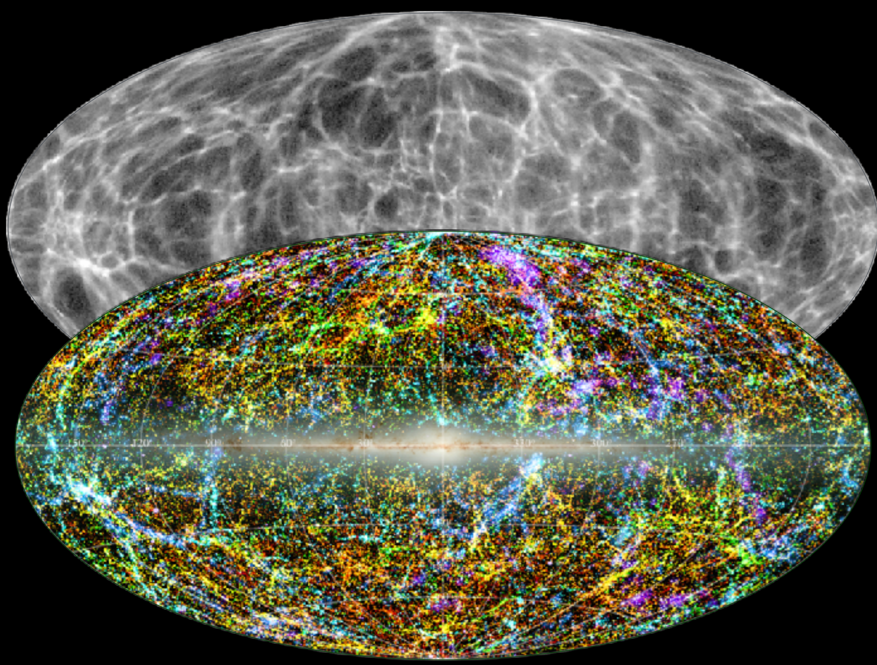
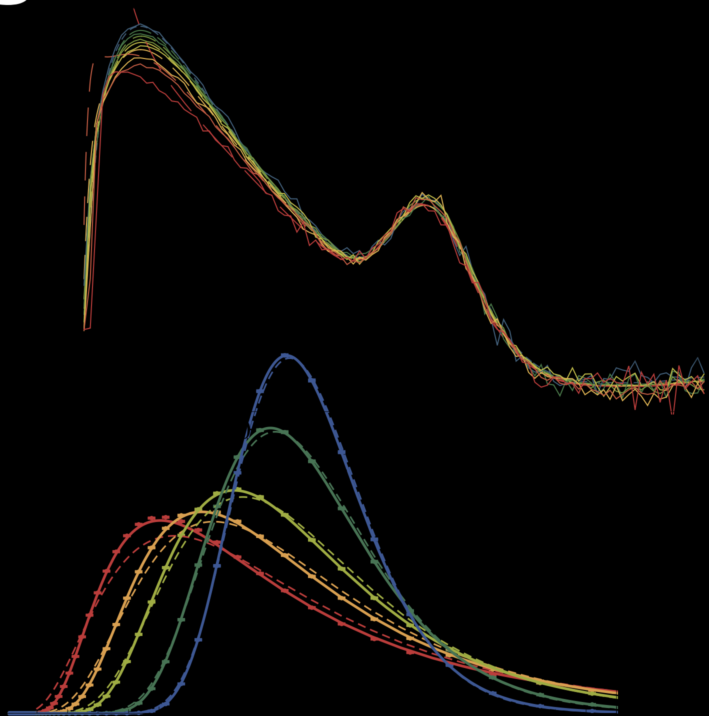
Large Scale Structure: Physics, Phenomenology, Statistics





Cora Uhlemann

Les Houches Dark Universe 2025

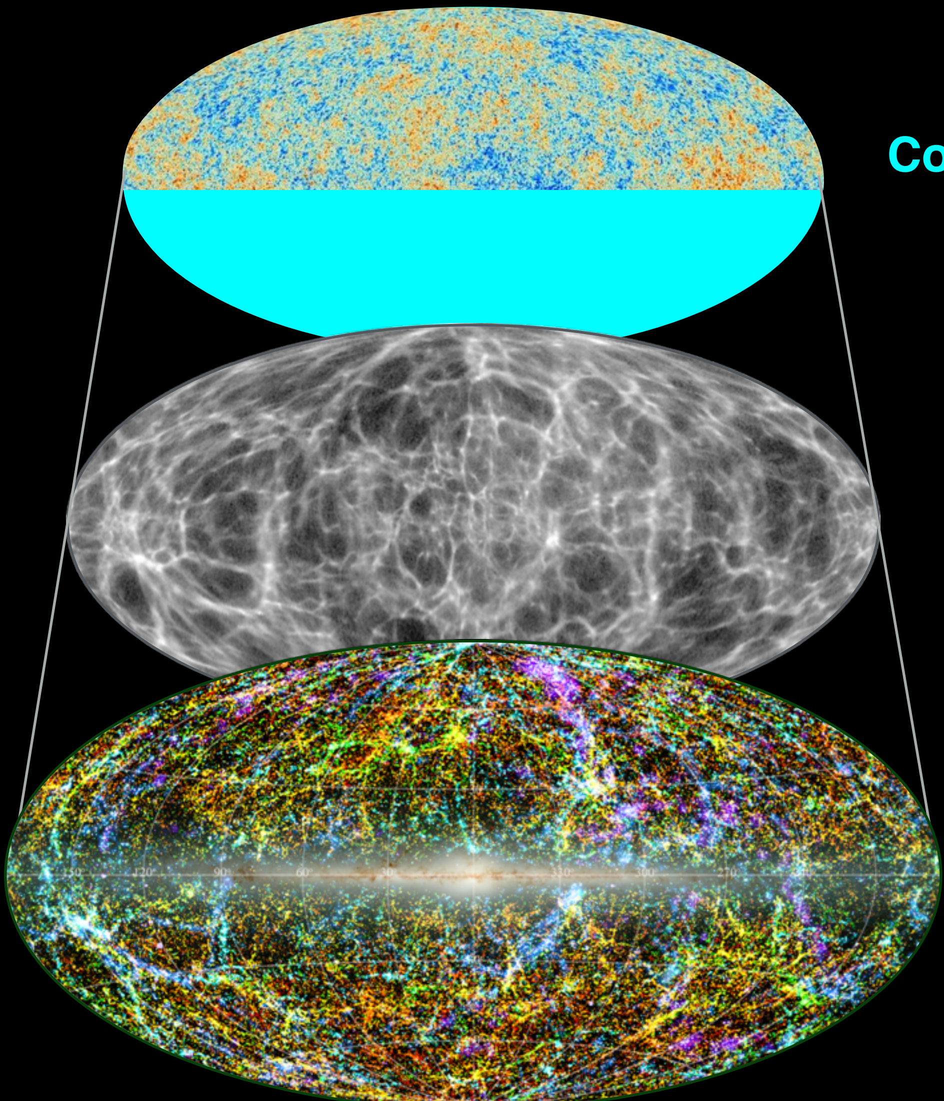
euclid consortium

erc

UNIVERSITÄT BIELEFELD

Cosmic Laboratory

beginning
nearly uniform



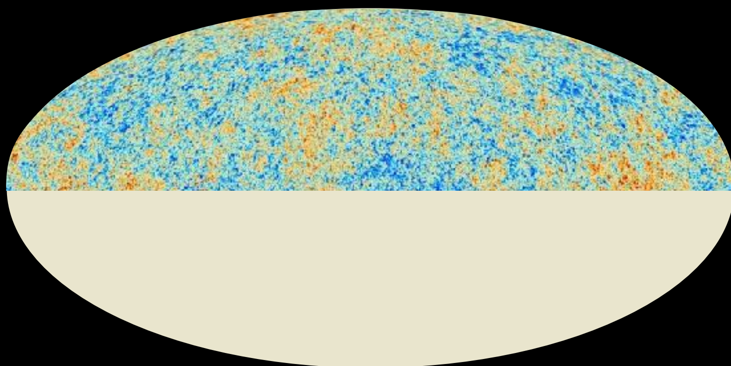
SEEDS
Cosmic Microwave Background

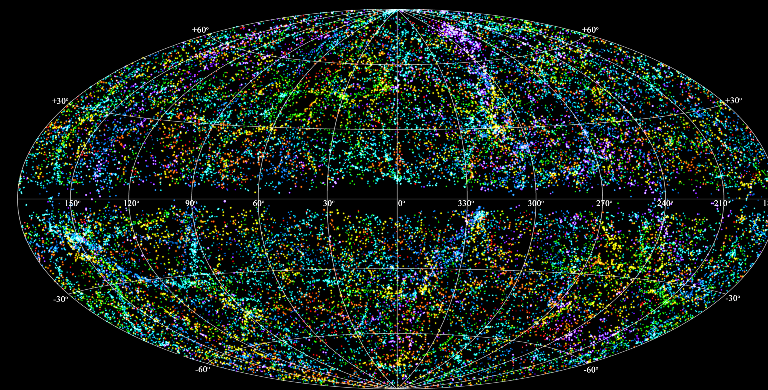
SKELETON
Dark Matter (simulated)

today
rich structure

COSMIC WEB
galaxies (observed)

CMB -> Large-Scale Structure





tiny density differences

~0.00001x mean density

large density differences

~100x mean density

density differences grow by a huge factor

Plan

Modelling dark matter dynamics

- Phase space
- Eulerian Perturbation Theory
- Lagrangian Perturbation Theory
- Spherical Collapse

Clustering statistics

- Two-point statistics
- Three-point statistics
- One-point statistics + …

Plan

From dark matter to observables

Tracer bias & stochasticity

Redshift space distortions

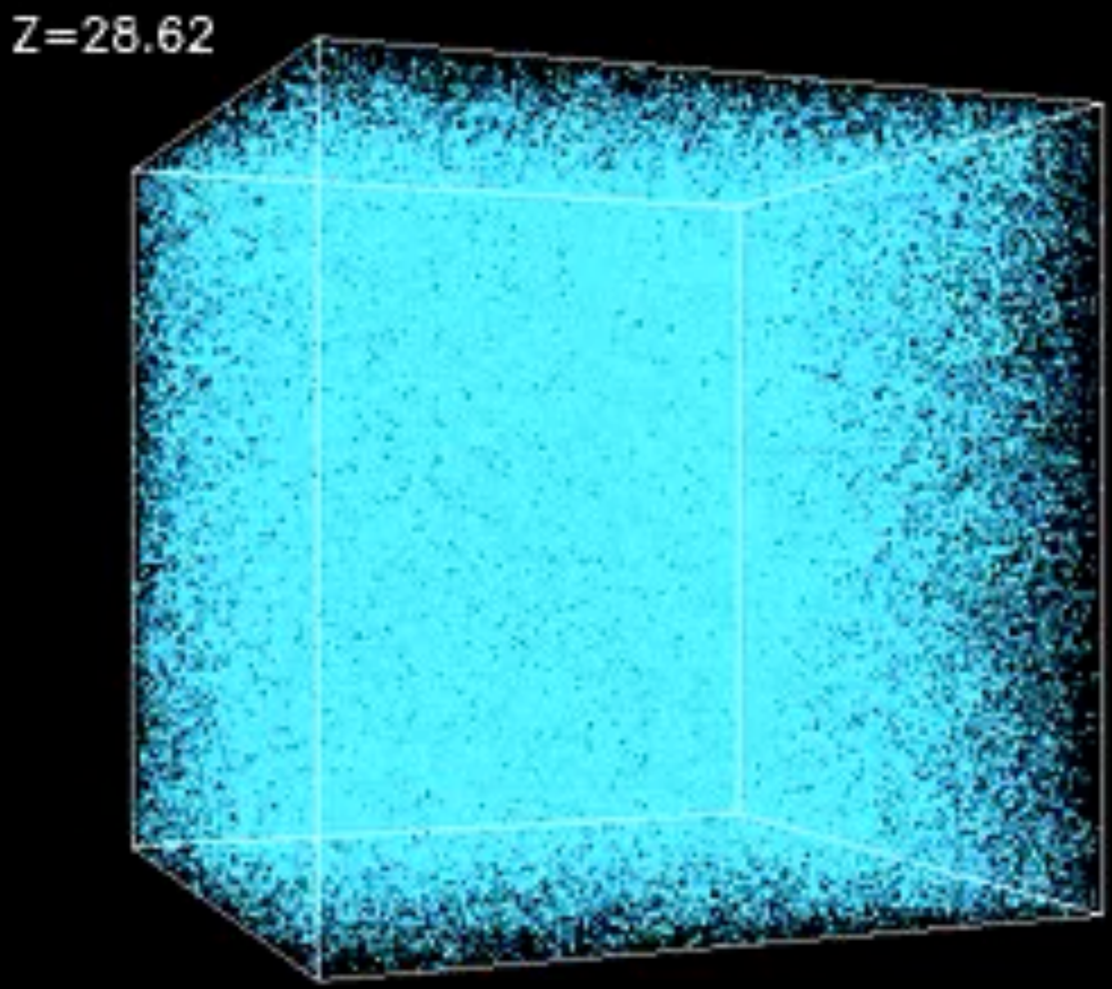
Projected densities

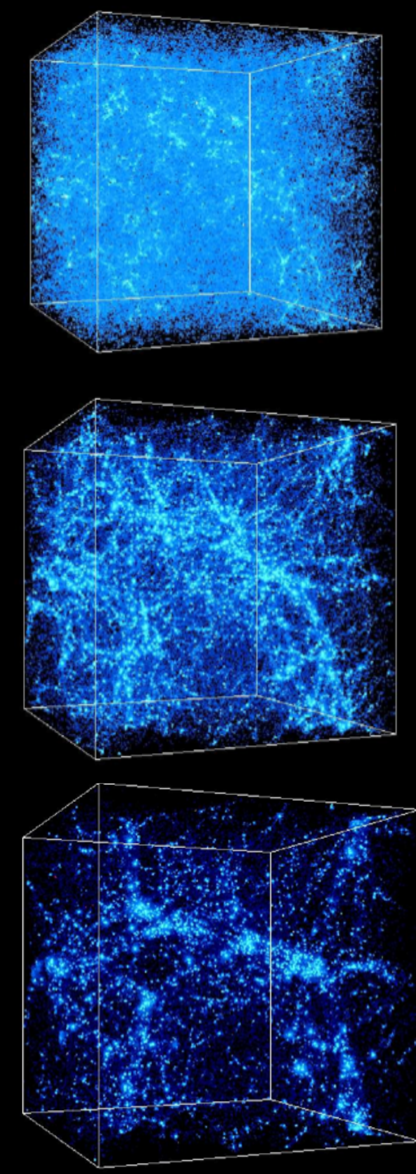
Large-scale structure probes

Spectroscopic clustering

Photometric clustering & weak lensing

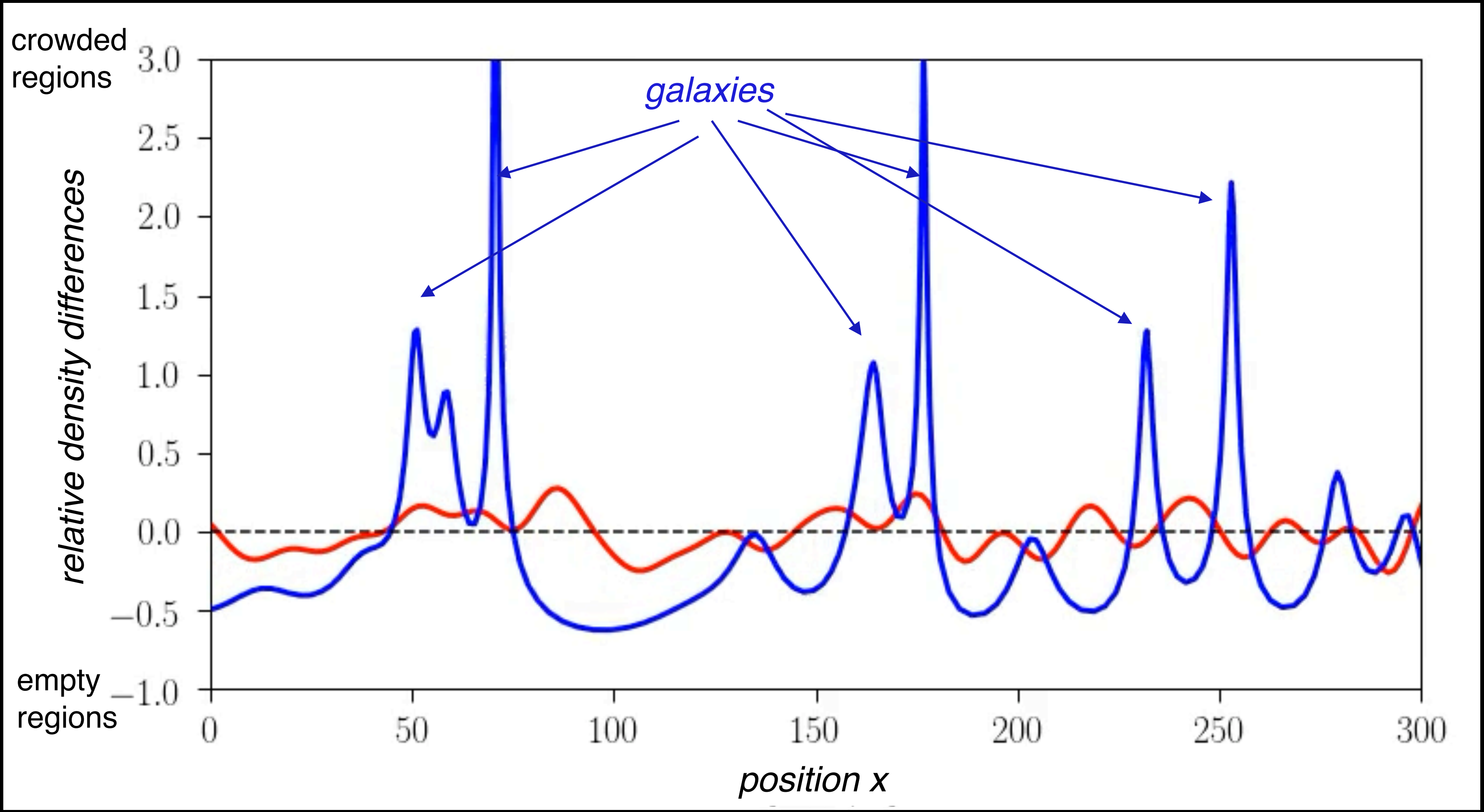
CMB -> Large-Scale Structure





National Center for Supercomputer Applications (A. Kravtsov & A. Klypin)

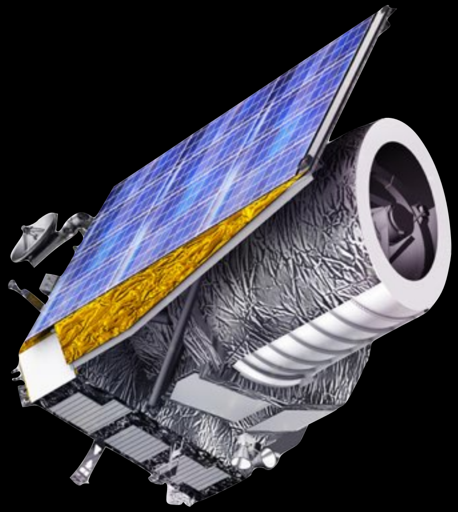
CMB -> Large-Scale Structure



video by Oliver Friedrich

Cosmic Laboratory

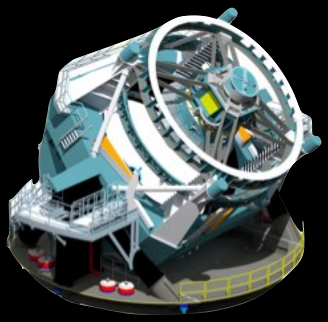
Cosmic Laboratory



Euclid

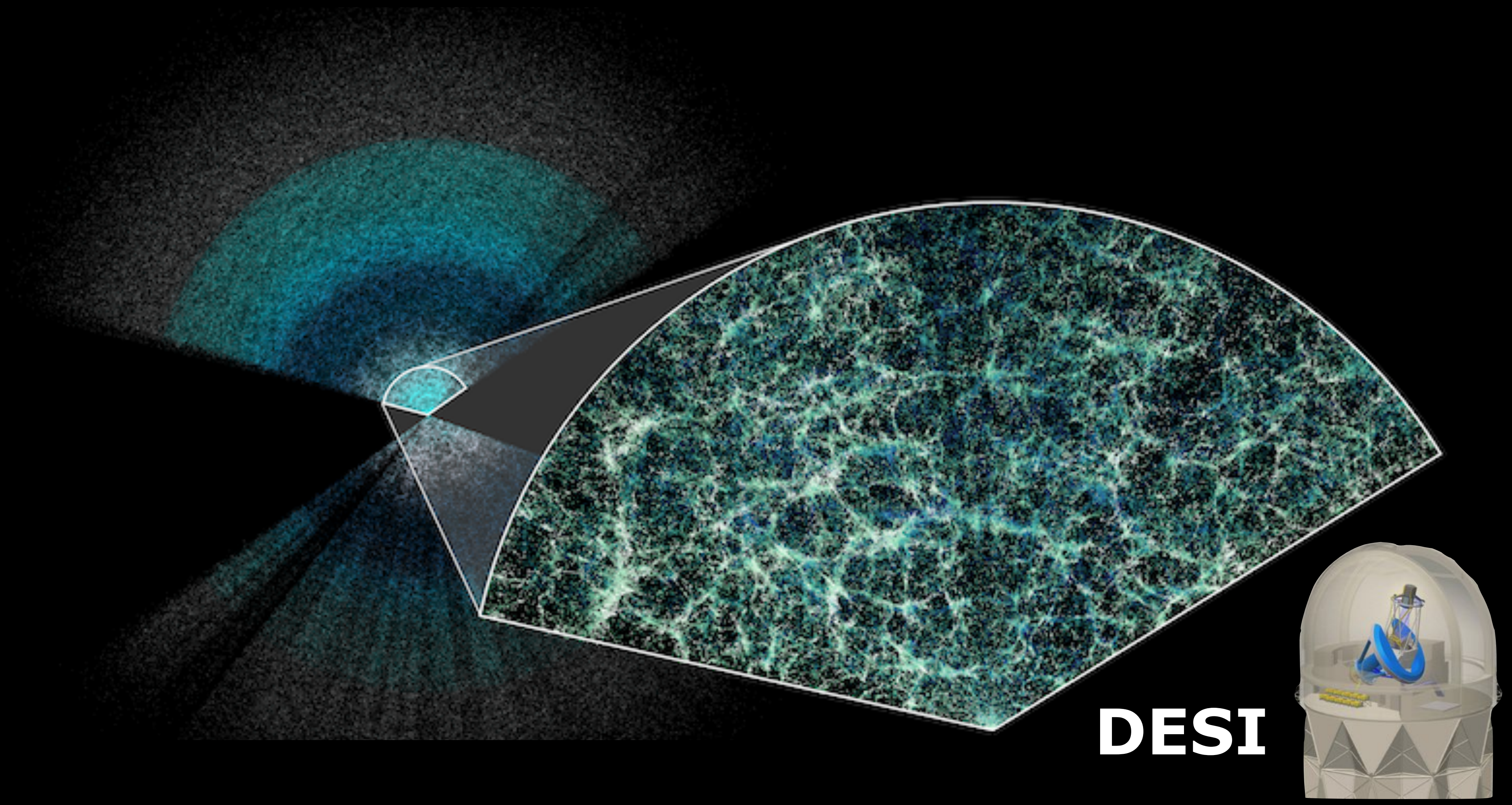
~1 billion €, 1/3 sky
10 billion years look-back
galaxy redshifts & shapes

Rubin LSST



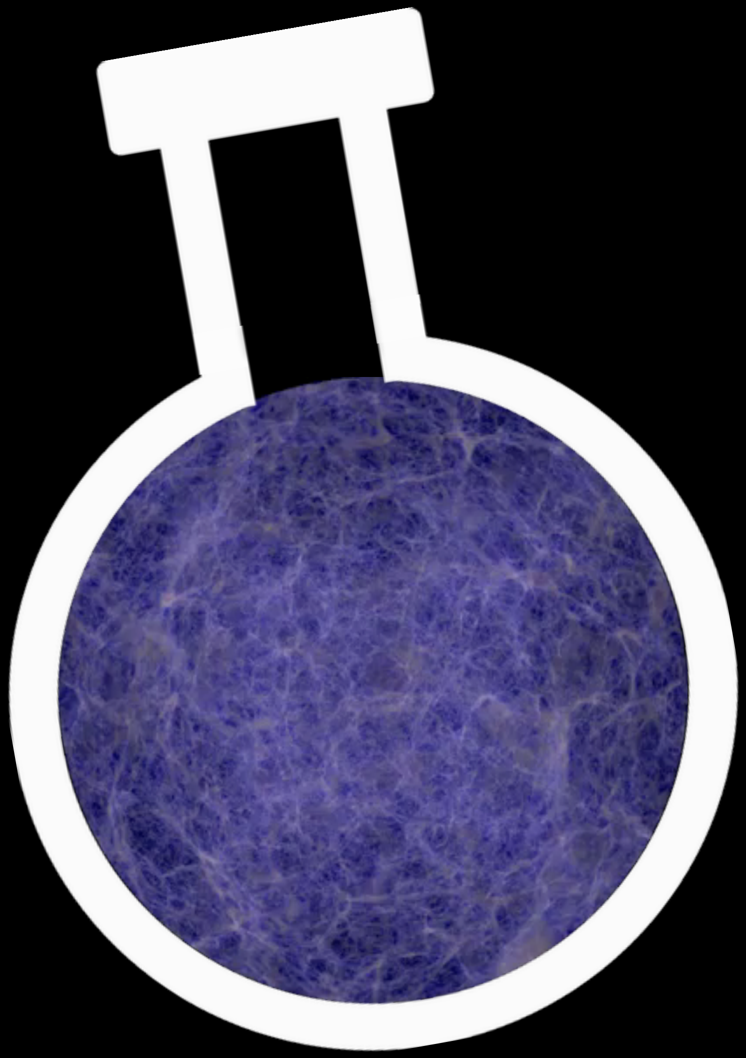
DESI

Cosmic Laboratory



Cosmic Laboratory

dark energy & gravity,
dark matter, neutrinos
early universe



Predict Clustering

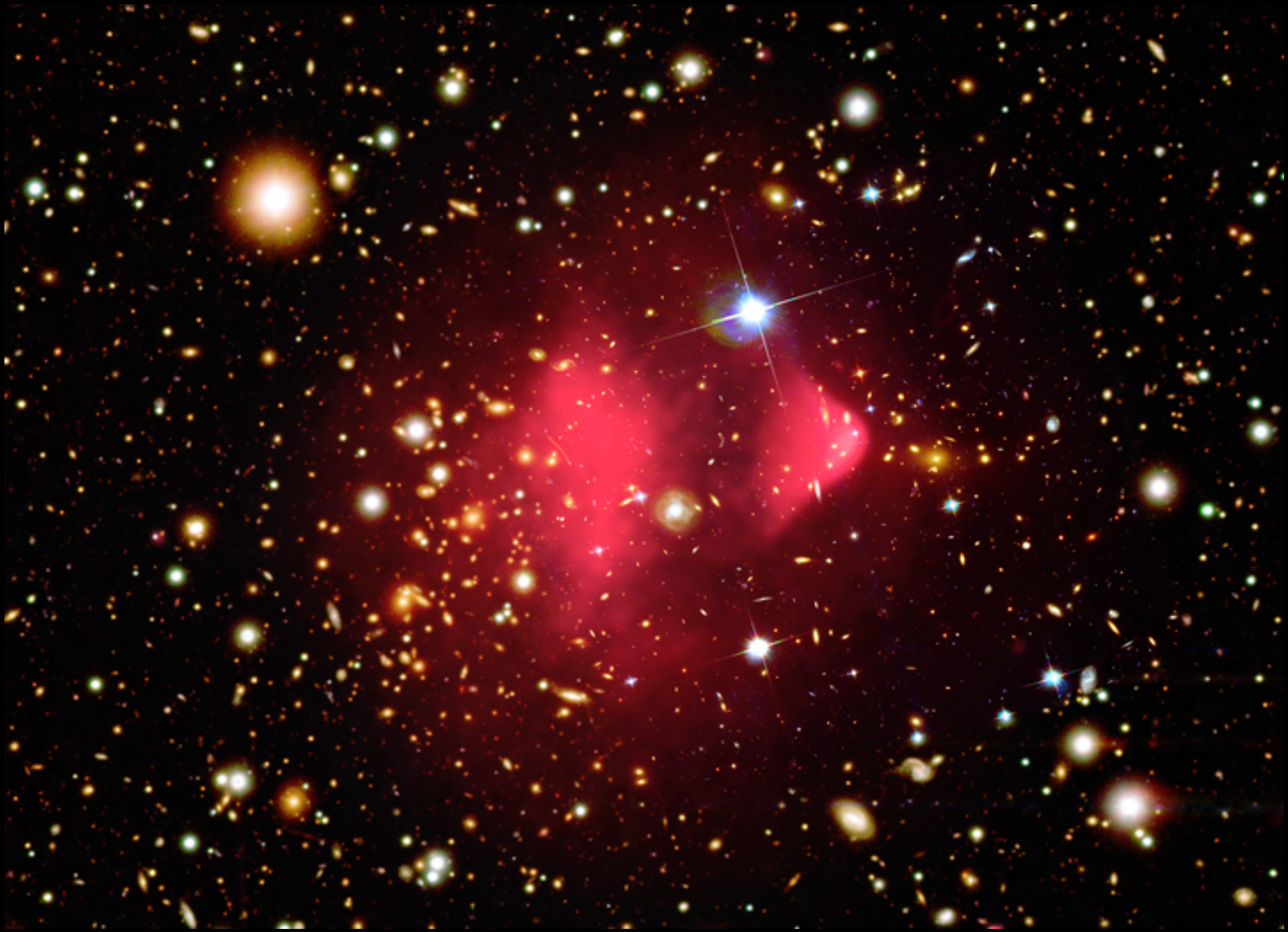
nonlinear dynamics

Extract Information

non-Gaussian statistics

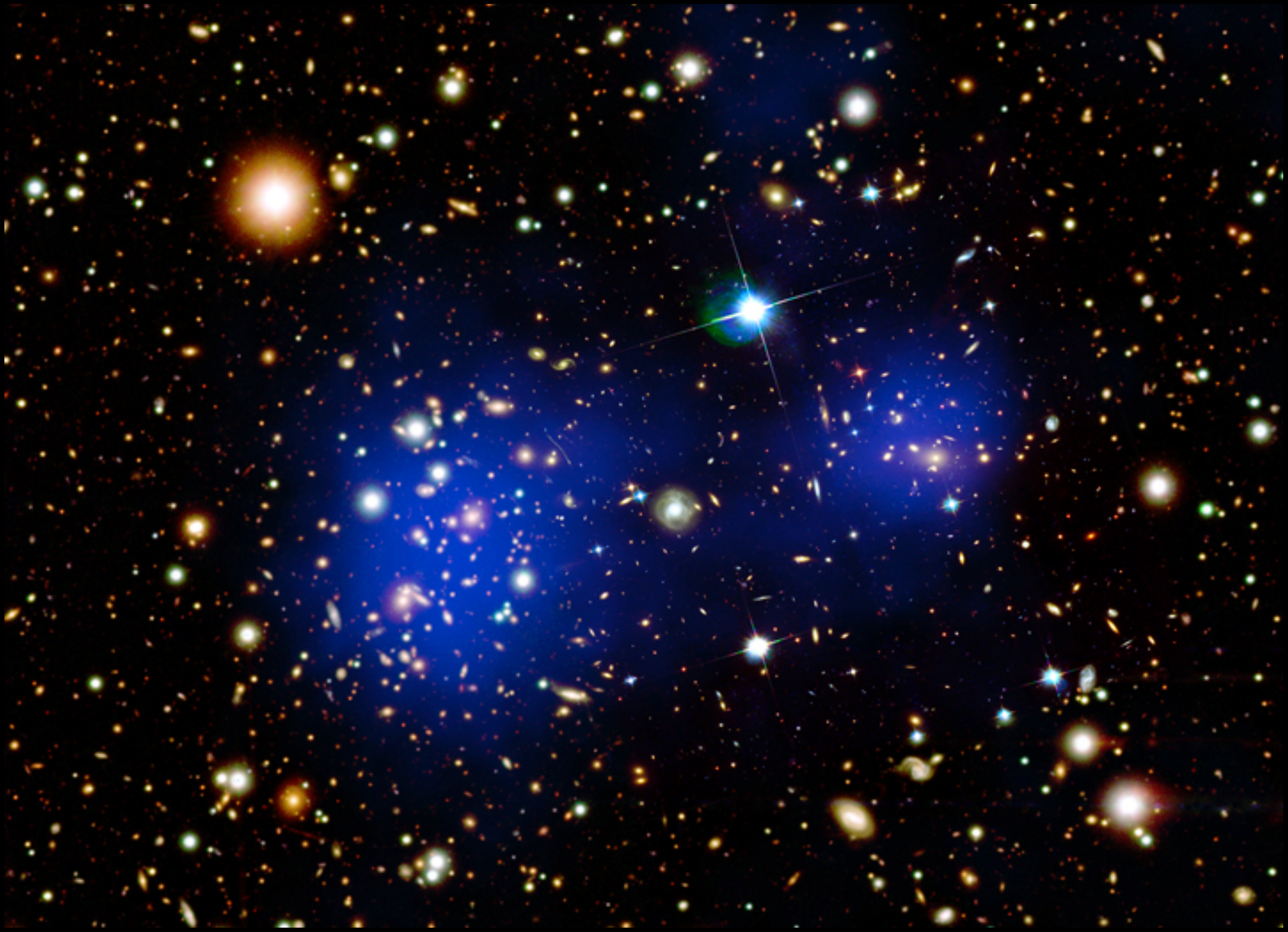
Collisionless Dark Matter

Bullet Cluster: X-Ray (gas)



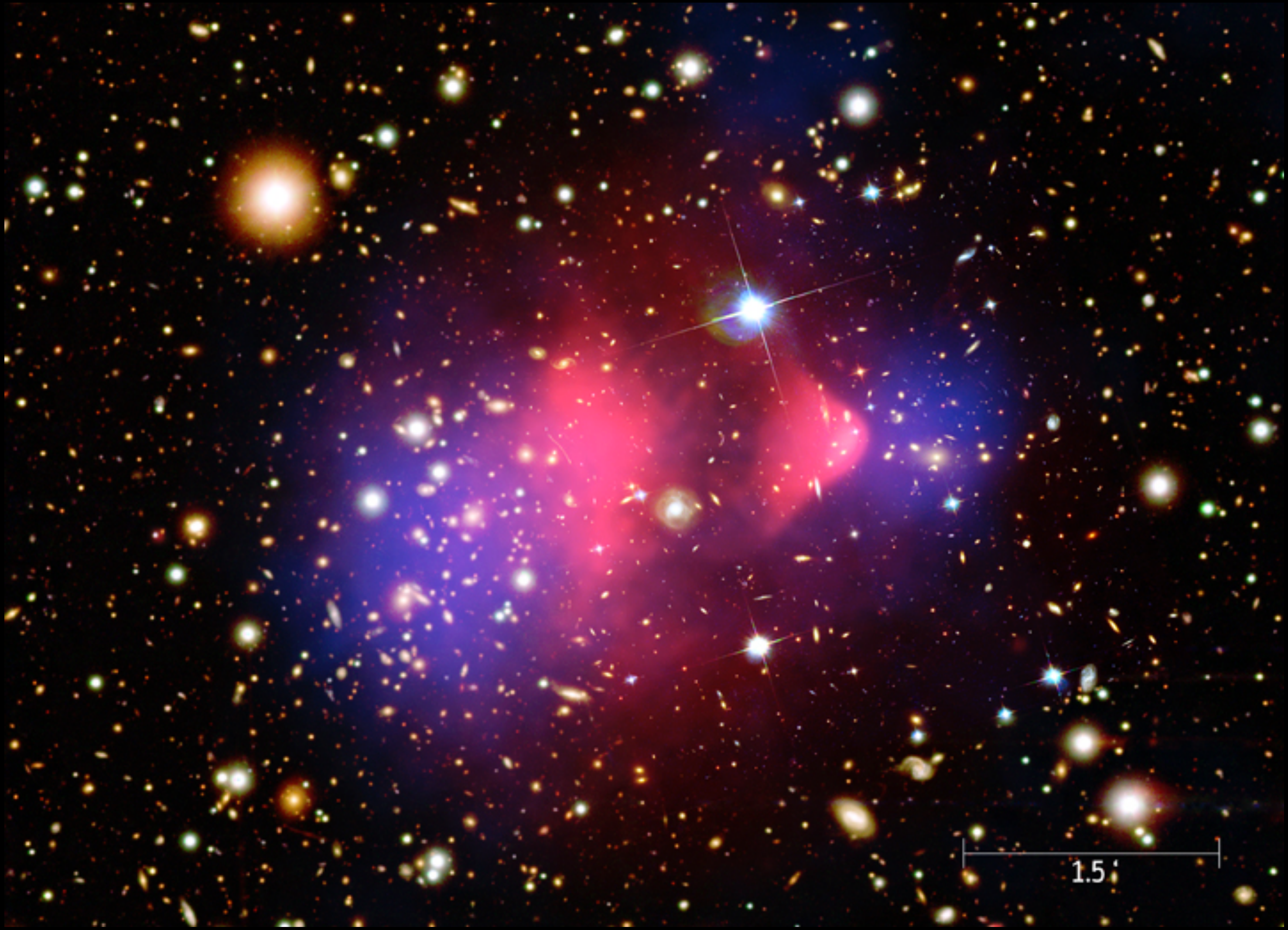
Collisionless Dark Matter

Bullet Cluster: weak lensing (mass)



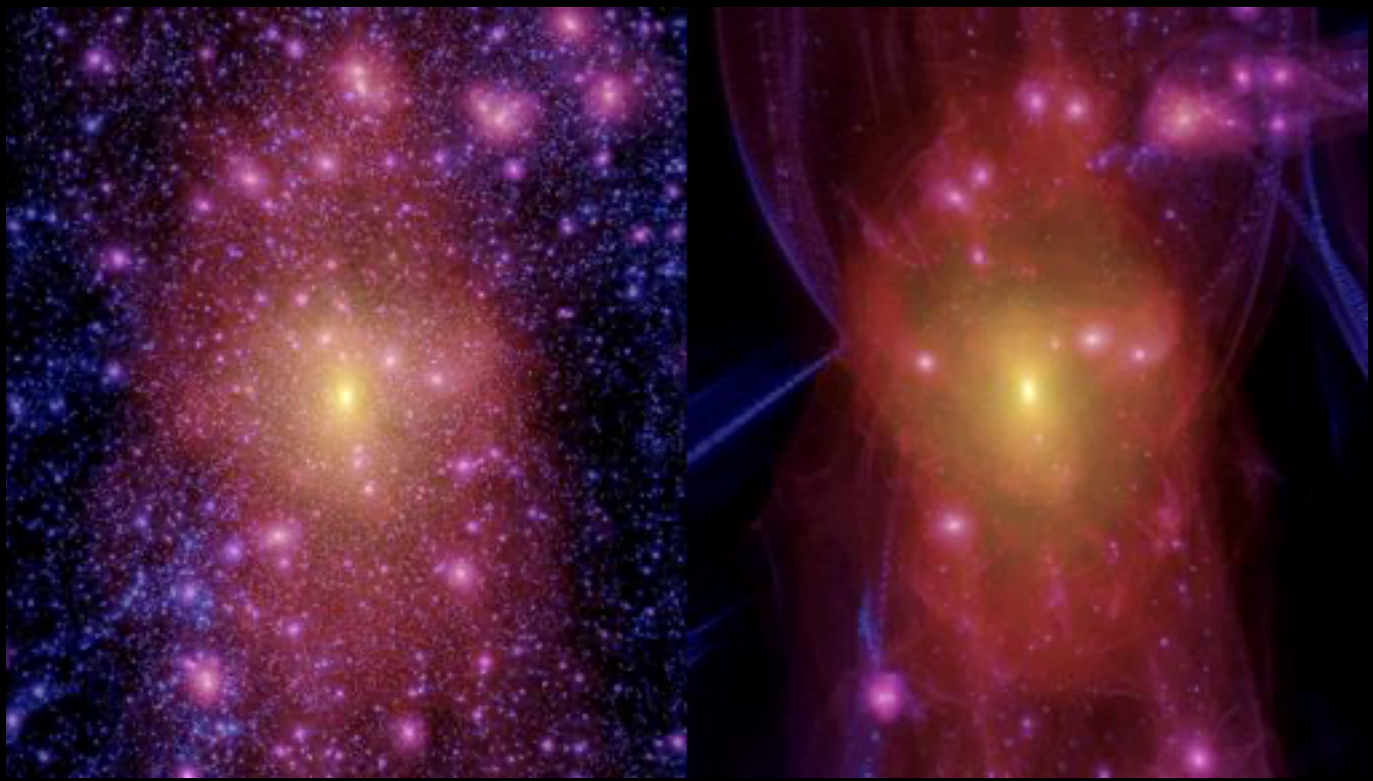
Collisionless Dark Matter

Bullet Cluster: X-Ray (gas) & weak lensing (mass)



Cold vs. Warm Dark Matter

higher streaming velocities wash out substructure



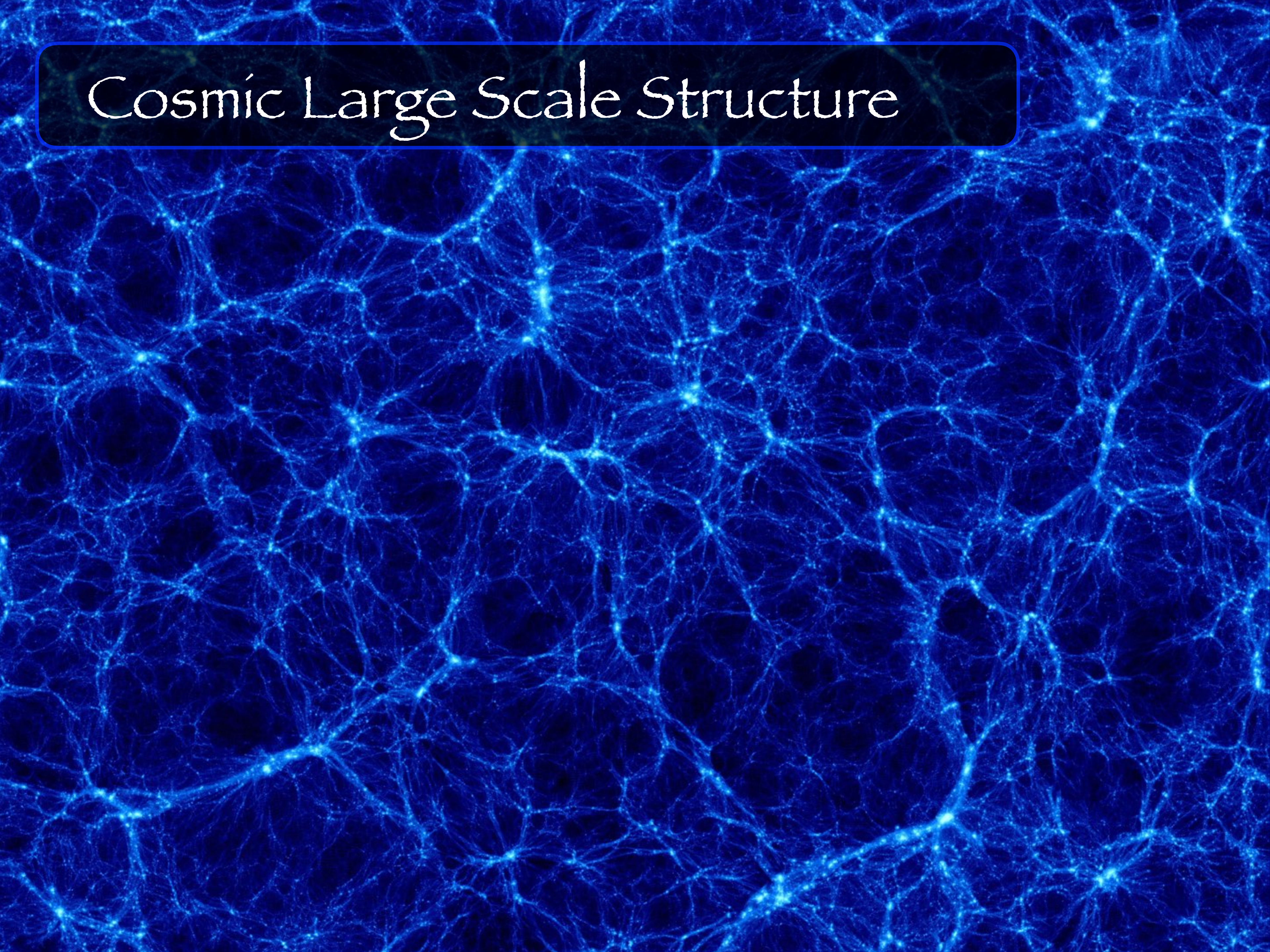
simulation: Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy '12

Cosmic Large Scale Structure

Gravitational Dynamics

Clustering Statistics

Cosmic Large Scale Structure



Cosmic Large Scale Structure

Cosmic Web

Skeleton

filamentary network

structural hierarchy

Halos

Galaxy Hosts

universal density profiles

mass distribution

Key Problem

Dark Matter Dynamics

Vlasov-Poisson equation

$$\partial_t f(\boldsymbol{x}, \boldsymbol{p}, t) = \{H, f\} \qquad \Delta V(\boldsymbol{x}, t) \propto \int f(\boldsymbol{x}, \boldsymbol{p}, t)\, \mathrm{d}^3 p - 1$$

3+3 dim

nonlinear

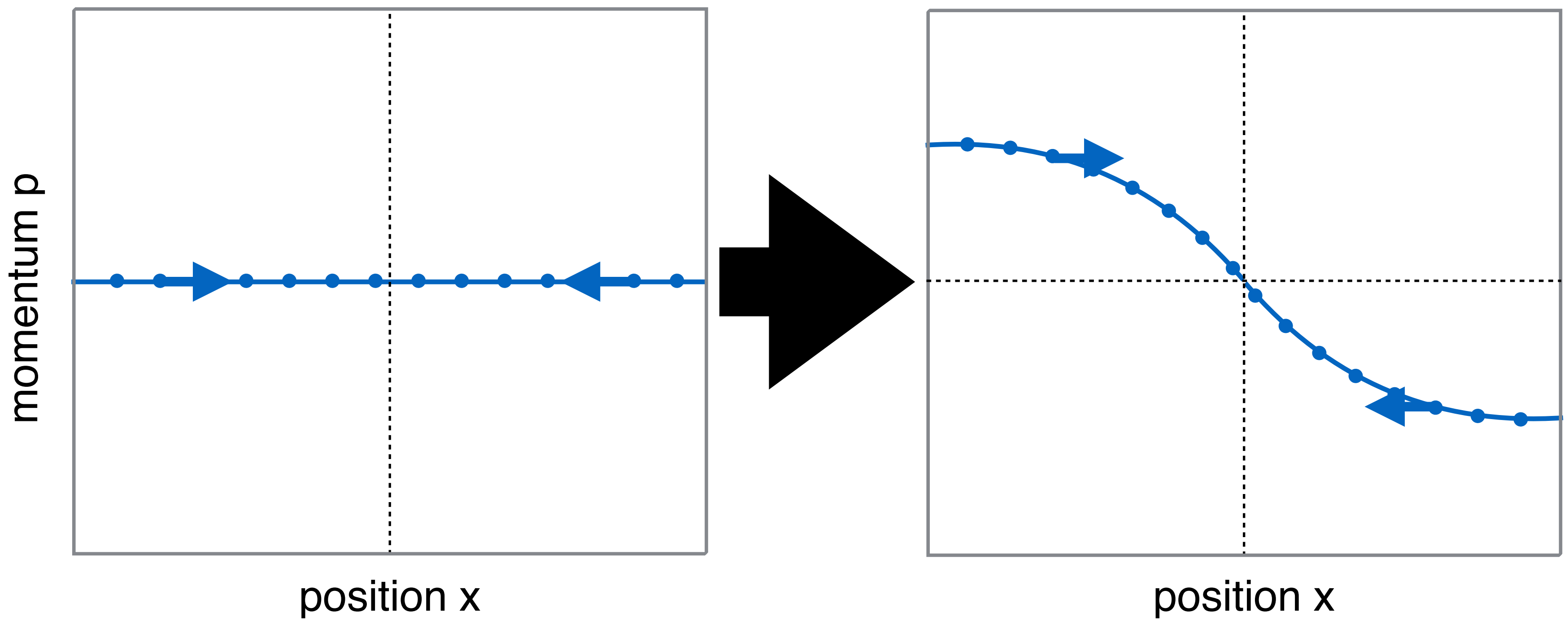
$$\partial_t f = -\frac{\boldsymbol{p}}{a^2 m} \cdot \boldsymbol{\nabla}_x f + m \boldsymbol{\nabla}_x V \cdot \boldsymbol{\nabla}_p f = \{H, f\}$$

cold initial conditions: flat sheet

Dark Matter Dynamics

perfect fluid: single stream

$$f_{\mathrm{fl}}(\boldsymbol{x},\boldsymbol{p}) = \rho(\boldsymbol{x})\delta_D(\boldsymbol{p} - m\boldsymbol{\nabla}\phi(\boldsymbol{x}))$$



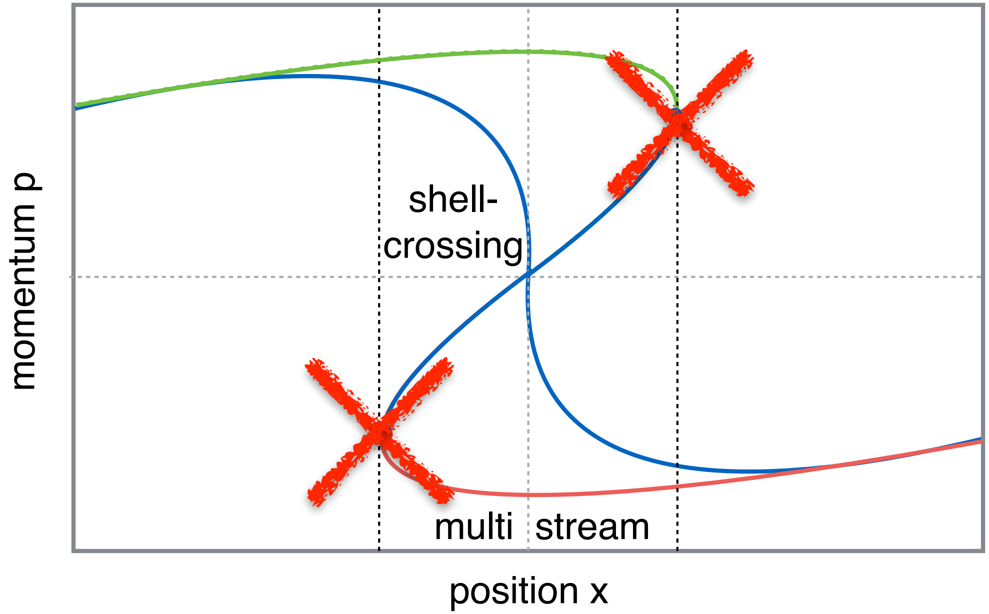
Phenomenology

Dark Matter Dynamics

perfect fluid: single stream

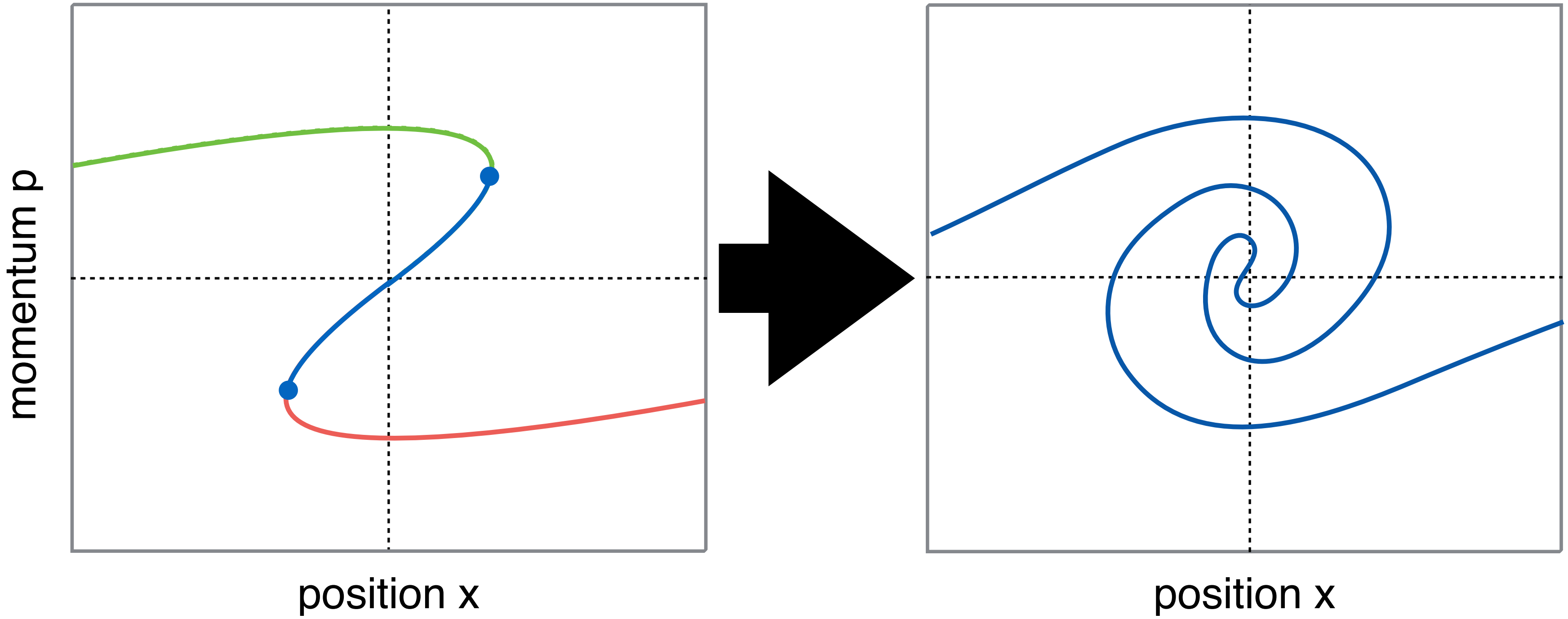
$$f_{\mathrm{fl}}(\boldsymbol{x},\boldsymbol{p}) = \rho(\boldsymbol{x})\delta_D(\boldsymbol{p} - m\boldsymbol{\nabla}\phi(\boldsymbol{x}))$$

fails at shell-crossing



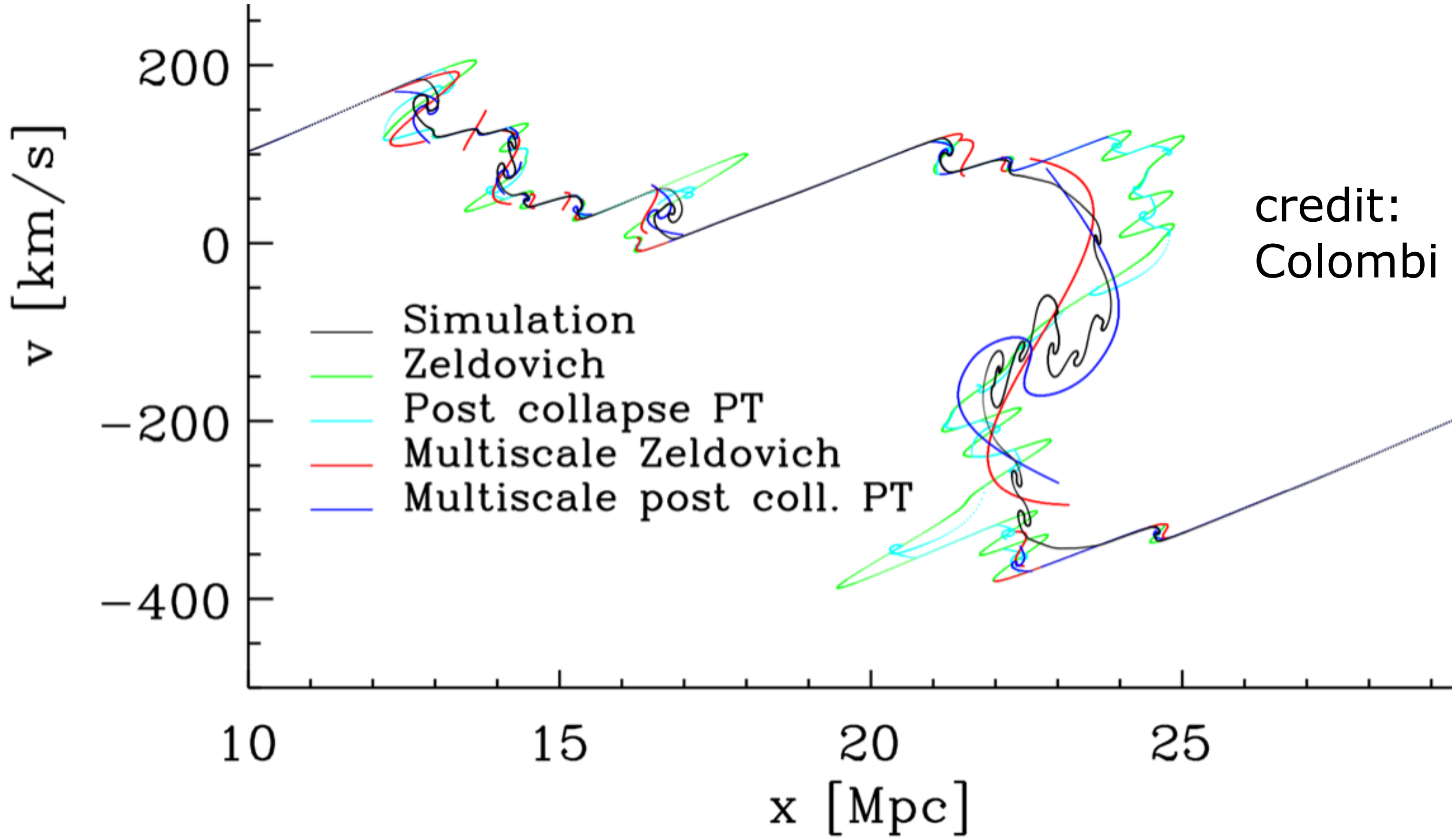
Dark Matter Dynamics

beyond perfect fluid: multi-stream



Dark Matter Dynamics

large-scale view



credit:
Colombi & Taruya

Challenges

numerical	analytical
N particles	2 fields
large-scales	small-scales
computational power	perturbative accuracy
limited sampling	limited features

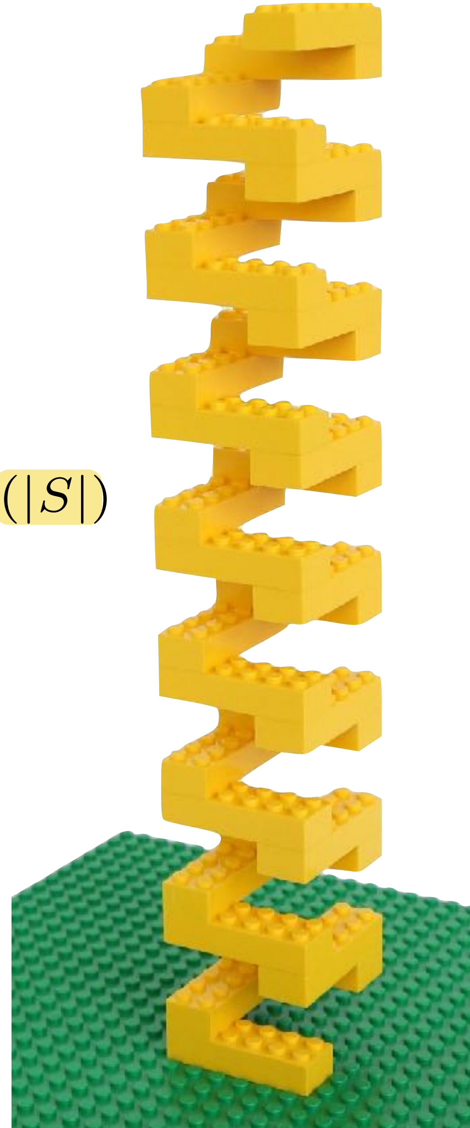
Key Problem

Cumulant Hierarchy

$$C^{(n)}_{i_1 \ldots i_n}(\boldsymbol{x}) \ni \left\{ \int d^3p\, p\, p_{i_1} \cdots p_{i_m} f(\boldsymbol{x}, \boldsymbol{p}) \right\}_{m \leq n}$$

density, velocity, ...

$$\partial_t C^{(n)} \simeq \nabla \cdot C^{(n+1)} + \sum_{|S|=0}^{n} C^{(n+1-|S|)} \cdot \nabla C^{(|S|)}$$

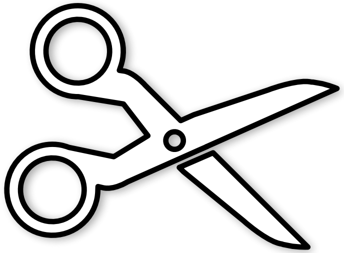


Key Problem

Cumulant Hierarchy

infinite & coupled

$$\partial_t C^{(n)} \simeq \nabla \cdot C^{(n+1)} + \sum_{|S|=0}^{n} C^{(n+1-|S|)} \cdot \nabla C^{(|S|)}$$

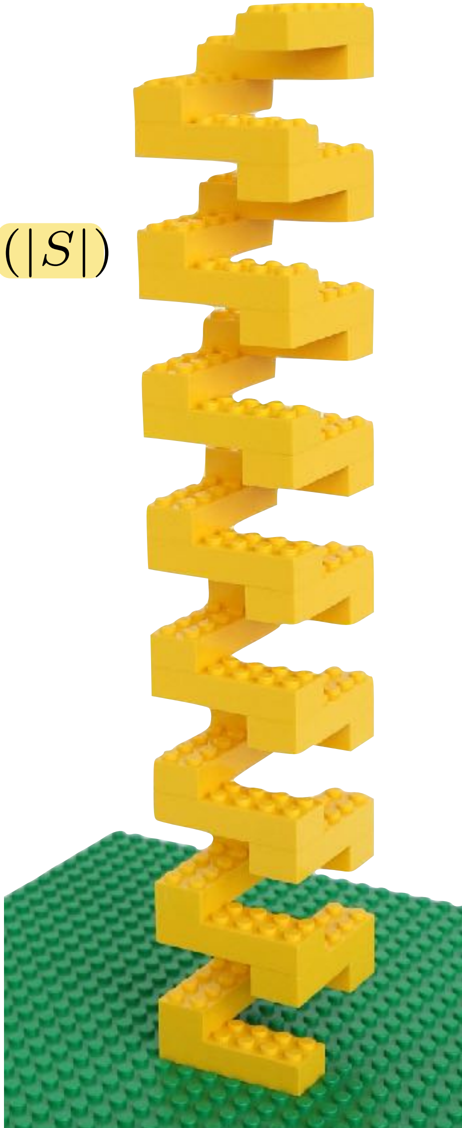


perfect fluid

$$C^{(n\geq 2)} \not\equiv 0$$

shell-crossing

Pueblas & Scoccimarro `08



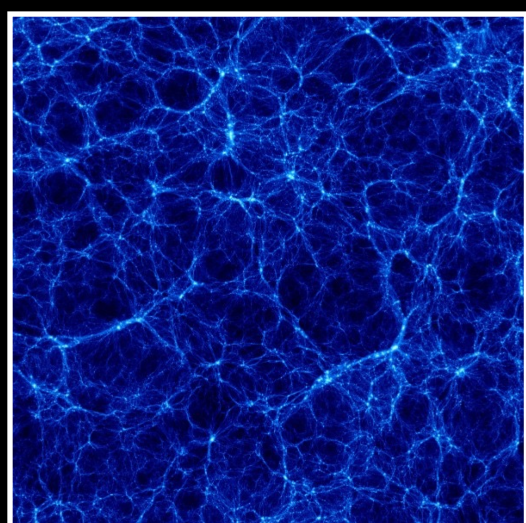
Dark Matter Dynamics

predictions require density contrast

dark matter as chocolate (effective fluid)

Eulerian: expand density & velocity

Lagrangian: displace particles (or fluid elements)



Eulerian Dynamics

density $\rho(\tau, x) = \bar{\rho}(\tau)(1 + \delta(\tau, x))$

velocity $v(\tau, x)$

nonlinear **initially small**

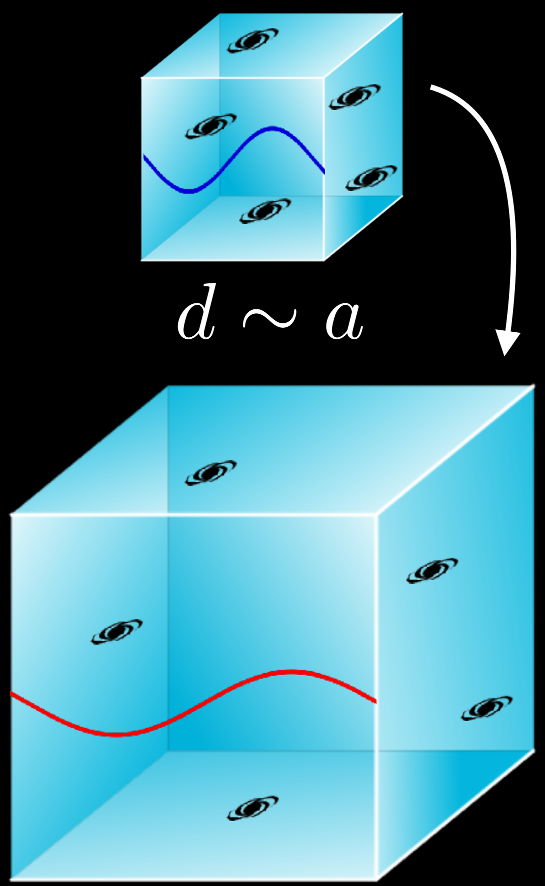
density $$\frac{\partial}{\partial \tau}\delta = -\frac{\partial}{\partial x}[(1 + \delta)v]$$

velocity $$\frac{\partial}{\partial \tau}v = -v\frac{\partial}{\partial x}v - \mathcal{H}(\tau)v - \frac{\partial}{\partial x}V$$

gravity force $$\frac{\partial^2}{\partial x^2}V = \frac{3}{2}\Omega_m \mathcal{H}^2(\tau)\delta$$

Expansion dilutes

distances grow, energy density = energy/volume



Radiation $\rho_\gamma \sim a^{-4}$

volume & wavelength grows

Matter $\rho_m \sim a^{-3}$

volume grows

Cosmological Constant

$$\rho_\Lambda \sim \text{const.}$$

3 Epochs

Dark Energy At Last

Λ

Cosmological Constant

$$\rho_\Lambda \sim \text{const.} \quad w_0 = -1$$

Dark Energy $\rho_{\rm DE} \sim a^{1+w(a)}$

equation of state (many models)

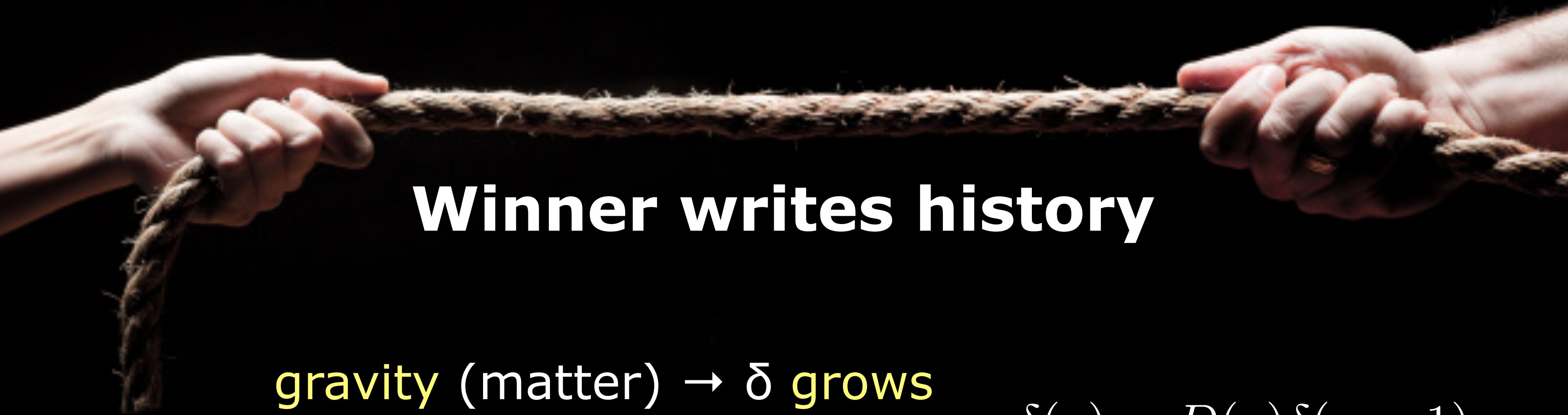
$w_0 w_a$

parametrise $w(a) = w_0 + w_a(1-a)$

Cosmic Tug of War

density contrast $$1 + \delta(x,t) = \frac{\rho(x,t)}{\bar{\rho}(t)}$$

$$\ddot{\delta} + [\text{expansion}]\,\dot{\delta} + [\text{pressure} - \text{gravity}]\,\delta = 0$$



Winner writes history

gravity (matter) → δ grows

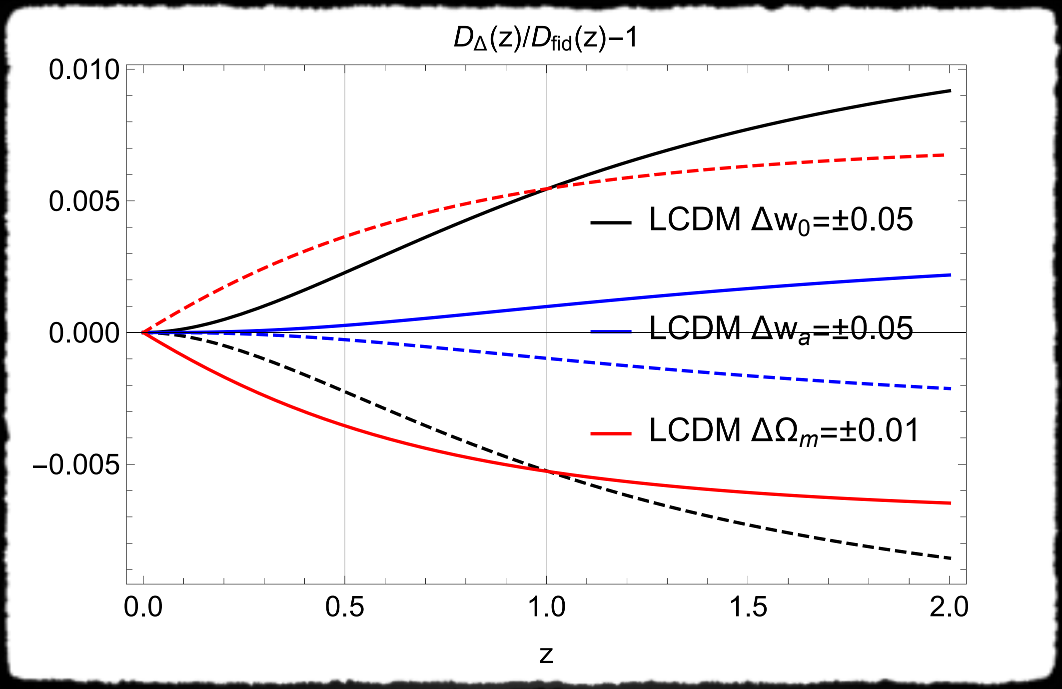
$$\delta(a) \sim D(a)\delta(a=1)$$

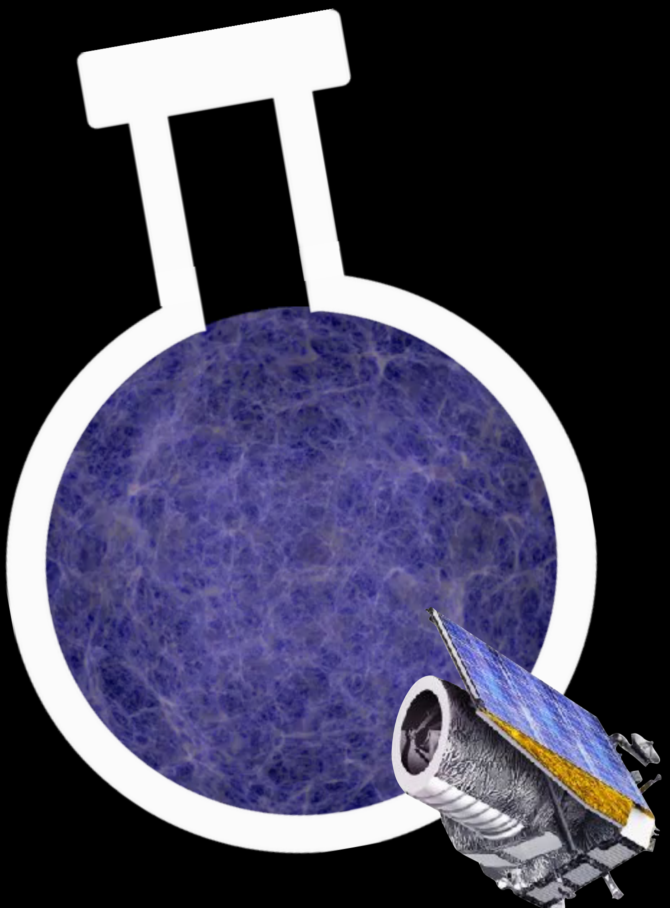
expansion (dark energy) → δ freezes

Linear Growth

records physics on large scales

measurable galaxy clustering & weak lensing

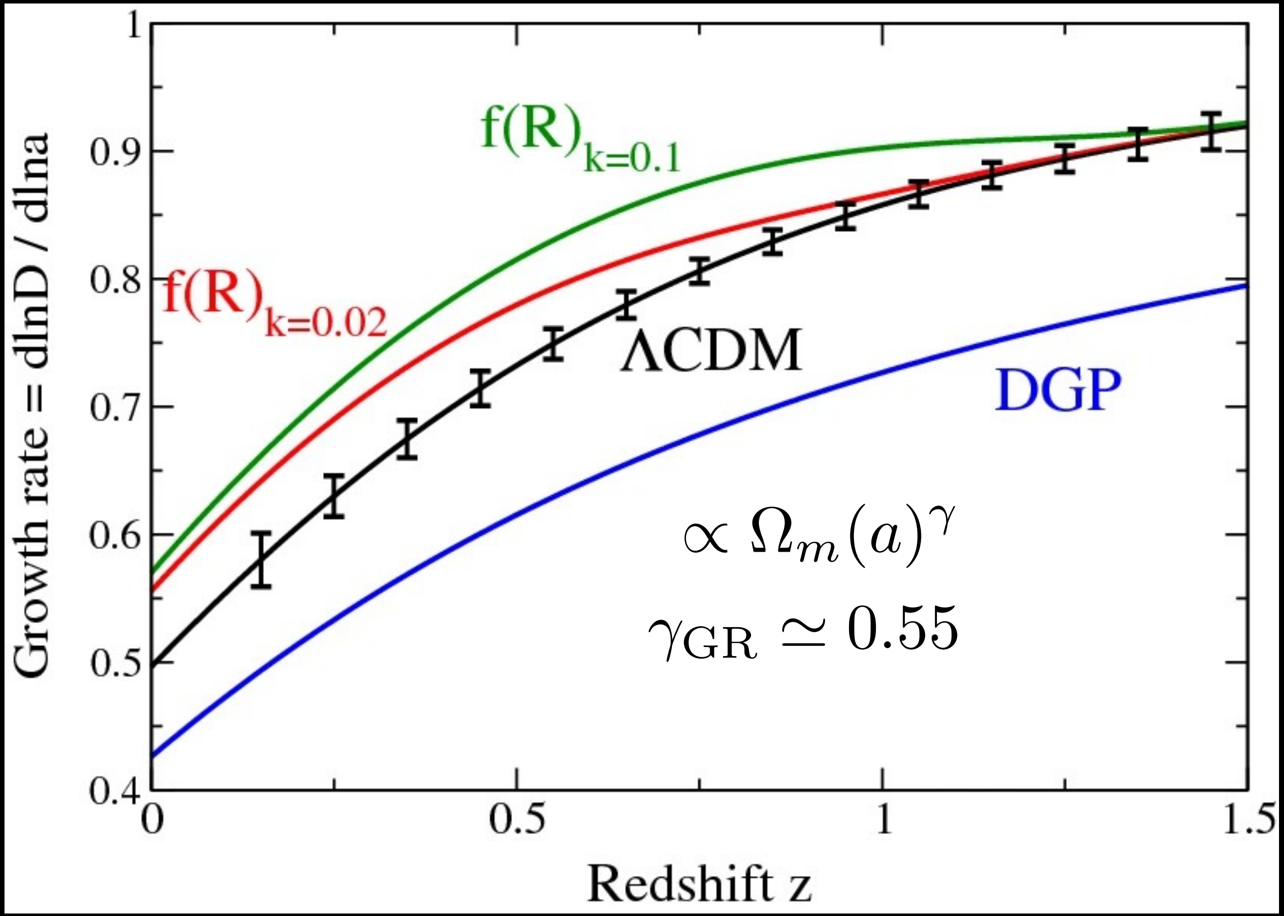


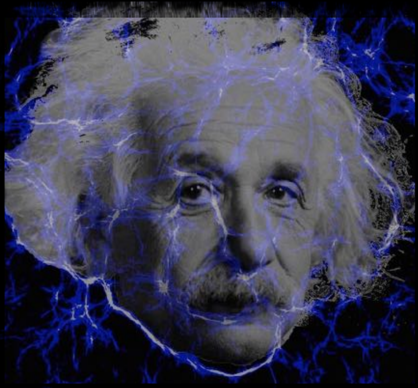


Modified Gravity Scalars

fifth force affects linear structure growth

depends on time and scale





credit: review
Ishak `19