From standard to constrained simulations

(CLONES)

Jenny Sorce
and many collaborators

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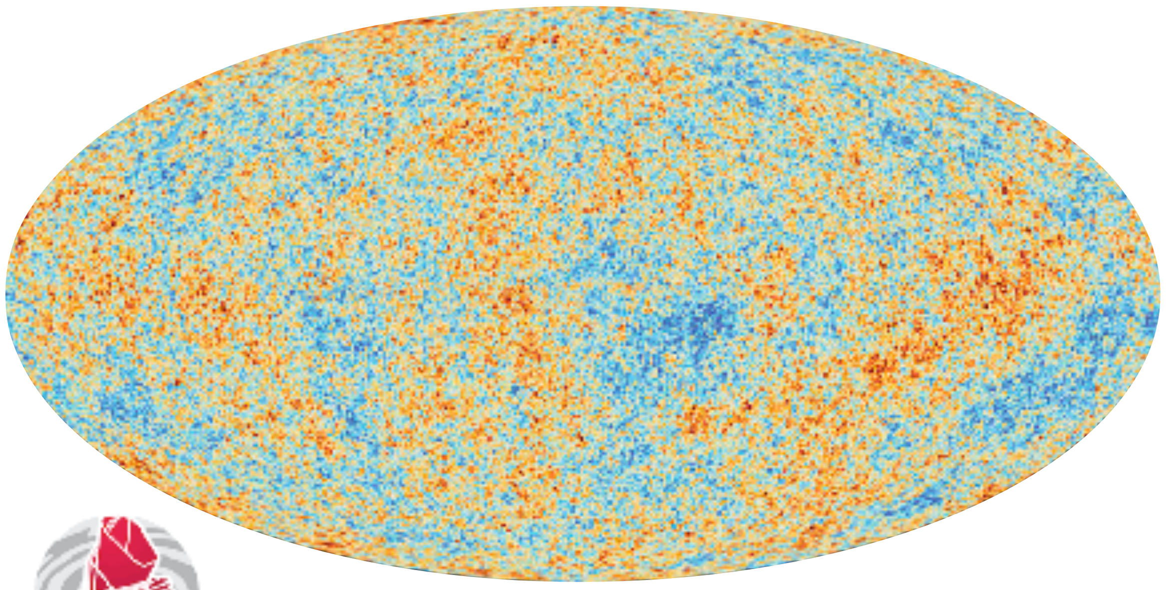
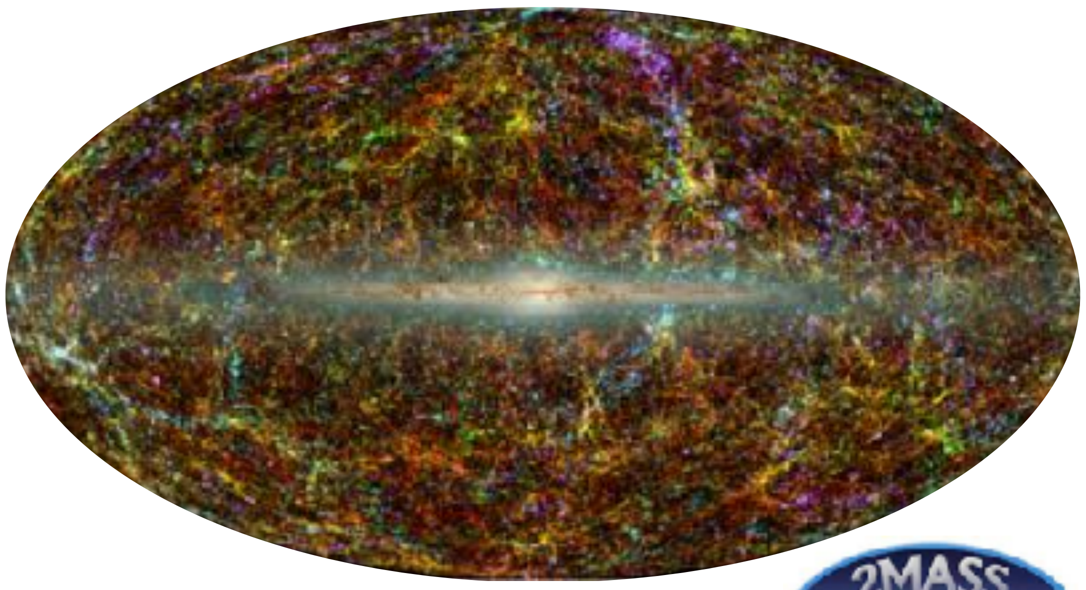
Guest researcher at AIP, Potsdam & CAS fellow at LMU, Munich

Paris-Saclay Astroparticle Symposium 2022 - November 10th 2022

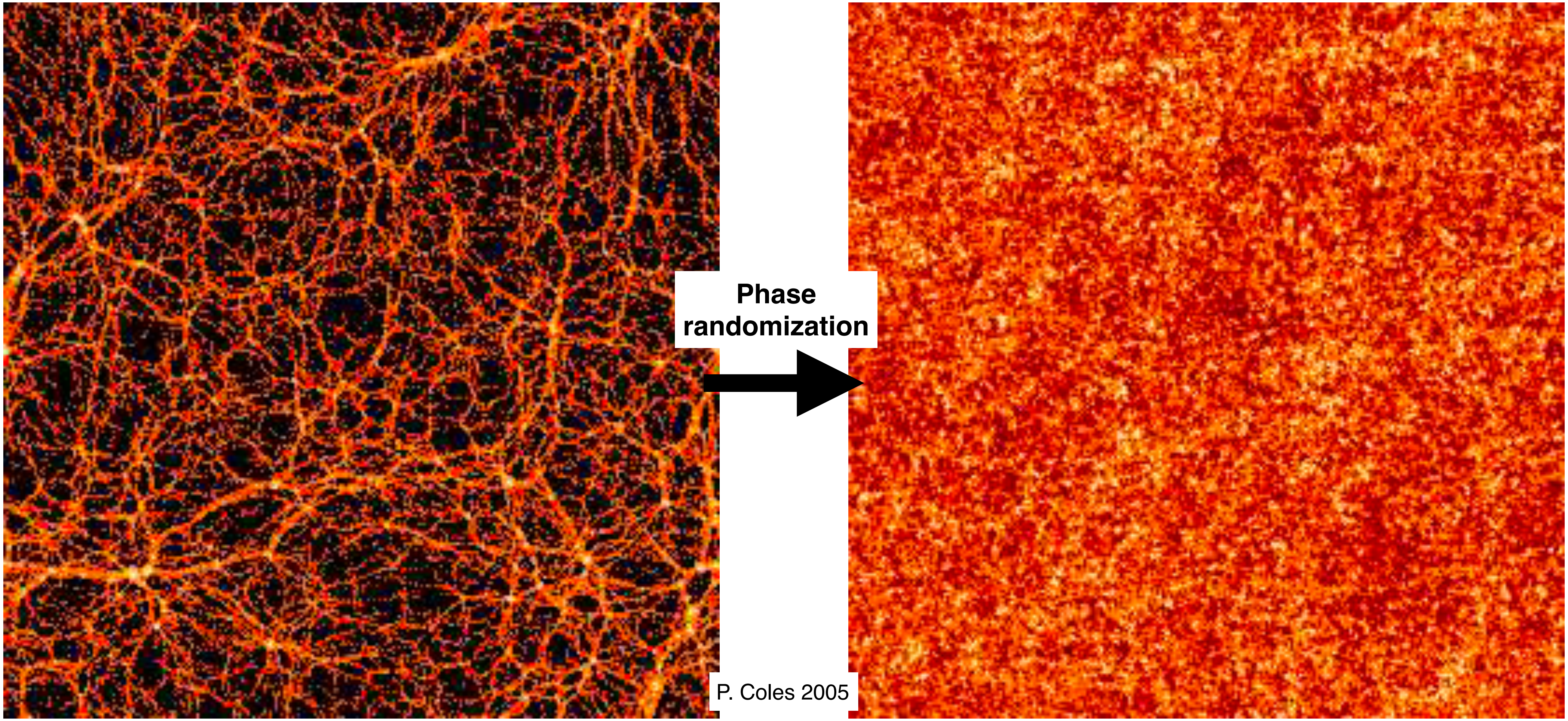
Motivation : ΛCDM? observations



?

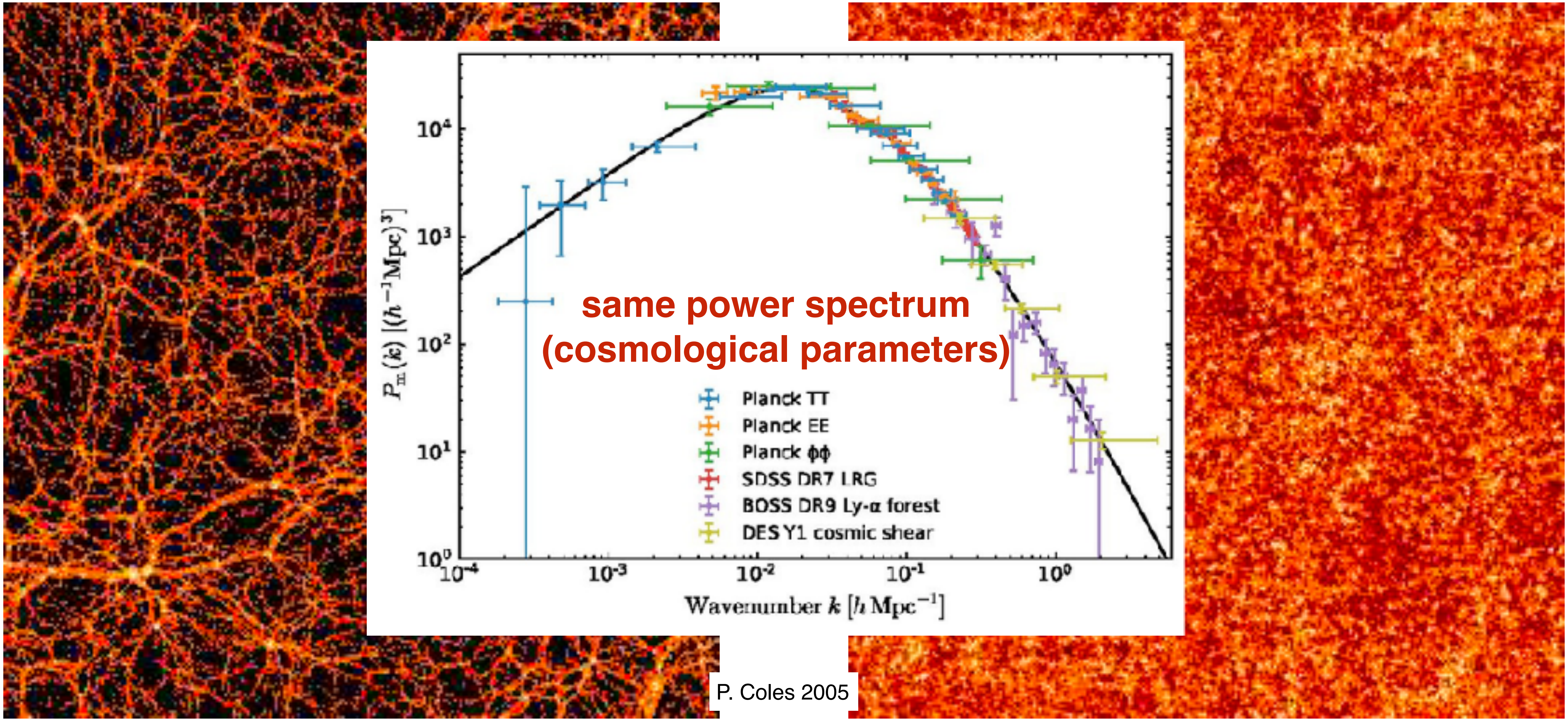


a beginning but …



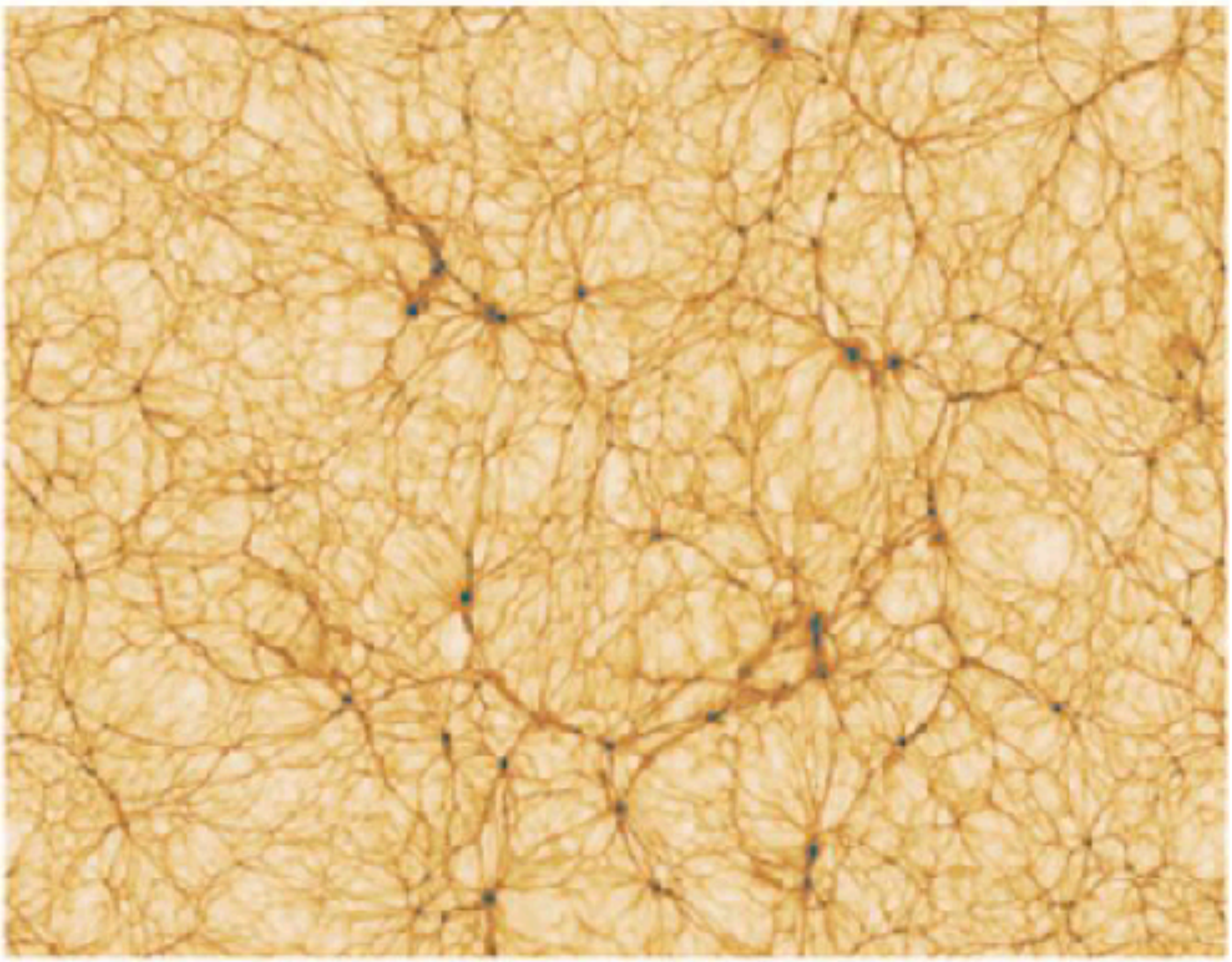
Motivation : ΛCDM? a story of power spectrum?

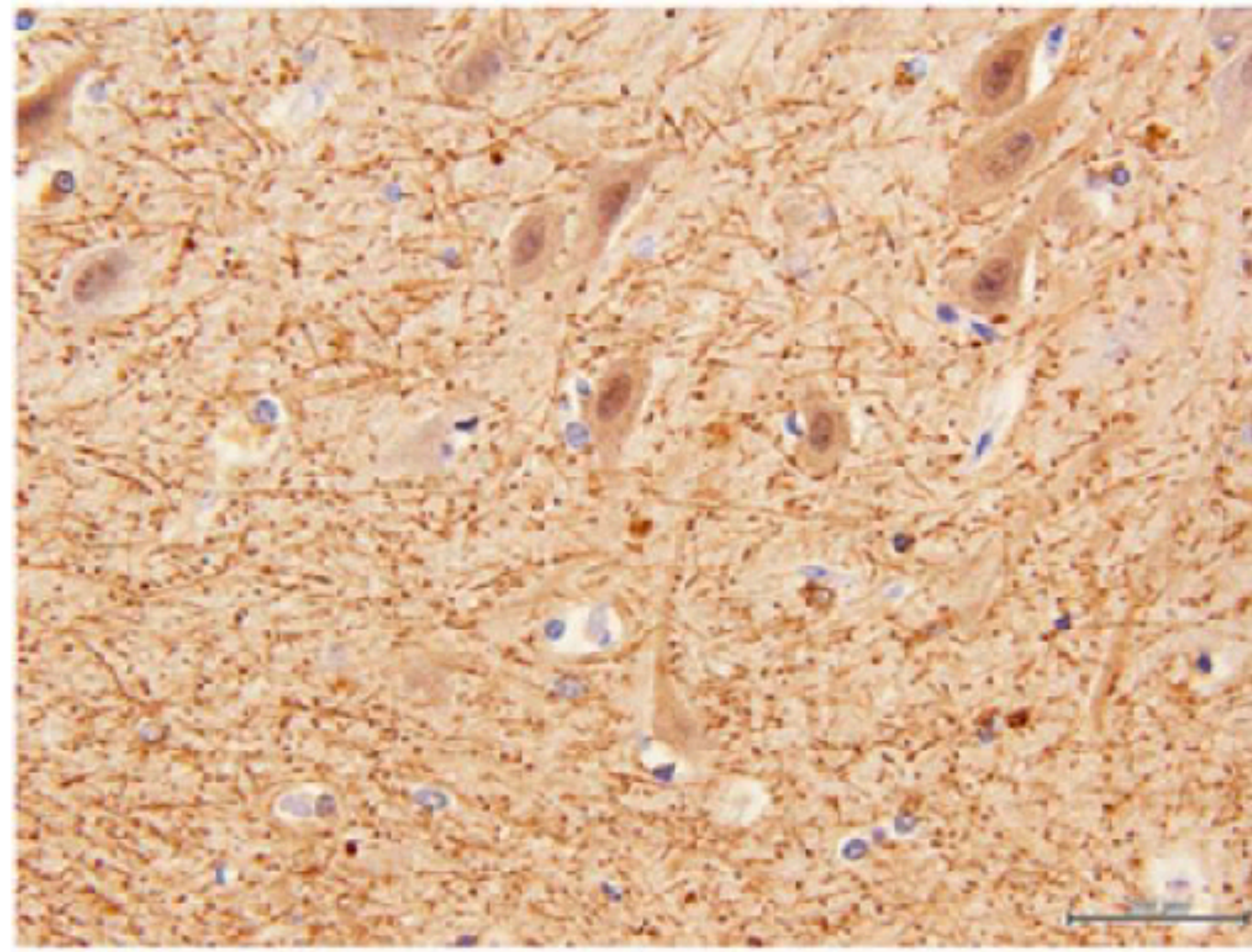
a beginning but …



not enough

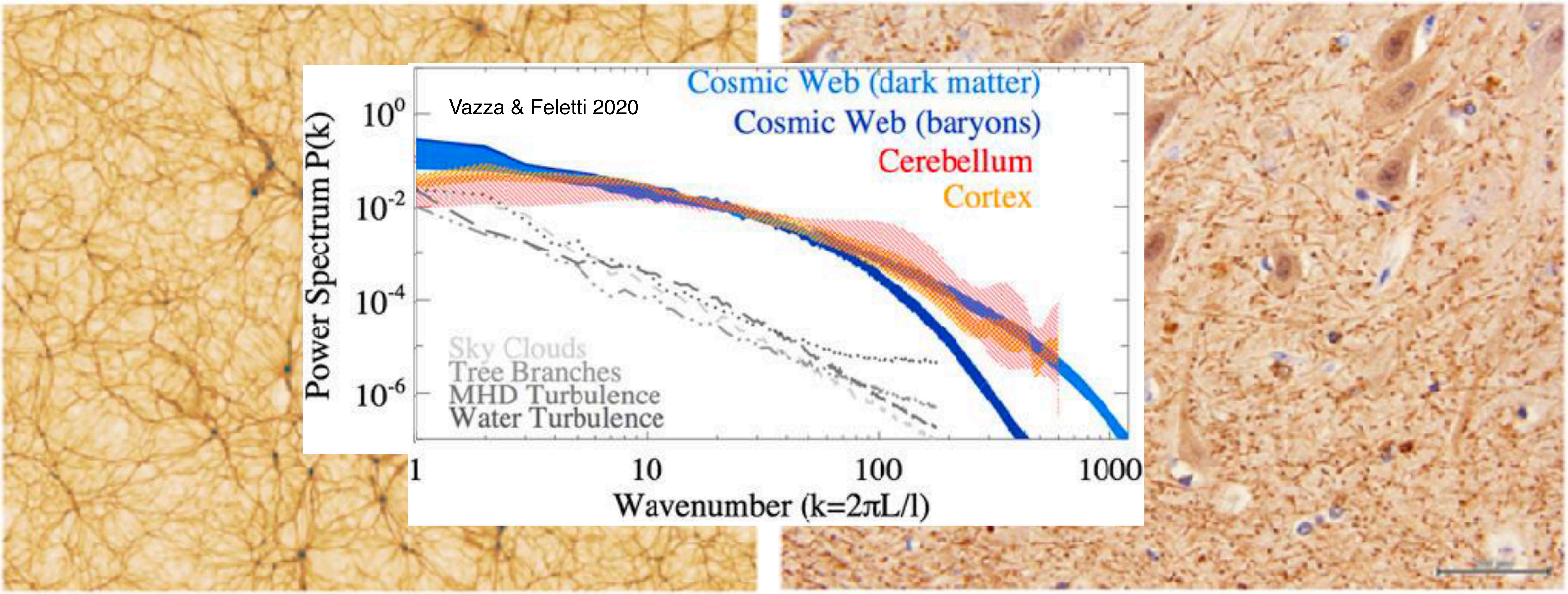
clearly





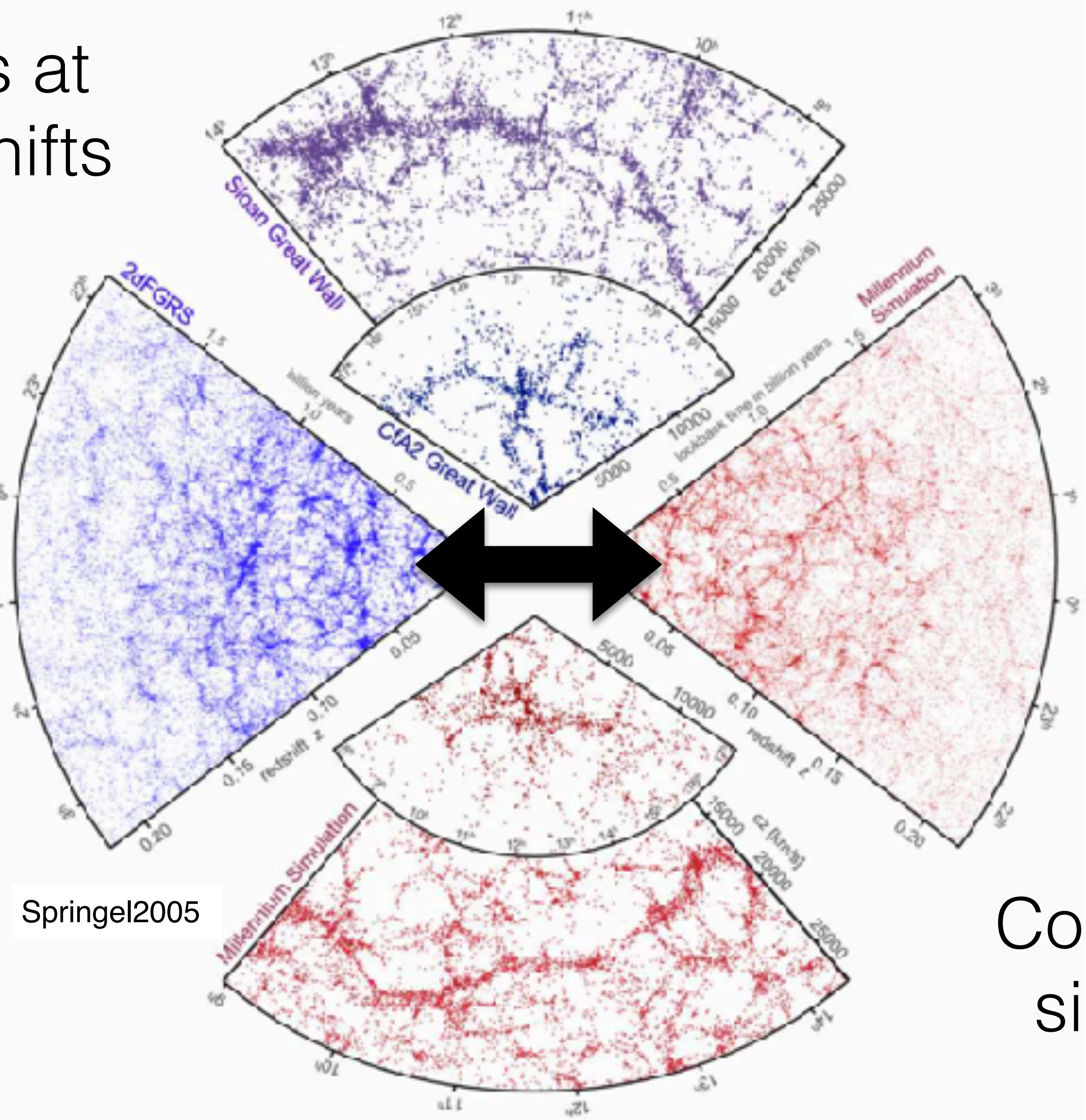
Motivation : ΛCDM? a story of power spectrum?

not enough



Motivation : ΛCDM? understand the full formation history?

Observations at different redshifts

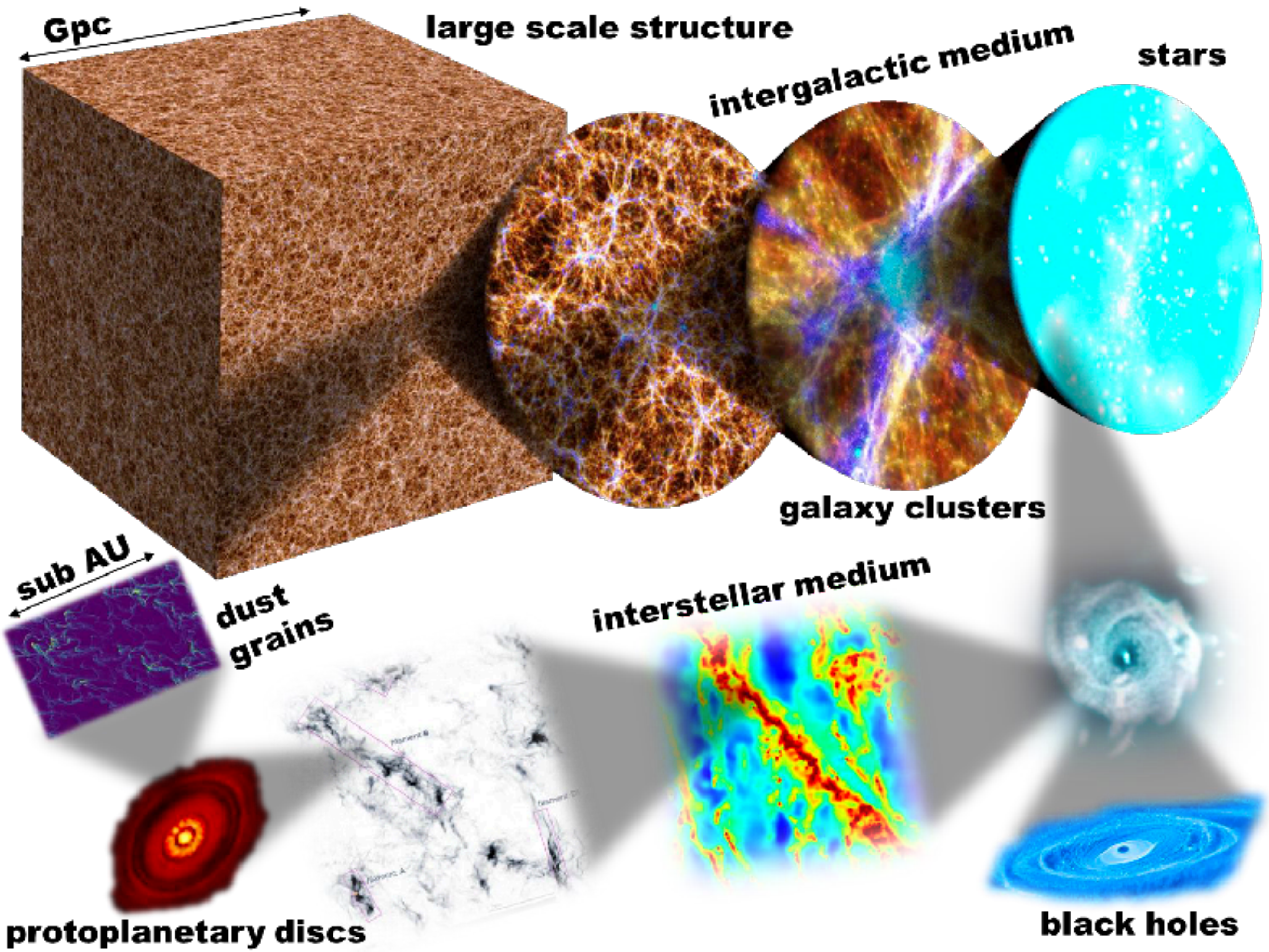


Springel2005

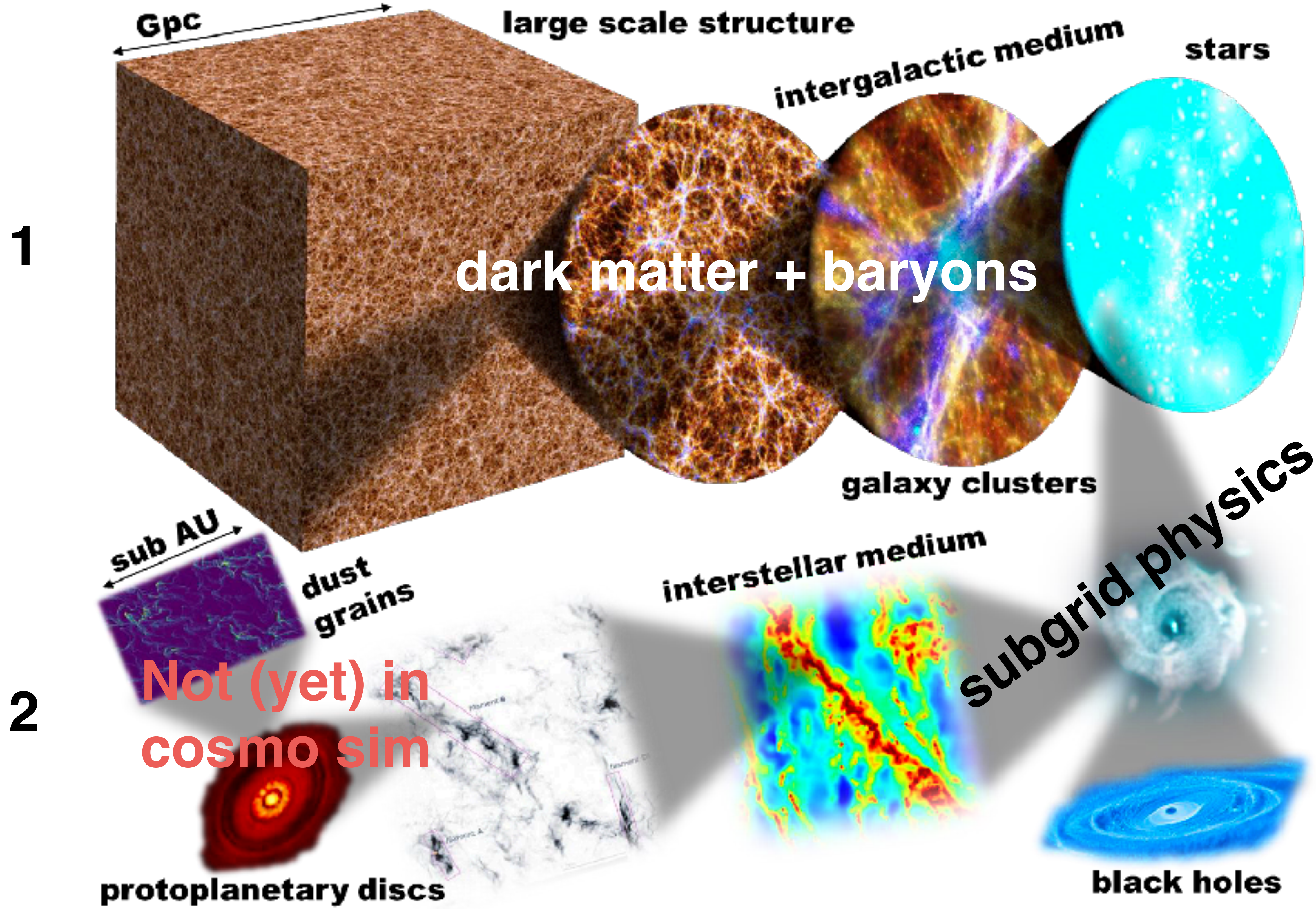
Cosmological simulations

Comparisons
Calibrations

Cosmological simulations ▶ the multi-scale challenge



courtesy K. Dolag



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1 Collisionless Boltzmann equation + Poisson equation

particle distribution function

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}} \cdot \mathbf{v} + \frac{\partial f}{\partial \mathbf{v}} \cdot \left(-\frac{\partial \Phi}{\partial \mathbf{x}}\right) = 0$$

$$\nabla^2 \Phi(\mathbf{x}, t) = 4\pi G \int f(\mathbf{x}, \mathbf{v}, t)\, \mathrm{d}\mathbf{v}$$

If 2-body relaxation time >> Hubble time -> **dark matter particles & star particles**

Difficult (sometimes impossible) to solve in non-trivial cases

1 Discretization = N-body approach

$$\ddot{\mathbf{x}}_i = -\nabla_i \, \Phi(\mathbf{x}_i)$$

$$\Phi(\mathbf{x}) = -G \sum_{j=1}^{N} \frac{m_j}{\left[(\mathbf{x} - \mathbf{x}_j)^2 + \epsilon^2\right]^{1/2}}$$

In **cosmological** simulation dark matter particles and star particles (comoving coordinates + periodic boundaries)

$$\frac{\mathrm{D}\mathbf{v}}{\mathrm{D}t} + H(t)\mathbf{v} = -\frac{1}{a}\nabla_x \phi$$

$$\nabla^2 \phi = 4\pi G \bar{\rho} a^2 \delta \qquad \phi = \Phi - \frac{2\pi G}{3}\bar{\rho} a^2 \mathbf{x}^2$$

1 Baryons = Gas = fluid = hydrodynamics

Lagrangian = particles (SPH)

Equation of motion: $\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho}$

Continuity equation: $\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho \nabla \cdot \mathbf{v} = 0$

Thermal energy equation: $\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho} \nabla \cdot \mathbf{v}$

Equation of state: $P = (\gamma - 1)\rho u$

Entropy equation: $\frac{\mathrm{d}A}{\mathrm{d}t} = 0 \qquad A \equiv \frac{P}{\rho^{\gamma}}$

Eulerian = grids (AMR)

Mass conservation: $\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = 0$

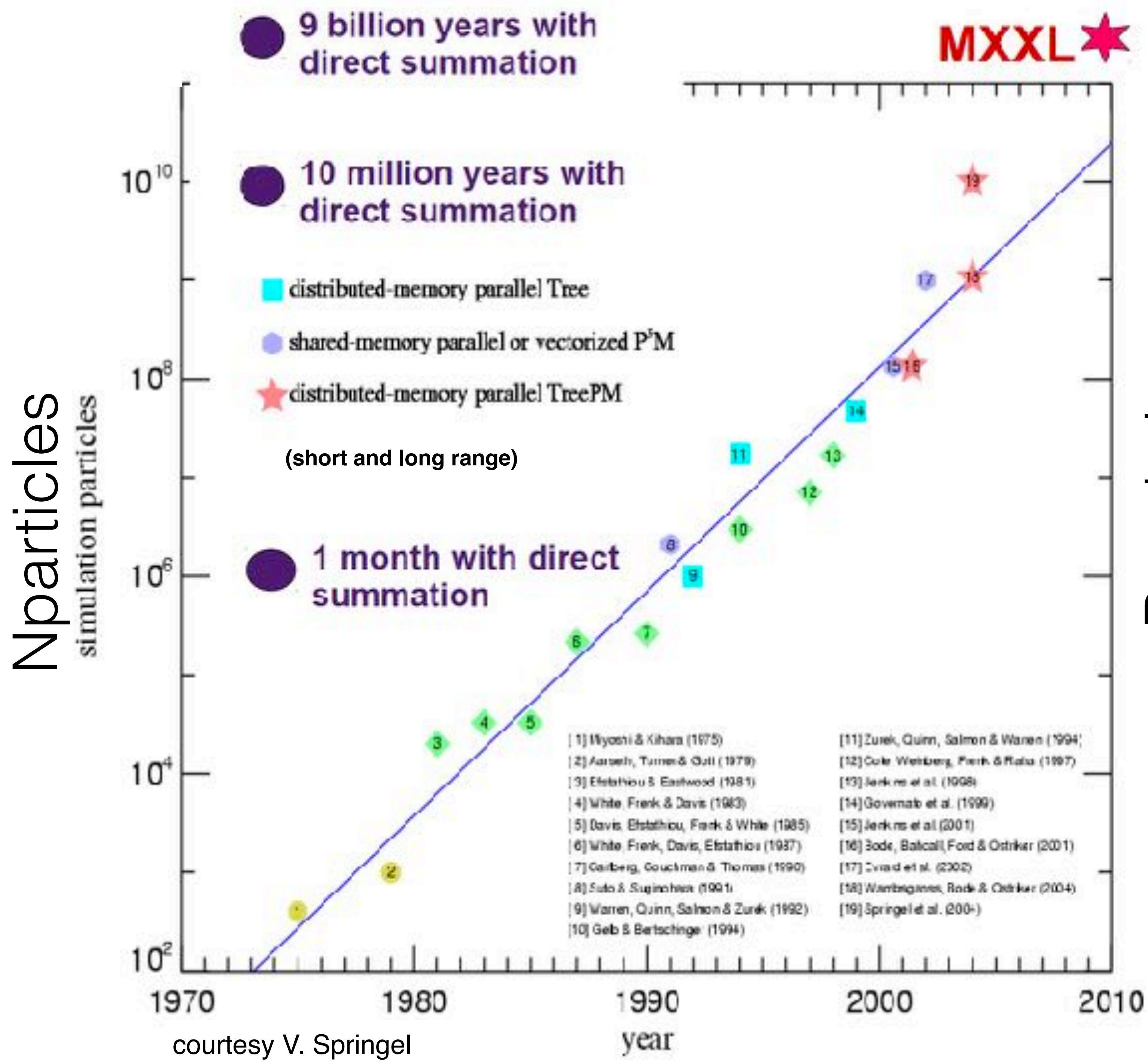
Momentum conservation: $\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla(\rho \mathbf{v}\mathbf{v}^T + P) = 0$

Energy conservation: $\frac{\partial}{\partial t}(\rho e) + \nabla[(\rho e + P)\mathbf{v}] = 0$

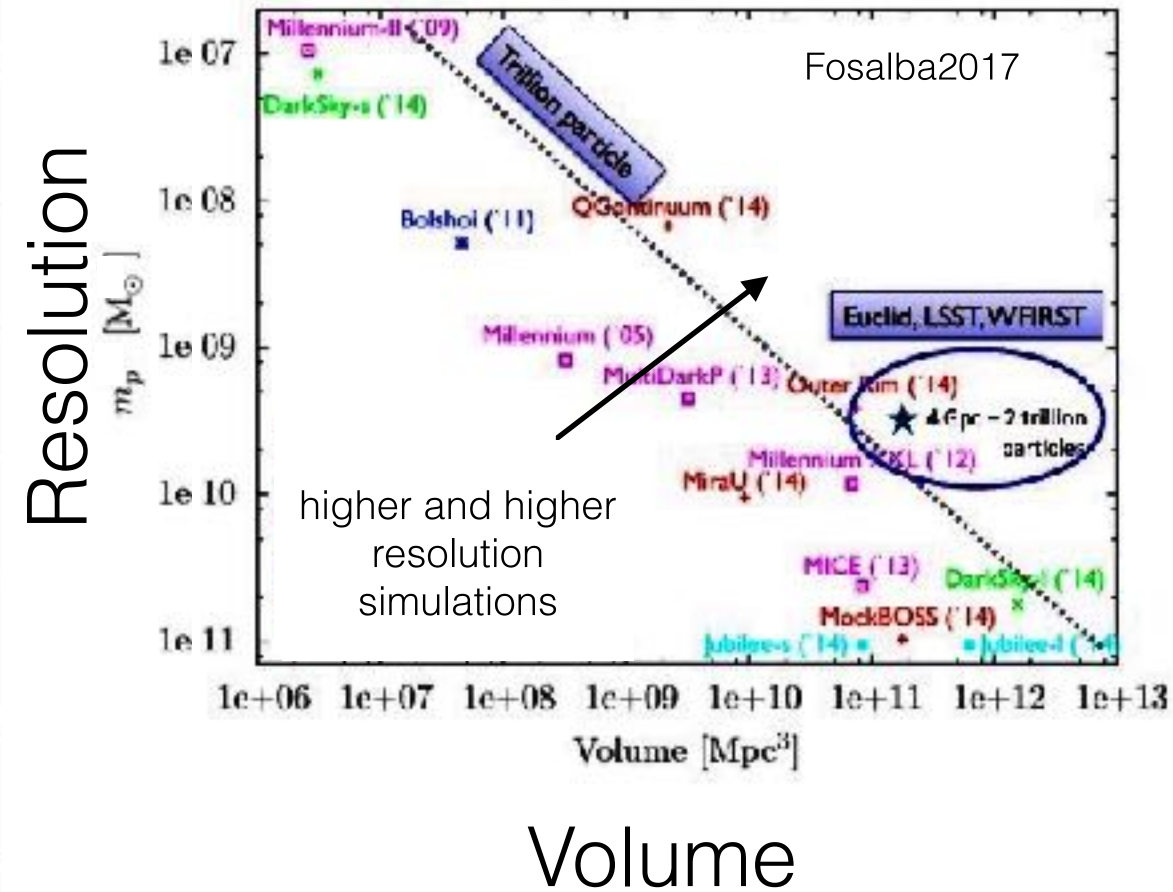
Total specific energy: $e = \frac{1}{2}\mathbf{v}^2 + u$

MHD: induction equation + divergence constraint -> modify Euler equations

1 Dark matter

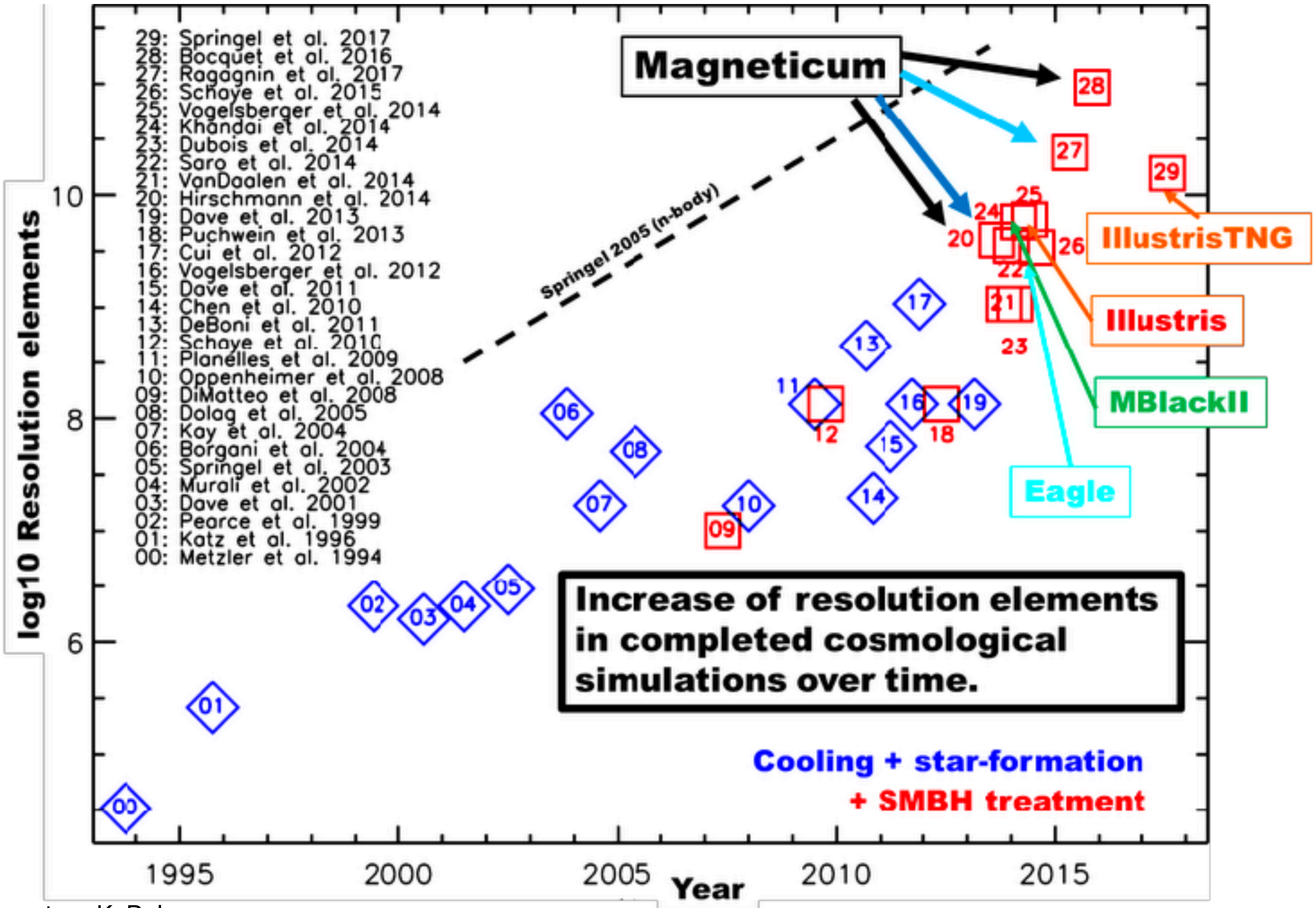


courtesy V. Springel



*apologies for any missing simulation, the lists are not exhaustive

1 Hydrodynamics



courtesy K. Dolag

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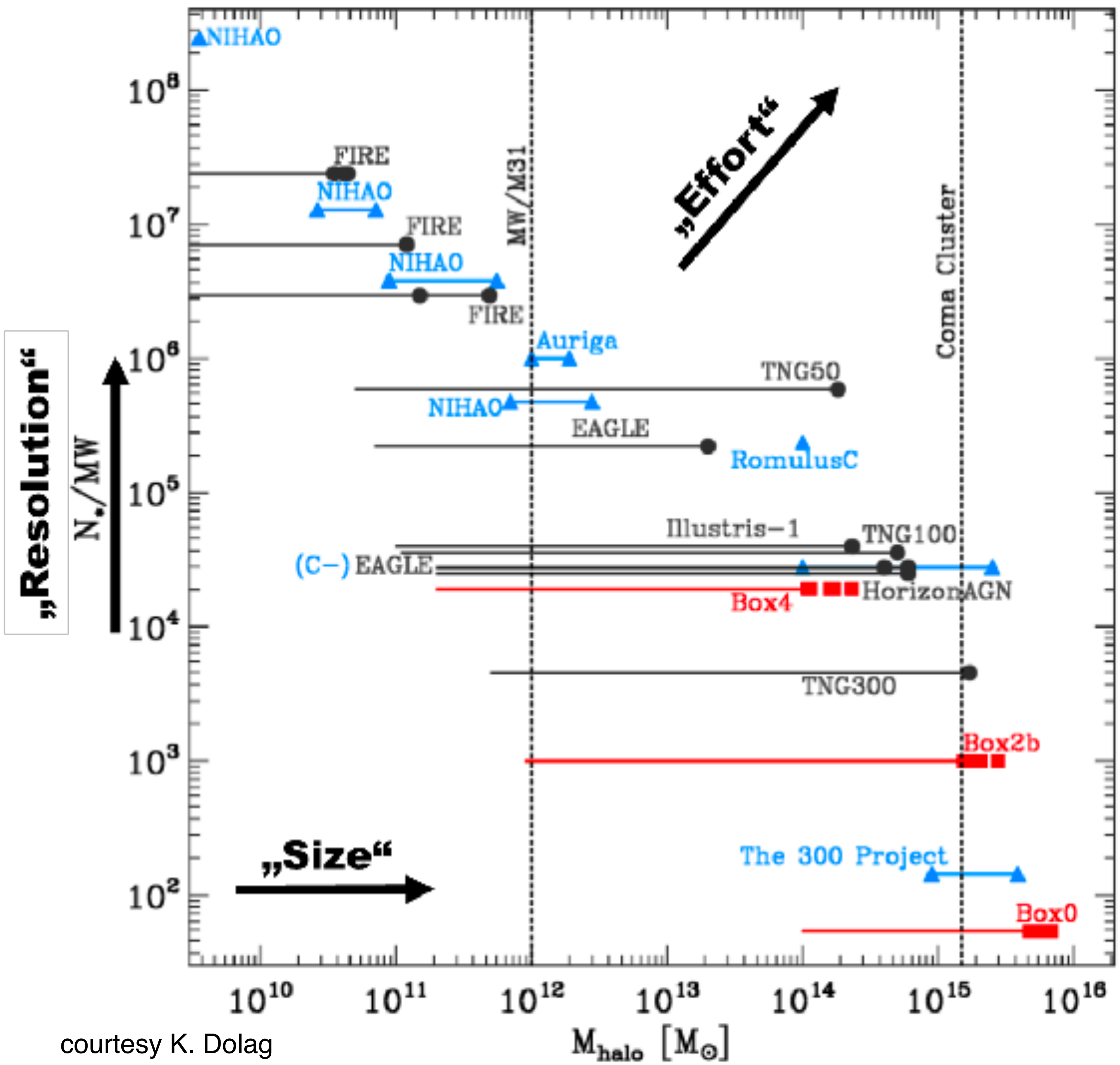
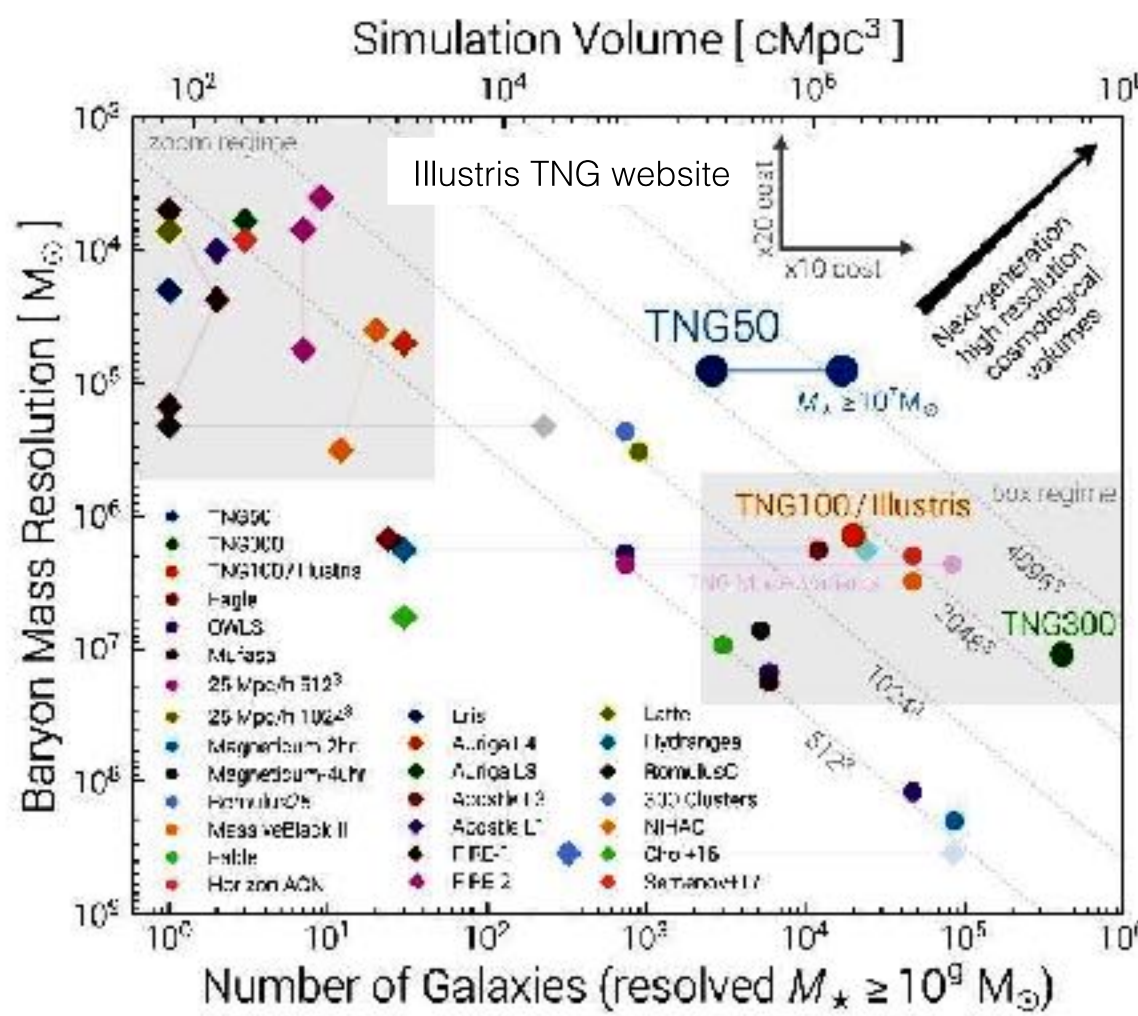
1 Mass range (zoom)





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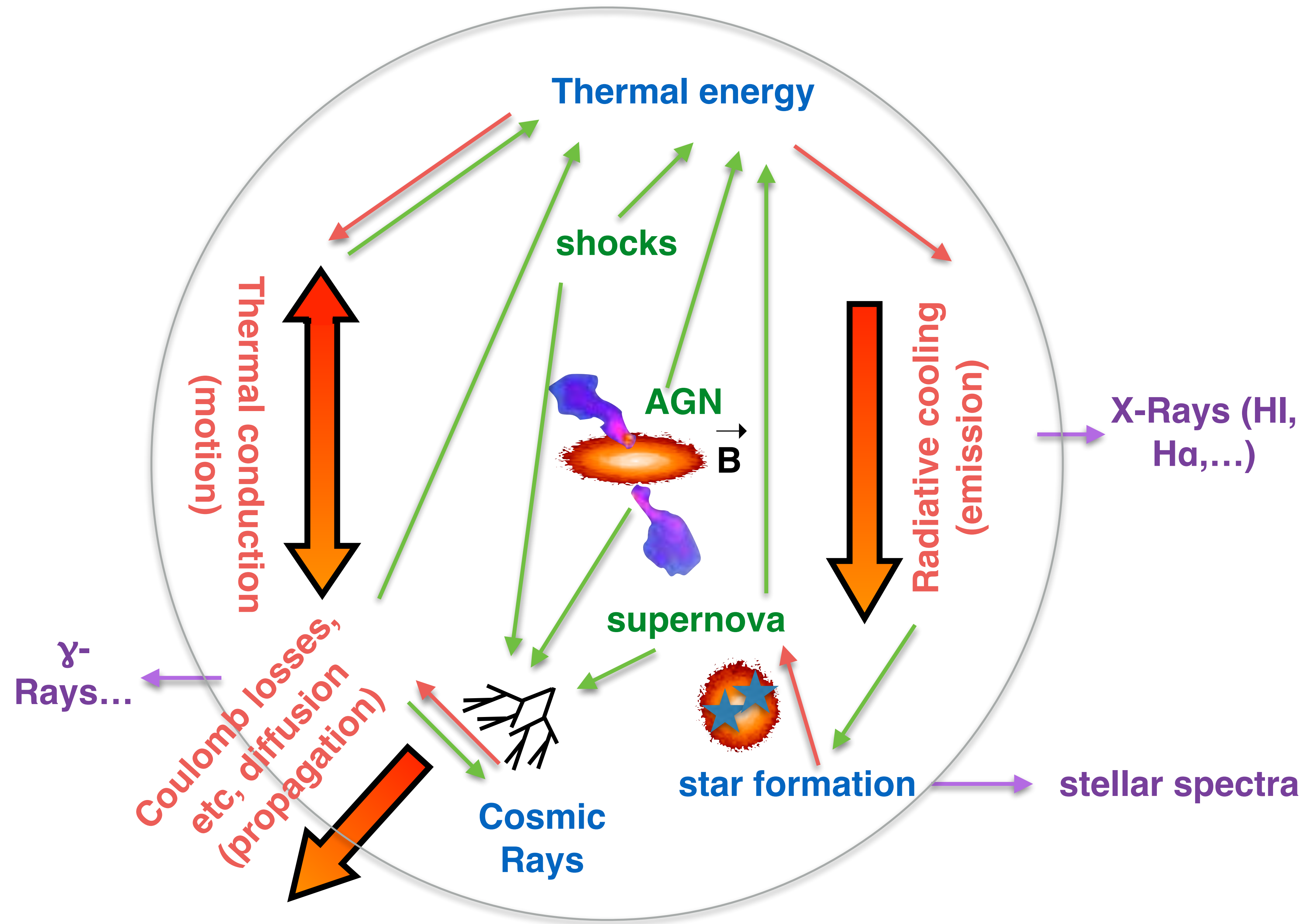
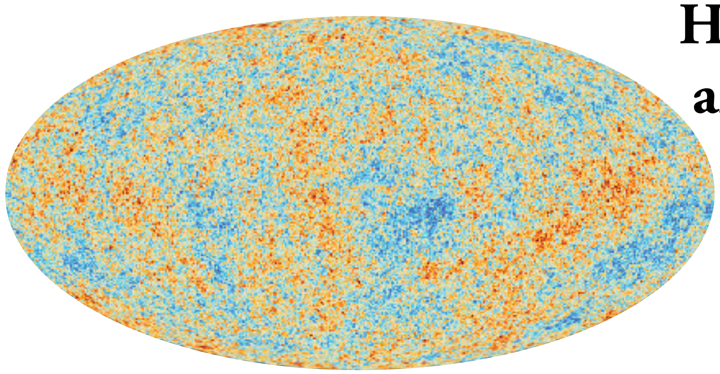
2 Subgrid physics



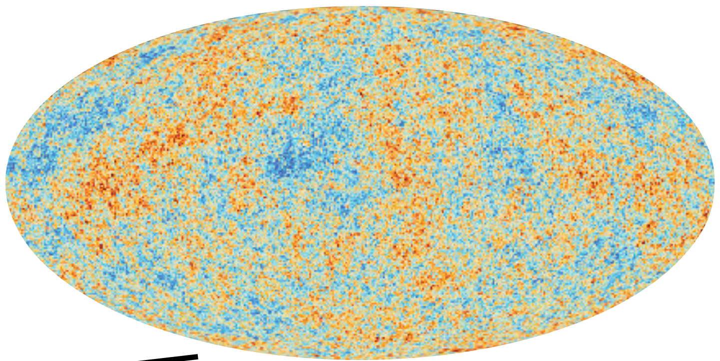
Cosmological simulations ▸ In practice?

Initial conditions (ICs)

Part of the Universe at 13.7 light-Gyr Photons received today have been emitted when it was ~380 000 yrs. old



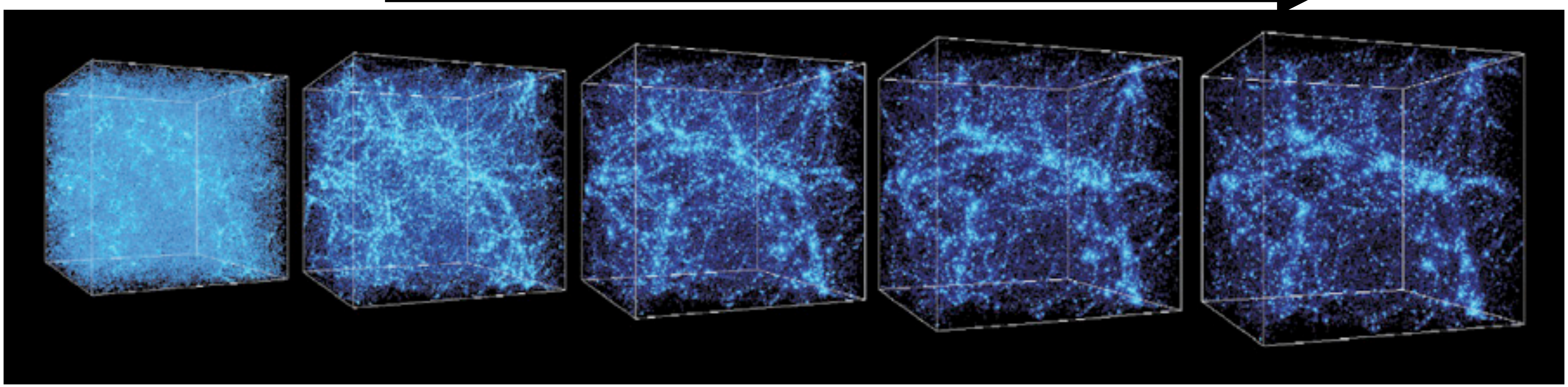
Homogeneous and Isotropic Universe → $P(k)$ **Gaussian initial density field** → $\delta(\mathbf{k}) = \sqrt{P(\mathbf{k})}.\omega(\mathbf{k})$ →



initial conditions of a random patch of the Universe

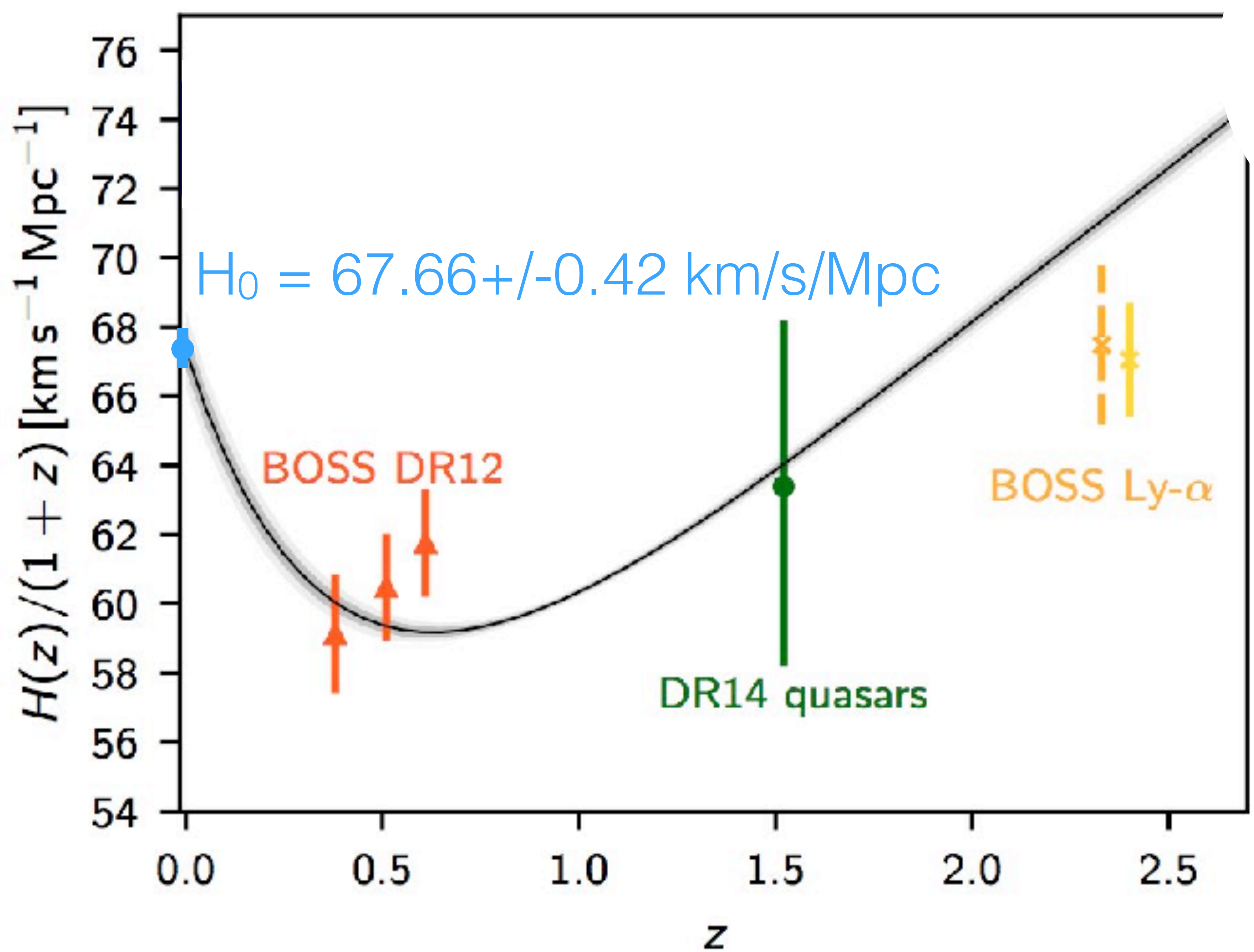
Zeldovich approximation

Evolution



Understand obs. / Test models

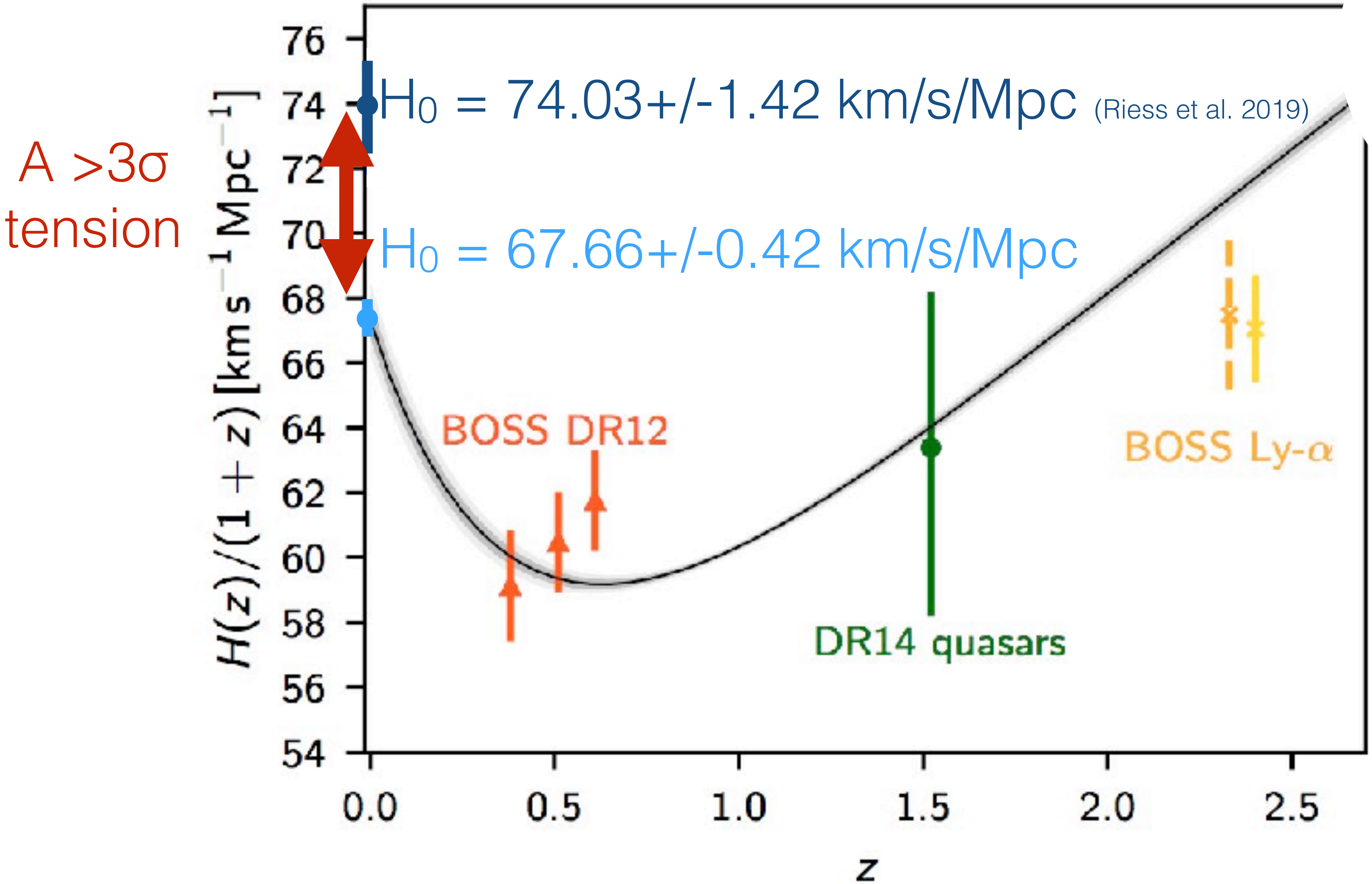
An example: H_0



Planck collaboration

Understand obs. / Test models

An example: H_0



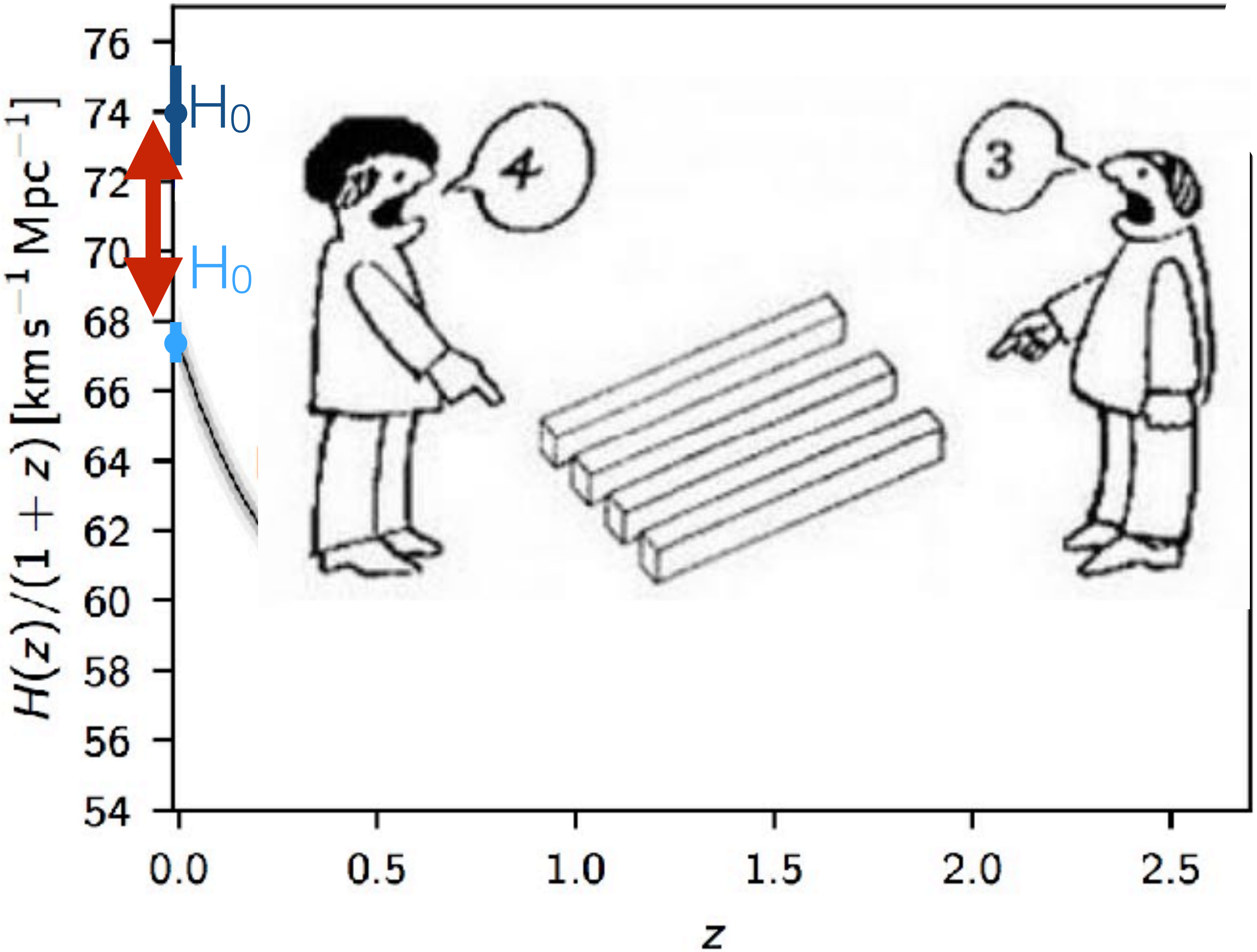
Planck collaboration

~~ΛCDM~~ ?

Understand obs. / Test models

An example: H_0

A >3σ tension



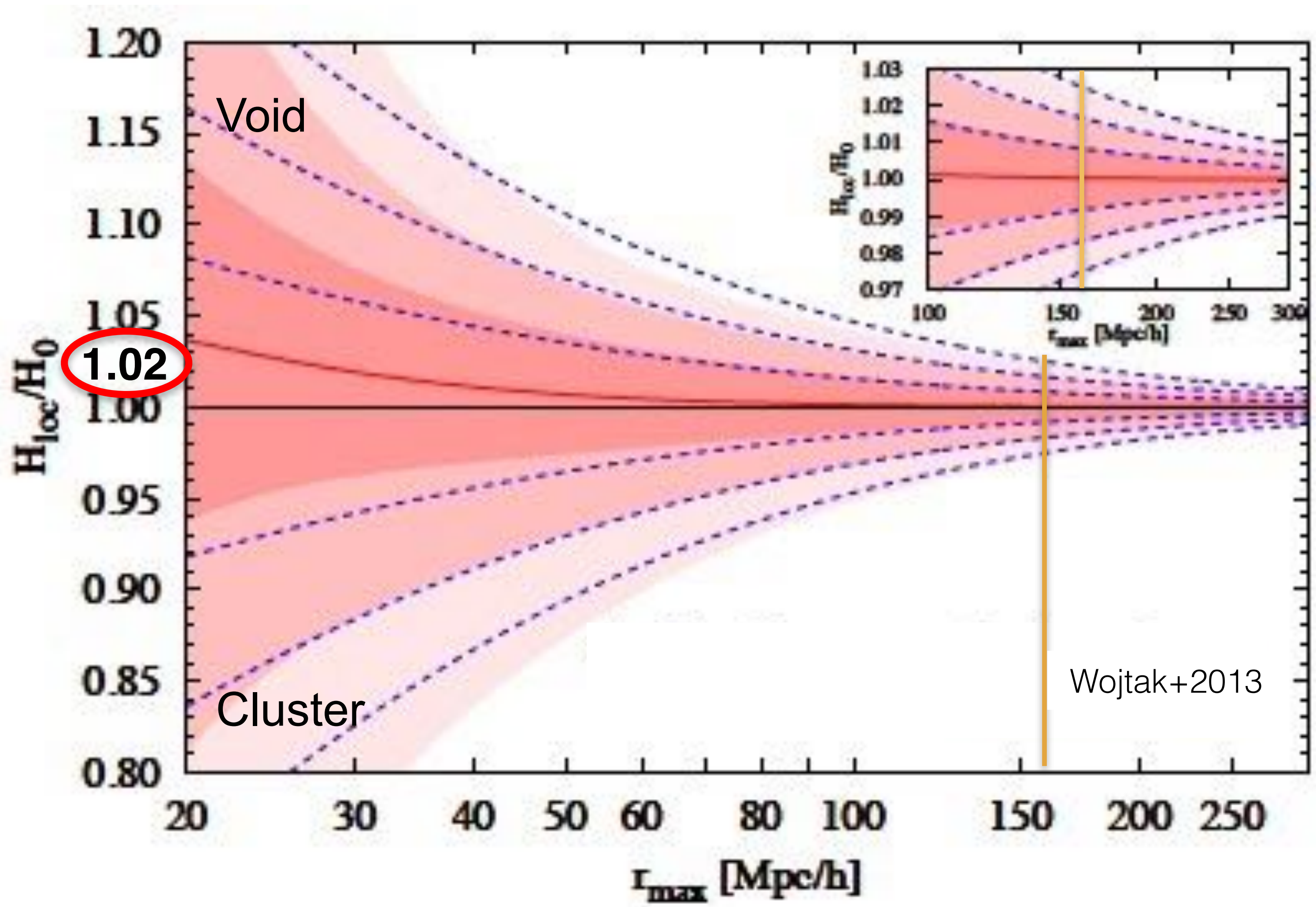
Planck collaboration

~~ΛCDM~~ or biases/systematic errors?

Cosmological simulations are a great tool to investigate statistically the possible biases.

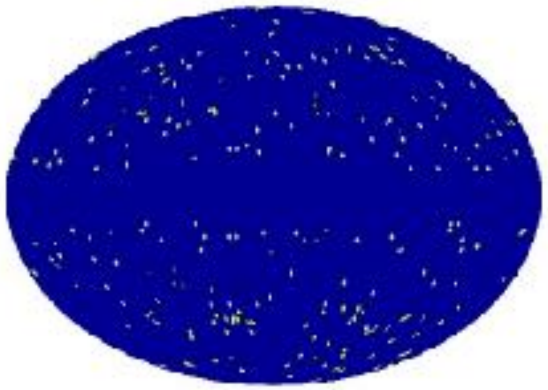
Impact of the local density

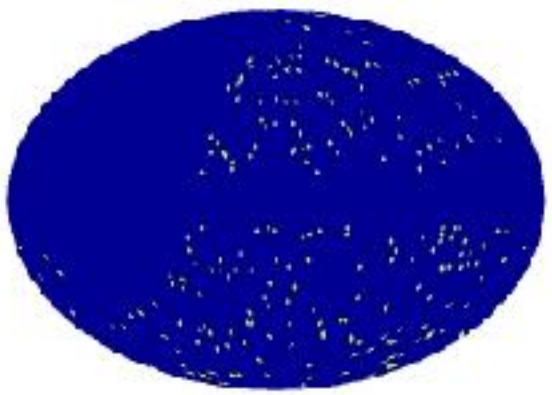
As many effects on values as environments

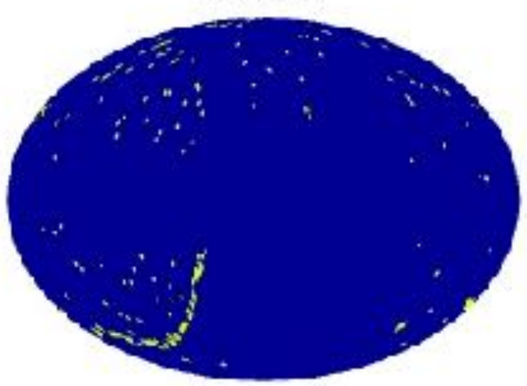


For an average environment: a 2% bias !

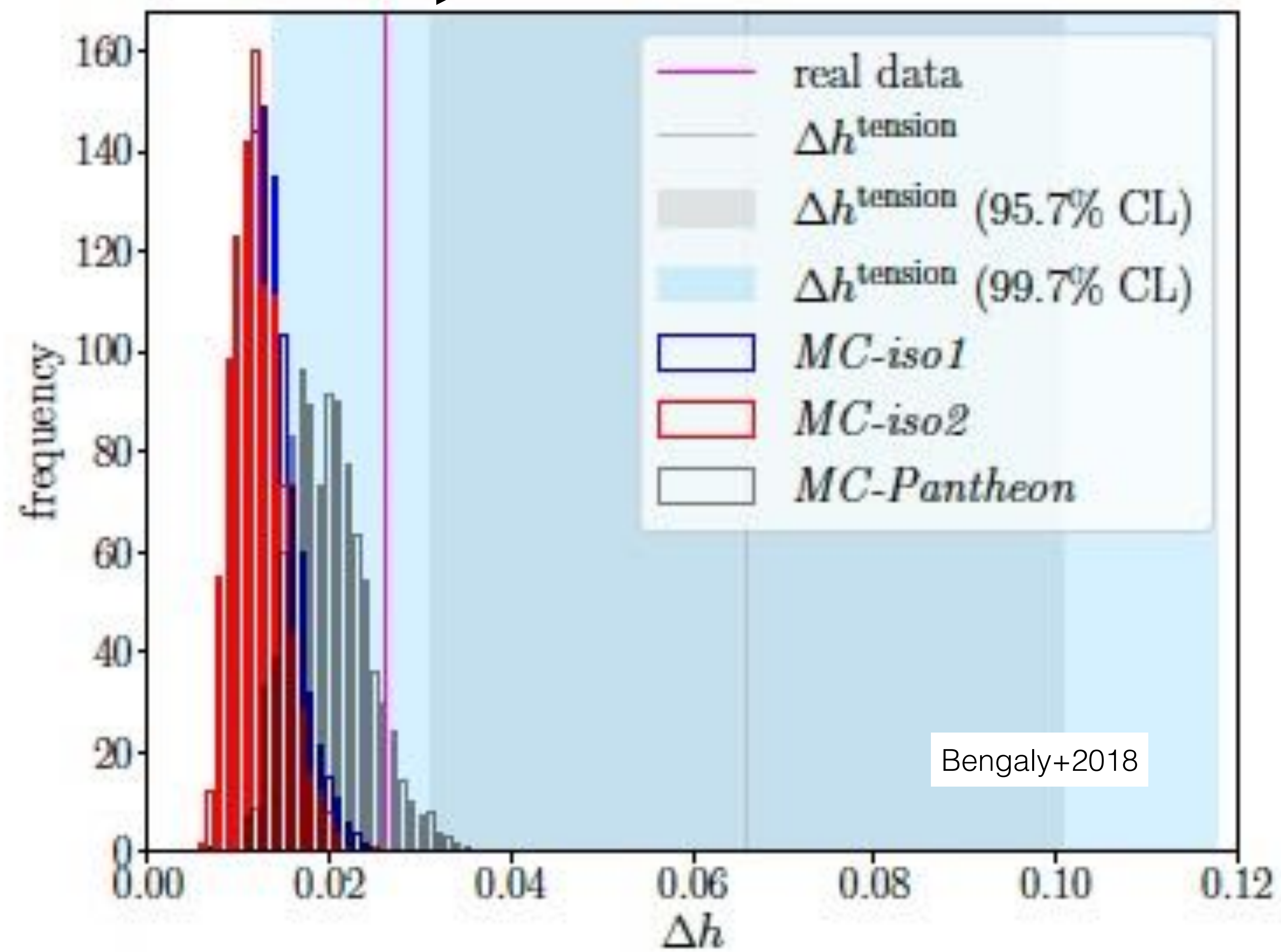
Impact of the survey anisotropy







increasing anisotropy →

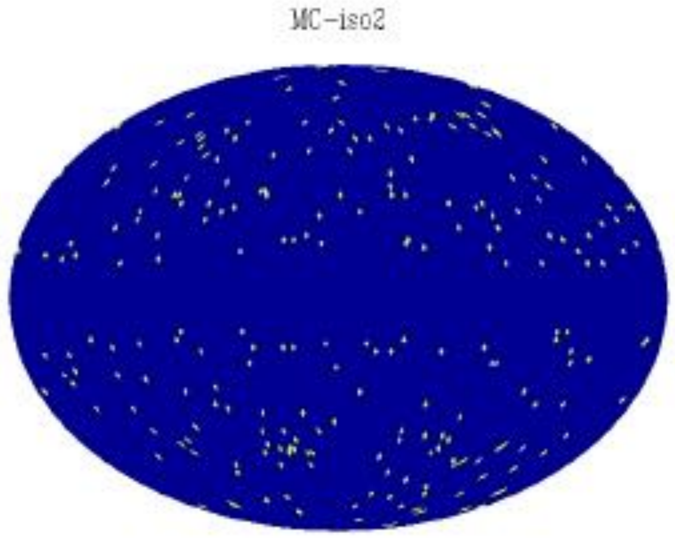


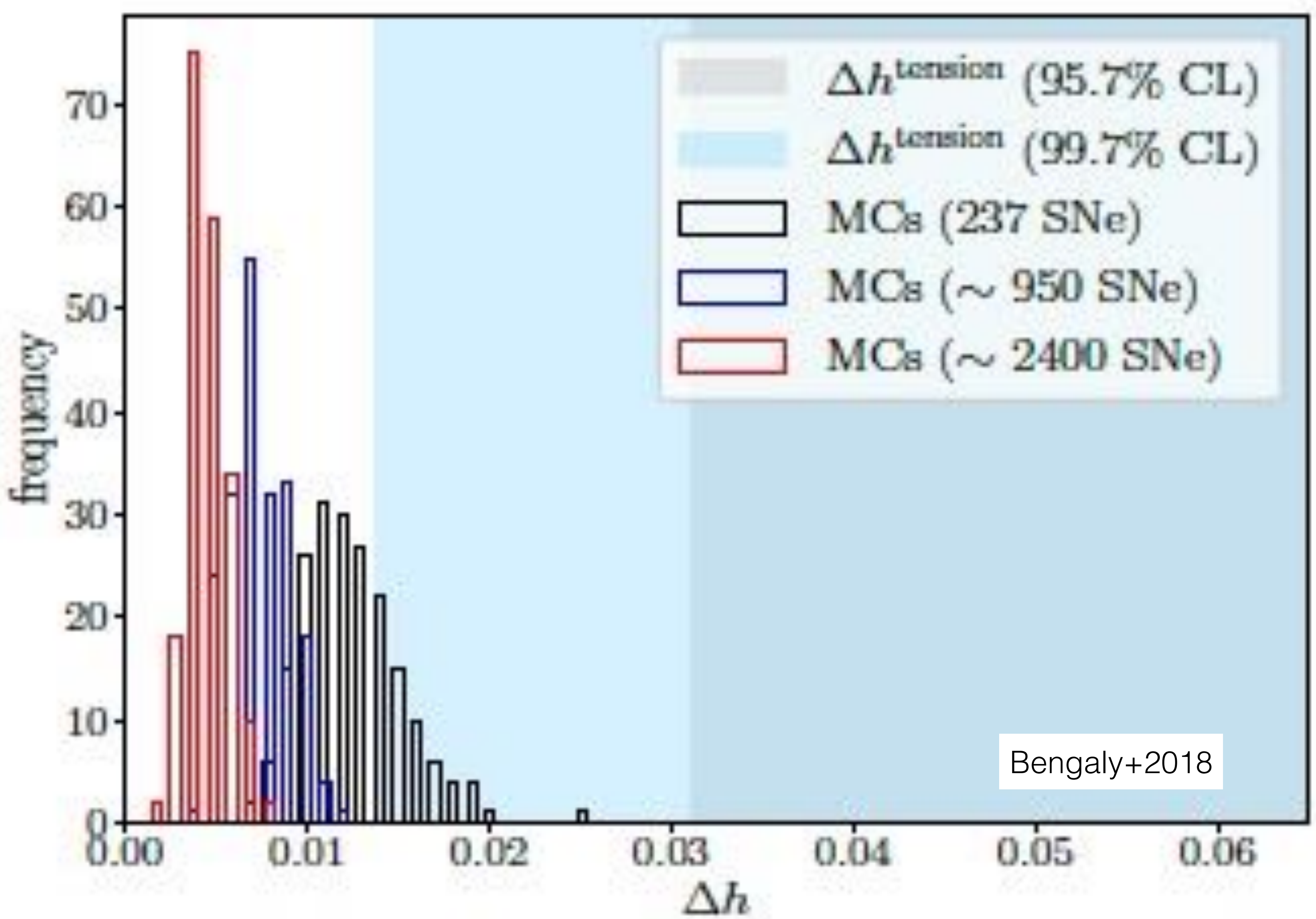
For an average survey: a 1-2% bias !

Possible biases?

Impact of the survey size

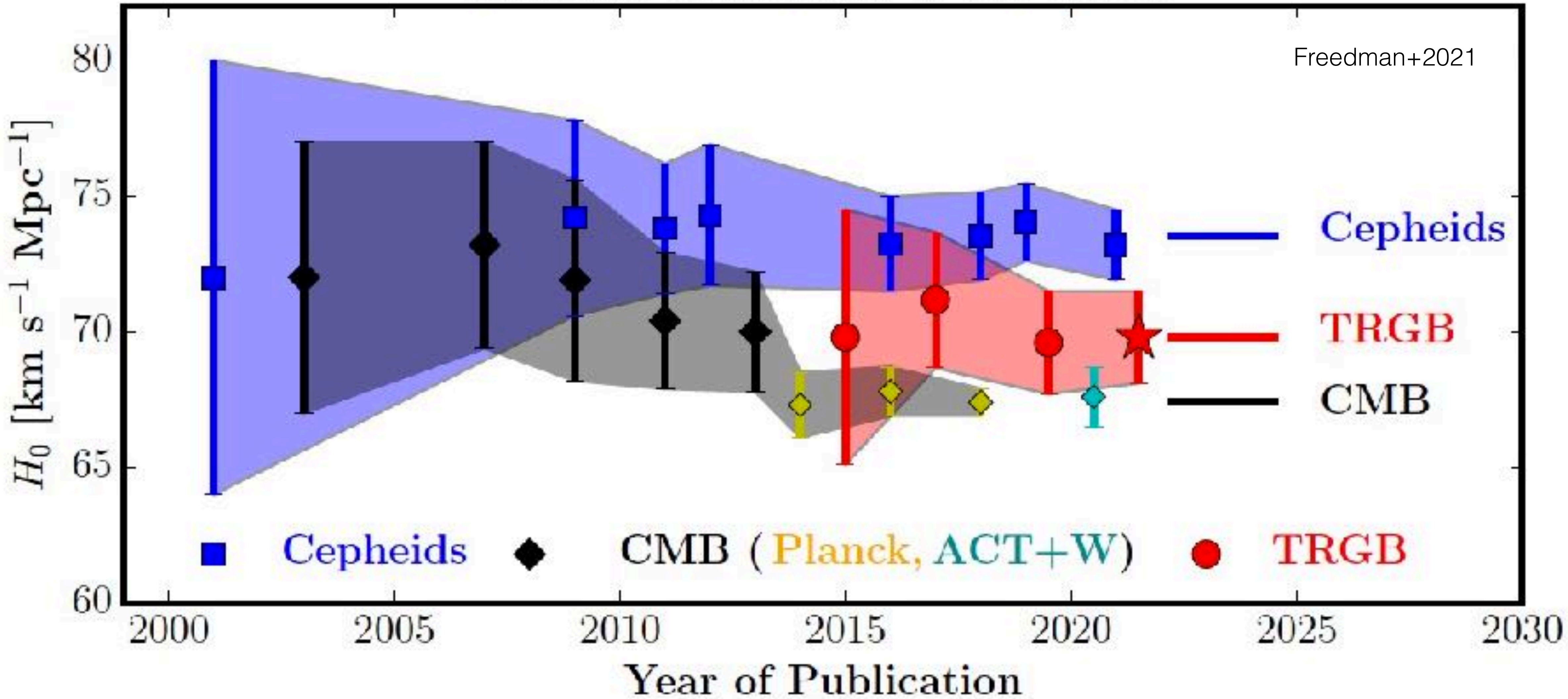
increasing size





For a survey size divided by 10: a 1-2% bias !

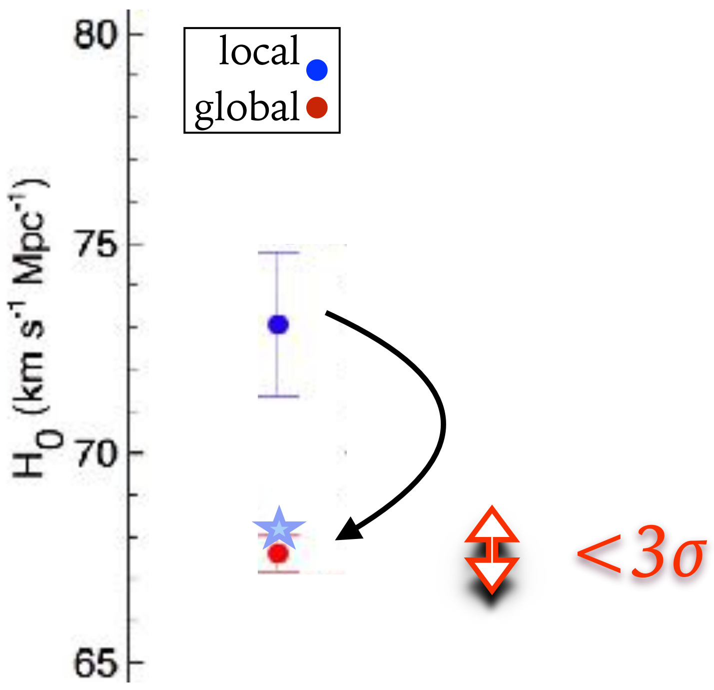
Impact of the calibrator nature



For different calibrators: a 5% difference !

Multiple biases

local density	For an average environment: a 2% bias !
survey anisotropy	For an average survey: a 1-2% bias !
survey size	For a survey size divided by 10: a 1-2% bias !
calibrator nature	For different calibrators: a 5% difference !



→ ΛCDM is not (yet) ruled out

Standard cosmological simulations can give the total uncertainty but cannot reduce the systematics

Sometimes it pays to know a little statistics.

PATH INTEGRAL METHODS FOR PRIMORDIAL DENSITY PERTURBATIONS: SAMPLING OF CONSTRAINED GAUSSIAN RANDOM FIELDS

EDMUND BERTSCHINGER
Center for Theoretical Physics, Center for Space Research, and Department of Physics, Massachusetts Institute of Technology
Received 1987 August 17; accepted 1987 September 10

ABSTRACT

Path integrals may be used to describe the statistical properties of a random field such as the primordial density perturbation field. In this framework the probability distribution is given for a Gaussian random field subjected to constraints such as the presence of a protovoid or supercluster at a specific location in the initial conditions. An algorithm has been constructed for generating samples of a constrained Gaussian random field on a lattice using Monte Carlo techniques. The method makes possible a systematic study of the density field around peaks or other constrained regions in the biased [illegible] effective for generating initial conditions for N-body simulations with rare objects in the computational volume

Bayes1761 Wiener1942 Hoffman & Ribak 1991 Zaroubi+1995 van der Weijgaert & Bertshinger 1996

"This identical twin of yours..
Can you describe him?"

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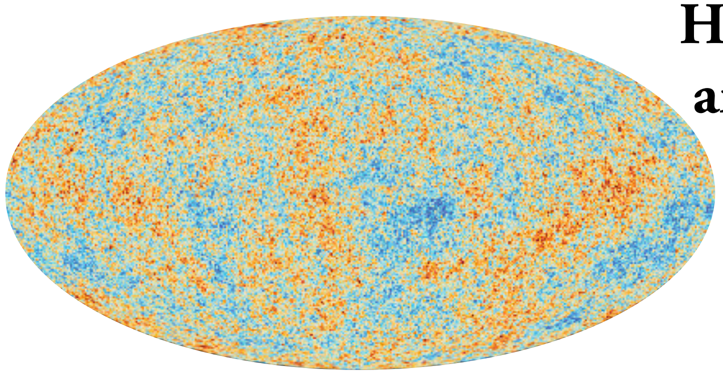
Photons received today have been emitted when it was ~380 000 yrs. old



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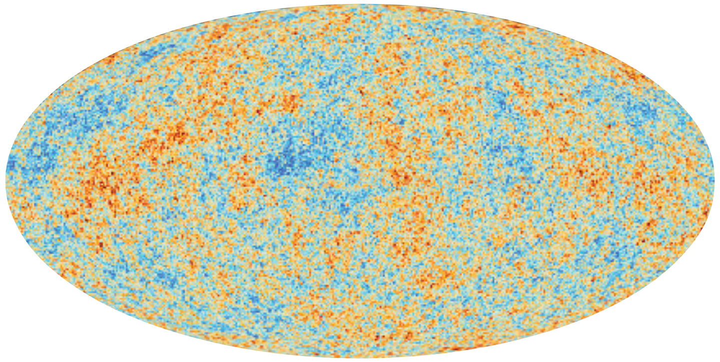
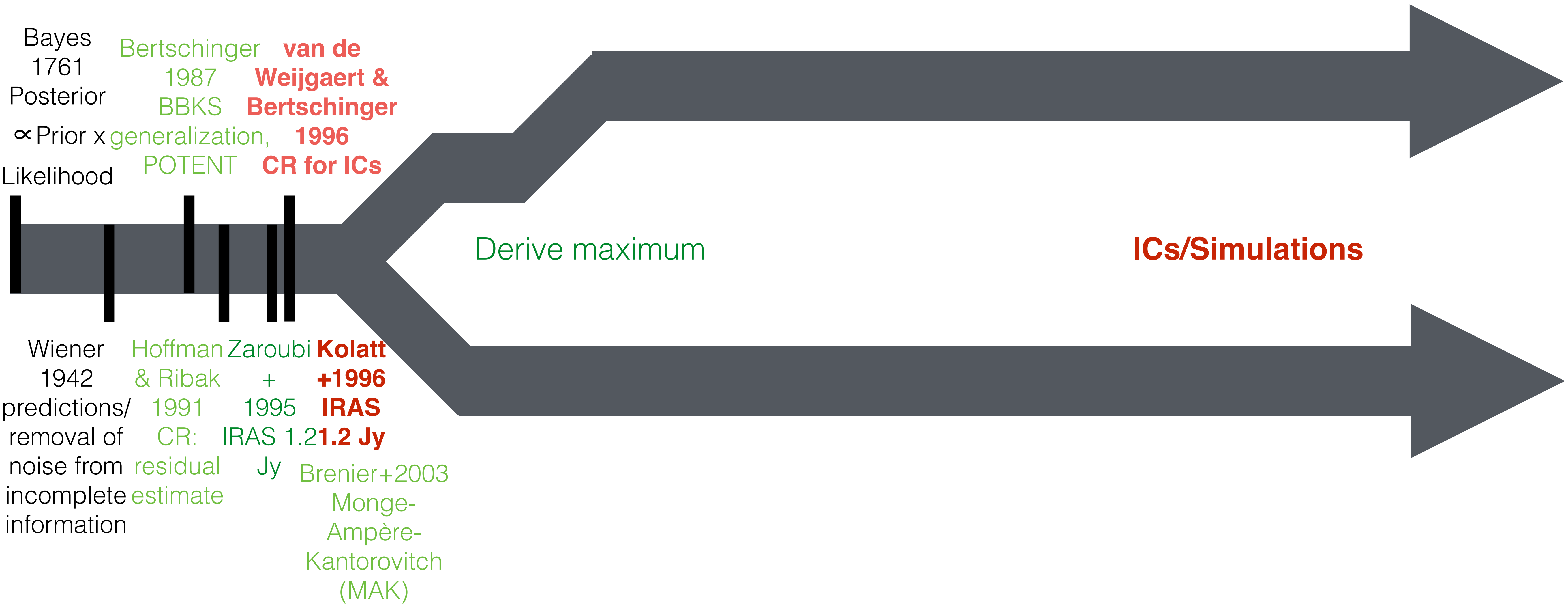
→



initial conditions of the local Universe

Applying local constraints from galaxy surveys

Constrained cosmological simulations ▶ Constrained ICs

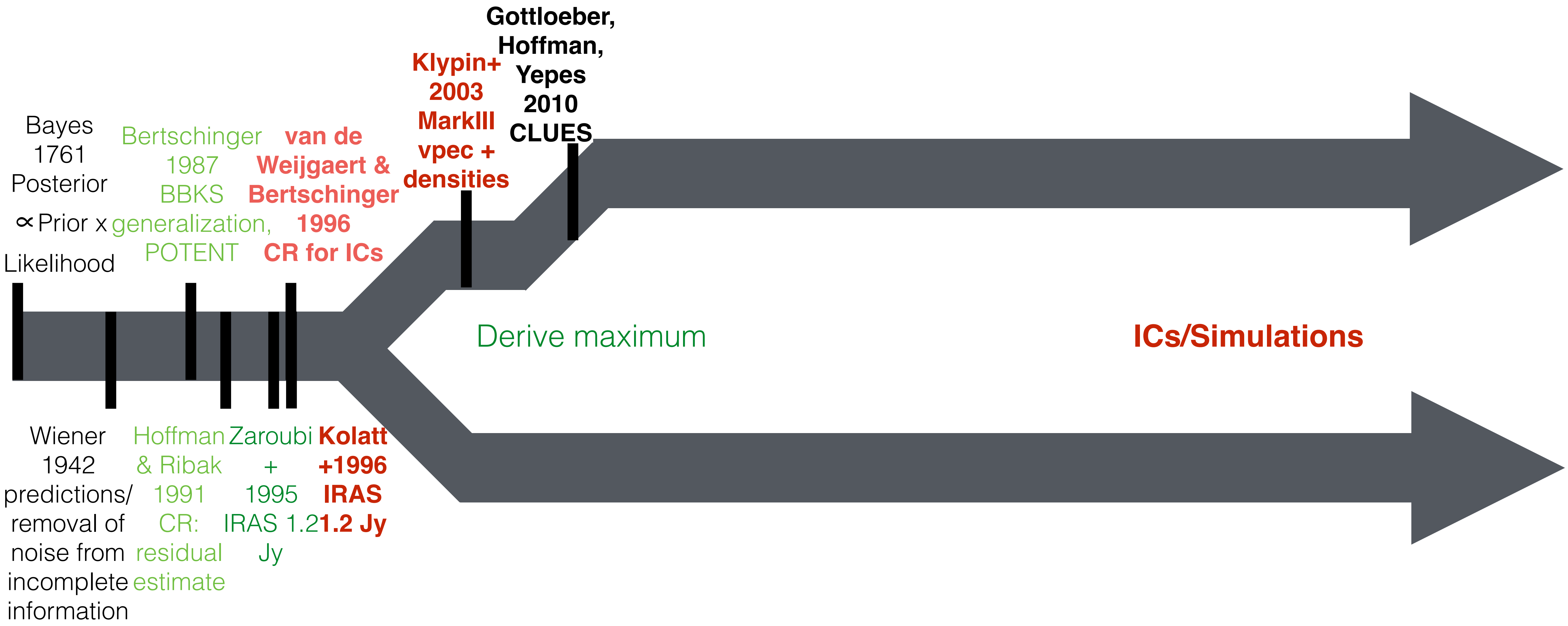


with densities (redshift surveys)

*apologies for any missing reference, please feel free to let me know so that I can add it

Constrained cosmological simulations ▶ Constrained ICs

with peculiar velocities+densities



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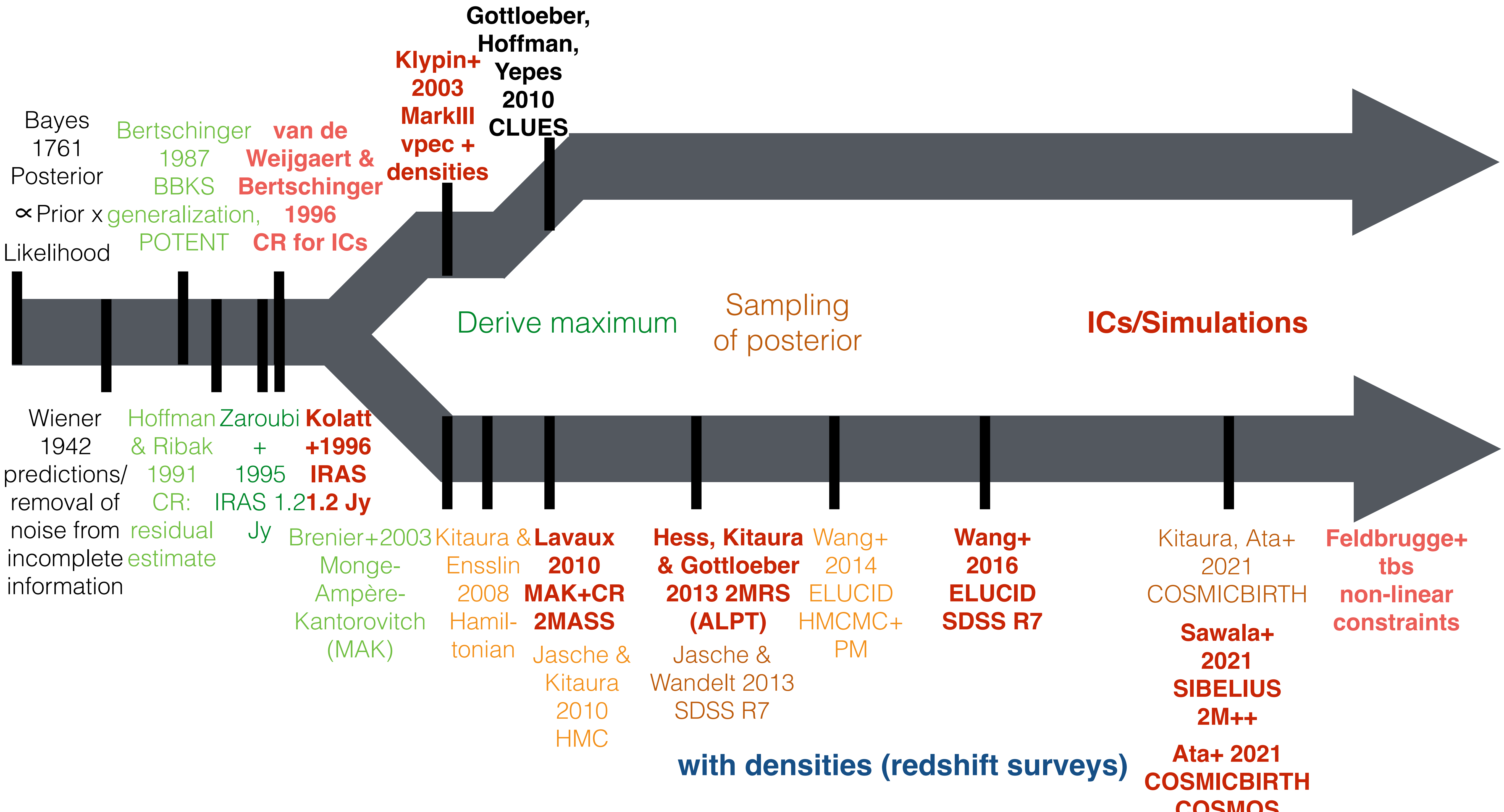

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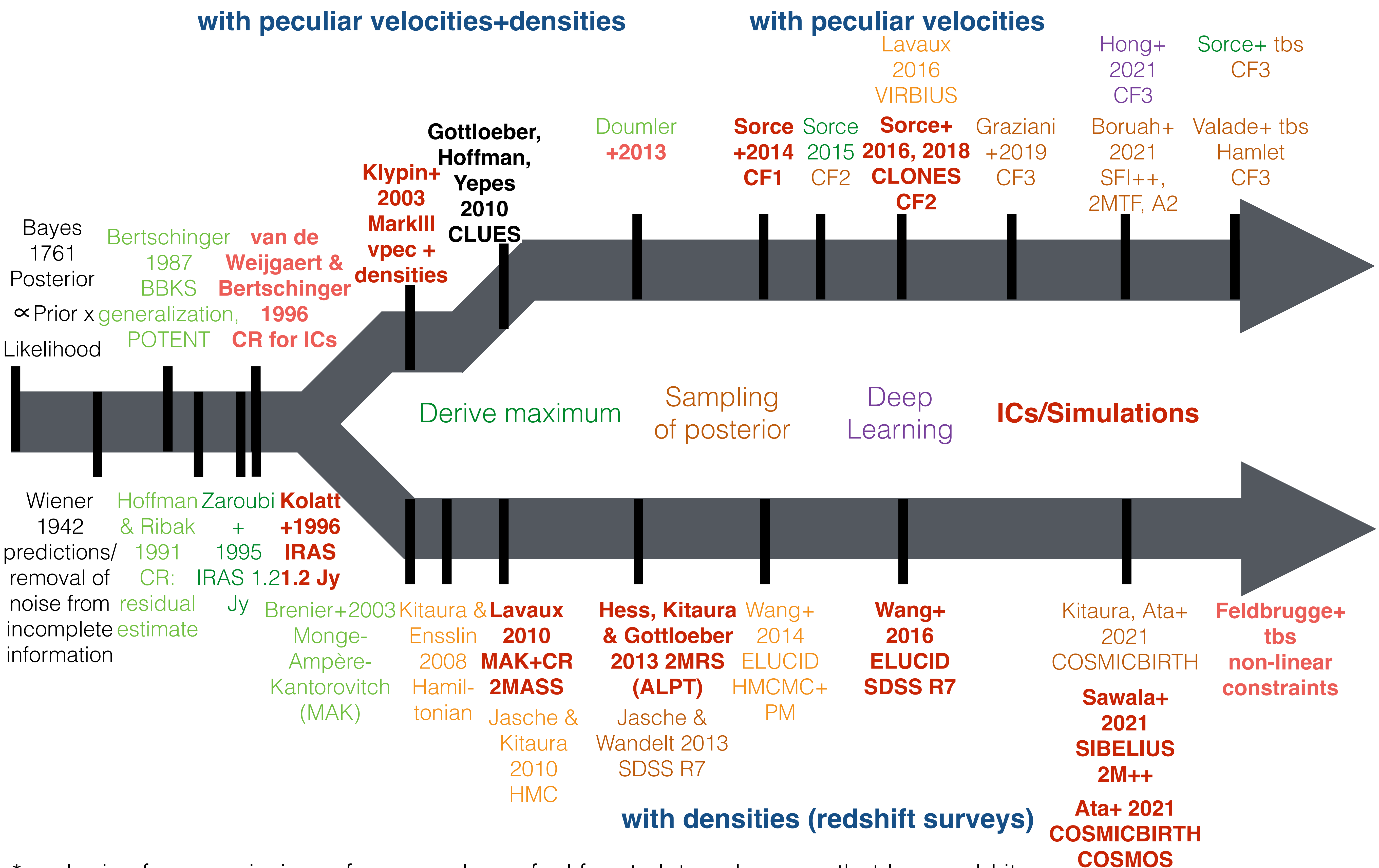

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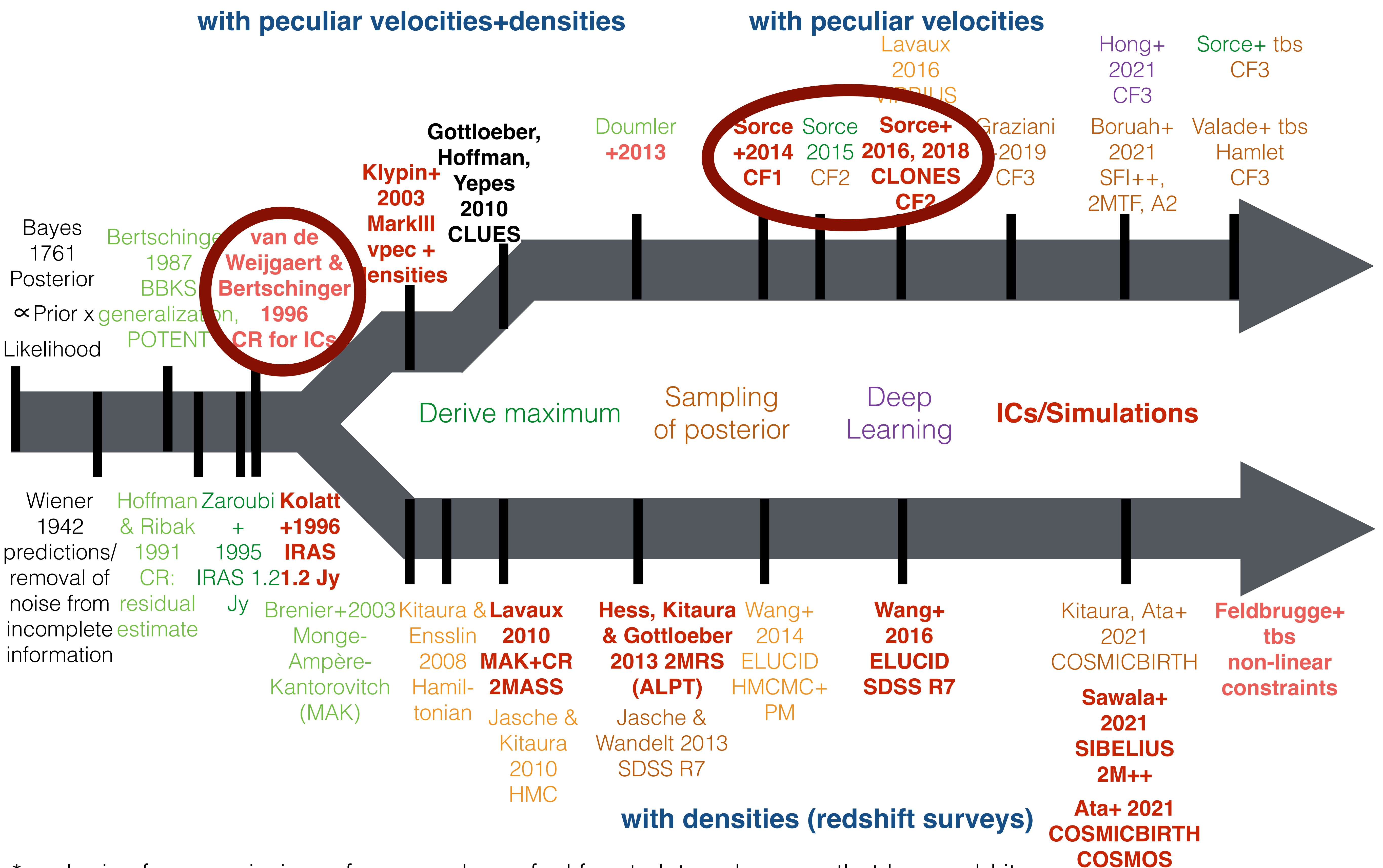
Constrained cosmological simulations ➤ Constrained ICs



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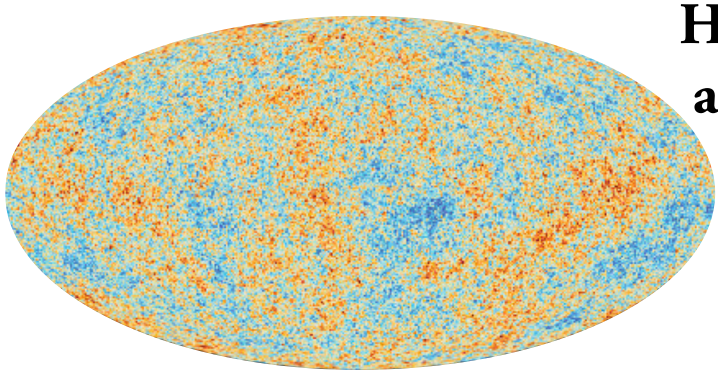

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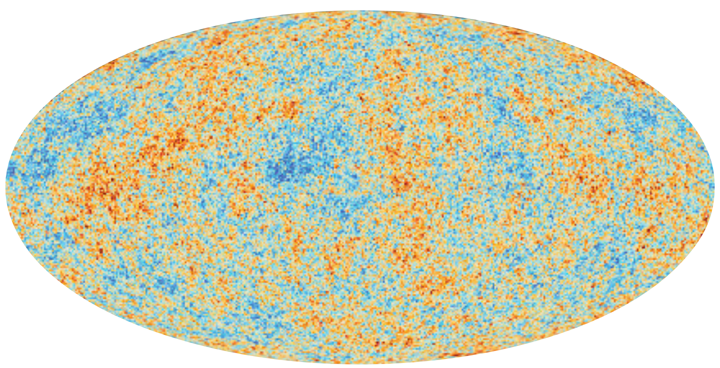
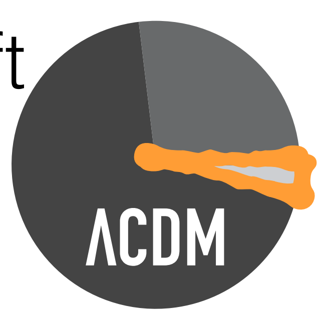
initial conditions of the local Universe



Applying local constraints from galaxy surveys

Redshift

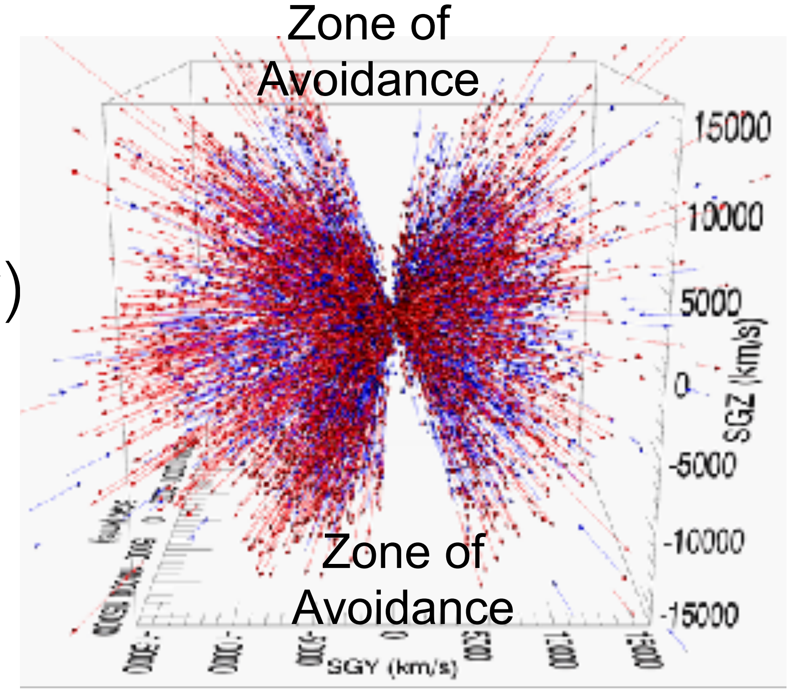


Peculiar velocity

Peculiar velocity catalog

- Account for the entire underlying gravitational field (no luminosity bias)
- Correlated on large scale (complete catalog unecessary)
- Highly linear (linear initial conditions)

e.g. Tully+(including Sorce)2013, Tully+(including Sorce)2016



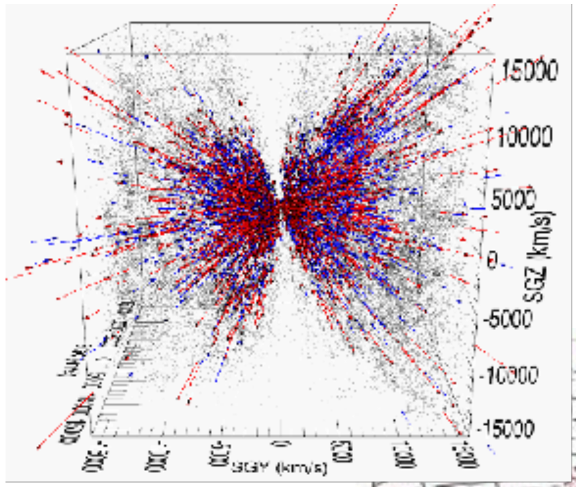
Sorce+2012ab, 2013,2014

m-M

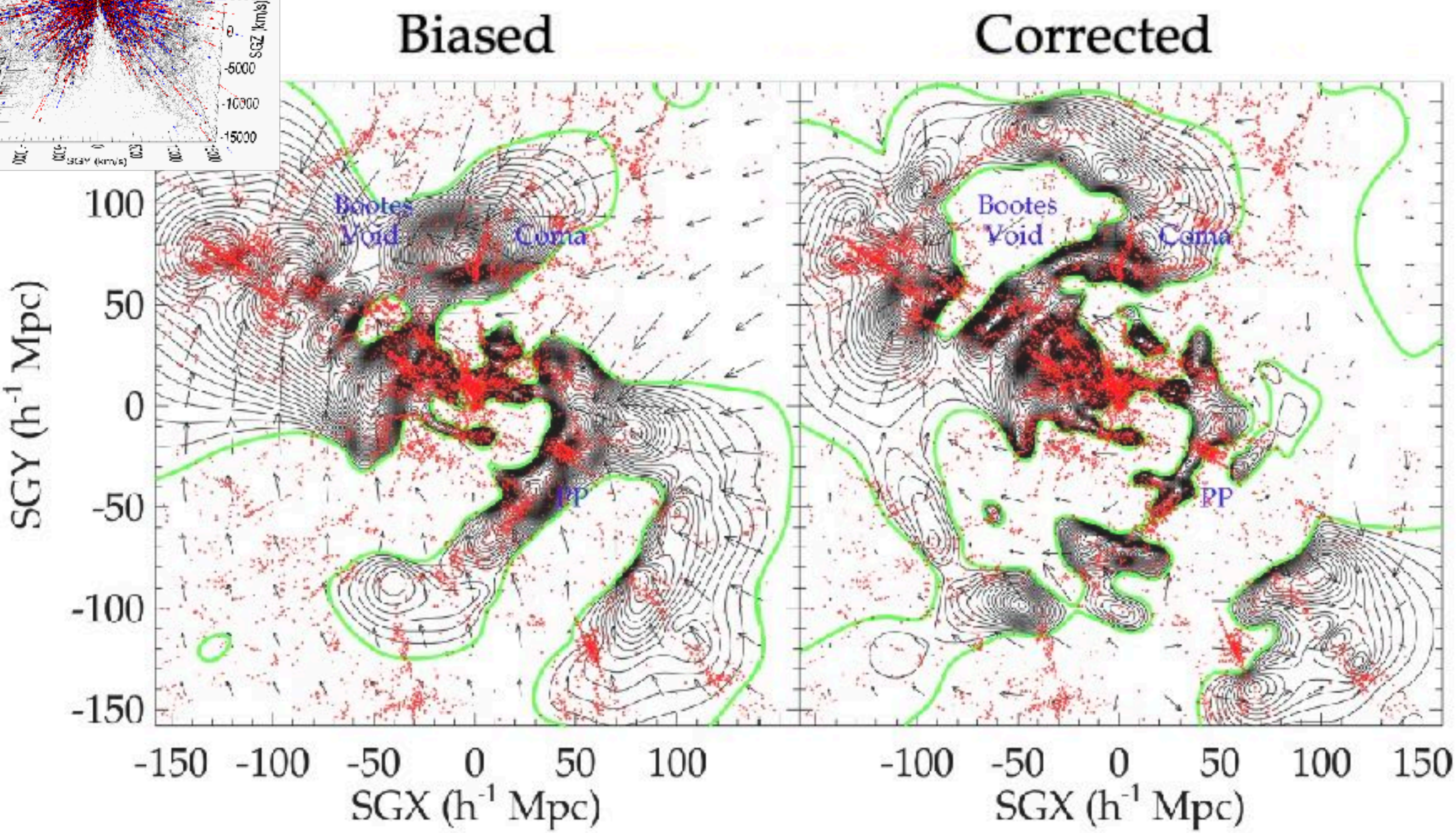
$$\mu = 5\log_{10}(d_{lum}\ (\mathrm{Mpc})) + 25$$ ← from distance indicators

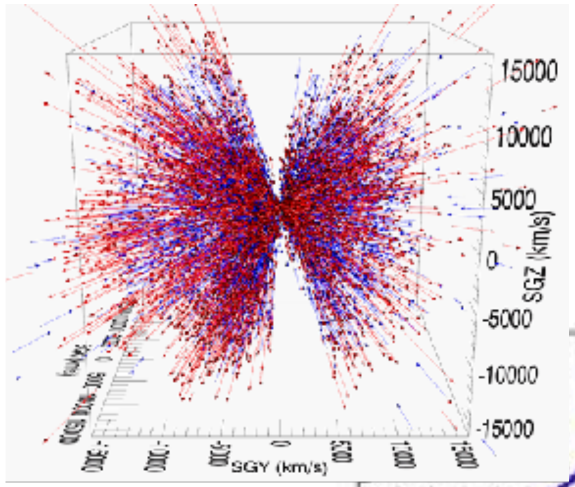
$$d_{lum} = (1+z_{cos}) \int_0^{z_{cos}} \frac{c\, dz}{H_0 \sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}}$$

$$v_{pec} = c\, \frac{z_{obs} - z_{cos}}{1+z_{cos}}$$

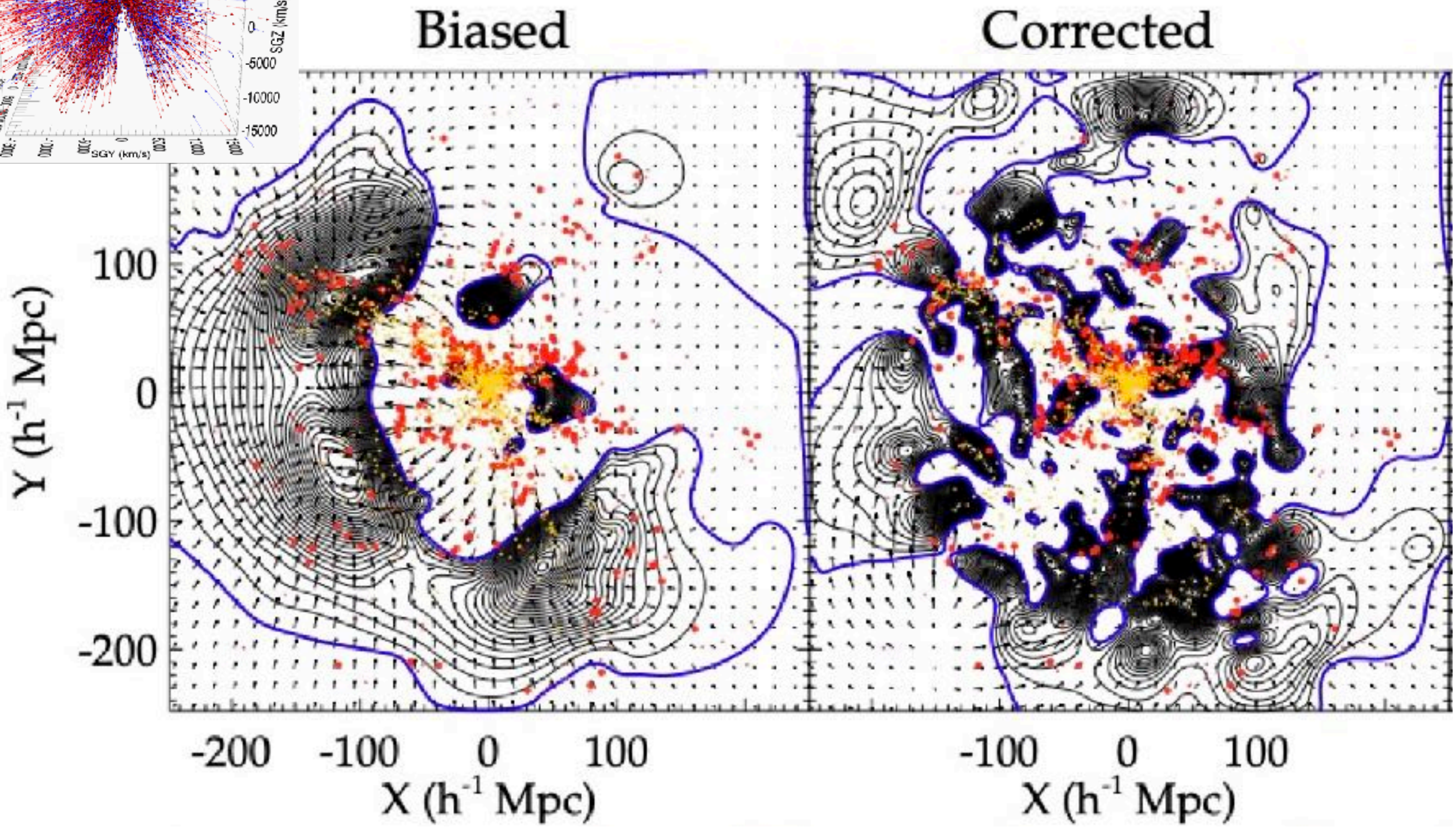


Biases - CF2 catalog case





Biases - CF3 catalog case



Constrained cosmological simulations

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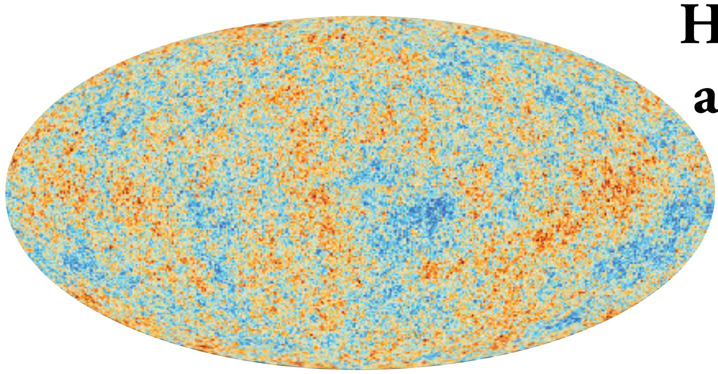

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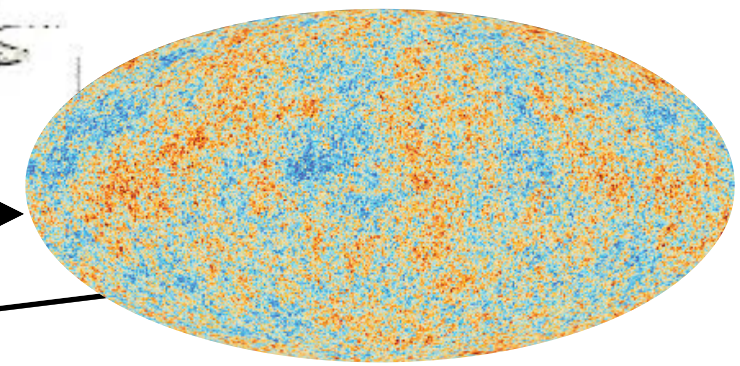
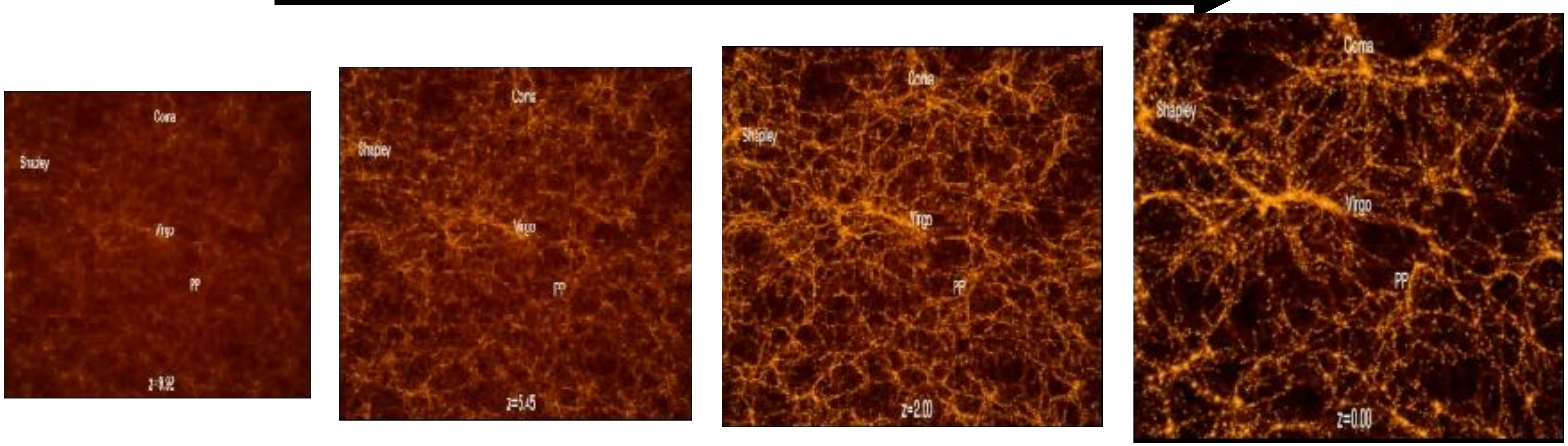
Applying local constraints from galaxy surveys

e.g. Sorce+2014, Sorce2015, 2018, Sorce & Tempel 2017,2018

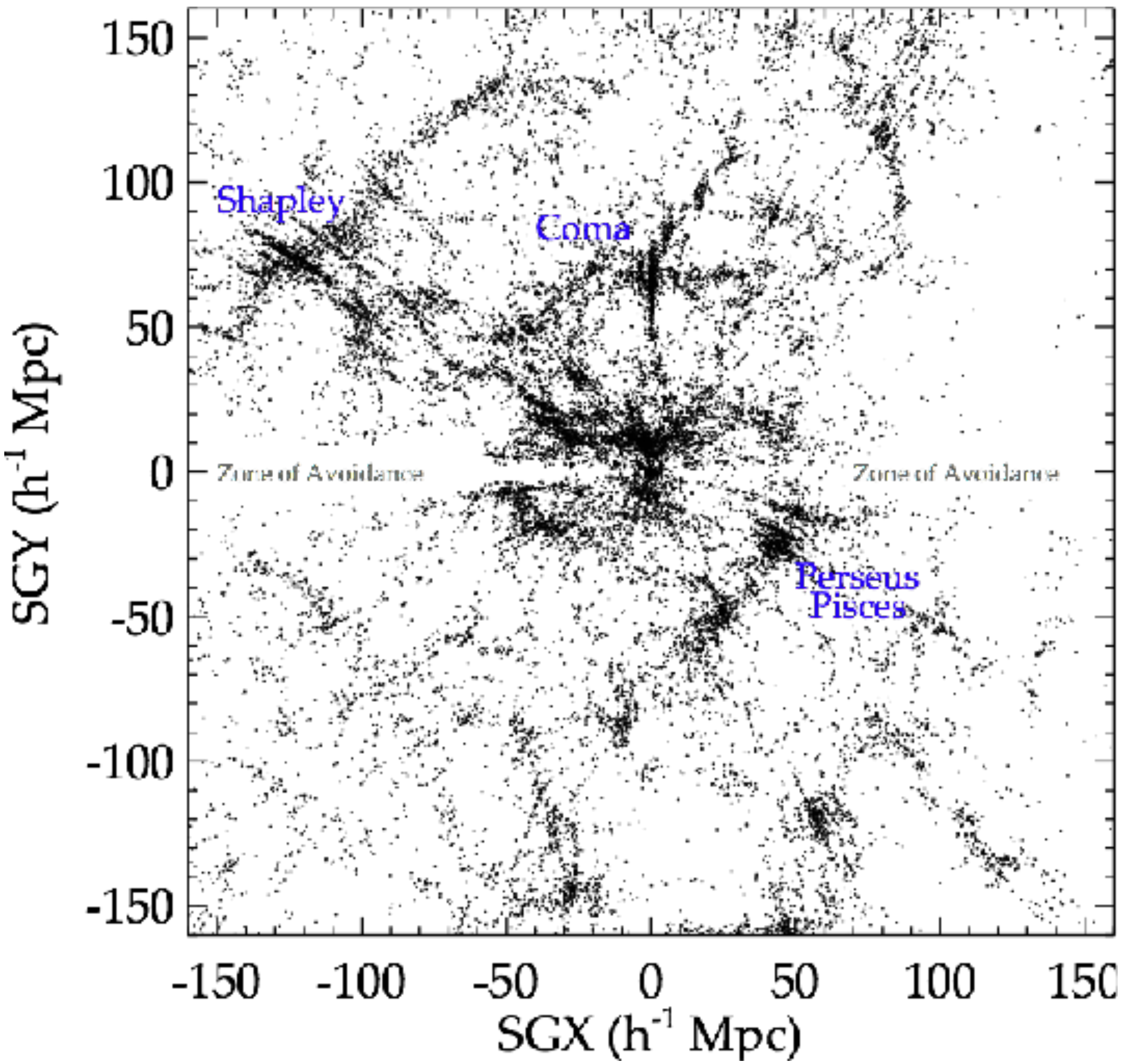
→ initial conditions of the local Universe



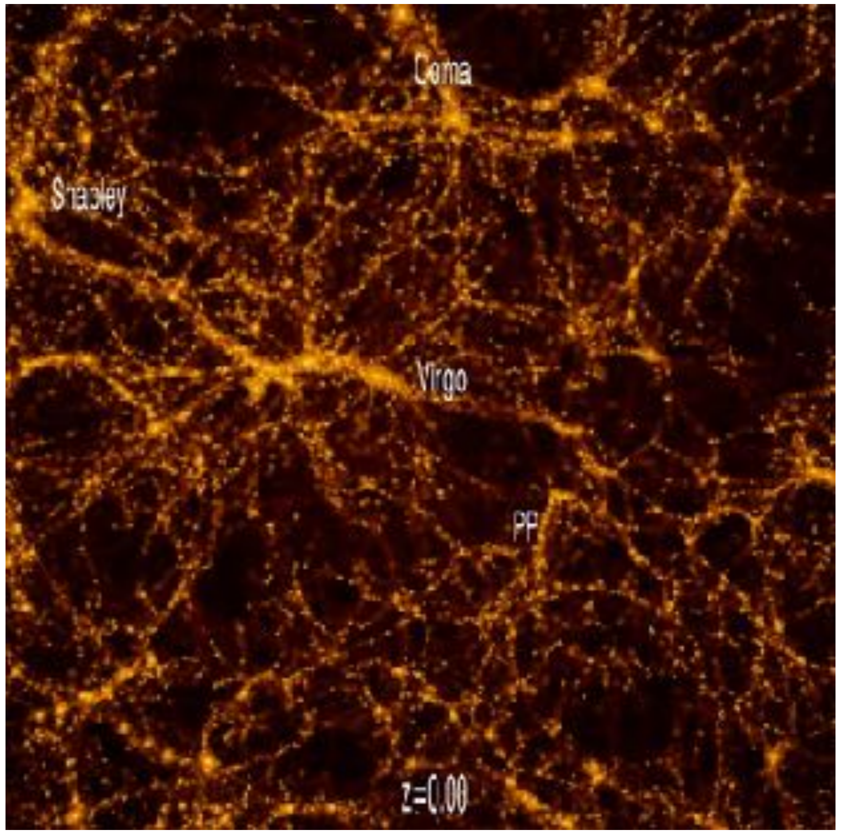
Evolution



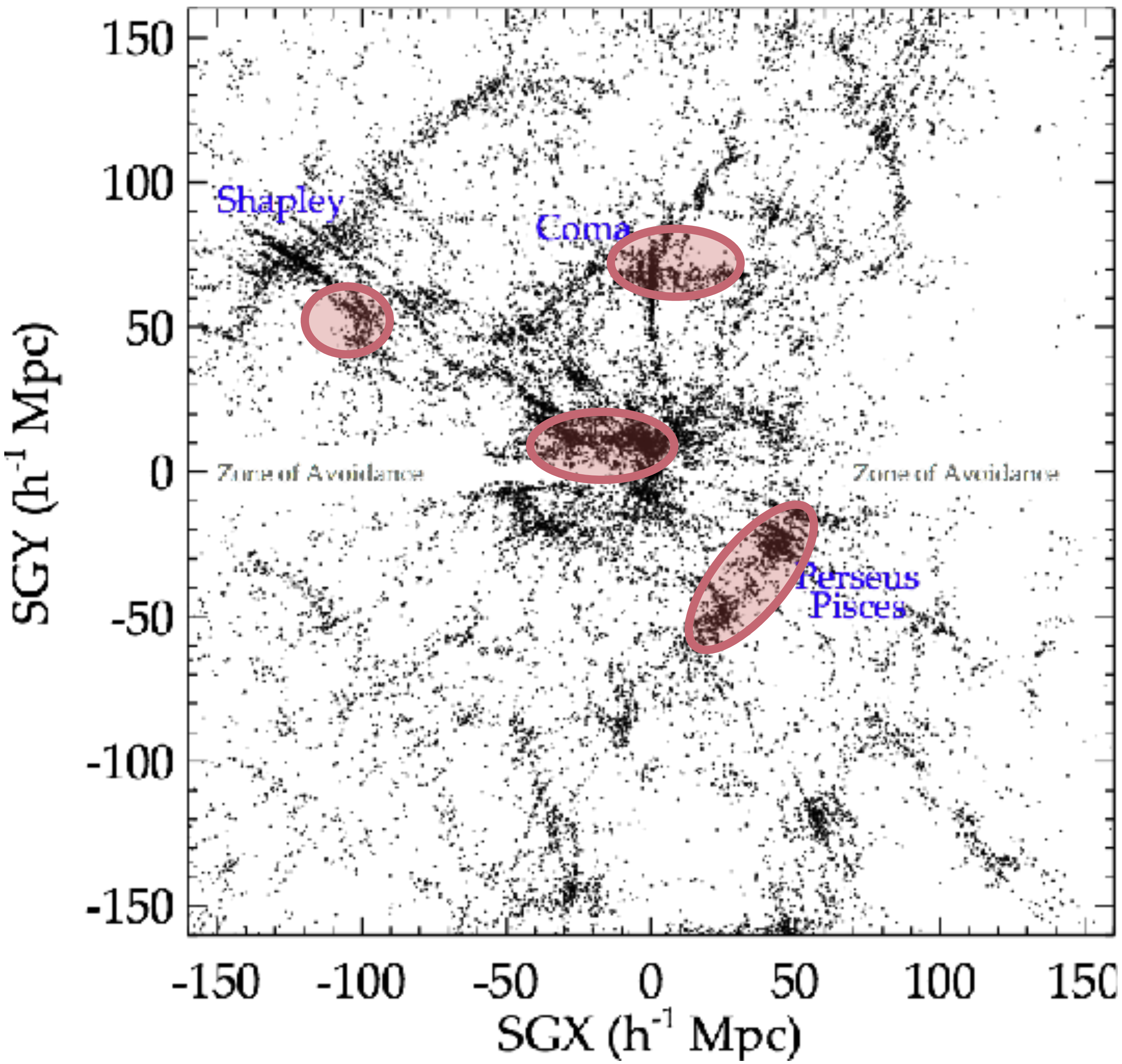
CLONES = Constrained LOcal & Nesting Environment Simulations



Note the fingers of gods



500 Mpc/h, 1024^3 particles, DM only, Planck cosmology



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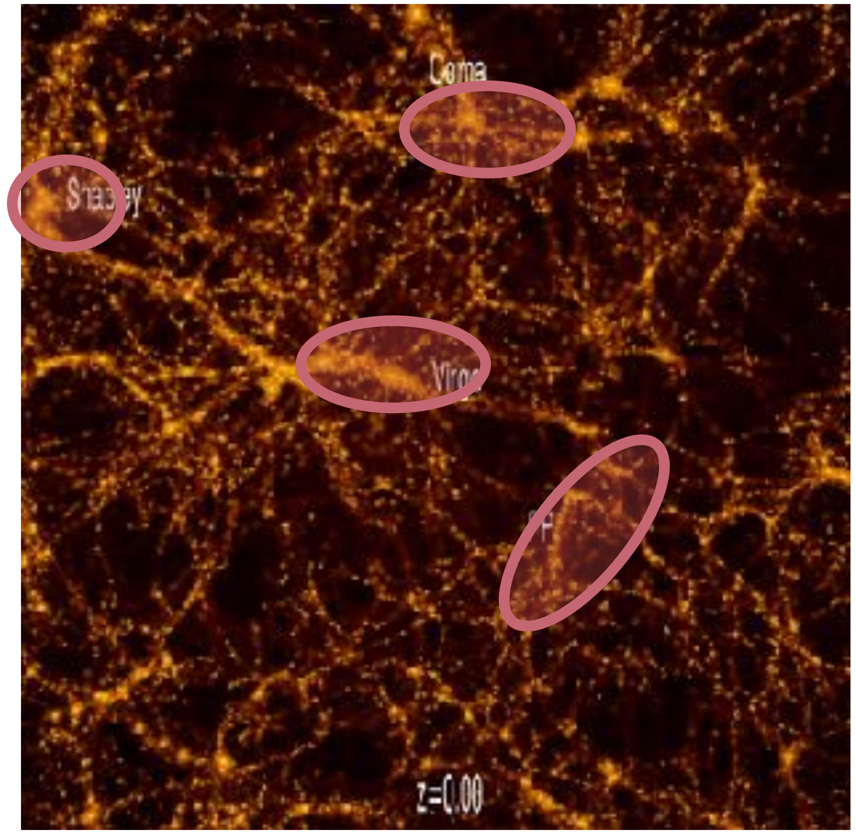
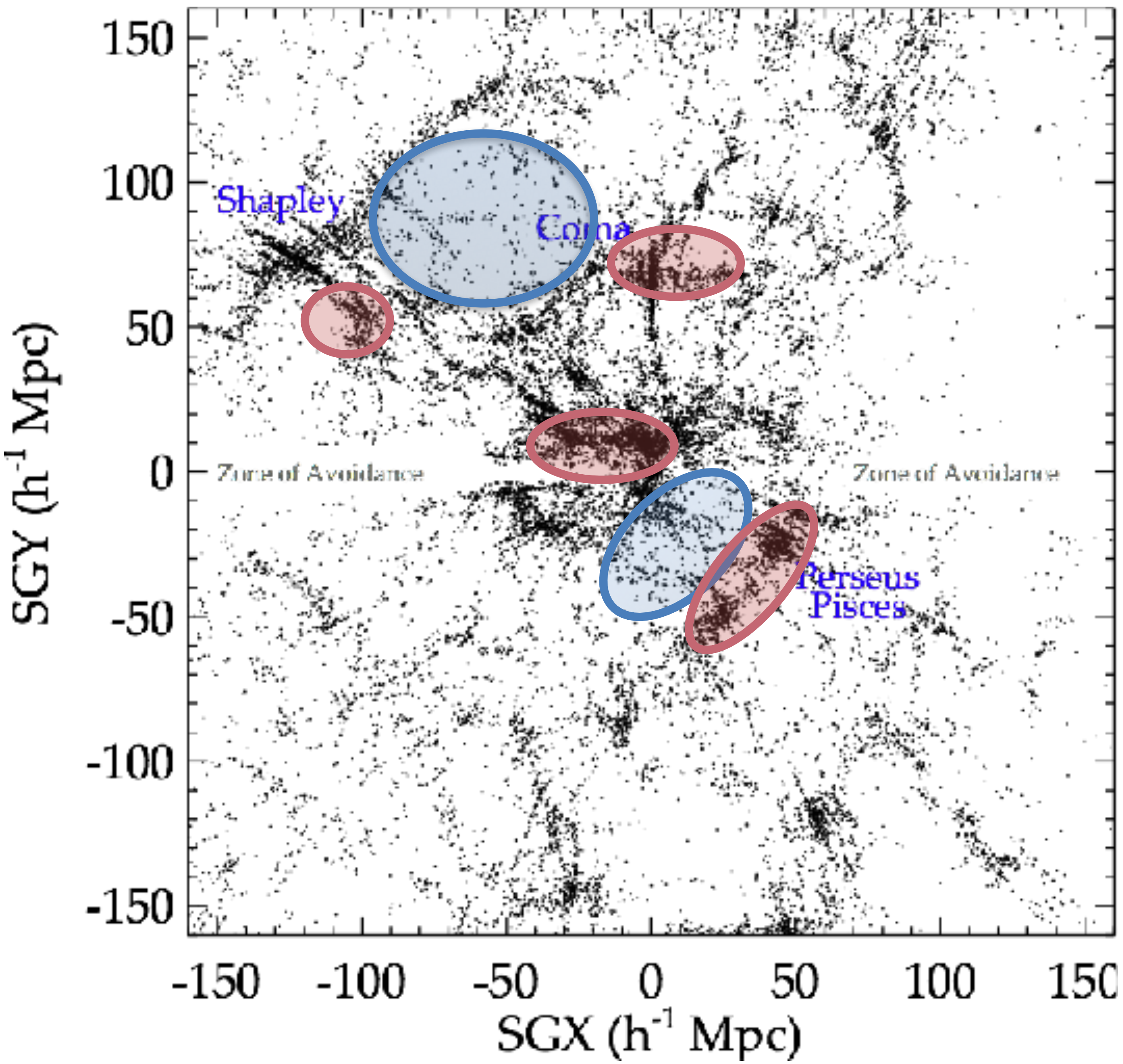
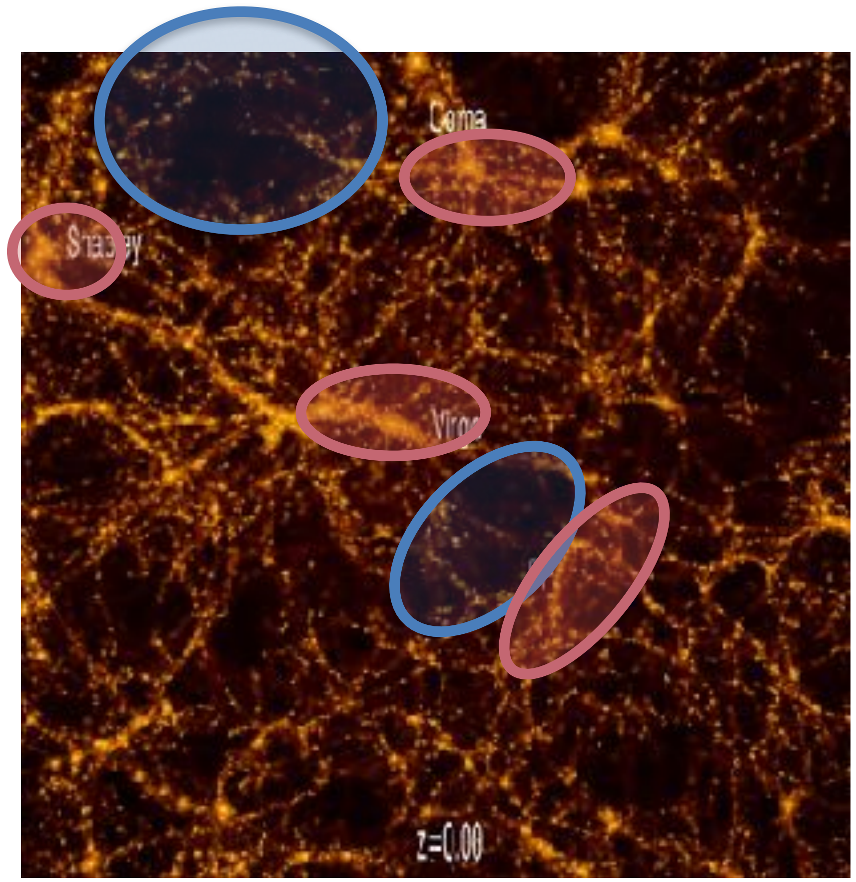


500 Mpc/h, 1024^3 particles,
DM only, Planck cosmology



Note the fingers of gods

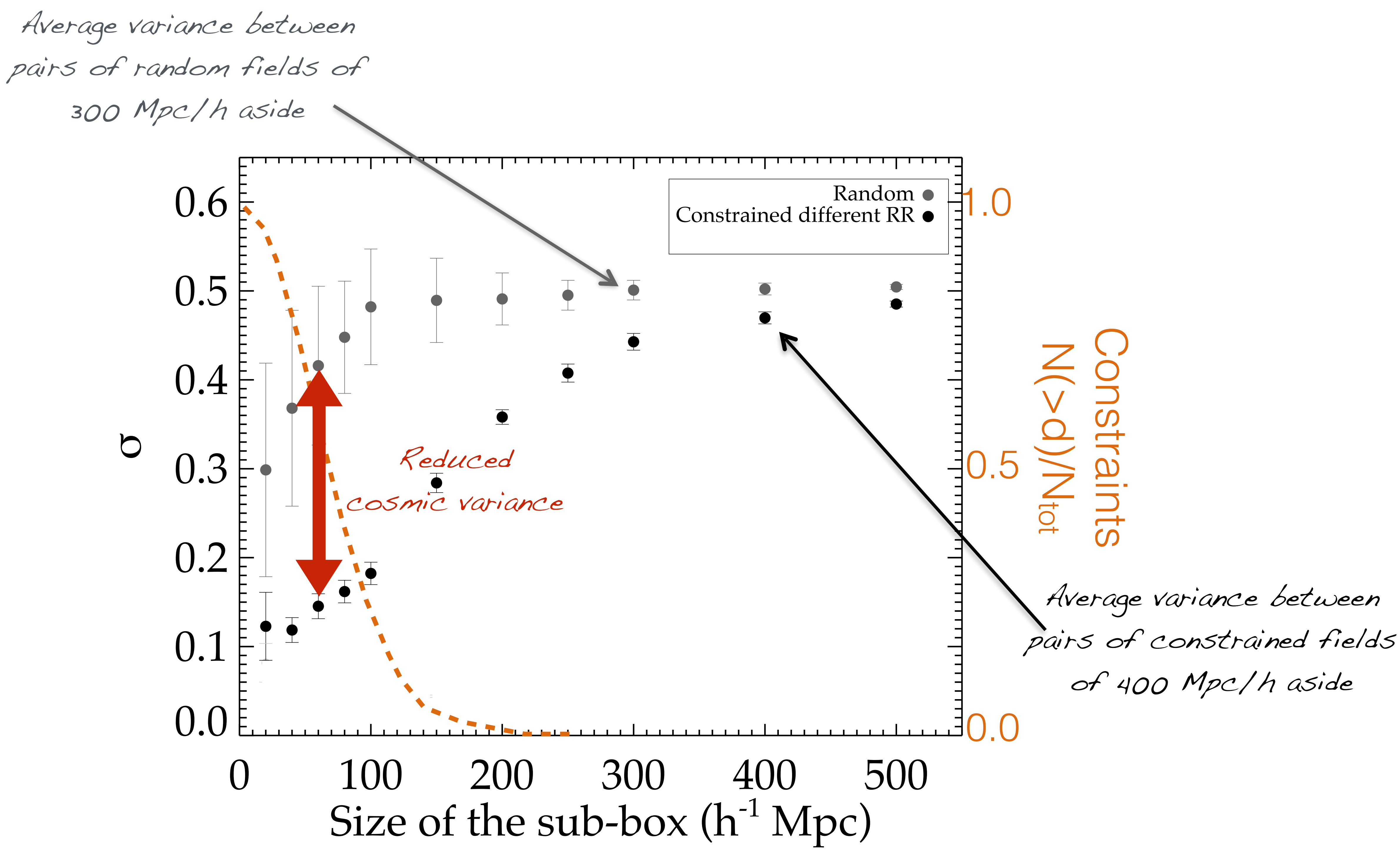


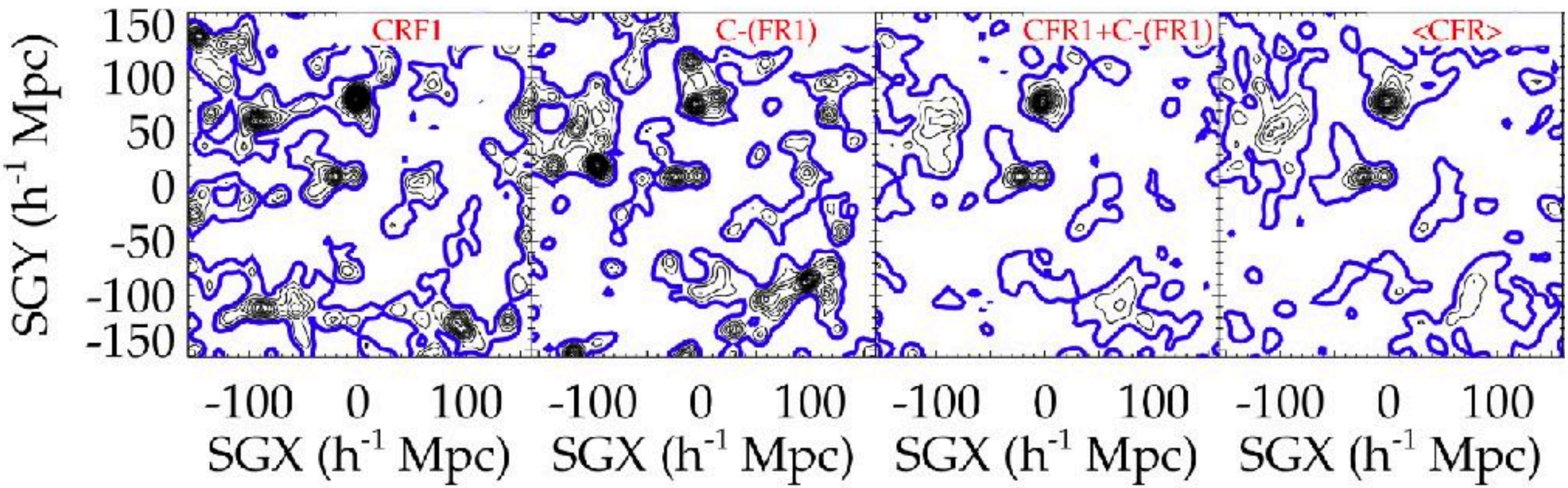
500 Mpc/h, 1024^3 particles, DM only, Planck cosmology

CLONES validity

Large scale

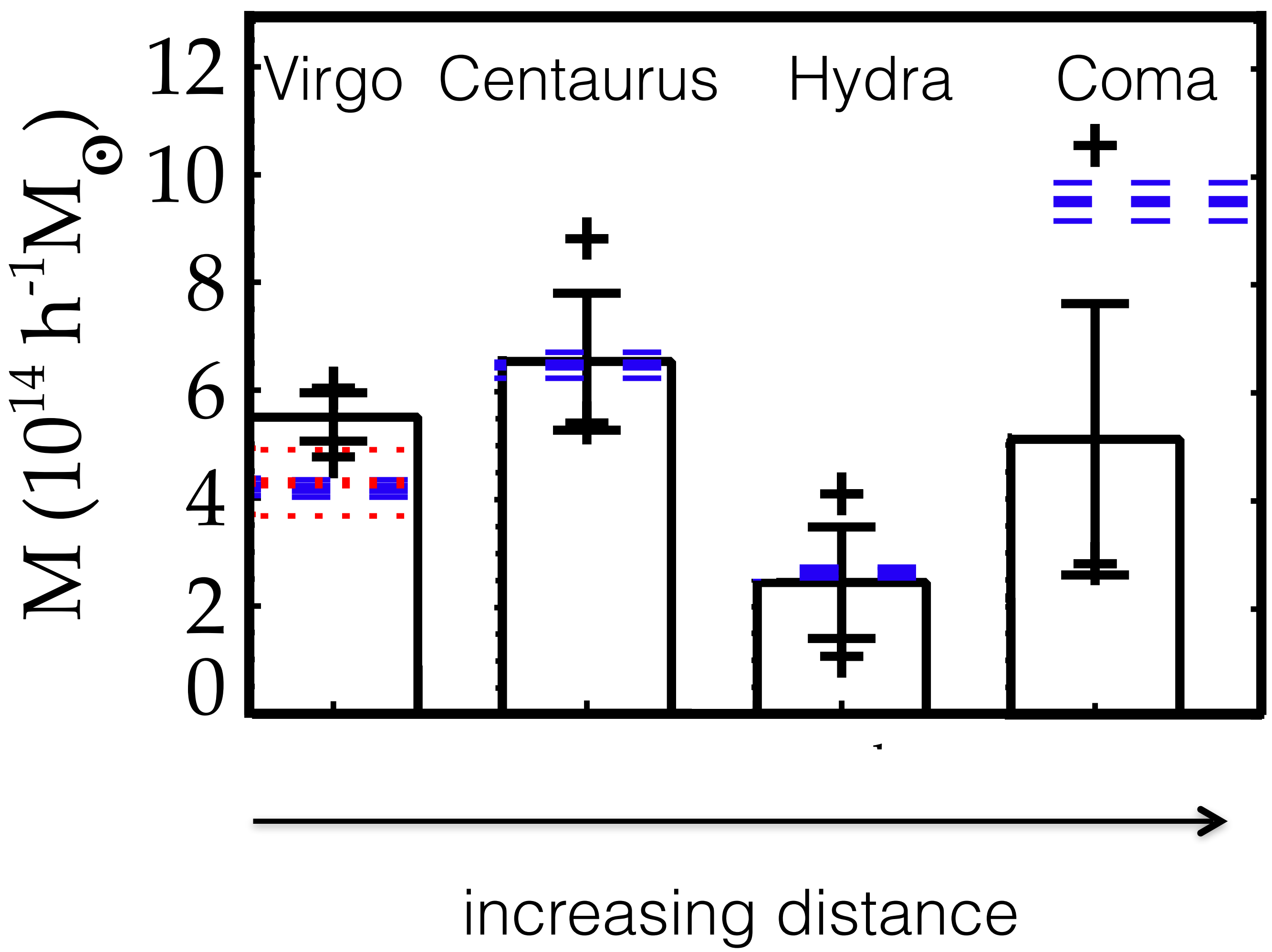
Sorce+2016

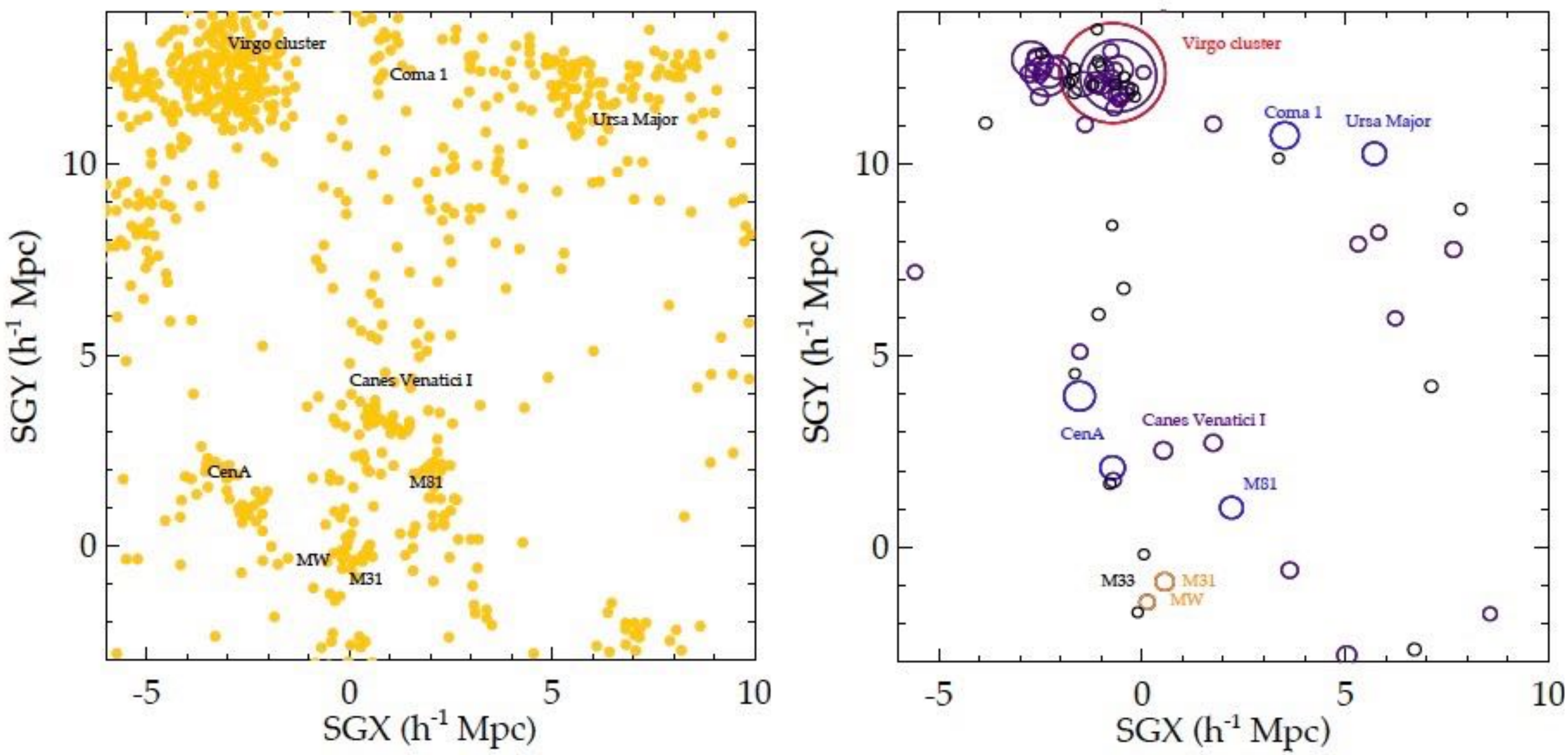




Residual cosmic variance with *two* CLONES !

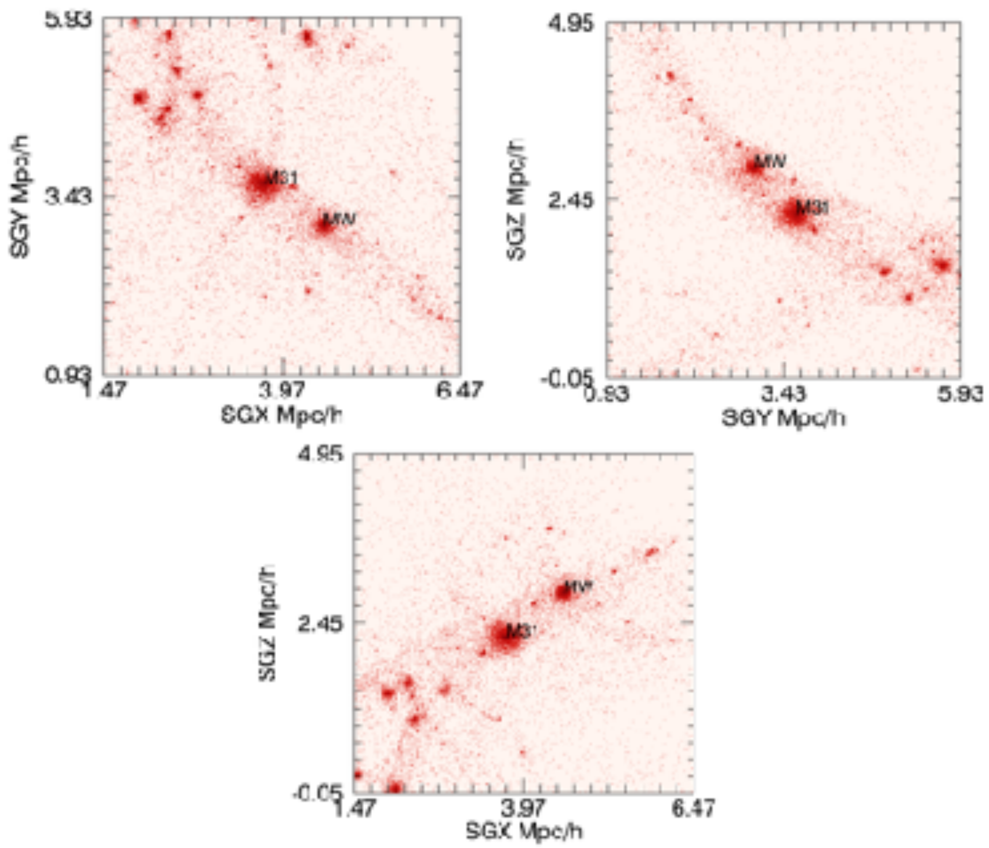
Dark matter halos = counterparts of observed local clusters





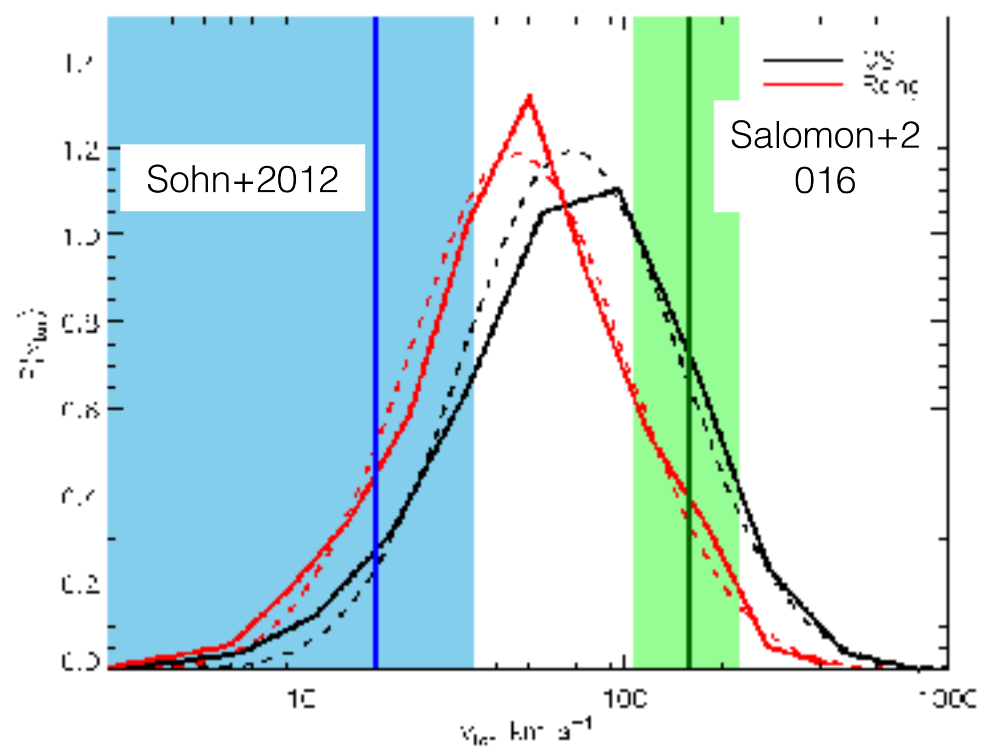
64 Mpc/h, 2048^3 particles, DM only, Planck cosmology

Ocvirk, Aubert, Sorce + 2020



induced by the local environment, not directly constrained (non-linear scales)

100 Mpc/h, 512[3] particles effective (5 Mpc/h zoom), DM only, Planck cosmology

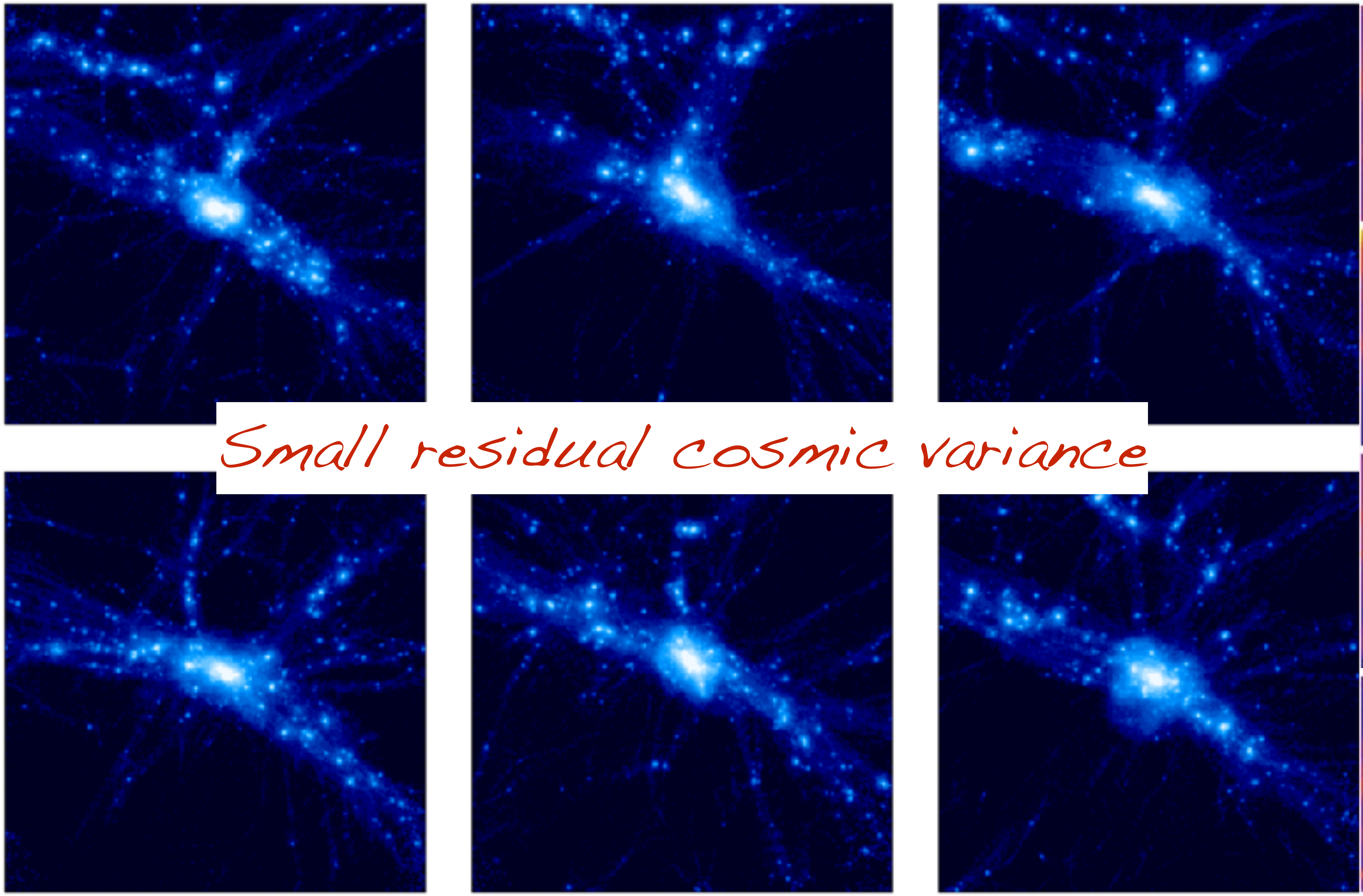


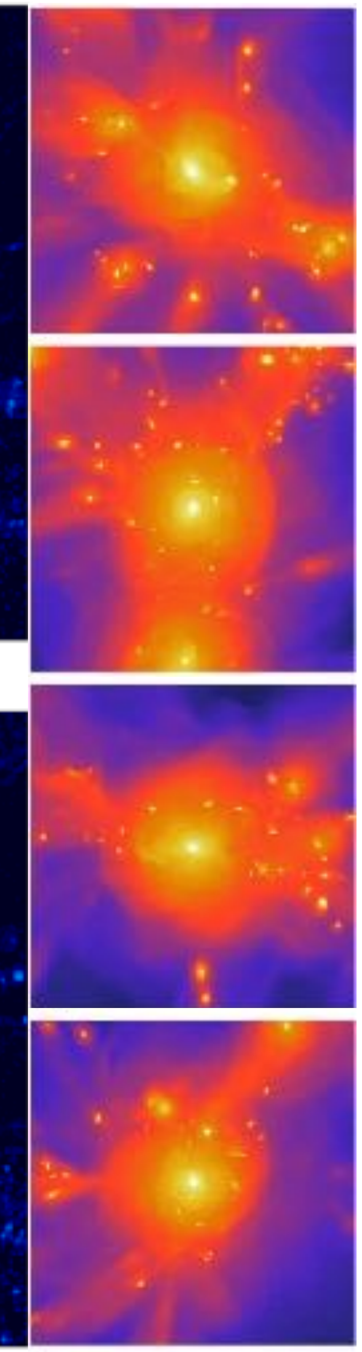
An example of application: in favor of a higher tangential velocity

Carlesi,Sorce+2016
Carlesi,Hoffman,Sorce+2016
Carlesi,Hoffman,Sorce+2017
Libeskind+(including Sorce)2020

100 Mpc/h, 4096[3] particles effective (5 Mpc/h zoom), hydrodynamical, 340 pc, Planck cosmology

Simulated Virgo & Random clusters



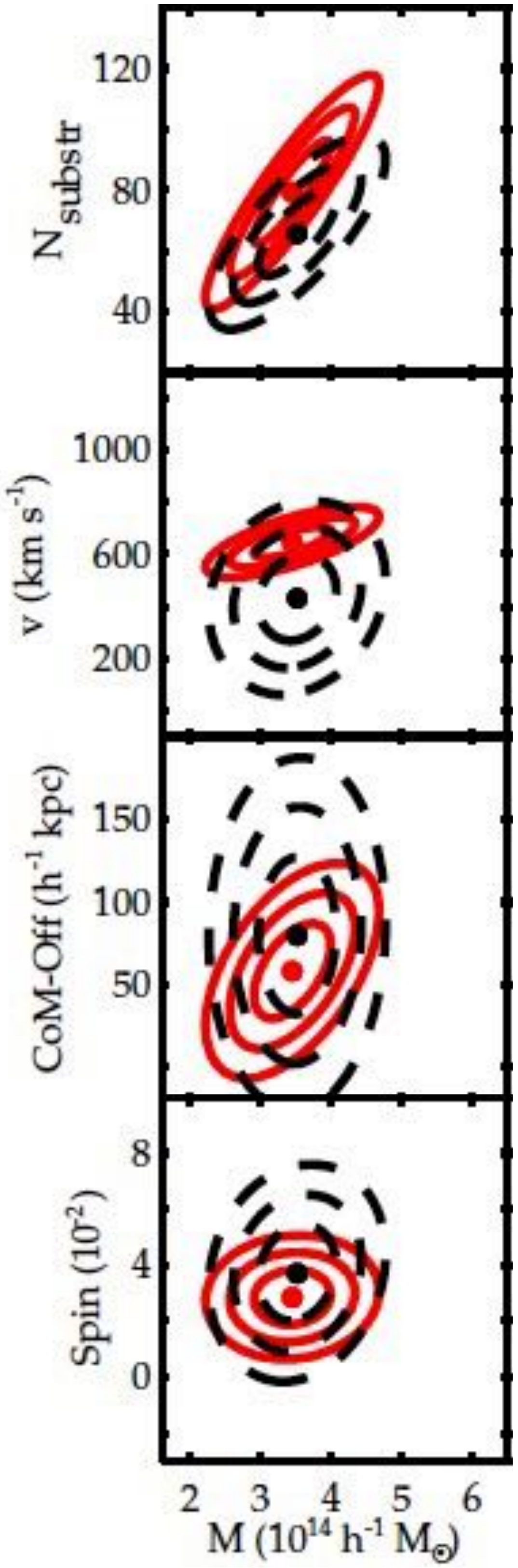


Rhapsody
(Hahn+2017)

500 Mpc/h, 2048^3 particles effective (20 Mpc/h zoom), 3.8 kpc/h, DM only, Planck cosmology

CLONES' uses

Virgo



Velocity

Spin

→ Environment

Number of substructures

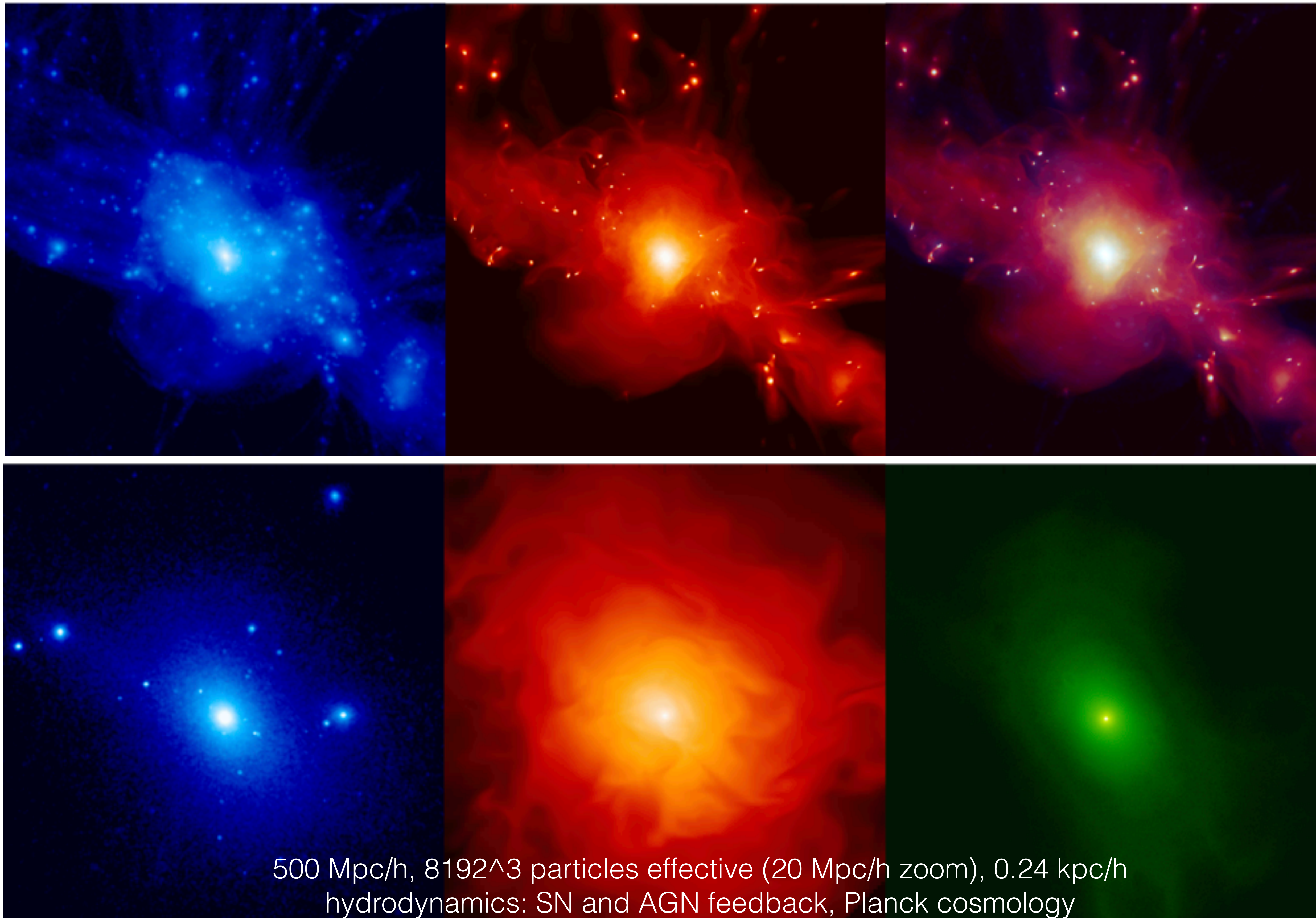
Center of mass offset wrt spherical center

→ History

Different from an average random cluster

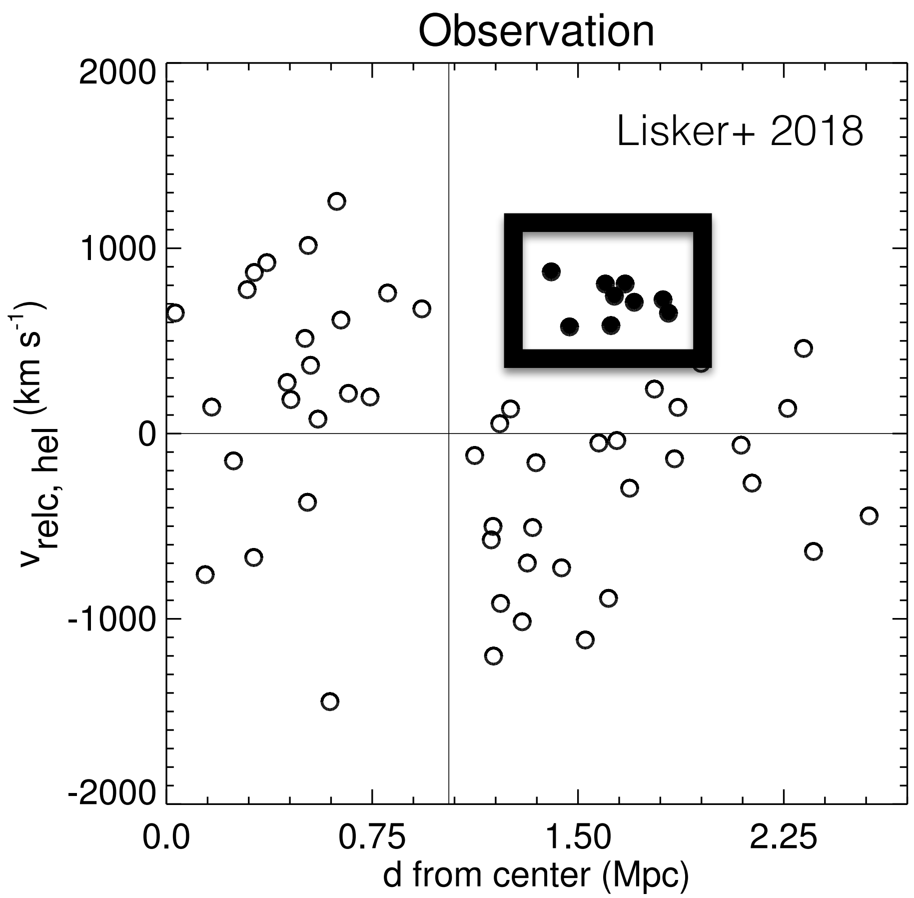
CLONES’ uses

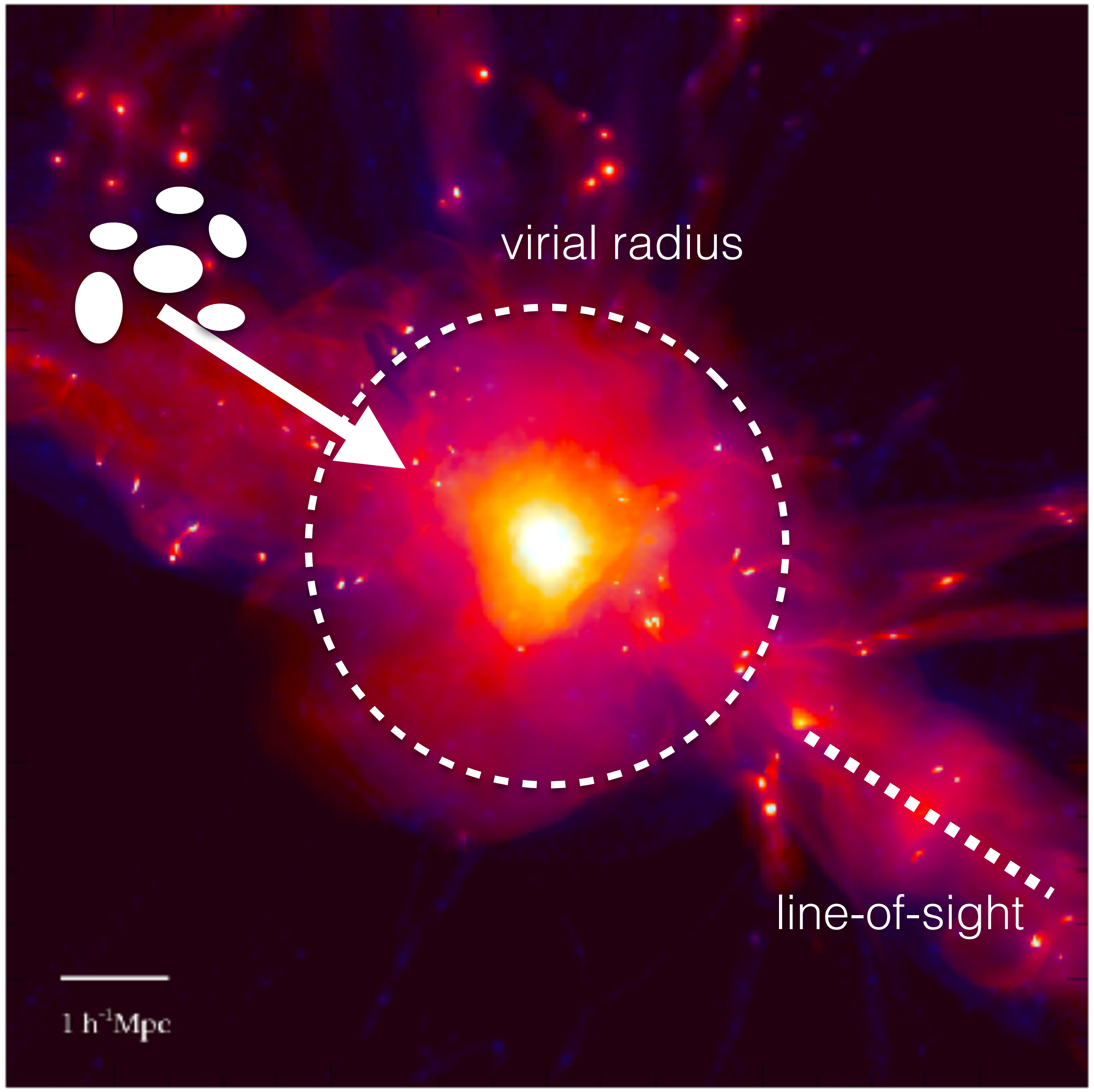
Virgo



500 Mpc/h, 8192^3 particles effective (20 Mpc/h zoom), 0.24 kpc/h
hydrodynamics: SN and AGN feedback, Planck cosmology

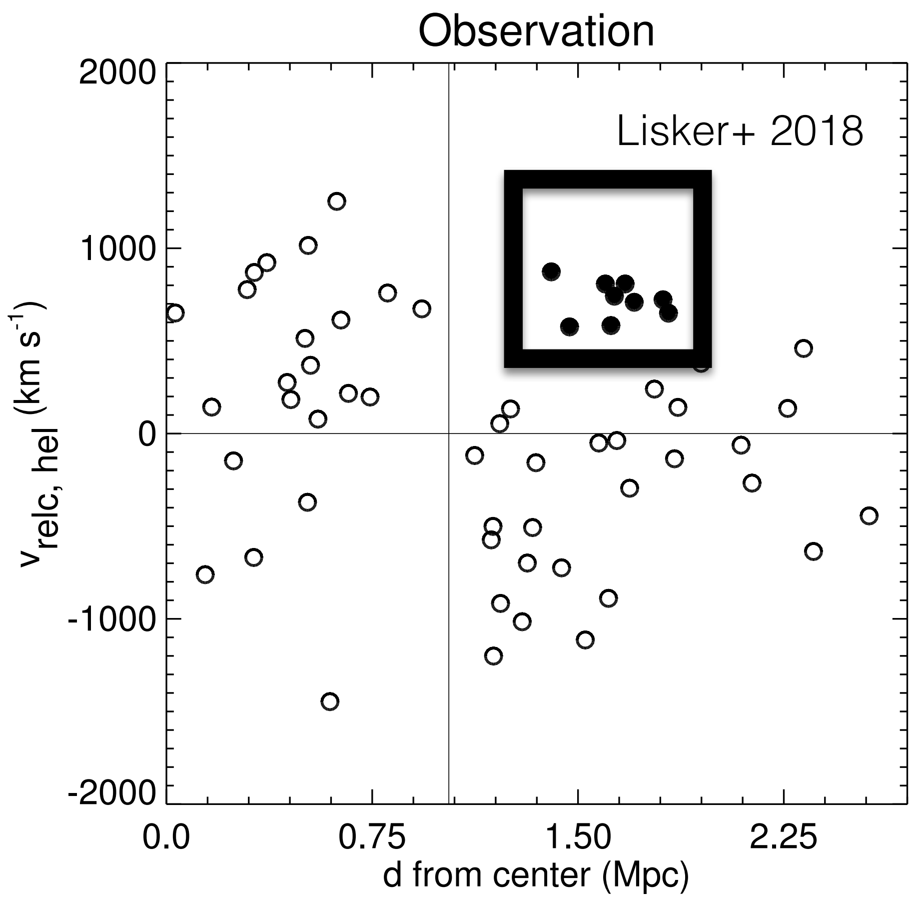
Simulated & Observed Virgo clusters

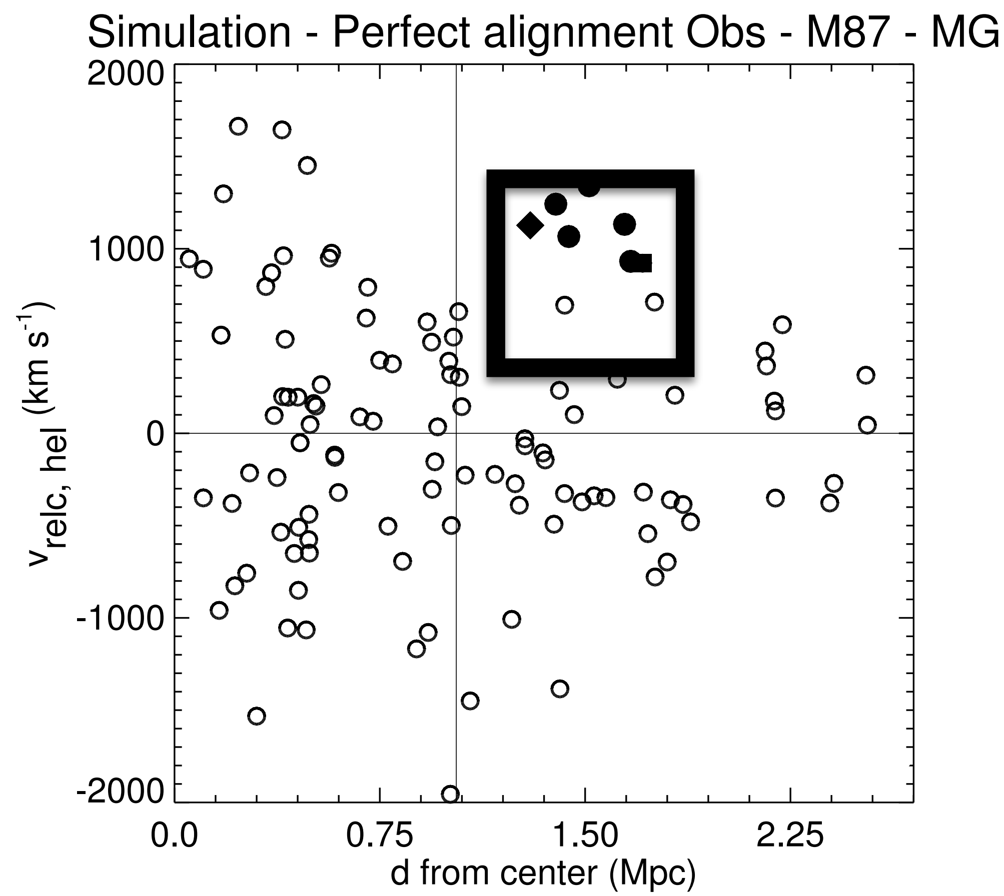




Group of galaxies that fell within the line-of-sight?

Simulated & Observed Virgo clusters

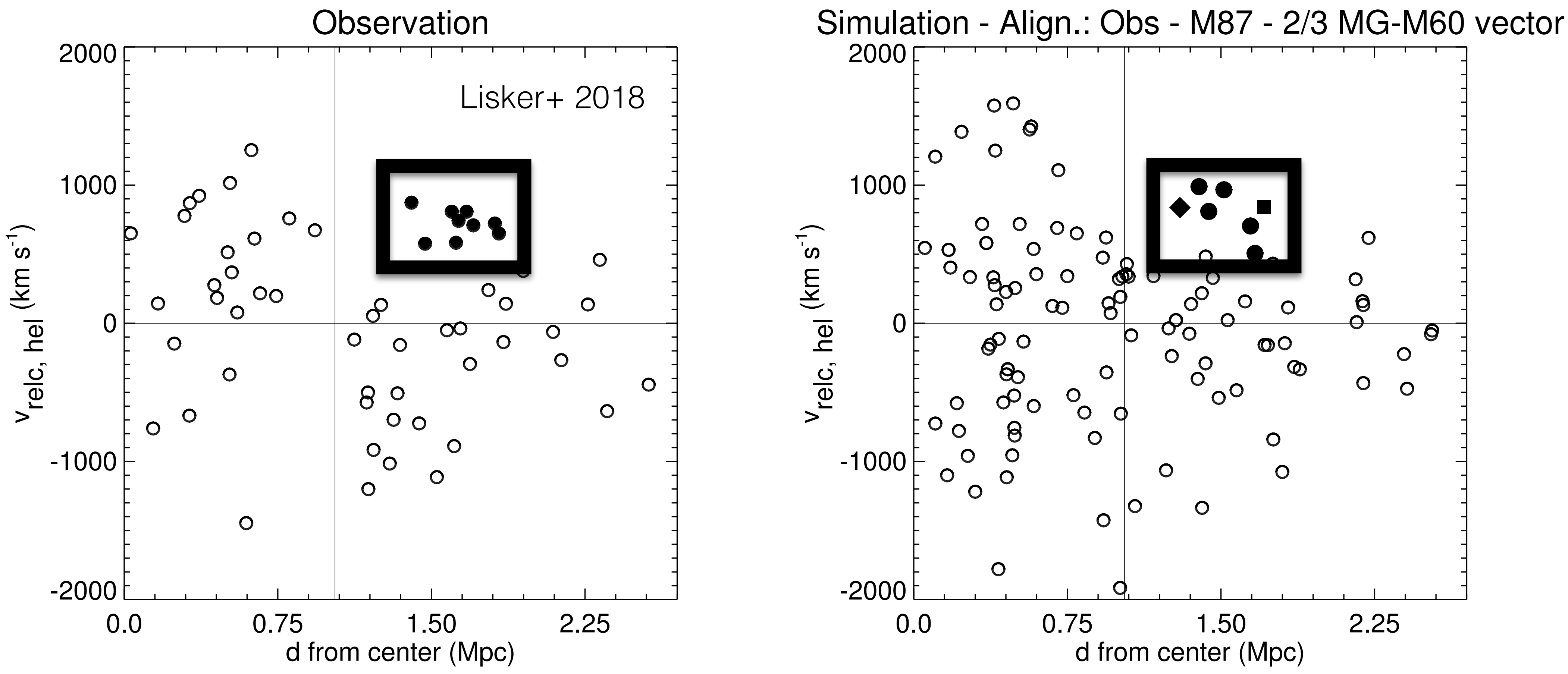




Group of galaxies that fell within the line-of-sight?

Sorce+2021

Simulated & Observed Virgo clusters



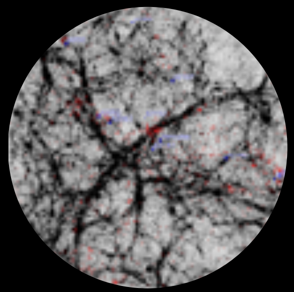
Group of galaxies that fell quasi within the line-of-sight

Sorce+2021

Agreement with observational predictions

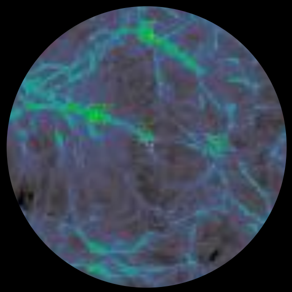
CLONES’ uses

and more…



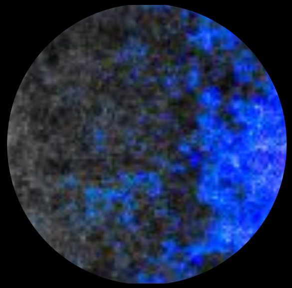
SLOW: local galaxies
(Sorce, Dolag +)

Zone of Avoidance
(Sorce+2017)

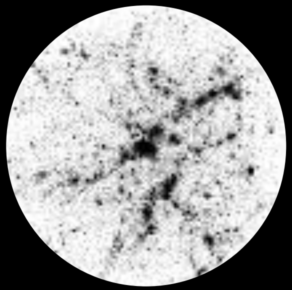


Cosmic Rays in the local Universe
(Hackstein+2018)

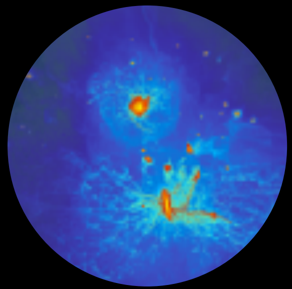
The Virgo Cluster
(Sorce+2016, 2019, 2021, in prep.
Olchanski & Sorce 2018)



CoDa: Reionization of the local Universe
(Ocvirk+2020, Lewis+2020, Gronke+2021,
Sorce+2022, Lewis+2022, Park+2022)



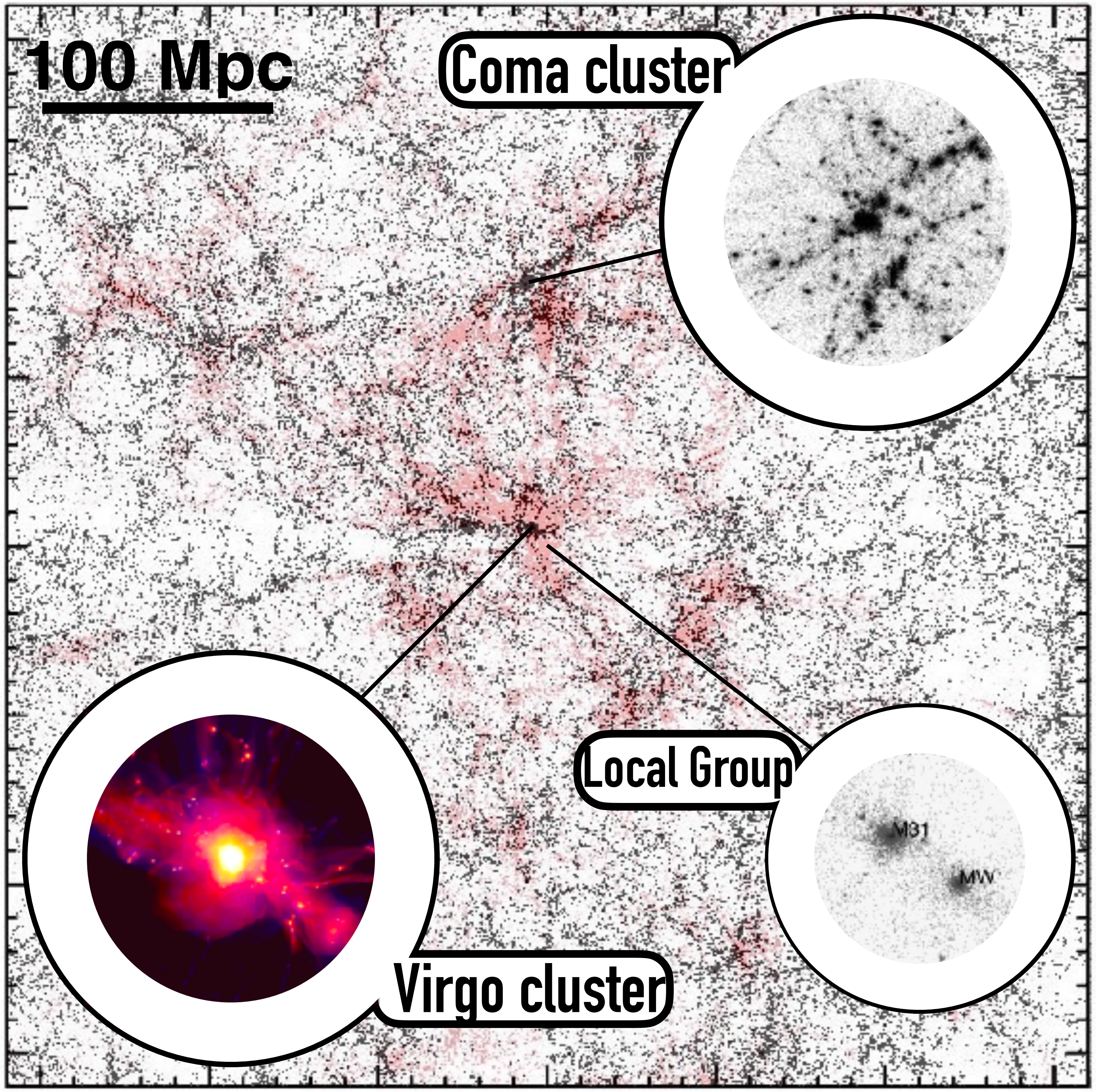
Coma connectivity
(Malavasi, Aghanim, Sorce+)



HESTIA: the Local Group
Carlesi,Sorce+2016, Carlesi+2016,2017
Libeskind+(including Sorce)2020,
Damle+2022, Newton+2022

Conclusion

- Standard simulations for statistics (full uncertainty)
- Constrained simulations required to reduce uncertainty (bias-free)
- CLONES are constrained simulations
  - based on peculiar velocities (no luminosity bias)
  - constrained down to the cluster scale
  - induced smaller scale (like Local Group)
  - constrained formation history
- CLONES are available, please contact me



Thank you, Merci, Grazie,

Gracias, Danke,

Mahalo, 谢谢, ありがとう,

תודה, Obrigada, Dank u,

Tak, Cảm ơn, Dziękuję, 감사합니다

Kiitos, Aitäh, diolch, dankewol,

ಧನ್ಯವಾದಗಳು, …*

* Missing your 'thanks' spelling? It means I did not get the chance to learn how to say it so far