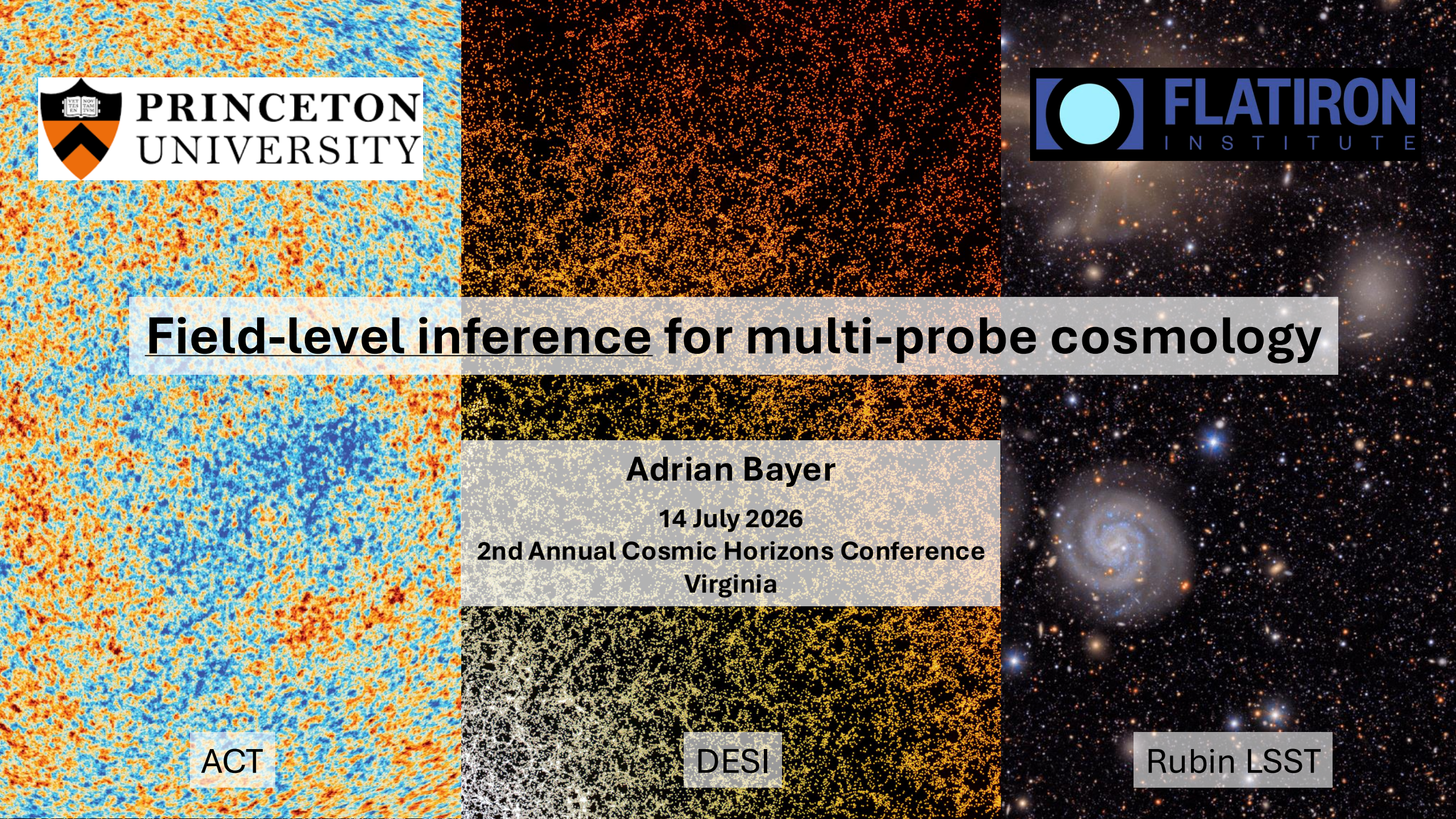
Adrian Bayer

14 July 2026
2nd Annual Cosmic Horizons Conference
Virginia

ACT

DESI

Rubin LSST



Field-level inference for multi-probe cosmology

Adrian Bayer

14 July 2026
2nd Annual Cosmic Horizons Conference
Virginia

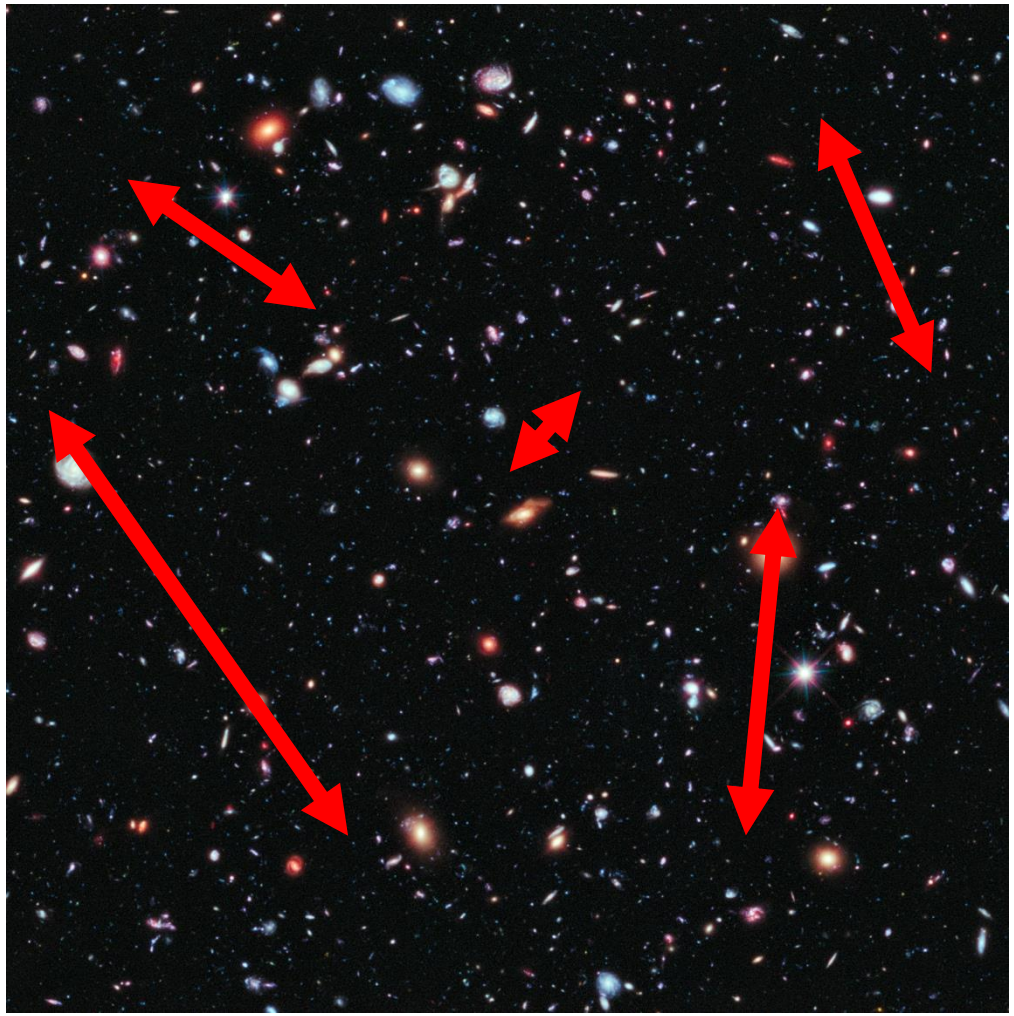
ACT

DESI

Rubin LSST

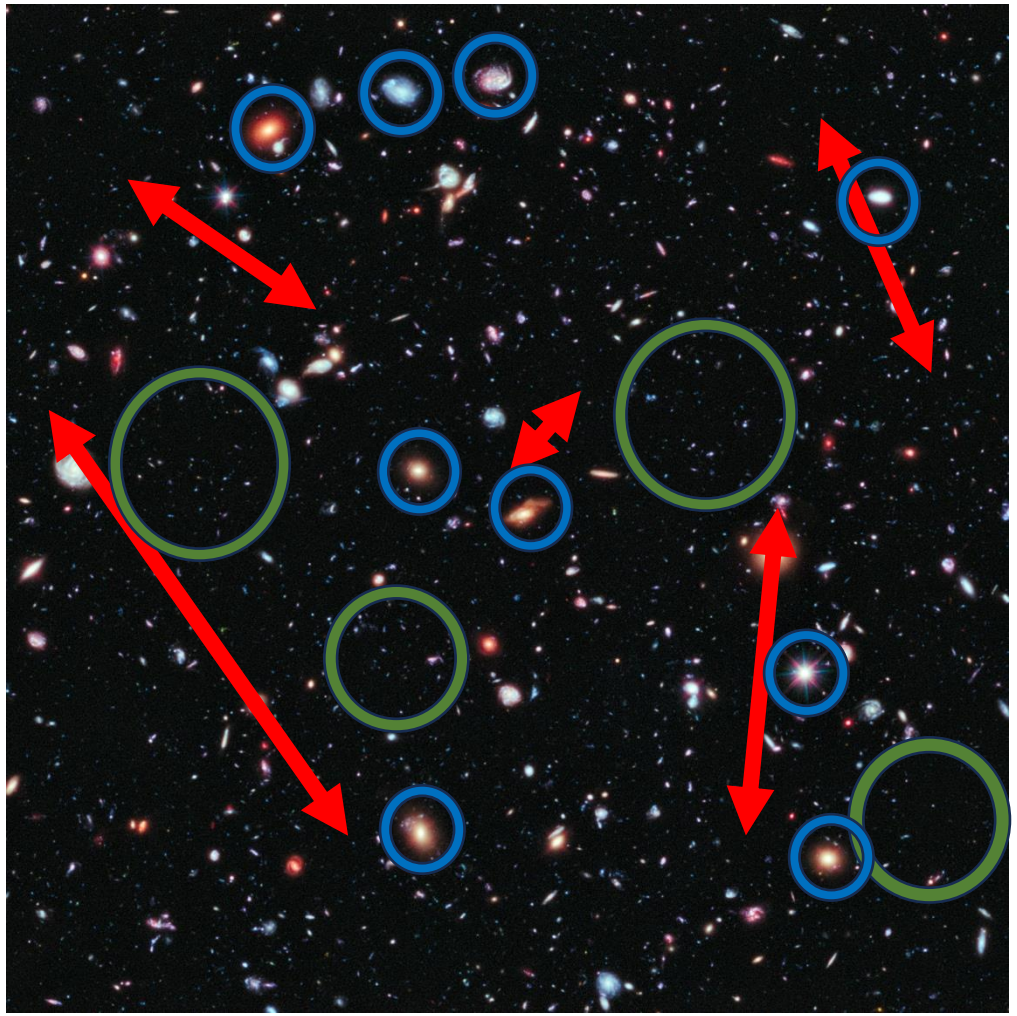
Traditional cosmology uses 2-pt information

but this is no longer optimal as we probe small, non-linear, scales



Higher-order statistics

can provide information beyond the 2-pt



Halo Mass Function

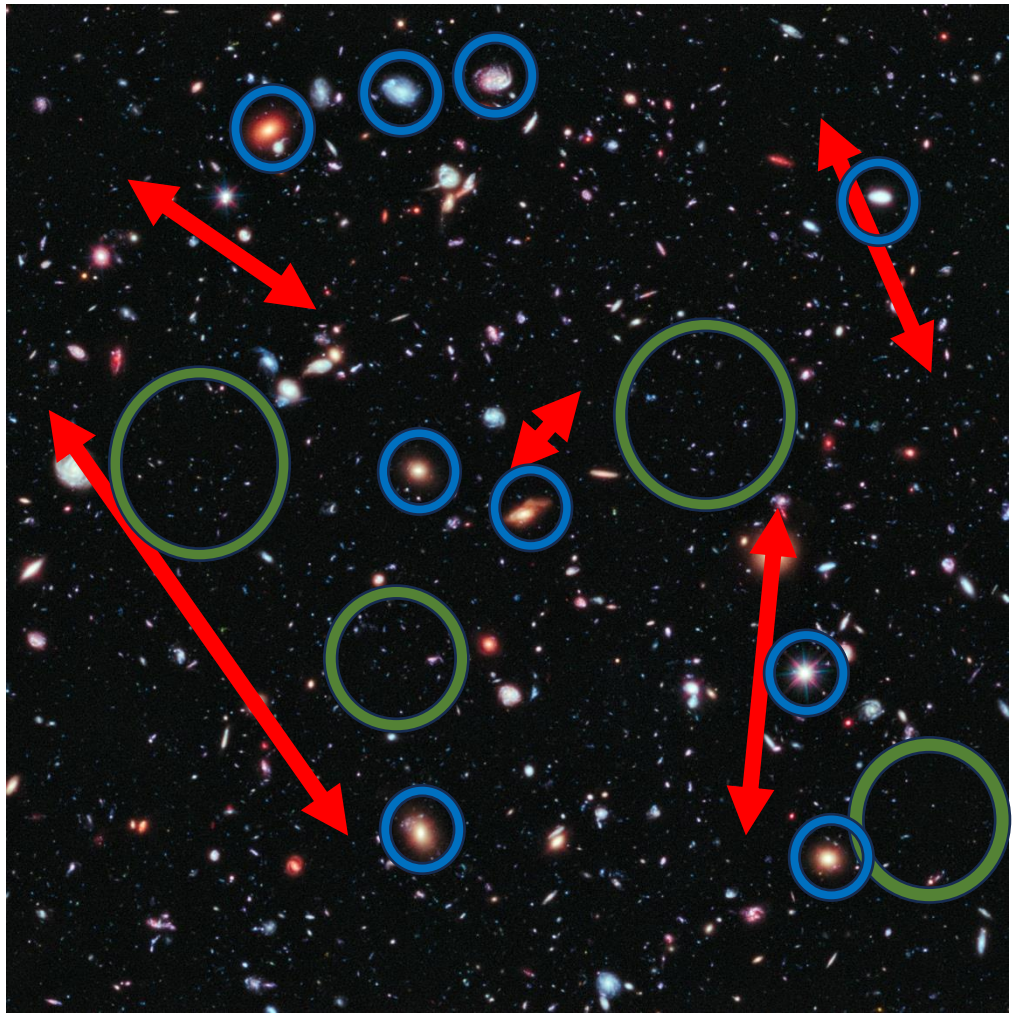
2-pt correlation

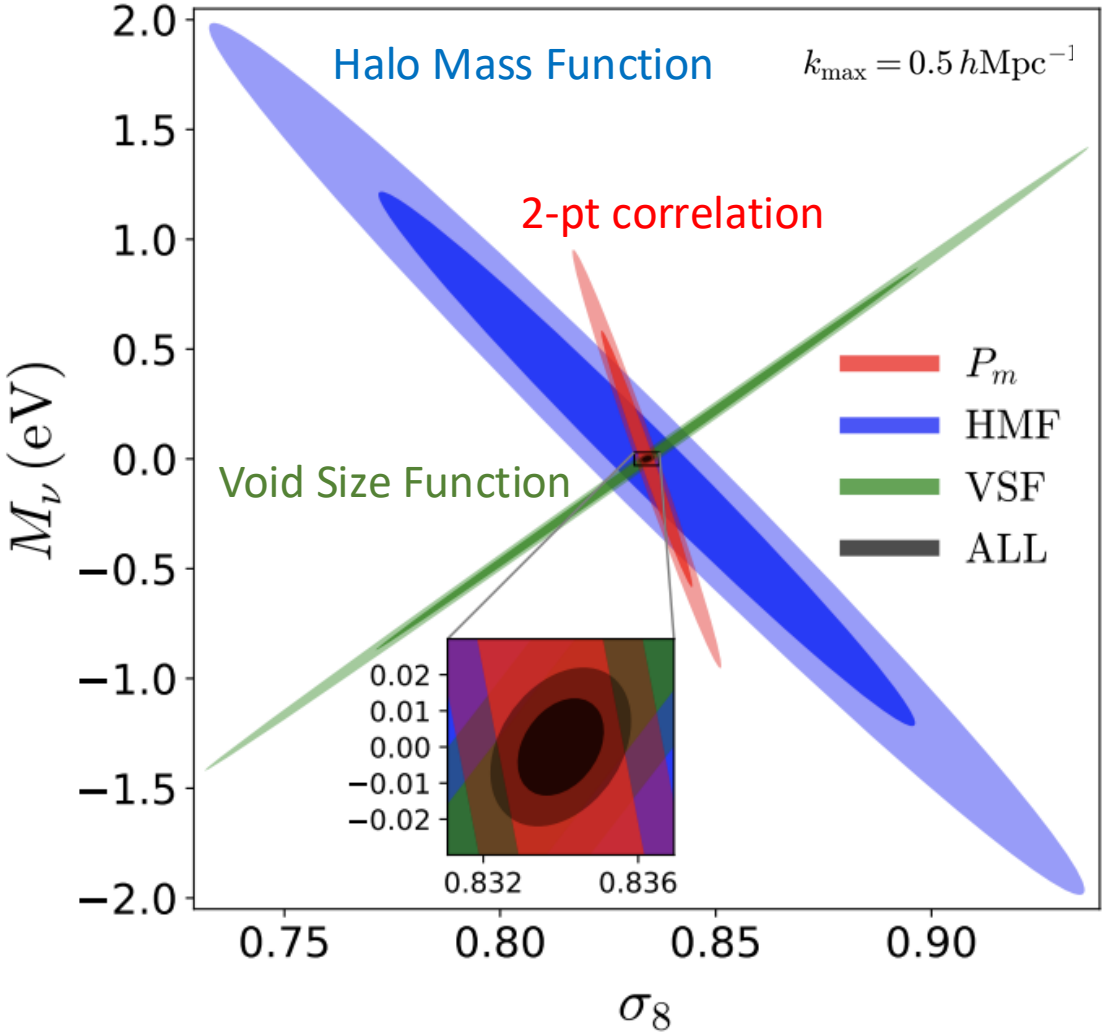
Void Size Function

Bayer+2021

Higher-order statistics

can provide information beyond the 2-pt

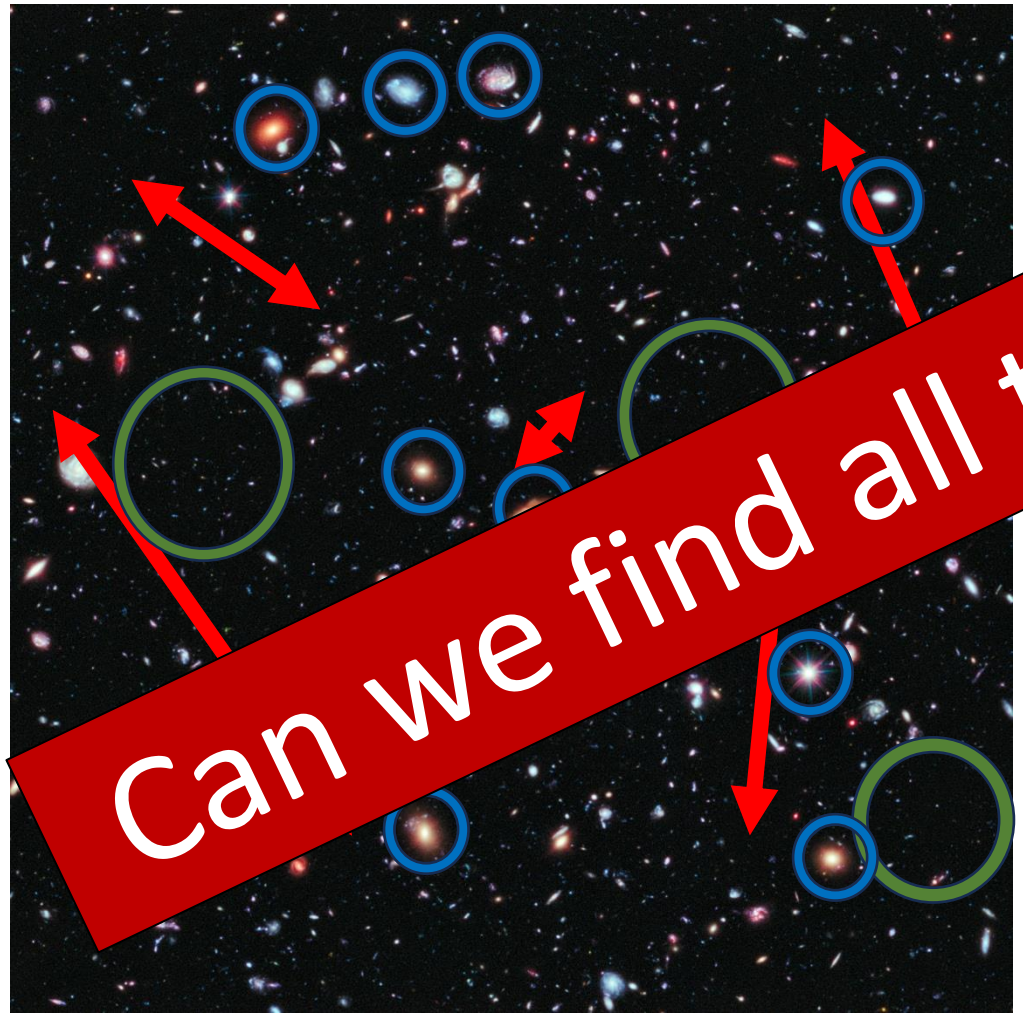




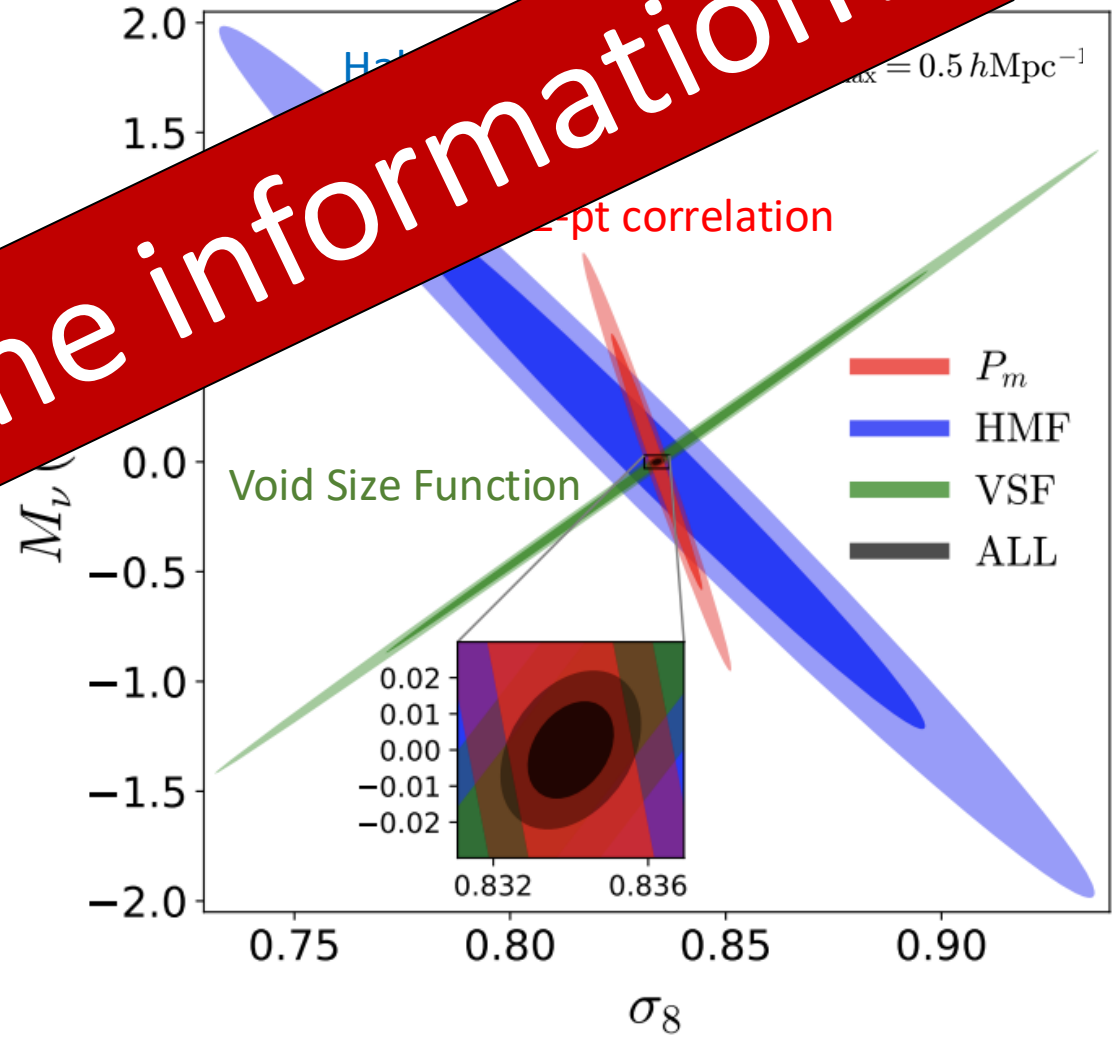
Bayer+2021

Higher-order statistics

can provide information beyond the 2-pt



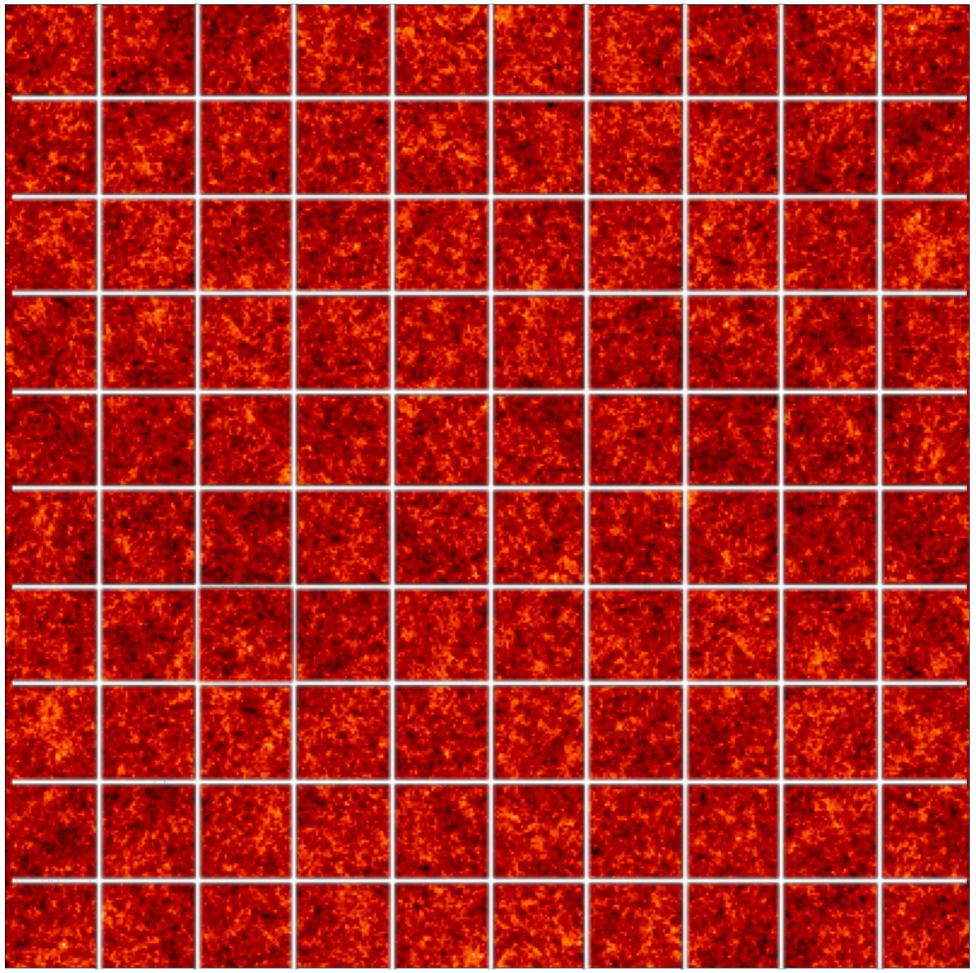
Can we find all the information?



Bayer+2021

Field-Level Inference

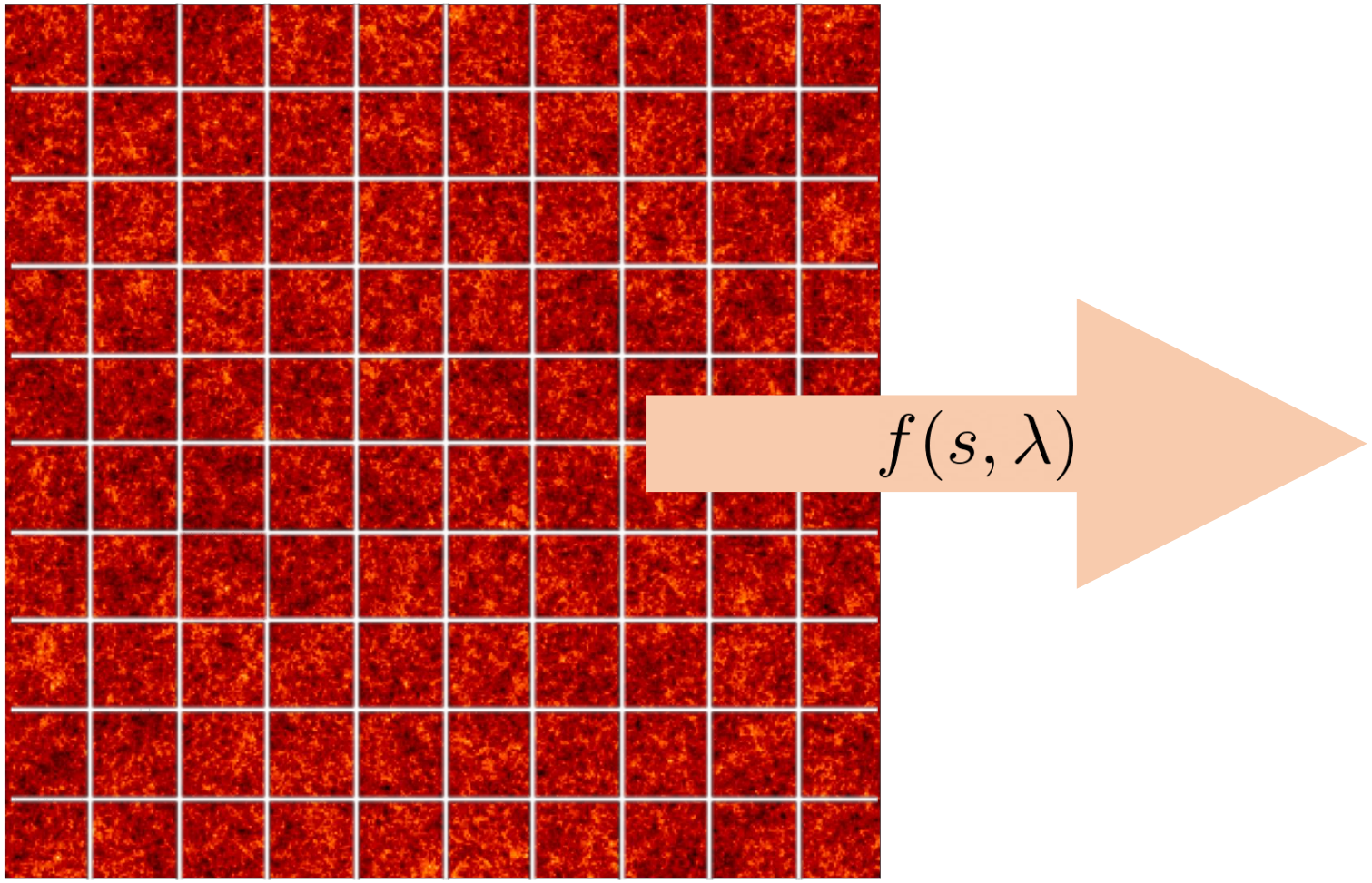
INITIAL s



Kitaura & Ensslin (2007), Jasche & Wandelt (2012), Jasche & Lavaux (2017), Seljak et al. (2017), Schmidt et al. (2020), …

Field-Level Inference

INITIAL s $\lambda = \{\Lambda\mathrm{CDM}, M_\nu, w, \dots\}$

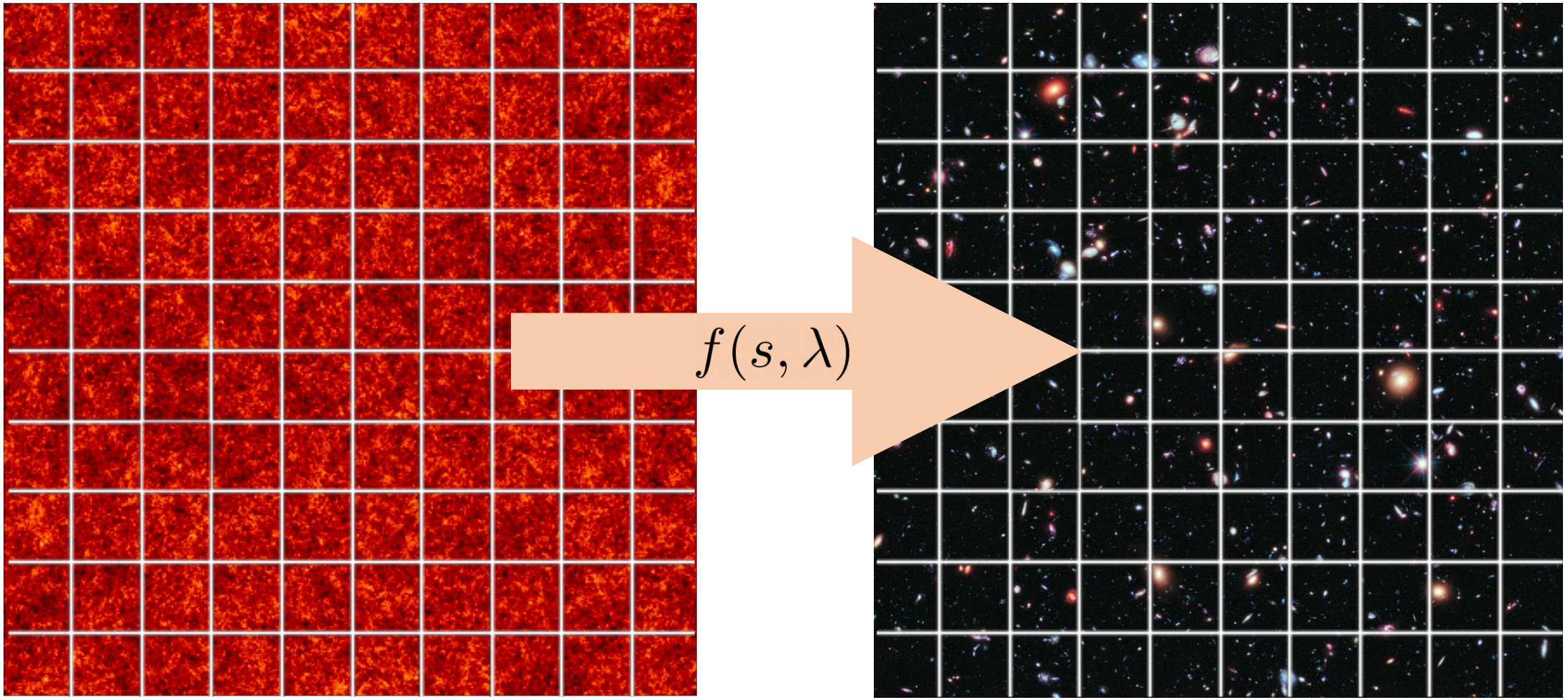


$f(s, \lambda)$

Kitaura & Ensslin (2007), Jasche & Wandelt (2012), Jasche & Lavaux (2017), Seljak et al. (2017), Schmidt et al. (2020), …

Field-Level Inference

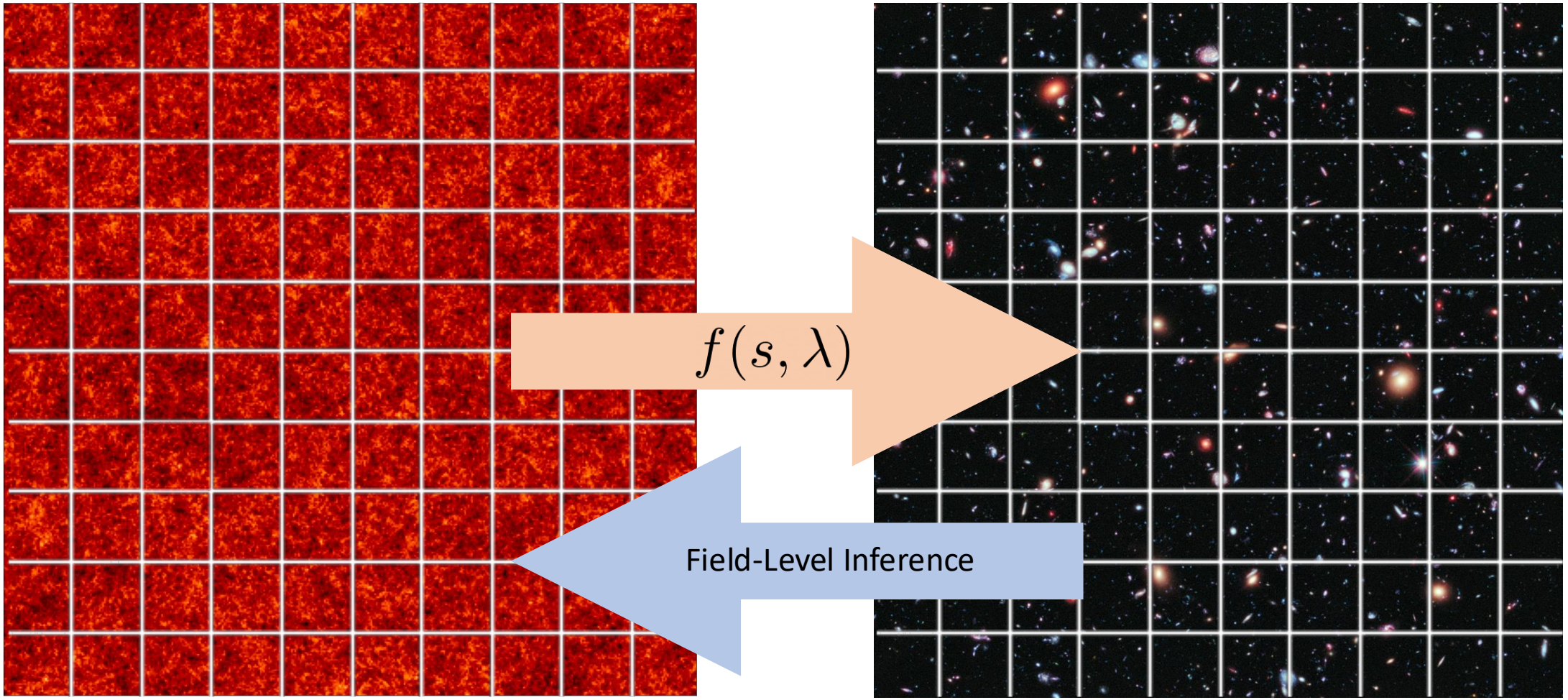
INITIAL s $\lambda = \{\Lambda\mathrm{CDM}, M_\nu, w, \dots\}$ FINAL



Kitaura & Ensslin (2007), Jasche & Wandelt (2012), Jasche & Lavaux (2017), Seljak et al. (2017), Schmidt et al. (2020), …

Field-Level Inference

INITIAL s $\lambda = \{\Lambda\mathrm{CDM}, M_\nu, w, \dots\}$ FINAL



Kitaura & Ensslin (2007), Jasche & Wandelt (2012), Jasche & Lavaux (2017), Seljak et al. (2017), Schmidt et al. (2020), …

Field-Level Inference

Given field data d and forward model f infer
initial modes s and cosmological parameters λ

$$-2\log P(s,\lambda|d) = \sum \left[\frac{|d - f(s,\lambda)|^2}{N} + \frac{|s|^2}{\mathcal{P}(\lambda)} \right]_{\vec{k}}$$

likelihood prior

CHALLENGE: Multimillion dimensional parameter space!

Explicit Field-Level Inference

- **Optimization**

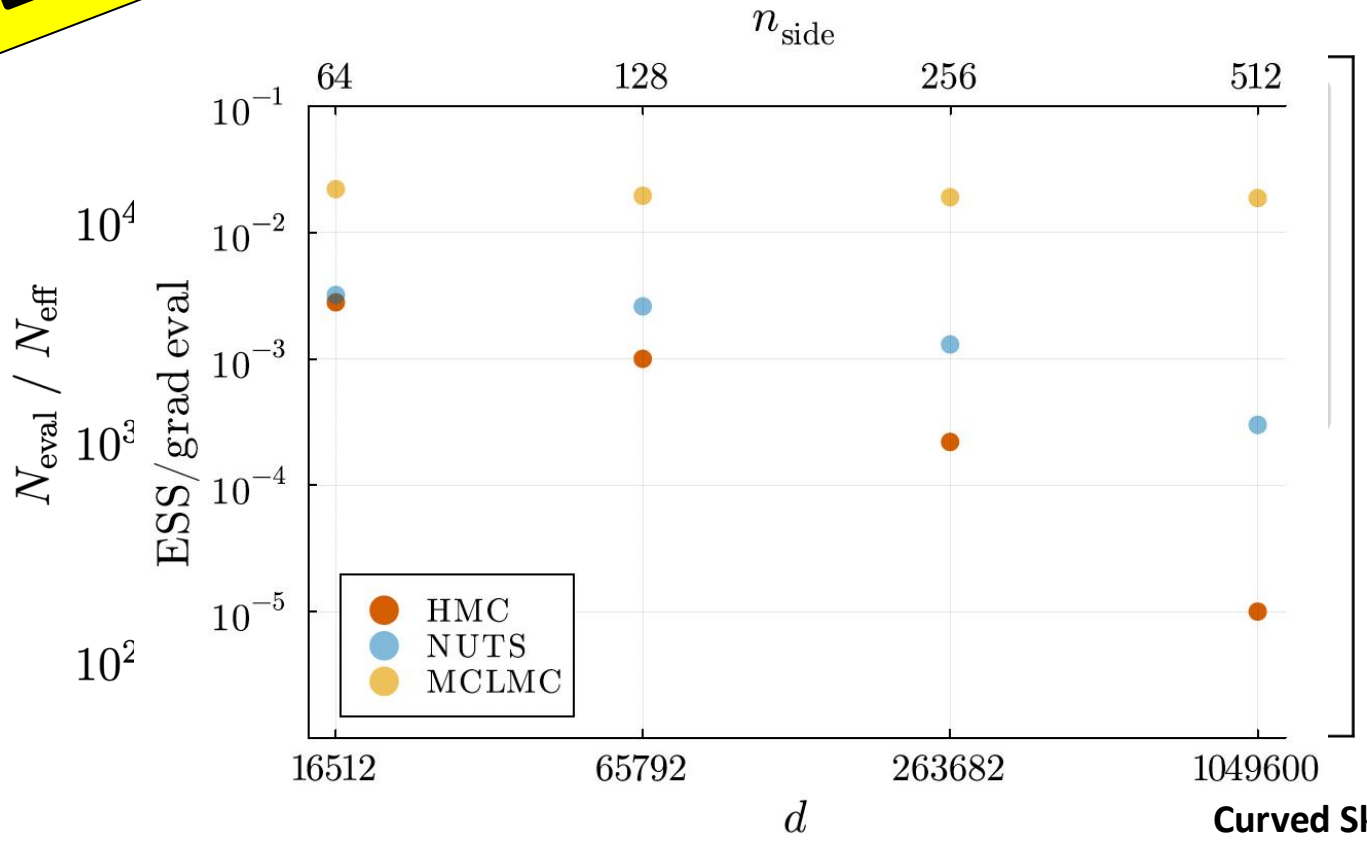
Explicit Field-Level Inference

- **Optimization**
- **Monte Carlo Sampling**

Explicit Field-Level I[illegible]ce

- **Optimization**
- **Monte C[illegible]ing**

CHALLENGE: What's the likelihood?



Curved Sky CMB ✅ Crespi, …, Bayer + (2025)
Biased Tracers ✅ Simon-Onfroy + (2025)
Bayer, Seljak, Modi (2023)

Explicit Field-Level Inference

- **Optimization**
- **Monte Carlo Sampling**

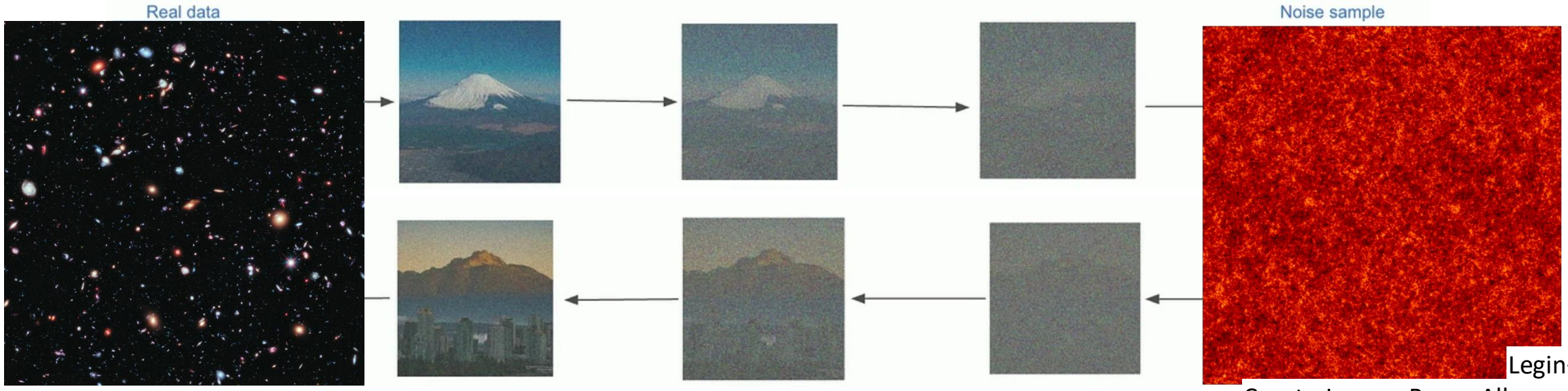
Implicit Field-Level Inference

Explicit Field-Level Inference

- **Optimization**
- **Monte Carlo Sampling**

Implicit Field-Level Inference

- **Diffusion Models / Stochastic Interpolants**



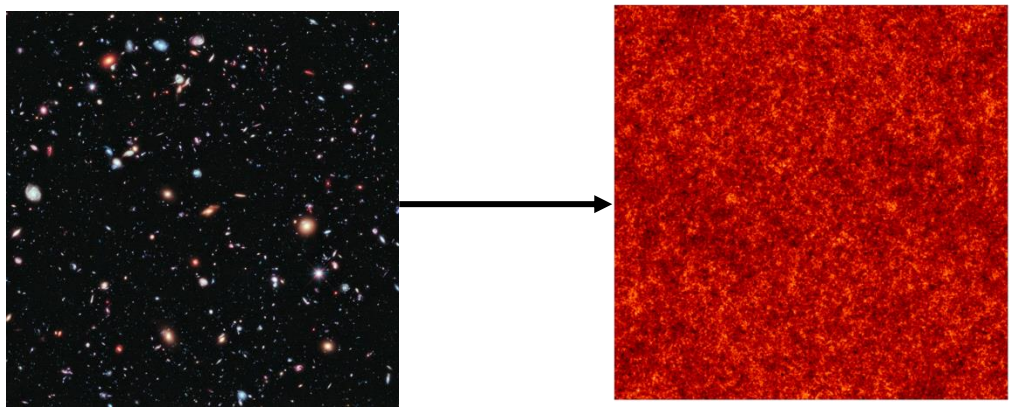
Legin+ (2023)
Cuesta-Lazaro, Bayer, Albergo+ (2024)

Explicit Field-Level Inference

- **Optimization**
- **Monte Carlo Sampling**

Implicit Field-Level Inference

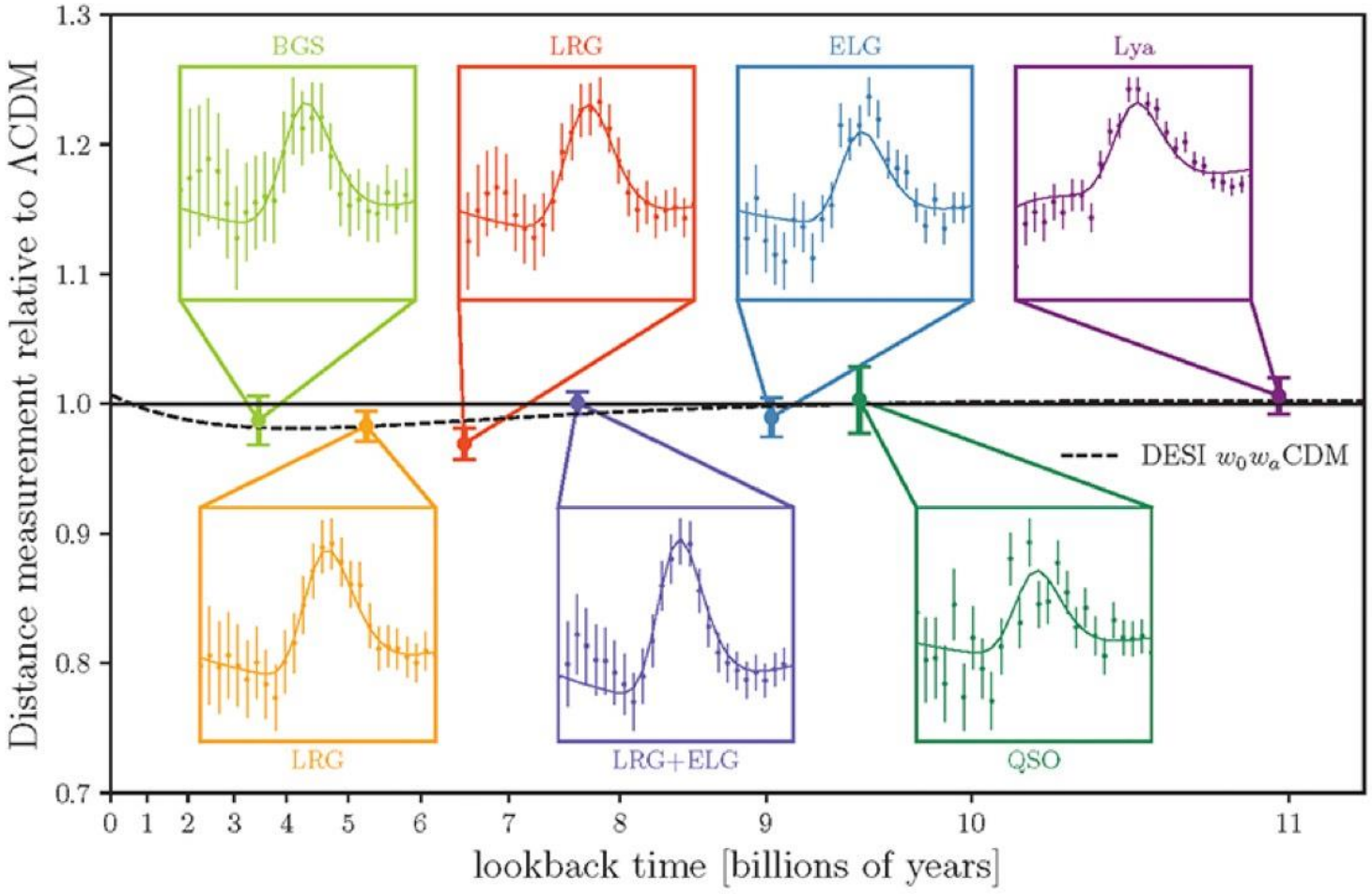
- **Diffusion Models / Stochastic Interpolants**
- **CNN as point estimator**



Liam Parker
Graduate Student
(UC Berkeley)

Parker, Bayer, Seljak (2025)

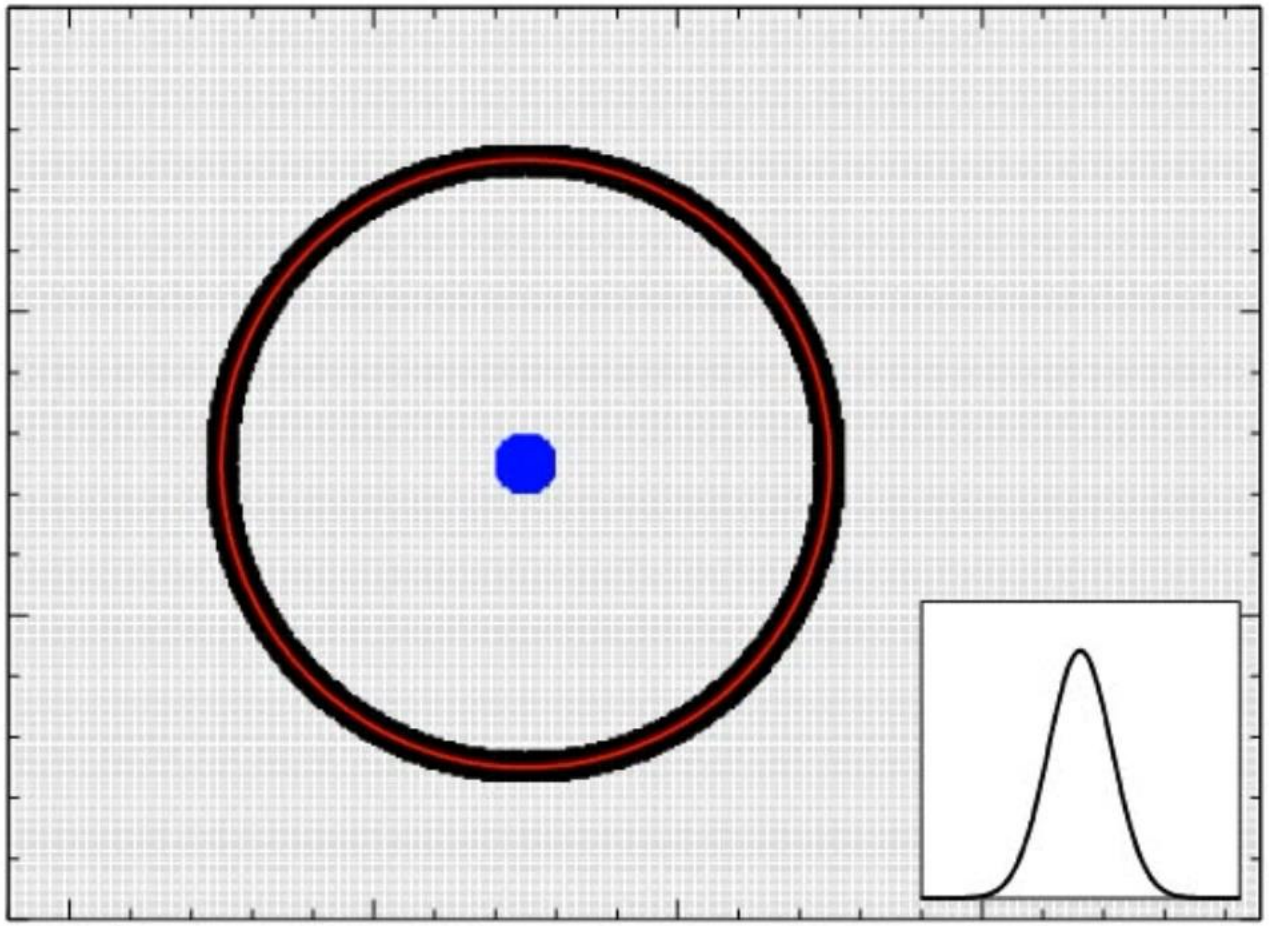
Baryon Acoustic Oscillations (BAO)



DESI DR2 (2025)

BAO Reconstruction

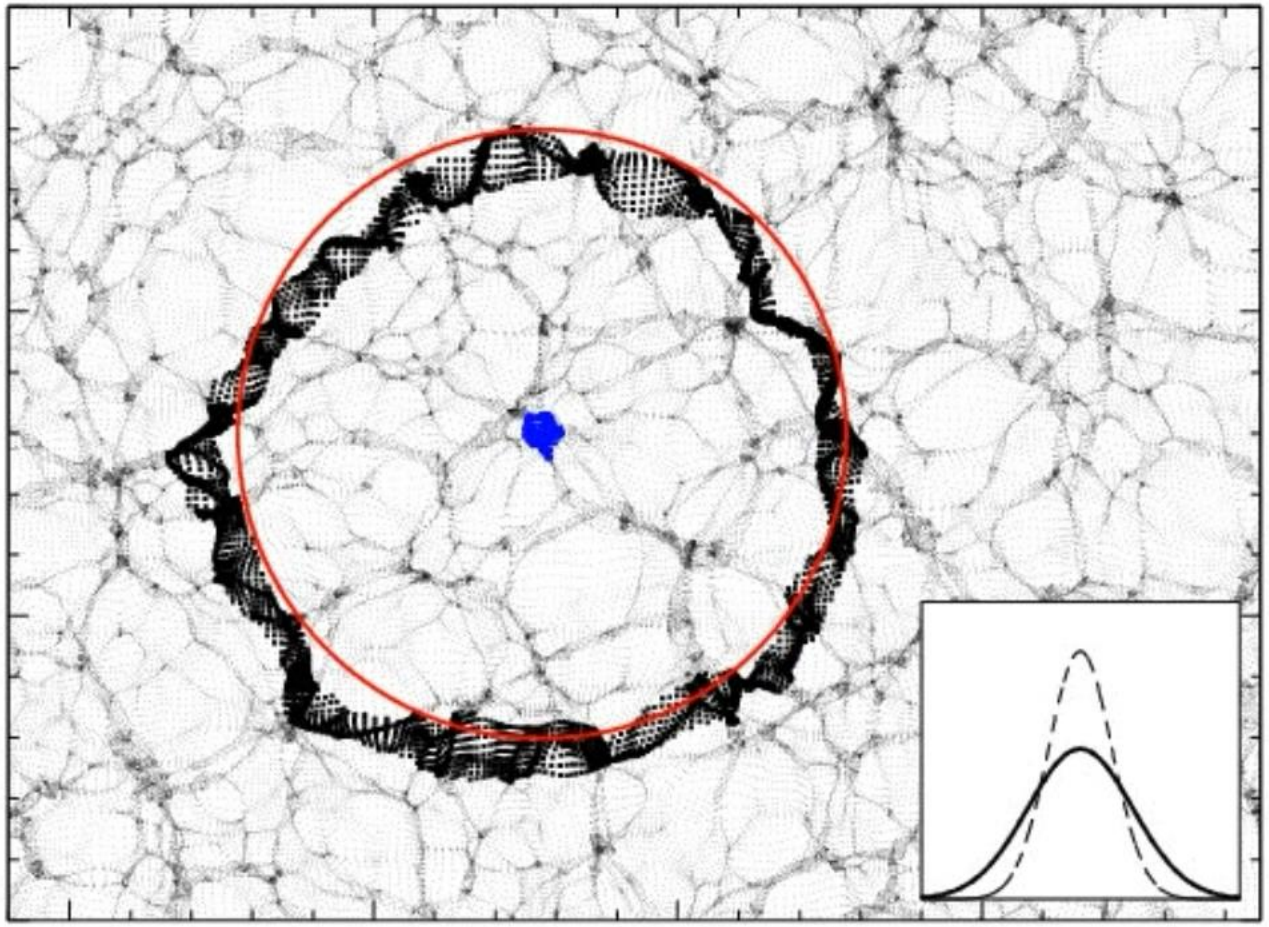
undo the non-linear evolution



Padmanabhan+ (2012)

BAO Reconstruction

undo the non-linear evolution

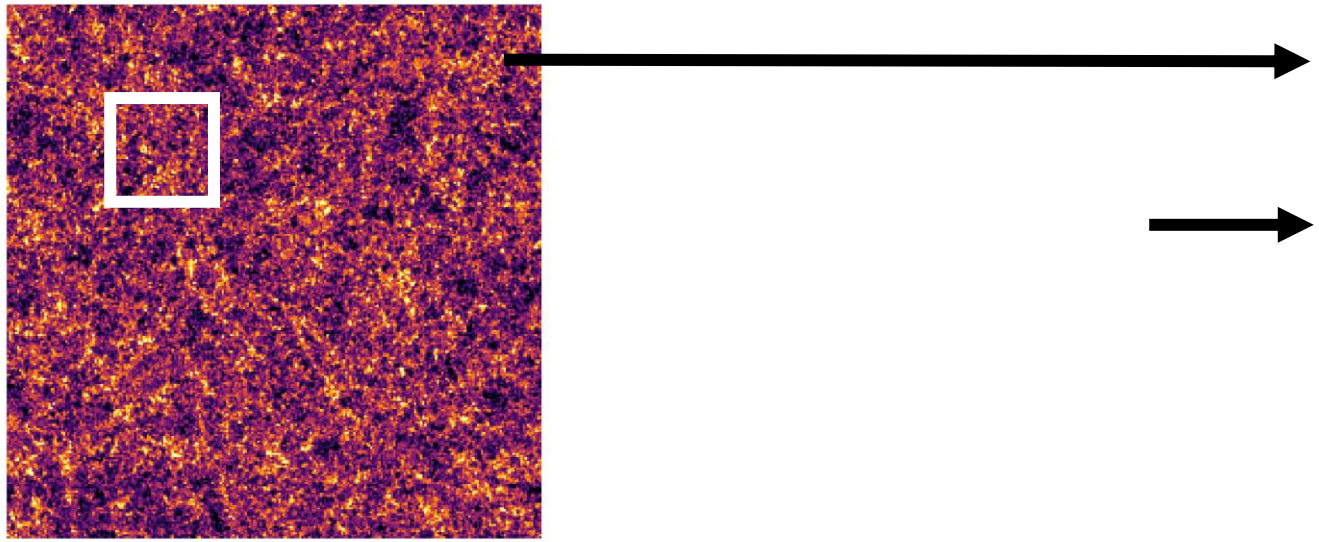


Padmanabhan+ (2012)

Use CNN to improve reconstruction

Liam Parker
Graduate Student
(UC Berkeley)

Galaxies

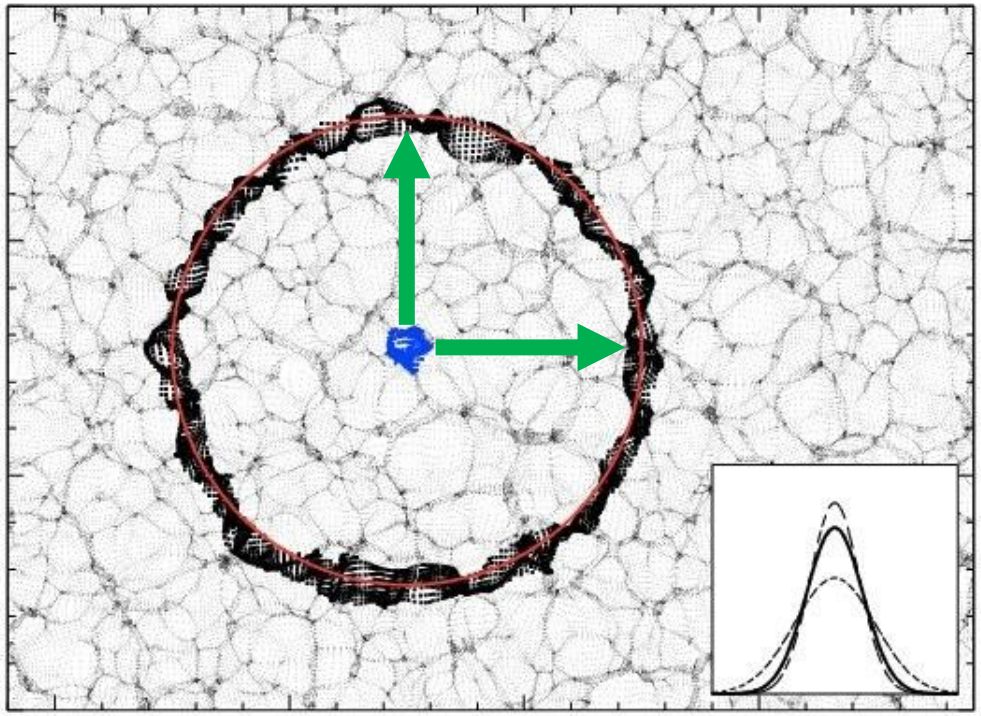


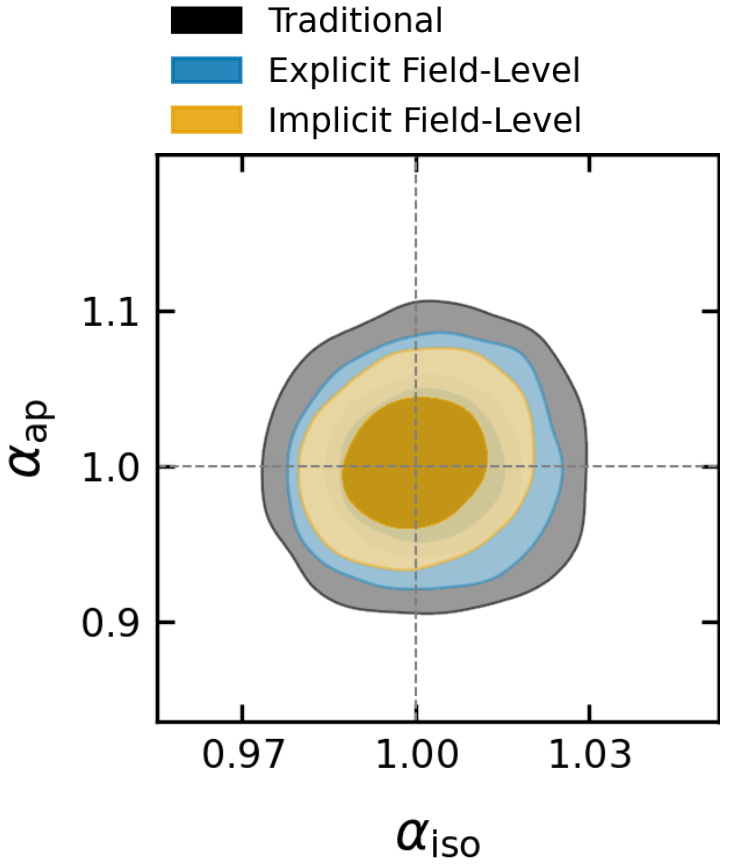
Perturbation theory gets large scales correct -> use sub-grid approach to scale up

Parker, Bayer, Seljak (2025)

Field-Level with DESI

2.4x improvement in BAO measurement forecasted





Bayer+ (2026)


DESI


Euclid


Rubin LSST


Subaru


SPHEREx


Simons Observatory


LiteBIRD

2024 2025 2026 2027 2028 2029 2030 2030s

Dark Energy Spectroscopic Instrument

Euclid Space Mission

Vera Rubin Observatory Legacy Survey of Space and Time (LSST)

Subaru Prime Focus Spectrograph (PFS)

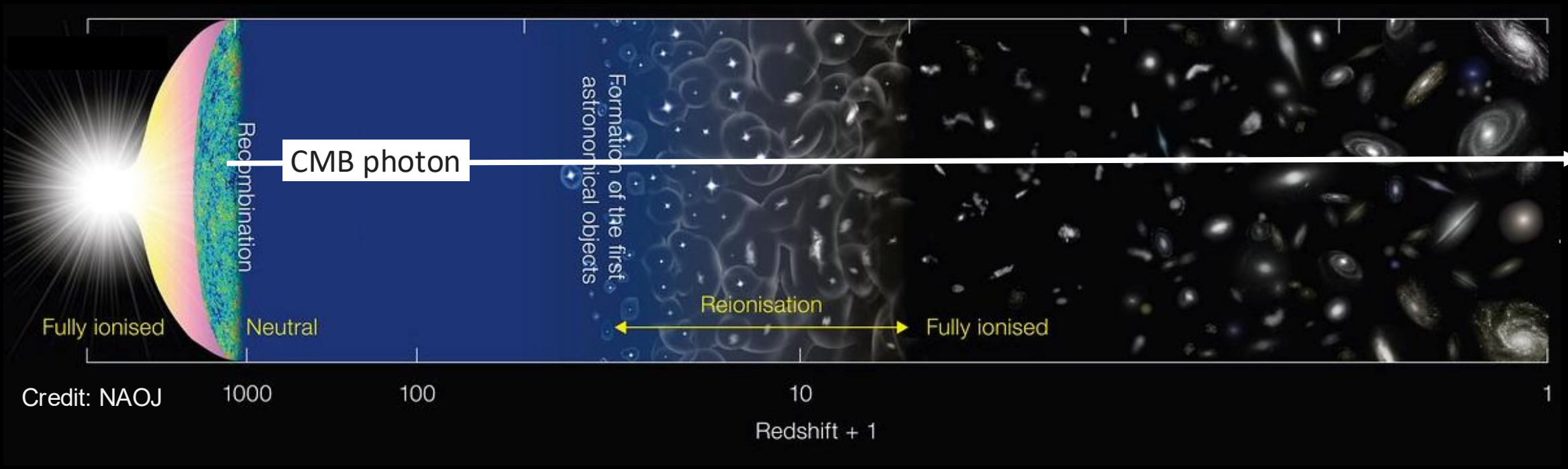
Nancy G. Roman Space Telescope

Simons Observatory

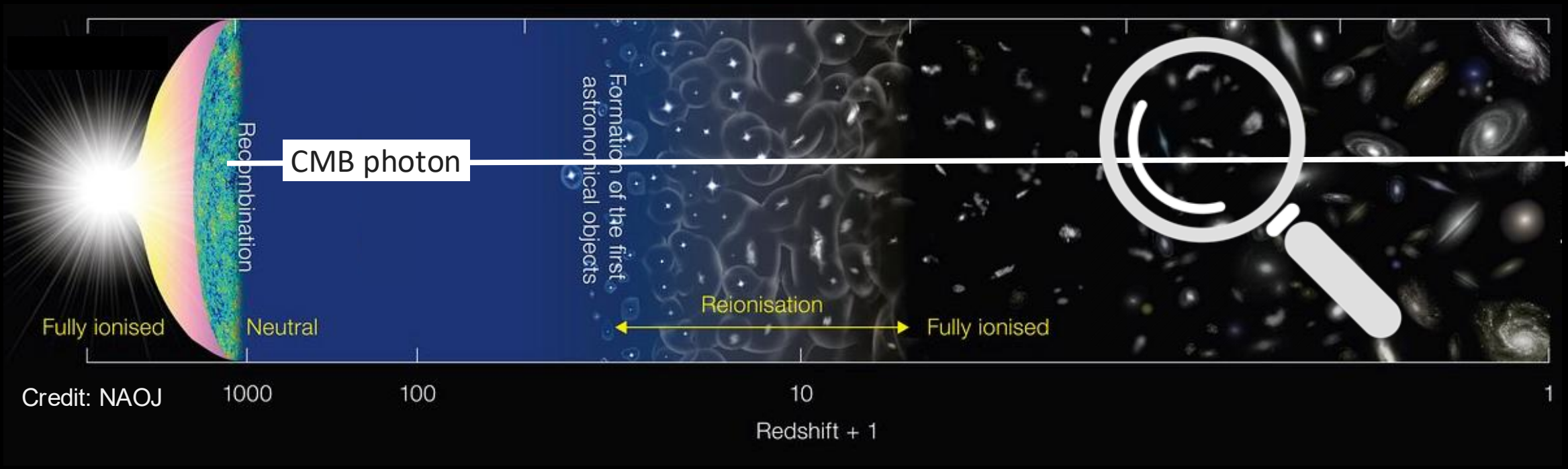
LiteBIRD

MULTI-PROBE ANALYSIS

1. Increases signal-to-noise to detect otherwise undetectable signals
2. Breaks degeneracies with astrophysical parameters
3. Mitigates systematics


Recombination
CMB photon
Formation of the first astronomical objects
Reionisation
Fully ionised
Neutral
Fully ionised
1000
100
10
1
Redshift + 1

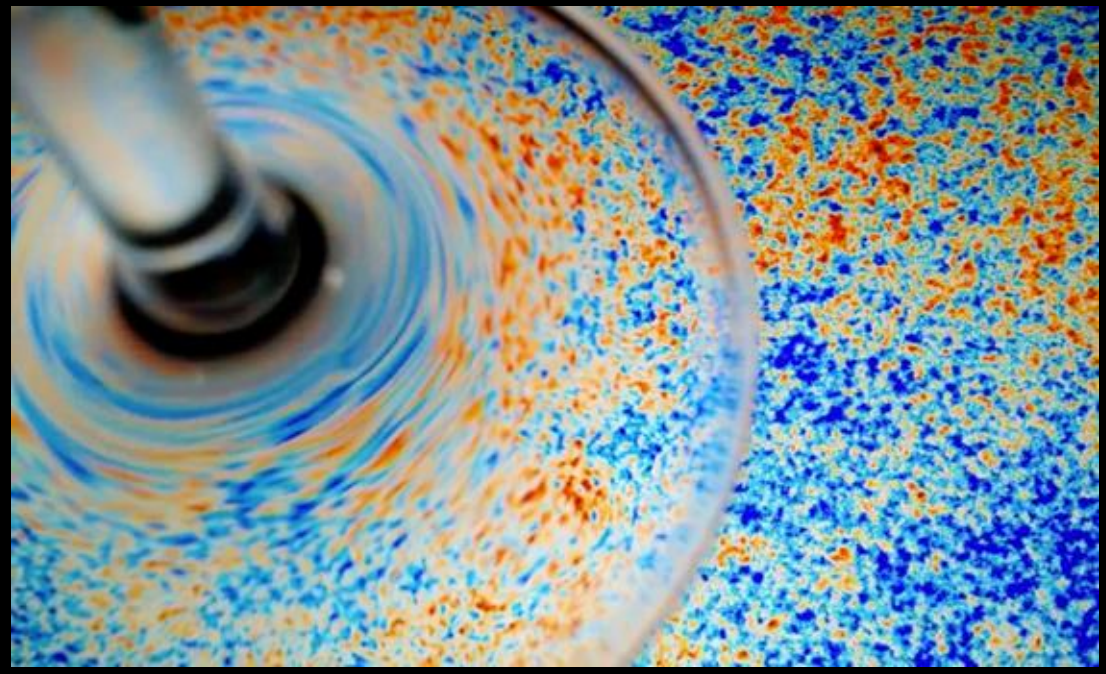
Credit: NAOJ



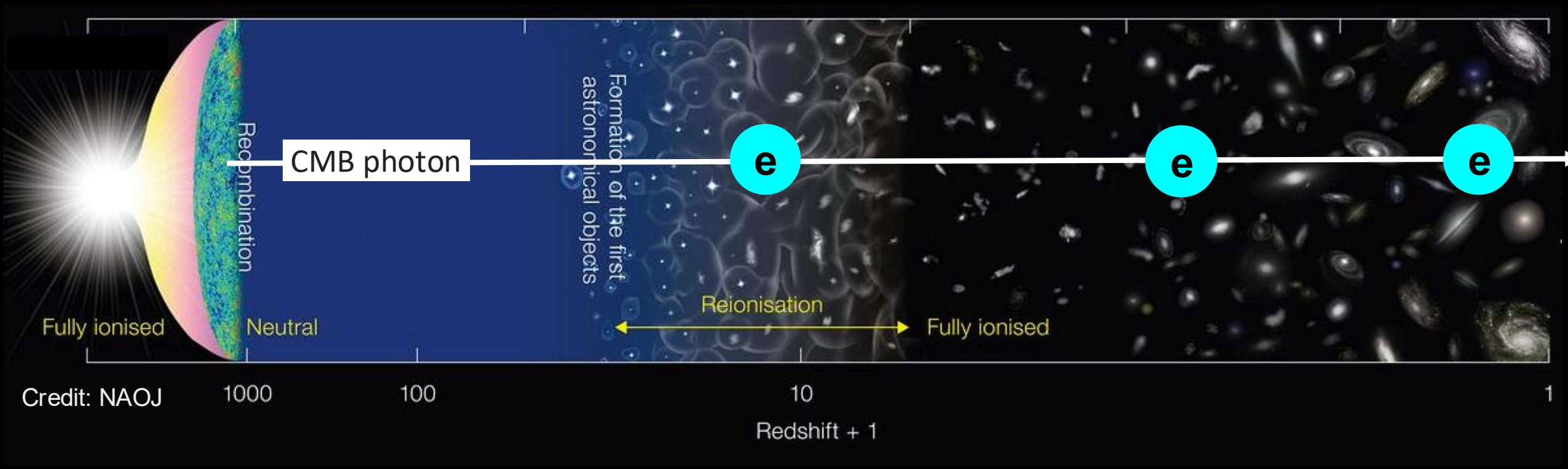
Credit: NAOJ

CMB Lensing

Photon's path bent by curved spacetime



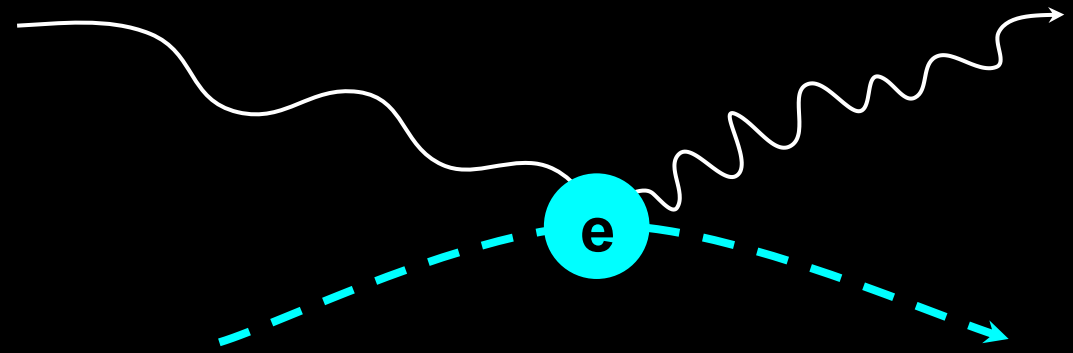
Credit: Emmanuel Schaan

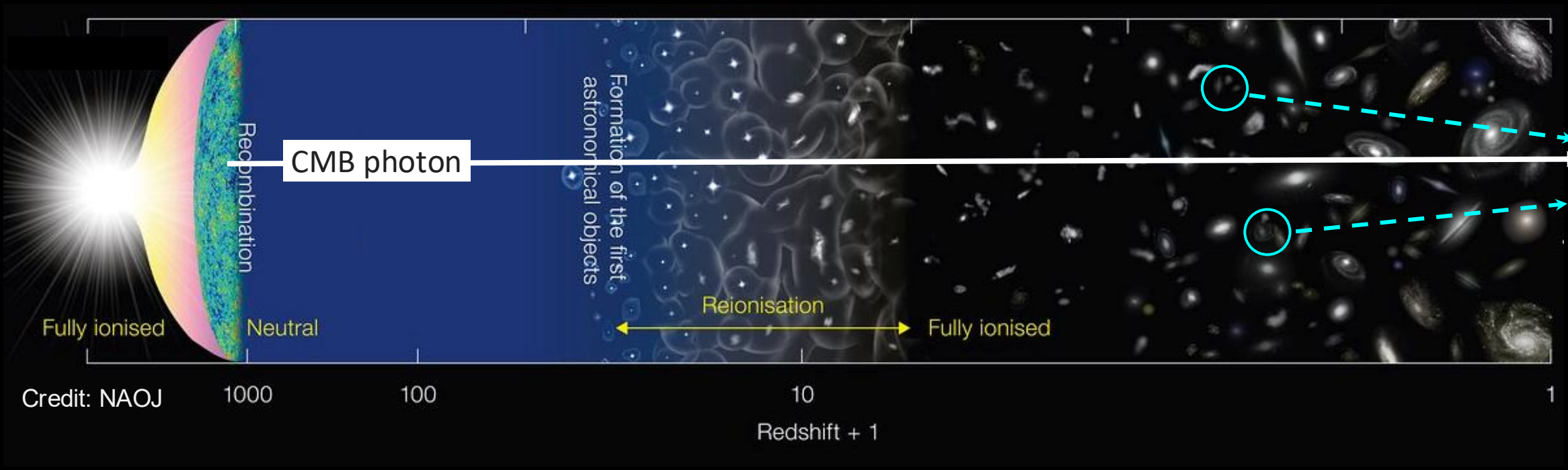


kinetic SZ

thermal SZ

Interaction with high energy electrons

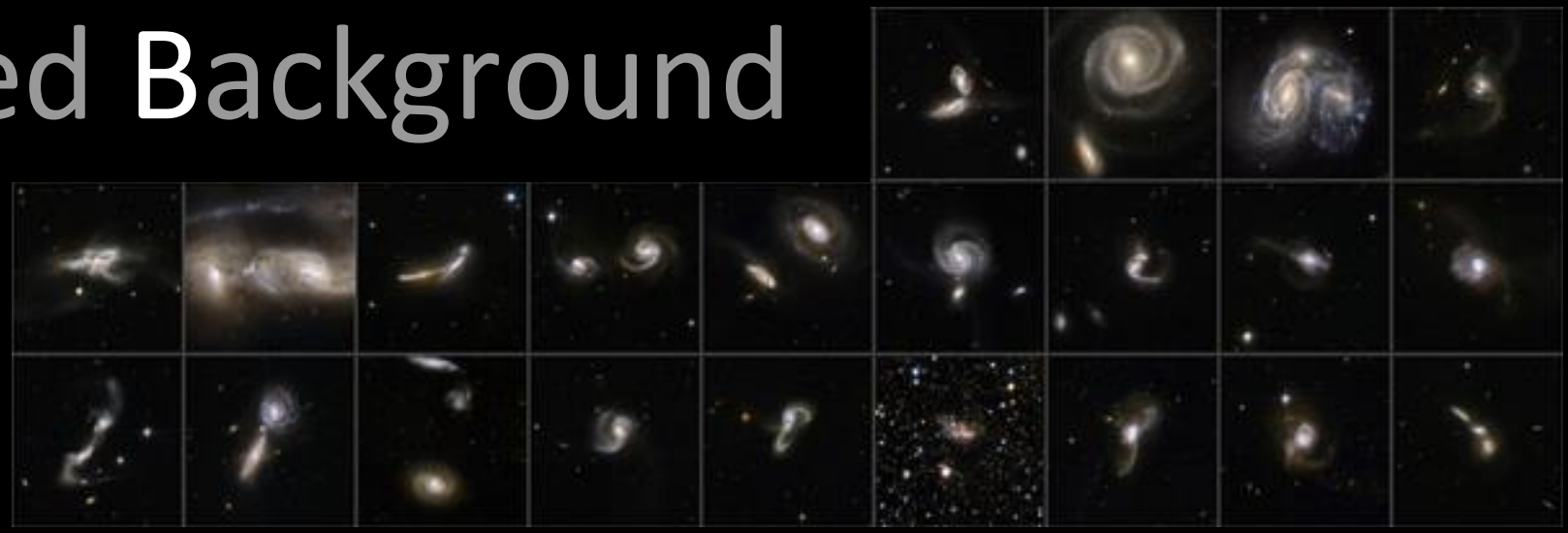




Credit: NAOJ

Cosmic Infrared Background

Emission from dusty galaxies

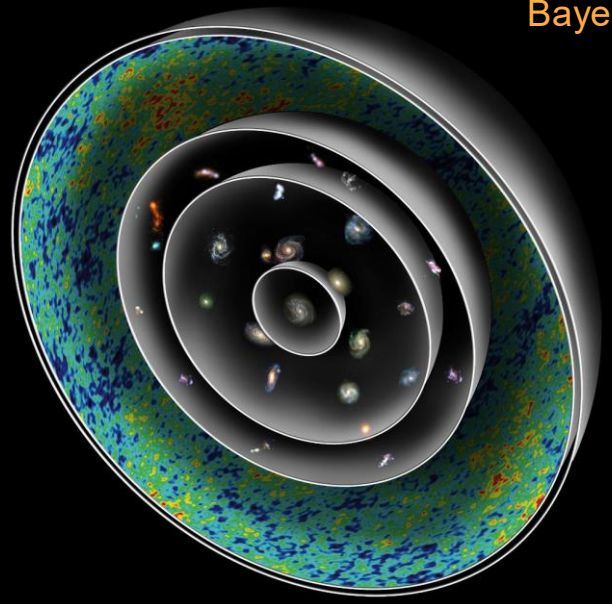


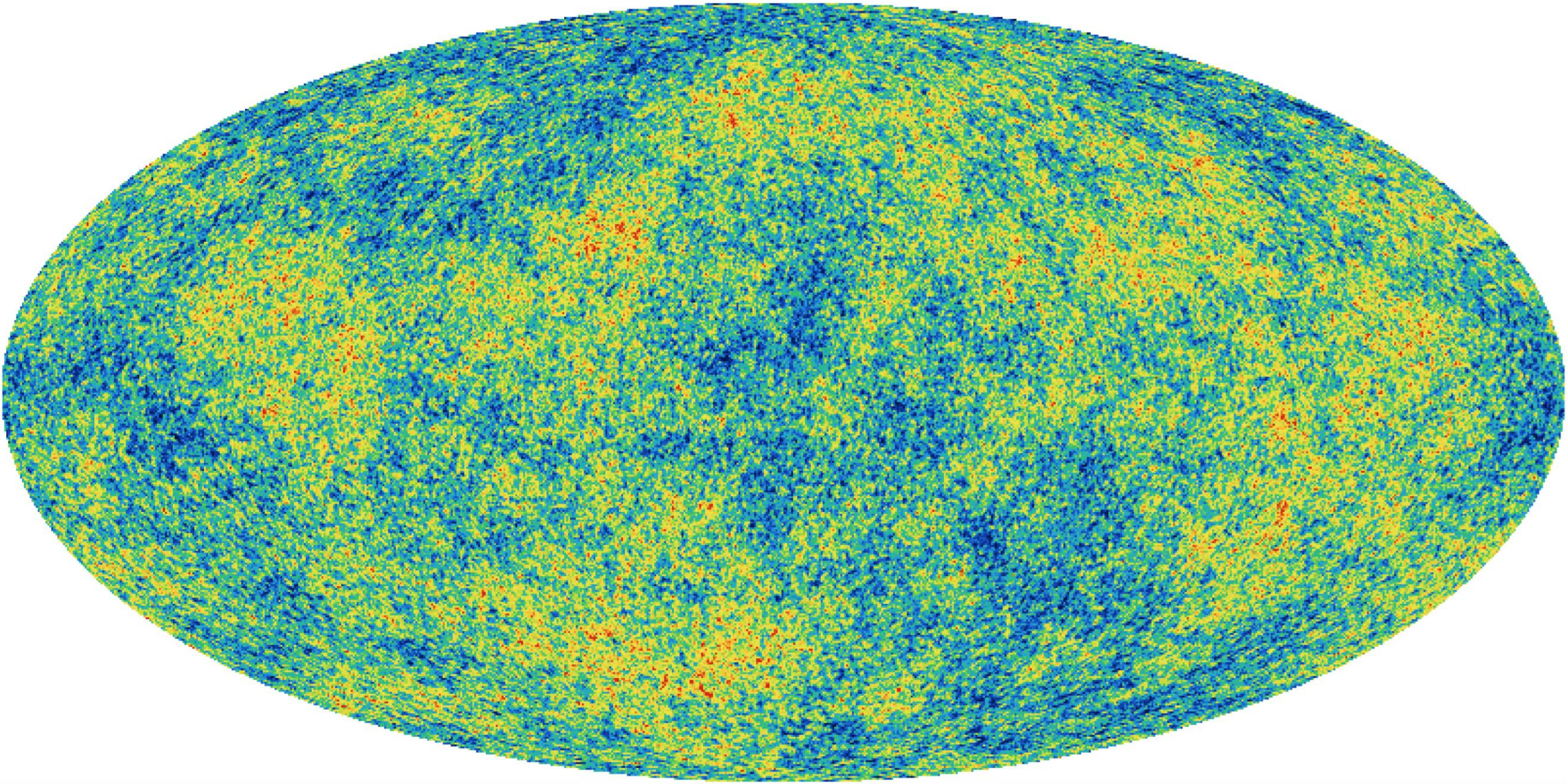
Credit: HST

Correlated Simulations of the Universe

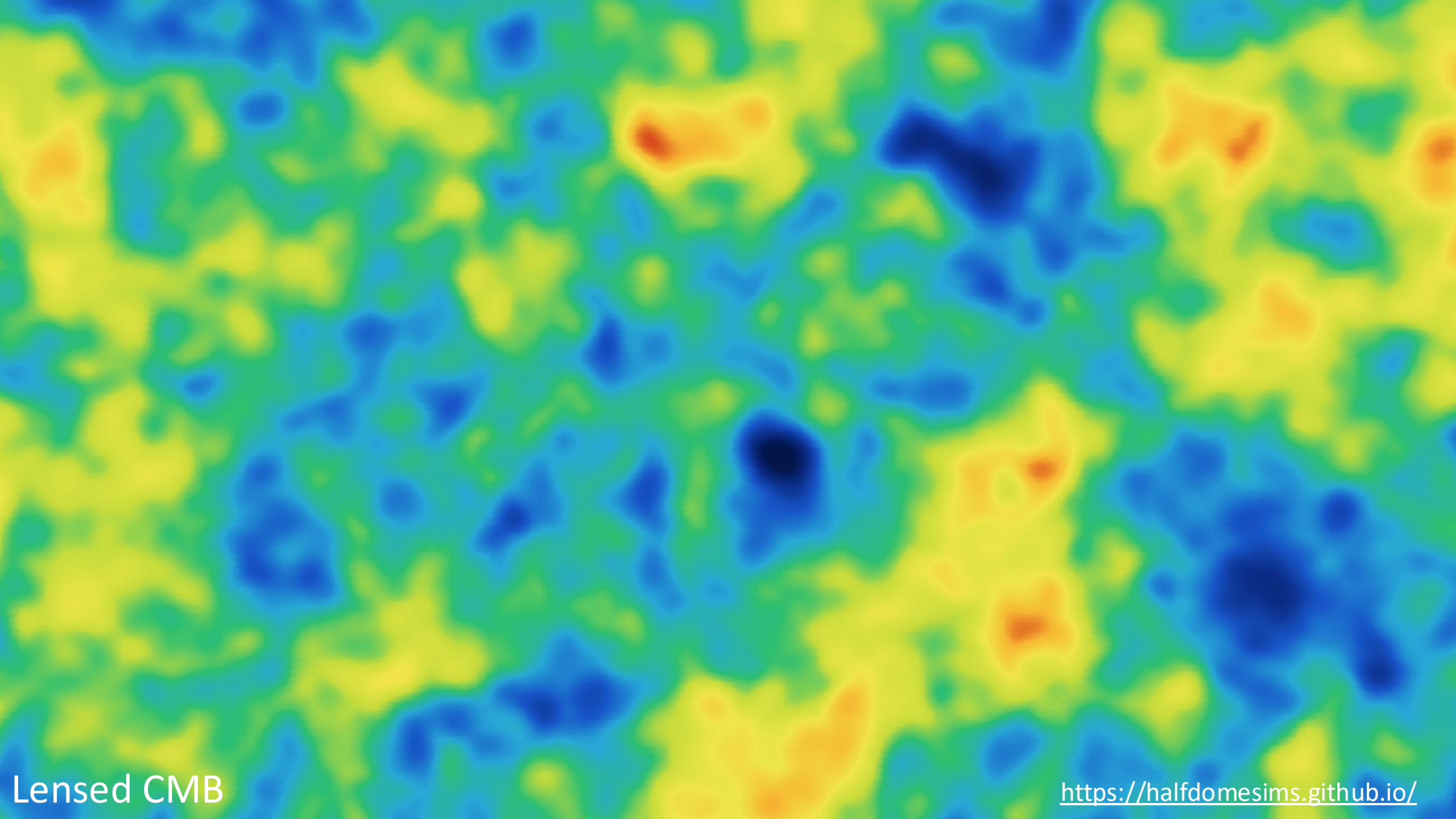
HalfDome

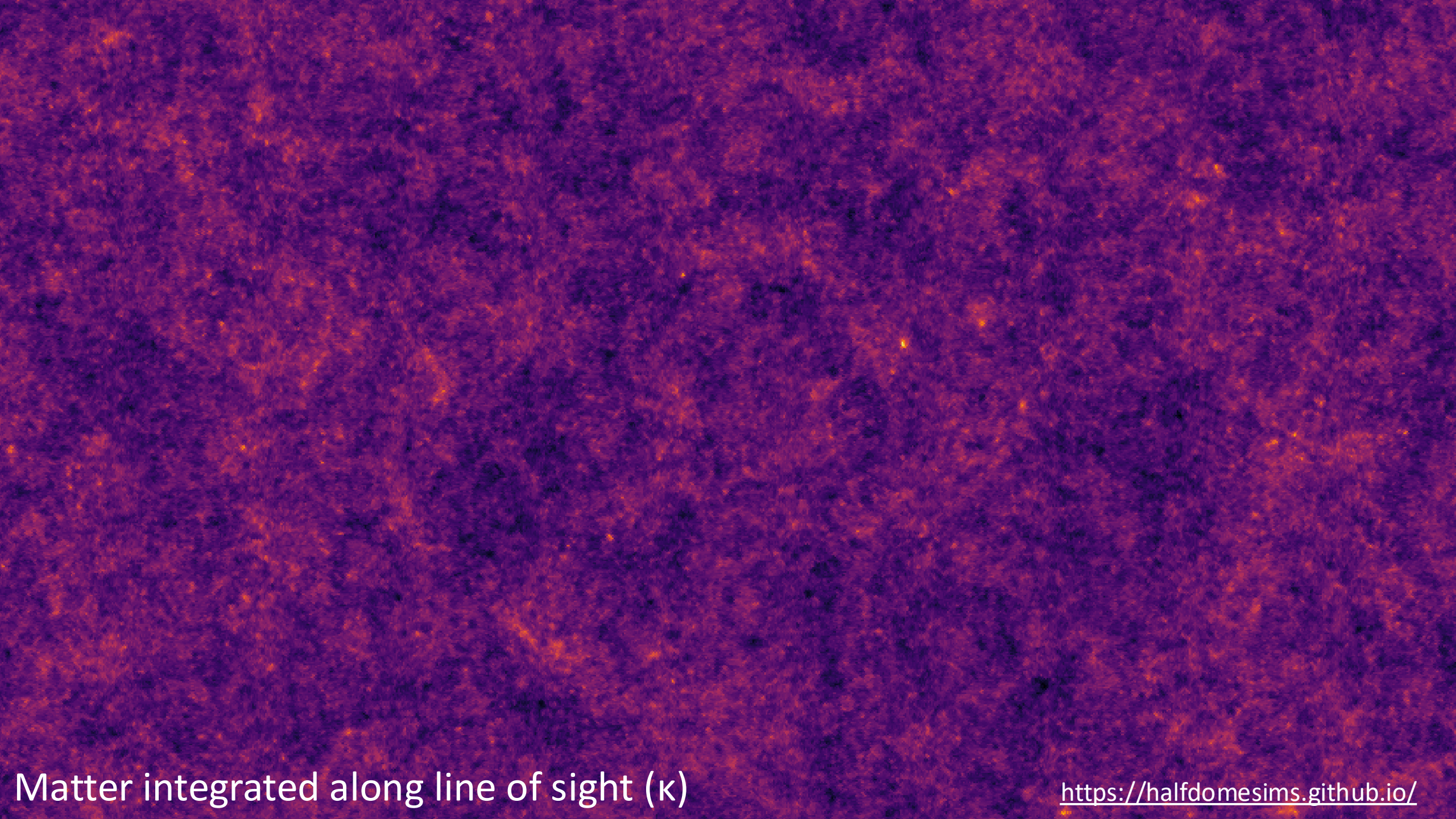
Bayer+2024





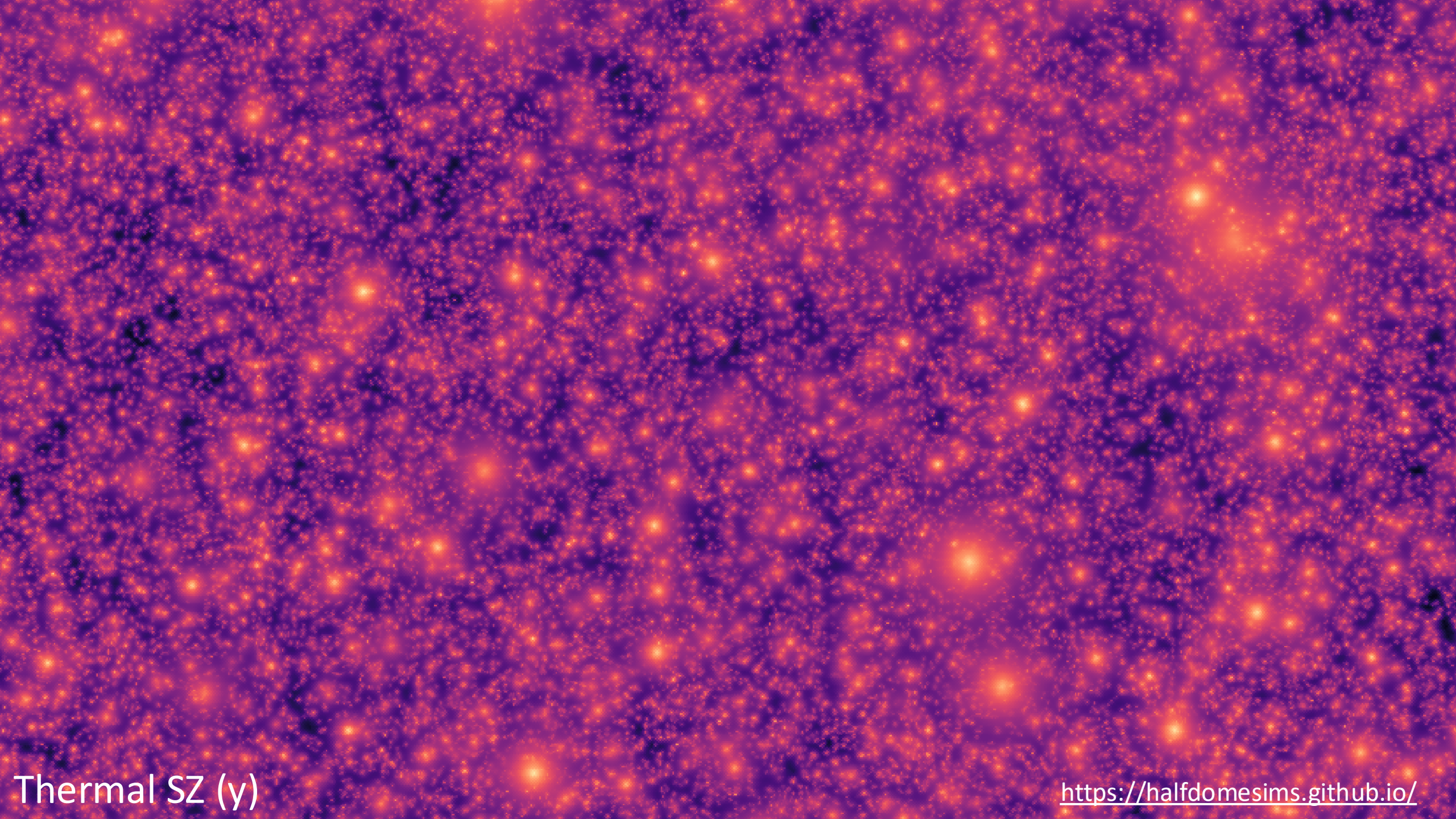
https://halfdomesims.github.io/

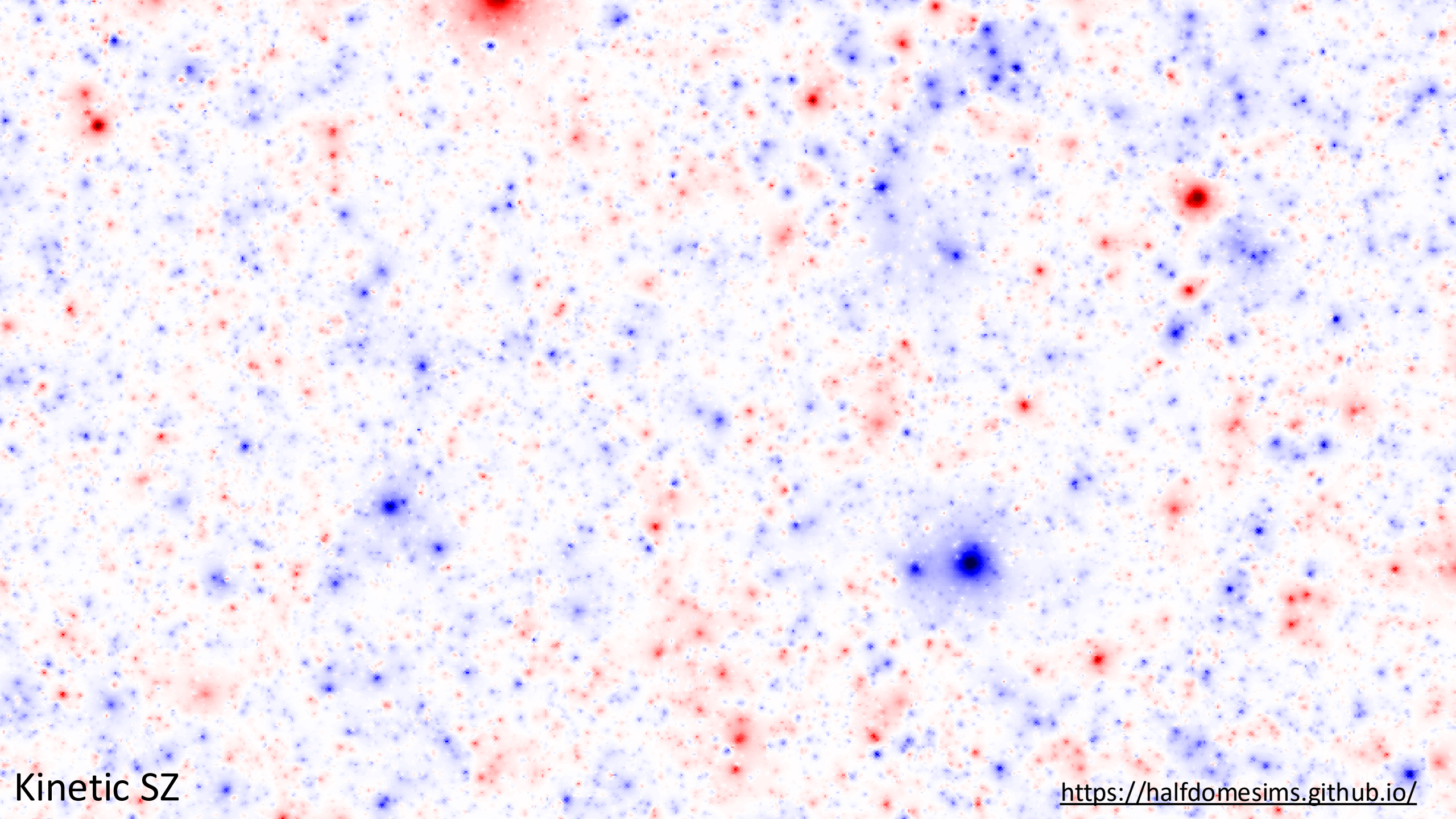

Lensed CMB
https://halfdomesims.github.io/



Matter integrated along line of sight (κ)

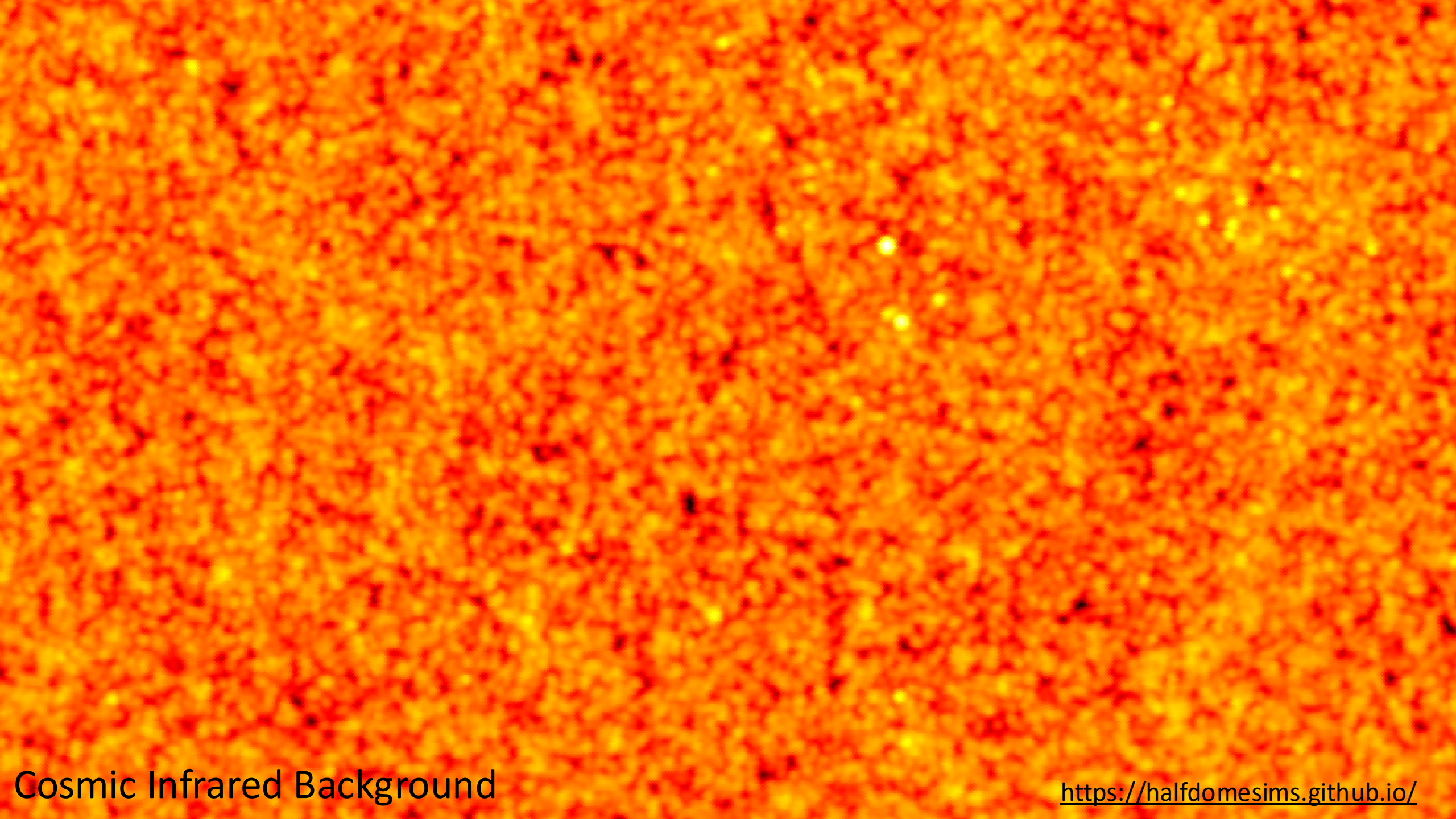
https://halfdomesims.github.io/


Thermal SZ (y)
https://halfdomesims.github.io/



Kinetic SZ

https://halfdomesims.github.io/



Cosmic Infrared Background

https://halfdomesims.github.io/

HalfDome Team

Adrian Bayer

Princeton/CCA

Zack Li

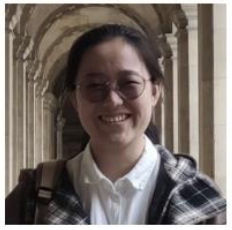
UC Berkeley/LBL

Joe DeRose

UC Berkeley/LBL

Jia Liu

Kavli IPMU



Yici Zhong

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Chenze Dong

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ANU

Ben Horowitz

Kavli IPMU

Joaquin Armijo

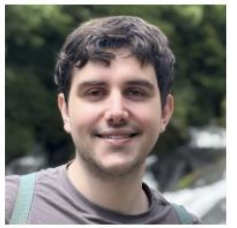
Kavli IPMU

Leander Thiele

Kavli IPMU

Yuka Yamada

U Tokyo



Miguel Ruiz Granda

IFCA

Giuseppe Puglisi

U Catania

Alex Laguë

U Penn

Mathew Madhavacheril

U Penn

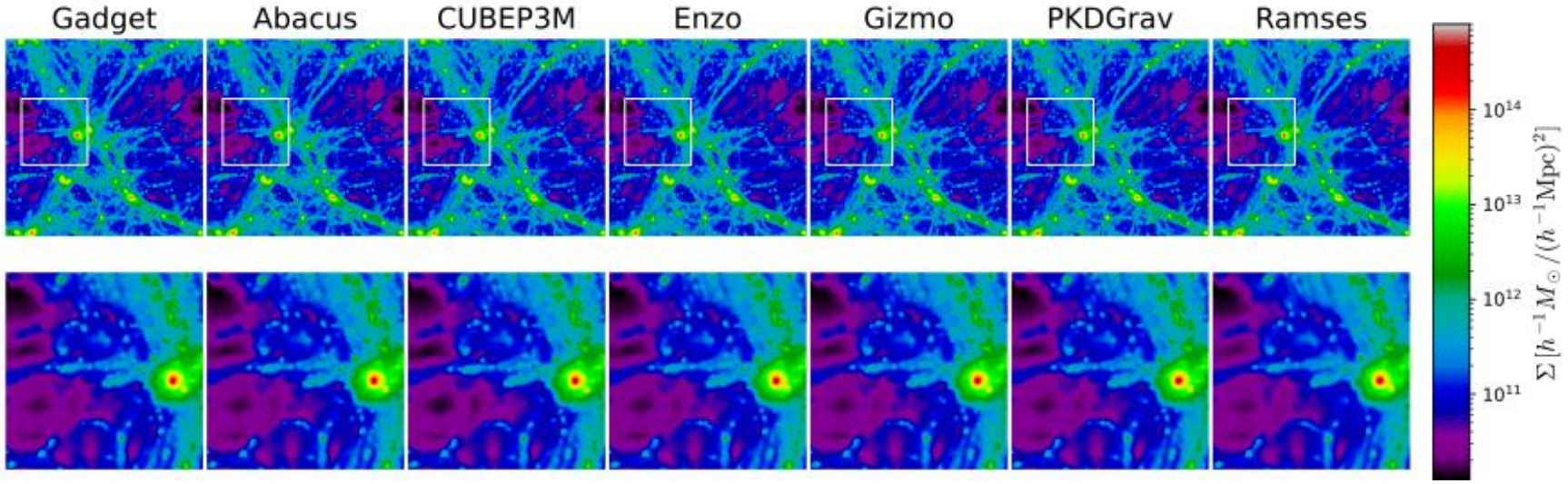
SIMONS OBSERVATORY

Sky Modelling Working Group

https://halfdomesims.github.io/

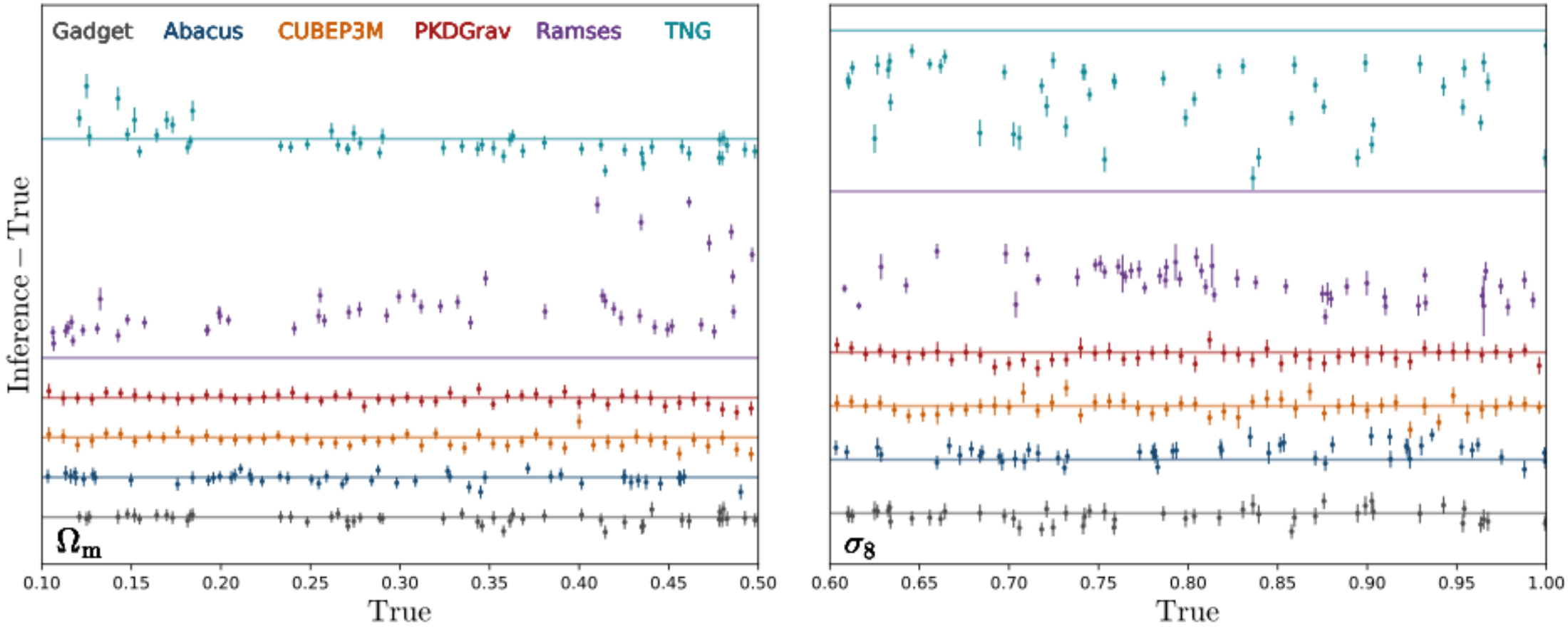
CosmicAI aims to grow transformative AI advances with the overarching goal to increase the accessibility of astronomy data and knowledge for researchers, students, and the public. CosmicAI leverages partnerships between academia, national facilities, nonprofits, and industry to develop capabilities that enable astronomical researchers to conceptualize, define, and execute research projects via trustworthy, efficient, robust, and explainable AI methods.

Field-Level Robustness of N-body Simulations



Bayer+ (2025)

Train on Gadget, test on Everything

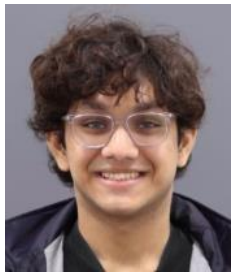


Bayer+ (2025)

Interpretability

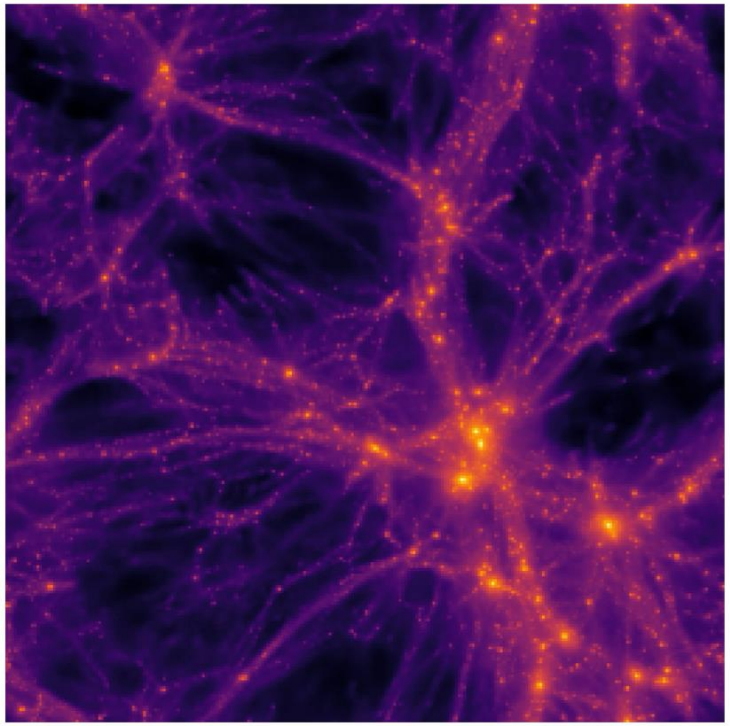
Measure response of network output with respect to input

Malika Golshan
Undergraduate
(Berkeley)



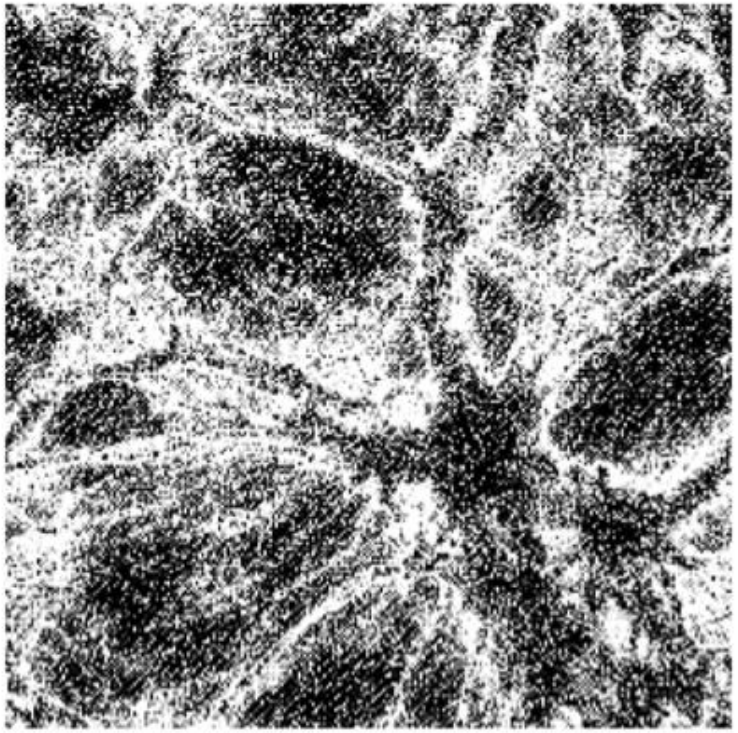
Arnab Lahiry
Graduate Student
(FORTH)

Density Field



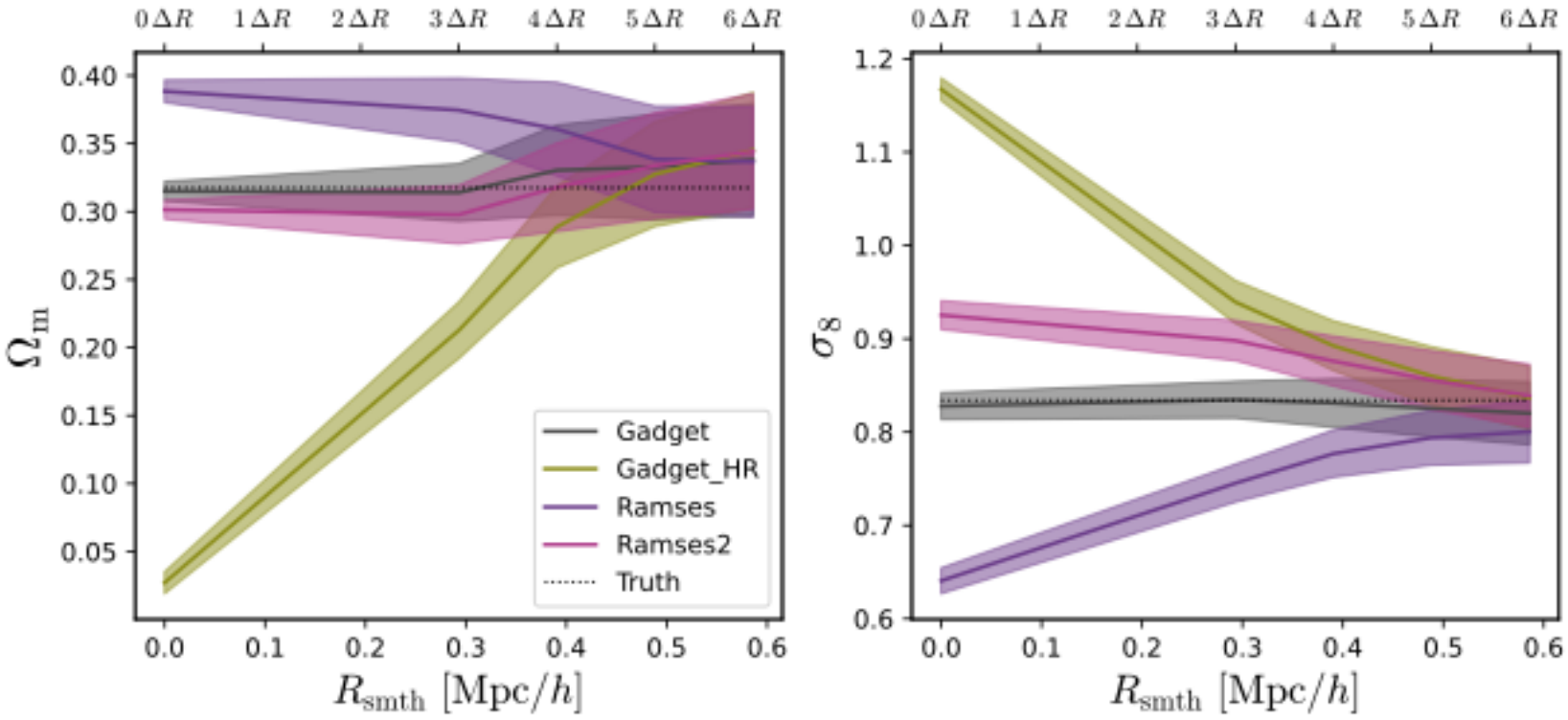
Ω_m

Integrated Gradient



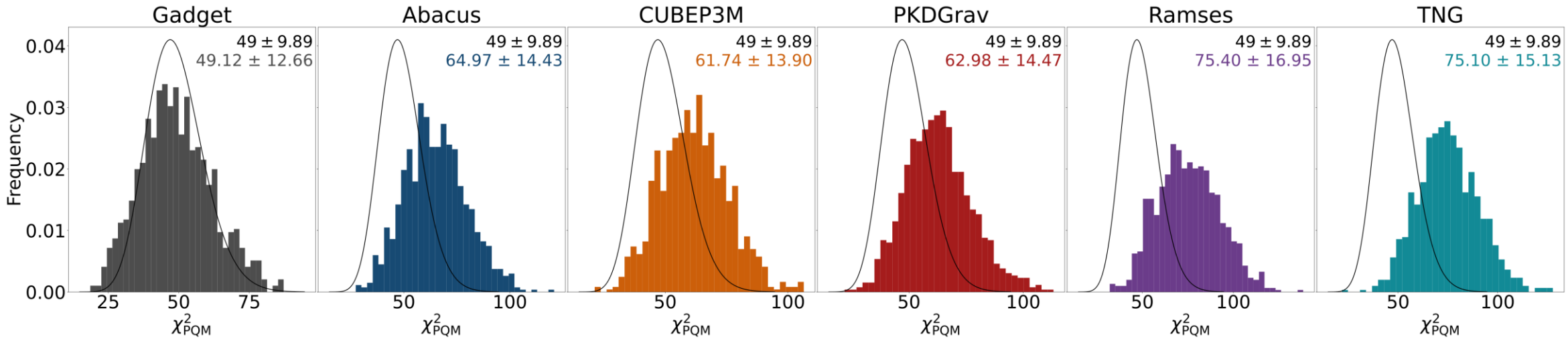
Golshan & Bayer (2024)
Lahiry, Bayer, Villaescusa-Navarro (2025)

Resolution is the Resolution

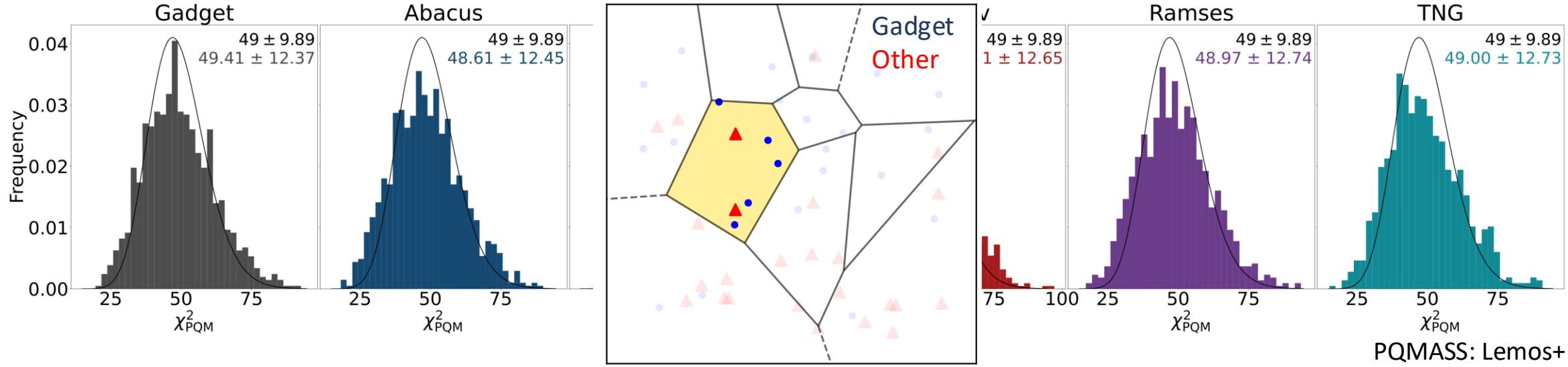


Bayer+ (2025)

Assessing robustness at data-vector level

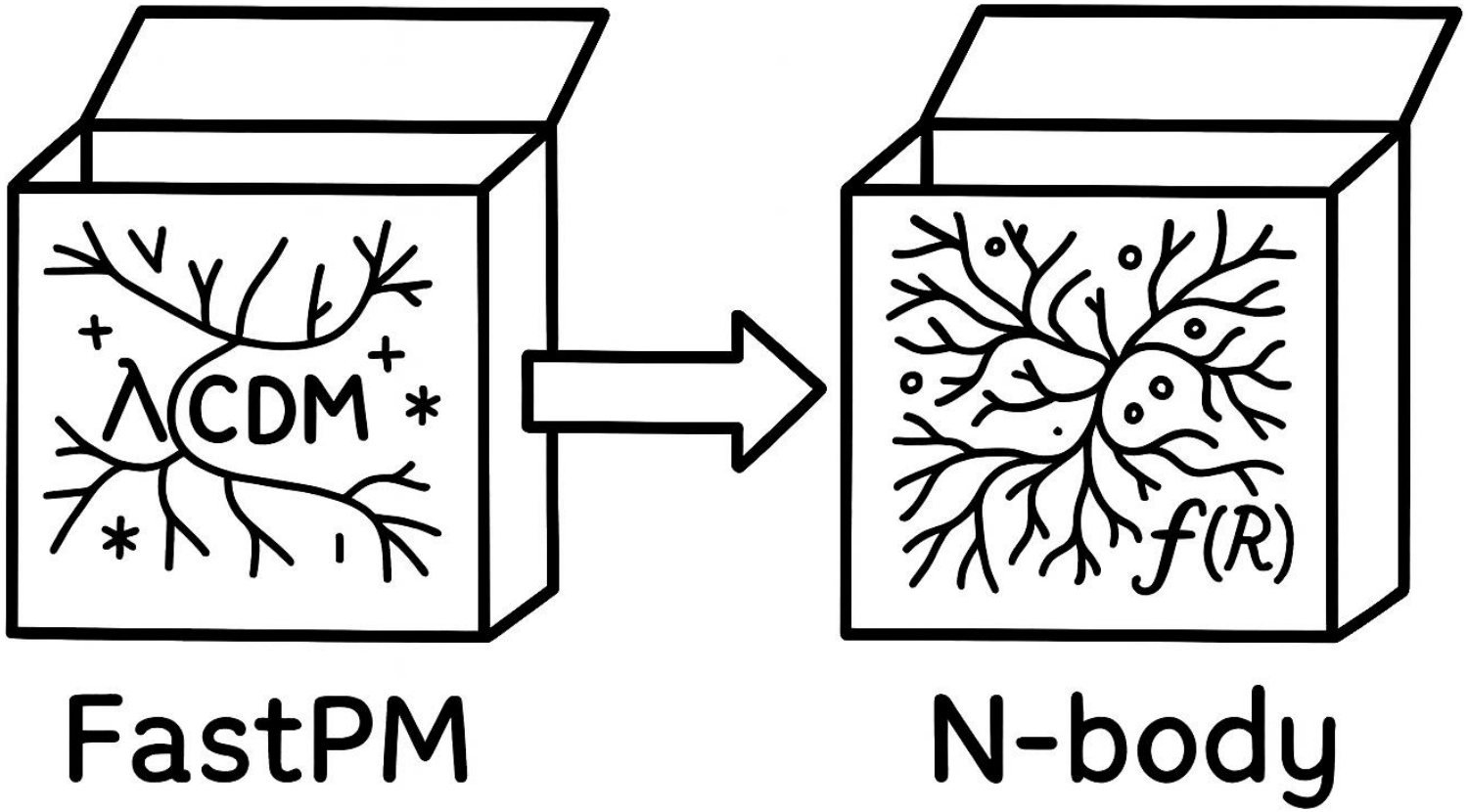


smooth



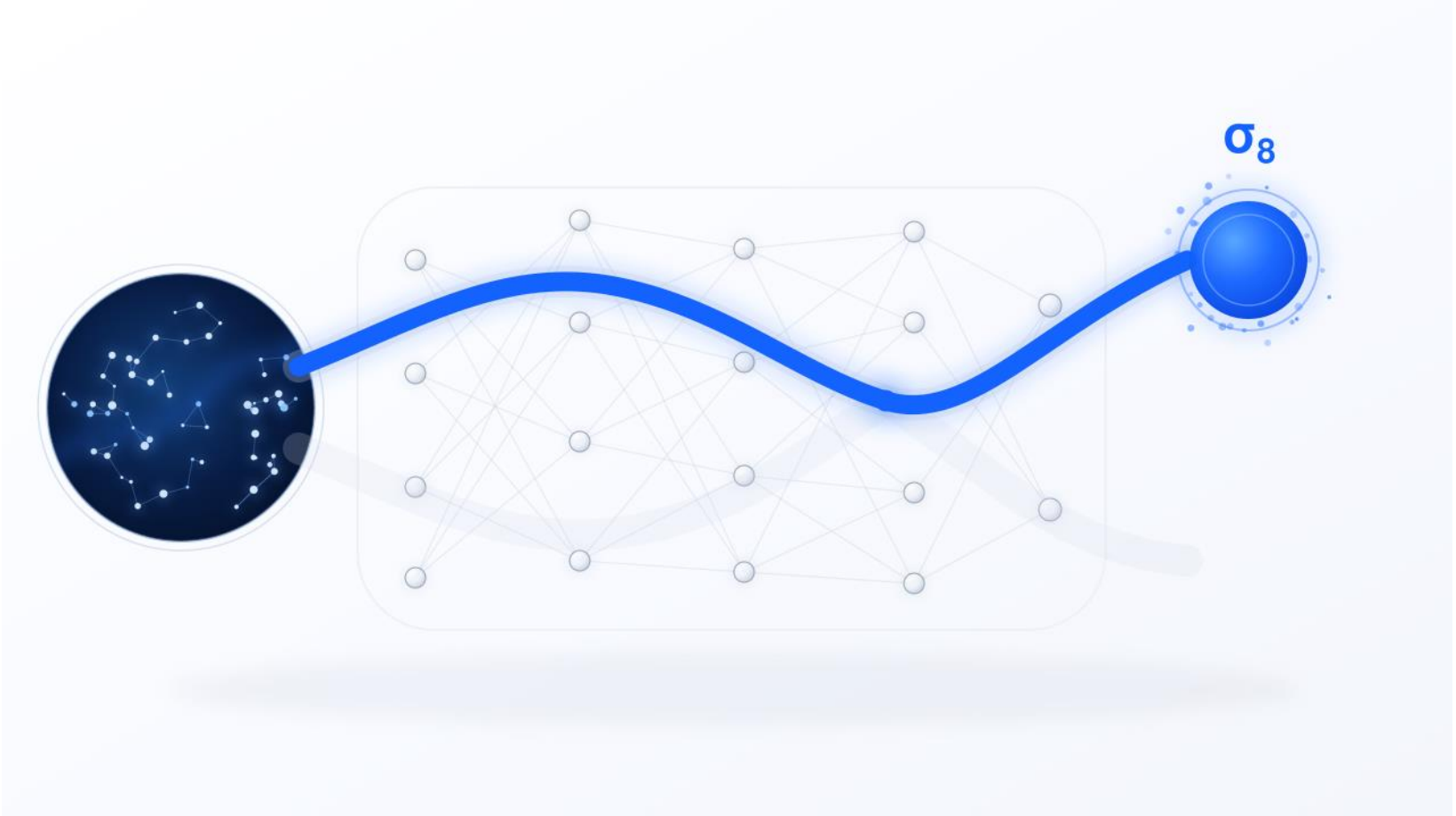
PQMASS: Lemos+ (2024)
Bayer+ (2025)

Transfer learning



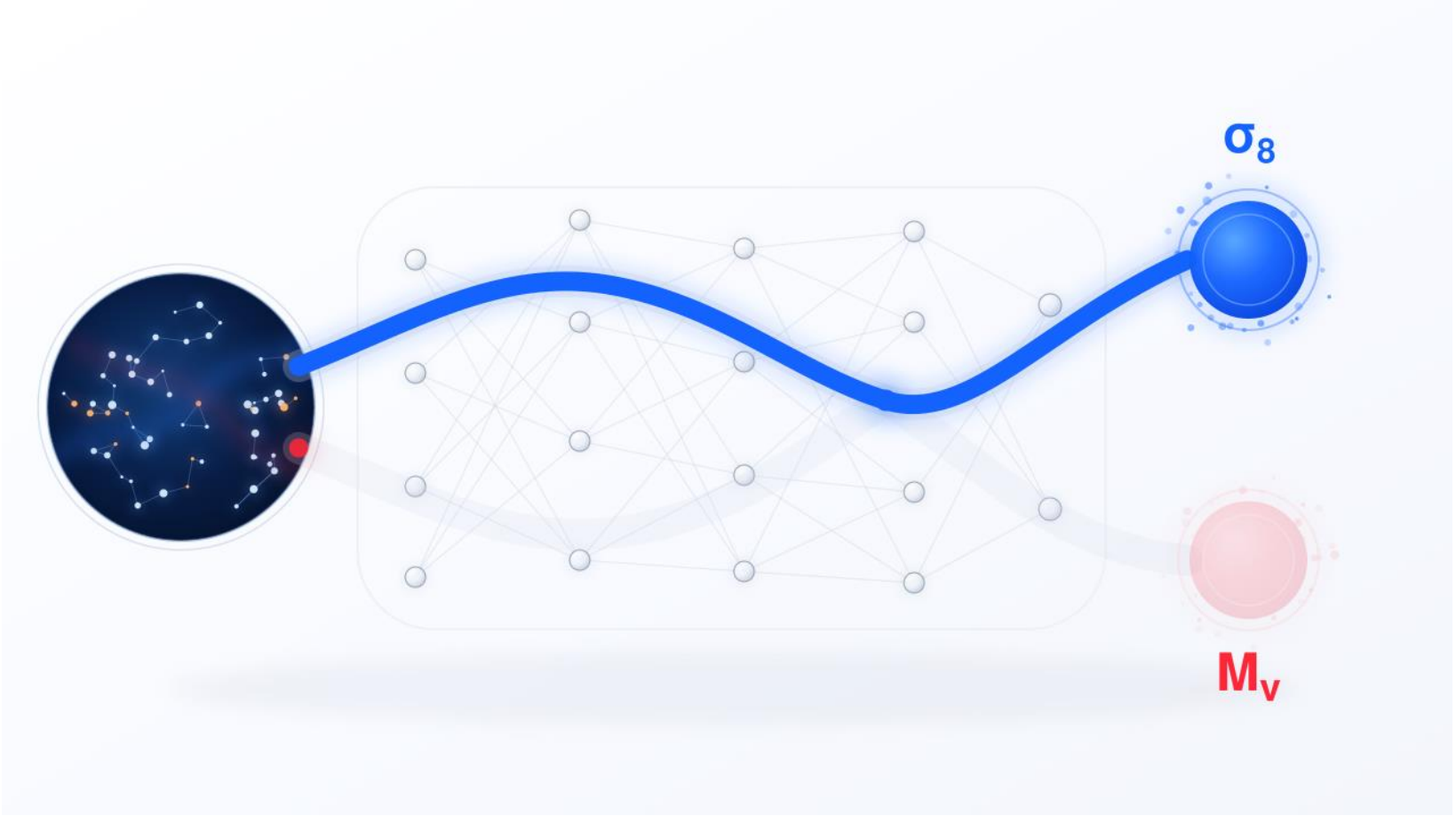
Negative learning

Veena Krishnaraj
Undergraduate Student
(Princeton)



Negative learning

Veena Krishnaraj
Undergraduate Student
(Princeton)



Negative learning

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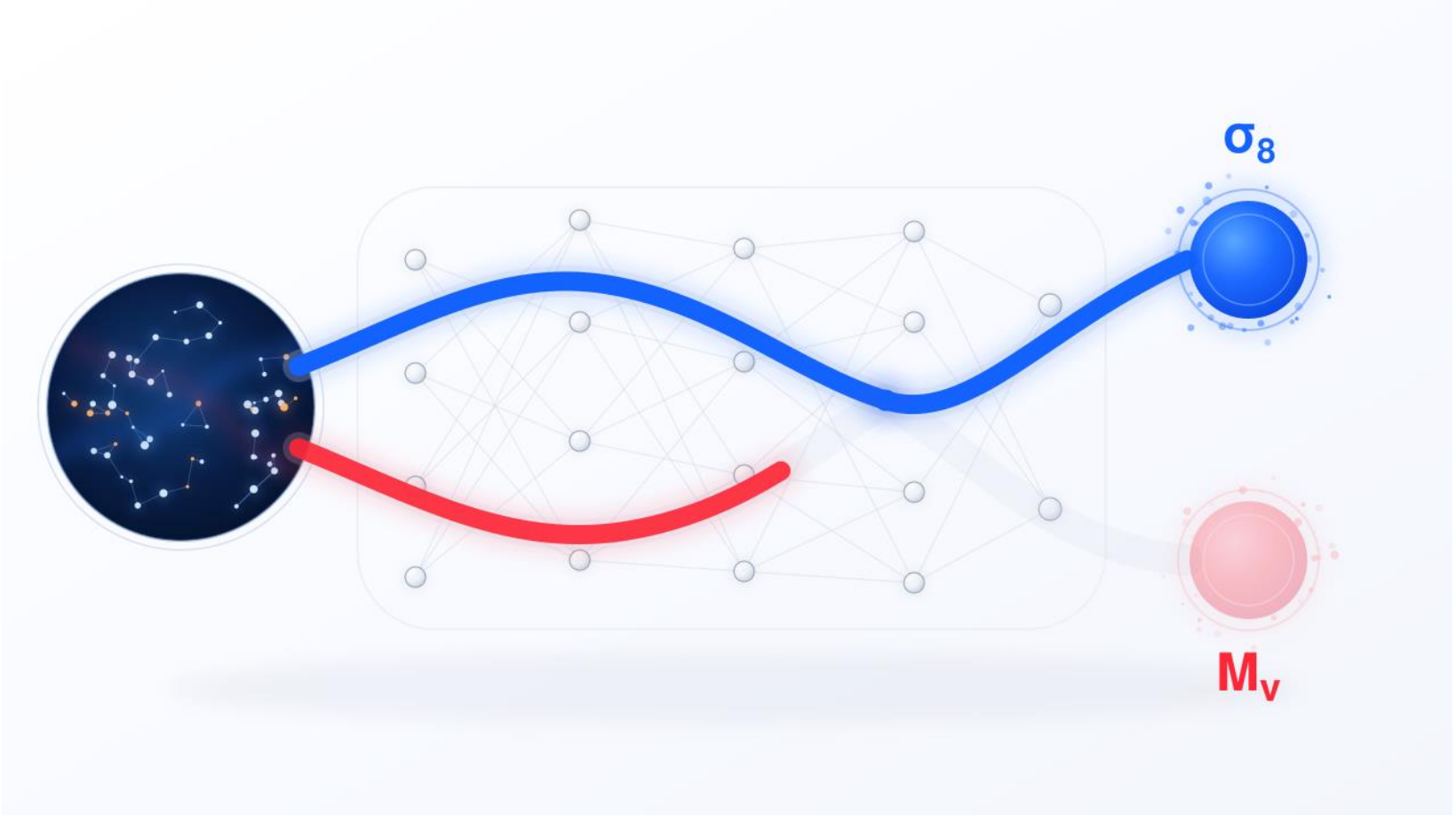

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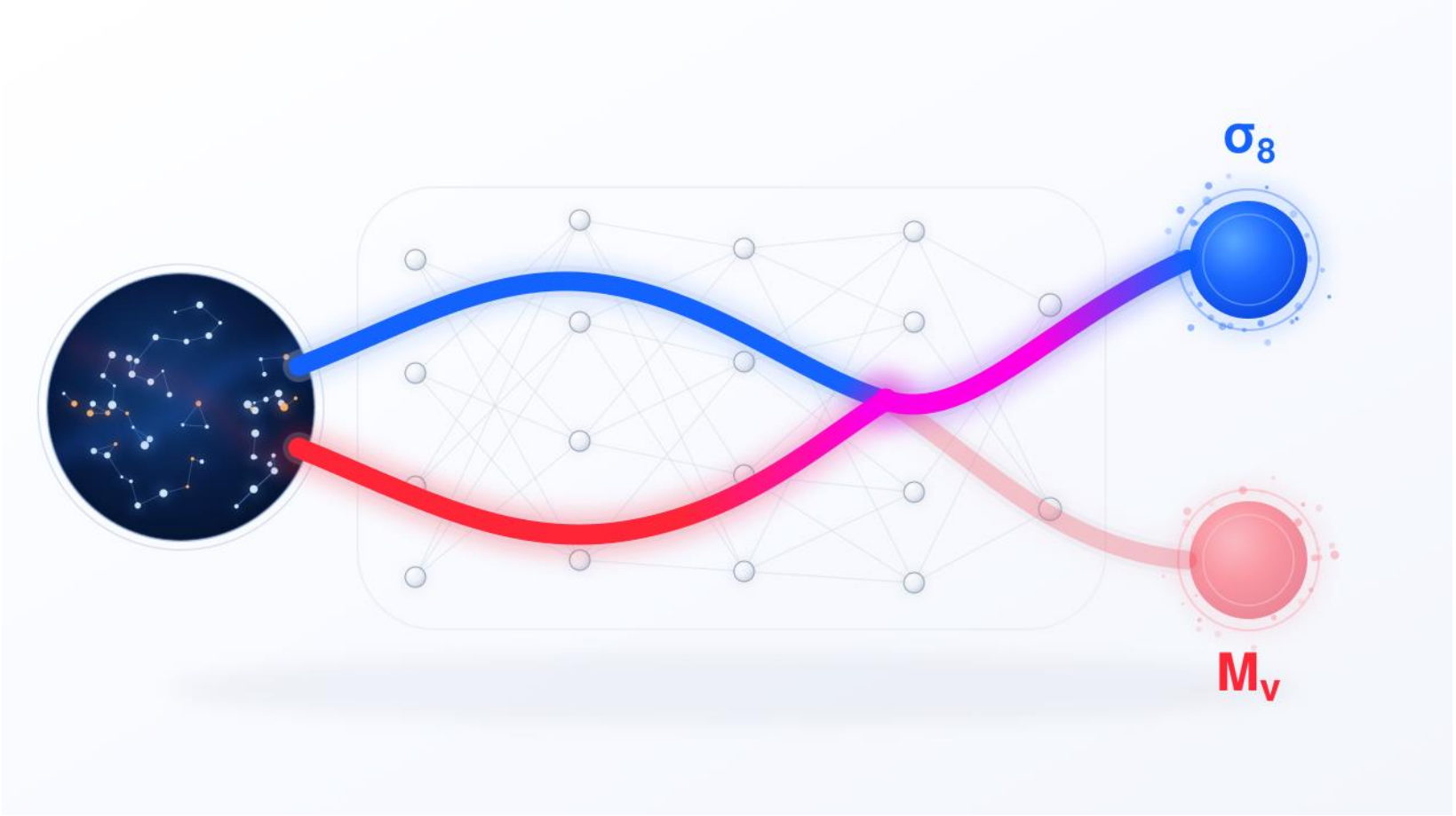

Negative learning

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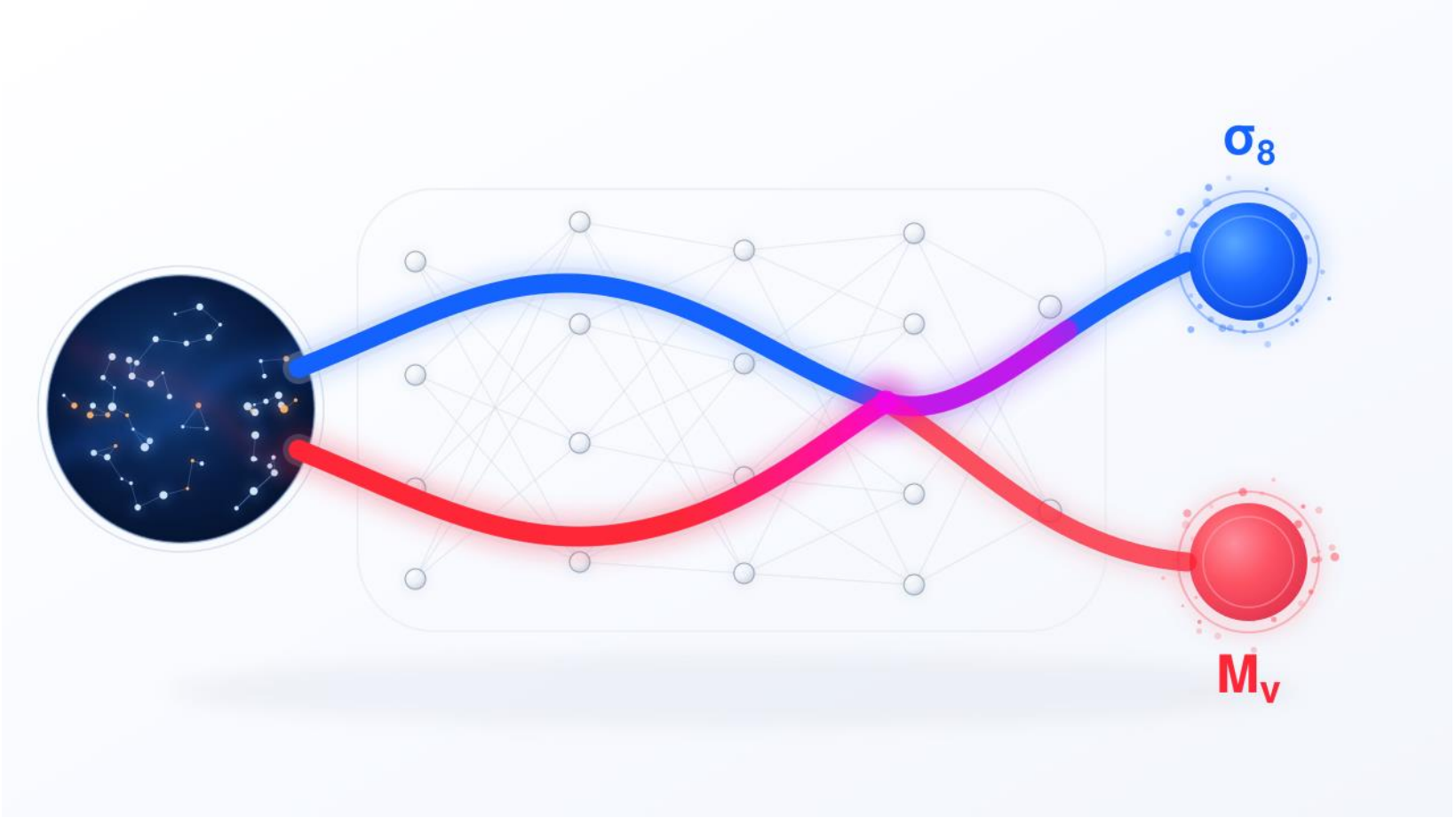

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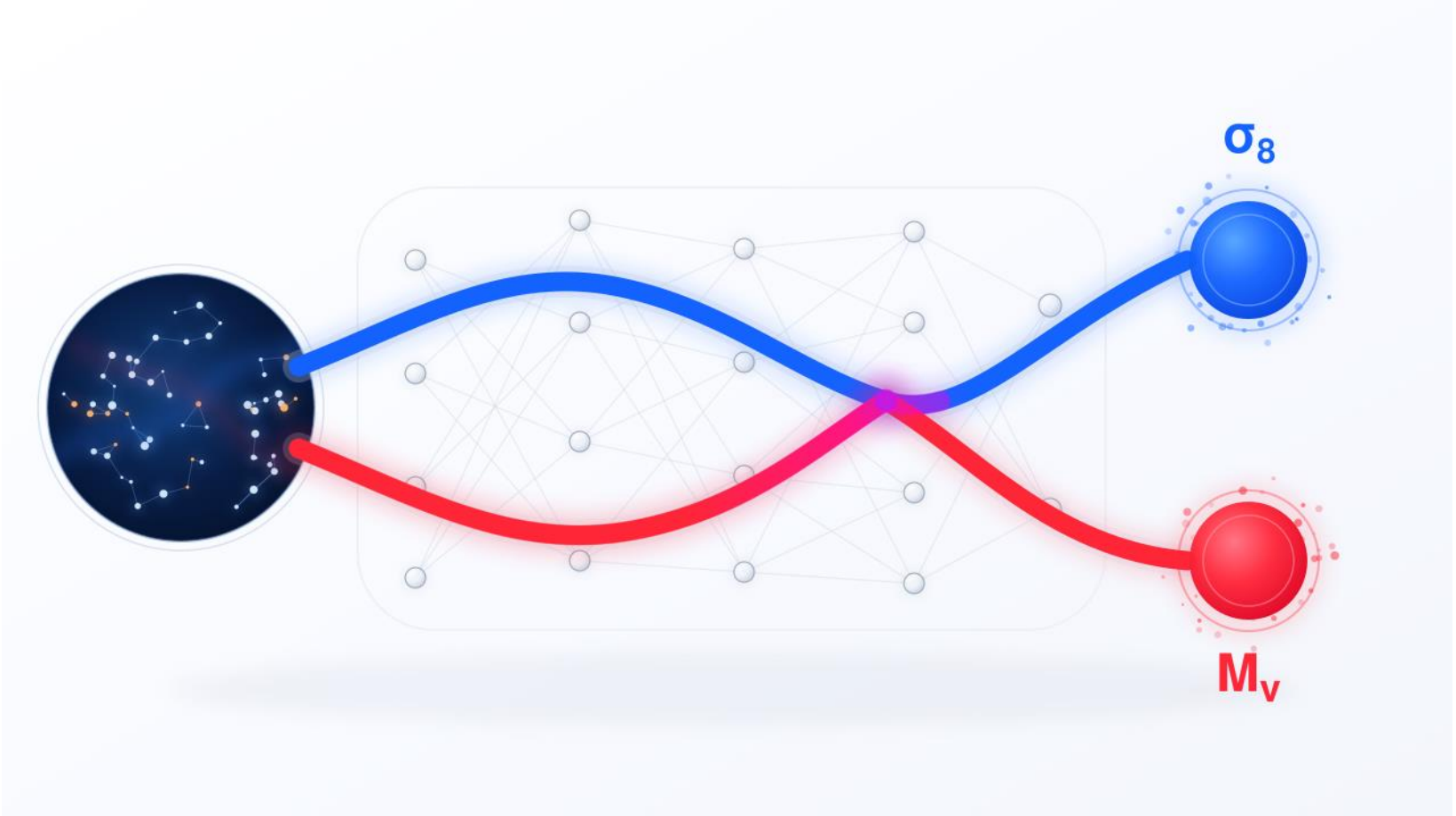

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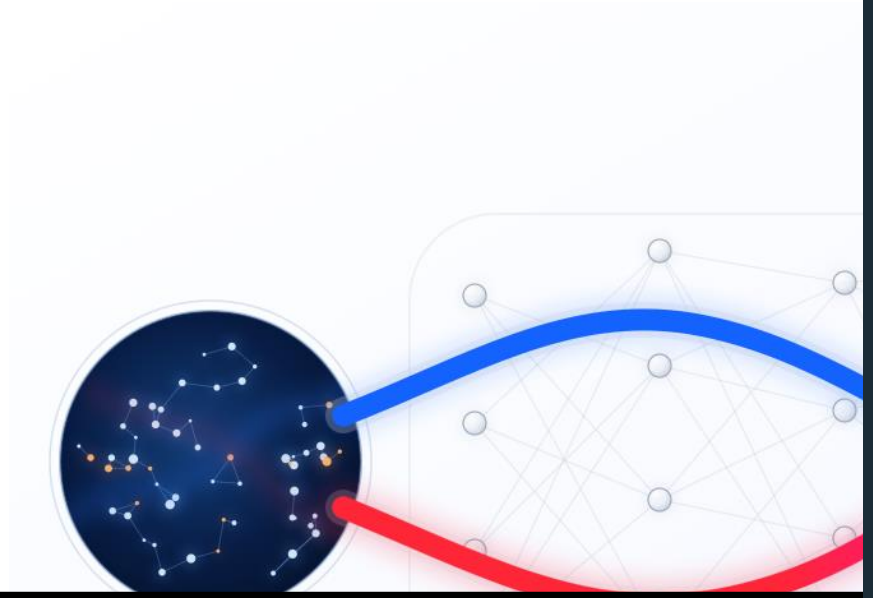

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BY GAYOUNG LEE PUBLISHED JUNE 11, 2026, 3:05 PM ET

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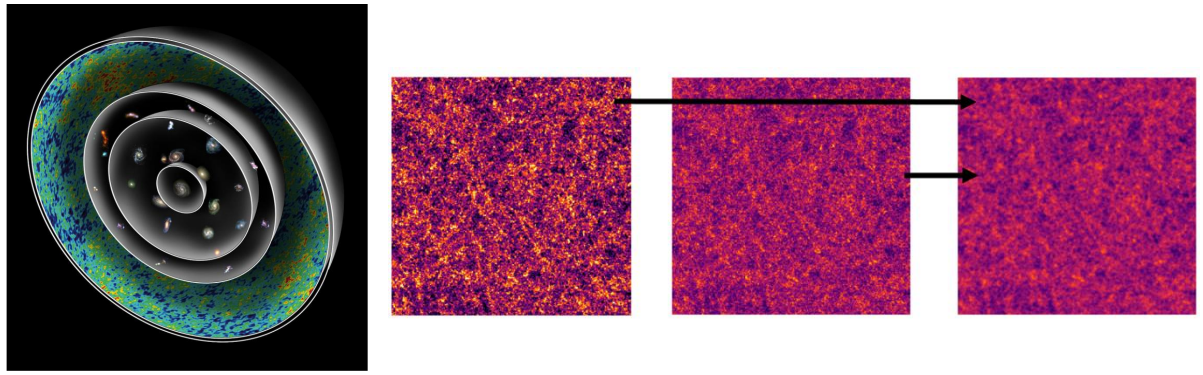
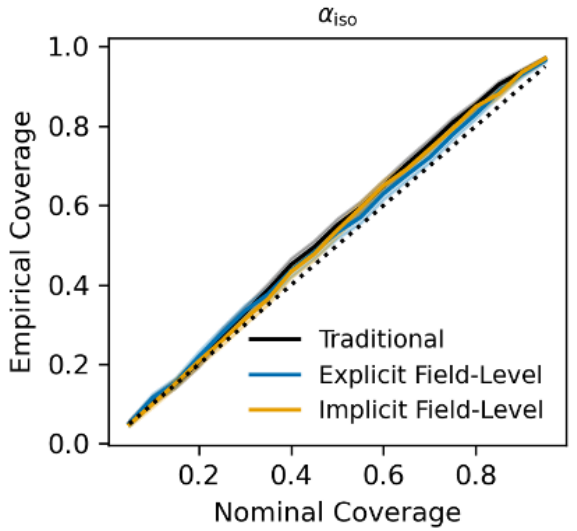
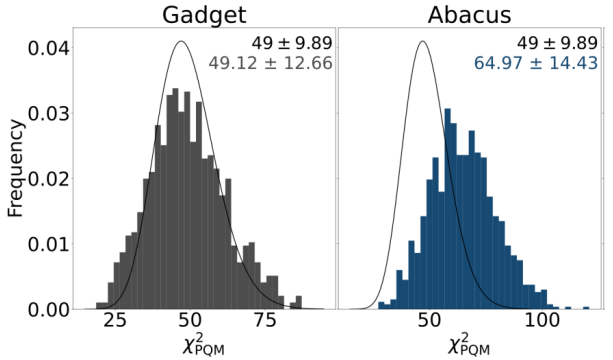
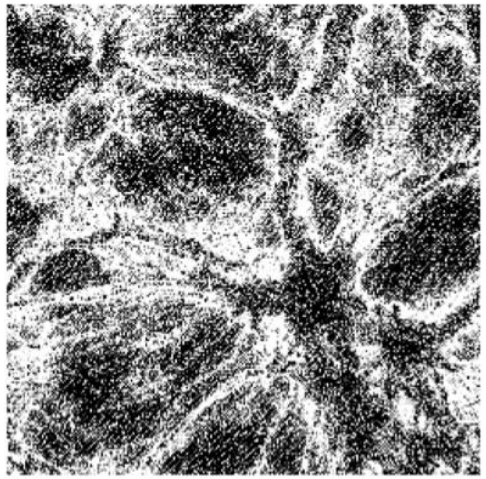


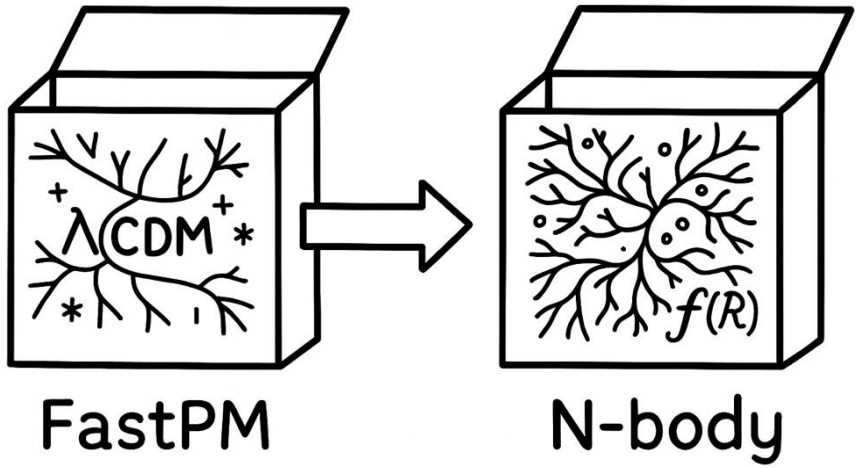
ROBUSTNESS







INTERPRETABILITY



EFFICIENCY

A British physicist and a Brooklyn filmmaker move through New York City, tracing a conversation between the deep Universe and life on Earth. The Cosmic Microwave Background emerges not as a distant echo, but as an infinite field of frequencies, the original hum of existence.

As these patterns unfold, they begin to echo in the rhythms of the city; movement, sound, and human connection. What emerges is not a translation, but a reflection: a search for harmony across scales, from the cosmos to the everyday.