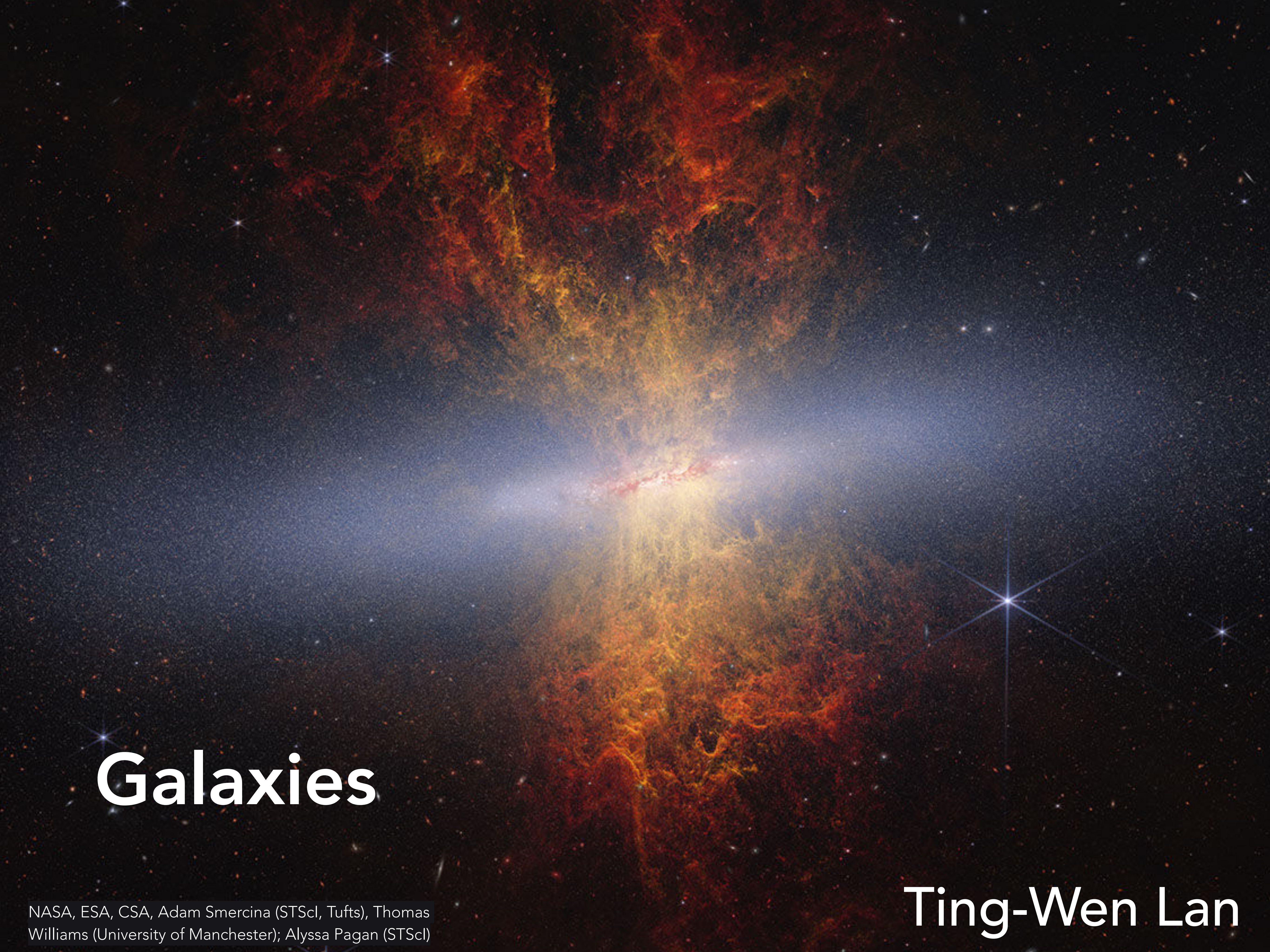


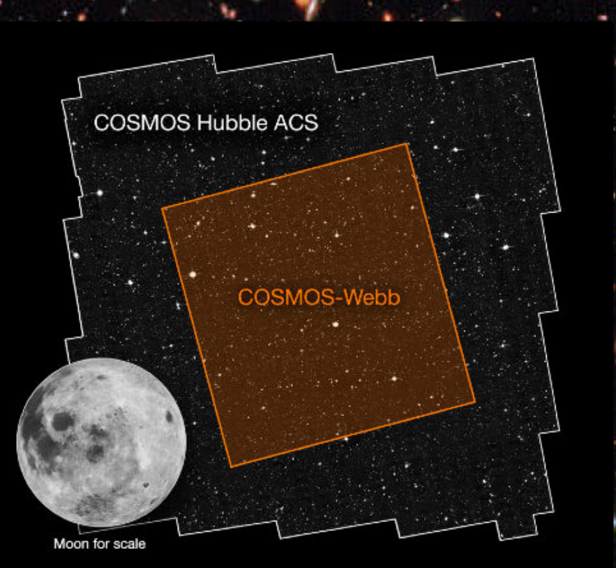
Galaxies

Ting-Wen Lan

NASA, ESA, CSA, Adam Smercina (STScI, Tufts), Thomas Williams (University of Manchester); Alyssa Pagan (STScI)

ESA/Webb, NASA, CSA, G. Gozaliasl, A. Koekemoer, M. Franco and the COSMOS-Web team

Question: Based on this image, how would you classify galaxies?



ESA/Webb, NASA, CSA, G. Gozaliasl, A. Koekemoer, M. Franco and the COSMOS-Web team

Question: Based on this image, how would you classify galaxies?

ESA/Webb, NASA, CSA, G. Gozaliasl, A. Koekemoer, M. Franco and the COSMOS-Web team

Question: Based on this image, how would you classify galaxies?

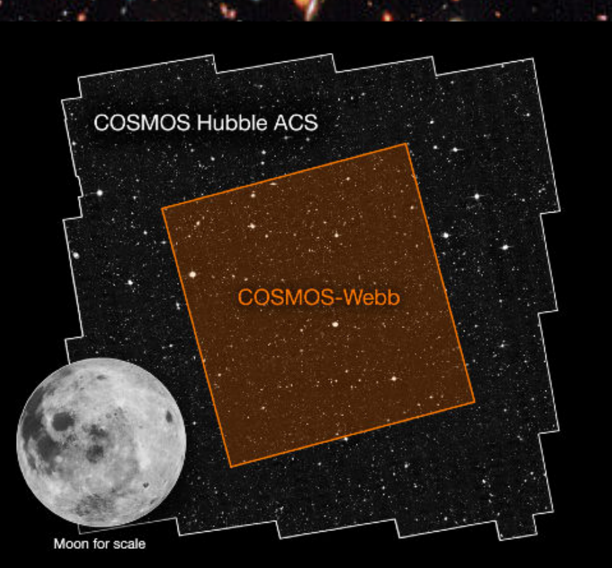
Color

Morphology

Size

Structure

etc

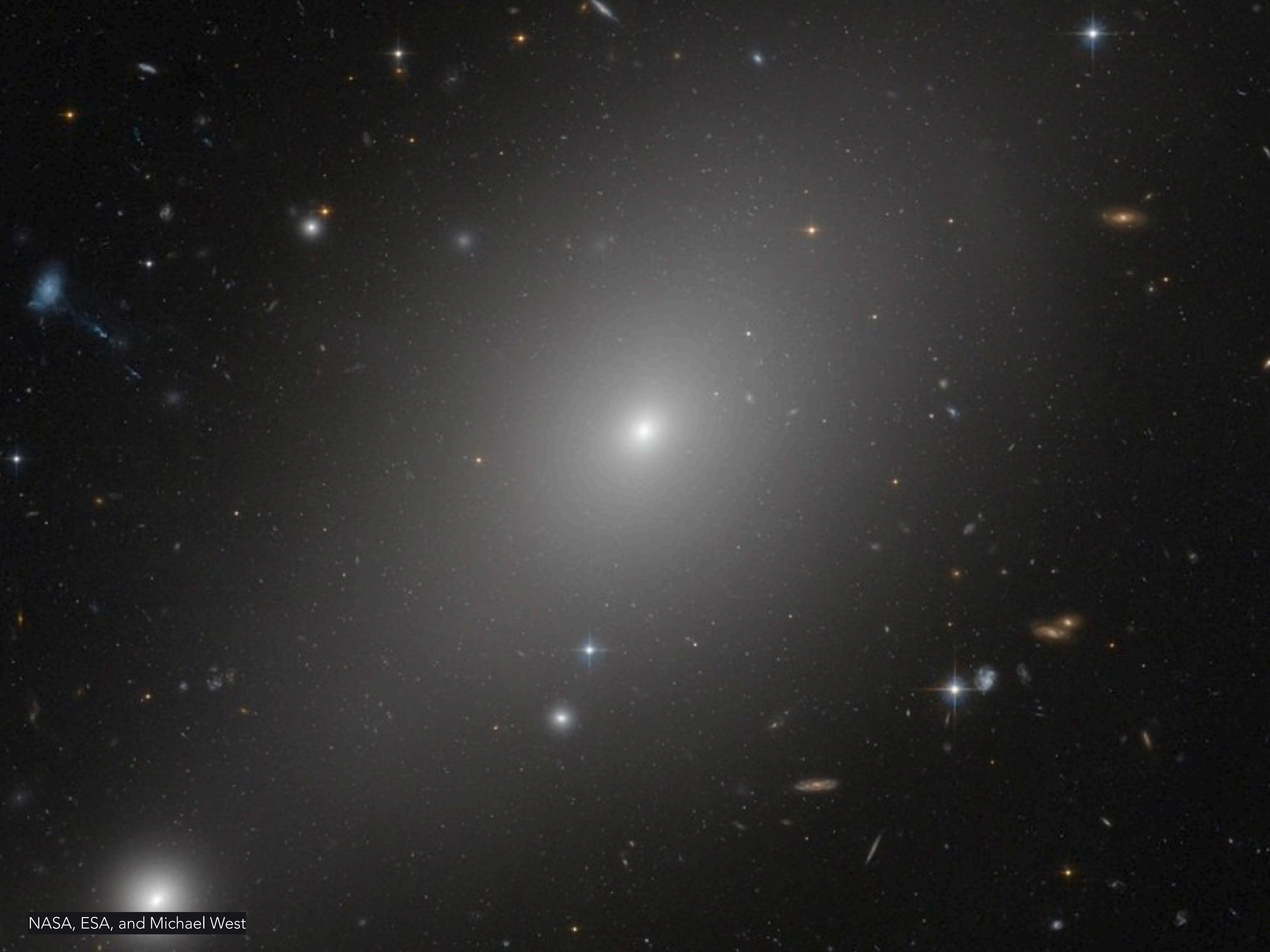


ESA/Webb, NASA, CSA, G. Gozaliasl, A. Koekemoer, M. Franco and the COSMOS-Web team


ESA/Hubble & NASA, L. Galbany, S. Jha, K. Noil, A.Riess

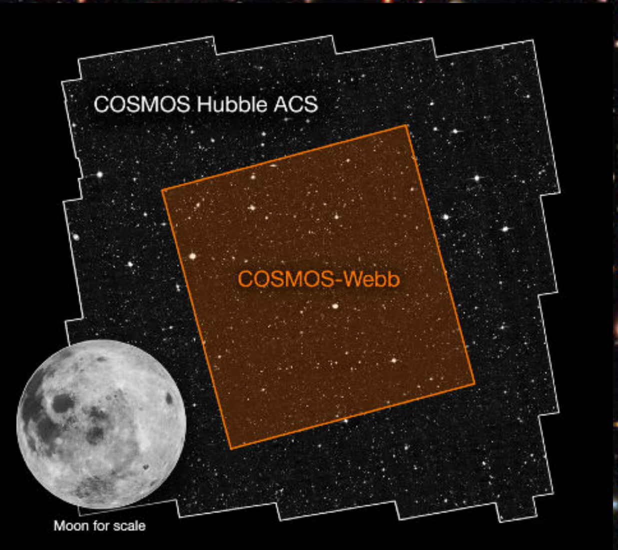

NASA, ESA, Imad Pasha, Pieter Van Dokkum

NASA, ESA, and the Hubble Heritage Team


NASA, ESA, and Michael West

Key question in galaxy research:

What drive the diversity of galaxy properties?



ESA/Webb, NASA, CSA, G. Gozaliasl, A. Koekemoer, M. Franco and the COSMOS-Web team

Observations:

Characterizing and understanding the components and the properties of galaxies and how they evolve with time.

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Theory:

Developing models and simulations can explain the observed properties and diversity of galaxies.

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Question: Besides stars, are there any other components in galaxies?
Stars
ESO

Question: Besides stars, are there any other components in galaxies?

Stars

Gas
- Neutral Hydrogen (HI)
- Molecular Hydrogen (H2)
- Metals

Dust

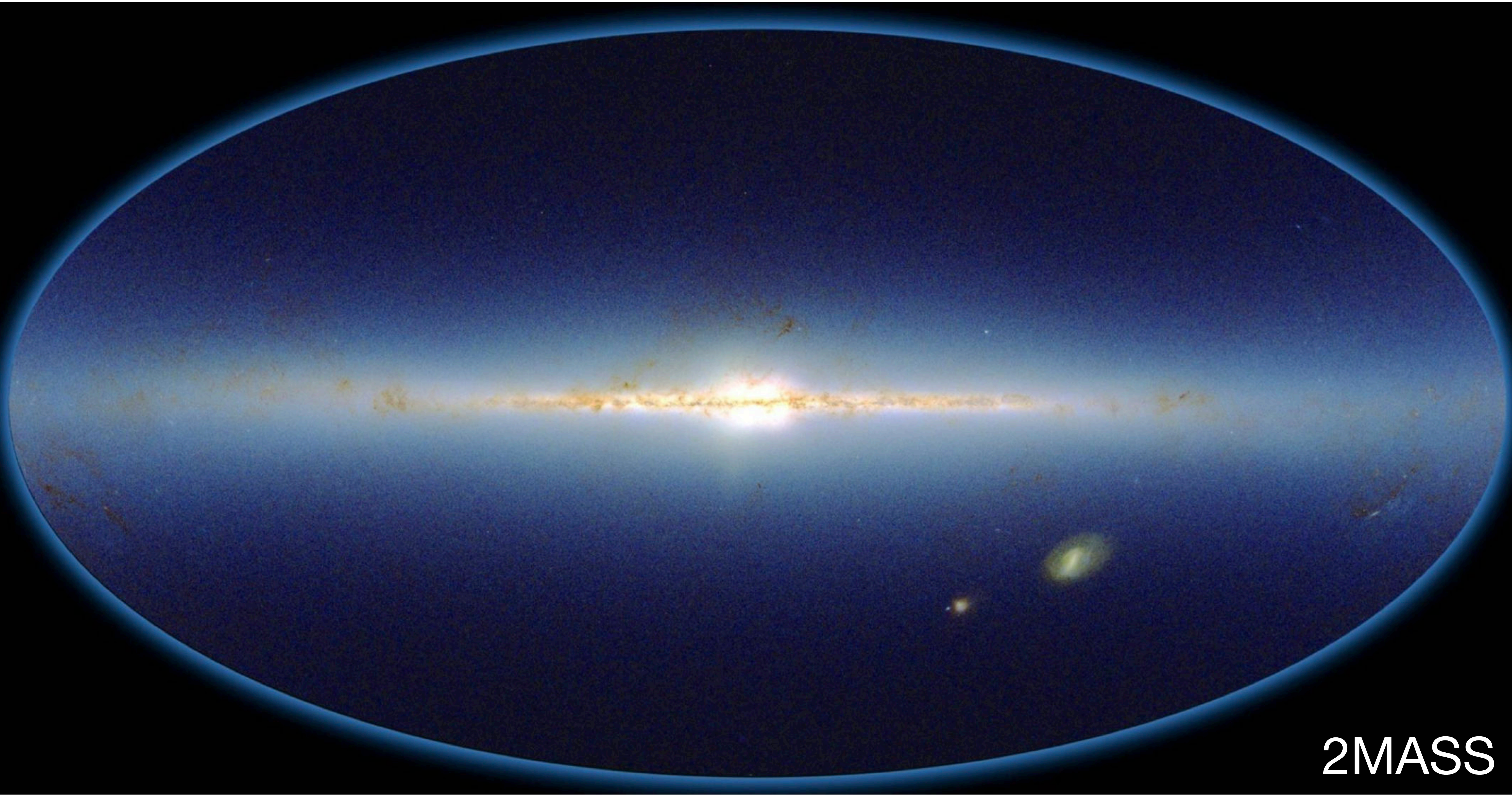
Supermassive black hole

Dark Matter

ESO

Multi-wavelength observation

Stars | UV, Optical and Infrared



Multi-wavelength observation

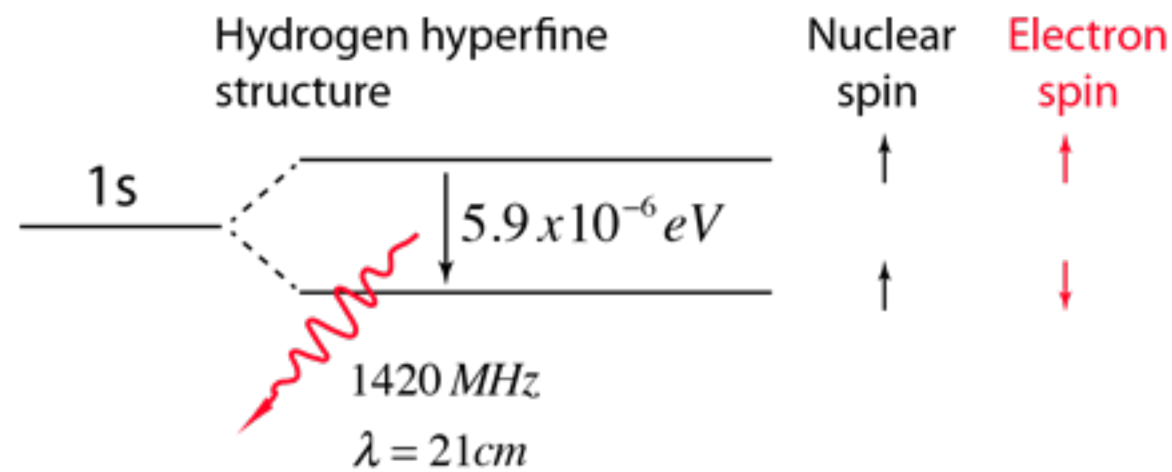
Stars

UV, Optical and Infrared

https://articles.adsabs.harvard.edu//full/2003JRASC..97...13C/0000013.000.html

Multi-wavelength observation

Stars		UV, Optical and Infrared
Gas	HI	Radio (21 cm emission)



https://articles.adsabs.harvard.edu//full/2003JRASC..97...13C/0000013.000.html

Multi-wavelength observation

Stars		UV, Optical and Infrared
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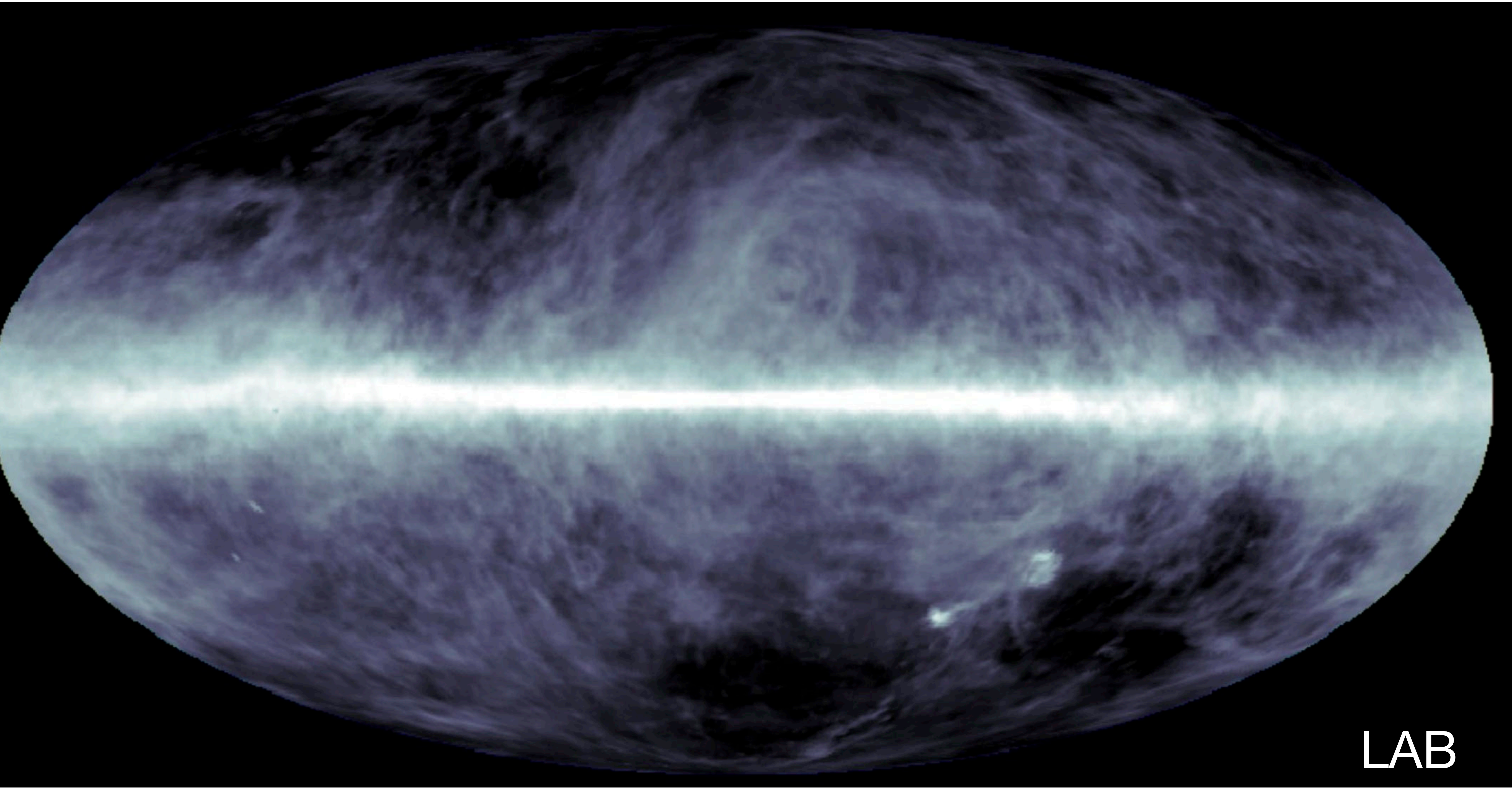
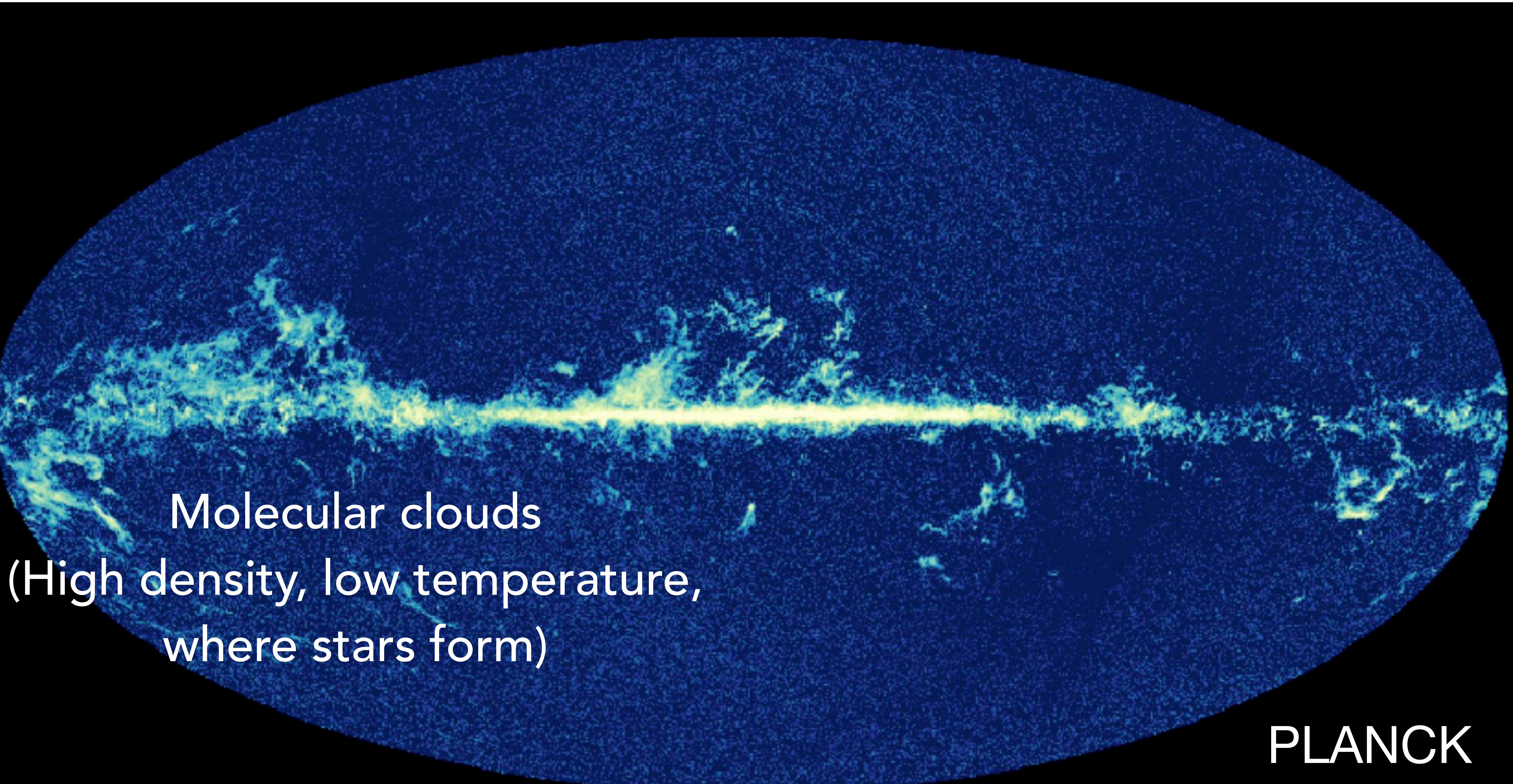


Multi-wavelength observation

Stars		UV, Optical and Infrared
Gas	HI	Radio (21 cm emission)
	H2	Microwave (CO emission)

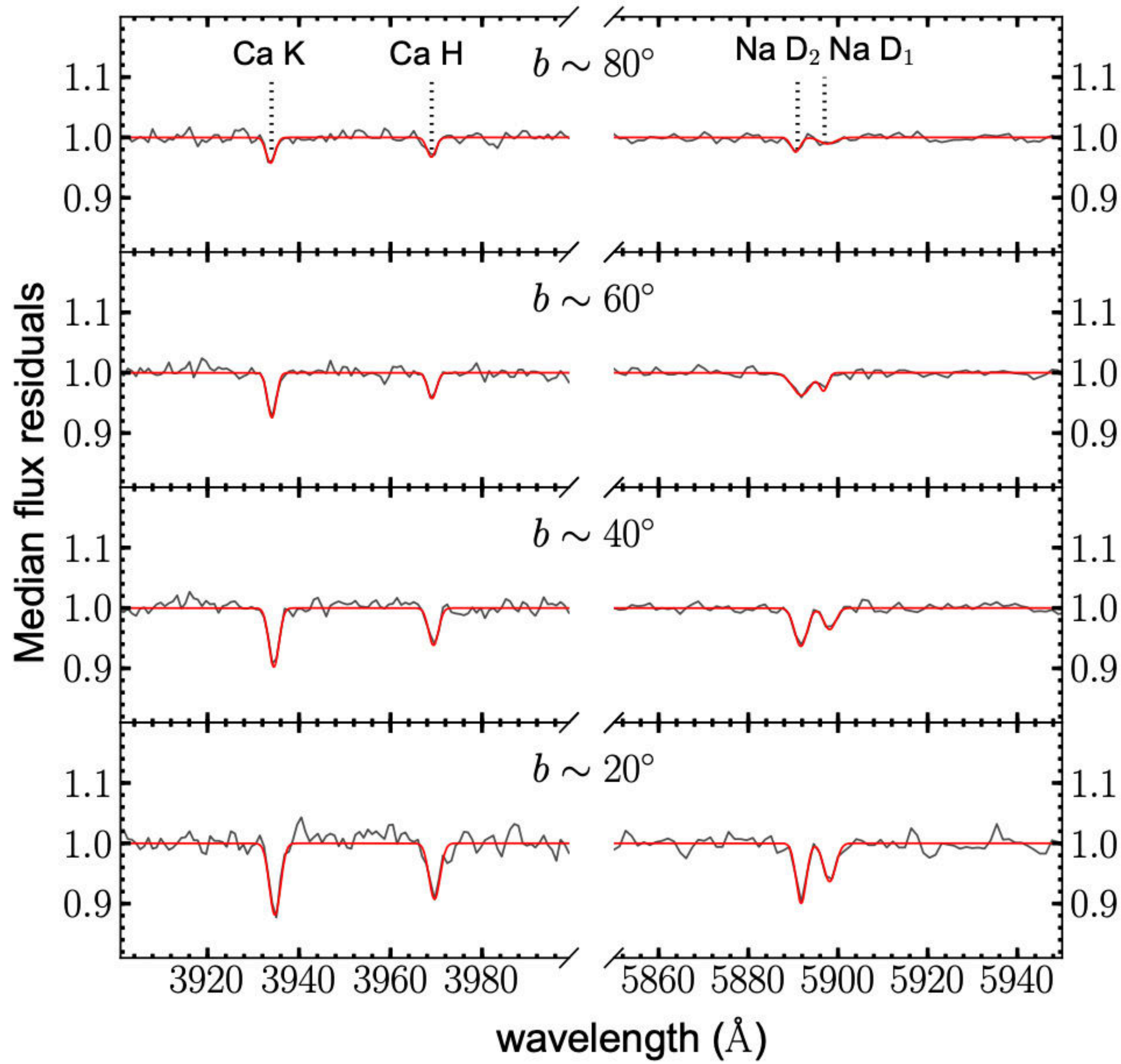


Multi-wavelength observation

Stars		UV, Optical and Infrared
Gas	HI	Radio (21 cm emission)
	H2	Microwave (CO emission)
	Metals	Metal absorption lines

Multi-wavelength observation

Using stars in the background to probe metals via absorption lines

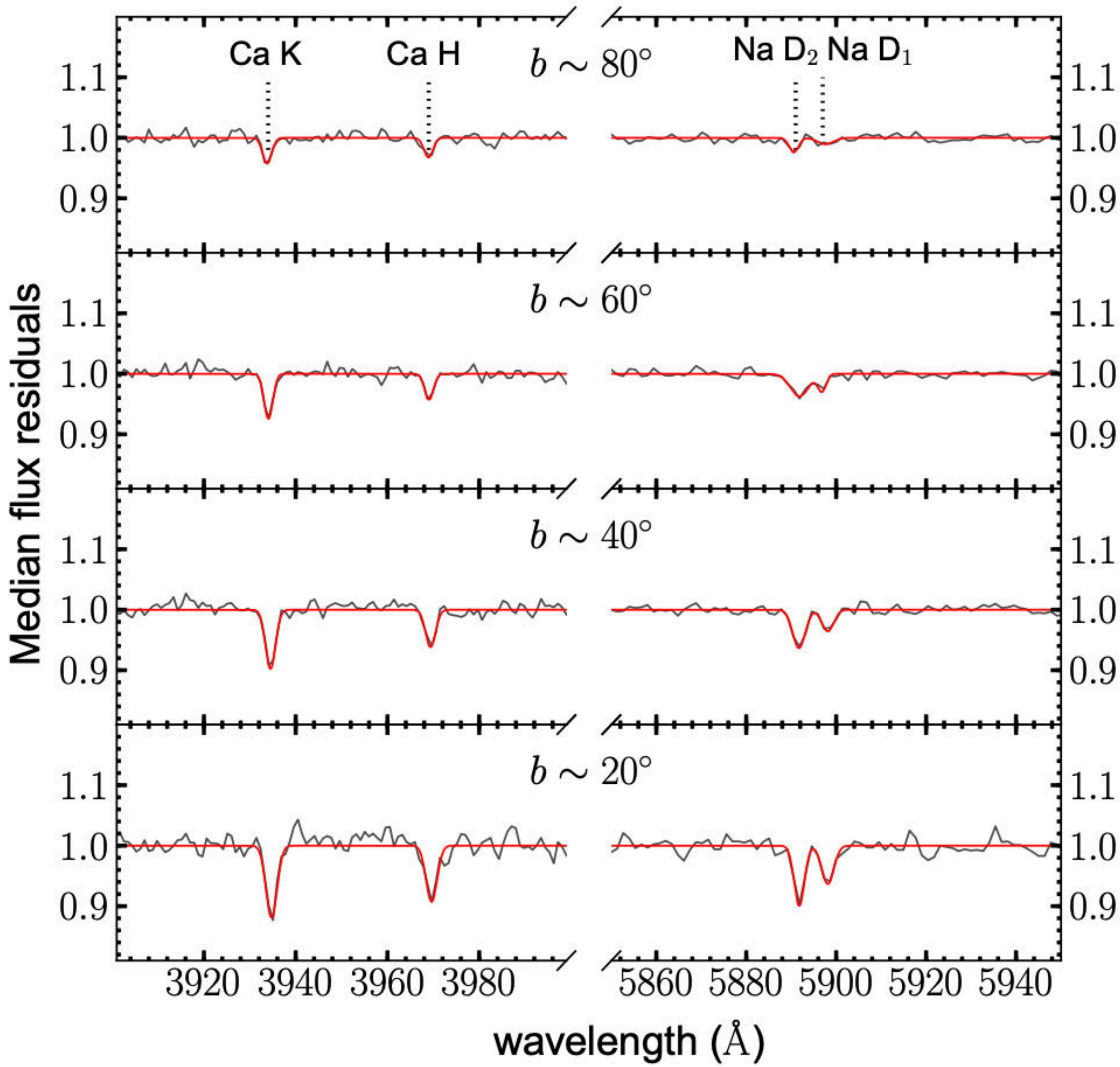


Murga et al. (2015)

Multi-wavelength observation

Using stars in the background to probe metals via absorption lines

Question: how do we know that the absorption lines are not induced by the stars themselves?



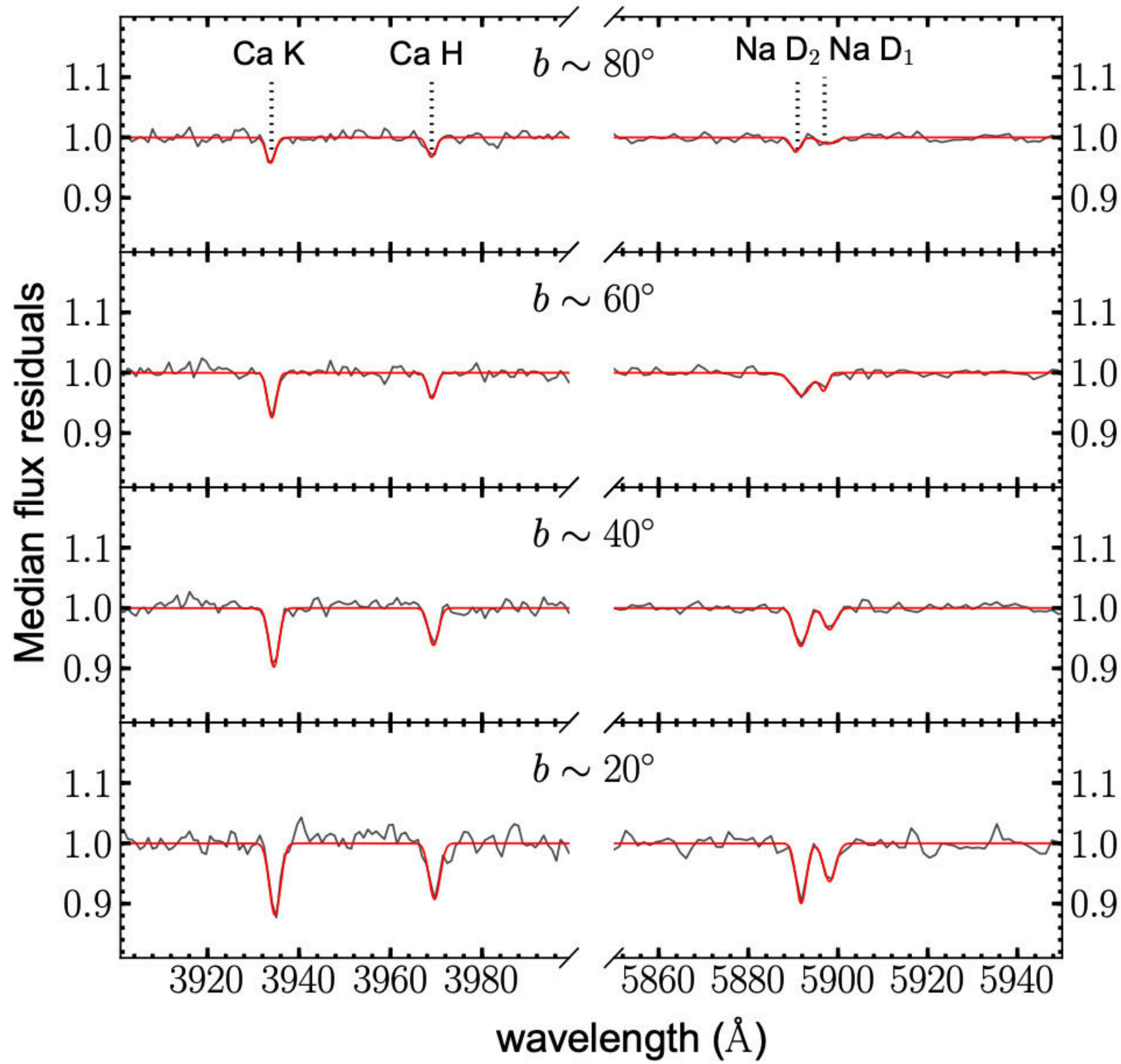
Murga et al. (2015)

Multi-wavelength observation

Using stars in the background to probe metals via absorption lines

Question: how do we know that the absorption lines are not induced by the stars themselves?

Binary stars!



Murga et al. (2015)

Multi-wavelength observation

INVESTIGATIONS ON THE SPECTRUM AND ORBIT OF δ *ORIONIS*.[1]

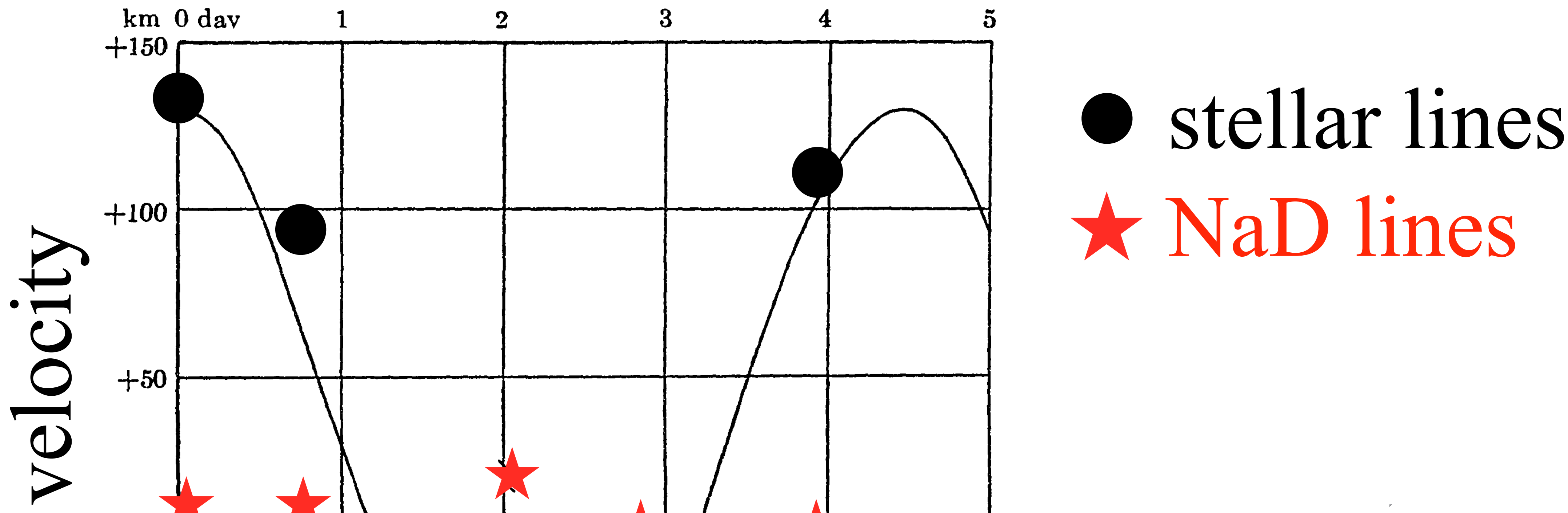
By J. HARTMANN.

"Among the lines...the calcium line at λ3934 [K] exhibits a very peculiar behavior. It...does not share in the periodic displacements of the lines caused by the orbital motion of the star."

1904 Discovery of Ca between stars (interstellar medium)

Johannes Hartmann

Multi-wavelength observation



Heger 1922

Mary Heger

1919 Discovery of Na

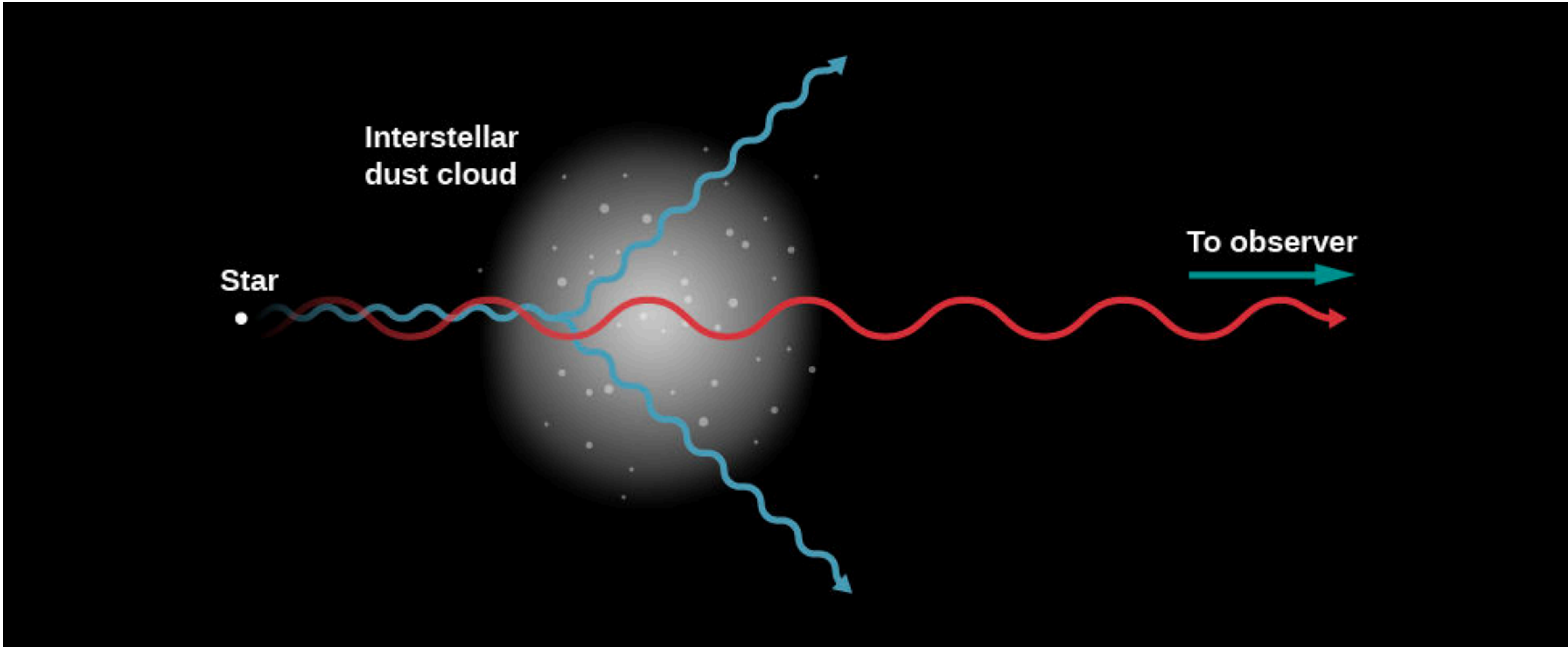
Multi-wavelength observation

Stars		UV, Optical and Infrared
Gas	HI	Radio (21 cm emission)
	H2	Microwave (CO emission)
	Metals	Metal absorption lines/ emission lines
Dust		UV, Optical, Infrared

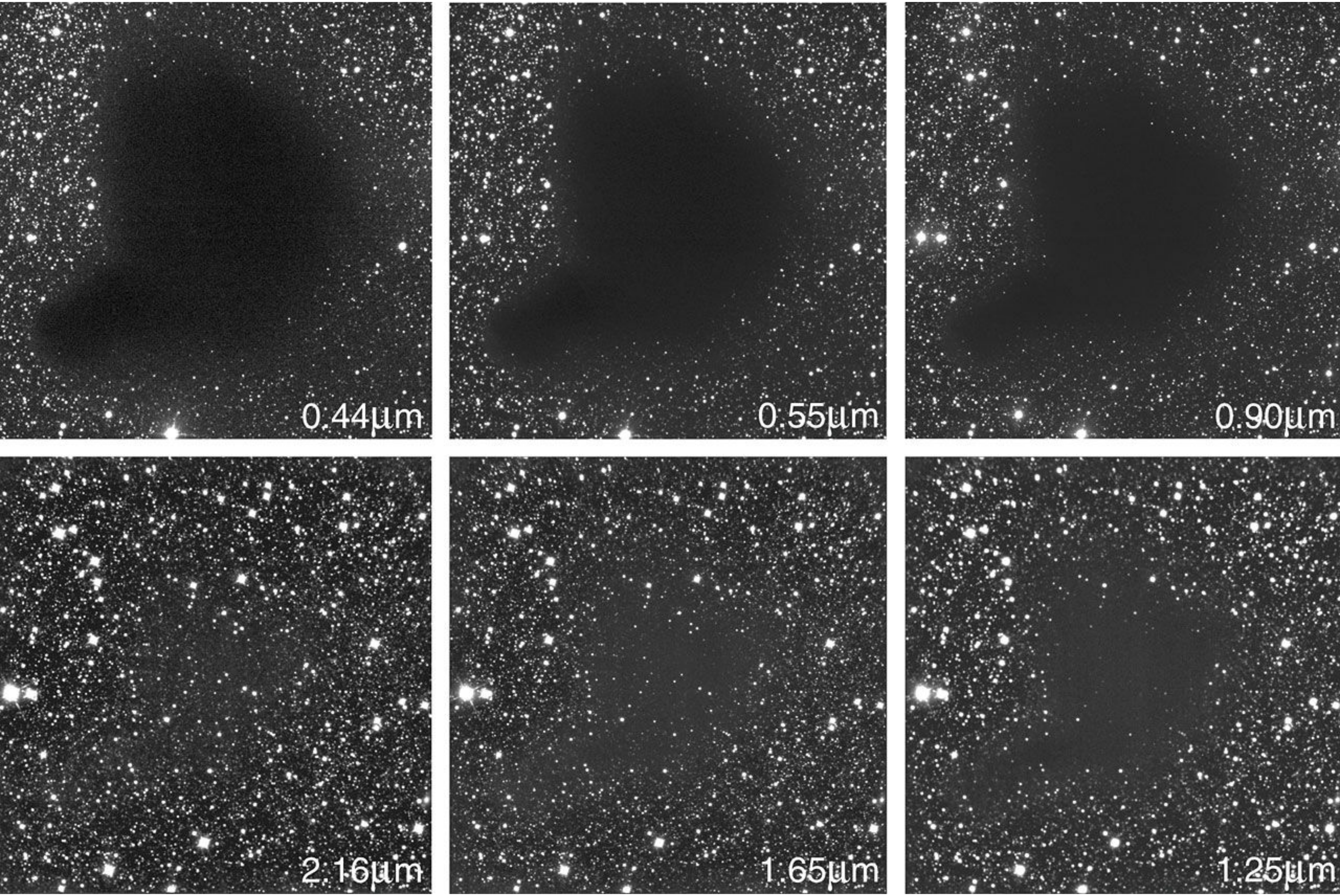
Multi-wavelength observation

Dust

Absorption + Scattering = Extinction



Wavelength dependence: stronger effect for blue light



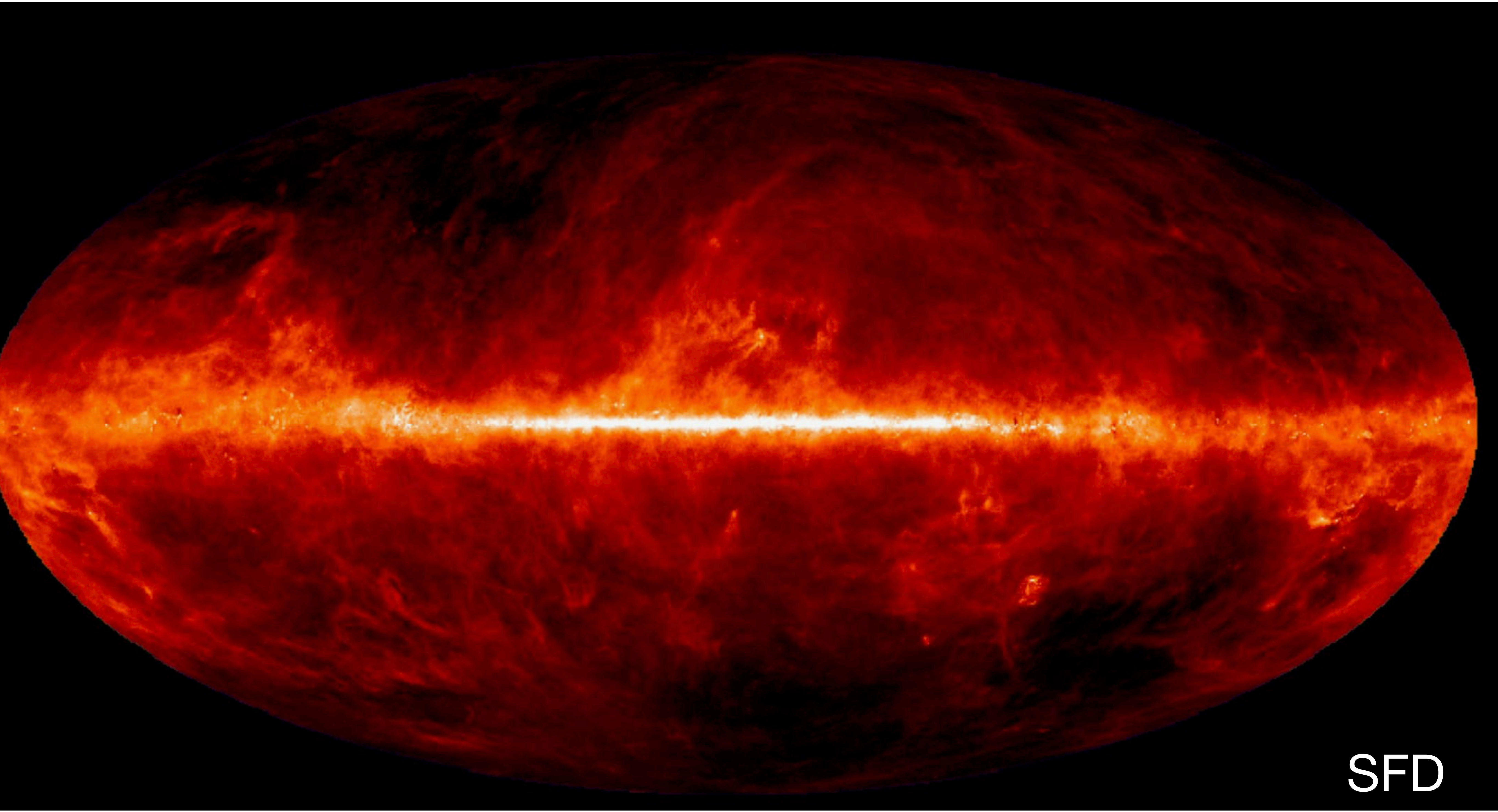
ESO

Multi-wavelength observation

Dust

Far-infrared

Absorption -> Black Body Radiation (~20 K)



Multi-wavelength observation

Stars		UV, Optical and Infrared
Gas	HI	Radio (21 cm emission)
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	Metals	Metal absorption lines/ emission lines
Dust		UV, Optical, Infrared
Supermassive black hole		

The discovery of quasars

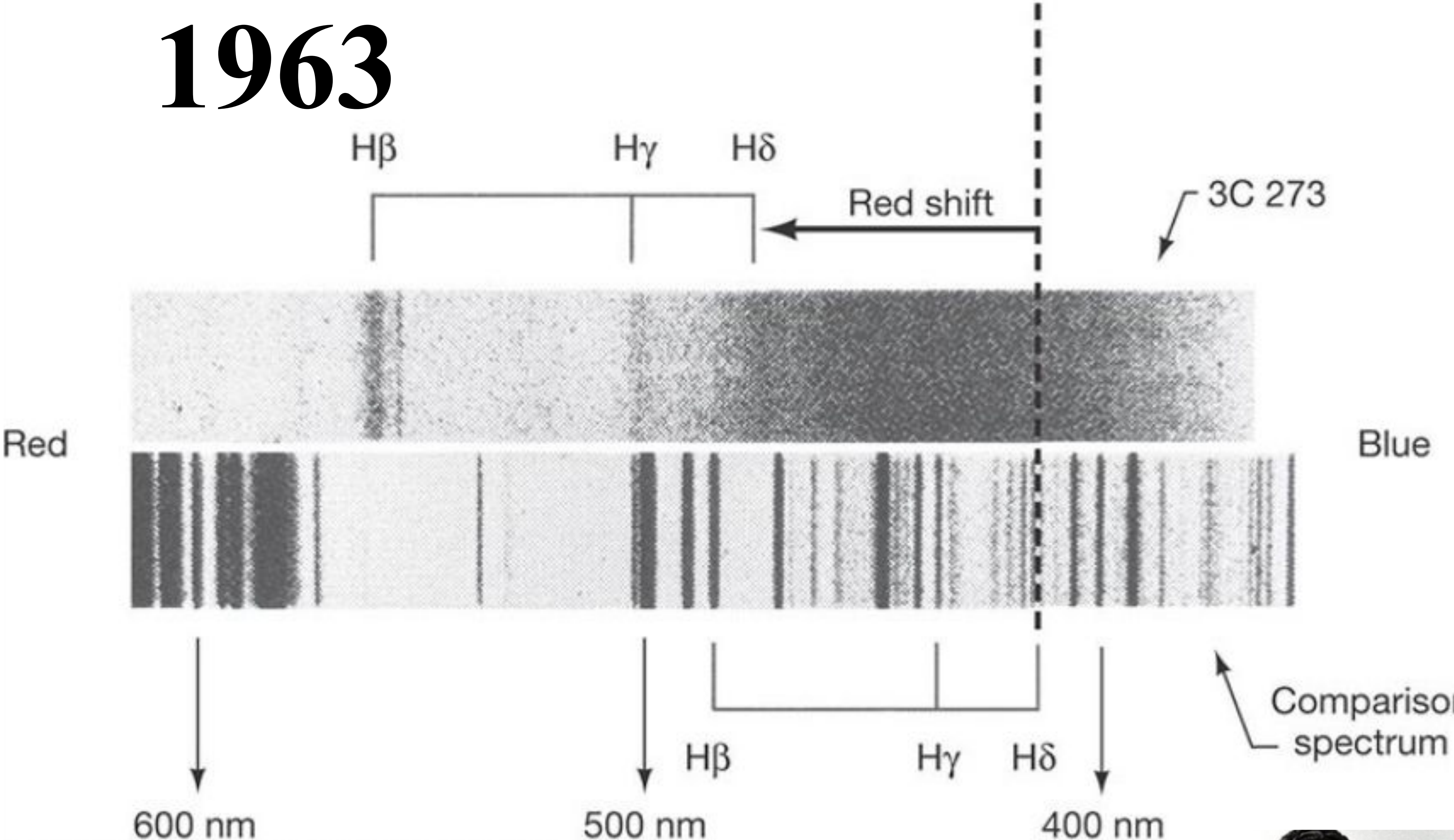
1950s

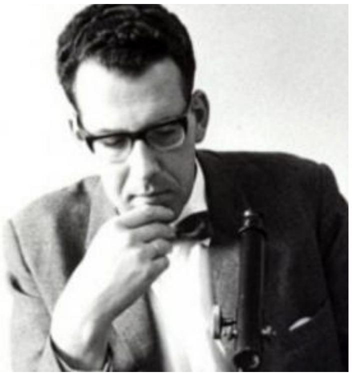
Radio observations revealed some sources producing very strong radio emission (3C catalog)

From optical observations, some of them look like stars.

What were those sources?

The discovery of quasars





https://articles.adsabs.harvard.edu//full/2003JRASC..97...13C/0000013.000.html

https://www.jstor.org/stable/pdf/23056831.pdf?refreqid=excelsior%3A3d60fc63d7160d6cd8967556e894aed2&ab_segments=&origin=

Maarten Schmidt

The discovery of quasars

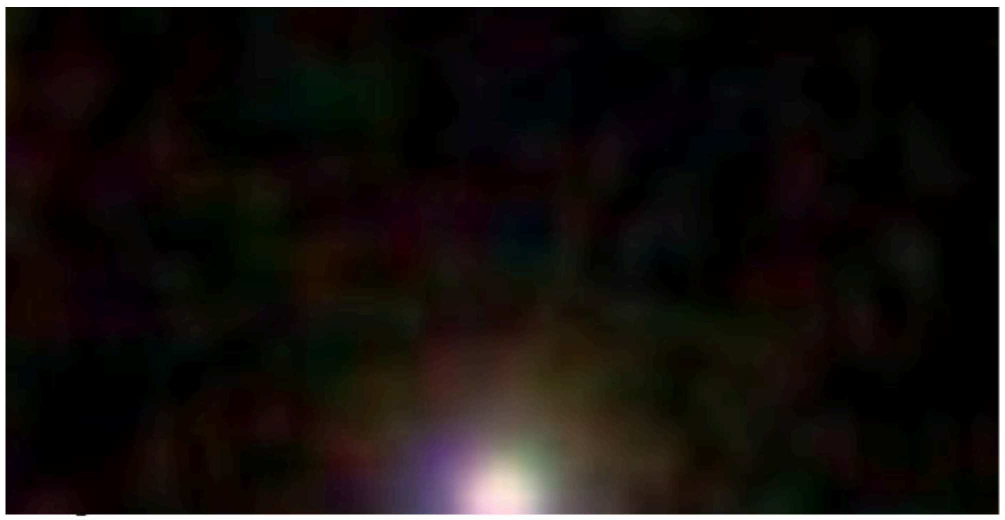
Quasars

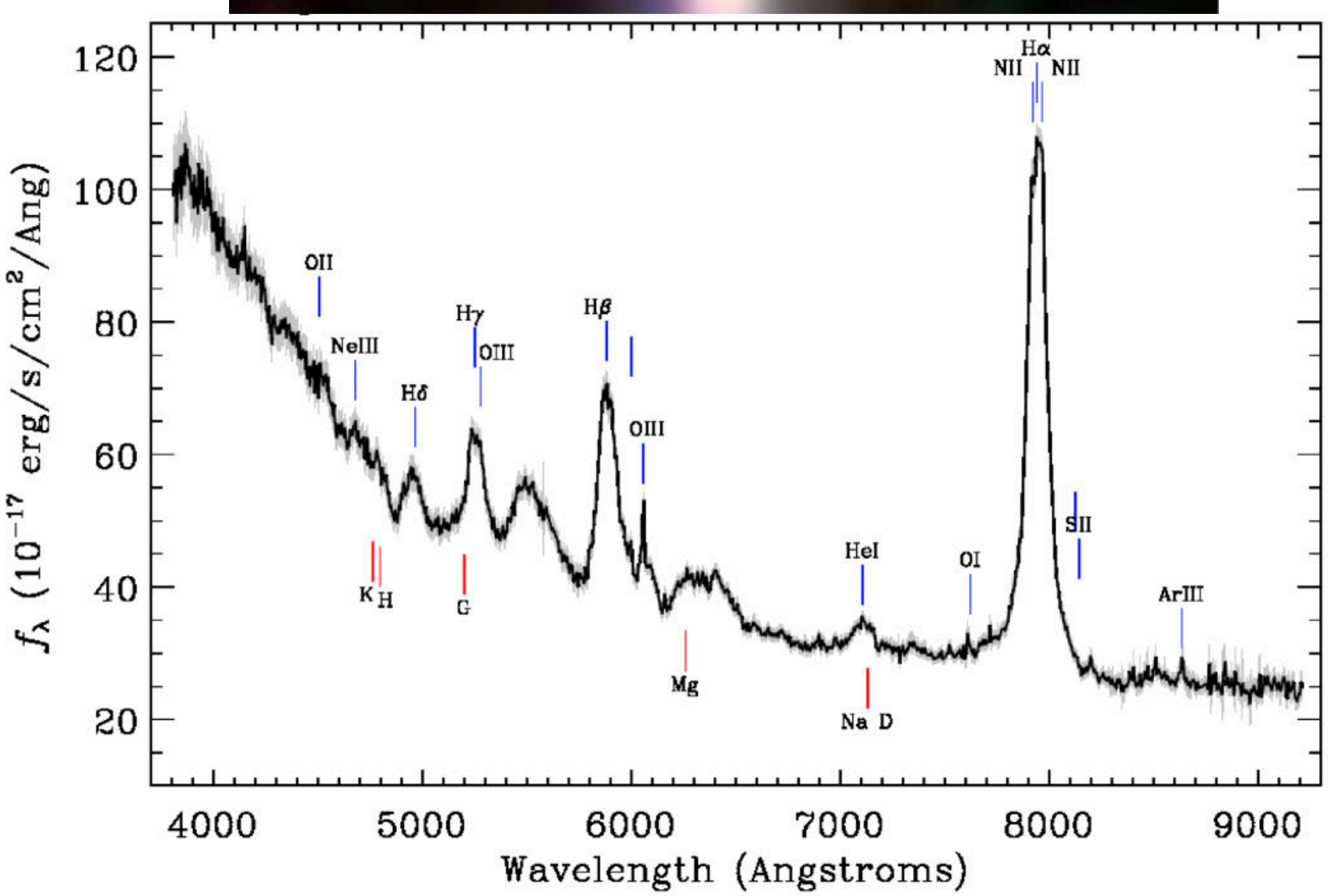
Stars

SDSS

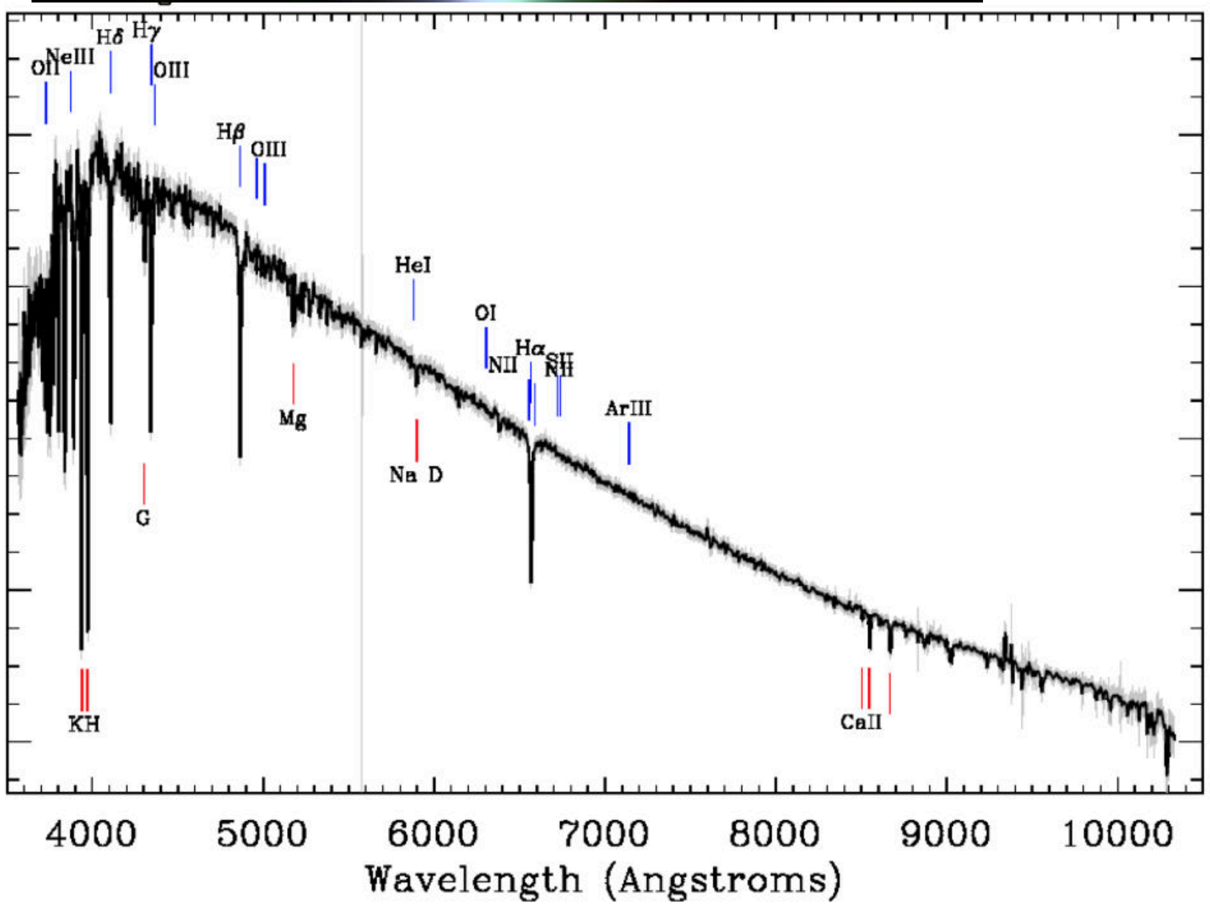
The discovery of quasars

Quasars





Stars



SDSS

The discovery of quasars

Quasars	Stars
	

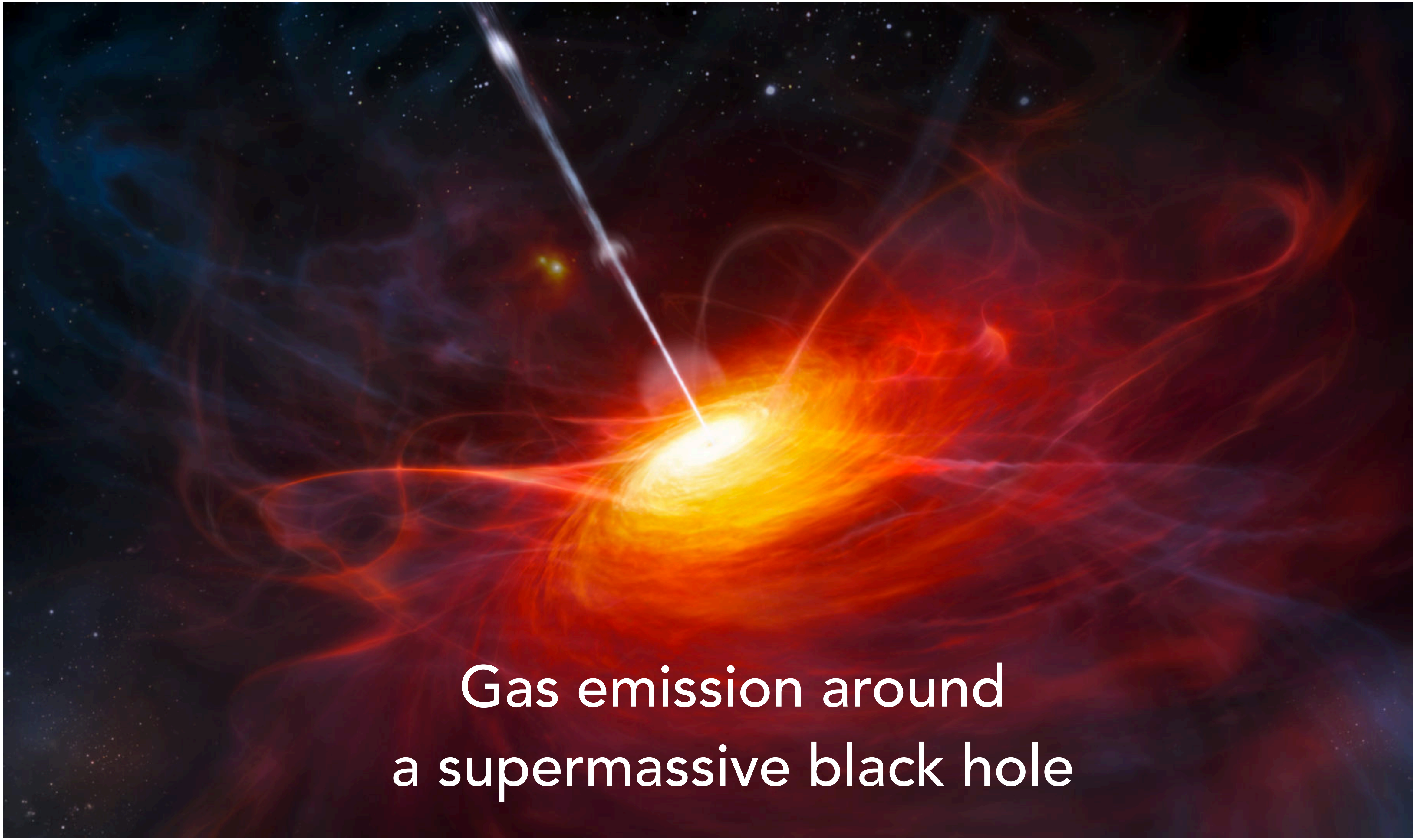
Distance $\sim 10^6$ kpc ~ 1 kpc

$$L_{quasar} \sim 10^{12}\ L_{star}$$

$$\sim 100\ L_{galaxy}$$

SDSS

The discovery of quasars

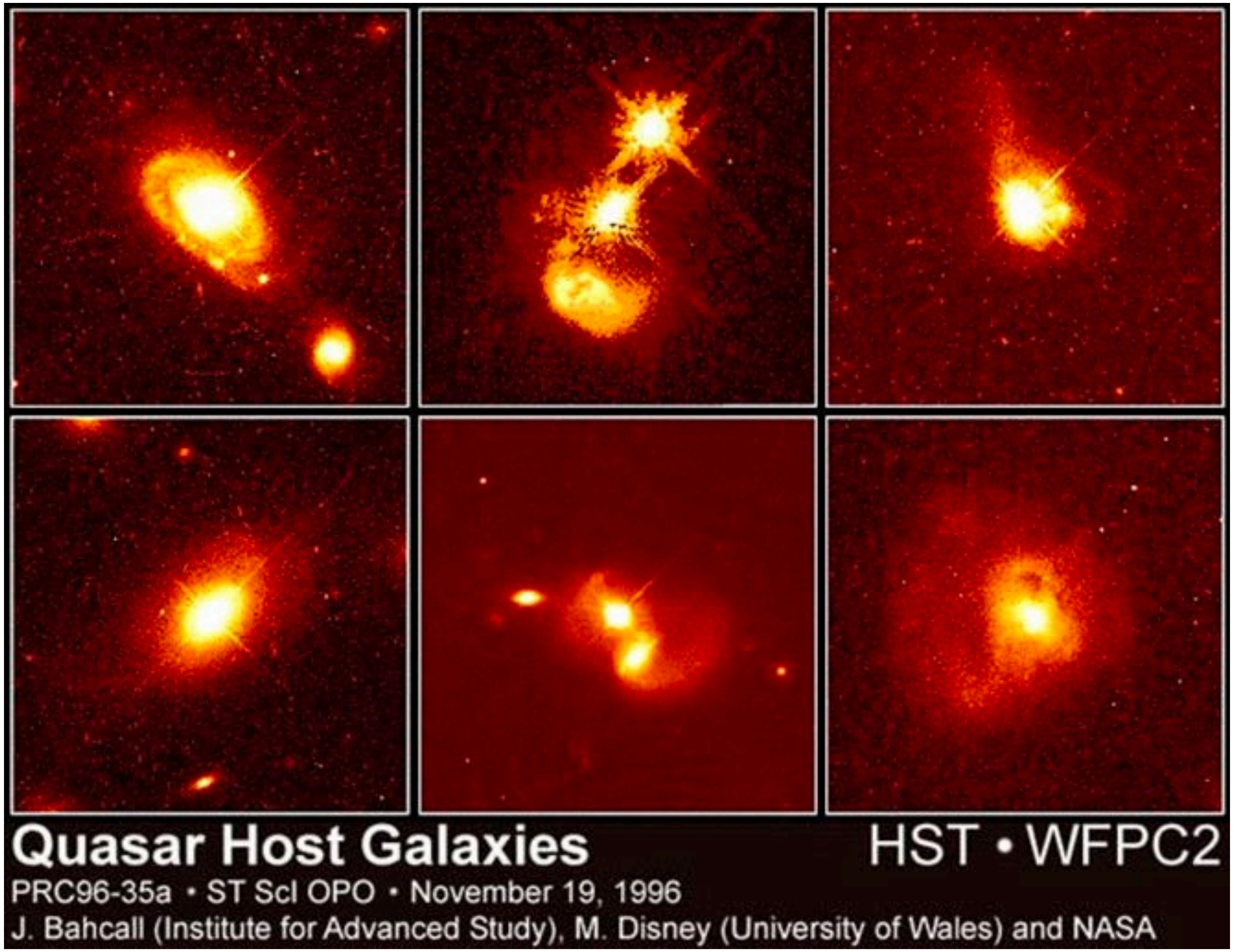


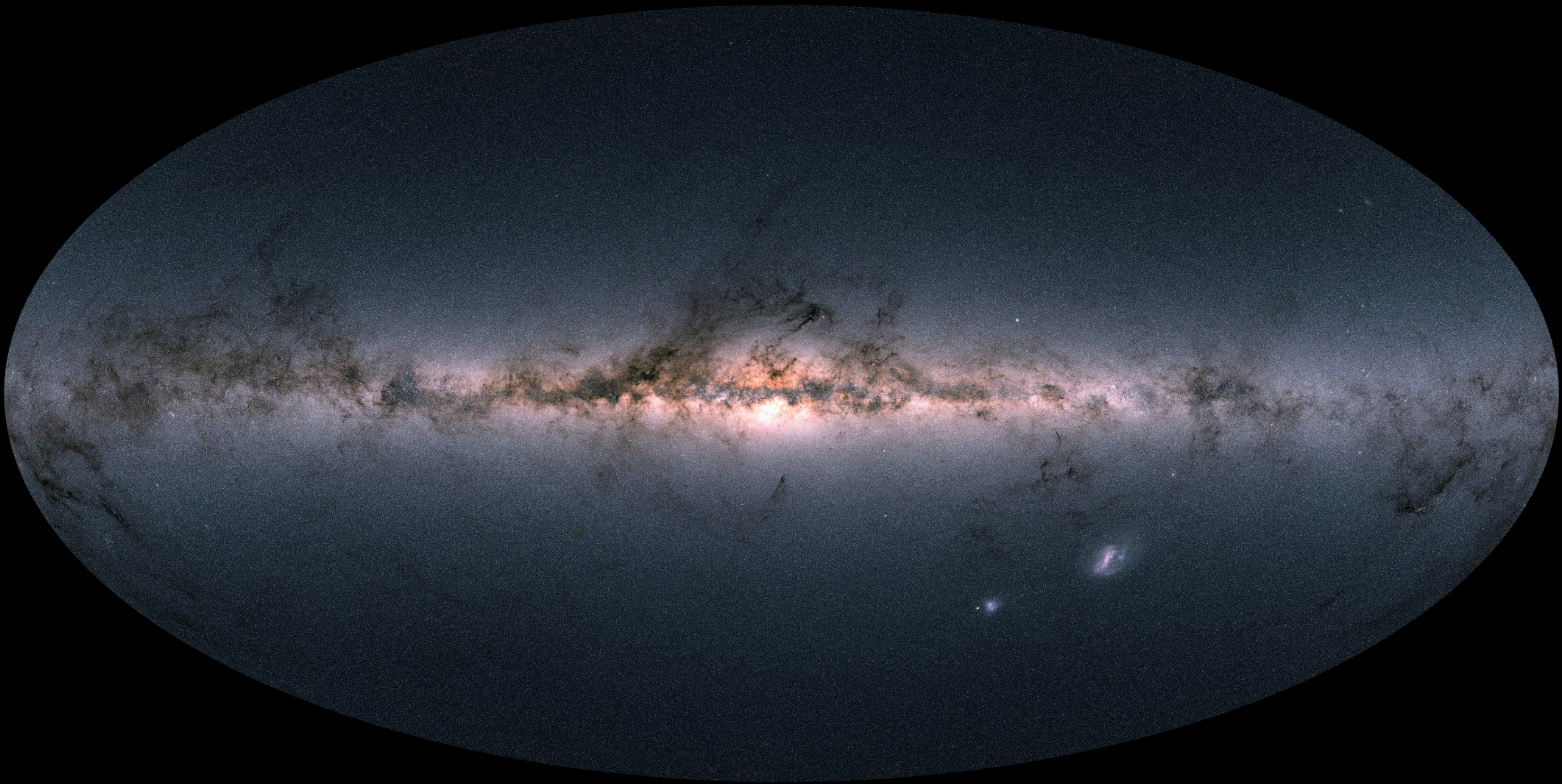
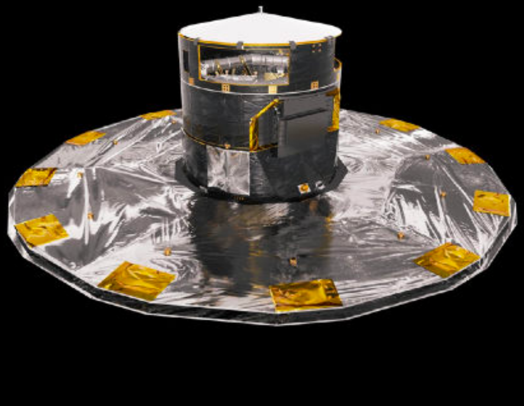
Artistic Visualization

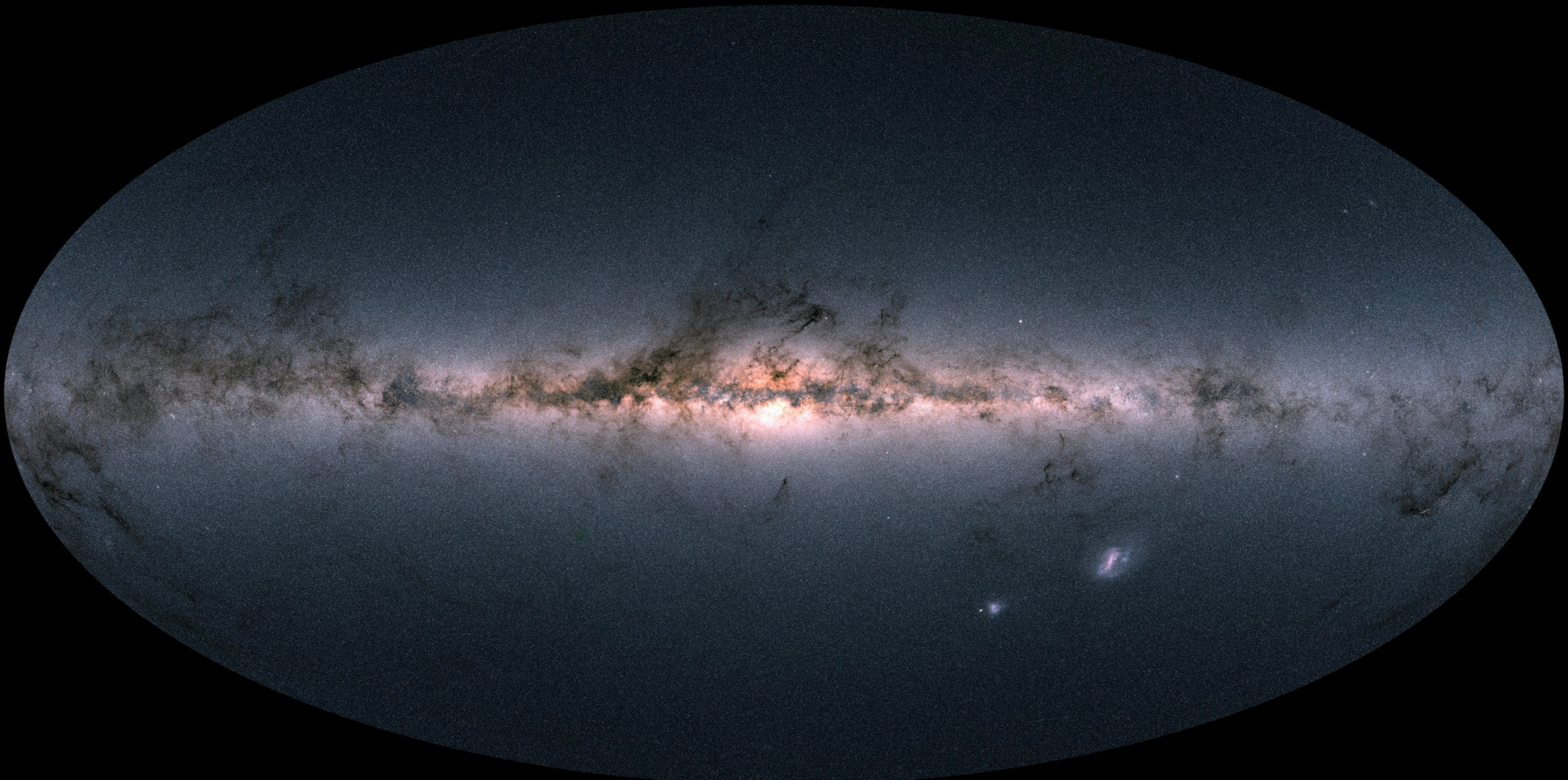
ESO/M. Kornmesser

Galaxies and Black Holes

Supermassive black holes sit in the center of galaxies

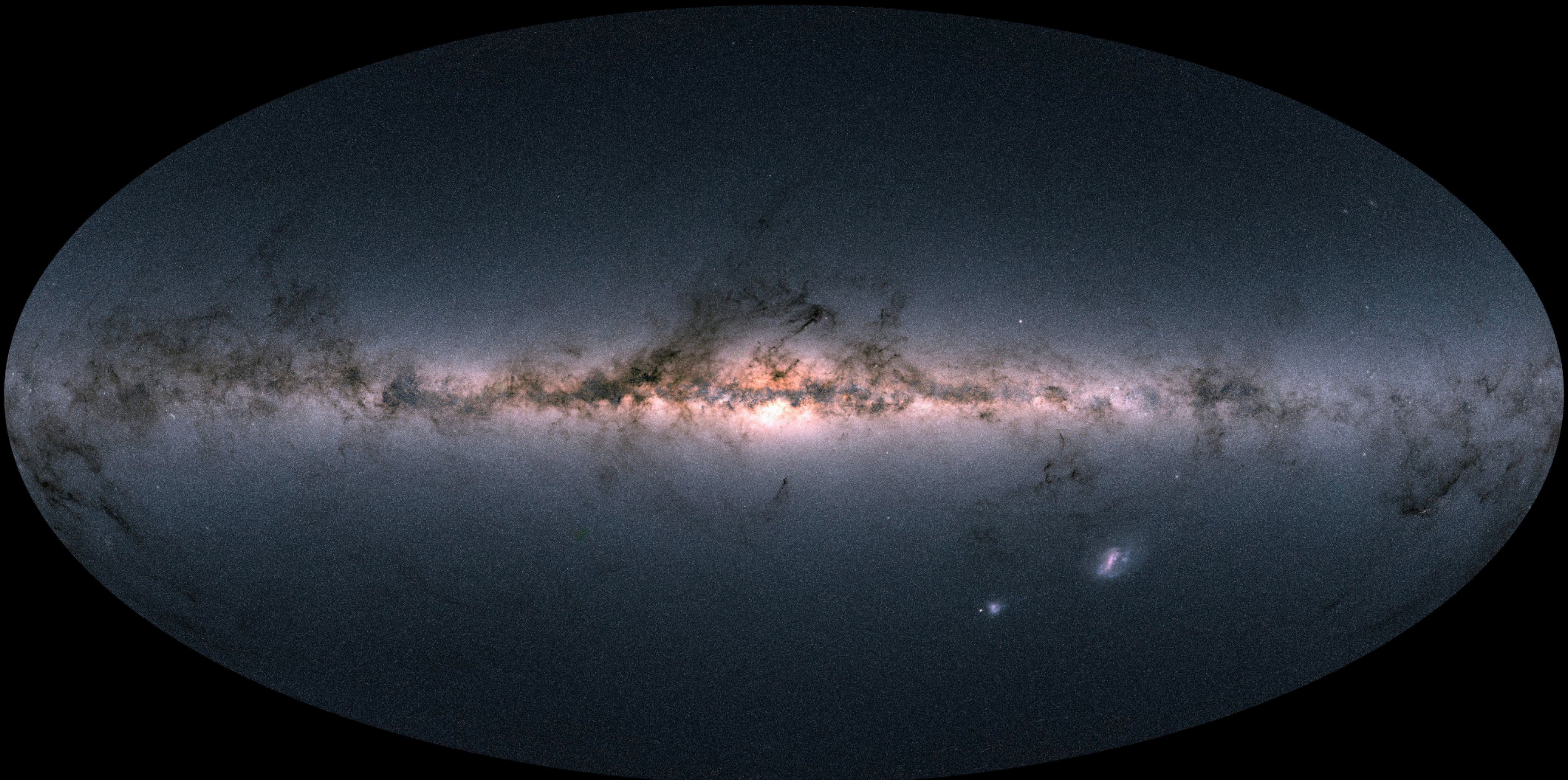




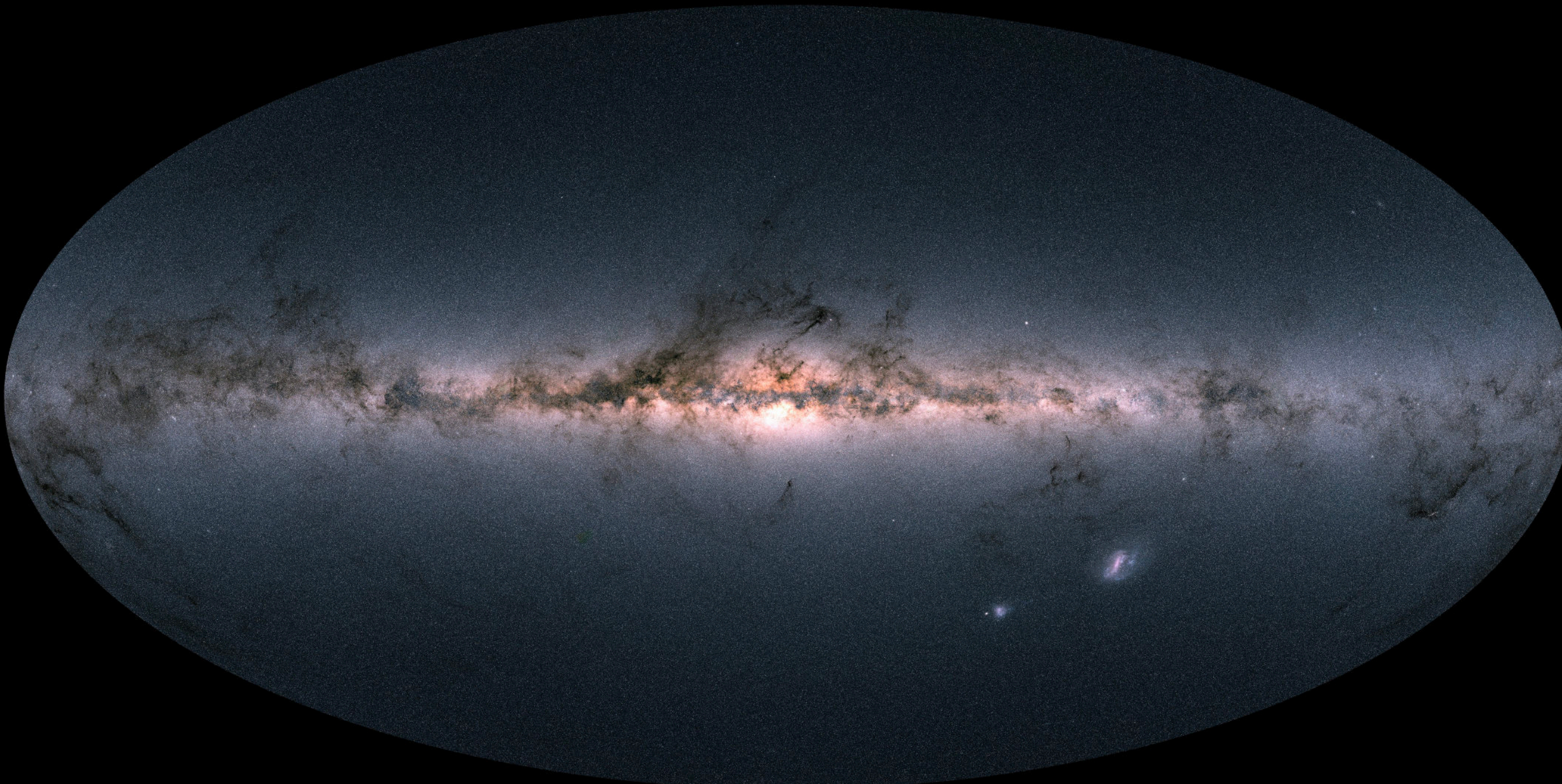
Two challenges to observe the center of MW:

1. Dust



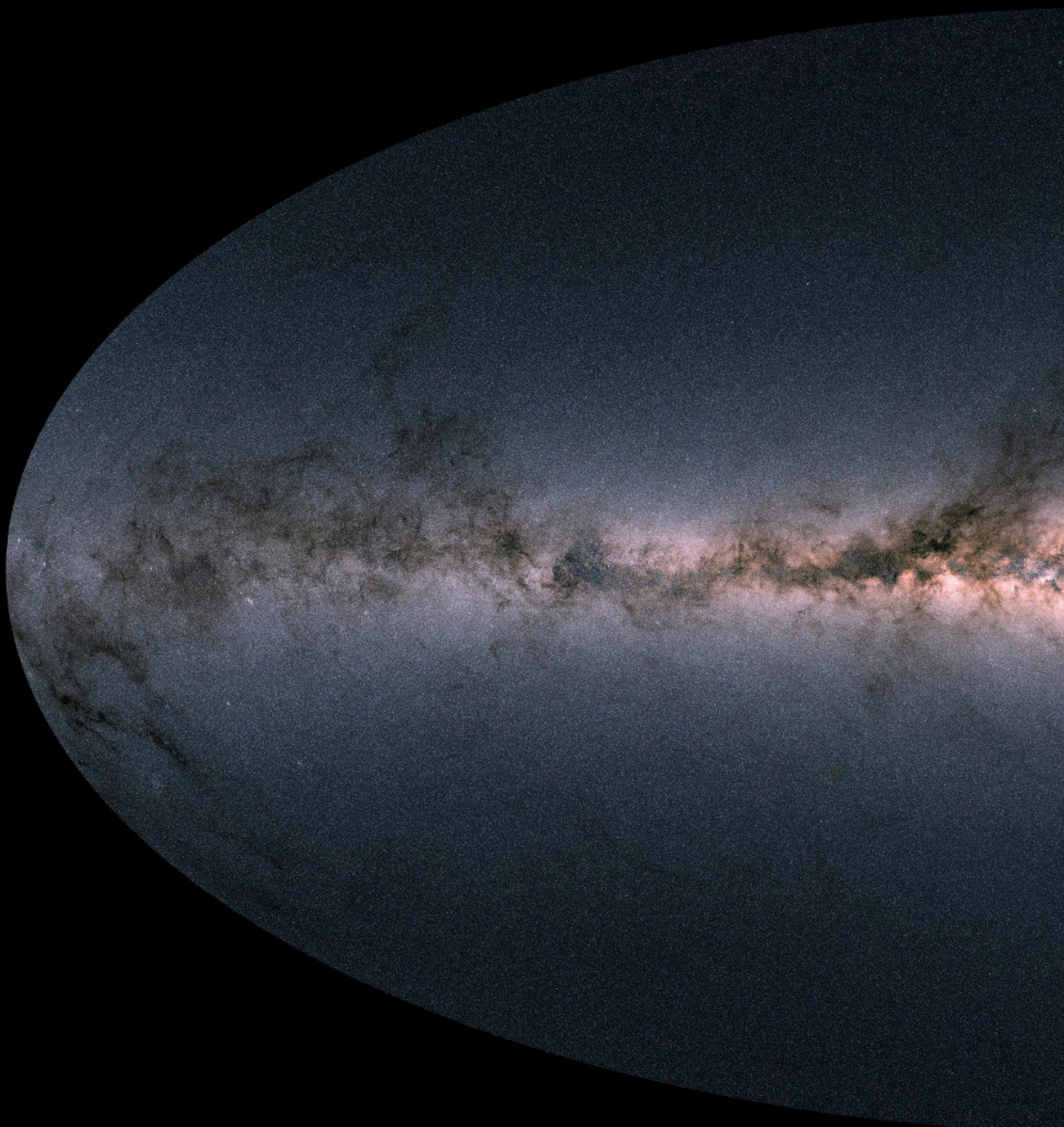
Two challenges to observe the center of MW:

1. Dust **Infrared observations**



Two challenges to observe the center of MW:

1. Dust **Infrared observations**
2. Atmosphere fluctuation



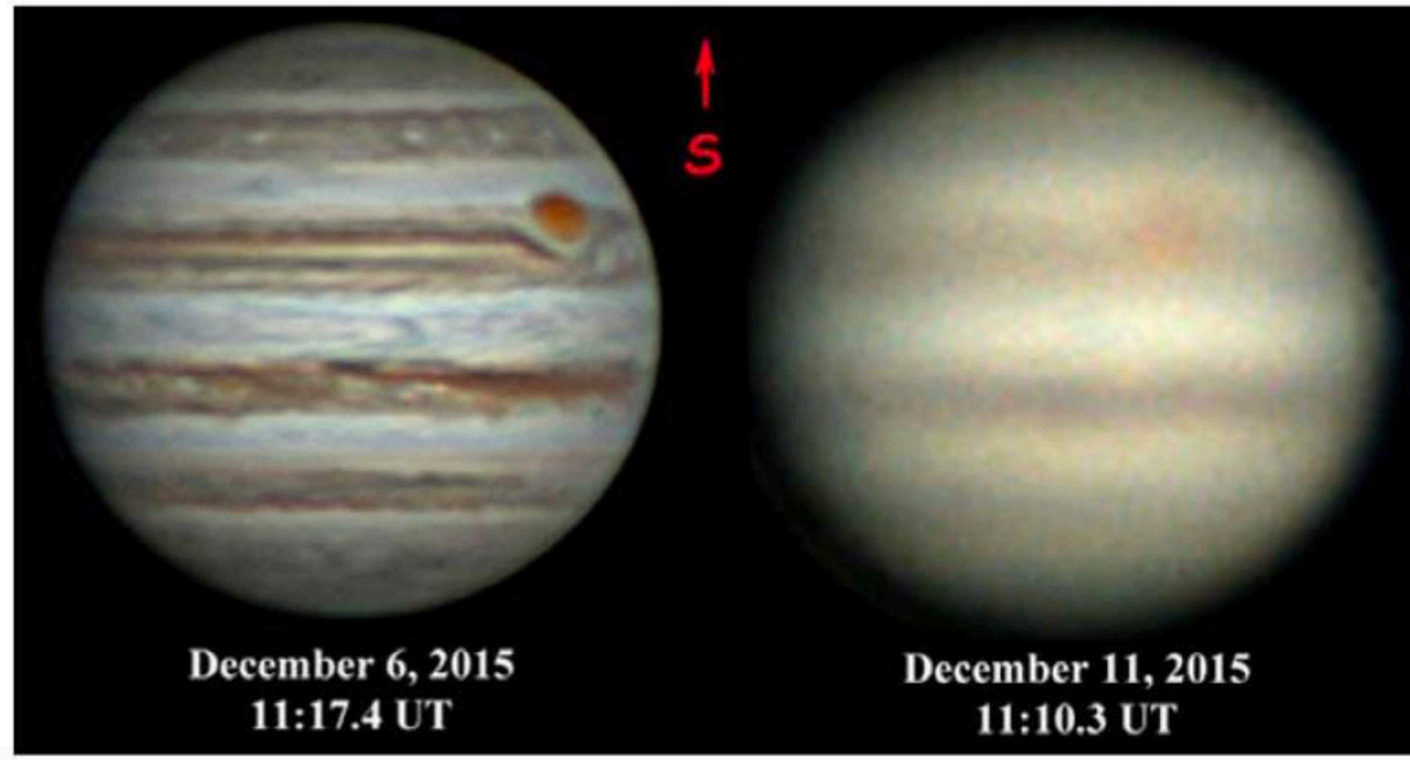


Figure 2. Jupiter, captured with the same equipment in good (left) and bad (right) seeing conditions. *Cliff Ashcraft, New Jersey, USA*

Two challenges to observe the center of MW:

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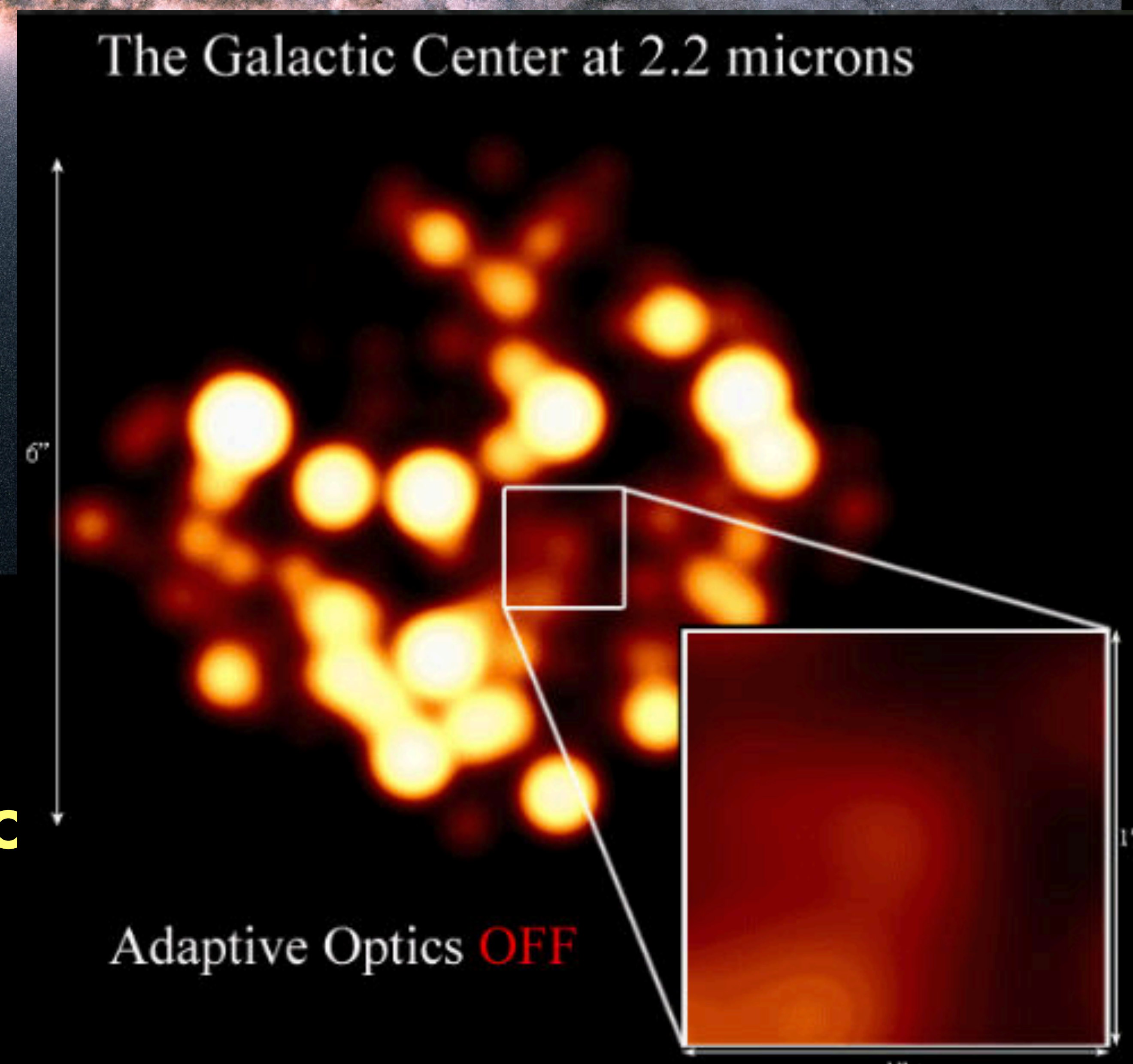
2. Atmosphere fluctuation



Two challenges to observe the center of MW:

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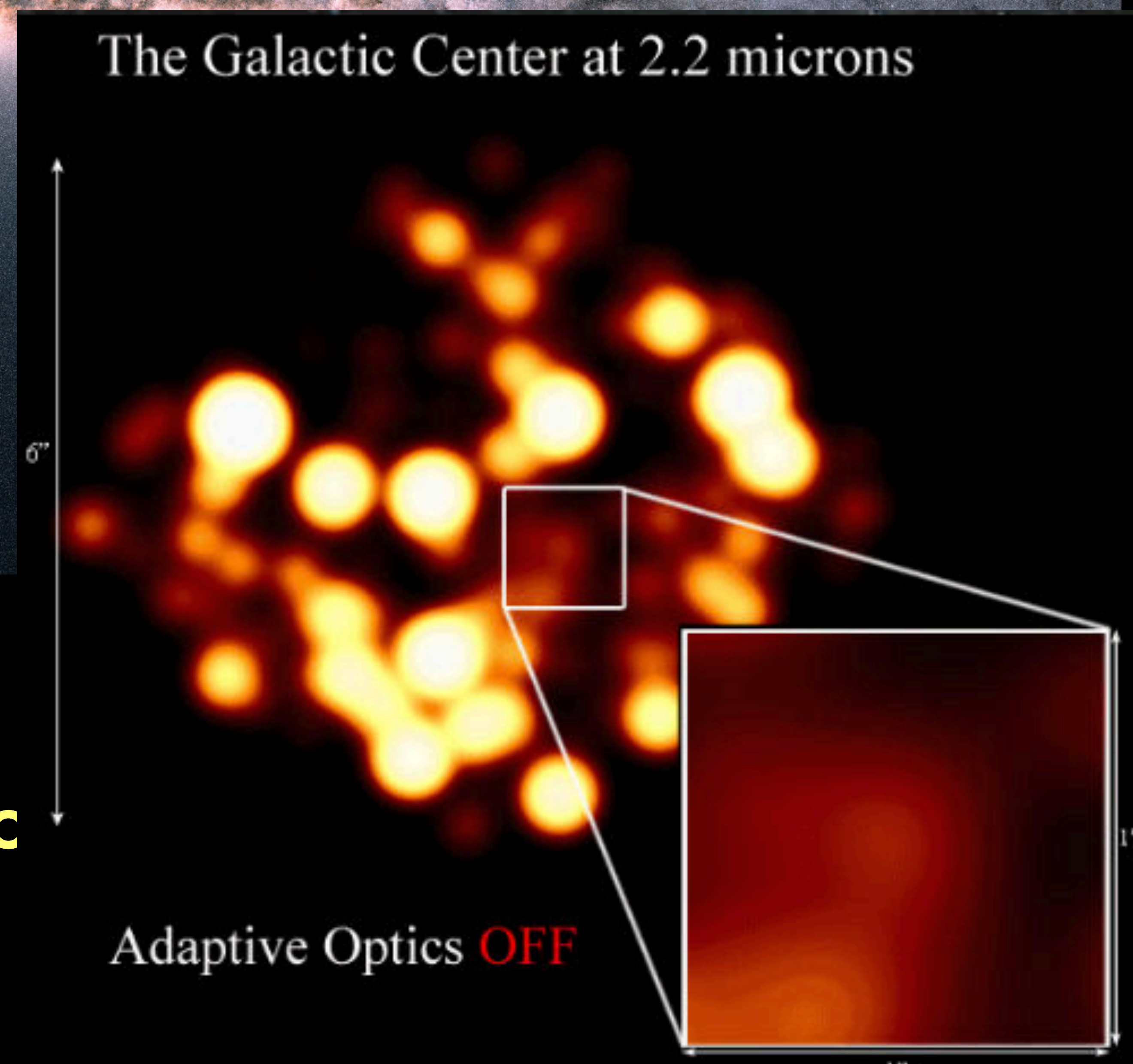

Two challenges to observe the center of MW:

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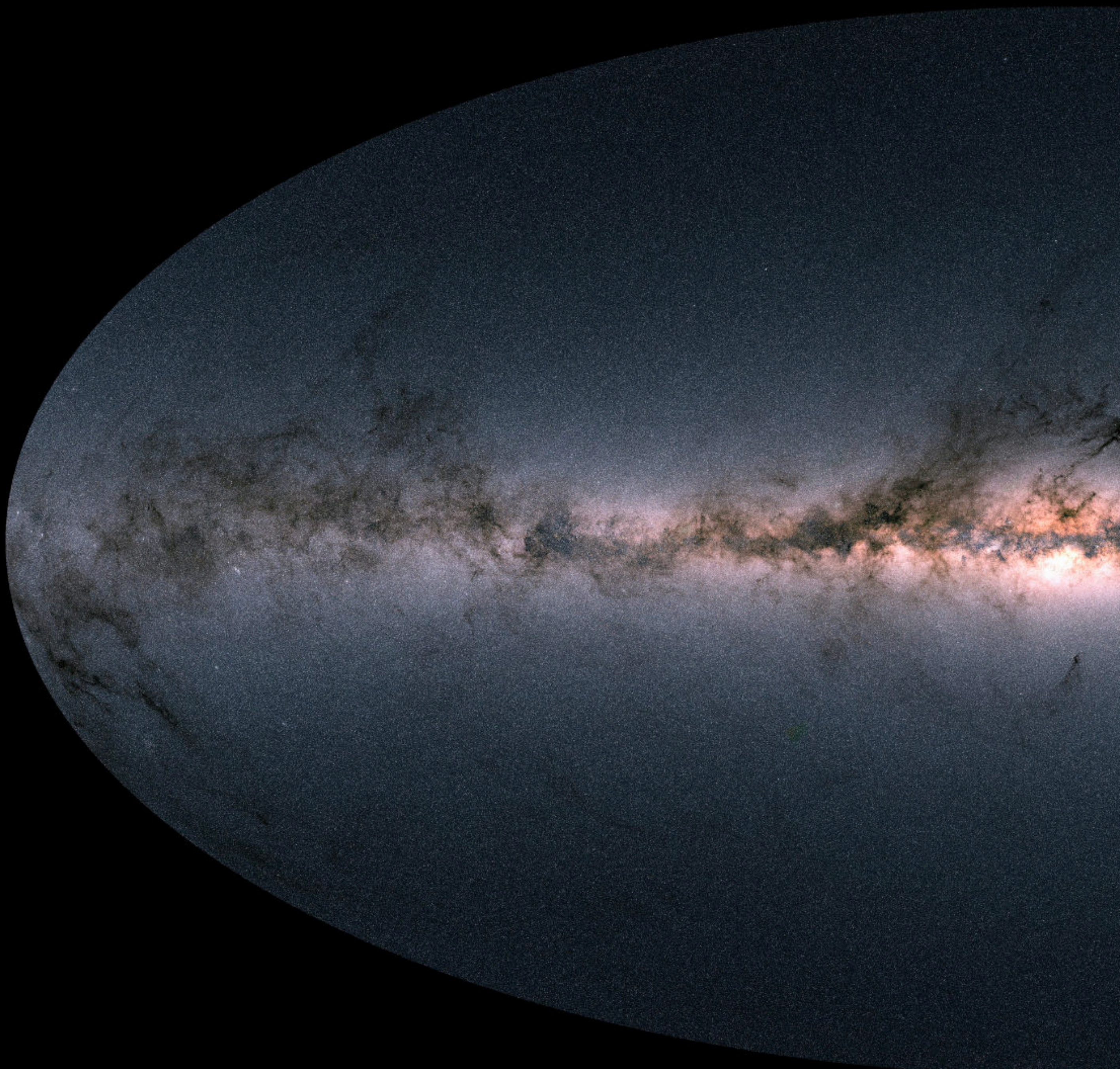

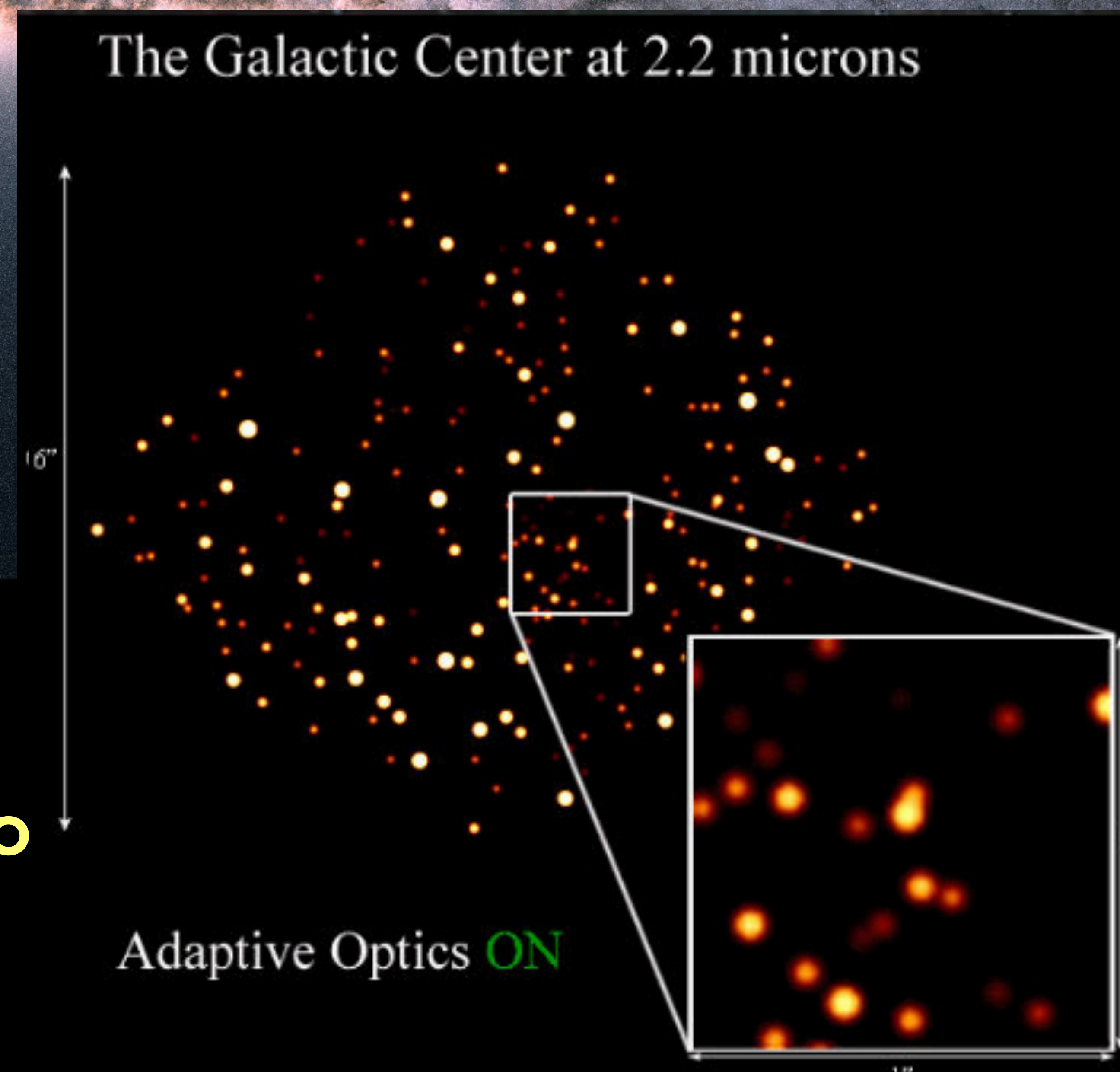

Two challenges to observe the center of MW:

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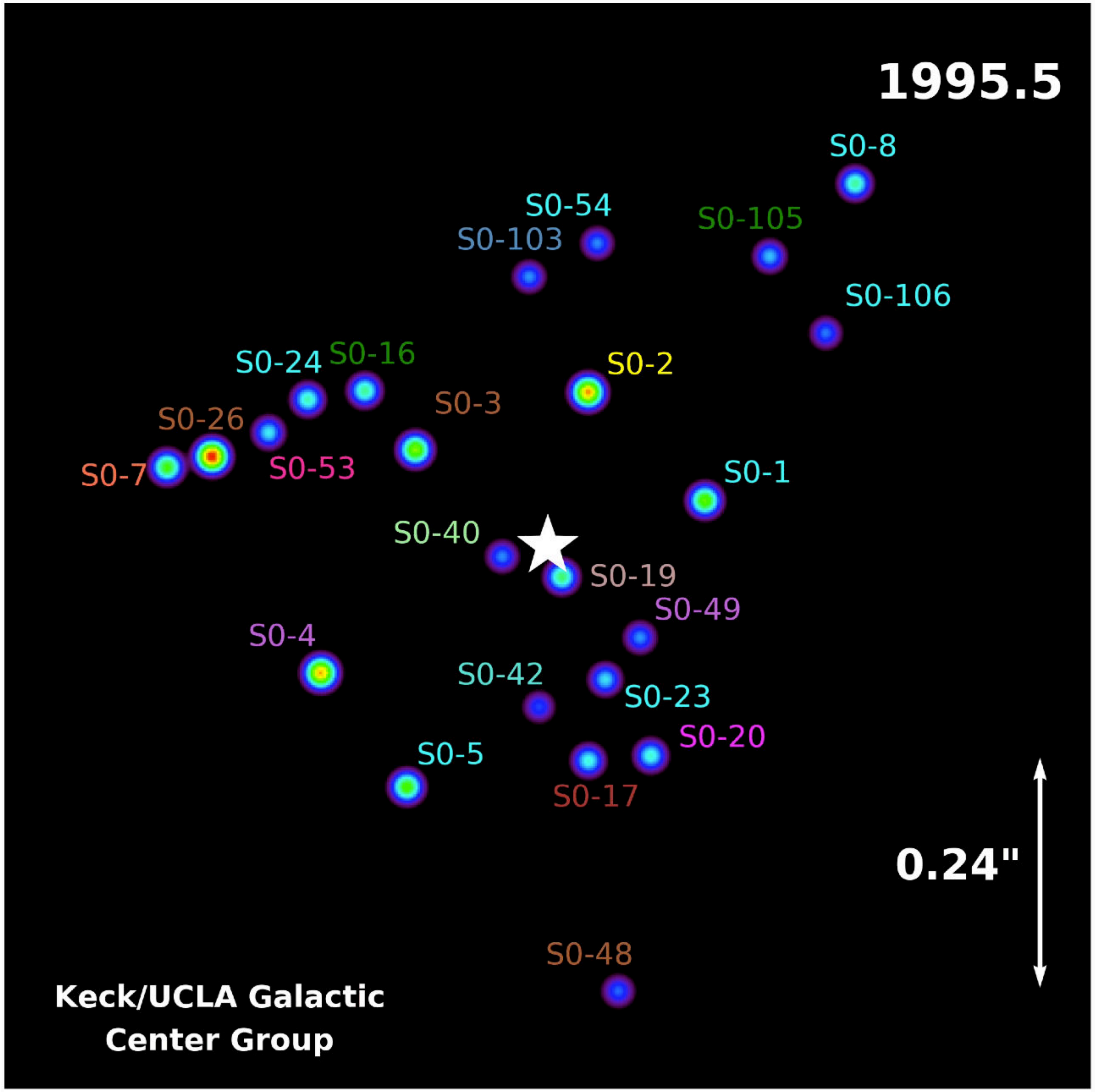
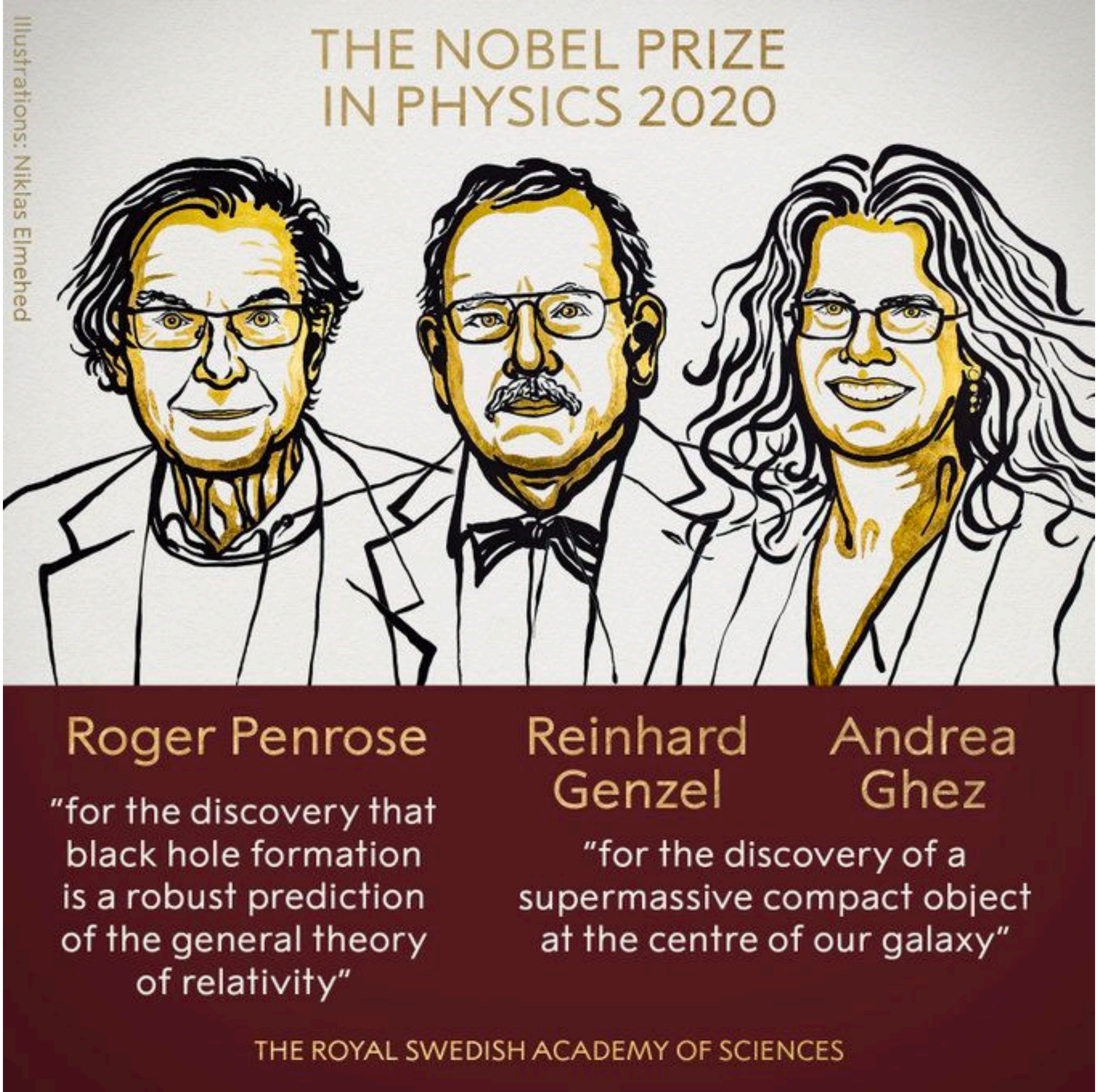


A supermassive black hole (~5x10^6 M$_\odot$)

at the center of MW


Illustrations: Niklas Elmehed
THE NOBEL PRIZE
IN PHYSICS 2020
Roger Penrose
"for the discovery that black hole formation is a robust prediction of the general theory of relativity"
Reinhard Genzel
Andrea Ghez
"for the discovery of a supermassive compact object at the centre of our galaxy"
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Multi-wavelength observation

Stars		UV, Optical and Infrared
Gas	HI	Radio (21 cm emission)
	H2	Microwave (CO emission)
	Metals	Metal absorption lines/ emission lines
Dust		UV, Optical, Infrared
Supermassive black hole		Multi-wavelength

Multi-wavelength observation

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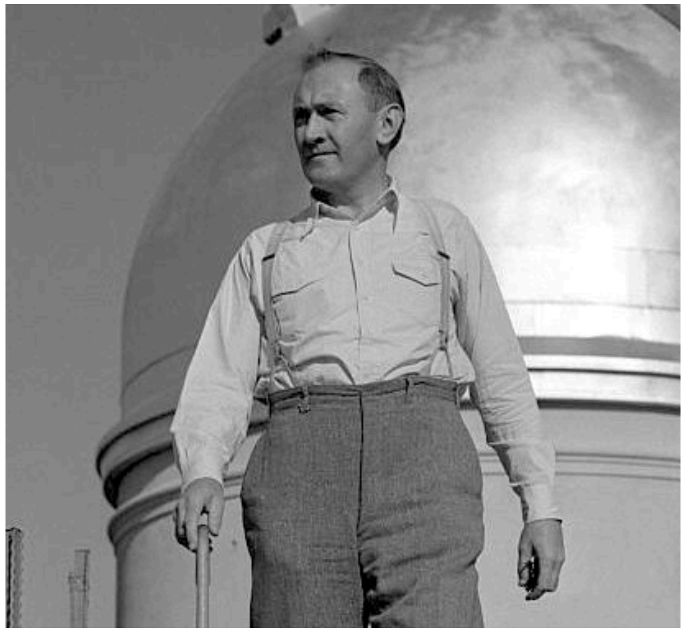
Dust		UV, Optical, Infrared
Supermassive black hole		Multi-wavelength
Dark matter		Gravitational effects

The Detection of Dark Matter



Fritz Zwicky

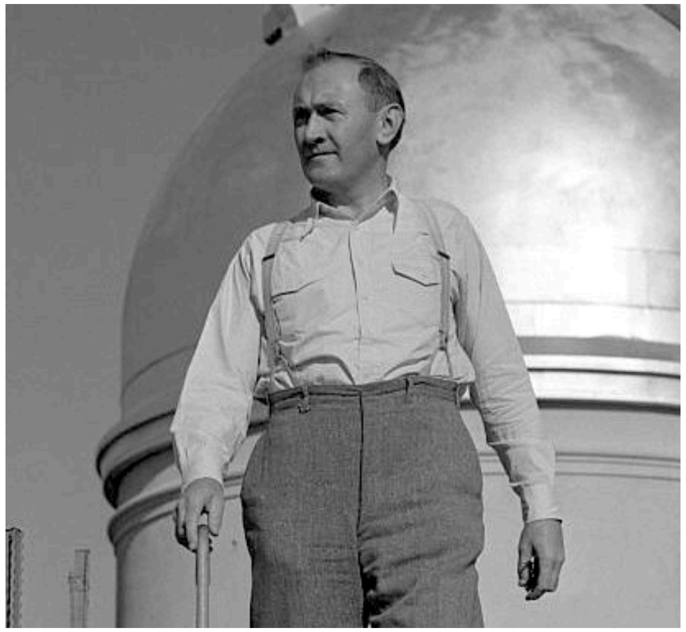
1933

Coma cluster

http://sprite.phys.ncku.edu.tw/astrolab/mirrors/apod_e/ap180326.html

https://lithub.com/the-humble-origins-of-the-man-who-discovered-dark-matter/

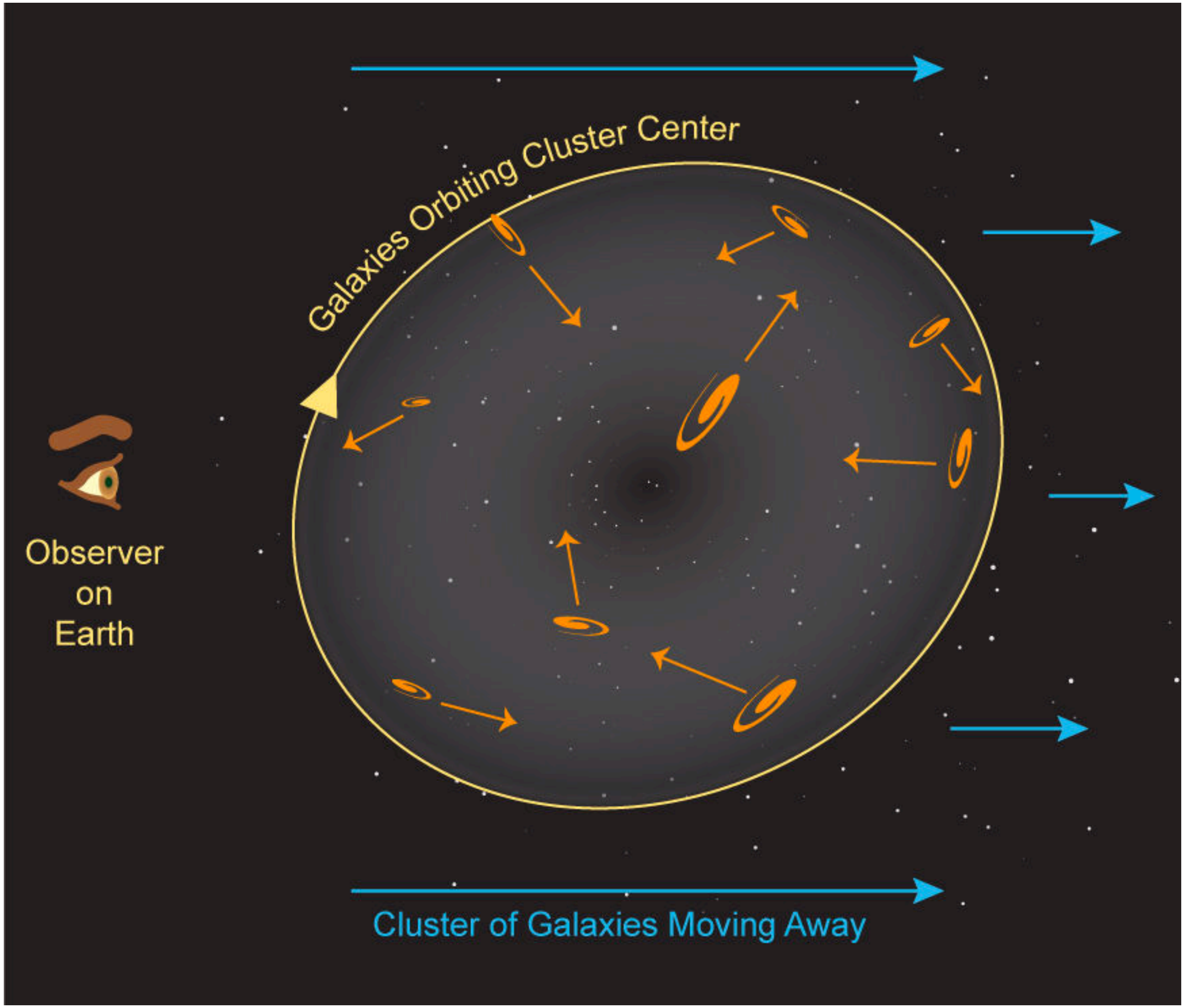
The Detection of Dark Matter



Fritz Zwicky

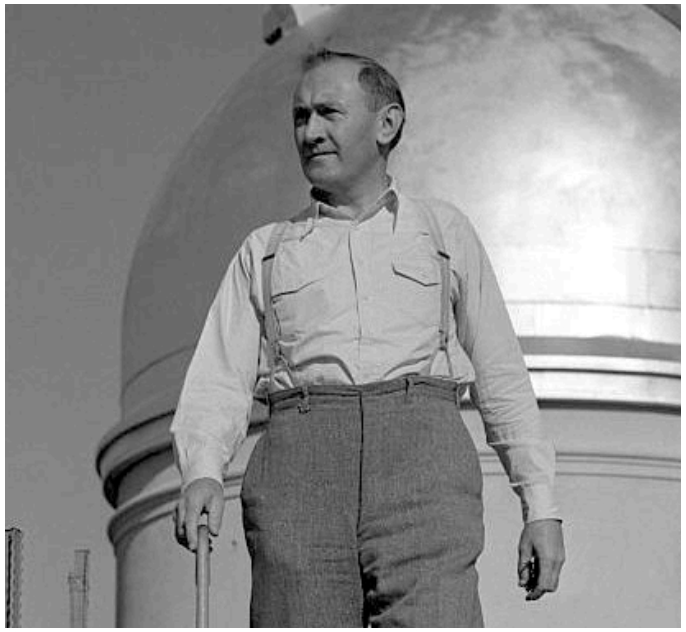
1933

$$\frac{GM}{r} = v^2$$



Credit: NASA/SSU/Aurore Simonnet

The Detection of Dark Matter



Fritz Zwicky

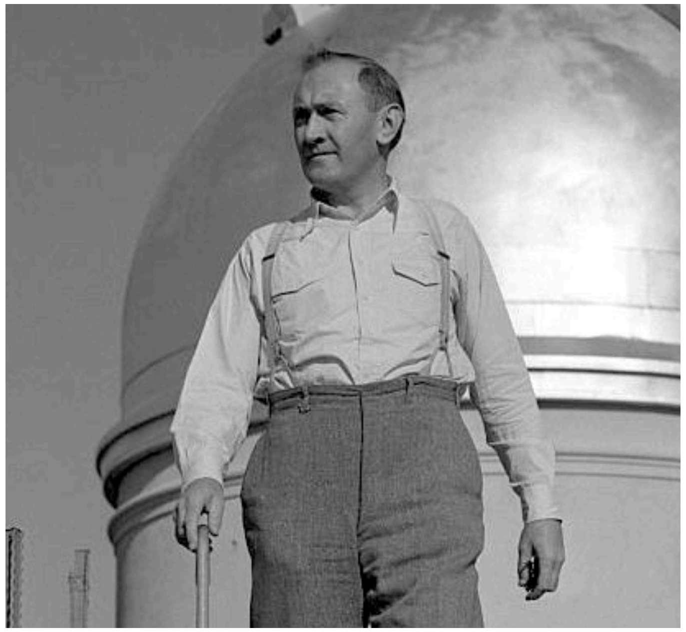
1933

$$\frac{GM}{r} = v^2$$

Coma cluster

$$\mathrm{M}_{\mathrm{dynamic}} \sim 100 \times \mathrm{M}_{\mathrm{stars}}$$

The Detection of Dark Matter



Fritz Zwicky

1933

$$\frac{GM}{r} = v^2$$

Coma cluster

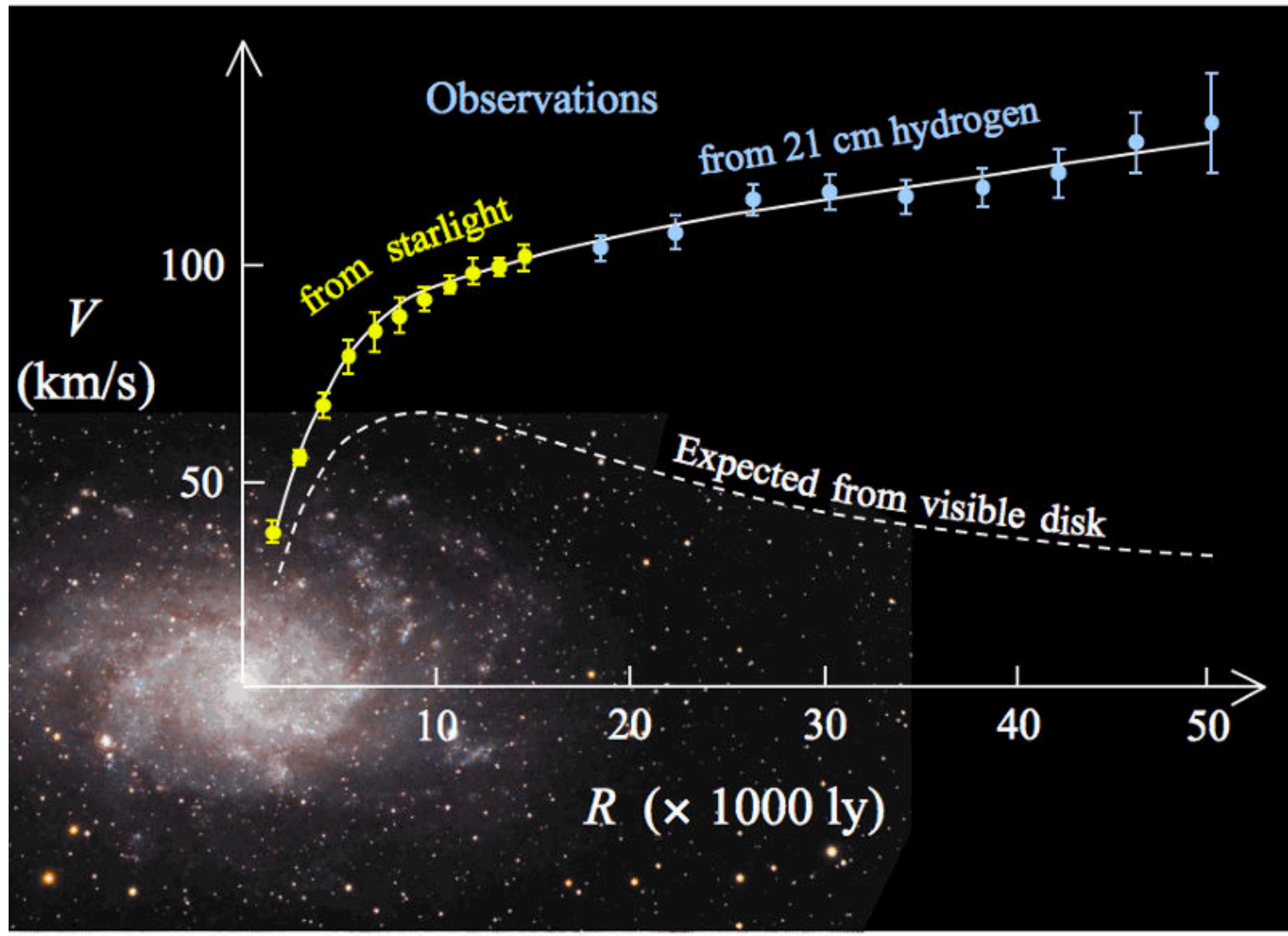
Dark matter $\mathrm{M_{dynamic}} \sim 100 \times \mathrm{M_{stars}}$

The Detection of Dark Matter

Vera Rubin

Late 1970s

$$\frac{GM}{r} = v^2$$



https://astronomy.com/news/2016/10/vera-rubin

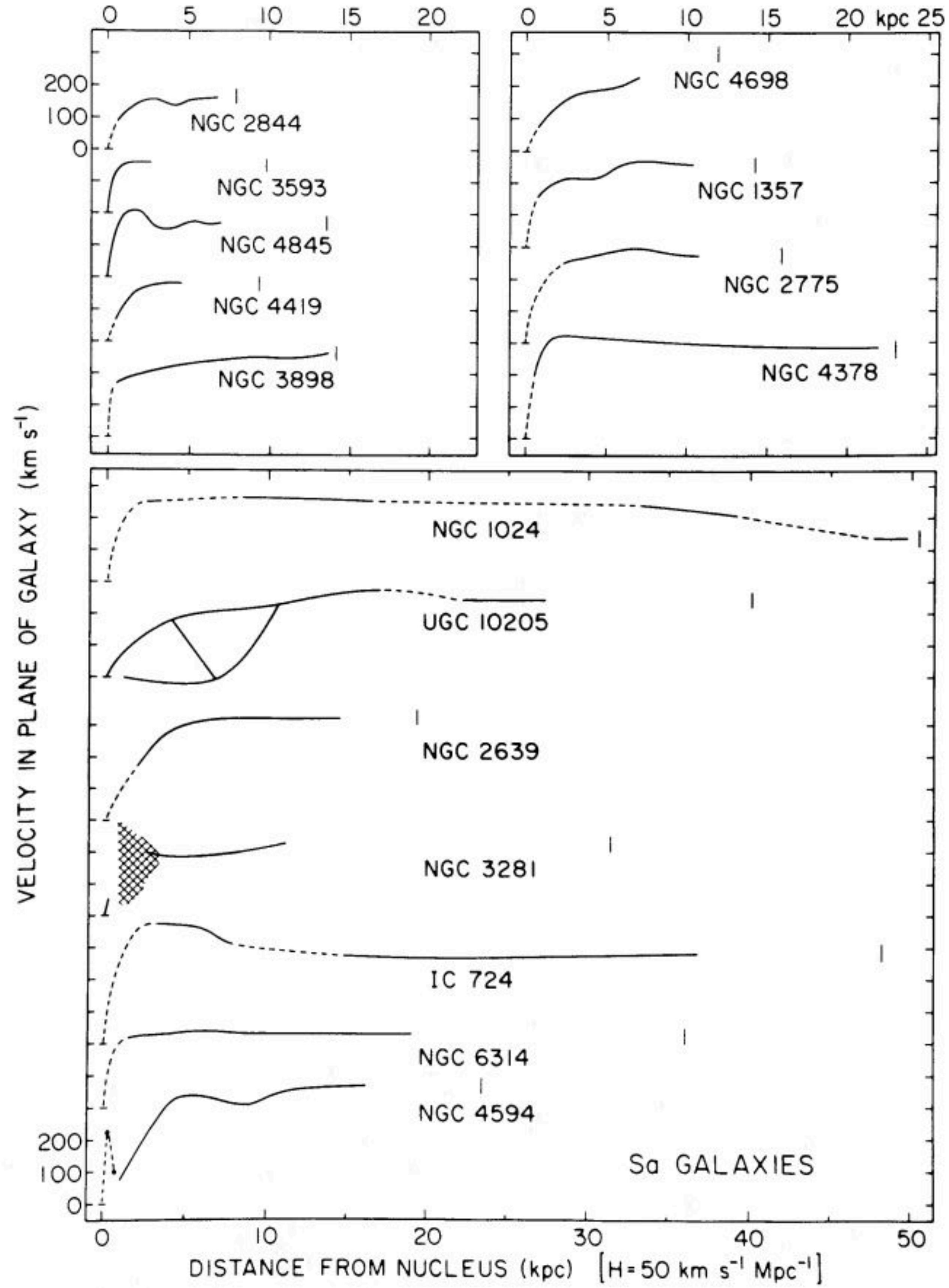
The Detection of Dark Matter

Vera Rubin

Late 1970s

$$\frac{GM}{r} = v^2$$

$$\mathrm{M_{dynamic}} > 10 \times \mathrm{M_{stars}}$$

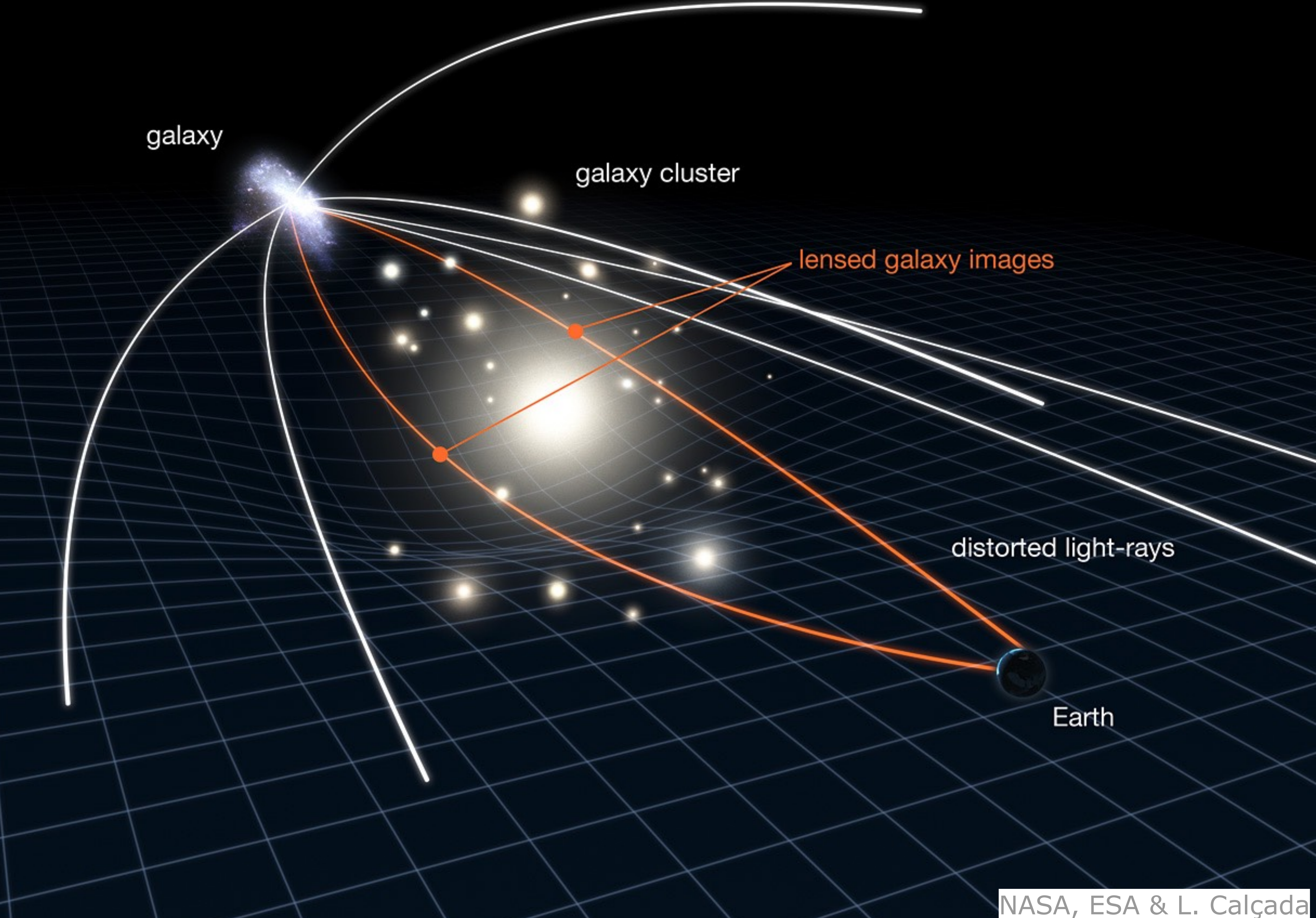


Rubin et al. (1980)

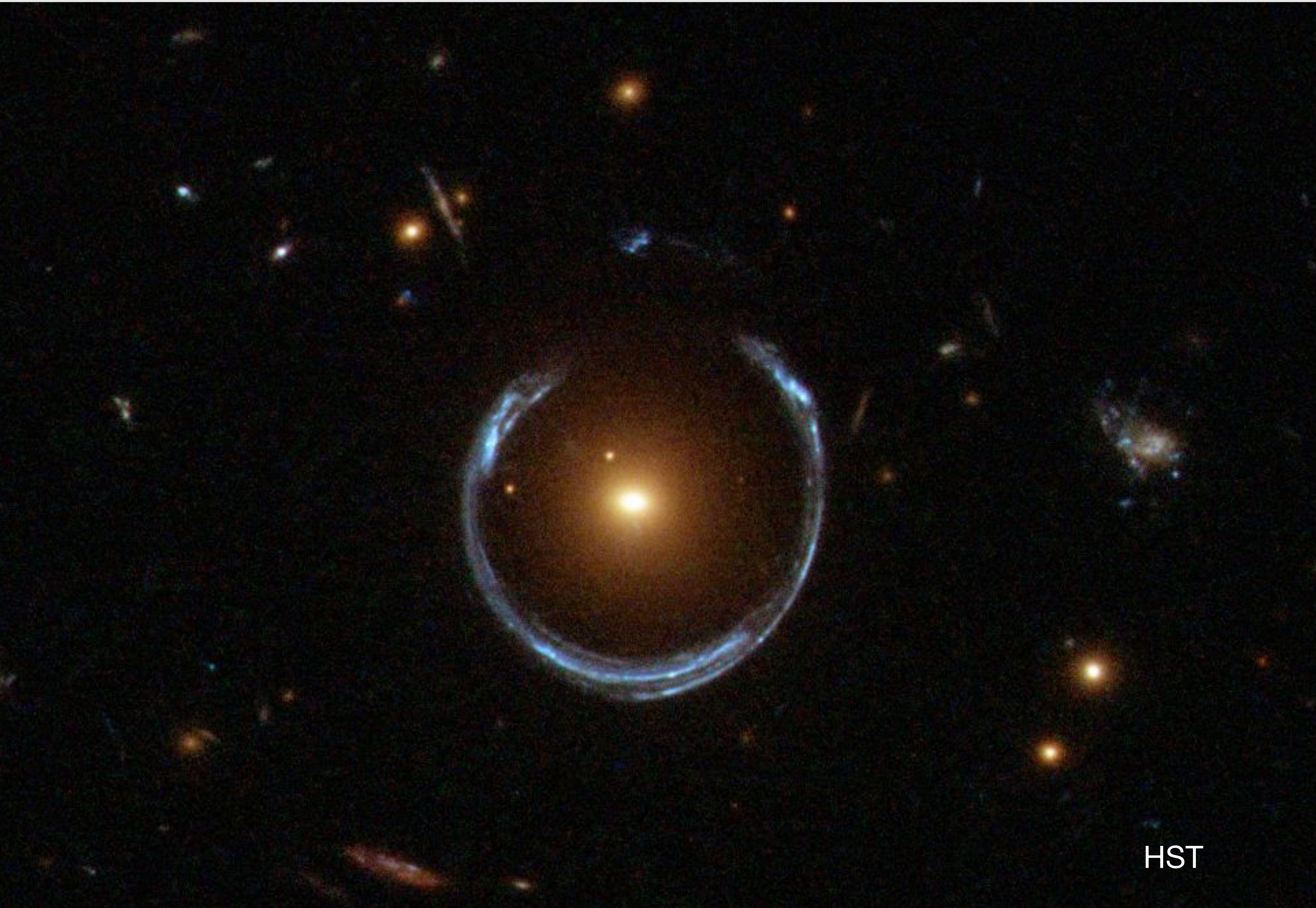
Rubin Observatory starts its 10 year program today!

NSF–DOE Vera C. Rubin Observatory/NOIRLab/SLAC/AURA/H. Stockebrand

Gravitational Lensing



Einstein Ring



Multi-wavelength observation

Stars

Gas

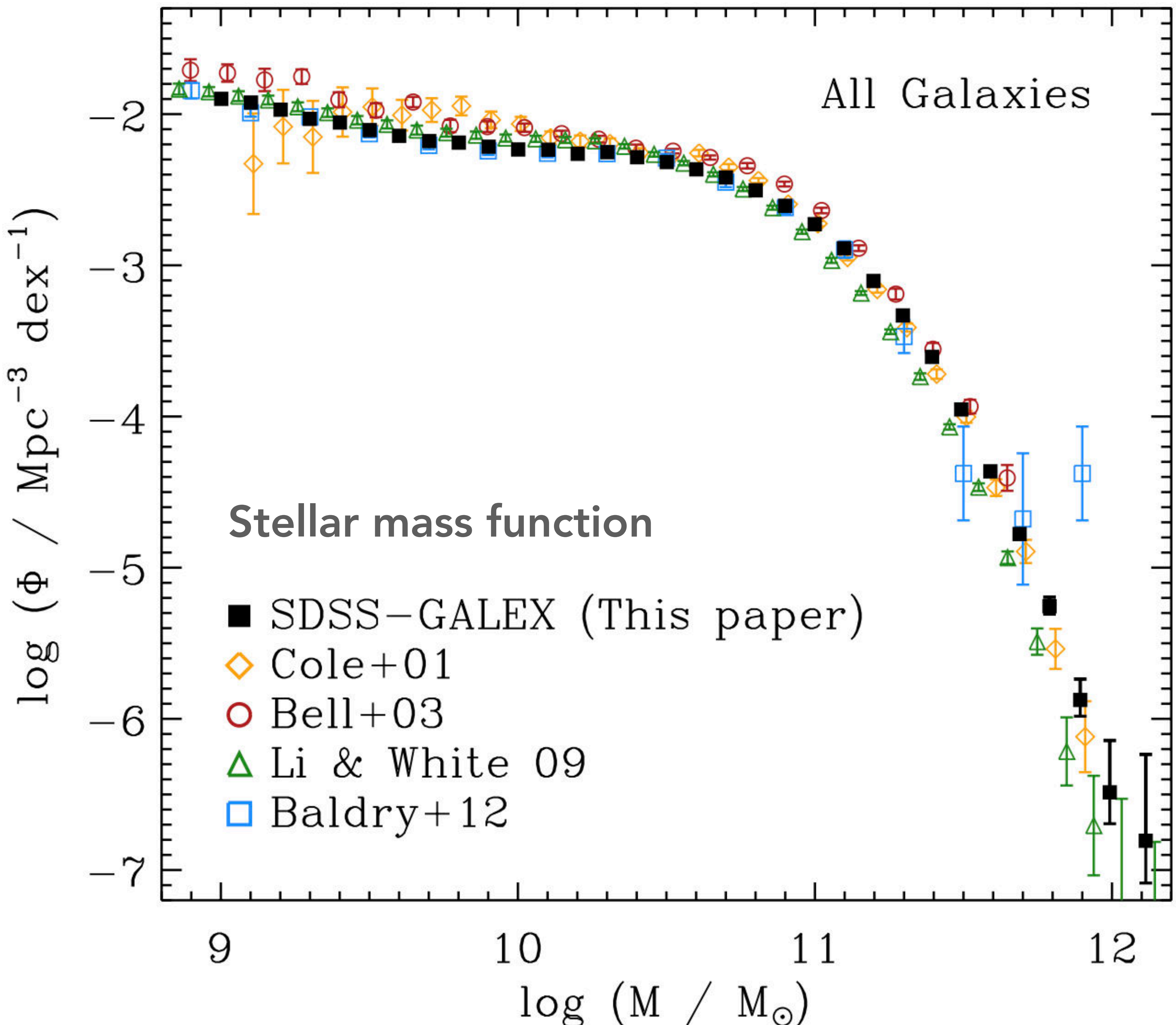
Supermassive black hole

Dust

Dark Matter

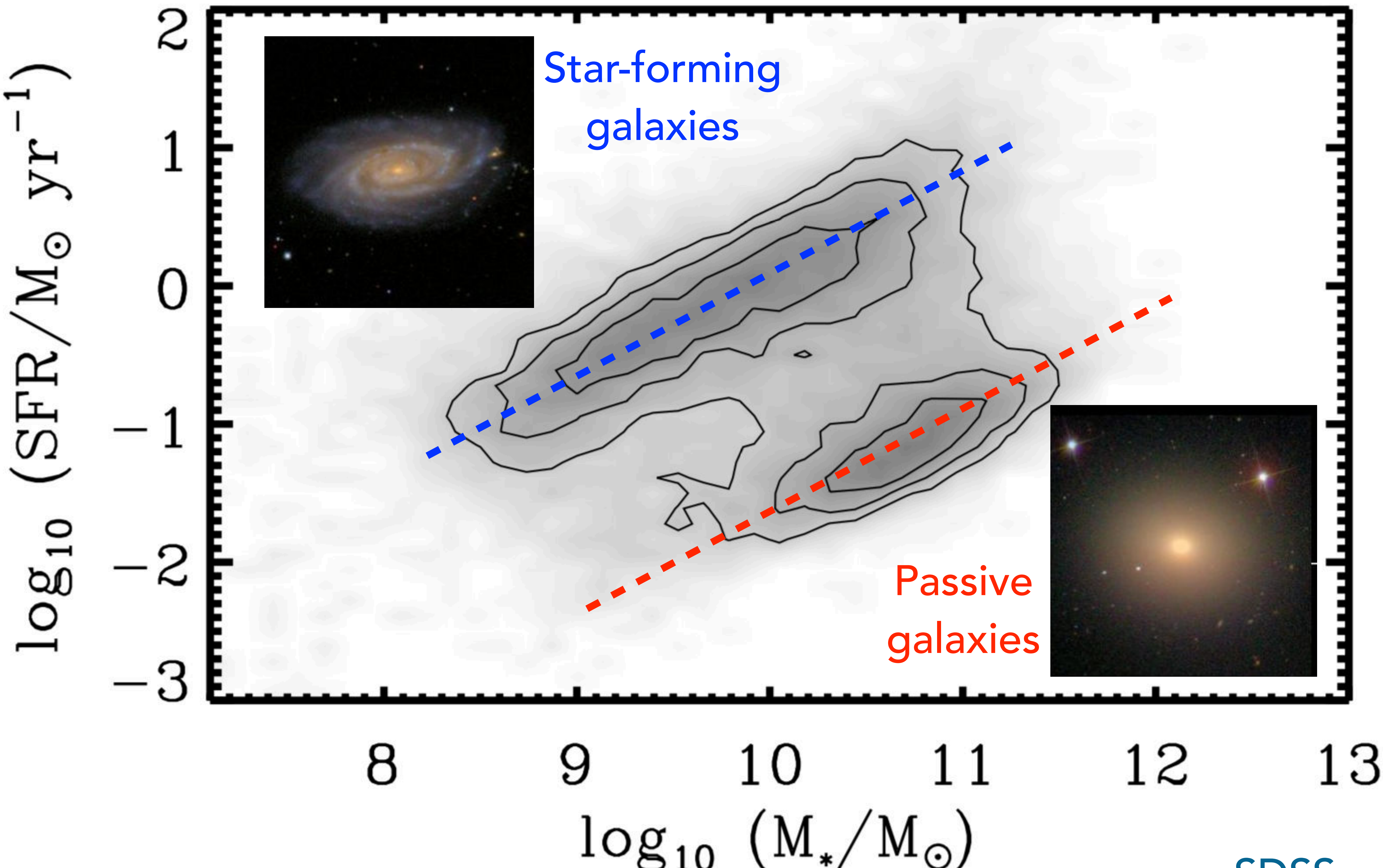
Statistical explorations of their properties and the connections with each other

Stellar mass function



Moustakas et al. (2013)

The dichotomy of galaxy types



SDSS

Multi-wavelength observation

Stars

Gas

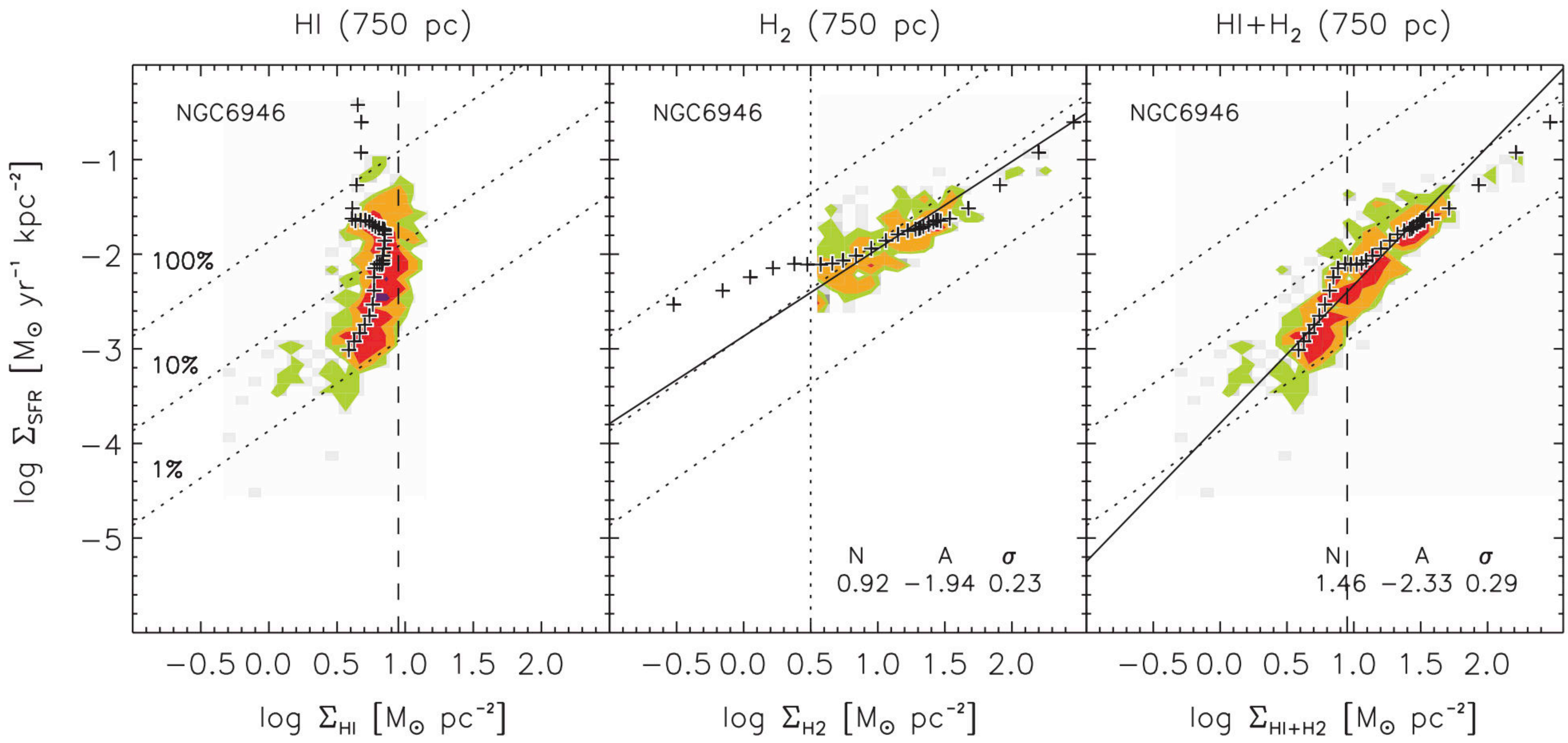
Supermassive
black hole

Dust

Dark Matter

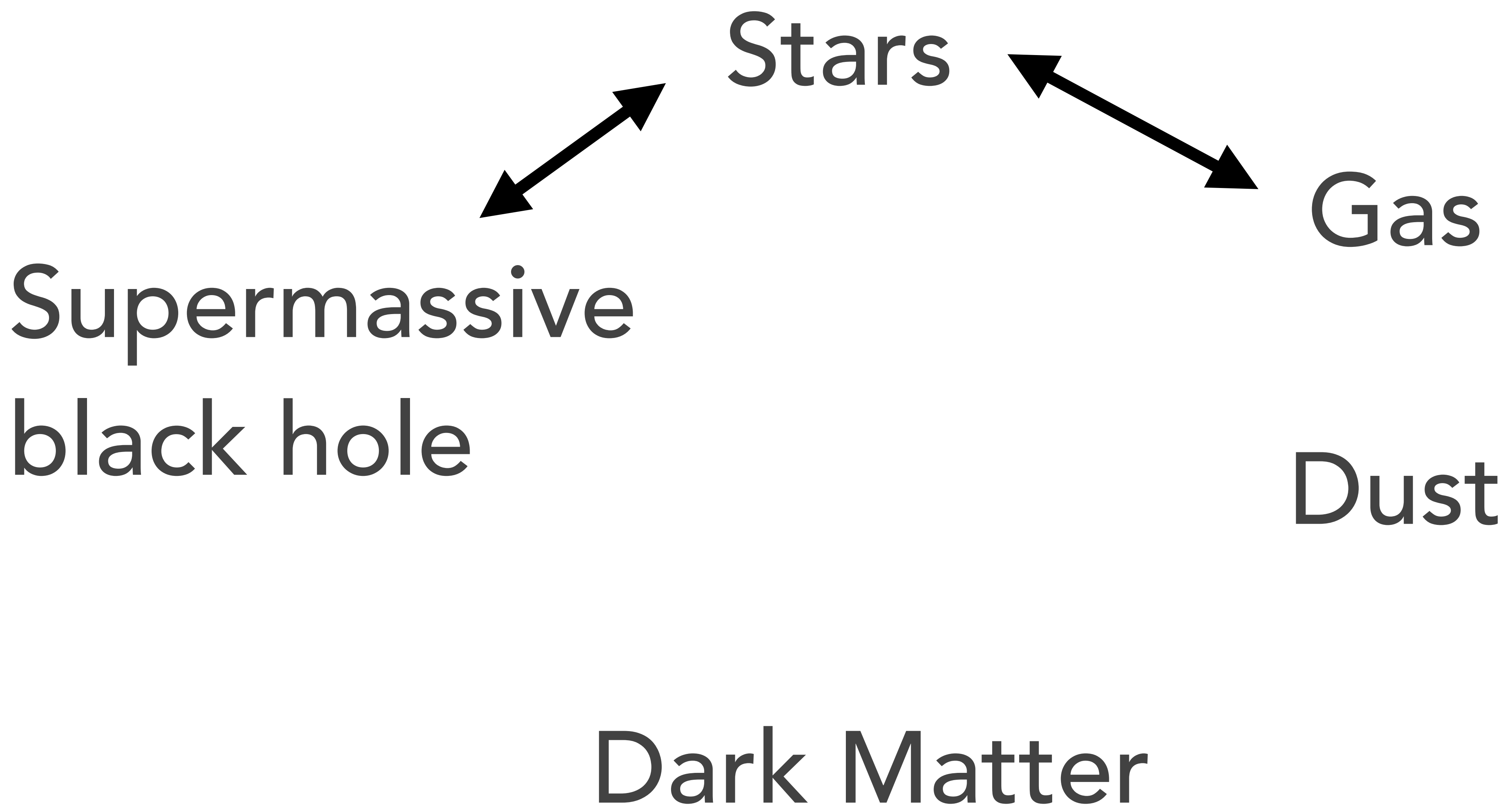
Statistical explorations of their properties and
the connections with each other

Gas mass and SFR relationship



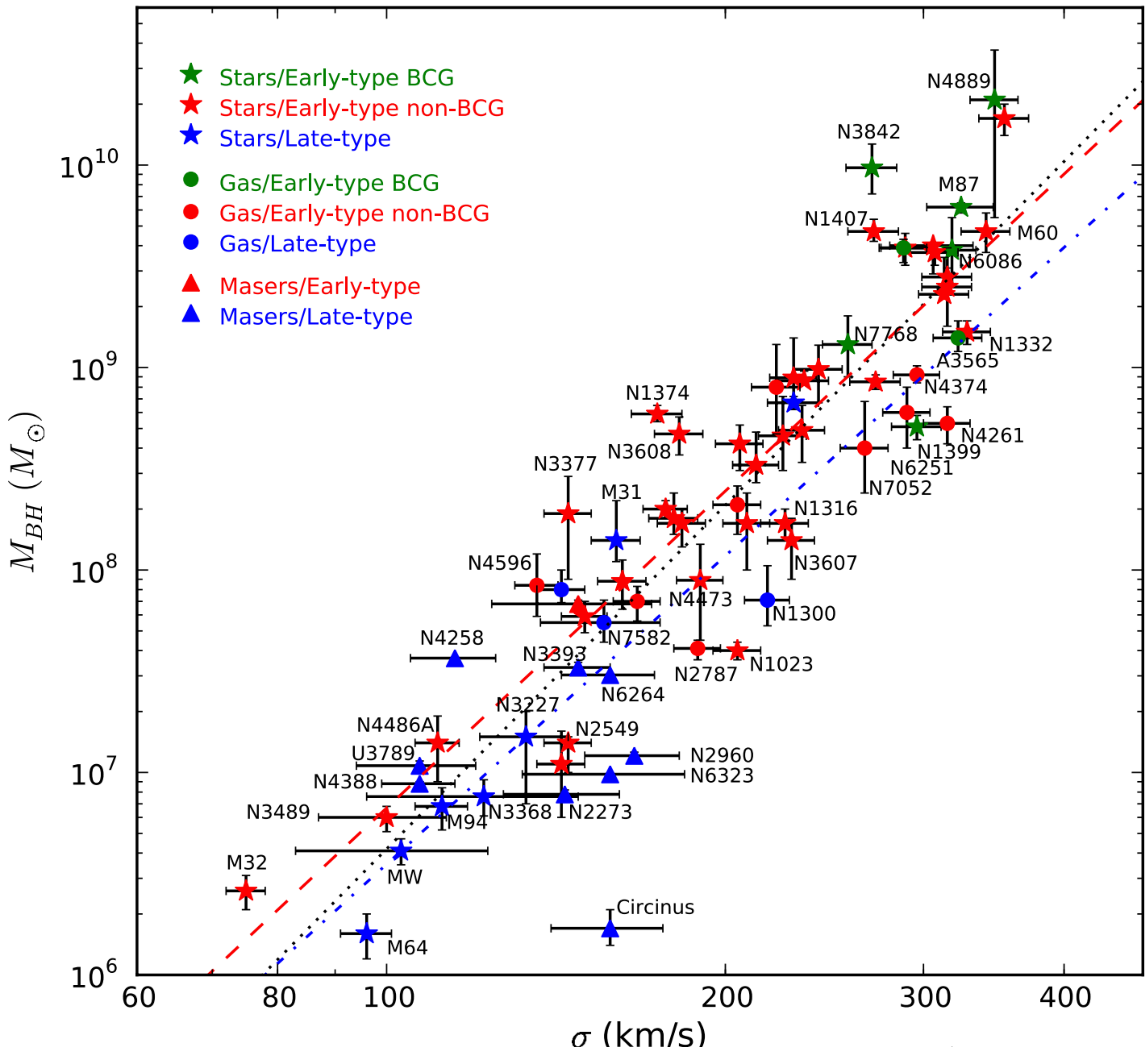
Bigiel et al. (2008)

Multi-wavelength observation



Statistical explorations of their properties and the connections with each other

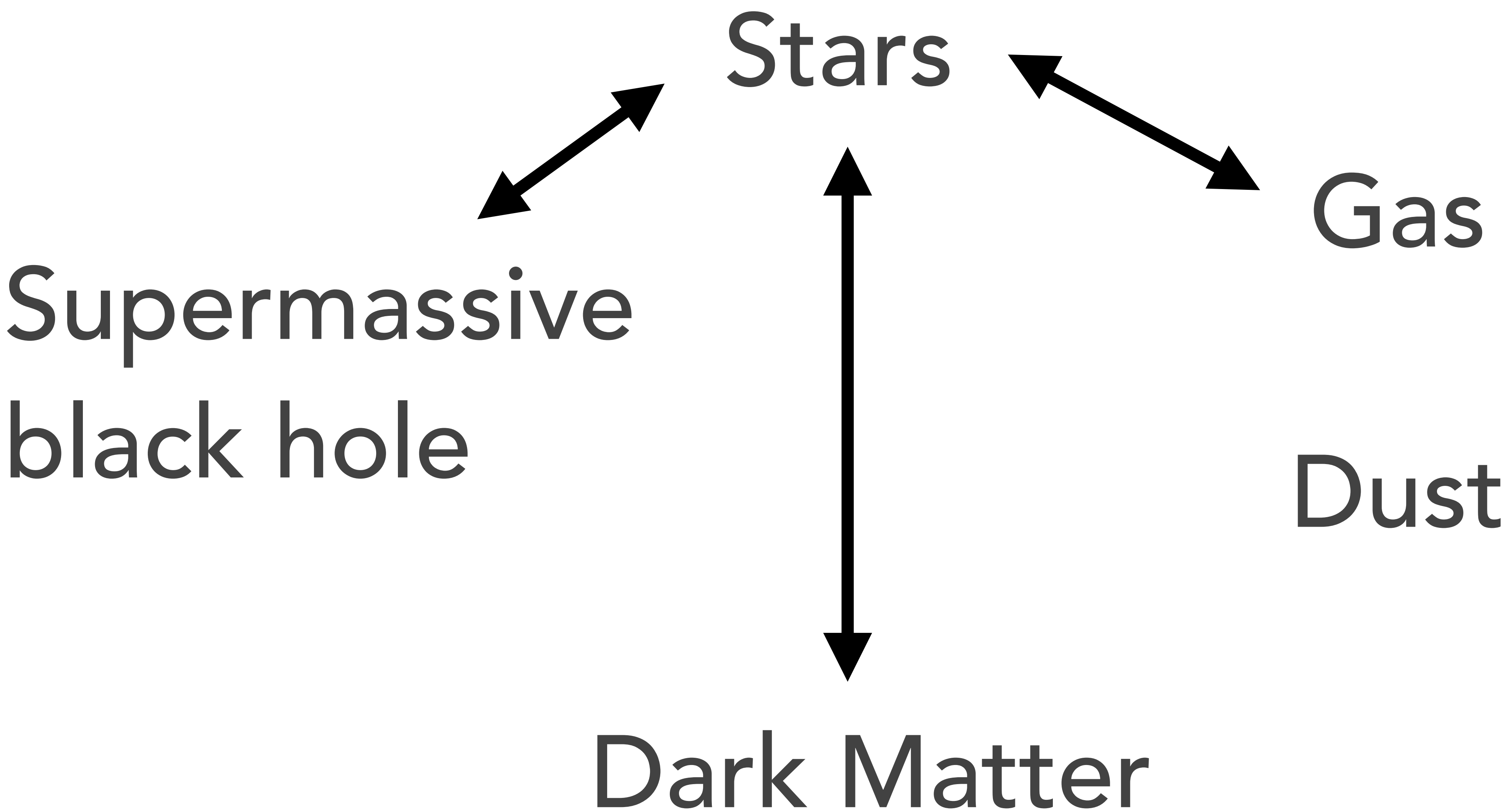
M-sigma relation



Stellar velocity dispersion within Reff

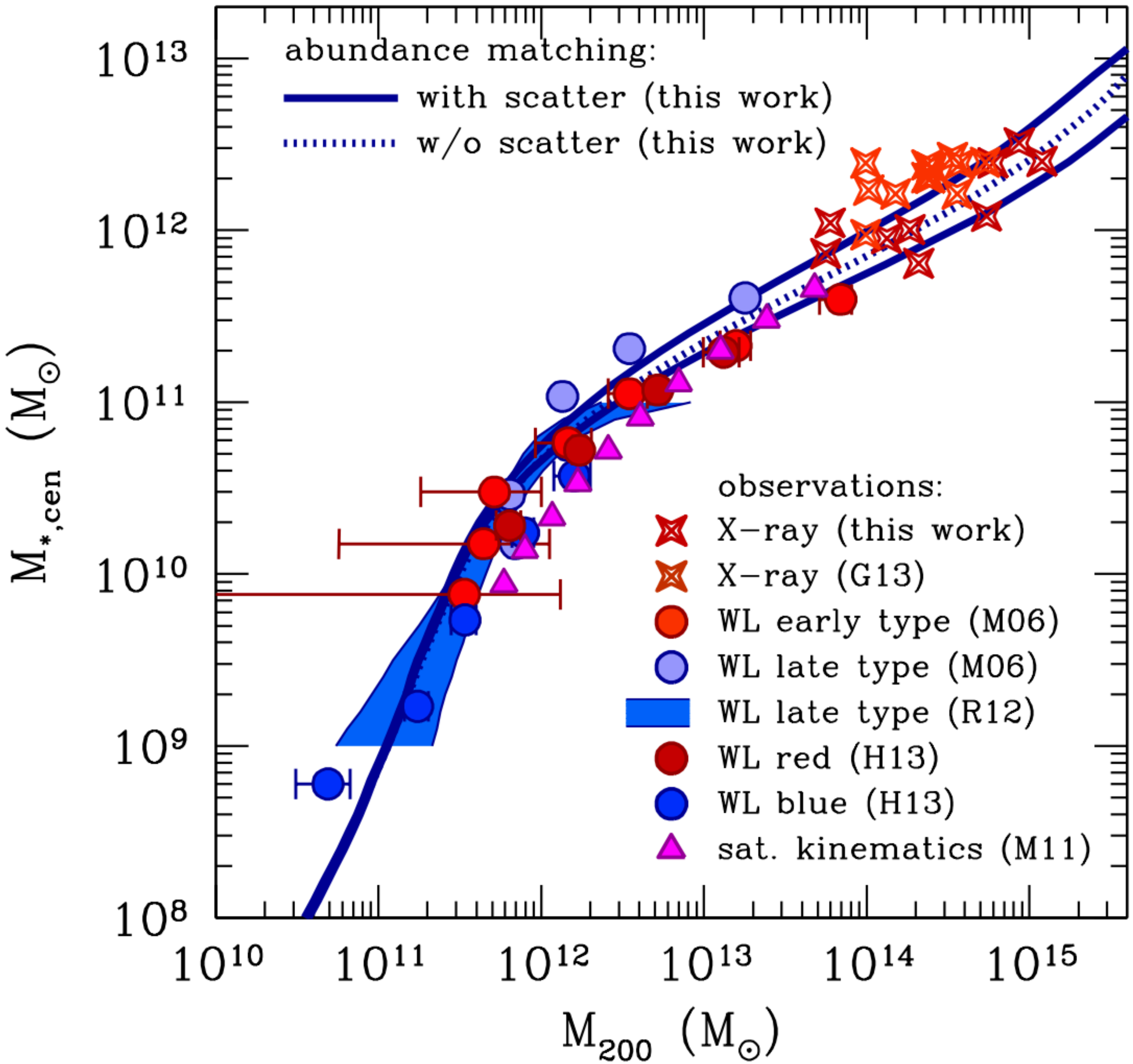
McConnell and Ma et al. (2013)

Multi-wavelength observation



Statistical explorations of their properties and the connections with each other

Stellar mass to halo mass relation



Kravtsov et al. (2014)

Observations:

Characterizing and understanding the components and the properties of galaxies and how they evolve with time.

Theory:

Developing models and simulations can explain the observed properties and diversity of galaxies.

Observations:

Characterizing and understanding the components and the properties of galaxies and how they evolve with time.

Theory:

Developing models and simulations can explain the observed properties and diversity of galaxies.

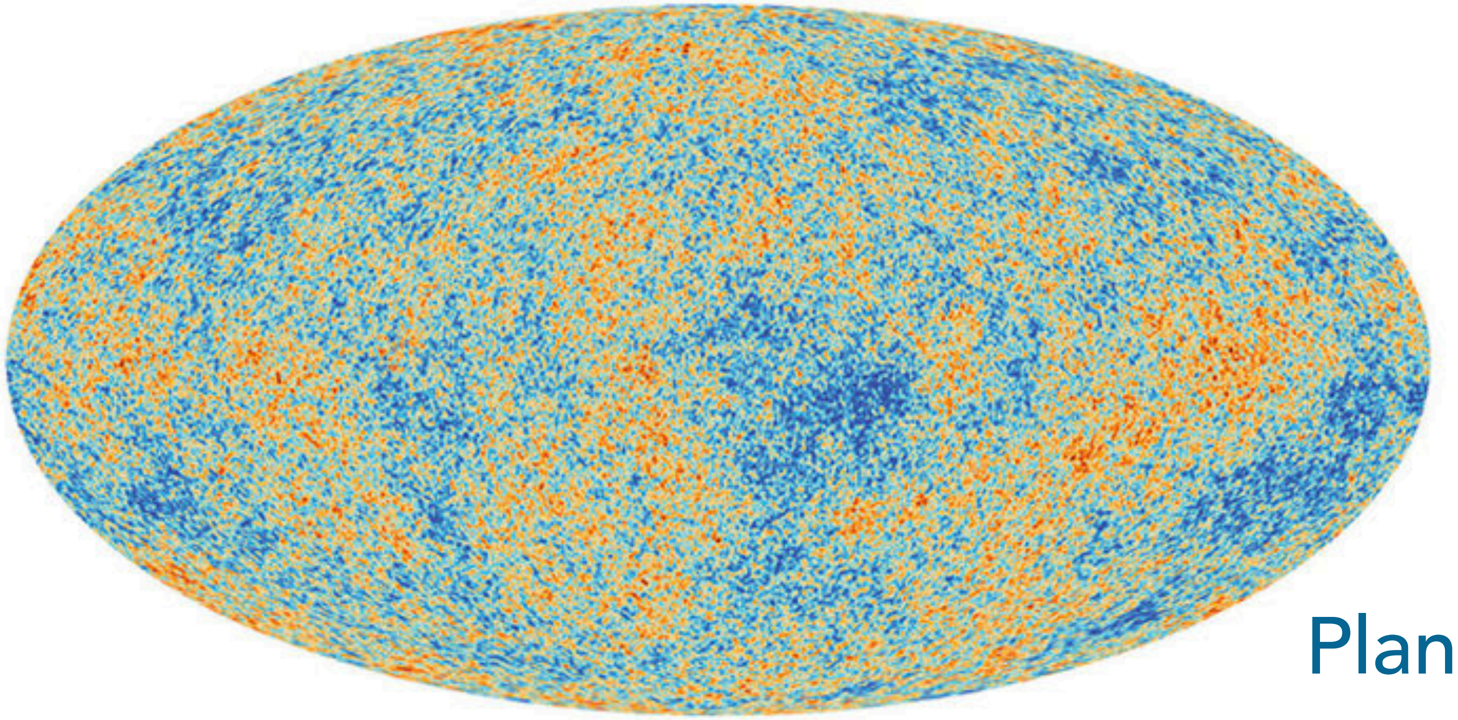
Question: What are the required processes and ingredients for modeling galaxies?

Astrophysics of galaxy evolution

Cosmology

ΛCDM model

Initial conditions



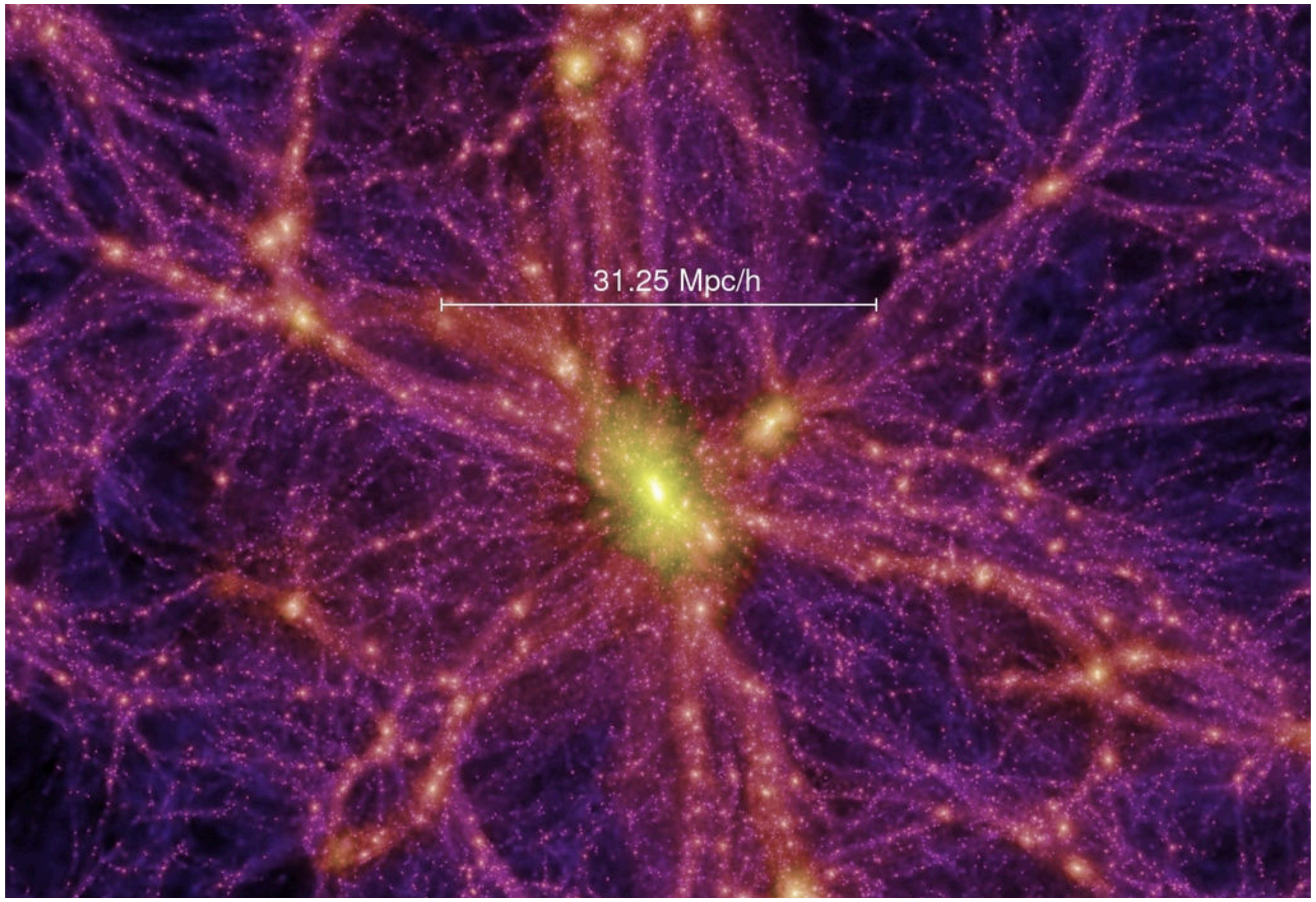
Planck

Gravity

The structure formation

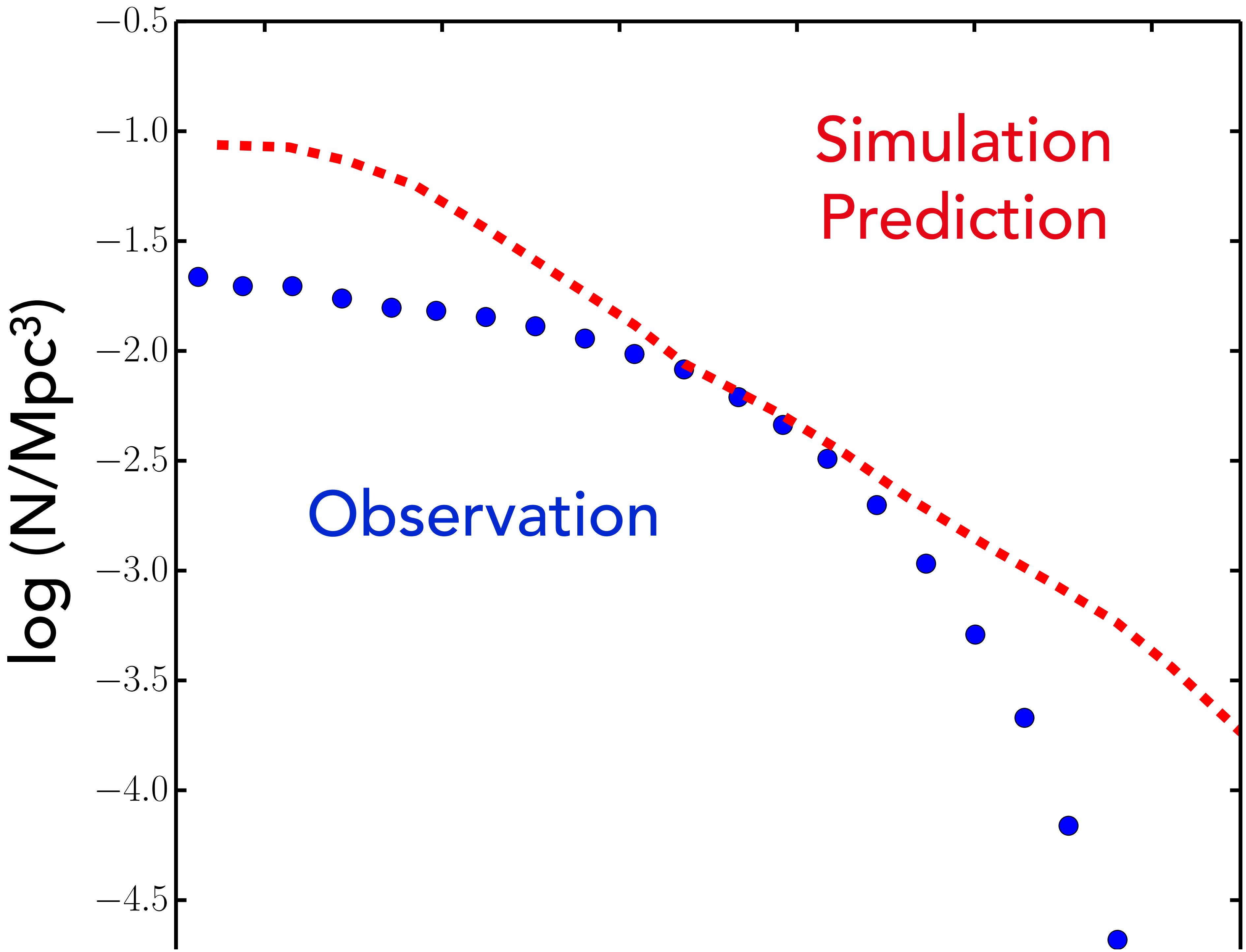
Hydrodynamics

Baryon evolution



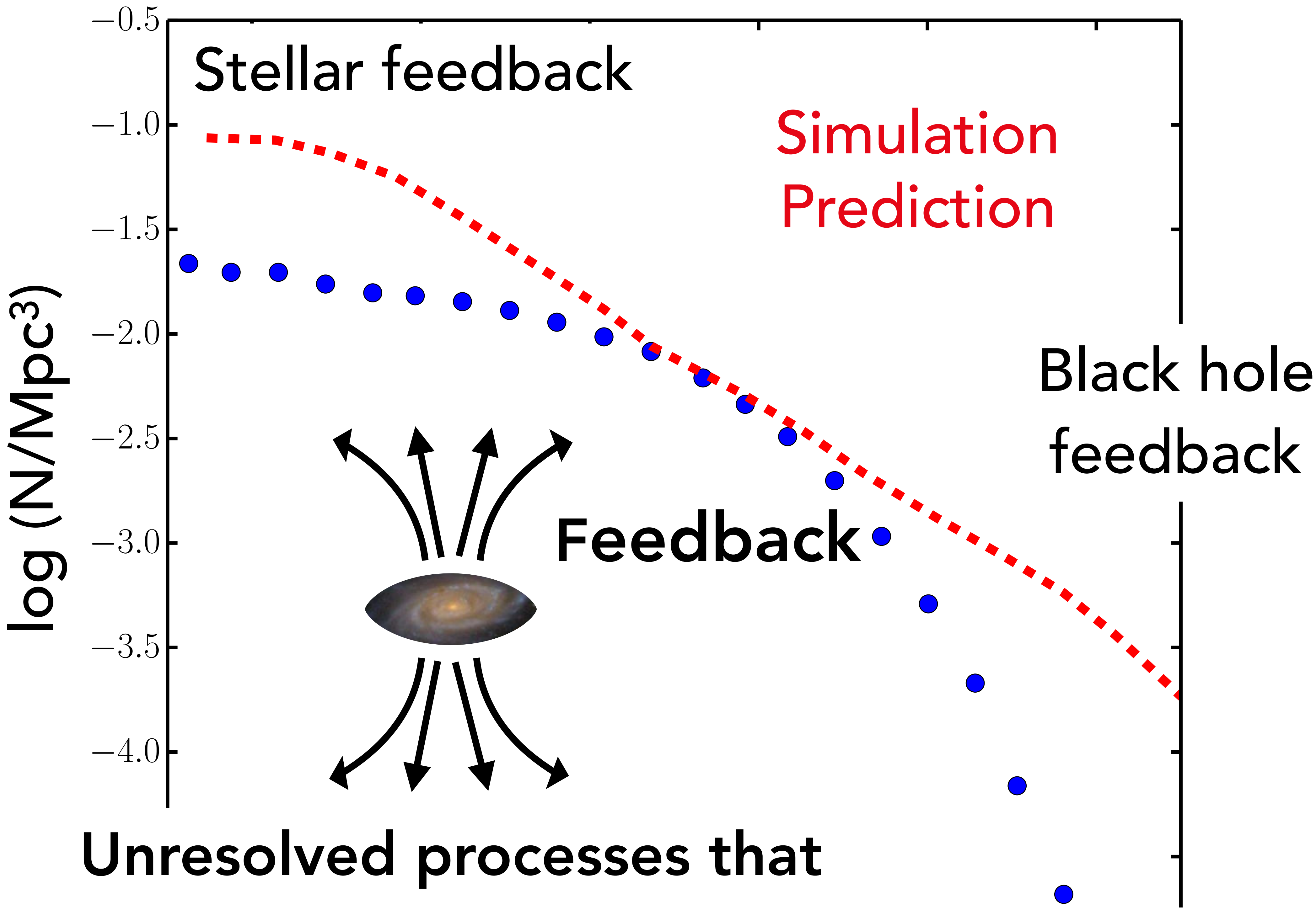
Millenium simulation

The challenge - the failure to reproduce the galaxy number

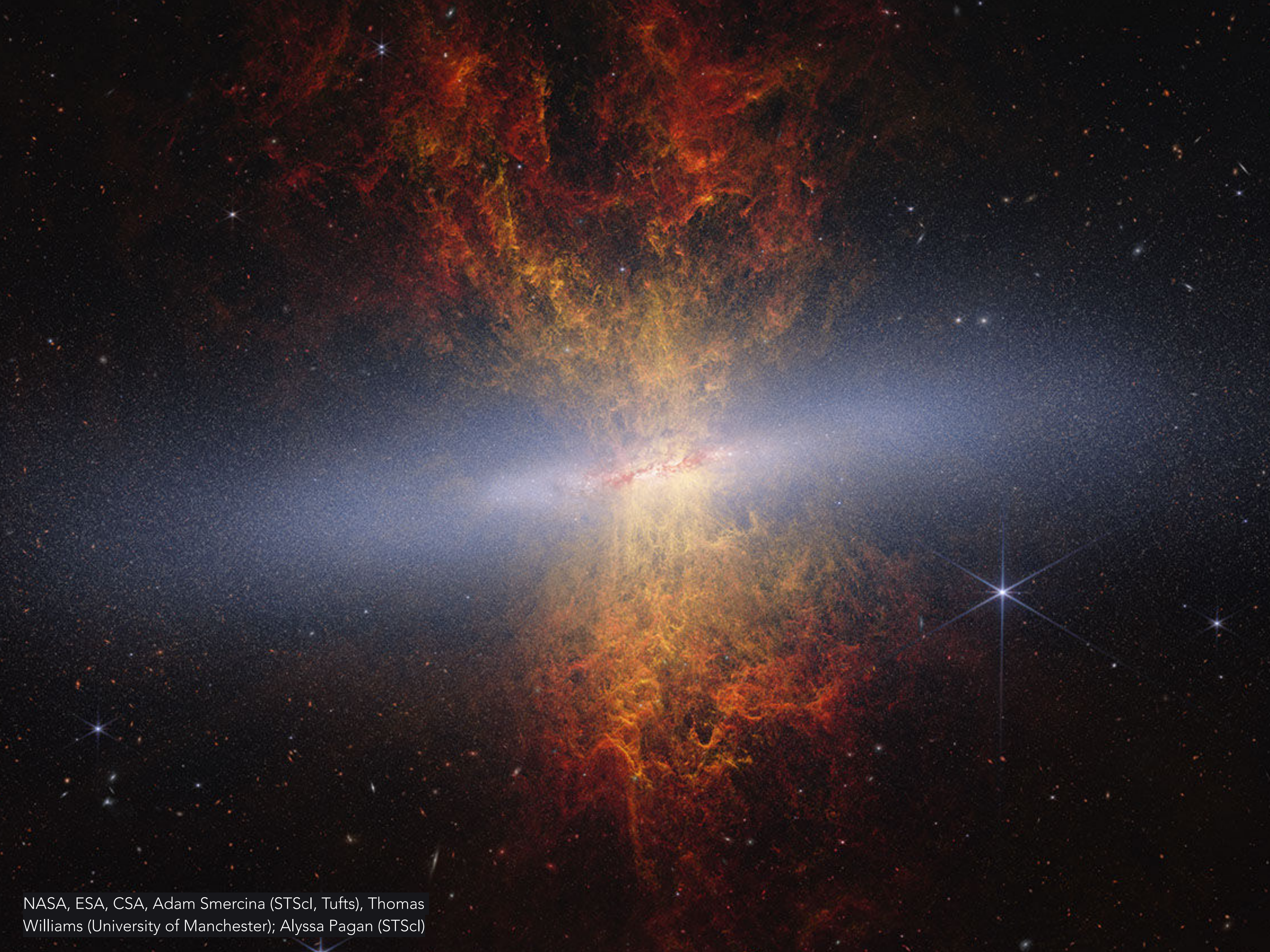


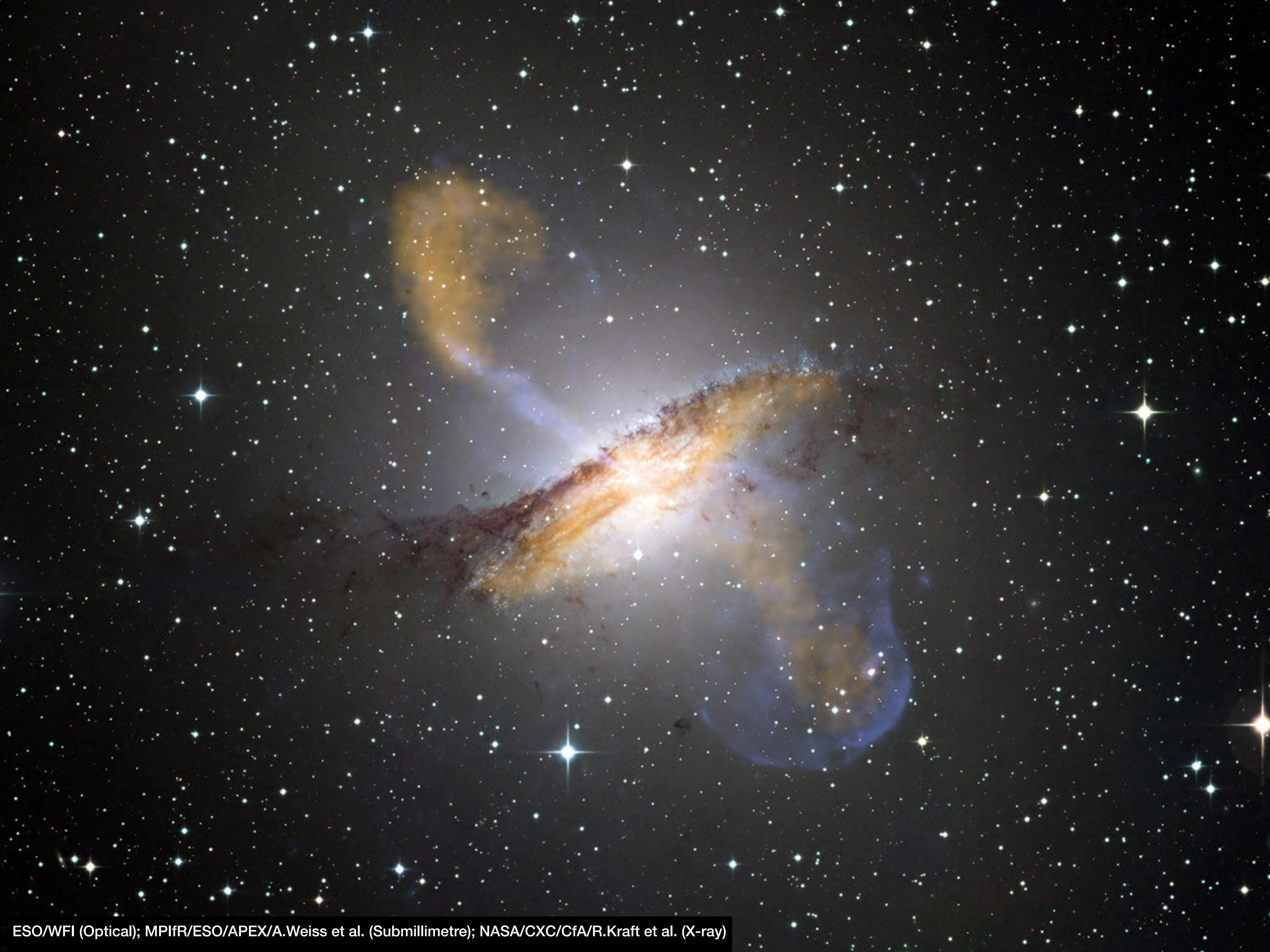
Simulations produce >10 times more galaxies than the real Universe.

The challenge - the failure to reproduce the galaxy number



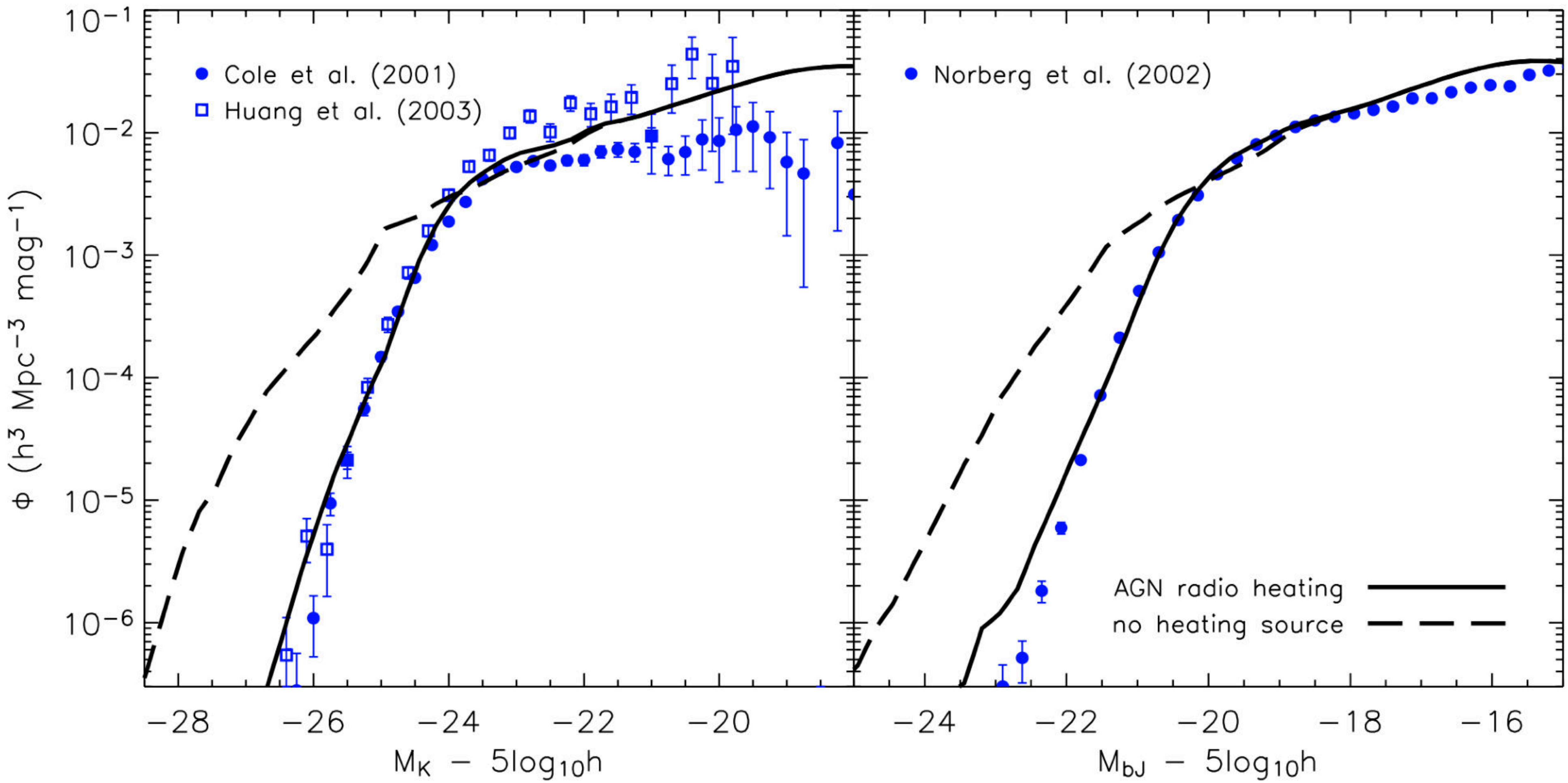
Unresolved processes that remove gas from galaxies


NASA, ESA, CSA, Adam Smercina (STScI, Tufts), Thomas Williams (University of Manchester); Alyssa Pagan (STScI)



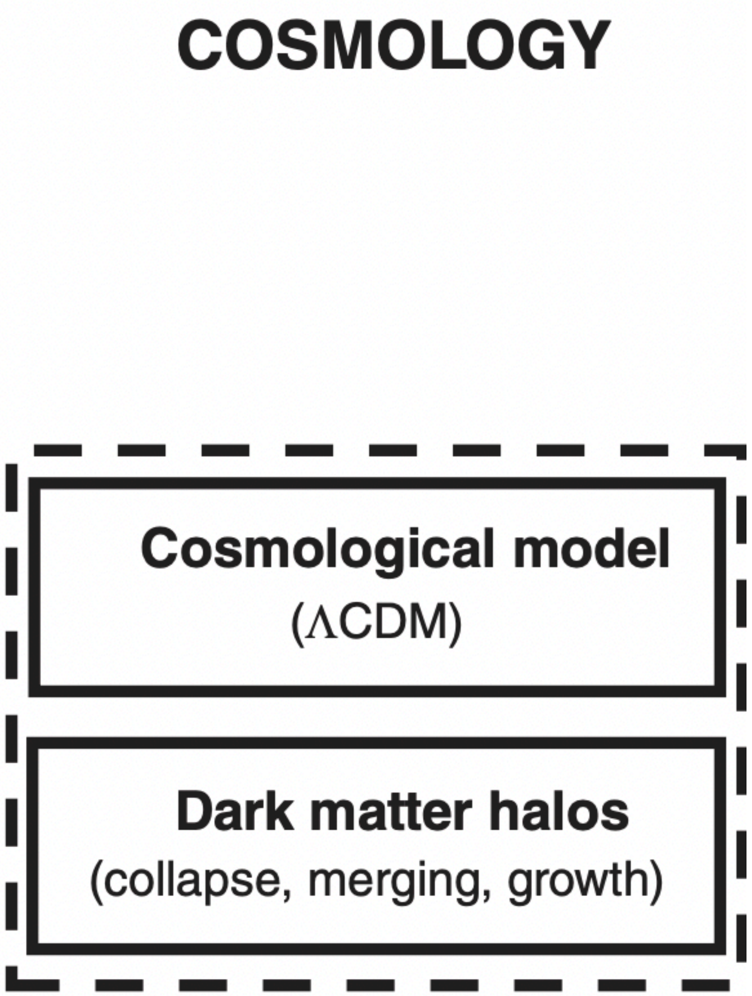
ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)

The challenge - the failure to reproduce the galaxy number

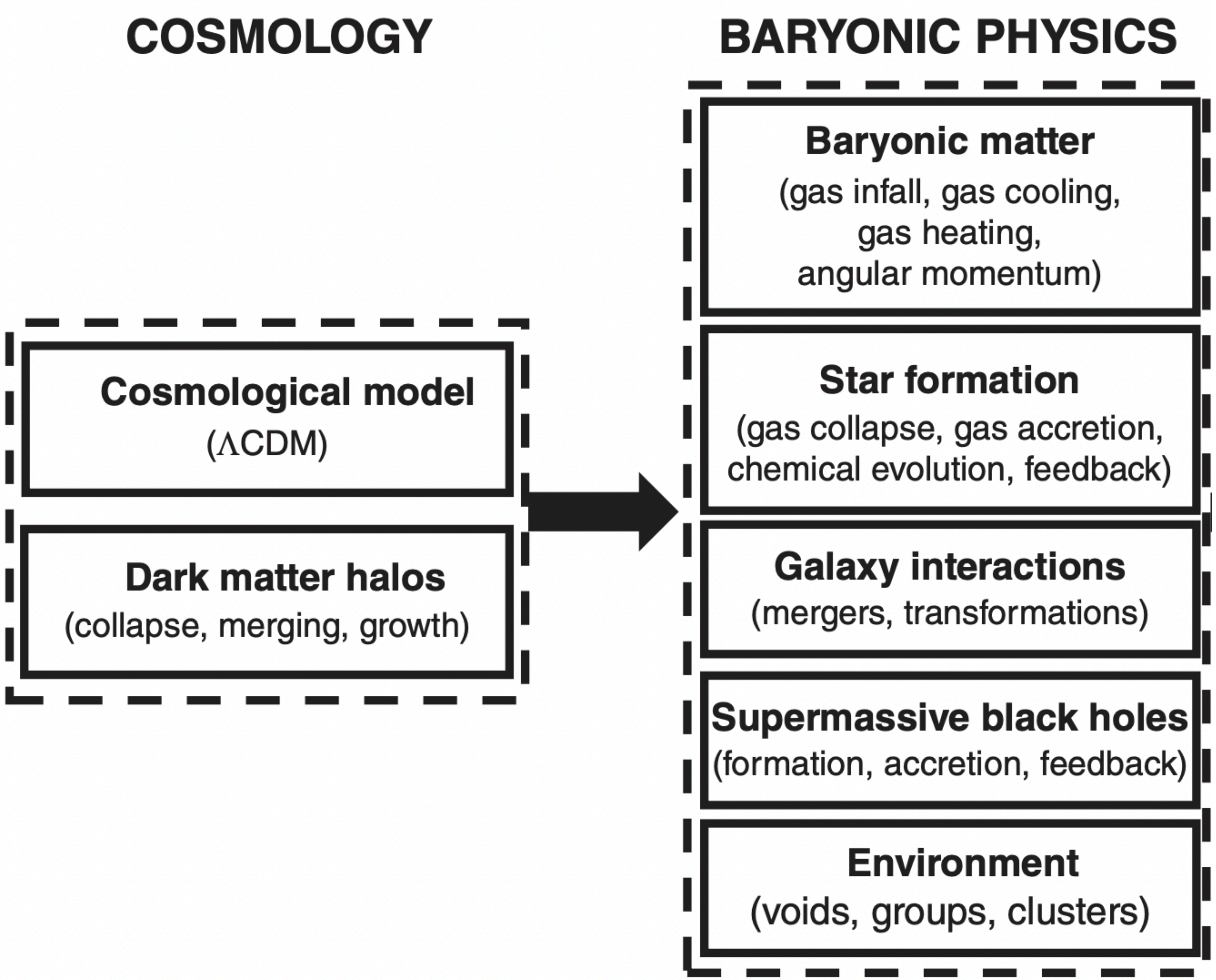


Croton et al. (2006)

Galaxy Formation and Evolution

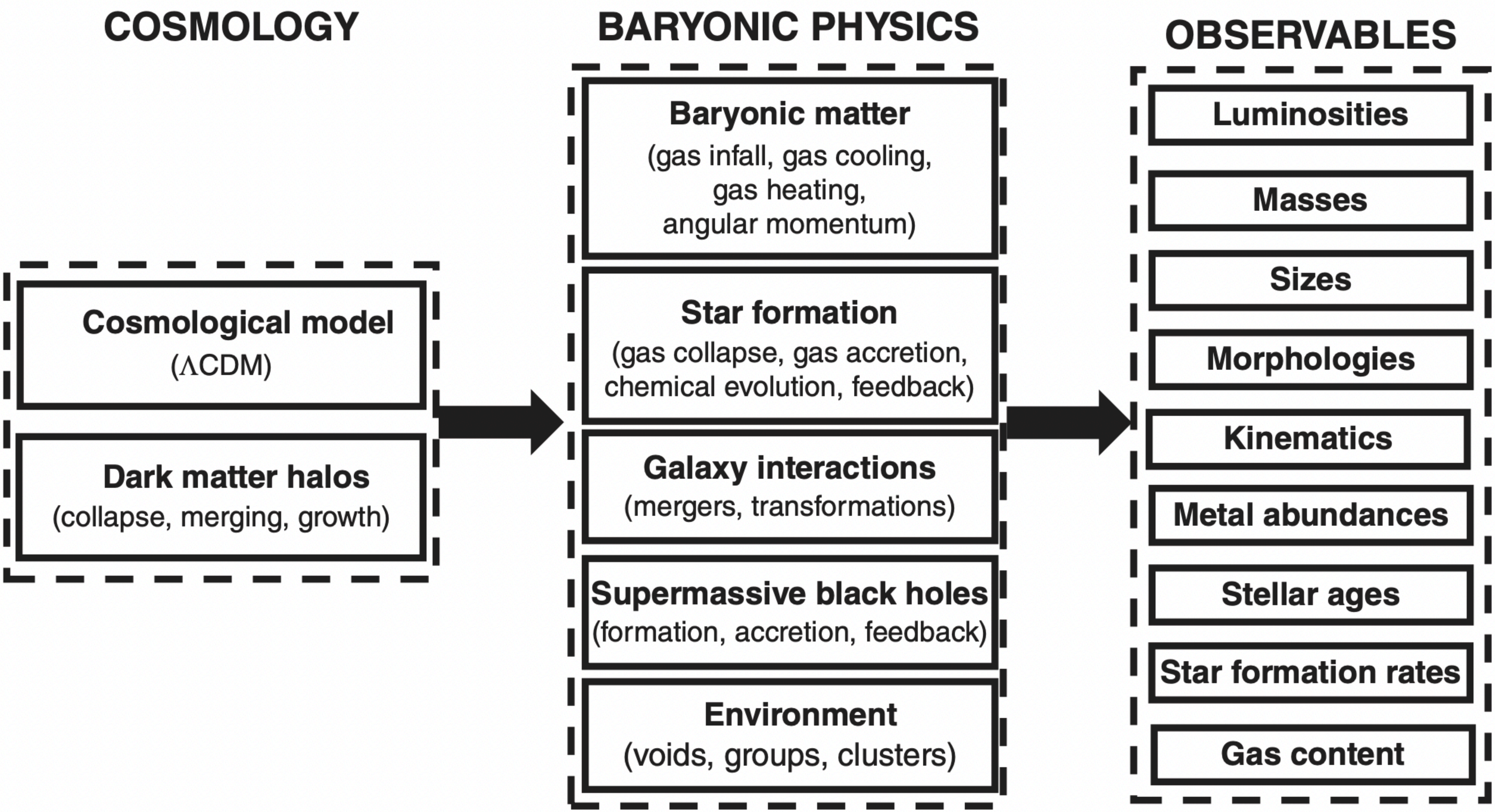


Galaxy Formation and Evolution



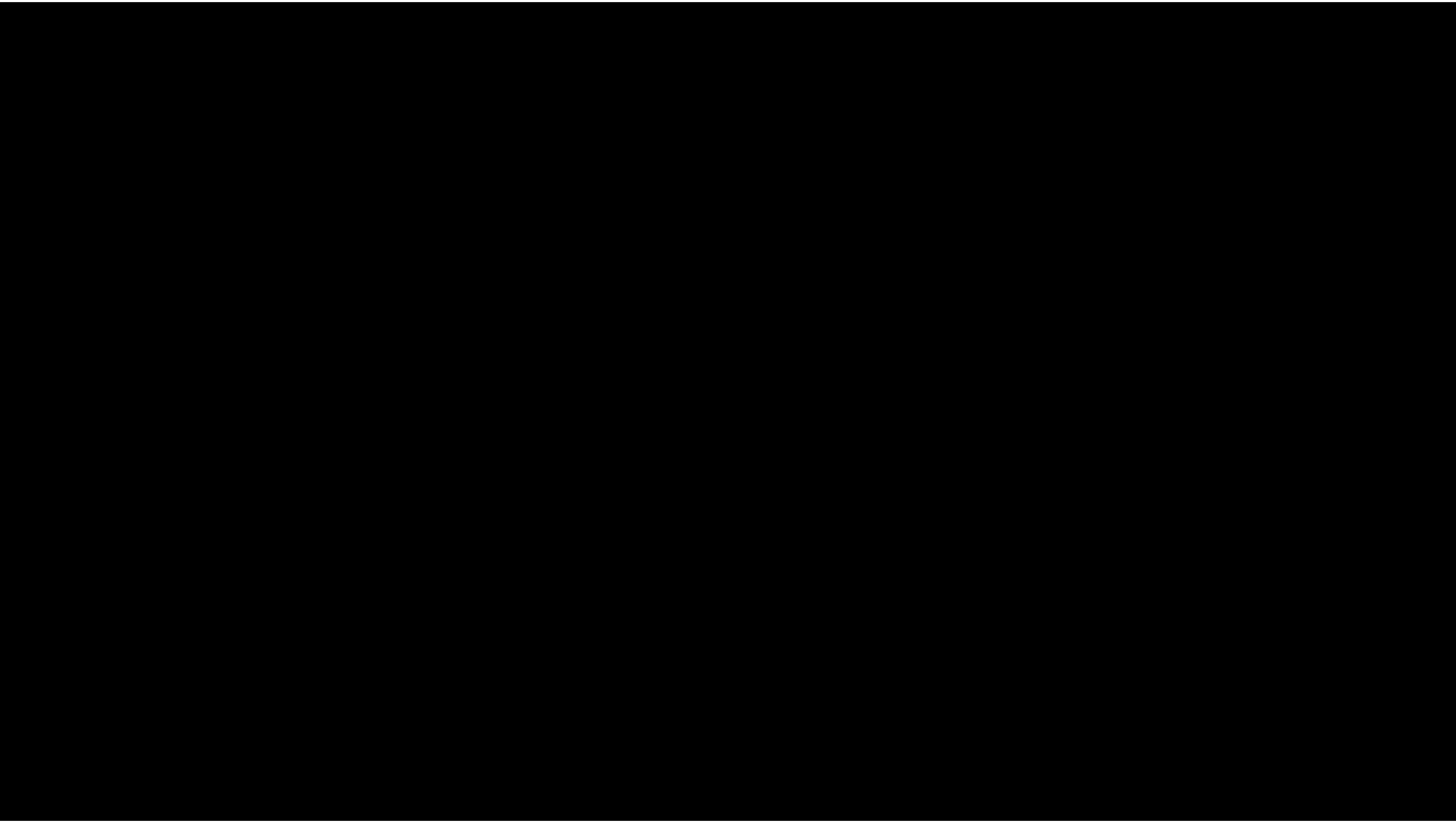
Introduction to Galaxy Formation and Evolution by Cimatti, Fraternali and Nipoti

Galaxy Formation and Evolution



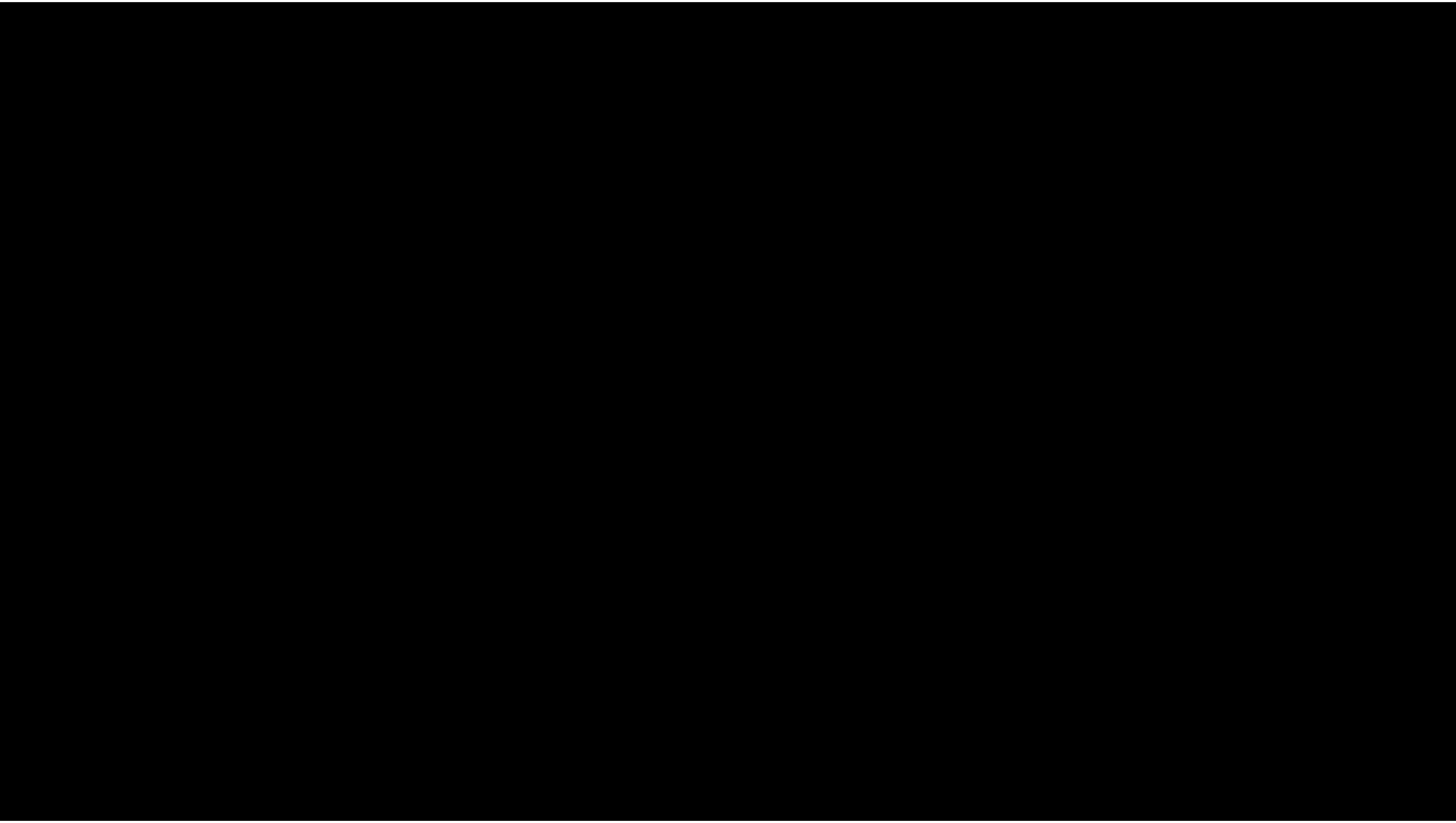
Introduction to Galaxy Formation and Evolution by Cimatti, Fraternali and Nipoti

TNG simulation

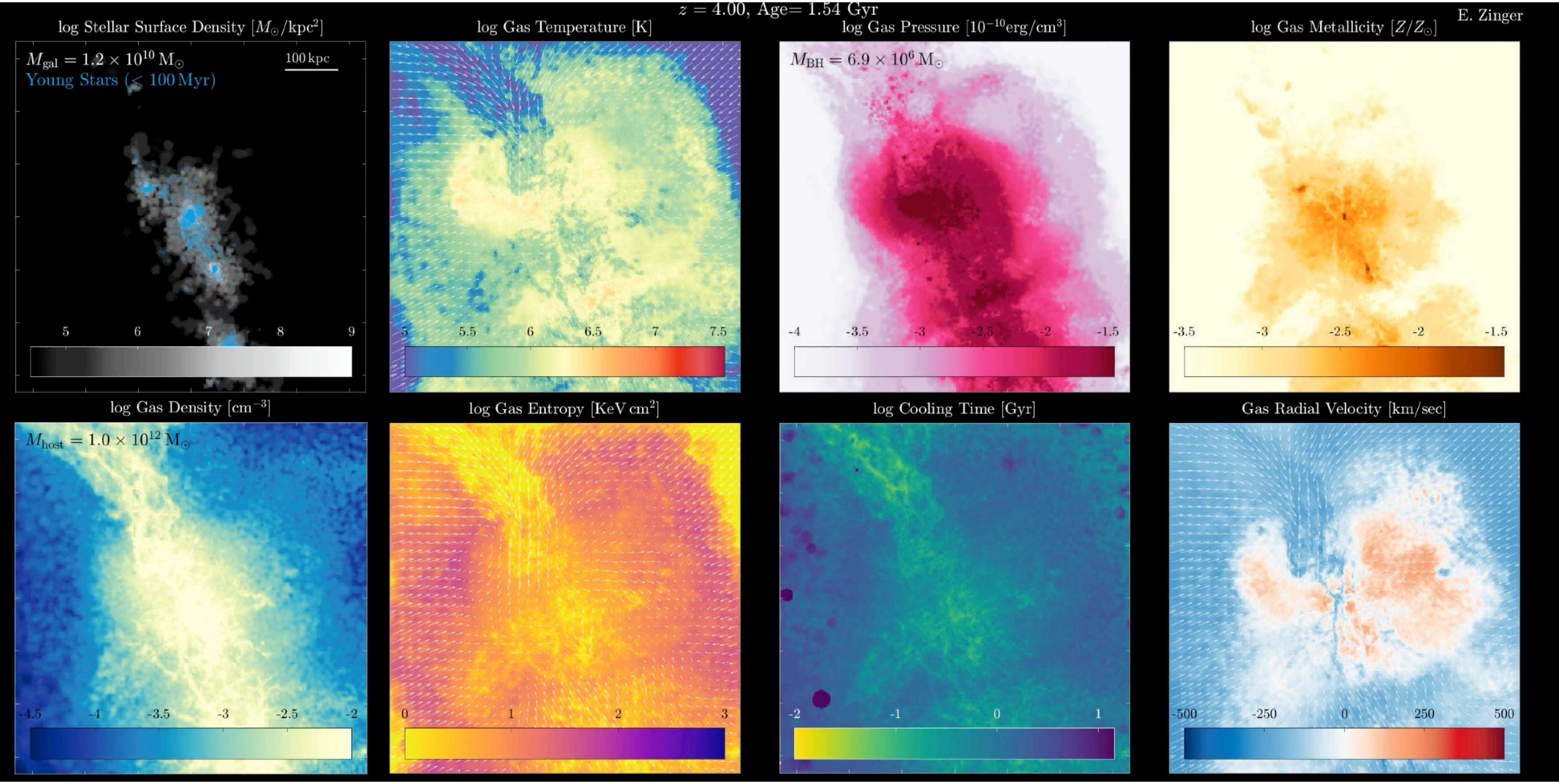


Very rich information!

TNG simulation

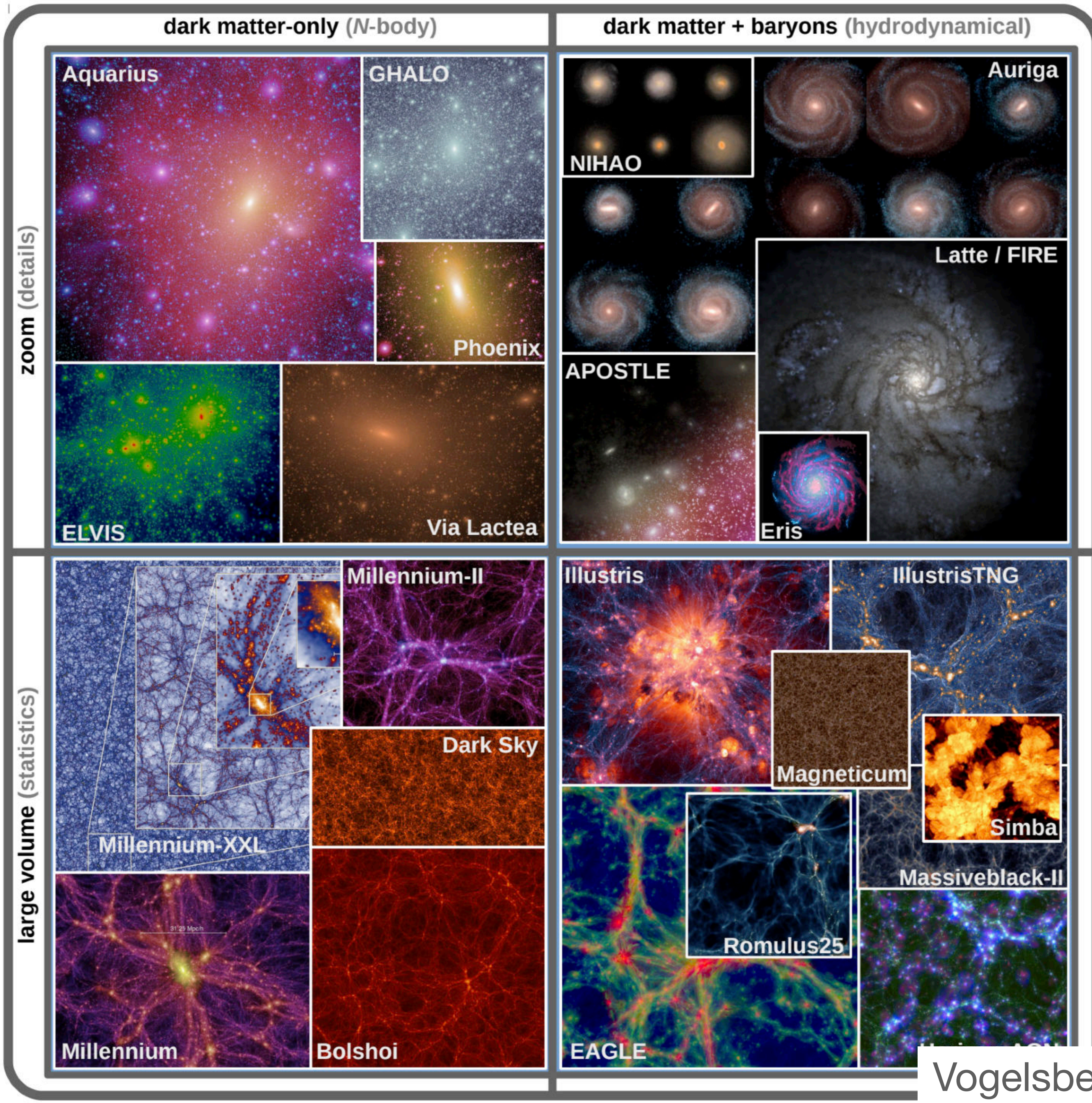


TNG simulation



TNG simulation

Galaxy Hydrodynamic Simulations



Vogelsberger et al. (2019)

Great!
We have solved everything about galaxies.

Great!

We have solved everything about galaxies.

Not really…

The simulations are very expensive!

To run a IllustrisTNG simulation with super computers,
how long will it take?

Illustris-TNG Nelson et al. (2017)

The simulations are very expensive!

Run name		TNG100-1	TNG100-2	TNG100-3	TNG300-1	TNG300-2
CPU Time	(Mh)	18.0	0.6	0.02	34.9	1.3
N_{cores}	–	10752	2688	336	24000	6000

18,000,000 h / 8 cores -> 250 years

18,000,000 h / 10000 cores -> 2 months

Illustris-TNG Nelson et al. (2017)

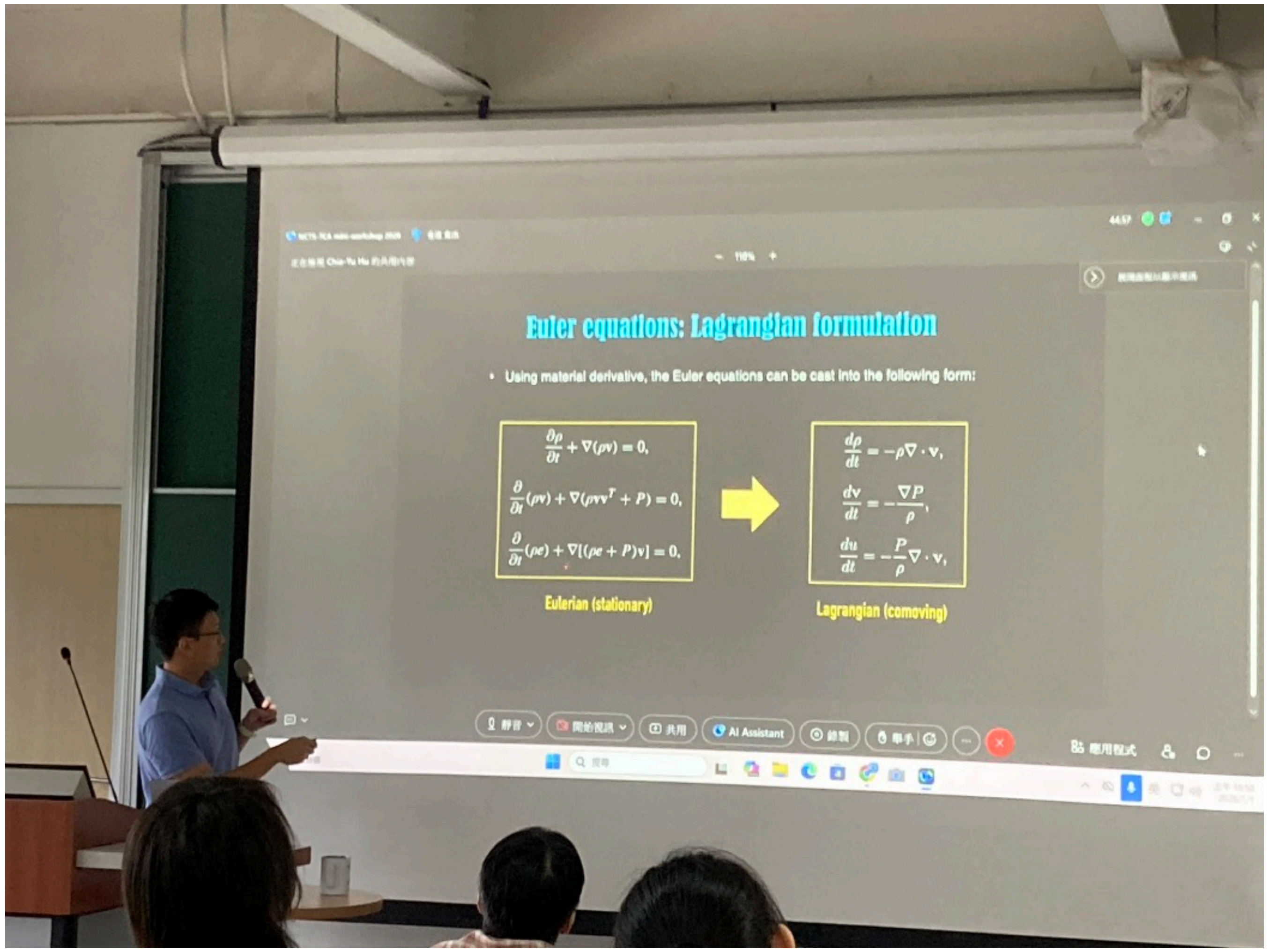
Galaxy Hydrodynamic Simulations

Reality: Simulations are limited by computational resources.
One can only do simulations with certain resolution.

Gravity

Fluid dynamics

Solving the Numerical methods



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?

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Resolution limit

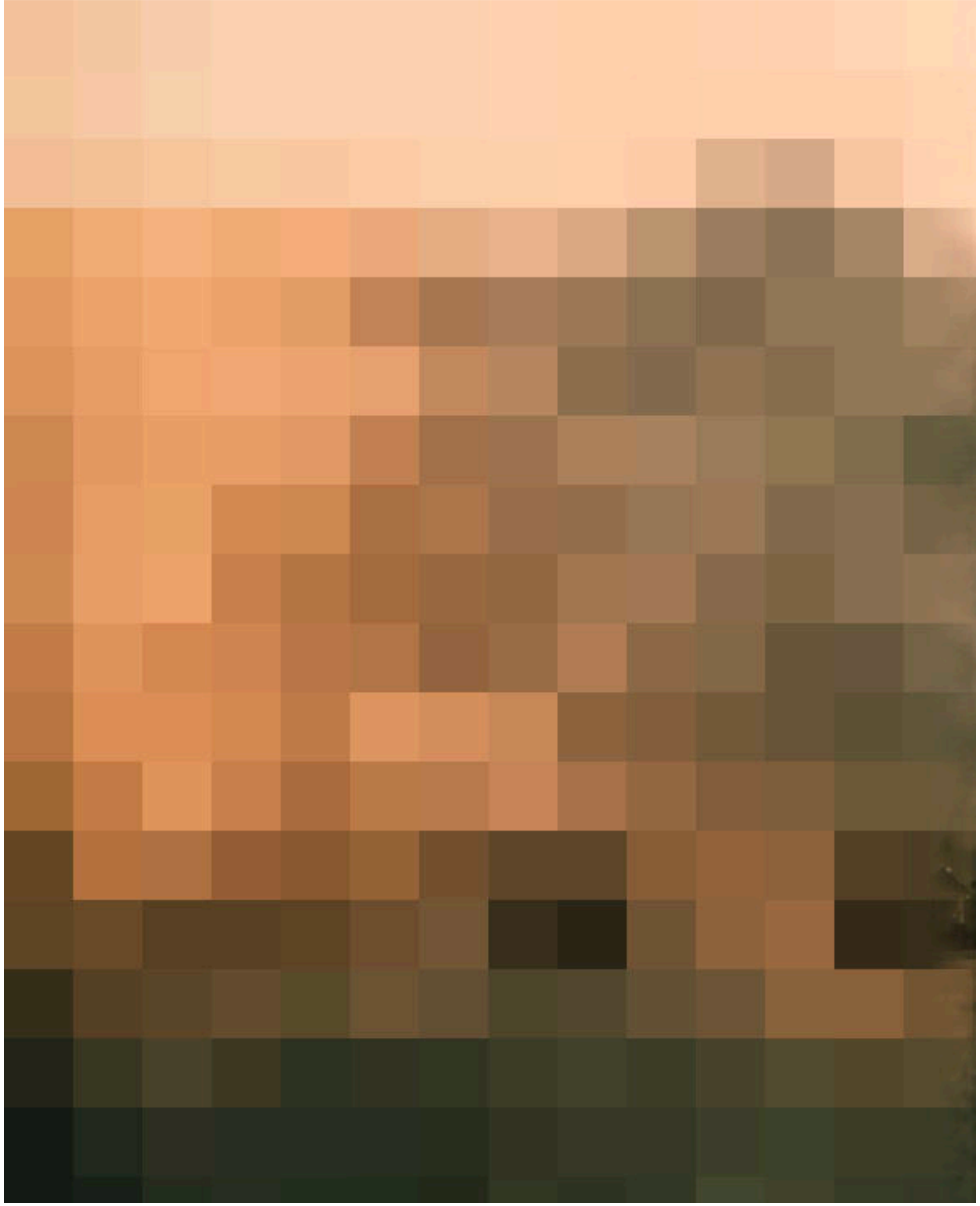
Subgrid models

(Assumptions about processes which can be not be resolved)

Relevant scales can not be resolved by simulations

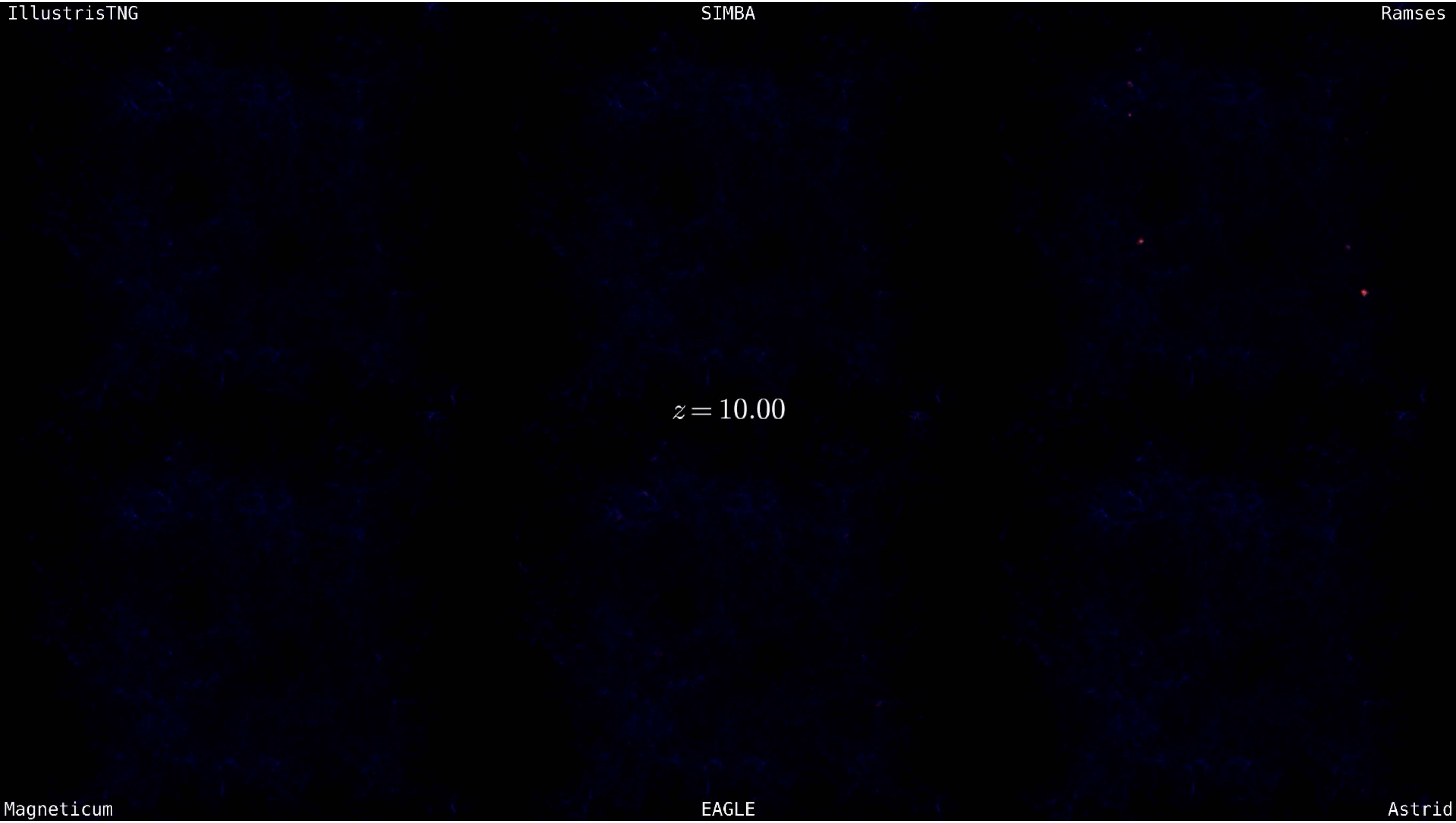
Current resolution	~ 10^{21} cm (1 kpc)
Stars	~ 10^{11} cm
Supermassive black hole	~ 10^{11} cm (10^6 $M_\odot$)

https://en.wikipedia.org/wiki/File:Dust-storm-Texas-1935.png



https://en.wikipedia.org/wiki/File:Dust-storm-Texas-1935.png

Different simulations produce different properties



Gas density

Gas temperature

https://www.youtube.com/watch?v=tSUFEIEPB3U

Galaxy Hydrodynamic Simulations

Reality: Simulations are limited by computational resources.
One can only do simulations with certain resolution.

Gravity

Fluid dynamics

Solving the Numerical methods

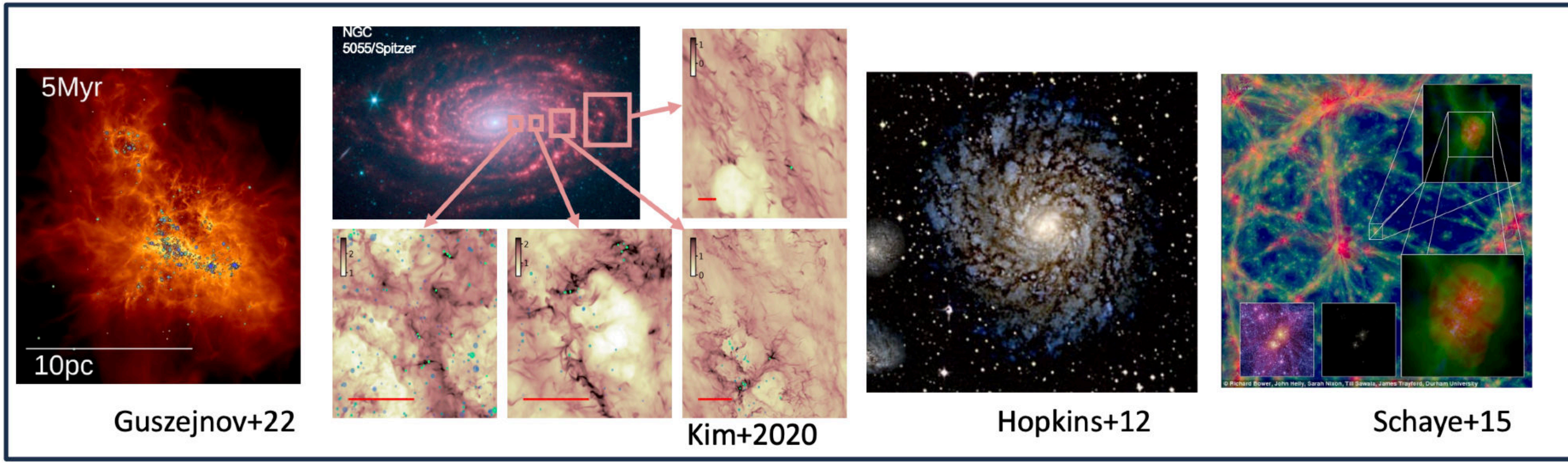
Resolution limit

A better understanding is needed!

Subgrid models

(Assumptions about processes that can be not be resolved)

A possible path forward



individual GMC or star cluster (STARFORGE)	ISM patch (TIGRESS, SILCC)	whole galaxy at single star resolution (GRIFFIN, Aeos)	cosmological zooms semi-resolved multiphase ISM (FIRE, SMUGGLE, FirstLight, SERRA)	cosmological volumes effective EoS, pop. averaged FB (TNG, SIMBA, EAGLE)
sub-pc sub M_{sun}	1-10 pc 1-4 M_{sun}		10's of pc 10^3-10^4 M_{sun}	100's of pc 10^4-10^6 M_{sun}

Somerville (2025)

Galaxies

NASA, ESA, CSA, Adam Smercina (STScI, Tufts), Thomas Williams (University of Manchester); Alyssa Pagan (STScI)

Observations:

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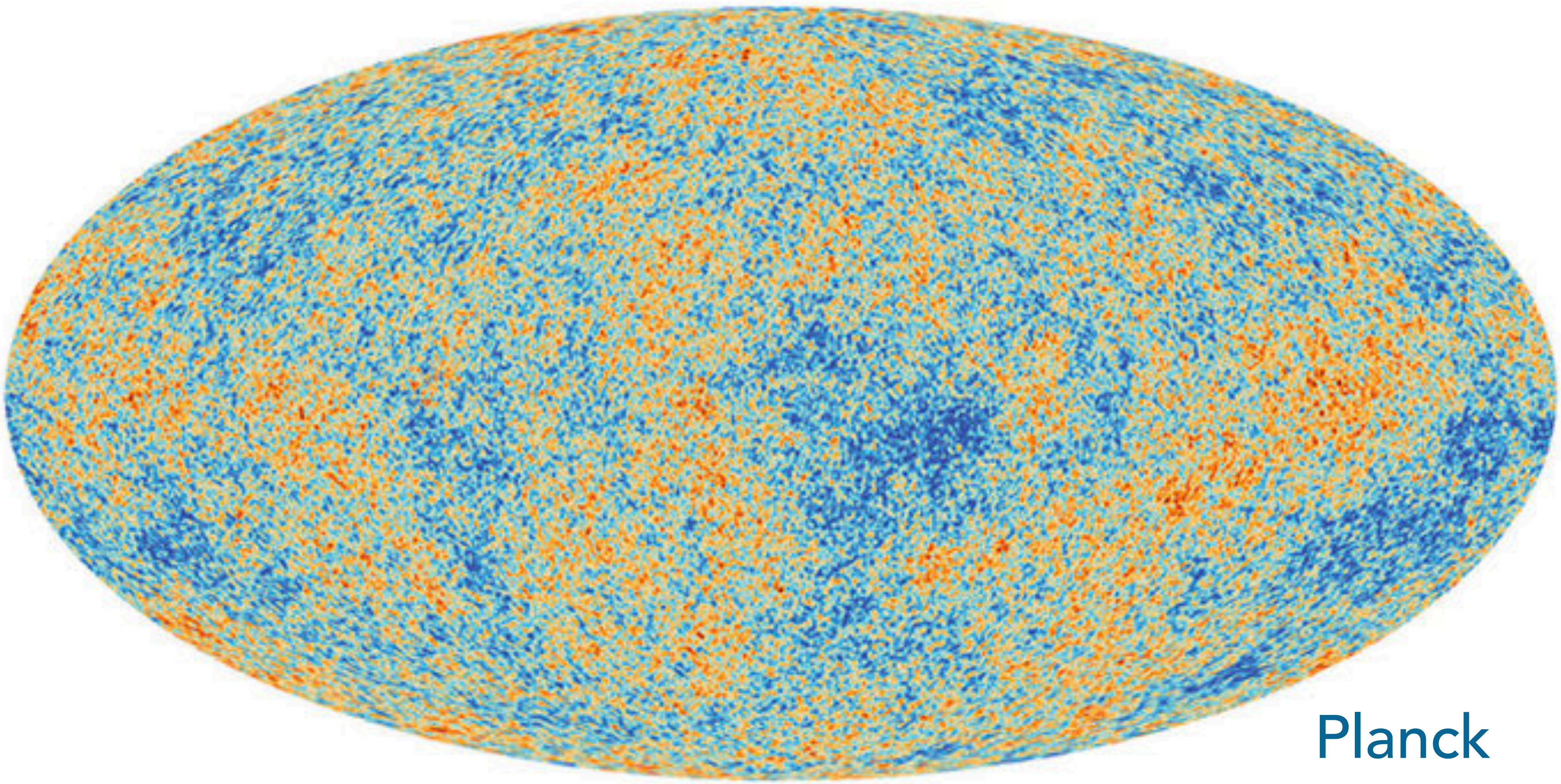
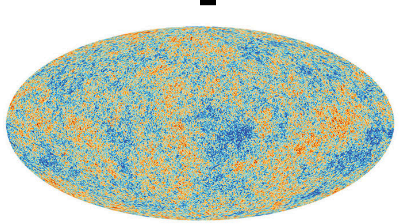
Galaxy Formation and Evolution



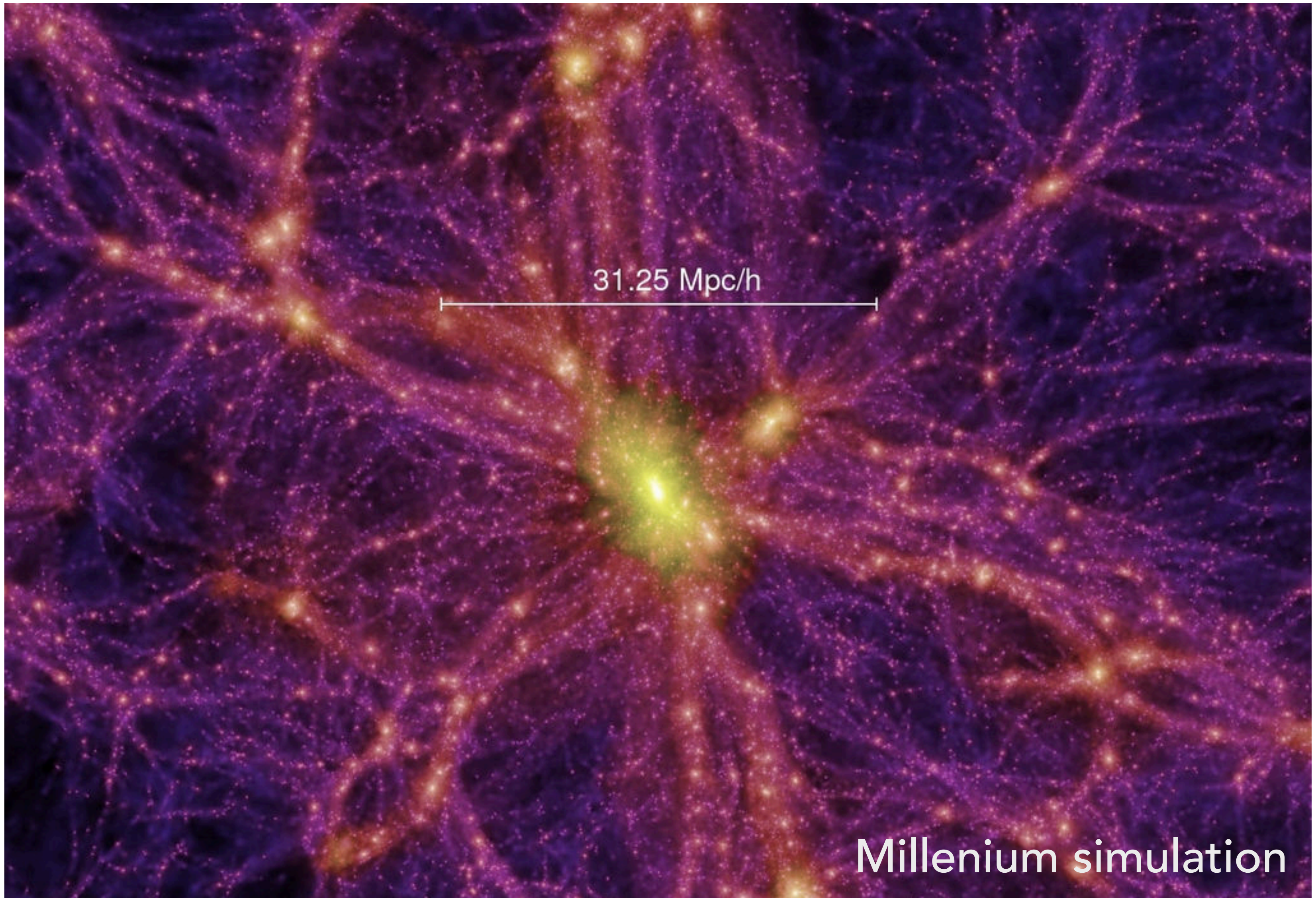
Planck

ΛCDM model



Initial conditions

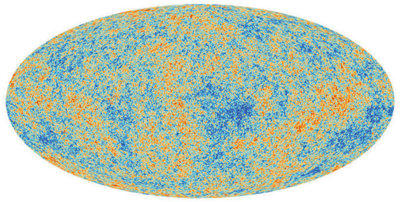
Galaxy Formation and Evolution



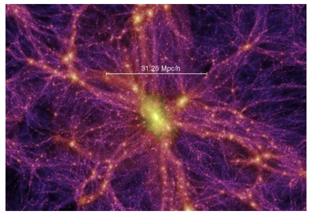
kpc ≈ 3×10^{21} cm

Large Scale Structure

100,000 kpc

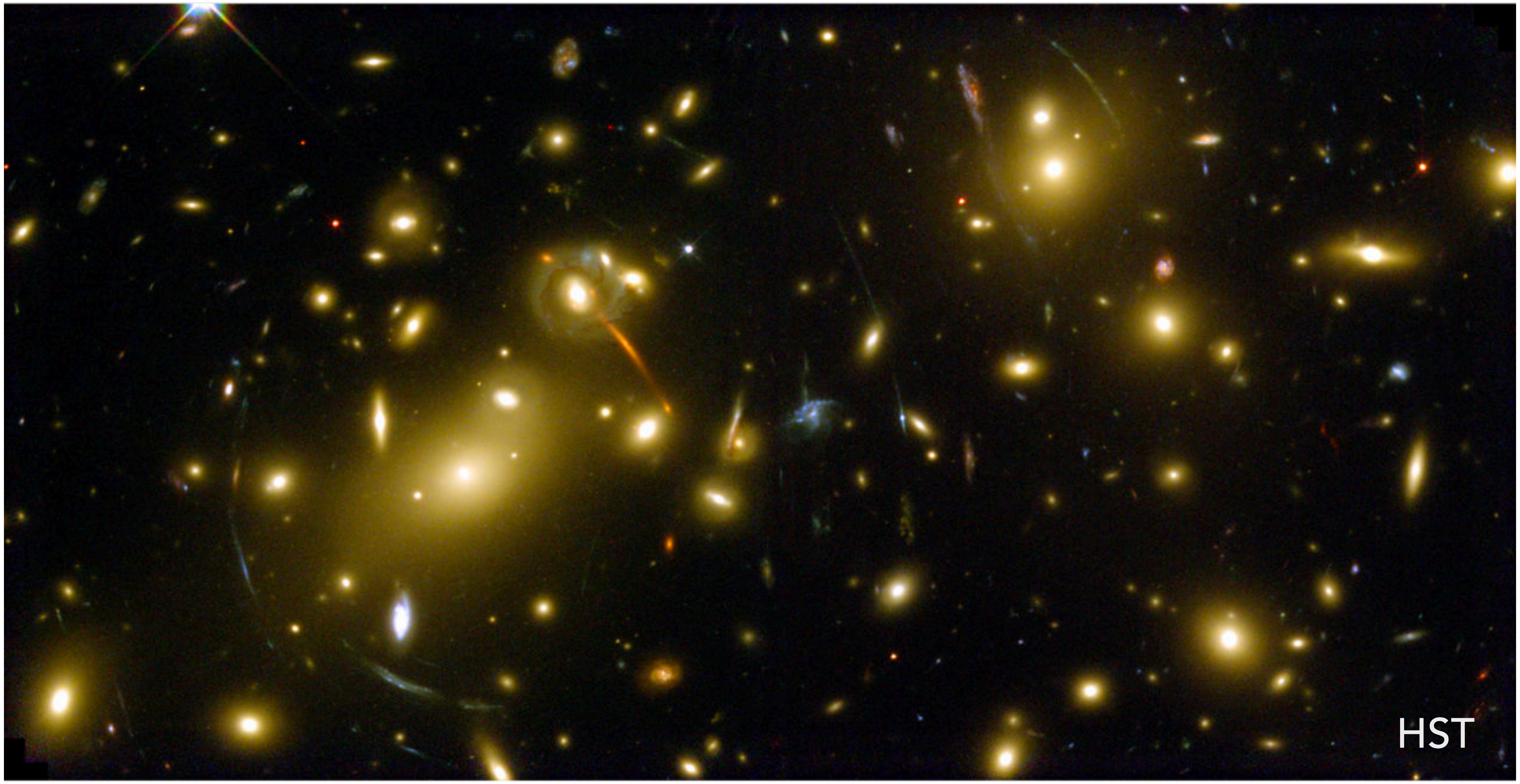


Initial conditions



Large scale structures

Galaxy Formation and Evolution

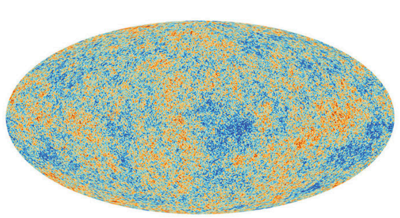


kpc = 3×10^{21} cm

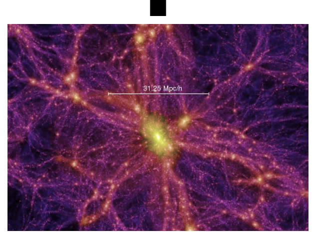
Galaxy Clusters

100,000 kpc

1,000 kpc



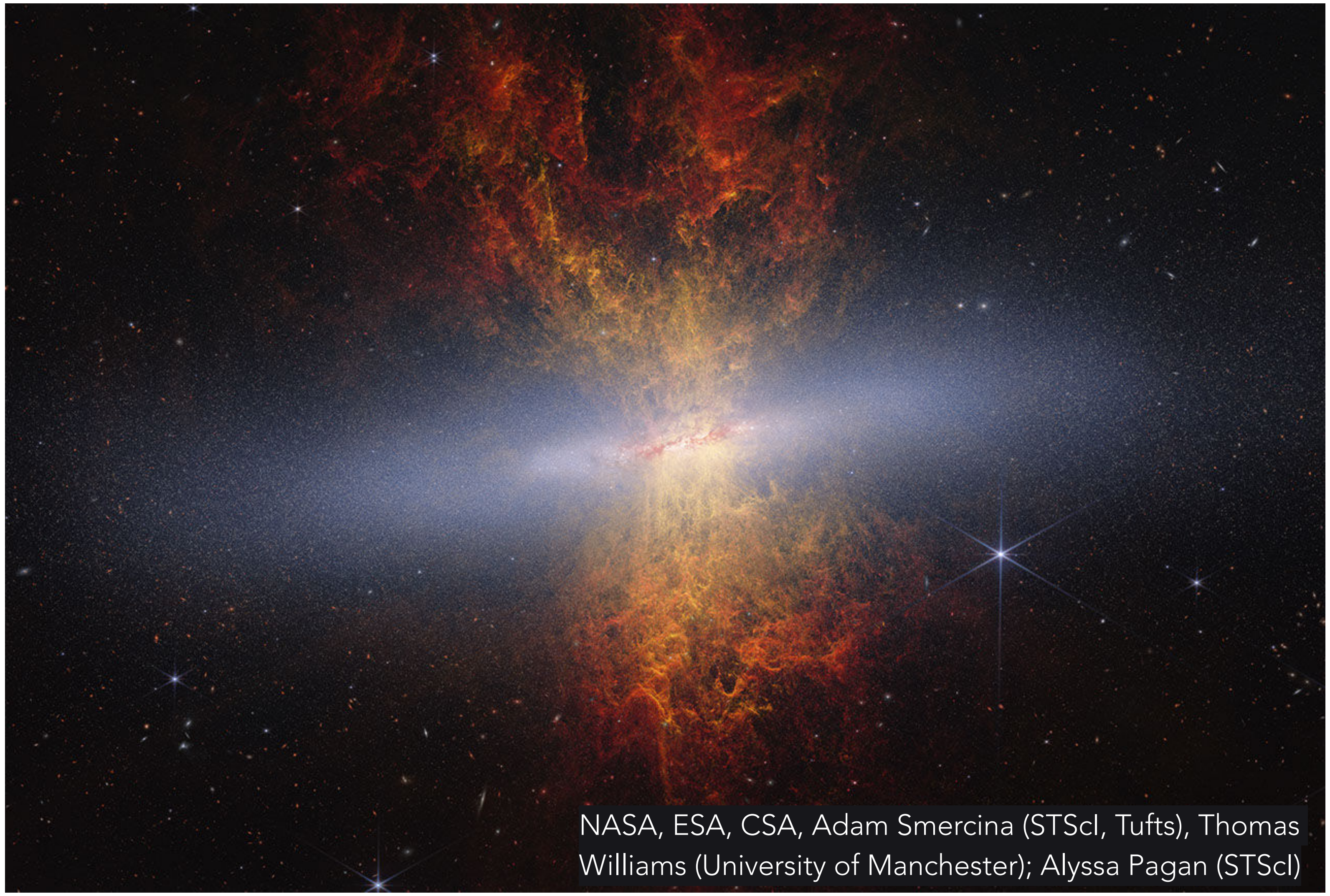
Initial conditions



Large scale structures

Galaxy clusters

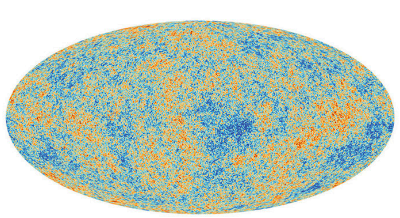
Galaxy Formation and Evolution



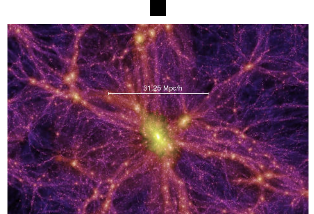
kpc ≃ 3×10^{21} cm

Galaxies

100,000 kpc — 1,000 kpc — 10 kpc

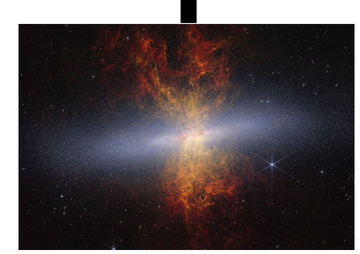


Initial conditions



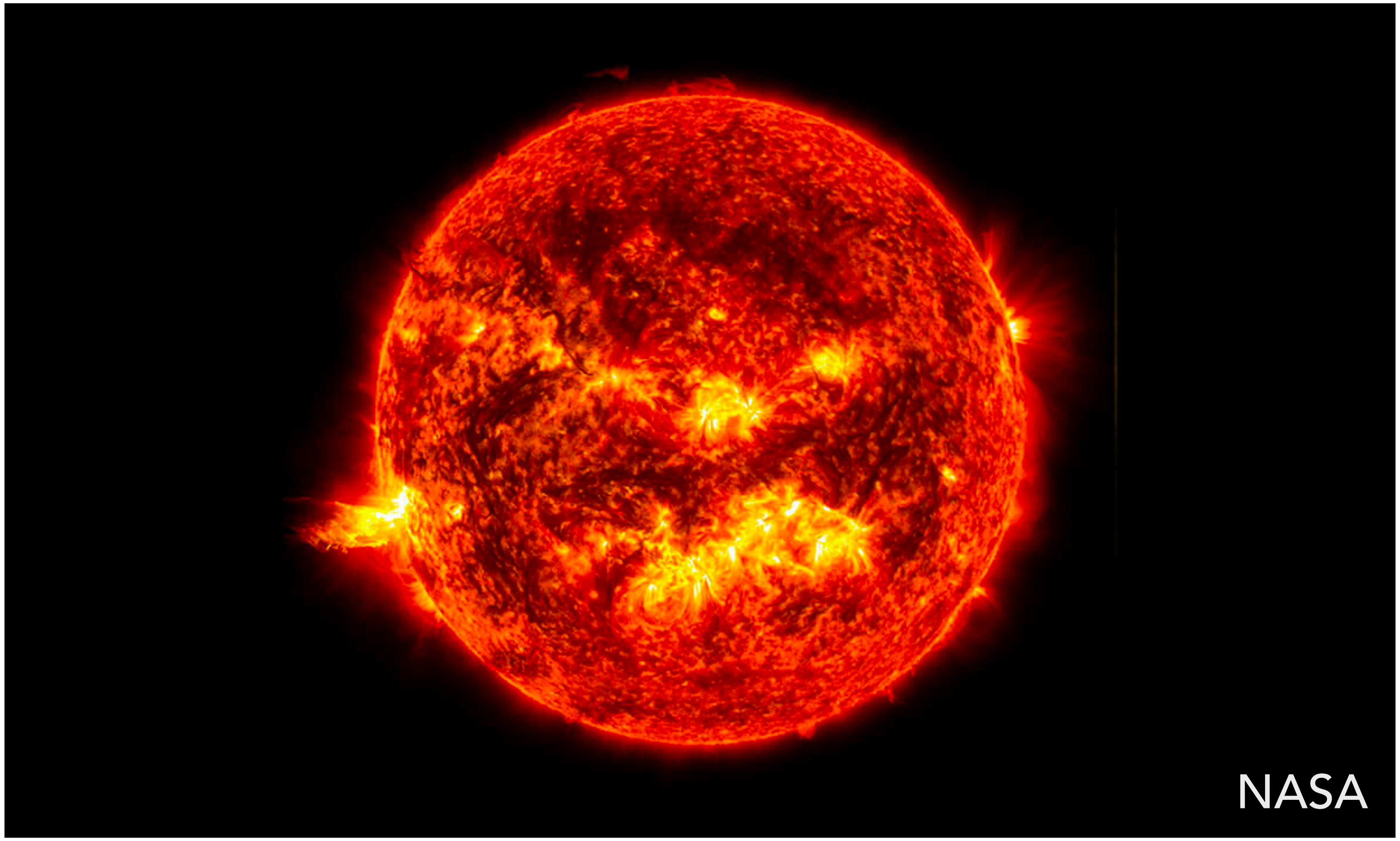
Large scale structures

Galaxy clusters



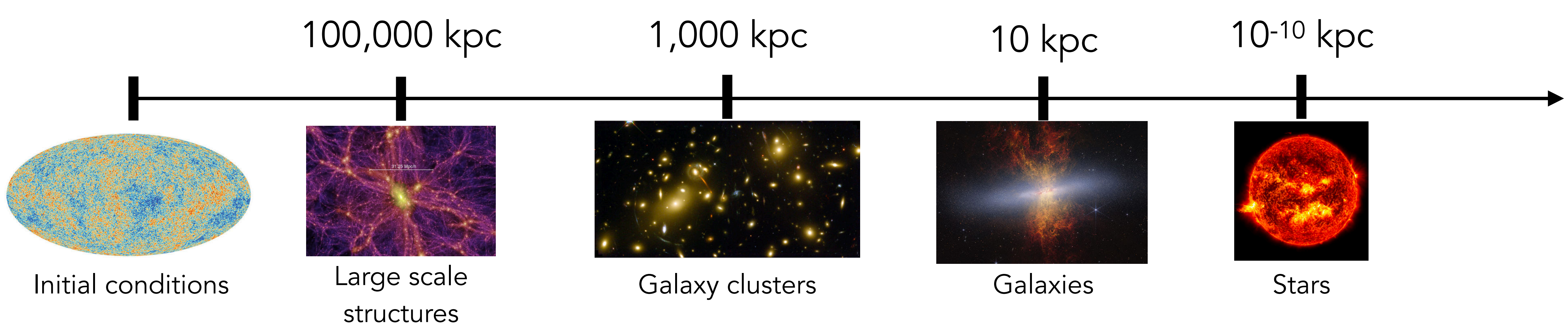
Galaxies

Galaxy Formation and Evolution

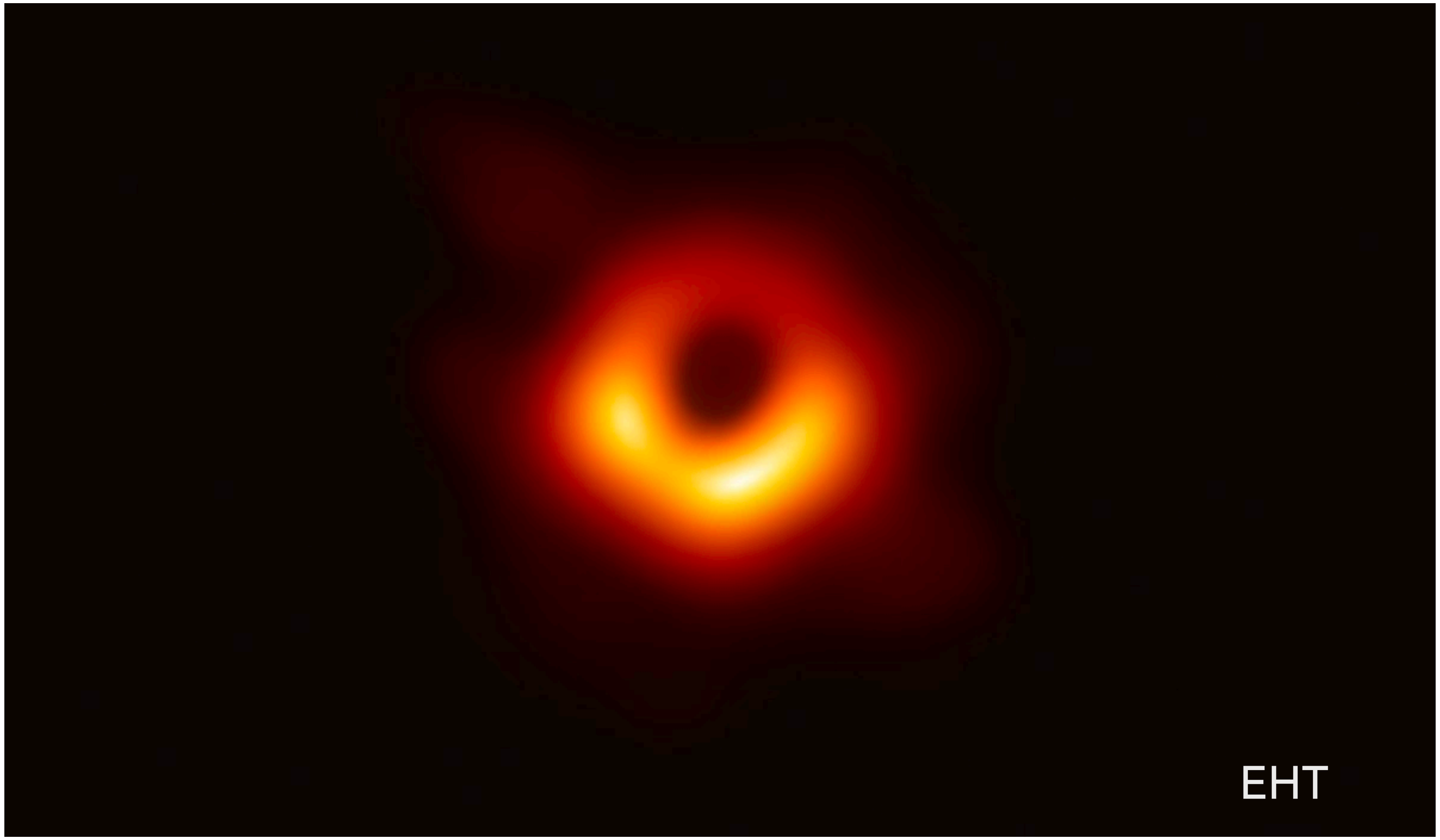


kpc ≃ 3×10^{21} cm

Stars

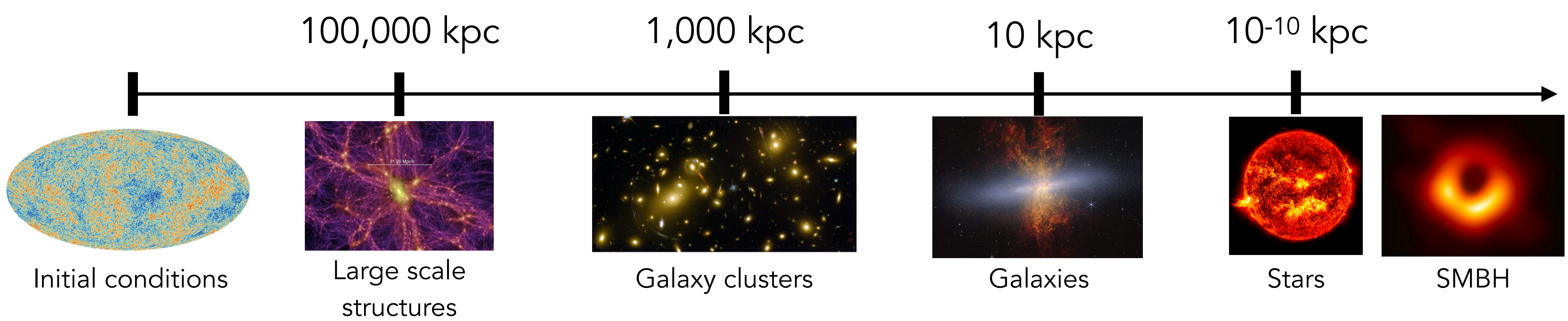


Galaxy Formation and Evolution



kpc ≃ 3×10^{21} cm

Black Holes



Galaxy Formation and Evolution

Astrophysics of galaxy evolution includes processes in scales covering more than 10 orders of magnitude.

The goal is to understand how each process at different scales shapes the properties of galaxies!