Initial density field reconstructions from high redshift galaxy surveys

THE UNIVERSITY OF TOKYO

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Metin Ata(IPMU)

with Khee-Gan Lee(IPMU), Francisco-Shu Kitaura(IAC), Daichi Kashino (ETH), Brian C. Lamaux (UCD)

Giving BIRTH to COSMOS: Initial Conditions from Distant Galaxy Surveys in the COSMOS Field

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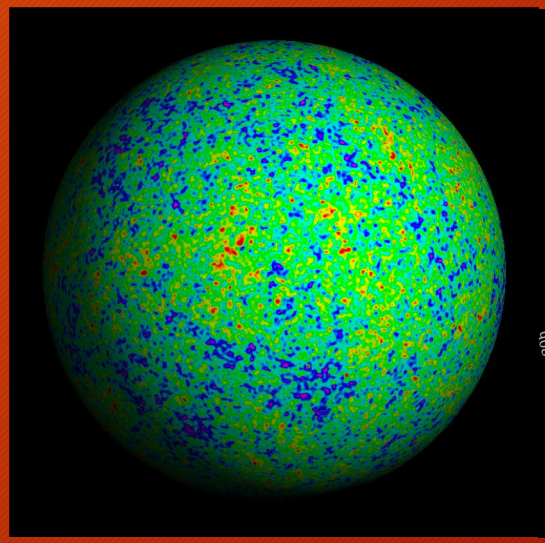
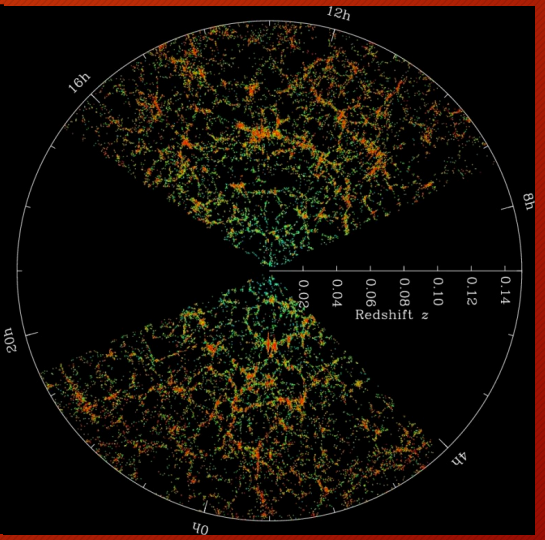
Starting Situation

- 3D maps of Galaxy surveys show spatial distribution of large-scale structure in the Universe
- Hierarchical structure formation, Pairs → Groups → Clusters → superclusters



Credit: M. Tegmark



Credit: M. Blanton SDSS

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Starting Situation

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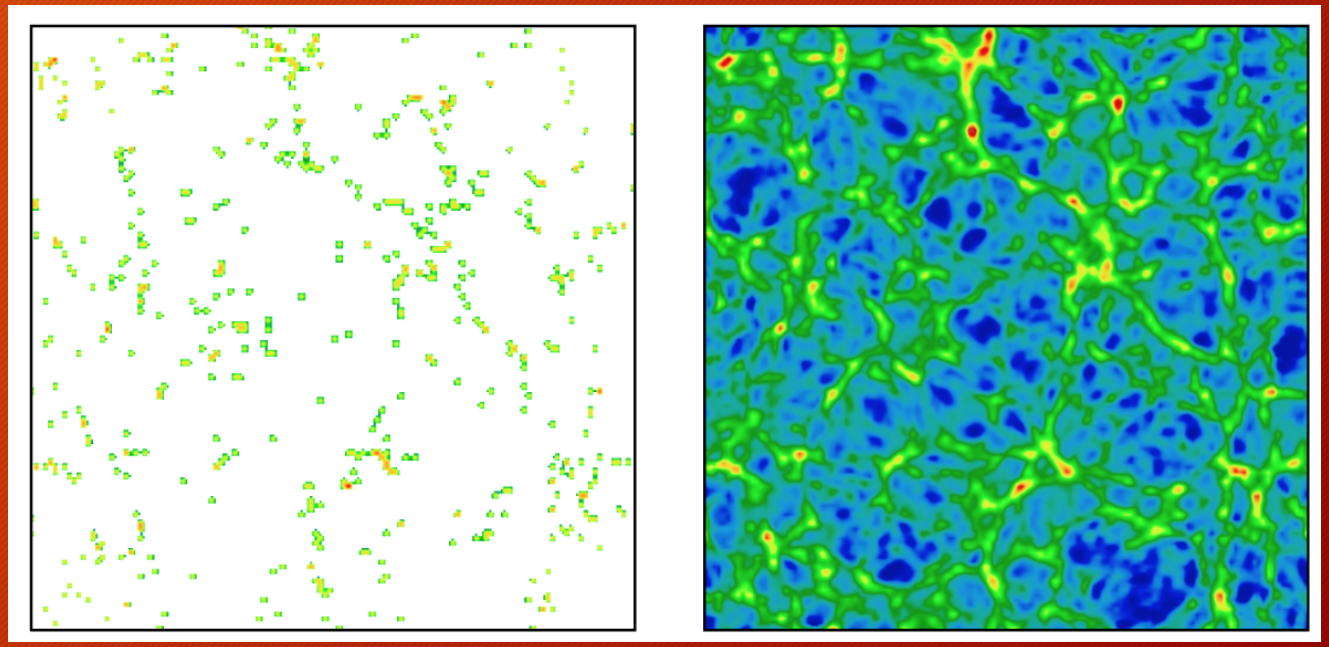
- Hierarchical structure formation, Pairs → Groups → Clusters → superclusters
- ΛCDM predicts galaxies to form at density peaks of DM, “Galaxies trace Dark matter”
- High redshift galaxy surveys like **PFS** are ideally suited to probe early structure formation at large redshift ranges



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Overview

- We want to know the cosmological initial density field inferred from observed galaxy distributions at high redshifts
- We want to combine the data of several surveys within a joint reconstruction

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- Three major problems for this work:
  - **Problem 1**: No selection functions available **(Observational)**
  - **Problem 2**: How to map initial and final conditions of density perturbations including an evolution along line of sight **(Theoretical)**
  - **Problem 3**: How to combine maps of different galaxy surveys that constrain same underlying density field **(Statistical)**

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- Discuss results

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Problem 1: Observations

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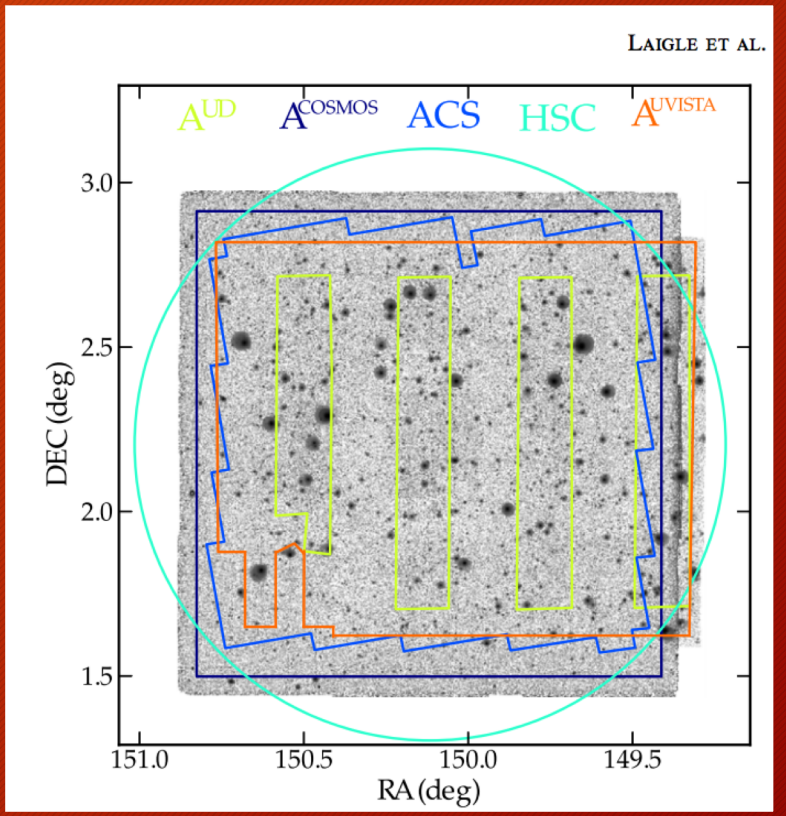
- Cosmic Evolution Survey (COSMOS), photometric galaxy catalog 1< z< 6



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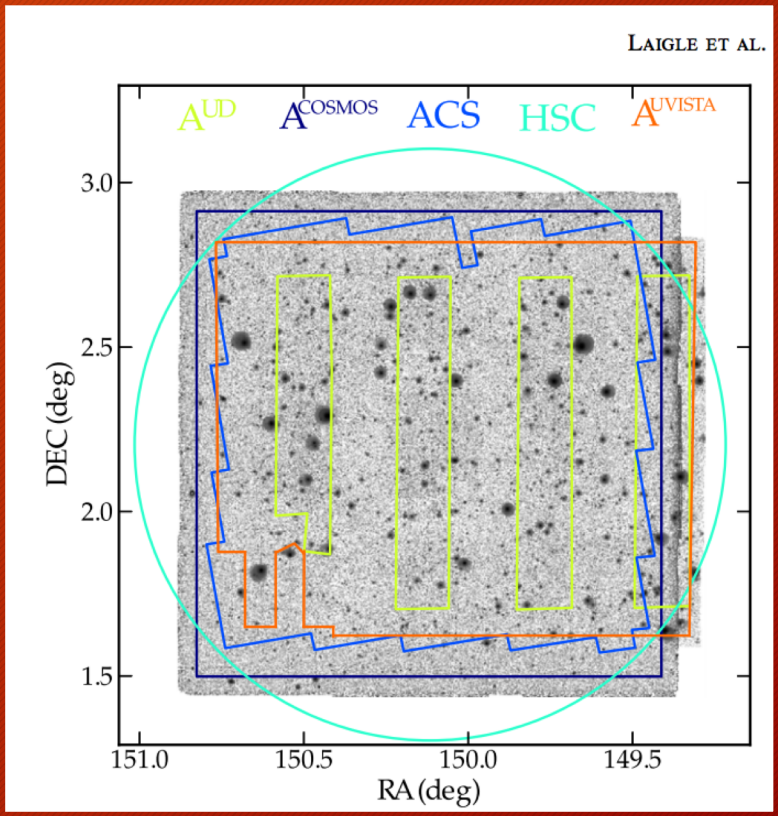
Problem 1: Observations

- Cosmic Evolution Survey (COSMOS), photometric galaxy catalog 1< z< 6
- Several spectroscopic surveys undertaken in this field:
  - zCOSMOS
  - VUDS
  - MODSEF
  - ZFIRE
  - FMOS-COSMOS



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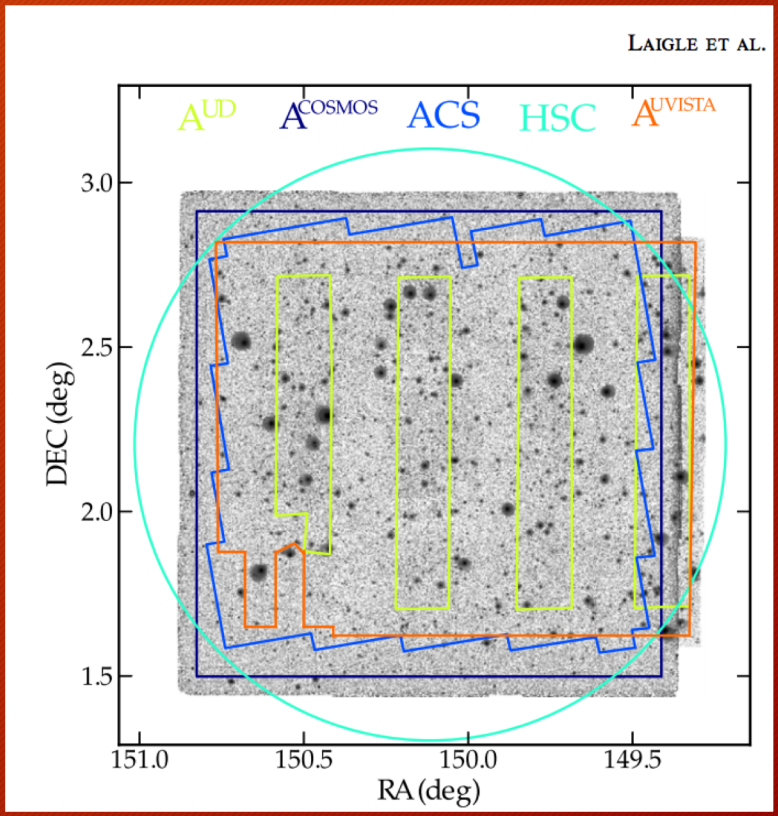
- Several spectroscopic surveys undertaken in this field:
  - zCOSMOS
  - VUDS
  - MODSEF
  - ZFIRE
  - FMOS-COSMOS
- Problem: main purpose of these surveys is to study galaxy evolution, and not estimate density field
  → No information of selection function



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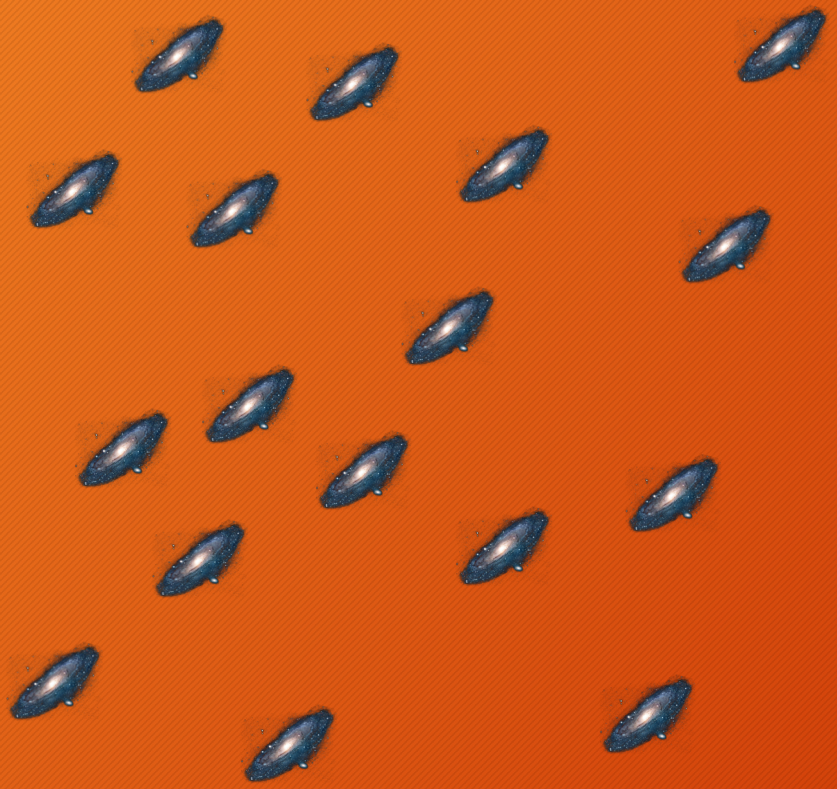
Selection function estimation



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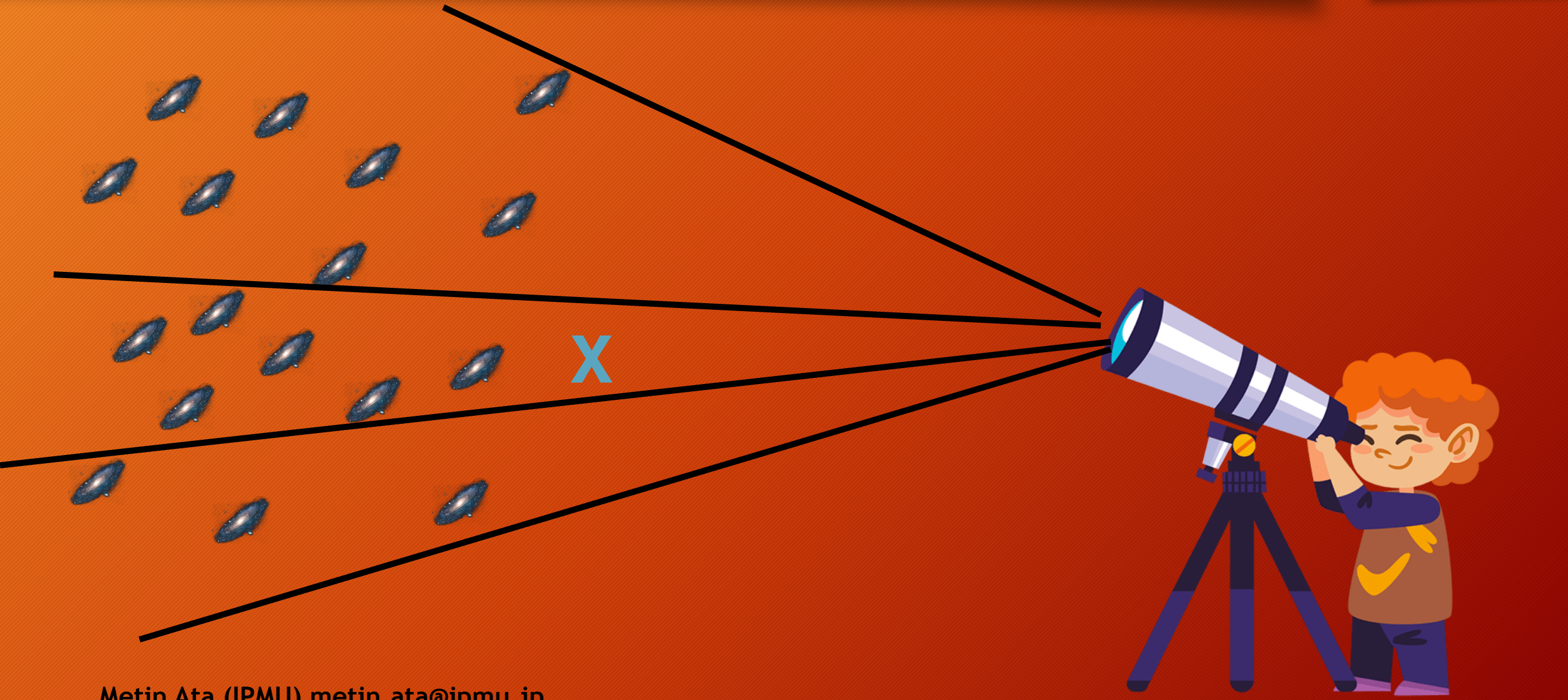

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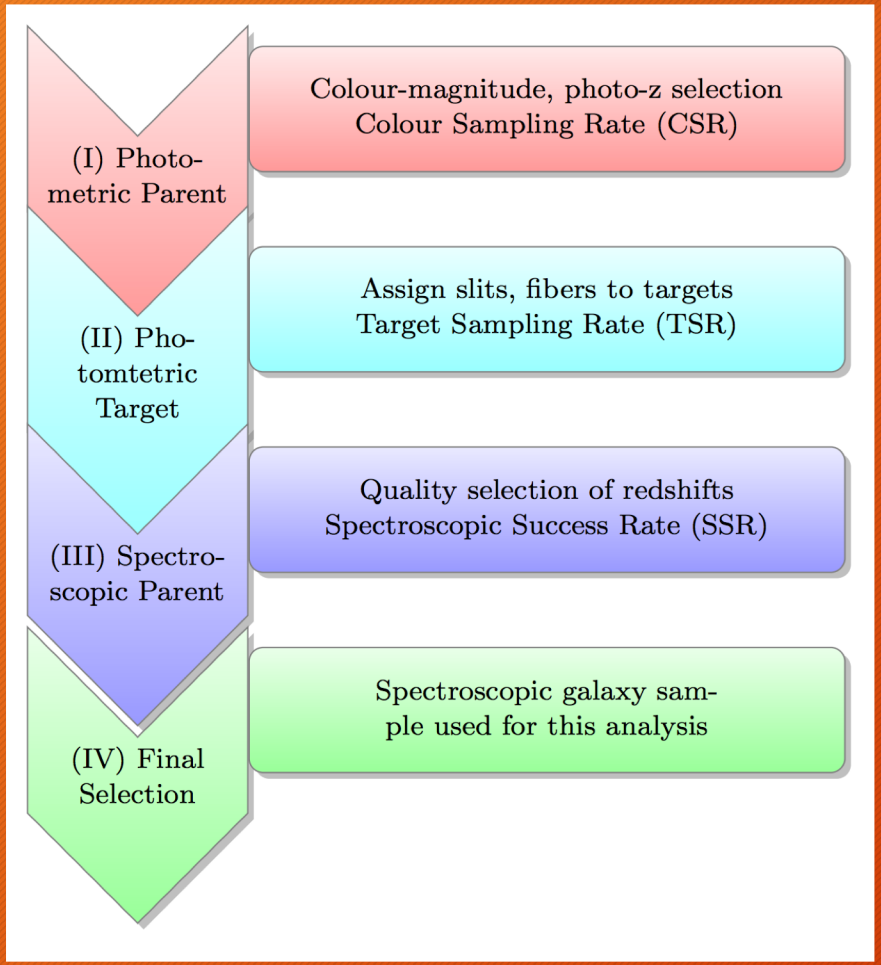
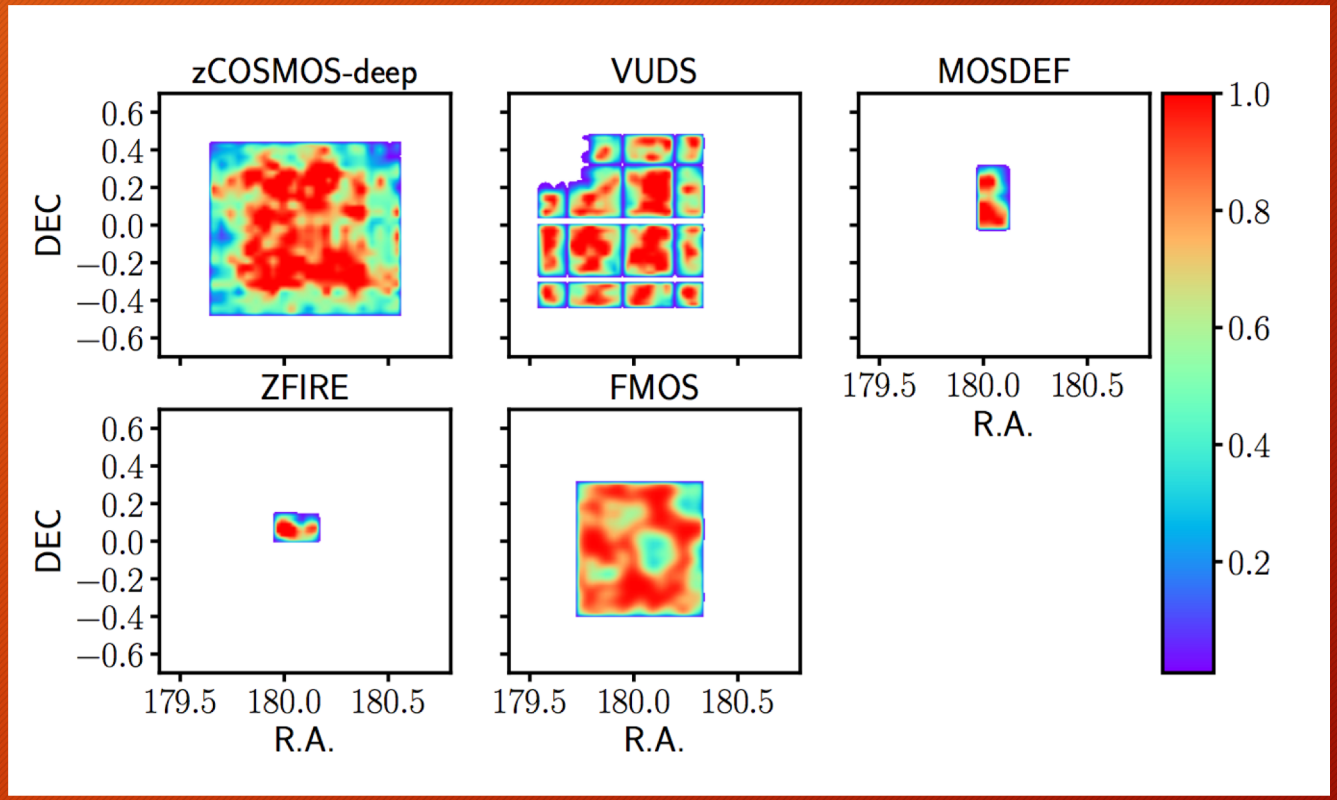
Problem 1: Solution





$$R = R^{\alpha} \times R^{LOS}$$

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Problem 2: Theoretical Framework

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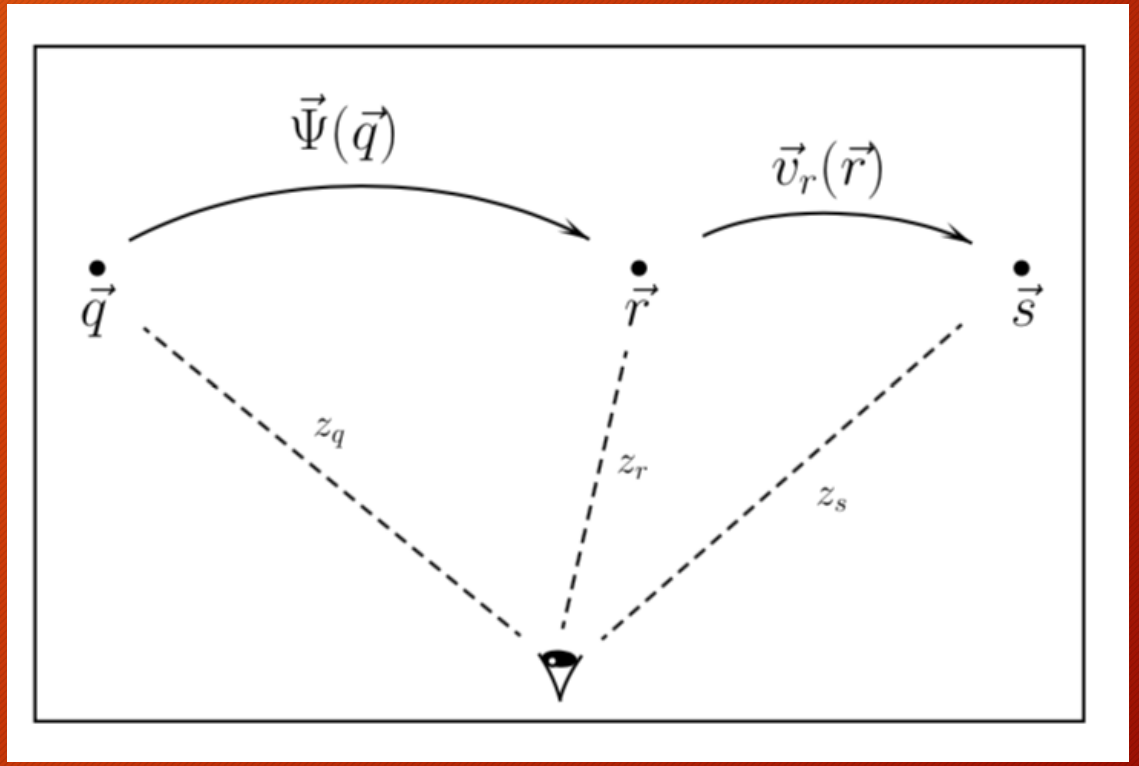
COSMIC BIRTH algorithm

- COSMIC BIRTH (arXiv:1911.00284) COSMological Initial Conditions from Bayesian Inference Reconstructions with THeoretical models

- Phase-space mapping problem:

$$\vec{q} = \vec{s} - \vec{\Psi}(\vec{q}) - \vec{v}_r(\vec{q})$$



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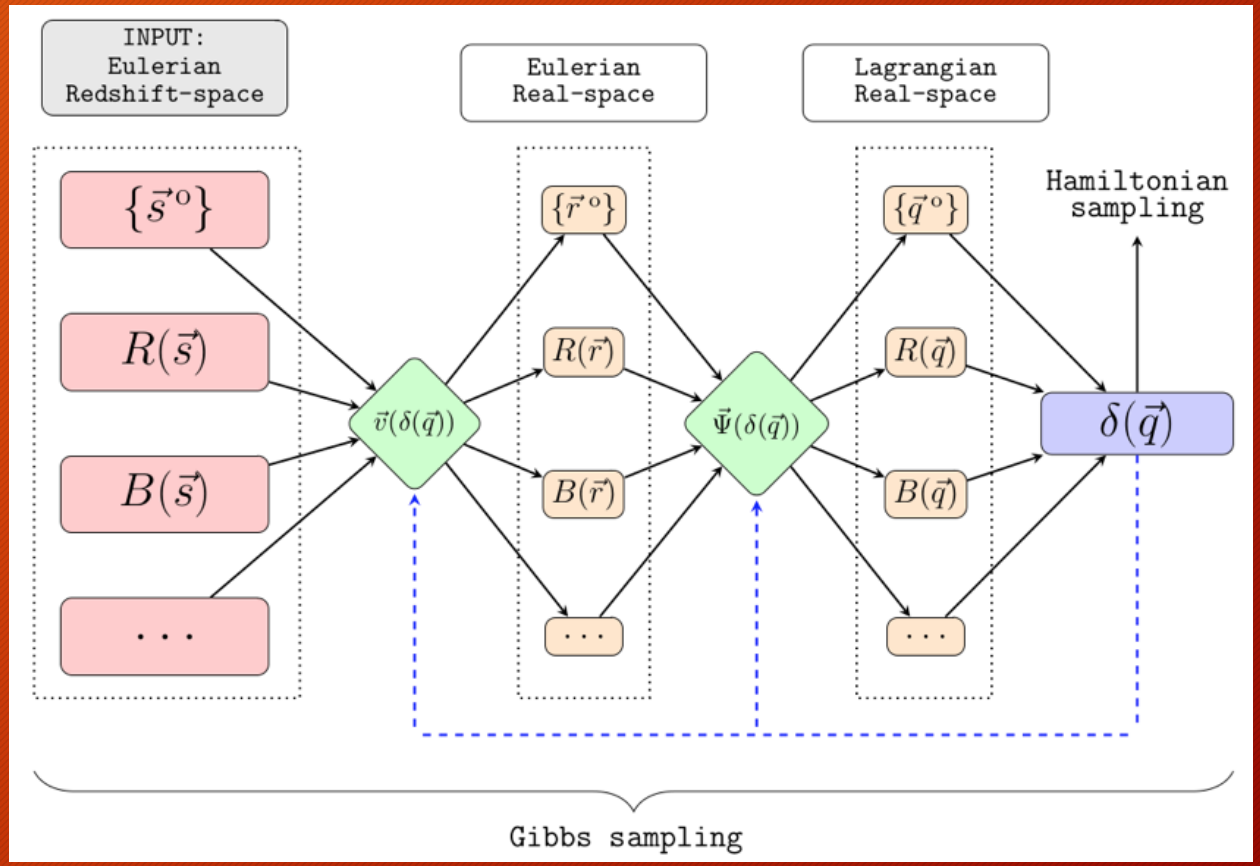
COSMIC BIRTH algorithm

- Move back all galaxies to Lagrangian positions and sample the Gaussian field on a regular grid
- Nested Gibbs sampling scheme to forward model:
  - Peculiar velocities,
  - Displacements,
  - Selection function,
  - Bias parameters,

$$\vec{q} = \vec{s} - \vec{\Psi}(\vec{q}) - \vec{v}_r(\vec{q})$$



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COSMIC BIRTH: nested Gibbs-sampling

- In a first step we assume all tracers to be at Lagrangian coordinates $\boldsymbol{q}$:

$$\boldsymbol{\delta(q)} \curvearrowleft \mathcal{P}(\boldsymbol{\delta(q)}|\{\boldsymbol{q}\}, \mathcal{B}(\boldsymbol{q}), \boldsymbol{R(q)})$$

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- In a first step we assume all tracers to be at Lagrangian coordinates $\boldsymbol{q}$:

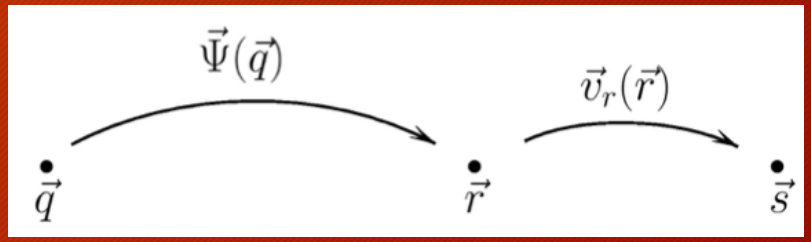
$$\boldsymbol{\delta(q) \curvearrowleft \mathcal{P}(\delta(q)|\{q\}, \mathcal{B}(q), R(q))}$$

- Secondly, we obtain the Lagrangian positions $\boldsymbol{q}$ with forward modelling

$$\boldsymbol{\{q\} \curvearrowleft \mathcal{P}(\{q\}|\{s^{obs}\}, \delta(q), R(q))}$$

$$\boldsymbol{r(z) = q + \Psi(q, z) = q + D(z)\nabla\phi(q)}$$

$$\boldsymbol{v(z) = \frac{dr(z)}{d\tau} = \frac{d\Psi(q, z)}{d\tau} = \dot{D}(z)\nabla\phi(q)}$$



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Density sampling with Hamiltonian Monte-Carlo (HMC)

$$\mathcal{P}(\delta|N_G, R) \propto \pi(\delta) \times \mathcal{L}(N_G|\lambda, R) \text{ with } \quad \lambda = \langle N_G \rangle = R\mathcal{B}(\delta)$$

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Problem 3: Combine surveys

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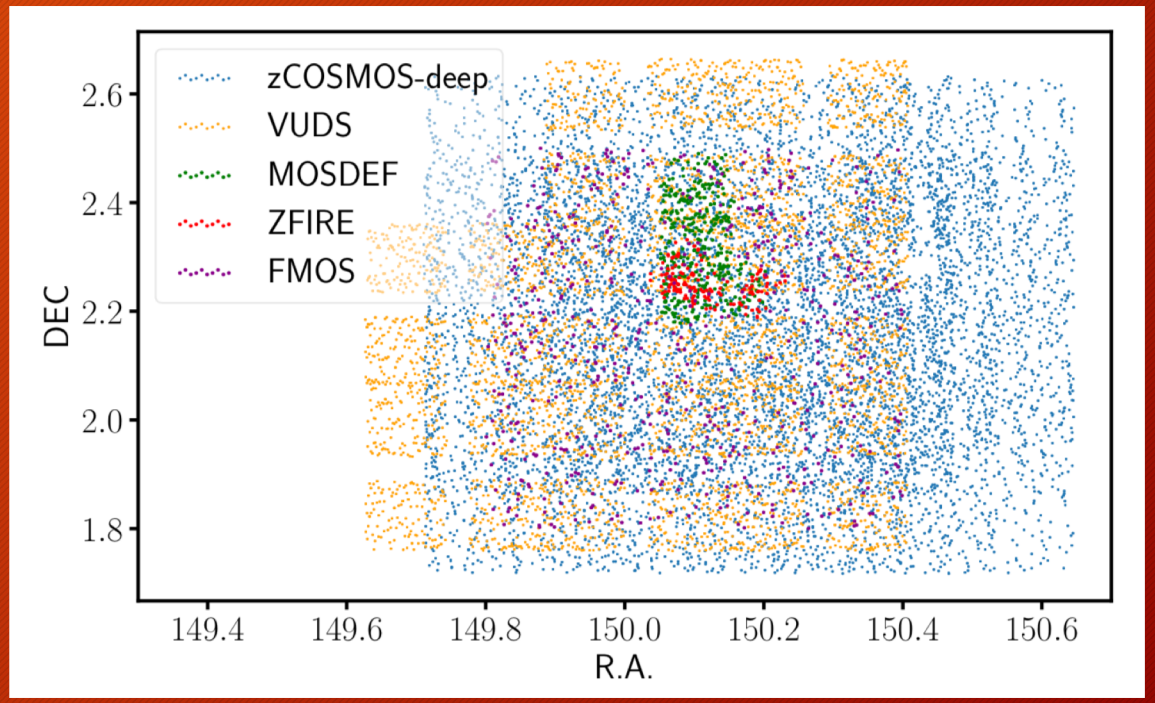
Combine surveys in probabilistic framework

- Combine contrains of distinct galaxy catalogs withing our Bayesian method:

$$\mathcal{L}^{multi}\left(N_G|\lambda,R\right) \propto \prod_k \mathcal{L}^{(k)}\left(N_G^{(k)}\middle|\lambda^{(k)},R^{(k)}\right) \qquad \lambda^{(k)} = \langle N_G \rangle^{(k)} = R^{(k)}\mathcal{B}^{(k)}(\delta)$$

- Likelihood generalized for *k* surveys with different
  - survey geometry
  - number density
  - galaxy bias
  - …
- Contraining the *joint* underlying density field



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Results

- We reconstruct on a rectangular grid with 2 cMpc/*h* resolution
  $1.4 < z < 3.6$

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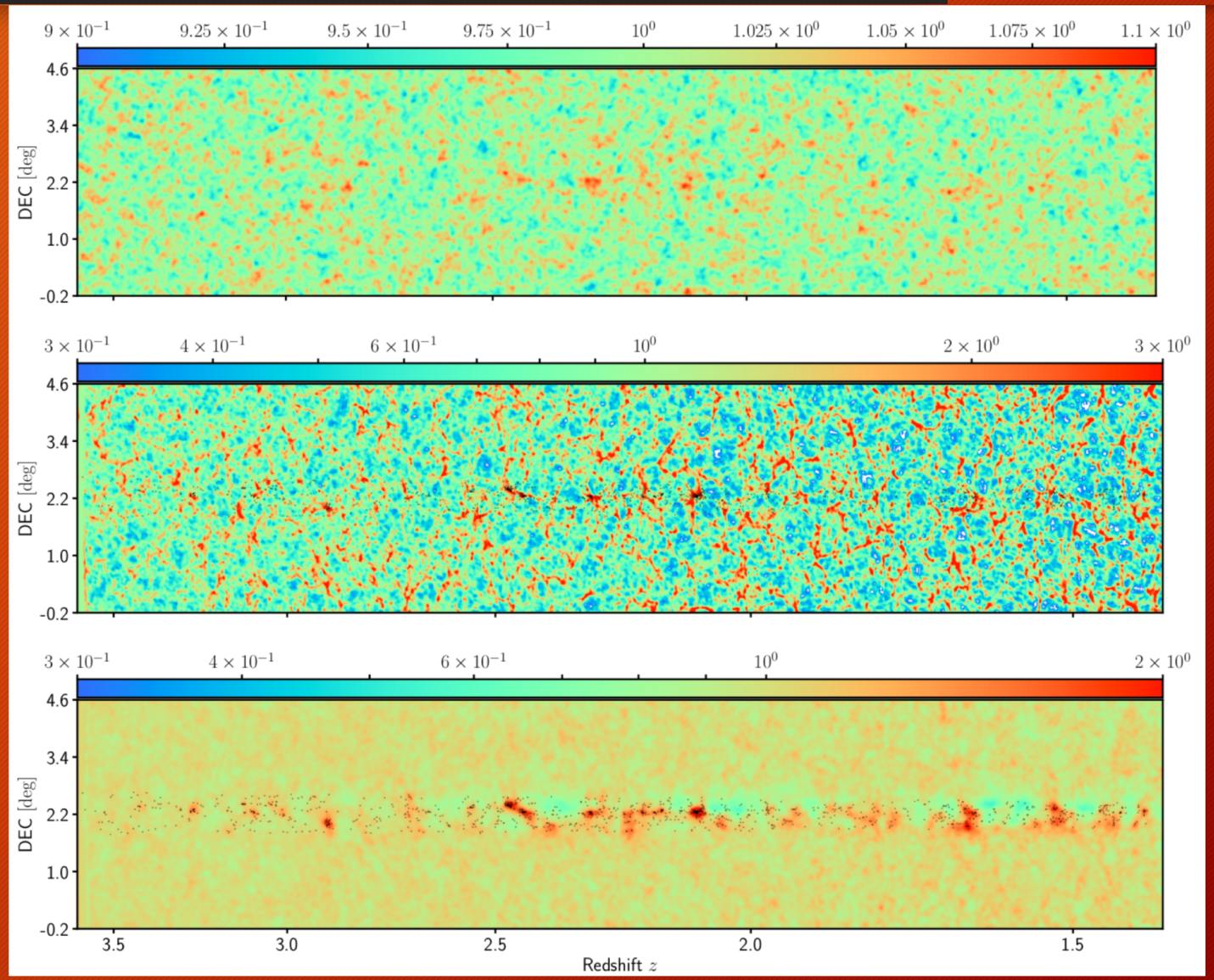
- Recover prominent proto-clusters around $2.< z < 2.5$



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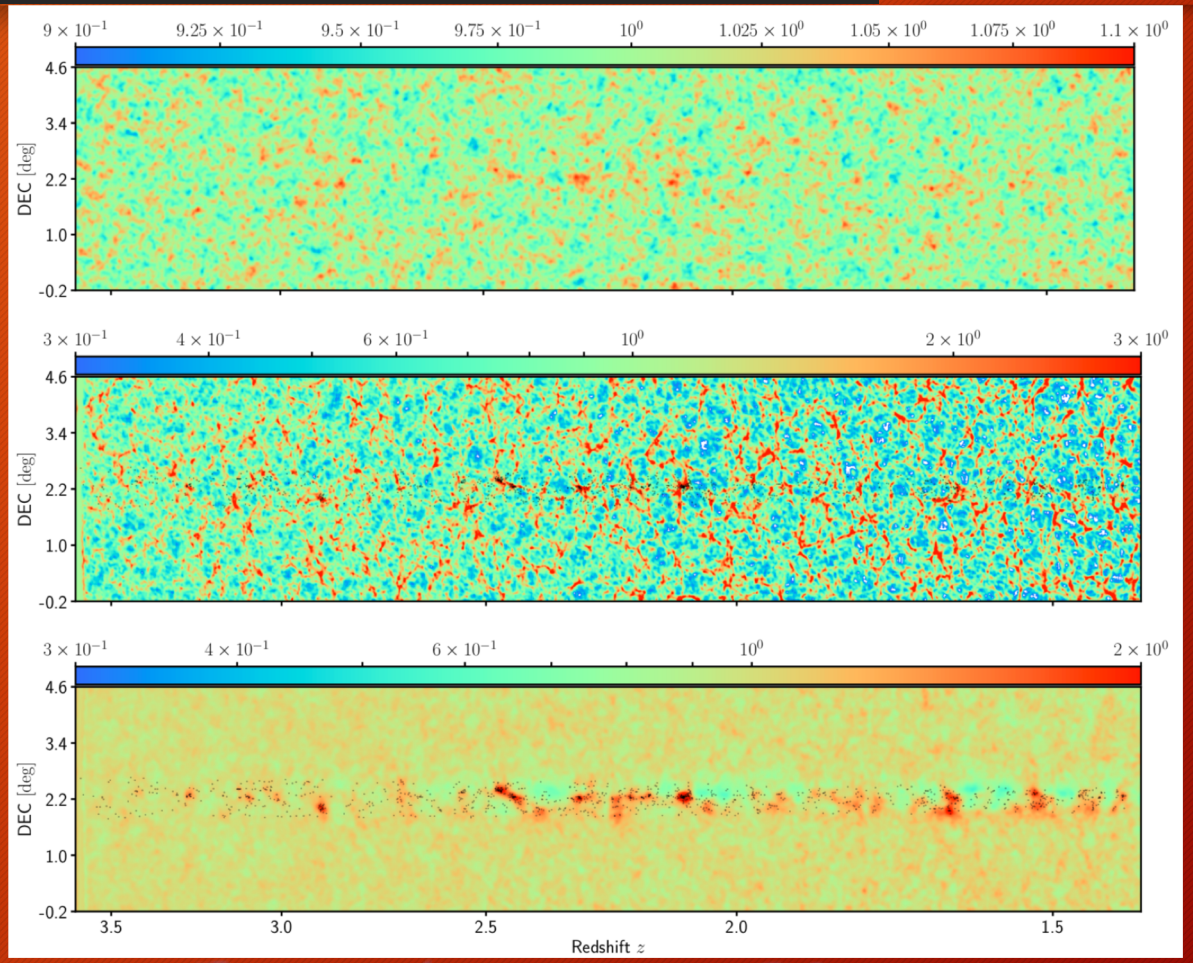

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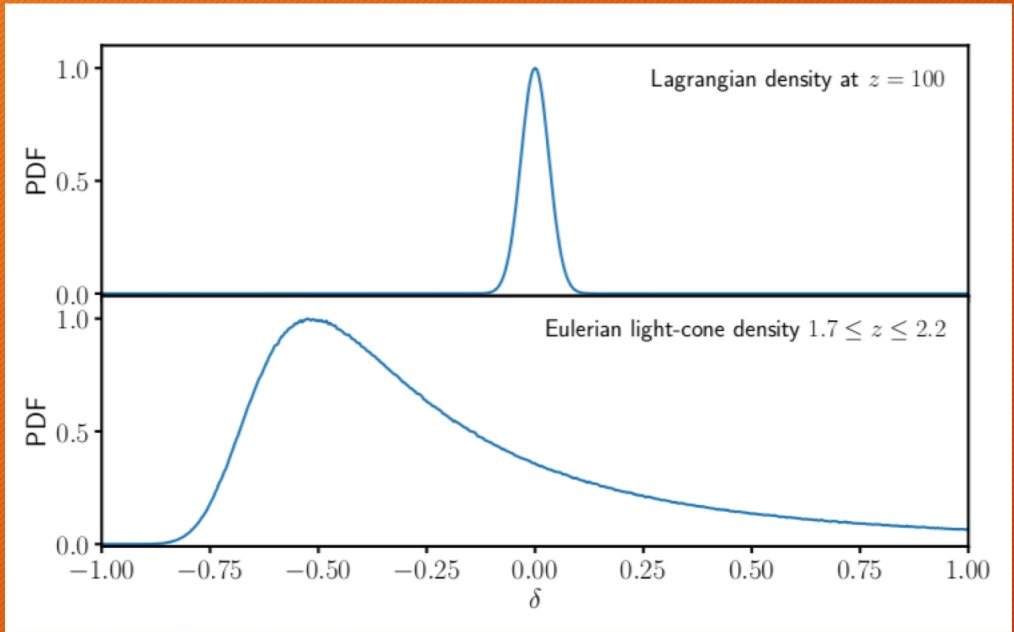

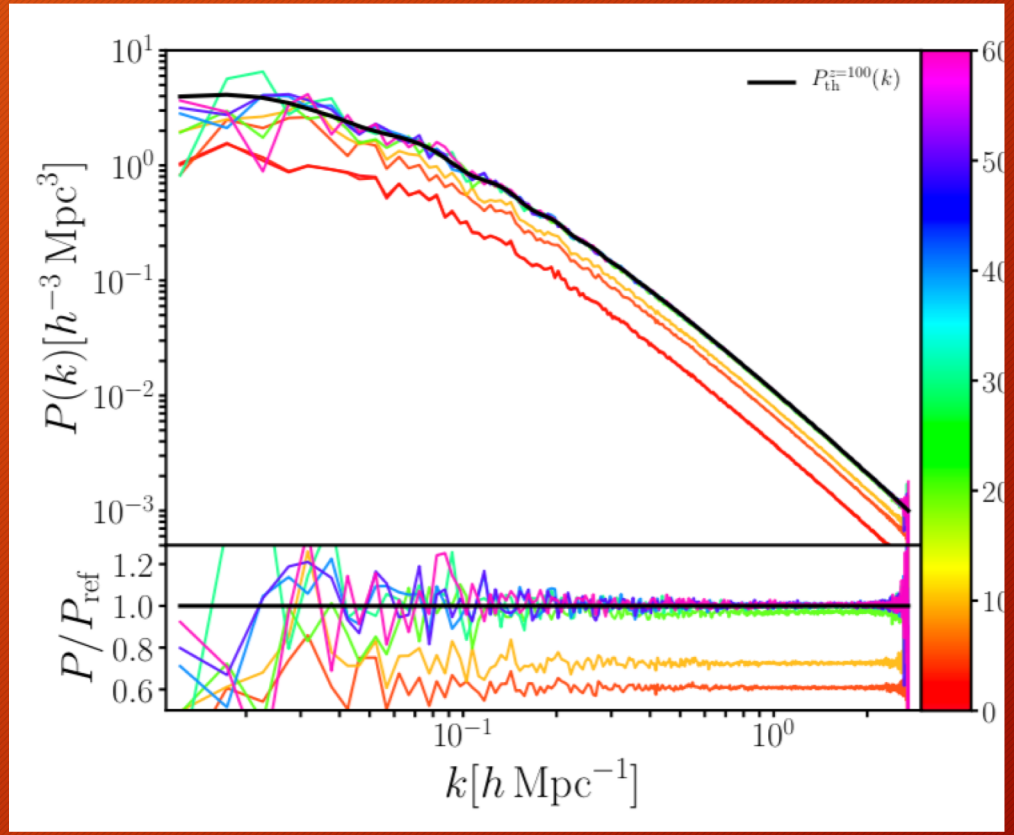

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More Results: Constrained Simulations

- Use density field at *z*=100 as initial conditions for *N*body simulation
- $\delta(q)$→white noise → 2LPT (Music code) → Tipsy → PKGRAV →DM particles
- 512^3 particles on a 480 cMpc/*h* → Mass resolution of ~$10^{10}\,M_\odot$

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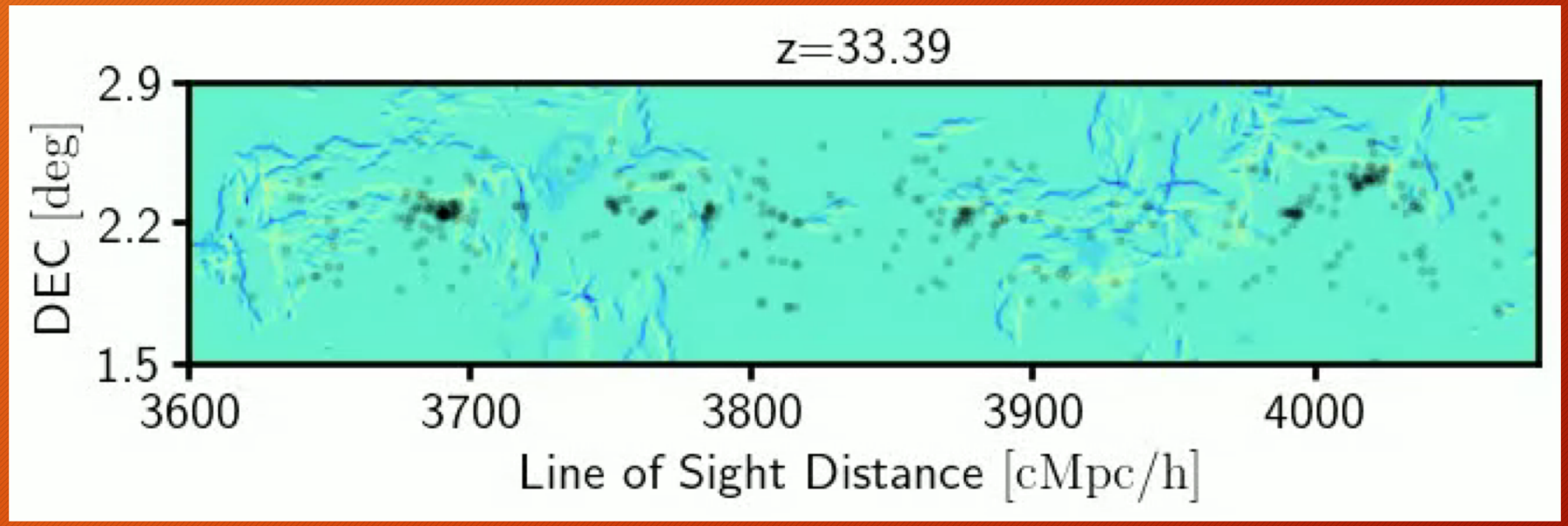

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Outlook

- We reconstructed initial conditions from 5 spectroscopic redshift surveys in the COSMOS field on a light-cone
- BIRTH is ready for PFS/deep surveys

- Succeeding works to do:
  - Compare dark matter maps from galaxy tracers to IGM tomography maps
  - Constrain (possible) masses of proto-clusters after full virialization

  - Implement BIRTH with *N*body solver iteratively

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