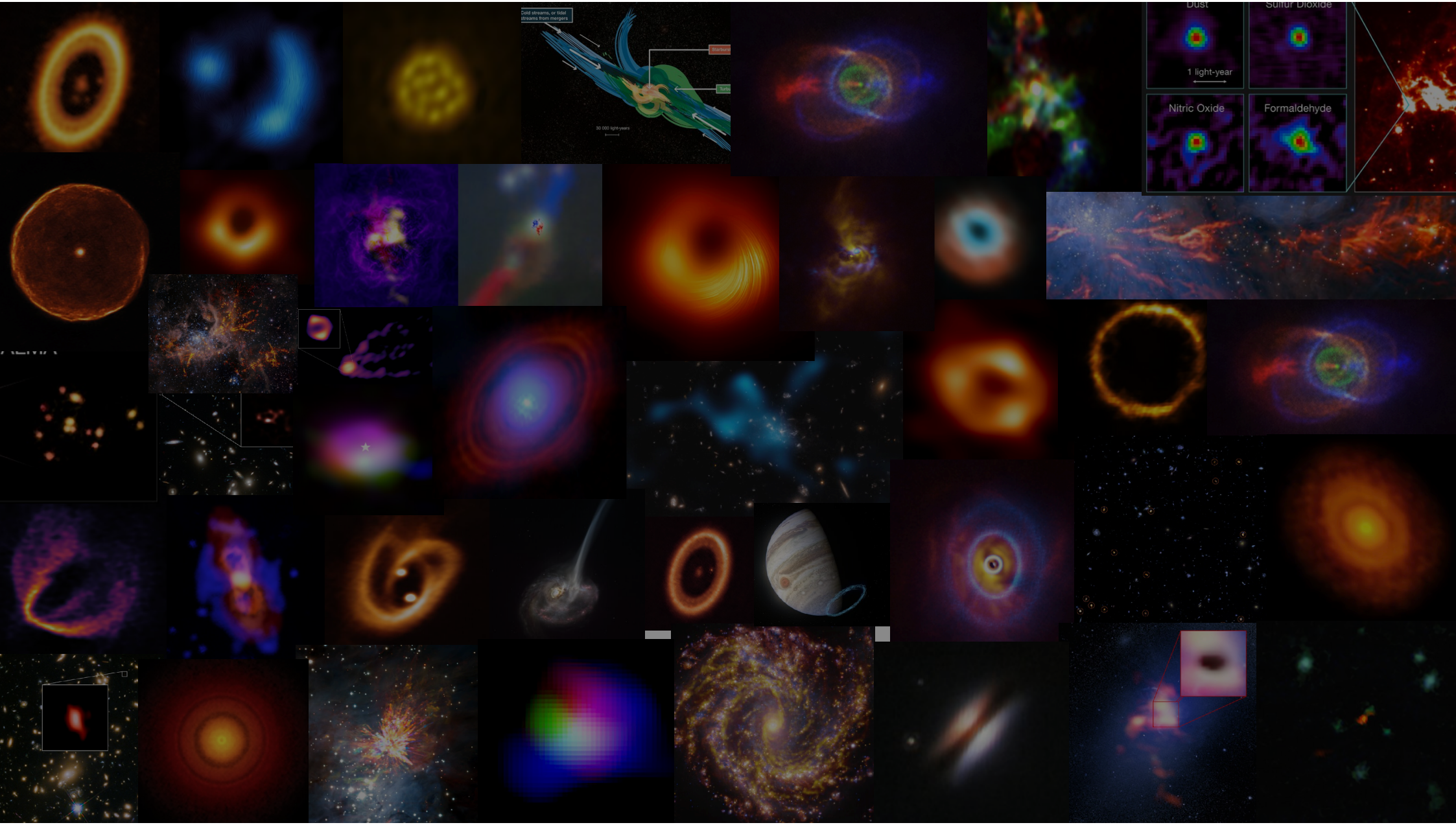
The high-definition future of mm/submm astronomy

Jacqueline Hodge (Leiden)

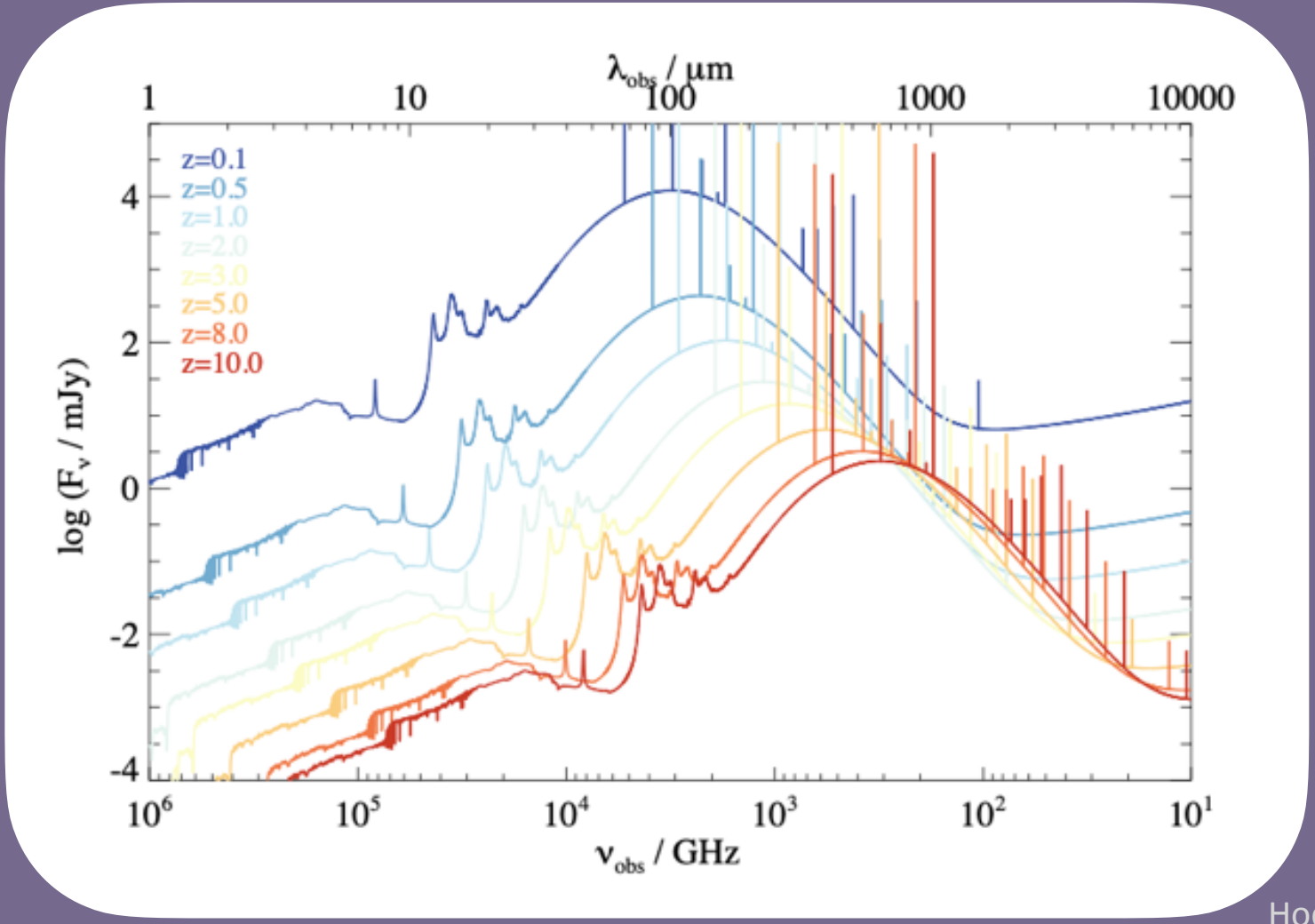
also on behalf of Stefano Facchini (Milano), Eva Schinnerer (MPIA), Gie Han Tan (TU Eindhoven), and the ALMA2040 initiative


Cold streams, or tidal streams from mergers
30 000 light-years
Dust
Sulfur Dioxide
1 light-year
Nitric Oxide
Formaldehyde

The Atacama Large (sub-)Millimeter Array (ALMA)

A recent analysis shows that currently, the impact factor for ALMA publications is larger than that of all other major astronomical facilities (Stoehr et al. 2026)*

Sub-mm provides essential access to the cold ISM



Hodge & da Cunha 2020

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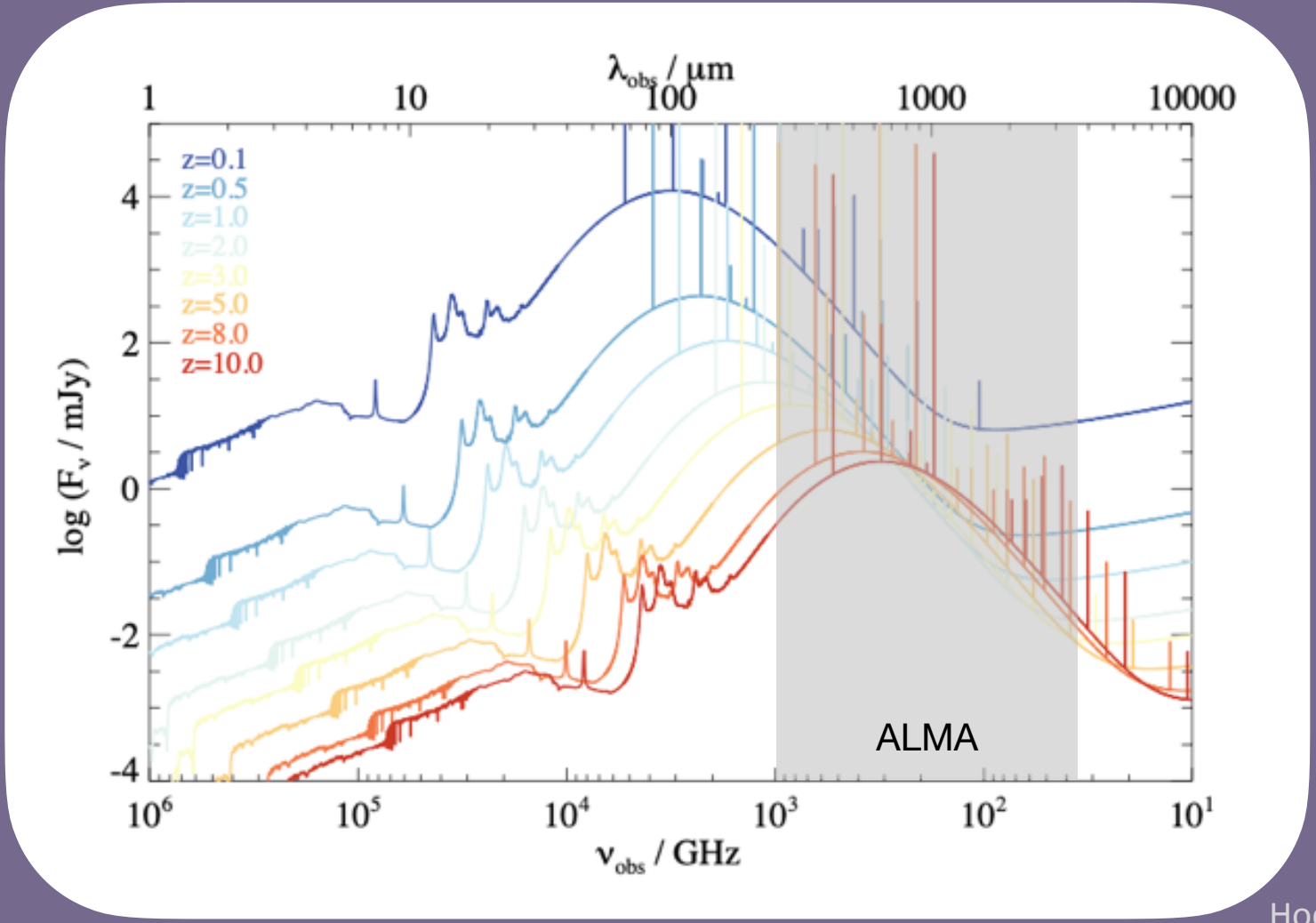
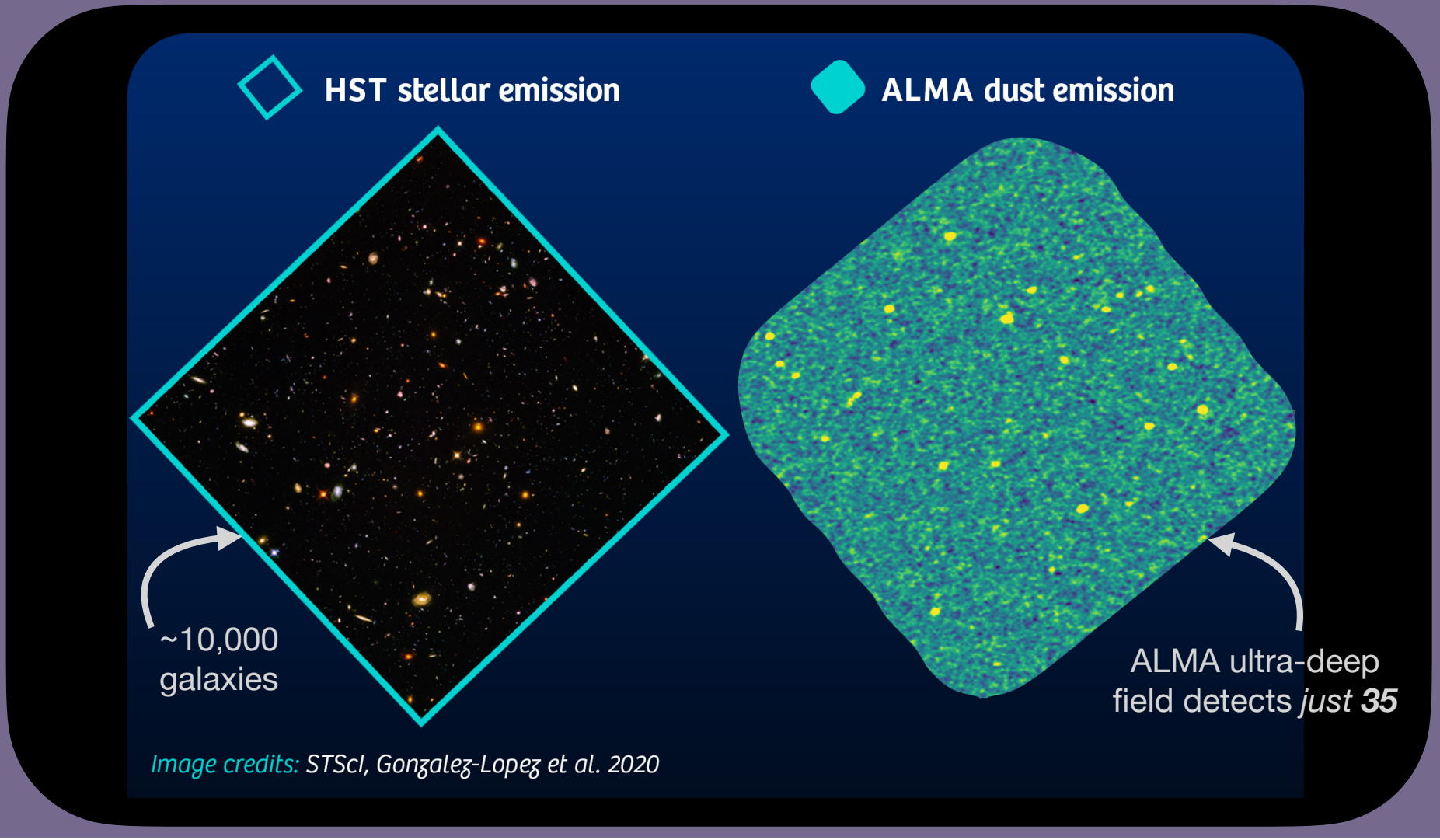


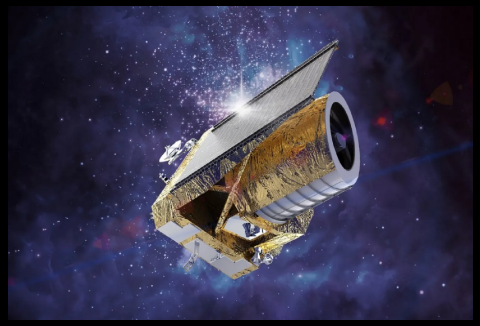
Hodge & da Cunha 2020

Even *before* JWST, the sub-mm was playing catch-up



And the next 15 years will widen the gap

Euclid

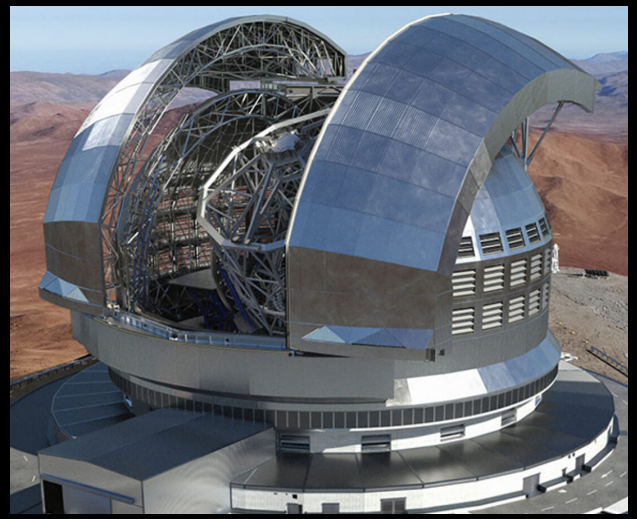


Optical-NIR telescope

Rubin

Optical-NIR telescope

ELT



Optical-MIR telescope

Roman

Optical-NIR telescope

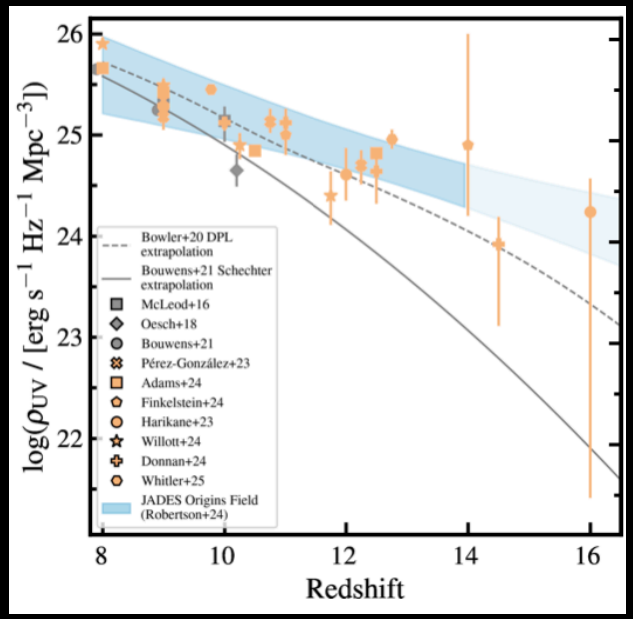
GMT

Optical-MIR telescope

JWST has opened a new window into the (early) universe

JWST has opened a new window into the (early) universe

Overabundance of galaxies at $z>10$



Stark et al. 2025

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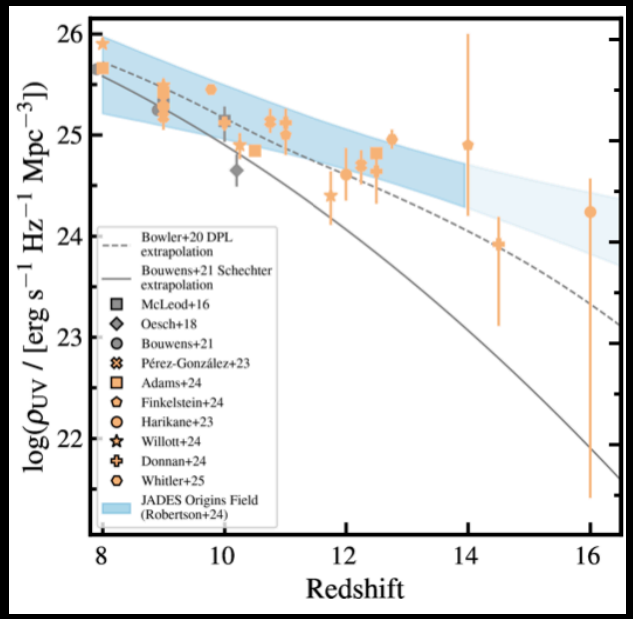
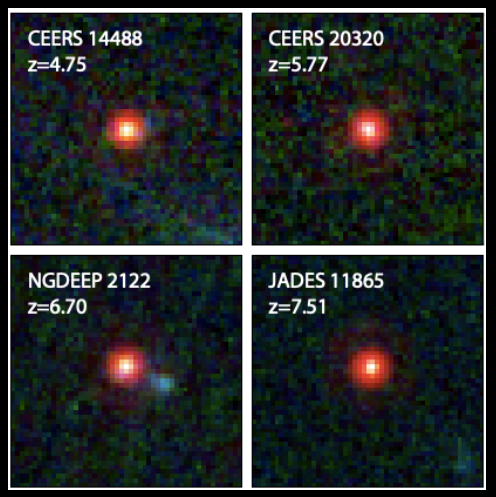


Stark et al. 2025

Heavily obscured black holes?



e.g., Kocevski et al. 2025

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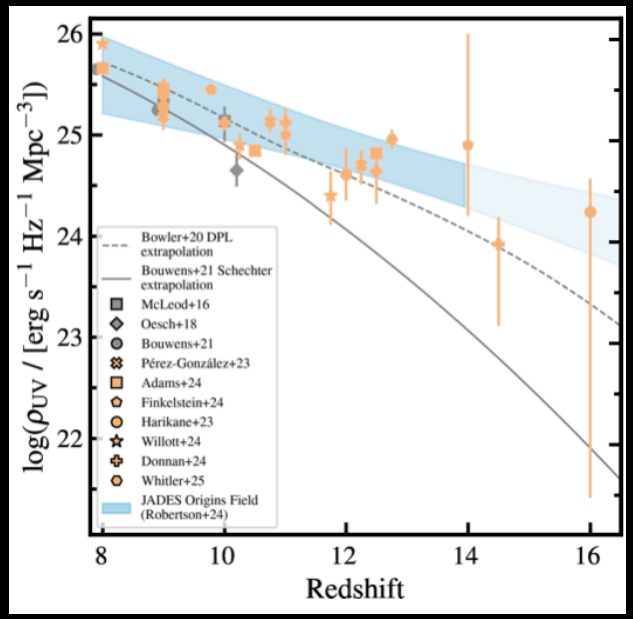

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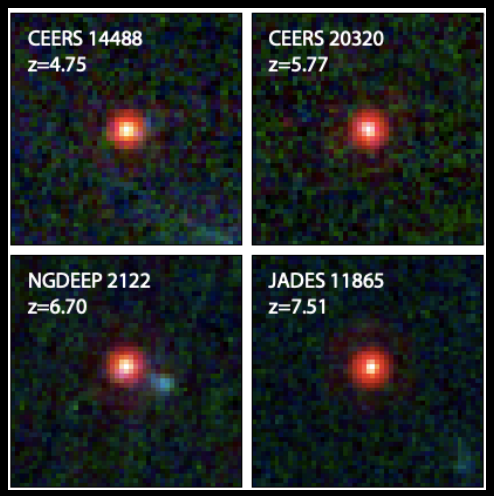

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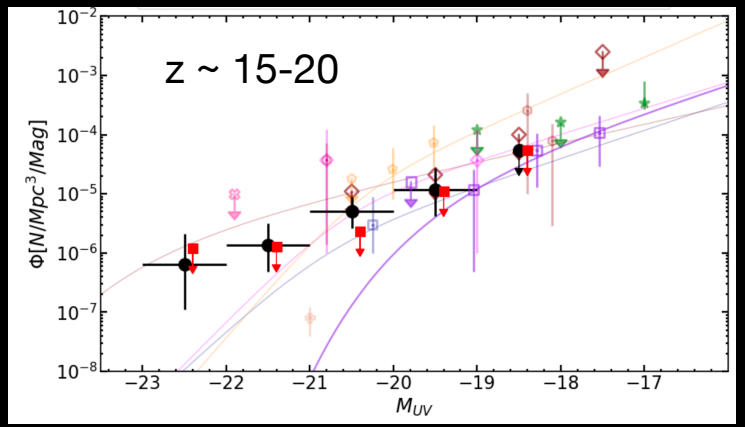
Galaxy candidates at ***z*>15**



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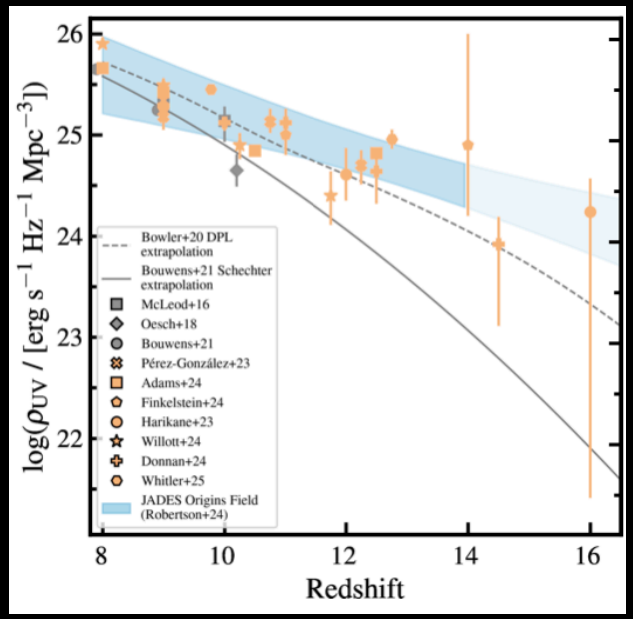

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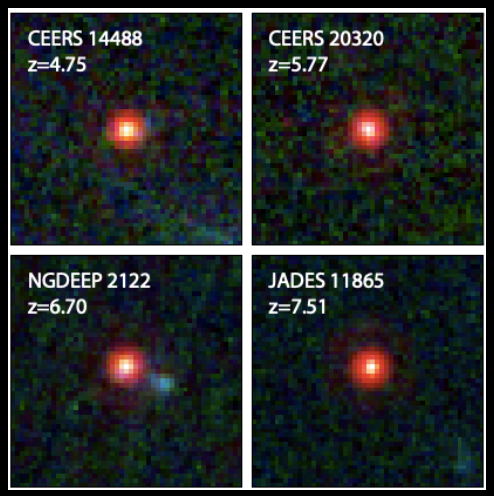

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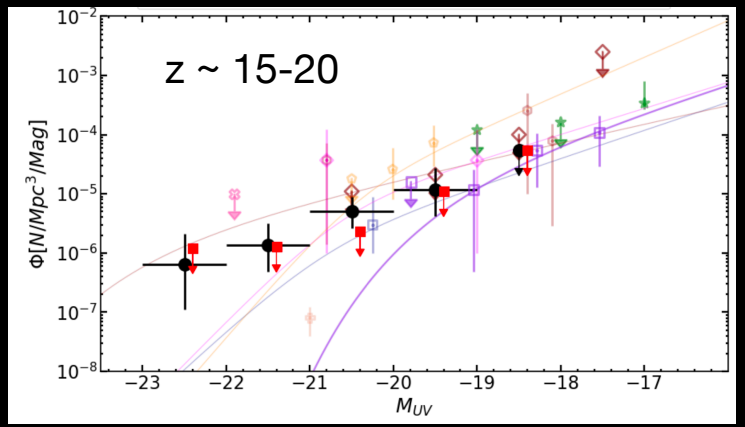
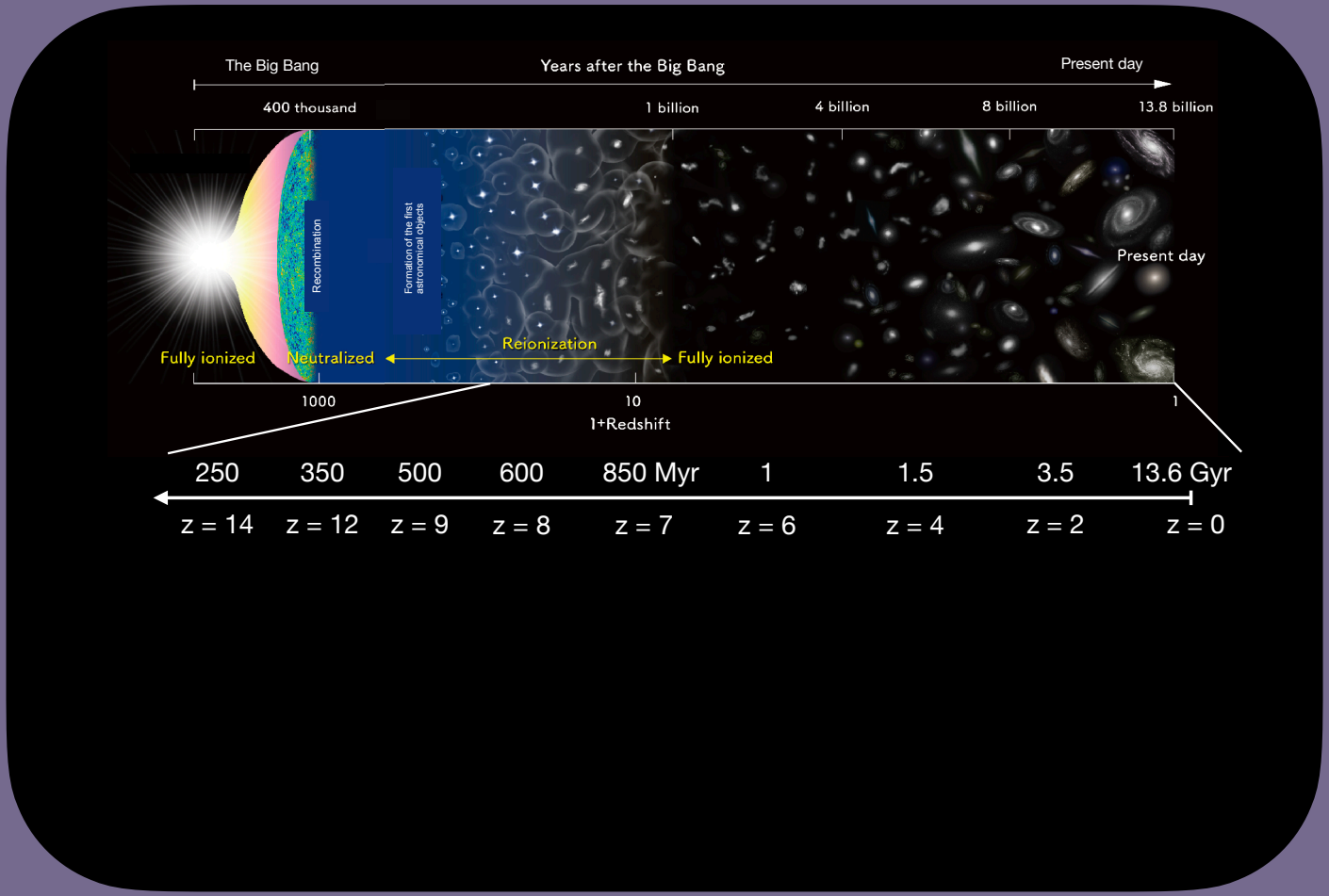


e.g., Castellano et al. 2025

Suggests extremely rapid evolution in early universe

How did the ***first galaxies*** form their stars?

Breaking the last cosmic frontier



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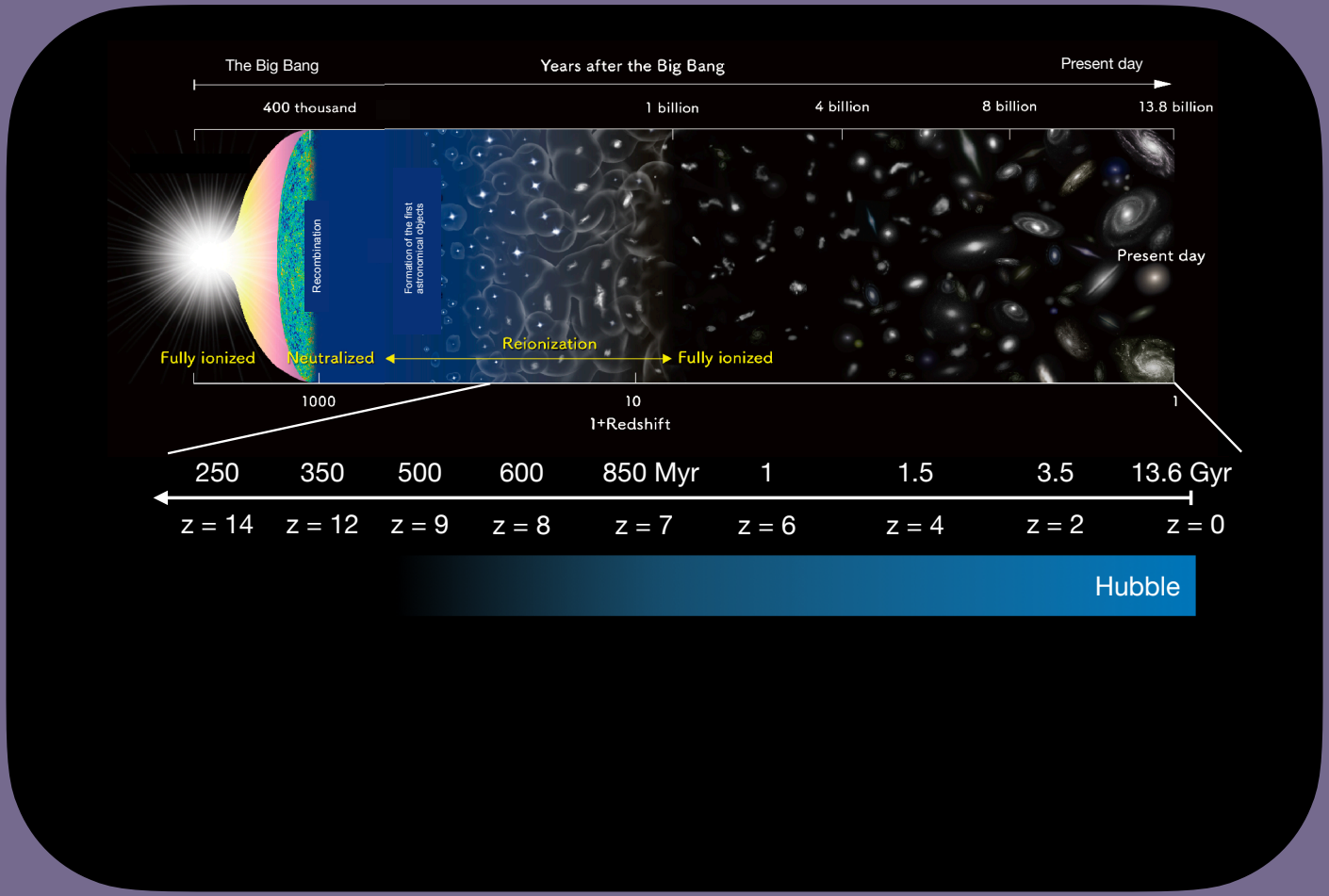

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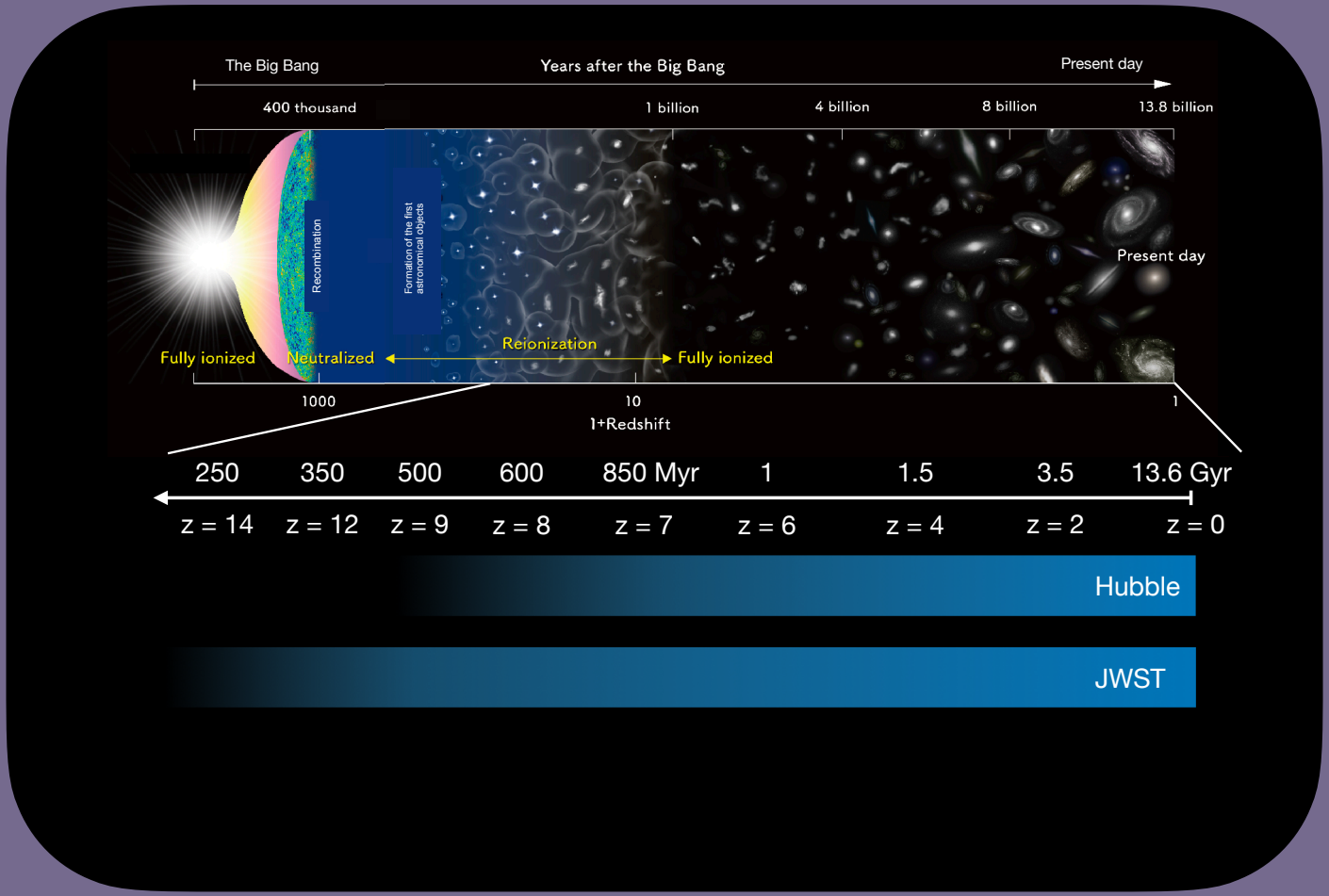

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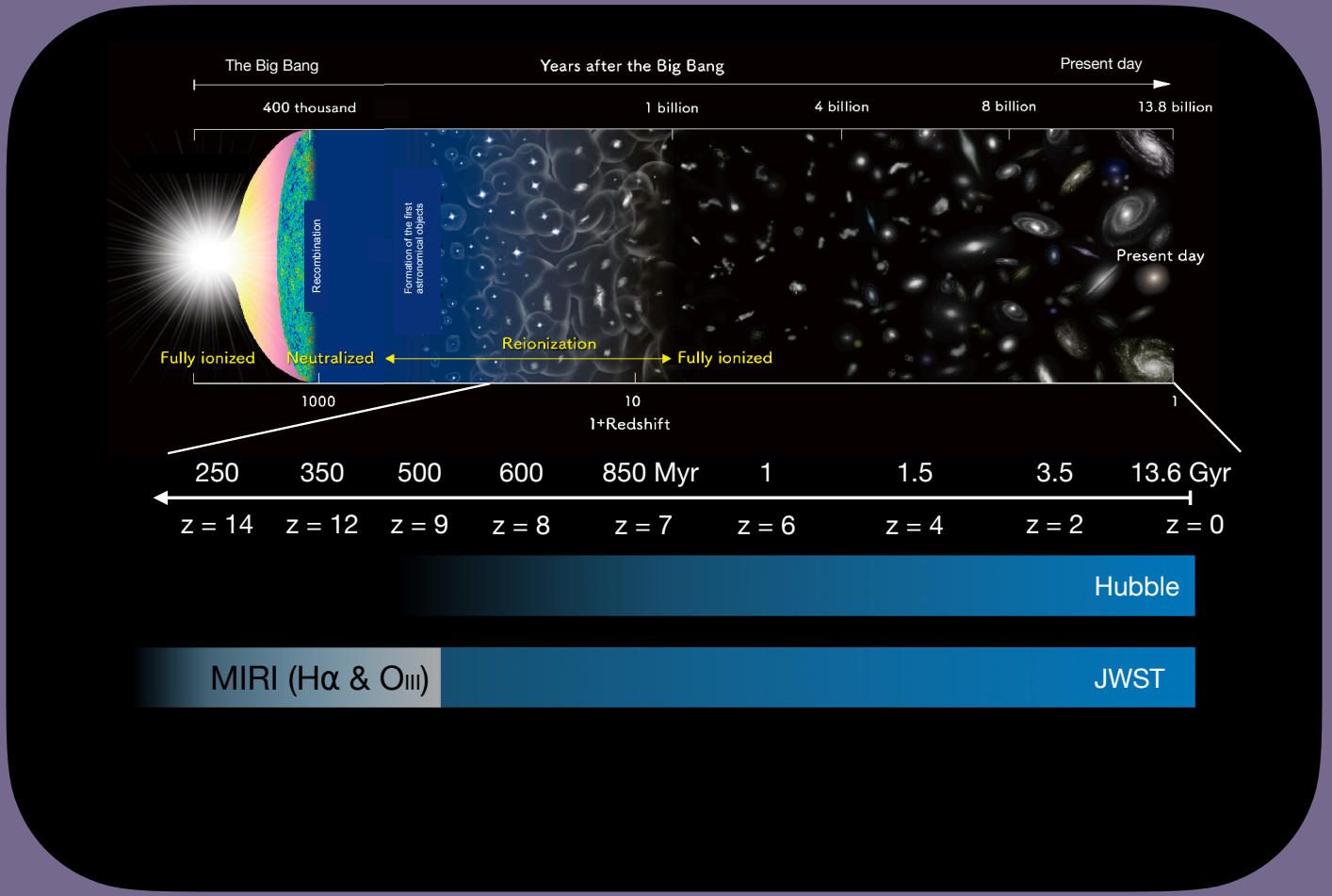

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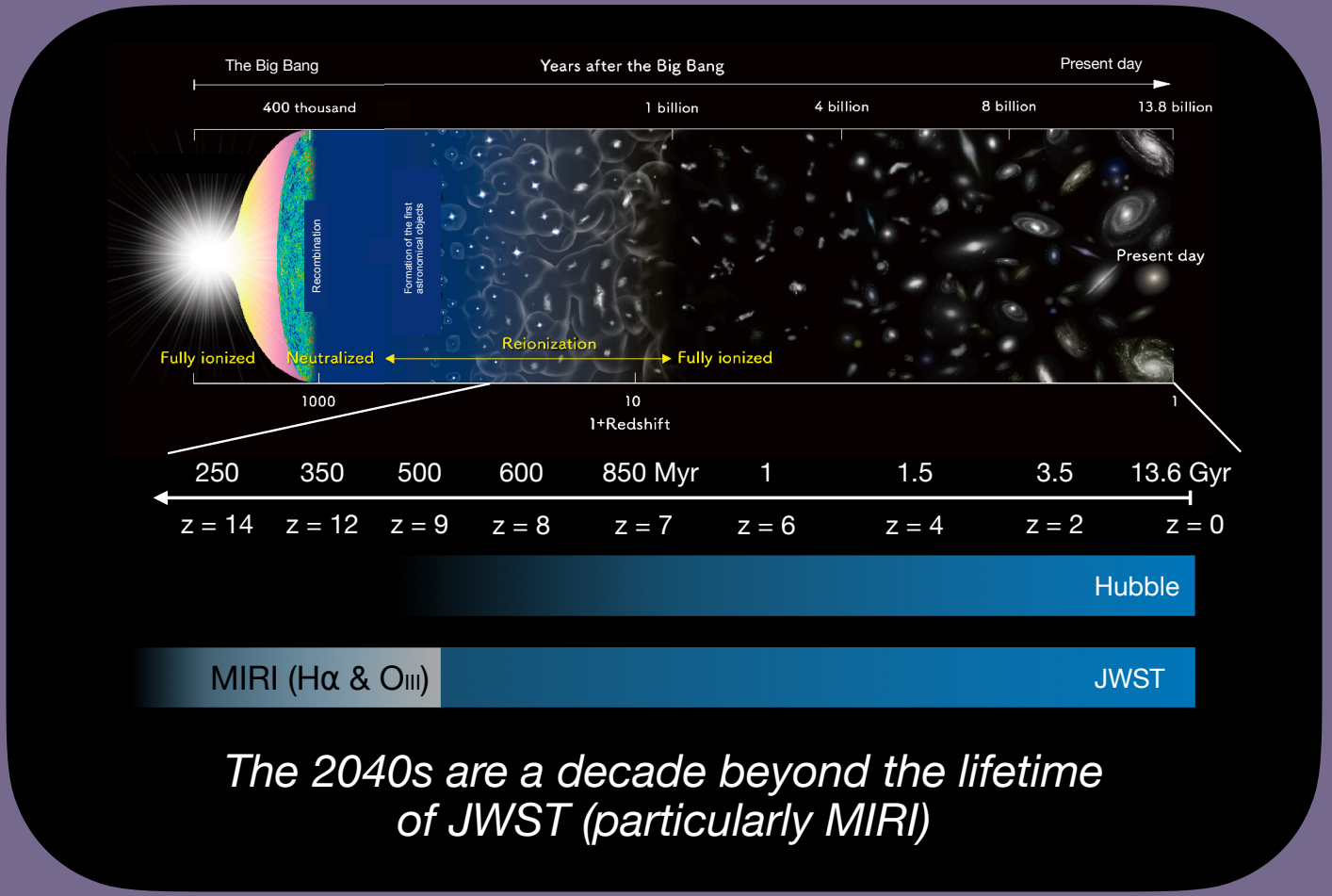
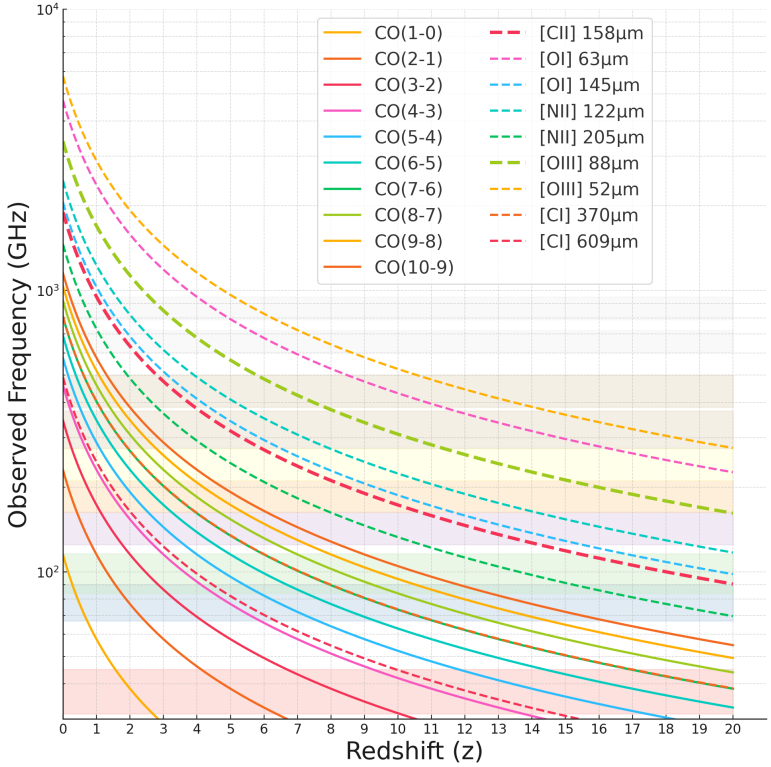


The 2040s are a decade beyond the lifetime of JWST (particularly MIRI)

How did the ***first galaxies*** form their stars?

Breaking the last cosmic frontier

Need to spectroscopically confirm galaxies out to *z*~20



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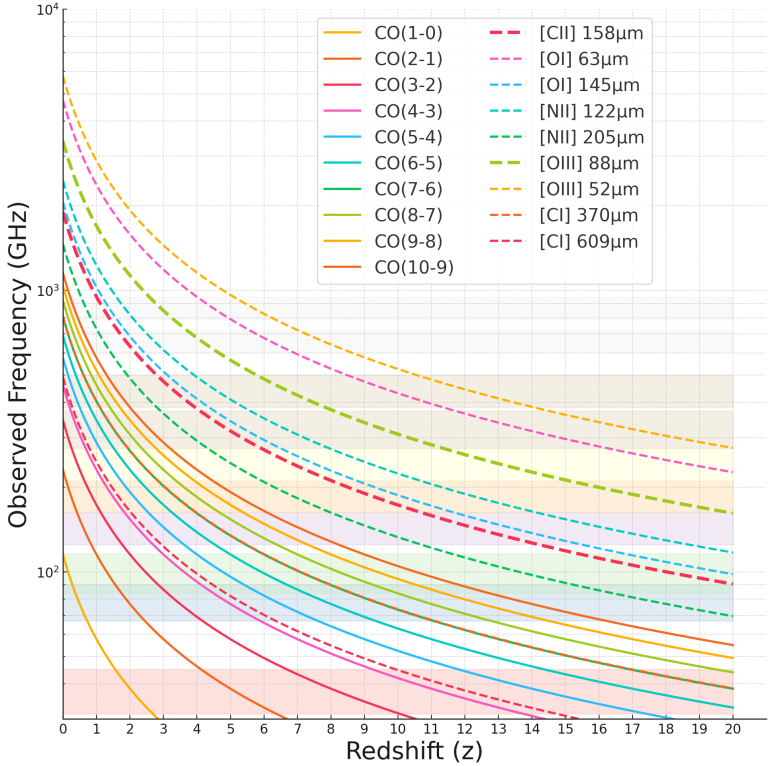
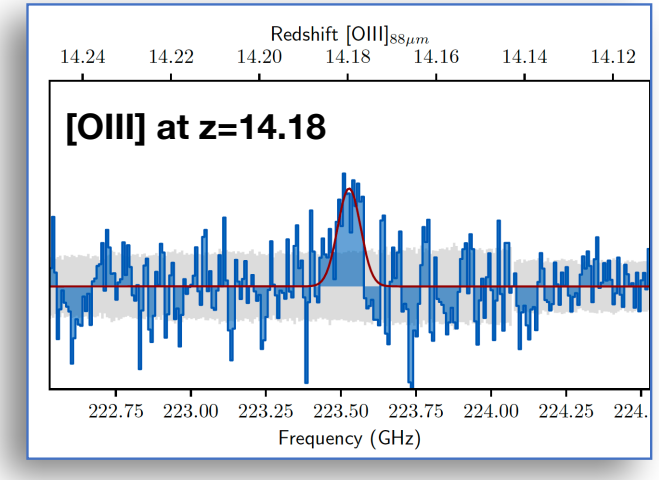
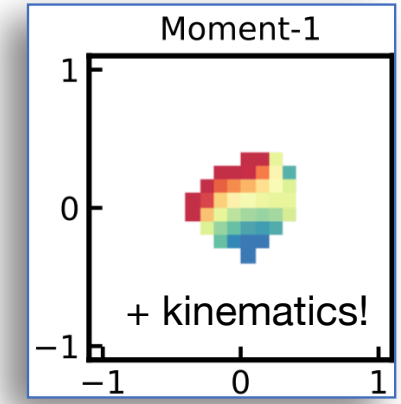


Proof of concept: Spectroscopic confirmation of a galaxy **at *z*>14** (only *300 Myr* after Big Bang)



Schouws et al. 2025; Carniani et al. 2025

ESO Press Release



Scholtz et al. 2025

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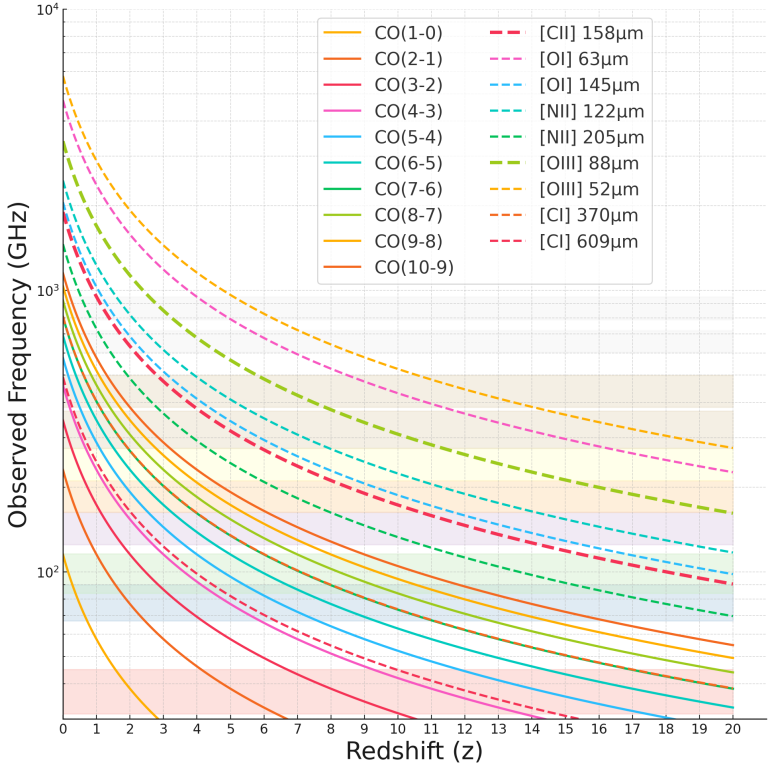

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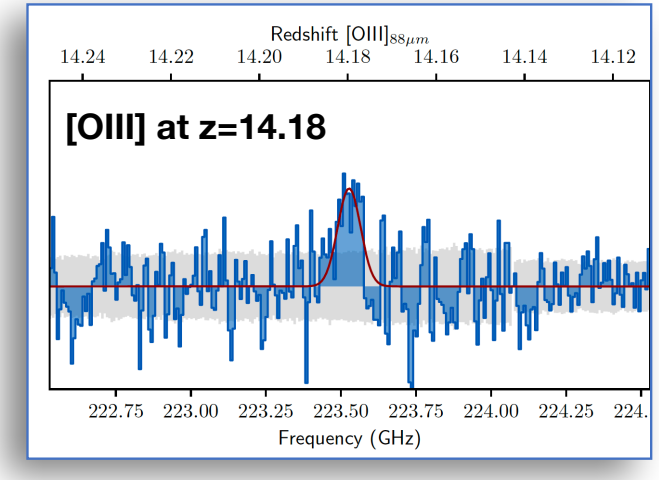

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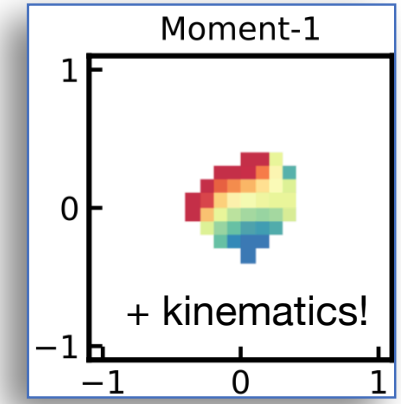


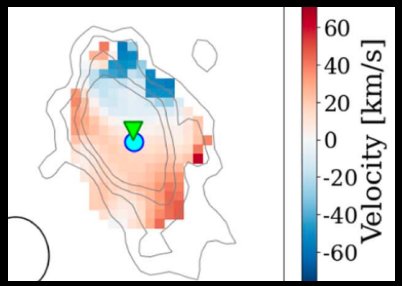
Scholtz et al. 2025

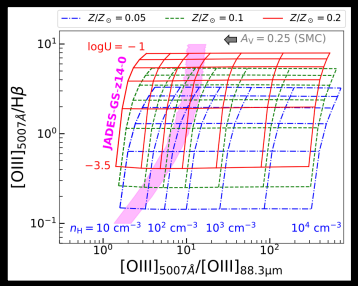
…but only barely probes tip of the iceberg

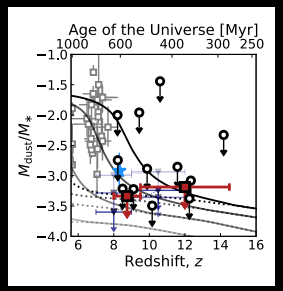
How did the ***first galaxies*** form their stars?

Breaking the last cosmic frontier

Need to resolve & characterize the nature of pristine galaxies







Refs: Ciesla+21; Tokuoka+22; Carniani+25; Schouws+25; Bakx+in prep

- *Multi-phase gas content*
- *Densities, temperatures & ionization*
- *Dust-free metallicities*
- *Kinematics & dynamical masses*
- *Emergence of the first dust & metals*

Proof of concept:

Sub-kpc mapping & kinematics of a cold **rotating disk galaxy** at z=7.3

Rowland et al. 2024, *ESO Press Release*

European-initiated effort towards an ALMA2040 vision

Transformational science with a (sub-)mm interferometer in the 2040s

Towards a next-generation ALMA-like observatory

www.euroalma2040.com

ALMA2040 science working groups

> 500 members, majority from Europe

High-redshift Universe

Leads: **Tom Bakx** (Chalmers) & **Francesca Rizzo** (U. Groningen)

Active Galactic Nuclei

Leads: **Roberto Decarli** (INAF Bologna) & **Miguel Pereira Santella** (IFF-CSIC)

Cosmology & Fundamental Physics

Leads: **Violette Impellizeri** (ASTRON) & **Hannah Stacey** (ESO)

Local Universe

Leads: **Jan Forbrich** (U. Hertfordshire) & **Miguel Querejeta** (OAN)

Interstellar Medium & Star Formation

Leads: **Maite Beltran** (INAF-Firenze) & **Jes Jørgensen** (Copenhagen)

Planet Formation

Leads: **Luca Matrà** (Trinity College) & **Catherine Walsh** (U. Leeds)

Sun & Stars

Leads: **Wouter Vlemmings/Theo Khouri** (Chalmers) & **Sven Wedemeyer** (U. Oslo)

Transients & Time-Domain Astronomy

Leads: **Kuo Liu** (MPIfR) & **Karri Koljonen** (NTNU)

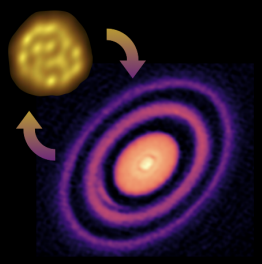
Solar System Bodies & Exoplanets

Leads: **Arianna Piccialli** (BIRA-IASB) & **Miriam Rengel** (MPS)

Coordinators:

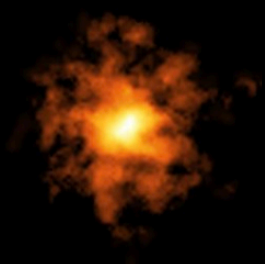
Stefano Facchini, Jacqueline Hodge, Eva Schinnerer

ALMA2040 Key Science Drivers



The life cycle of planetary systems & stars

Including the formation of rocky planets down to ~AU scales

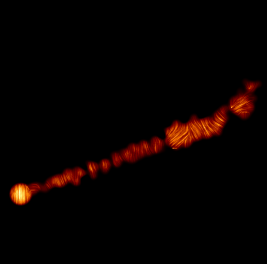


The formation and evolution of structure

Including primordial galaxies and black holes out to z~20

Evolution of the cosmic baryon cycle

Including dust & the development of chemical complexity that leads to life



Physics of the extreme universe

Including resolving (BH) jet engines in space, time, and polarization

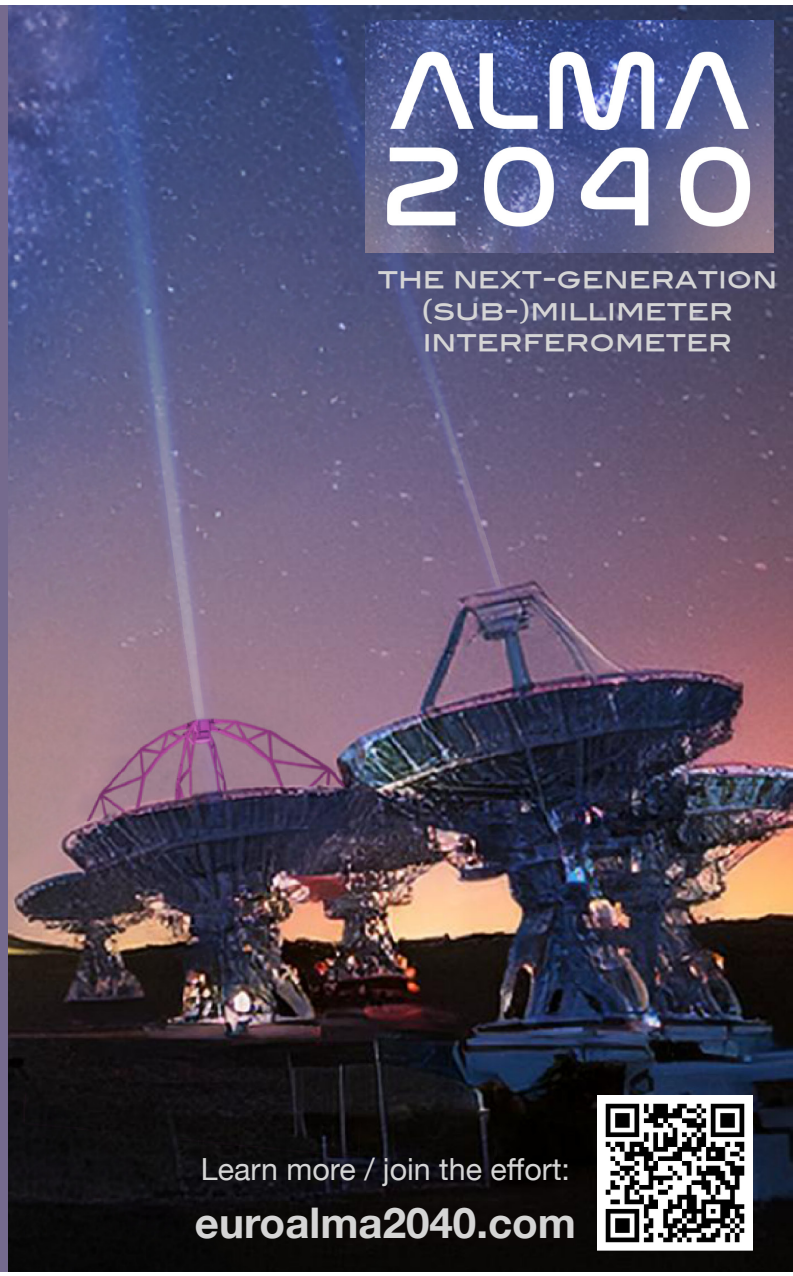
Foreseen capabilities:

> 5-10× line sensitivity

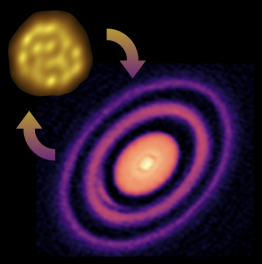
> 3-5× angular resolution

Simultaneous multi-band observing

On-the-fly calibration



ALMA2040 Key Science Drivers



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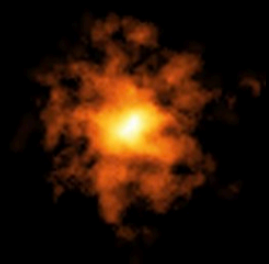

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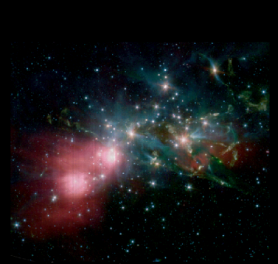
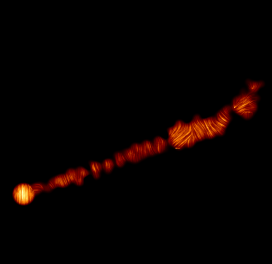


Evolution of the cosmic baryon cycle

Including dust &



Physics of the extreme universe

Including resolving

Great complementarity to ELT on similar (or better) scales

Foreseen capabilities:

> 5-10× line sensitivity

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On-the-fly calibration

ALMA 2040

THE NEXT-GENERATION (SUB-)MILLIMETER INTERFEROMETER

Learn more / join the effort:

euroalma2040.com

Towards an ALMA2040 vision

in 2025/2026

- **Submitted 27 White Papers to ESO (2025 Q4)**
- **Compiled science & systems requirements (2026 Q1)**
- **Drafted first base concept at 2nd Lorentz meeting (2026 Q1)**

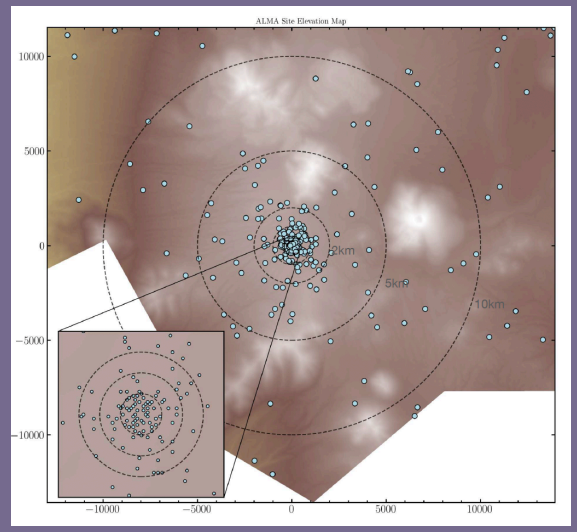
Lorentz II: Progress toward base concept

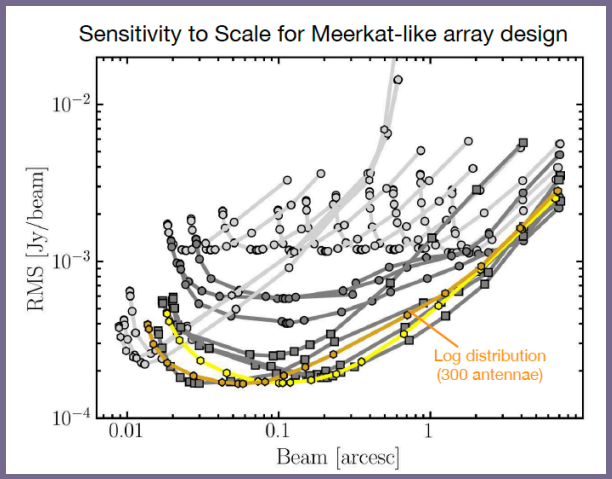
Requirements from consolidated key science goals:

- ~200-300 antennas
- Short-spacing capabilities
- Covering full (current) frequency range (at least for core)
- FULL instantaneous bandwidth
- Solar observing capabilities
- Strict polarization purity
- ToO capabilities (including for VLBI) — within minutes
- Coordination with multi-messenger facilities
- Sub-arraying capabilties
- Real-time calibration

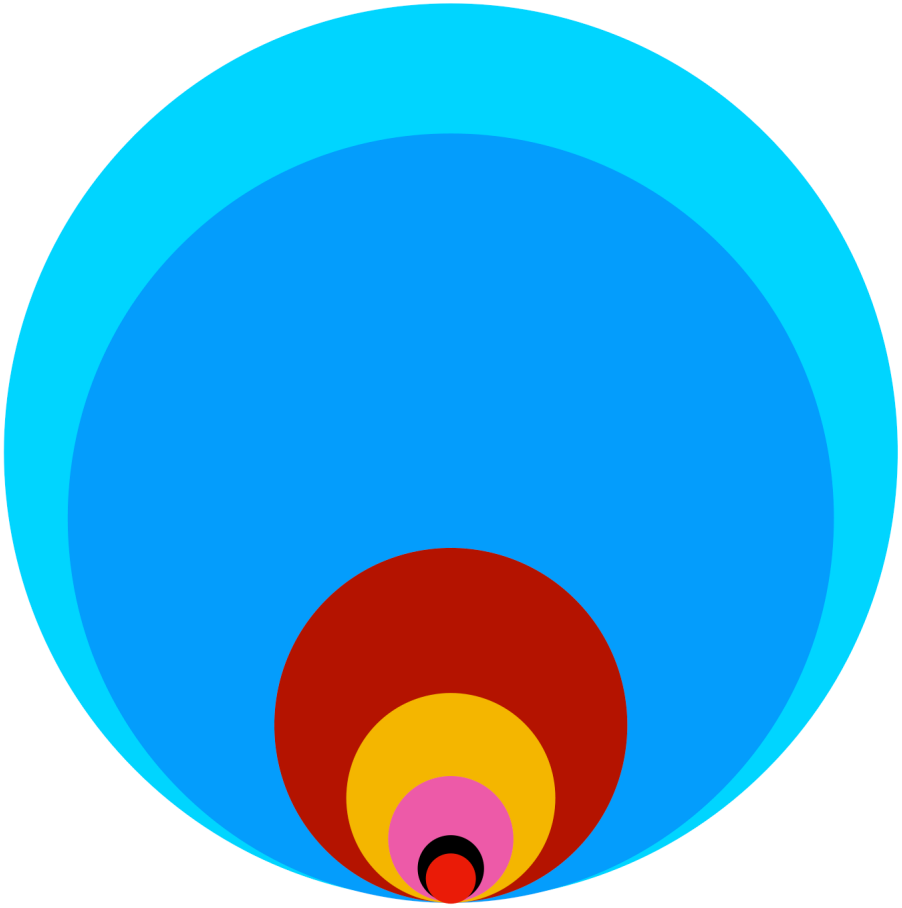
Still under discussion

- Fixed or movable array
- Optimal configuration





Leap in sensitivity compared to other facilities



ALMA2040 300-array (equiv. 225m dish)

ALMA2040 200-array (equiv. 180m dish)

ALMA 12m array (equiv. 84m dish)

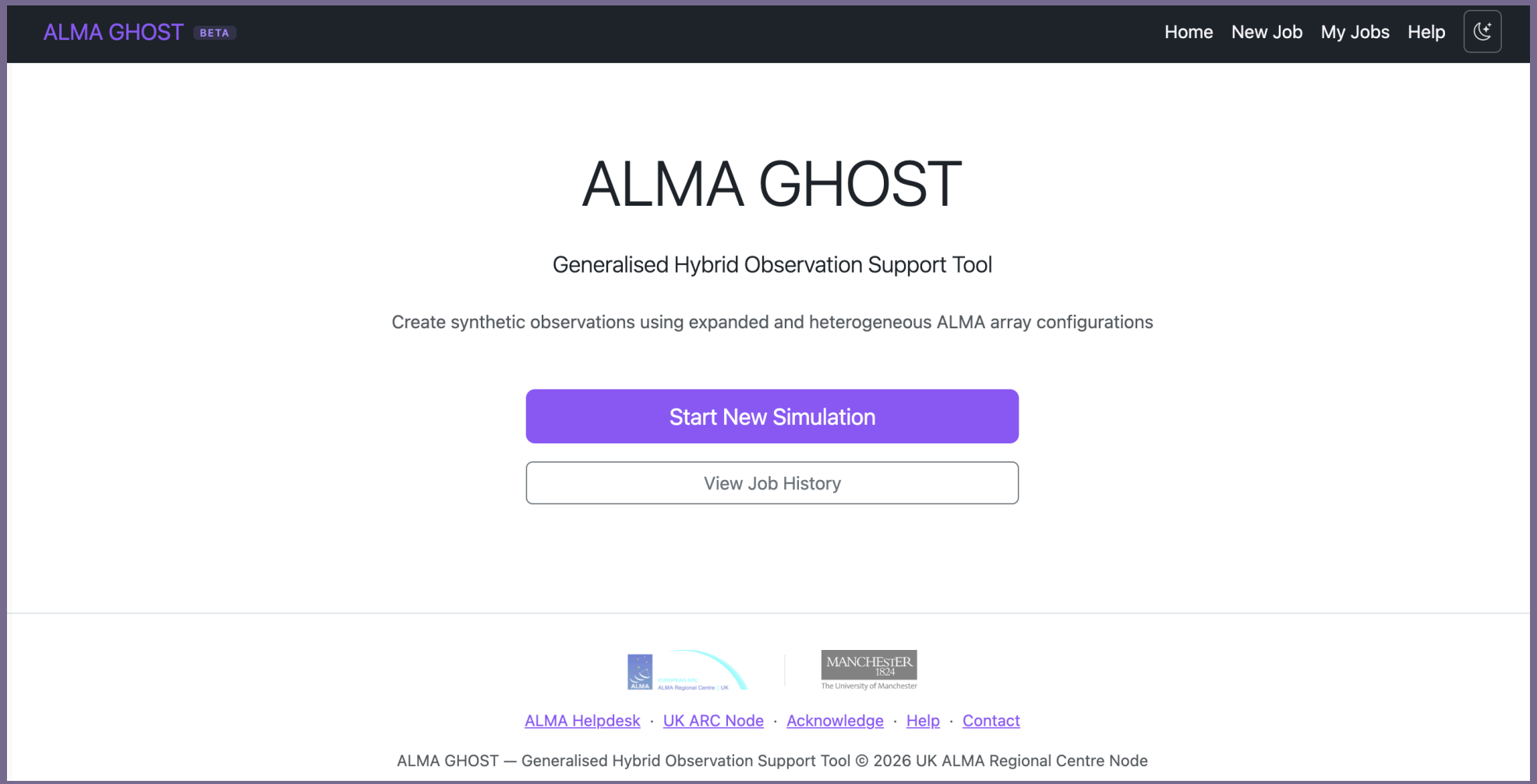
AtLAST & LMT (50m dish)
NOEMA (equiv. 50m dish)

IRAM 30m (30m dish)

SMA (equiv. 15m dish)
JCMT (15m dish)

Apex (12m dish)

Release of dedicated GHOST simulation tool



https://alma-ghost.jb.man.ac.uk/

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- **Global call for scientific & technical 'ALMA2040 White Papers'**
  - In coordination with North America, East Asia, and Chile
  - Call issued end of April 2026 in EU, NA, EA; Due September 2026

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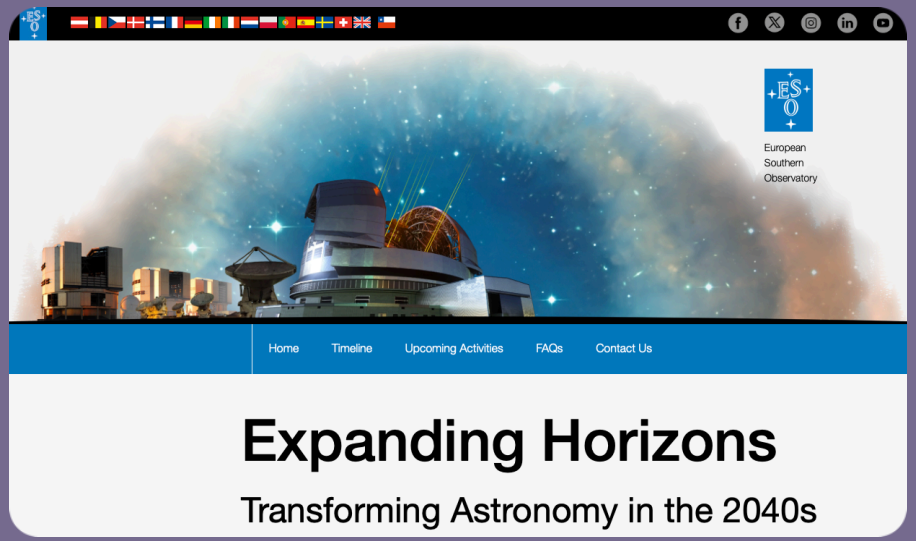
- **Explore technical options (array configurations, receivers, front/backend, correlator, data, operations, …) in 2026 Q2 (invited to join RADIONET as guest instrument)**
- **On-going dialogue with industry to assess cost trade-offs of the antennas**
- **Global call for scientific & technical 'ALMA2040 White Papers'**
  - In coordination with North America, East Asia, and Chile
  - Call issued end of April 2026 in EU, NA, EA; Due September 2026
- **ESO Expanding Horizons workshop July 13-17 in Garching**
- **Full design concept by Fall 2026**
- **Submit letter of intent to ESO's Expanding Horizon call (2026 Dec 1)**

Towards an ALMA2040 vision

in 2027

- **Prepare required document for proposal idea (January to May 2027)**
- **Submit idea proposal to ESO's Expanding Horizon call (current deadline 2027 June)**
- **Approved IAU *Focus Meeting* at the IAU General Assembly in Rome, August 2027**

Co-Chairs: Jacqueline Hodge (NL), Sean Andrews (USA), Bunyo Hatsukade (Japan), Chiara Mazzucchelli (Chile)



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Summary

- ALMA2040 is a community-driven effort for a next-generation mm/submm interferometer
- It will address fundamental open questions from the emergence of the **first galaxies (z~20)** to the birth of **terrestrial planets** and their **paleo-biospheres**
- Interested in defining the high-definition future of mm/submm astronomy? Global call for White Papers out now