A 'How To' Guide To Simulating The Universe

Dr. Adam Batten

Swinburne University of Technology

Public Astronomy Lecture
27-05-2022

SWINBURNE UNIVERSITY OF TECHNOLOGY

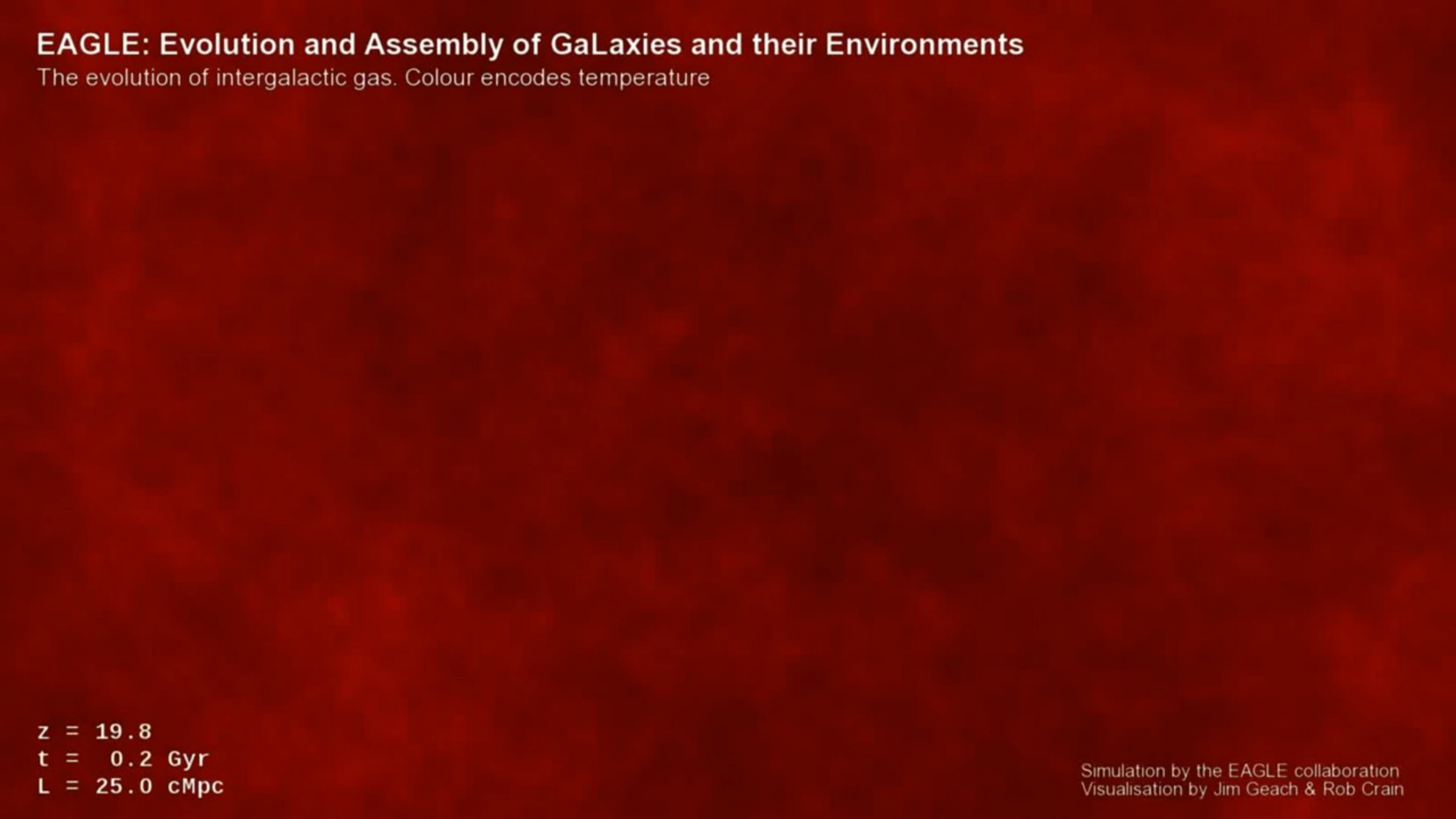
EAGLE: Evolution and Assembly of GaLaxies and their Environments
The evolution of intergalactic gas. Colour encodes temperature
z = 19.8
t = 0.2 Gyr
L = 25.0 cMpc
Simulation by the EAGLE collaboration
Visualisation by Jim Geach & Rob Crain

Image Credit: https://www.epcc.ed.ac.uk


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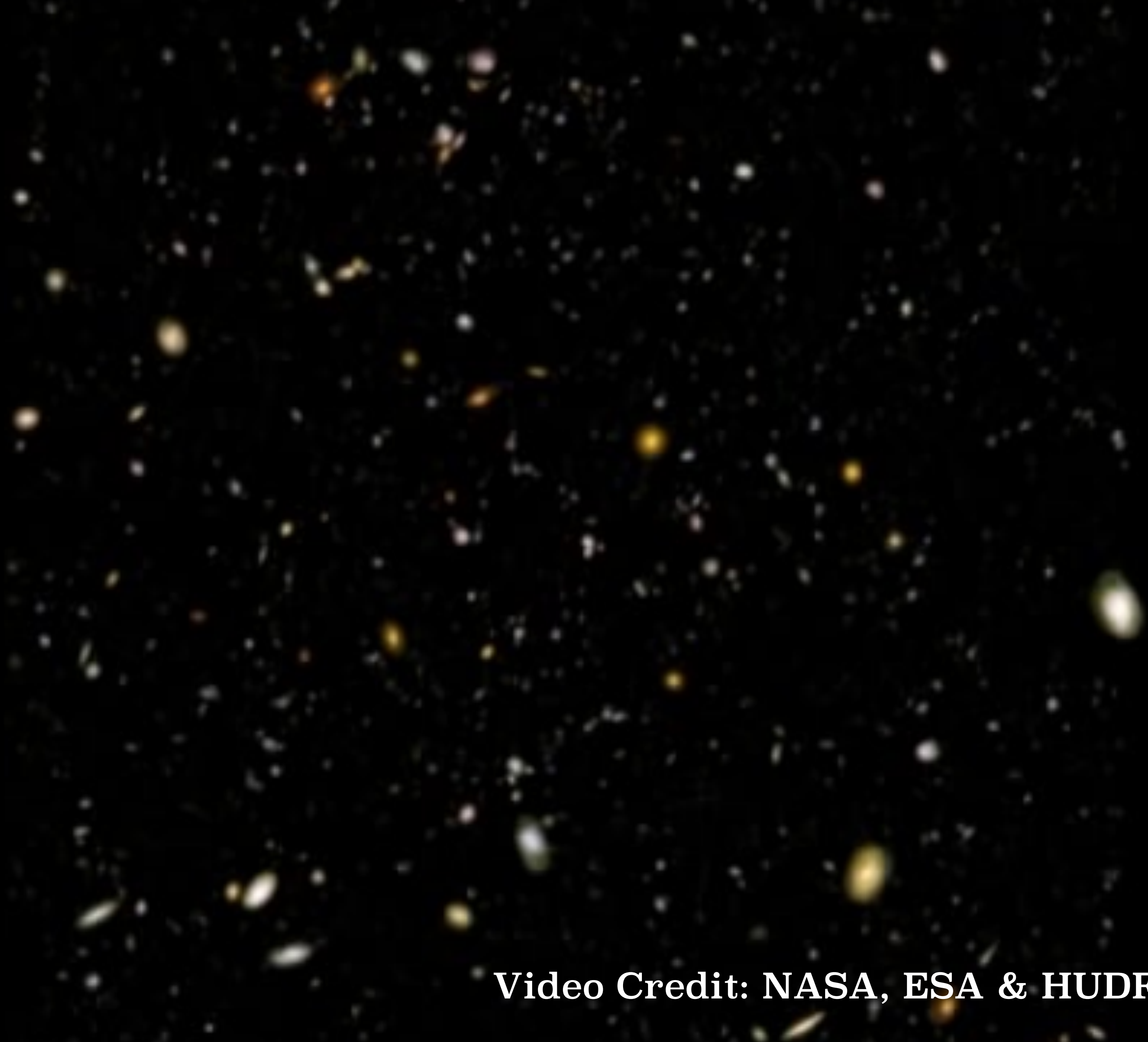
TECHNOLOGY
OzSTAR
Supercomputing

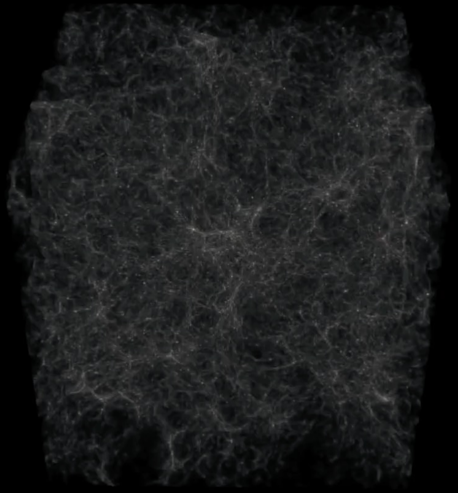
The necessary bits required to simulate the Universe

0. Gravity
1. Cosmic Microwave Background
2. Dark Matter
3. Atoms
4. Stars
5. Black Holes
6. Feedback

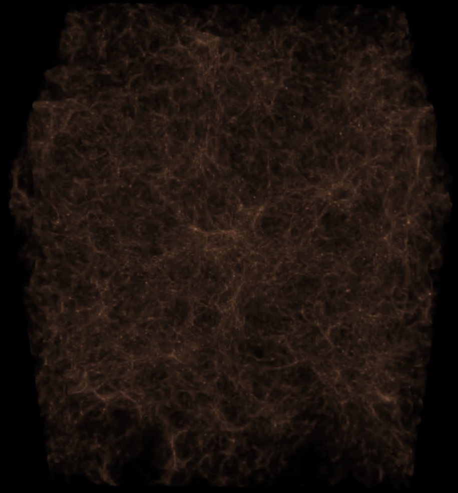
Image Credit: Ángel R. López-Sánchez (AAO-MQ)



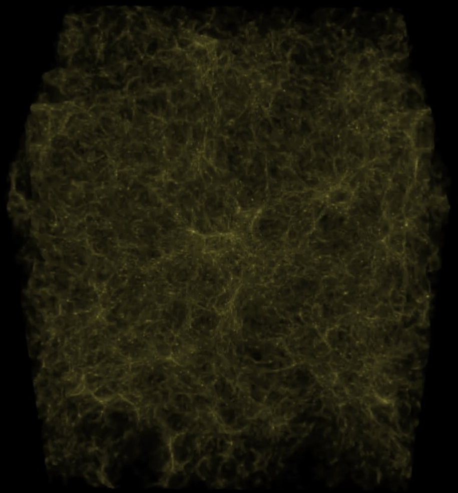
Video Credit: NASA, ESA & HUDF Team (STScI)



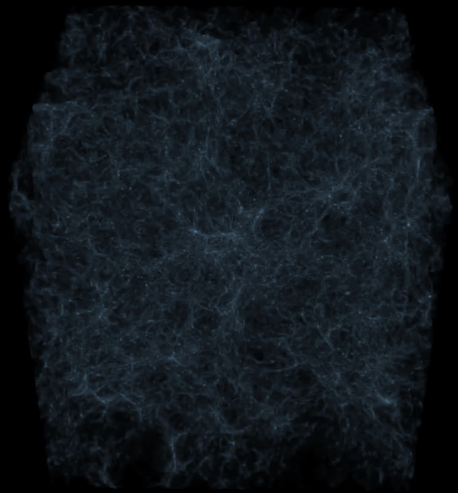
Normal Universe



No Supermassive Black Holes



Strong Supermassive Black Holes



Stronger Supernovae

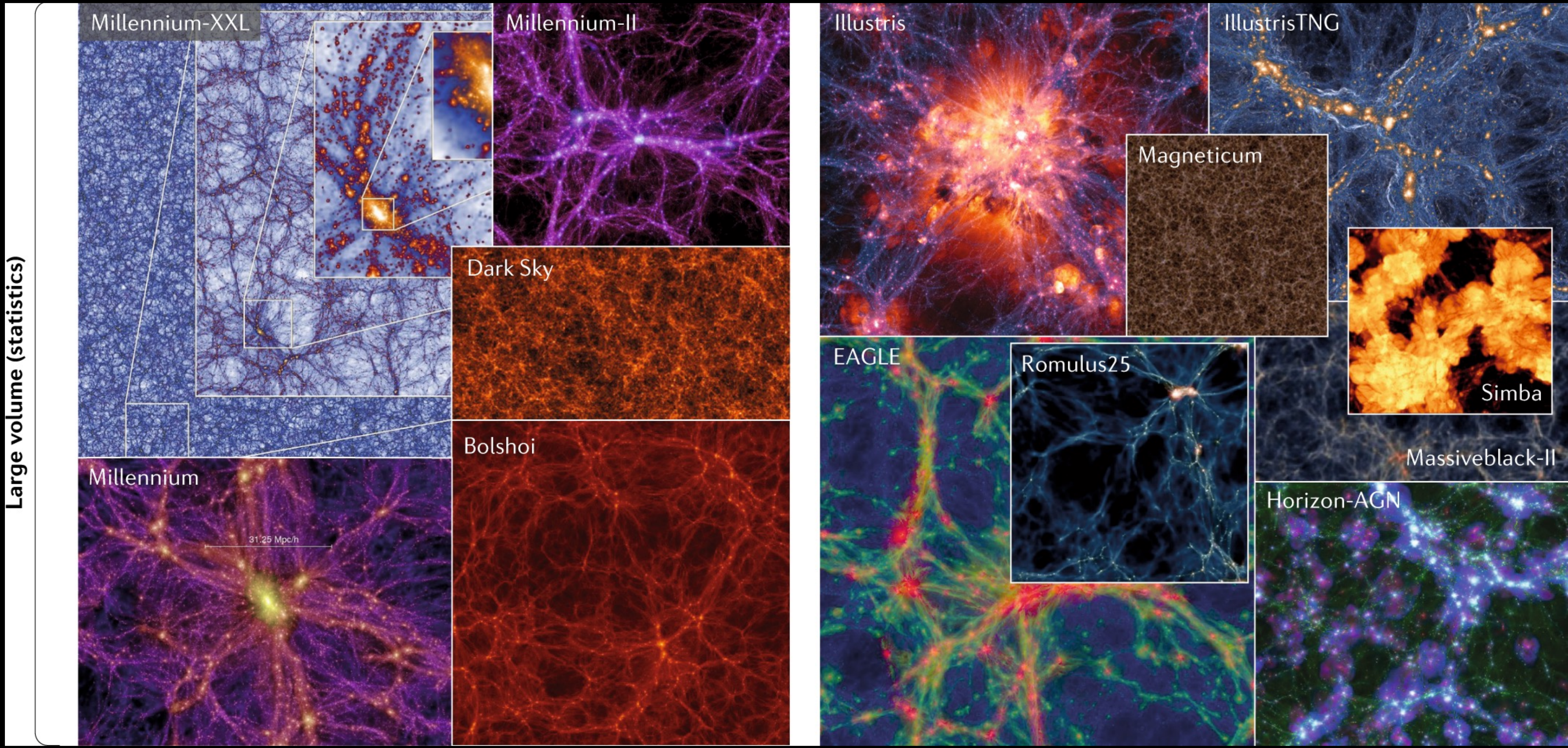


Image Credit: Vogelsberger et al. (2020)

0. Gravity

0. Gravity

General Relativity:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi \mathrm{G}}{c^4} T_{\mu\nu}$$

0. Gravity

~~**General Relativity:**~~

$$\cancel{G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}}$$

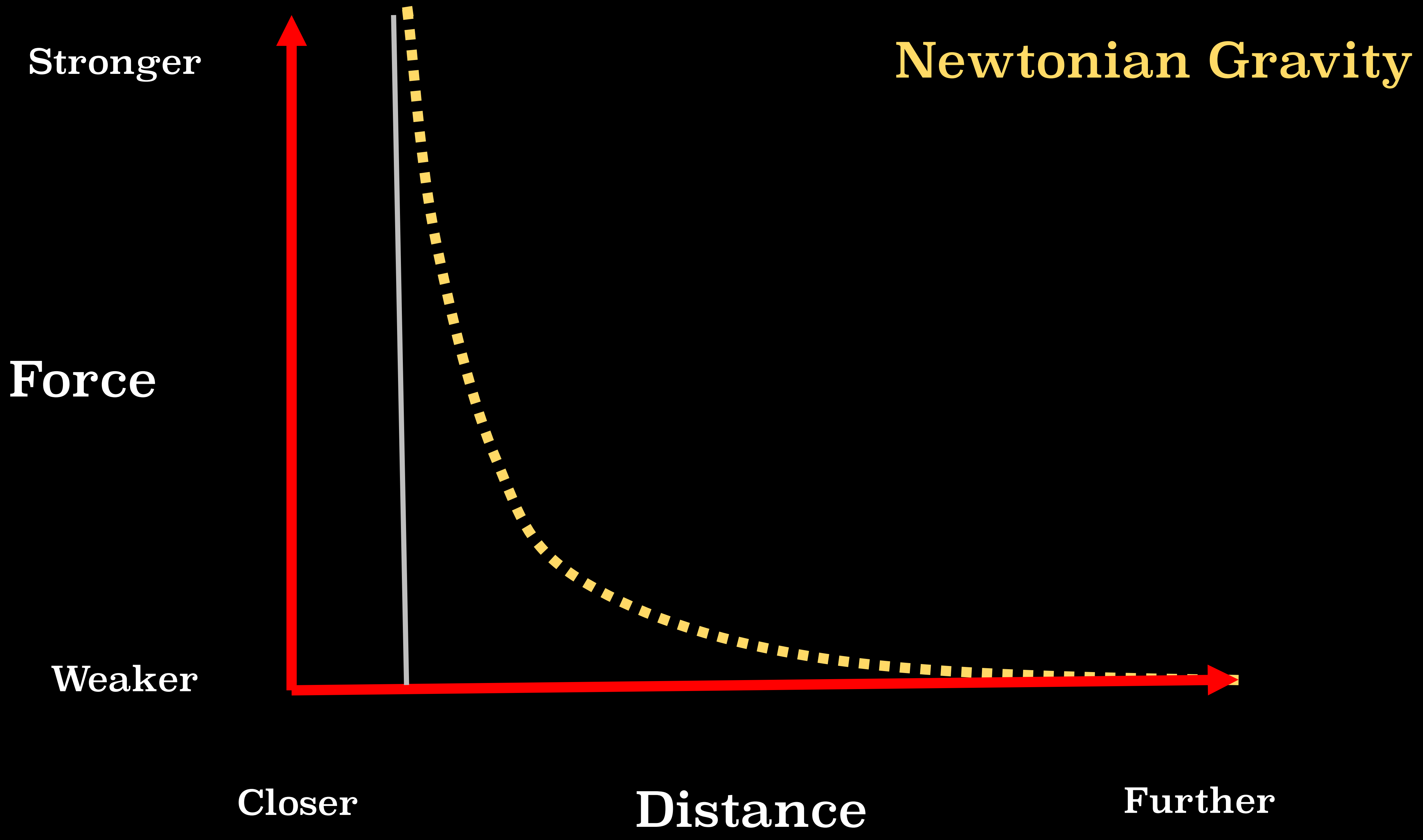
0. Gravity

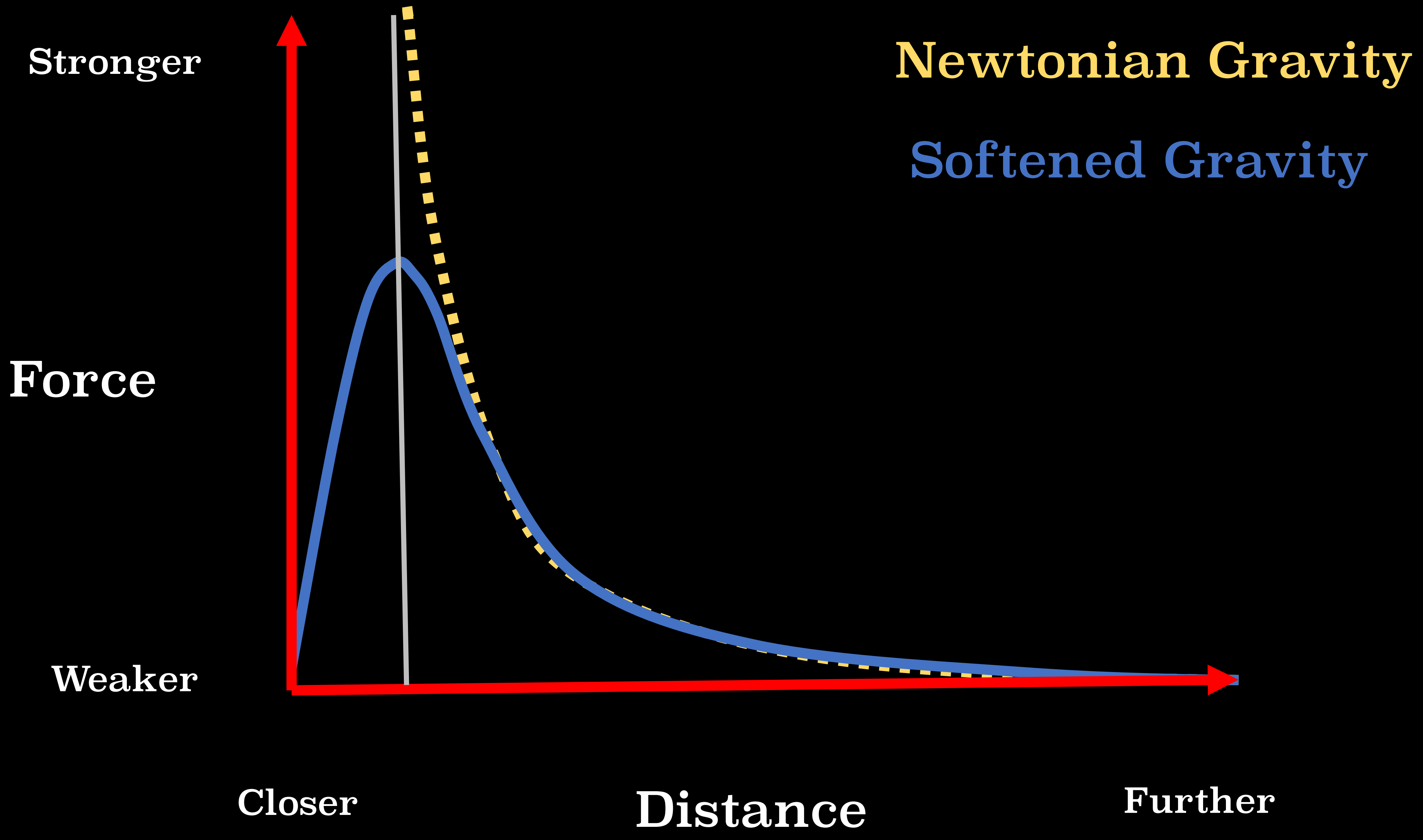
~~General Relativity:~~

$$\cancel{G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi \mathrm{G}}{c^4} T_{\mu\nu}}$$

Newtonian Gravity:

$$F = -\frac{G m_1 m_2}{r^2}$$

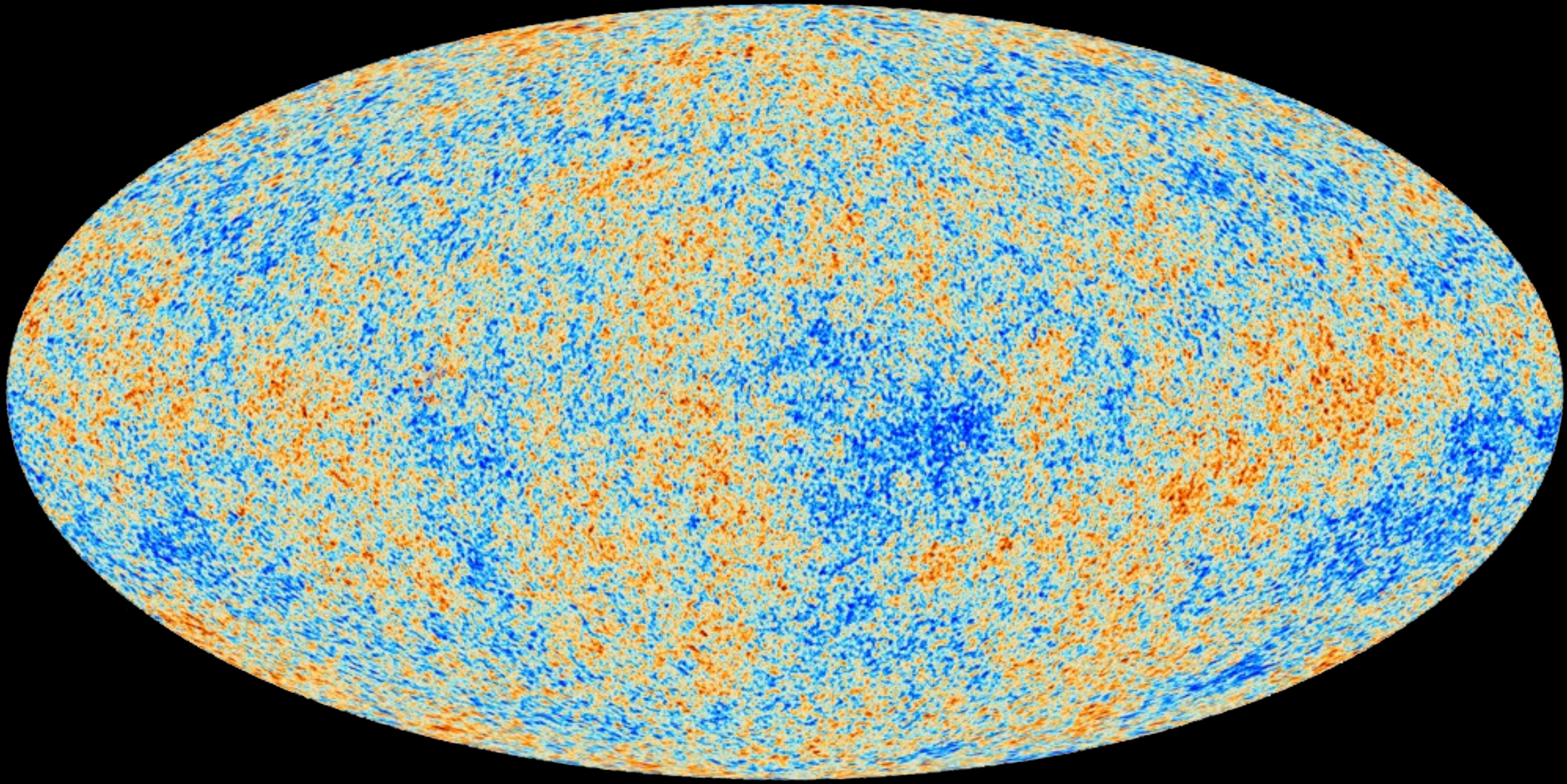

Newtonian Gravity
Stronger
Force
Weaker
Closer
Distance
Further


Newtonian Gravity
Softened Gravity
Stronger
Force
Weaker
Closer
Distance
Further

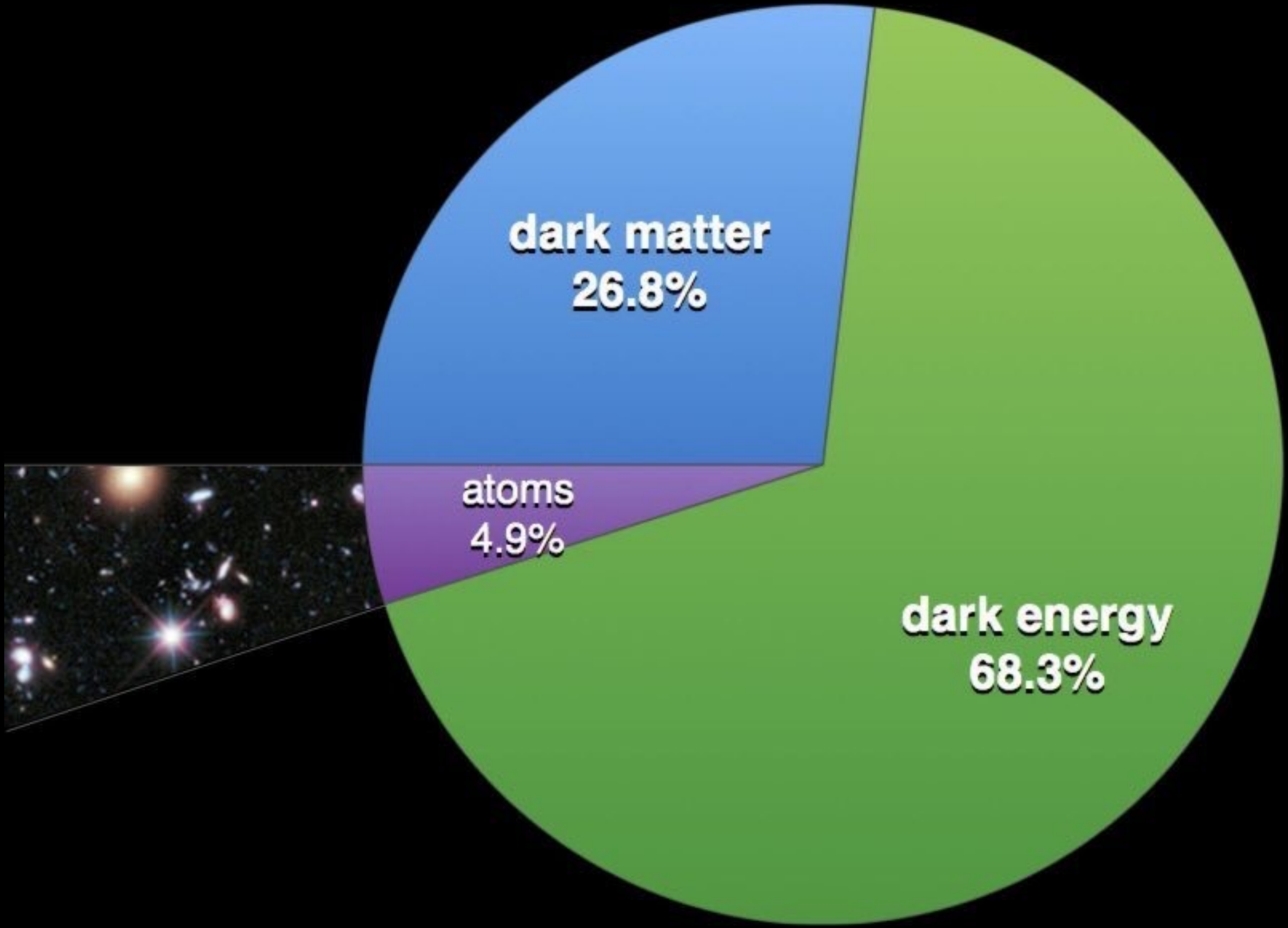
Where do we start everything?

1. Cosmic Microwave Background

1. Cosmic Microwave Background

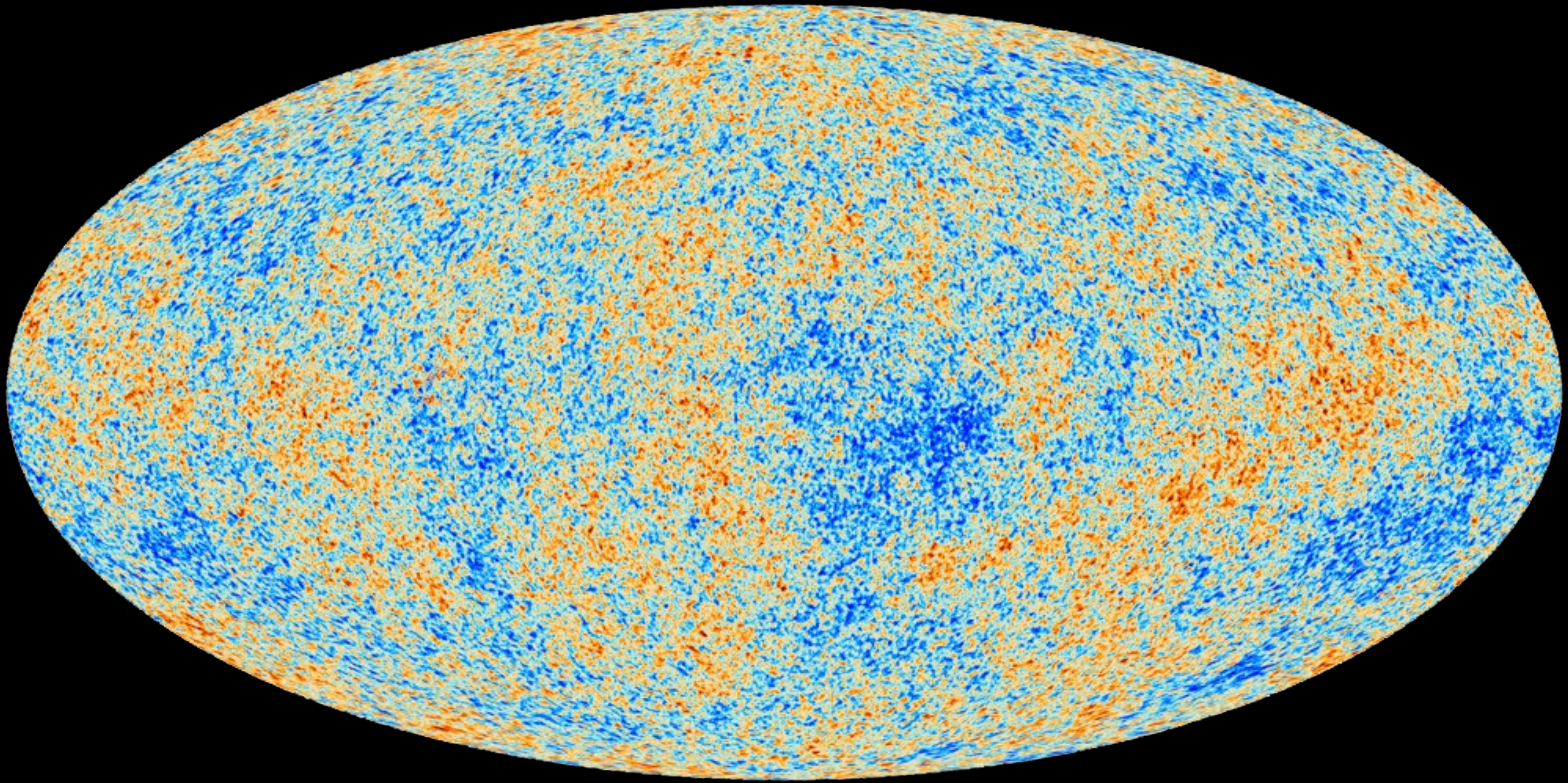


2. Dark Matter



@AstroKatie/Planck13

1. Cosmic Microwave Background

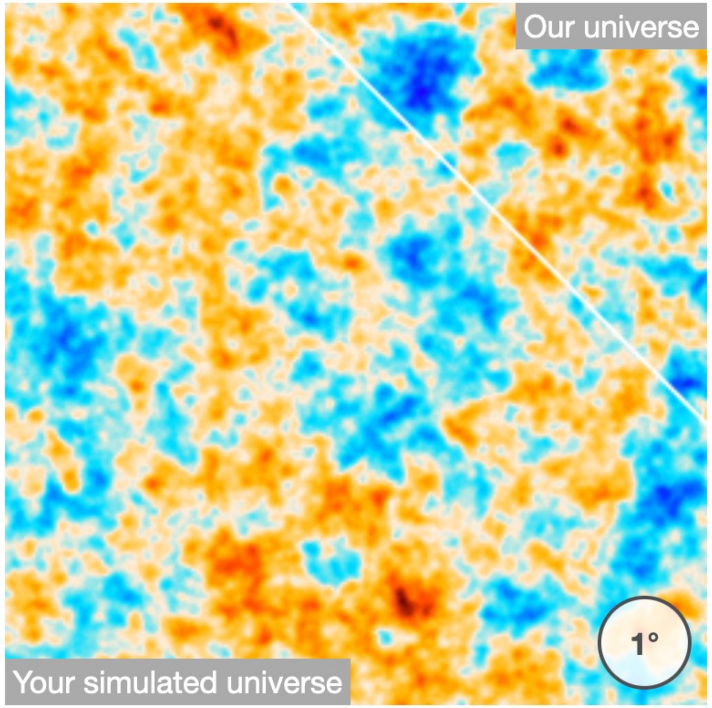


planck CMB Simulator

Normal Matter ($\Omega_b = 0.05$)

Dark Matter ($\Omega_c = 0.275$)

Dark Energy ($\Omega_\Lambda = 0.675$)



Normal matter only

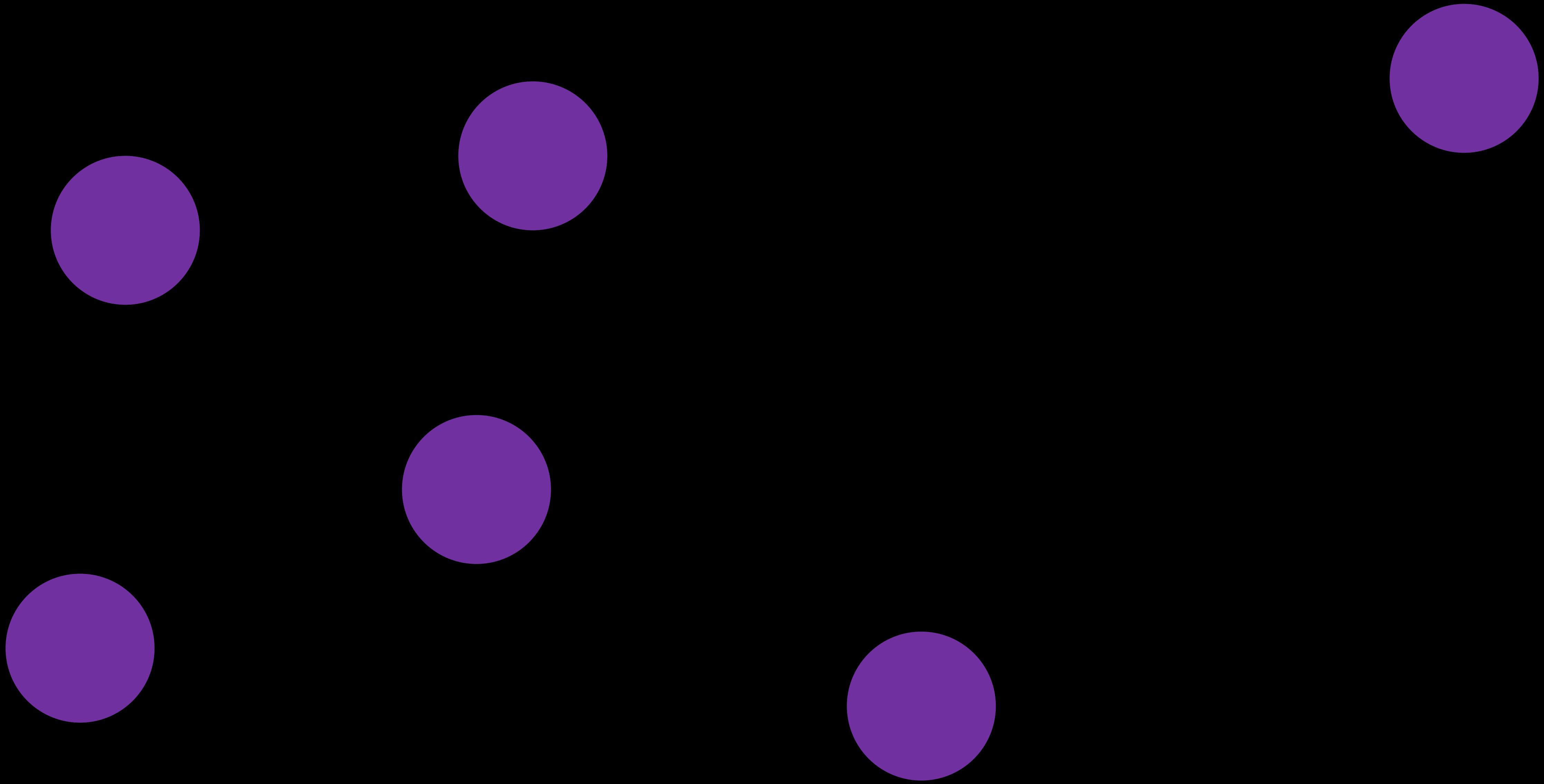
13.8 billion years old - just right

flat universe

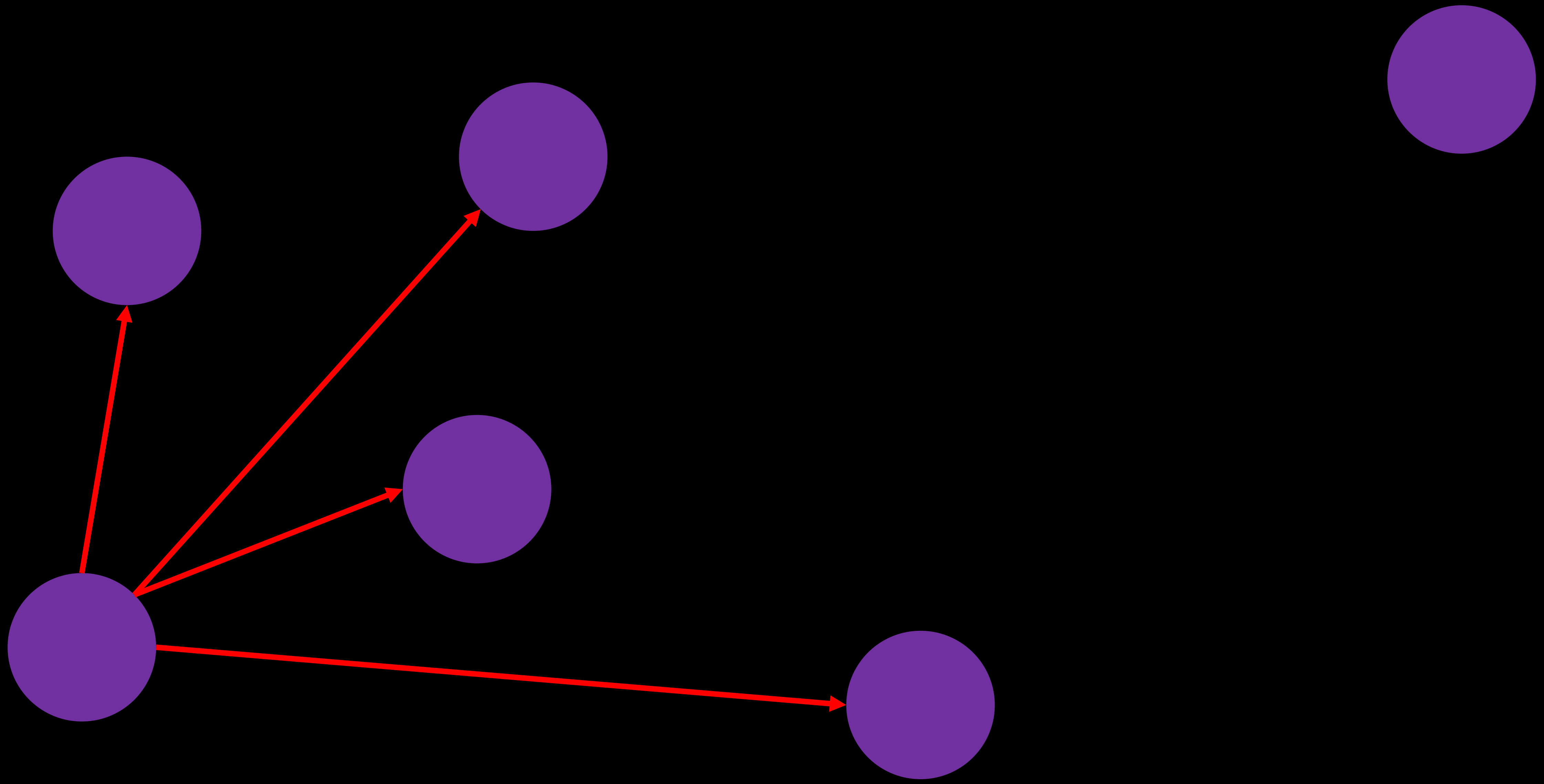
Fundamental scale ~0.8°

Universe similarity **100%** - the same as our universe

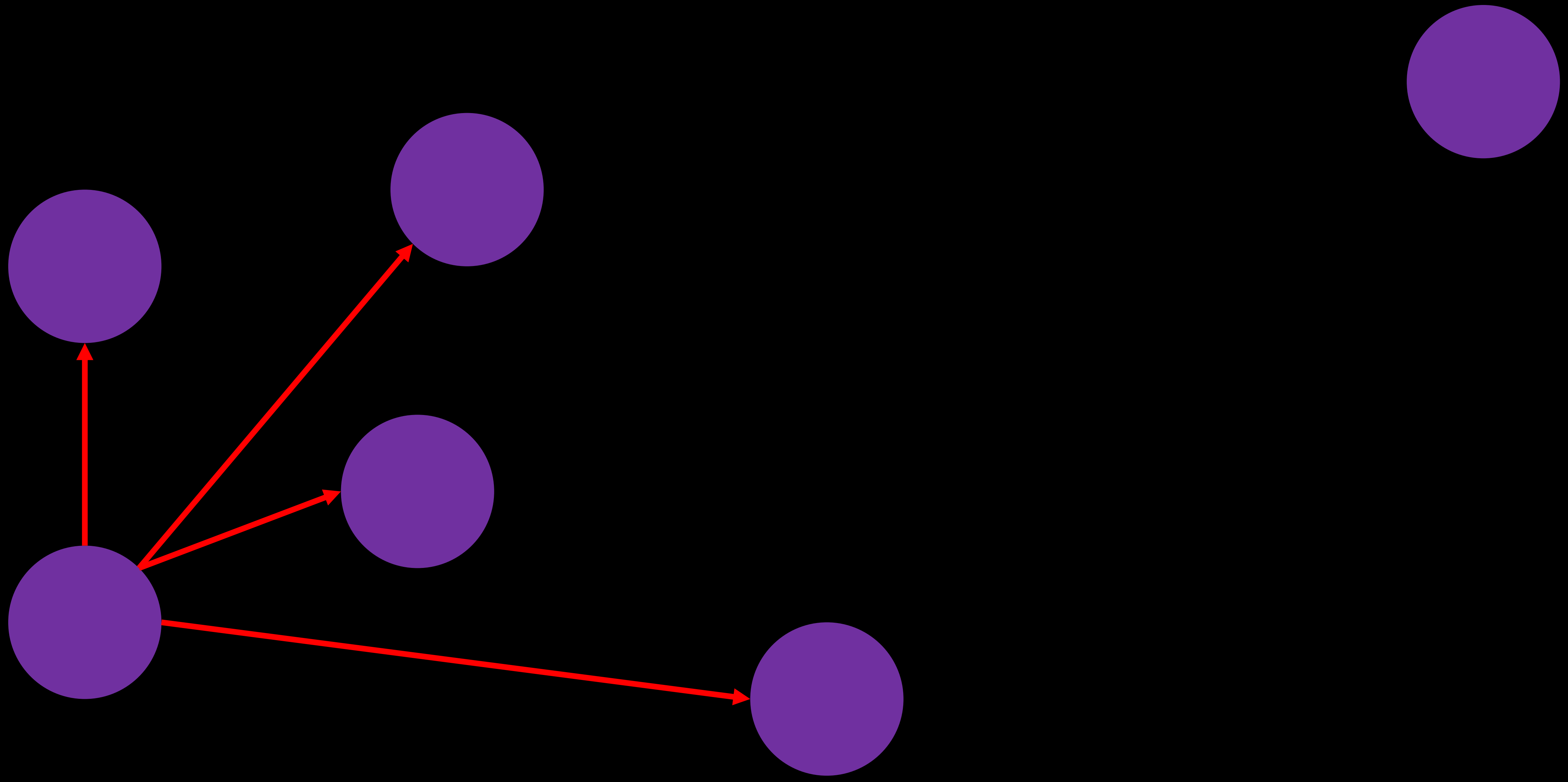
https://plancksatellite.org.uk/cmb-sim/



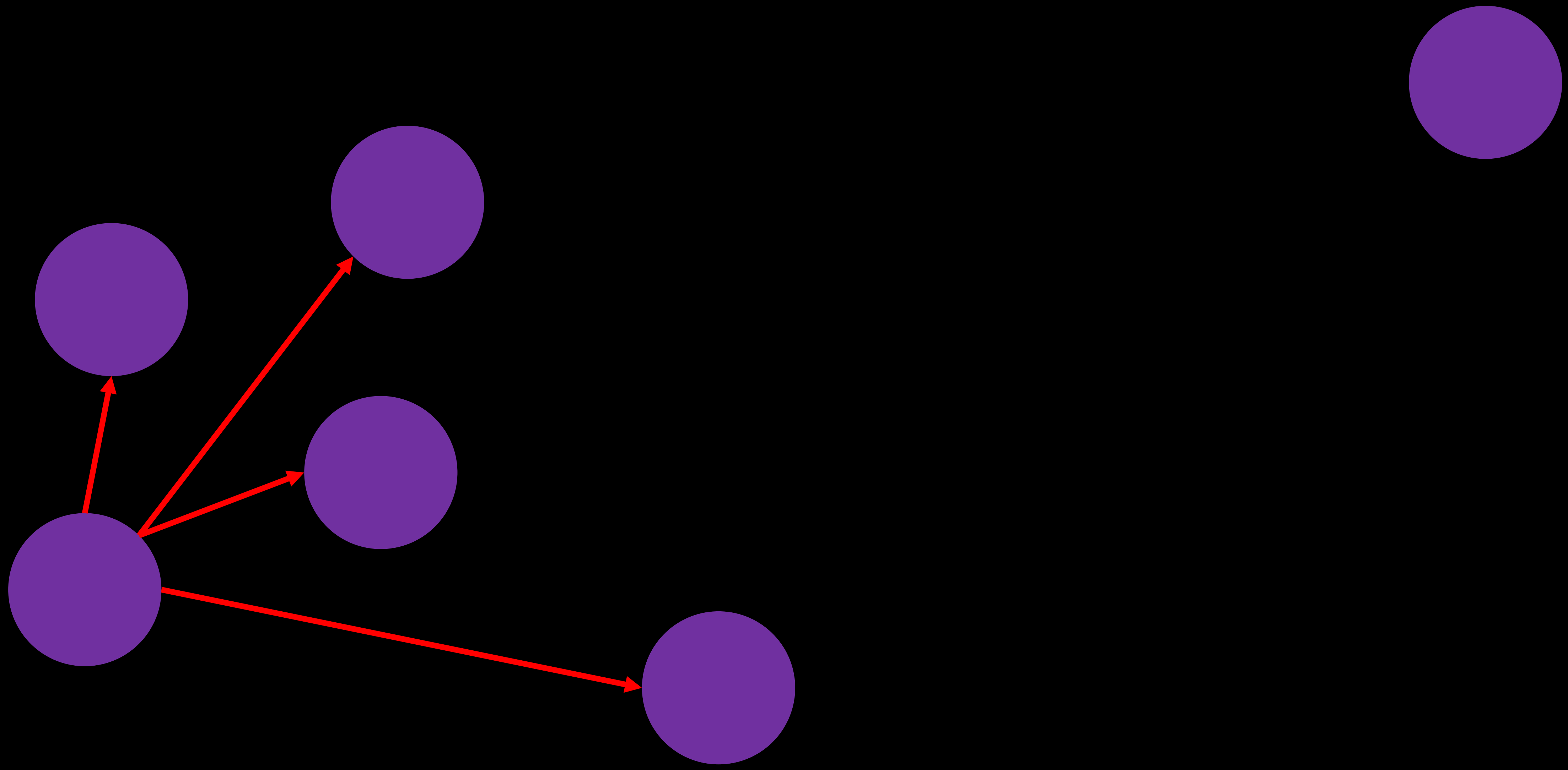
N-Body Problem



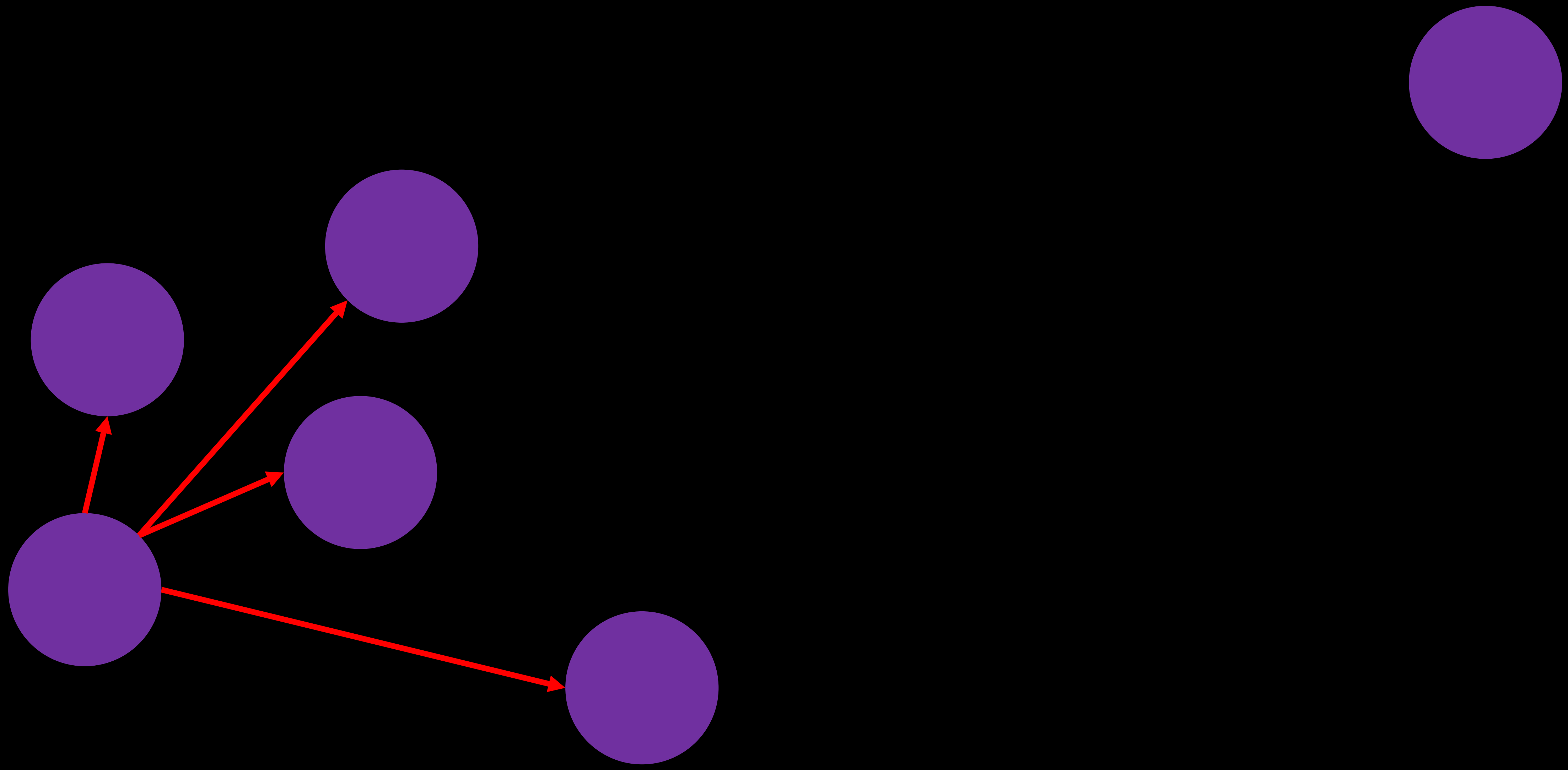
N-Body Problem



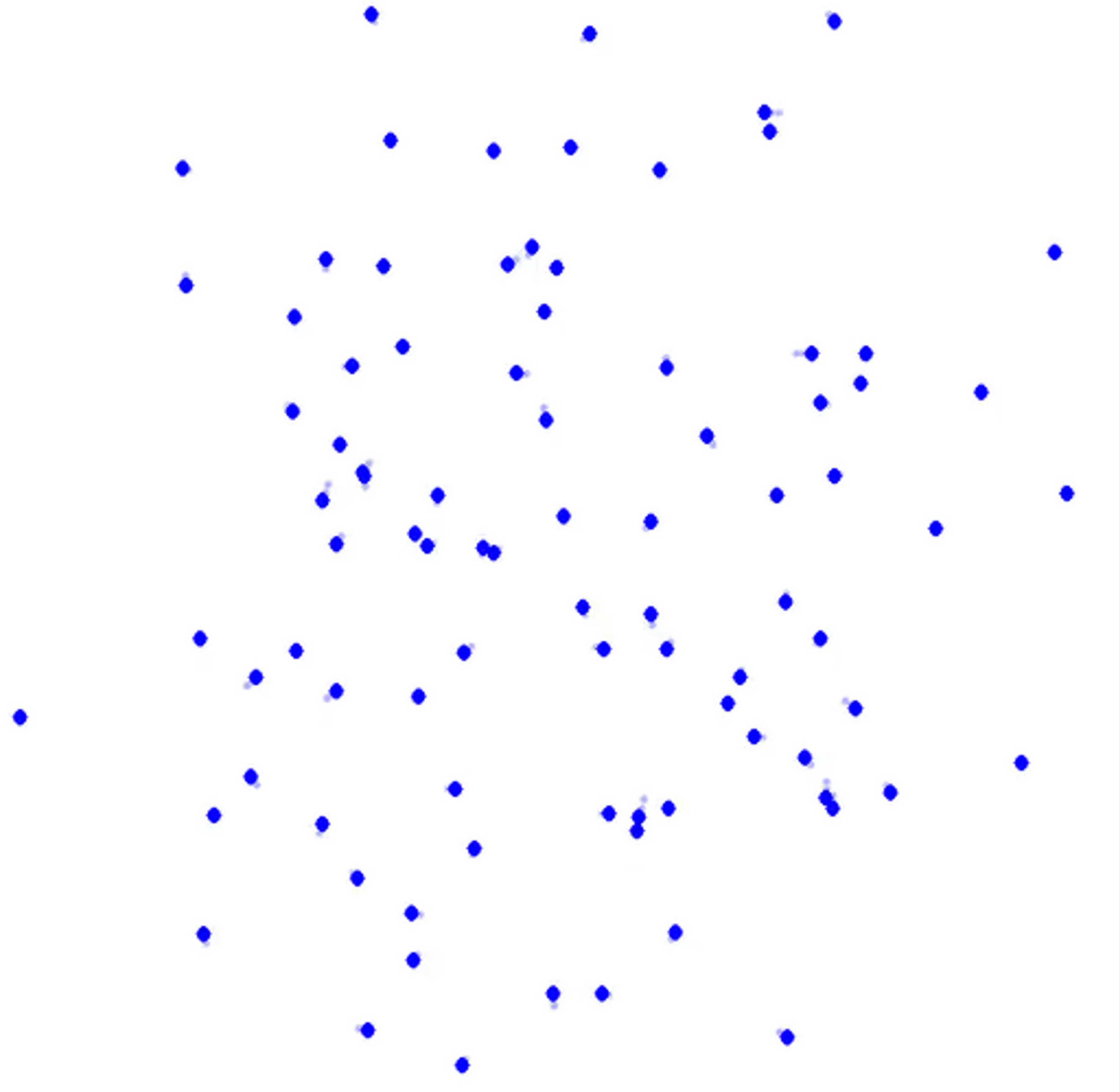
N-Body Problem



N-Body Problem

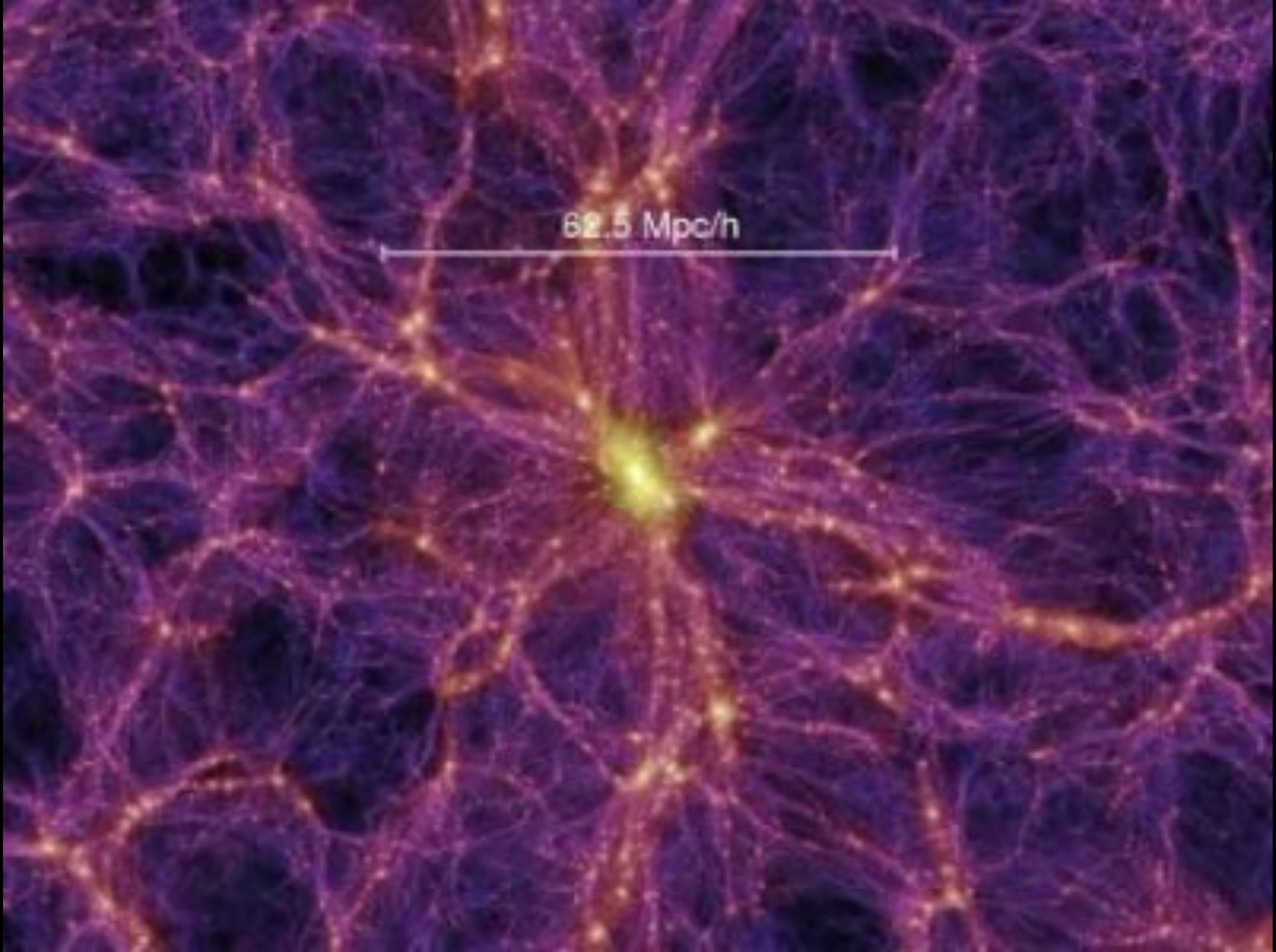


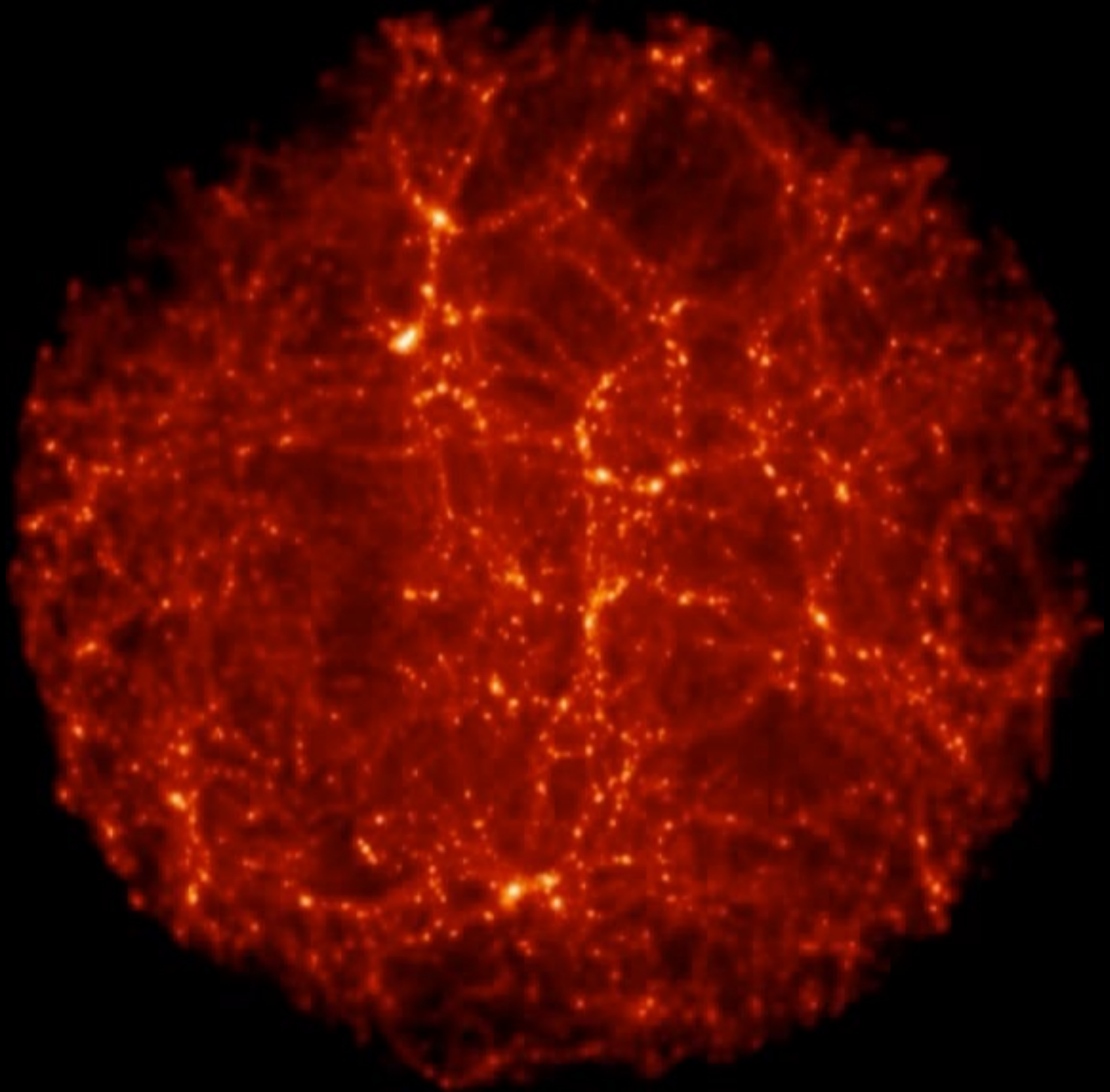
N-Body Problem



N-Body Simulations are actually relatively easy!

https://medium.com/swlh/create-your-own-n-body-simulation-with-python-f417234885e9


62.5 Mpc/h



3. Atoms

3. Atoms (Gas)

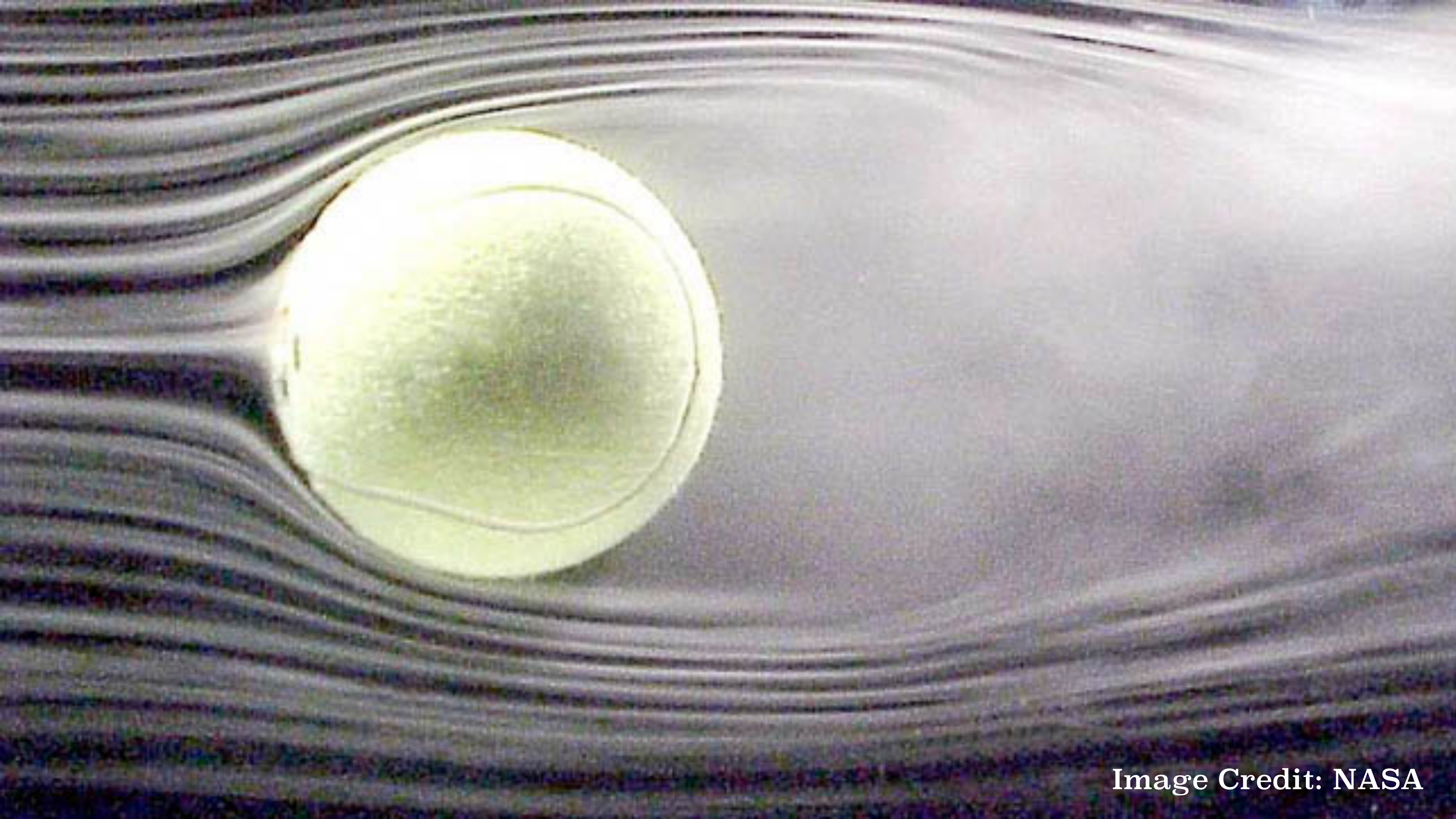
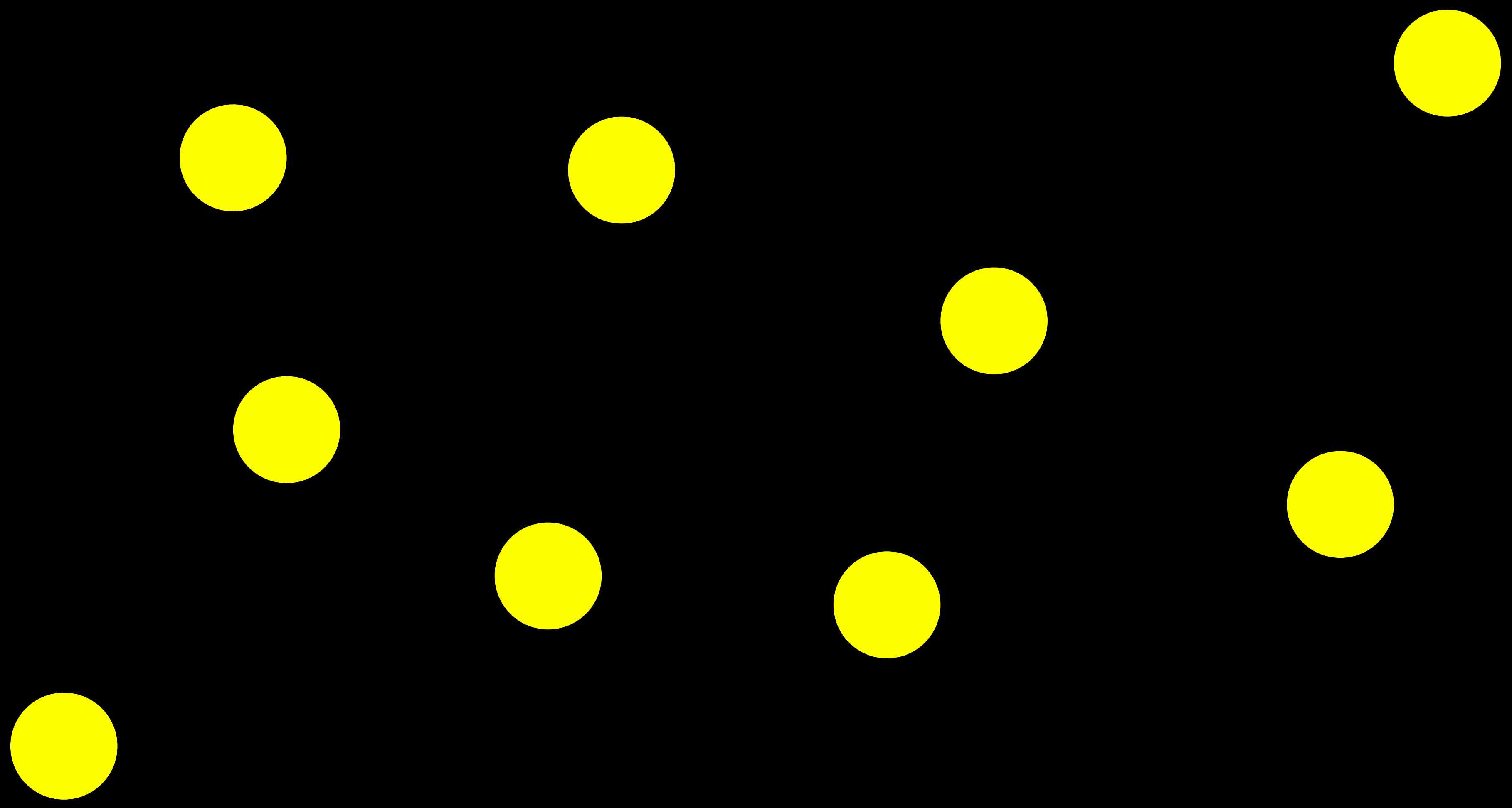
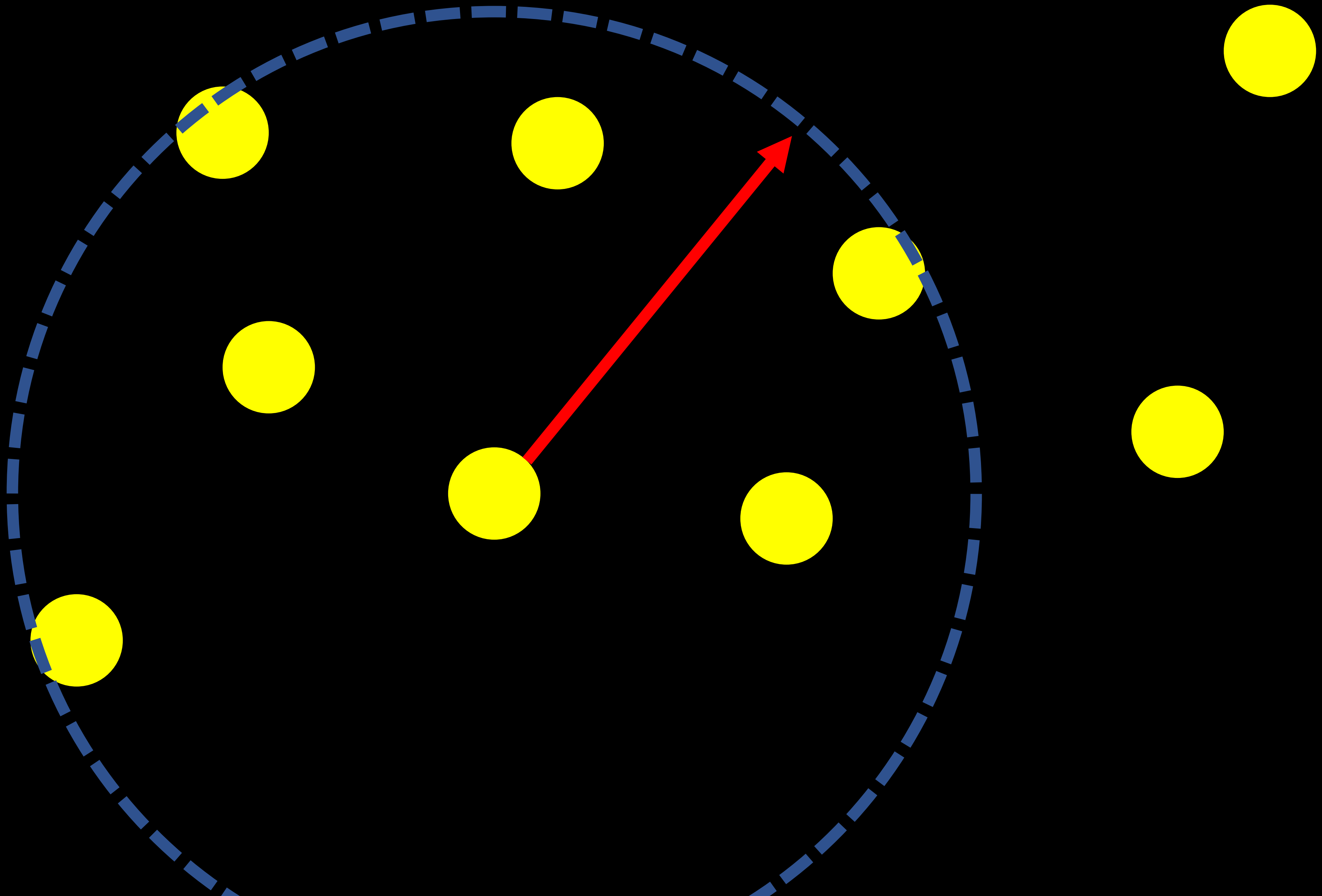
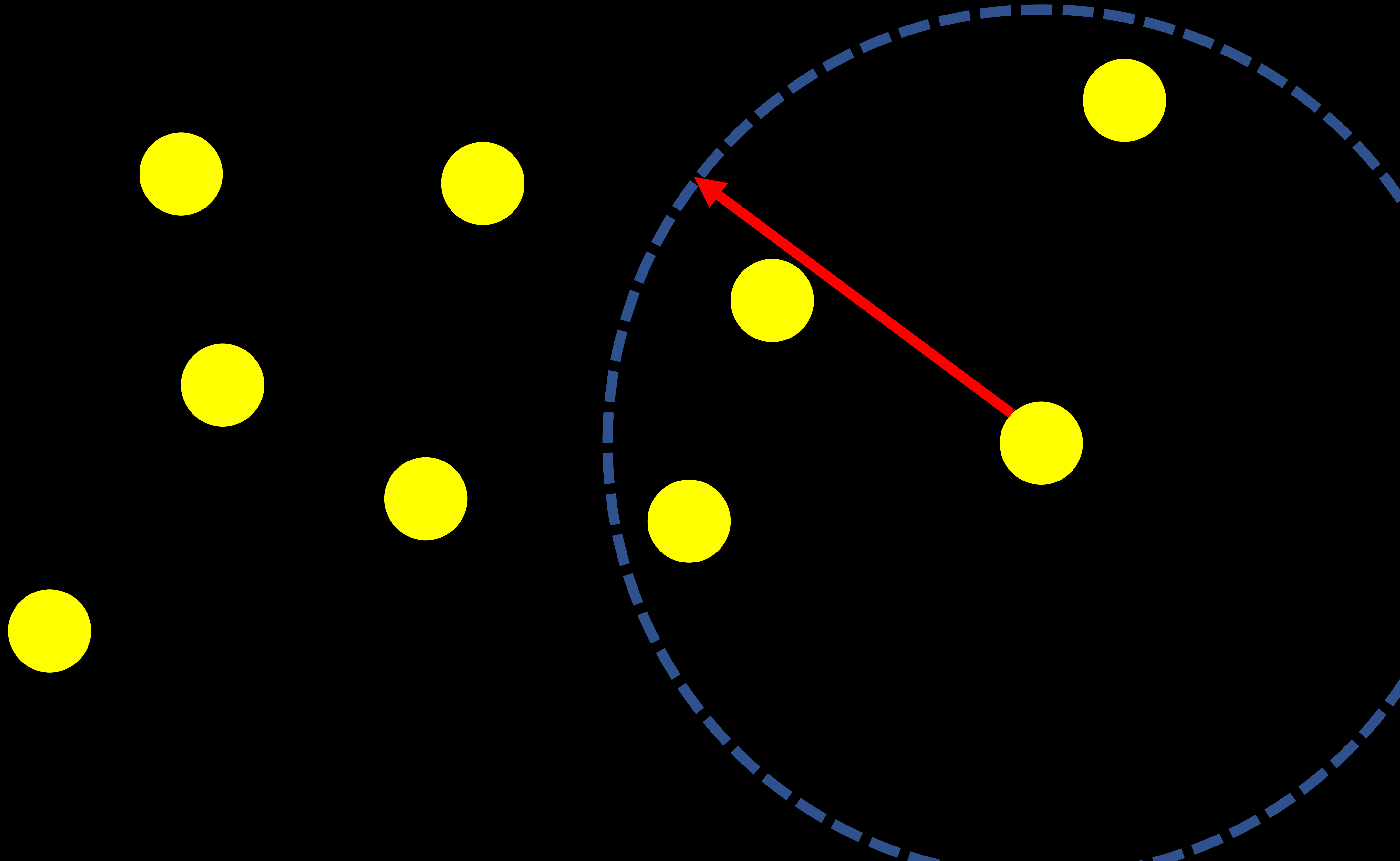
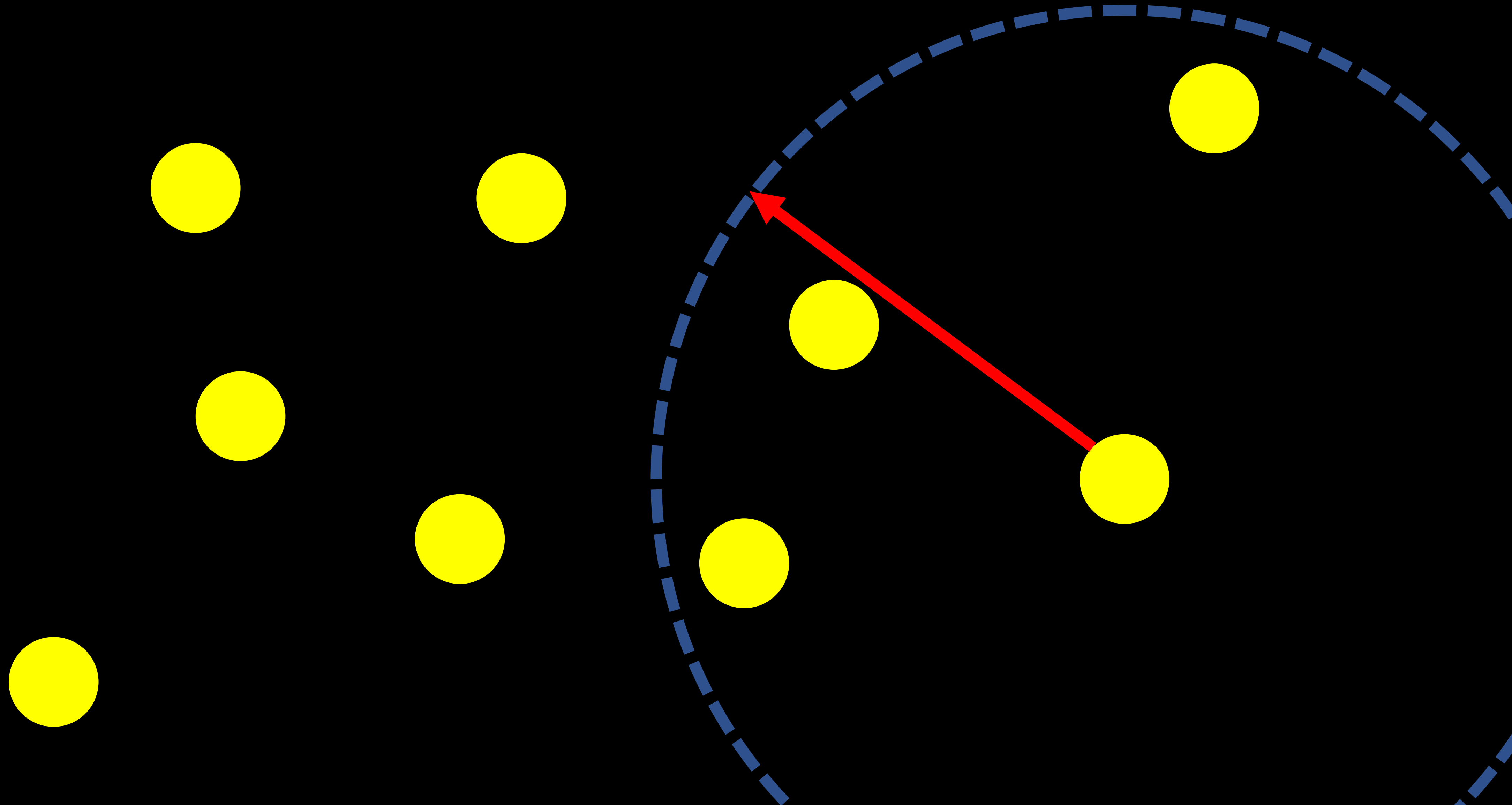


Image Credit: NASA

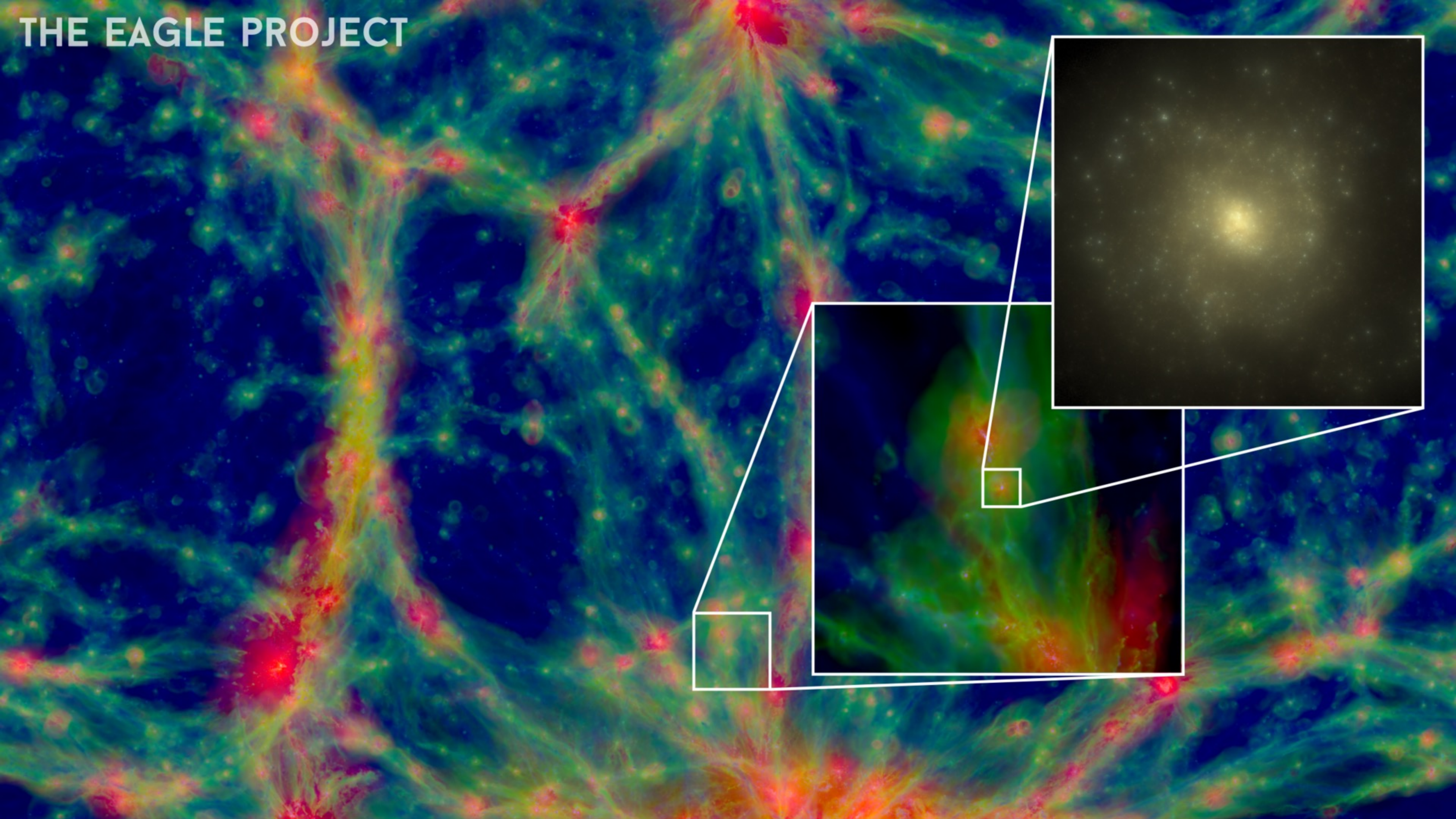




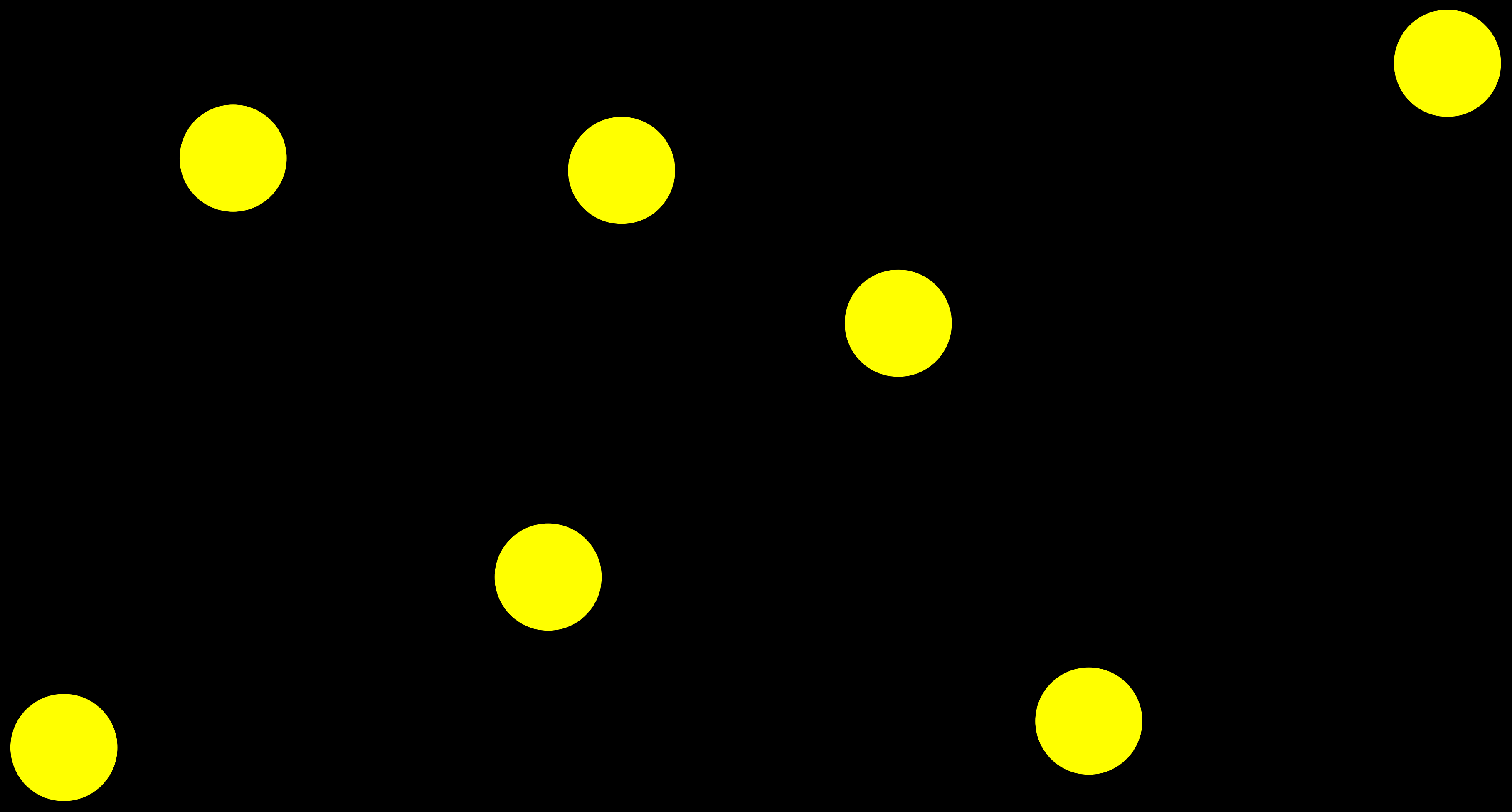


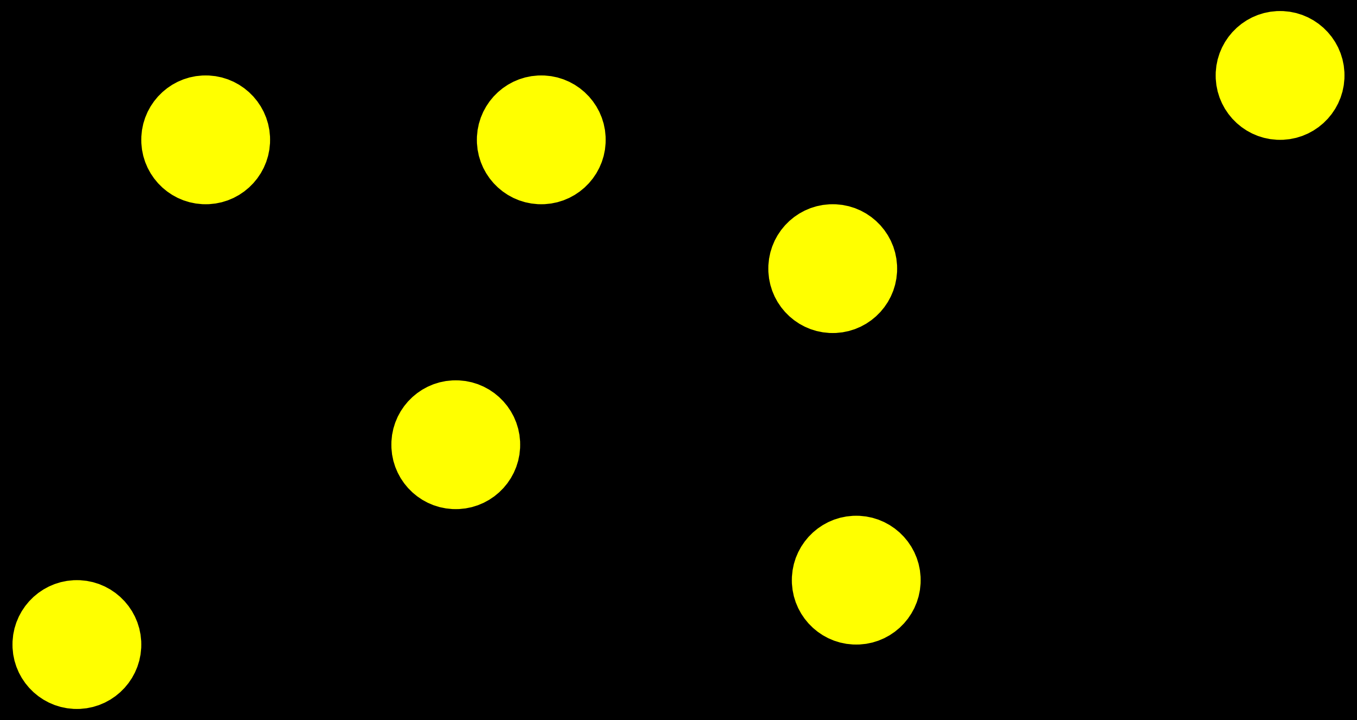


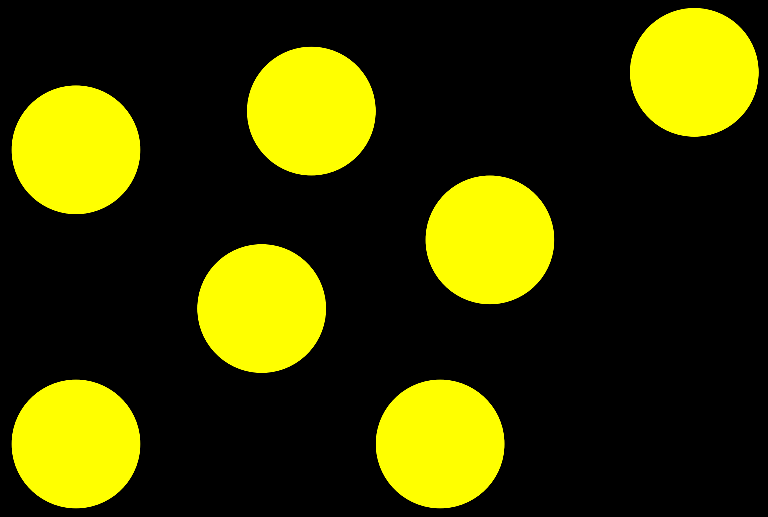
Smooth Particle Hydrodynamics

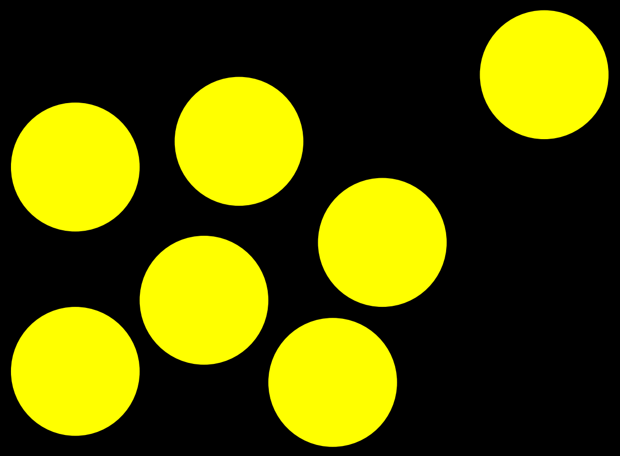

THE EAGLE PROJECT

4. Stars

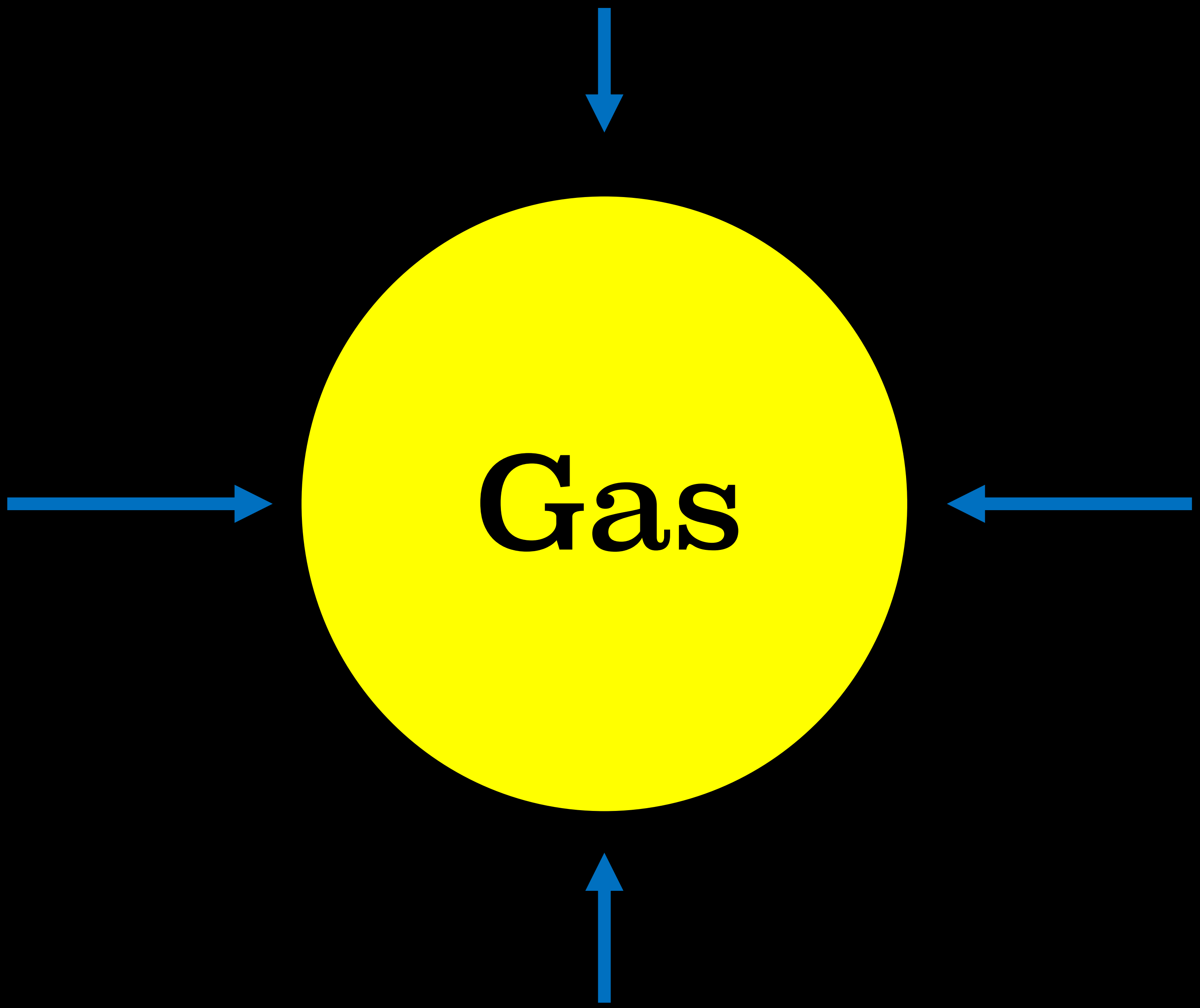


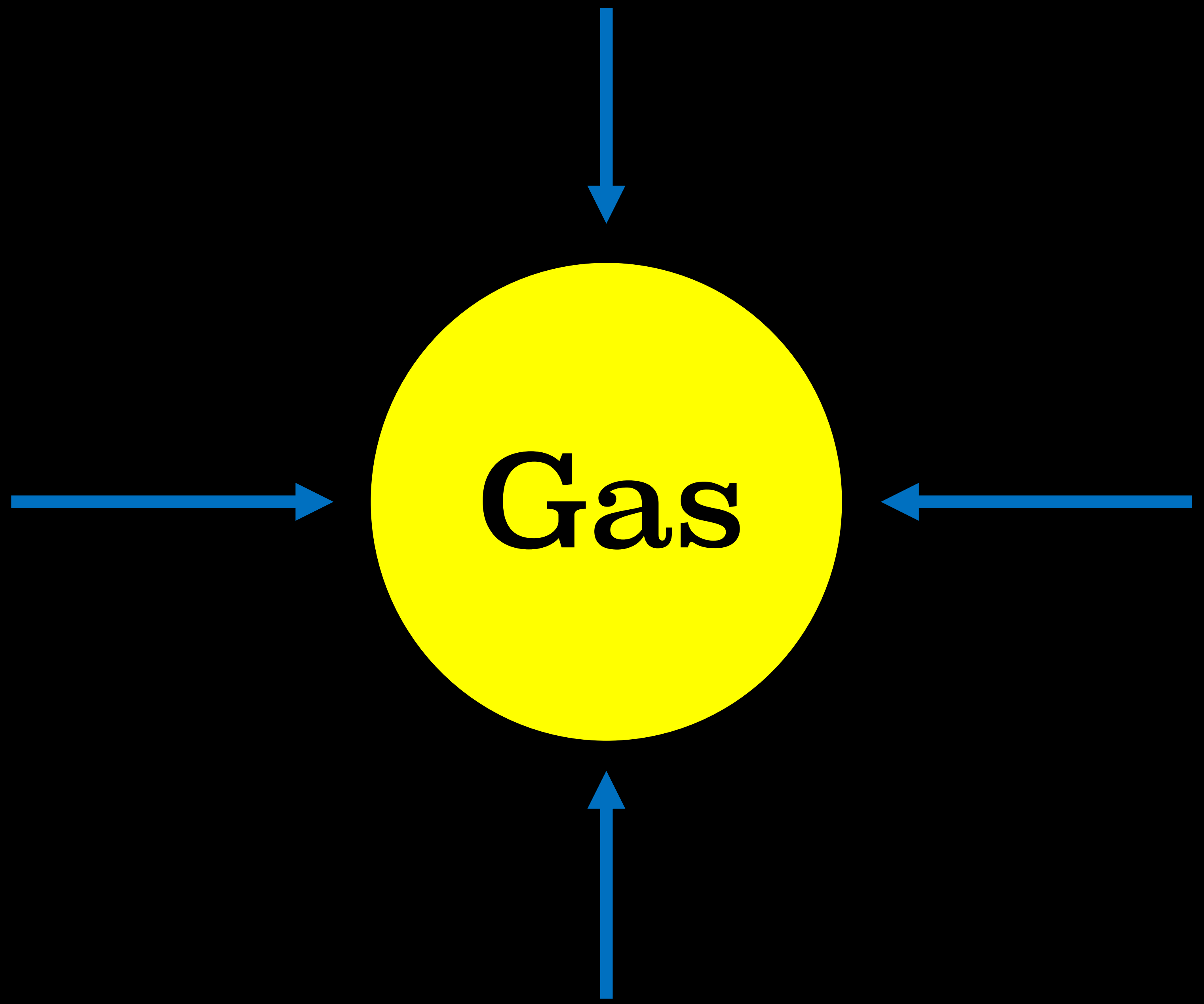




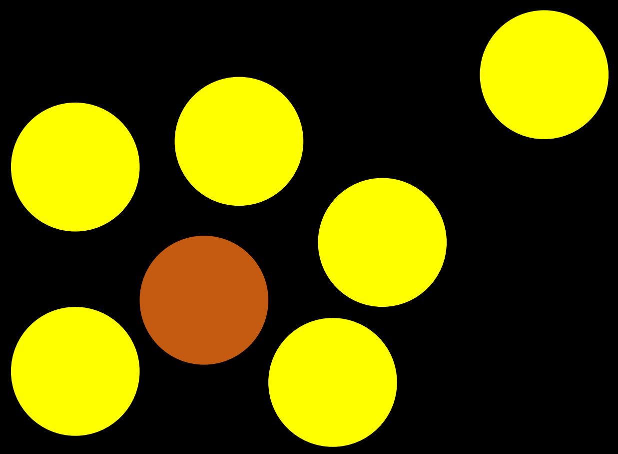


Gas


Gas


Gas

Star



Gas Evolution

Stars Evolution

Videos Credit: Adam Ussing (Swinburne)

5. Black Holes

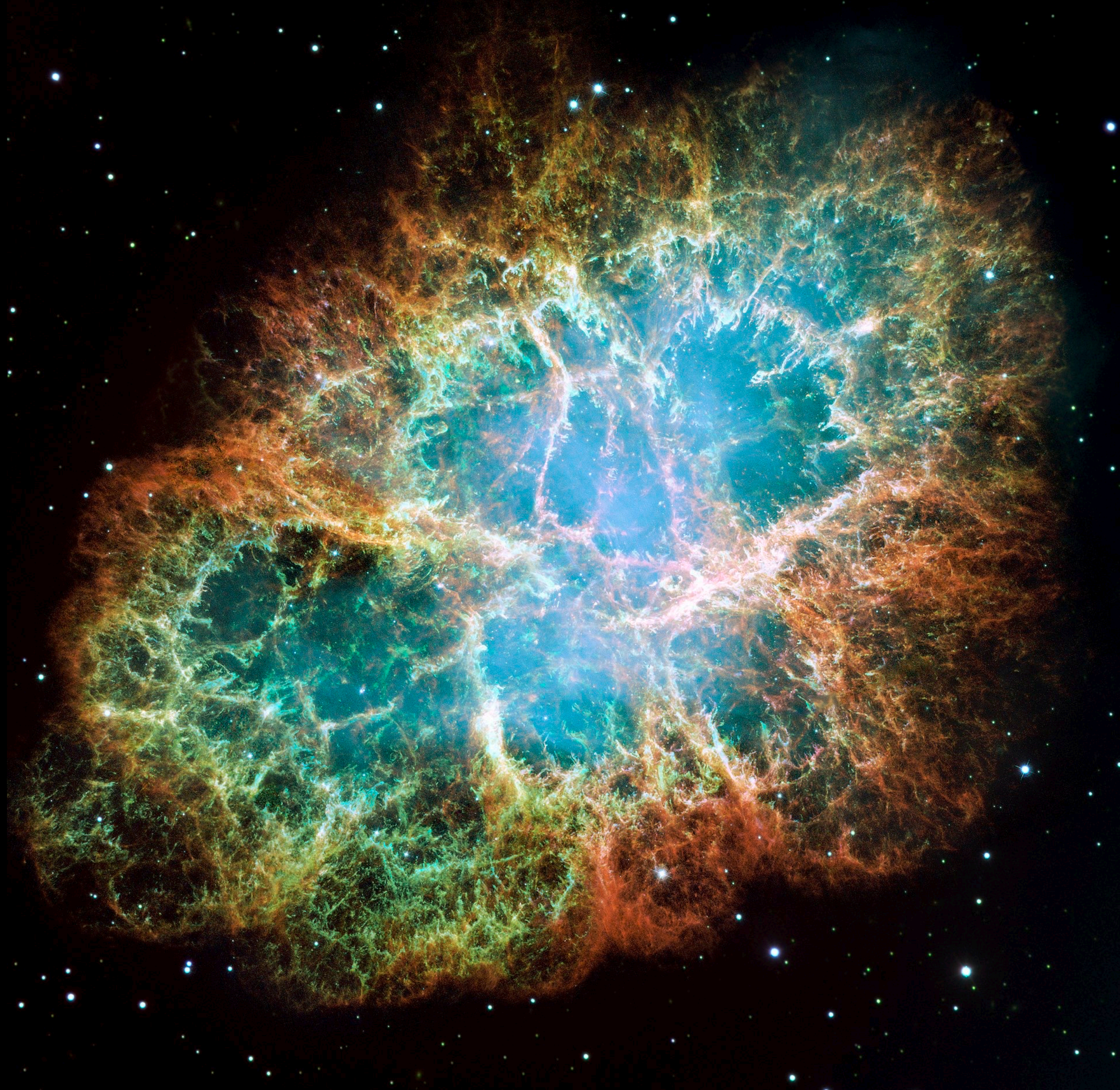
Supermassive black holes are added to the centre of a galaxy when it grows to 10 billion solar masses

6. Feedback

Star Formation Feedback

Supermassive Black Hole Feedback

Star Formation Feedback



Supermassive Black Hole Feedback

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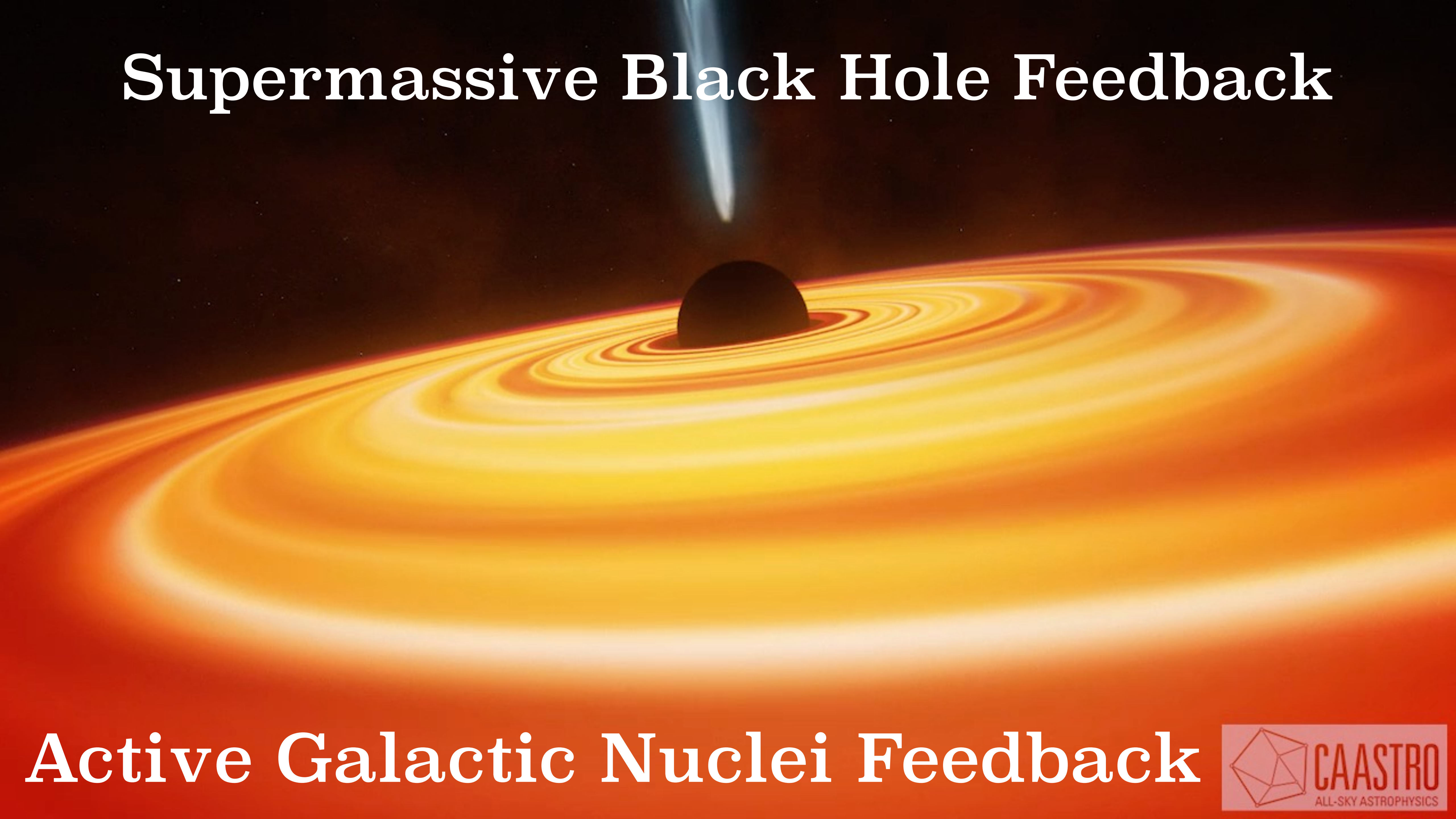
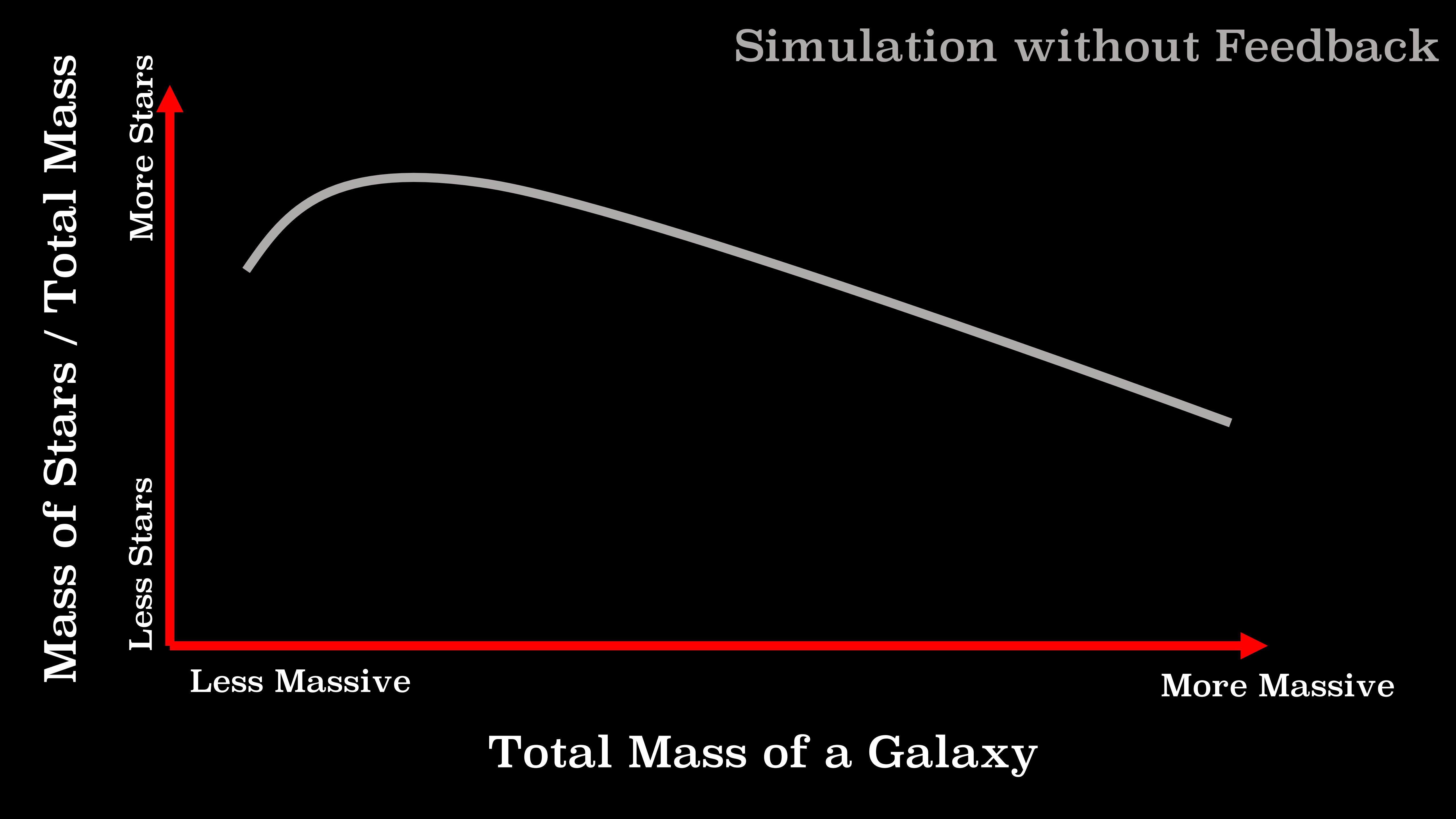
ALL-SKY ASTROPHYSICS

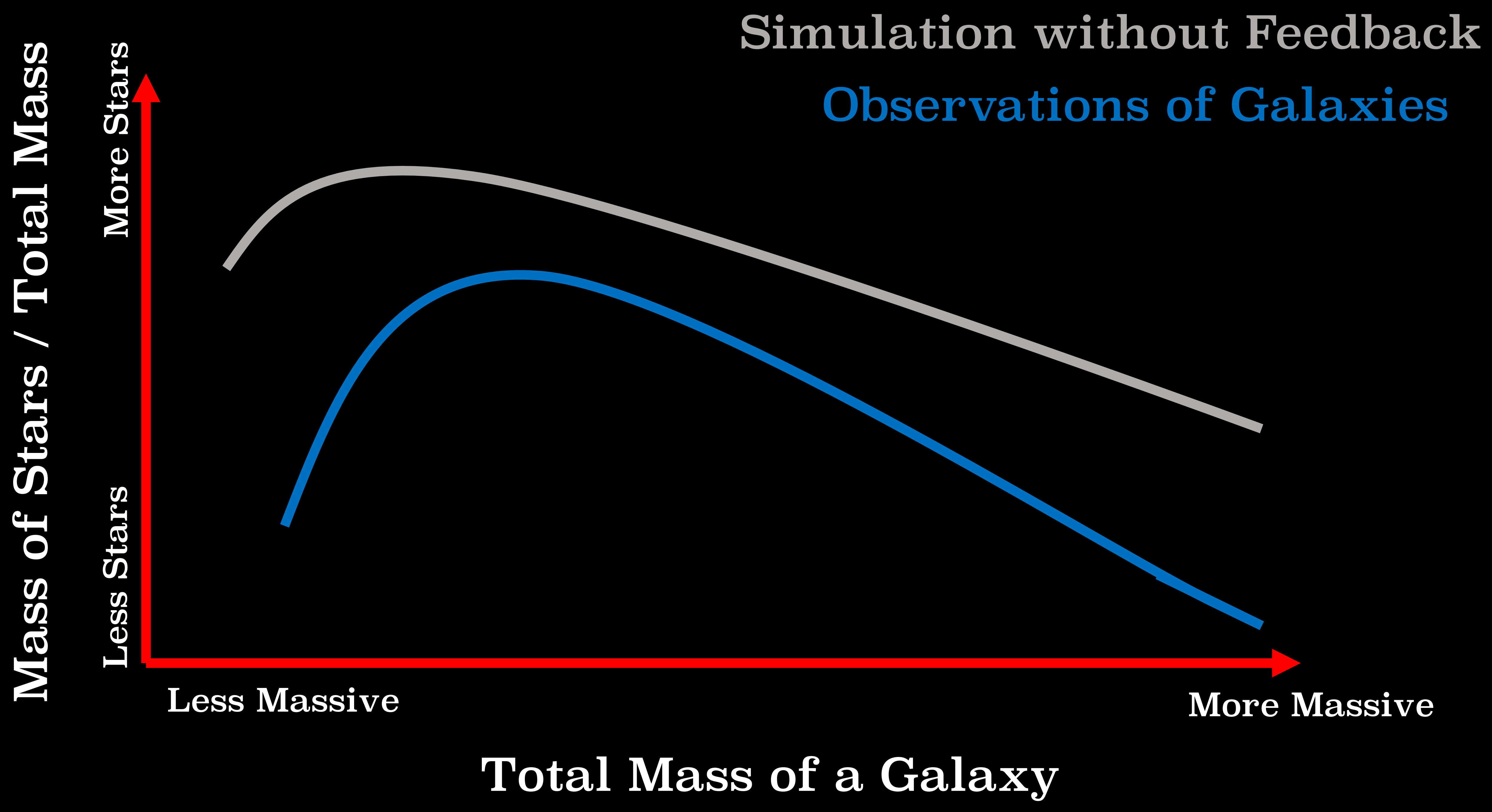
Supermassive Black Hole Feedback



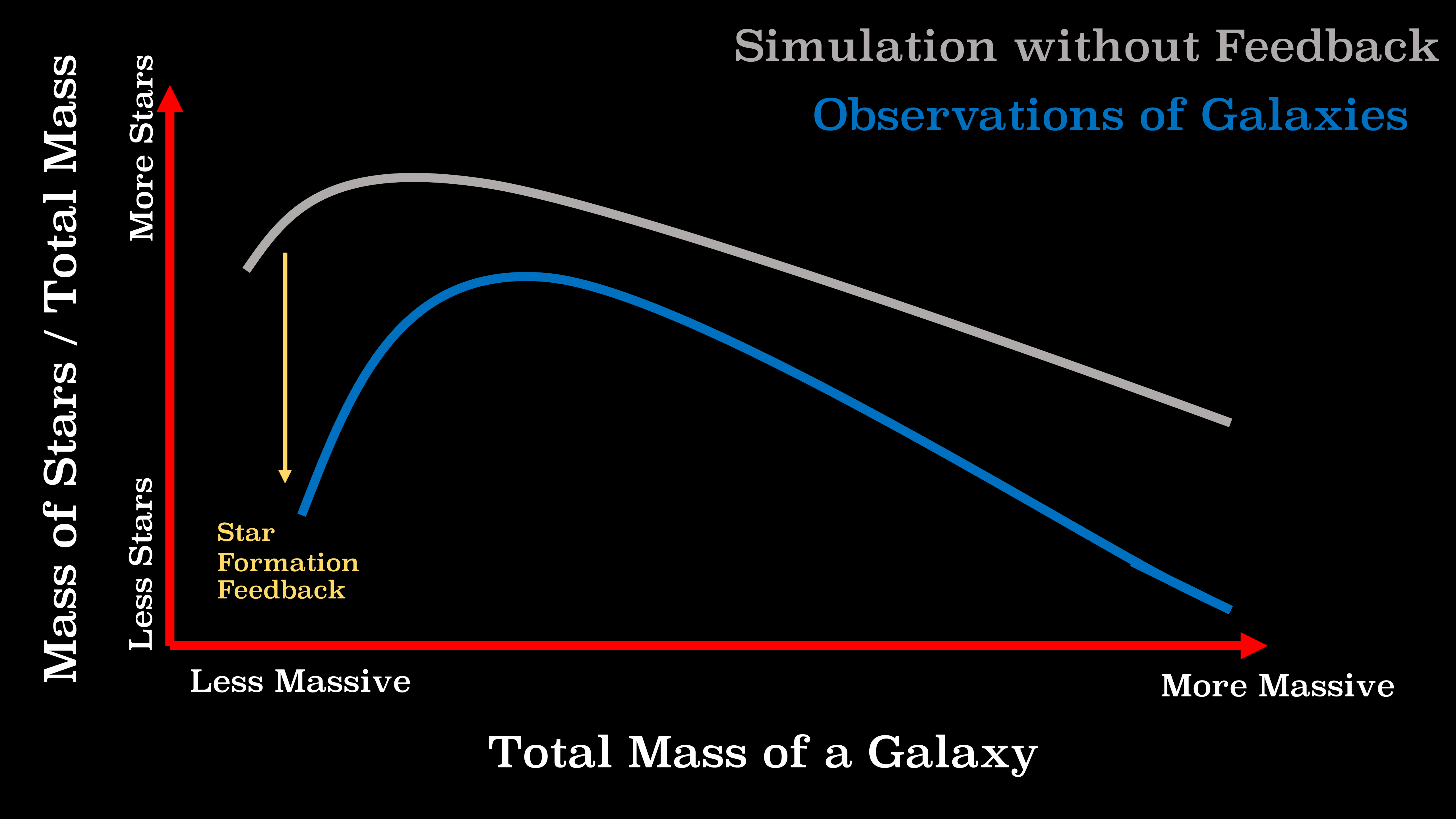
Active Galactic Nuclei Feedback

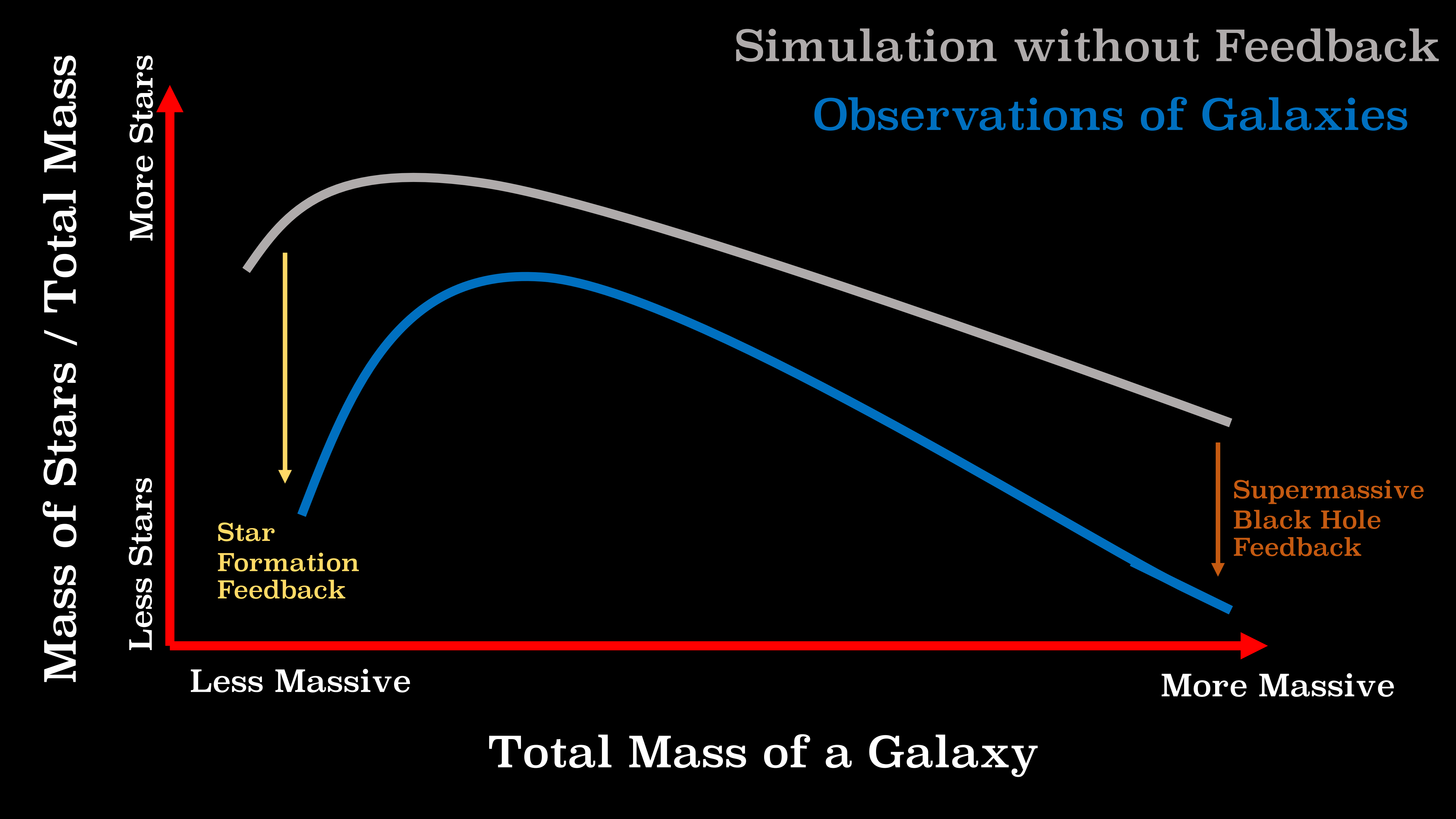

Mass of Stars / Total Mass
More Stars
Less Stars
Less Massive
More Massive
Total Mass of a Galaxy

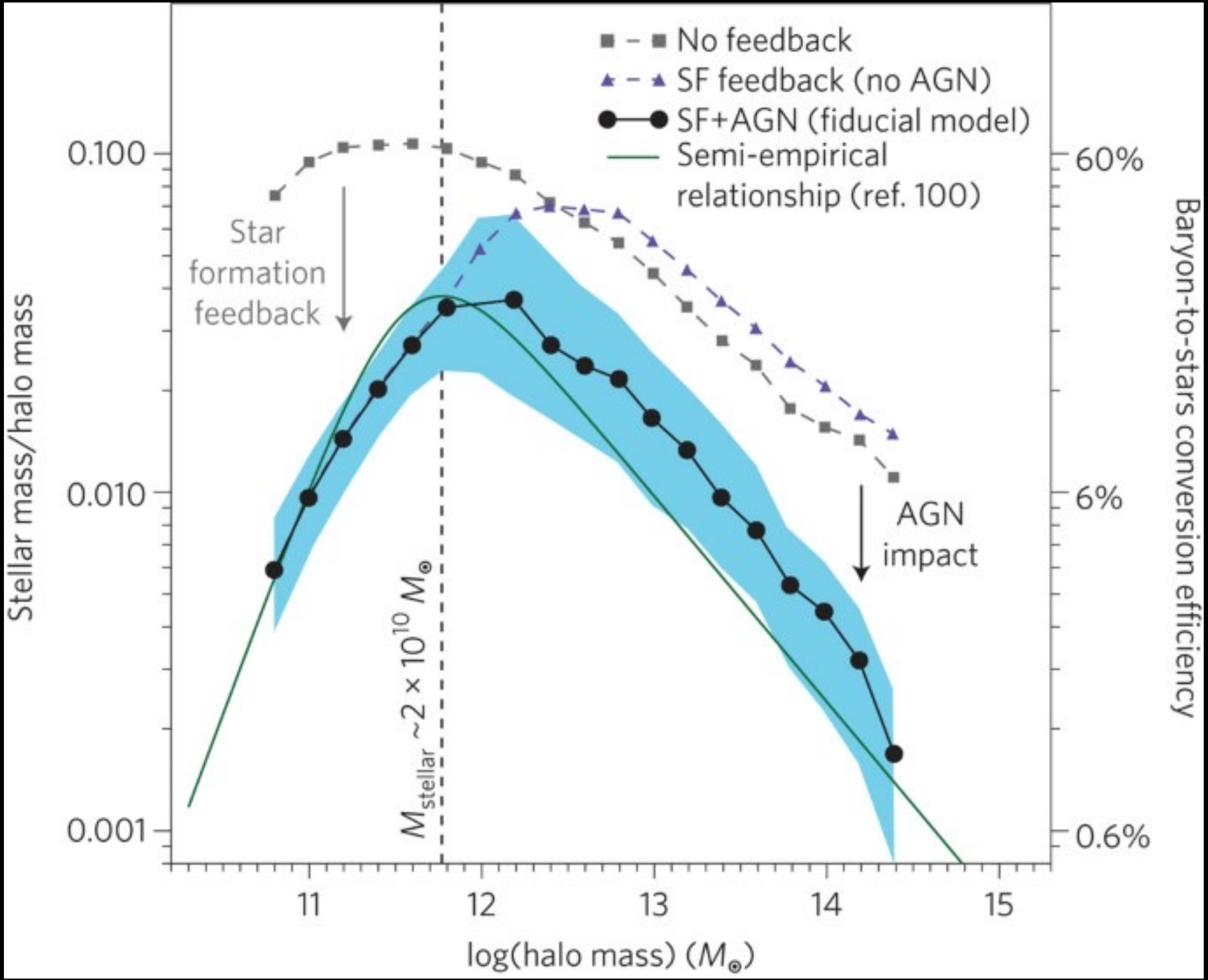

Simulation without Feedback
Mass of Stars / Total Mass
More Stars
Less Stars
Less Massive
More Massive
Total Mass of a Galaxy



Simulation without Feedback
Observations of Galaxies
Mass of Stars / Total Mass
More Stars
Less Stars
Less Massive
More Massive
Total Mass of a Galaxy

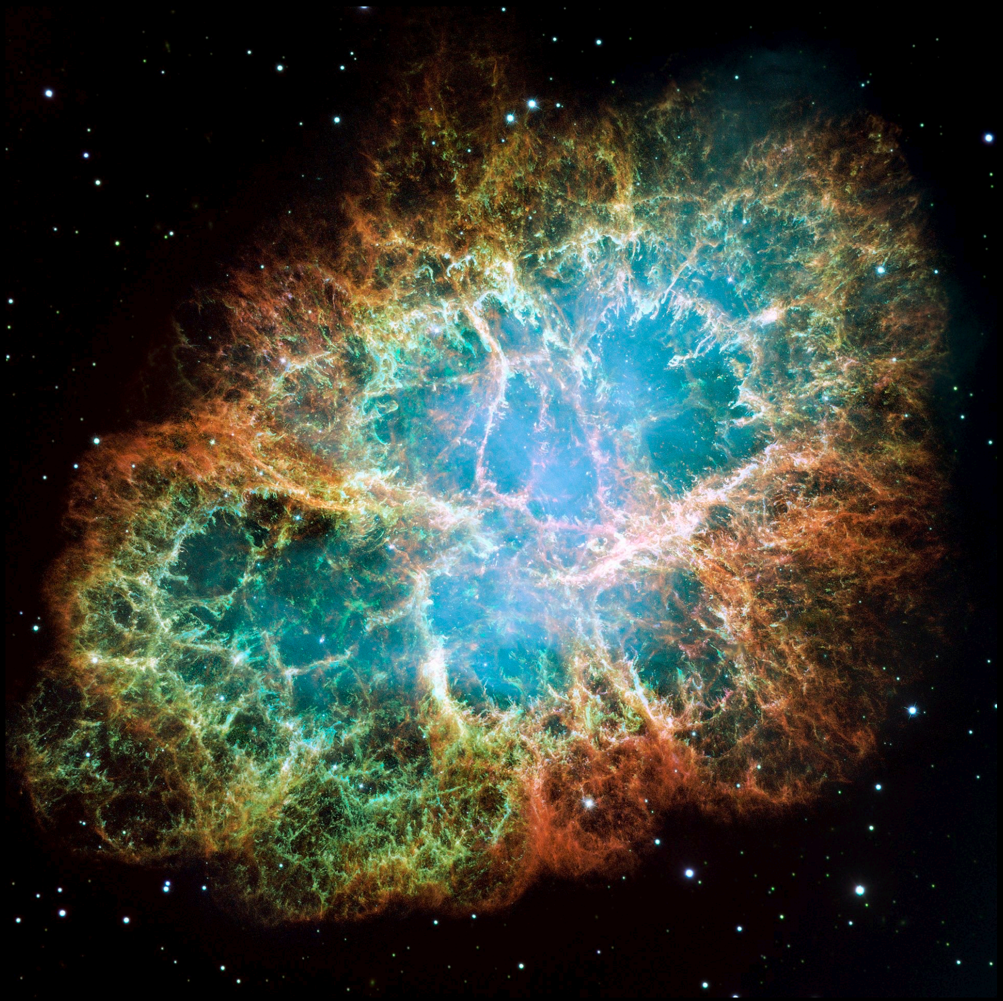

Simulation without Feedback
Observations of Galaxies
Mass of Stars / Total Mass
More Stars
Less Stars
Star
Formation
Feedback
Less Massive
More Massive
Total Mass of a Galaxy

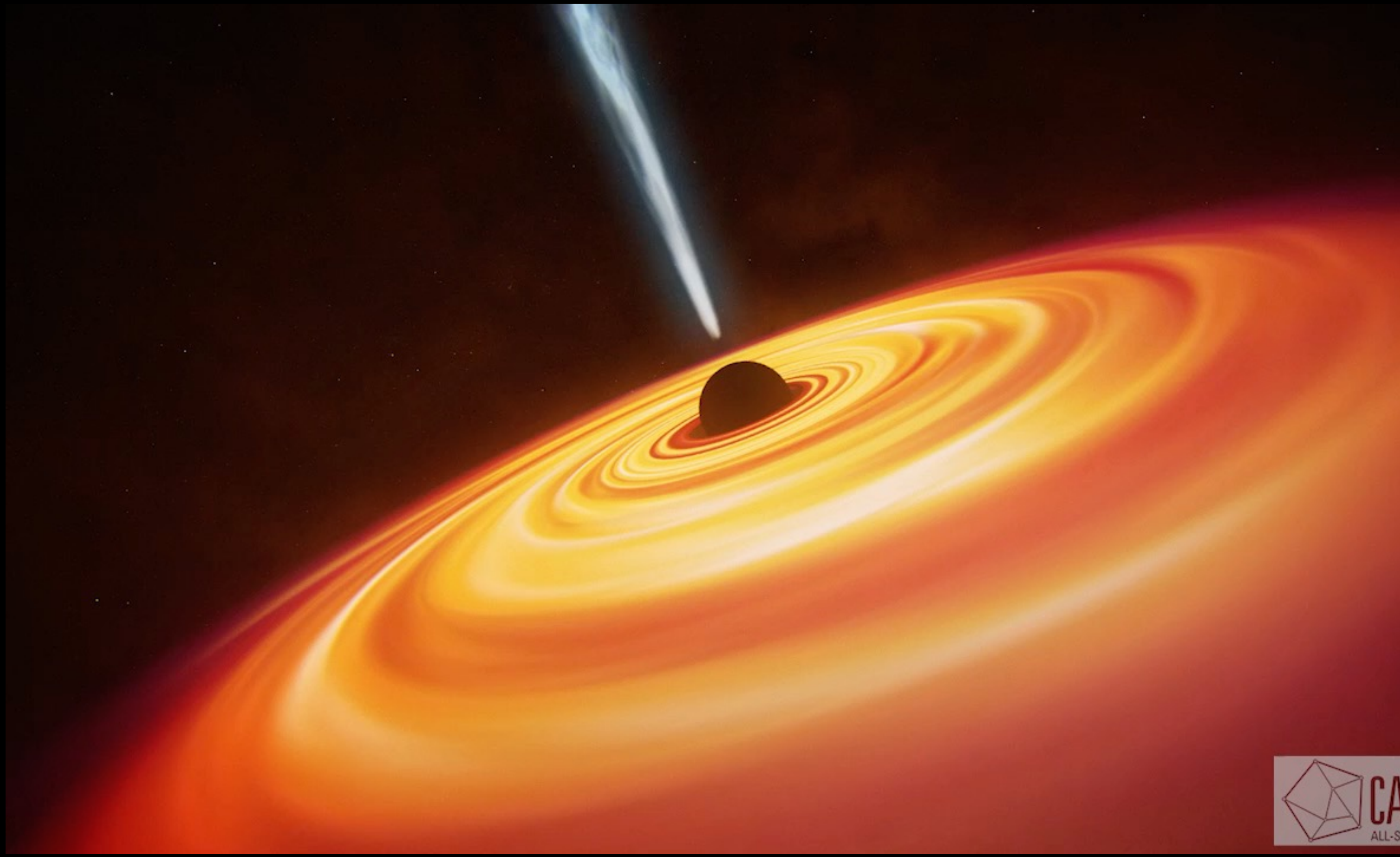

Simulation without Feedback
Observations of Galaxies
Mass of Stars / Total Mass
More Stars
Less Stars
Star
Formation
Feedback
Supermassive
Black Hole
Feedback
Less Massive
More Massive
Total Mass of a Galaxy

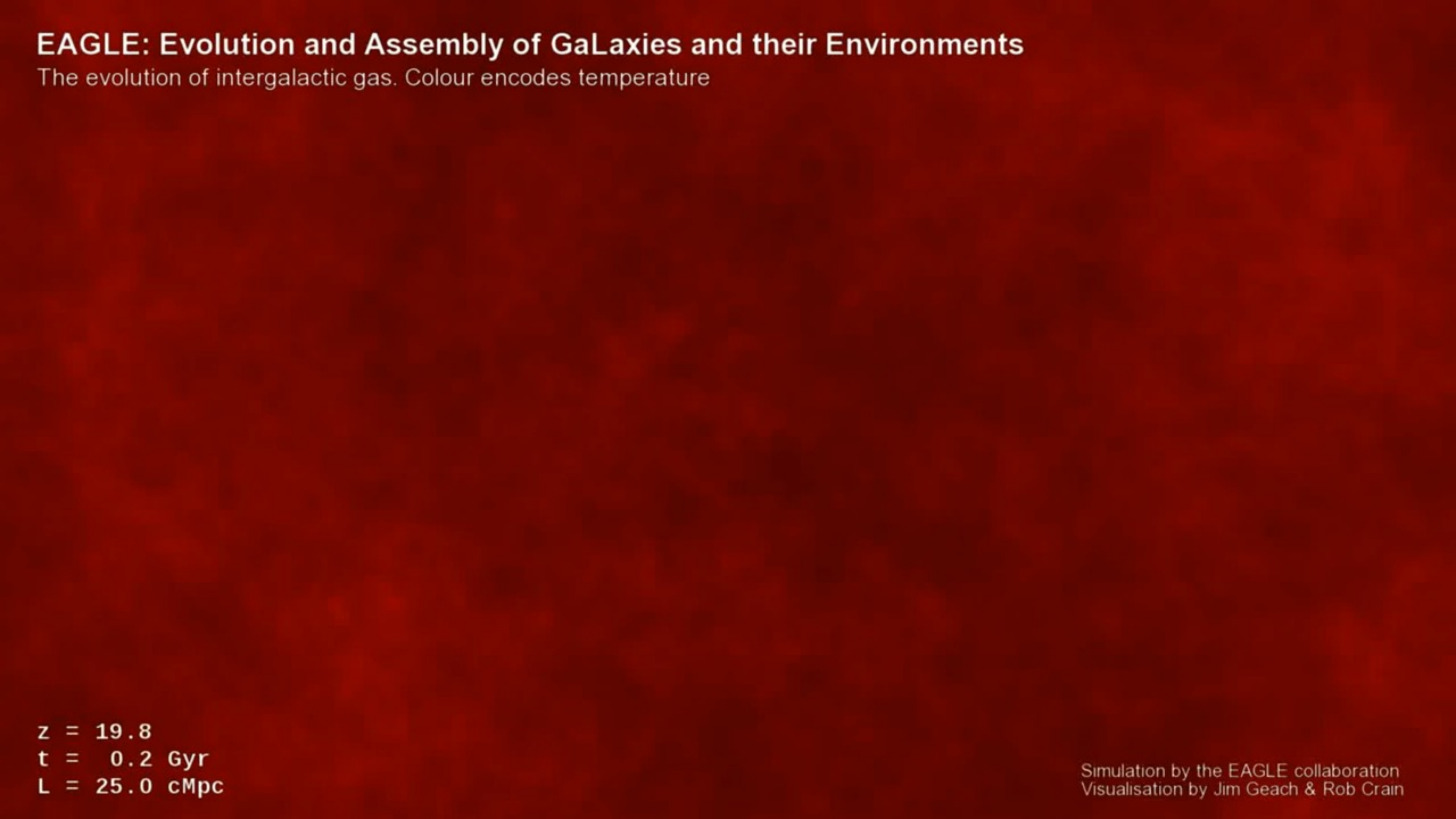


No feedback
SF feedback (no AGN)
SF+AGN (fiducial model)
Semi-empirical relationship (ref. 100)
Star formation feedback
AGN impact
$M_{stellar} \sim 2 \times 10^{10} M_{\odot}$
Stellar mass/halo mass
0.100
0.010
0.001
Baryon-to-stars conversion efficiency
60%
6%
0.6%
11
12
13
14
15
log(halo mass) ($M_{\odot}$)

6. Feedback



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The evolution of intergalactic gas. Colour encodes temperature
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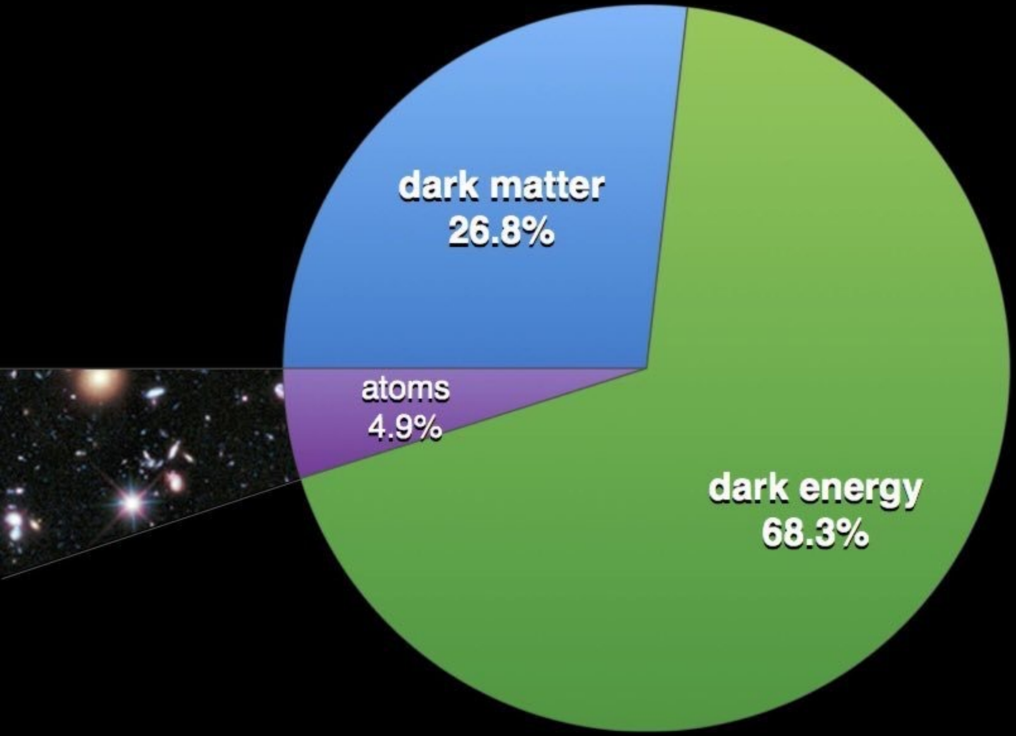
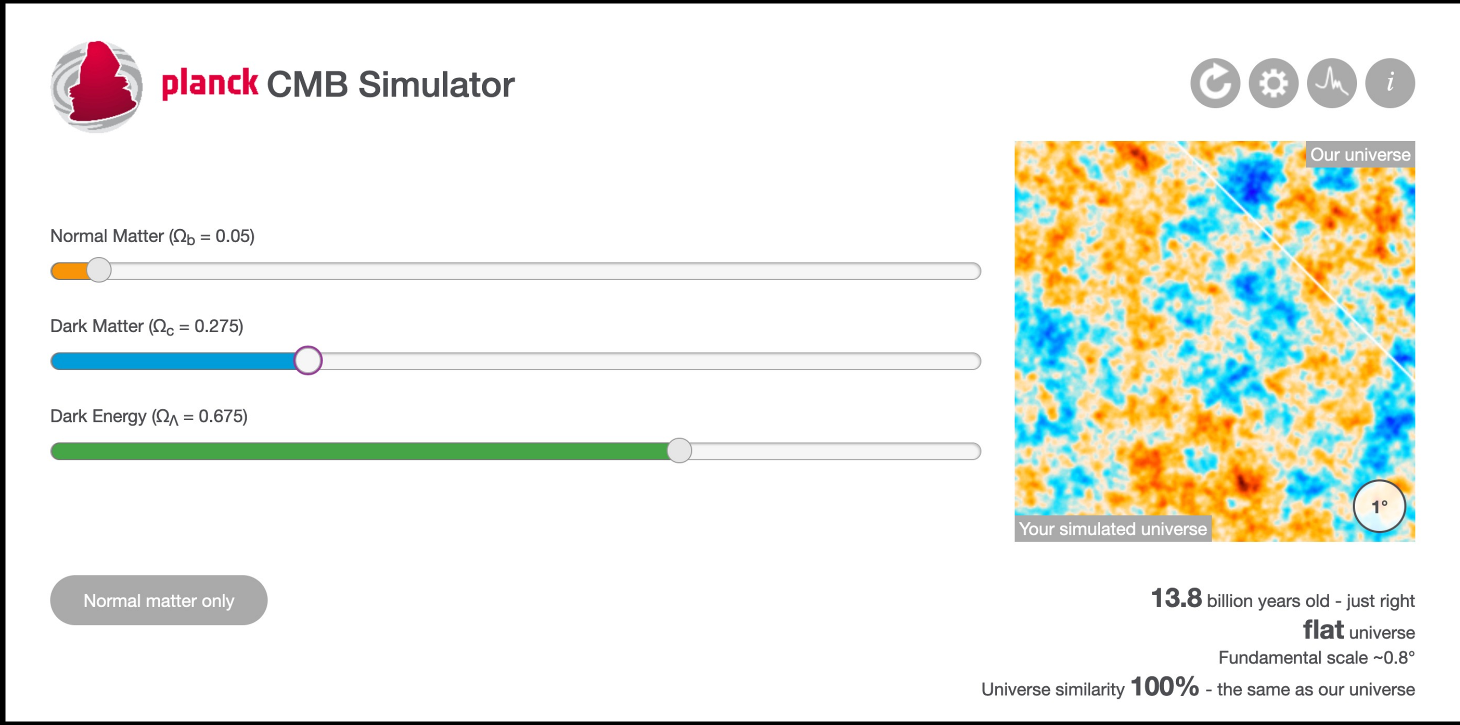
L = 25.0 cMpc
Simulation by the EAGLE collaboration
Visualisation by Jim Geach & Rob Crain

Dark Energy?





@AstroKatie/Planck13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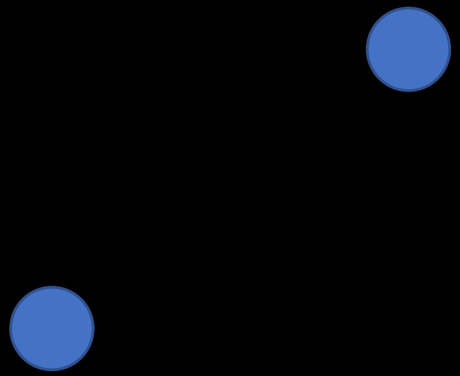
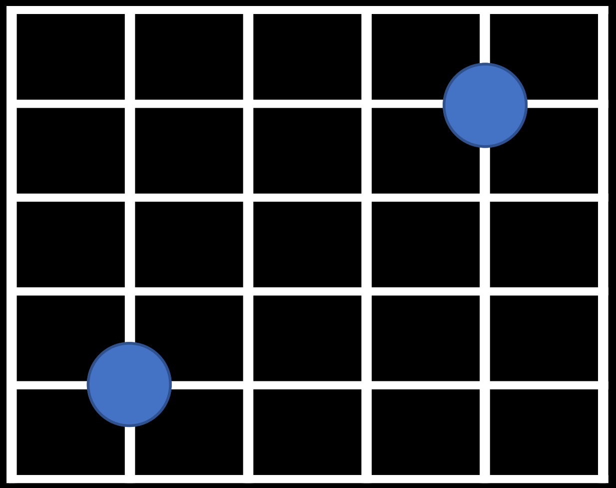
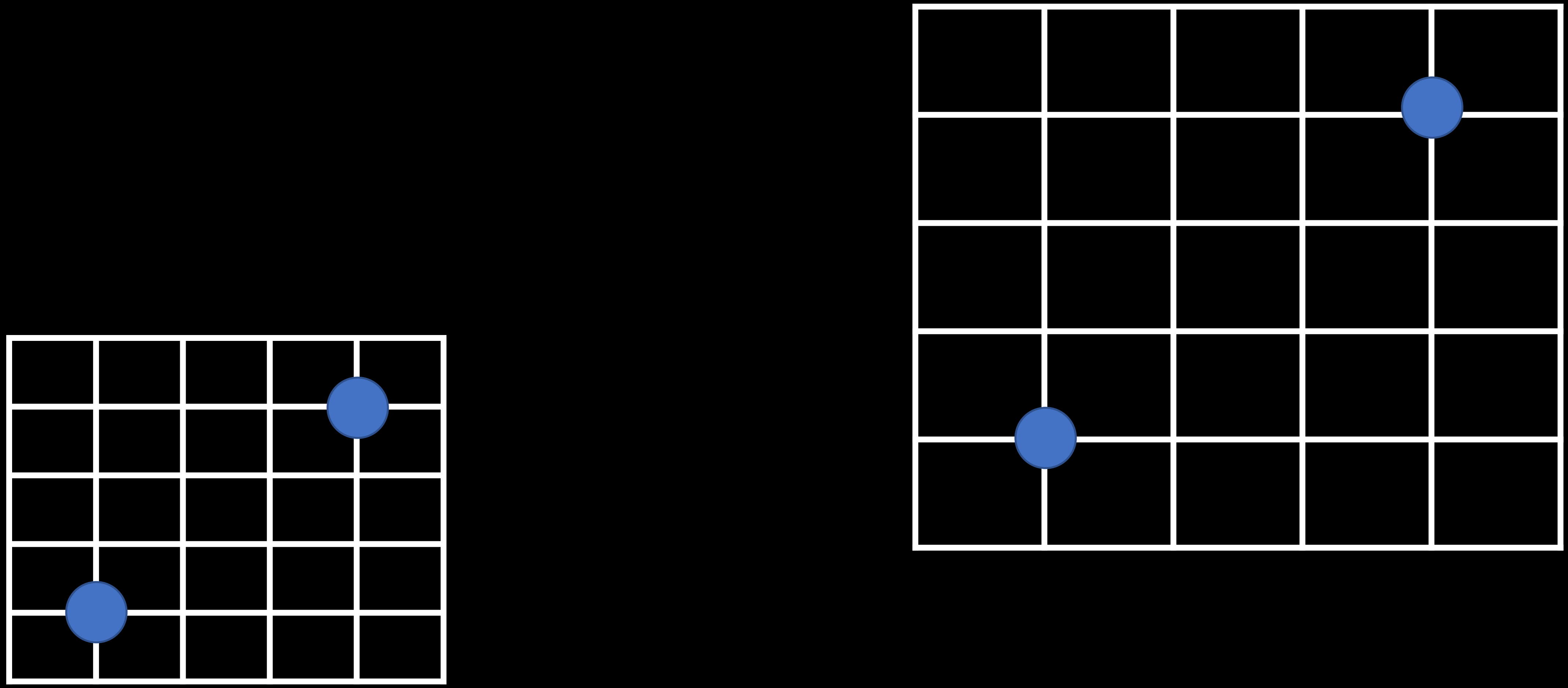
Comoving Coordinate System



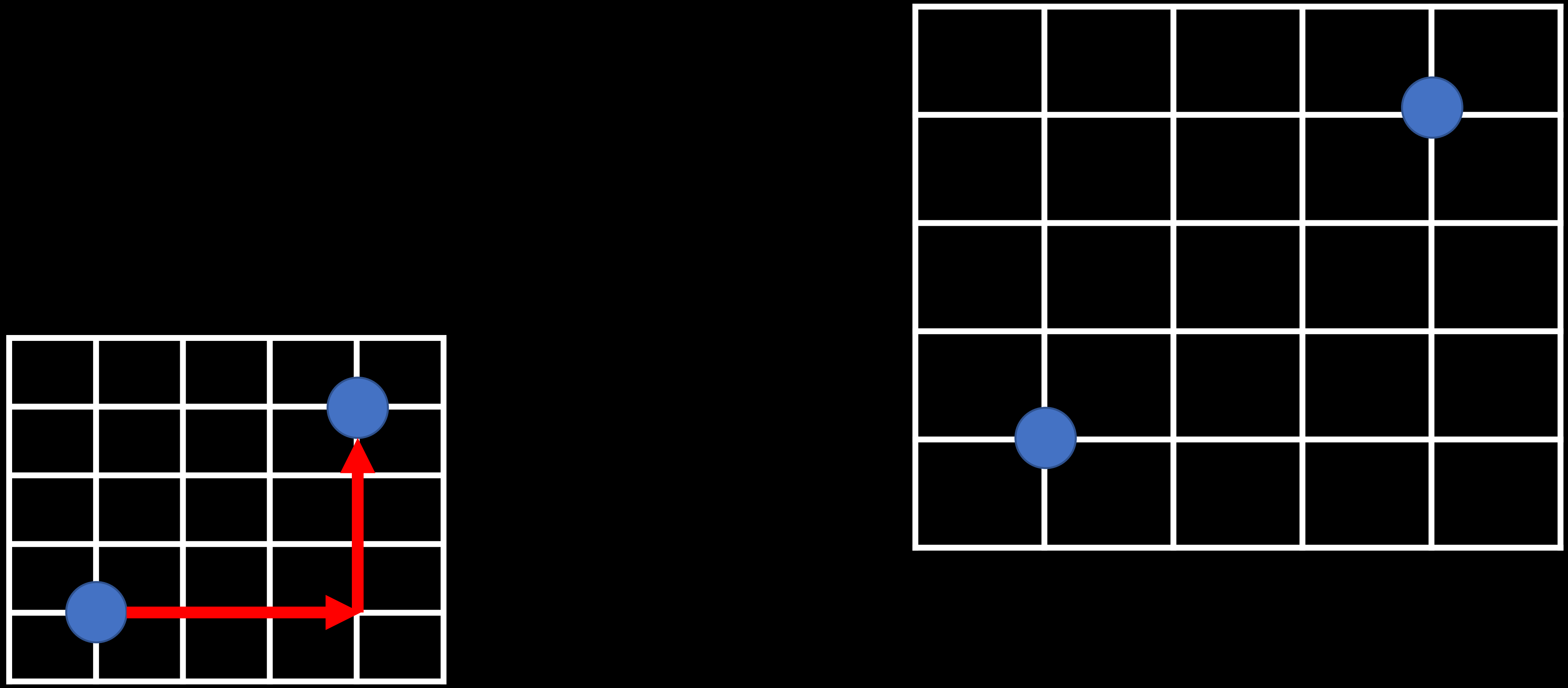
Comoving Coordinate System



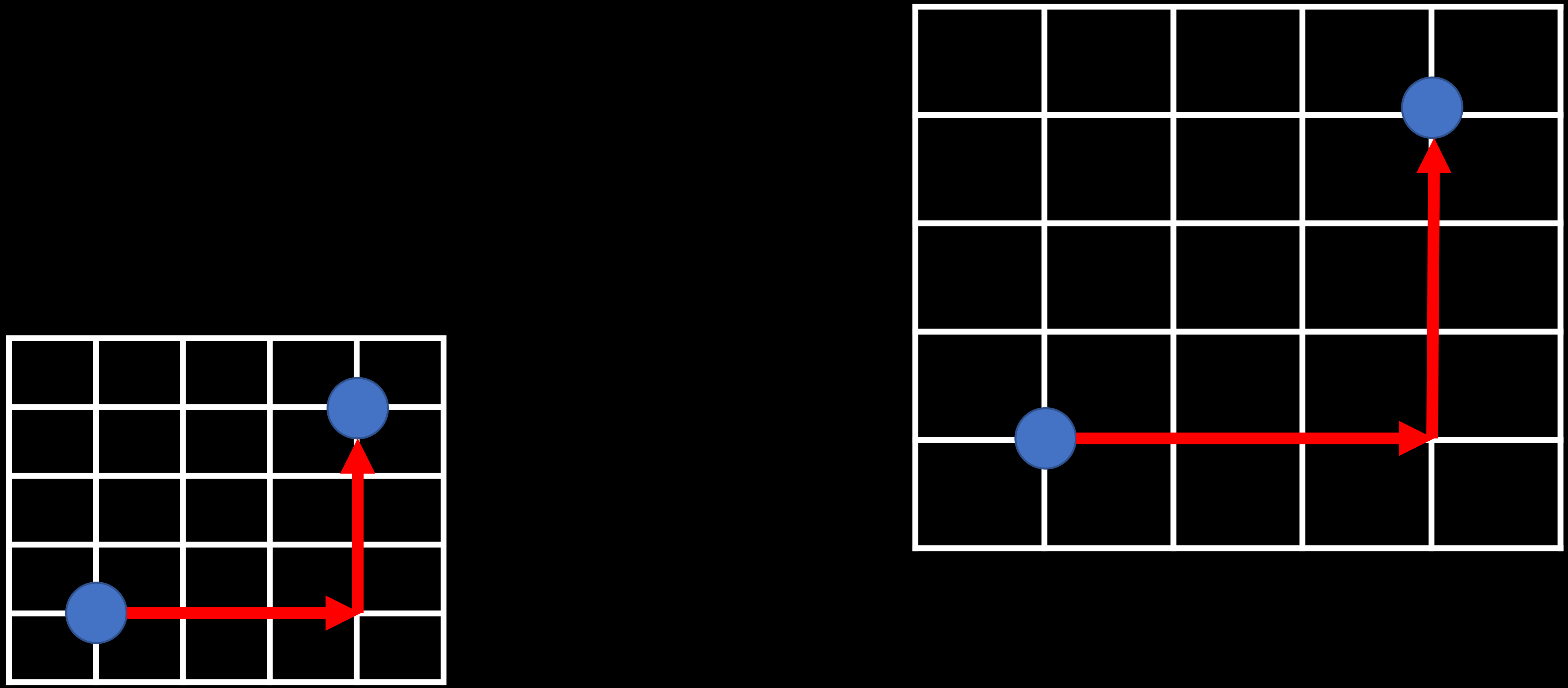
Comoving Coordinate System



Comoving Coordinate System



Comoving Coordinate System



What have we learnt from simulations?

Black holes can drive galaxy evolution

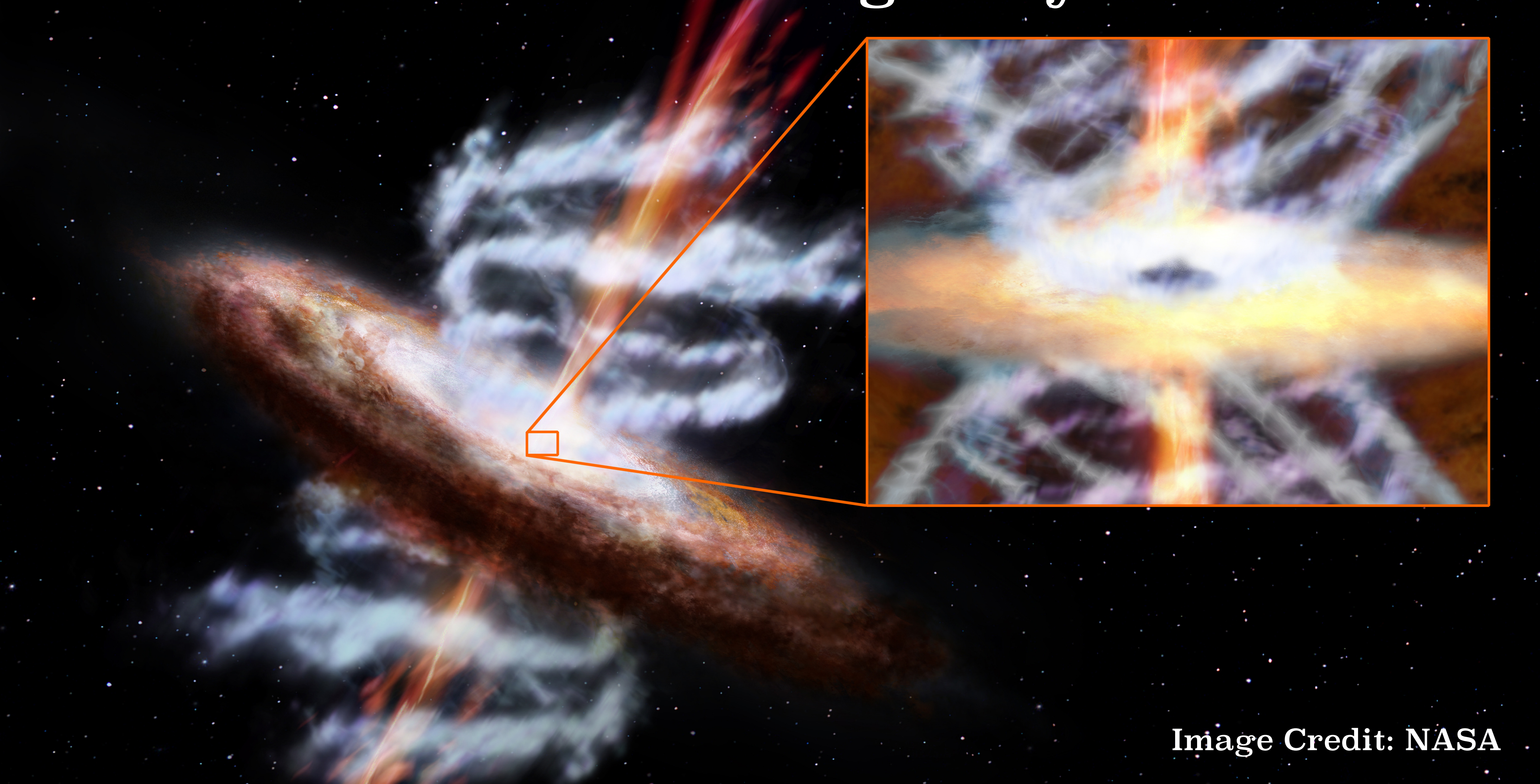
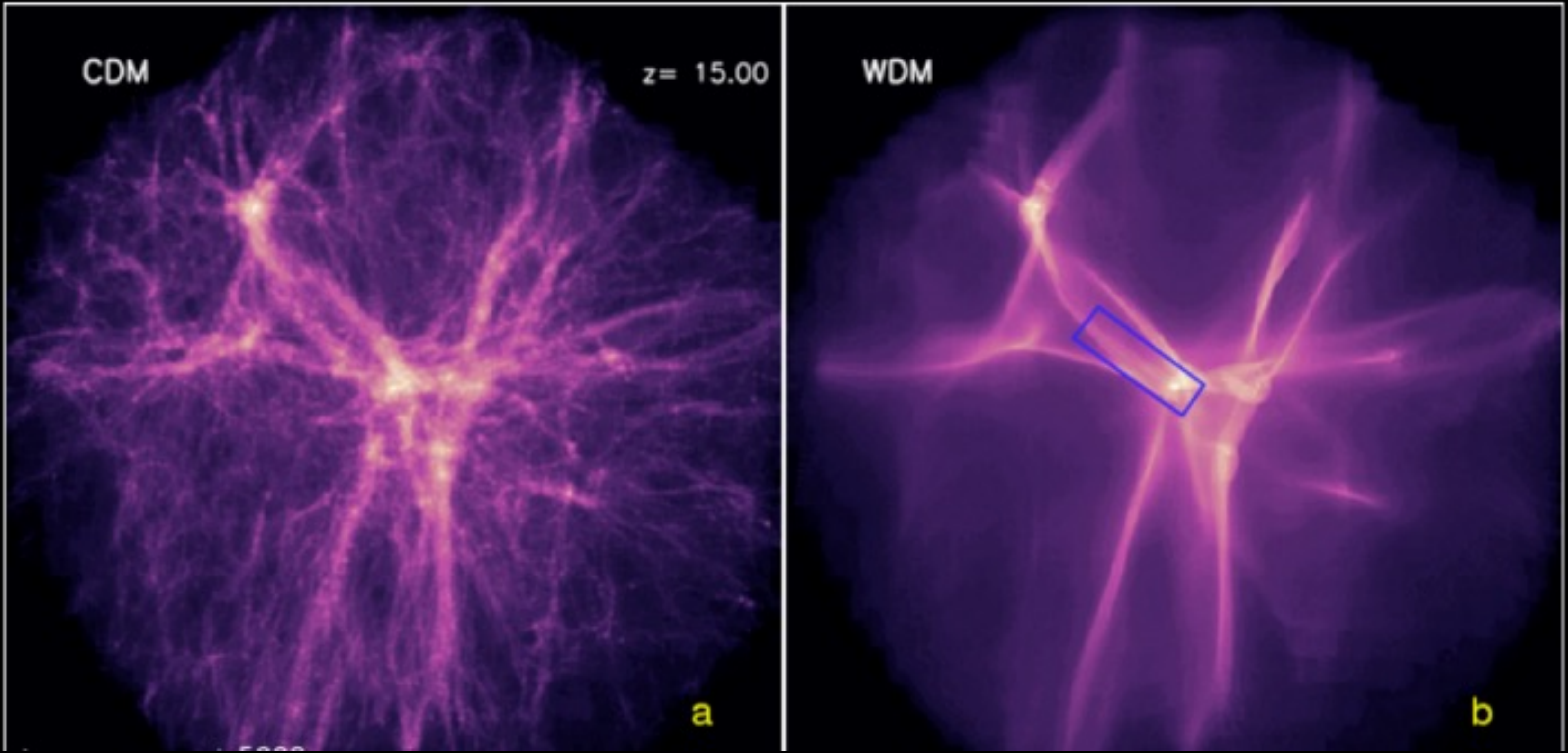
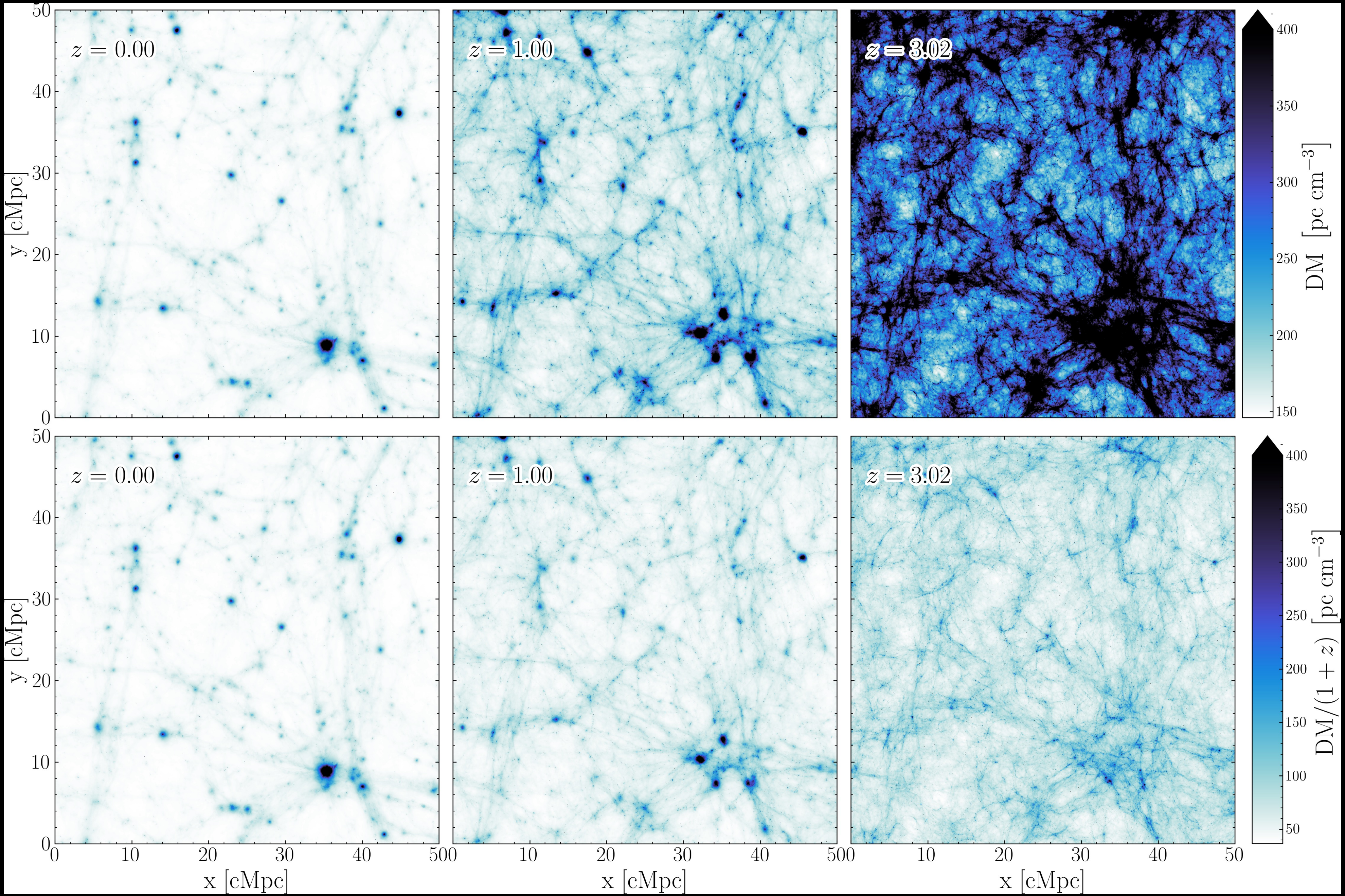


Image Credit: NASA



What are the properties of dark matter?

Image Credit: Gao & Theuns (2007)



Helping to reveal the location of the missing baryons.

Summary

Twitter: @adamjbatten

We use simulations to test our understanding of the laws of the Universe, and make predictions based on what we already know.

0. Gravity
1. Cosmic Microwave Background
2. Dark Matter
3. Atoms
4. Stars
5. Black Holes
6. Feedback

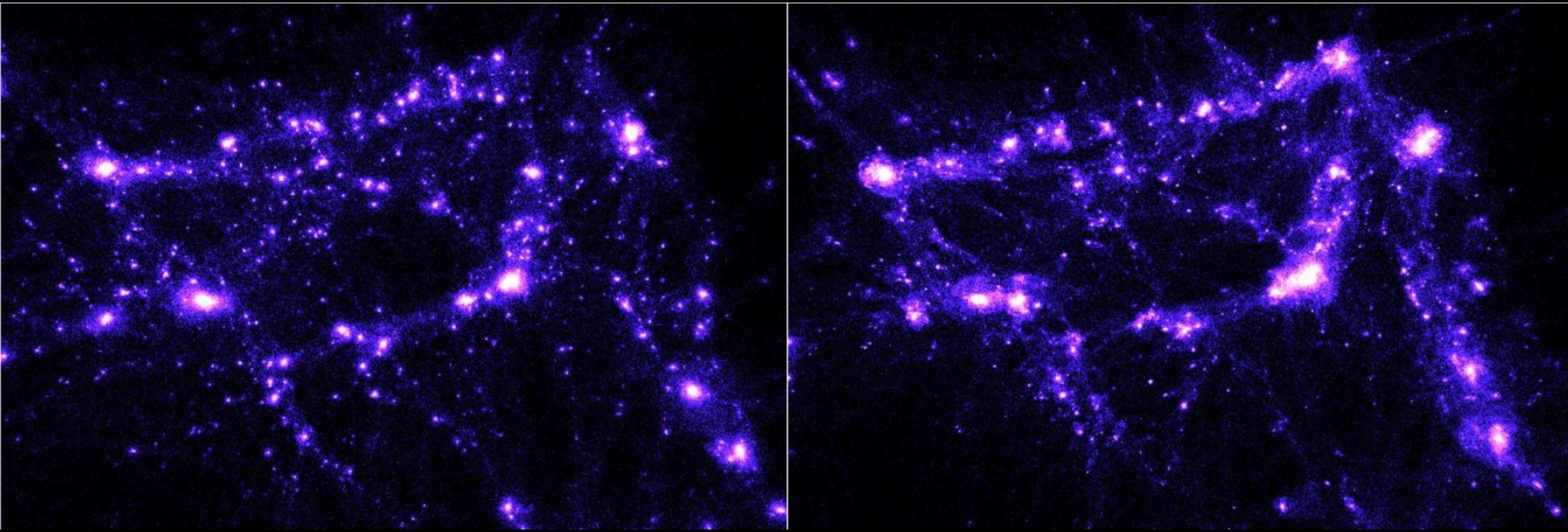
Slides: https://adambatten.com/talks/

$$\frac{1}{2}g^{\alpha\beta}\partial_\alpha\partial_\mu g_{\beta\nu}+\frac{1}{2}g^{\alpha\beta}\partial_\alpha\partial_\nu g_{\mu\beta}-\frac{1}{2}g^{\alpha\beta}\partial_\alpha\partial_\beta g_{\mu\nu}-\frac{3}{2}g^{\alpha\beta}\partial_\mu\partial_\nu g_{\alpha\beta}$$

$$-\frac{1}{2}g^{\beta\lambda}g^{\alpha\rho}\partial_\alpha g_{\rho\lambda}\partial_\mu g_{\beta\nu}-\frac{1}{2}g^{\beta\lambda}g^{\alpha\rho}\partial_\alpha g_{\rho\lambda}\partial_\nu g_{\mu\beta}$$

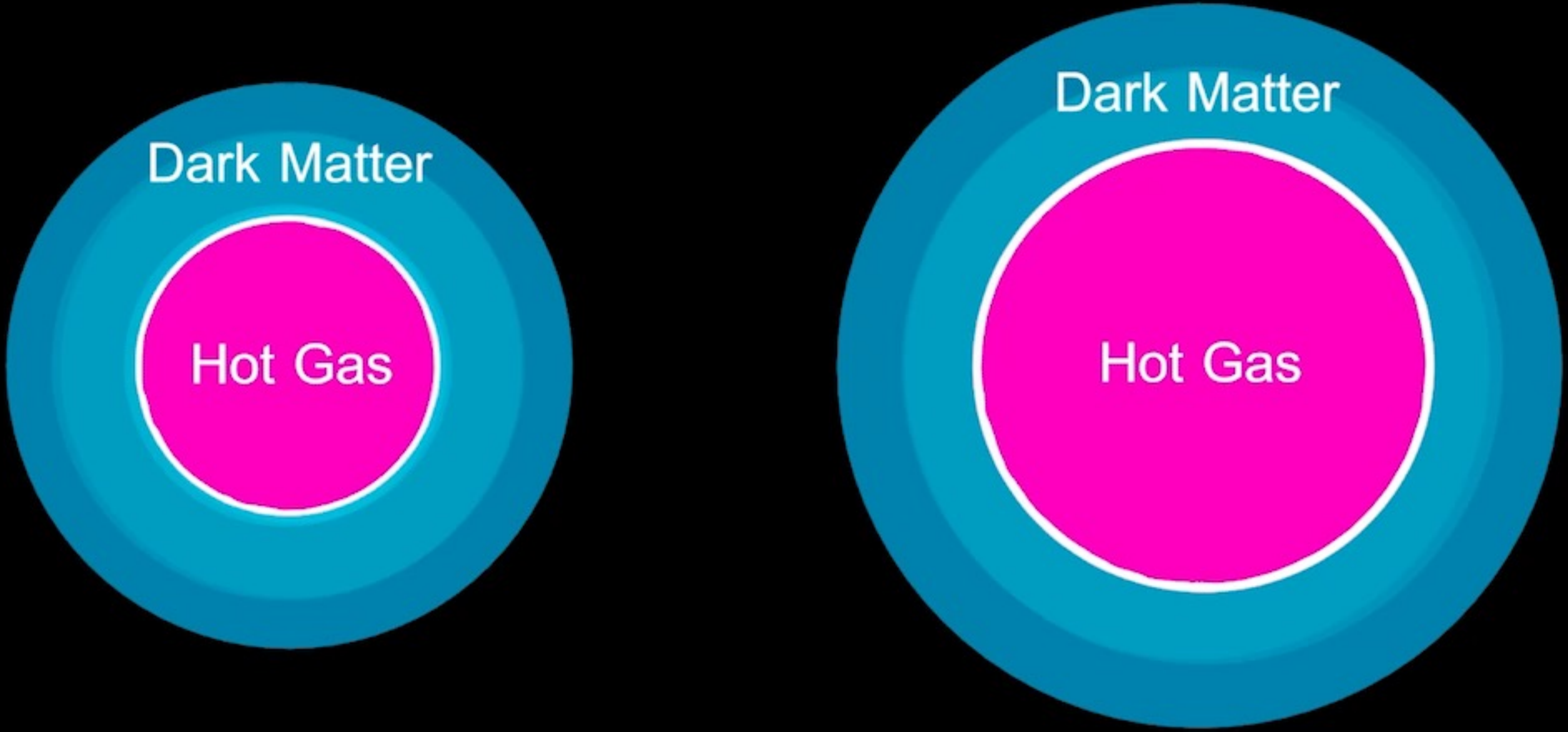
$$+\frac{1}{4}g^{\beta\lambda}g^{\alpha\rho}\partial_\nu g_{\alpha\lambda}\partial_\mu g_{\rho\beta}+\frac{1}{4|g|}g^{\alpha\beta}\partial_\beta|g|\partial_\nu g_{\mu\alpha}$$

$$-\frac{1}{4|g|}g^{\alpha\beta}\partial_\beta|g|\partial_\alpha g_{\mu\nu}-\frac{1}{4|g|}g^{\alpha\beta}\partial_\beta|g|\partial_\mu g_{\alpha\nu}+\Lambda g_{\mu\nu}=\frac{8\pi G}{c^4}T_{\mu\nu}$$



Dark Matter + Dark Energy

Modified Newtonian Dynamics



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