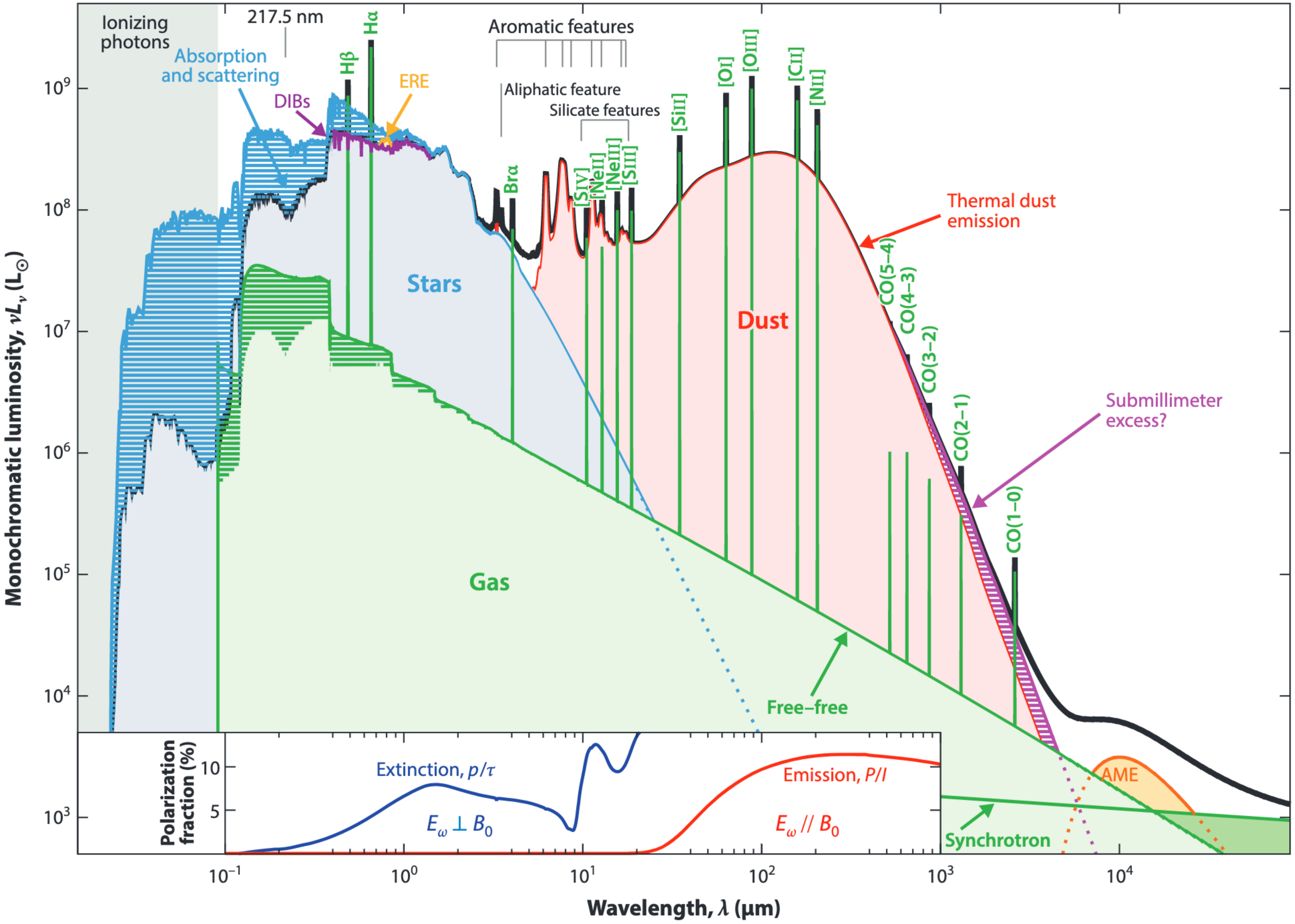
ALMA2040

The cold universe in high definition

Eva Schinnerer (MPIA) on behalf of
Jacqueline Hodge (Leiden), Stefano Facchini (Milano), Maria Diaz Trigo (ESO)
and the ALMA2040 collaboration

the (sub-)mm is a unique window into the cold universe



Galliano et al. (2018)

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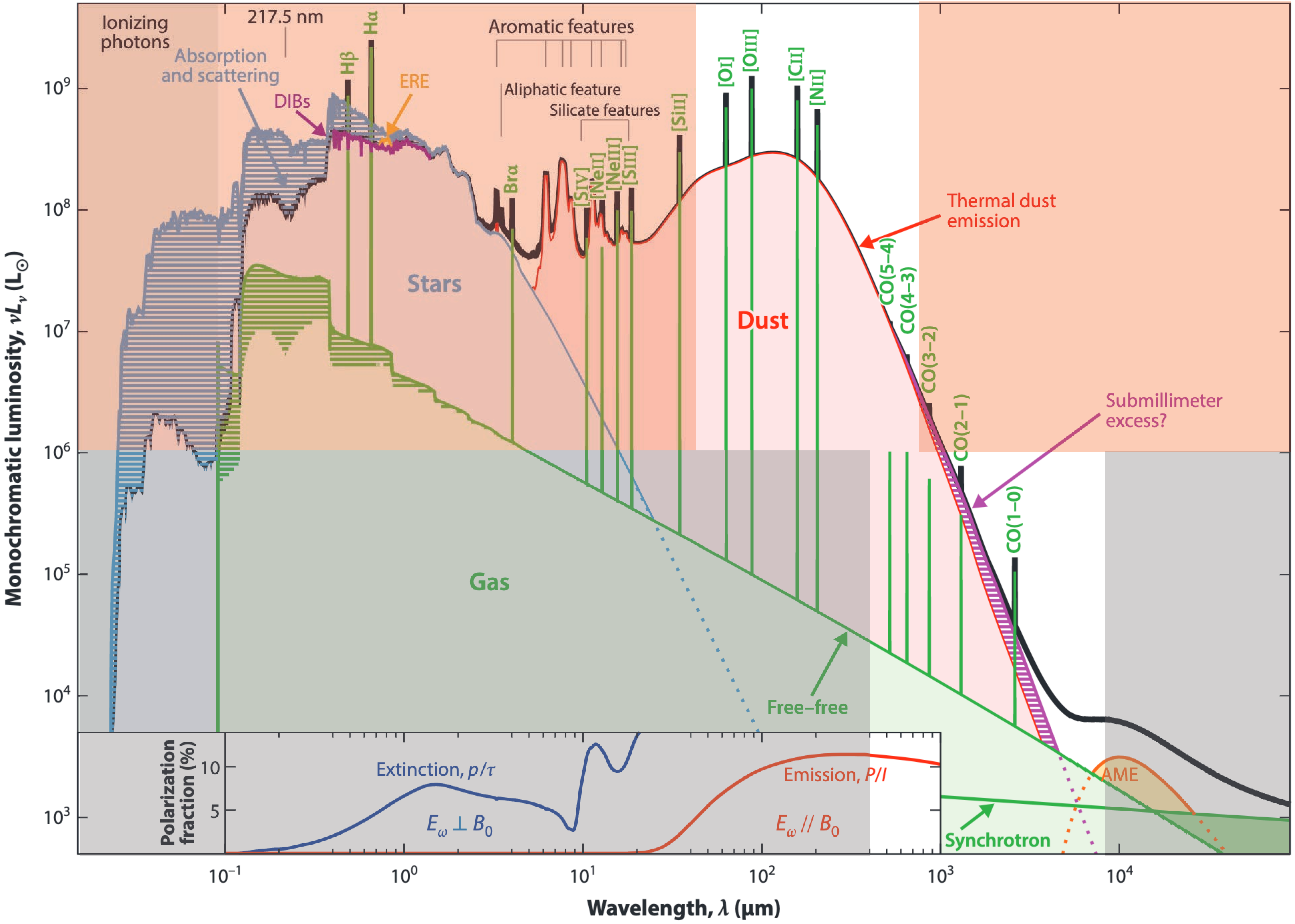


z=10

z=0

Galliano et al. (2018)

Why think now about a (sub-)mm array for the 2040s?

10+ Years of Amazing ALMA Science

Cycle 1 started in January 2013

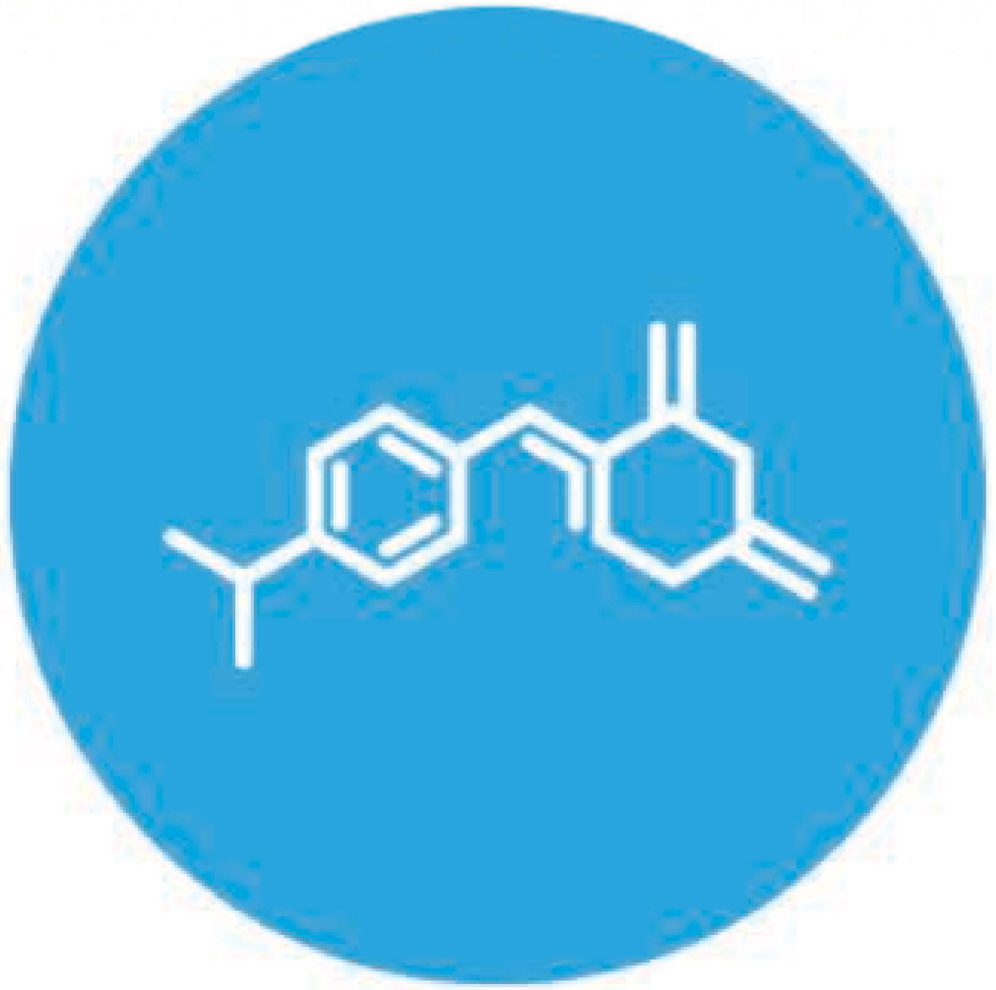
Why think now about a (sub-)mm array for the 2040s?

- ALMA Wideband Sensitivity Upgrade (WSU) done in ~2030

ALMA Wideband Sensitivity Upgrade (~2030)

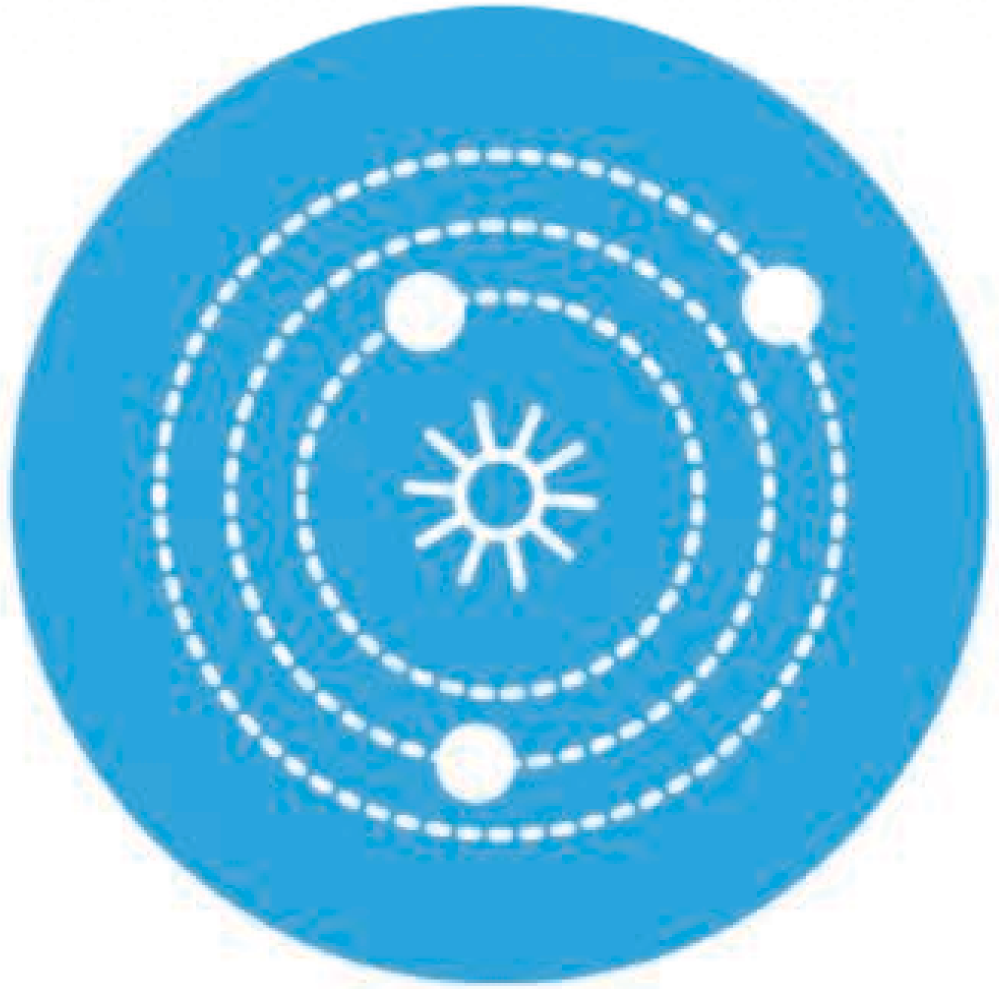
ORIGINS OF GALAXIES

Trace the cosmic evolution of key elements from the first galaxies (z>10) through the peak of star formation (z=2–4) by detecting their cooling lines, both atomic ([CII], [OIII]) and molecular (CO), and dust continuum, at a rate of 1-2 galaxies per hour.



ORIGINS OF CHEMICAL COMPLEXITY

Trace the evolution from simple to complex organic molecules through the process of star and planet formation down to solar system scales (~10-100 au) by performing full-band frequency scans at a rate of 2-4 protostars per day.



ORIGINS OF PLANETS

Image protoplanetary disks in nearby (150 pc) star formation regions to resolve the Earth forming zone (~ 1 au) in the dust continuum at wavelengths shorter than 1mm, enabling detection of the tidal gaps and inner holes created by planets undergoing formation.

Increase of the available IF band width by a factor of 4 (32 GHz per polarization), while retaining full spectral resolution over the entire bandwidth

Upgrade of the full signal chain of ALMA – from the receivers and digitizers, all the way through to the correlated data

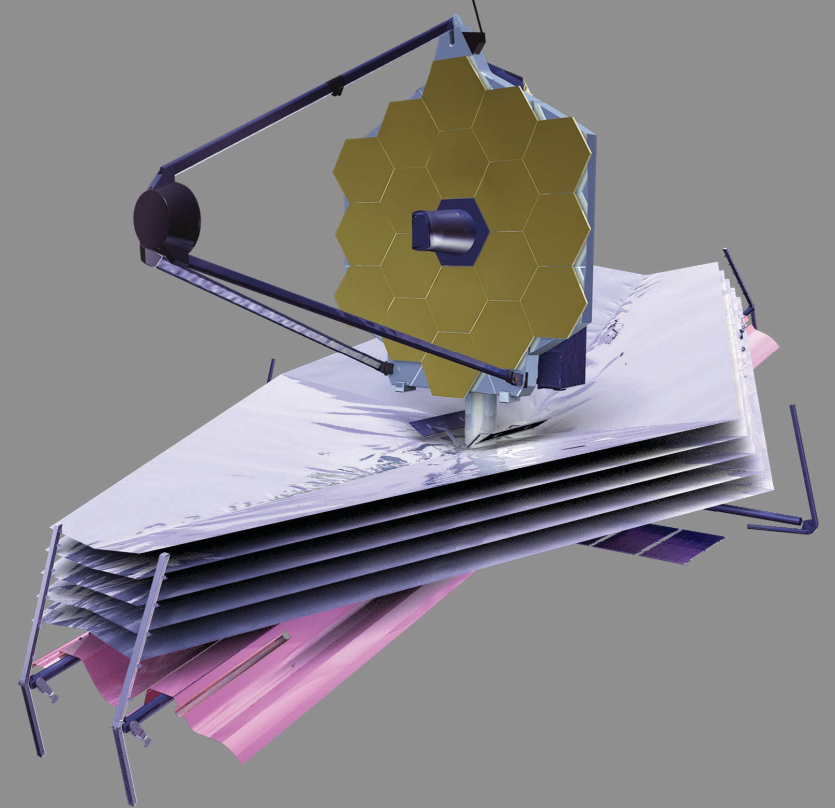
Slide content courtesy of Maria Diaz Trigo

Why think now about a (sub-)mm array for the 2040s?

- ALMA Wideband Sensitivity Upgrade (WSU) done in ~2030
- Very different facility landscape in 2040s

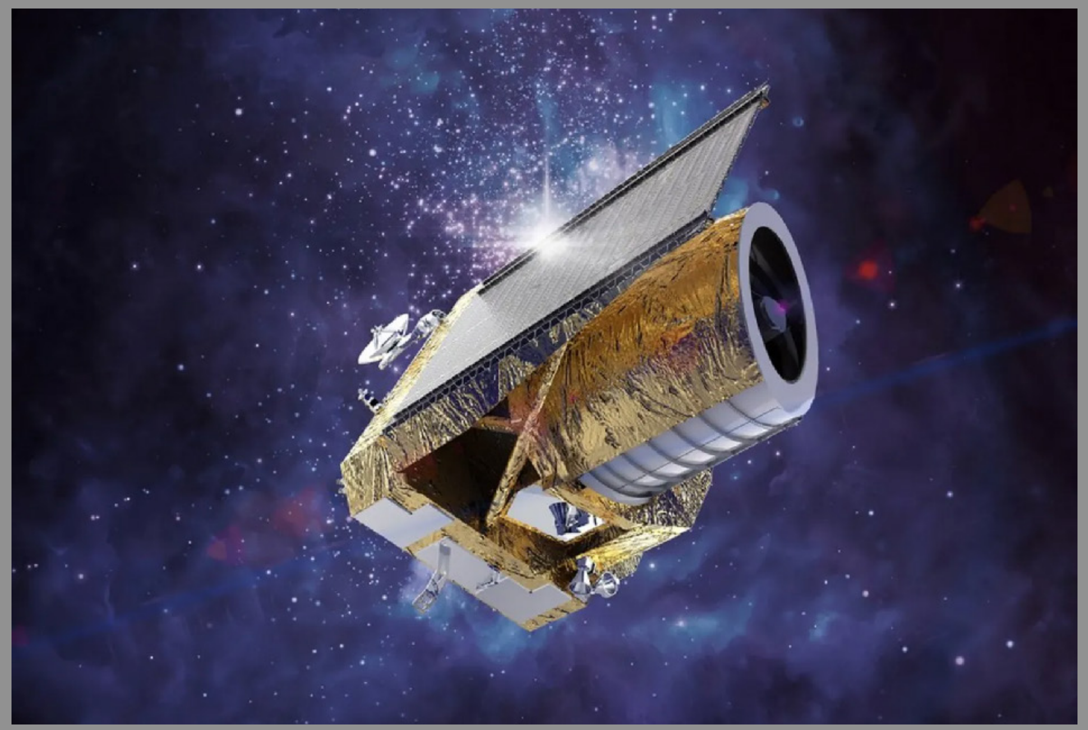
New facility landscape in the 2040s

JWST



NIR-MIR telescope

Euclid

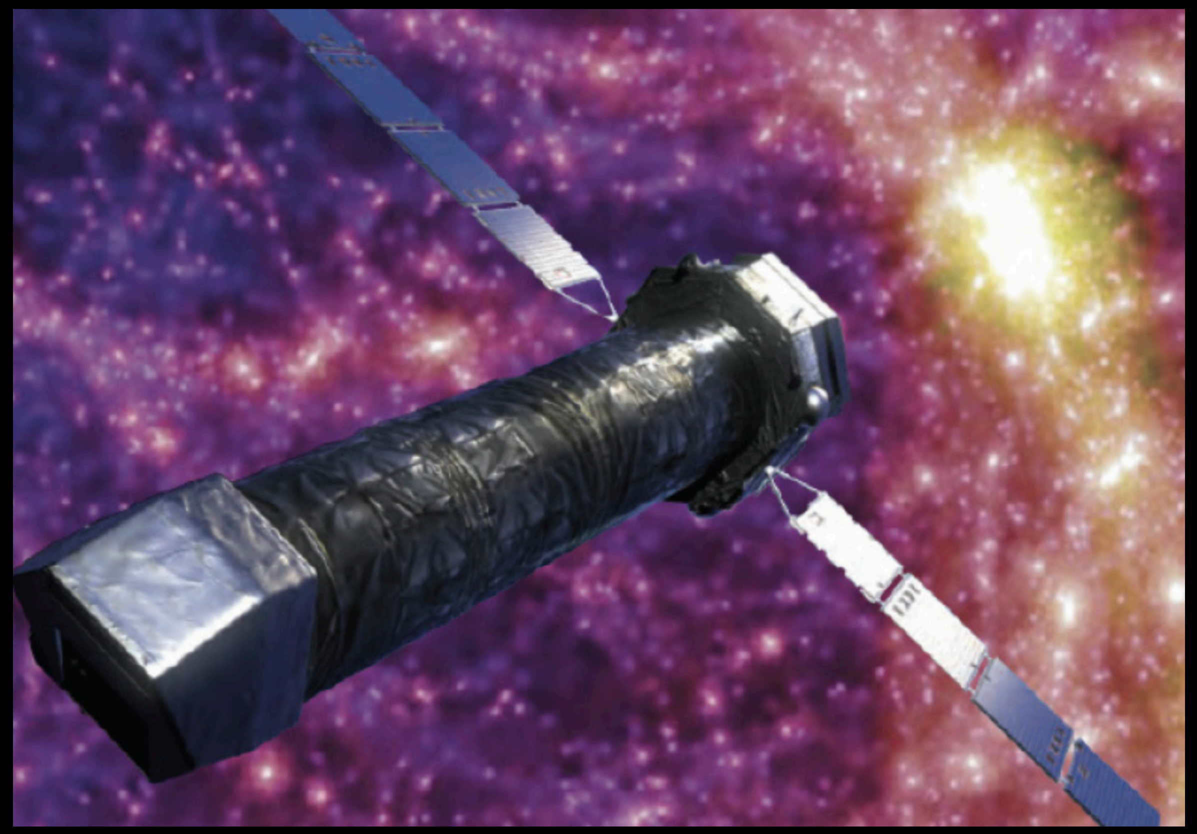


Optical-NIR telescope

Roman

Optical-NIR telescope

NewAthena



X-ray telescope

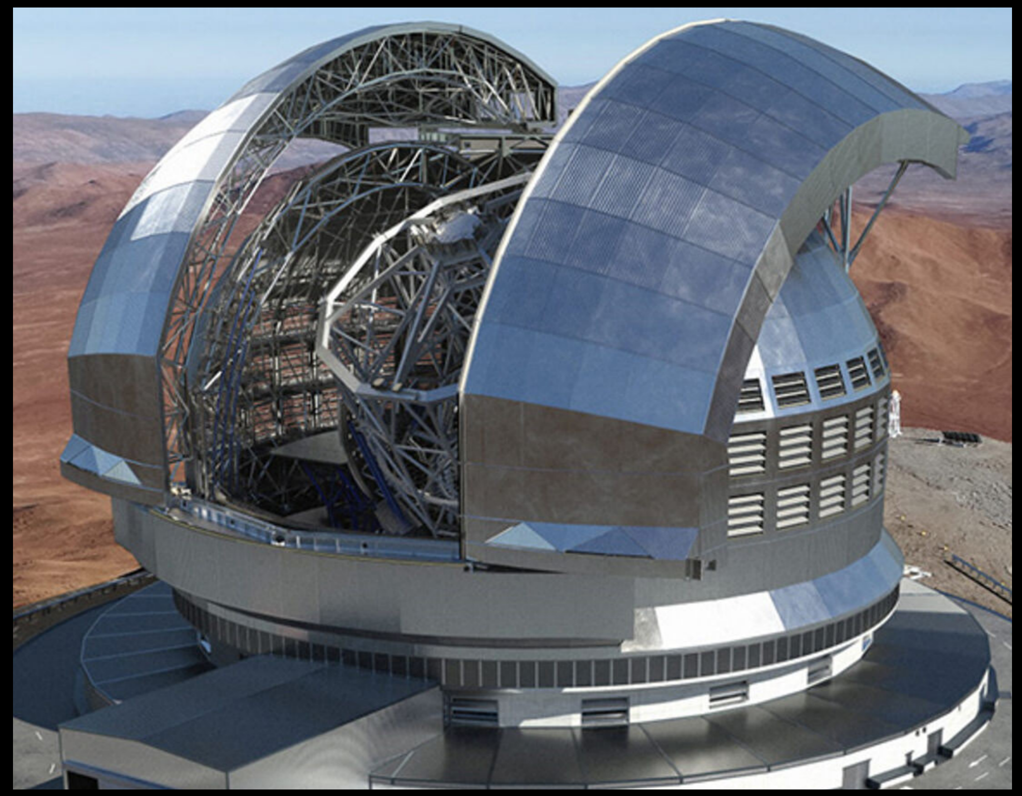
LSST/Rubin

Optical-NIR telescope

SKA

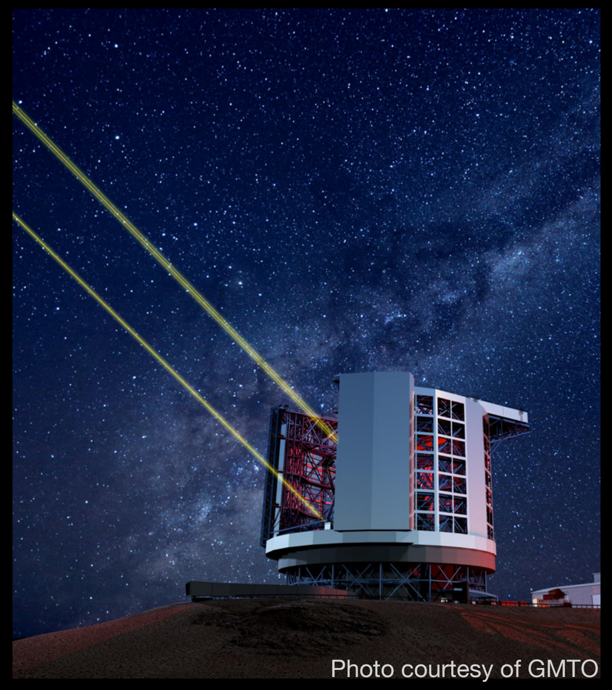
Radio telescopes

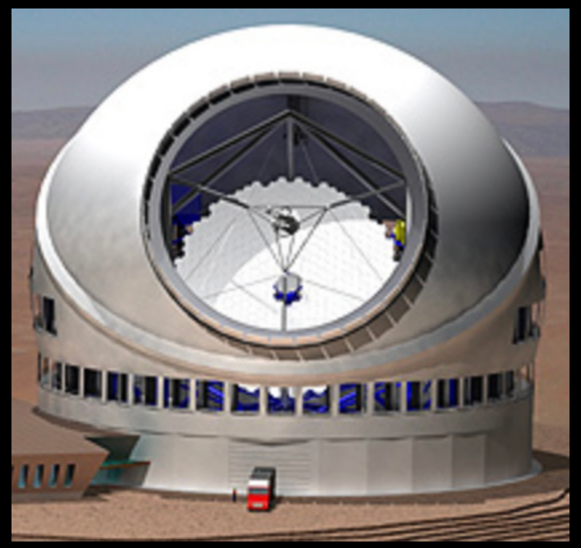
ELT



Optical-MIR telescope

GMT, TMT





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New facility landscape in the 2040s

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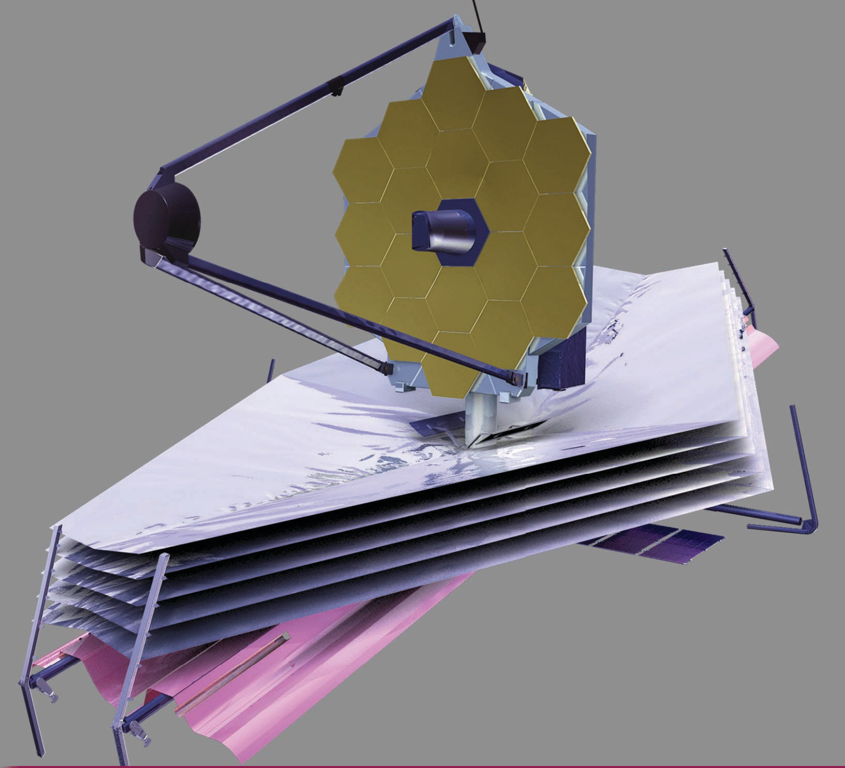
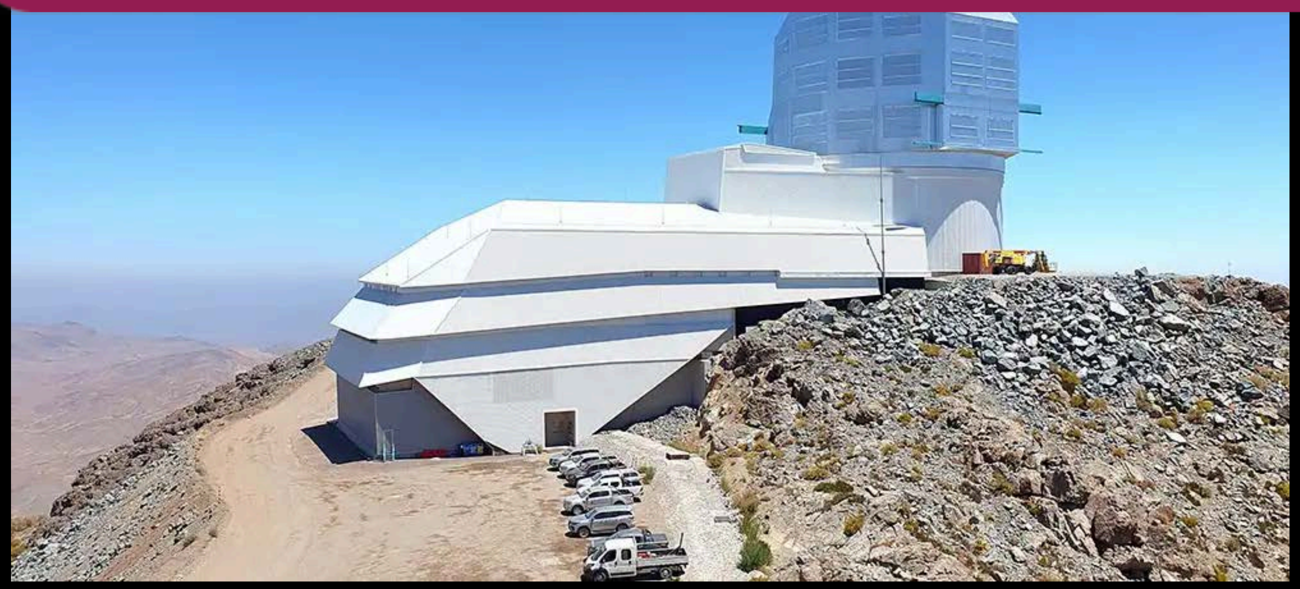


Euclid

Roman

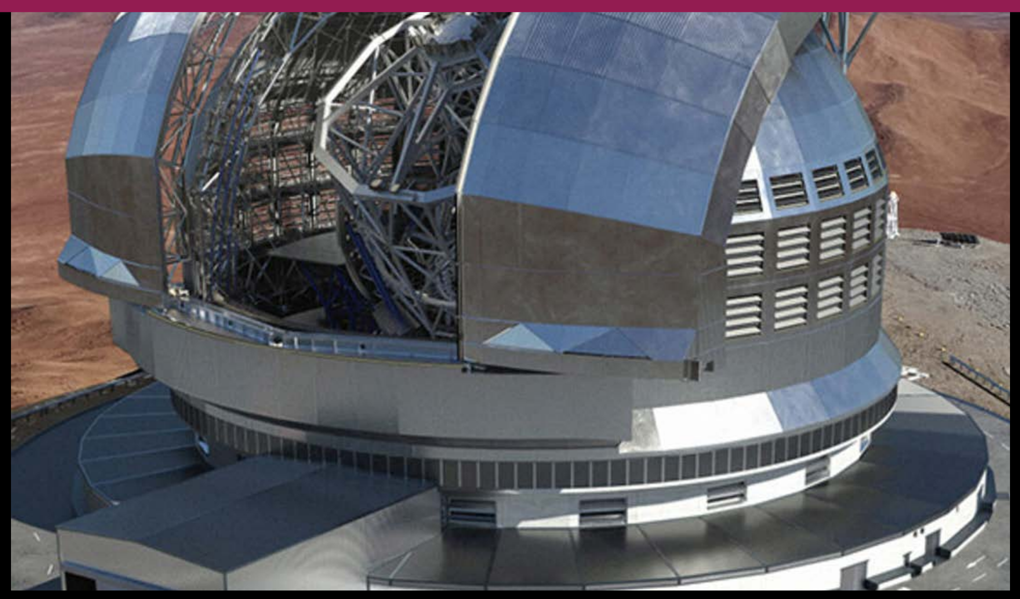
NewAthena

Unprecedented science opportunities in the 2040s



Optical-NIR telescope

Radio telescopes



Optical-MIR telescope


Photo courtesy of GMTO

Optical-MIR telescope

Why think now about a (sub-)mm array for the 2040s?

- ALMA Wideband Sensitivity Upgrade (WSU) done in ~2030
- Very different facility landscape in 2040s
- Needs identified by Kavli-IAU report on global coordination

Report of the Kavli-IAU Workshop on Global Coordination

Probing the Universe from far-infrared to millimeter wavelengths: future facilities and their synergies

Workshop held March 26-28, 2024 at Caltech, Pasadena, CA, USA

https://arxiv.org/pdf/2409.07570

European effort towards an ALMA2040 vision

www.euroalma2040.com

ALMA2040 science working groups

>350 members, so far mostly 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** (Chalmers) & **Sven Wedemeyer** (U. Oslo)

- **Transients & Time-Domain Astronomy**

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

- **Solar System Bodies & Exoplanets**

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

Coordinators:

Stefano Facchini, Jacqueline Hodge, Eva Schinnerer

European effort towards an ALMA2040 vision

in 2025

- **Identify primary science drivers**
  - based on 70+ science pitches received in March/April 2025
  - developed further within the 9 science working groups
  - and discussed at 3.5-day workshop in May 2025


ALMA
2040


ALMA2040: Science
Opportunities in the 2040s
2025 May 19 - 22

European effort towards an ALMA2040 vision

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- **Identify primary science drivers**
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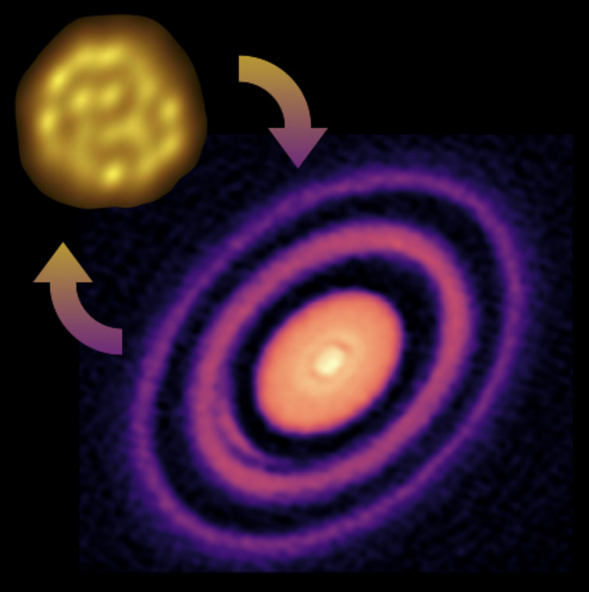
ALMA2040: The next-generation observatory for (sub-)millimeter observations at high angular resolution

ALMA2040 represents a community-driven effort to develop the requirements for a next-generation and transformational (sub-)millimetre telescope that will address the top scientific questions in astronomy in the 2040s and beyond. The initial effort in Europe is focused on preparing a proposal for ESO's Expanding Horizons call, which represents its search for the next big astronomical ground-based programme. Currently, the ALMA2040 effort is the result of the work of ~350 members of the European astronomical community who have united themselves in a set of nine science working groups (SWGs). Representatives from the nine SWGs met in Heidelberg from Monday, 19 May 2025, to Thursday, 22 May 2025, to identify key science drivers for such a facility as well as some of the technical requirements that follow from

lma2040.com

ALMA2040 Key Science Drivers



The life cycle of planetary systems & stars

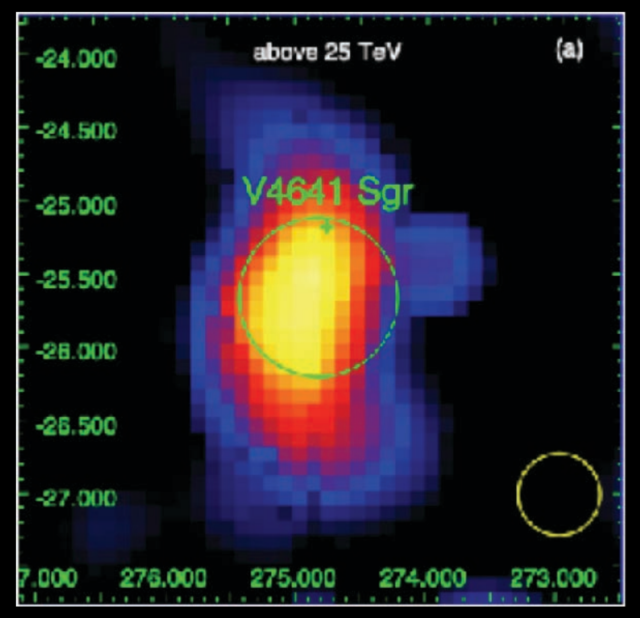
Including the formation of rocky planets down to ~AU scales

The formation and evolution of structure

Including primordial galaxies and black holes out to z~20

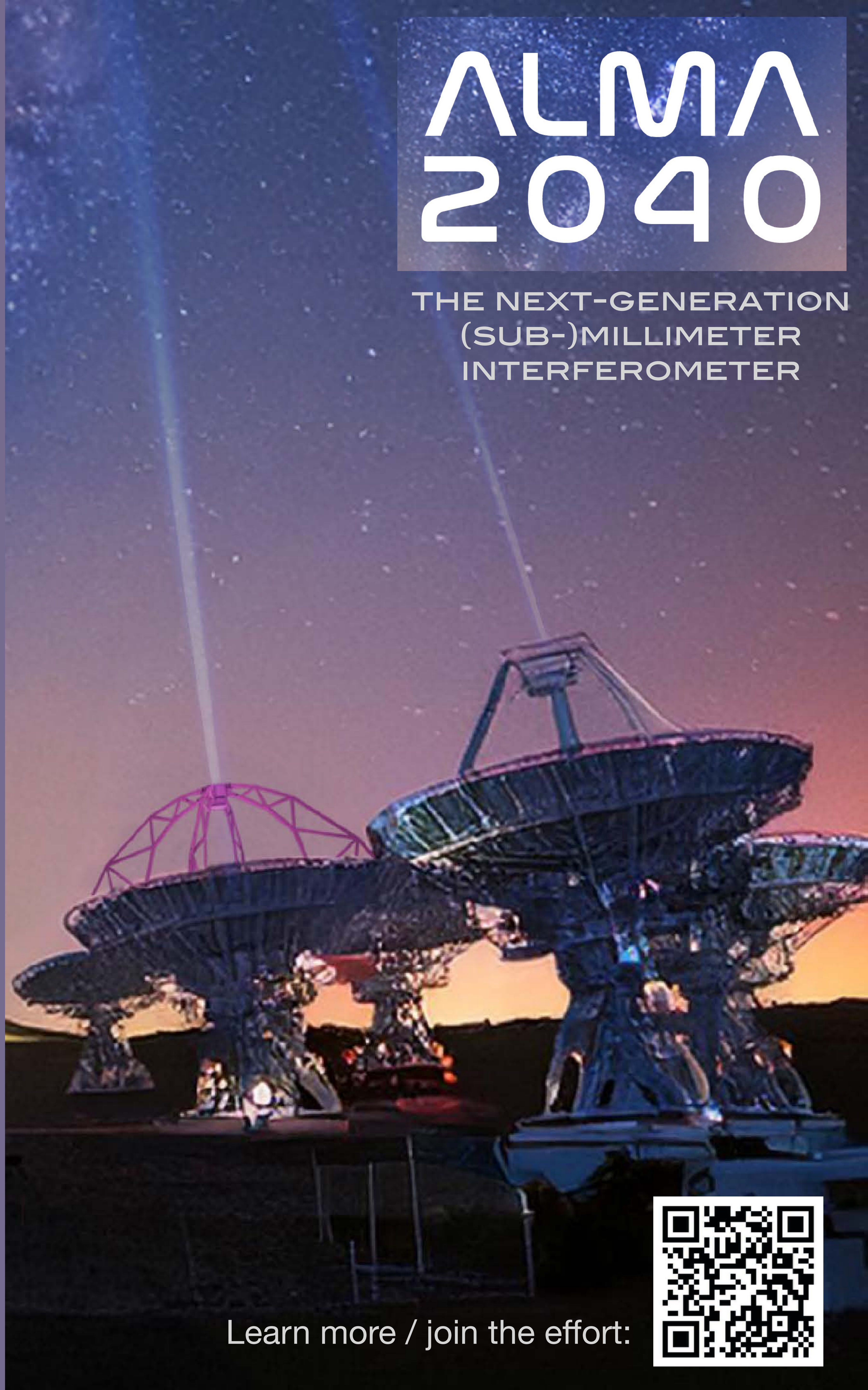
Evolution of the cosmic baryon cycle

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

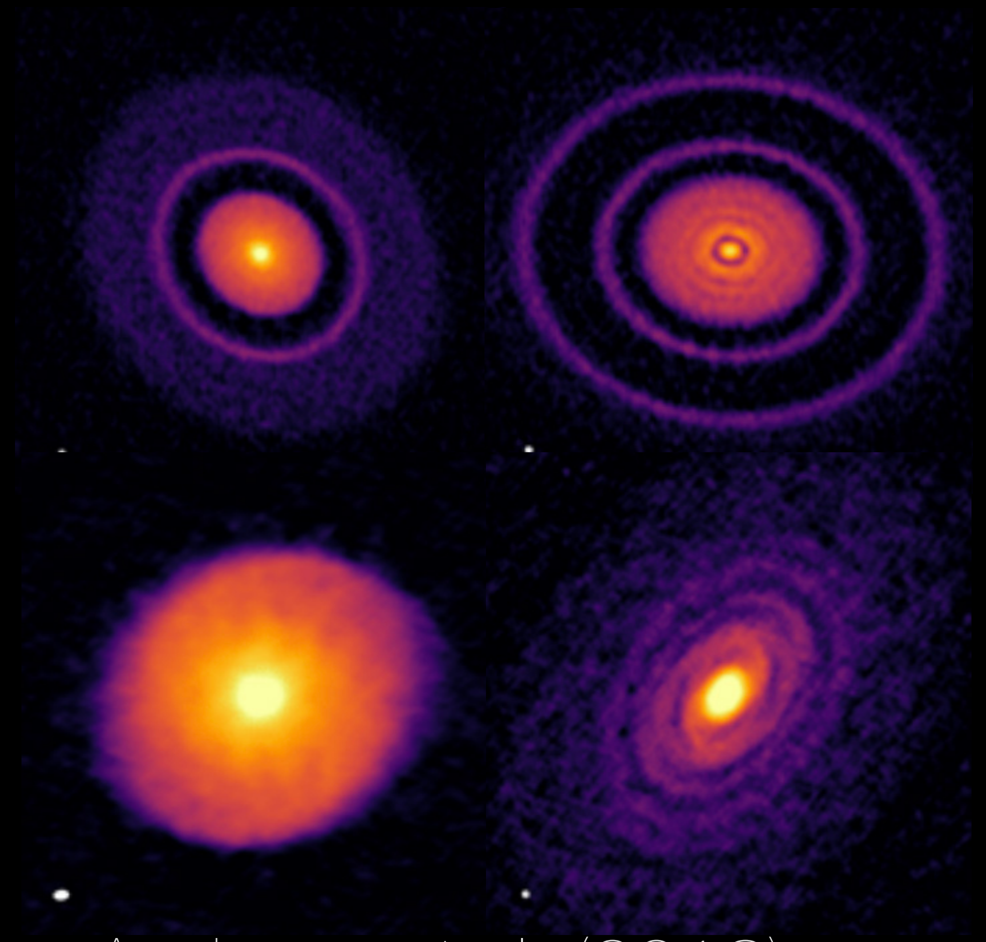


Cosmic explosions and acceleration

Including multi-messenger astronomy in the 2040s



The life cycle of planetary systems



Andrews et al. (2018)

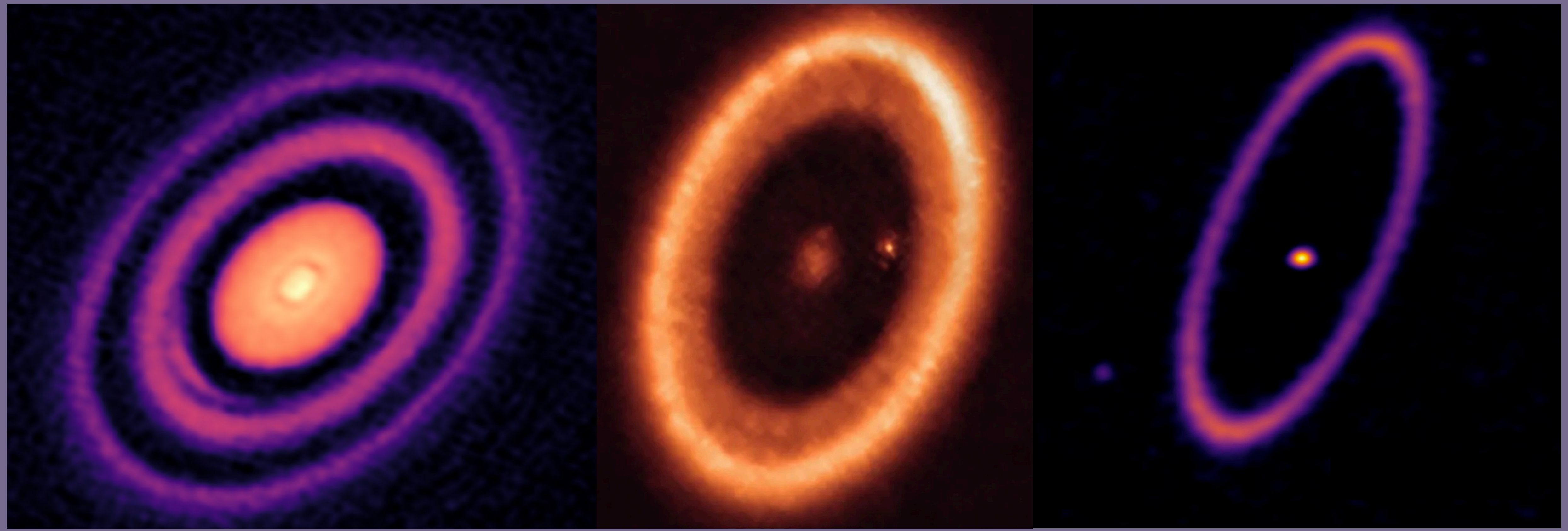
Observe the formation of **solar system analogues** down to rocky planets and their paleo-biospheres

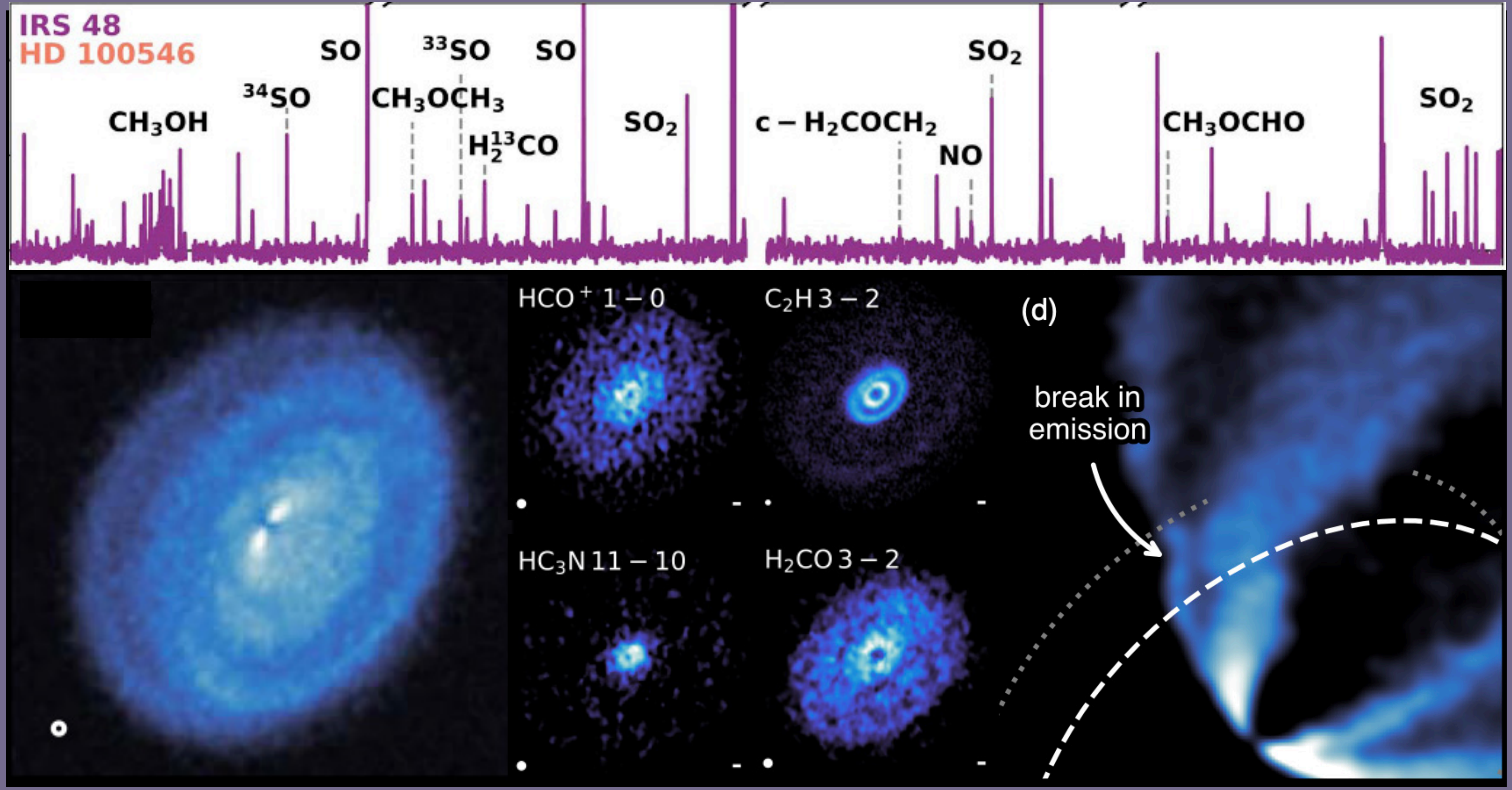
Planet Formation

ALMA2040 Science Goals

Observe planet formation in action down to AU scales, across evolutionary stages and around the most common stars in the galaxy

Reveal pathways to planet compositions and chemical complexity across the water snowline





ALMA2040 Requirements

Cont. sensitivity: factor ~ 20 x improvement

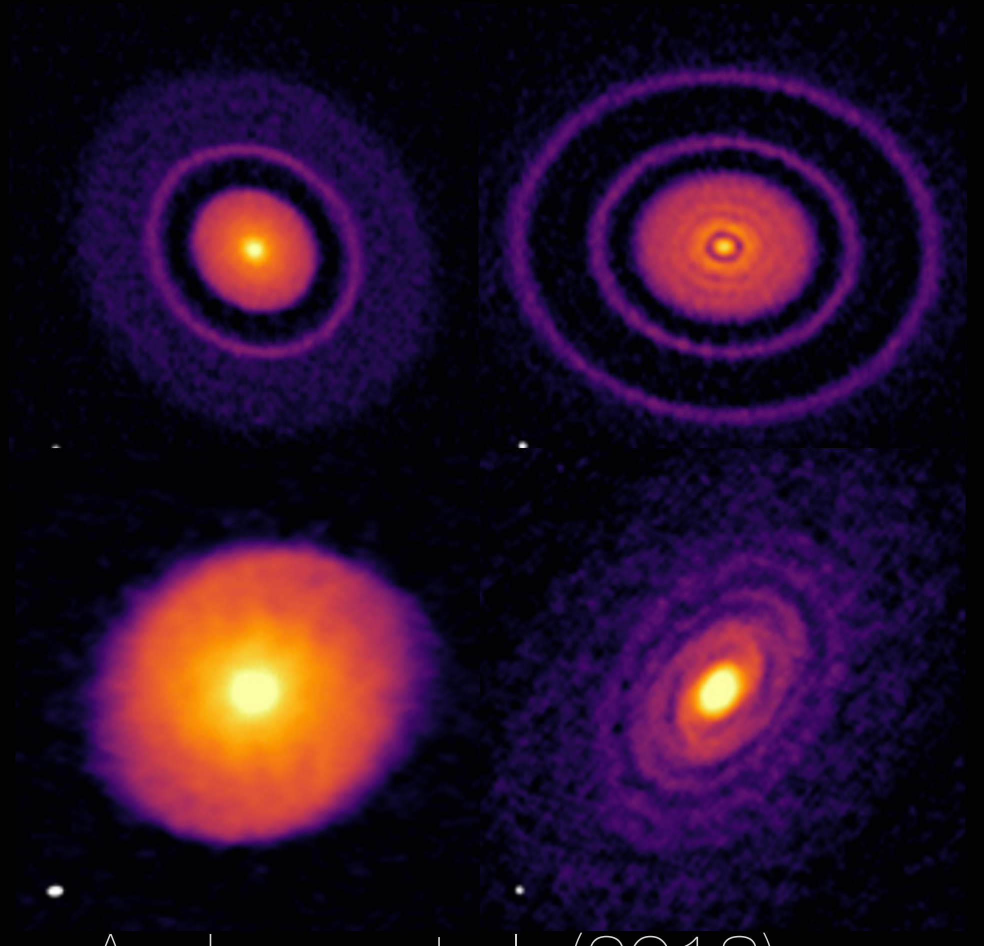
Line sensitivity: ~10 x improvement

Need sensitivity first to boost resolution

Spatial resolution: factor ~ 3 x improvement to resolve 1 AU @150 pc

Isella et al. 2016; McGregor et al. 2017; Benisty et al. 2021; Oberg et al. 2021; Pinte et al. 2023; Booth et al. 2024; Teague et al. 2025

The life cycle of planetary systems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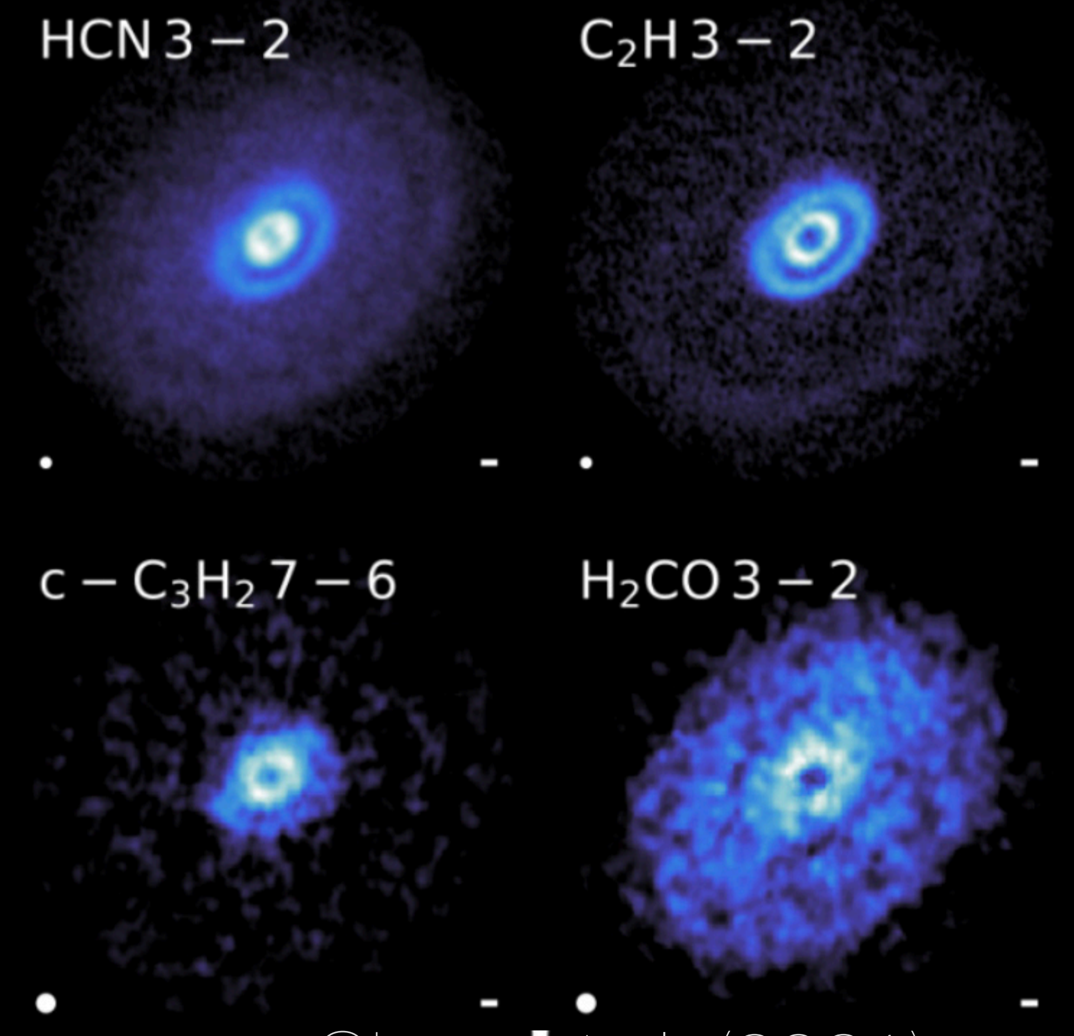
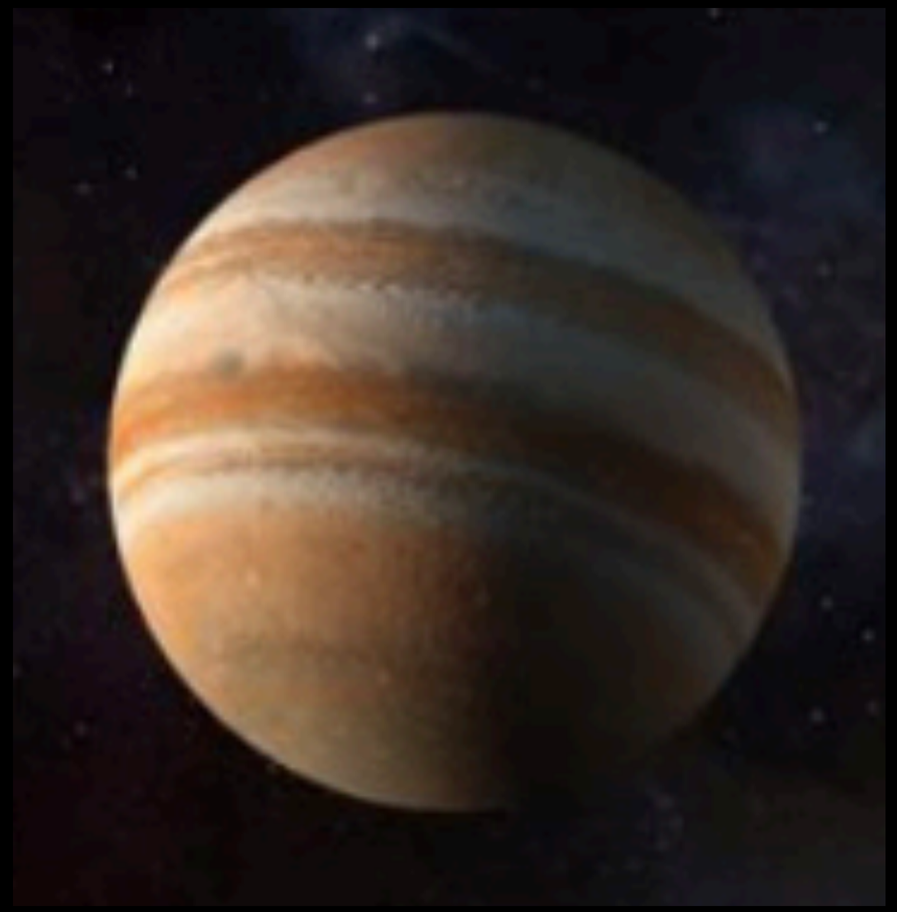
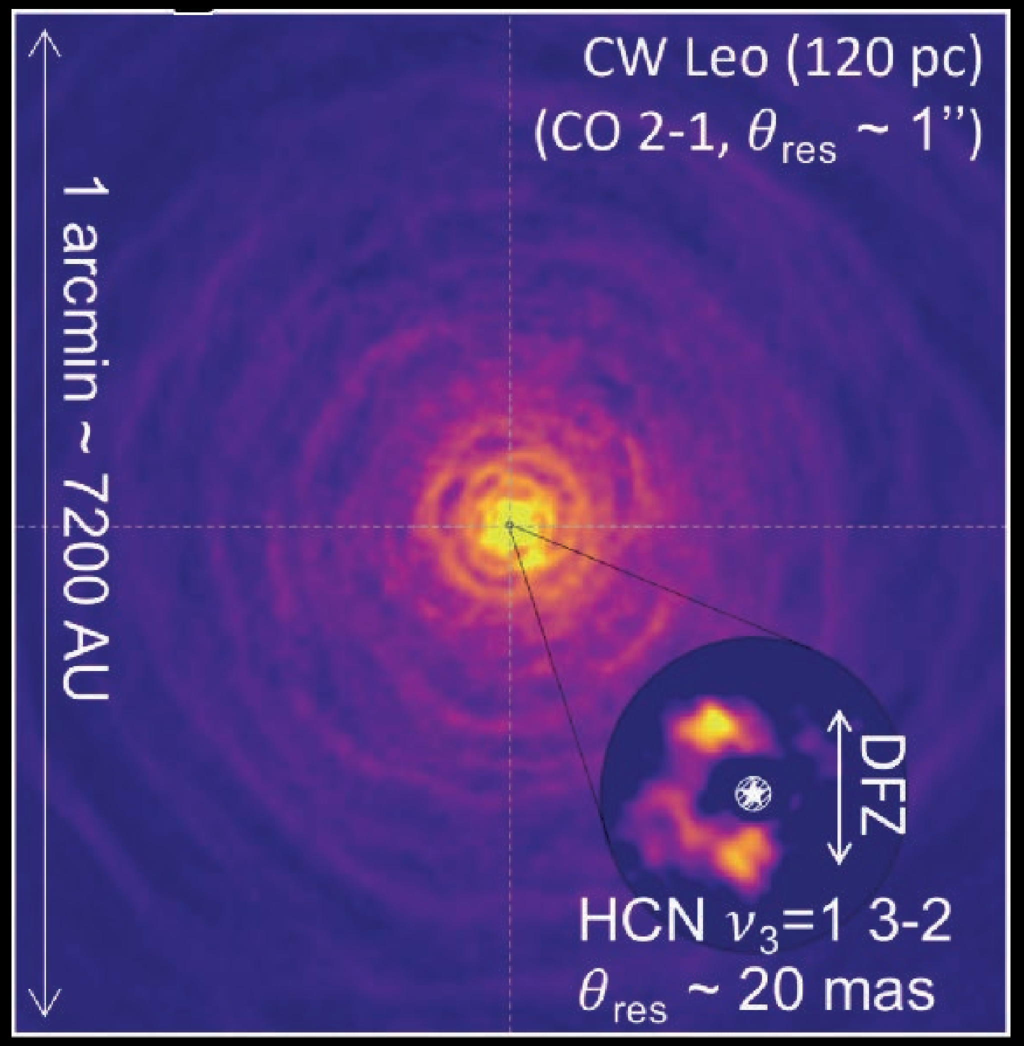


Oberg et al. (2021)

Uncover the emergence of **complex organics** across photo-planetary disks & solar system bodies

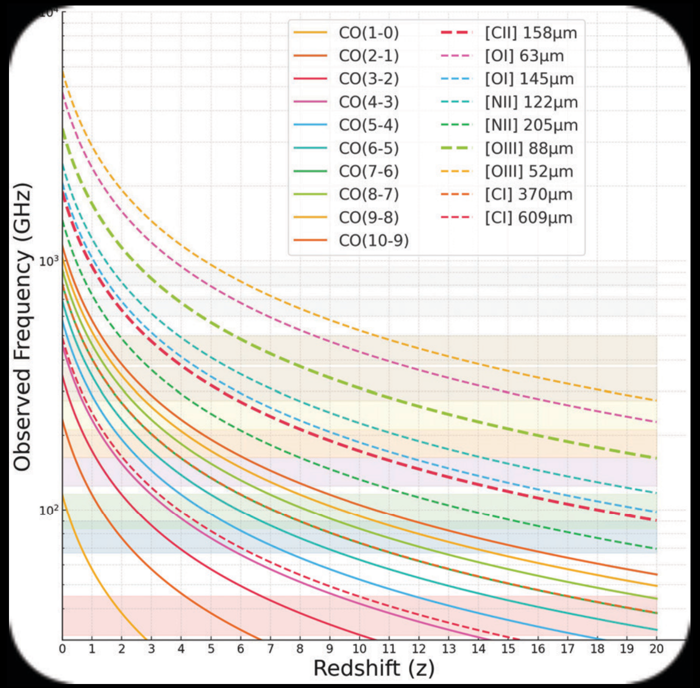


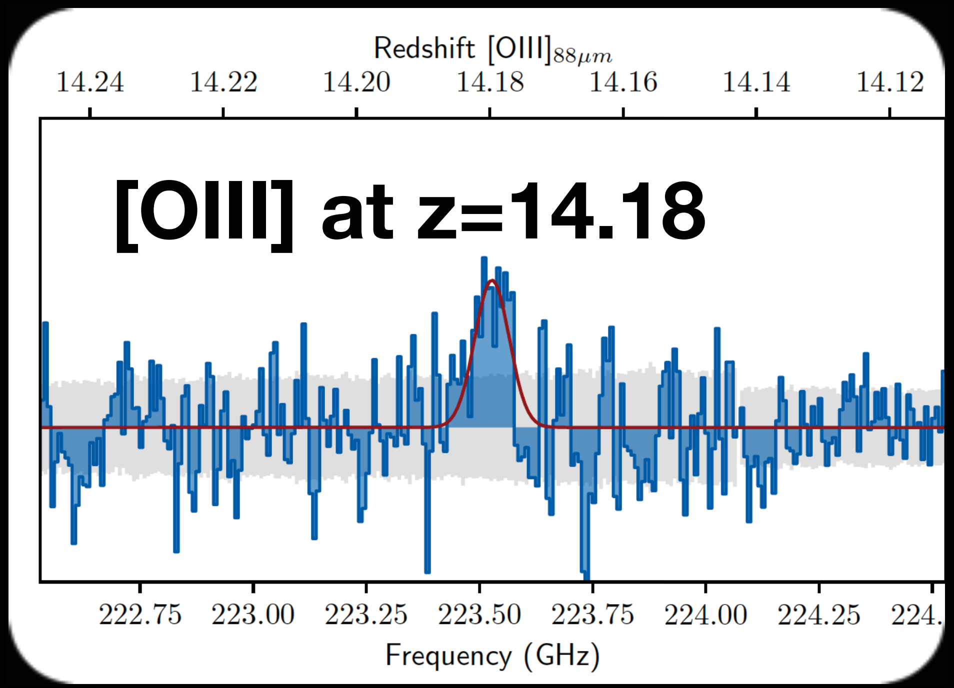
Open a new window into **(exo)planetary physics**



Reveal the impact of **stellar evolution** on the planetary life cycle

The formation and evolution of structures in the Universe

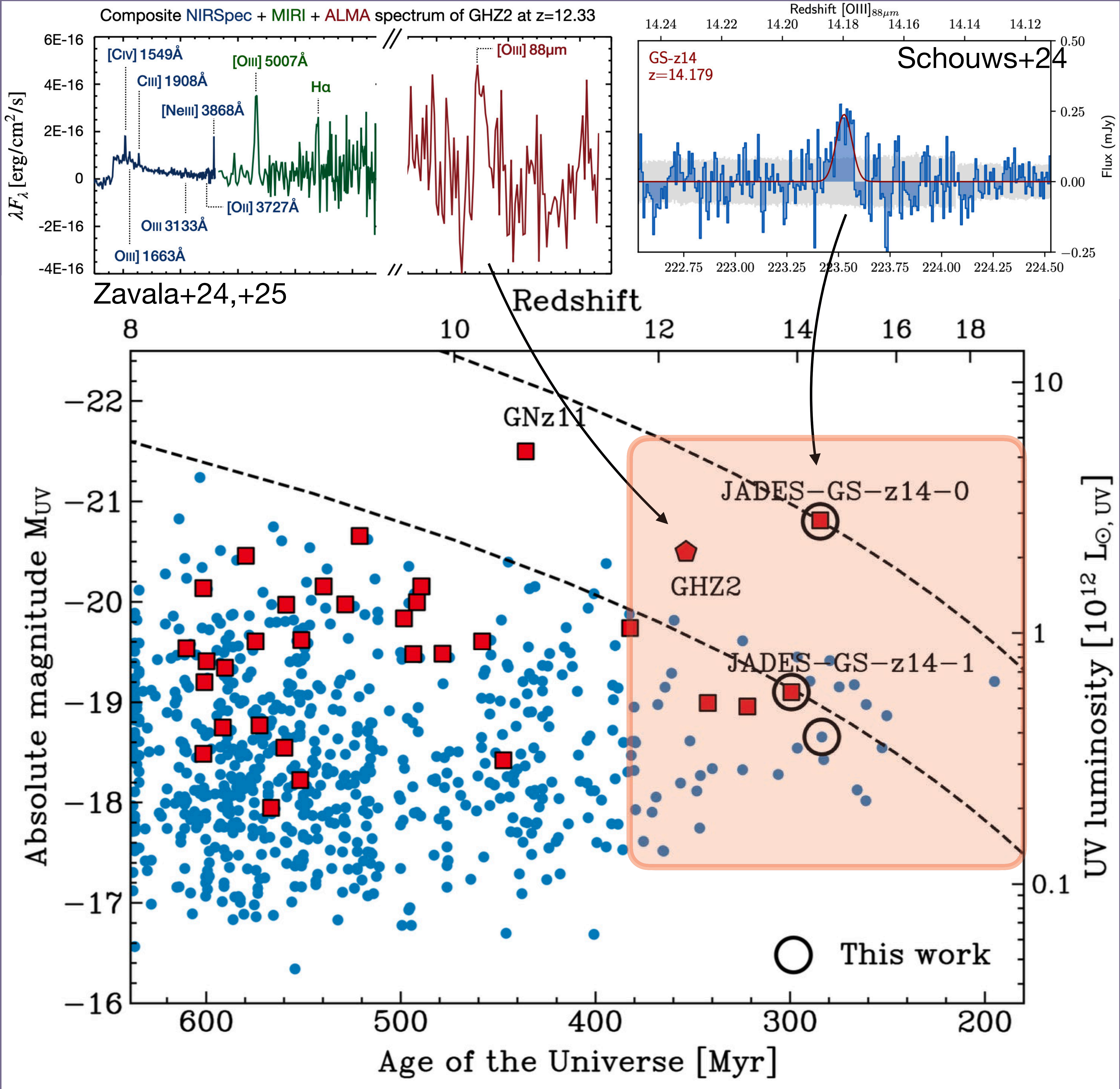




Schouws et al. (2025), Carniani et al. (2025)

Study the evolution of **galaxies** and **their environments** from the early Universe to today

Characterise galaxies in the early universe, out to z≈20



What are the properties of the interstellar medium in proto-galaxies at z > 10 (first 400 Myr after the Big Bang)?

➡ detecting dust and FIR emission lines

In what ways do the small-scale processes of gas and star formation influence galactic structure and the overall evolution of galaxies?

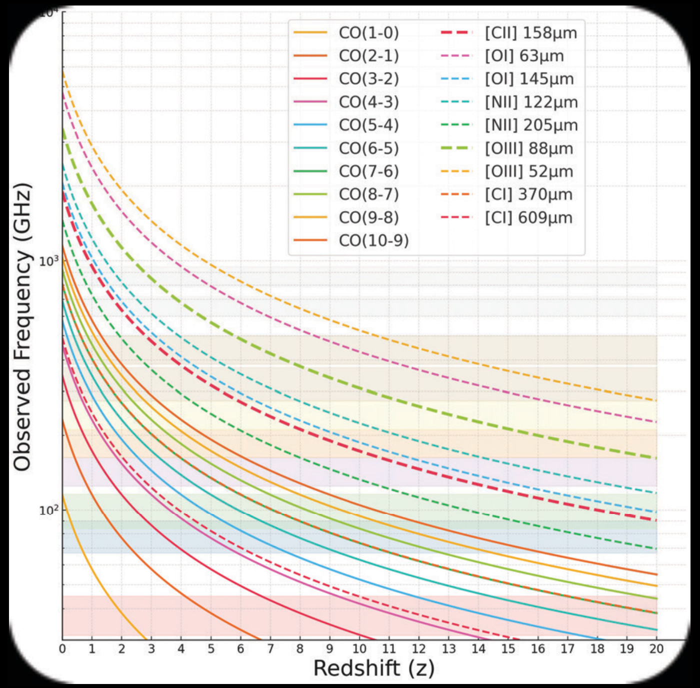
➡ spatially resolved observations of gas emission lines and dust up to z ~ 7 (90% of cosmic history)

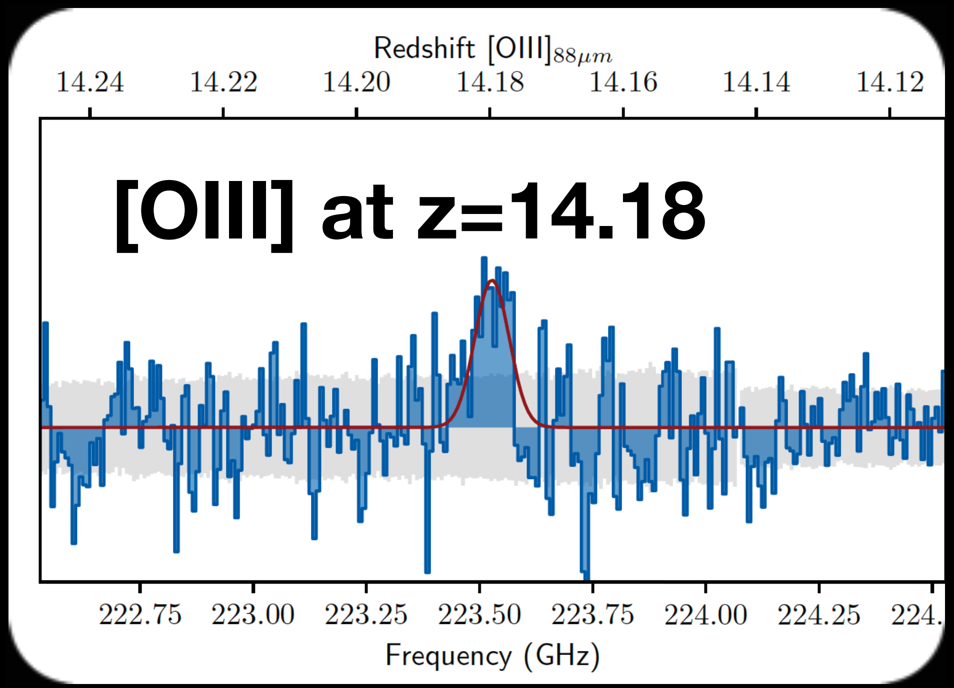
Increasing the line sensitivity by a factor 10x will allow for:

- Detecting [OIII] line at z = 14 @ 1'' in 22 min (vs 38 hours)
- Resolving CO(3-2) at z ~ 2 @ 0.05'' in 20 hours (vs 2000 hours): from brightest objects to the bulk of galaxy population

Slide courtesy of T. Bakx & F. Rizzo

The formation and evolution of structures in the Universe





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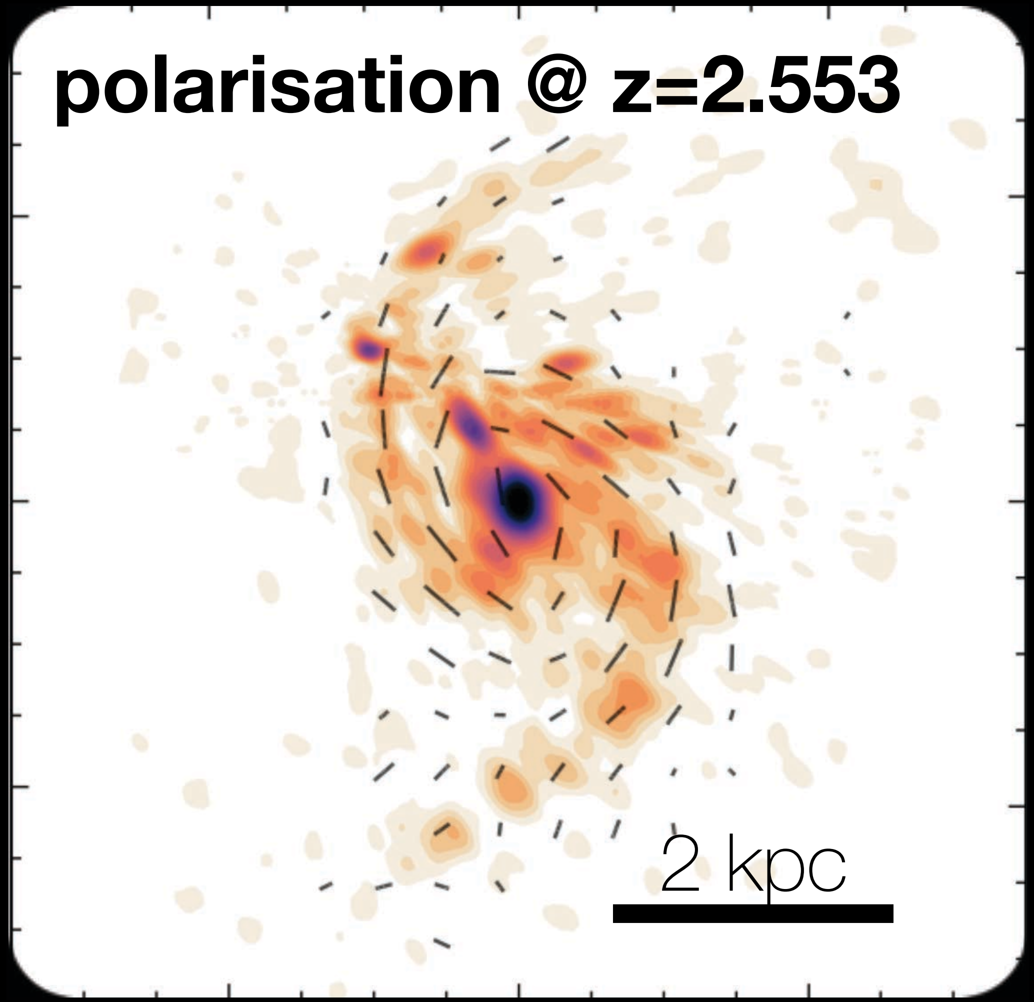
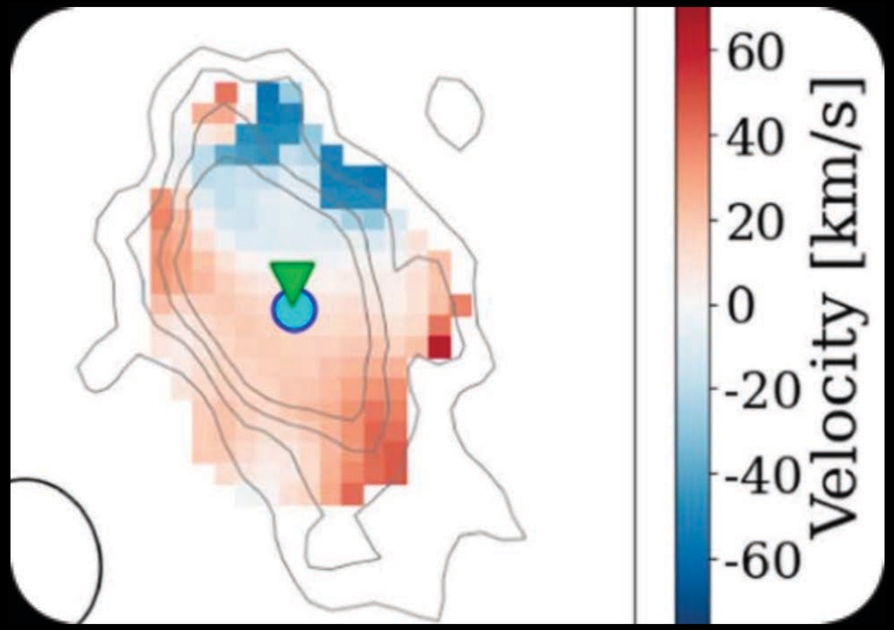
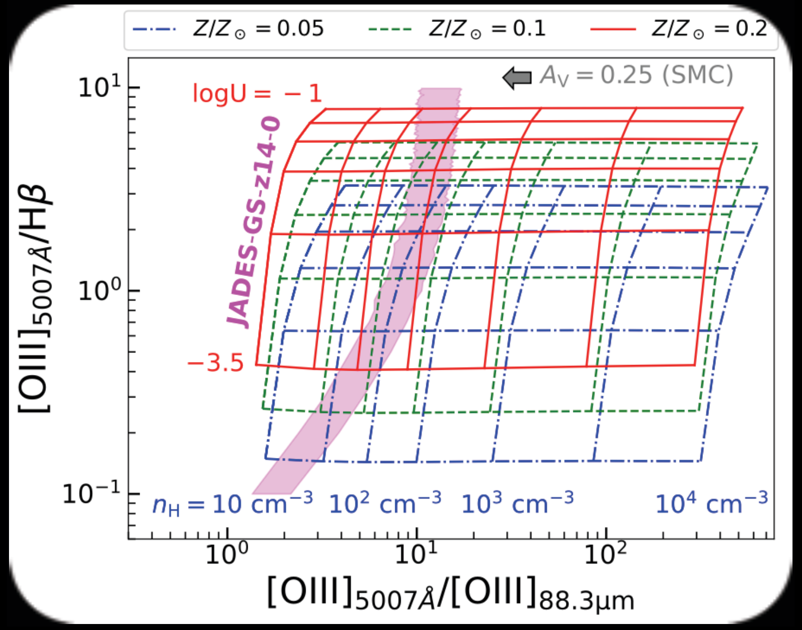
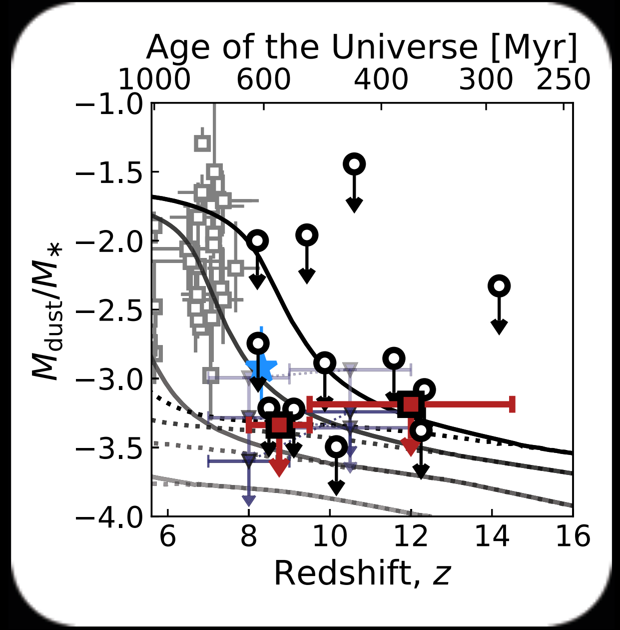


de Roo et al. (2024)

Uncover the emergence and impact of **black holes** and **magnetic fields**

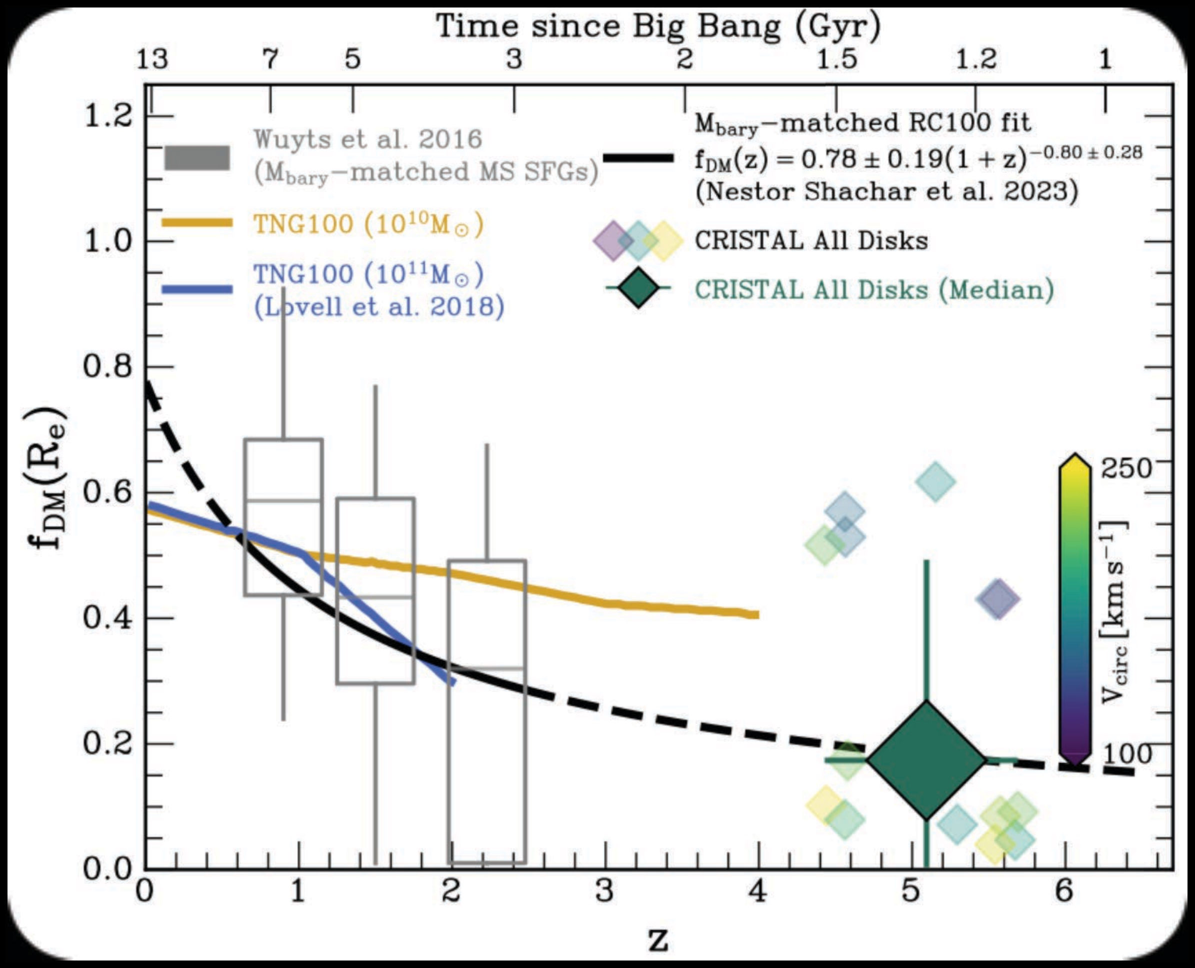






Ciesla+21; Tokuoka+22; Carniani+25; Schouws+25; Bakx+in prep

Characterise the physical conditions of **(primordial) galaxies** out to z=20



Lee et al. (2025)

Measure the **dark matter haloes** (of Milky Way) progenitors across cosmic time

Evolution of the cosmic baryon cycle in galactic ecosystems across cosmic time

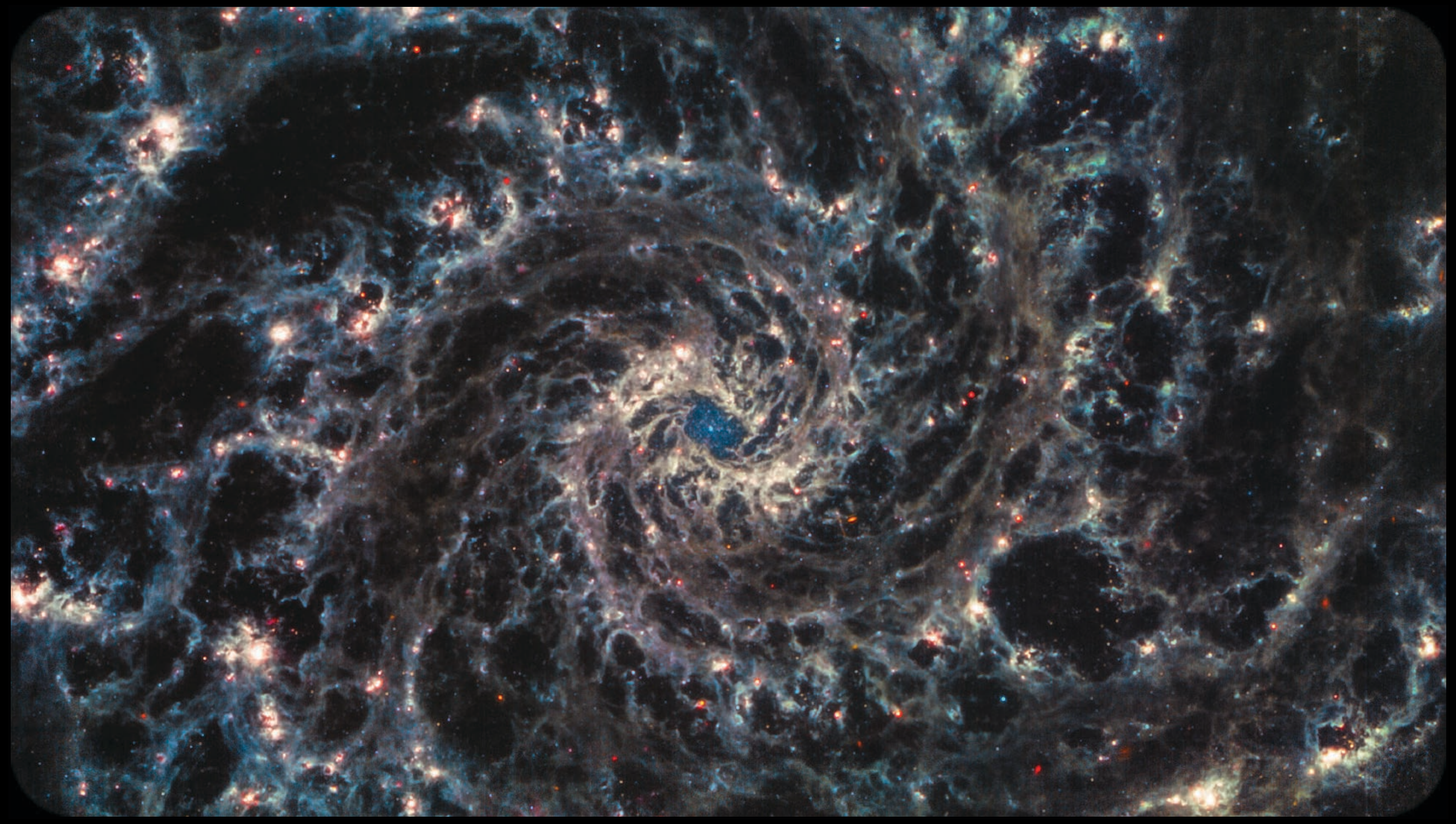
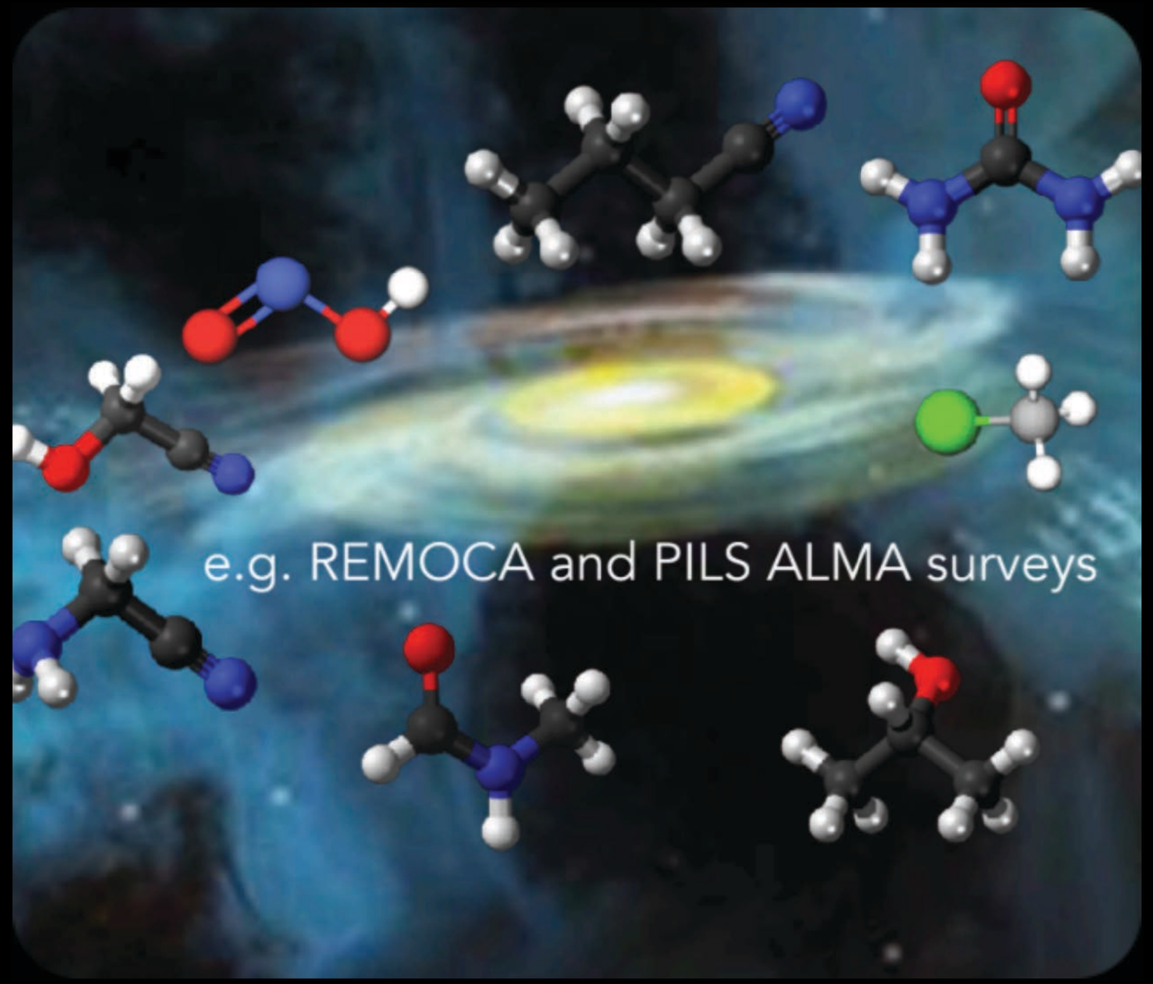


Chart the evolution of the **star-forming interstellar medium** across cosmic time

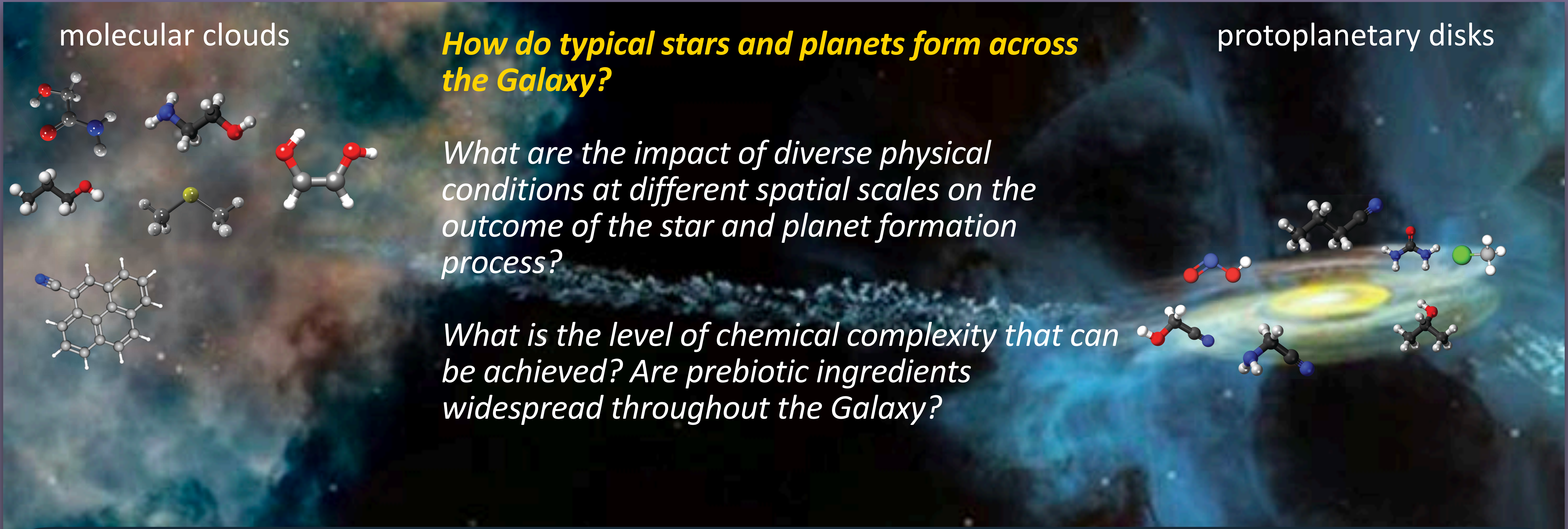
Lee et al. (2023)



Uncover the origin of **chemical complexity** that led to life

ALMA surveys, e.g. REMOCA, PILS

Uncovering the chemical complexity that led to life

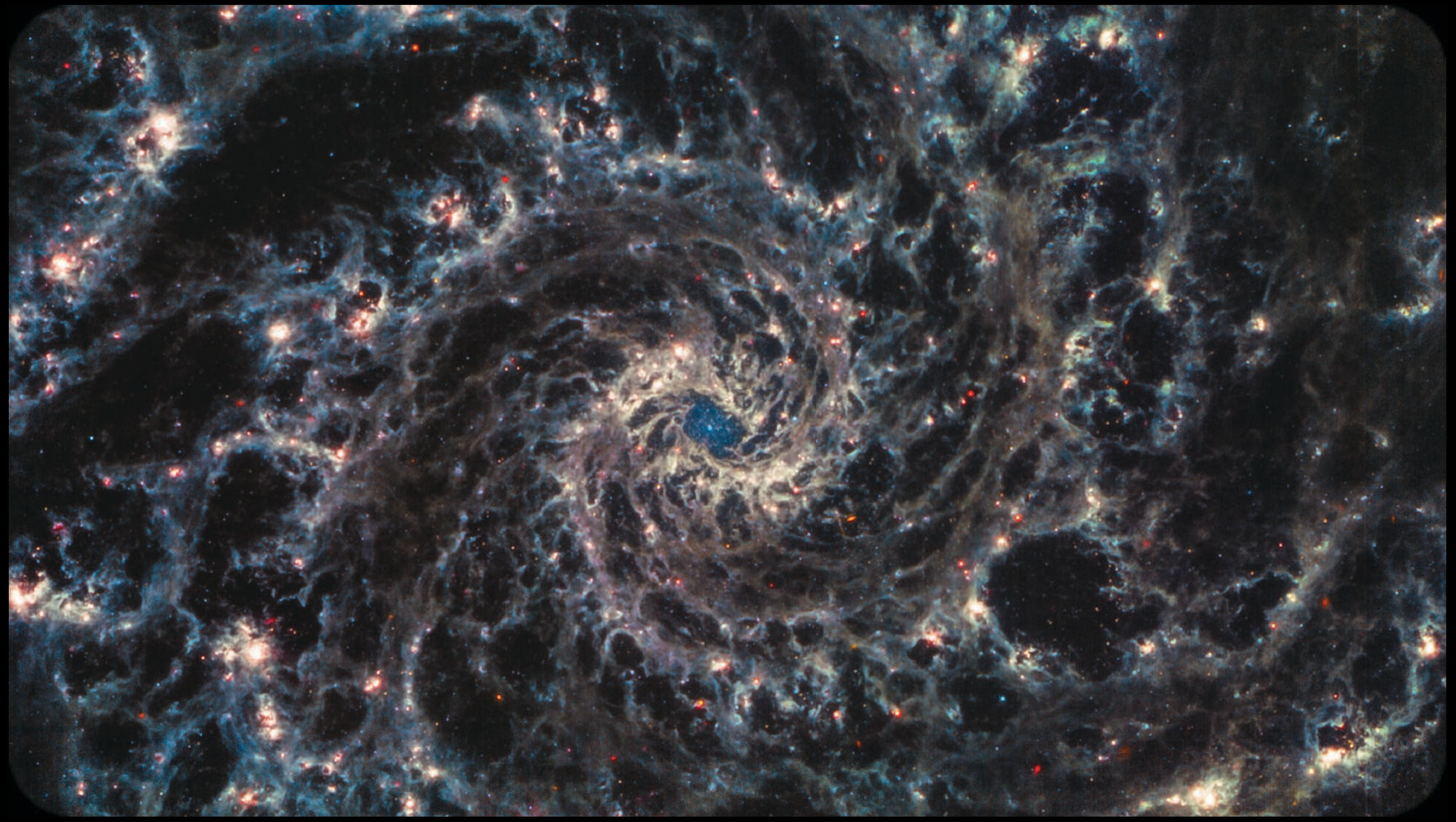


ALMA 2040

- Higher sensitivity and larger FOVs: fast surveys of many sources and detection of rare molecular species, including e.g. nucleobases
- Studies of star formation and planet formation in diverse Galactic environments.
- Origin and inheritance of chemical complexity and importance of conditions in natal molecular clouds.

Slide courtesy of M. Beltran & J. Jørgenson

Evolution of the cosmic baryon cycle in galactic ecosystems across cosmic time



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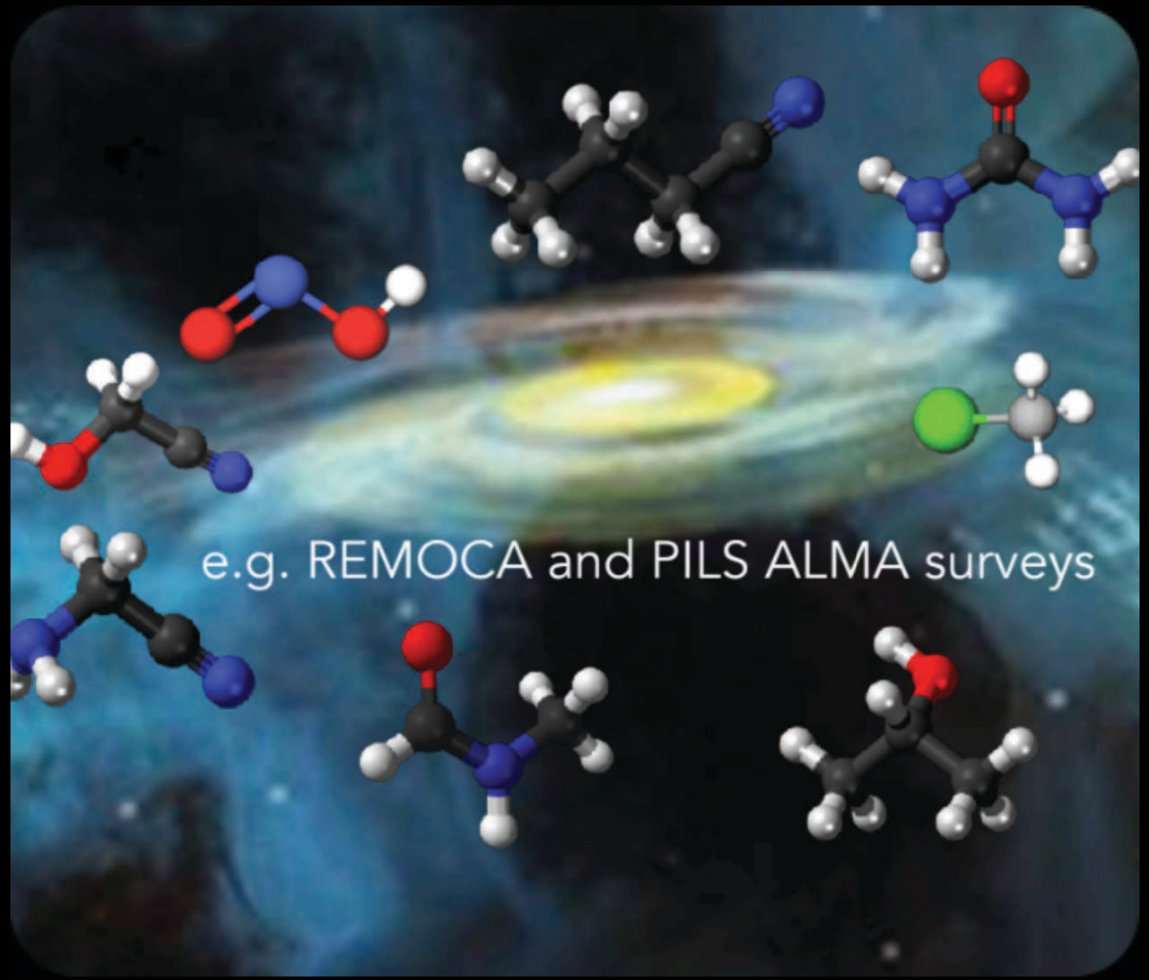

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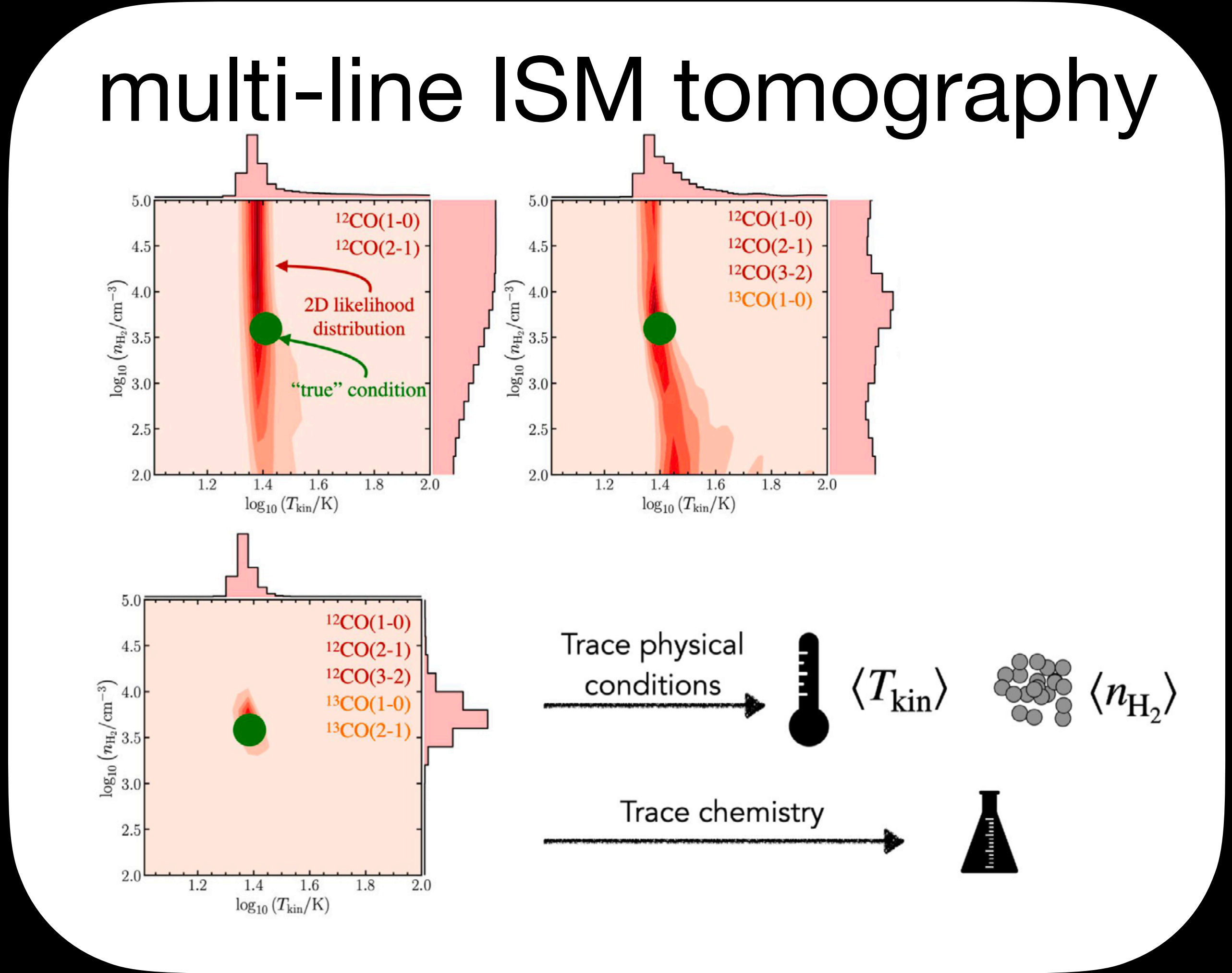
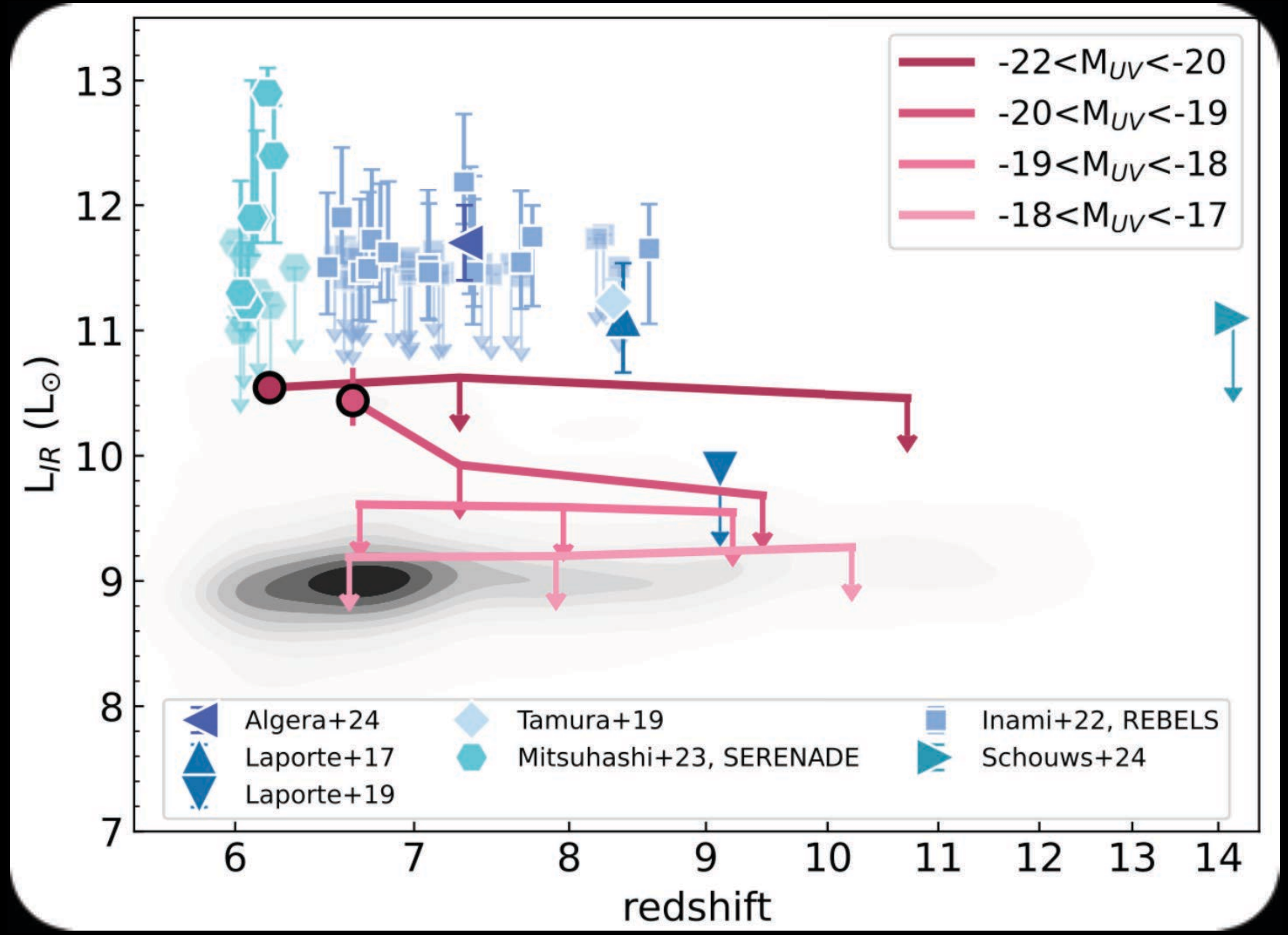


Characterise the **multi-phase gas** in and around galaxies

courtesy: J. den Brok, M. Querejeta

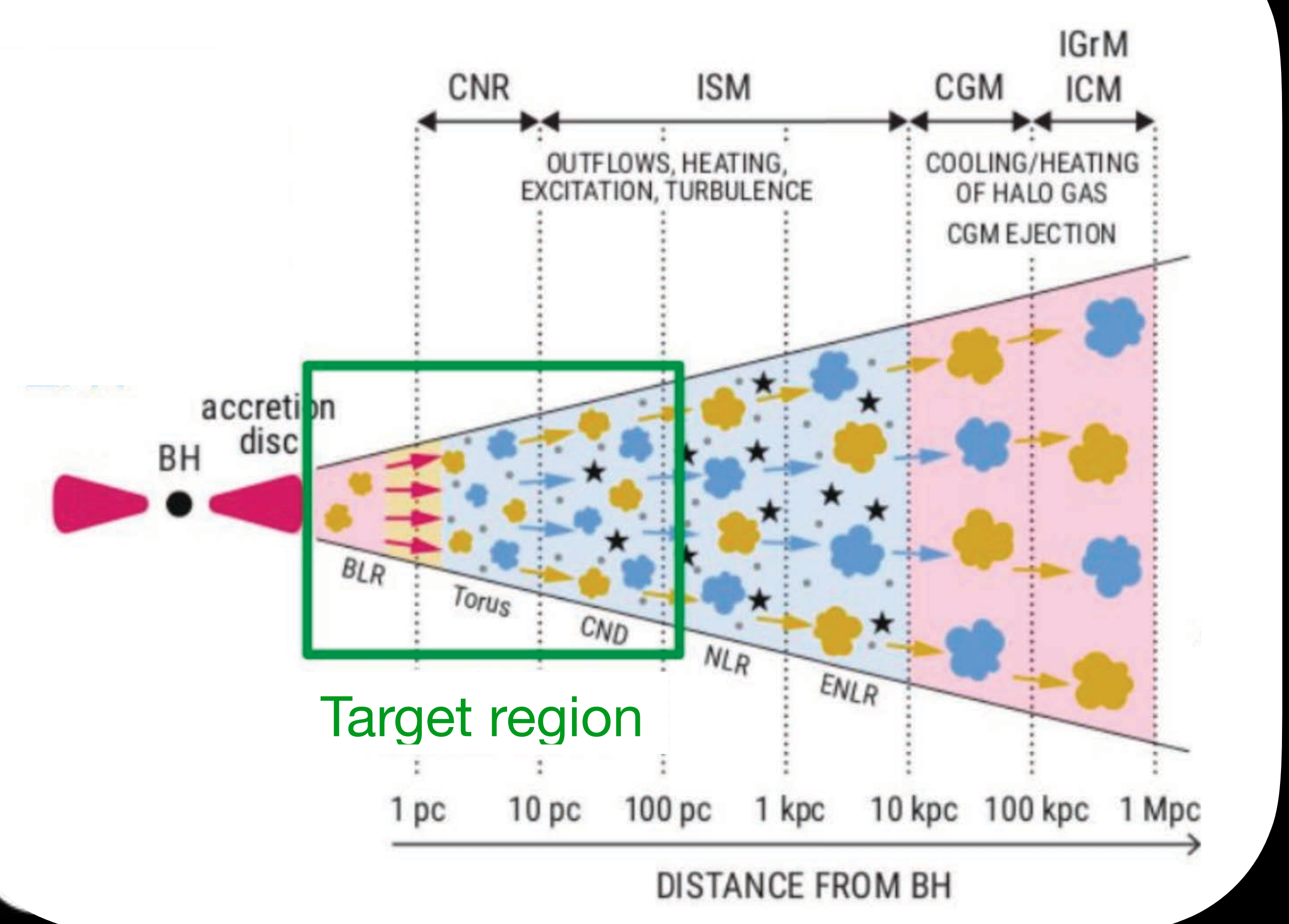


Reveal the origin of the **very first dust** and follow the pathways of **dust production**

Ciesla et al. (2025)

Understanding cosmic explosions, accelerations, and their engines

Super-massive BH & its *dusty molecular torus*



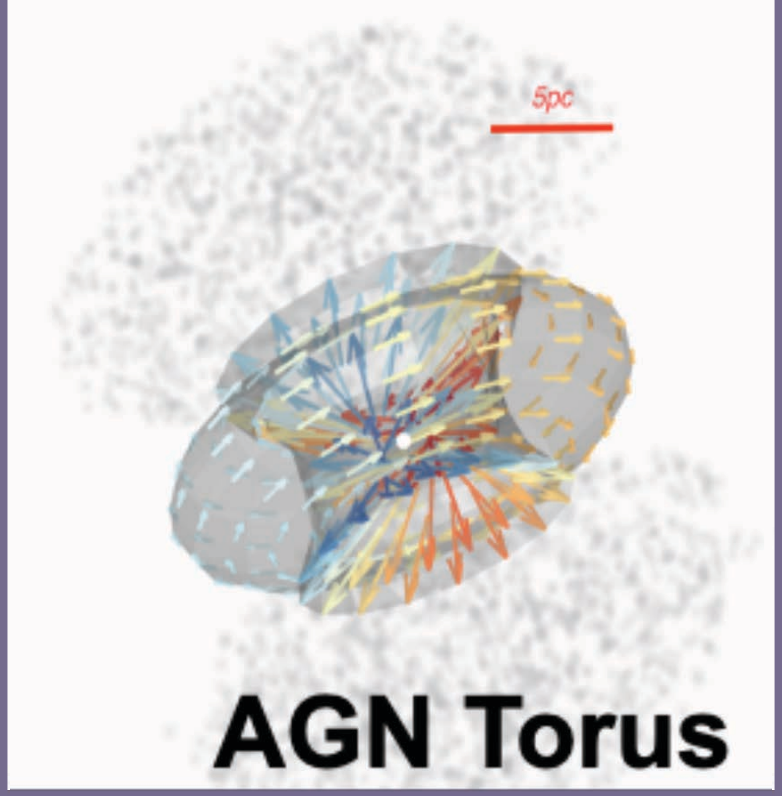
Harrison & Ramos-Almeida (2024)

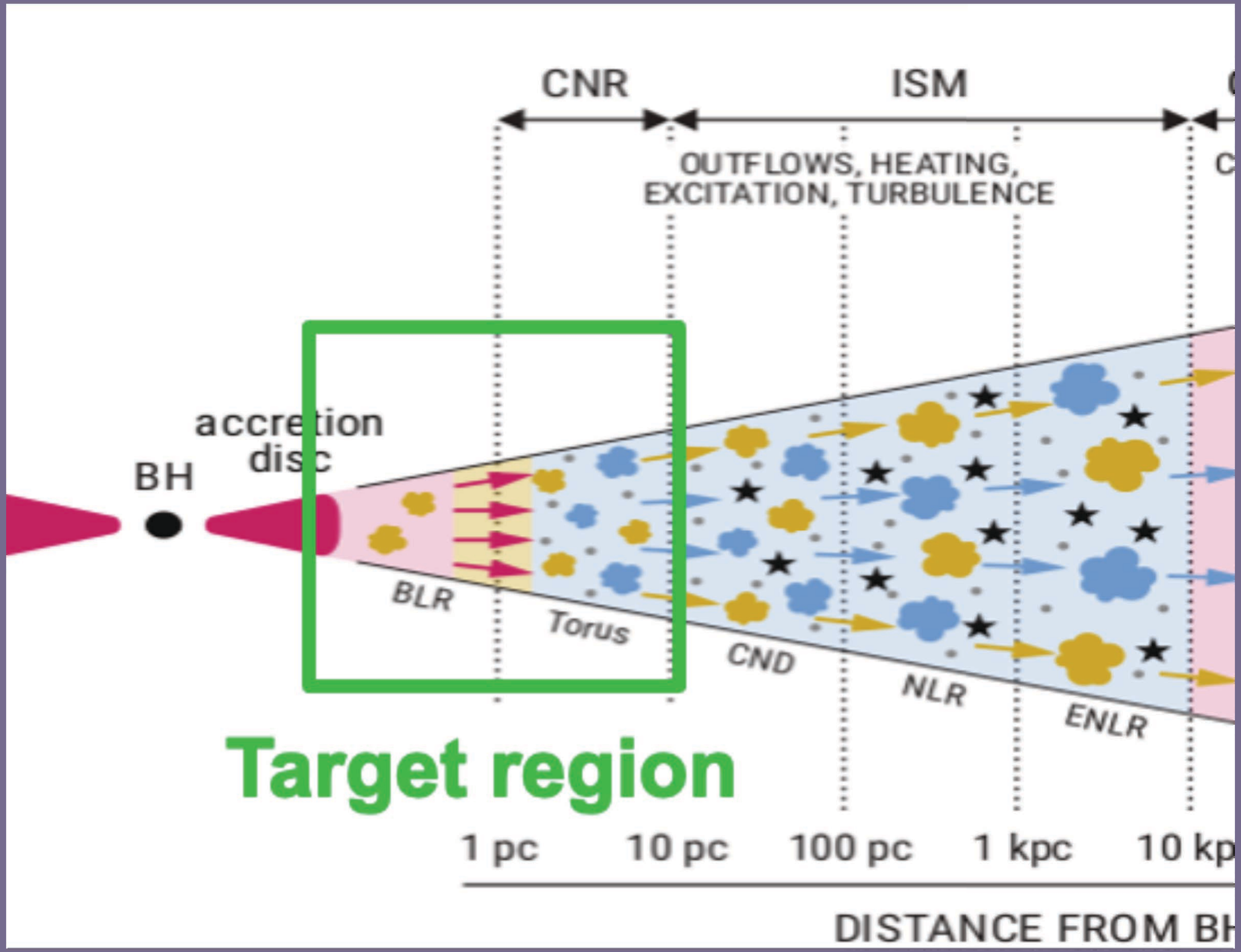
Resolve the **feeding of active super-massive BHs** & their feedback (from torus to accretion disk) over cosmic time

Supermassive Black Holes and Galaxy Evolution

SMBH growth. How material reaches the accretion disk? *Feeding*

SF quenching. How massive outflows are launched by AGN? *Feedback*





Molecular gas kinematics – angular momentum transport – within Torus and CND:

1. *Feeding*: Fraction of material reaching accretion disk
2. *Feedback:* Outflow launching mechanism and efficiency

ALMA2040 4 mas @ 300 GHz and x5 sensitivity

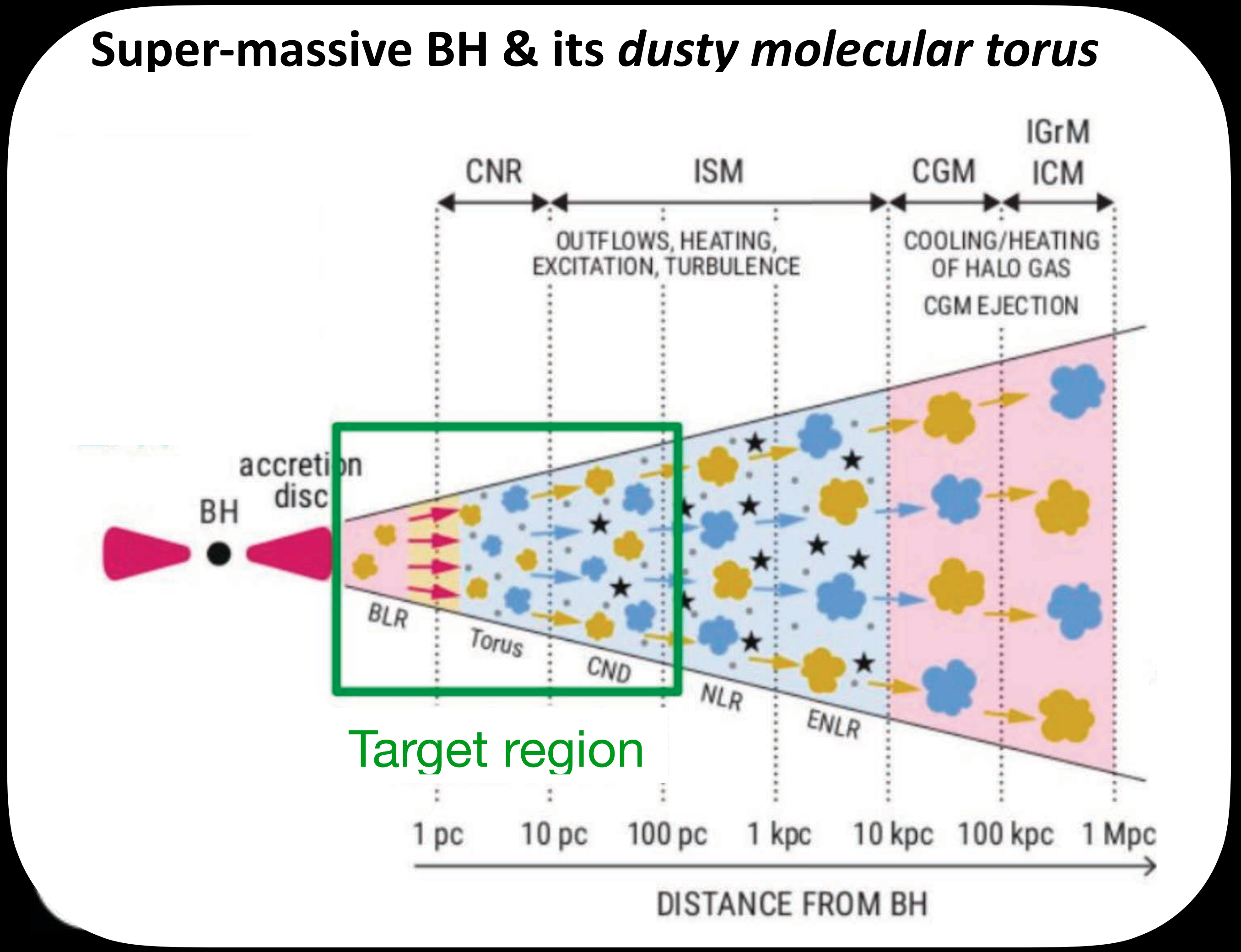
Nearby AGN Torus kinematics down to dust sublimation radius

Local QSO 1st time resolved torus. Extreme feedback & feeding

Up to z~6 QSO Kinematics of CND, direct BH mass across cosmic times

Slide courtesy of M. Pereira Santaella & R. Decarli

Understanding cosmic explosions, accelerations, and their engines



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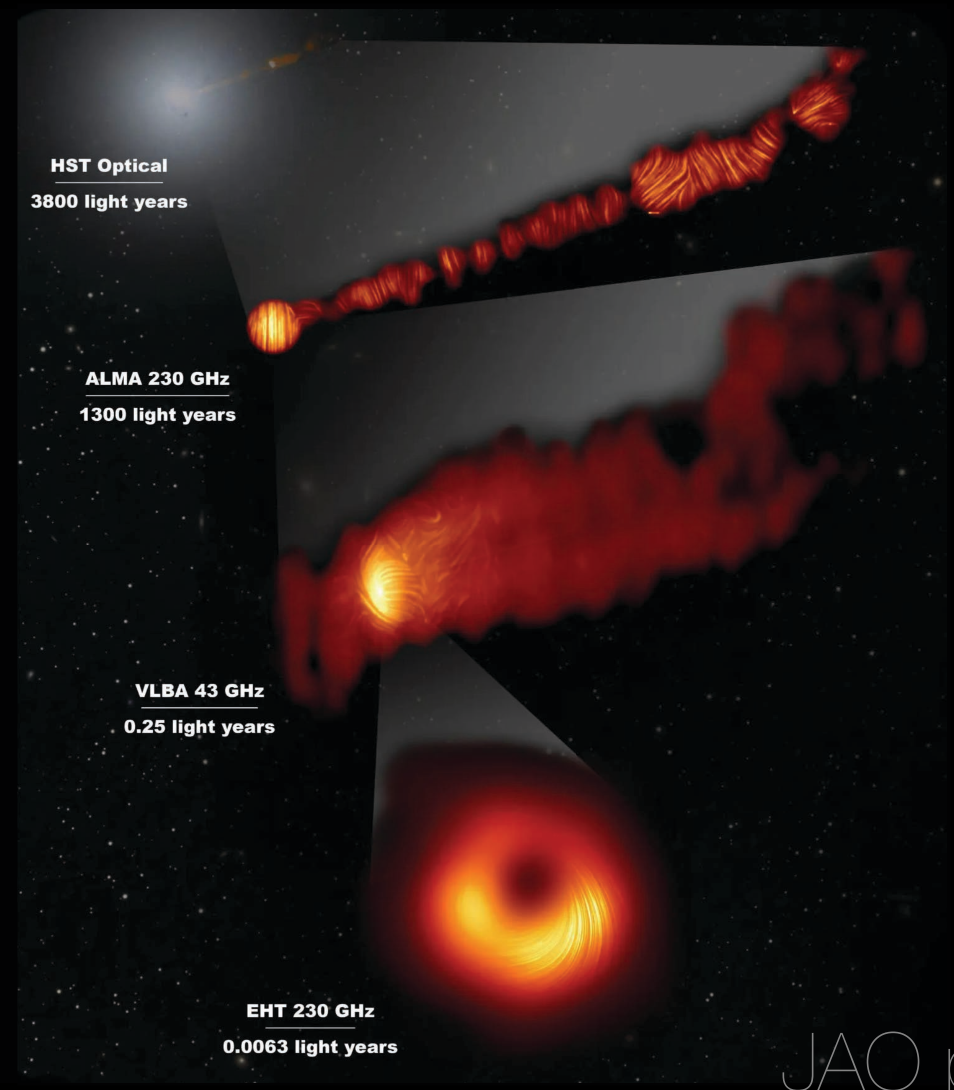
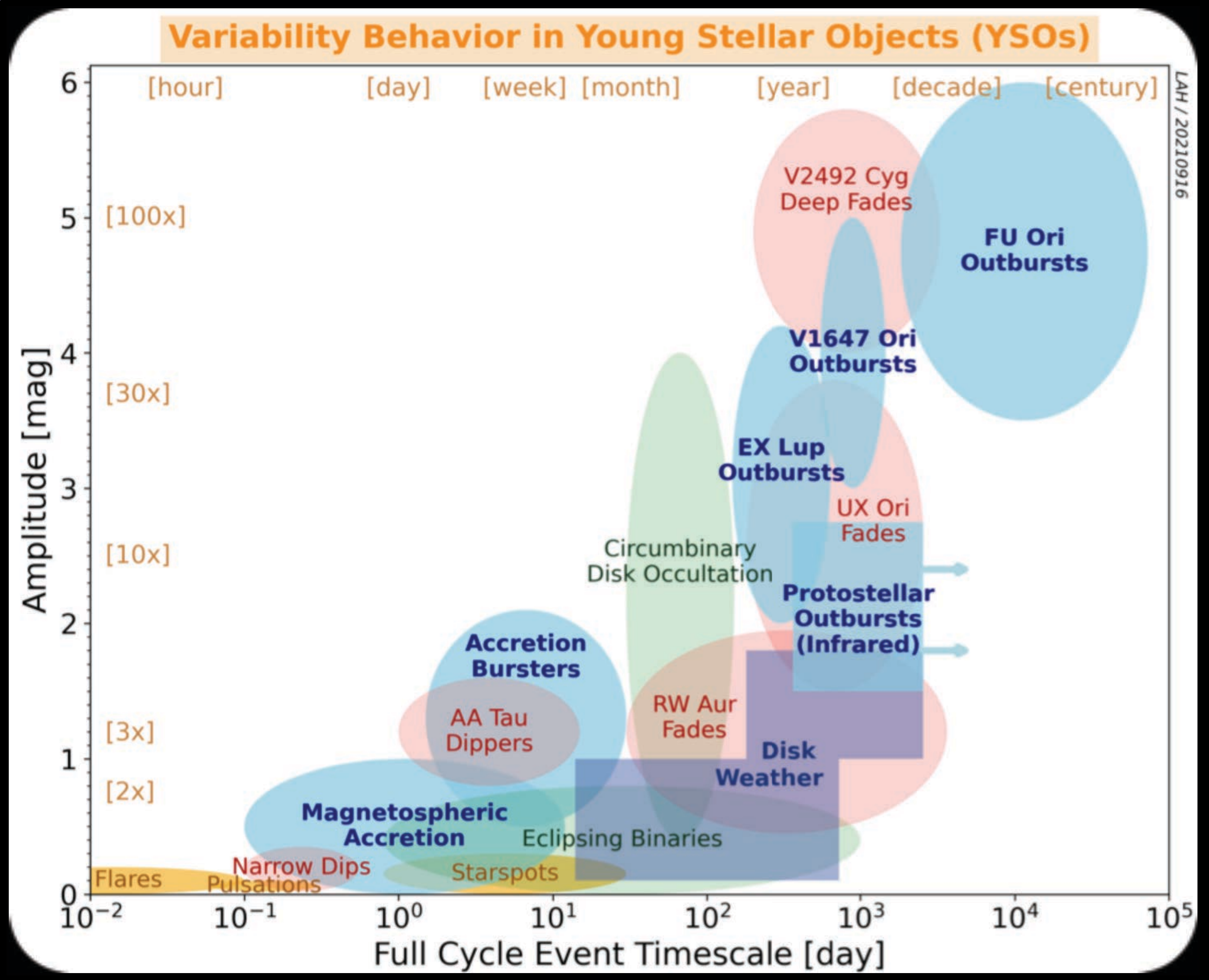


JAO press release (2021)

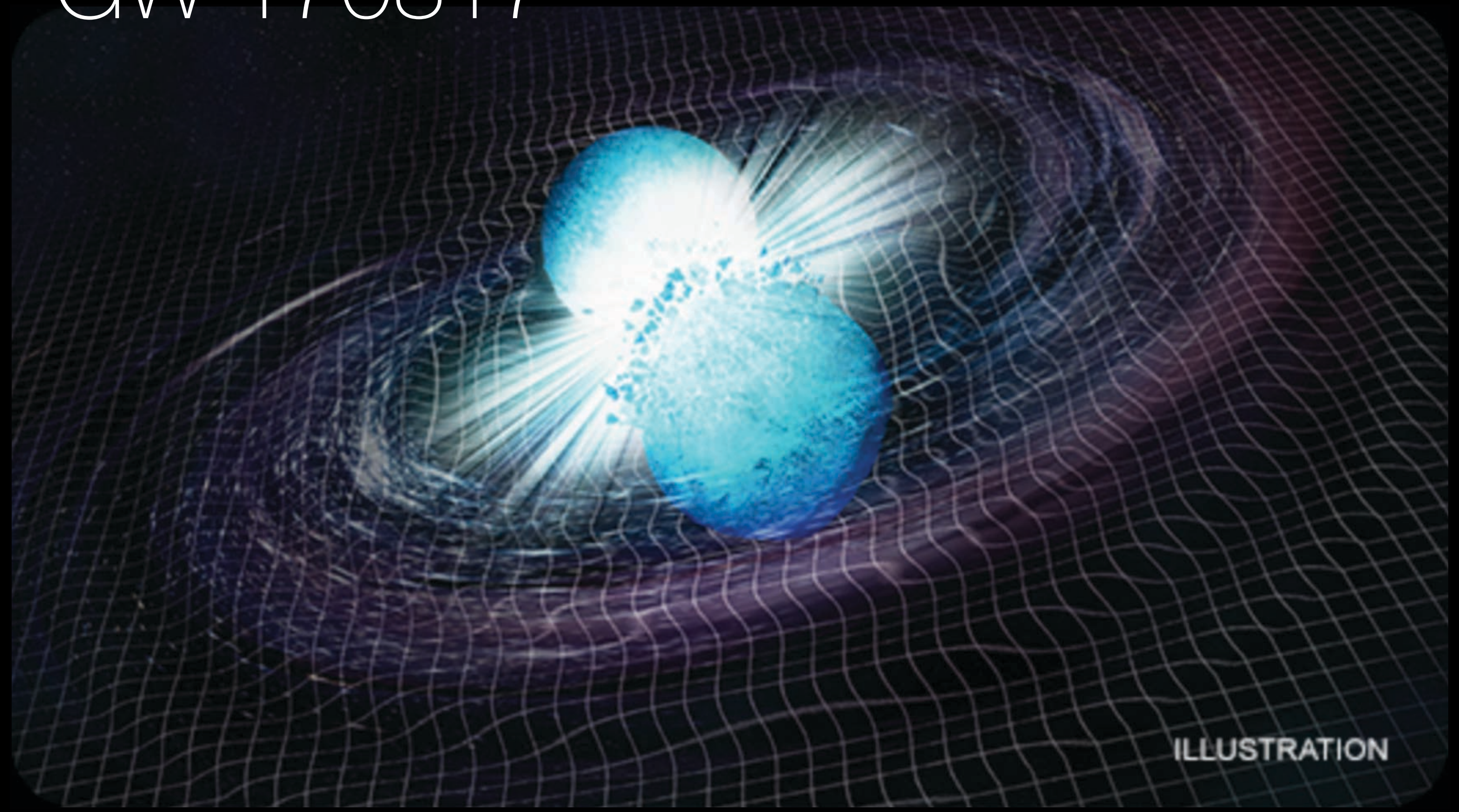
Zoom-in on physical properties of central **super-massive black holes**



Uncover the dynamics and time evolution of **cosmic explosions, jets** and **outflows**

Fisher et al. (2023), PP VII

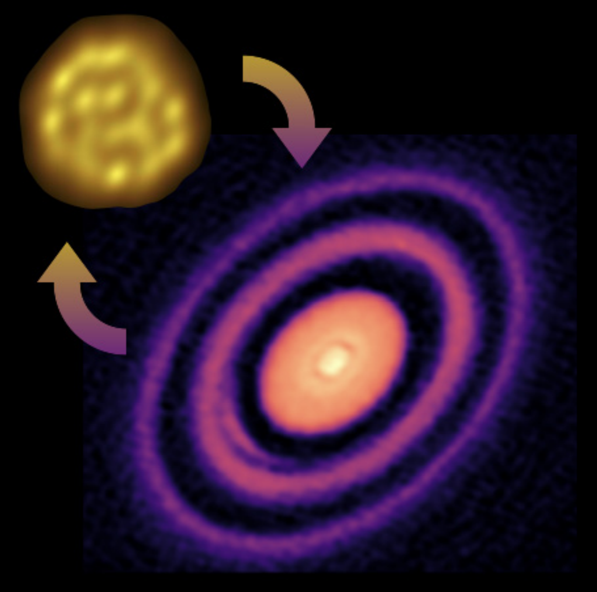
GW 170817



CXO press release (2018)

Follow up and resolve **multi-messenger sources** in the 2040's

ALMA2040 Key Science Drivers



The life cycle of planetary systems & stars

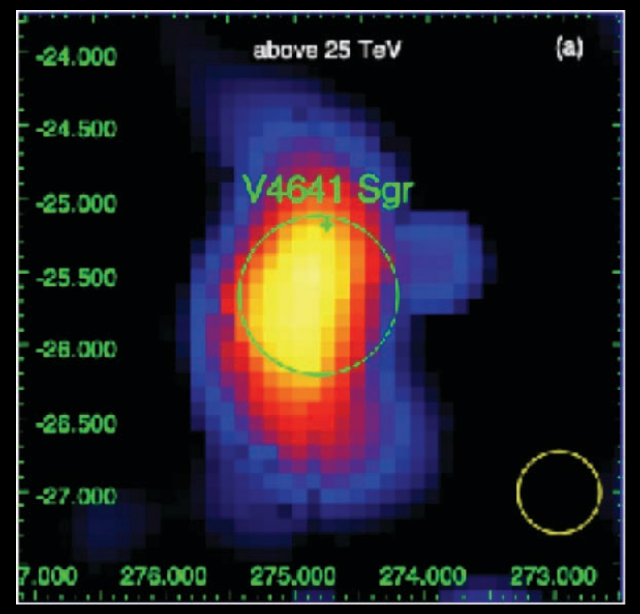
Including the formation of rocky planets down to ~AU scales

The formation and evolution of structure

Including primordial galaxies and black holes out to z~20

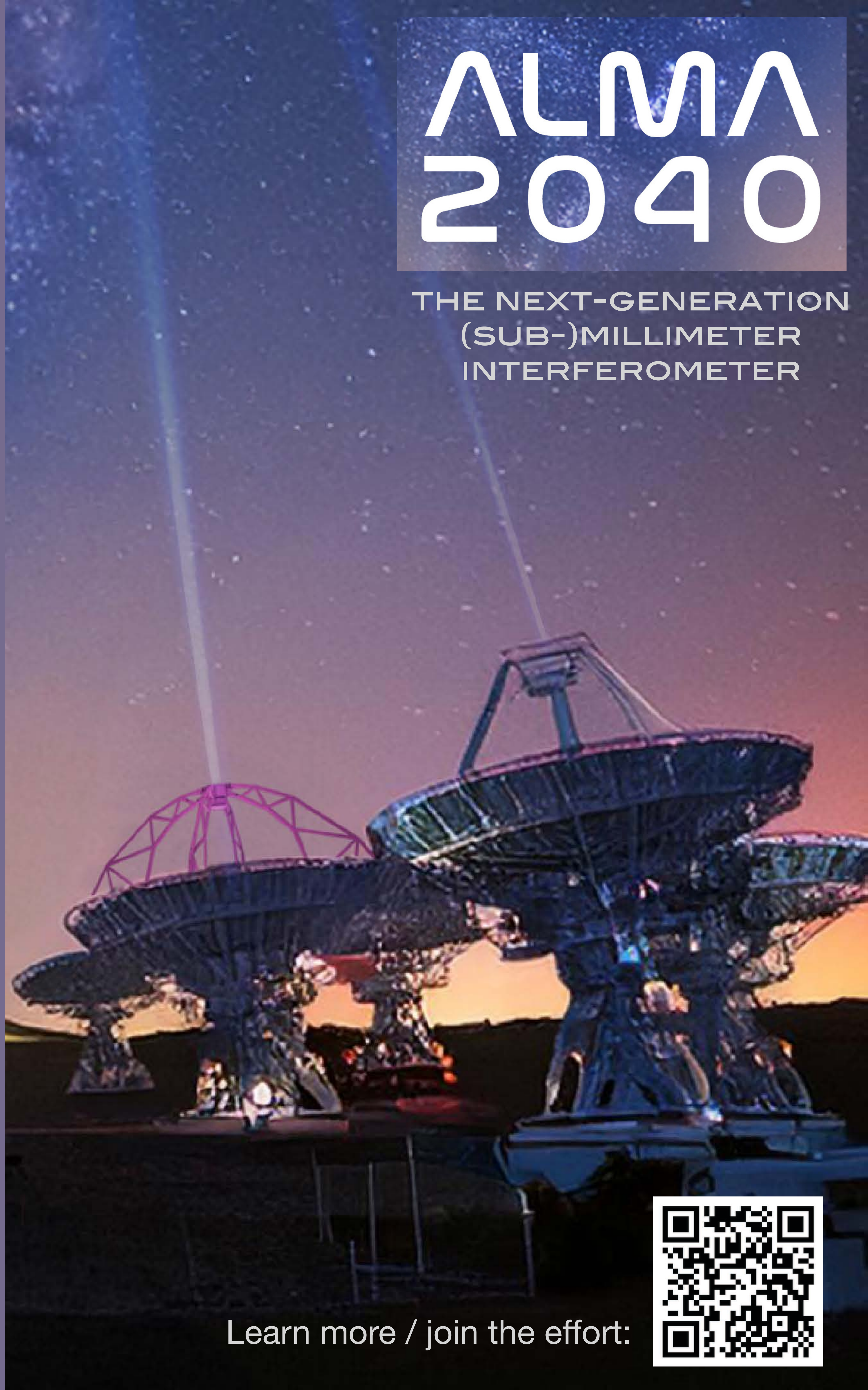
Evolution of the cosmic baryon cycle

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

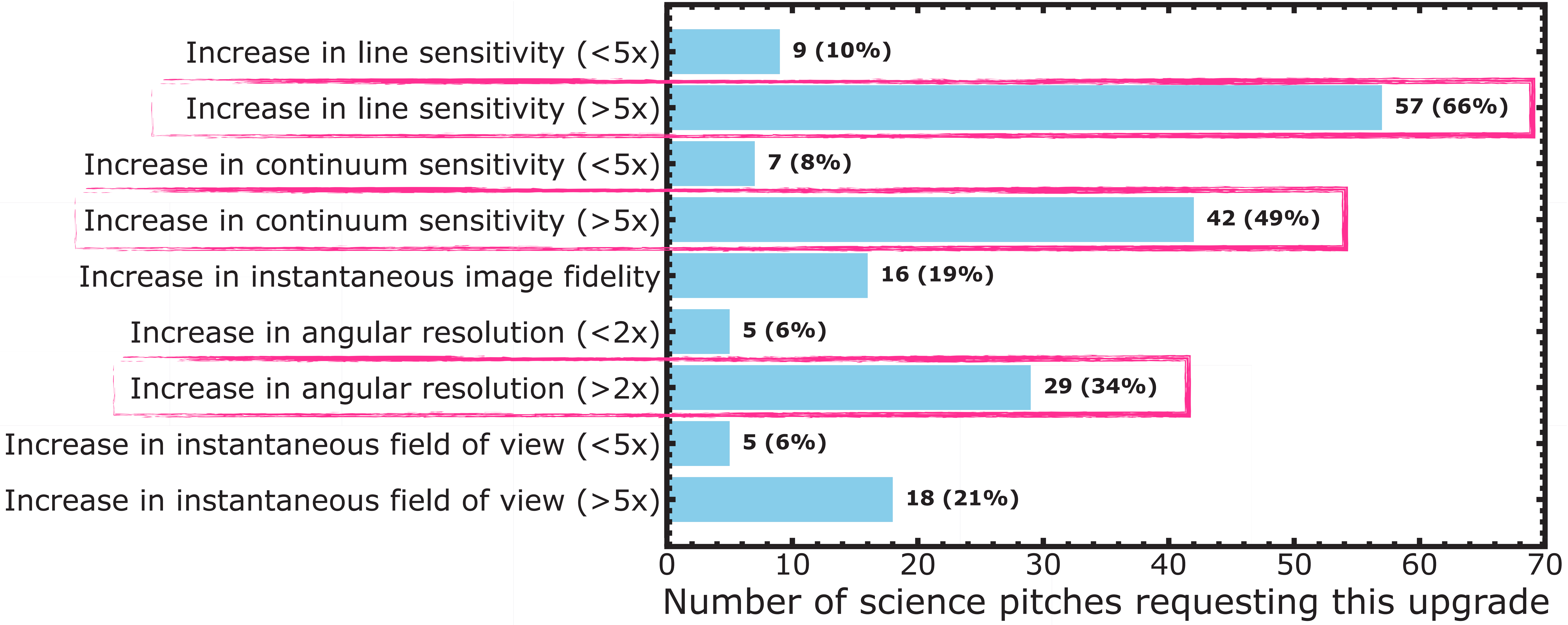


Cosmic explosions and acceleration

Including multi-messenger astronomy in the 2040s



Most required radical upgrades



Increasing line sensitivity by up to a factor of 10

- **moderate (~20-30%) improvements for receivers (frontend + backend)**

- **substantial increase in collecting area:**
  - ~250 antennas;
    scaling from ngVLA achievable for 250 antennas up to ~500 GHz
  - need to evaluate optimal ratio between telescope diameter and cost

3 - 5 times better angular resolution

- **assume fixed array configuration, i.e. no relocation of antennas**
- **use existing infrastructure, i.e. pad locations** (174 for 12-m, 18 for 7-m)
- **potentially possible to move beyond current ESO concession**
- **explore hybrid array options, e.g. large antenna at longest baselines**
- **exploration of extended antenna configurations started**

further technical considerations

- **broad wavelength coverage/wideband receivers** $\Longrightarrow$ improved multiplexing, improved calibration, less receivers (10 $\rightarrow$ maybe 4 receivers)
- **multi-band observations** $\Longrightarrow$ improved multiplexing, improved calibration, possible band-to-band calibration for high frequencies
- **solar observations**
- **polarisation purity (line & continuum)**
- **sub-second time resolution**
- **monitoring and time-sensitive observations**
- **VLBI**

Technical working groups under construction

- **Science and System Requirements Working Group (SSRWG)** led by *Maria Díaz Trígo (ESO)*
  - Set of unified science requirements $\Longrightarrow$ derive high-level system, key performance, technical requirements for guidance to other non-science working groups
- **Instrument Working Group (IWG)** led by ***TBD***
  - Hardware + real-time and monitor & control software, e.g. antenna main structure, antenna optics, receiver architecture, signal transport, real-time signal processing, on-line calibration, instrument monitor & control system
- ***Operations Working Group (OWG)*** led by *Elizabeth Humphries (ESO)*
  - Science operations, multi-messenger astronomy, maintenance operations, cost efficient operations
- **Data Archive & Processing Working Group** led by ***TBD***
  - Off-line data processing, off-line calibration, data archiving, data management, infrastructure for processing, QA & Science Archive

European effort towards an ALMA2040 vision

in 2025

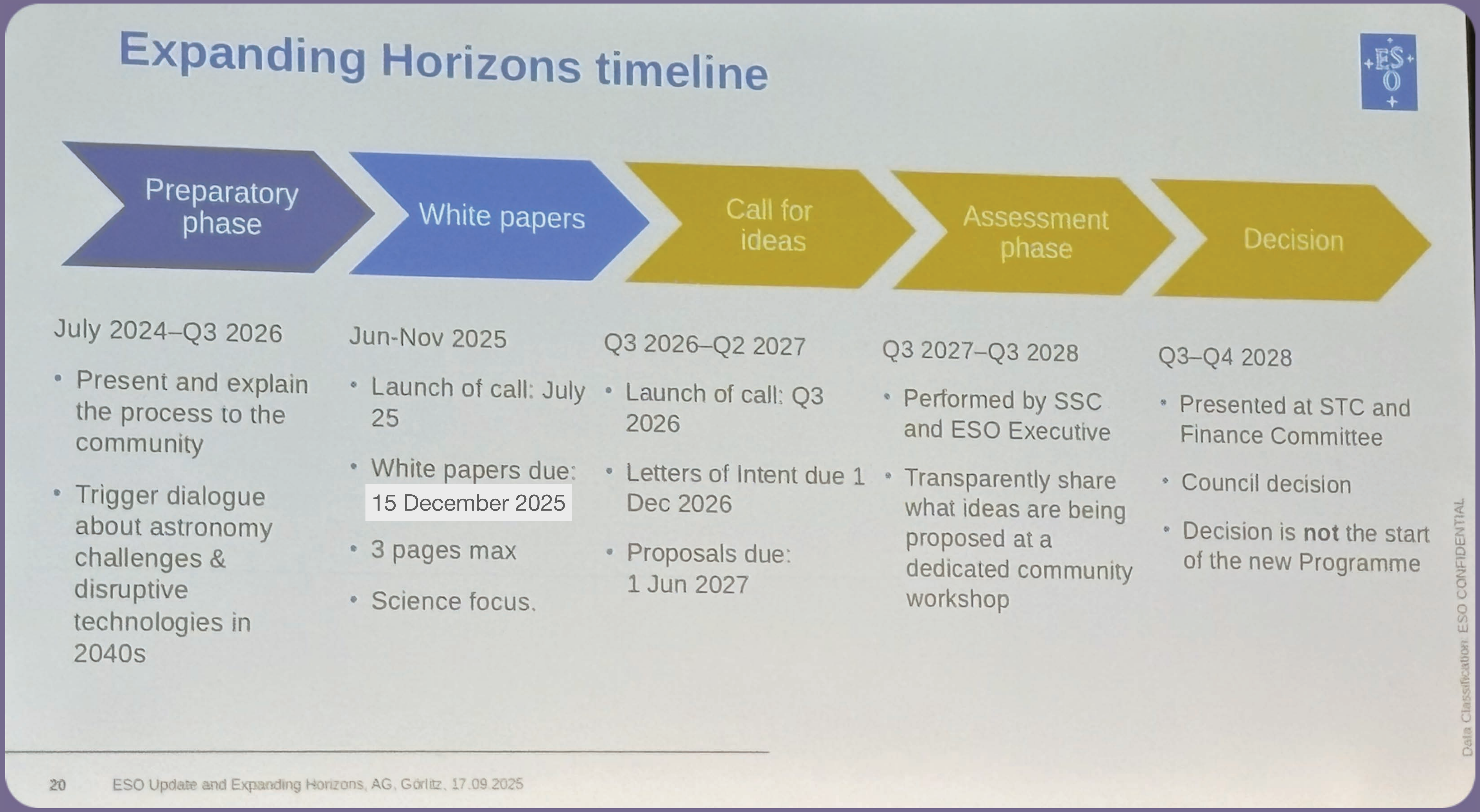
- **Identify primary science drivers**
    - based on 70+ science pitches received in March/April 2025
    - developed further within the 9 science working groups
    - and discussed at 3.5-day workshop in May 2025
- ***Evaluate technical specifications, explore technical opportunities***
- ***Prepare 3-page White Papers for ESO's call (deadline: 2025 Dec 15)***
    - refine key science goals at 3.5 day workshop in November 2025

www.euroalma2040.com

European effort towards an ALMA2040 vision

2026 to 2027 June 1

- collaborate with other ALMA partner communities for a combined ALMA2040 vision
- prepare white papers on ALMA2040 science
- define technical specifications & requirements



from ESO DG's presentation at AG meeting 2025

- submit proposal to ESO's Expanding Horizons Call for Ideas

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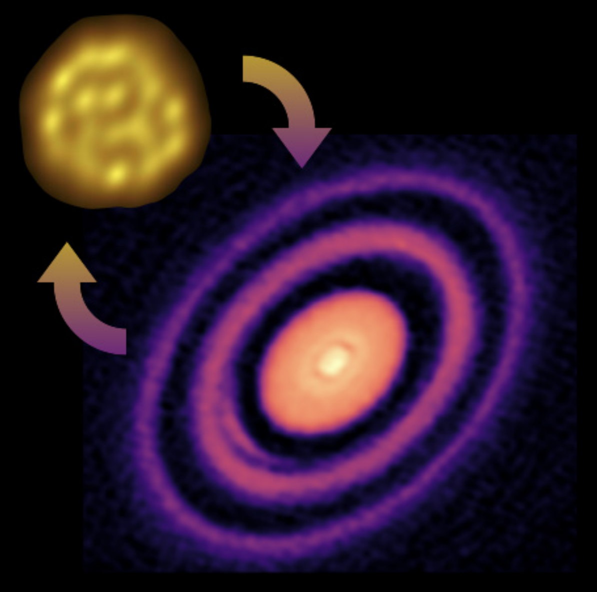
ALMA2040 Key Science Drivers



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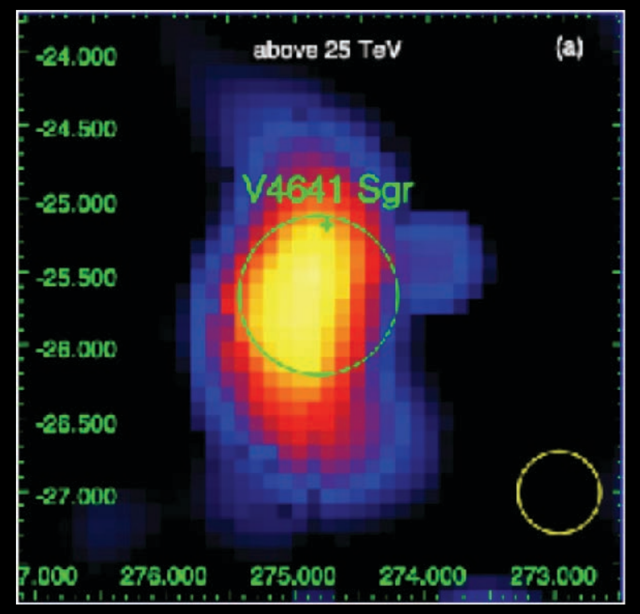

Cosmic explosions and acceleration

Including multi-messenger astronomy in the 2040s

Foreseen capabilities:

> 5-10× line sensitivity

> 3-5× angular resolution

Simultaneous multi-band observing

On-the-fly calibration