High redshift galaxy clusters as a cosmological tool

galaxy clustering -- density field reconstructions -- constrained simulations

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arXiv:1605.09745, arXiv:1911.00284, arXiv:2004.11027

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Context

- Cosmology: Physics of the origin and dynamics of the Universe
- Cosmological principle: Universe is homogenous and isotropic at large enough scales.
- Standard model of Cosmology at present ΛCDM

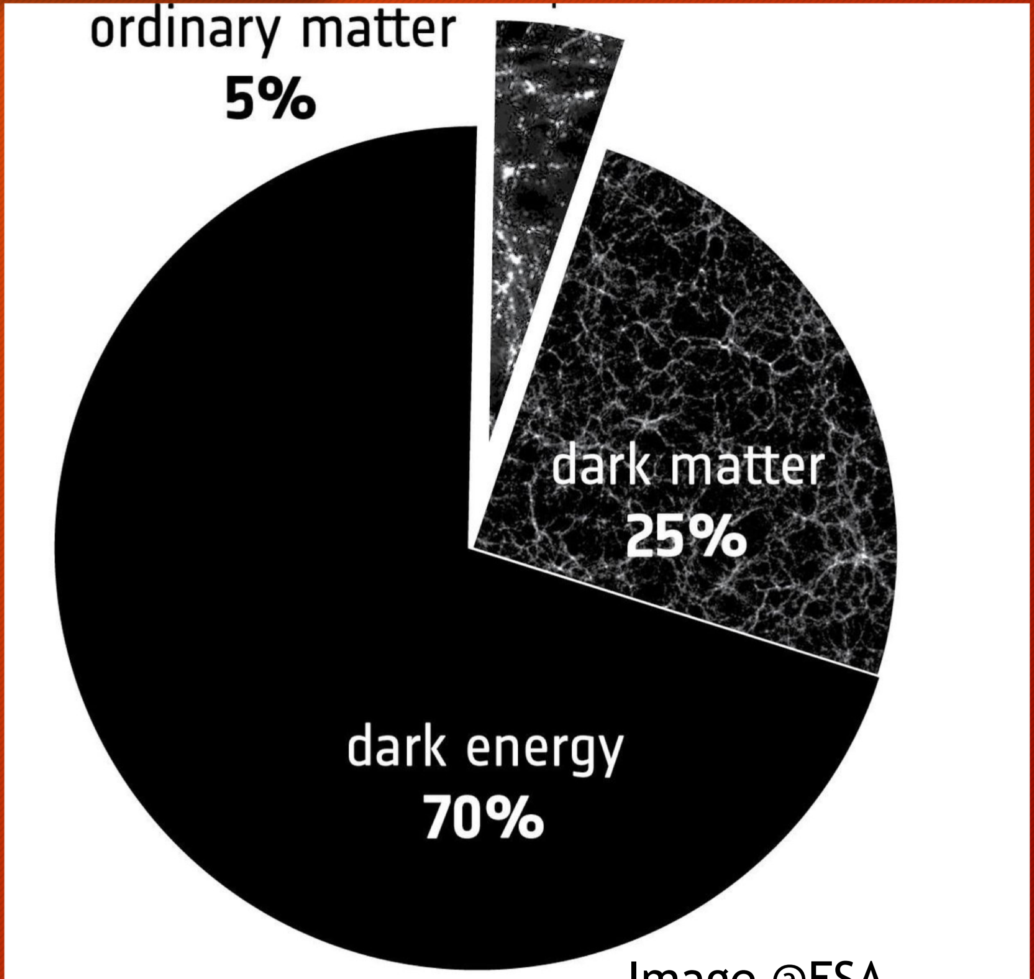


Image @ESA

Menu of this talk

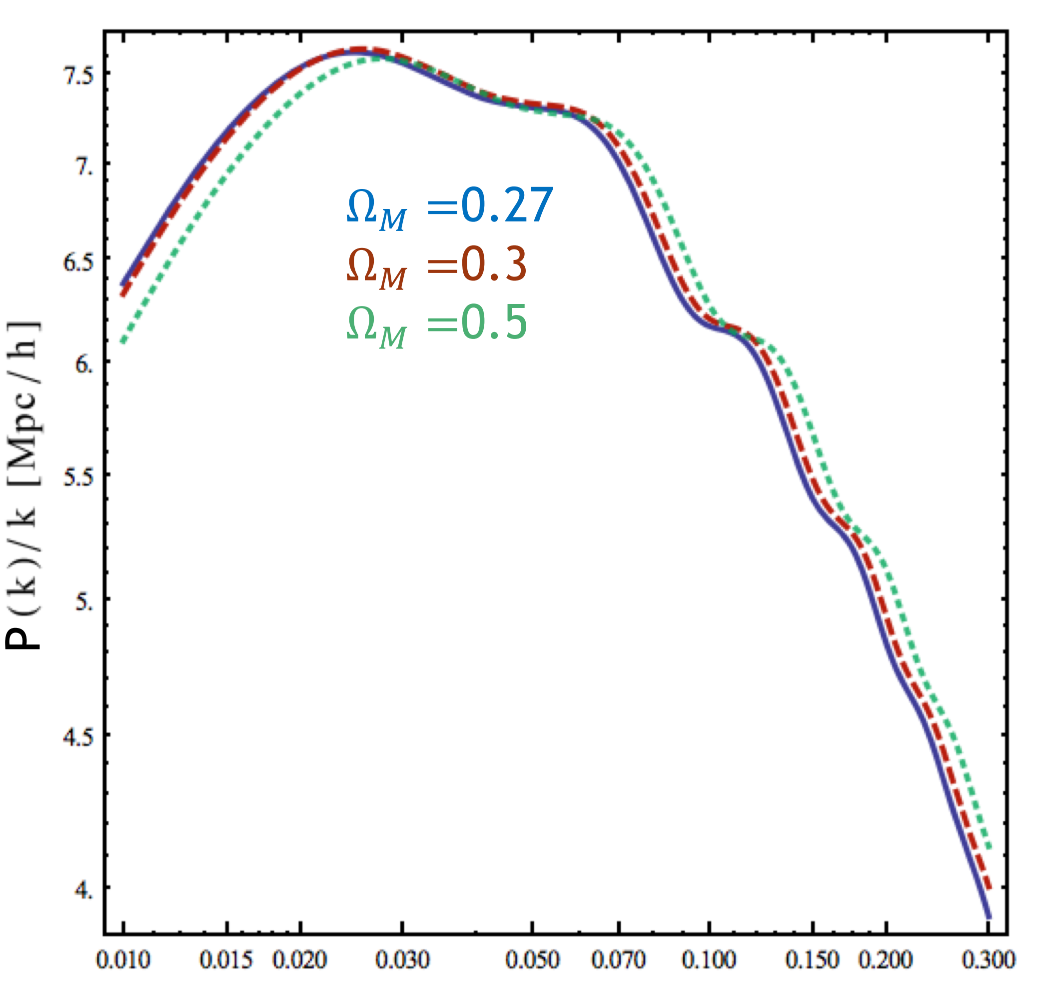
- Galaxy clustering / Galaxy surveys
- Density field & Initial conditions reconstructions
- Constrained simulations
- Conclusions

Menu of this talk

- Galaxy clustering / Galaxy surveys

Galaxy clustering / Galaxy surveys

- Analyze the spatial , $\delta(\vec{k}) \rightarrow P(|\vec{k}|)$
- Correlation functio
  - Cosmological parar
  - Clustering history
  - Angular/line-of-sig



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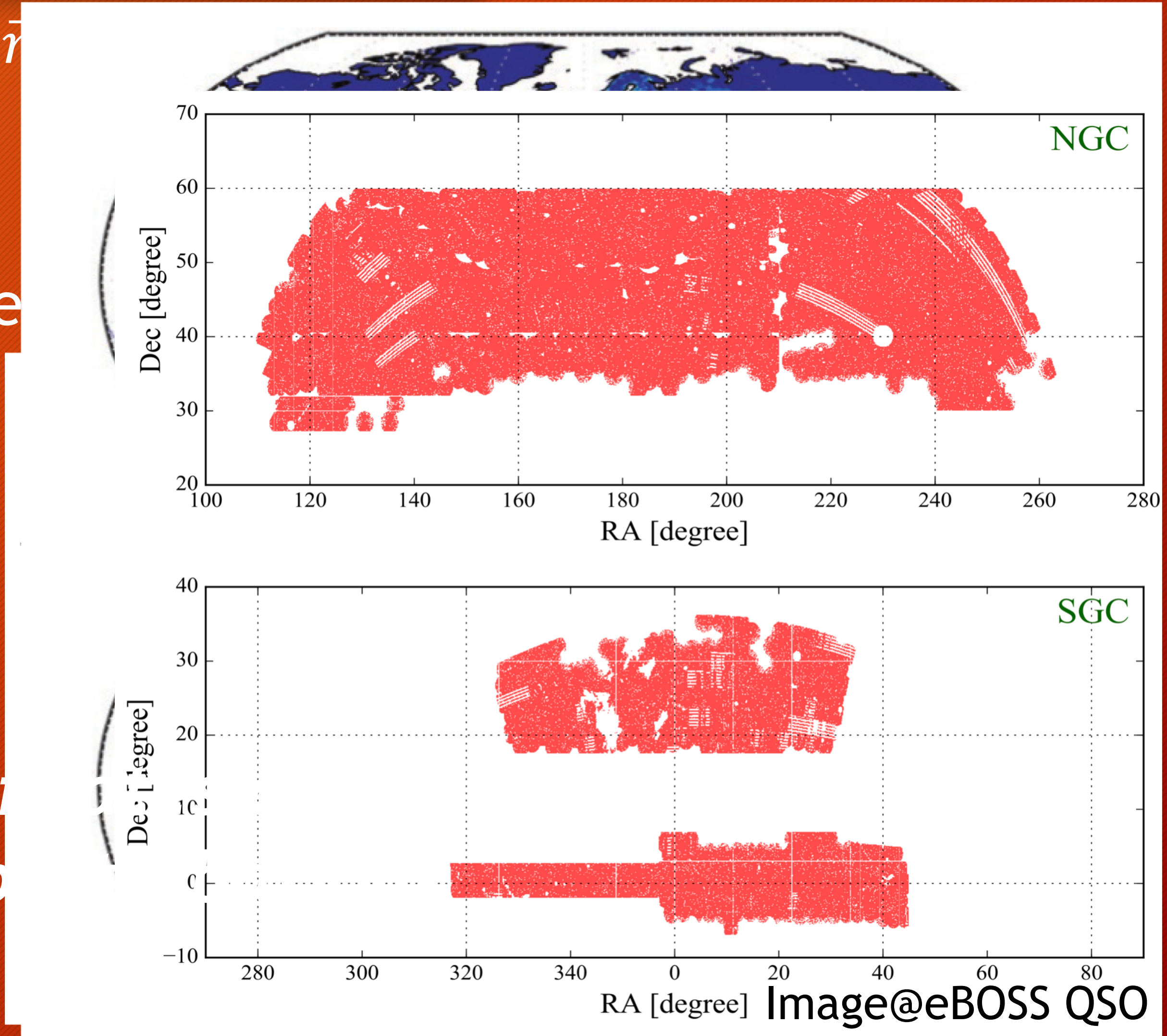
Galaxy clustering / Galaxy surveys

- Galaxy surveys observe 3D galaxy positions $\vec{r}$
- We observe luminous matter
  - → There is a galaxy bias $\delta_{\mathrm{Gal}} = \mathcal{B}(\delta_{\mathrm{DM}})$
- Trade-off between number density and cove
  - → Complex survey geometry and completeness
- Measure redshifts, ***not*** distances
  - → $z \approx \frac{H_0 D + v_r}{c}$: Redshift Space Distortions
  - → $\vec{r} = \vec{s} - ((\vec{v}_r(\vec{r}) \times \hat{r})/H(a)a)\ \hat{r}$

We need unbiased esti
matter density p



Image@eBOSS QSO

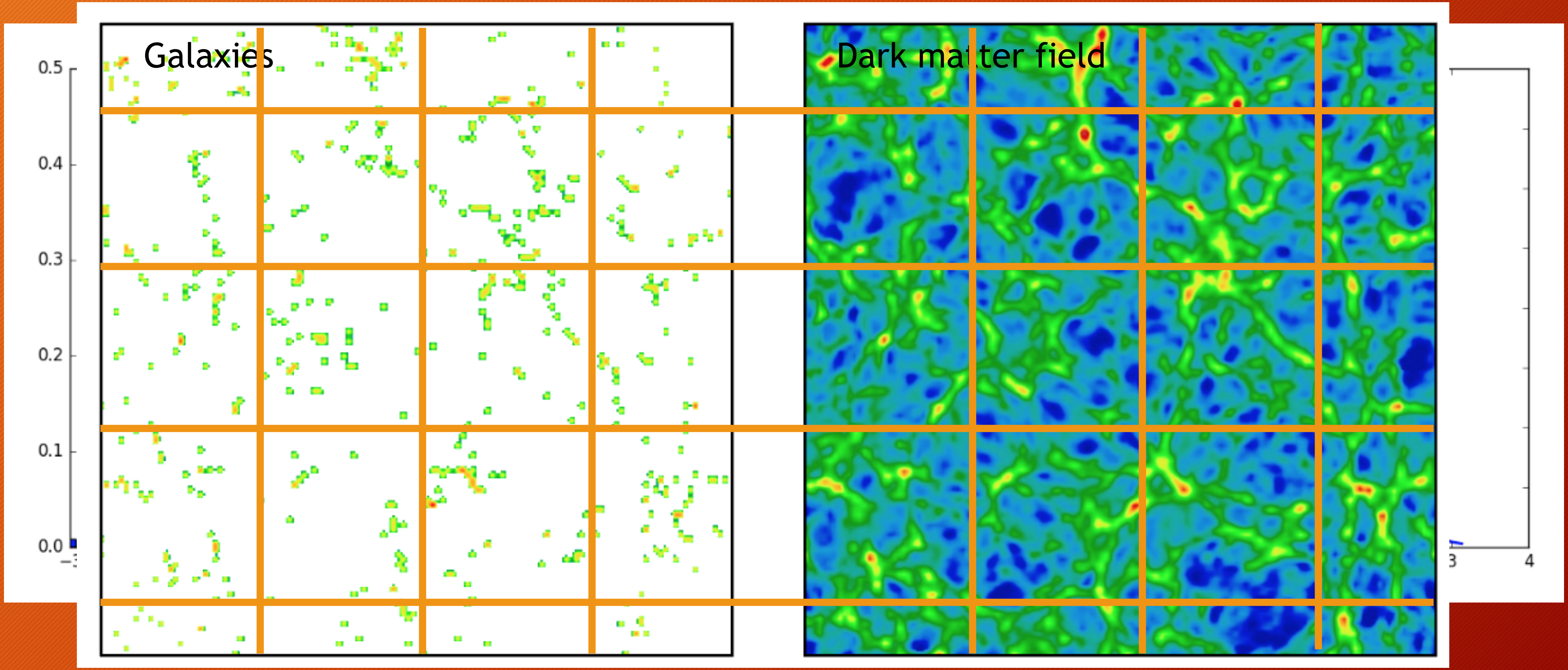
Menu of this talk

- Galaxy clustering / Galaxy surveys

- Density field & Initial conditions reconstructions

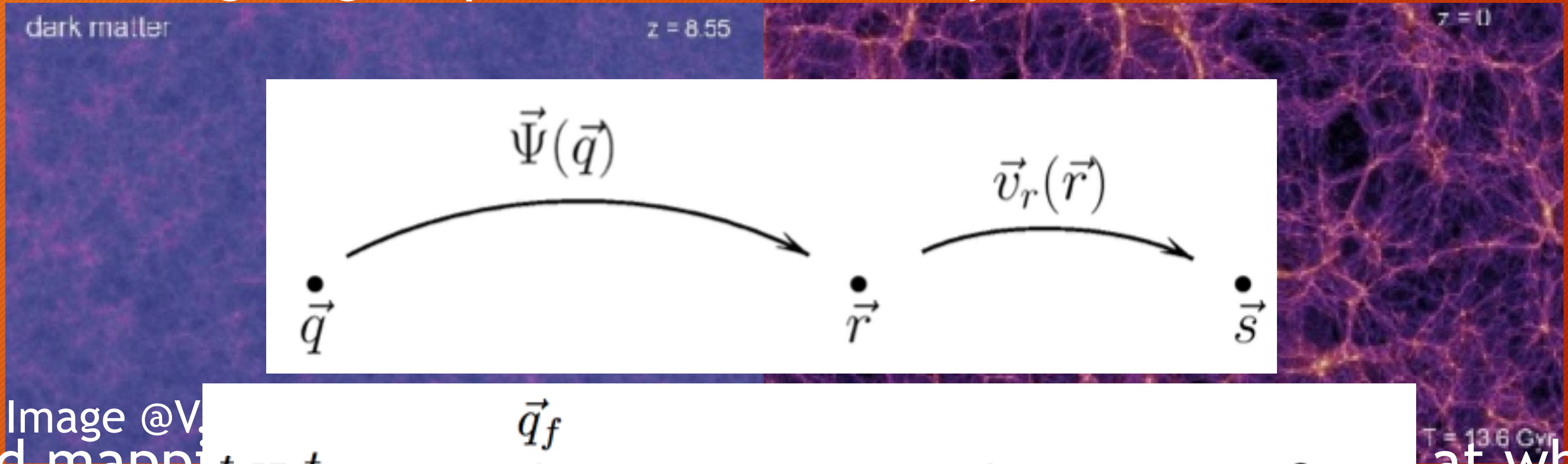
Density field & Initial conditions reconstructions

- Statistical approach



Density field & Initial conditions reconstructions

- Initial (Lagrangian) positions $\vec{q}$ to final (Eulerian) $\vec{r}(\vec{q})$ mapping with gravity
- Connected via Lagrangian perturbation theory $\vec{q} = \vec{s} - \vec{\Psi}(\vec{q}) - \vec{v}_r(\vec{q})$



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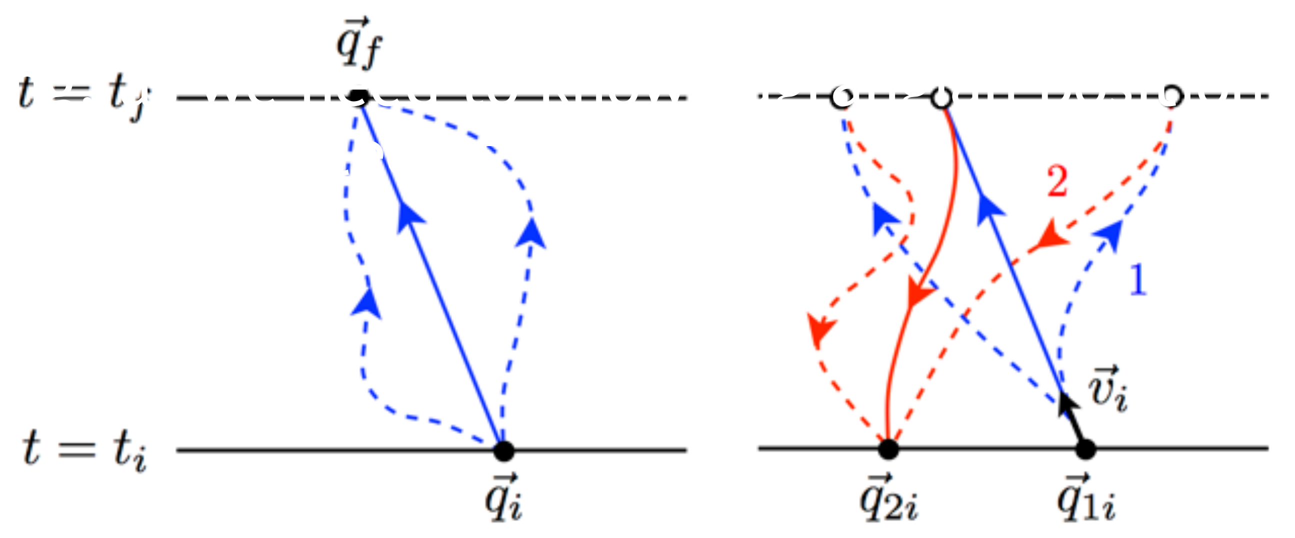
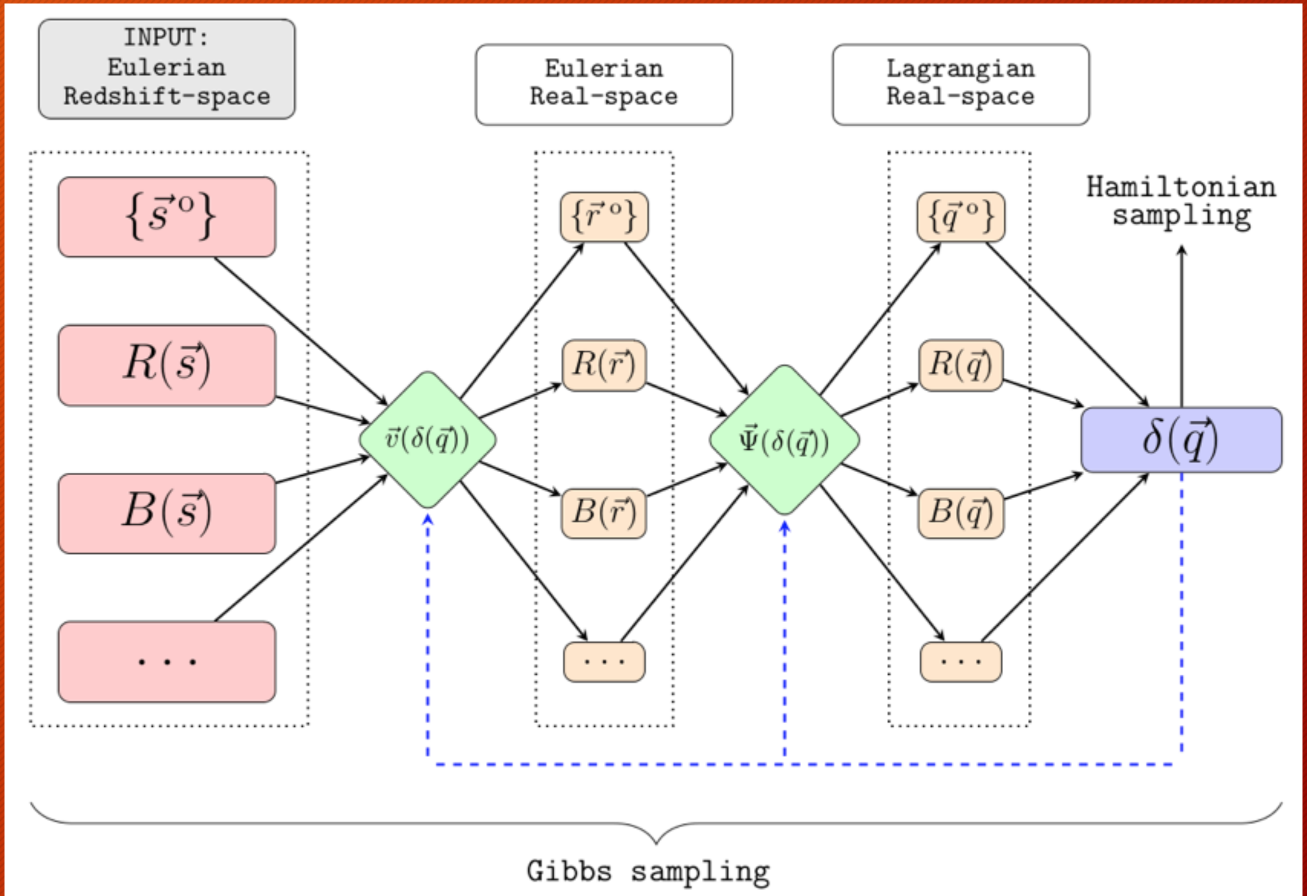


- Ill defined mappi … at which velocity and displacement fie…

COSMIC BIRTH algorithm I

- COSMIC BIRTH (Kitaura, F.-S., MA et al 2019) arXiv:1911.00284 (Based on KIGEN arXiv:1205.5560 and ARGO e.g. arXiv:1605.09745)
- Move galaxies back to initial positions and infer the Gaussian density field at Lagrangian frame $\delta(\vec{q})$ with Hamiltonian Monte-Carlo
- Then use nested Gibbs sampling
  - Peculiar velocities,
  - Displacements, (ALPT Kitaura F.-S., Hess S., 2013)
  - Response function of the survey,
  - Bias parameters



COSMIC BIRTH algorithm II

- Density sampling: $\delta(\vec{q}) \curvearrowleft \wp(\delta(\vec{q})|(\vec{q}), R, B(\vec{q}))$

$$\mathcal{P}_\delta\left(\boldsymbol{\delta}_{\rm M}|N_{\rm G}\left(\boldsymbol{r}\right), w(\boldsymbol{r}), \mathbf{C}\{p_{\rm C}\}, \{p_{\rm B}\}\right) = \frac{1}{\sqrt{(2\pi)^{N_{\rm c}}, \det(\mathbf{C})}} \exp\left(-\frac{1}{2}\sum_{\alpha\beta}[\log(1+\delta_\alpha)-\mu], C^{-1}_{\alpha\beta}[\log(1+\delta_\beta)-\mu]\right) \times$$

$$\prod_{i=1}^{N_{\rm c}}\left(\frac{[f_{\bar{N}}w(r_i)(1+\delta_i)^b\Theta(\delta_i-\delta_{\rm th})]^{N_i}}{N_i!}\frac{\Gamma(\beta+N_i)}{\Gamma(\beta)(\beta+[f_{\bar{N}}w(r_i)(1+\delta_i)^b\Theta(\delta_i-\delta_{\rm th})])^{N_i}}\frac{1}{\left(1+\frac{[f_{\bar{N}}w(r_i)(1+\delta_i)^b\Theta(\delta_i-\delta_{\rm th})]}{\beta}\right)^{\beta}}\right)$$

  - Kinetic artificial term $K(q) = \frac{1}{2}p^T M^{-1} p$, so that we sample $U(q) = -\ln(P(q))$
  - Bayesian statistics: $-\ln P = -\ln \pi - \ln \mathcal{L}$
  - Evolve system with Hamiltonian Equations of motion

COSMIC BIRTH algorithm III

- Evolve system with Hamiltonian Equations of motion
- Numerical integration with leap-frog symplectic scheme

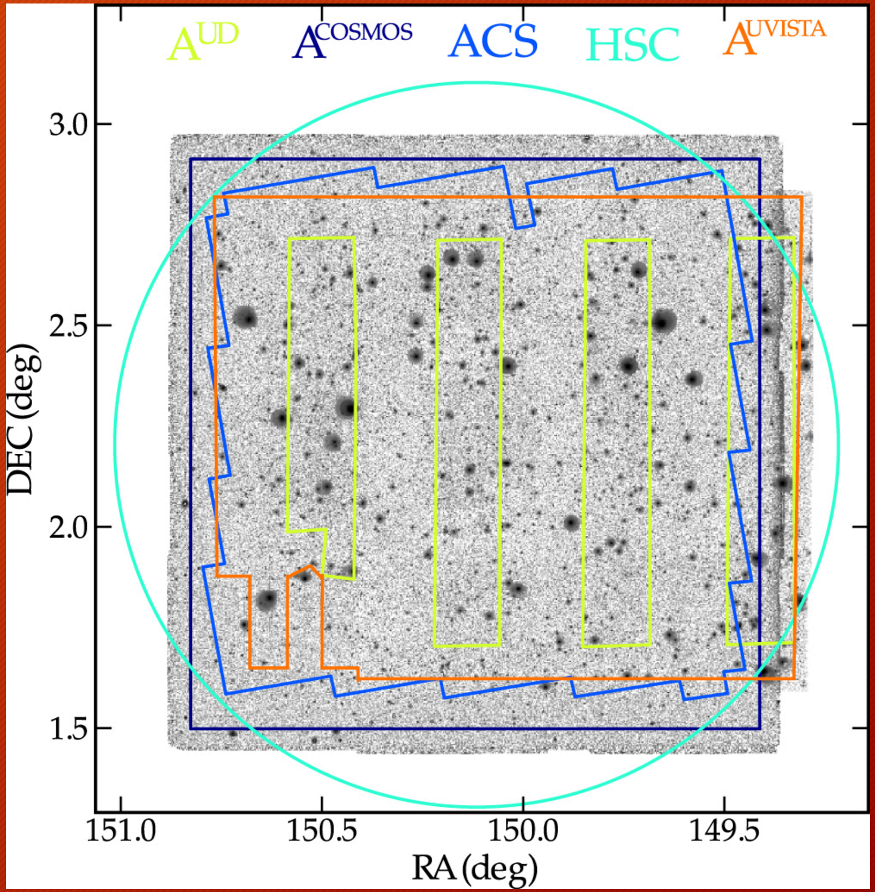
$$\frac{\mathrm{d}\boldsymbol{q}}{\mathrm{d}t} = \frac{\partial \mathcal{H}(\boldsymbol{q},\boldsymbol{p})}{\partial}$$

$$\mathcal{T}_2(\epsilon) = \mathcal{T}_p(\epsilon/2)\mathcal{T}_q(\epsilon)\mathcal{T}_p(\epsilon/2)$$

$$\begin{aligned}
\boldsymbol{p}\left(t+\frac{\epsilon}{2}\right) &= \boldsymbol{p}(t) - \frac{\epsilon}{2}\frac{\partial \mathcal{U}}{\partial \boldsymbol{q}}(\boldsymbol{q}(t)) \\
\boldsymbol{q}(t+\epsilon) &= \boldsymbol{q}(t) + \epsilon\,\mathbf{M}^{-1}\boldsymbol{p}\left(t+\frac{\epsilon}{2}\right) \\
\boldsymbol{p}(t+\epsilon) &= \boldsymbol{p}\left(t+\frac{\epsilon}{2}\right) - \frac{\epsilon}{2}\frac{\partial \mathcal{U}}{\partial \boldsymbol{q}}(\boldsymbol{q}(t+\epsilon))
\end{aligned}$$

BIRTH of the COSMOS Field (MA et al 2020 arXiv:2004.11027)

- We apply our method to the COSMOS field (e.g. Capak et al. 2007,Laigle et al. 2016), because:
  - Deep field ($1 < z < 6$), with $5{\times}10^5$ galaxies,
  - Covering the peak of star formation (Madau&Dickinson 2014, Chiang et al 2017)
  - Ideal test lab for early structure formation
  - Lyα tomography:
    CLAMATO (Lee et al. 2014a,b, 2016,2018),
    LATIS (Newman et al. 2020) in same field
  - Hosting several high redshift massive galaxy protoclusters observed
    (Diener et al. 2013, 2015; Chiang et al. 2015;
    Casey et al. 2015; Wang et al. 2016;
    Lee et al. 2016; Cucciati et al. 2018; Lemaux et al. 2018;
    Darvish et al. 2020)

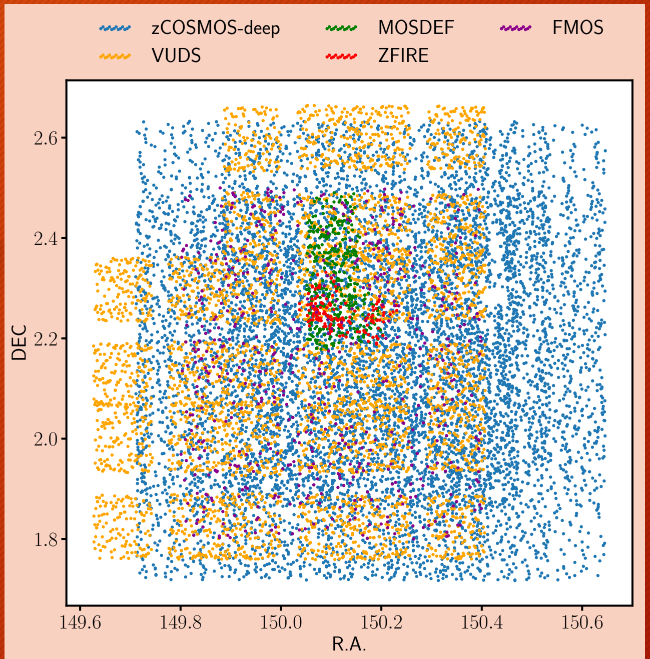


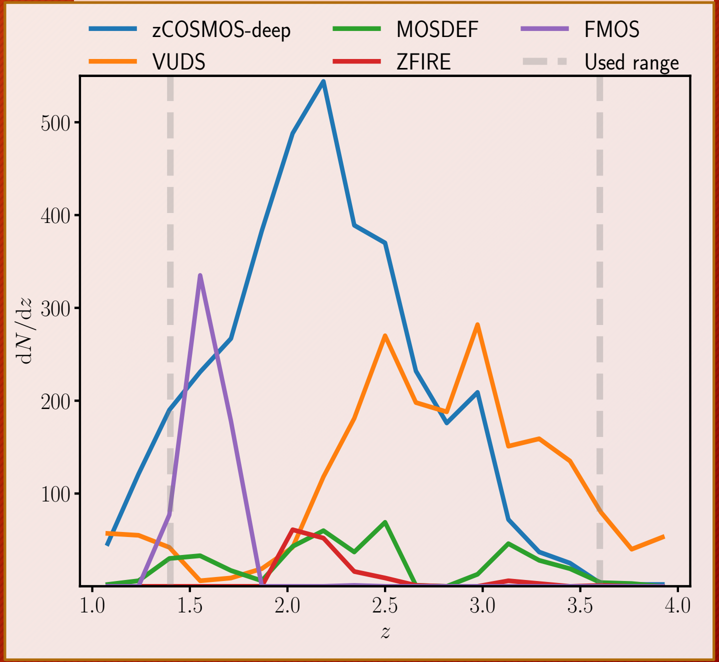
BIRTH of the COSMOS Field (MA et al 2020 arXiv:2004.11027)

- Several spectroscopic surveys operated in the COSMOS field
  - Pro: More reliable redshift estimates
  - Con: Fewer galaxies
  - Con: Non-uniform selection function

- Surveys have different number densities, footprints, selection functions, biases

- Multi-survey & multi-tracer reconstruction needed

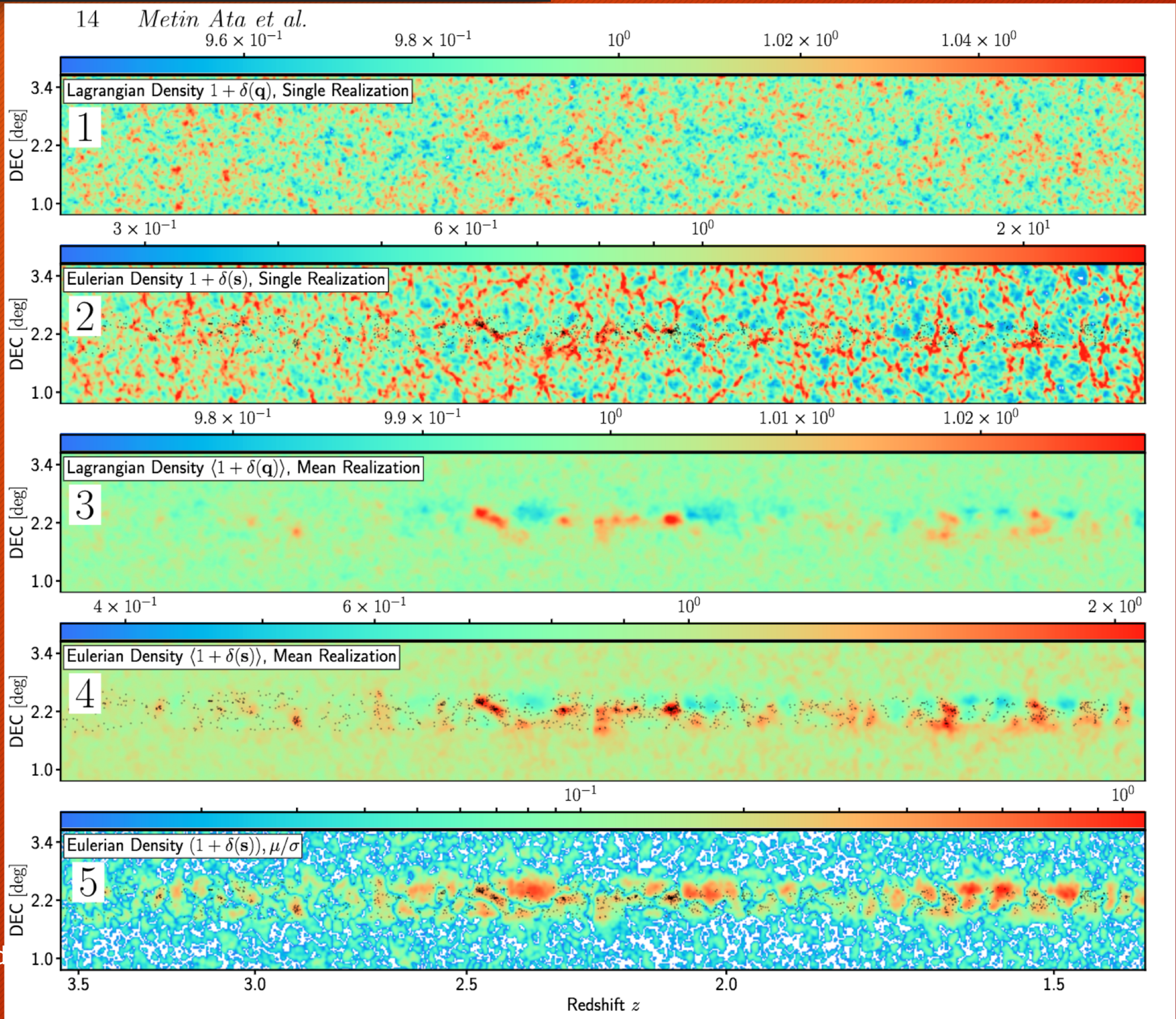




BIRTH of the COSMOS Field (MA et al 2020 arXiv:2004.11027)

- Work in a comoving Cartesian frame:
- $d_{\mathrm{LOS}} = 1896\ h^{-1}\mathrm{Mpc},\ d_{\mathrm{Trans}} = 66 - 74\ h^{-1}\mathrm{Mpc}$
- Cell resolution of $2\ h^{-1}\mathrm{Mpc}$ per side
- Using fiducial CLAMATO cosmological parameters for immediate comparability

  Drawing ~8000 samples of the posterior



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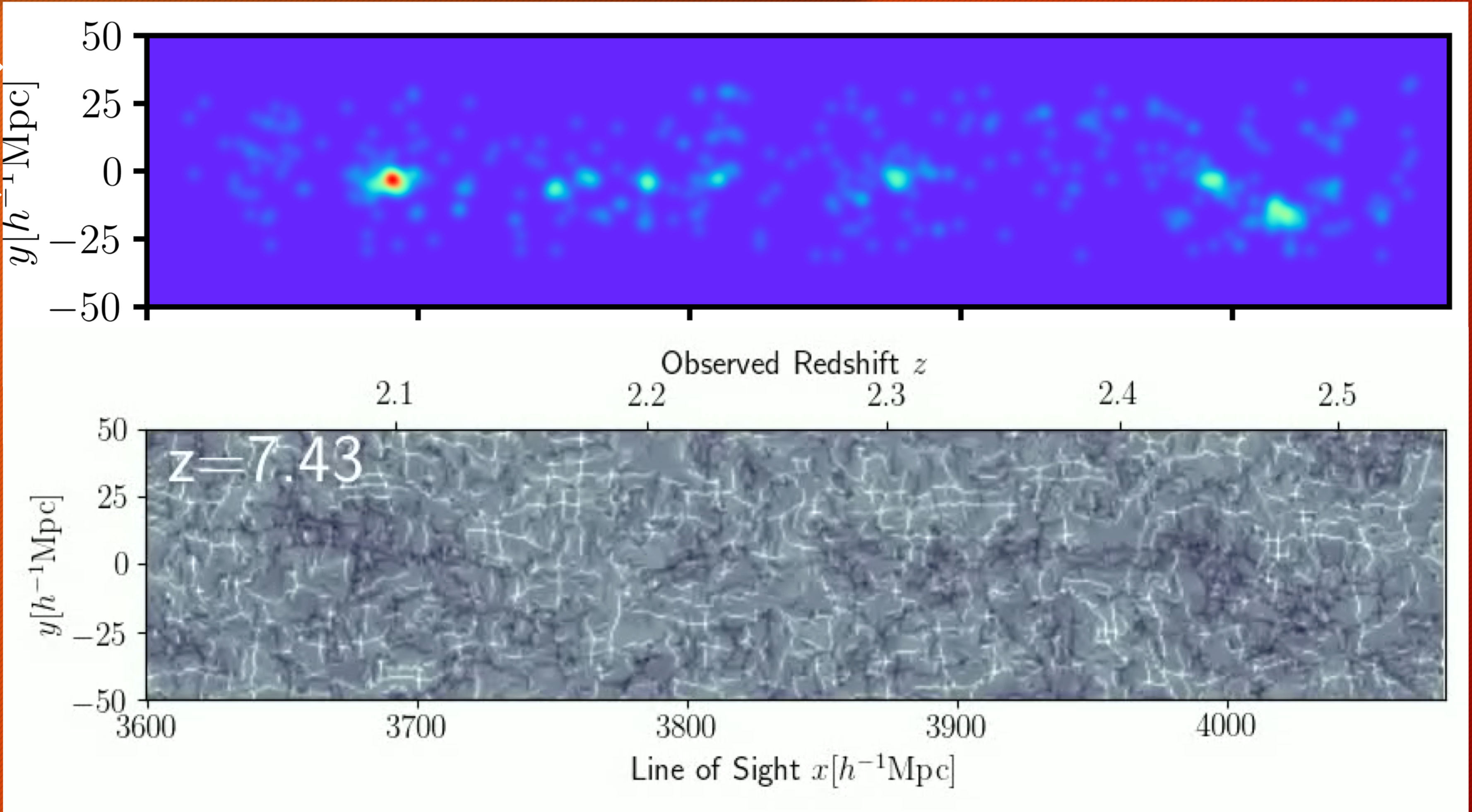
Constrained simulations

- What are Protoclusters? – arXiv:1506.08835
- Protocluster *candidates* are spatial concentrations of galaxies
- Not yet a galaxy cluster (virialization, gravitationally bound)
- Strong environmental dependency whether or not protocluster candidate evolves to cluster
- Galaxy surveys observe positions in redshift space
- Not straight forward to predict z=0 mass from distant observations

Use constrained simulations on top of inferred initial conditions to predict the fate of the protoclusters today

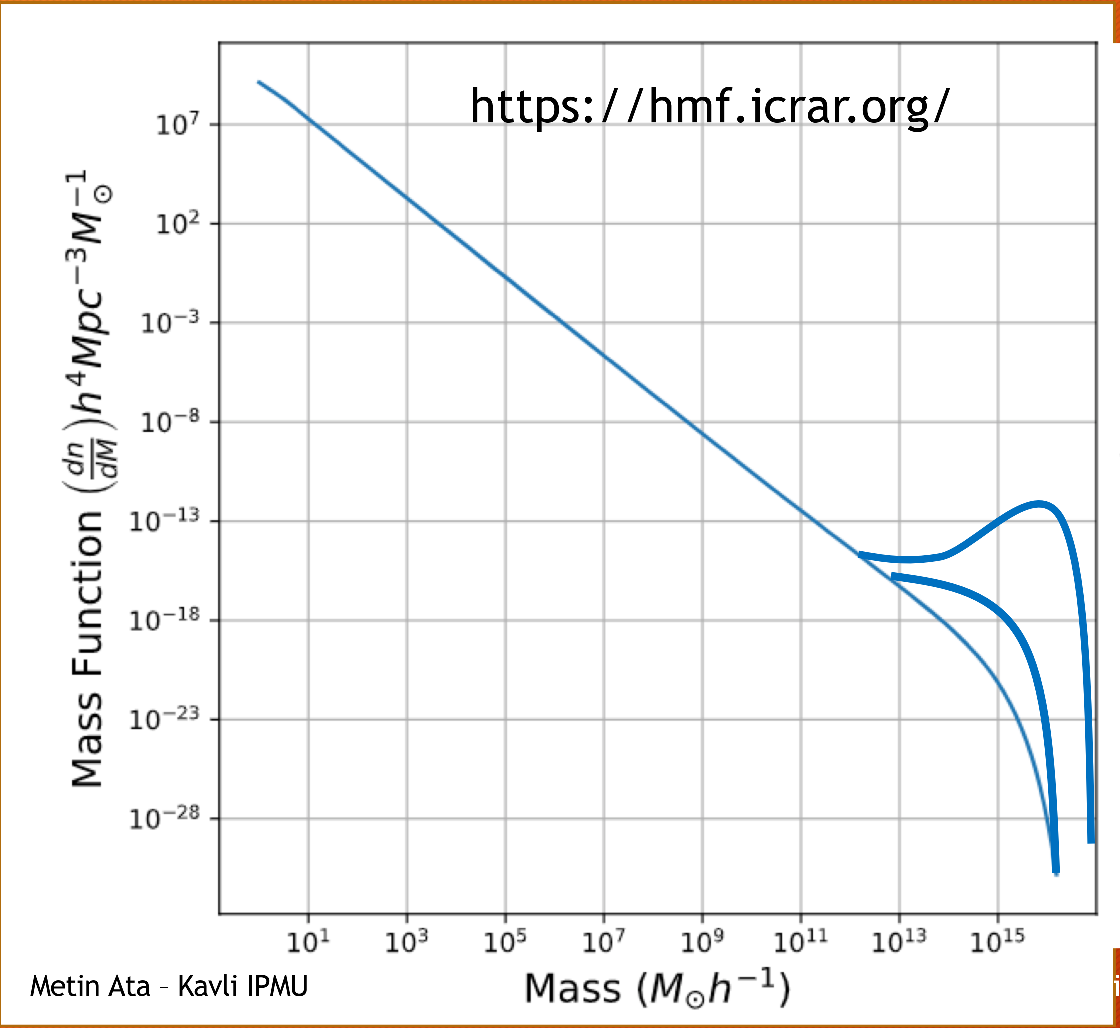
Constrained simulations II

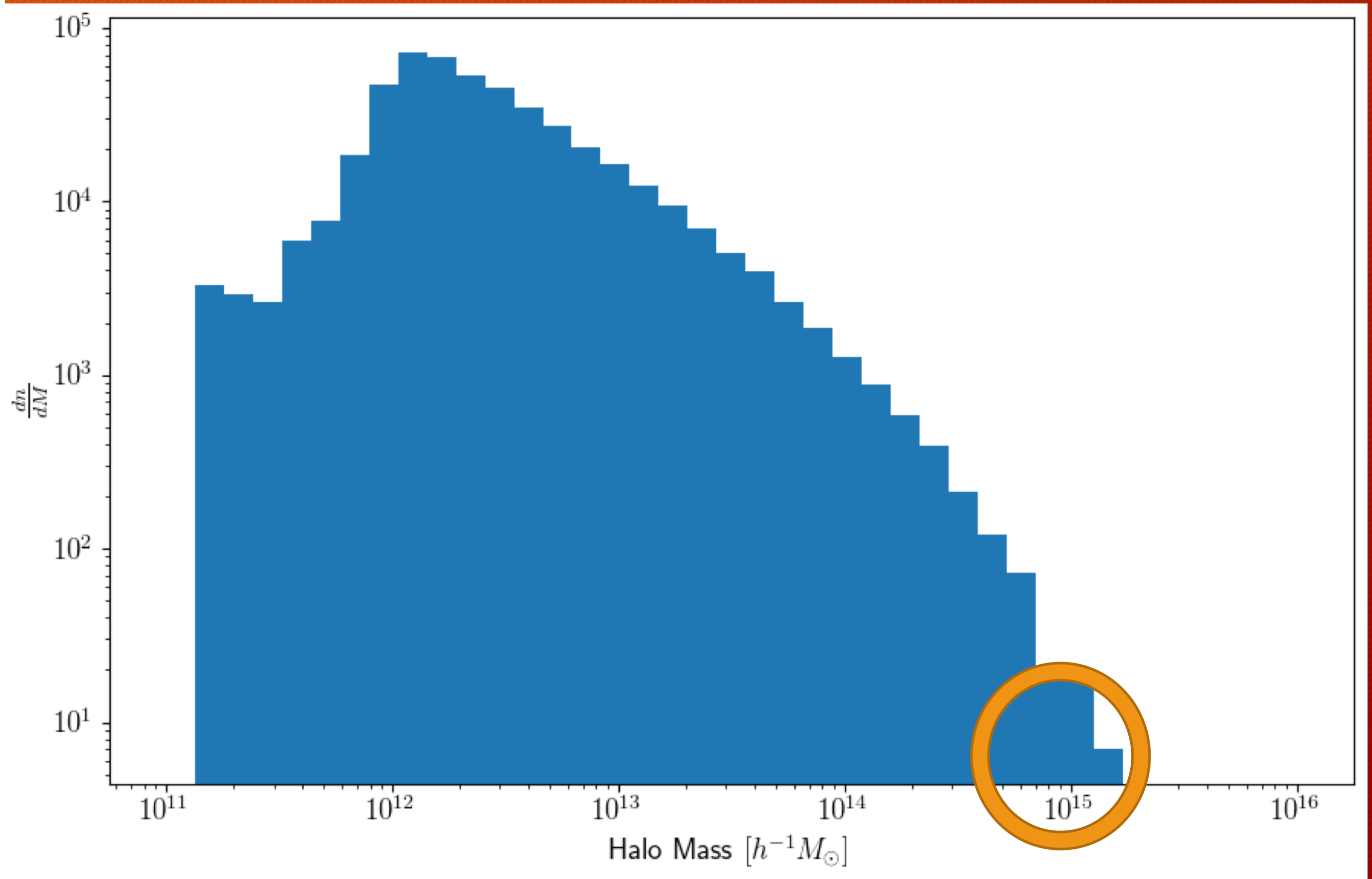
Spectroscopic Galaxy catalogs →
Initial Density (*BIRTH*, *(F.-S.Kitaura, MA et al. 2019)*)→
Initial Conditions (*MUSIC*, *(O.Hahn&T.Abel 2011)*) →
Nbody Sim(*PKDGRAV3* *(D.Potter et al. 2016)*) →
Halo Catalogs (*Rockstar*, *(P.Behroozi et al. 2013a)*) →
Trees (*Consistent trees*, *(P.Behroozi et al. 2013b)*)



Constrained simulations III: Results for z=0

- Closer look at most massive halos





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Conclusions

- Matter clustering important to learn about cosmological parameters/models
- Density field reconstructions from spectroscopic galaxy surveys great tool
- Constrained simulations enable us to analyze observed structures on simulation level with full phase-space information