UPPSALA UNIVERSITET

The James Webb Space Telescope and Fundamental Physics

Martin Sahlén

Astronomy & Space Physics, Uppsala University

HEP/Nuclear Physics/FREIA seminar, 10 March 2022

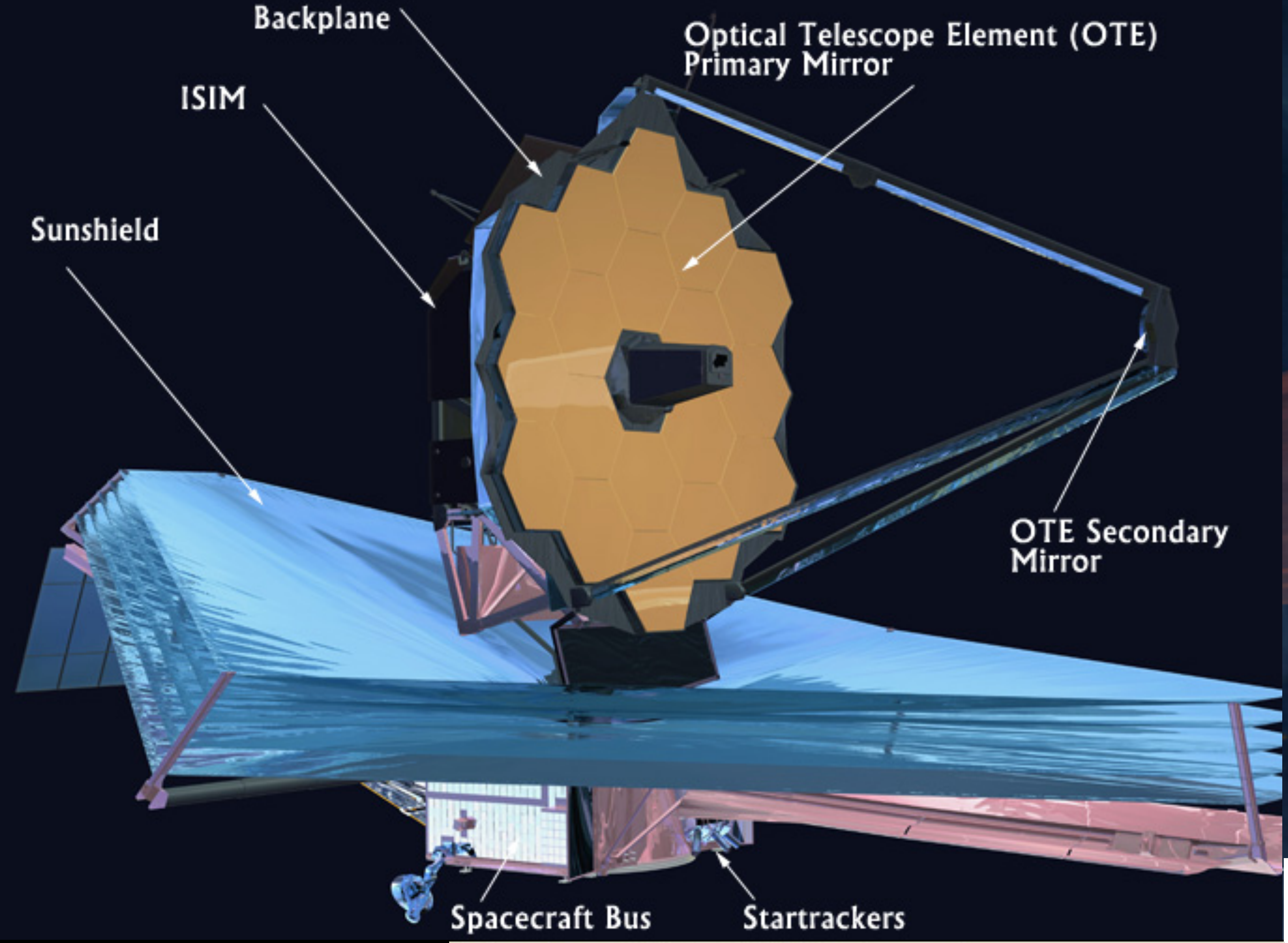
SCIENCE GOALS FOR THE JWST

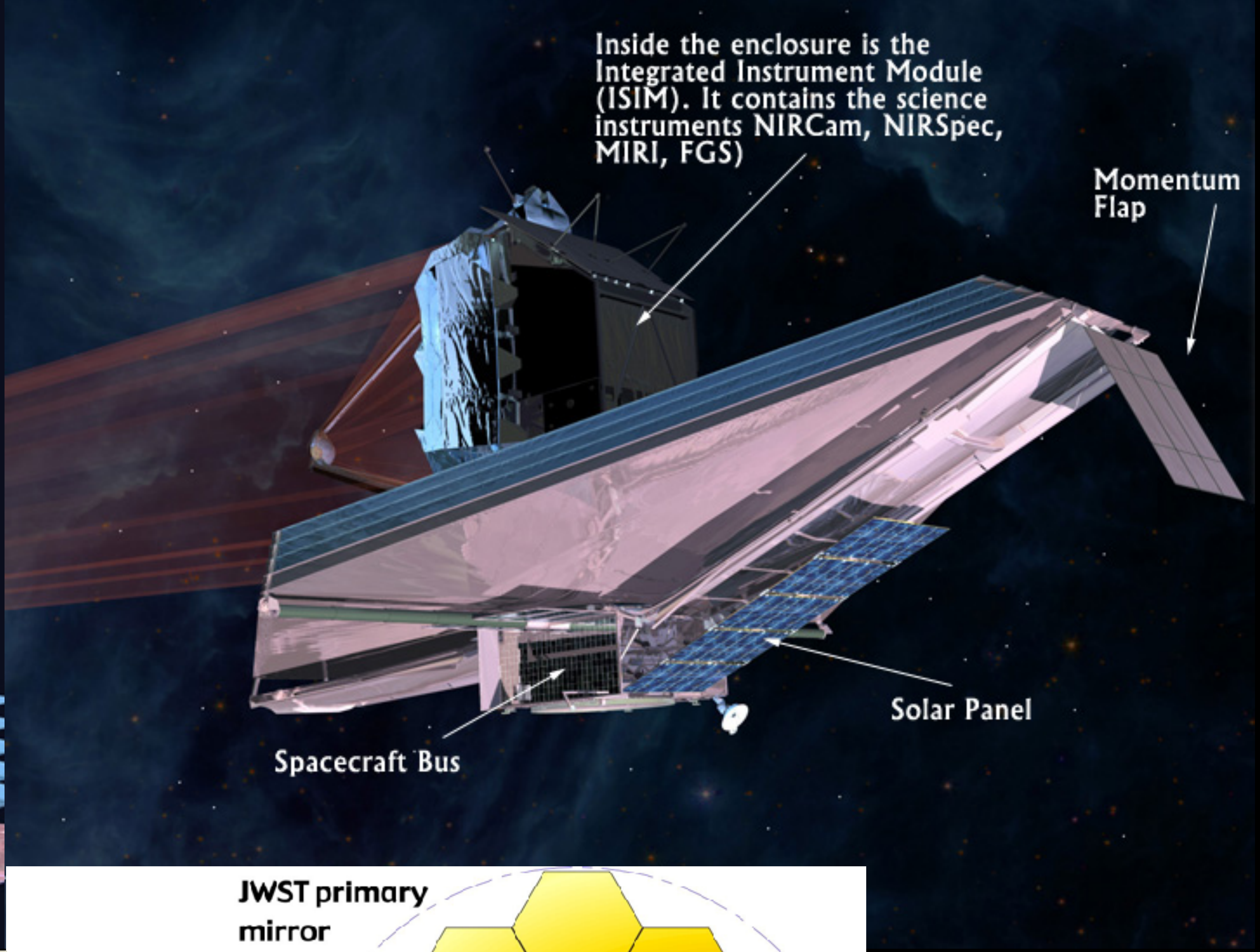
The JWST is intended to solve outstanding key questions concerning our place in the evolving Universe. It is a multi-purpose observatory covering a wide range of astronomical topics.

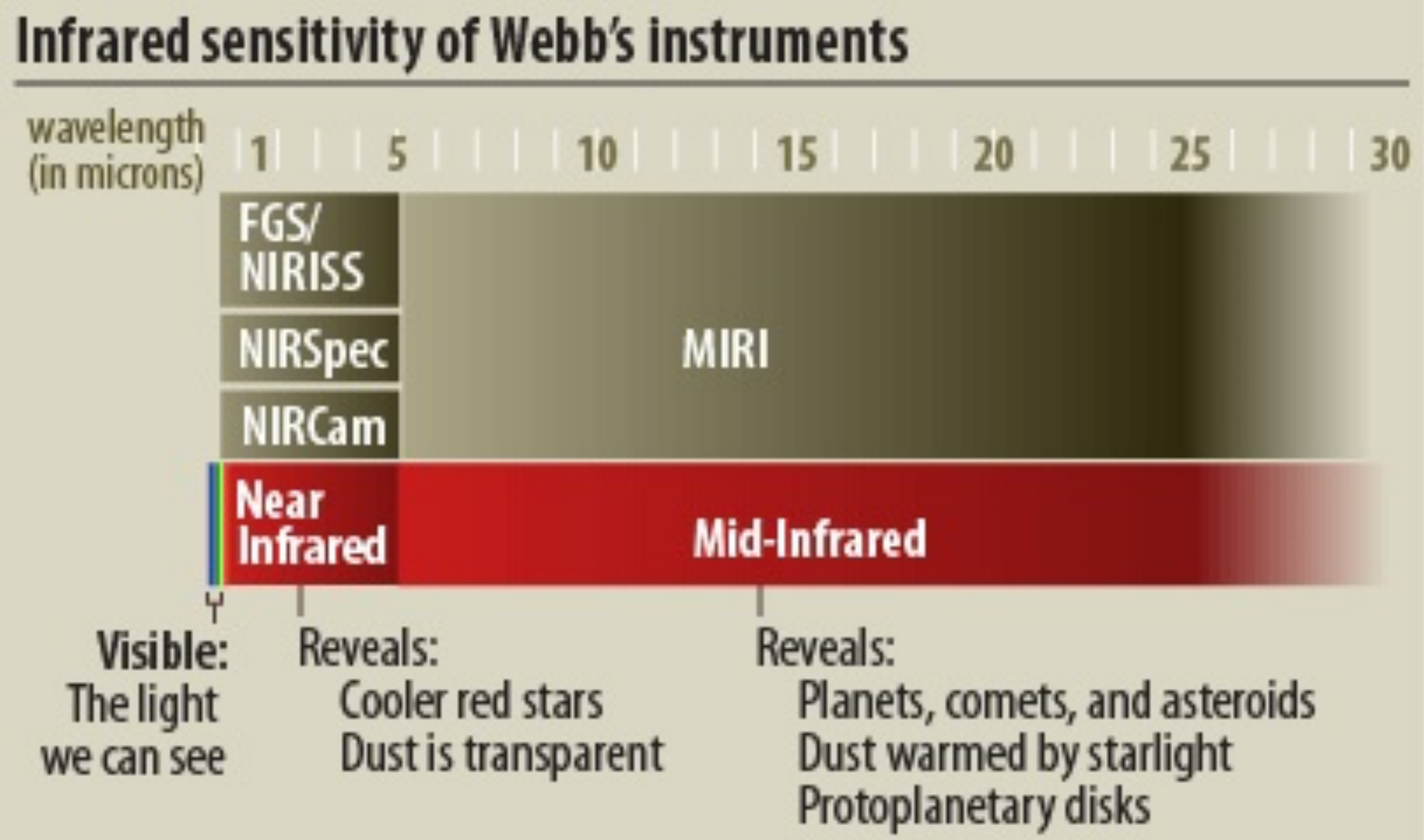
In order to guide the design of the telescope and its instruments, scientists identified four general topics as the core scientific themes for the JWST.

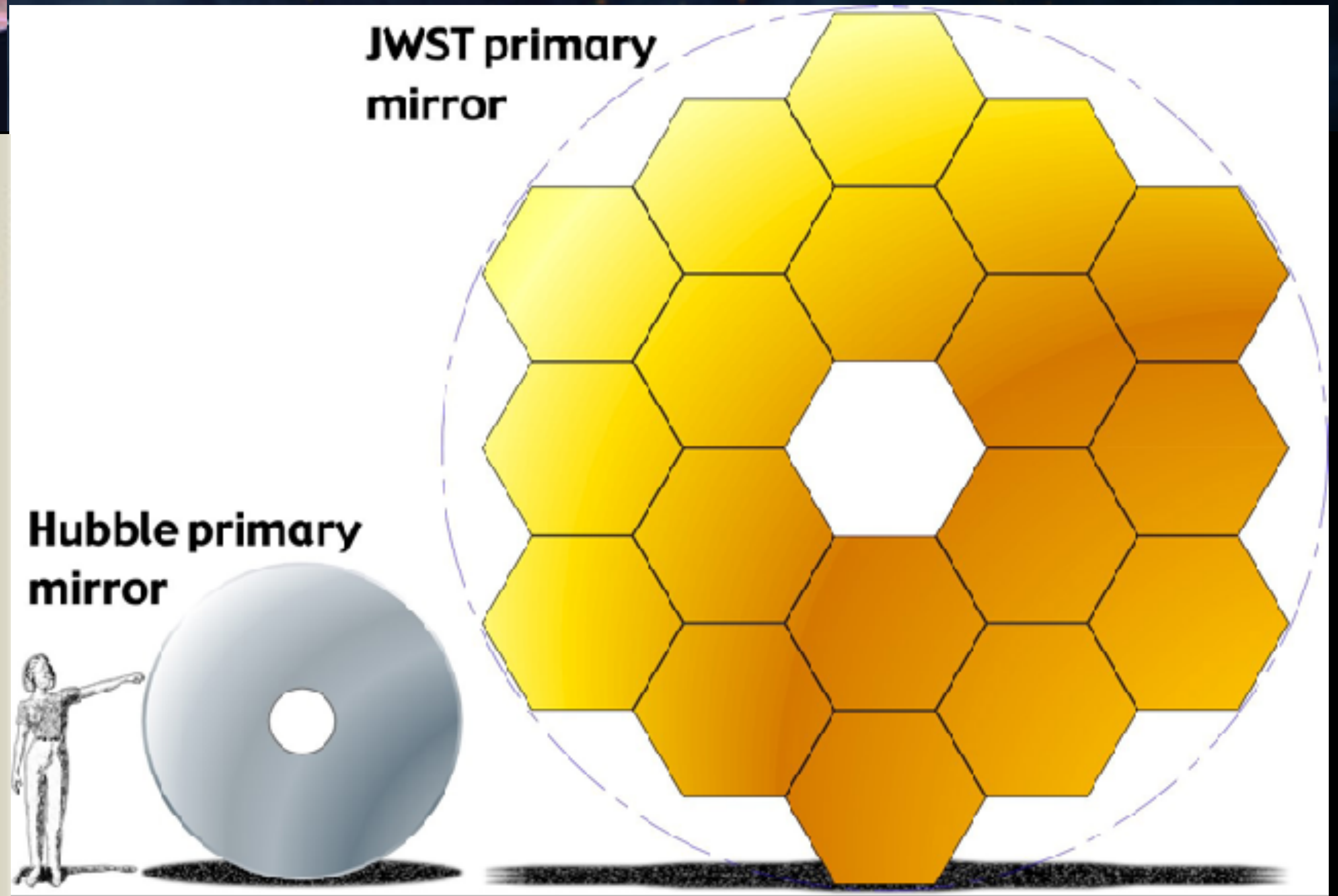
- **The early Universe:** What did the early Universe look like? When did the first stars and galaxies emerge?
- **Galaxies over time:** How did the first galaxies evolve over time? What can we learn about dark matter and dark energy?
- **The lifecycle of stars:** How and where do stars form? What determines how many of them form and their individual masses? How do stars die and how do their deaths impact the surrounding medium?
- **Other worlds:** Where and how do planetary systems form and evolve?

Instruments


Backplane
Optical Telescope Element (OTE)
Primary Mirror
ISIM
Sunshield
OTE Secondary
Mirror
Spacecraft Bus
Startrackers


Inside the enclosure is the
Integrated Instrument Module
(ISIM). It contains the science
instruments NIRCam, NIRSpec,
MIRI, FGS)
Momentum
Flap
Solar Panel
Spacecraft Bus

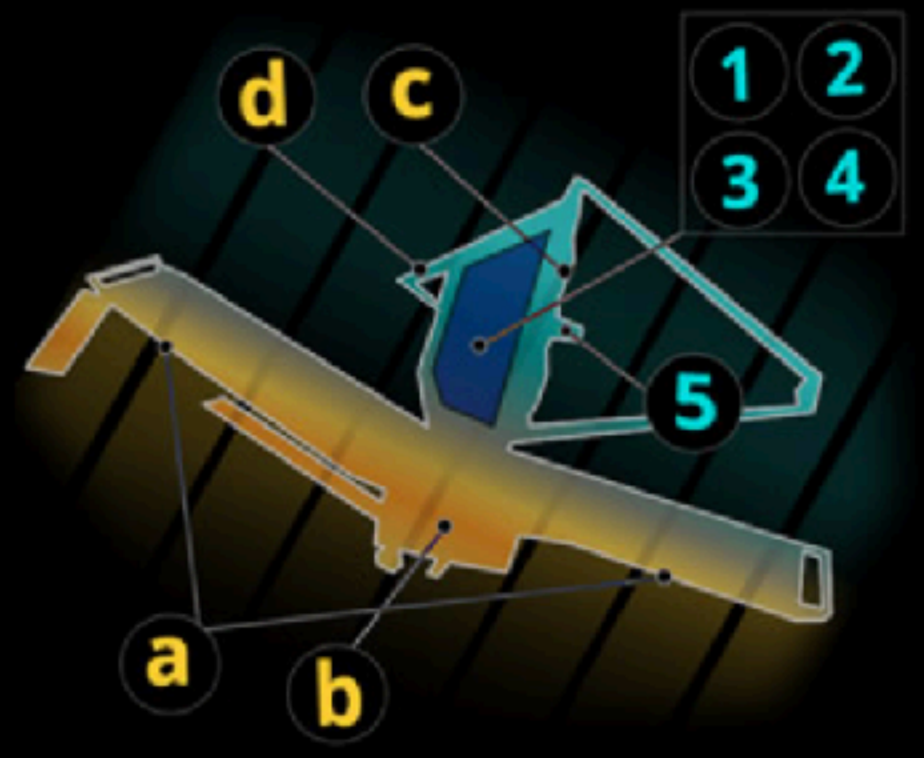

Infrared sensitivity of Webb's instruments
wavelength
(in microns)
1
5
10
15
20
25
30
FGS/
NIRISS
NIRSpec
MIRI
NIRCam
Near
Infrared
Mid-Infrared
Visible:
The light
we can see
Reveals:
Cooler red stars
Dust is transparent
Reveals:
Planets, comets, and asteroids
Dust warmed by starlight
Protoplanetary disks


JWST primary
mirror
Hubble primary
mirror

WHERE IS WEBB? | About This Page | English <> Metric

128F 327K (a)
62F 290K (b)
Hot Side >

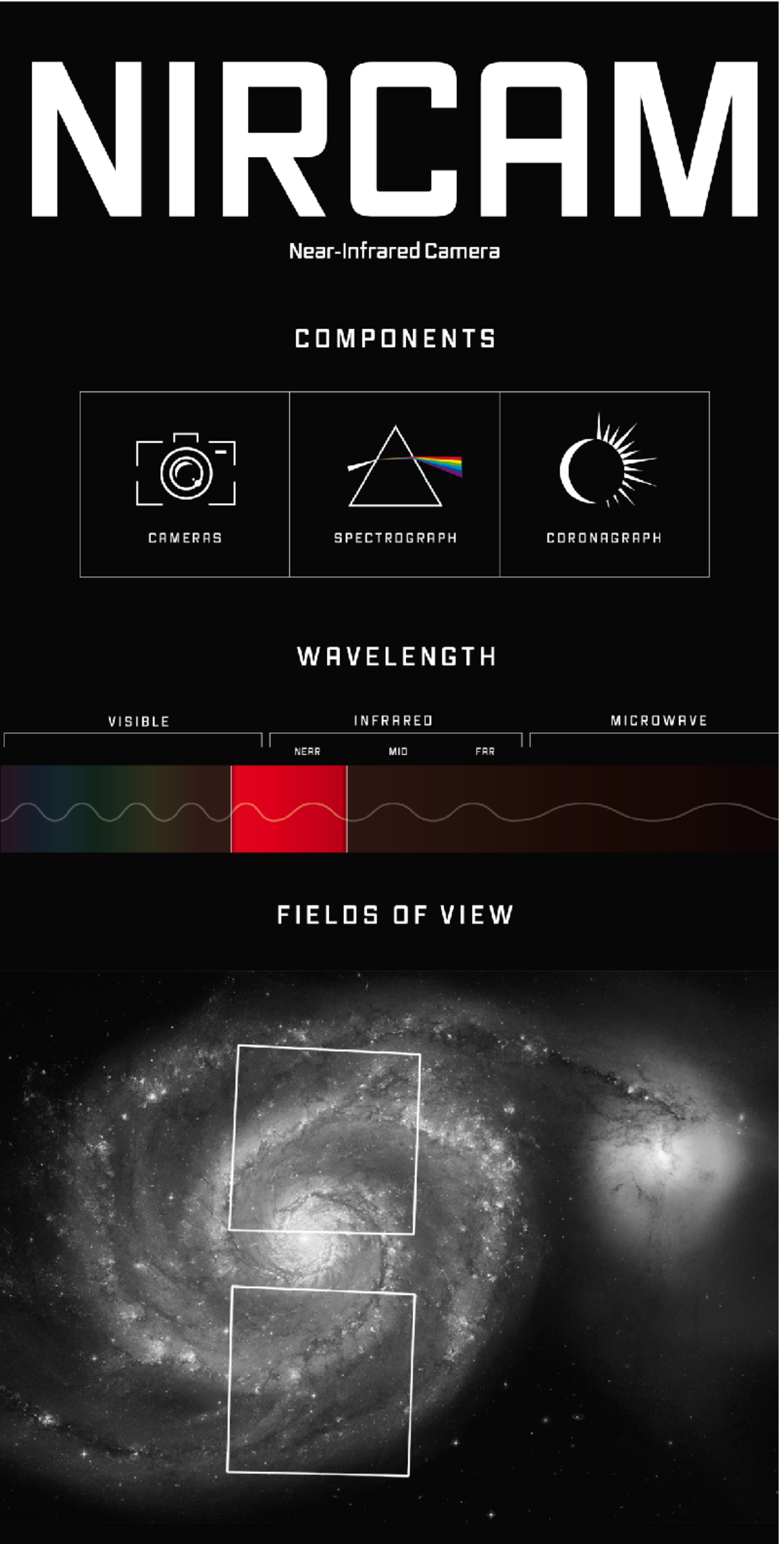
-381F 44K (c)
-389F 39K (d)
Cold Side



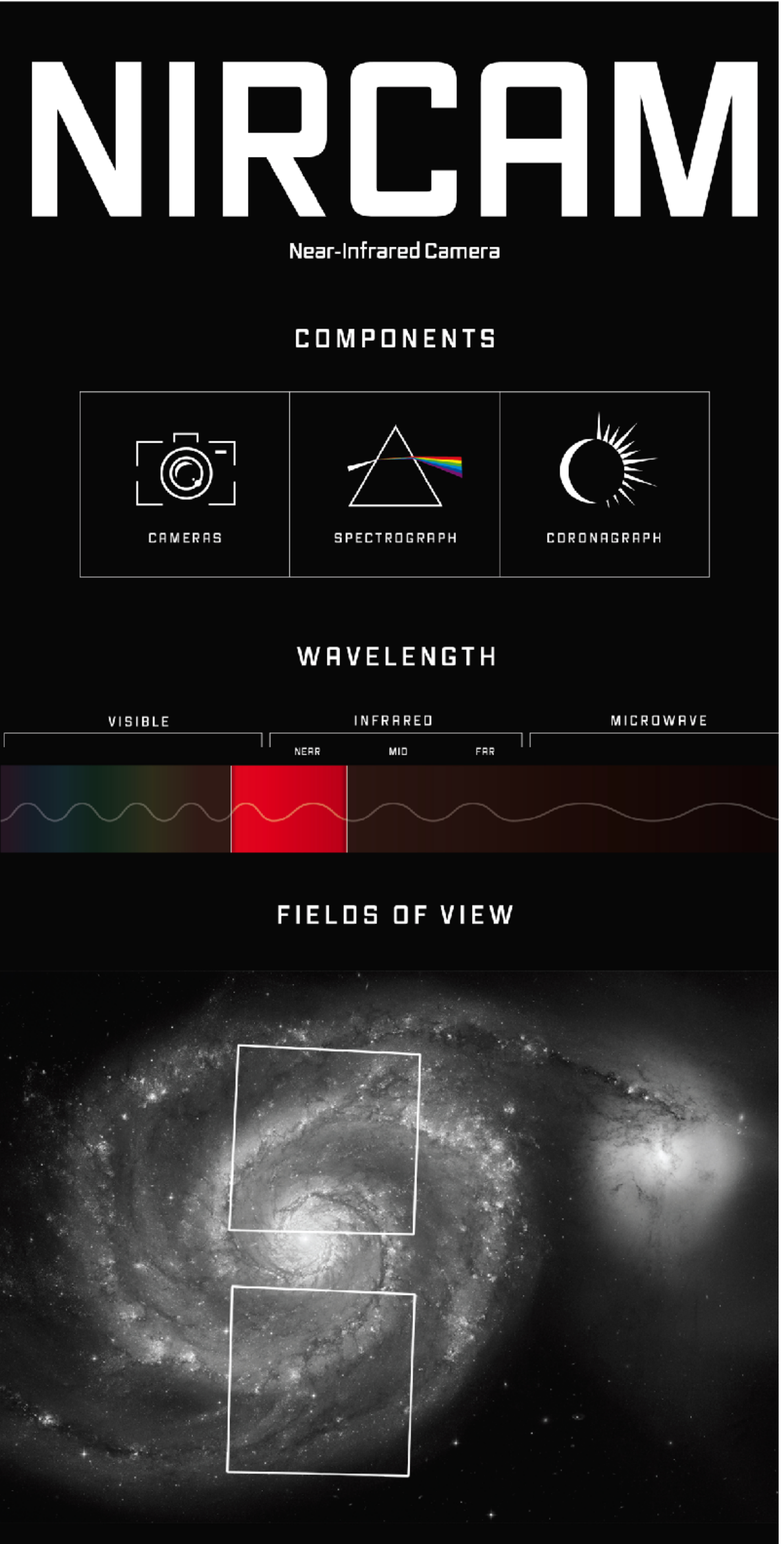
-276F 102K (1)
-384F 42K (2)
-390F 39K (3)
MIRI / NIRCam / NirSpec

-377F 46K (4)
-396F 36K (5)
FGS-NIRISS / FSM

4



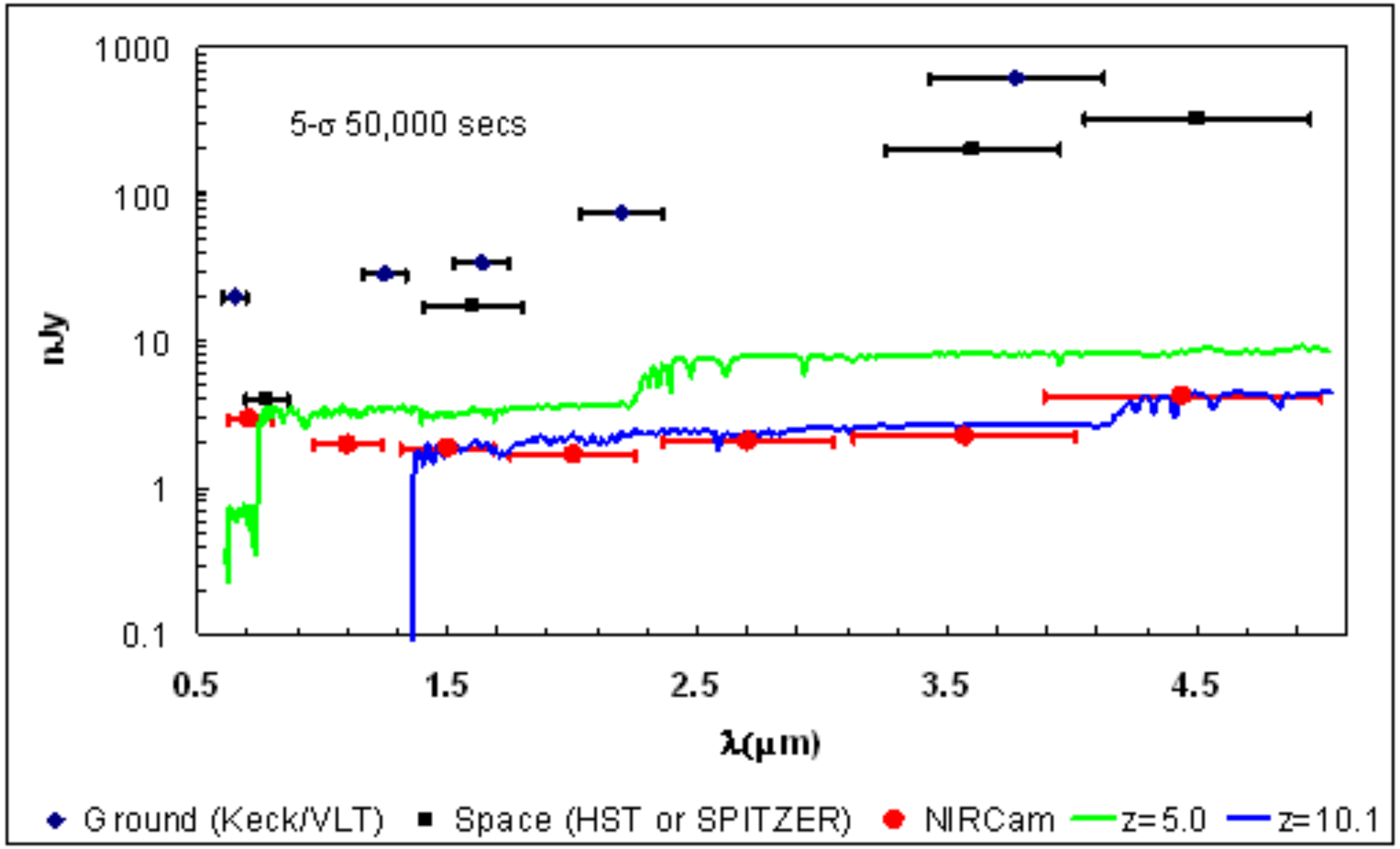
- Near-Infrared (0.5-6 μm) Imaging and Spectroscopy
- Earliest stars and galaxies
- Stellar populations in nearby galaxies
- Young stars in Milky Way
- Kuiper Belt objects
- Circumstellar disks and planets

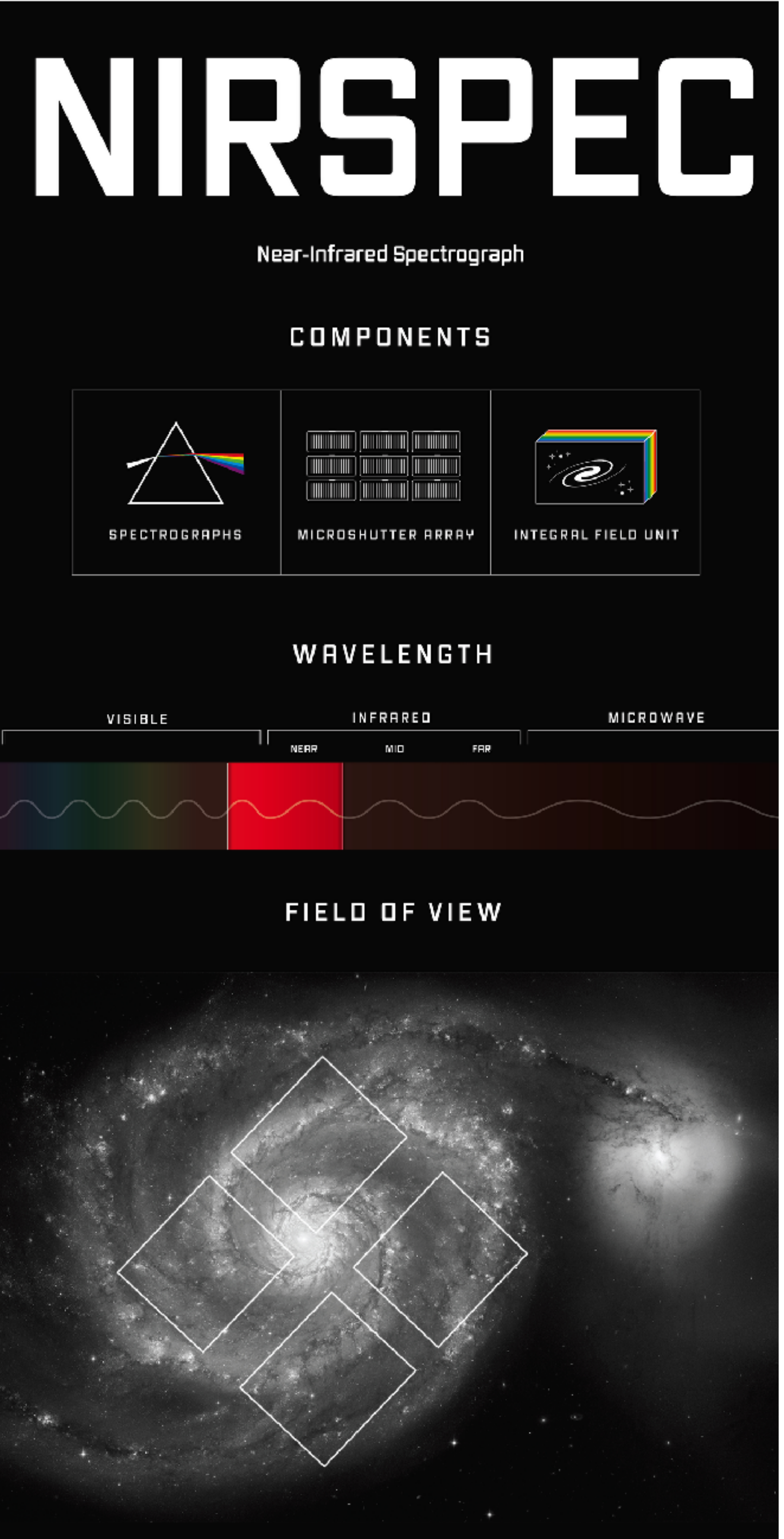


Earliest Galaxies

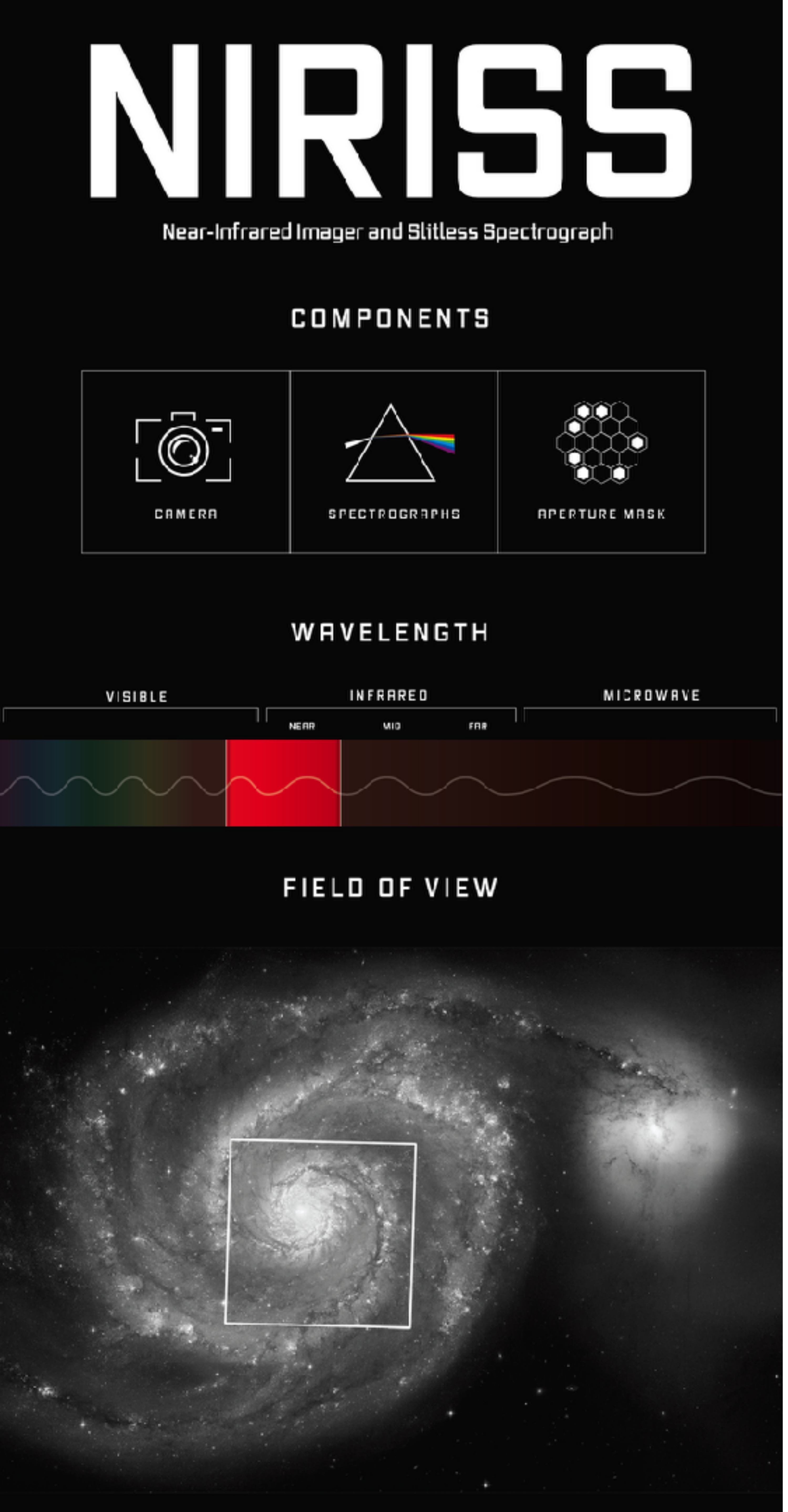
Few hundred Myr - 1 Gyr after Big Bang

- Redshift z ~ 6 - 15 -> NIR-IR

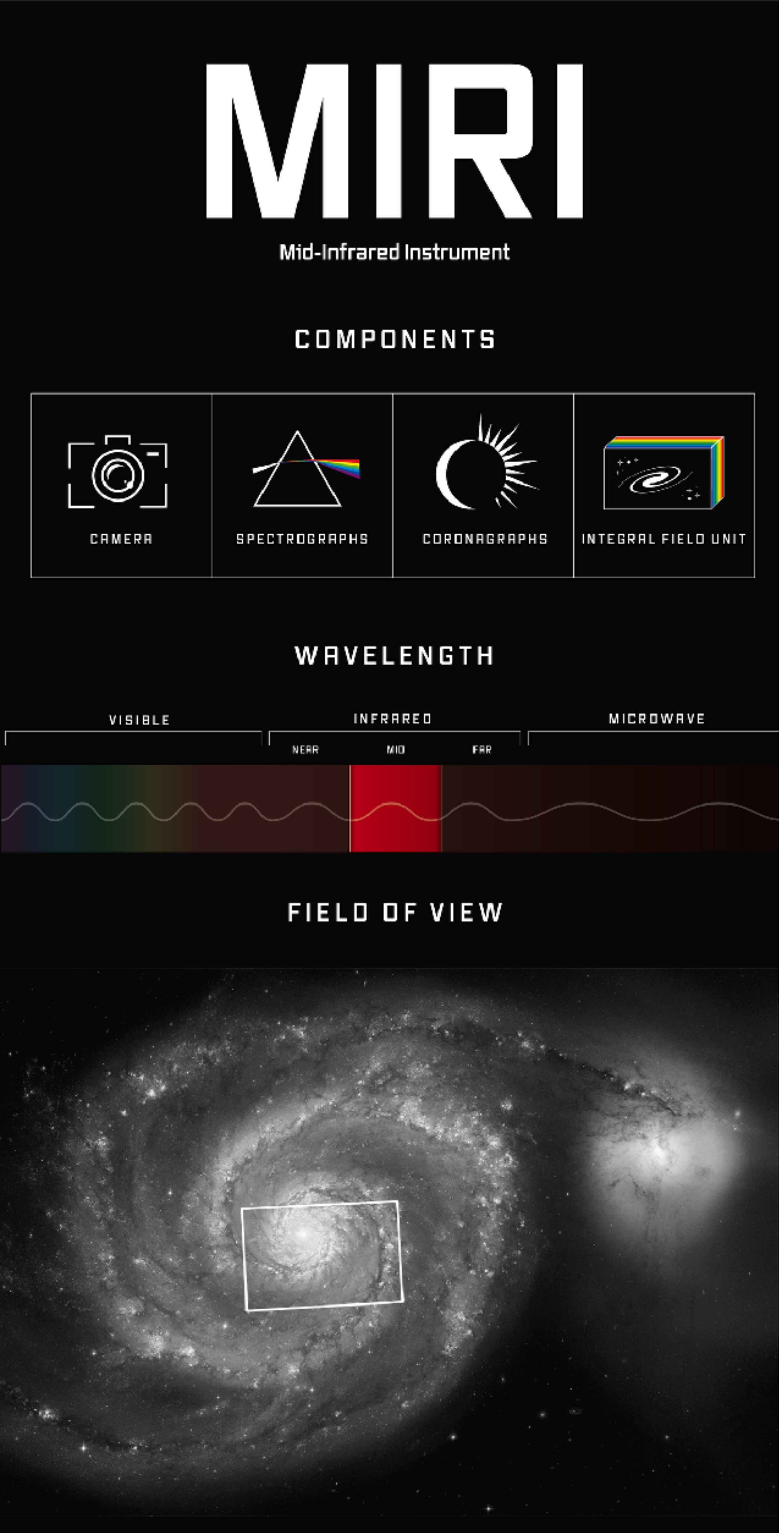




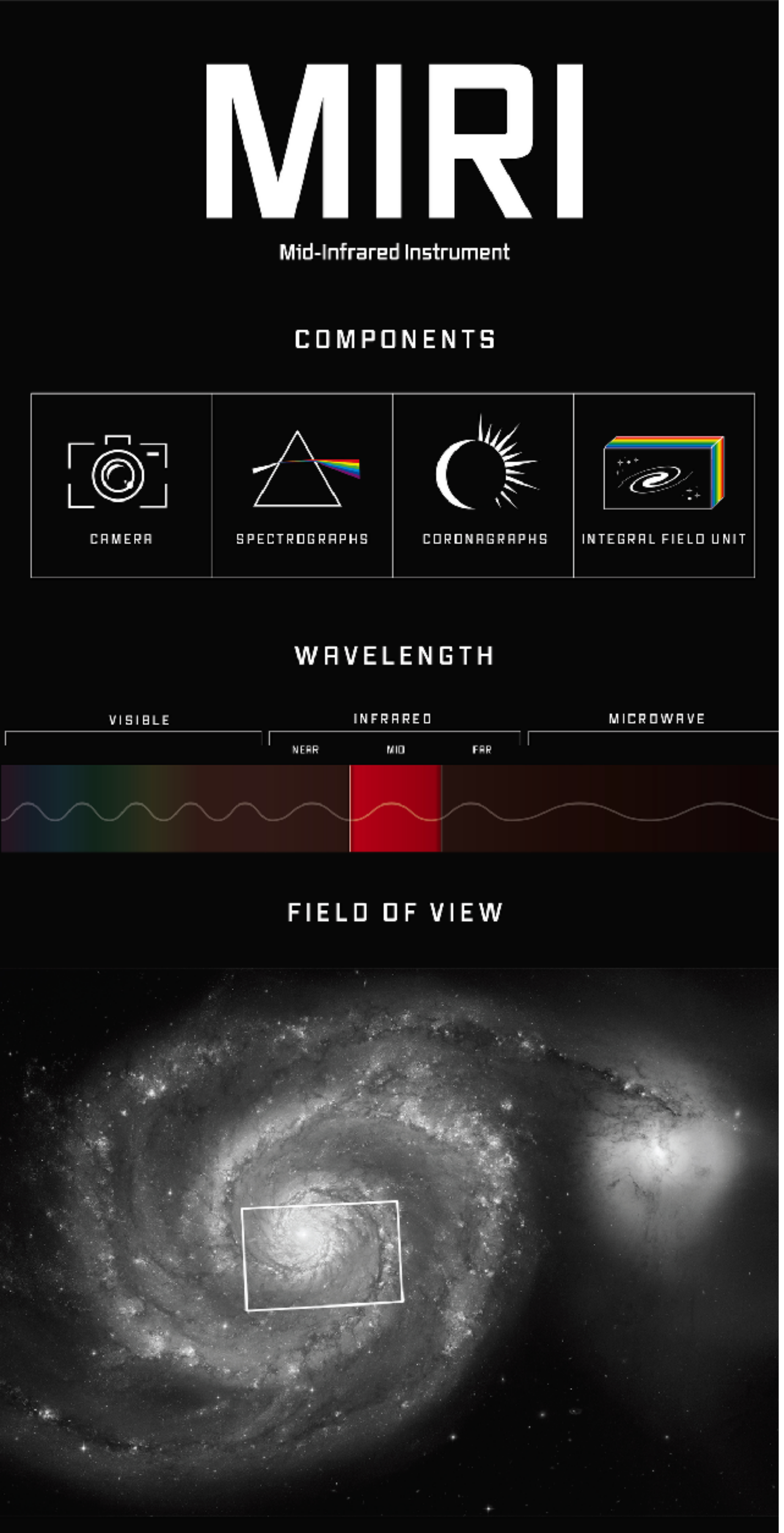
- Near-Infrared (0.5-6 μm) Spectroscopy
- Multi-object (200) Spectroscopy - Microshutter array
    - Block interfering nearby light
- Large spectroscopic surveys: early galaxies
- Single-object: transiting exoplanets



- Near-Infrared (0.8-5 µm) Imaging and Spectroscopy
- Earliest galaxies detection
- Exoplanet detection, characterisation, transit spectroscopy
- Complementary resolution capabilities to NIRCam+NIRSpec

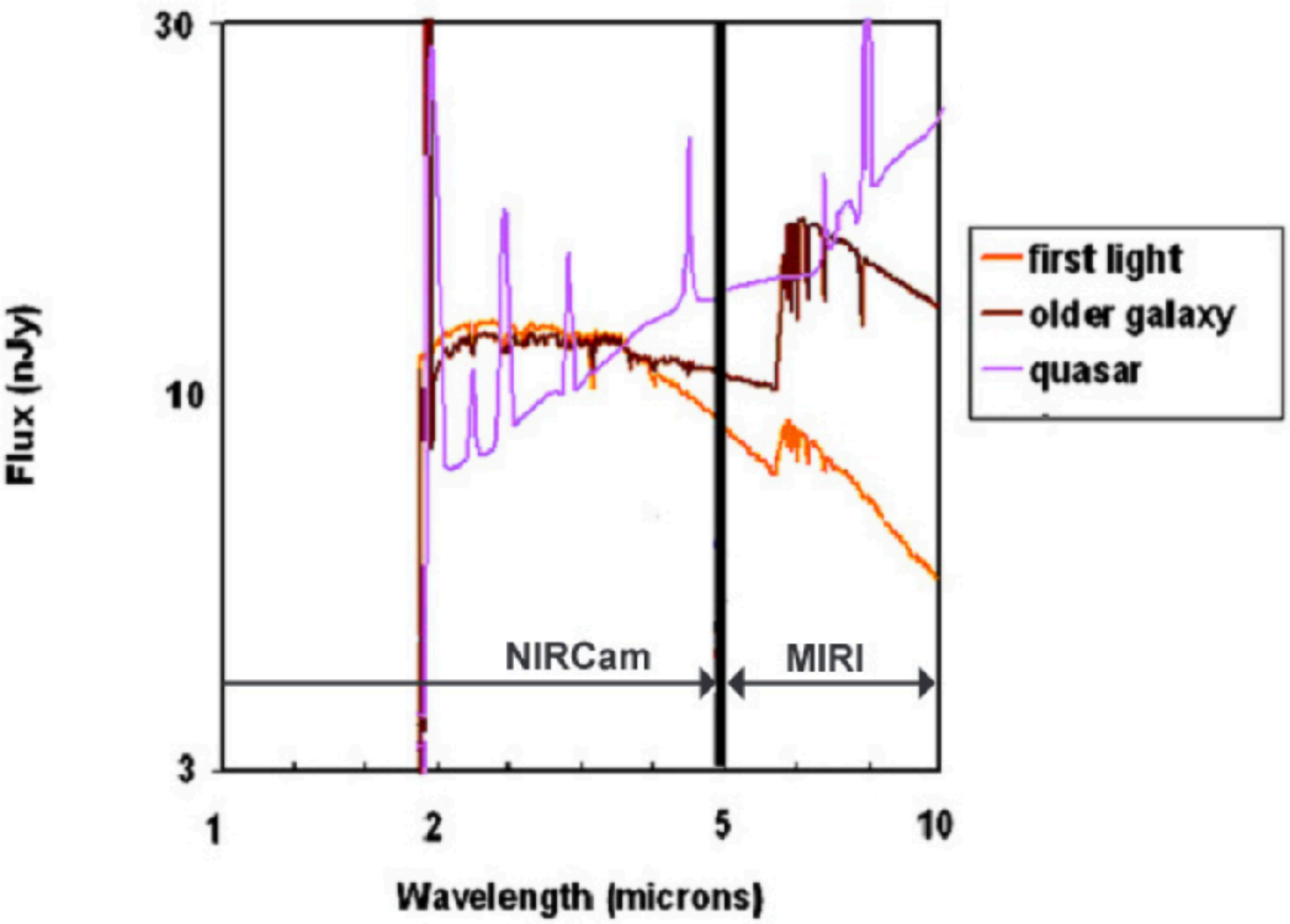


- Mid-Infrared (5-28 μm) Imaging and Spectroscopy
- Earliest stars and galaxies
- Stellar populations in nearby galaxies
- Young stars in Milky Way
- Kuiper Belt objects
- Circumstellar disks and planets



Earliest Galaxies

Few hundred Myr - 1 Gyr after Big Bang



Physics

- Stellar evolution properties; light new particle interactions (8.3)
- High-redshift sources (9.2.1)

EuCAPT White Paper

Opportunities and Challenges for Theoretical Astroparticle Physics in the Next Decade

EuCAPT

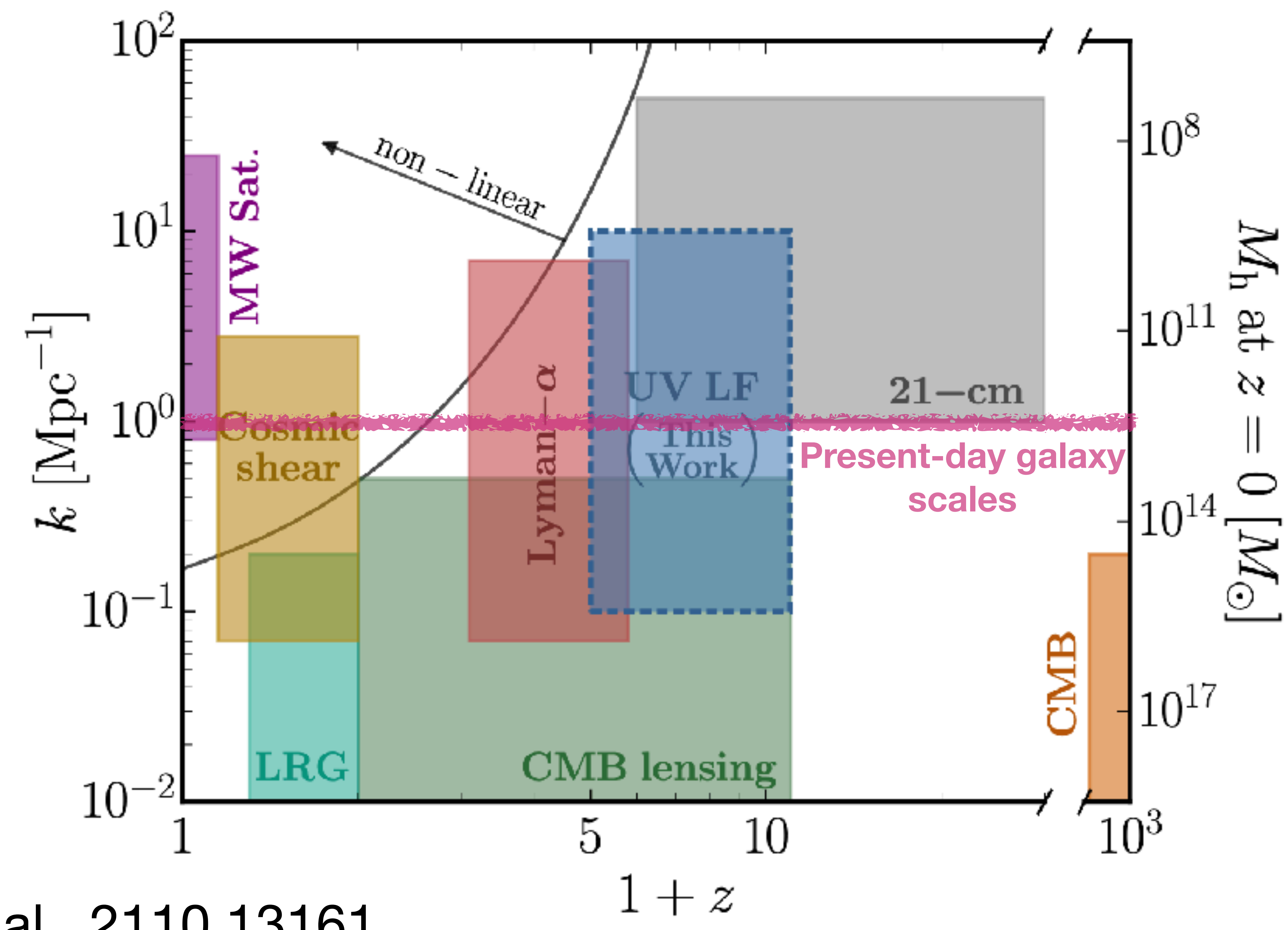
arXiv:2110.10074

The First Stars and Galaxies

- Before the first stars turned on, a primordial night of hydrogen gas and dark matter ruled the universe - the dark ages. Gravity attracted gas and dark matter together, until stars and galaxies started lighting up the universe at cosmic dawn, in turn gradually ionizing the sea of hydrogen gas
- Unique information about the big bang, gravity, dark matter, early dark energy and other exotic physics is imprinted in vast 3D atlases of stars, black holes, galaxies and hydrogen gas during these epochs - hidden from view in the later universe
- Observations of the first stars, black holes and galaxies (optical/NIR/IR) and gas observables (radio) can unveil the secrets of this final frontier

Early-Universe Physics

Early-Universe structure and gas observables allow a unique, clean view of potentially exotic physics on the smallest scales - “eaten” by baryonic processes at later times

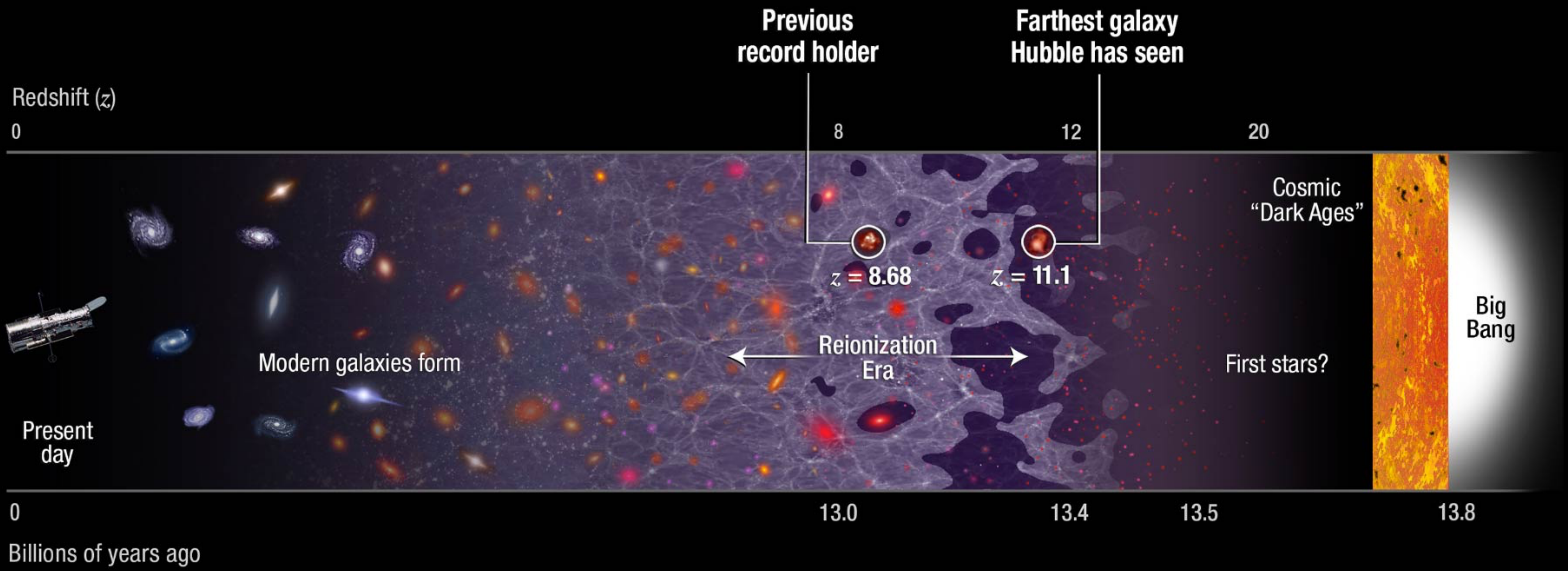


Sabti et al., 2110.13161

Broad Features

- Probes on small scales
  - Population III stars
  - Black holes (primordial, direct-collapse)
  - Quasars
  - Galaxies

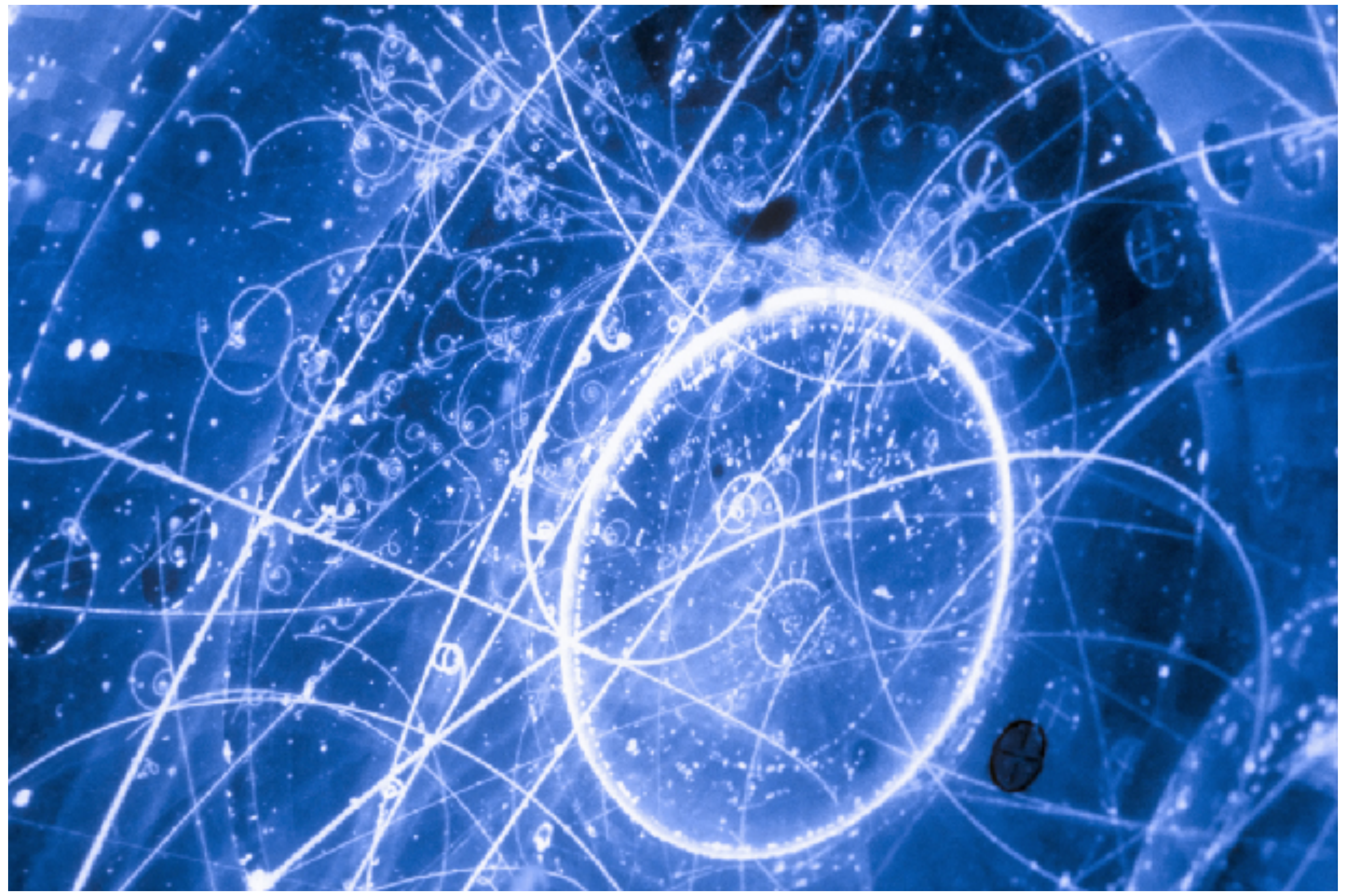
- Models with features on small scales
  - Free-streaming suppression due to light degrees of freedom
  - Features on small scales due to e.g. primordial black hole formation mechanism
  - Non-Gaussian density fluctuation statistics due to inflationary mechanism
  - Novel physics in the early Universe: e.g. mixed / interacting dark matter, early dark energy, extensions to General Relativity


Previous record holder
Farthest galaxy Hubble has seen
Redshift (z)
0
8
12
20
Cosmic "Dark Ages"
z = 8.68
z = 11.1
Big Bang
Modern galaxies form
Reionization Era
First stars?
Present day
0
13.0
13.4
13.5
13.8
Billions of years ago

Yung et al. 2019

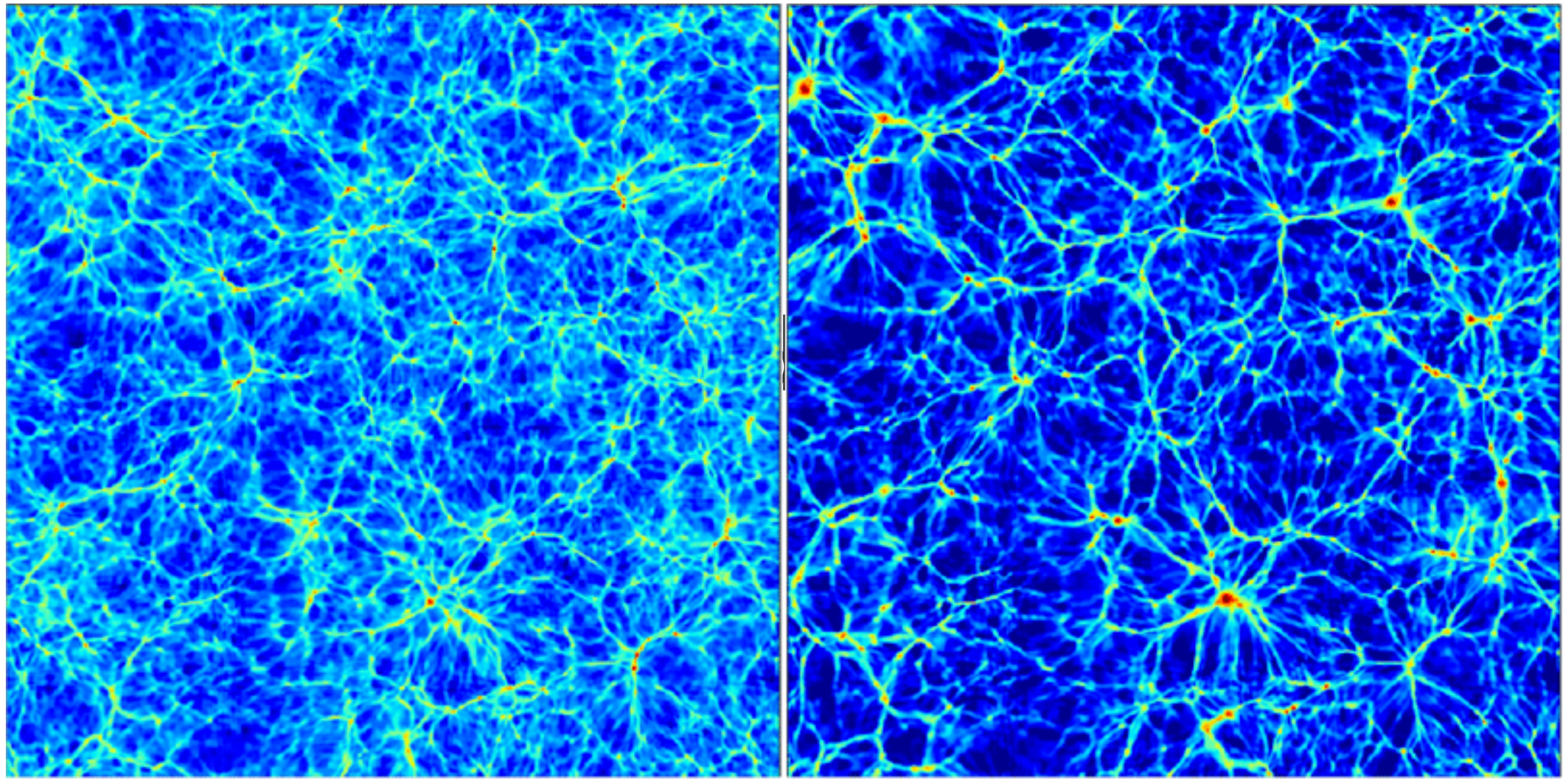
Light Dark Matter and Structure Formation

- May alter pre-recombination physics (relativistic, dark radiation) -> Hubble tension
- Light particles like warm dark matter (keV) have large thermal velocities and can free-stream over large distances in and out of gravitational potentials, since they also have very weak non-gravitational interactions
- They are generally not gravitationally bound to galaxies
- The formation of halos/galaxies on scales smaller than the mean-free path of the particles will be suppressed accordingly



Light Dark Matter and Structure Formation

Massive neutrinos　　　　Massless neutrinos



Simulations

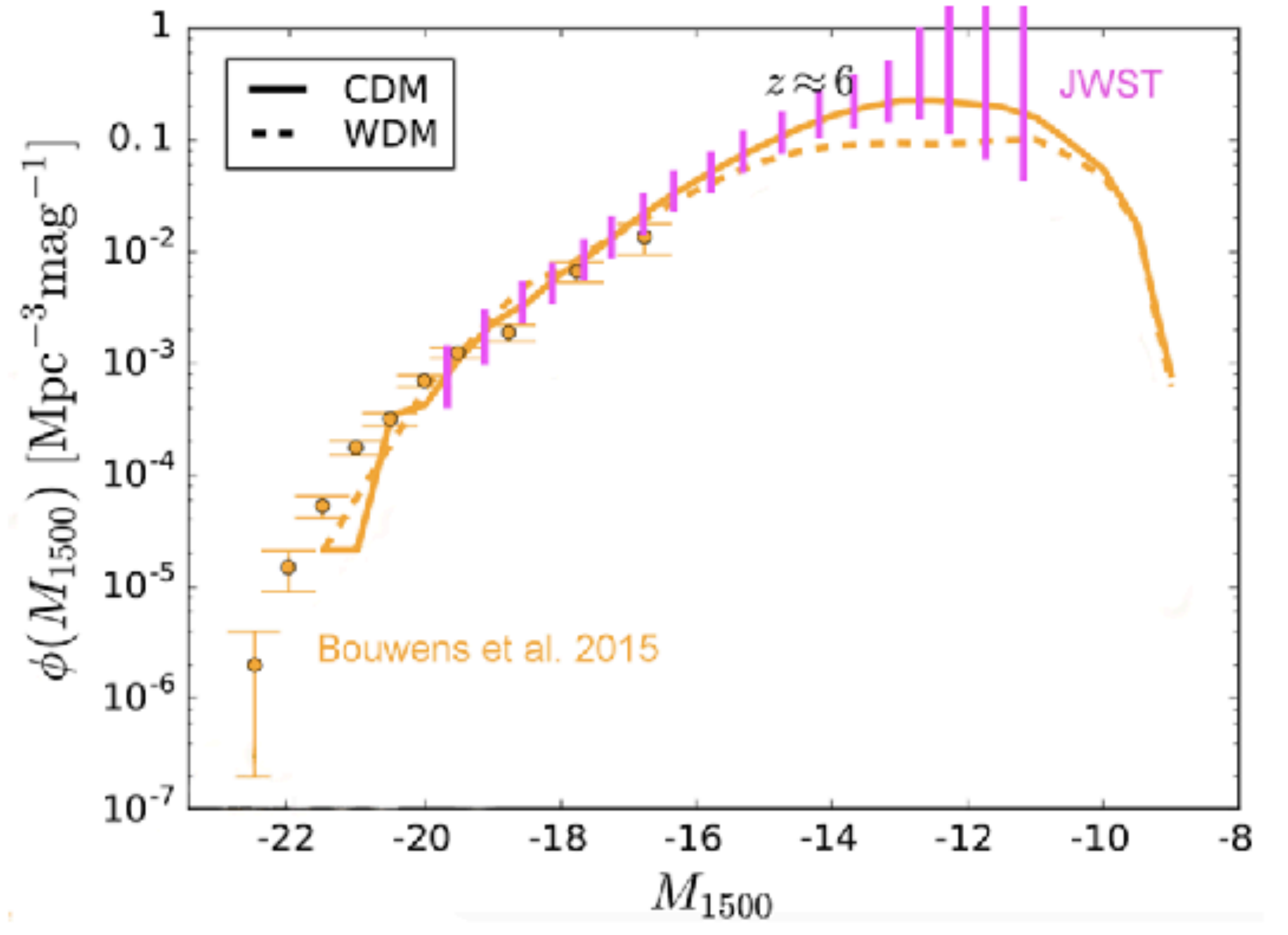
The lighter the particle, the larger the mean-free path, the less structure on small scales

Light Dark Matter Prevents Galaxy Formation

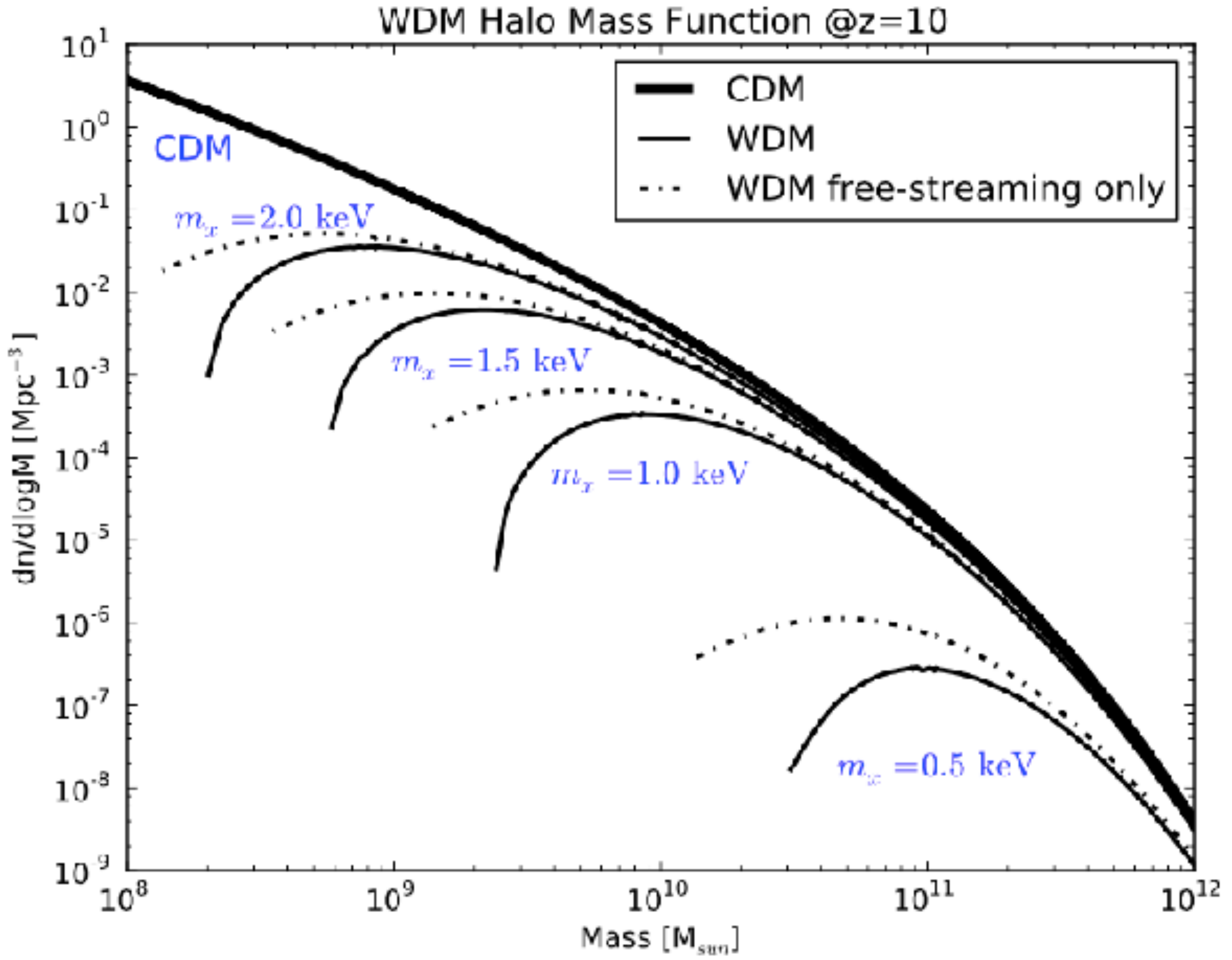
-> Star formation starts later, in more massive halos, and proceeds faster, than in CDM

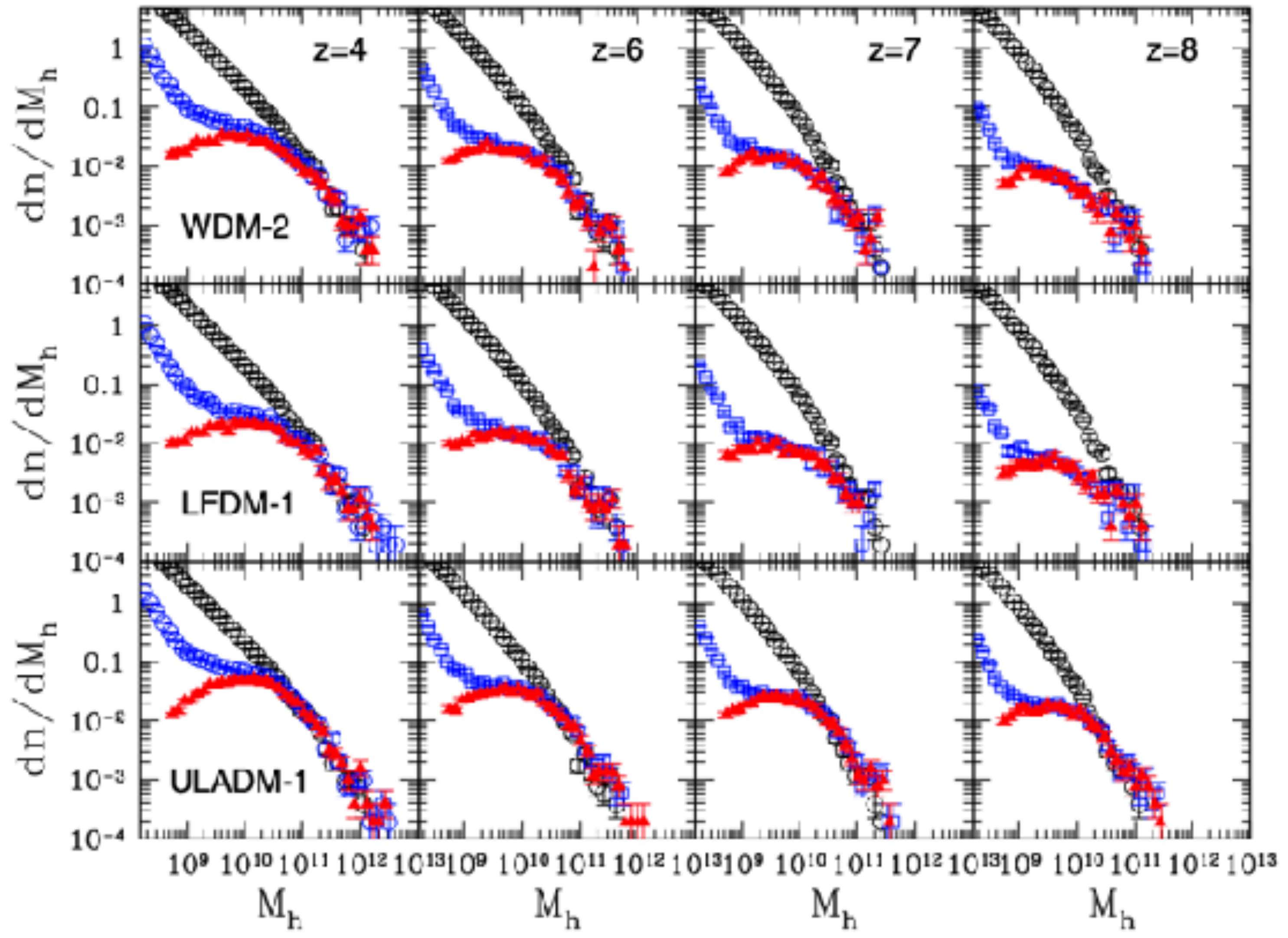
-> Correlation function of galaxies / sources tighter, due to more massive halos

-> Additional indirect feedback effects



Bode+ 2001, Pacucci+2013

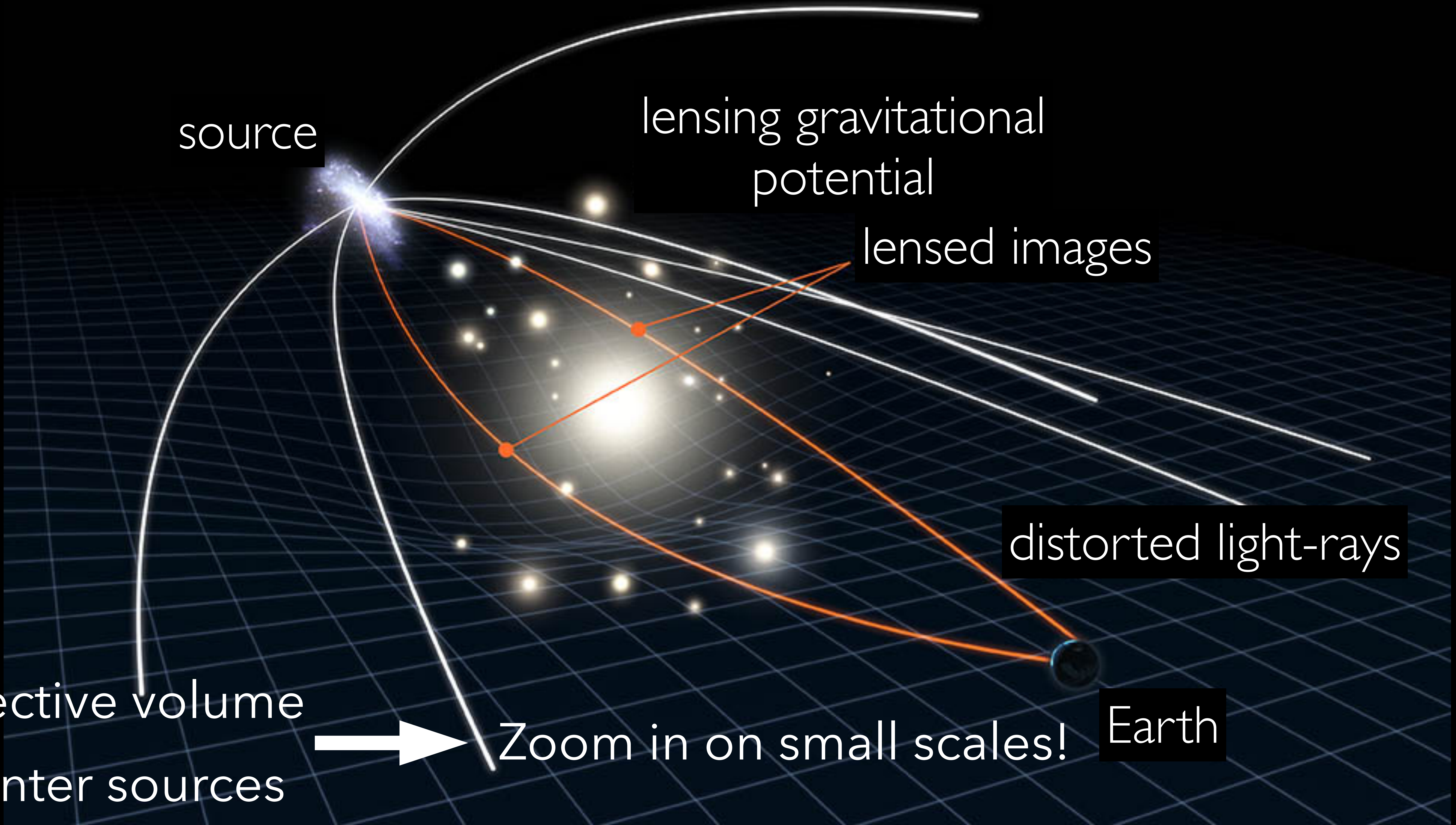




Corasaniti et al. 2017

GRAVITATIONAL LENSING

Magnifies and brightens distant, faint sources

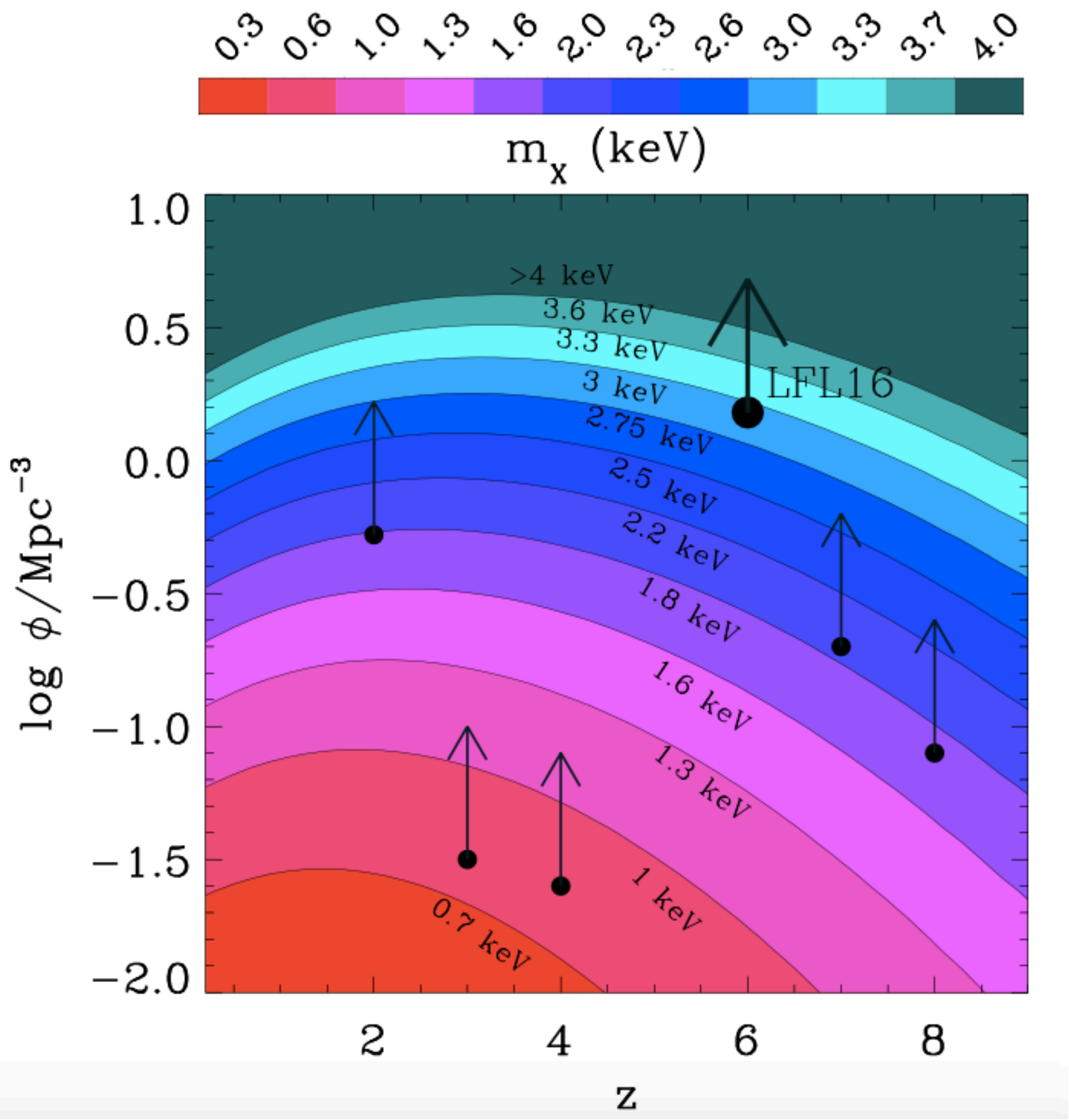


Reduces effective volume

Pushes to fainter sources

→ Zoom in on small scales!

Constraints on WDM mass from 167 z~6 galaxies

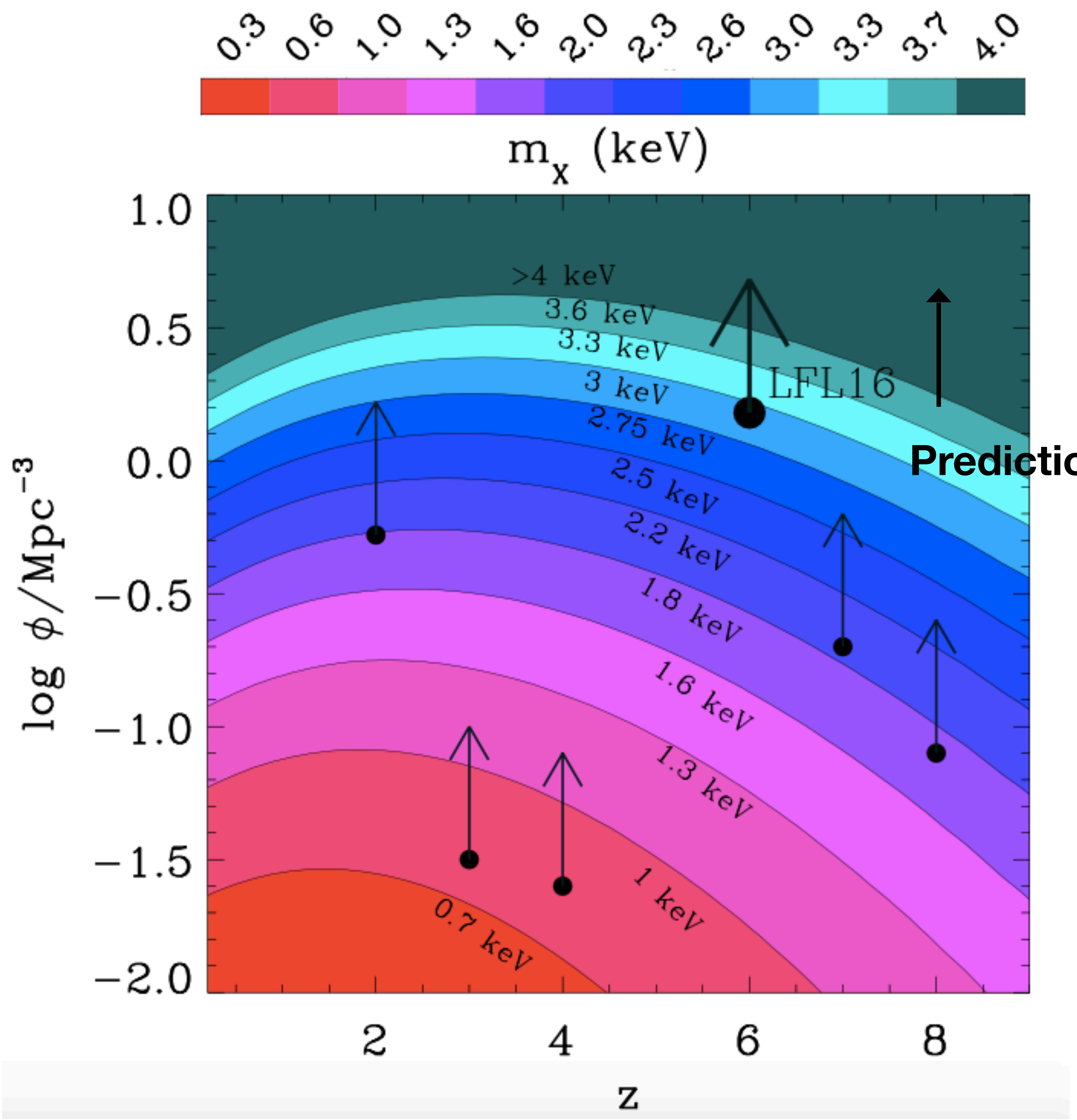


Hubble Frontier Fields

m_{WDM} > 2.4 keV (95%)

Menci+2016

JWST UD Lensing z = 8



Prediction: JWST UD lensing

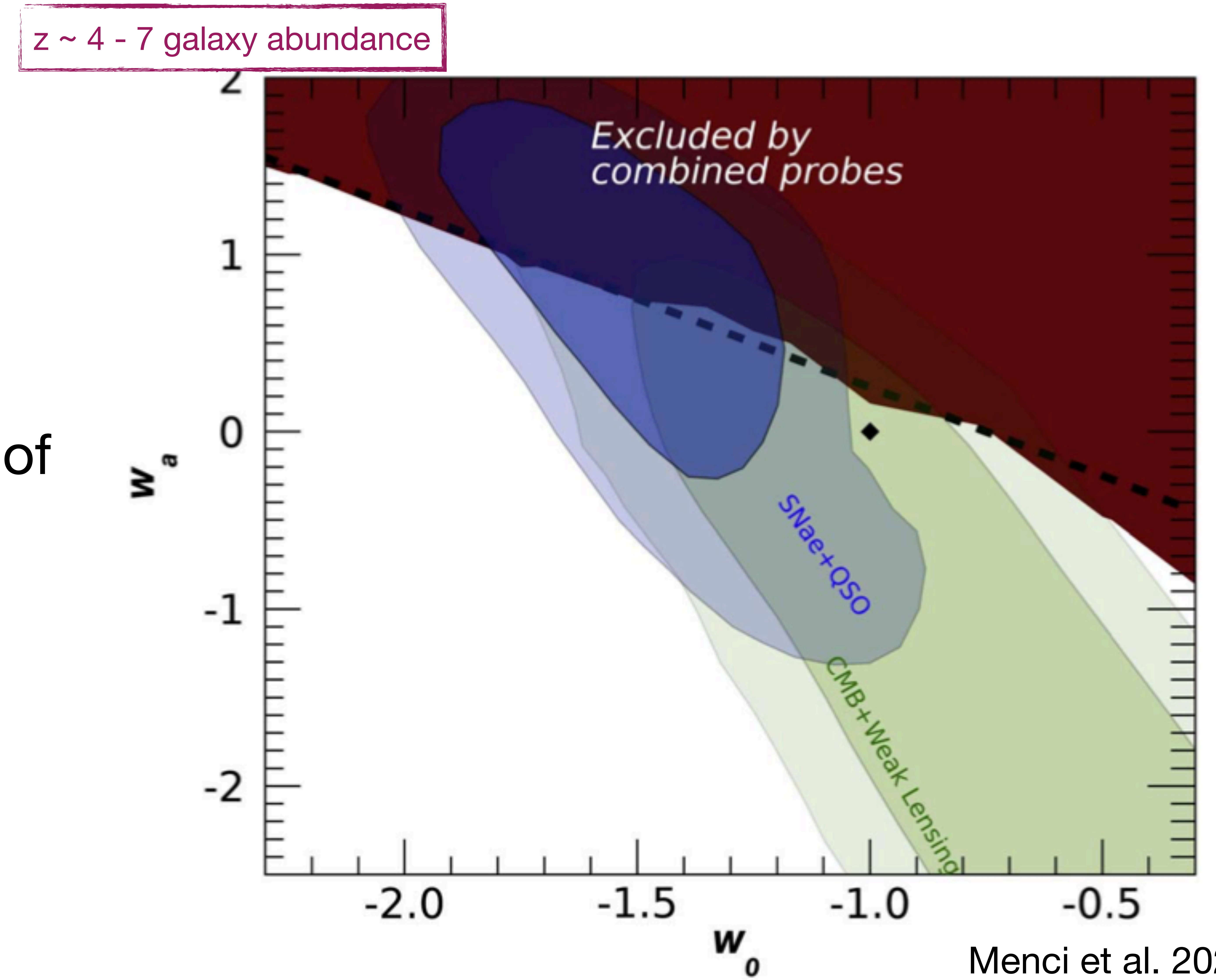
m_{WDM} > 3.5 keV (68%)

UD ($m_{\rm lim} = 32.0$)
~ 40 arcmin^2

Sahlén, Pacucci & Mesinger, in prep.

Evolving Dark Energy Models

- Influences expansion and gravitational growth histories
- E.g. Early Dark Energy could influence pre-recombination physics and relativistic degrees of freedom —> Hubble tension



Menci et al. 2020

http://galaxymc.cloud

GALAXYMC

galaxymc.cloud v1.0p1 / M. Sahlén, Astronomy and Space Physics, Uppsala University 2021.
Paper I version. Computes galaxy UV luminosity functions based on the Sahlén & Zackrisson 2021 model.

Status: *v1.0p1 in normal operation.*

SNIC Science Cloud

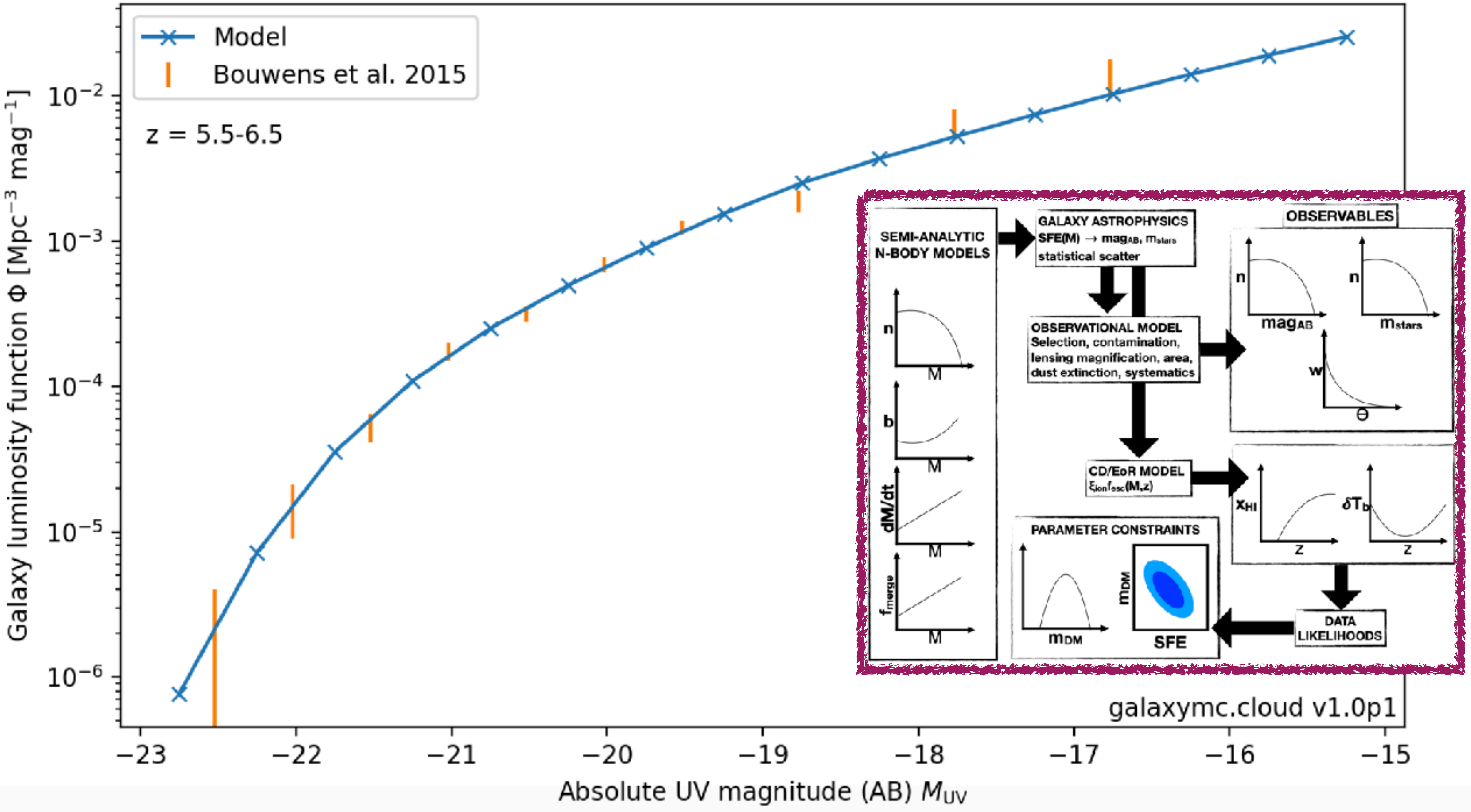
Compute

Cosmology

Ω_m	0.298
Ω_b	0.0412
H_0 [km/s/Mpc]	73.48
σ_8	0.813
n_s	0.9649

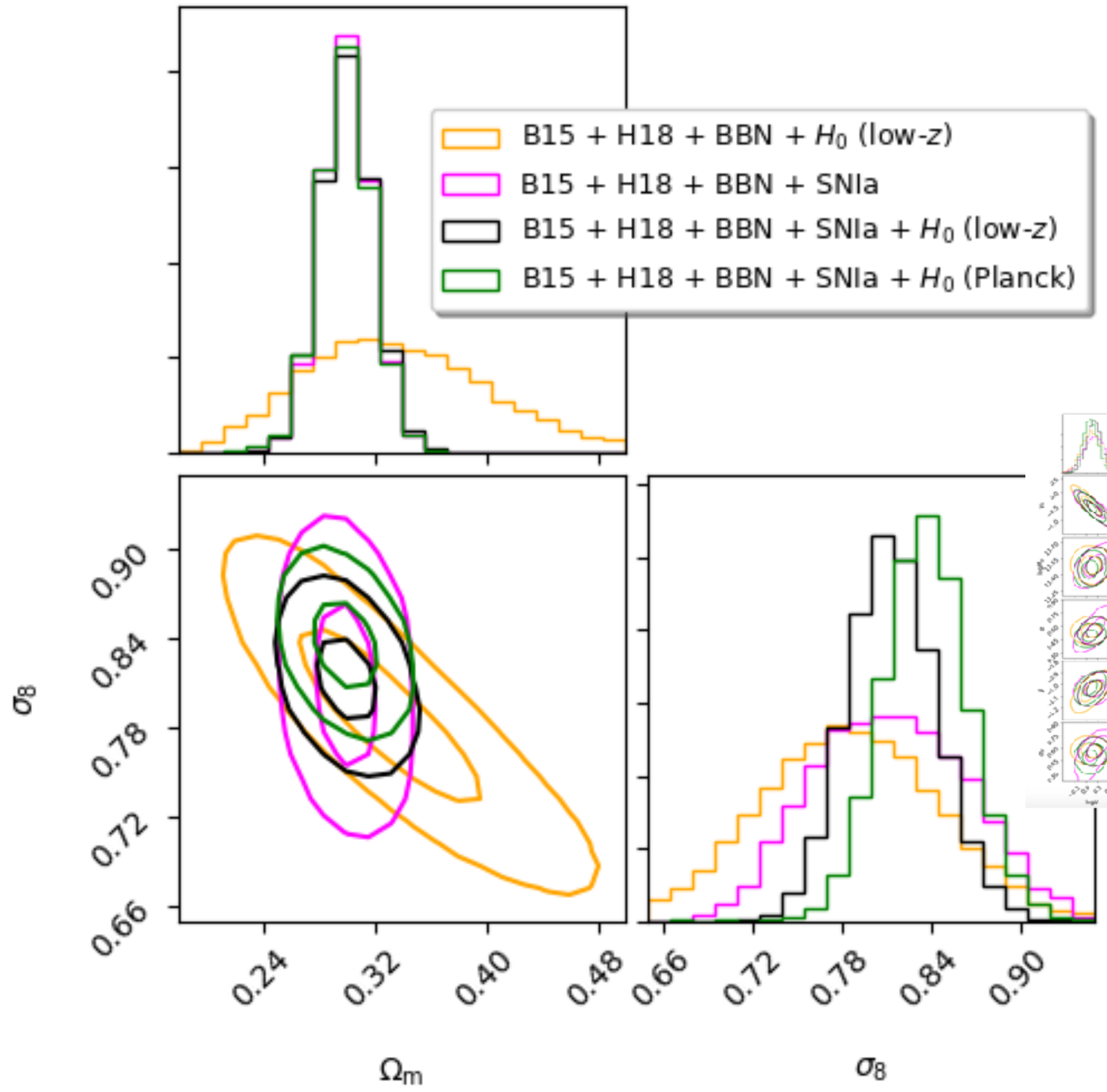
Star formation

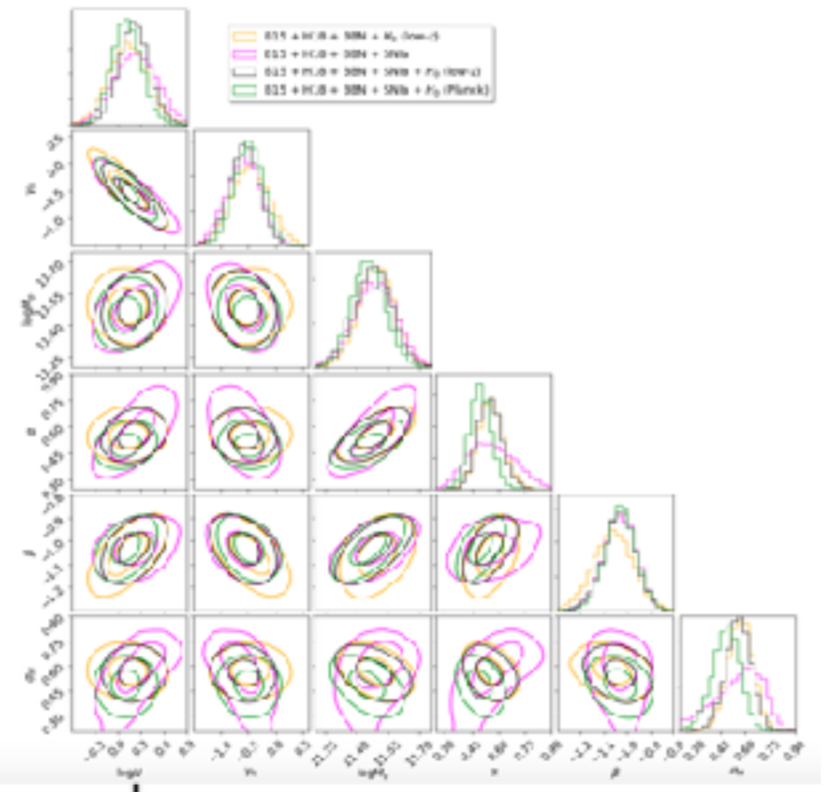
log N	0.21
γ_N	-0.58
log M_p	11.48
α	0.55
γ_α	0.0
β	-1.03



Download plot data

Testing Cosmology and Astrophysics Models





arXiv:2105.05098

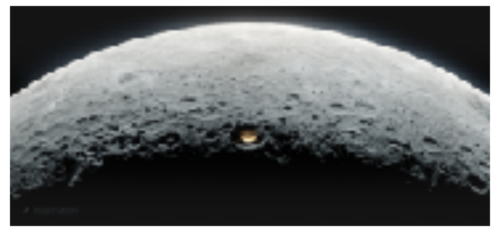
The First Galaxies and IGM

- Combine observations from future optical/infrared and radio telescopes to help answer questions about early-Universe physics:
  - How did the Universe begin?
  - Does gravity behave the same in the early and late epochs of the Universe?
  - What is Dark Matter made of?
  - Is there new exotic physics?
  - When and how did the first stars, black holes and galaxies form? What are their properties?
  - How did the vast cosmic reservoirs of hydrogen gas become ionized in the early Universe?

2027-2080: SKA Observatory
The square-kilometre-size radio telescope array across multiple continents will create detailed 3D atlases of matter back to the first hundred million years.

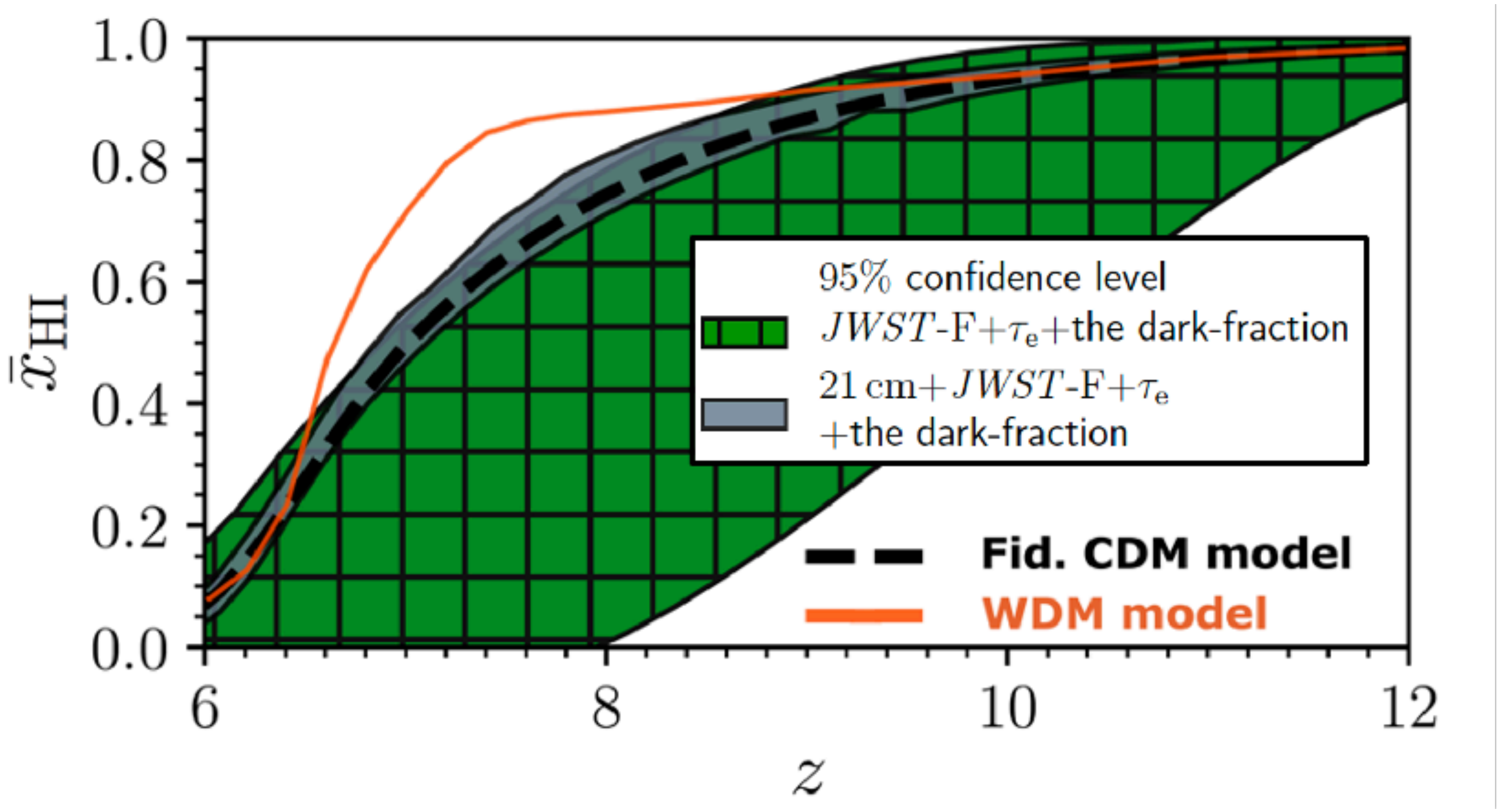
SKAO

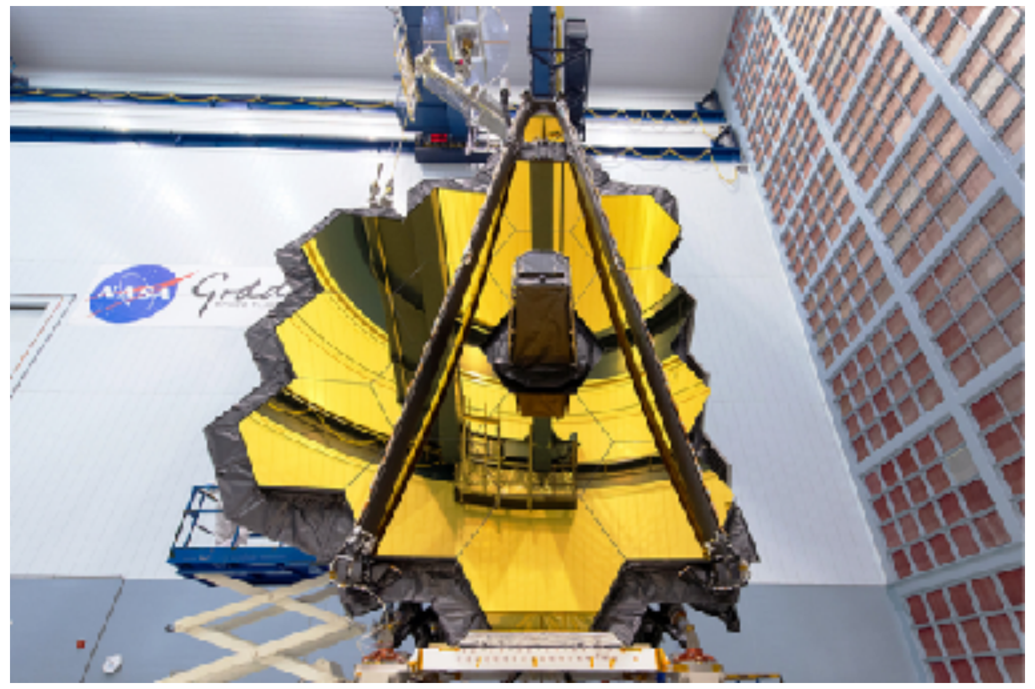
2030s: Lunar Radio Telescopes



Current and Future Work

- Full modelling of galaxy correlation function
- Inclusion of non-standard dark matter models
- Integration of 21cm IGM modelling
- Galaxy + 21cm synergy statistics
- Machine learning emulator/ accelerator





JWST CEERS Survey (ERS)	100 sq. arcmin.	~29.5 mag AB	7 – 13	20-80, ~5 - 50 z > 10
JWST GLASS (ERS) **lensing**	~10 sq. arcmin.	~29.5 mag AB	7 – 13+	350 typical/faint ~9 z > 10
JWST Medium-Deep Fields (GTO) **lensing**	240 sq. arcmin.	28 mag AB	6 – 12	~100-200

Rymdstyrelsen
Swedish National Space Agency

CARL TRYGGERS STIFTELSE
FÖR VETENSKAPLIG FORSKNING

Observational Plans

https://www.stsci.edu/jwst/science-execution/approved-programs

STScI | SPACE TELESCOPE SCIENCE INSTITUTE

SEARC

Home > James Webb Space Telescope > Science Execution

Programmatic Categories of JWST Science Observations

- General Observer (GO) Programs: Observations and archival research proposed by the community and selected by peer review.
- Director's Discretionary Early Release Science (DD-ERS) Programs: Observations to be executed within the first five months of science operations and immediately released to the community.
- Guaranteed Time Observations (GTO) Programs: Observations defined by members of the instrument and telescope science teams, as well as a number of interdisciplinary scientists.
- Calibration Programs: Observations used to calibrate the science instruments in support of all the other science programs.

Director's Discretionary Early Release Science Programs

To realize the James Webb Space Telescope's full science potential, it is imperative that the science community quickly learns to use its instruments and capabilities. To get the community up to speed, STScI and the JWST Advisory Committee developed the Director's Discretionary-Early Release Science (DD-ERS) program.

The DD-ERS observations will take place during the first 5 months of JWST science operations, following the 6-month commissioning period. The program selections were made in November 2017 and represent six science categories.

To view details about a specific program, select a science category below, then click the Program ID. For a description of the program and its expected impact on the community, click the Program Title instead.

AR

Archival Research

ERS Programs have no exclusive access period and can be used as a basis for GO Cycle 1 Archival Research (AR) Proposals.

Galaxies and Intergalactic Medium

[–]

ID	Program Title	PI & Co-PIs	Instruments
1324	Through the Looking GLASS: A JWST Exploration of Galaxy Formation and Evolution from Cosmic Dawn to Present Day	**PI:** Tommaso Treu (University of California - Los Angeles)	NIRCam NIRISS NIRSpec
1328	A JWST Study of the Starburst-AGN Connection in Merging LIRGs	**PI:** Lee Armus (California Institute of Technology) **Co-PI:** Aaron Evans (University of Virginia)	MIRI NIRCam NIRSpec
1345	The Cosmic Evolution Early Release Science (CEERS) Survey	**PI:** Steven Finkelstein (University of Texas at Austin)	MIRI NIRCam NIRSpec
1355	TEMPLATES: Targeting Extremely Magnified Panchromatic Lensed Arcs and Their Extended Star Formation	**PI:** Jane Rigby (NASA Goddard Space Flight Center) **Co-PI:** Joaquin Vieira (University of Illinois)	MIRI NIRCam NIRSpec

Stellar Physics

[–]

ID	Program Title	PI & Co-PIs	Instruments
1288	Radiative Feedback from Massive Stars as Traced by Multiband Imaging and Spectroscopic Mosaics	**PI:** Olivier Berne (Universite de Toulouse) **Co-PIs:** Emilie Habart (Institut d'Astrophysique Spatiale) and Els Peeters (University of Western Ontario)	MIRI NIRCam NIRSpec
1309	IceAge: Chemical Evolution of Ices during Star Formation	**PI:** Melissa McClure (Universiteit van Amsterdam) **Co-PIs:** Abraham C. Boogert (University of Hawaii) and Harold Linnartz (Universiteit Leiden)	MIRI NIRCam NIRSpec
1349	Establishing Extreme Dynamic Range with JWST: Decoding Smoke Signals in the Glare of a Wolf-Rayet Binary	**PI:** Ryan Lau (ISAS, Japan Aerospace Exploration Agency)	MIRI NIRISS

Stellar Populations

[–]

ID	Program Title	PI & Co-PIs	Instruments
1334	The Resolved Stellar Populations Early Release Science Program	**PI:** Daniel Weisz (University of California - Berkeley)	NIRCam NIRISS

General Observer Programs in Cycle 1

The Cycle 1 General Observers (GO) program provides the worldwide astronomical community with the first extensive opportunity to make observations with JWST. Approximately 6,000 hours were awarded to observing programs using the full suite of JWST instrumentation. Scientists also proposed for archival analysis of data from DD ERS programs and public GTO programs, theoretical investigations, and the development of software tools relevant to JWST observations. Science observations will begin following a 6-month commissioning period after launch.

To view details about a specific program, select a category below, then click the Program ID. For reference:

- Small programs: ≤ 25 hours
- Medium programs: > 25 and ≤ 75 hours
- Large programs: >75 hours

Galaxies

[-

? Filter Table

ID	Program Title	PI & Co-PIs	Exclusive Access Period (months)	Prime/ Parallel Time (hours)	Instrument/ Mode	Type
1433	Physical Properties of the Triply-Lensed z = 11 Galaxy	**PI:** Dan Coe	0	11.3	NIRCam/Imaging NIRSpec/MOS	GO
1567	Early Galaxy Assembly Uncovered with ALMA and JWST: A Remarkably UV and [CII] Bright, Strongly Lensed Sub-L* Galaxy at z=6.072	**PI:** Seiji Fujimoto	12	12.3	NIRCam/Imaging NIRSpec/IFU	GO
1571	PASSAGE– Parallel Application of Slitless Spectroscopy to Analyze Galaxy Evolution	**PI:** Matthew Malkan	0	0/591	NIRISS/WFSS	GO, Pure Parallel
1572	Mapping, Resolving and Penetrating into the Dusty Spiderweb Protocluster with Unique Pa-beta Imaging	**PI:** Helmut Dannerbauer **Co-PI:** Yusei Koyama	12	3.6	NIRCam/Imaging	GO
1895	FRESCO: The First Reionization Epoch Spectroscopic COmplete Survey	**PI:** Pascal Oesch	0	53.1	NIRCam/WFSS	GO
1914	The AURORA Survey: First Direct Metallicity Calibrations at High Redshift	**PI:** Alice Shapley **Co-PI:** Ryan Sanders	12	63.8	NIRSpec/MOS	GO
1933	Anatomy of an Ionized Bubble at z=6.6: Which Galaxies Reionized the Universe?	**PI:** Jorryt Matthee **Co-PI:** Rohan Naidu	12	18.2	NIRCam/WFSS	GO
1963	UDF Medium Band Survey: Using H-alpha Emission To Reconstruct Ly-alpha Escape during the Epoch of Reionization	**PI:** Christina Williams **Co-PIs:** Michael Maseda and Sandro Tacchella	0	20.4/15.5	NIRCam/Imaging	GO
1991	Lifting the Veil on the Most Obscured Galaxies in the Universe	**PI:** George Privon	12	8.5	MIRI/MRS NIRSpec/IFU	GO
2079	The Webb Deep Extragalactic Exploratory Public (WDEEP) Survey: Feedback in Low-Mass Galaxies from Cosmic Dawn to Dusk	**PI:** Steven Finkelstein **Co-PIs:** Casey Papovich and Norbert Pirzkal	0	121.7/96.4	NIRISS/WFSS	GO, Treasury

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Stellar Physics and Stellar Types

1984	Fine-Tuned Search for Kilonova Emission in a Short Gamma-Ray Burst: Implications for Gravitational Wave Sources and r-Process Nucleosynthesis	**PI:** Edo Berger	0	11.9	NIRCam/Imaging NIRSpec/FS	GO, Disruptive ToO
2050	Mid-infrared Molecular Absorption in the Atmospheres of K Giants	**PI:** Gregory Sloan	12	5.3	MIRI/MRS	GO
2061	Nucleosynthesis, Astrophysics, and Cosmology with IR Observations of a Gravitational Wave Counterpart	**PI:** Ryan Foley	0	17.2	MIRI/Imaging NIRCam/Imaging NIRSpec/FS	GO, Disruptive ToO
2072	See Through Supernovae: Nebular Spectroscopy of Exploding White Dwarfs	**PI:** Saurabh Jha	0	19.8	MIRI/LRS NIRSpec/FS MIRI/MRS	GO, Non-Disruptive ToO
2091	Detecting the Synthesis of the Heaviest Elements with Photometry of a Kilonova in the Optically Thin Phase	**PI:** Maria Drout	0	9.3	NIRCam/Imaging MIRI/Imaging	GO
2114	MIR Spectroscopy of Type Ia Supernovae: The Key To Unlocking Their Explosions and Element Production	**PI:** Chris Ashall **Co-PIs:** Peter Hoeflich and Eddie Baron	0	21.1	MIRI/MRS	GO, Non-Disruptive ToO

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- Large programs: >75 hours

Large Scale Structure of the Universe

? Filter Table

ID	Program Title	PI & Co-PIs	Exclusive Access Period (months)	Prime/ Parallel Time (hours)	Instrument/ Mode	Type
1638	Securing the TRGB Distance Indicator: A Pre-Requisite for a JWST Measurement of H_0	**PI:** Kristen McQuinn	12	6.8/2	NIRCam/Imaging	GO
1727	COSMOS-Web: The JWST Cosmic Origins Survey	**PI:** Jeyhan Kartaltepe **Co-PI:** Caitlin Casey	0	207.8/81.3	NIRCam/Imaging	GO, Treasury
1794	100% Gain in Precision and Accuracy of H0 Measurement from JWST Stellar Kinematics of a Lens Galaxy	**PI:** Akin Yildirim **Co-PIs:** Sherry Suyu and Tommaso Treu	12	9.5	NIRSpec/IFU	GO
1871	The First Observations of the Ionizing Luminosity of Galaxies within the Epoch of Reionization	**PI:** John Chisholm	12	22.2	NIRSpec/MOS	GO
1995	Answering the Most Important Problem in Cosmology Today: Is the Tension in the Hubble Constant Real?	**PI:** Wendy Freedman **Co-PI:** Barry Madore	12	25.8/11.2	NIRCam/Imaging	GO

Guaranteed Time Observations Programs in Cycle 1

The JWST Guaranteed Time Observations (GTO) program is designed to reward scientists who helped develop the key hardware and software components or technical and inter-disciplinary knowledge for the observatory. The program provides a total of about 16% use of the observatory over the first 3 cycles of operation. The approved GTO programs are listed below organized by science topic.

To view details about a specific program, select a science category below, then click the Program ID.

AR

Archival Research

Programs with this icon have components that have no exclusive access period, and can be used as a basis for GO Cycle 1 Archival Research (AR) Proposals.

Deep Fields [–]

ID	Program Title	AR?	Principal Investigator	Instrument
1180	NIRCam-NIRSpec Galaxy Assembly Survey - GOODS-S - Part #1		Daniel Eisenstein (Harvard University)	NIRCam NIRSpec
1181	NIRCam-NIRSpec Galaxy Assembly Survey - GOODS-N		Daniel Eisenstein (Harvard University)	NIRCam NIRSpec
1207	MIRI in the Hubble Ultra-Deep Field		George Rieke (University of Arizona)	MIRI NIRSpec
1283	The MIRI HUDF Deep Imaging Survey		H.U. Norgaard-Nielsen (Danish Space Research Institute)	MIRI

Targeted Galaxies [–]

ID	Program Title	AR?	Principal Investigator	Instrument
1176	JWST Medium-Deep Fields -- Windhorst IDS GTO Program	AR	Rogier Windhorst (Arizona State University)	NIRCam NIRSpec

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