CLONES: Digital Twins of the local Universe for bias-free inference

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and collaborators

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&
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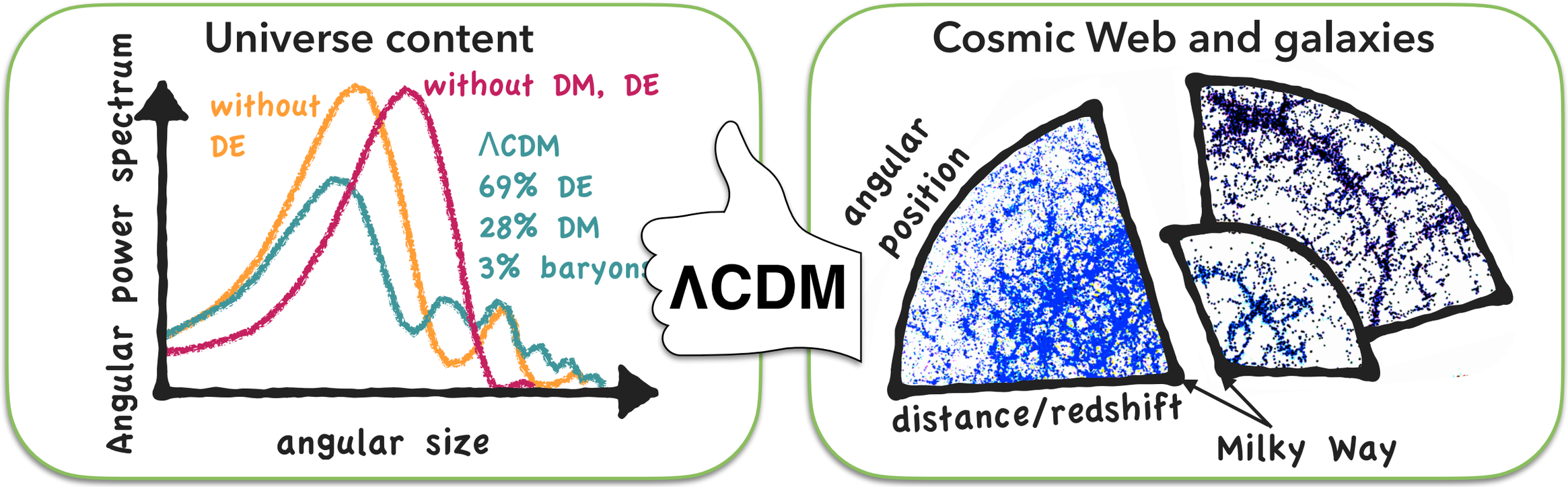
CosmoVerse Workshop, Napoli - May 21st, 2025

Cosmology: ΛCDM?



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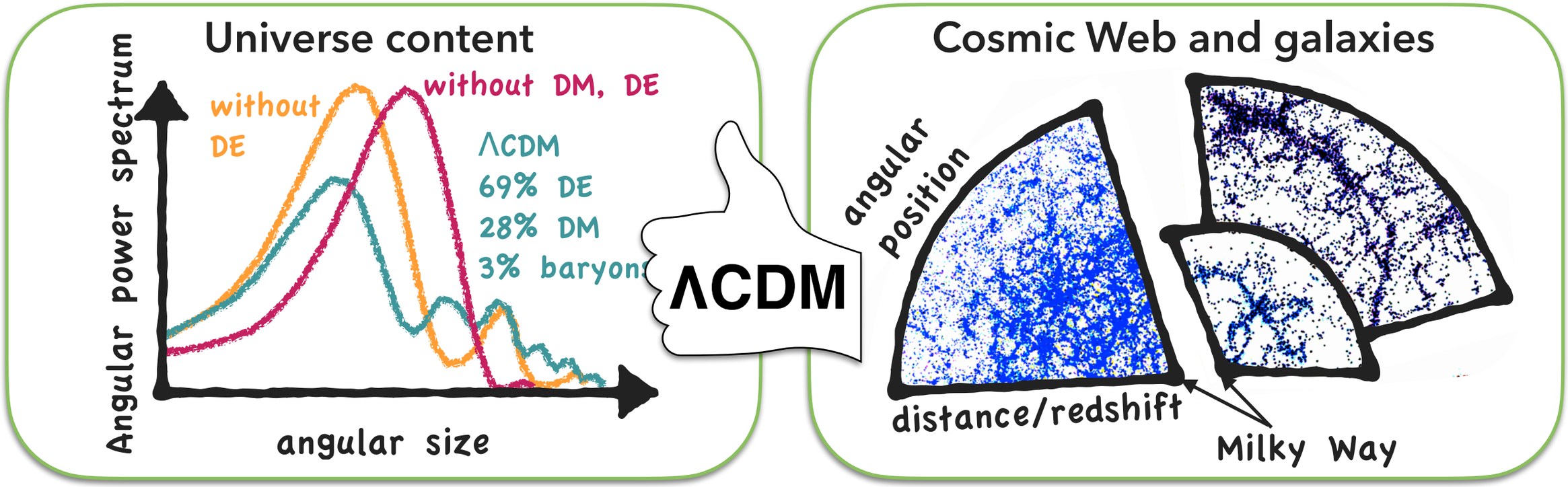

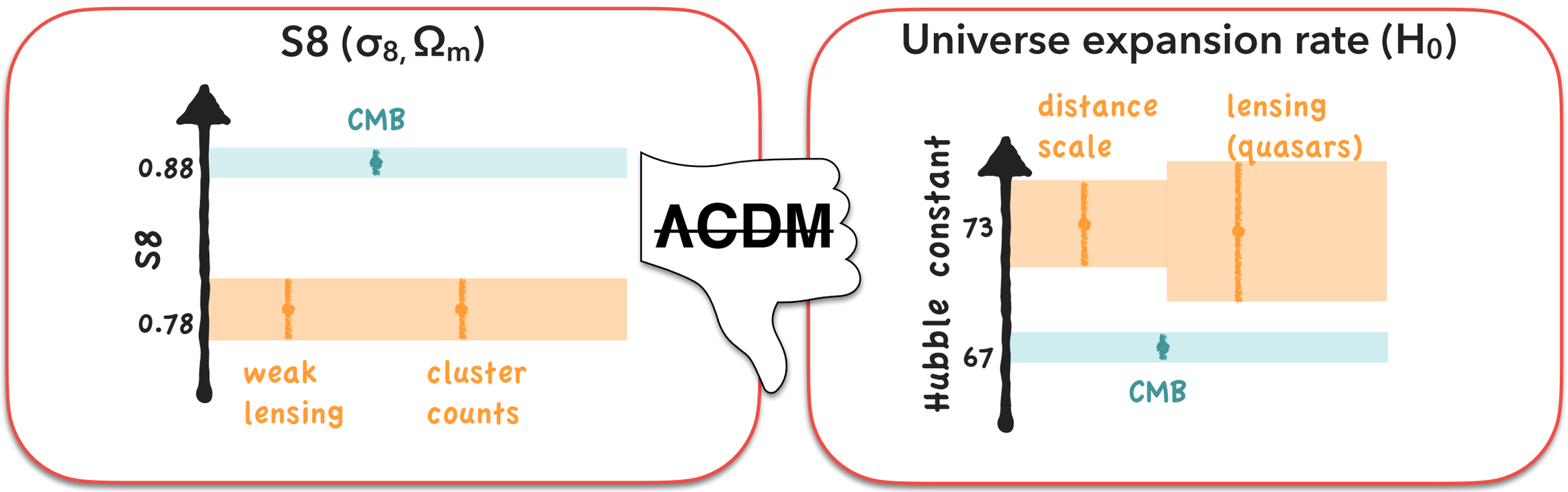

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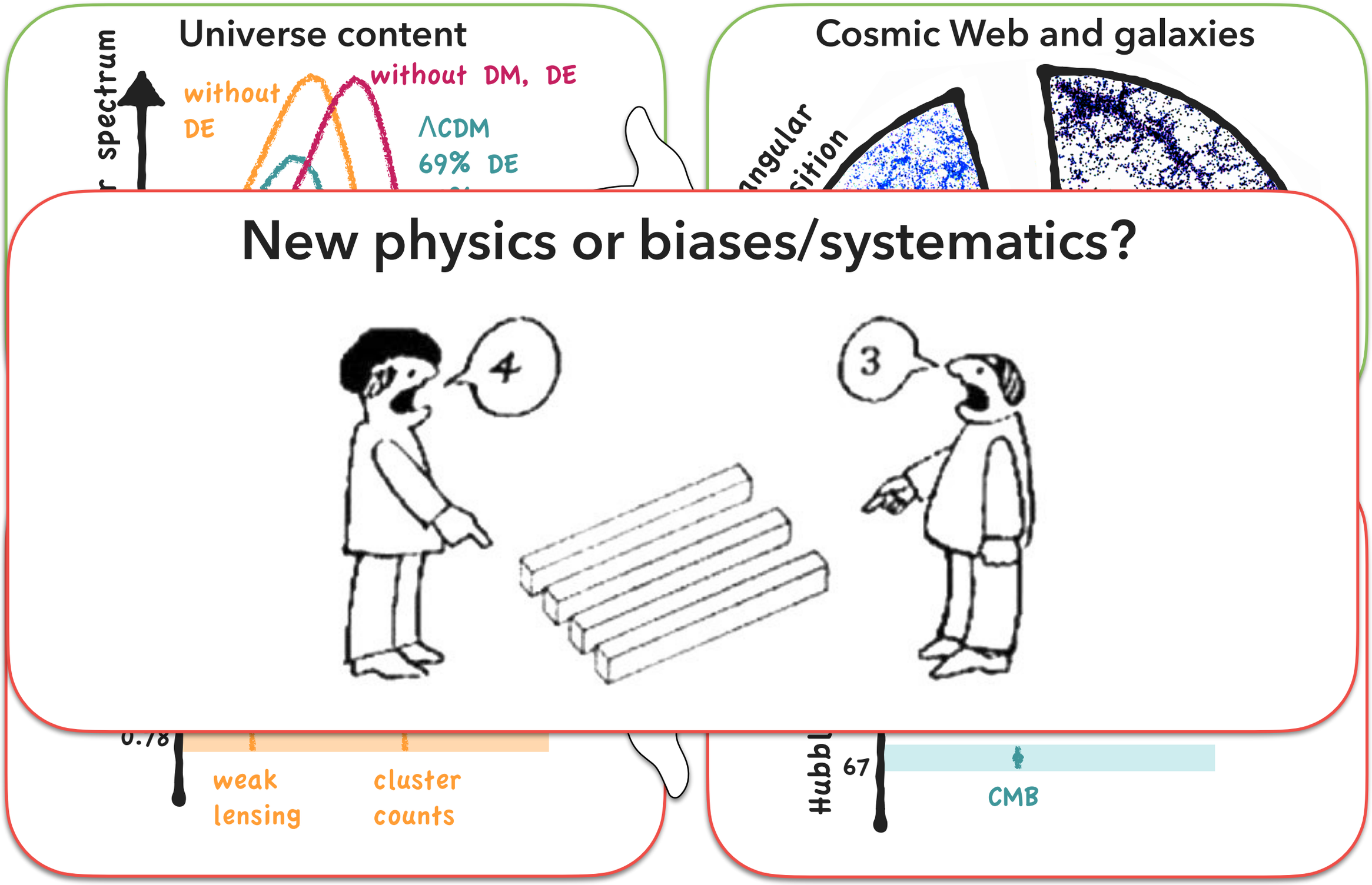
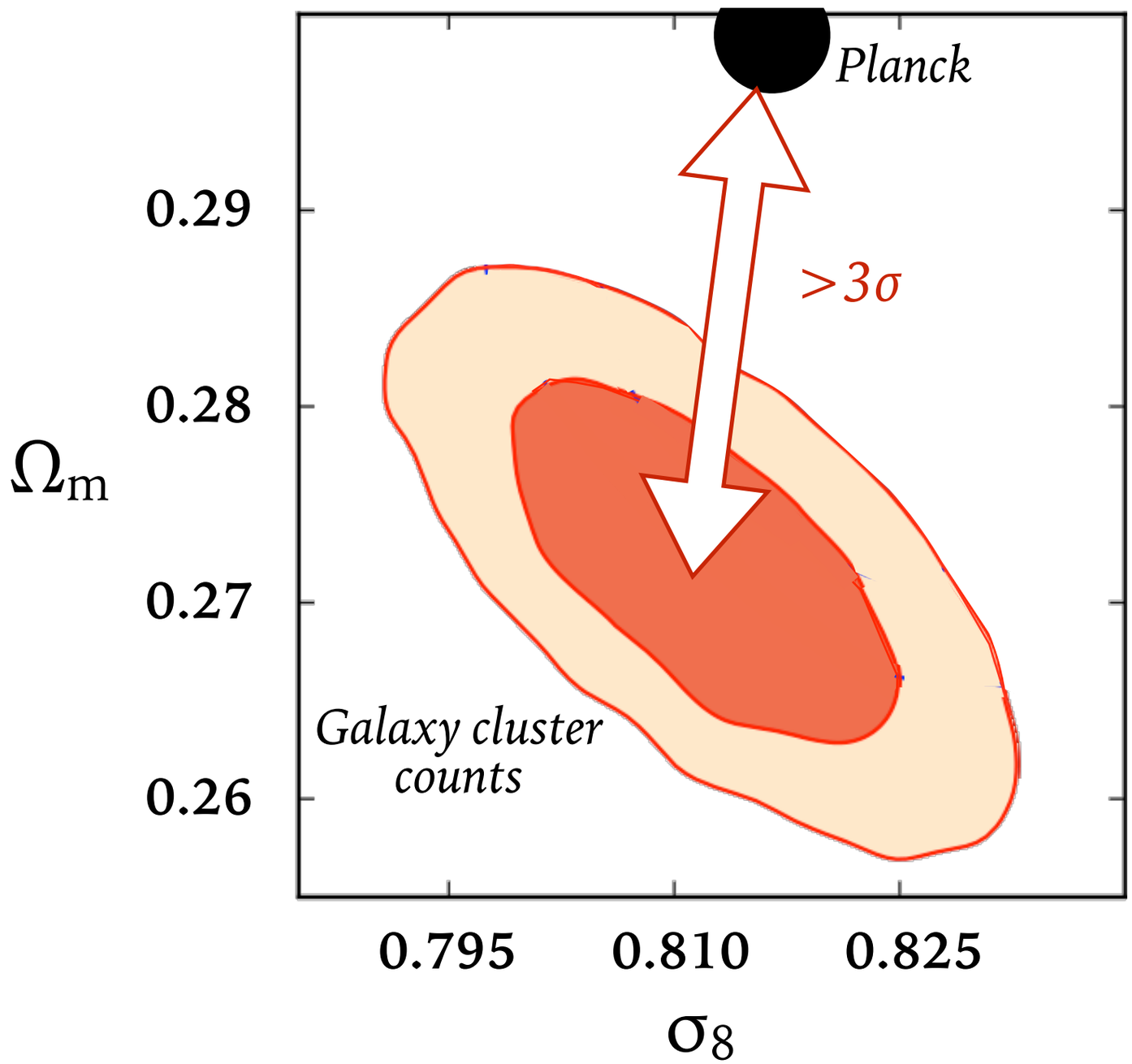
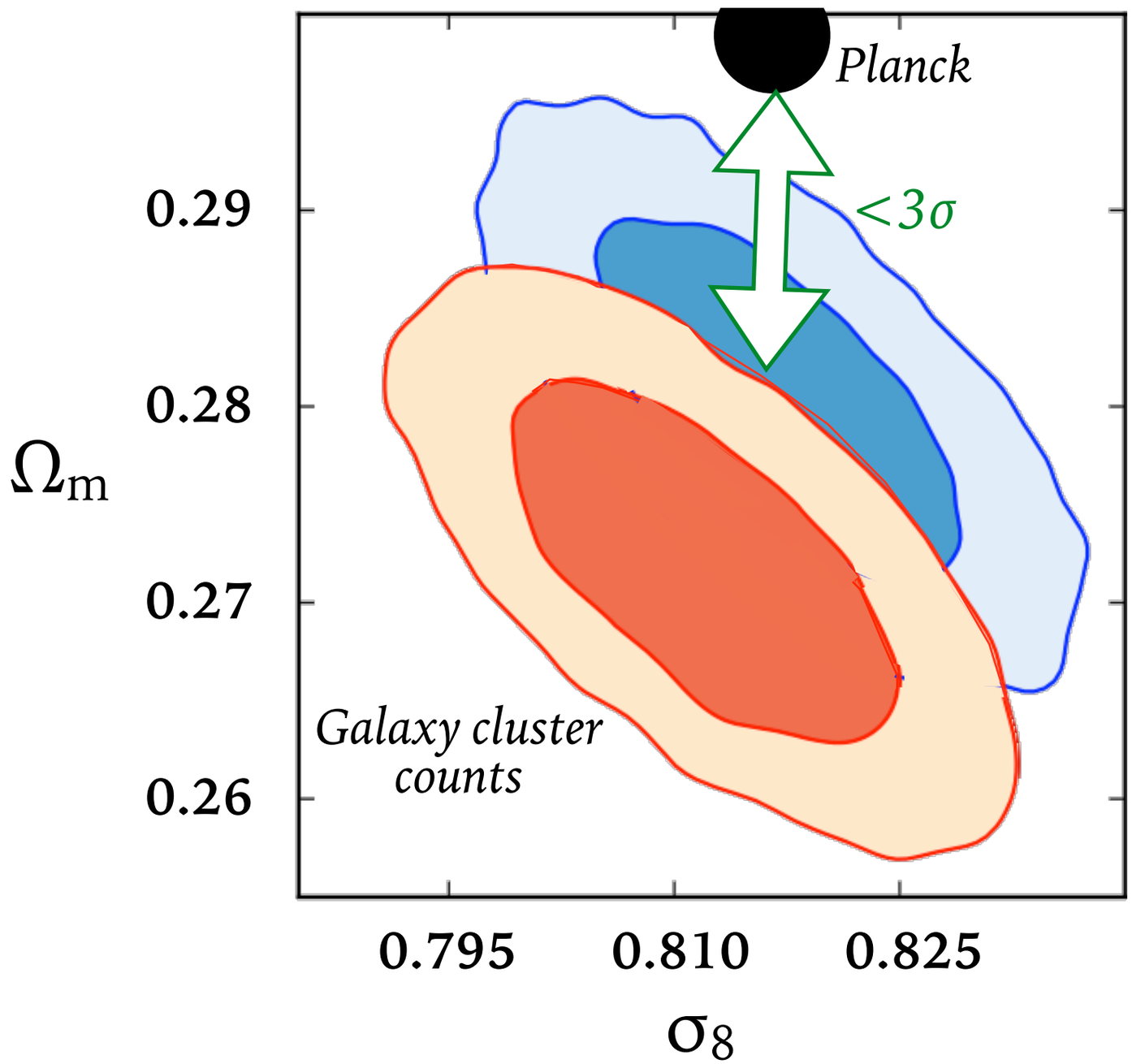


Example of S8 (σ_8, Ω_m) Galaxy cluster mass function



Planck Collaboration, Pratt+2018

Example of S8 (σ_8, Ω_m) ▶ Changing mass calibration



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Example of S8 (σ_8, Ω_m) What and Why?

Hydrostatic equilibrium : intracluster medium

$$\frac{dP}{dr} = -\frac{G\rho M_{HE}}{r^2}$$

Spherical symmetry + no turbulent/magnetic pressure :

$$\Rightarrow M_{HE}(r) = -\frac{rP_{th}(r)}{G\mu m_p n_e(r)} \frac{d\ln \mathrm{P_{th}(r)}}{d\ln \mathrm{r}}$$

Gravitational potential well : DM + Baryons

$$M_{tot} = M_{DM} + M_{gas} + M_{stars}$$

$$\downarrow$$

Hydrostatic mass bias

$$\longrightarrow \quad M_{HE} = (1-b)M_{tot}$$

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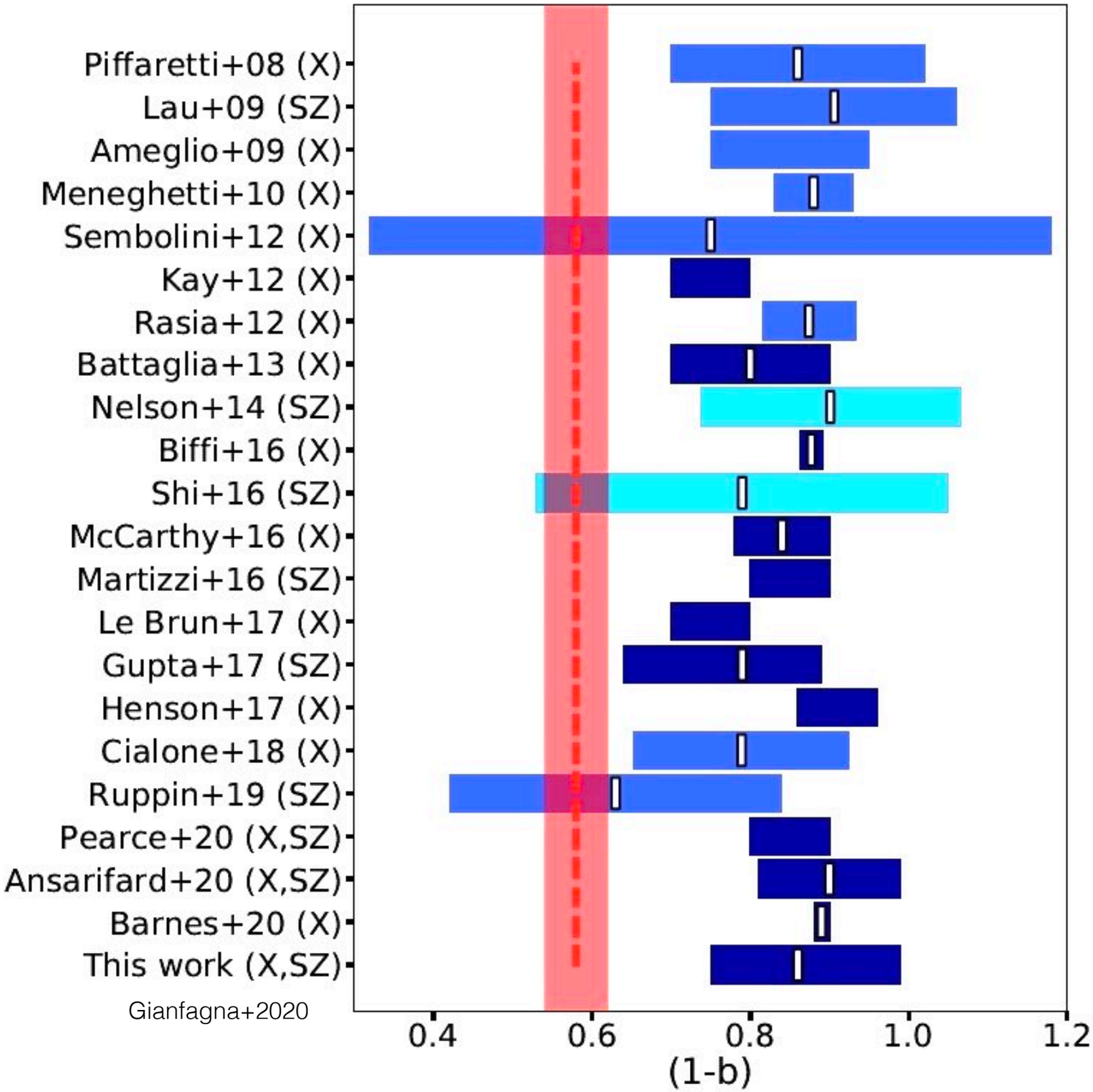
$\longrightarrow$ From cosmological simulations

Example of S8 (σ_8, Ω_m) ▶ Huge disparity



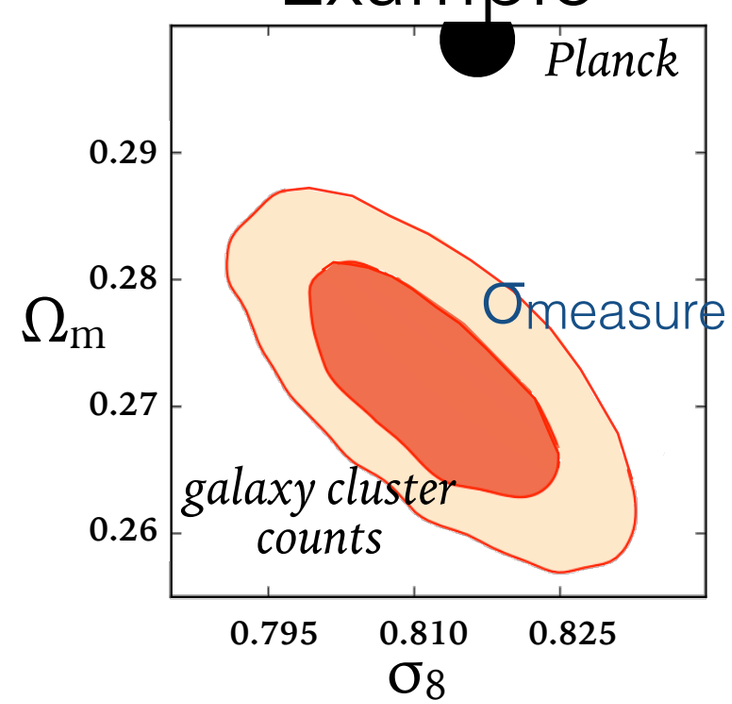
Gianfagna+2020

Simulations & systematics

Cosmo Param (H_0, S_8) = X +/- $\sigma_{measure}$ +/- $\sigma_{systematics}$

- **nb measurements/obs.**
- **instruments/tools sensitivity**
  = precision

Example



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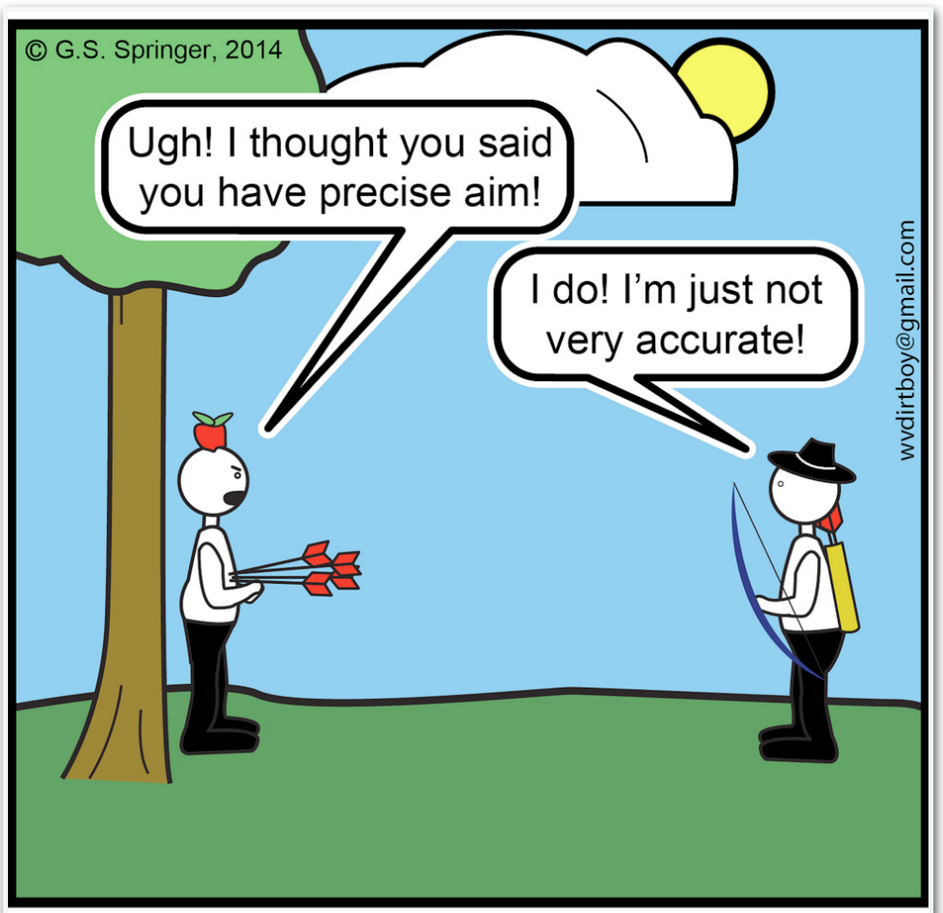
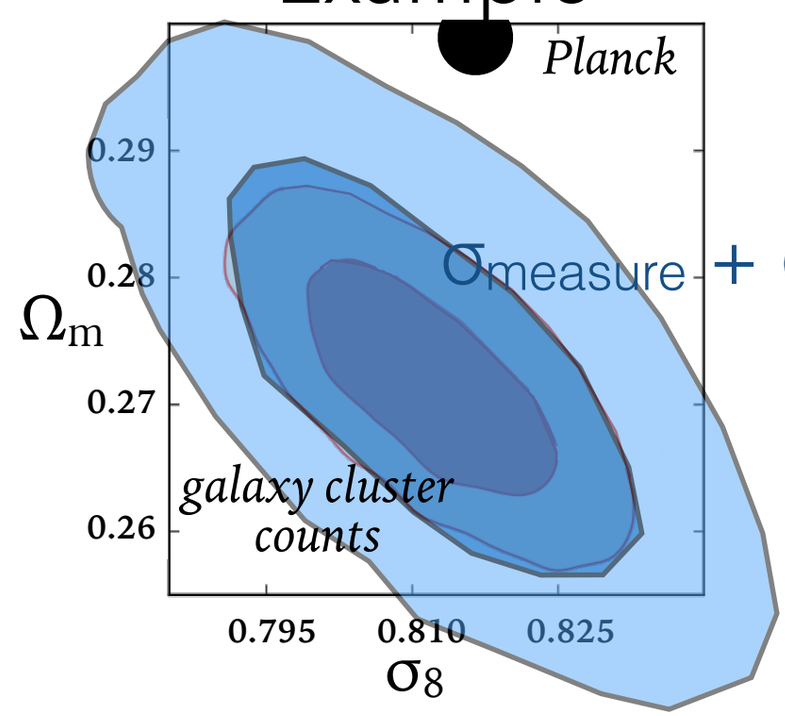
Standard cosmological simulations can give the total uncertainty but cannot reduce the systematics



Sometimes it pays to know a little statistics.

Example



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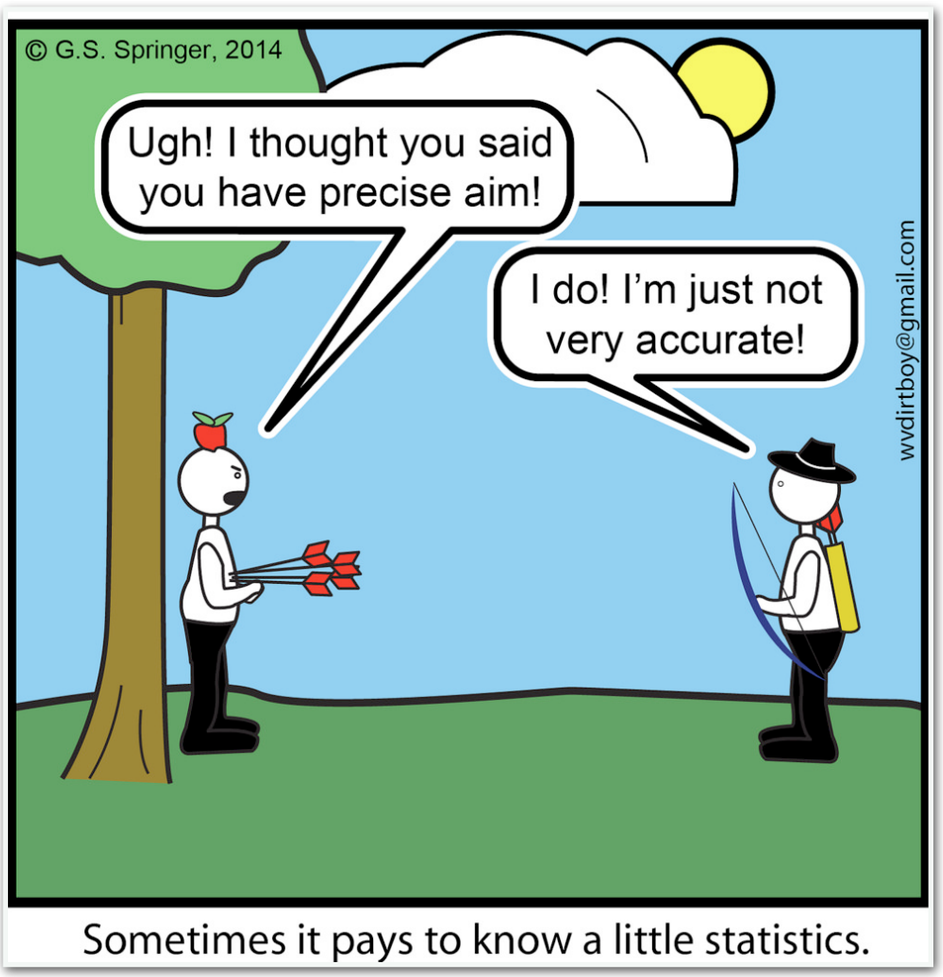

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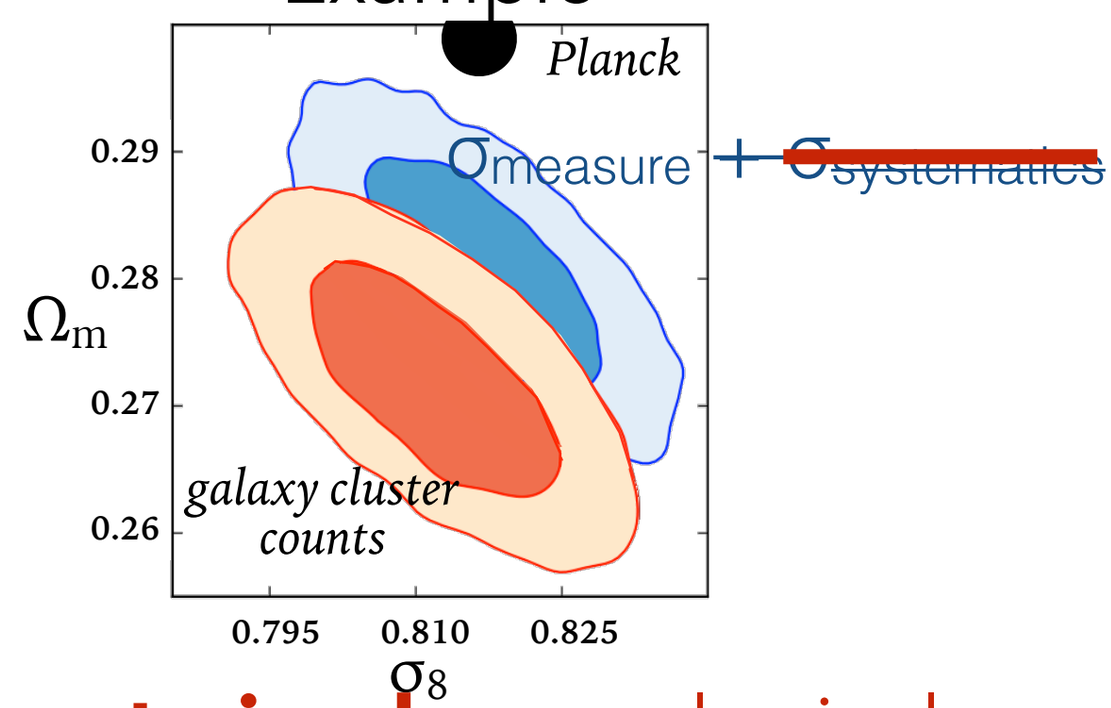
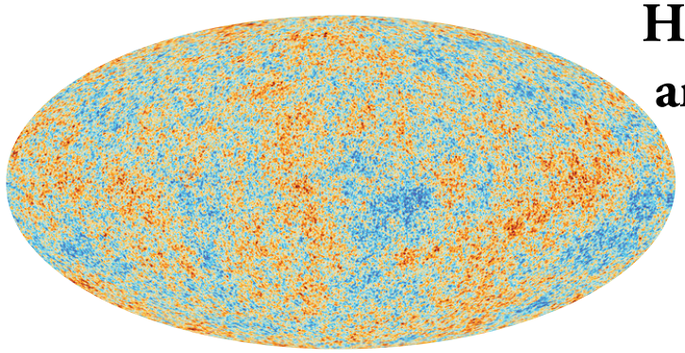


Constrained cosmological simulations can help reduce biases

Standard cosmological simulations

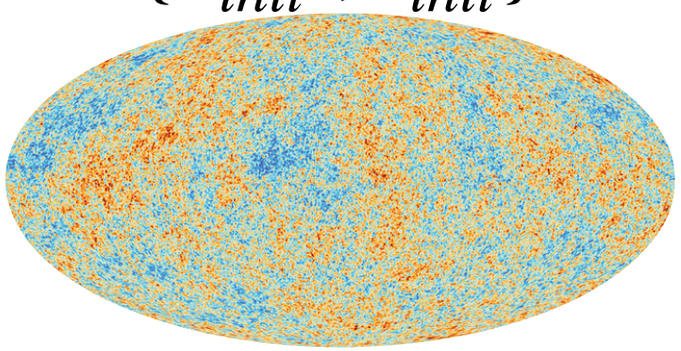
Part of the Universe at >13.7 light-Gyr
Photons received today have been emitted when it was ~380 000 yrs. old



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

initial conditions of a random patch of the Universe

$$\{\delta_{init}\ ,\ v_{init}\}$$



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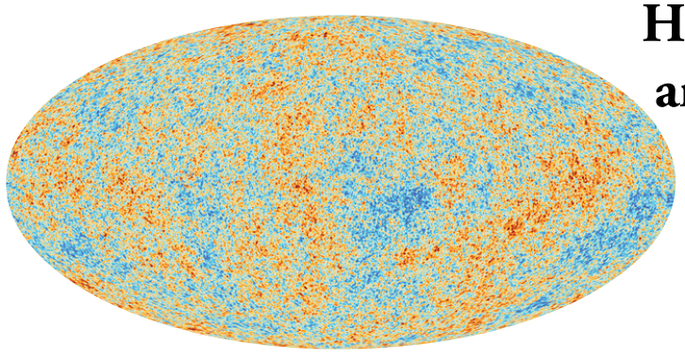
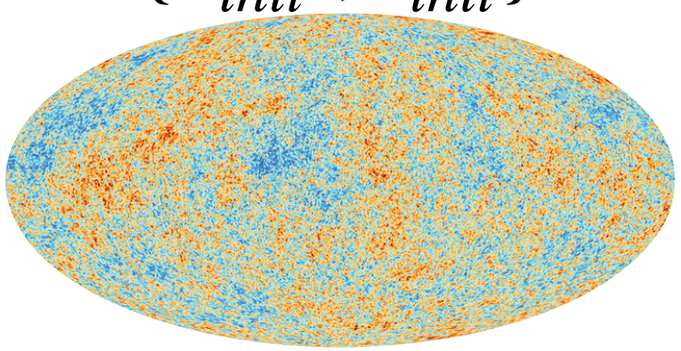


Homogeneous and Isotropic Universe → $P(k)$ → **Gaussian initial density field** →

$$\delta(\mathbf{k}) = \sqrt{P(\mathbf{k})}.\omega(\mathbf{k})$$

? ↔ **initial conditions of the local Universe**

$$\{\delta_{init}\ ,\ v_{init}\}$$



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e.g. CLONES = Constrained LOcal & Nesting Environment Simulations

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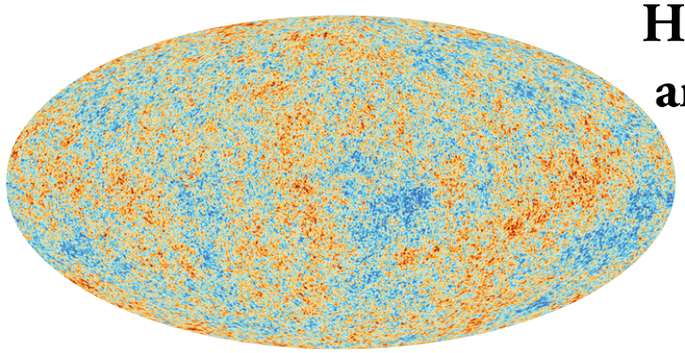

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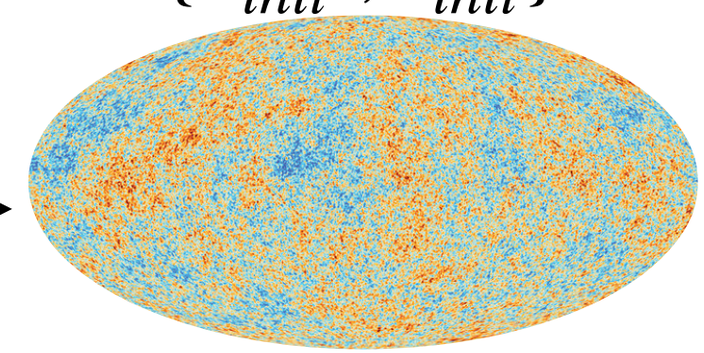

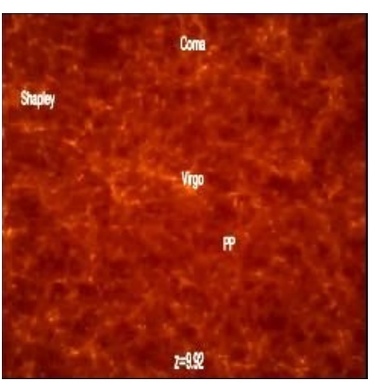

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Sorce+2016, Sorce2018

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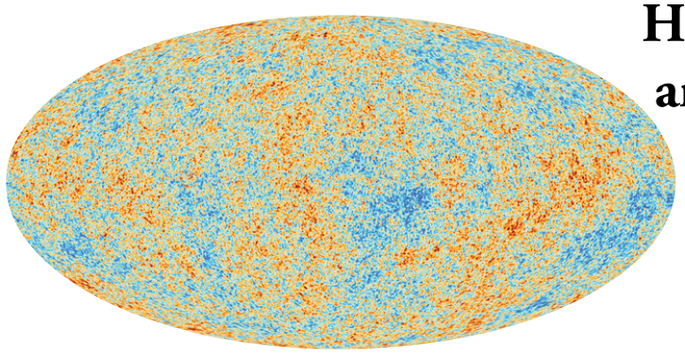

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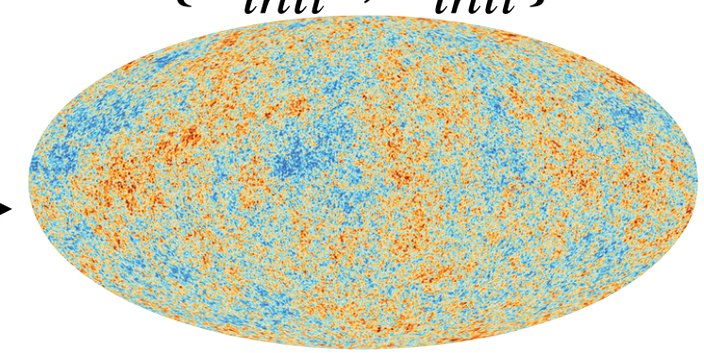

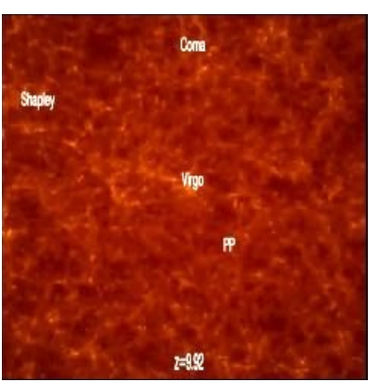

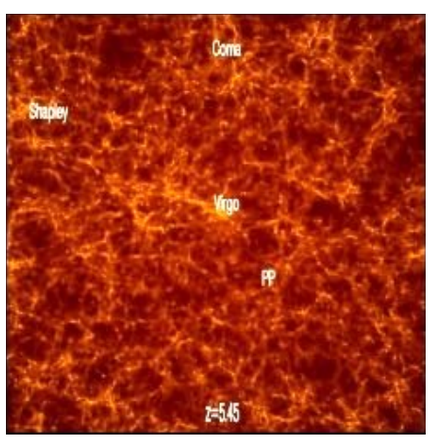

Evolution →

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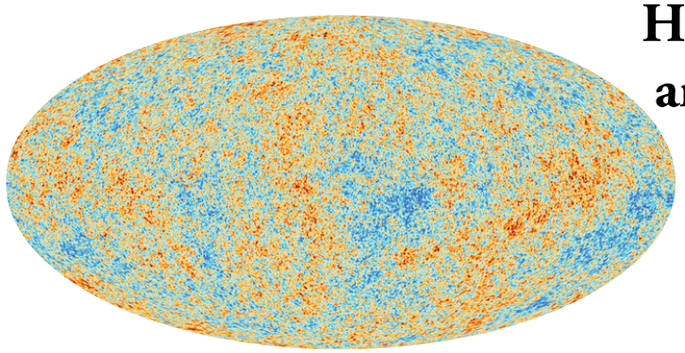

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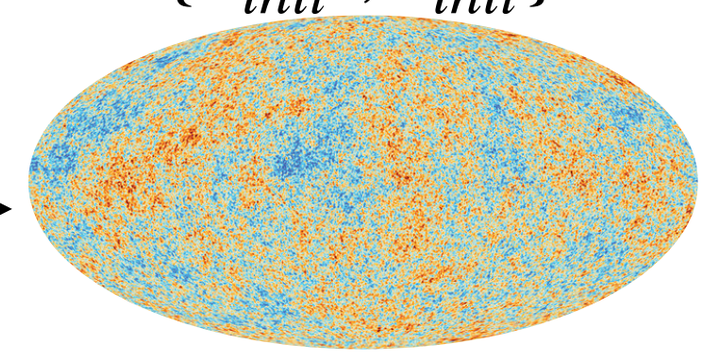

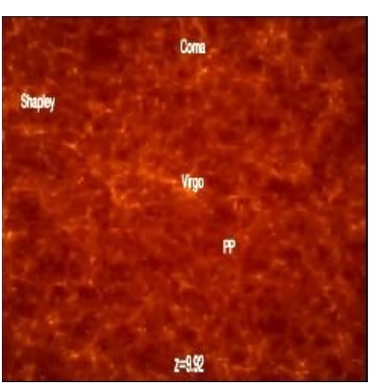

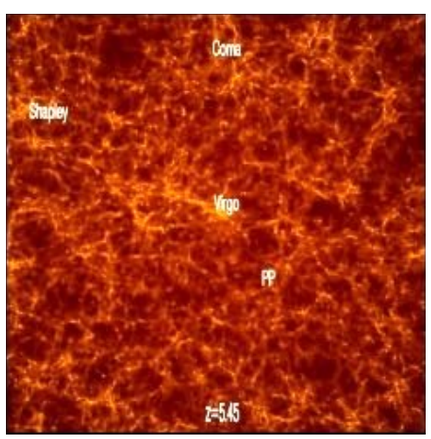

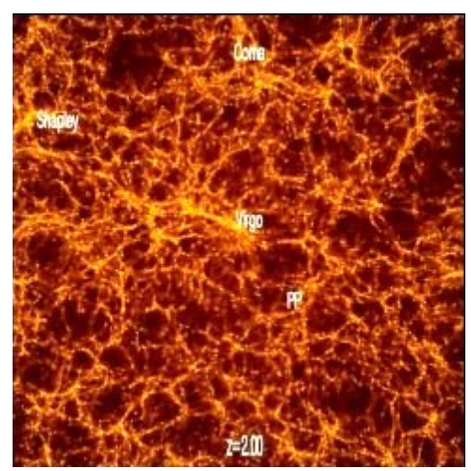

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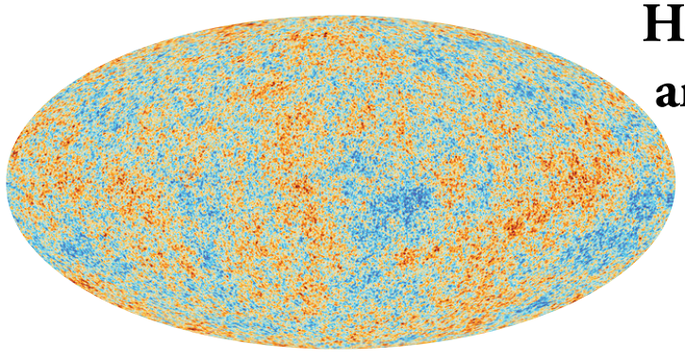

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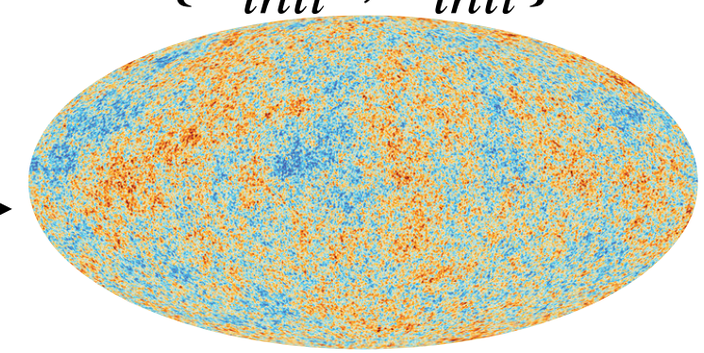

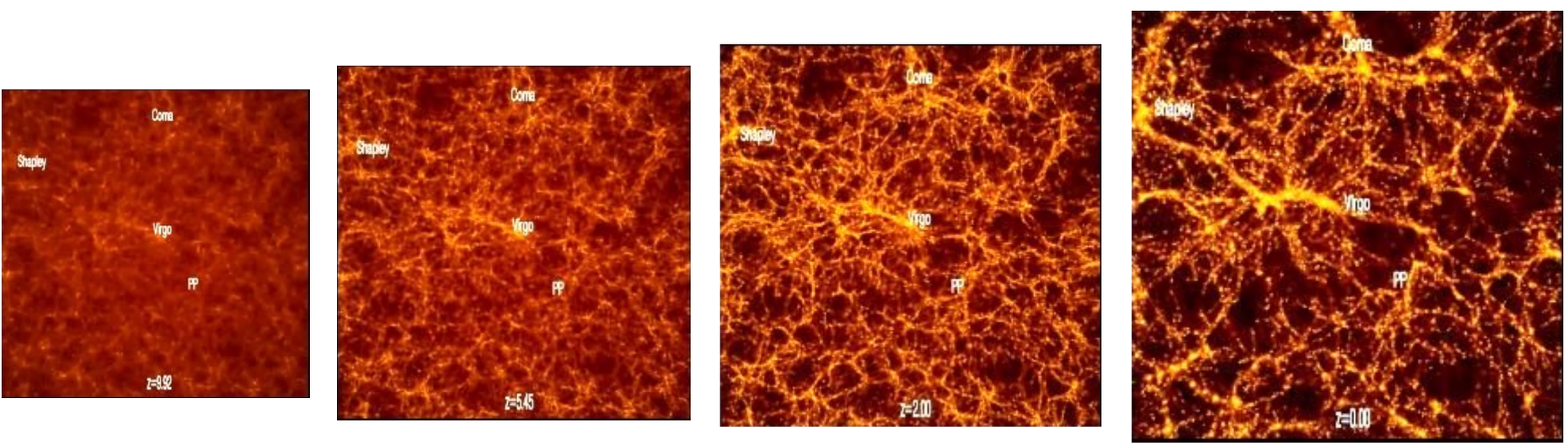

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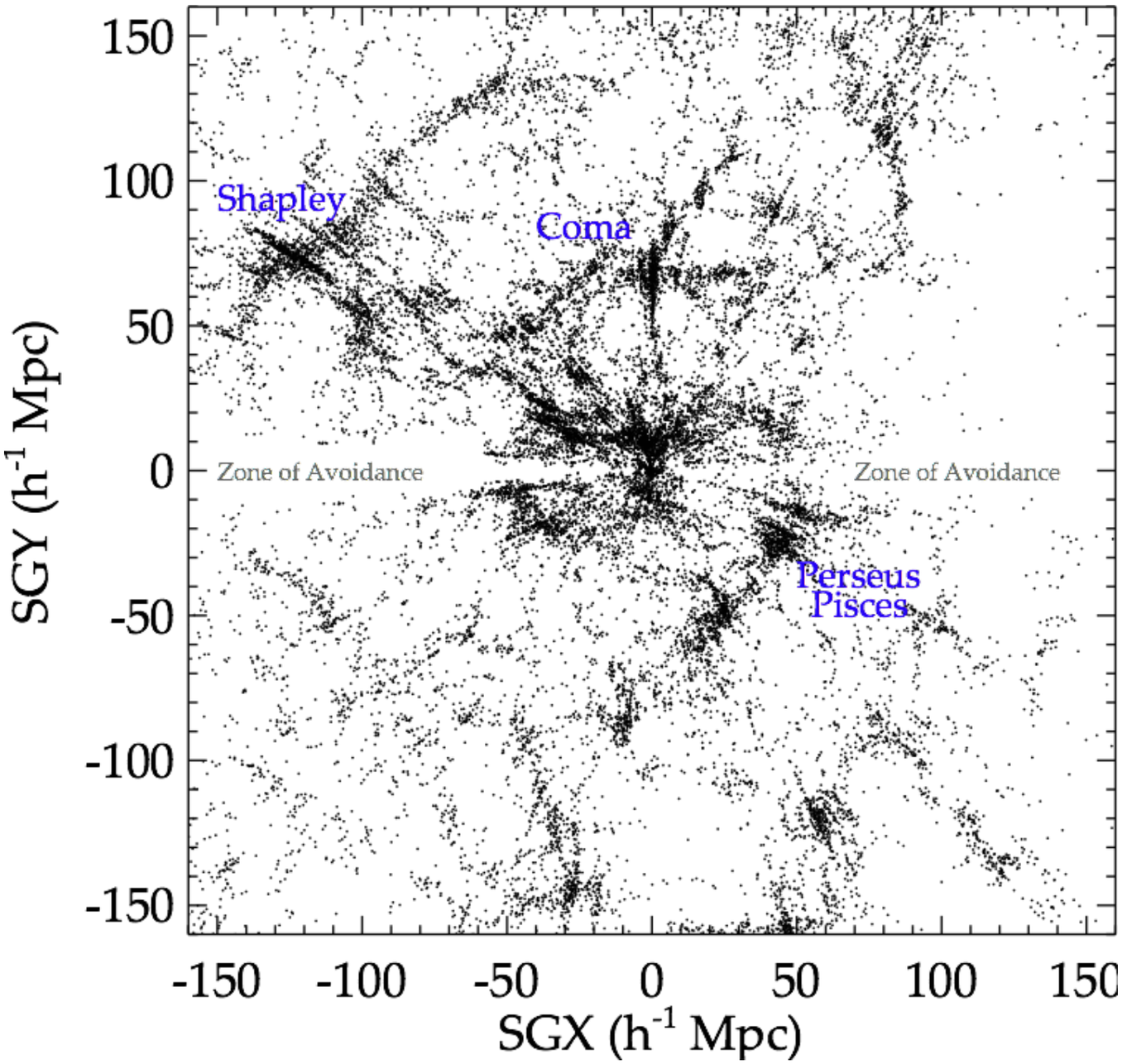
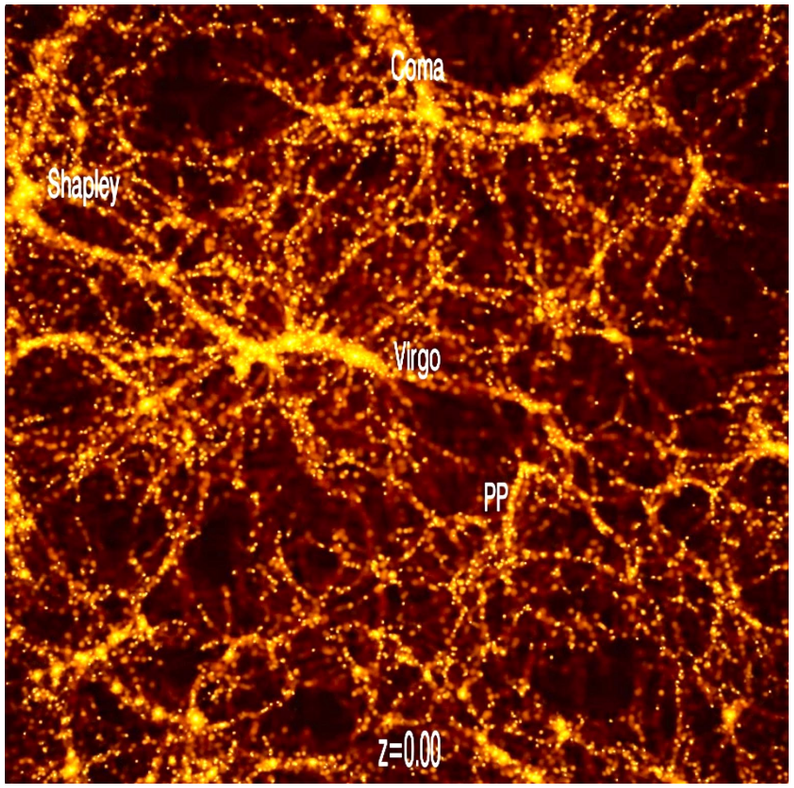
CLONES and the local LSS



Note the fingers of gods



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

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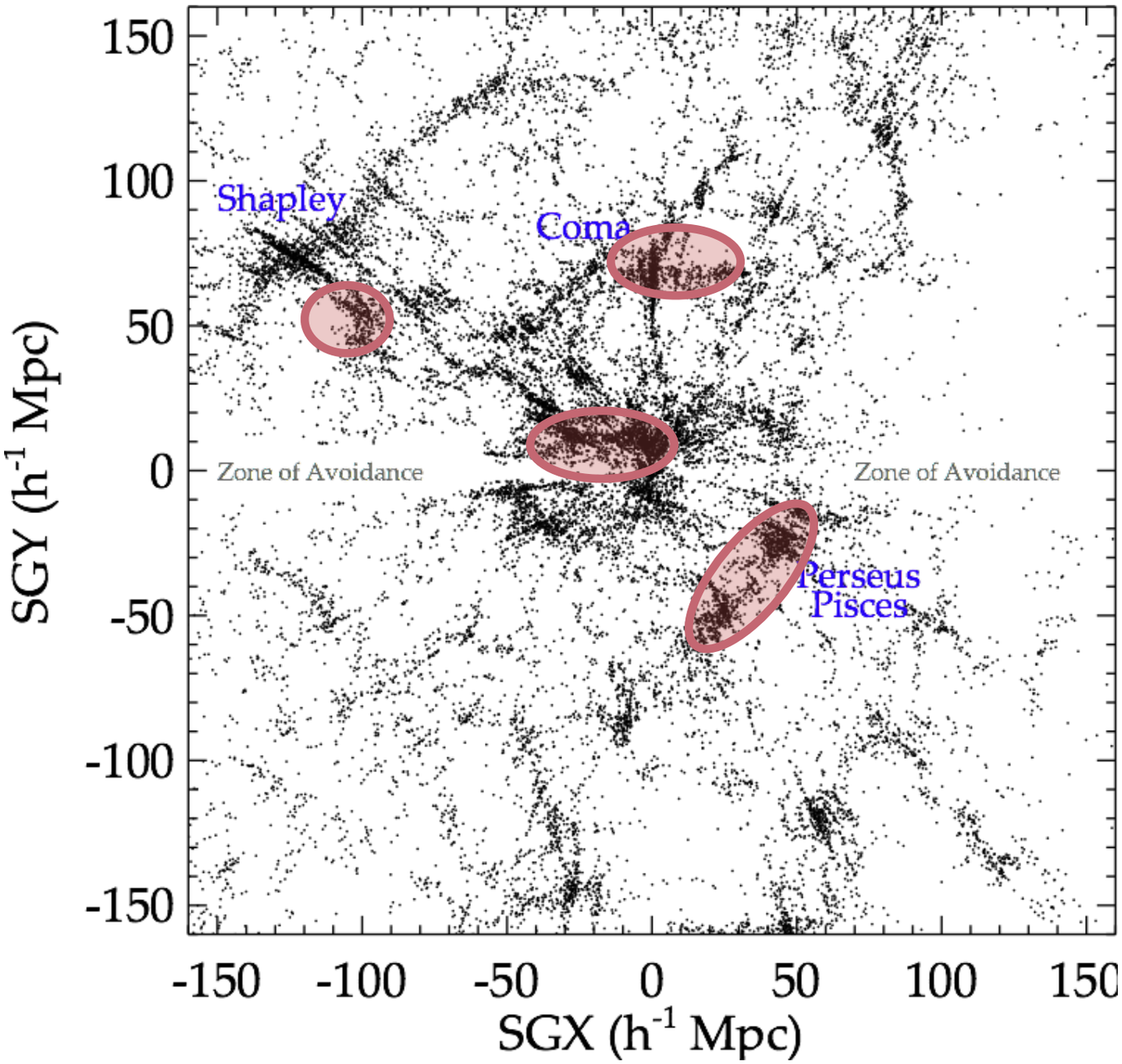

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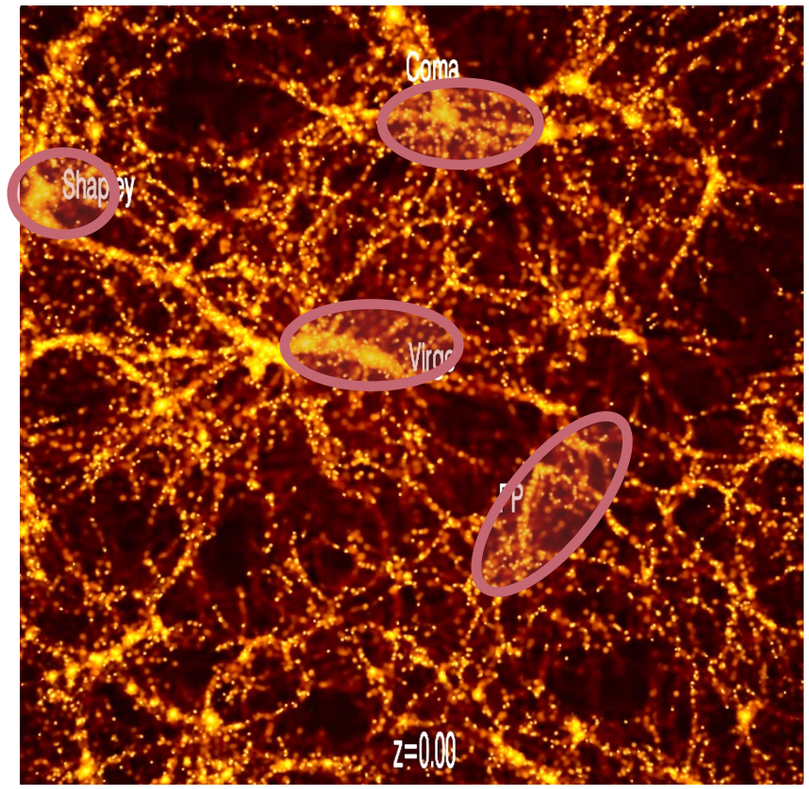

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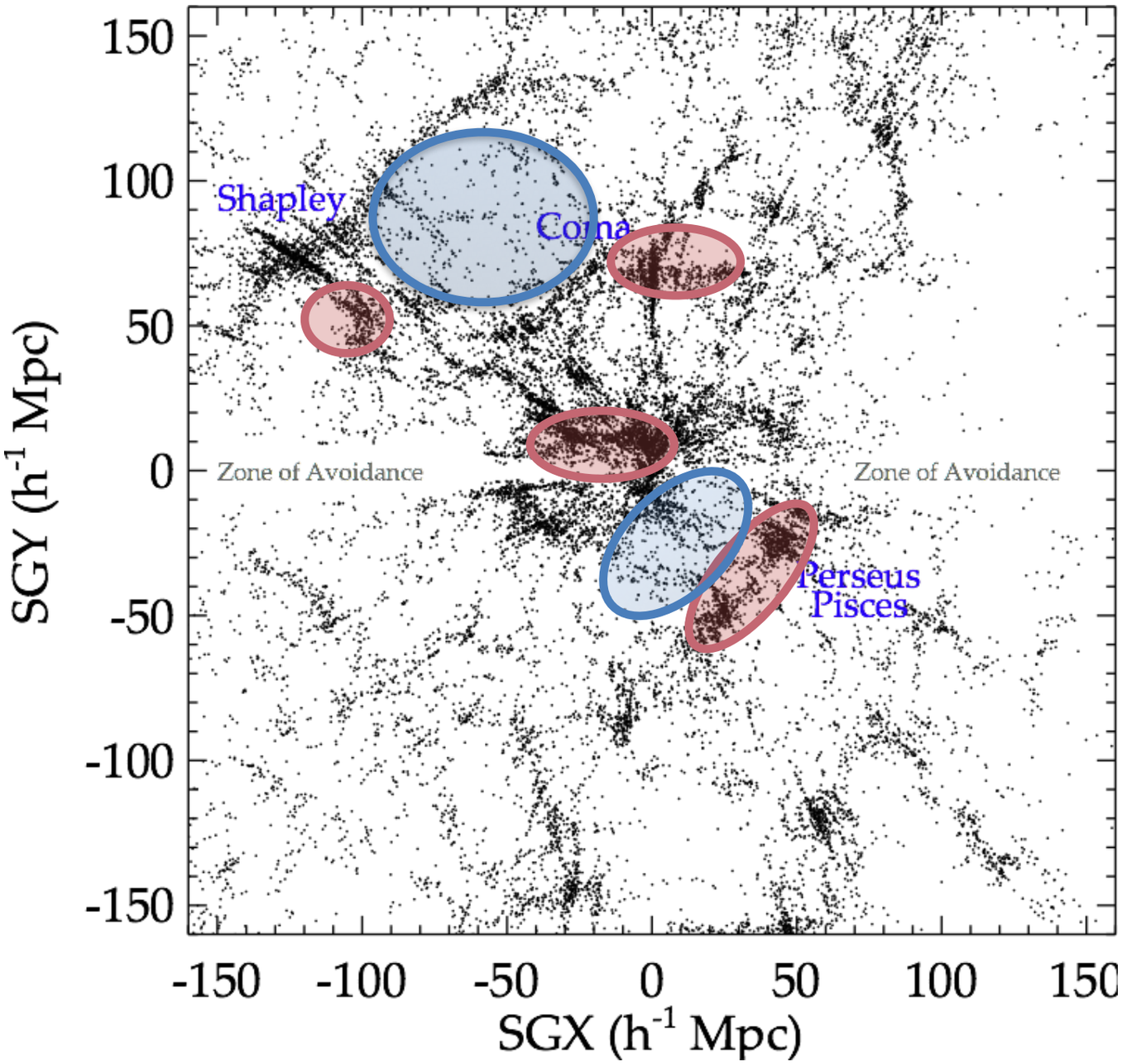

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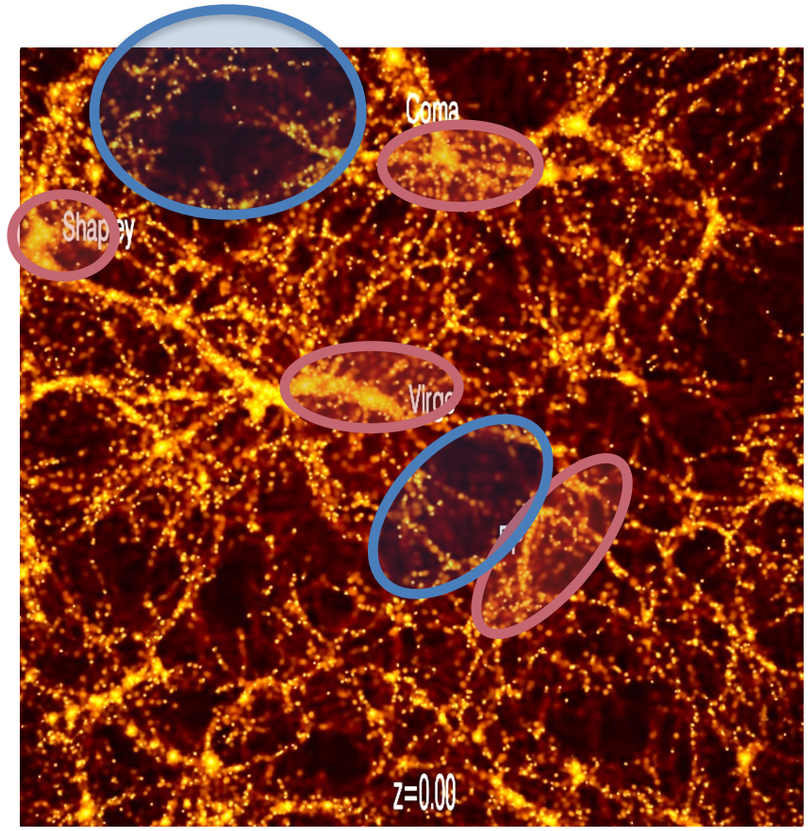

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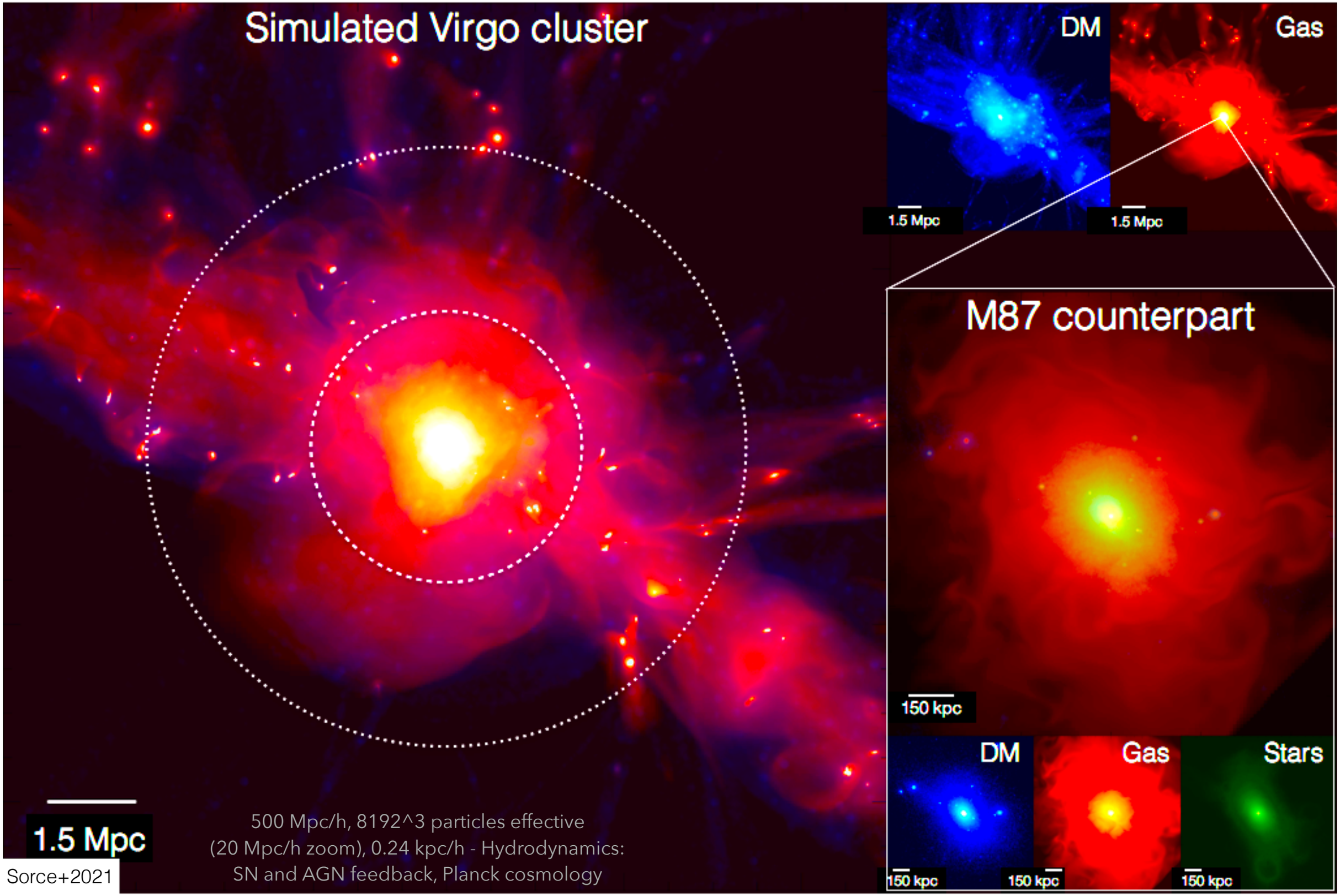
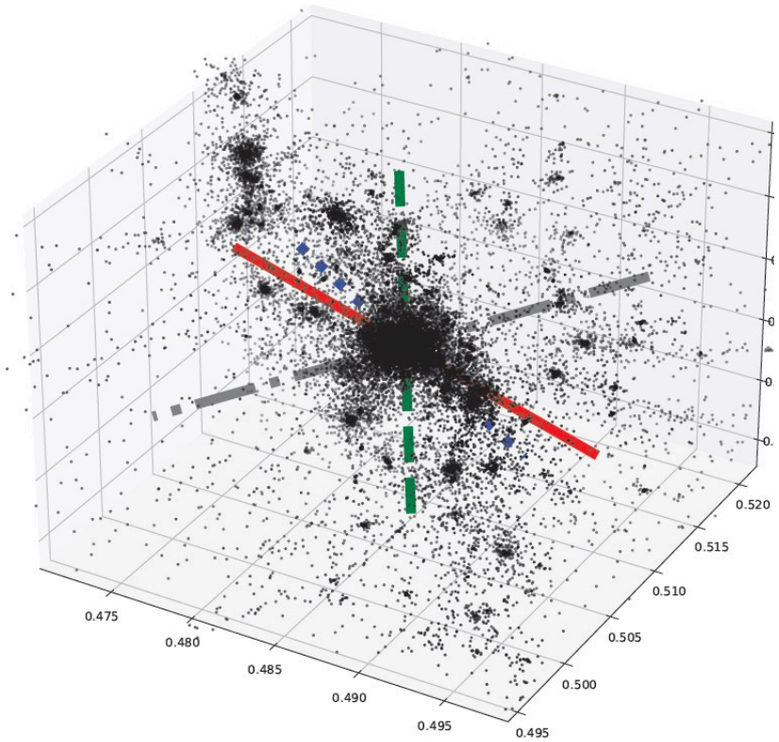
CLONES: hydrostatic mass bias & projection effects

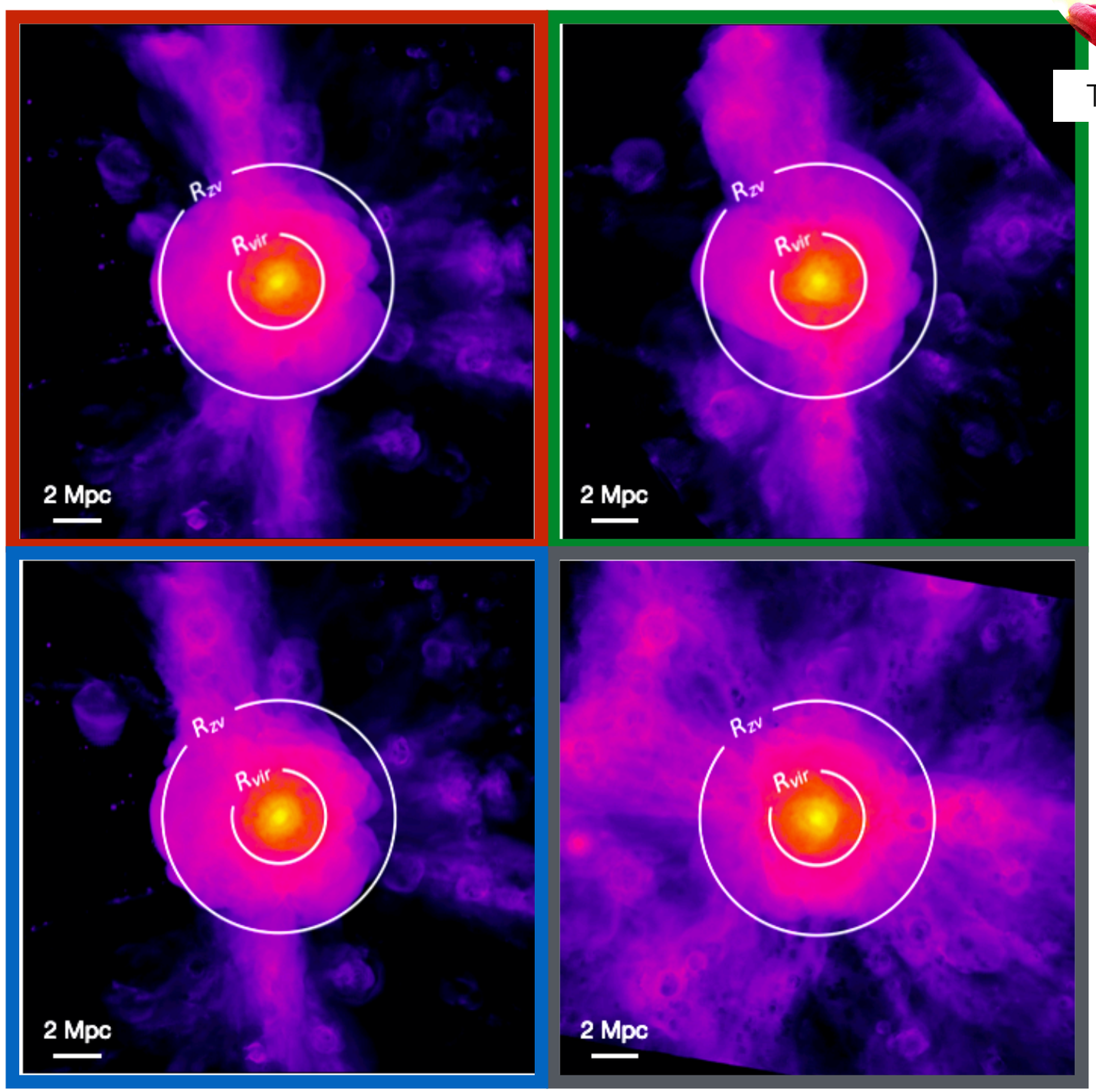


Sorce+2021

CLONES: hydrostatic mass bias & projection effects

Théo Lebeau





Filament

$\perp_1$ filament

$\perp_2$ filament

line of sight

Lebeau, Sorce+2023

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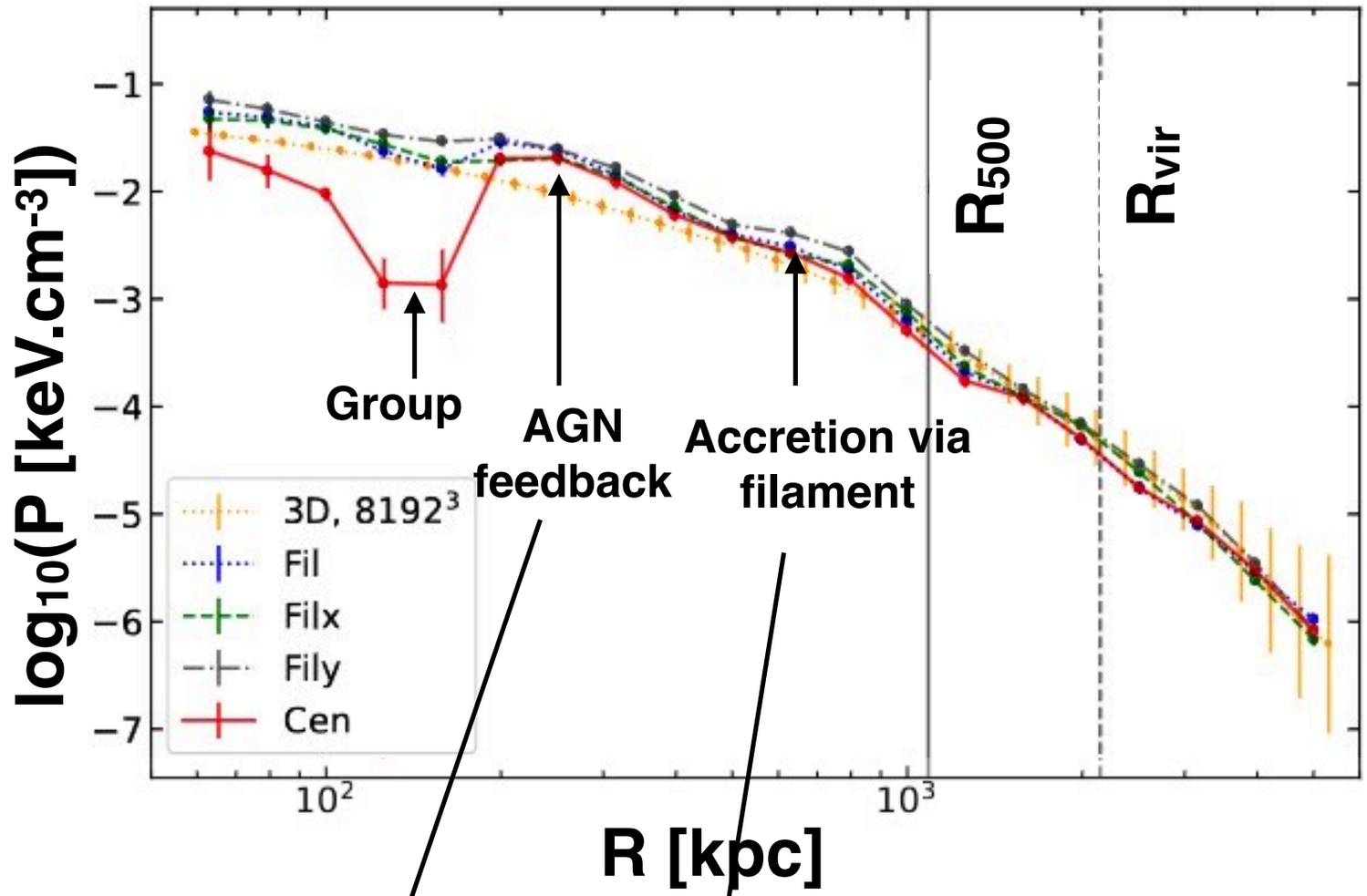

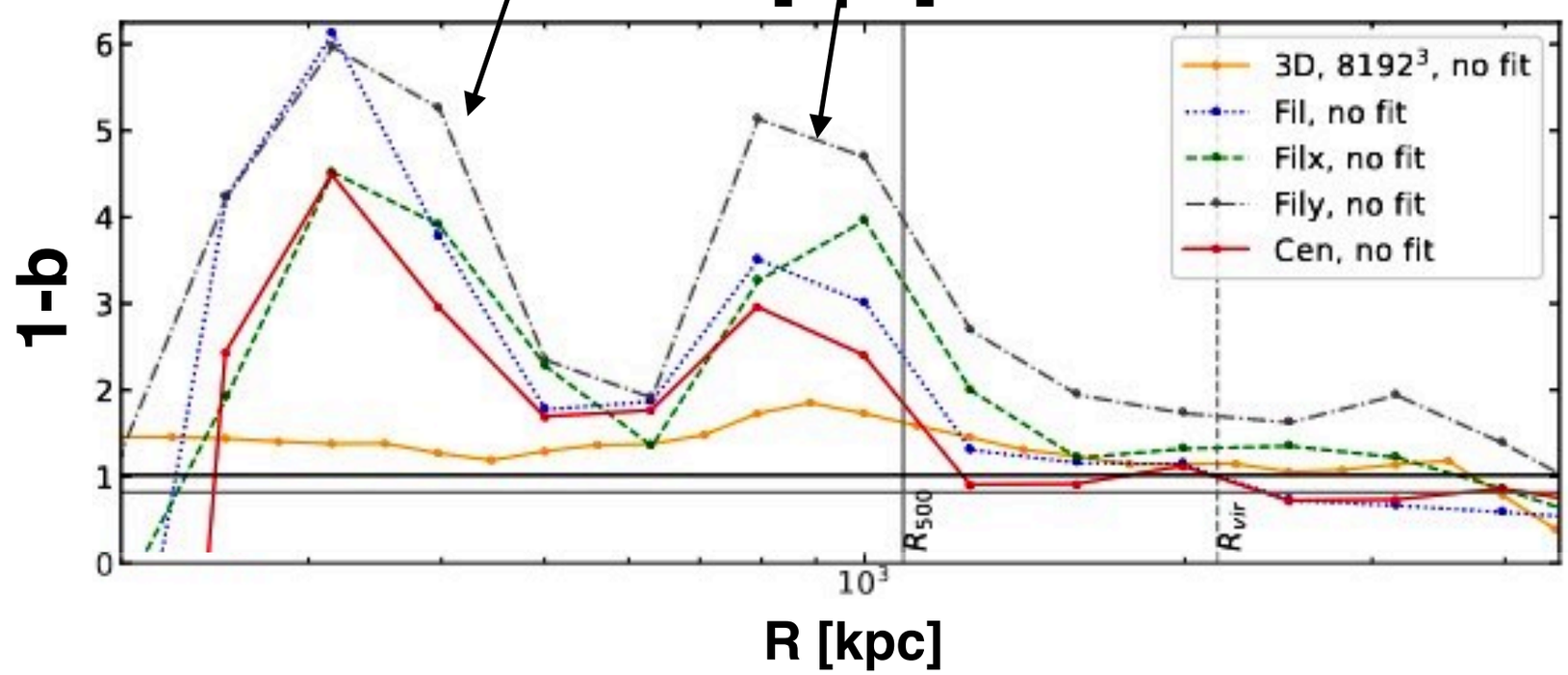

Varies with R and projection !

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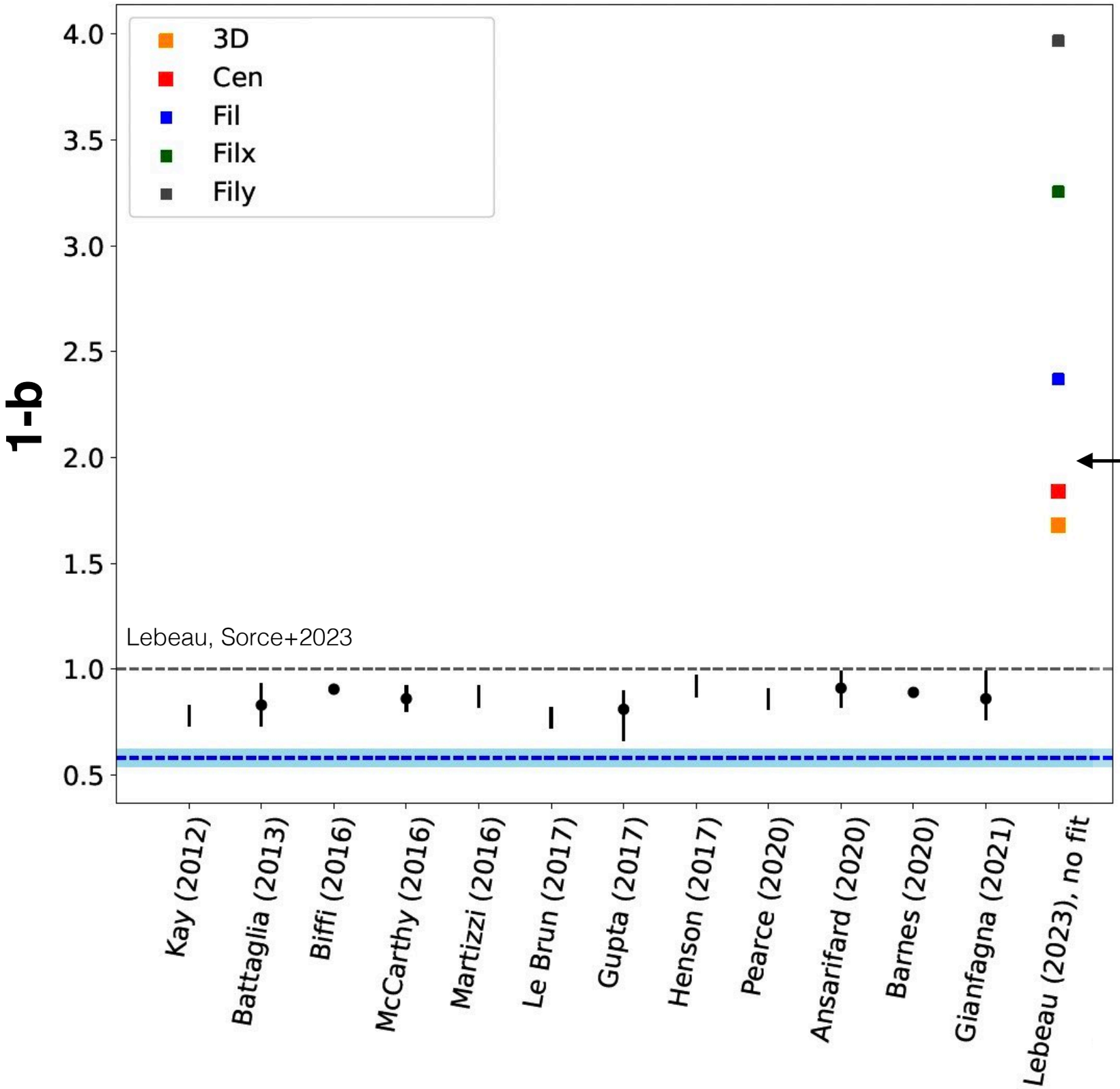

Projection effects on the hydrostatic mass bias = potential S8 problem !

CLONES: Only non-thermal pressure ?

Hydrostatic equilibrium : intracluster medium

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→ No other sources of pressure (other than thermal) ?

CLONES: Only non-thermal pressure ?

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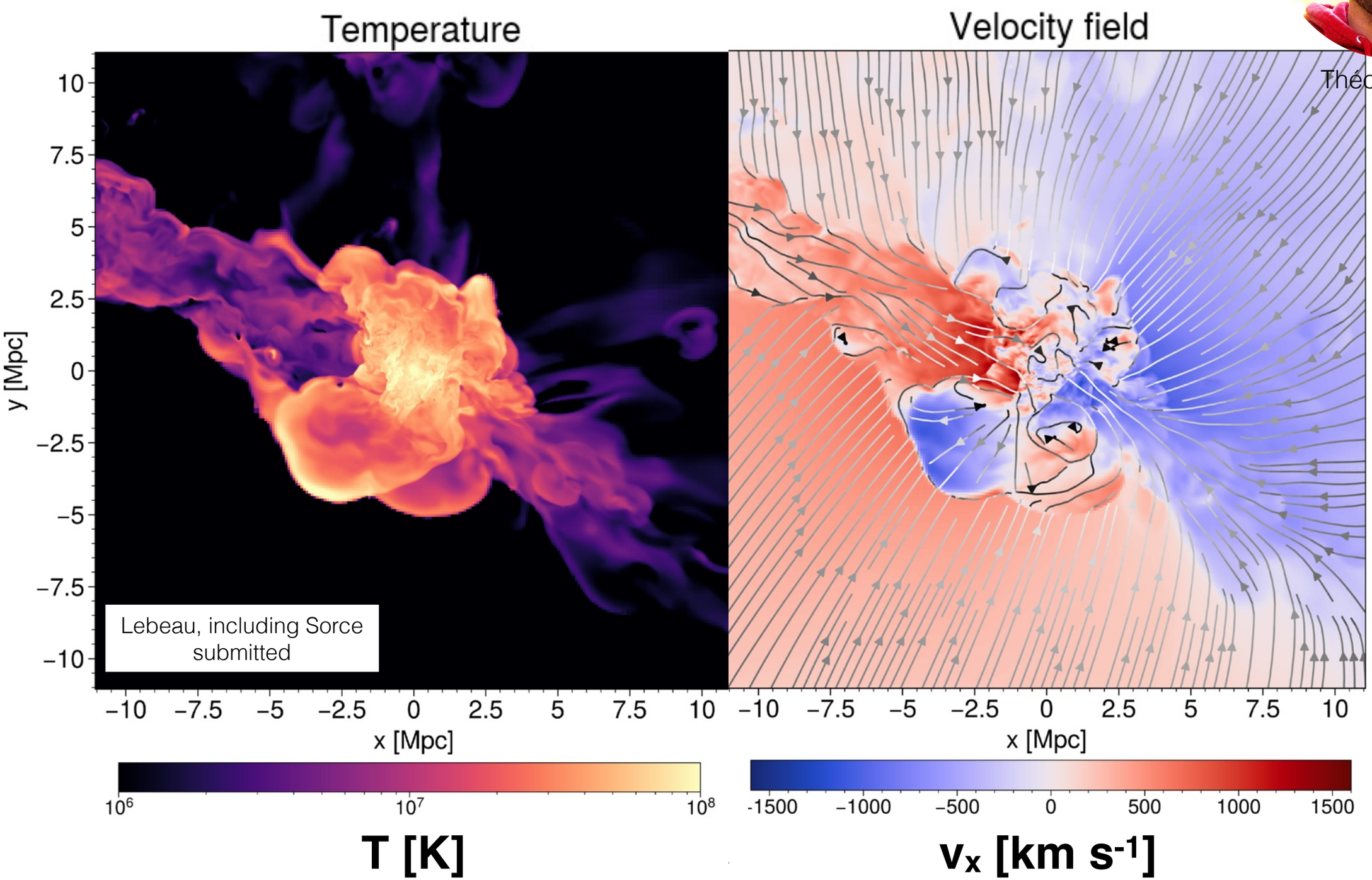

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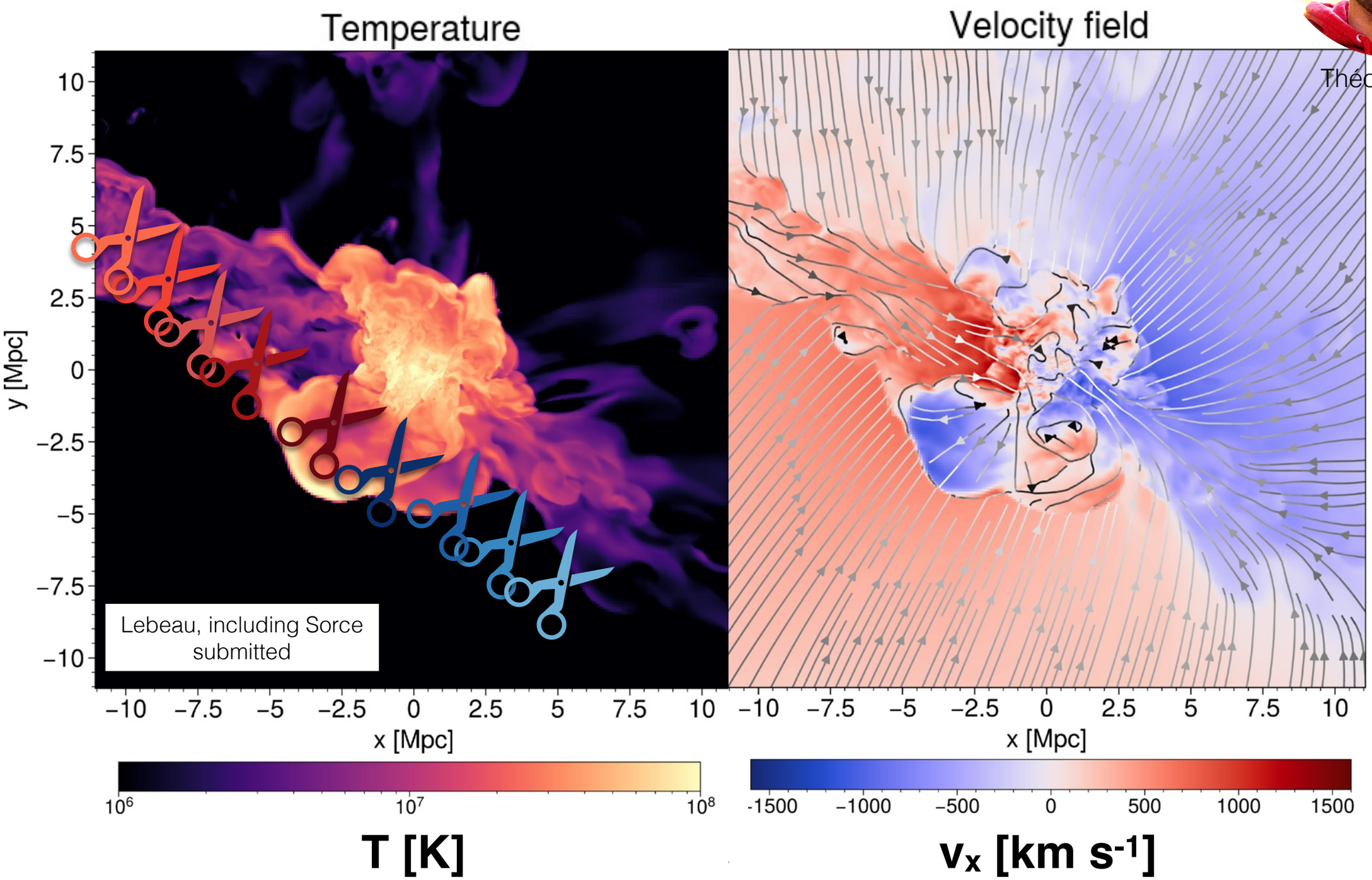
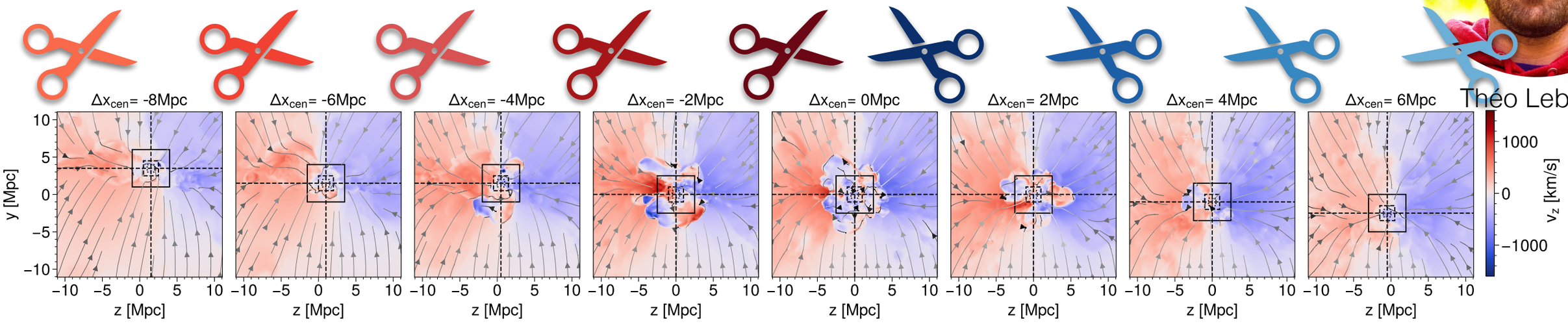
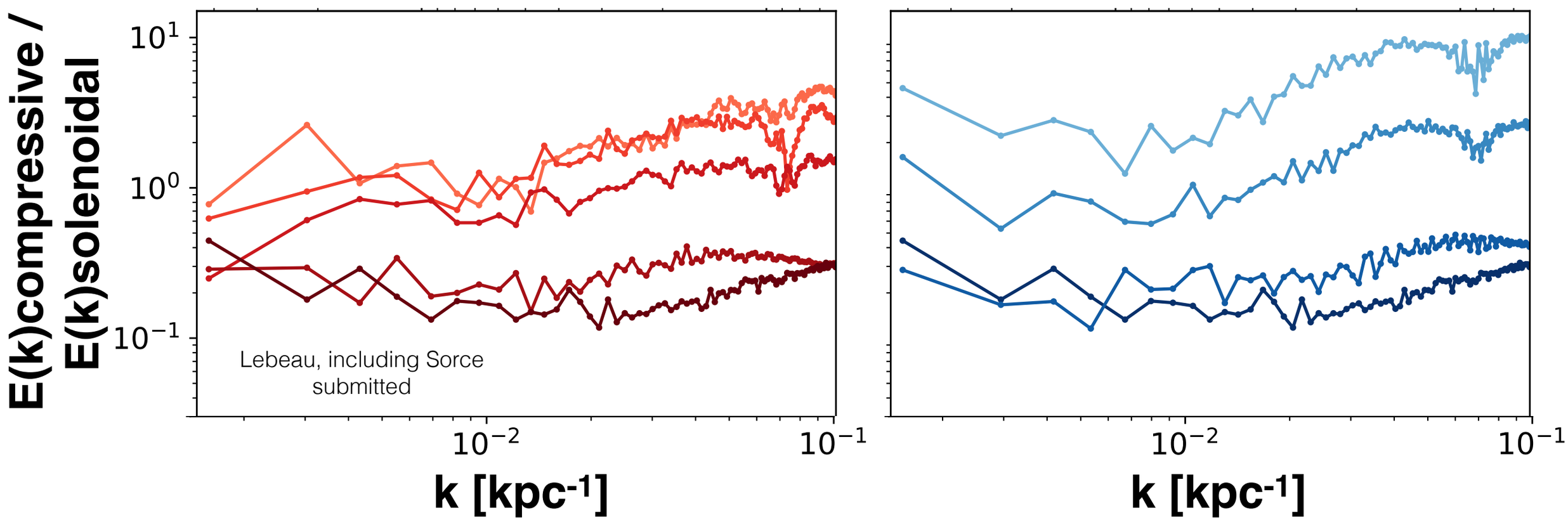


CLONES: Only non-thermal pressure ?

Théo Lebeau

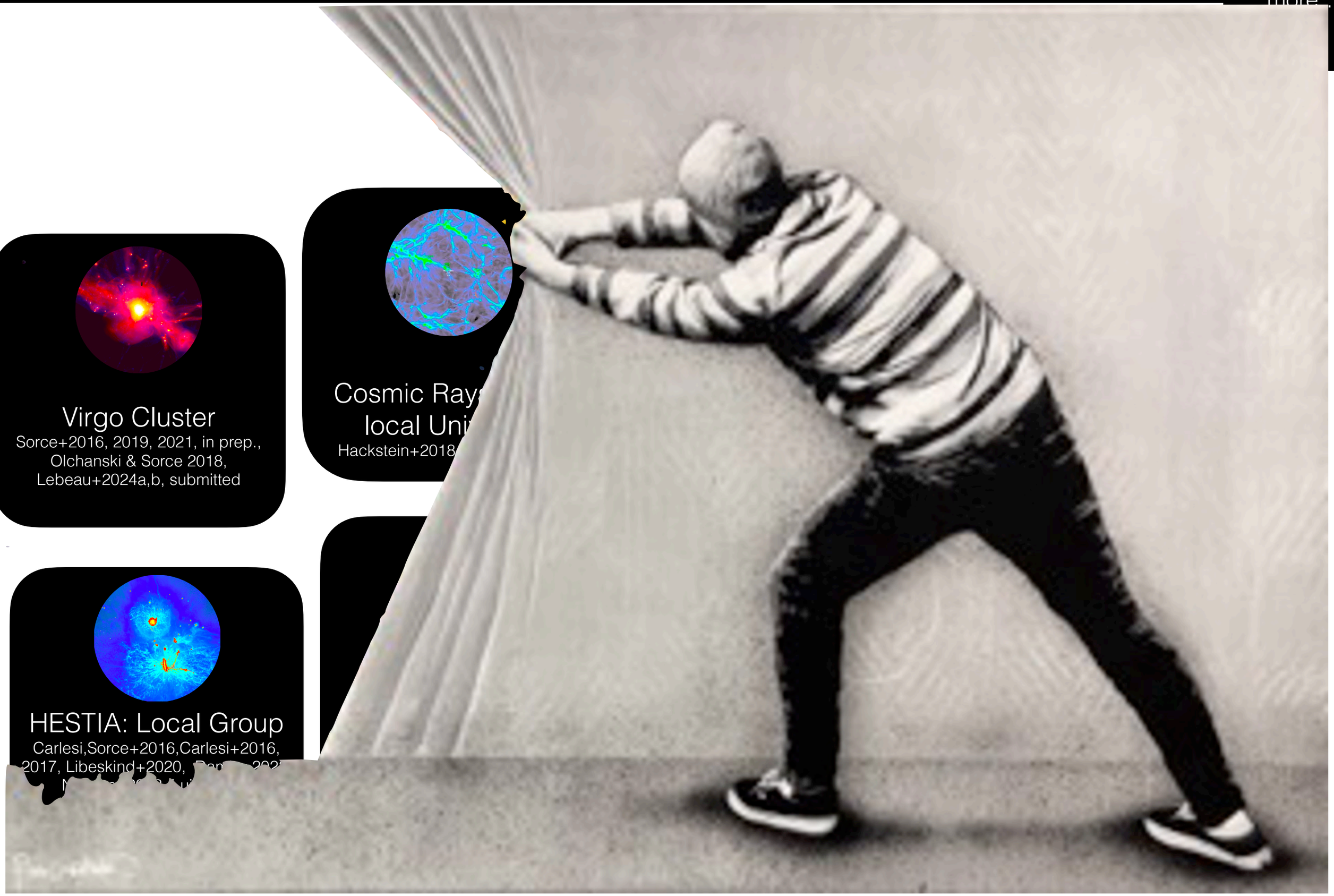


Compressive solenoidal Solenoidal compressive



Multiple learnings from CLONES

and more...



Virgo Cluster

Sorce+2016, 2019, 2021, in prep., Olchanski & Sorce 2018, Lebeau+2024a,b, submitted

Cosmic Rays local Uni

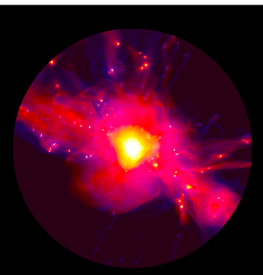
Hackstein+2018

HESTIA: Local Group

Carlesi,Sorce+2016,Carlesi+2016, 2017, Libeskind+2020,

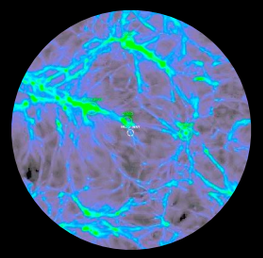
Multiple learnings from CLONES

and more…



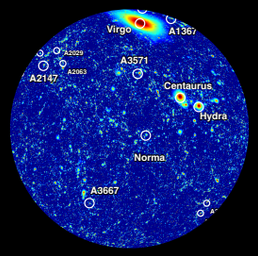
Virgo Cluster

Sorce+2016, 2019, 2021, in prep., Olchanski & Sorce 2018, Lebeau+2024a,b, submitted



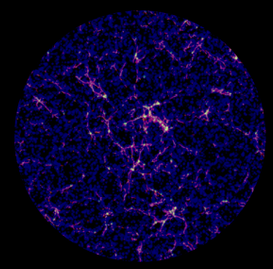
Cosmic Rays in the local Universe

Hackstein+2018, Boess+ 2024



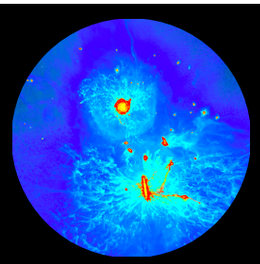
SLOW: local web

Dolag, Sorce+2023, Hernandez+2024, Seidel+submitted, Jung+2024, Sommer+2024



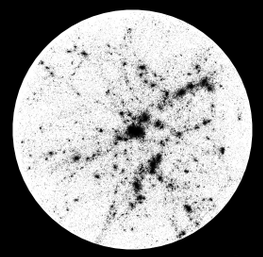
LOCALIZATION: local cluster signatures

Sorce+ in prep.



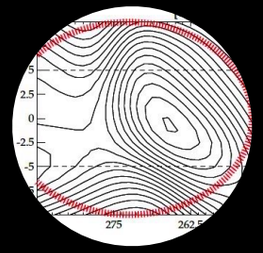
HESTIA: Local Group

Carlesi,Sorce+2016,Carlesi+2016, 2017, Libeskind+2020, Damle+2022, Newton+2023, Luis+2022, Dupuy+2022, Arora+2022, Khoperskov+2022a,b,c, Osipova+2023



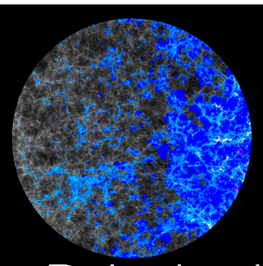
Coma connectivity & Distorsion in Hubble diagram

Malavasi, Sorce+ 2023 Sorce+2024



Zone of Avoidance

Sorce+2017



CoDa: Reionization of the local Universe

Ocvirk+2020, sub. Lewis+2020,2022, Gronke+2021, Sorce+2022, Park+2022, sub., Dawoodbhoy+2023, Iliev+sub., Ziegler+sub.

Conclusion

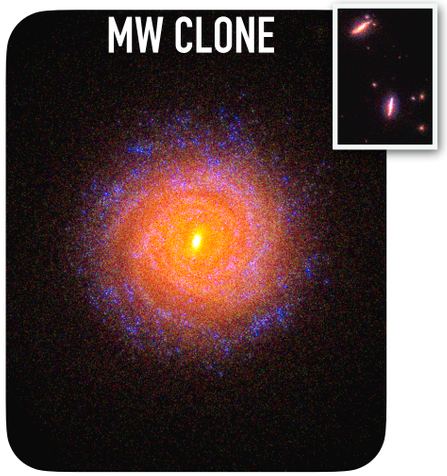
- **Standard** cosmological simulations give only the full uncertainty

- **Constrained** cosmological simulations permit **bias-free inference**

- **CLONES are constrained** cosmological simulations valid down to the cluster scales with induced smaller scales

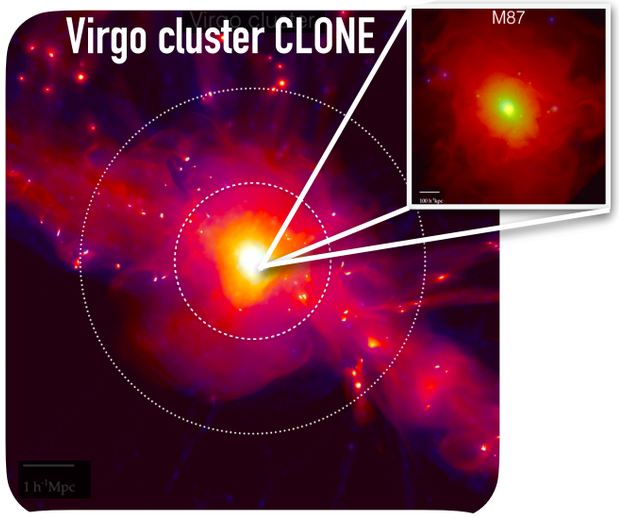
Galaxy

30Mcpu.h
100 Mpc/h,
4096^3 particles
effective (5 Mpc/h zoom),
340 pc



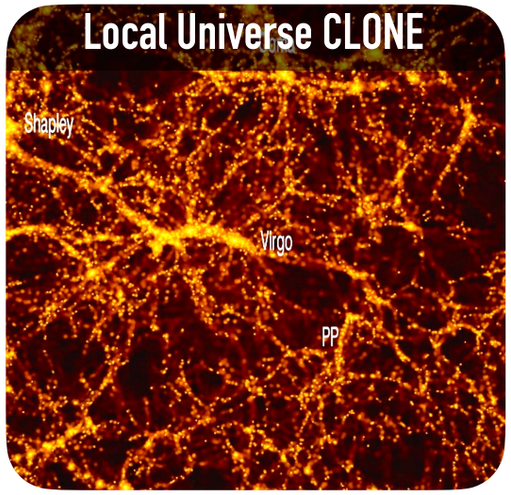
Cluster

6 Mcpu.h
500 Mpc/h,
8192^3 particles
effective (30 Mpc/h zoom),
300 pc



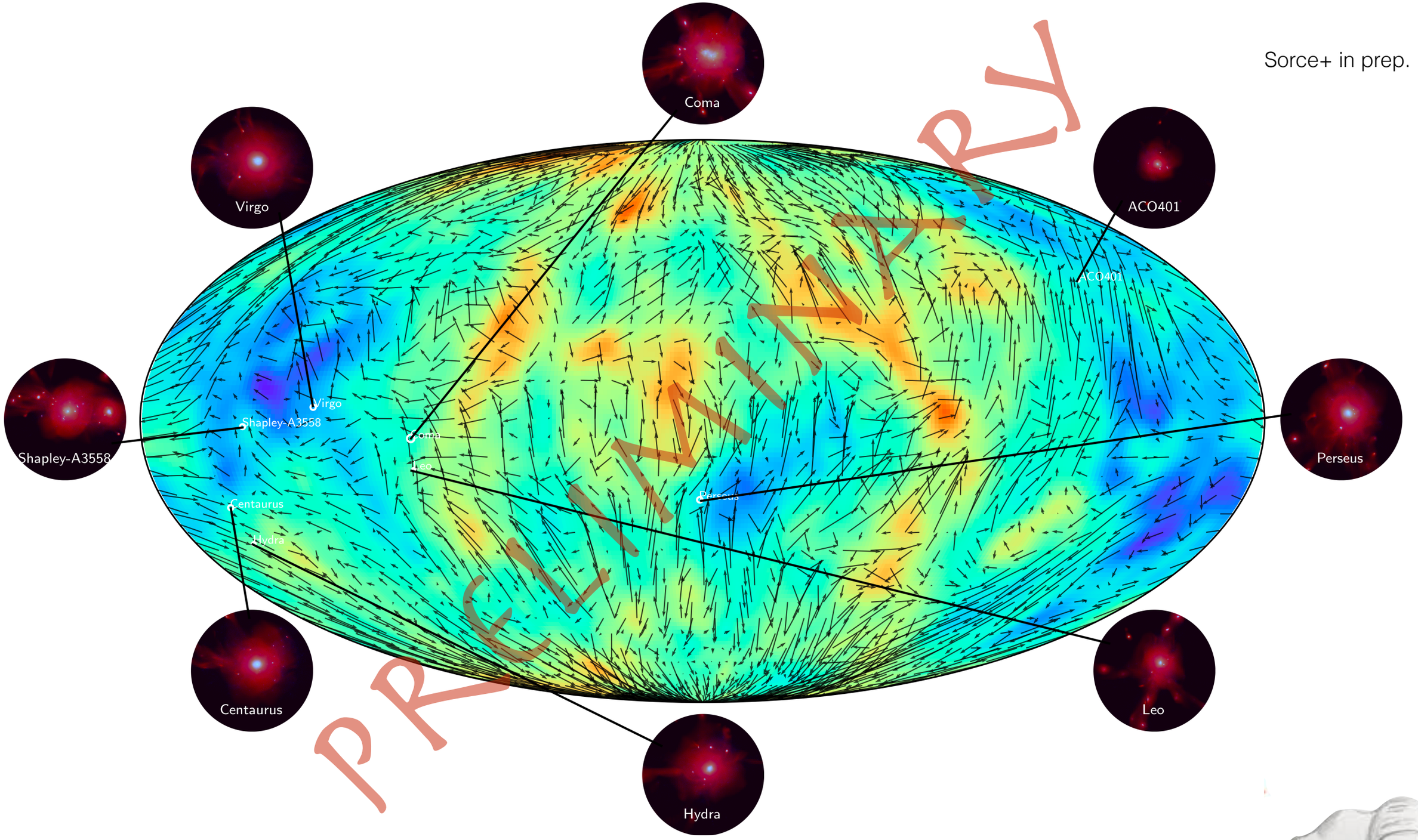
LSS

50 Mcpu.h
500 Mpc/h,
2048^3 particles,
1.9 kpc/h



Perspectives

Sorce+ in prep.



New hydro twin to be released stay tuned

other twins already available and maybe your are the next users !

Thank you, Merci, Grazie,
Gracias, Danke, ευχαριστώ
Mahalo, 谢谢, ありがとう, Дякую,
תודה, спаси́бо, Obrigada, Dank u,
Tak, Cảm ơn, Dziękuję, 감사합니다
Kiitos, Aitäh, diolch, dankewol,
ಧನ್ಯವಾದಗಳು, شكرًا, …*

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