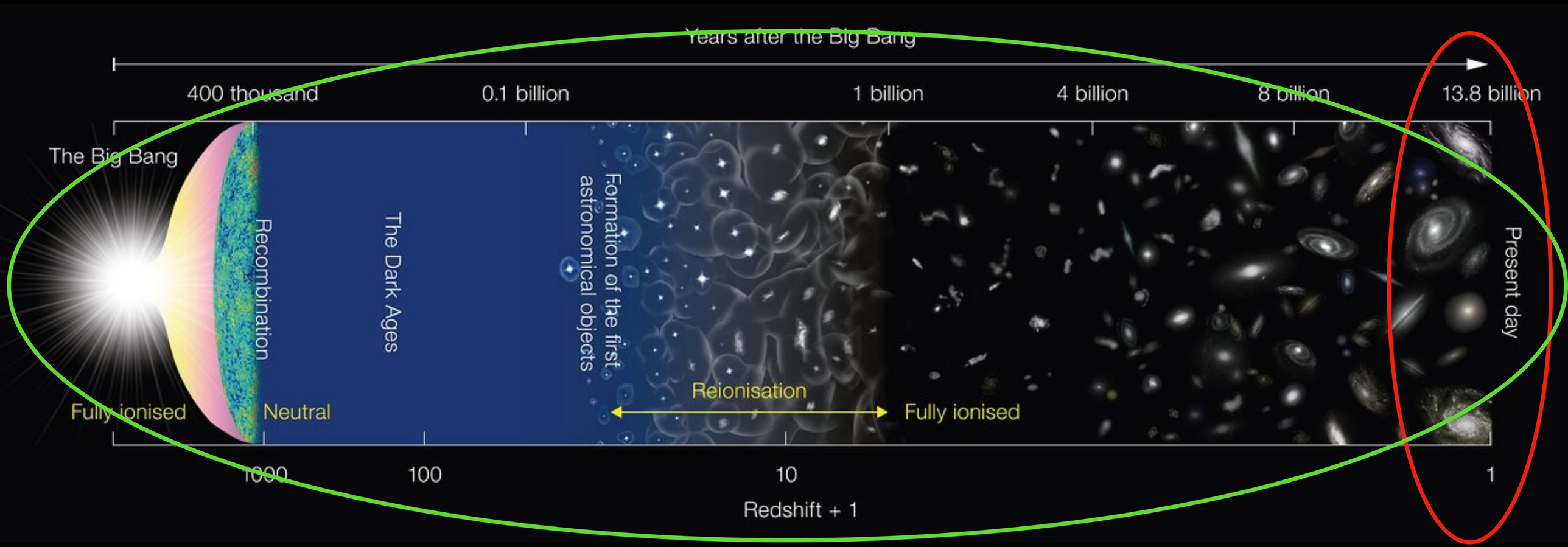
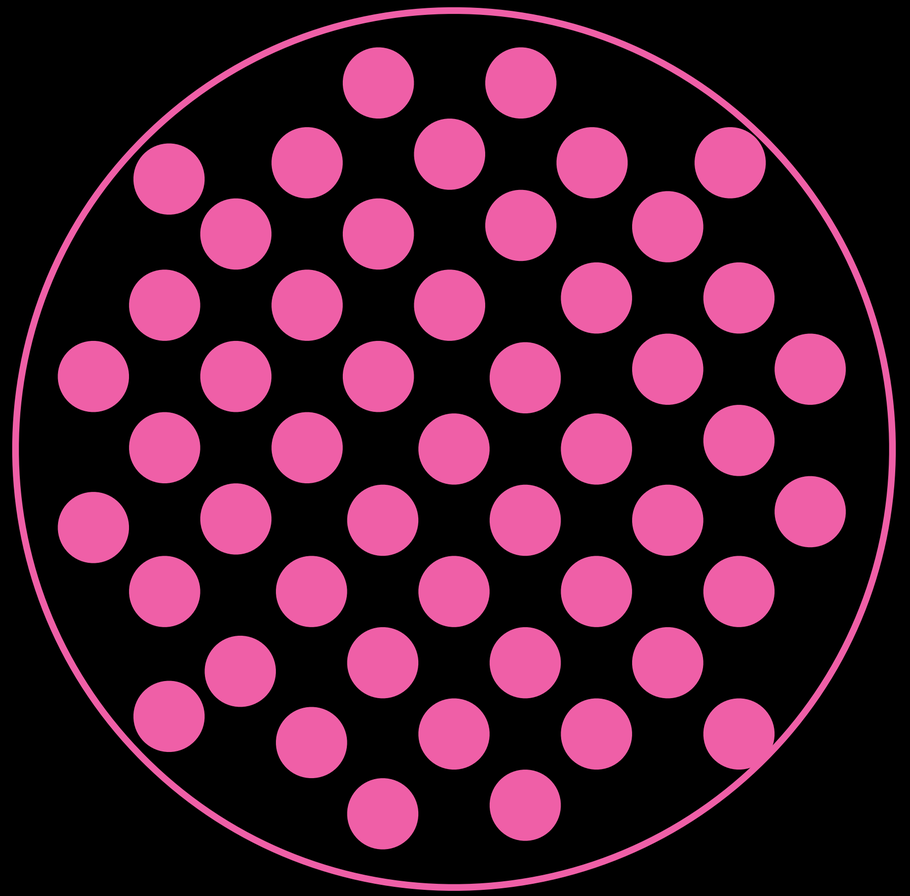


Image: National Observatory of Japan /EOS

The Cosmological Principle

On large scales, the Universe is homogeneous *and* isotropic



(Ignore the edge)

The Universe is flat (Euclidean)

Parallel lines meet

Angles in triangle add up to > 180 degrees

Closed

Parallel lines diverge

Angles in triangle add up to < 180 degrees

Open

Parallel lines remain equidistant, never meet

Angles in triangle add up to = 180 degrees

Flat

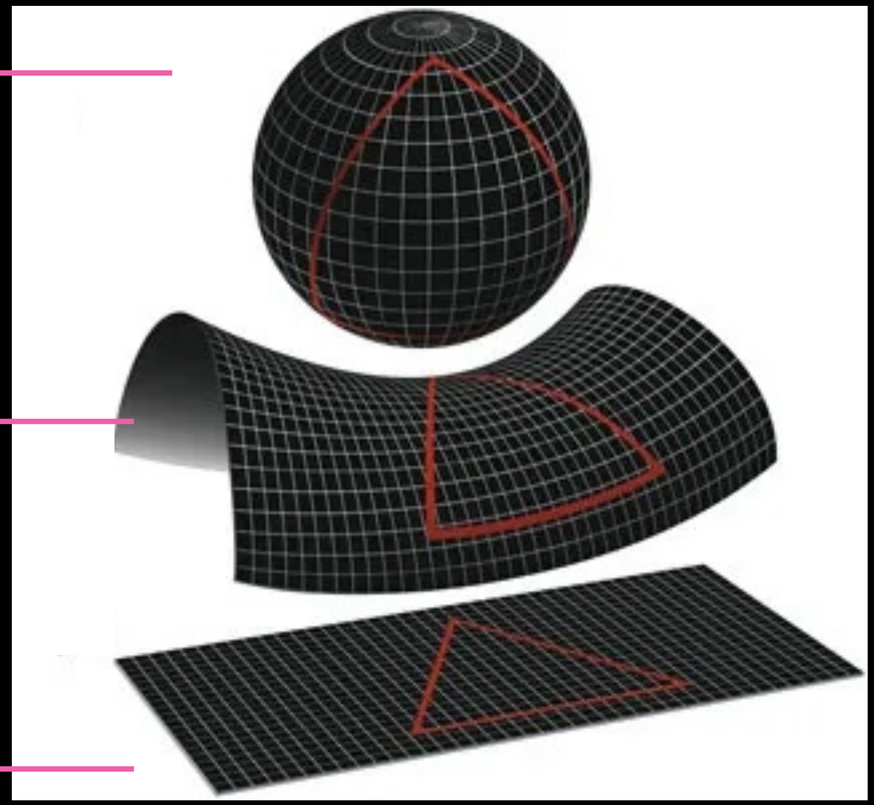
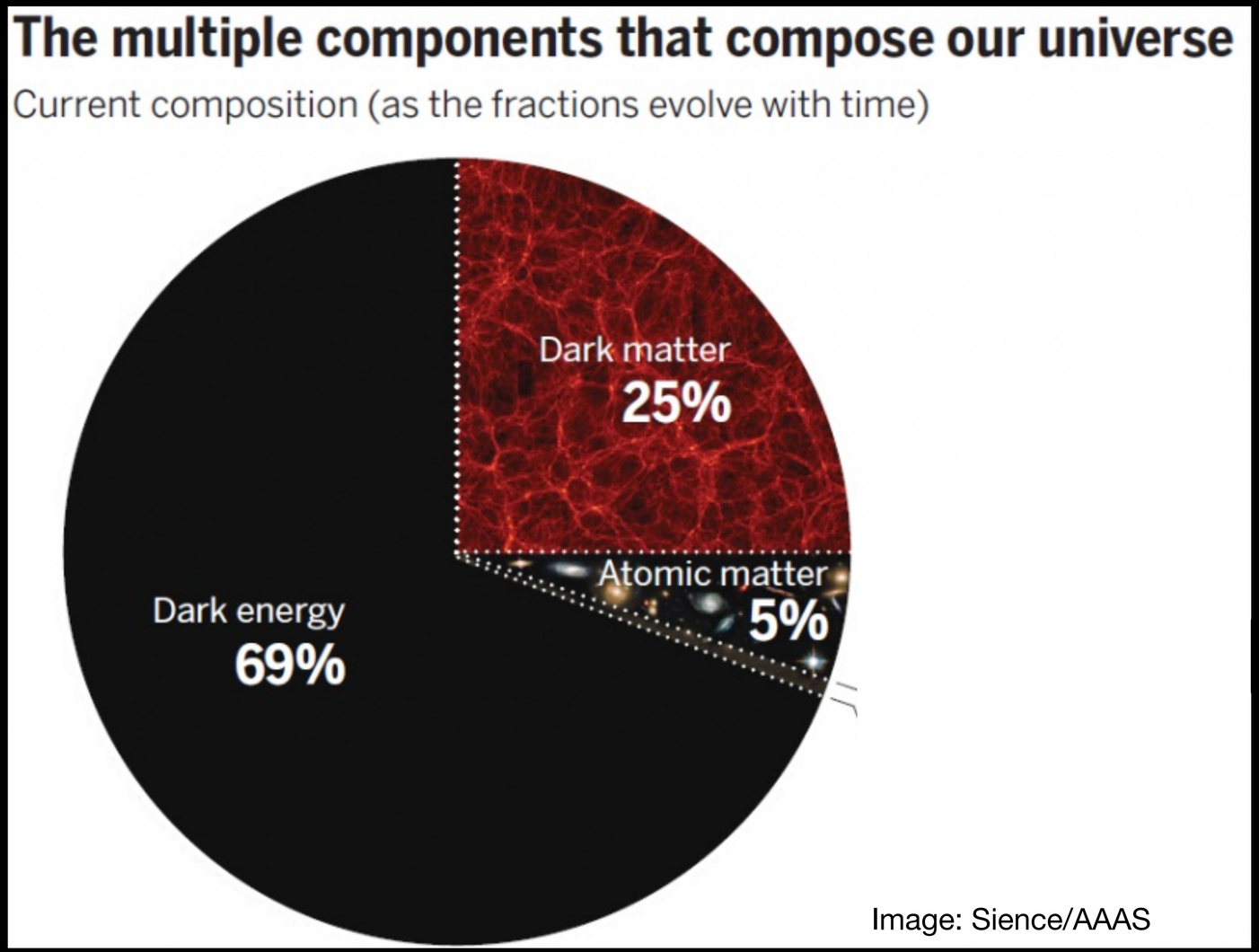


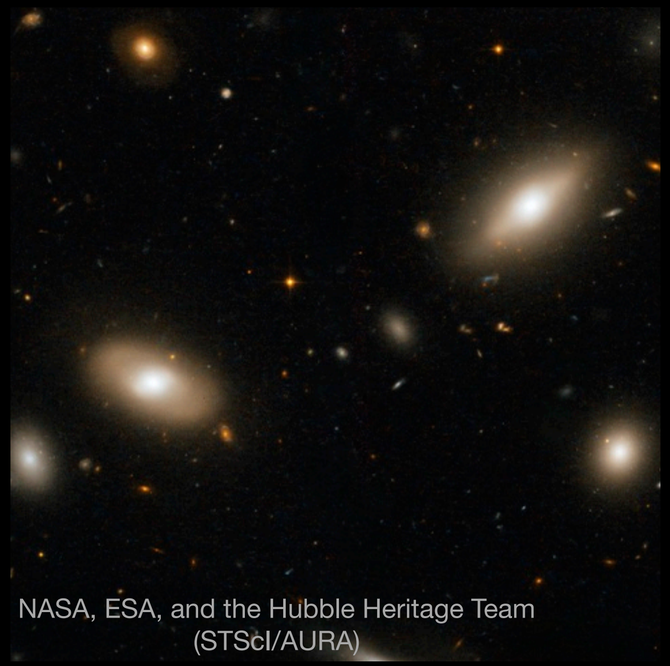
Image: NASA

Composition of our Universe



Matter in the Universe

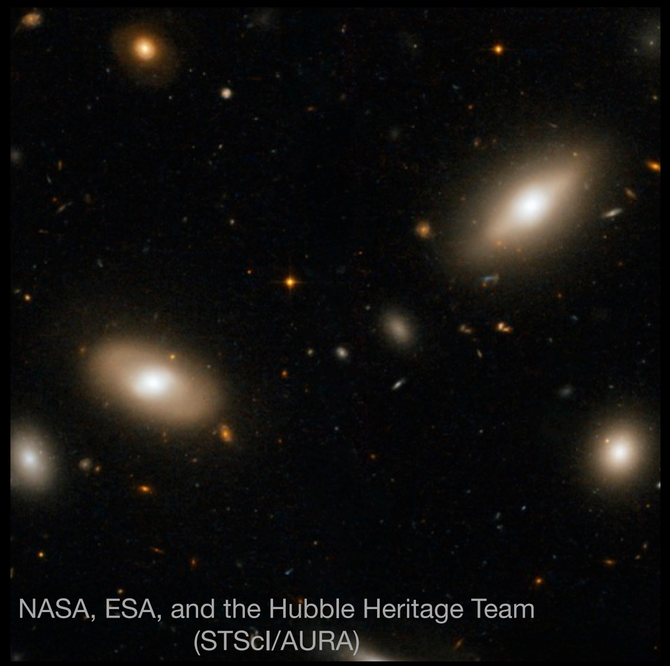
Matter in the Universe is made of baryonic matter *and* dark matter



NASA, ESA, and the Hubble Heritage Team
(STScI/AURA)

Matter in the Universe

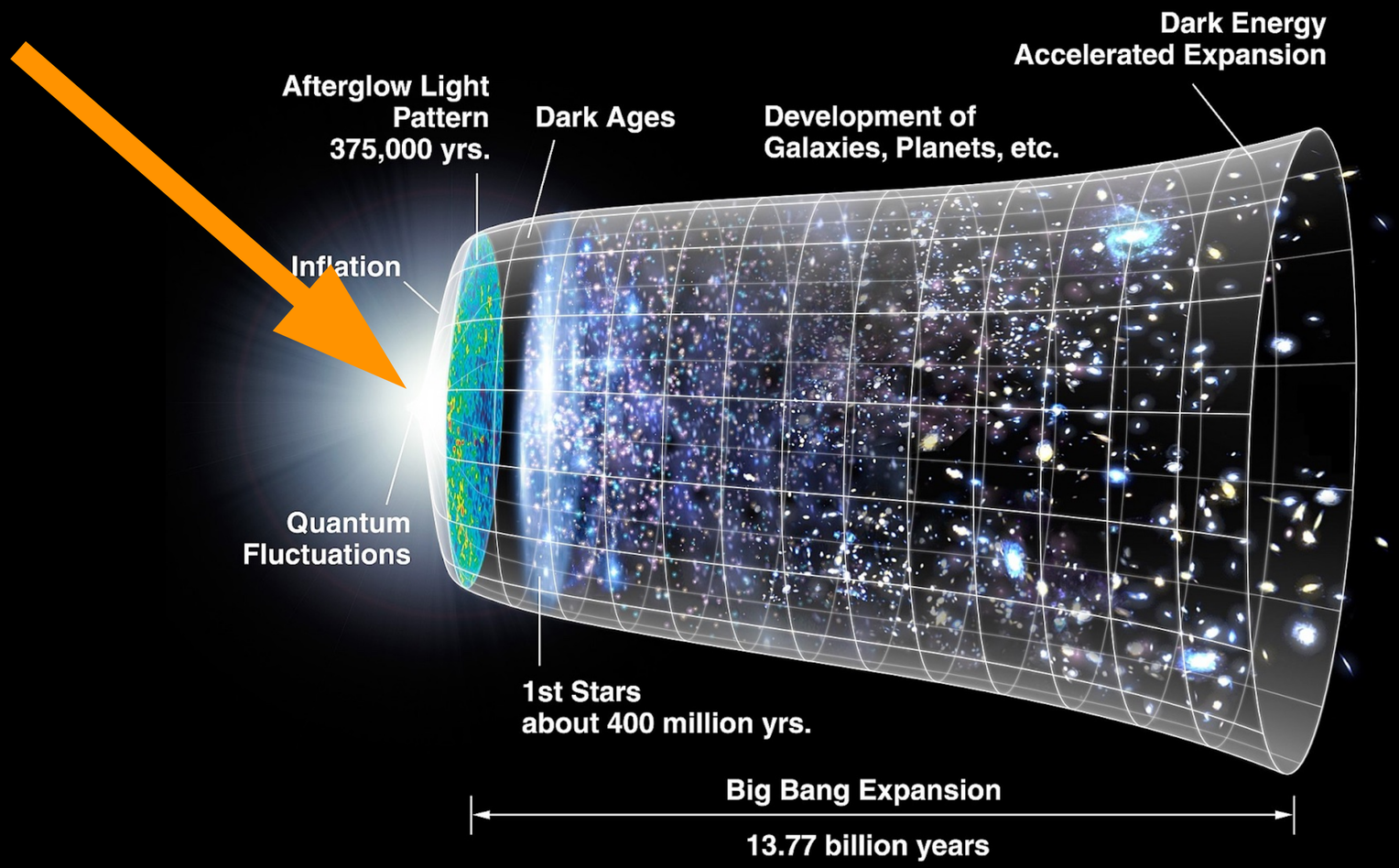
Baryons are what we can see as gas, stars, galaxies, (ordinary or atomic matter)



NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

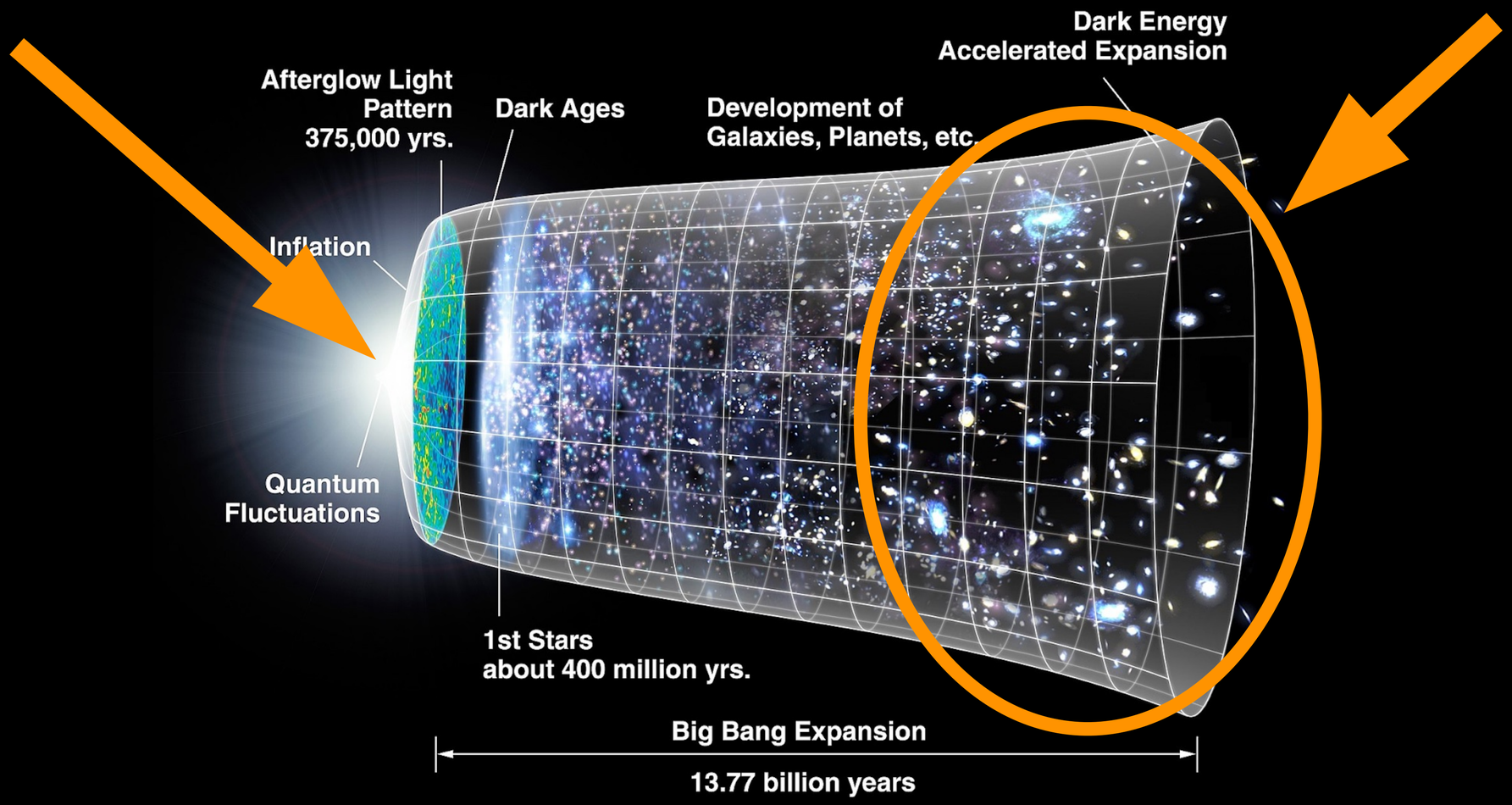
Dark matter is an unseen material only known by its gravitational effects.

Tiny fluctuations here…



Tiny fluctuations here…

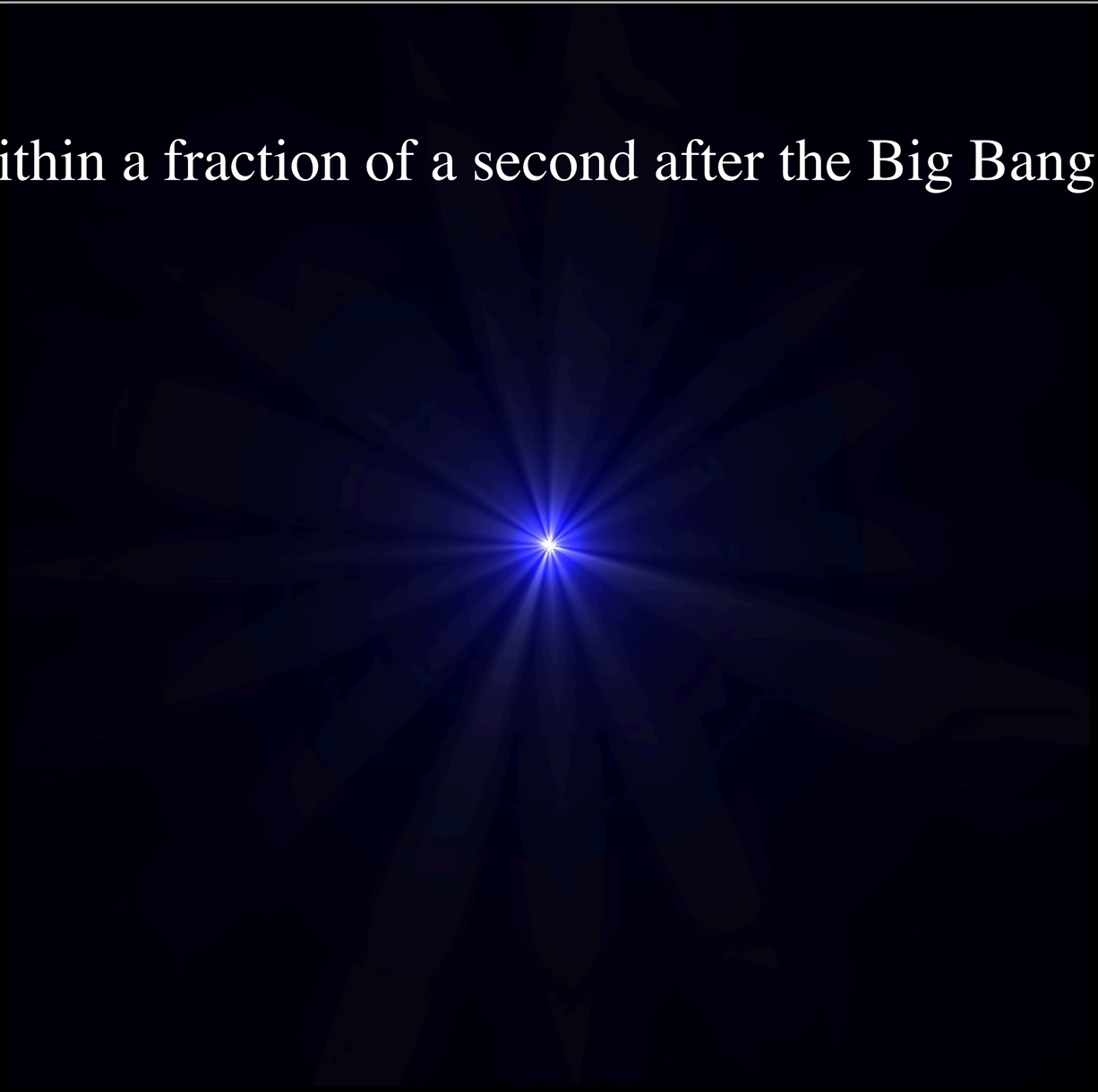
Large-scale structure today



The Large-Scale Structure: A very brief history

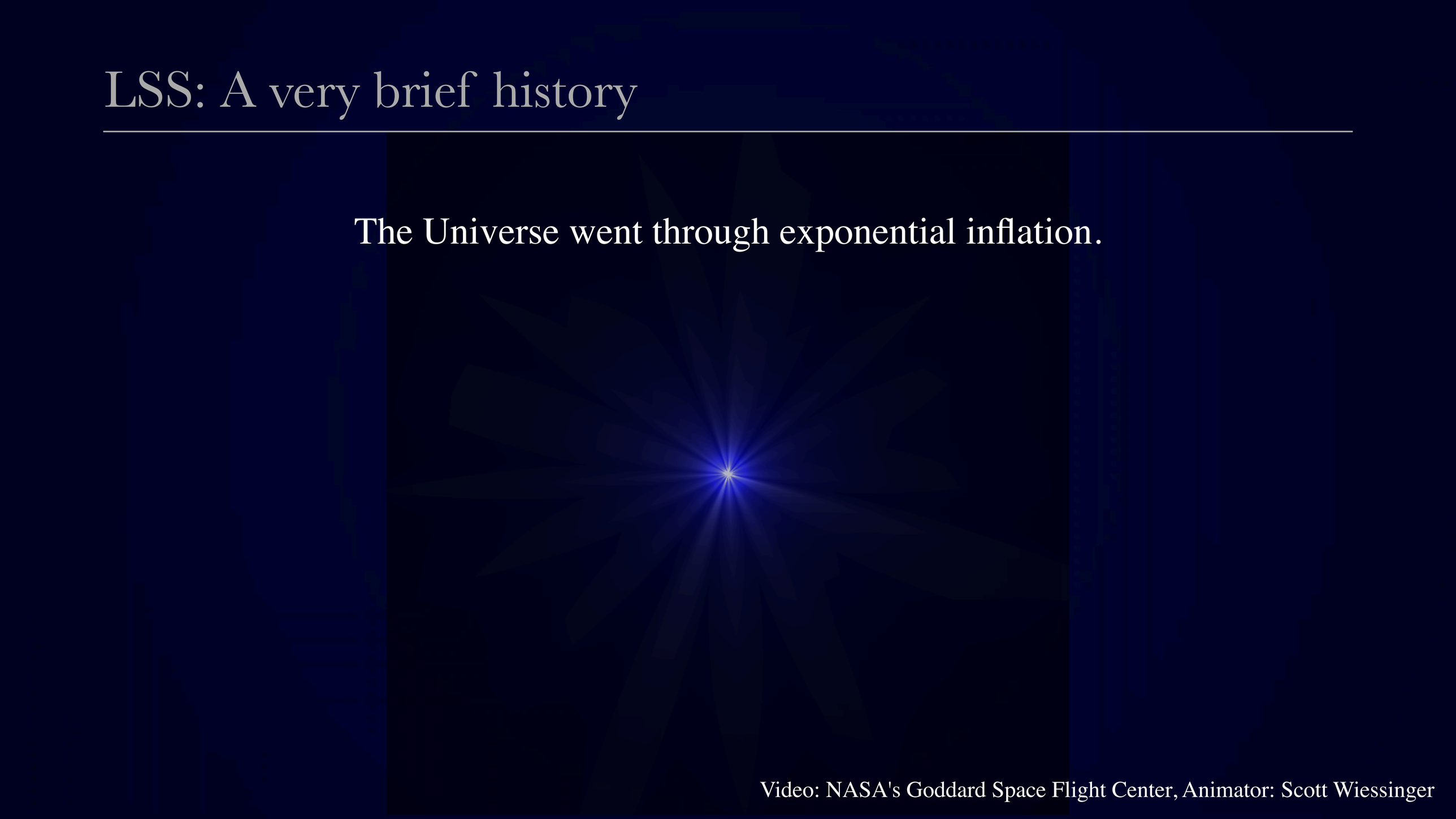
LSS: A very brief history

Within a fraction of a second after the Big Bang…



LSS: A very brief history

The Universe went through exponential inflation.



Video: NASA's Goddard Space Flight Center, Animator: Scott Wiessinger

LSS: A very brief history

Tiny quantum fluctuations captured by inflation became the seeds for gravity.

Video: NASA's Goddard Space Flight Center, Animator: Scott Wiessinger

LSS: A very brief history

The Universe was an unimaginably hot and dense primordial soup…

Video: NASA's Goddard Space Flight Center, Animator: Scott Wiessinger

LSS: A very brief history

It was so hot that neutral atoms could not form.
Baryons (ordinary matter) and photons were strongly interacting.
(Baryons and photons were “coupled”.)

Video: NASA's Goddard Space Flight Center, Animator: Scott Wiessinger

LSS: A very brief history

Dark matter, however, interacts only gravitationally.

Video: NASA's Goddard Space Flight Center, Animator: Scott Wiessinger

LSS: A very brief history

A baryon-photon fluid oscillated in a struggle between gravity and radiation…

Video: NASA's Goddard Space Flight Center, Animator: Scott Wiessinger

LSS: A very brief history

Meanwhile, the Universe was very slowly expanding… and cooling…

Video: NASA's Goddard Space Flight Center, Animator: Scott Wiessinger

LSS: A very brief history

… until photons were liberated from baryons.
Neutral atoms could now begin to form.
(Often called the *Time of Decoupling*)

Video: NASA's Goddard Space Flight Center, Animator: Scott Wiessinger

LSS: A very brief history

Without radiation pressure from photons the waves stalled and froze in place.
Fluctuations due to gravity began to grow against an expanding background.

Video: NASA's Goddard Space Flight Center, Animator: Scott Wiessinger

LSS: A very brief history

Neutral hydrogen was free to be attracted to the gravity of dark matter, cool and form stars.

Video: NASA's Goddard Space Flight Center, Animator: Scott Wiessinger

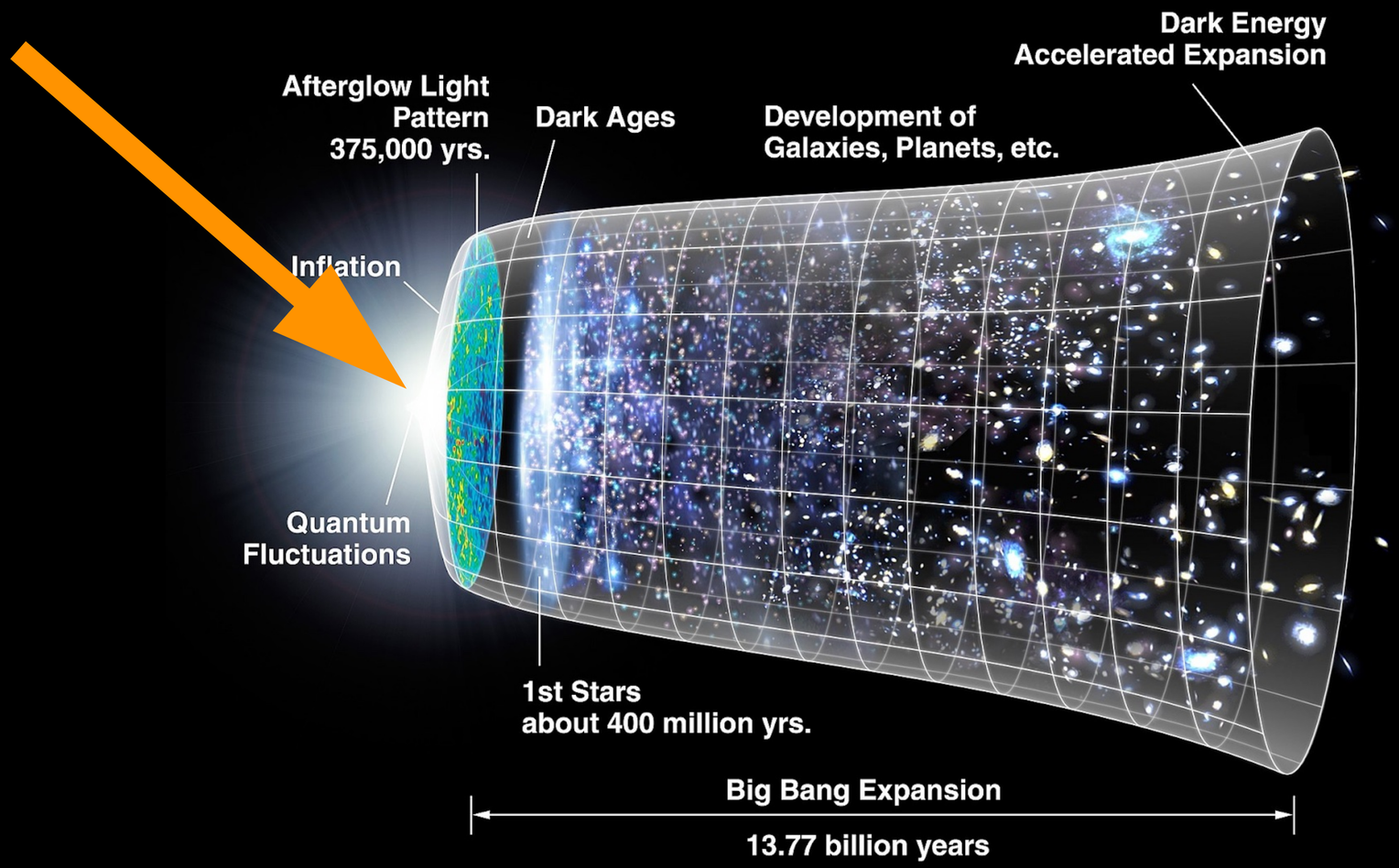
LSS: A very brief history

Fast forward 13.8 billion years later and we see a Universe with a large-scale structure traced by galaxies.

Video: NASA's Goddard Space Flight Center, Animator: Scott Wiessinger

LSS: A very brief history

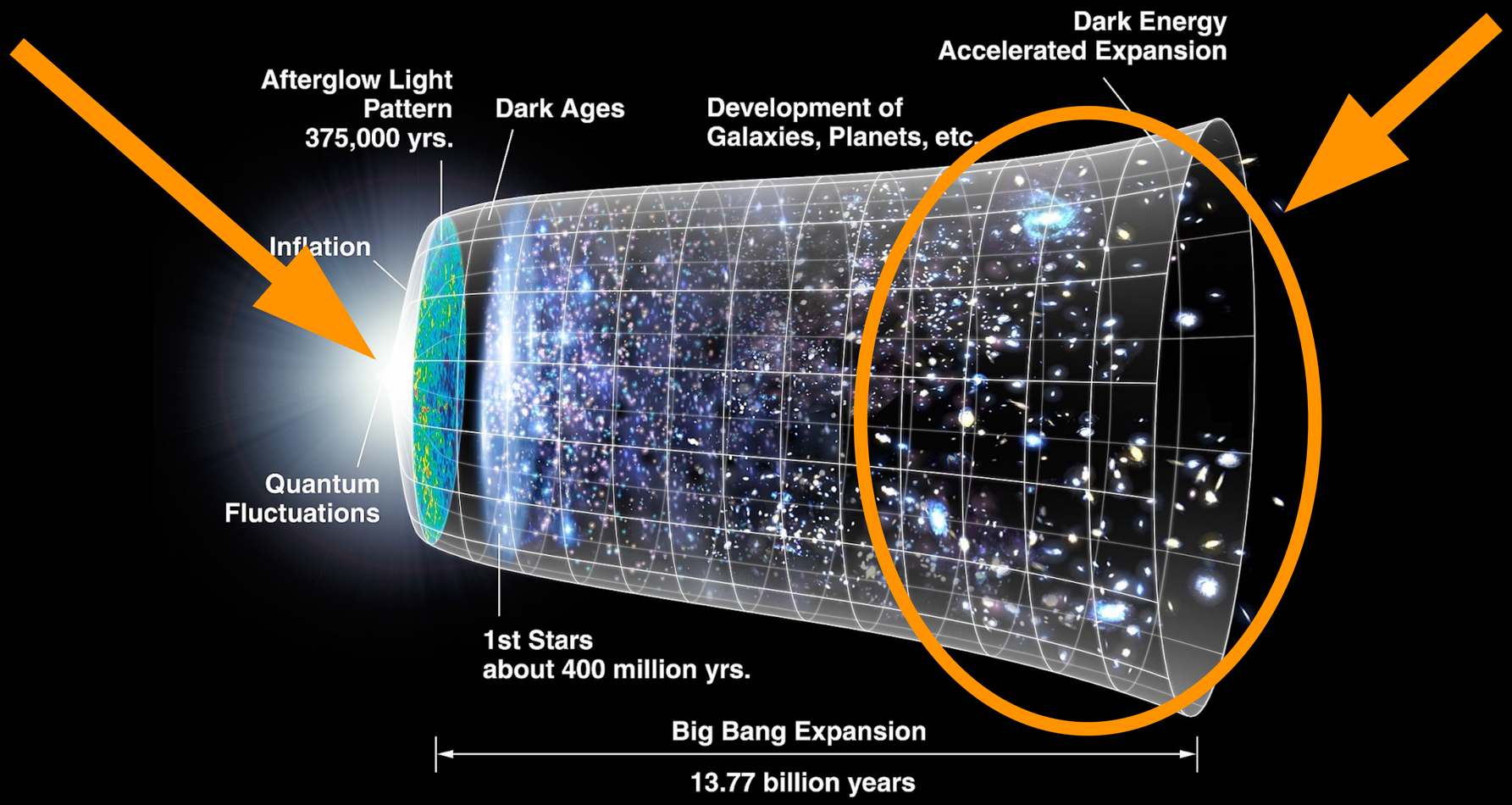
Tiny fluctuations here…



LSS: A very brief history

Tiny fluctuations here…

Large-scale structure today



LSS: A very brief history

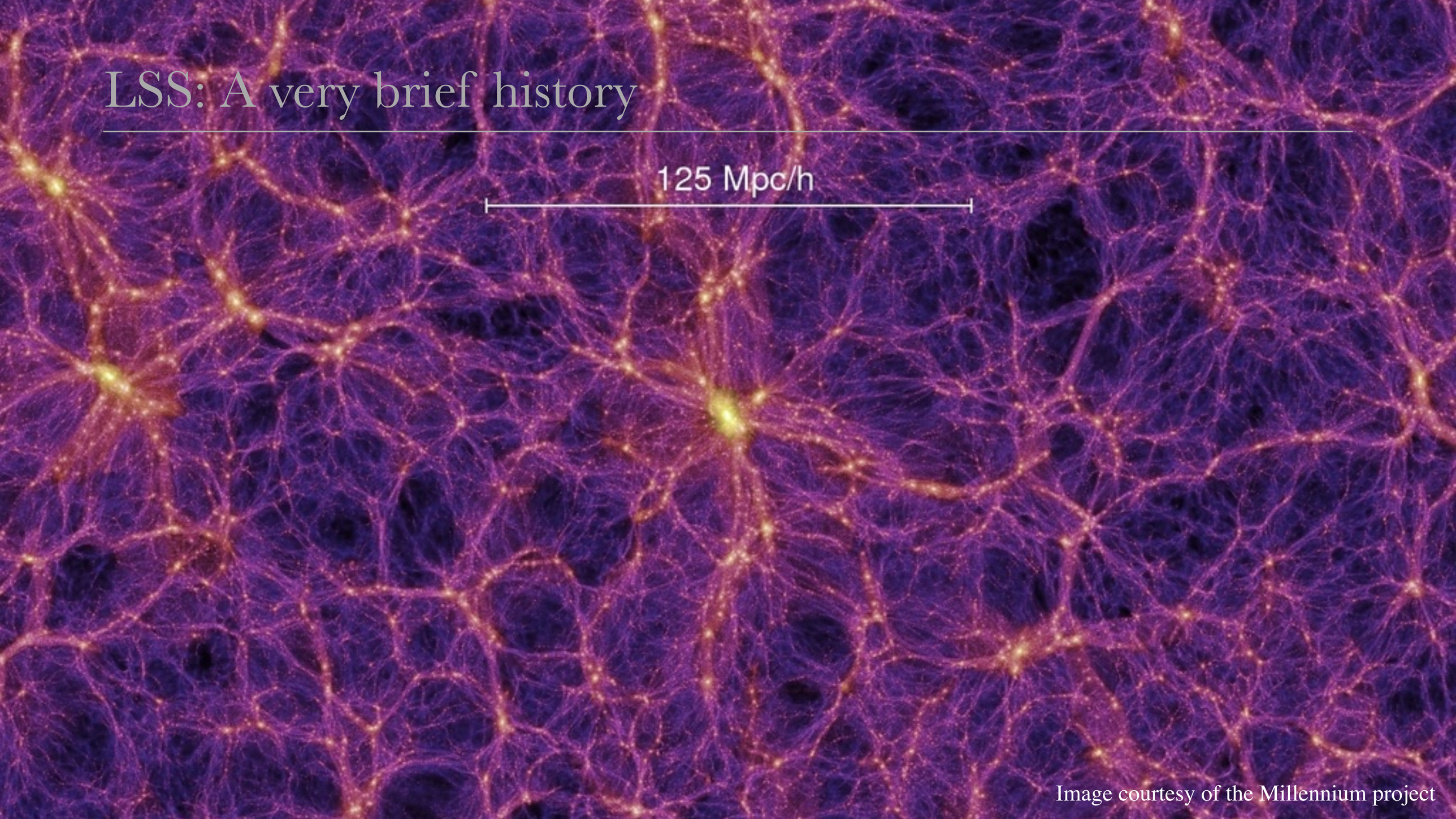


Image courtesy of the Millennium project

LSS: A very brief history

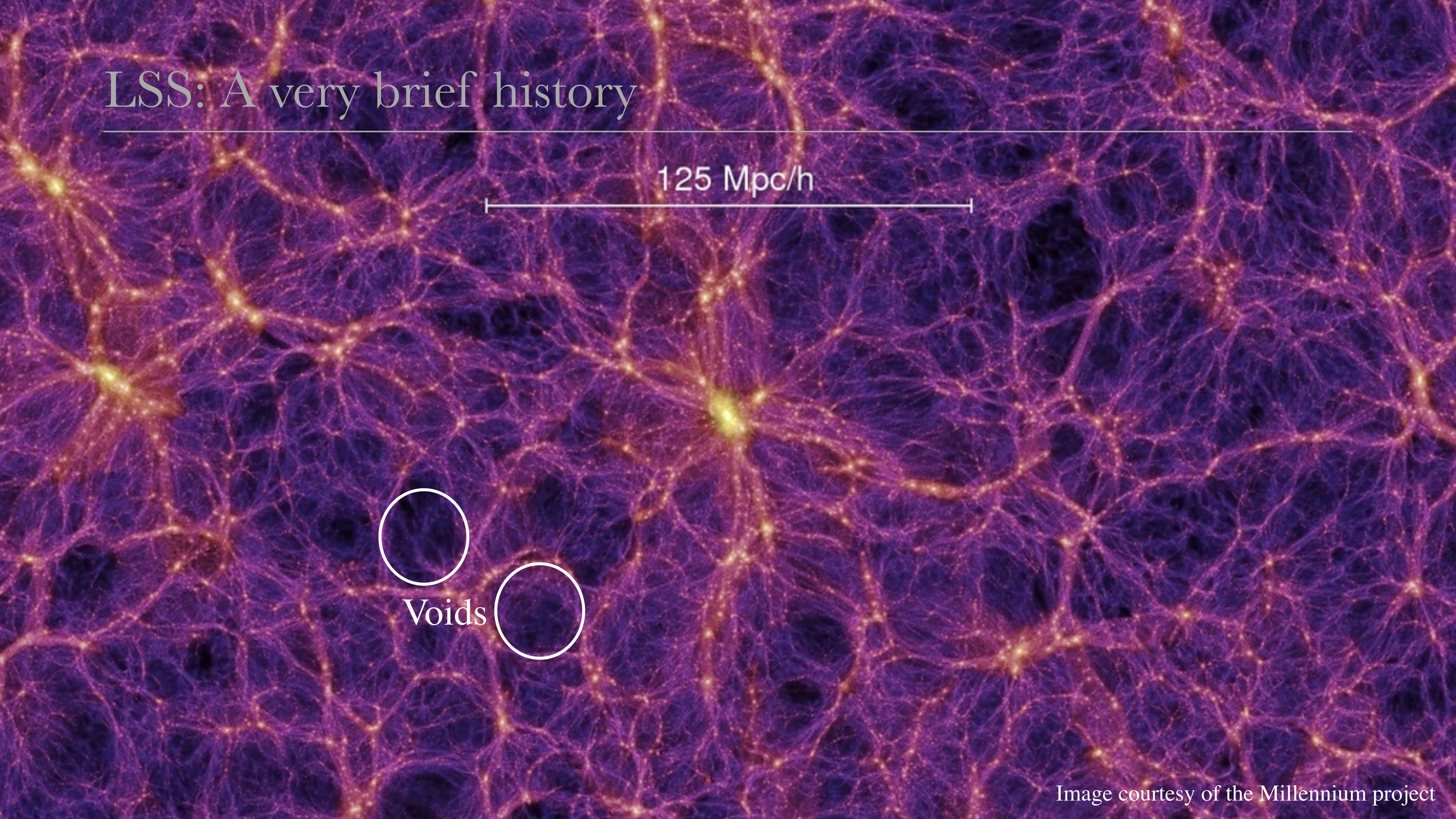


Image courtesy of the Millennium project

LSS: A very brief history

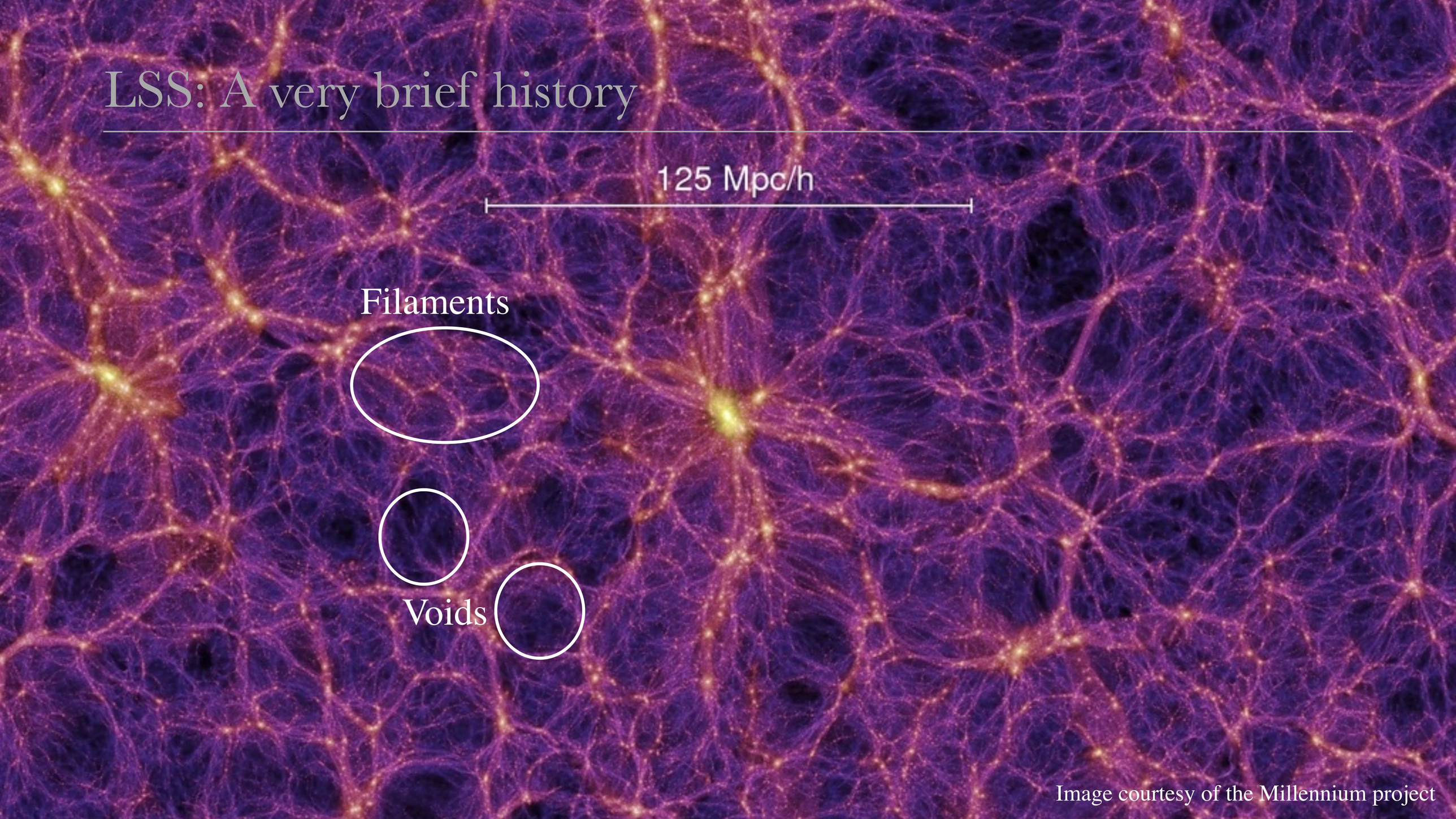


Image courtesy of the Millennium project

LSS: A very brief history

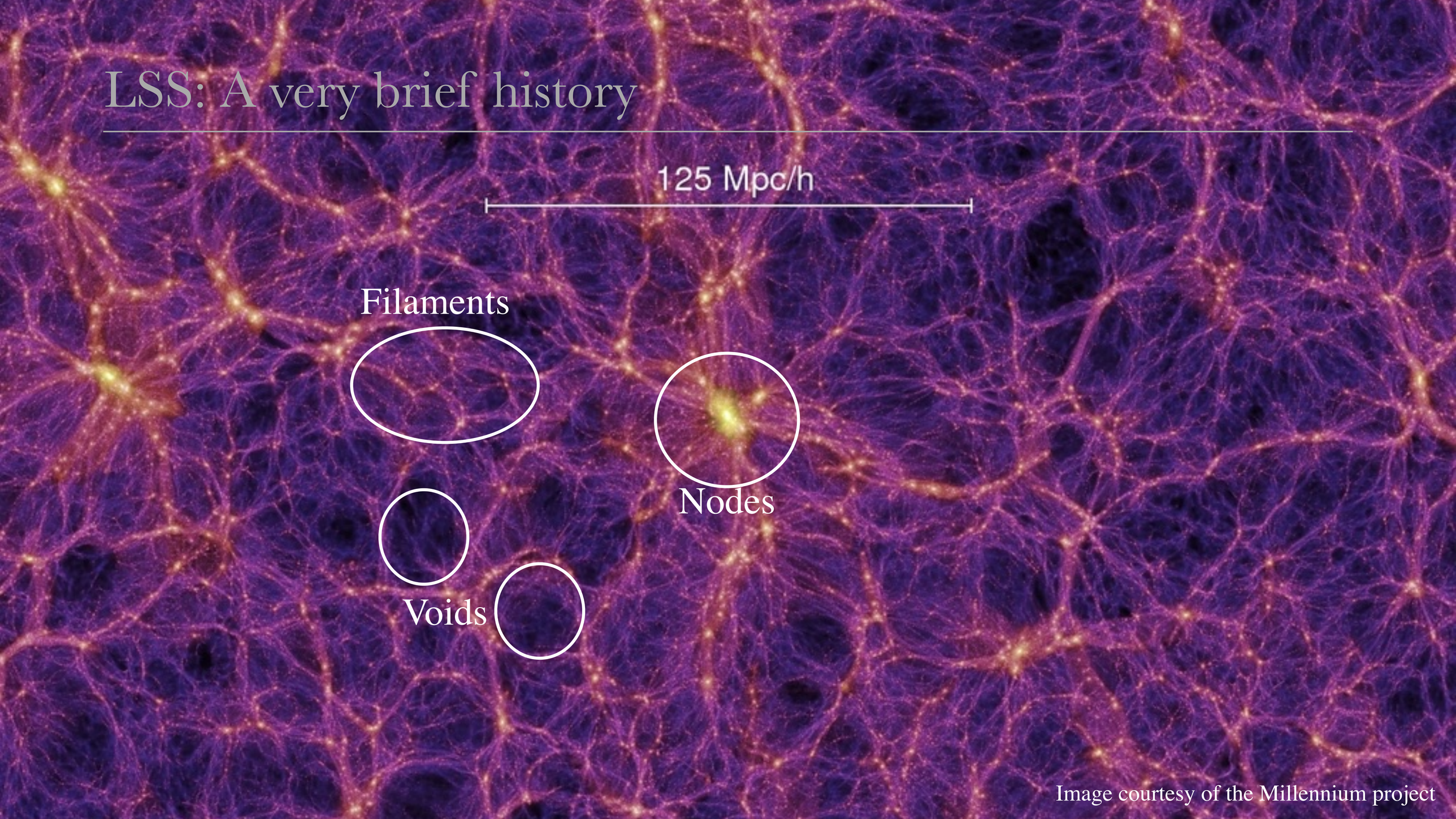


Image courtesy of the Millennium project

LSS: A very brief history

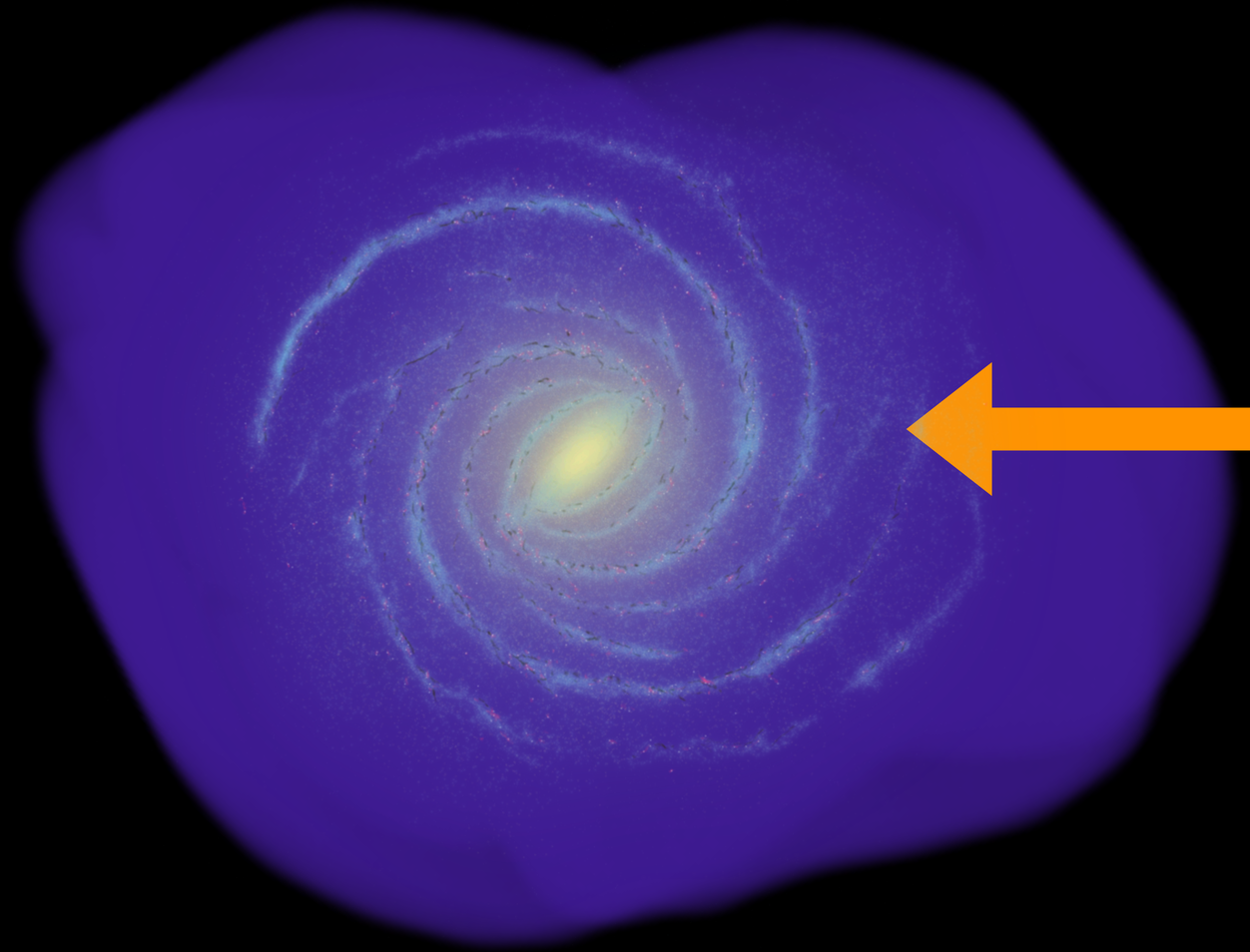
LSS: A very brief history

What happens within the DM Halo?

LSS: A very brief history

Courtesy of IllustrisTNG project

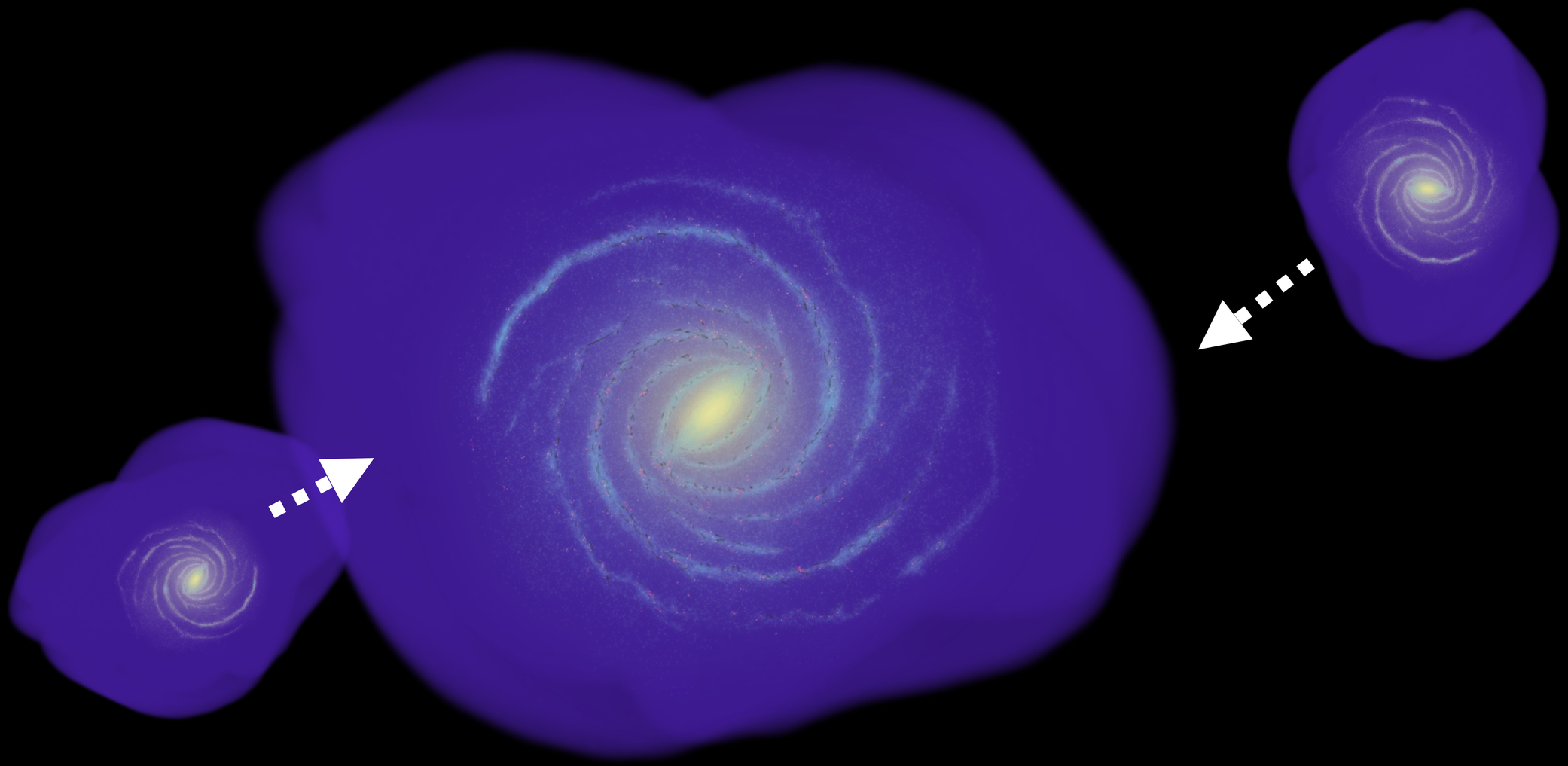
LSS: A very brief history



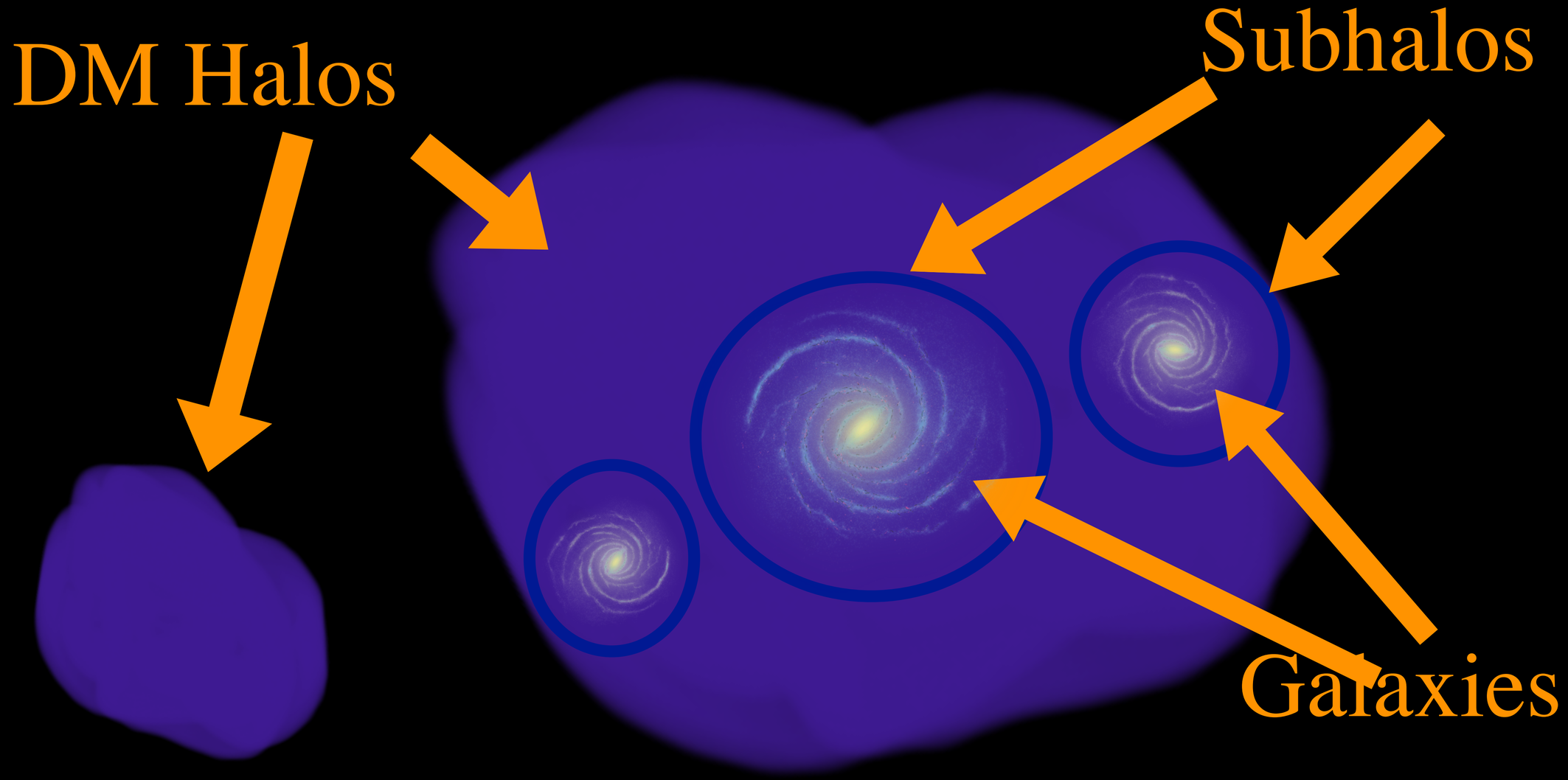
Galaxy

galaxy image: wikimedia

LSS: A very brief history



LSS: A very brief history



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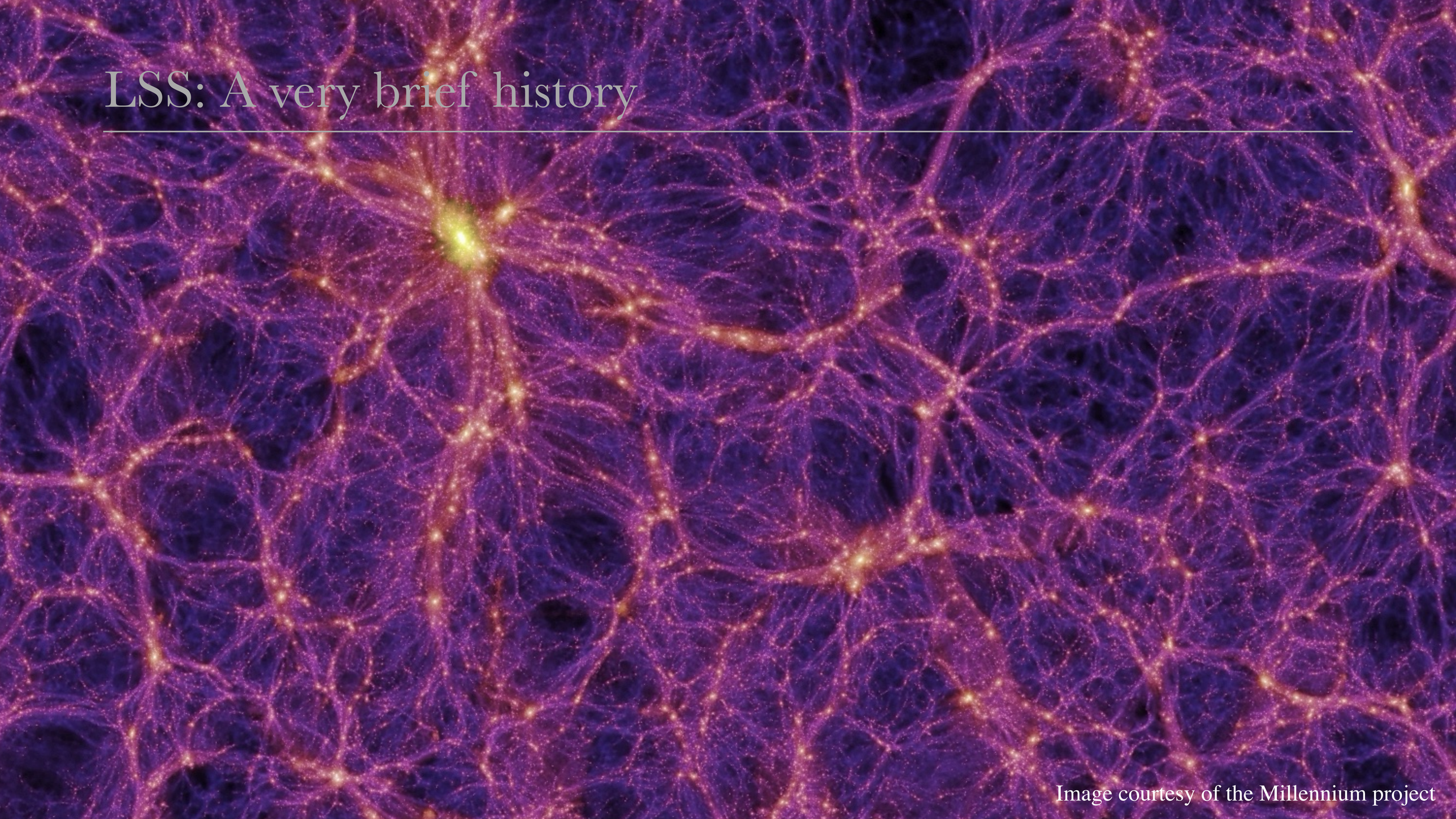


Image courtesy of the Millennium project

LSS: A very brief history

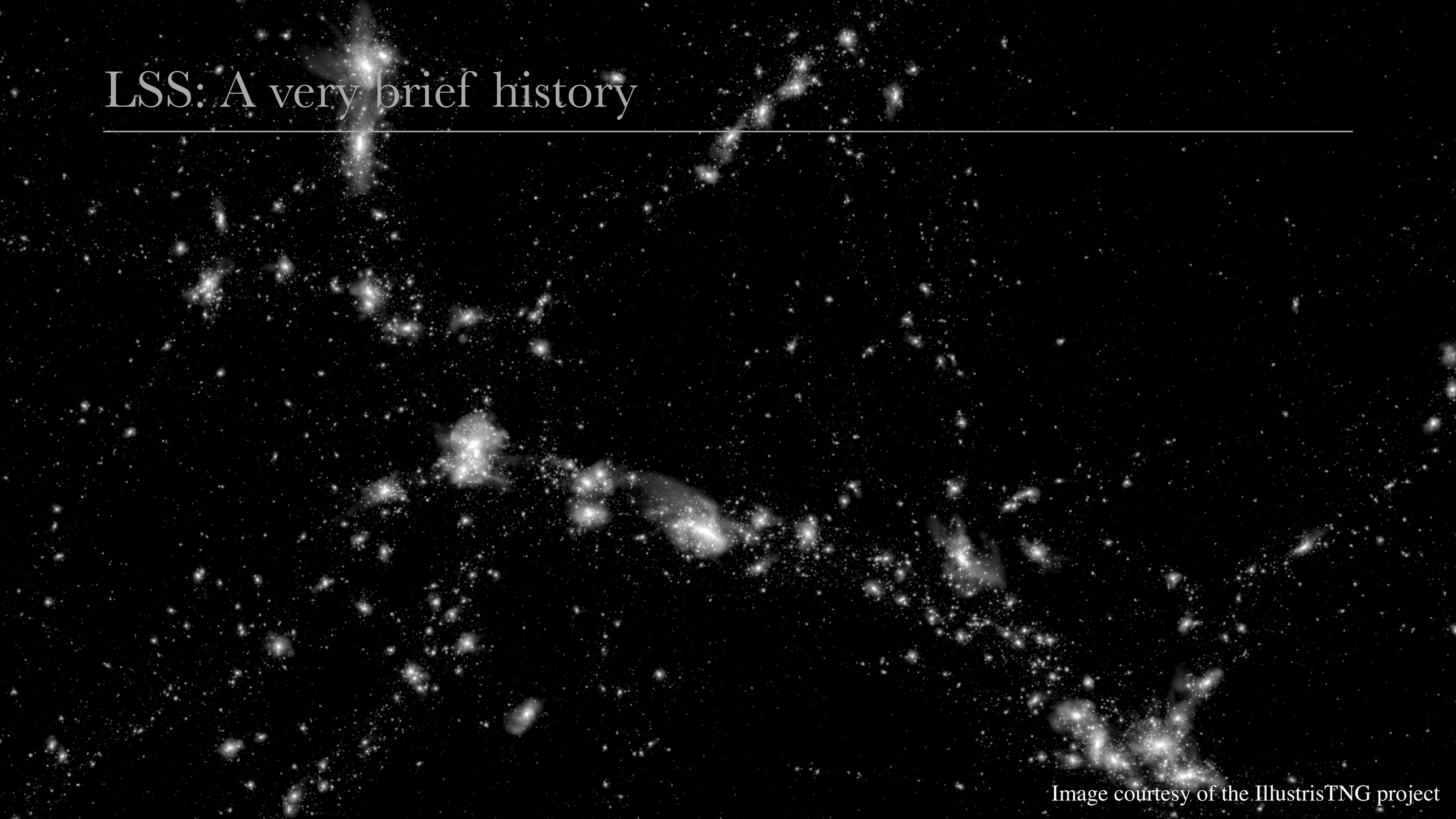


Image courtesy of the IllustrisTNG project

Motivation

We want to unravel the LSS to learn about our origin, evolution and fate.

Motivation

We want to unravel the LSS to learn about our origin, evolution and fate.

We do this by:

1. Mapping galaxies, which allows us to “see” dark matter structure

Mapping galaxies allows us to "see" dark matter structure

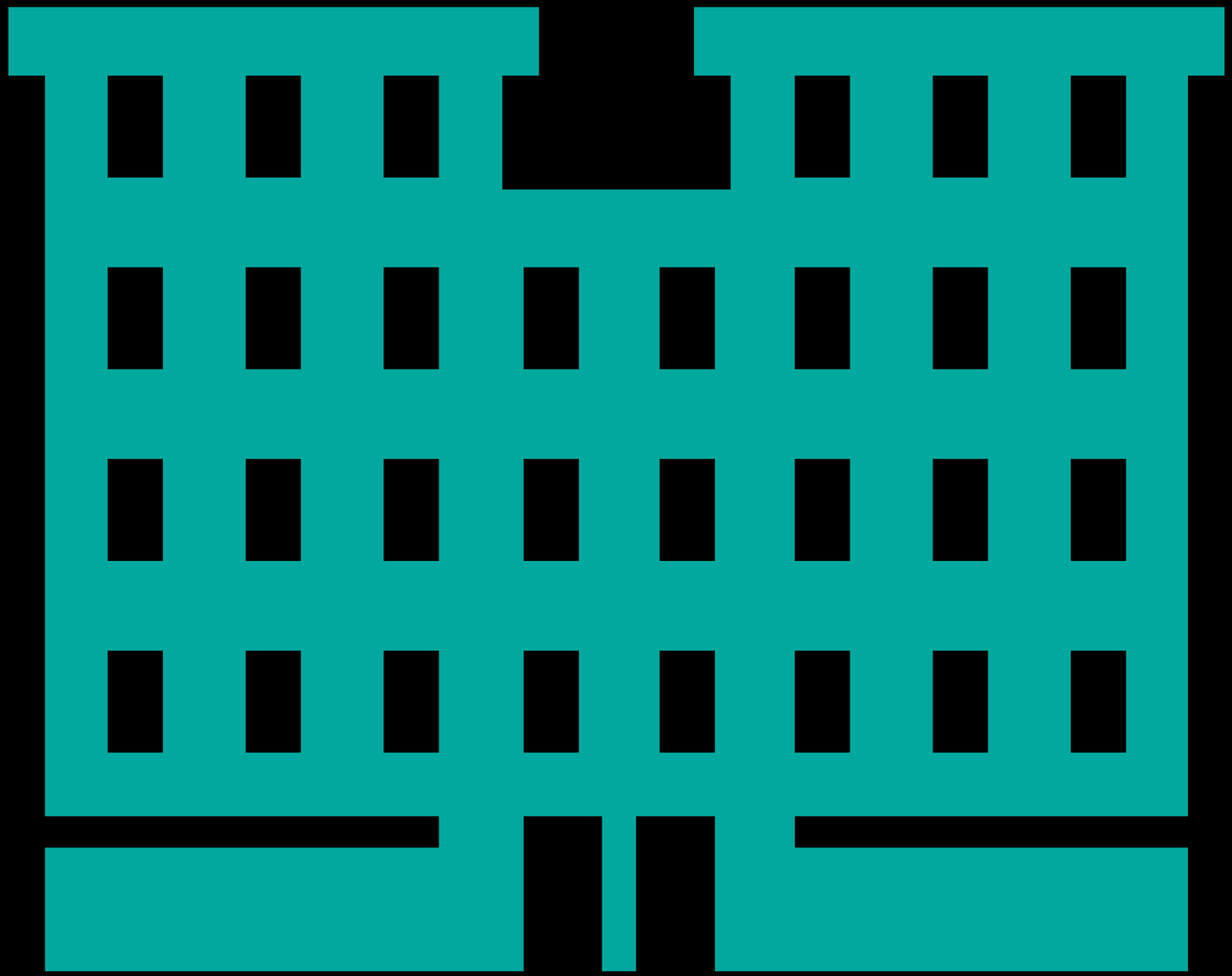
Galaxies don't trace the underlying distribution of dark matter *exactly*.

They are said to be *biased* tracers.

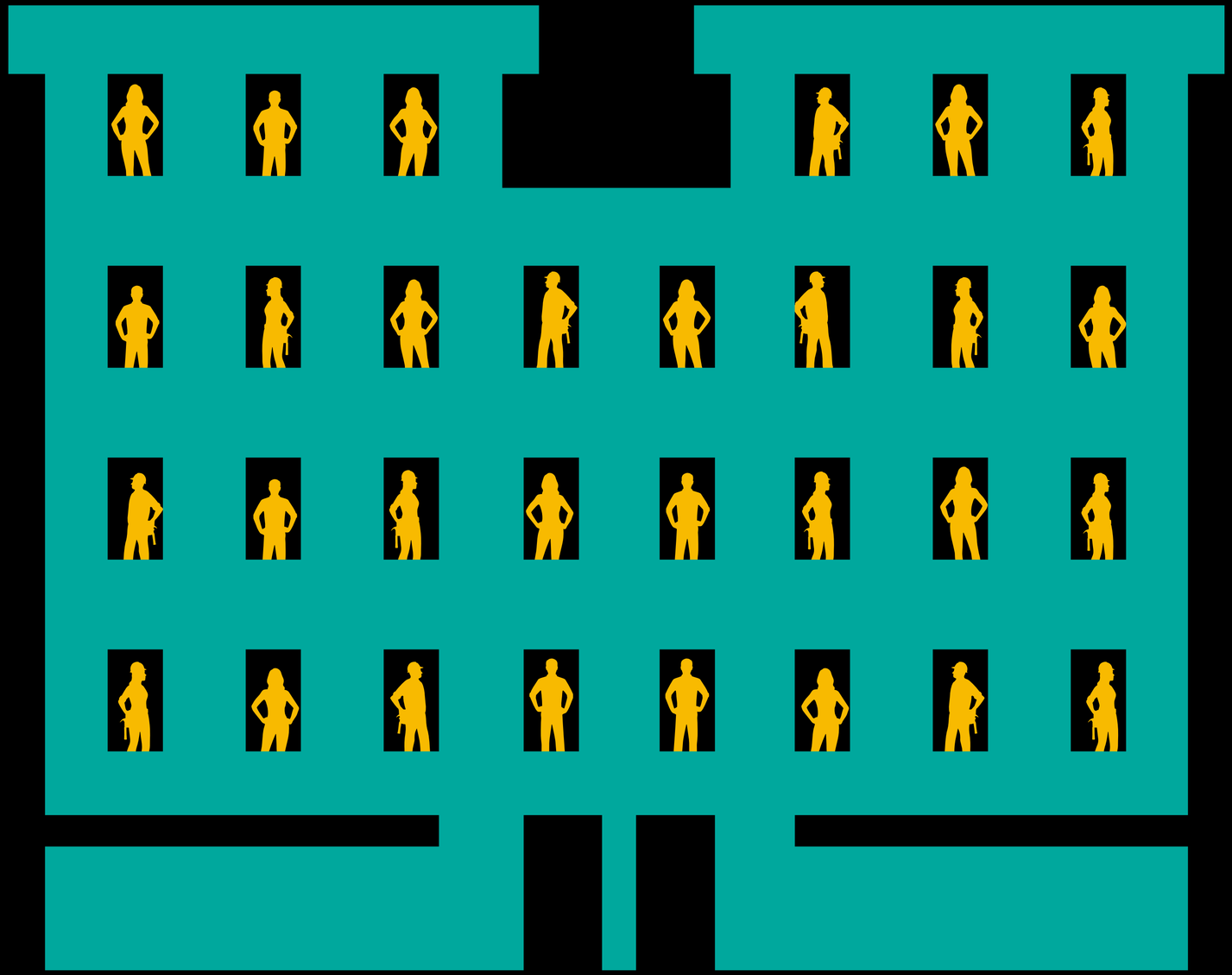
Mapping galaxies allows us to “see” structure

What is a *biased* tracer?

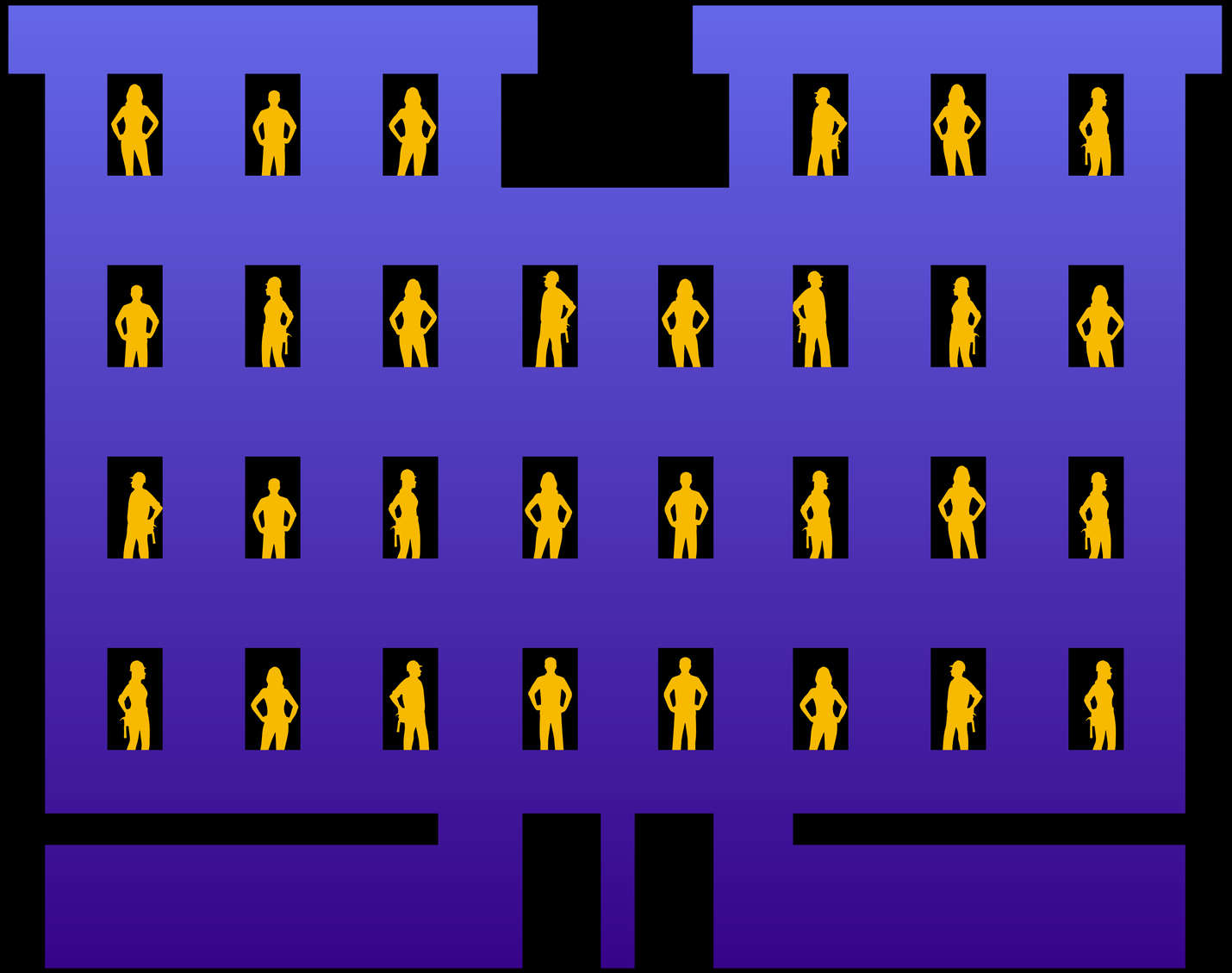
apartment building



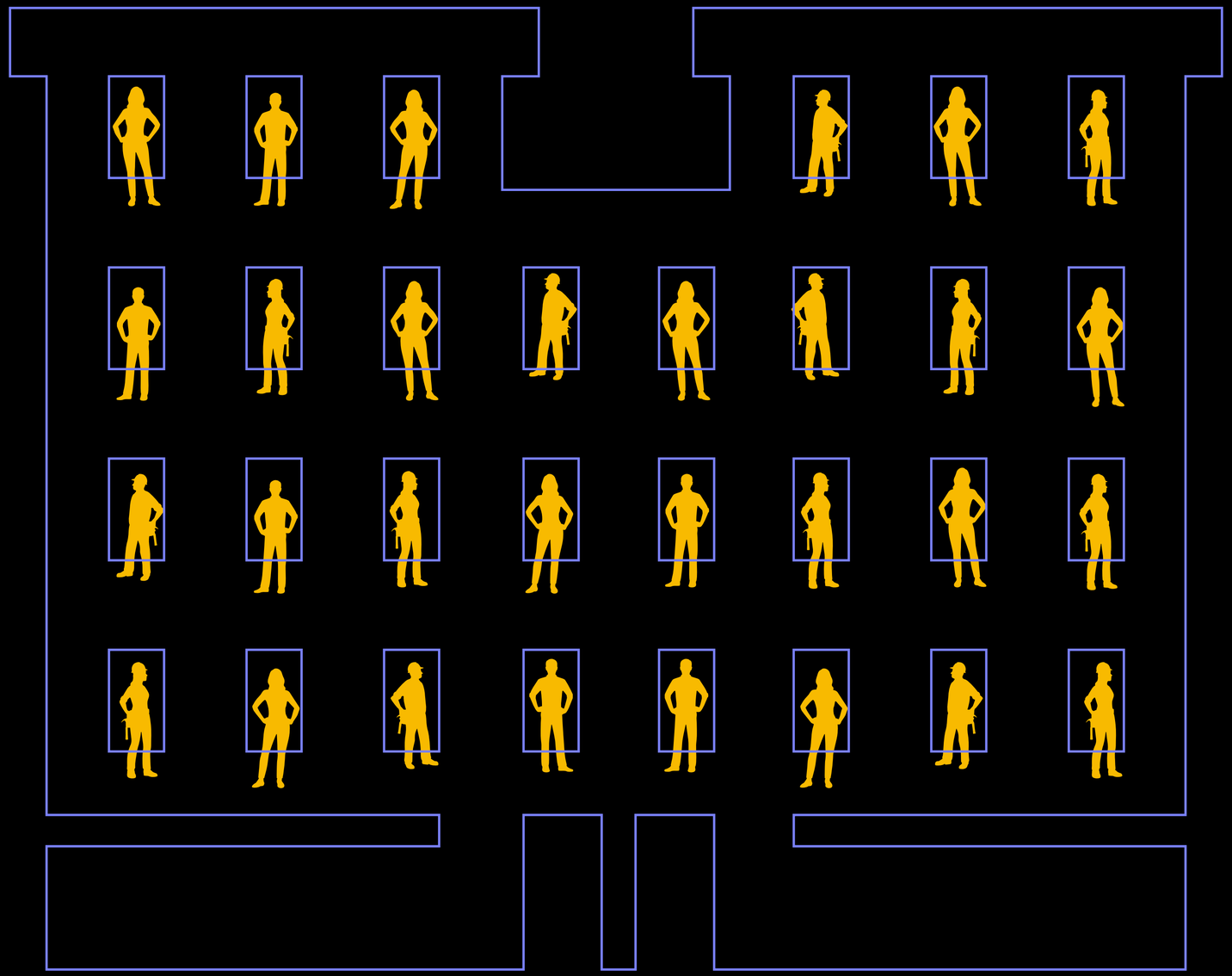
One person lives in each apartment



apartment building made of dark matter



people are made of ordinary matter



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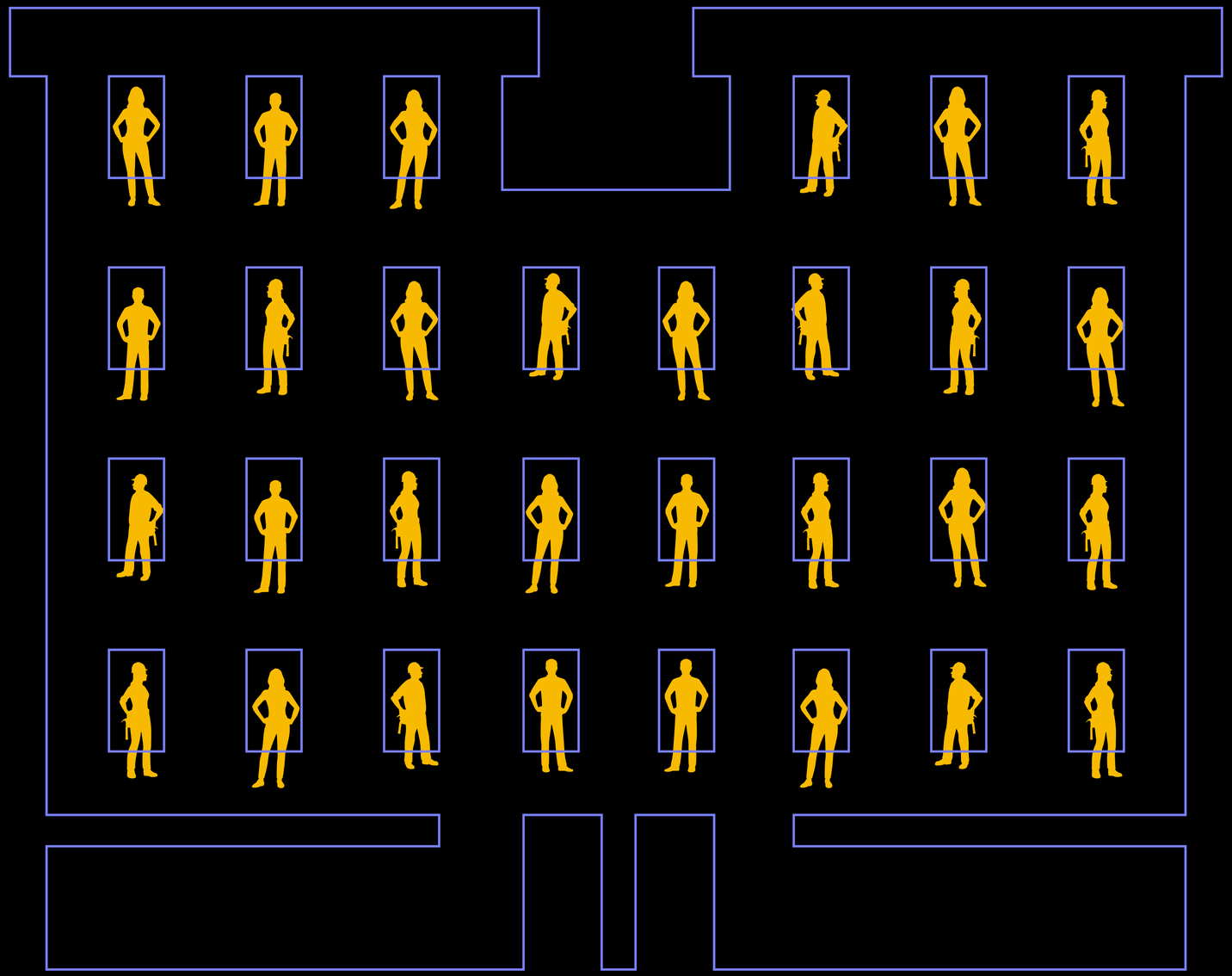
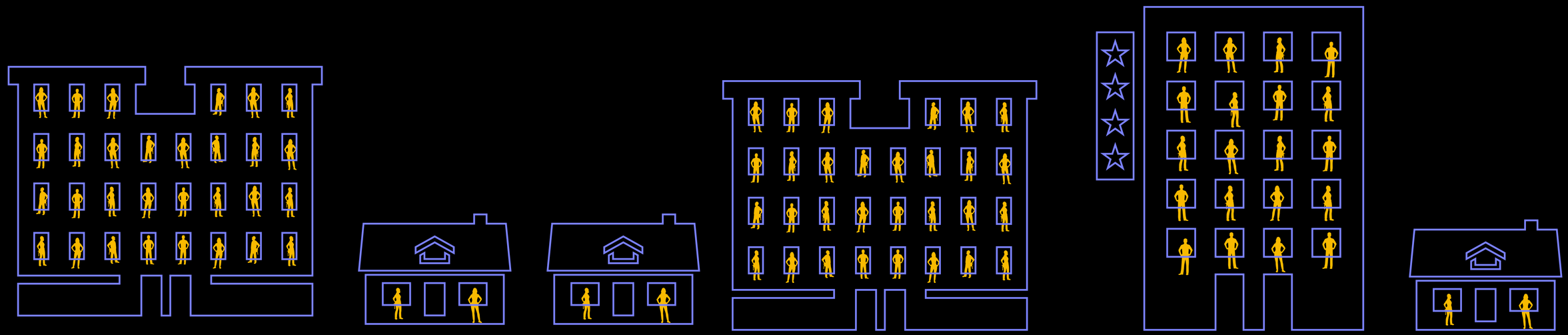


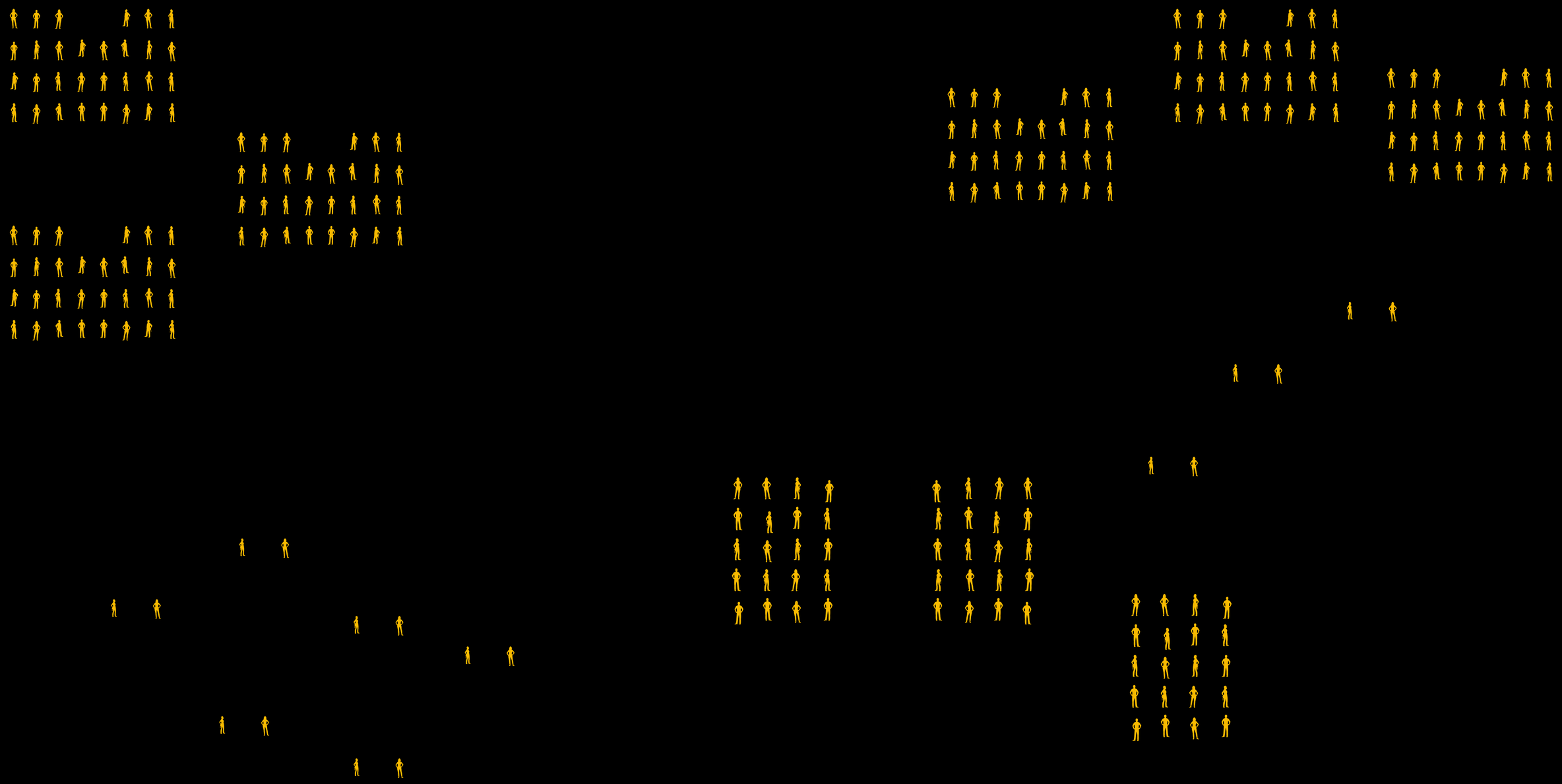
People are visible

Buildings are invisible!

Size of building can be determined by number of people



We can map a city by the distribution of its people.



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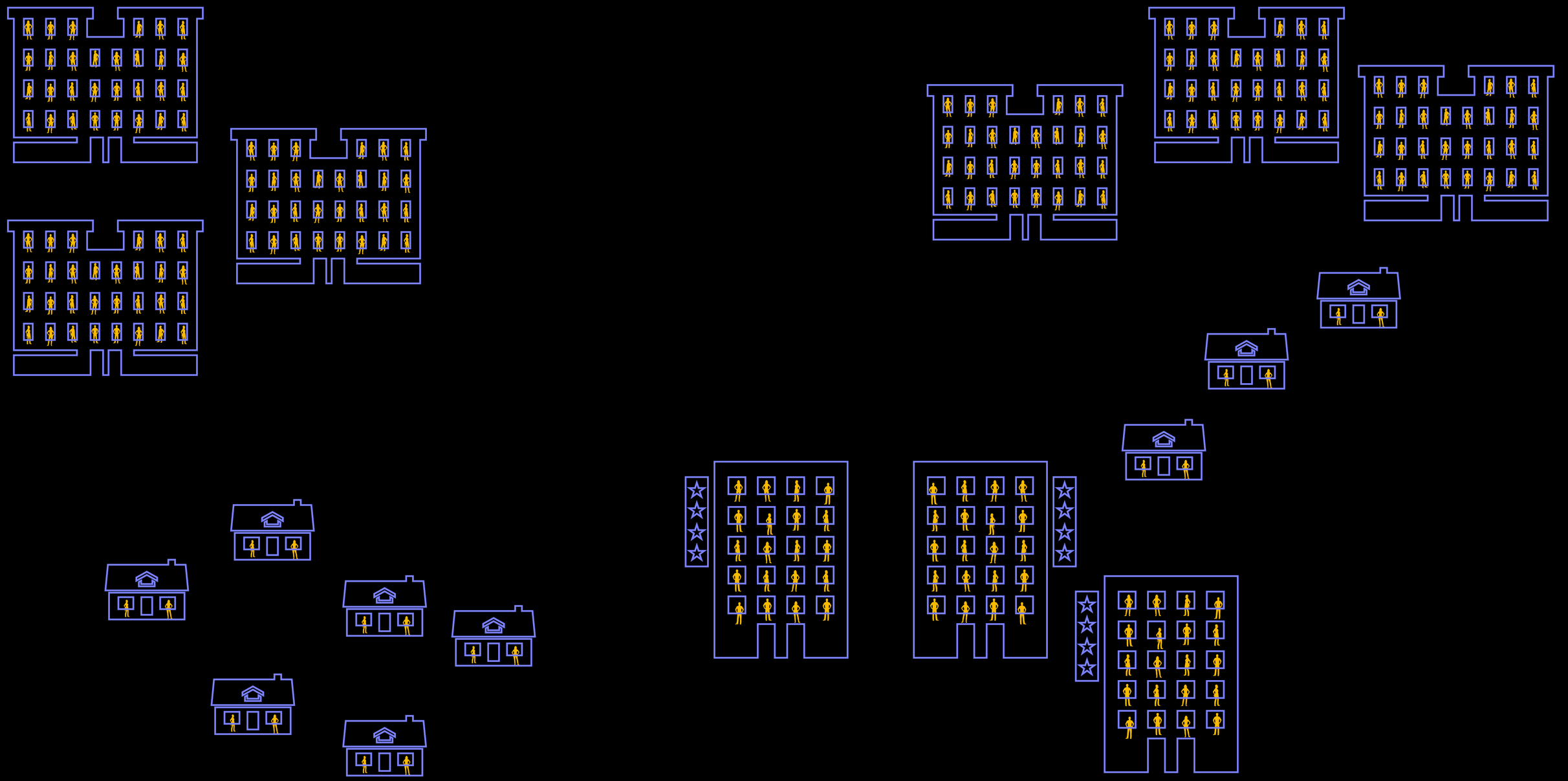
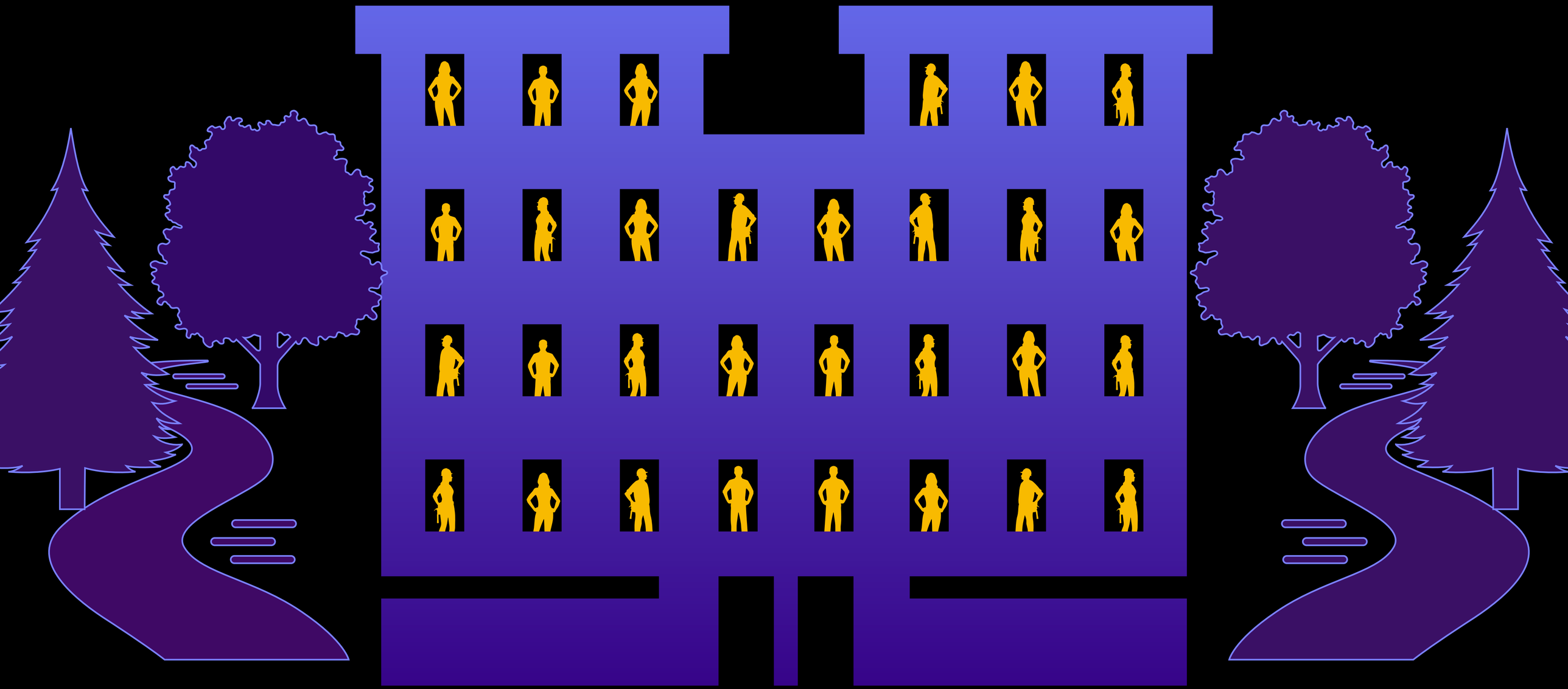
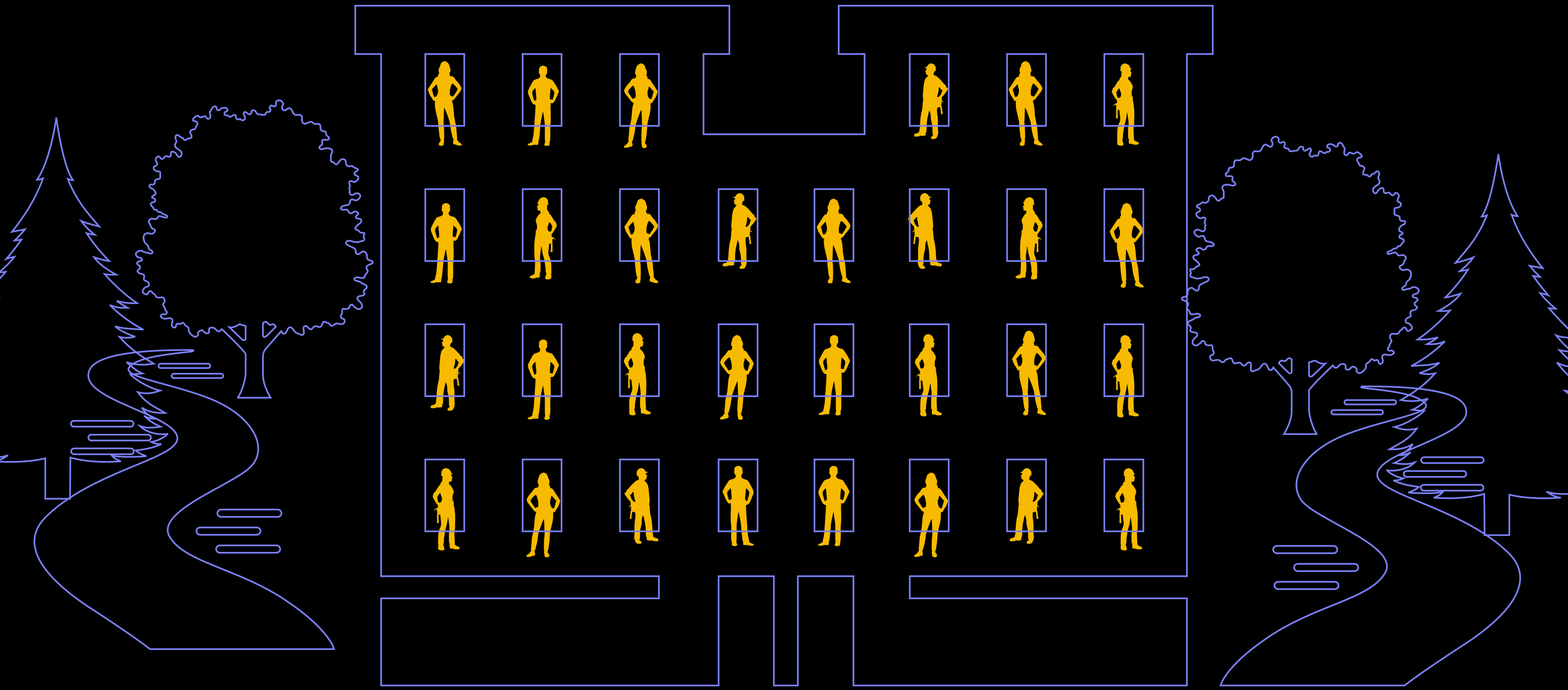


However…

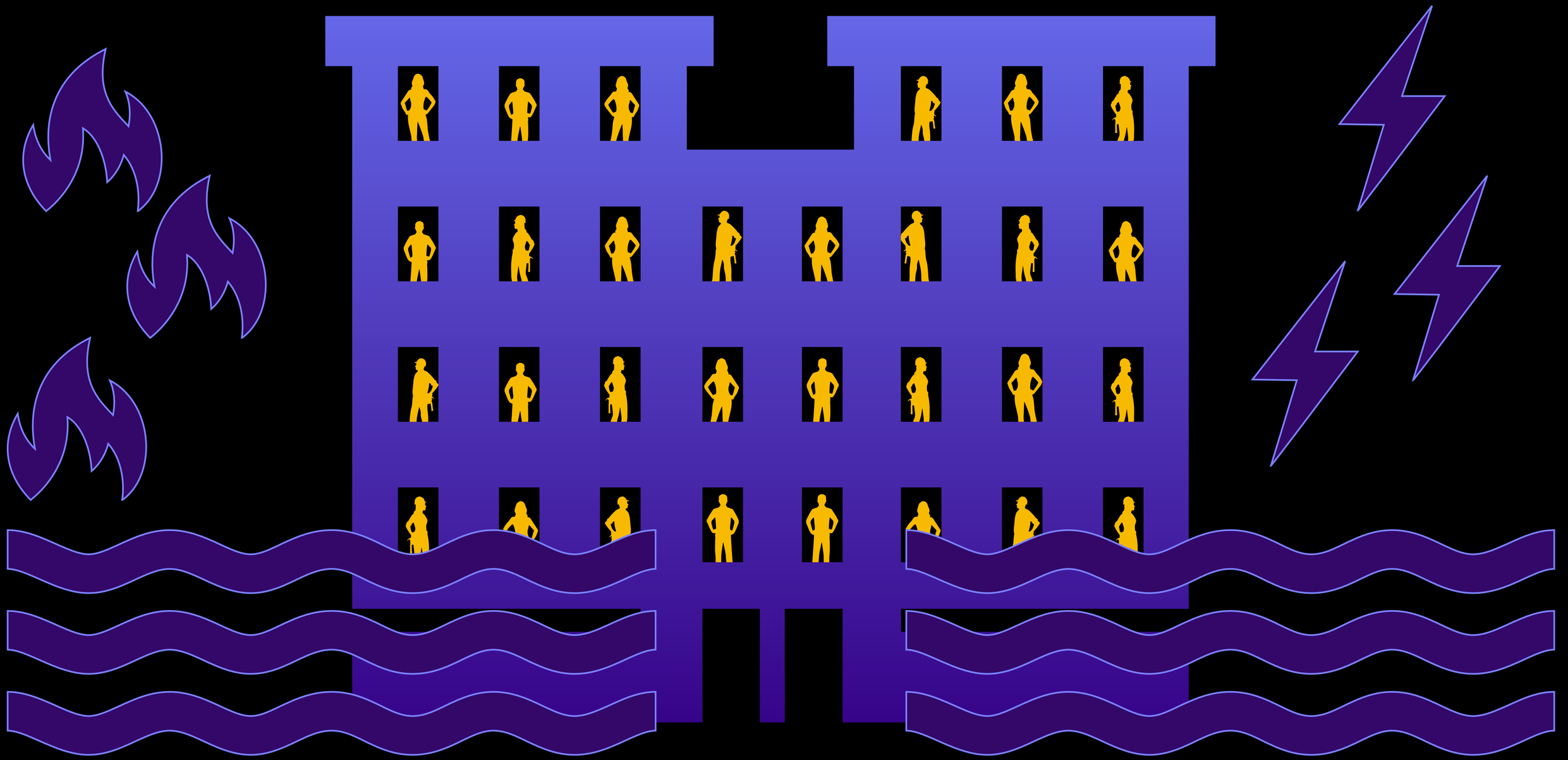
Some buildings have perfect environment



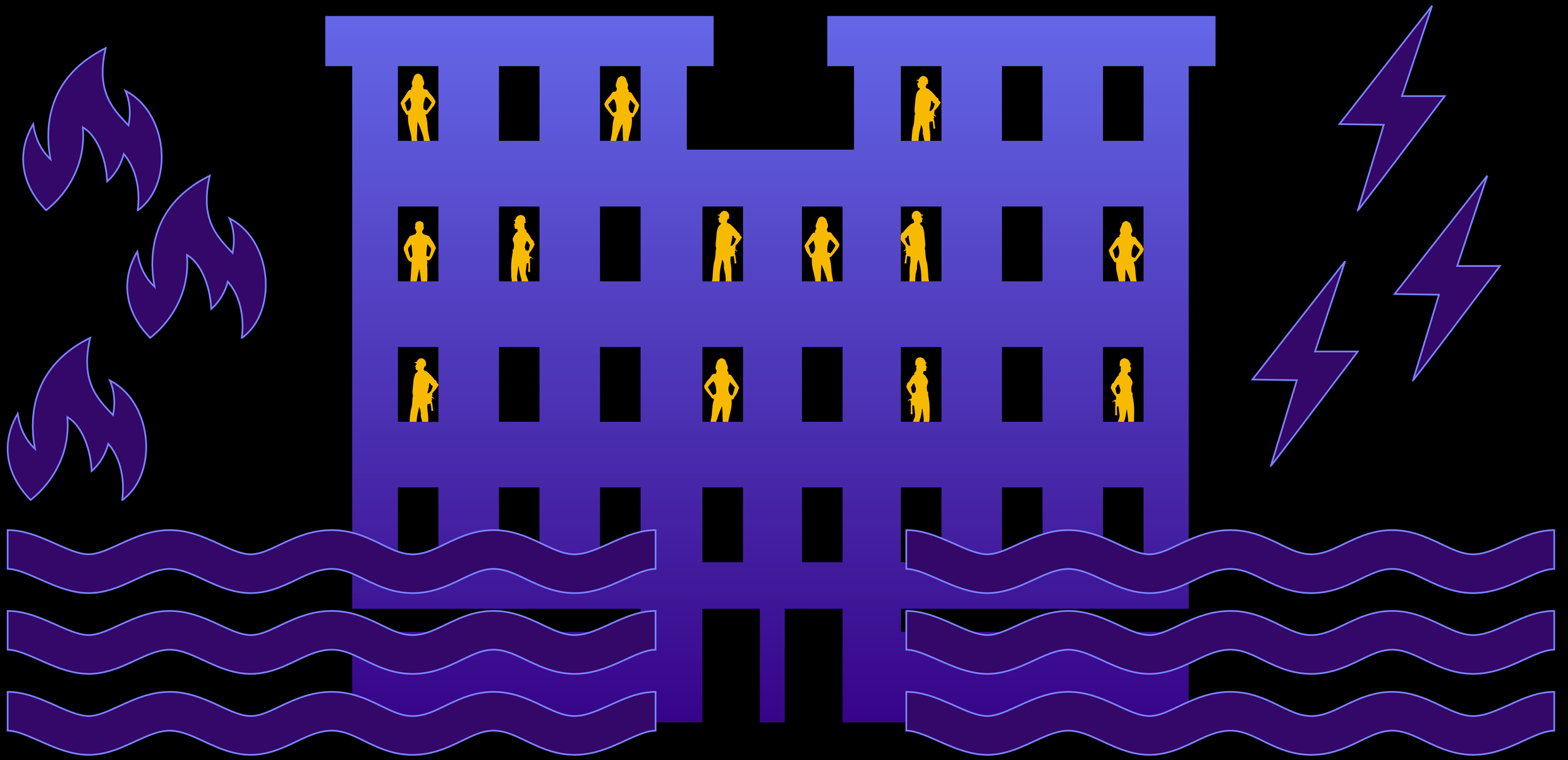
Some buildings have perfect environment



Some buildings have environmental hazards



So less people reside in that building



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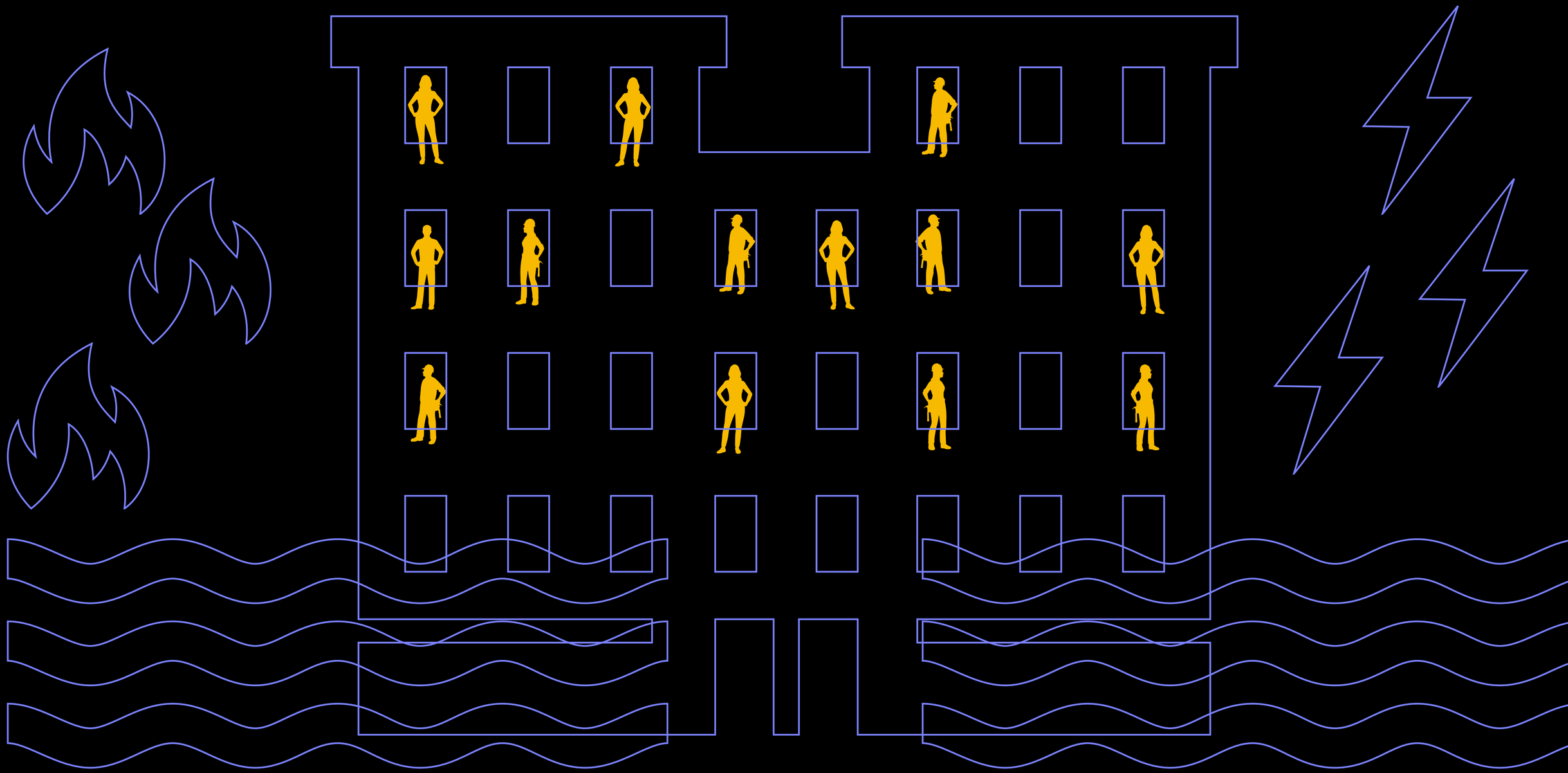
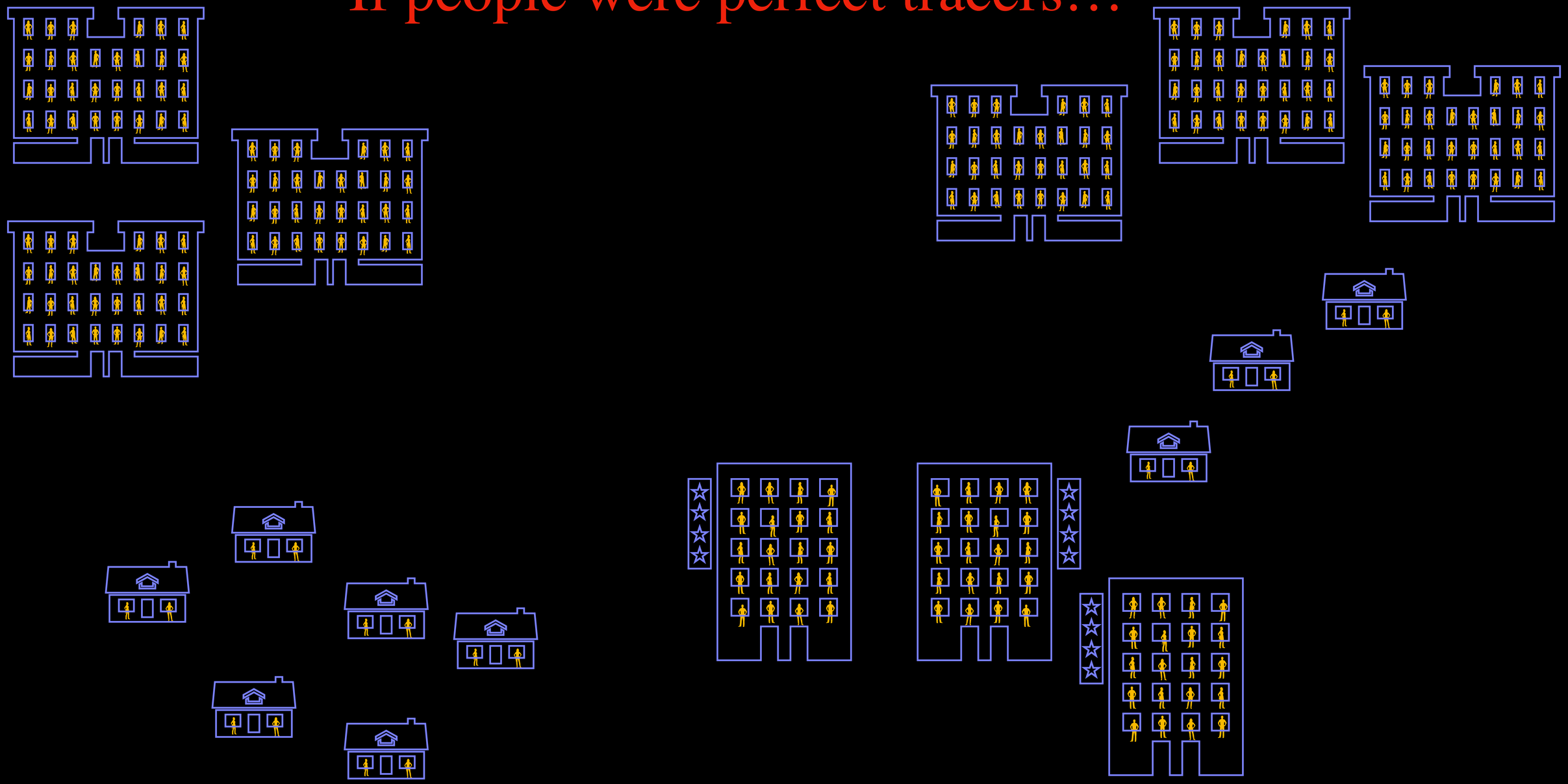
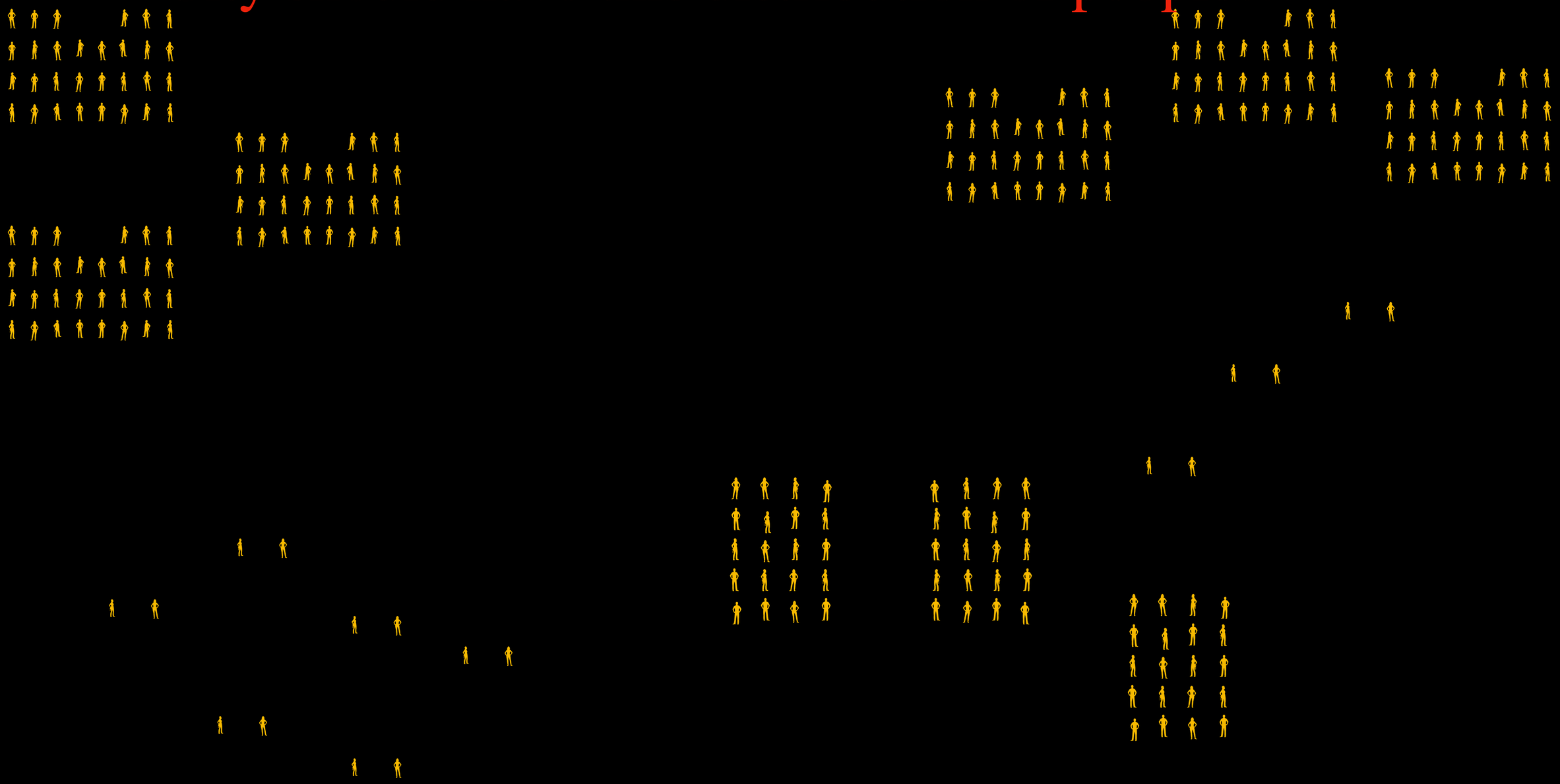


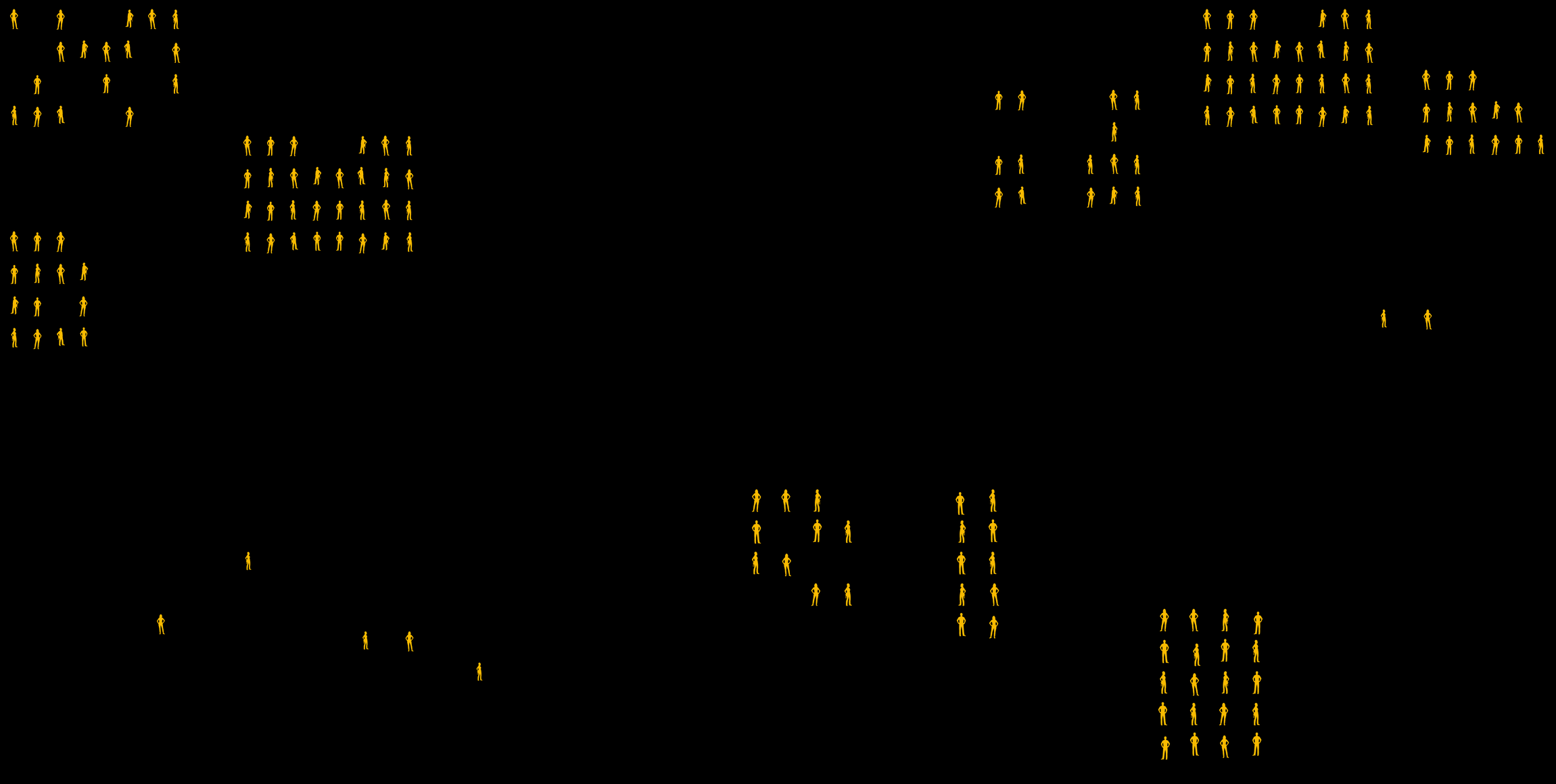
If people were perfect tracers…



City should have this distribution of people…



But has this distribution of people.

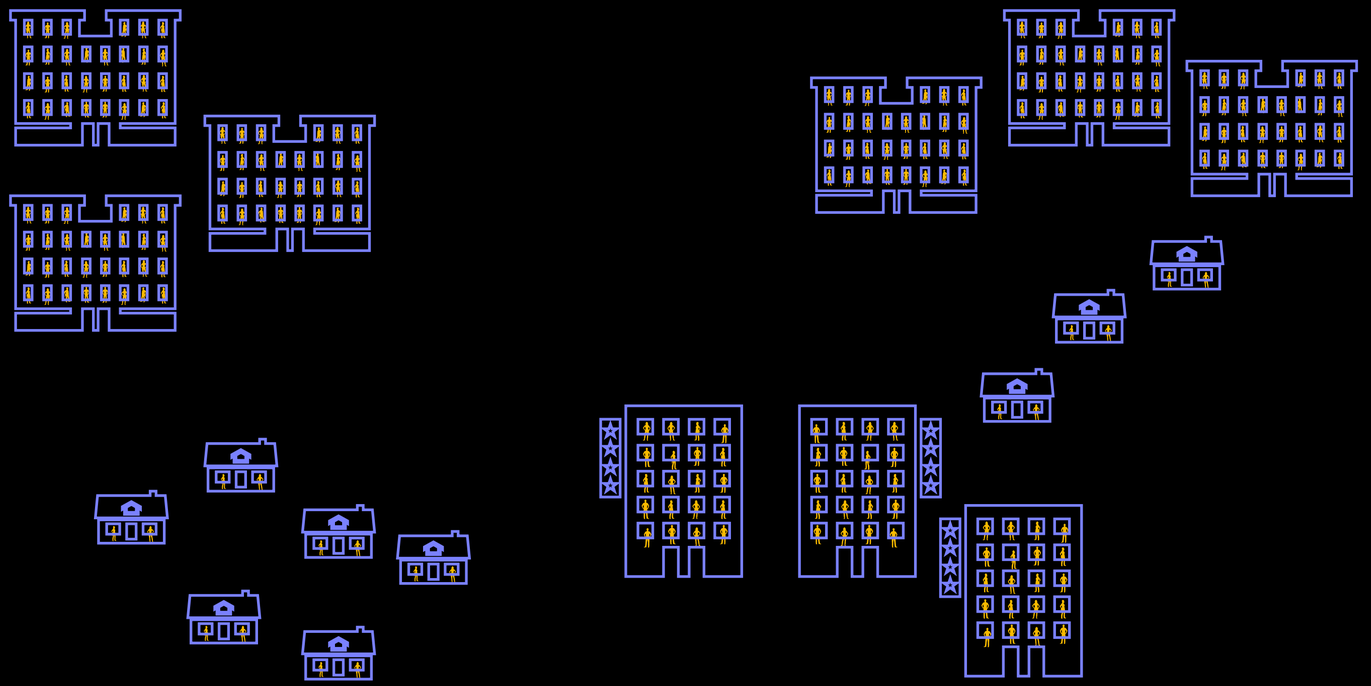



People are
biased tracers
of the city structure

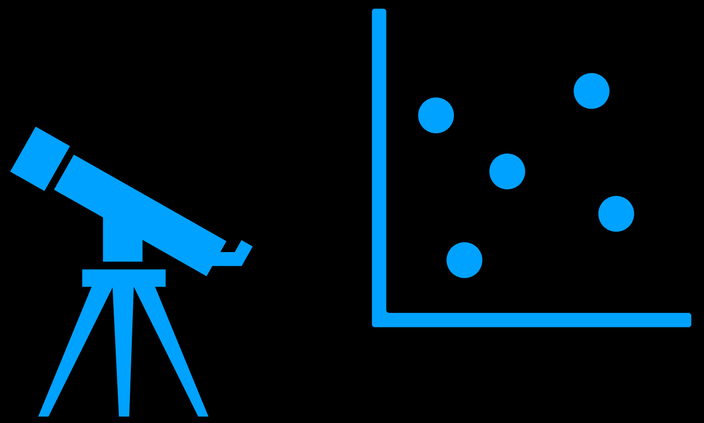
Why is this a problem???

Why is this a problem???

If we want to measure the true clustering of matter in Cartoon City…

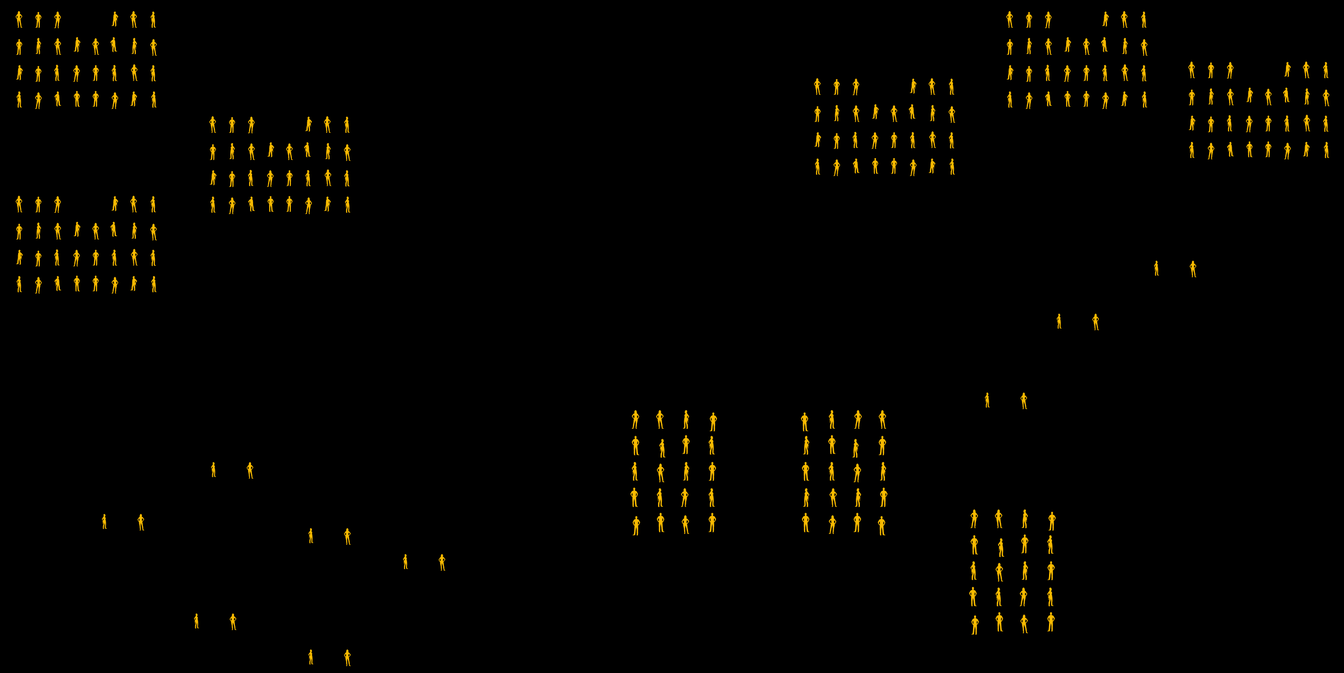


"Measurement of
the distribution of matter"



Why is this a problem???

And we use the clustering of people as a proxy…



"Measurement of
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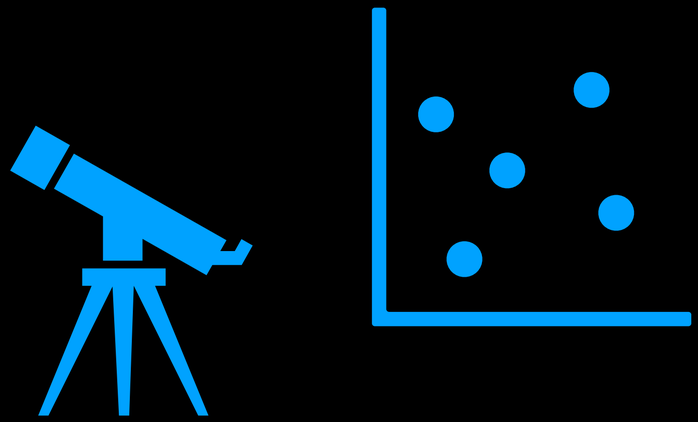
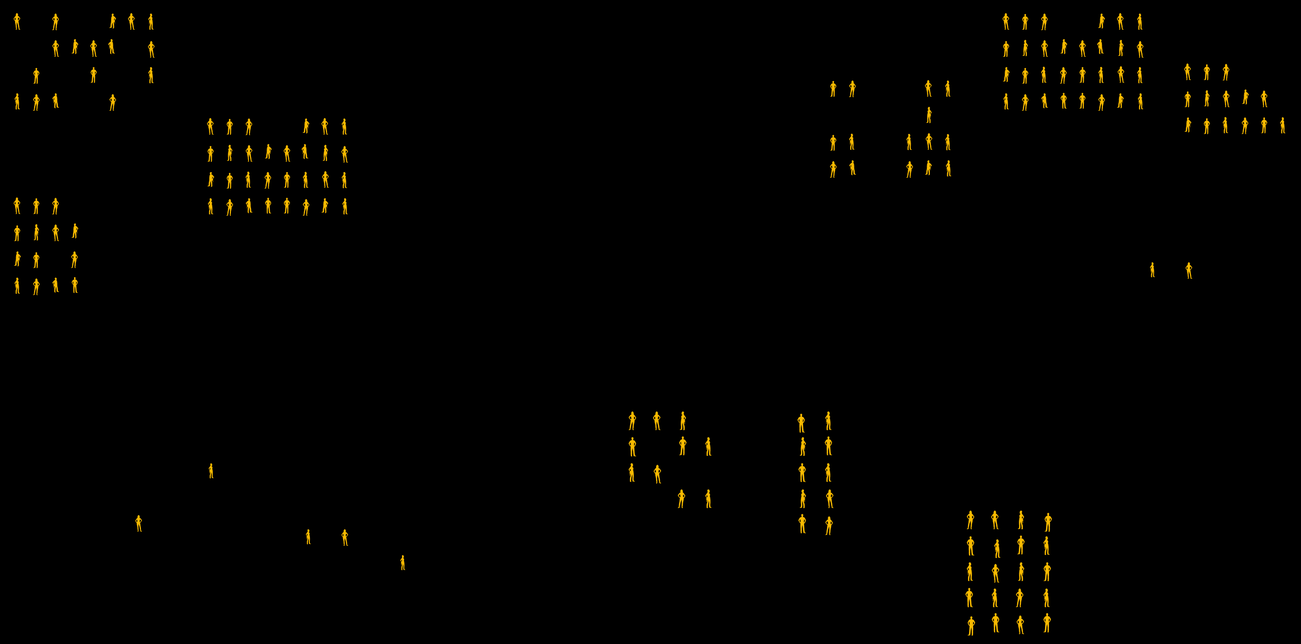
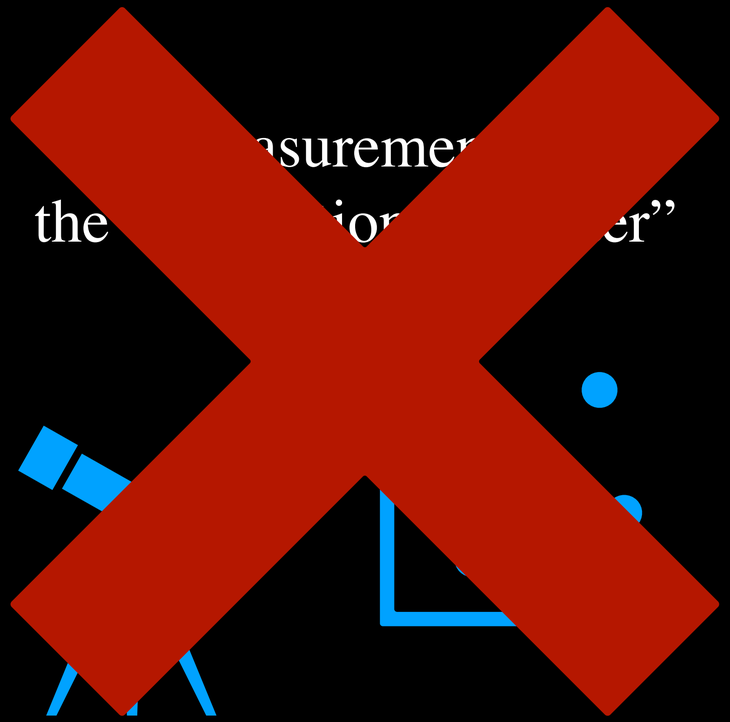


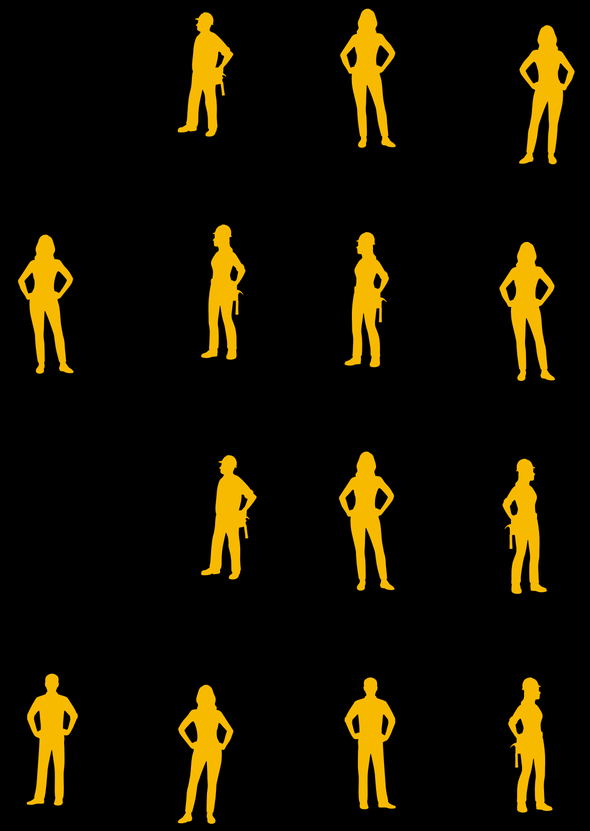
Why is this a problem???

Our clustering measurement won’t accurately represent the true distribution because our tracers are biased.





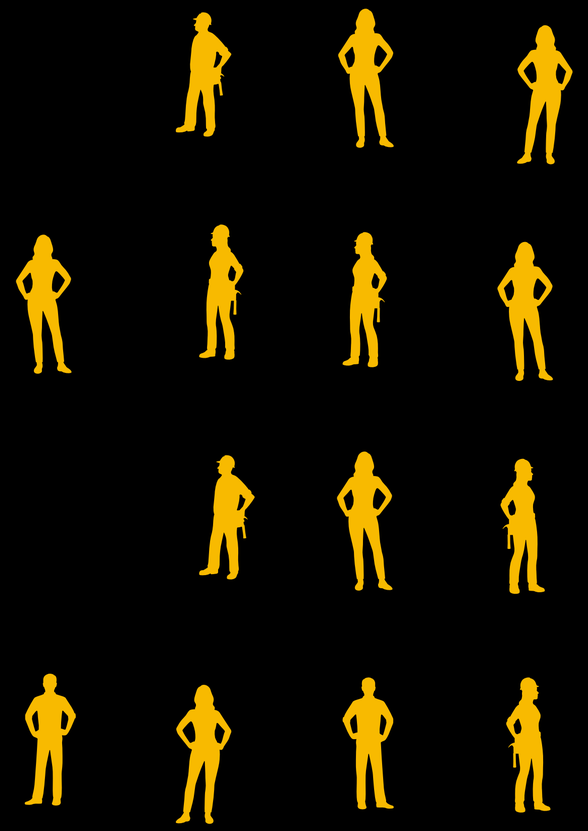
We must use what we *can* see to learn about what we *can't* see.



We must use what we *can* see to learn about what we *can't* see.

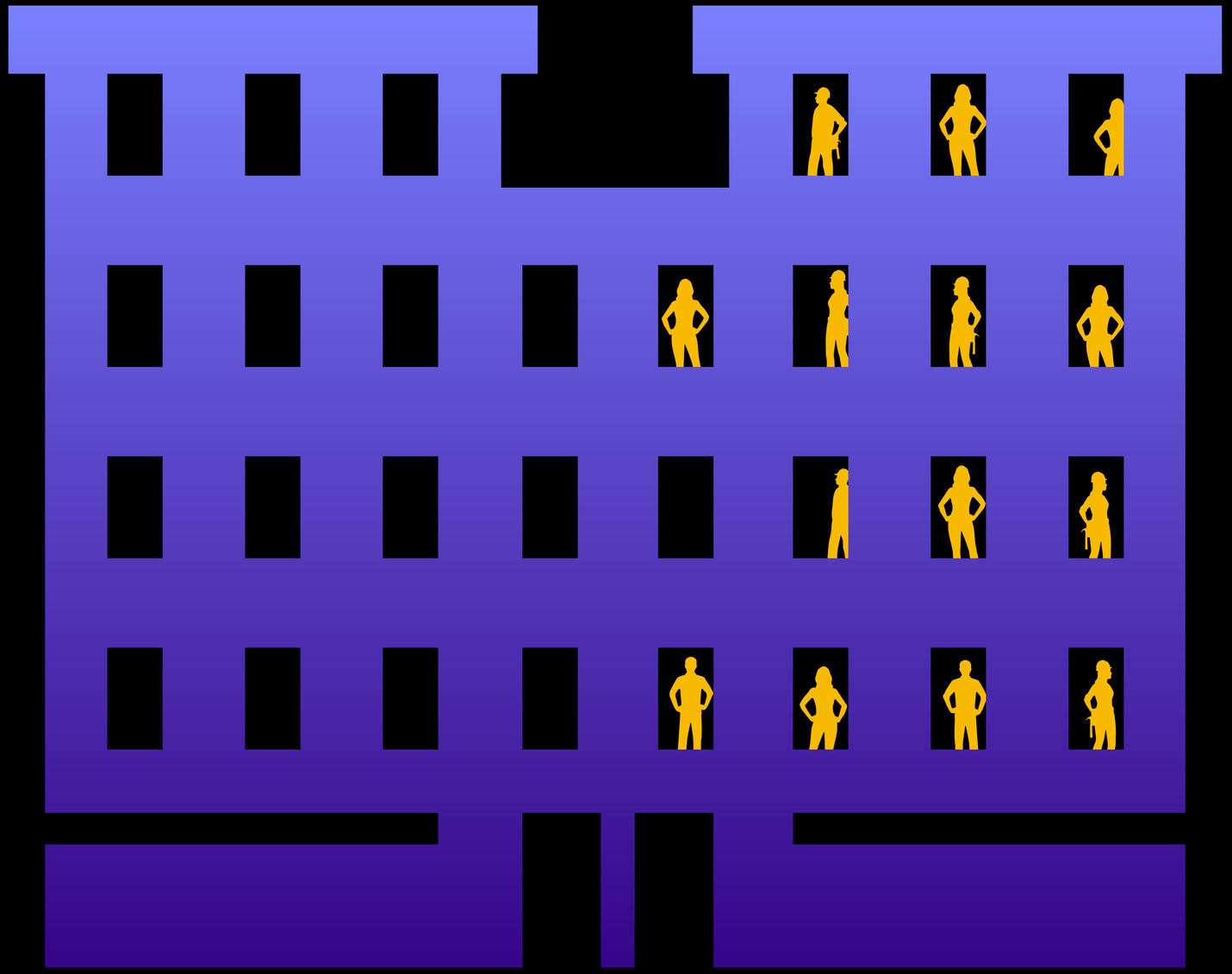
We want to connect the average number of people

$$\langle N_{\text{people}} \rangle$$



$$\langle N_{\text{people}} \rangle = f(\text{Size}_{\text{building}} \cdots)$$

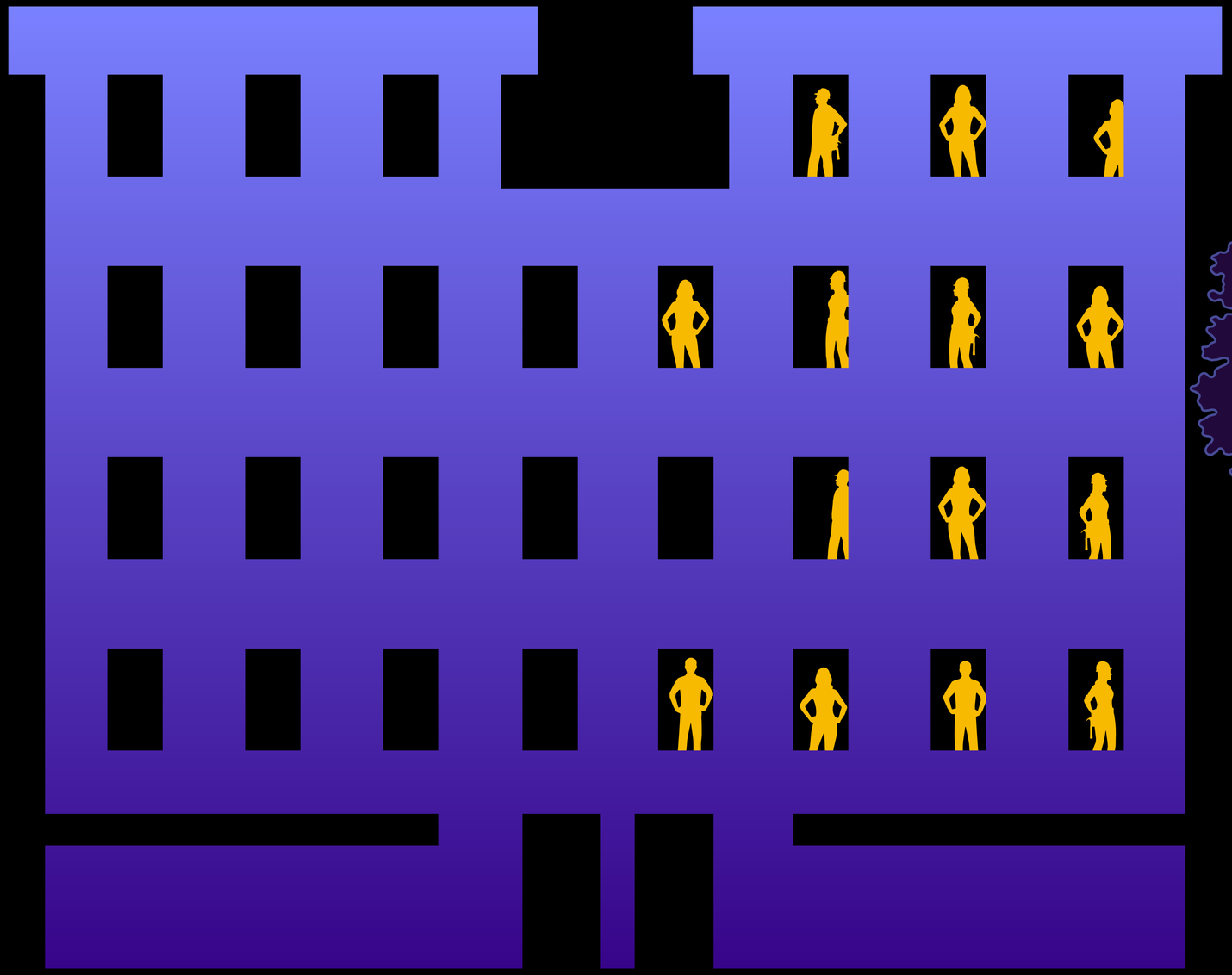
We want to connect the average number of people



To the building size

$$\langle N_{\text{people}} \rangle = f(\text{Size}_{\text{building}}, \text{Env}_{\text{building}})$$

We want to connect the average number of people



To the building size

And to the building's environment

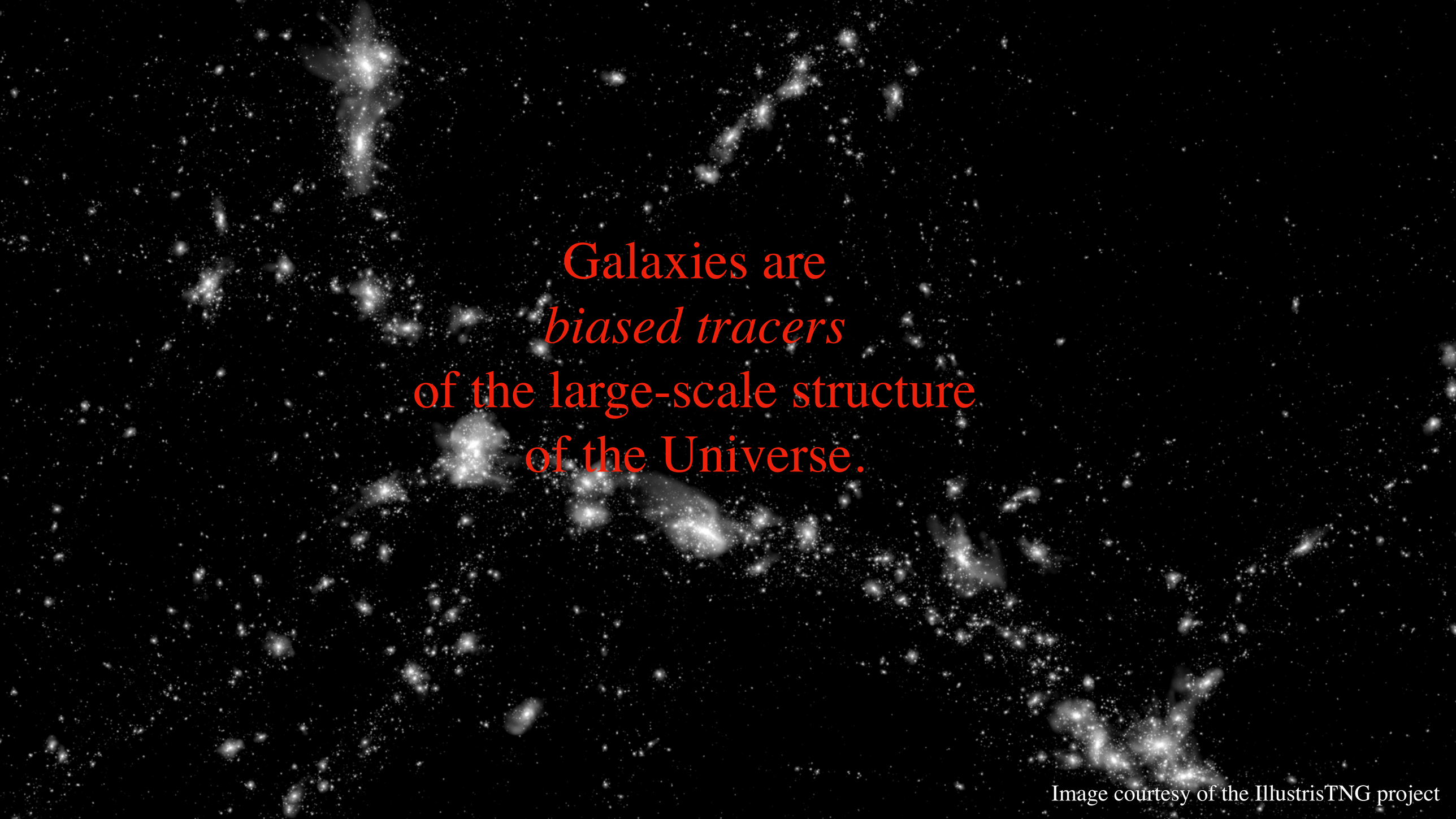
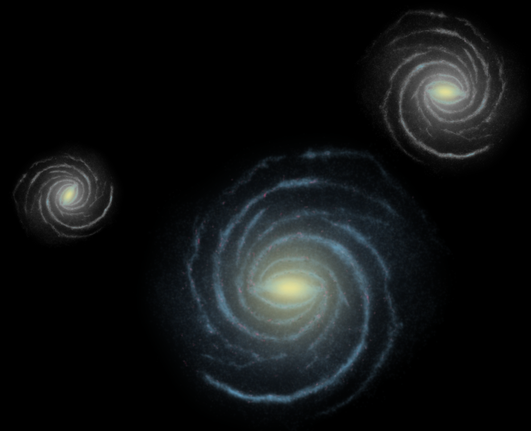
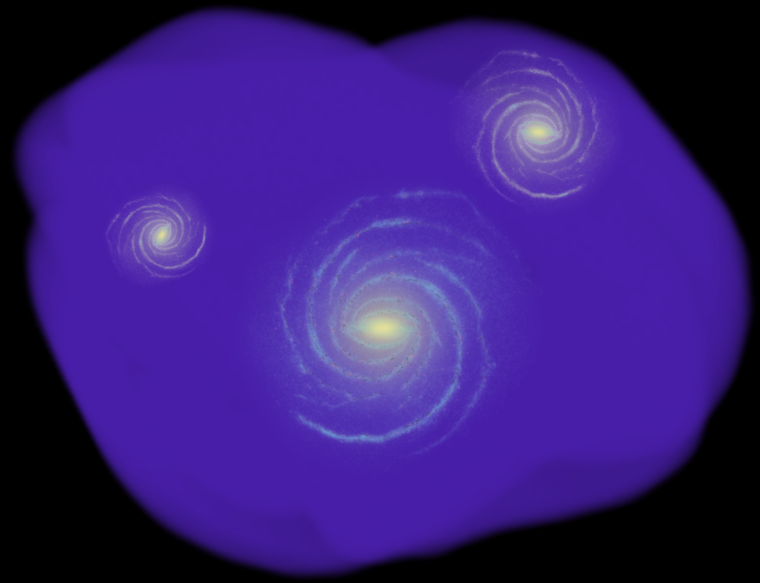


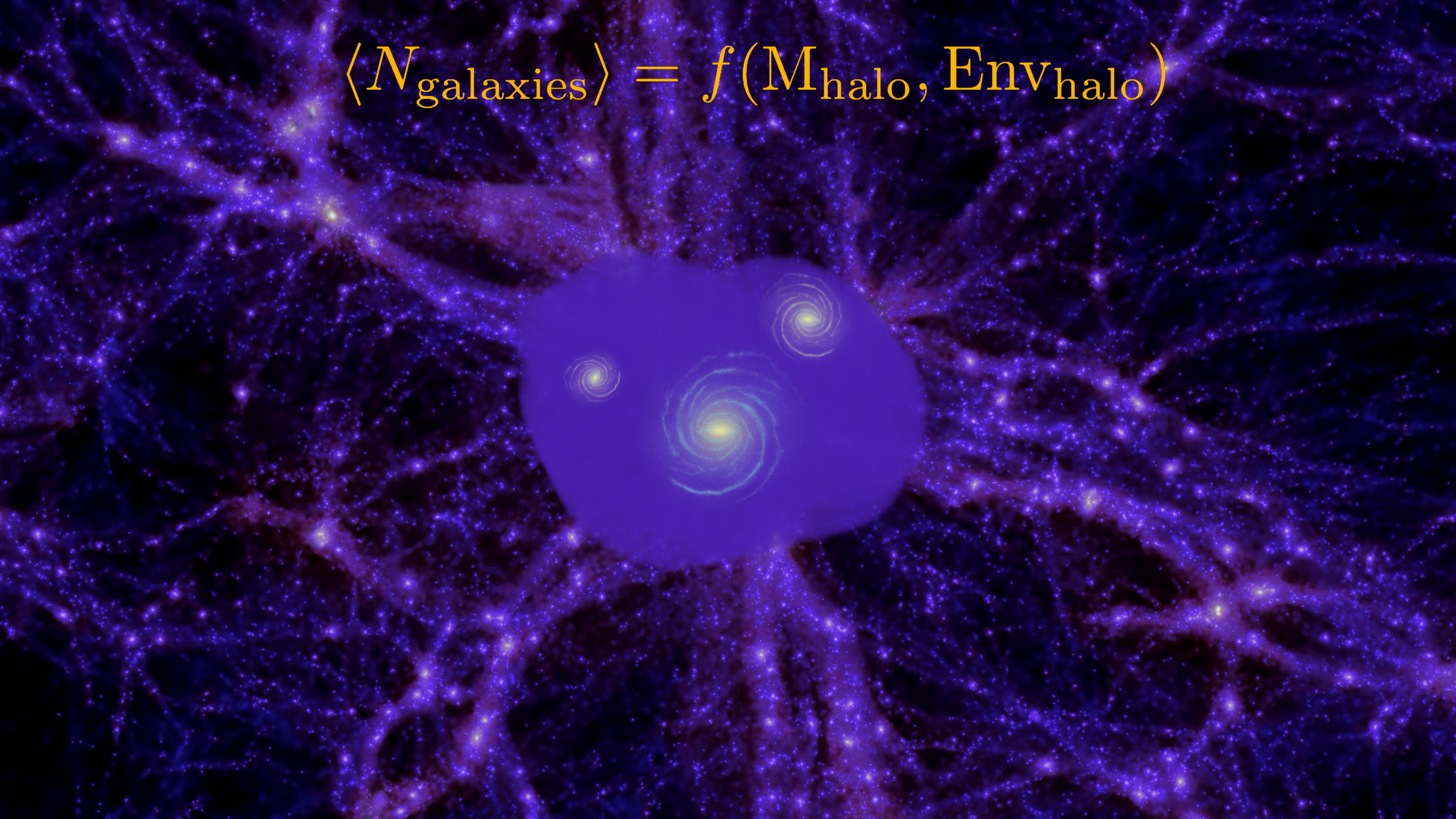
Image courtesy of the IllustrisTNG project

$$\langle N_{\text{galaxies}} \rangle$$



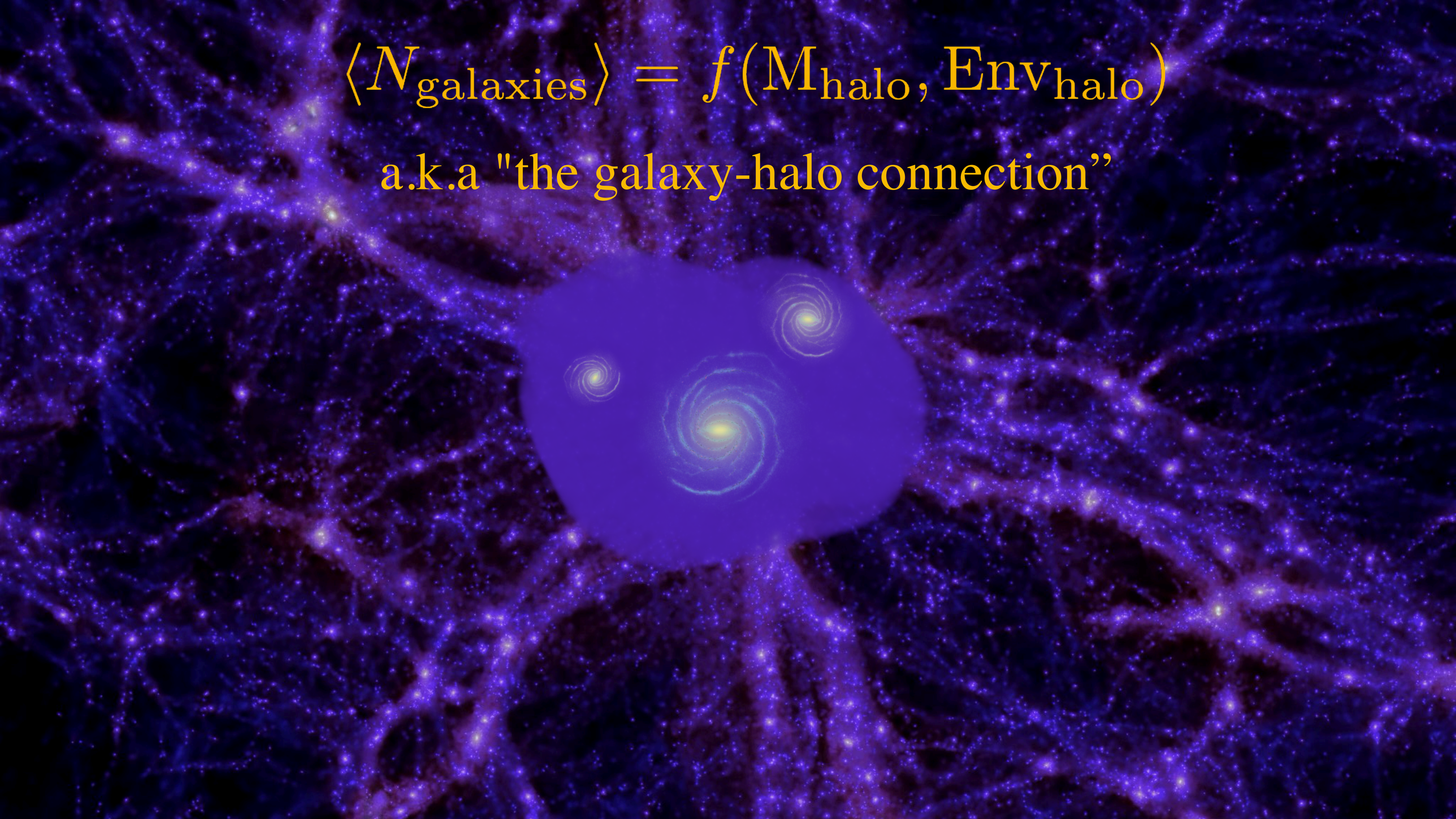
$$\langle N_{\mathrm{galaxies}} \rangle = f(\mathrm{M_{halo}} \cdots)$$




$\langle N_{\rm galaxies} \rangle = f(\mathrm{M_{halo}}, \mathrm{Env_{halo}})$

$$\langle N_{\rm galaxies} \rangle = f({\rm M_{halo}}, {\rm Env_{halo}})$$

a.k.a "the galaxy-halo connection”

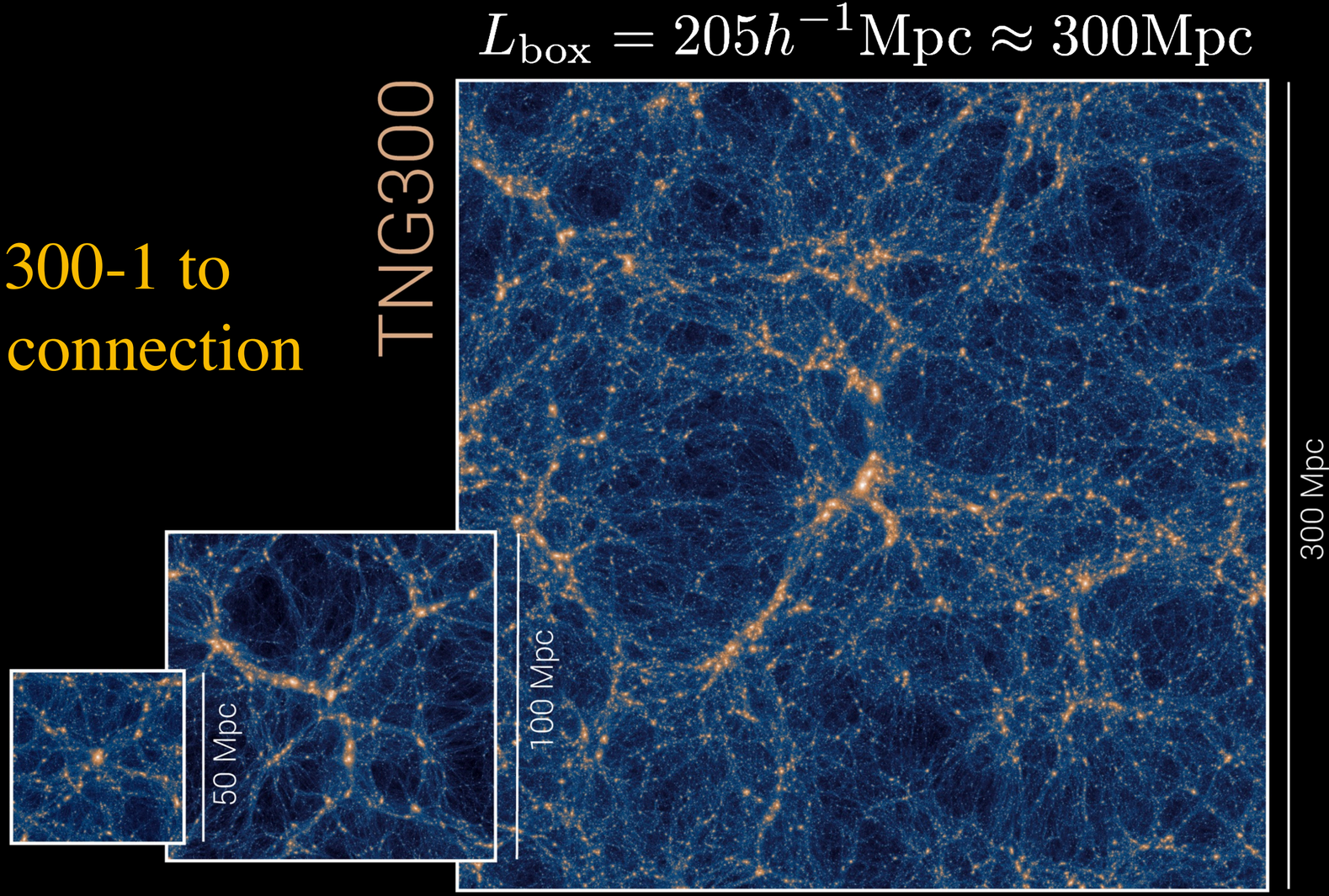


Modeling the galaxy-halo connection with machine learning

Delgado+ 2022 MNRAS.515.2733D

Cosmological Simulations

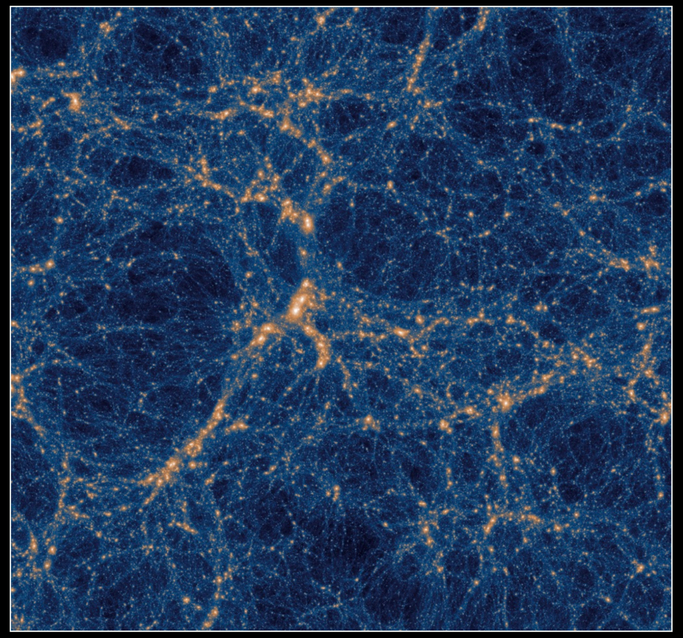
This work uses IllustrisTNG 300-1 to better model the galaxy-halo connection

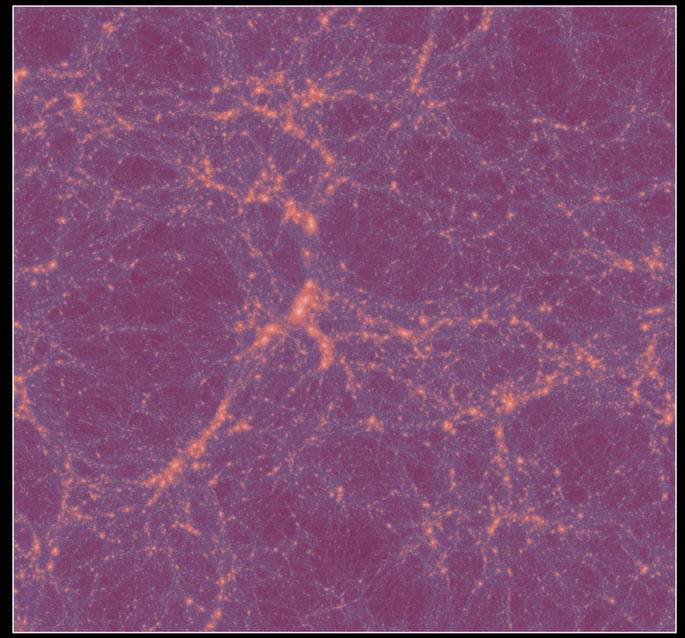


Cosmological Simulations

IllustrisTNG 300 to better model the galaxy-halo connection

Paired N-body and hydrodynamic simulations

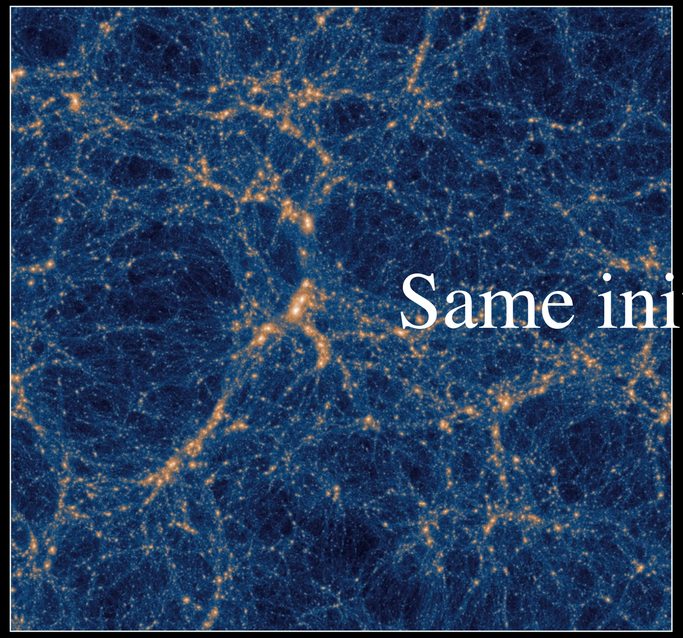




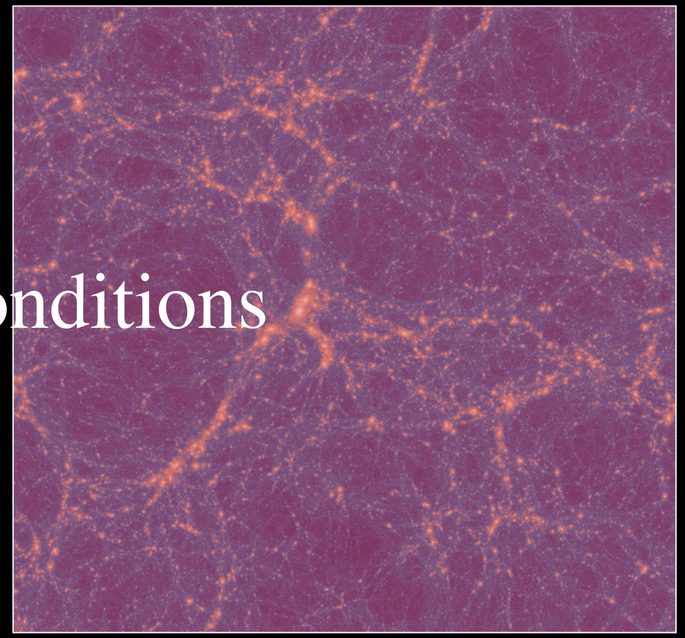
Cosmological Simulations

IllustrisTNG 300 to better model the galaxy-halo connection

Paired N-body and hydrodynamic simulations



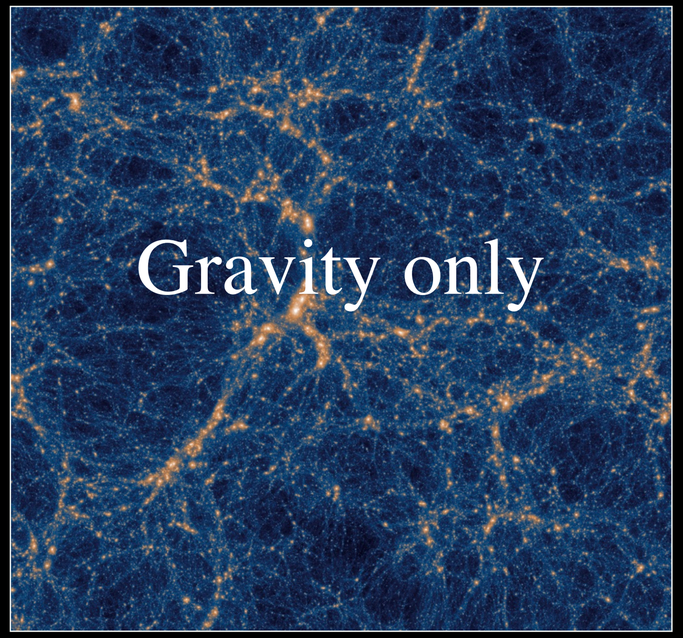
Same initial conditions

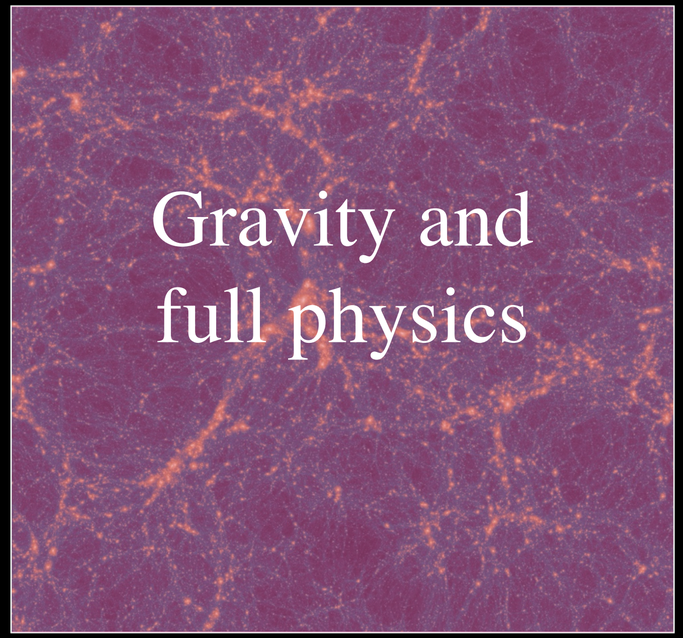


Cosmological Simulations

IllustrisTNG 300 to better model the galaxy-halo connection

Paired N-body and hydrodynamic simulations

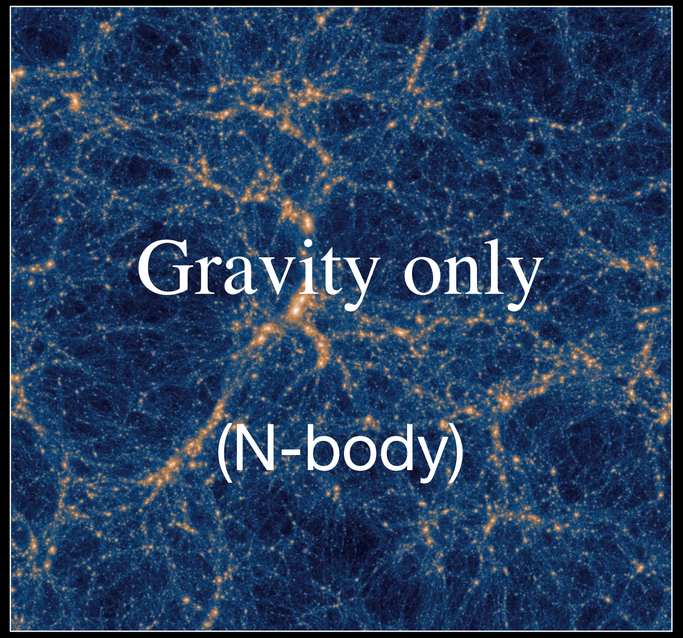


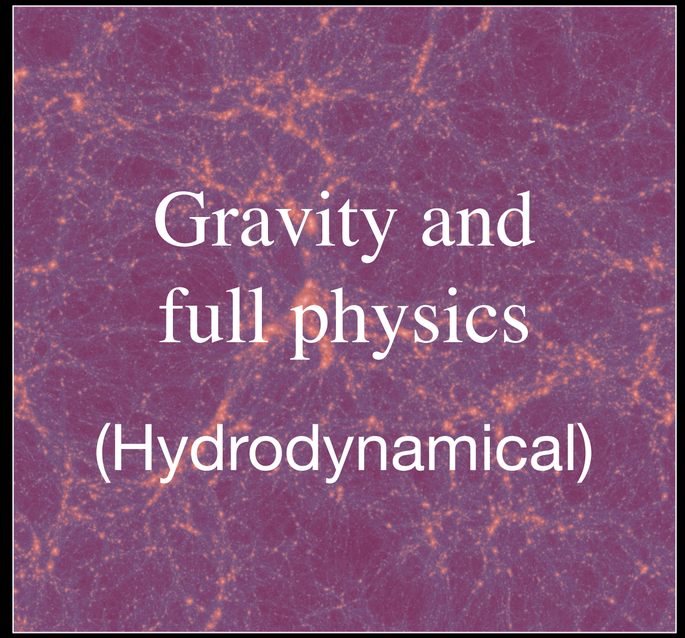


Cosmological Simulations

IllustrisTNG 300 to better model the galaxy-halo connection

Paired N-body and hydrodynamic simulations

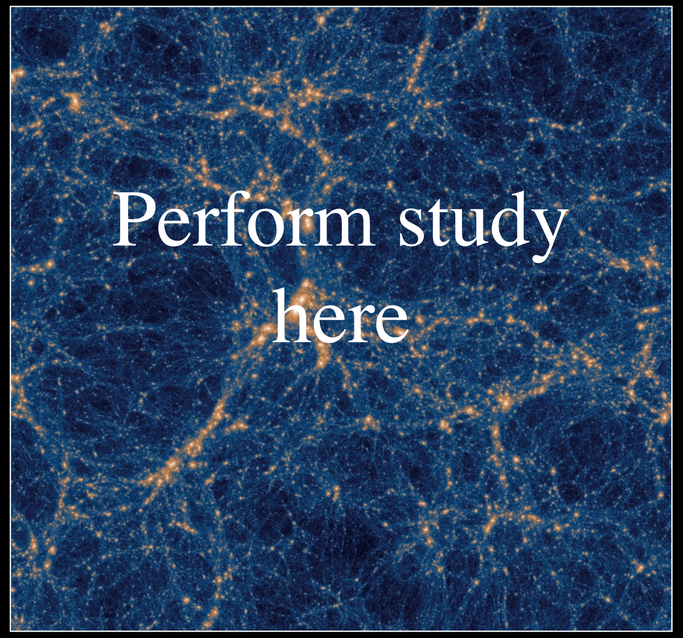


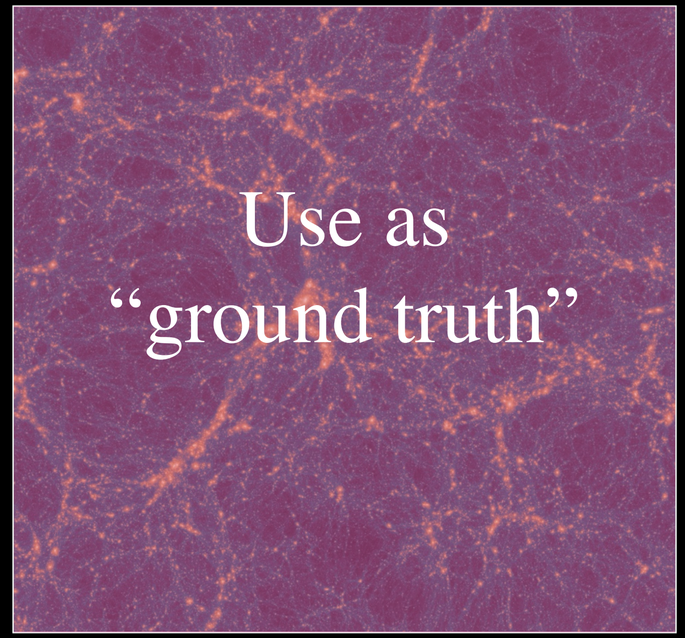


Cosmological Simulations

IllustrisTNG 300 to better model the galaxy-halo connection

Paired N-body and hydrodynamic simulations

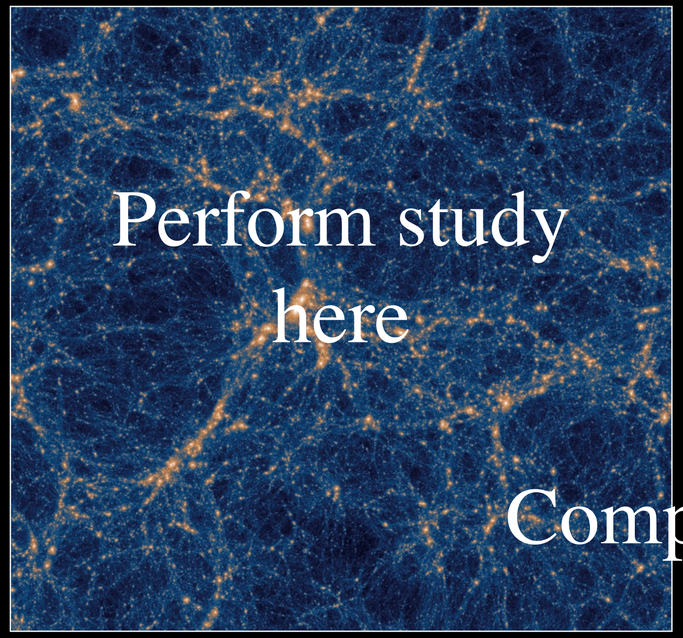


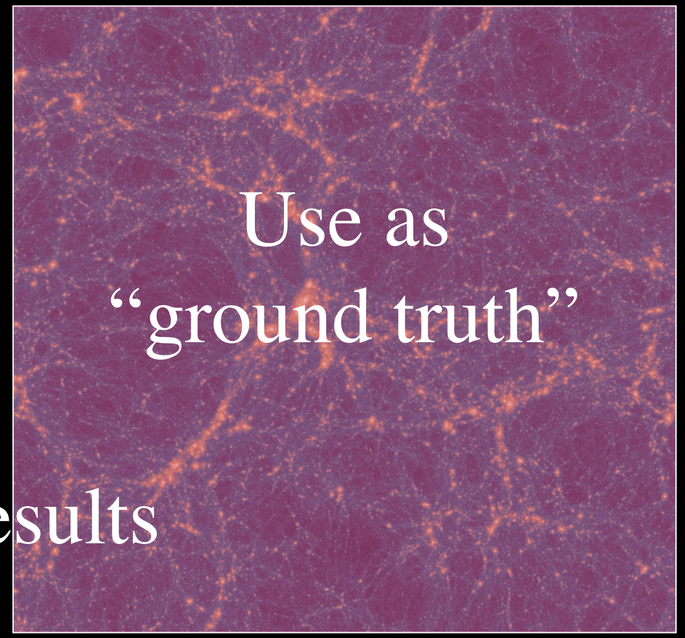


Cosmological Simulations

IllustrisTNG 300 to better model the galaxy-halo connection

Paired N-body and hydrodynamic simulations





Compare results

Model for the Galaxy-Halo Connection

Halo Occupation Distribution (HOD)

Describes:

the average number of galaxies

at a given mass for a

Dark Matter Halo

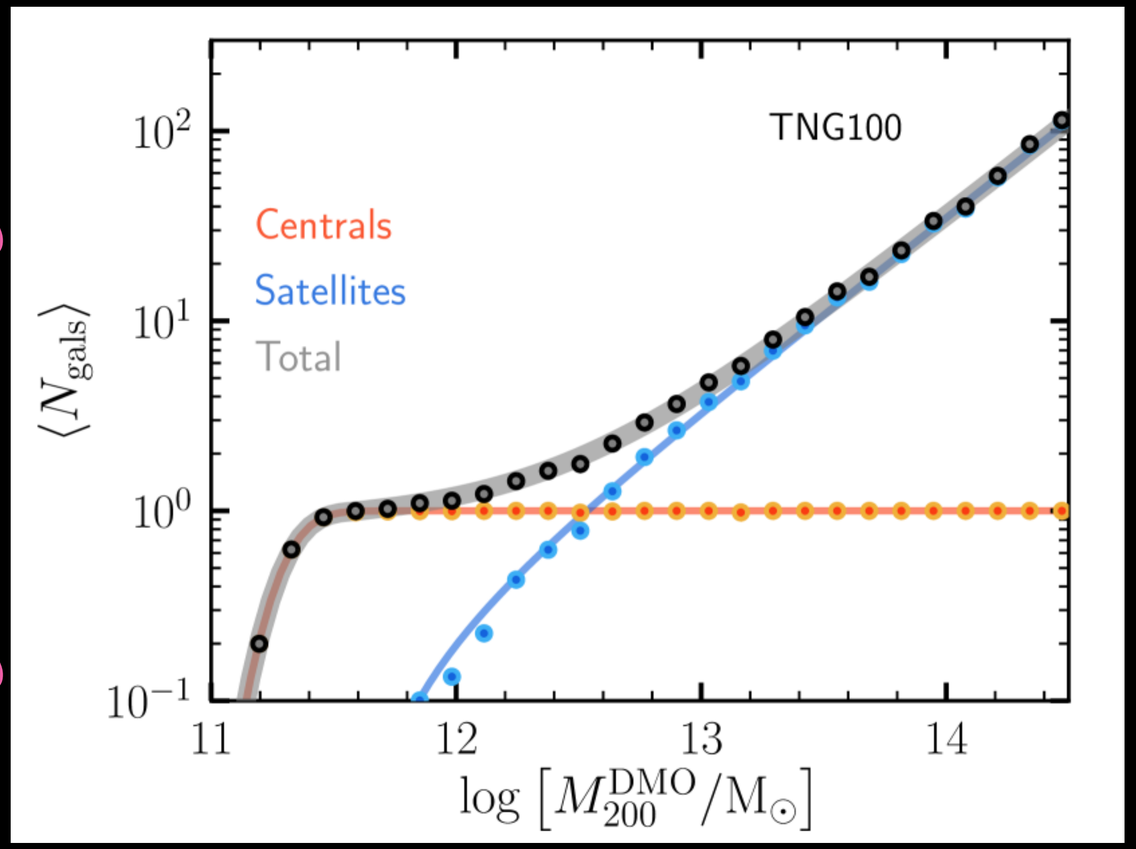
$$\langle N_{\text{galaxies}} \rangle = f(M_{\text{Halo}})$$

Model for the Galaxy-Halo Connection

What a Halo Occupation Distribution (HOD) "looks" like

Bose et al., 2019

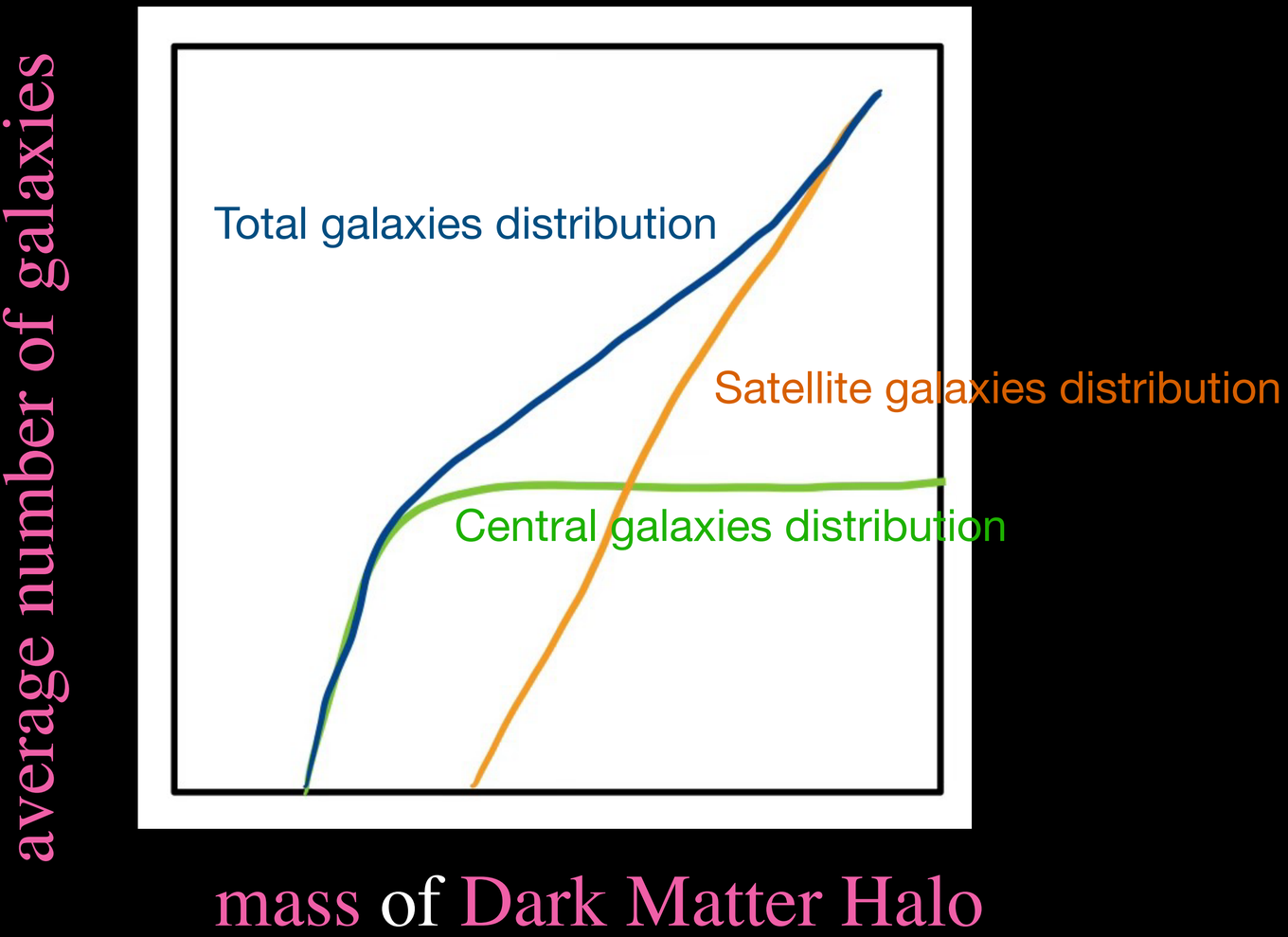
average number of galaxies



mass of Dark Matter Halo

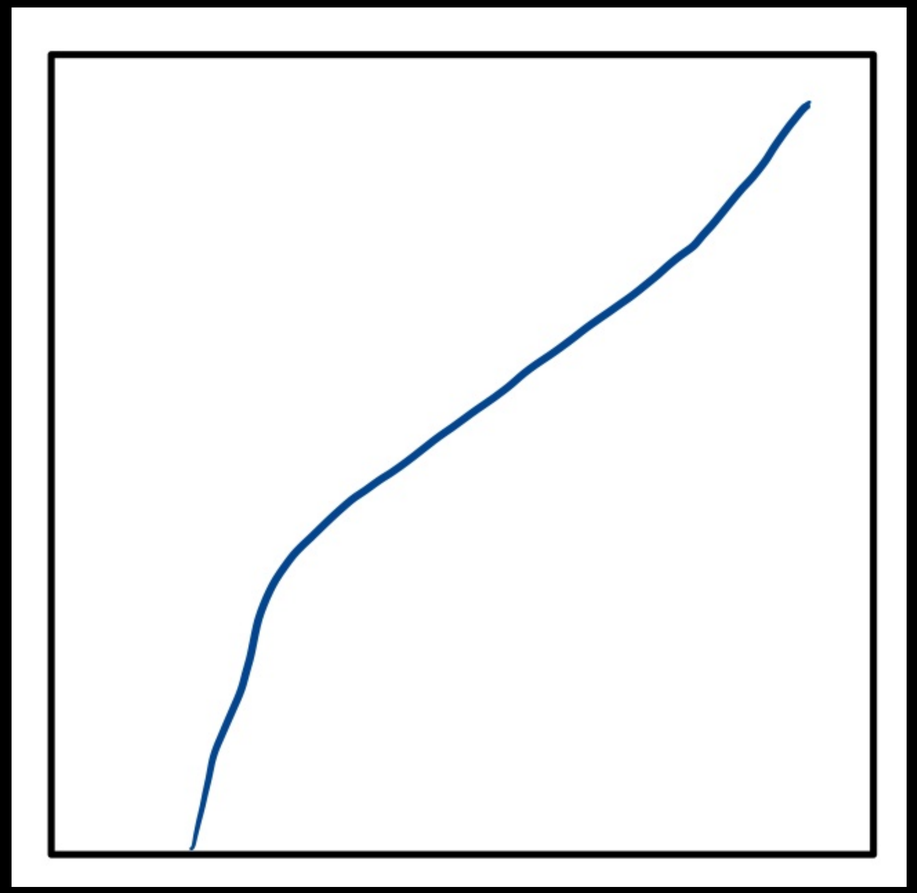
Model for the Galaxy-Halo Connection

What a Halo Occupation Distribution (HOD) “looks” like



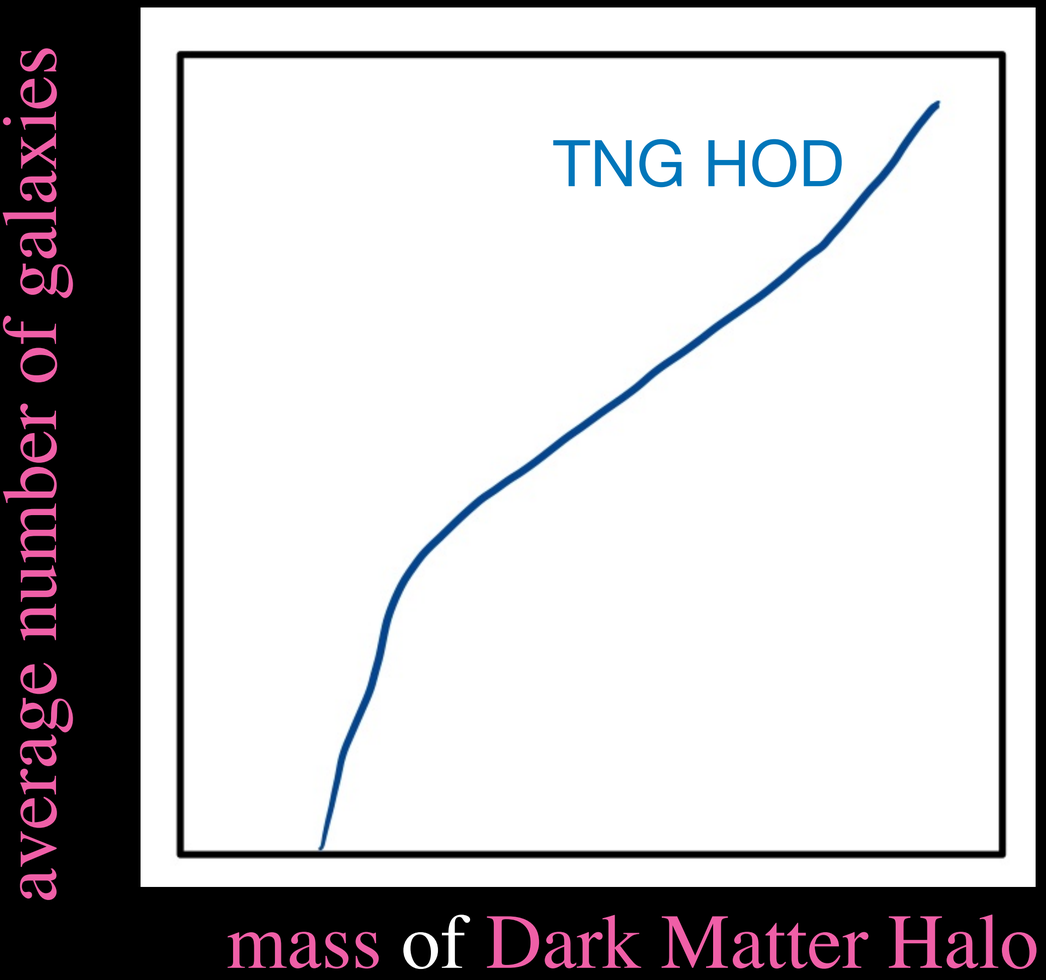
Model for the Galaxy-Halo Connection

What if we want to only model this HOD?



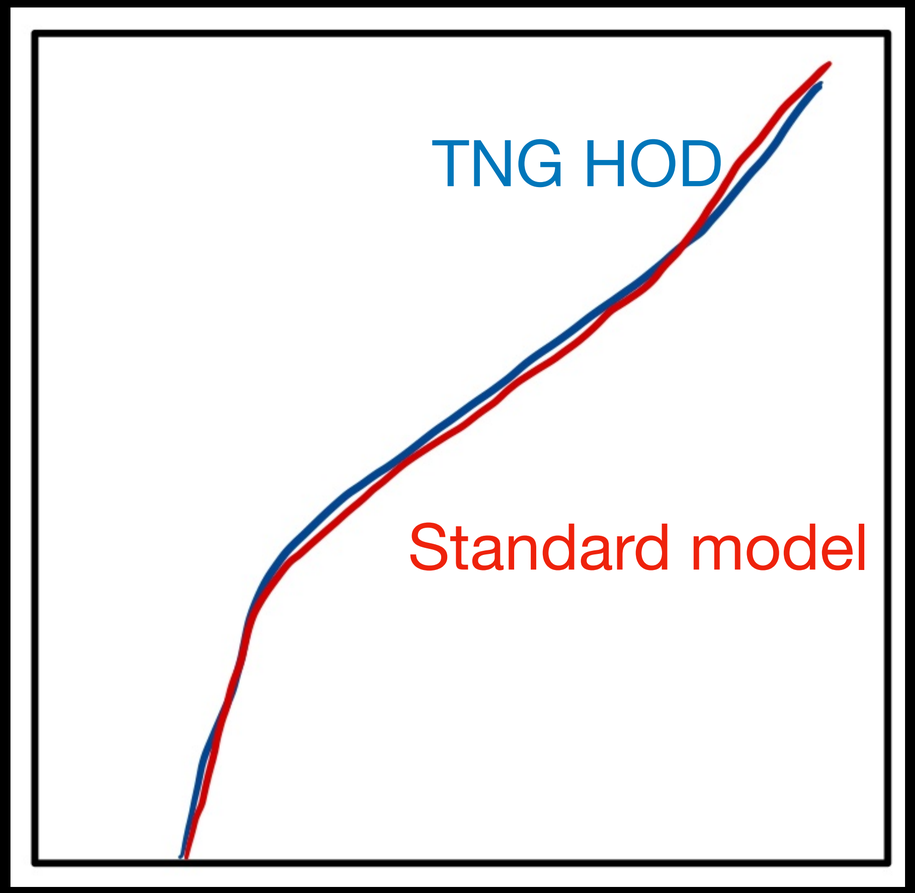
Model for the Galaxy-Halo Connection

We use TNG as “truth”



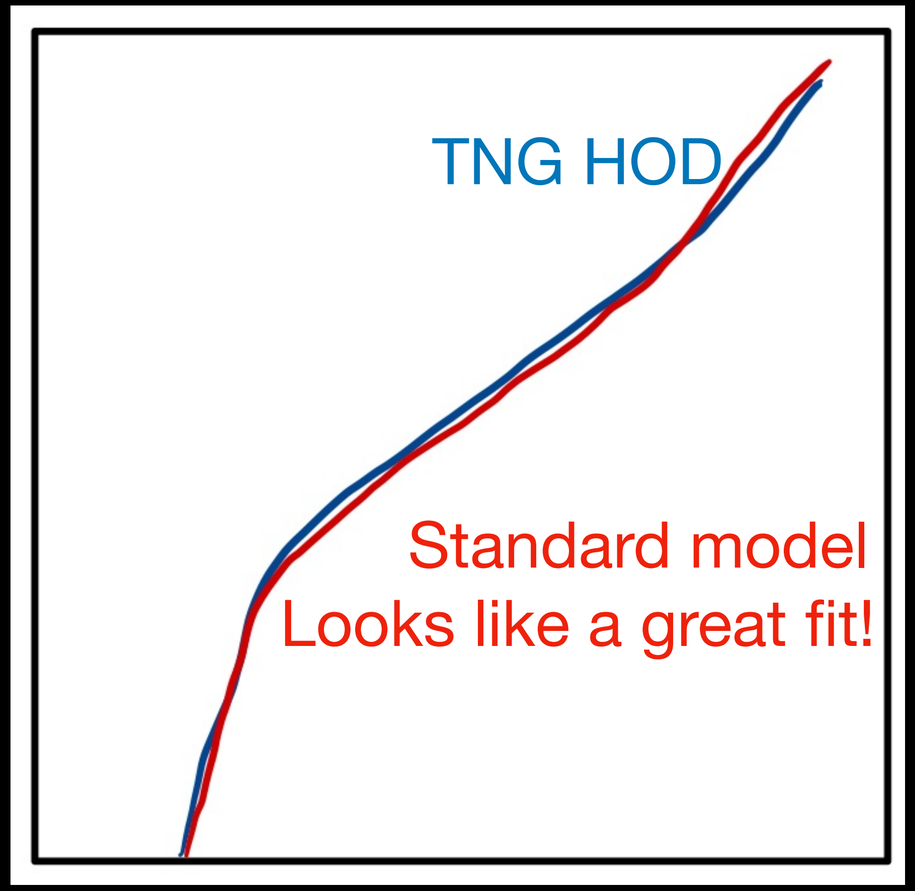
Model for the Galaxy-Halo Connection

We create a standard model (using mass only) and compare.



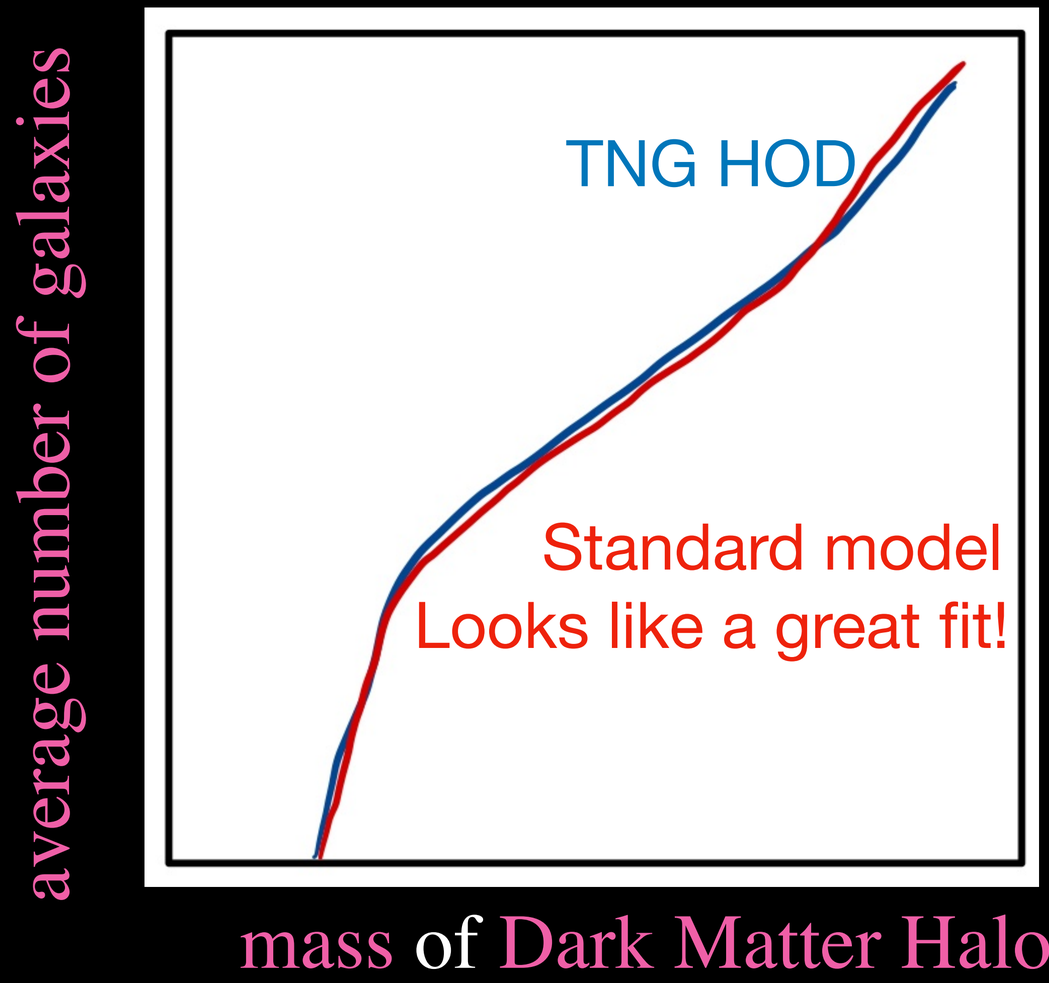
Model for the Galaxy-Halo Connection

We create a model (using ML) and compare.



Model for the Galaxy-Halo Connection

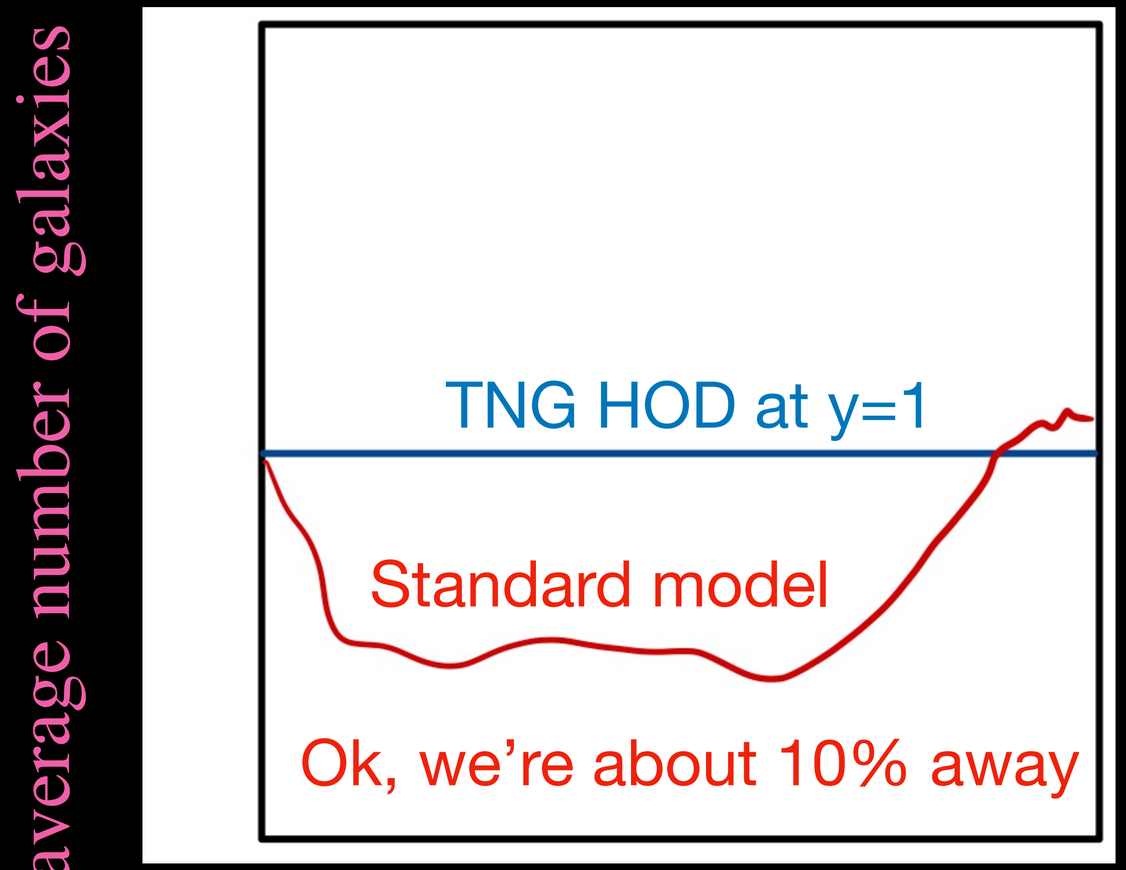
We create a model (using ML) and compare.



But we need to consider a more robust evaluation!

Model for the Galaxy-Halo Connection

We can compare as a *ratio with* TNG HOD



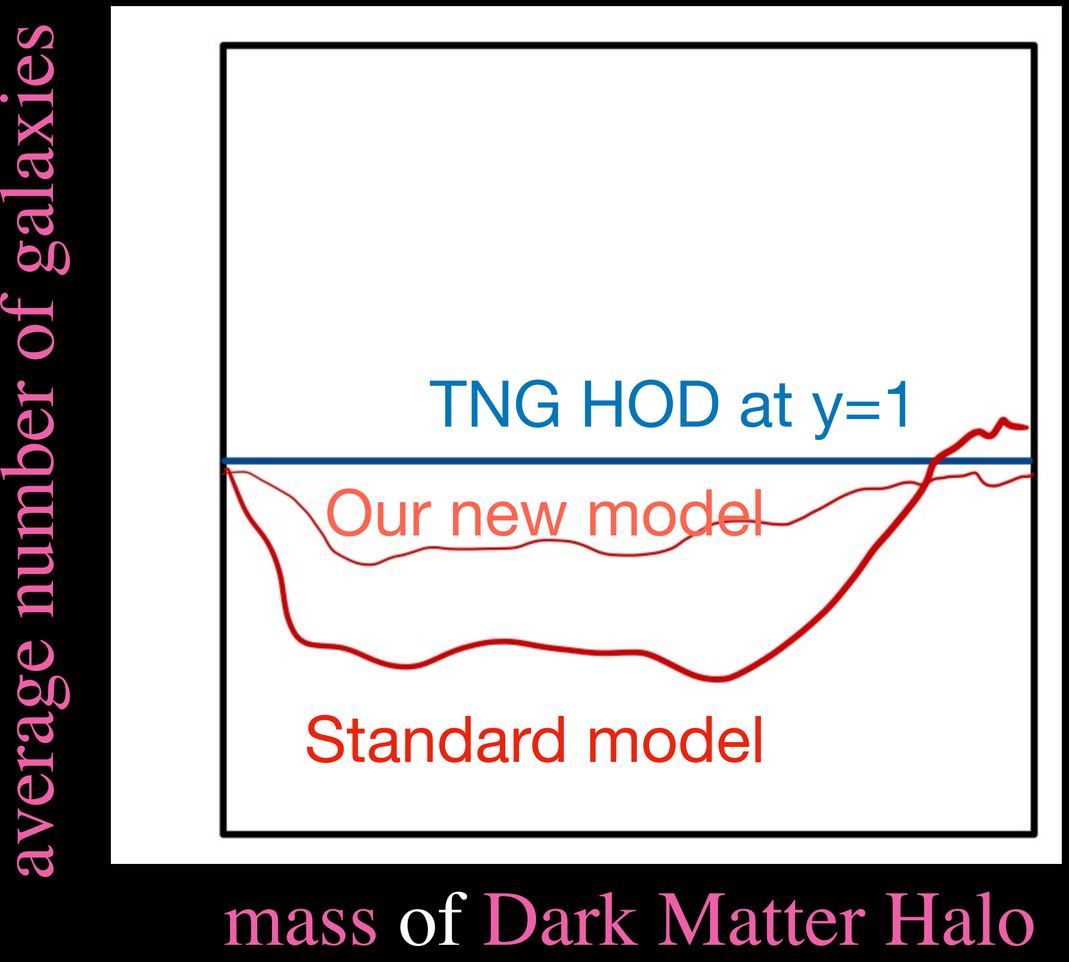
TNG HOD / TNG HOD

model / TNG HOD

Model for the Galaxy-Halo Connection

We create a *new* model (again, using ML).

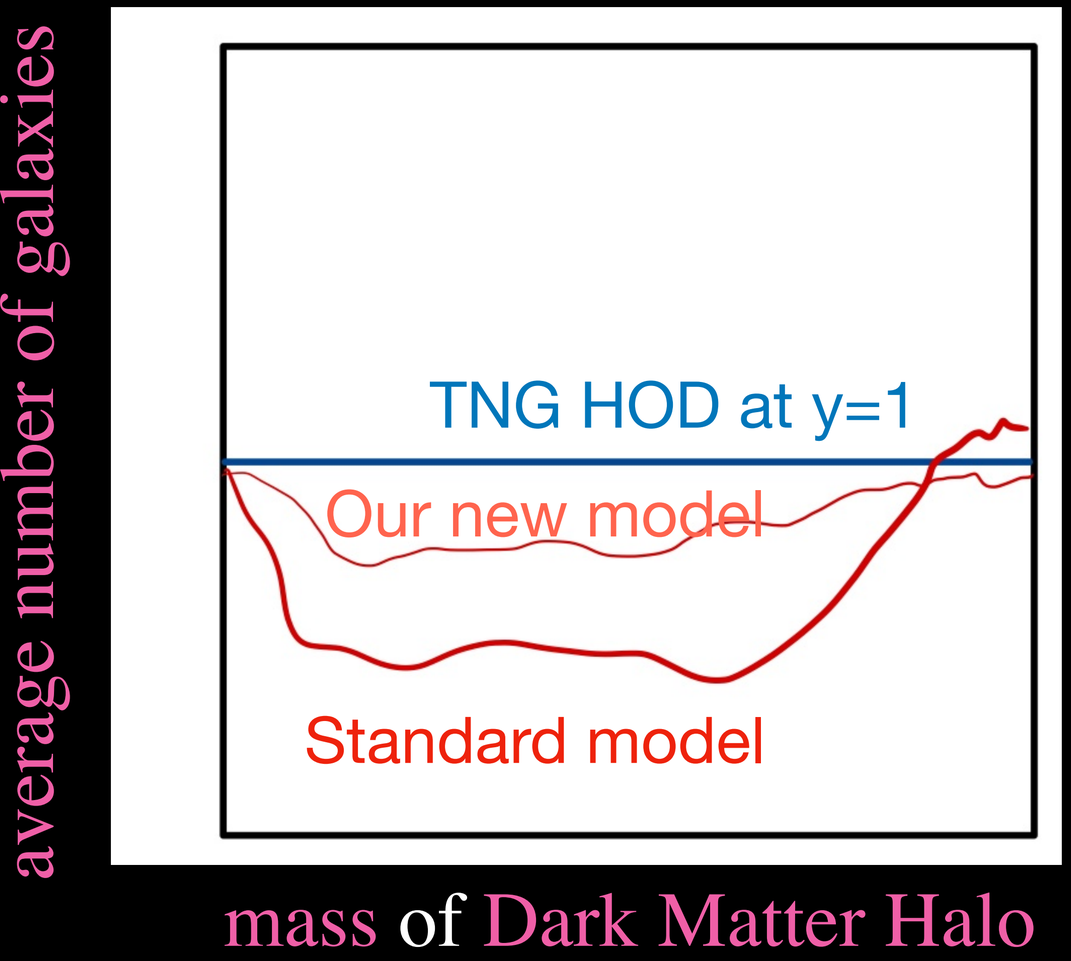
Compare new model as a *ratio with* TNG HOD



Model for the Galaxy-Halo Connection

We create a *new* model (again, using ML).

Compare new model as a *ratio with* TNG HOD



Our new model is closer!