Science with JVLA and ALMA

From science fiction to fact

- Focus on last ~ 5 years (highlights from NSF reports, APR, POP, LRP…)
- Emphasize complimentarity: multi-wavelength, multi-messenger

Decadal Survey 2020

I. Worlds and Suns in Context: Pathways to Habitable Worlds

- a. Planet Formation
- b. Planetary Science
- c. Exospace Weather

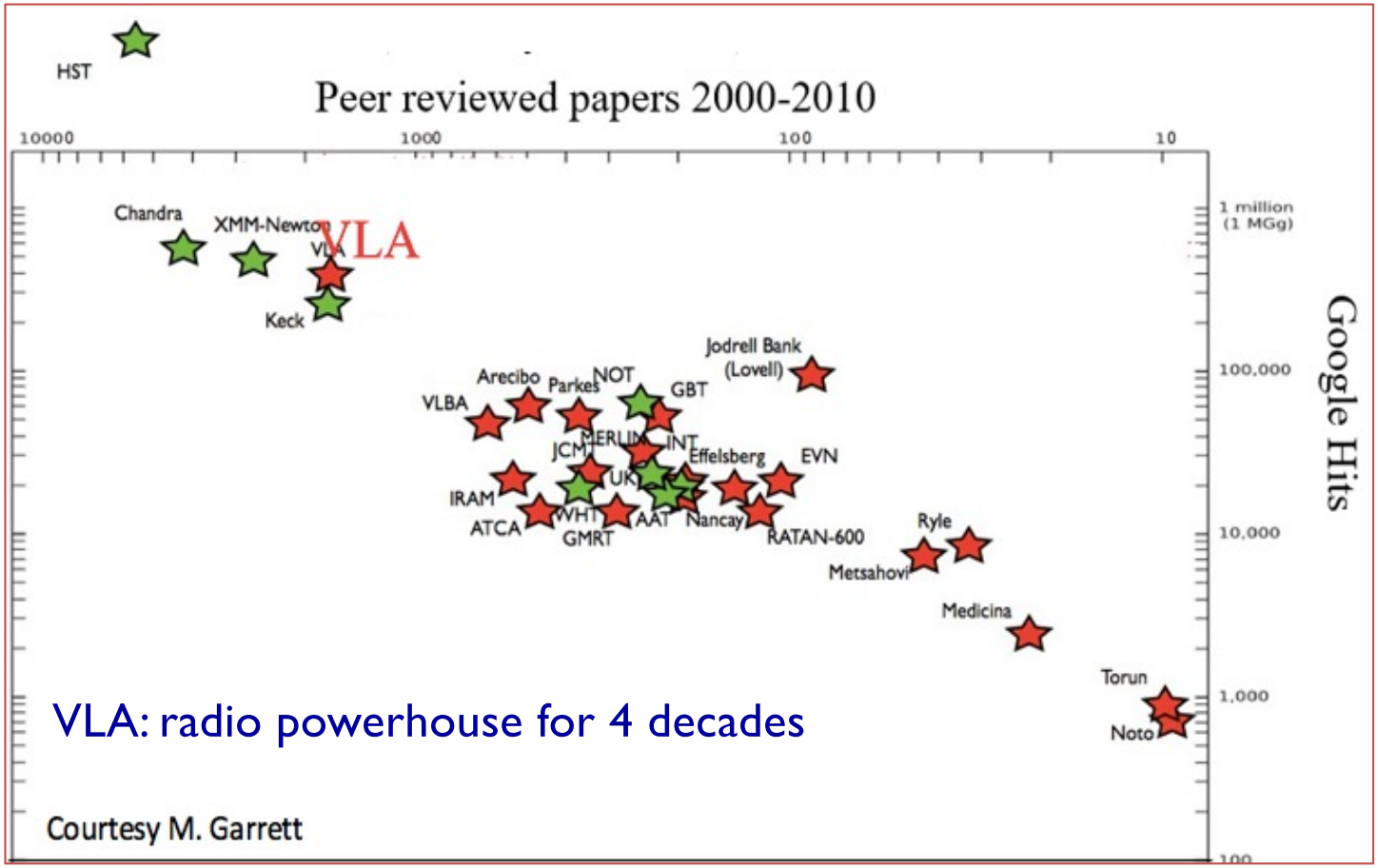
II. Cosmic Ecosystems: Unveiling the drivers of Galaxy Growth

- b. Star Formation Laws
- c. First Galaxies

III. New messengers, New Physics: New Windows on the Dynamic Universe

- a. Gravitational Wave Sources
- b. Explosive Universe

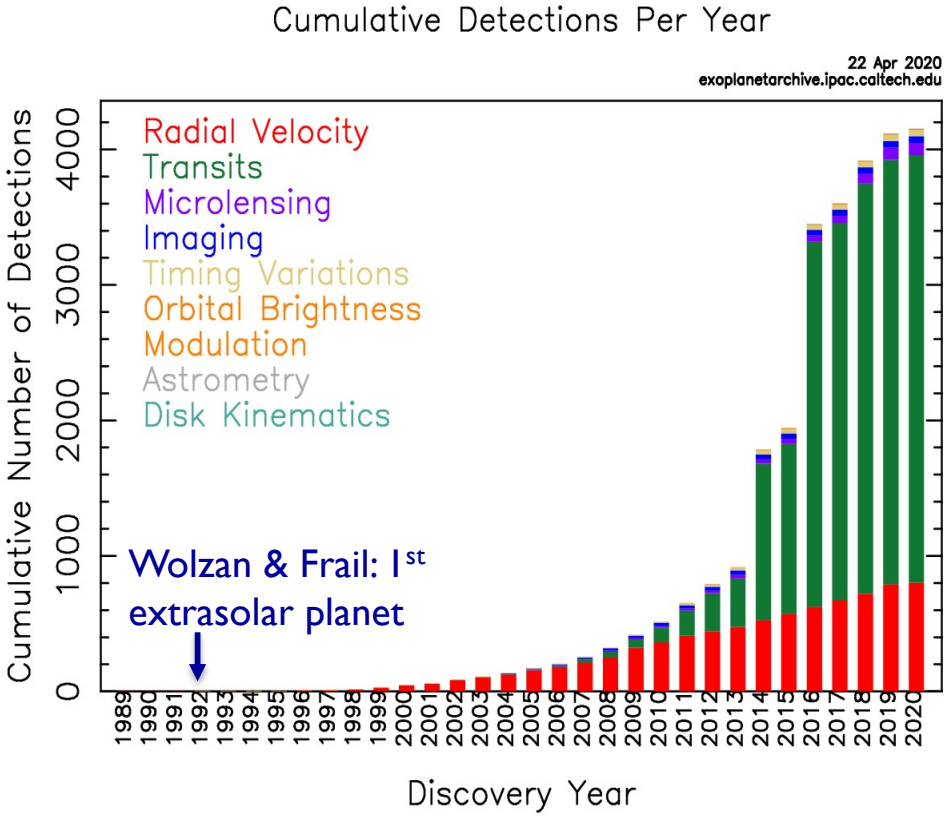
ALMA: close to 2000 proposals per year ~ 50% more than HST or JWST!

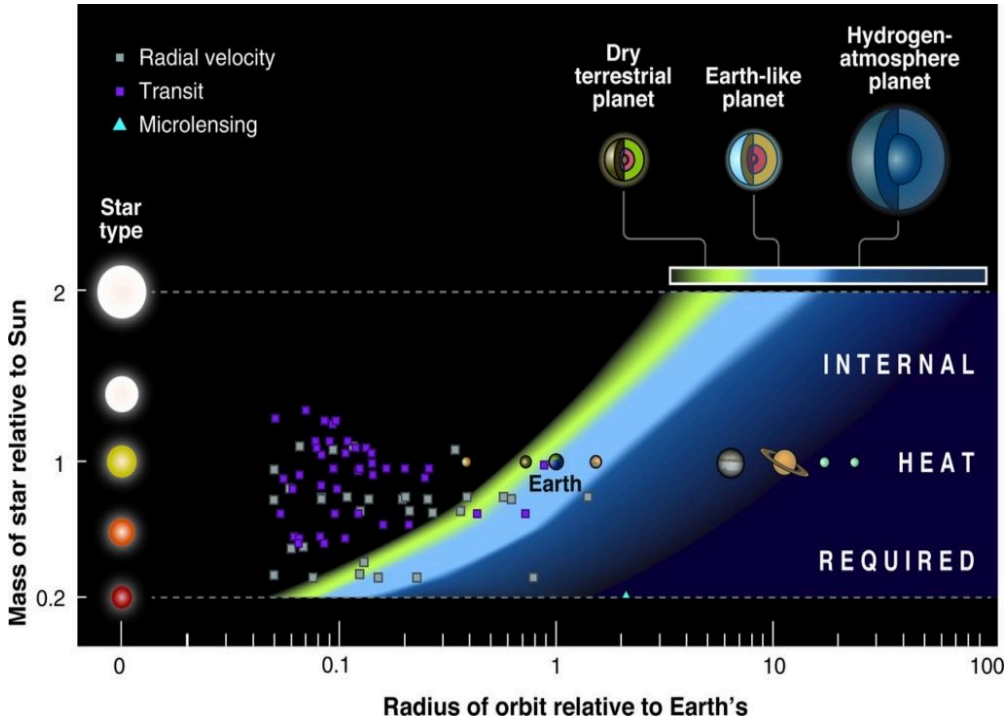


VLA: radio powerhouse for 4 decades

Pathways to Habitable Worlds

Exoplanets: Biggest Advance in Astronomy in last two decades

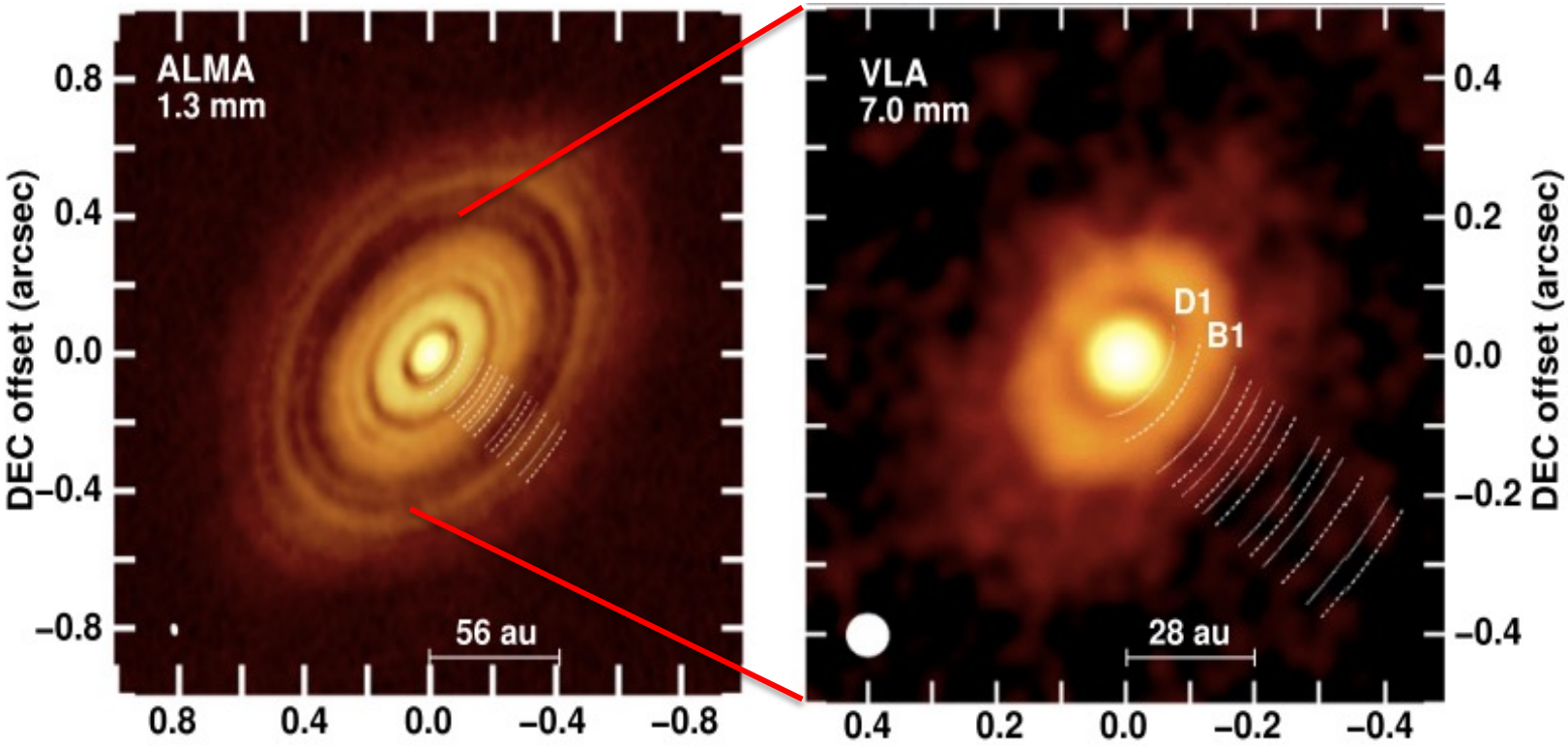




Thousands of exoplanets, w. hundreds in 'habitable zone'

ALMA and JVLA imaging of planet formation on few AU scales

HL Tau: the archetype dusty disk surrounding a 1 M_o, 1 Myr old proto-star at 140 pc distance. JVLA and ALMA imaging at ~ 40mas (5 AU) resolution trace the growth of dust grains into planetesimals, and the gaps and clumps that result from the influence of early planets on the disks themselves.



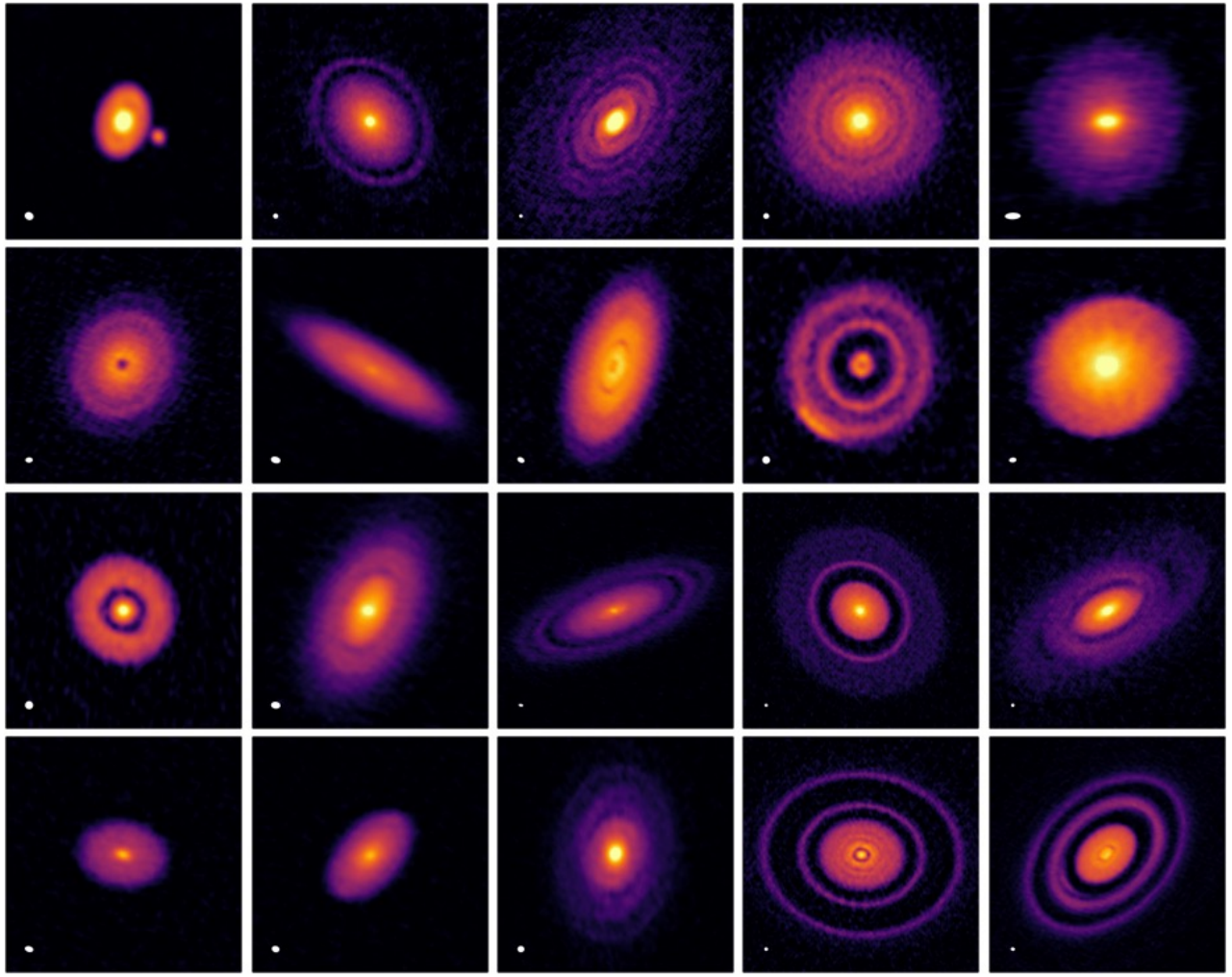
Brogan ea. 2014

Carrasco-Gonzales ea. 2016

Planet Formation as an Industry

DSHARP: ALMA 250 GHz images of thermal emission from dust in 20 protoplanetary disk at 40mas (5AU) scales.

- *Concentric emission rings and depleted gaps.*
- *Occasional spiral patterns and small arc-shaped asymmetries => dynamic*
- *Wide range of radii: a few to more than 100 AU*
- *Wide range in brightness contrast*

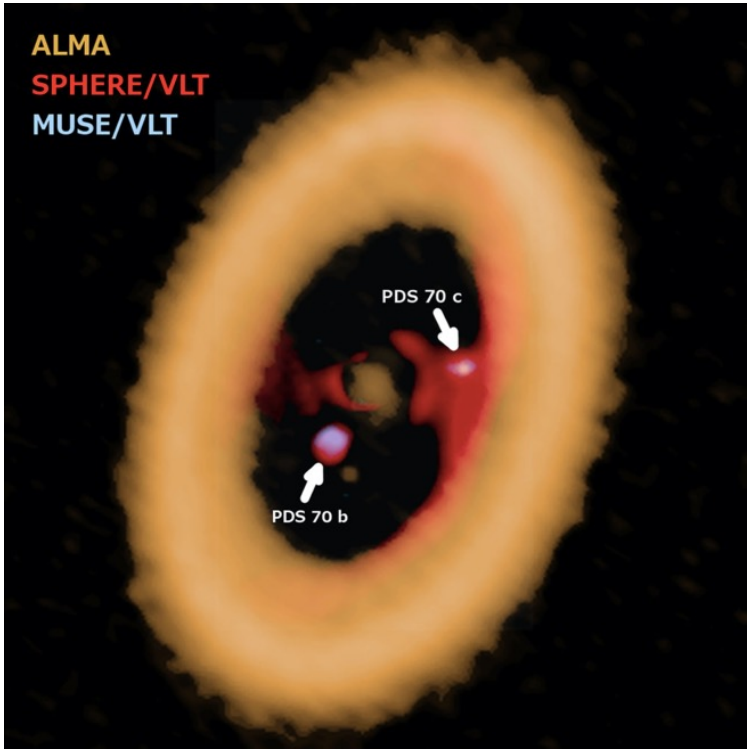


Andrews ea. 2018

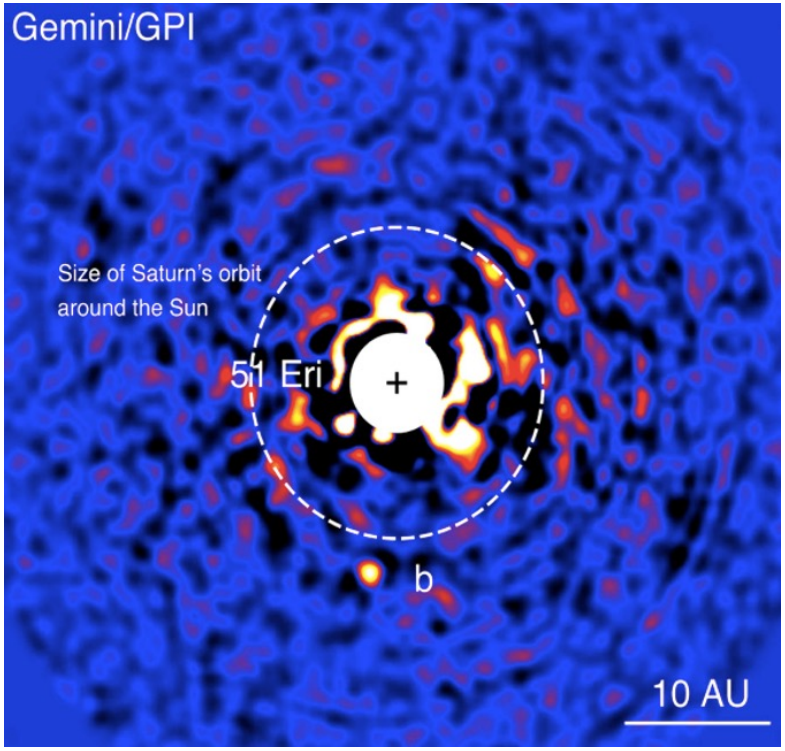
NRAO

Pathways to Habitable Worlds

Lifecycle of Planets



ALMA 350 GHz and VLT images of circumplanetary disks in PDS 70 (Isella et al. 2019): accretion onto two protoplanets at 50mas resolution.



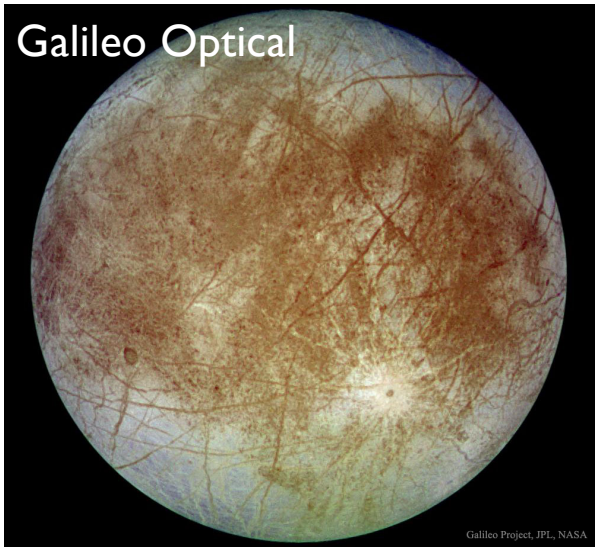
Gemini direct imaging of gas giant planet 51 Eridani b (Macintosh ea. 2015)

NRAO

Pathways to Habitable Worlds

The Ocean of Europa

Europa is one of the more plausible sites for development of life in the Solar system, due to a likely subsurface salt water ocean.

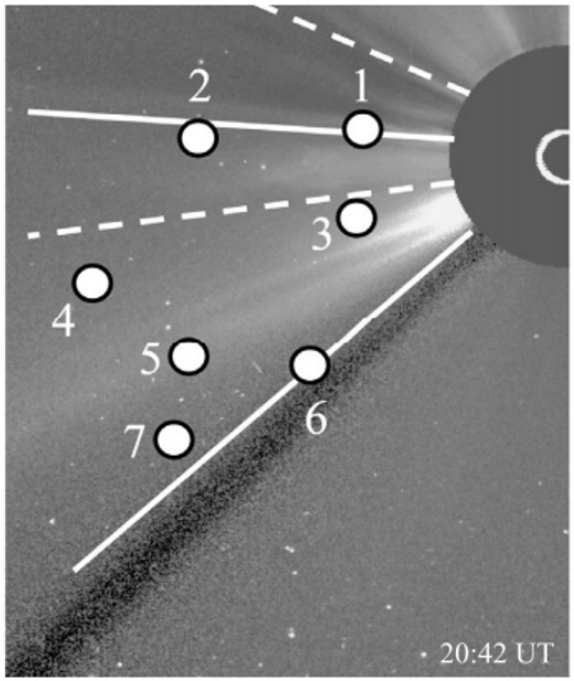


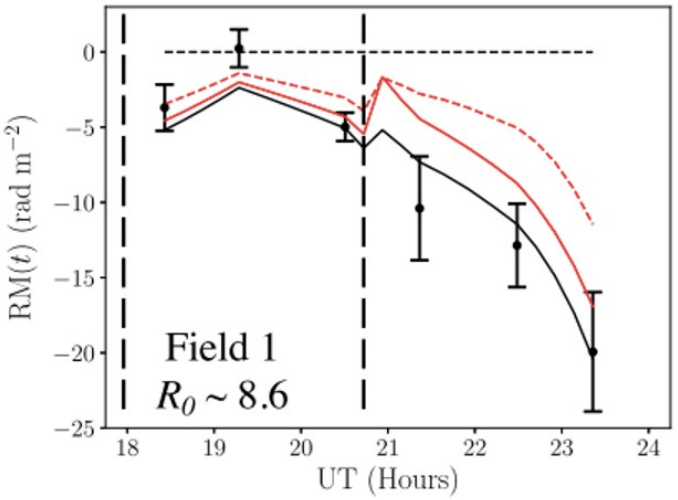
- ALMA temperature map at 200 km resolution shows complex structure from 30 K to 90 K, and unexplained cold and hot spots, possibly associated with subsurface activity.
- Consistent with fractured, dynamic, icy surface ~ 20 km thick, possibly much thinner in places, with subsurface liquid water ocean, and a rocky core.

Severe Space Weather

- Coronal mass ejections (CME) are the most violent space weather phenomenon, traveling at ~1000 km/s, with potential for major impact on the Earth.
- Faraday rotation measurements with the VLA, plus real-time *in situ* density measurements by Parker Probe, yield the most precise measurement of the magnetic field in a CME of 30mG at 10 R_o. Strong fields 'focus' the CME as it travels from the Sun.

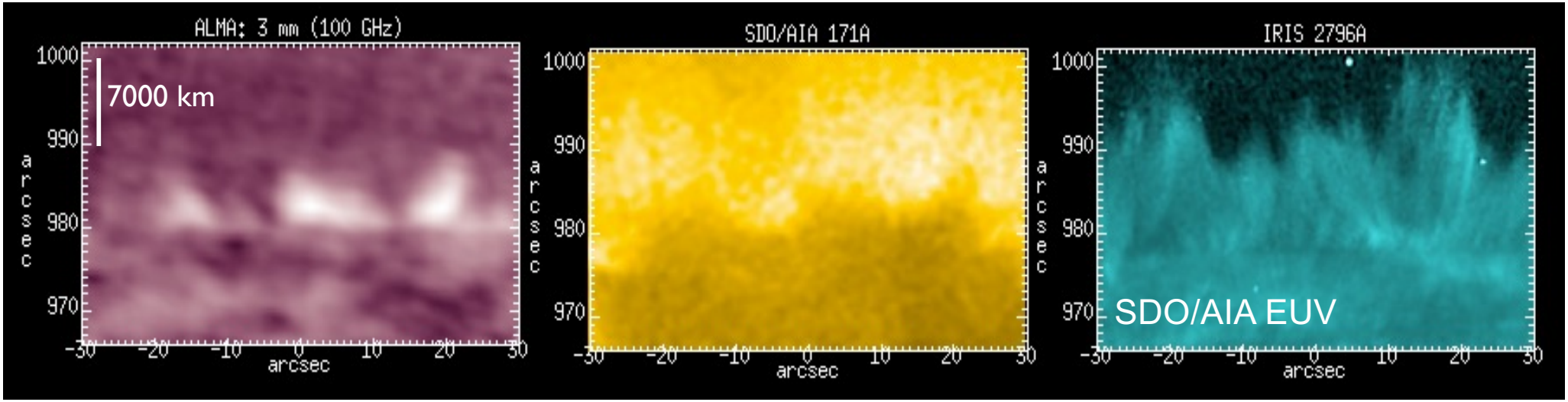
Left: SOHO image of a CME, with location of background radio sources used for VLA RM measurements. Right: time behavior of the RMs of source 1 with passage of the CME (Kooi et al. 2021).





Space Weather: Solar dynamic imaging

- Solar spicules are ubiquitous jets of cool (10^4 K) material launched from the chromosphere into the corona at up to 100 km/s, thereby heating the corona and powering Solar wind. Launch mechanism remains unknown.
- 3mm free-free and UV line emission are complementary, formed under LTE and non-LTE, respectively, and can be used to determine gas temperature and densities.

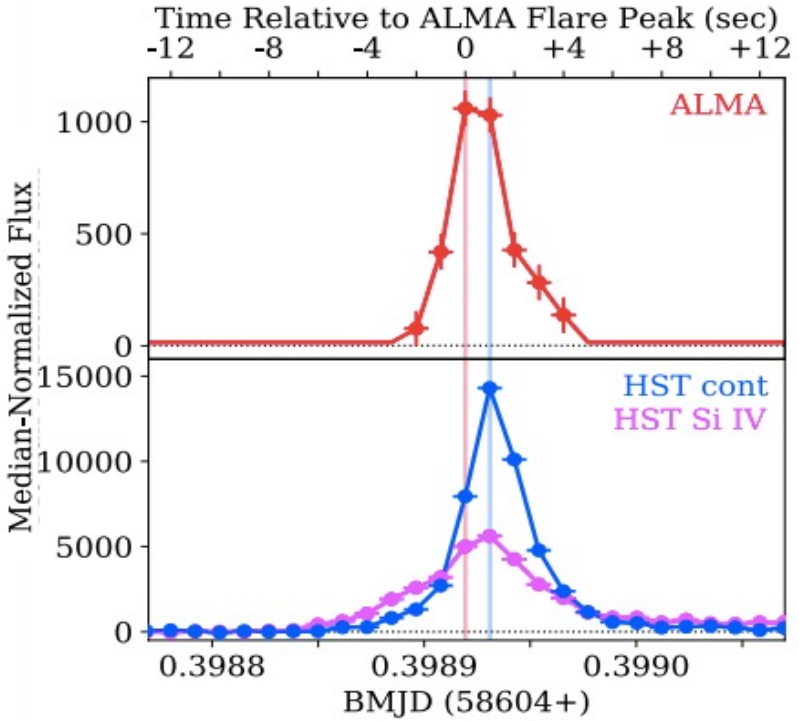


ALMA 3mm and SDO/IRIS dynamic observations of Spicules on the Solar limb (Bastian et al. 2021), at 6sec cadence, 1.5" (1100 km) resolution, over 10min.

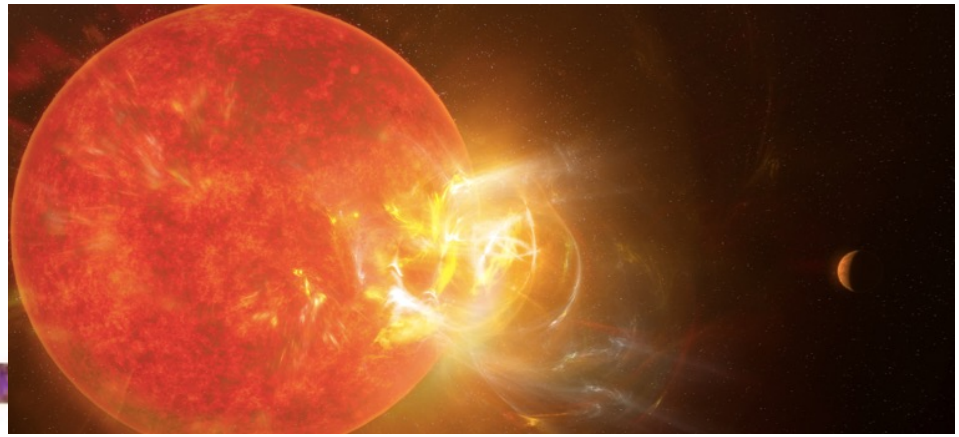
NRAO

Exo-Space Weather and Life

- M-dwarfs: most common star likely to host habitable planets. Often very magnetically active, with extreme flares and aurorae indicating strong magnetic fields and star-planet interactions.
- Proxima Centauri (0.12 M_o): closest exoplanetary system (1.3 pc) with an Earth-mass planet at 0.05 AU and T~230.
- ALMA, HST, and others, have detected the most extreme flare from Prox Cen,: 7sec, factor 1,000 increase at 1.3mm!
- Extreme flares driven by magnetic reconnection: extreme activity could be detrimental to the formation of life = new term in Drake equation

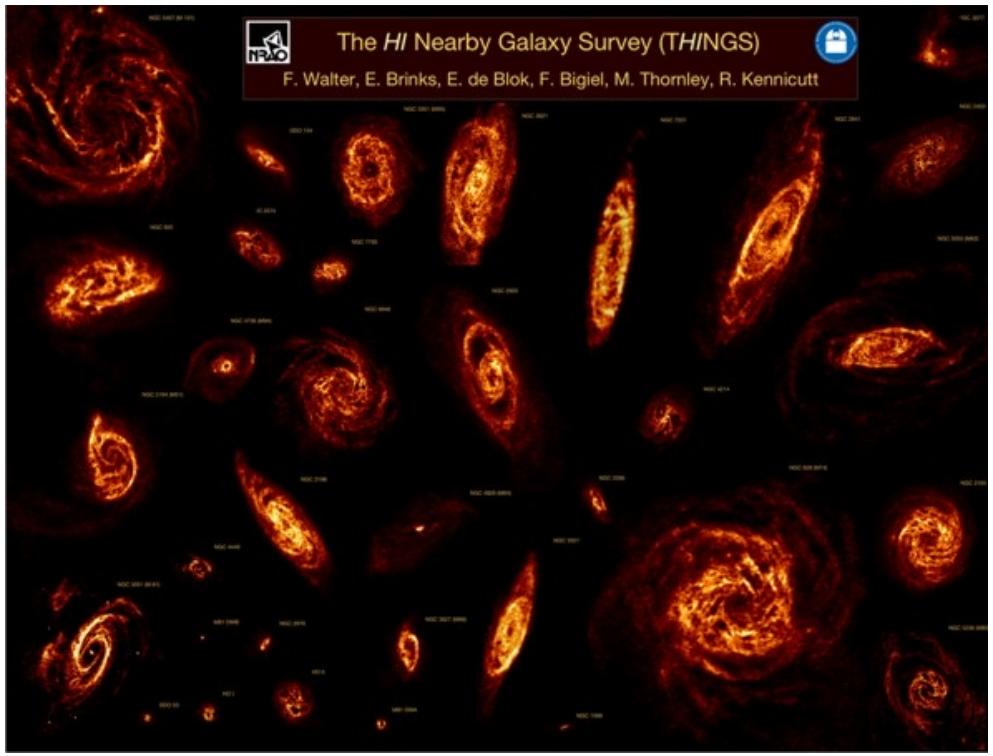


ALMA 250 GHz and HST UV light curves of the extreme flare from Proxima Centauri (Macgregor et al. 2021)

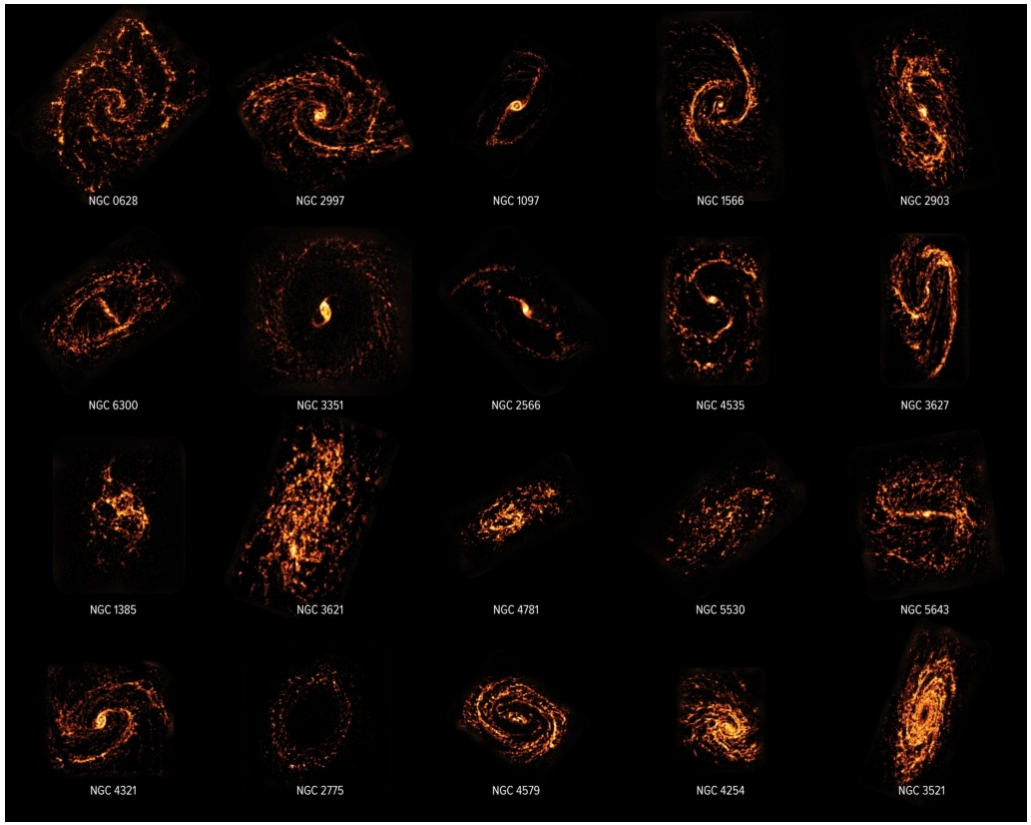


Cosmic Ecosystems: Unveiling the drivers of Galaxy Growth

Cosmic Baryon Cycle: How do galaxies convert gas into stars?

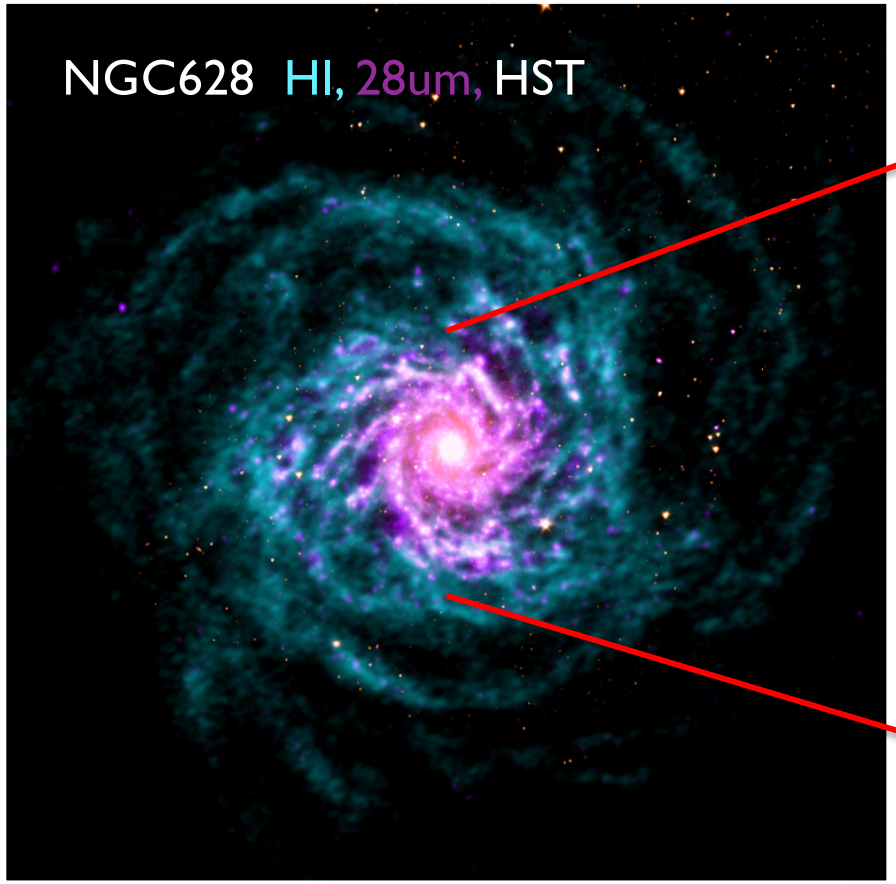


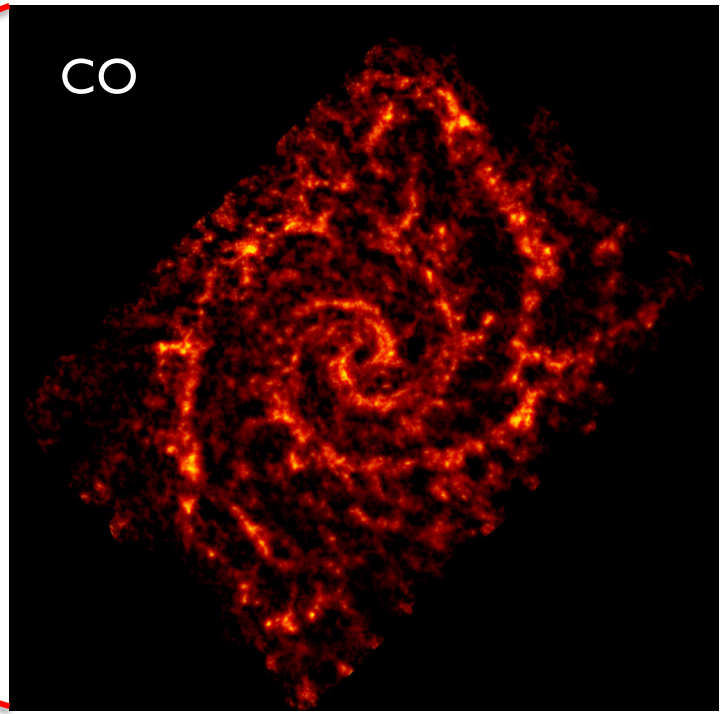
VLA/THINGS survey: HI 21cm imaging of atomic gas in a representative sample of disk galaxies at 200pc resolution (Walter et al. 2008).

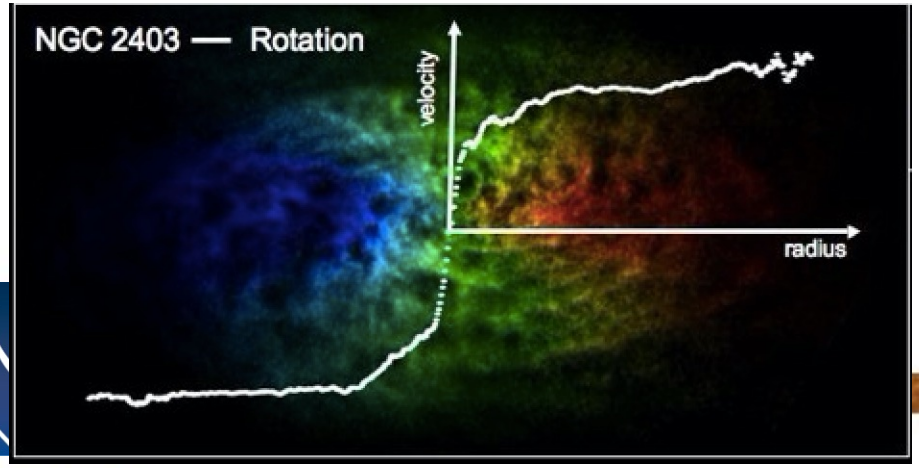


ALMA/PHANGS survey: CO 2-1 imaging of molecular gas in representative sample of disk galaxies at 200pc resolution (Leroy et al. 2018)

NRAO





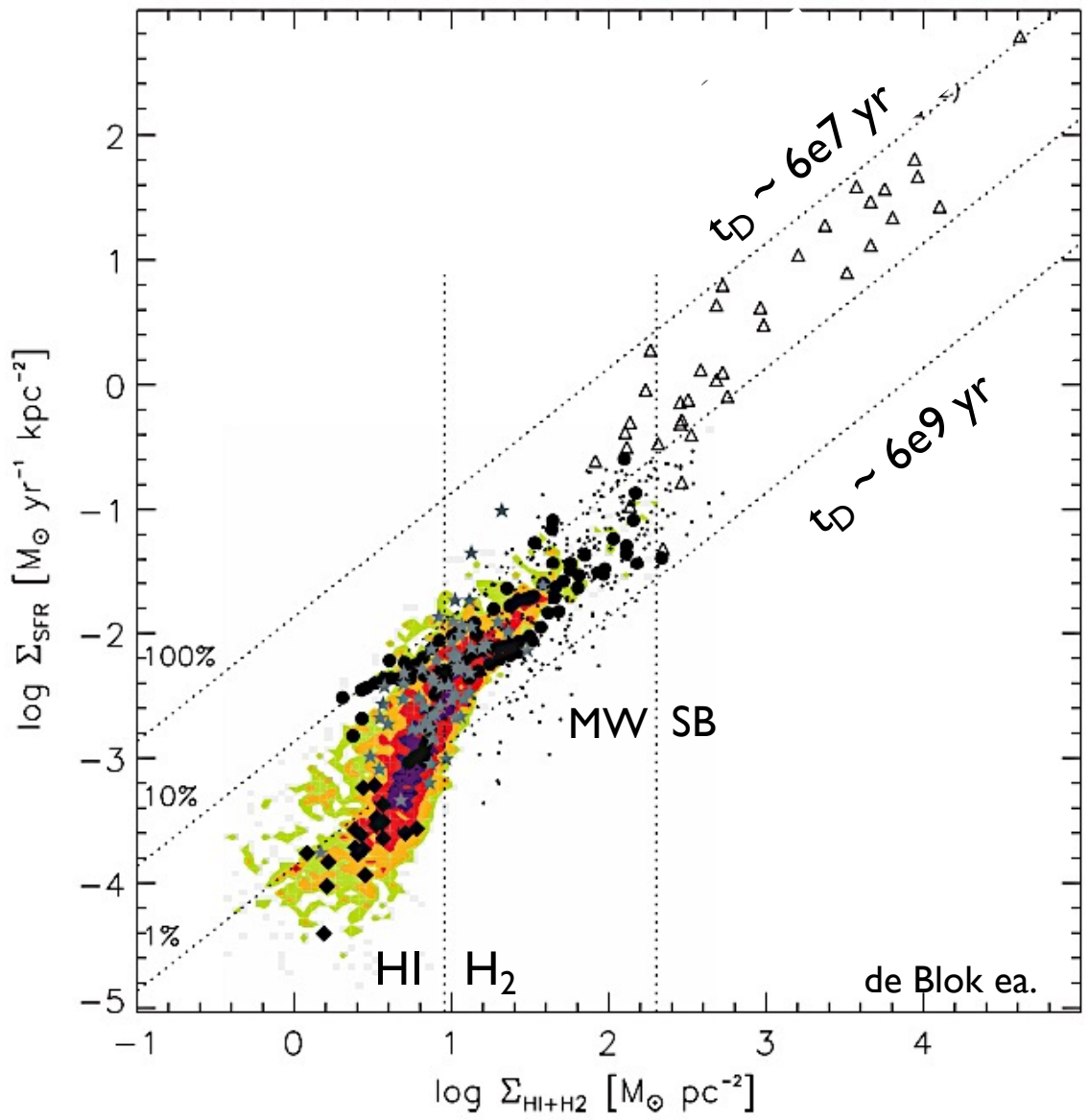


Observe 100,000 giant molecular clouds => relationships between: HI, H_2, SF, Stars, and influence of galaxy dynamics

Star Formation Law

relationship between gas ar star formation in galaxies

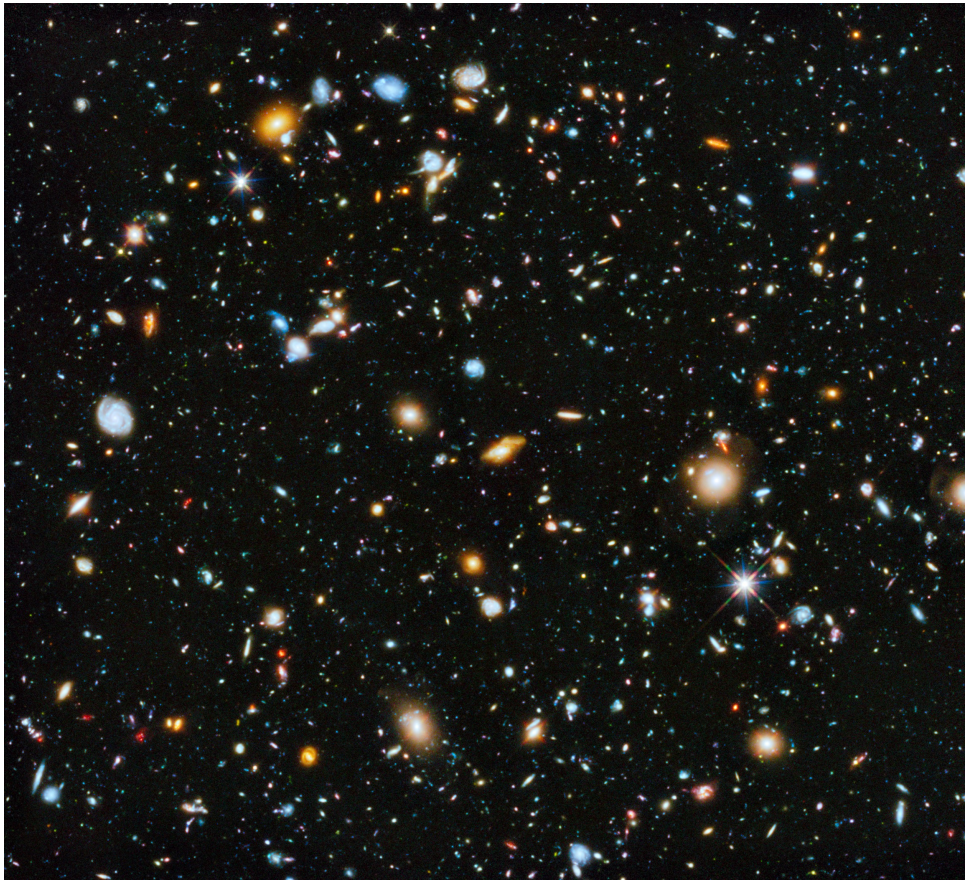
- Stars form in molecular clouds (not HI)
- Normal galaxies (Milky Way): gas depletion timescale ~ 2.5e9 yr
- Starburst galaxies: gas depletion timescales ~ 2.5e8 yr
- $t_D < t_H$ => requires gas resupply from IGM (HII HI → H_2)



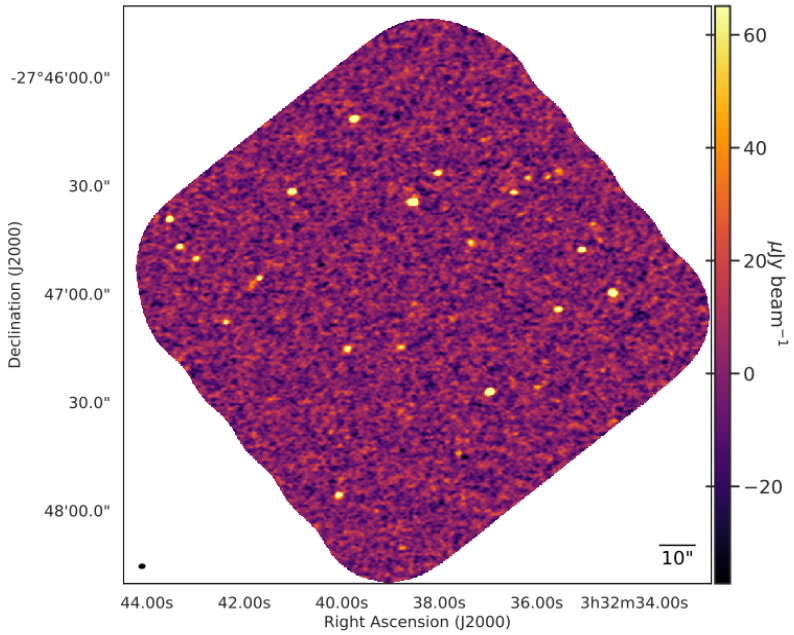
Galaxies into the Dark Ages

Cosmological Deep Fields

HST UDF



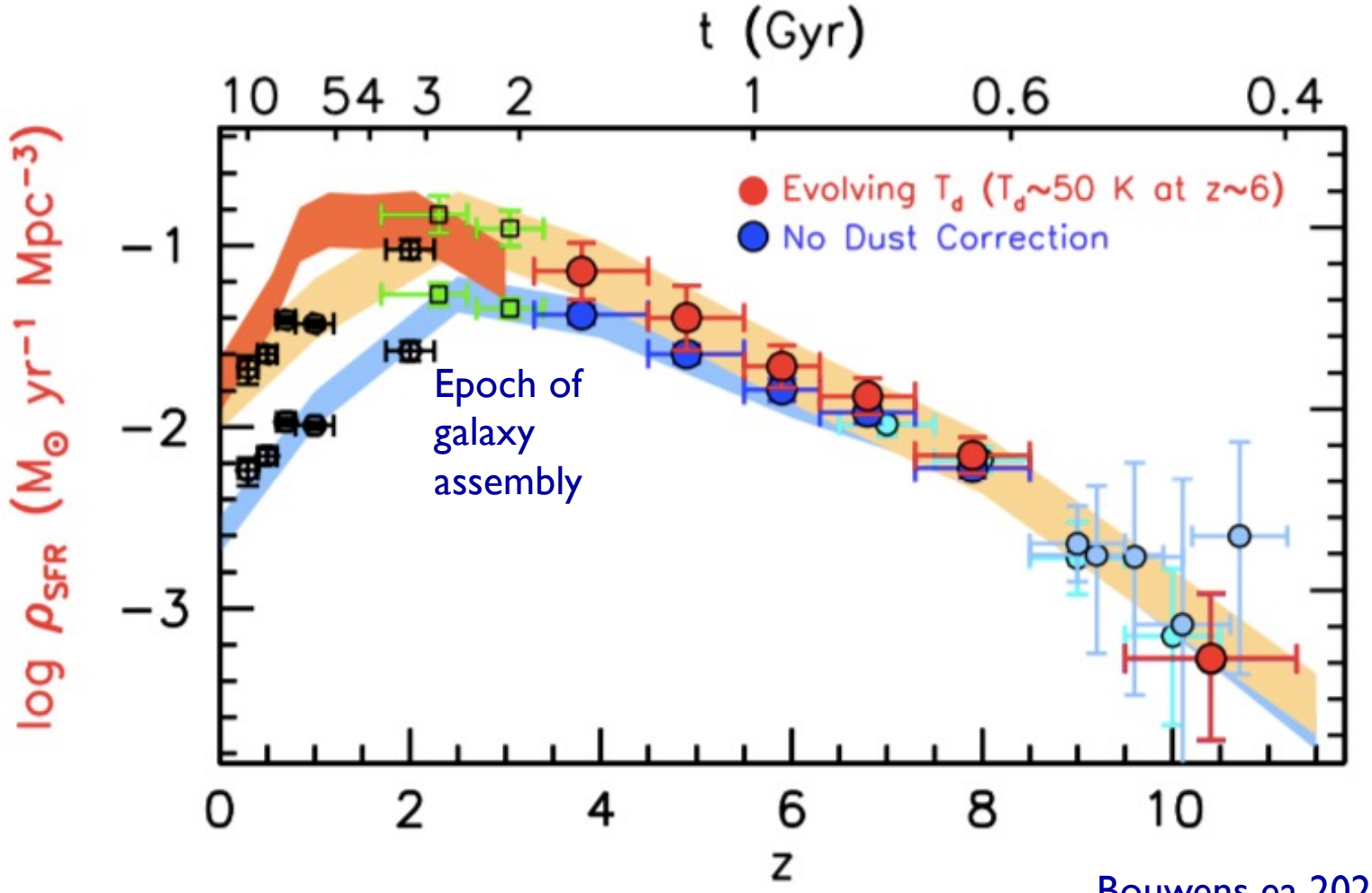
ALMA 250 GHz rms = 9.5 uJy



Thousands of galaxies in optical, radio, and dust, out to to z ~ 9, or just 500 Myr after the Big Bang

NRAO

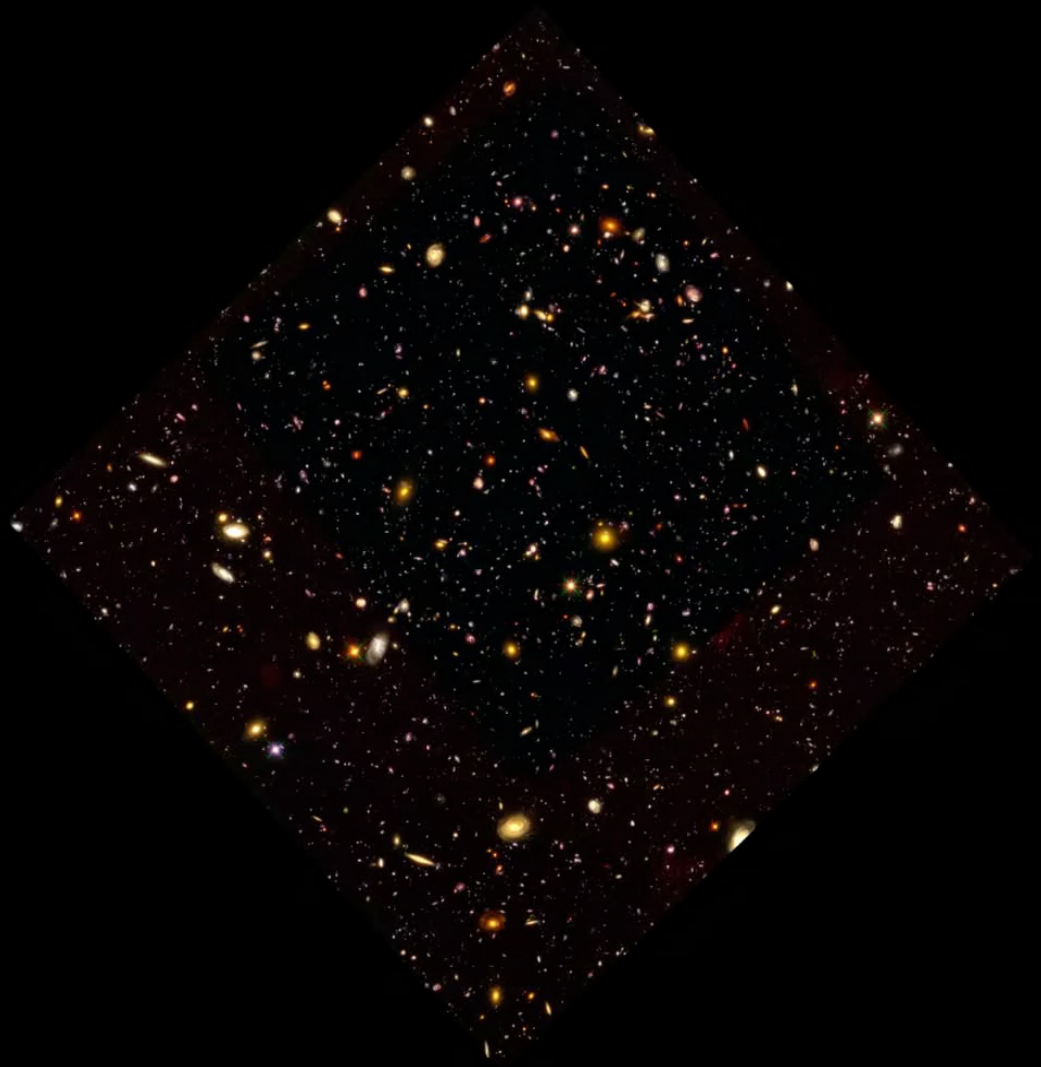
Star Formation History of Universe



Bouwens ea 2021

NRAO

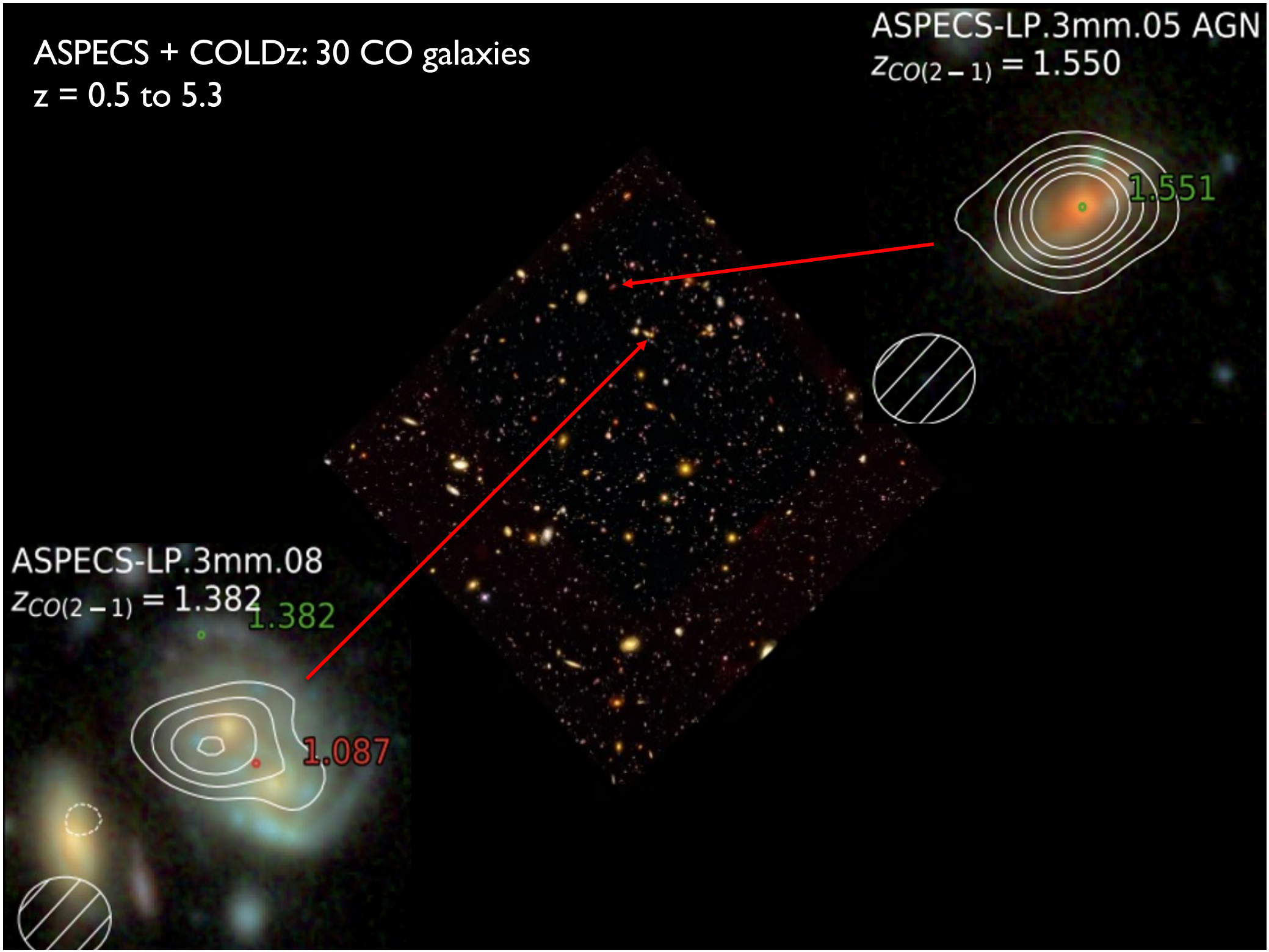
What about the Gas?



ASPECS: Full spectral scans of ALMA 90m 250 GHz, in UDF,

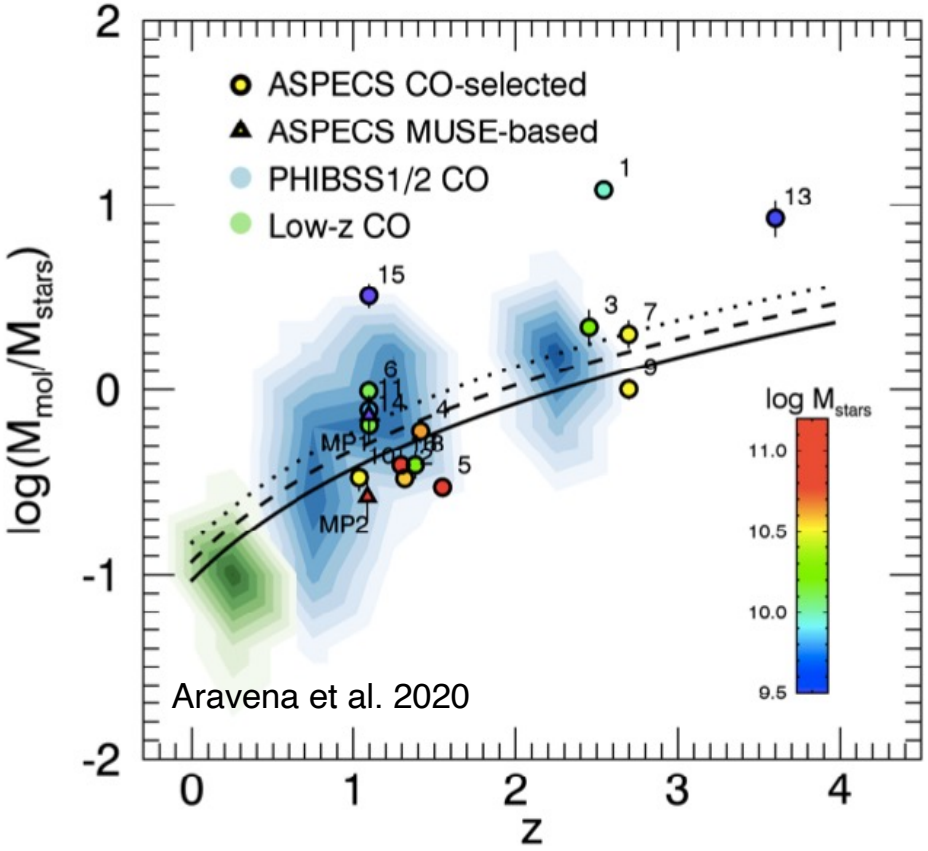
COLDz: scan VLA 32 band in COSMOS, GOODS-N

Unbiased Search for CO from z = 0 to 5.3


ASPECS + COLDz: 30 CO galaxies
z = 0.5 to 5.3
ASPECS-LP.3mm.05 AGN
$z_{CO(2-1)} = 1.550$
1.551
ASPECS-LP.3mm.08
$z_{CO(2-1)} = 1.382$
1.382
1.087

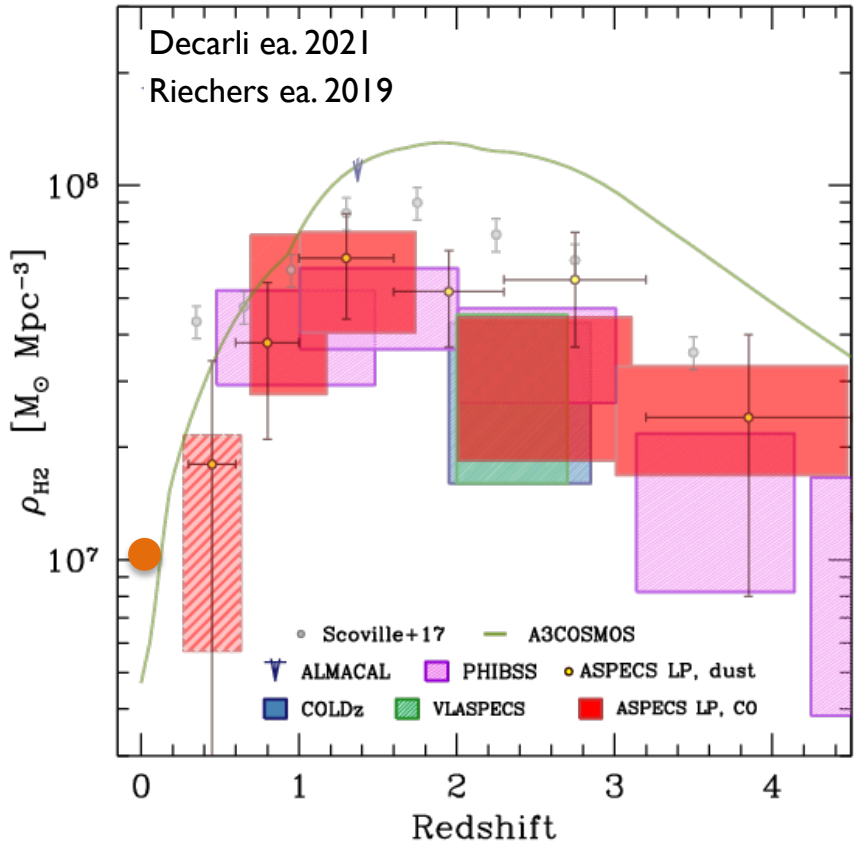
Dense Gas History of the Universe

Fundamental change in galaxy properties over time



Gas dominated galaxies at z>2

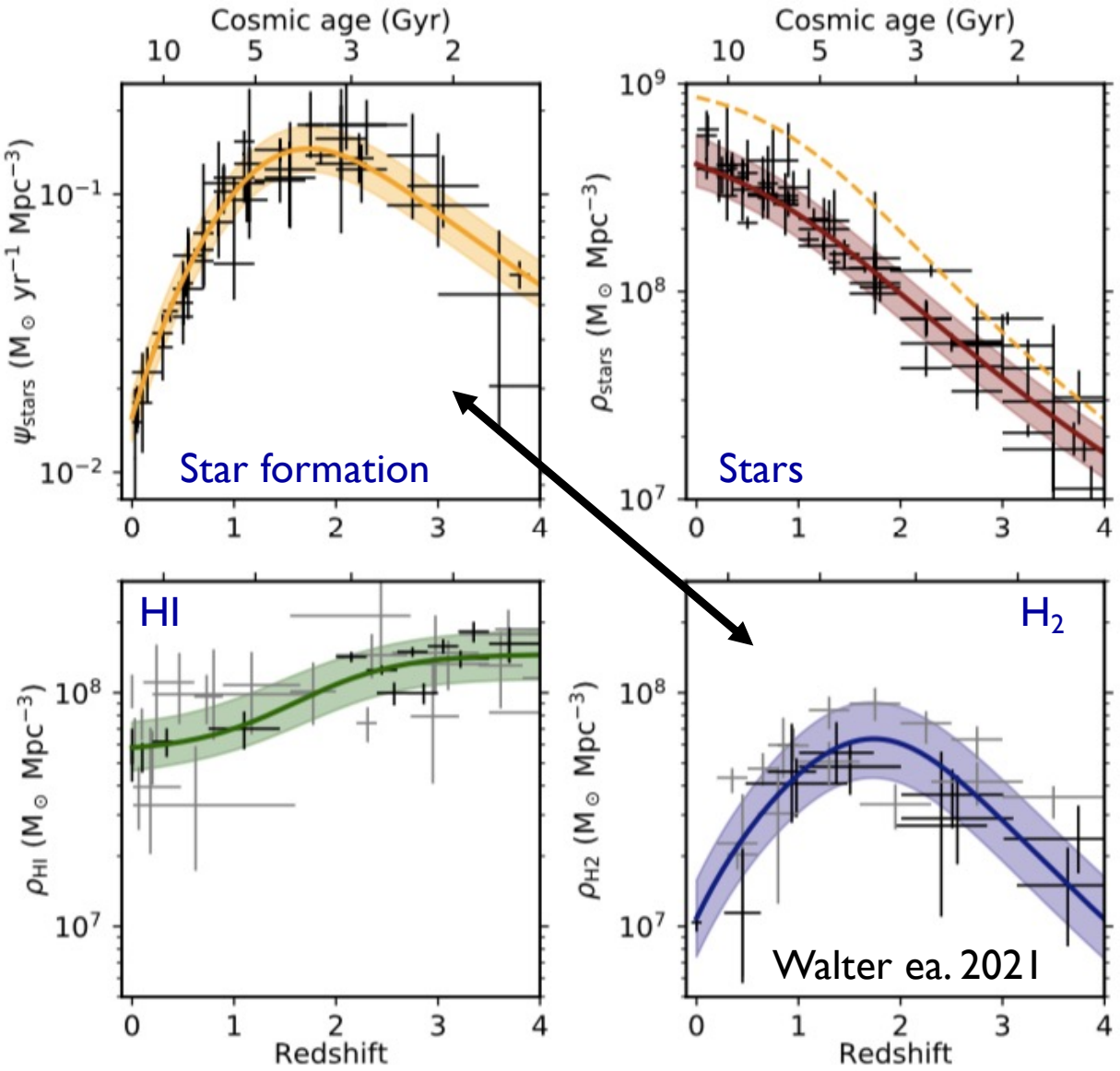
- ➢ $\lesssim$ 0.1 at z ~ 0
- ➢ $\gtrsim$ 1.0 at z > 2



Rise and fall of cosmic density of molecular gas with redshift

Cosmic Ecosystems: Unveiling the drivers of Galaxy Growth

Cosmic Baryon Cycle over Time

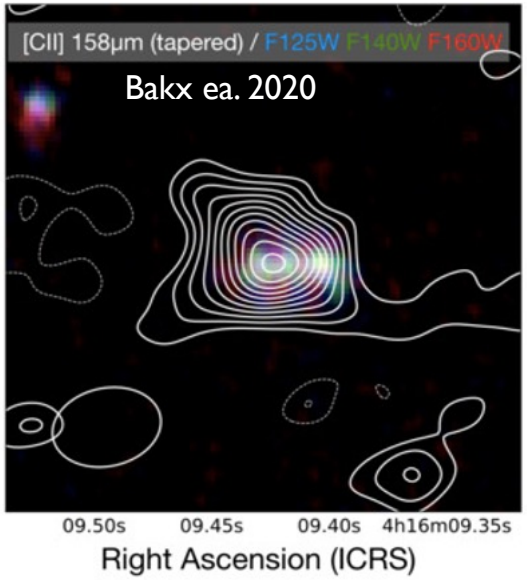


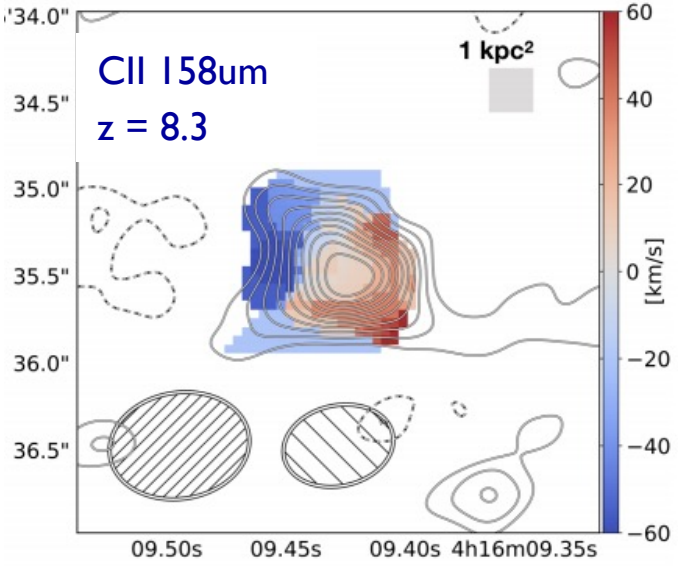
- Build up of stars is consistent with integral of SFHU
- HI ~ flat => transition phase from IGM: HII to HI to H_2
- Rise and fall of H_2 parallels (and drives) cosmic star formation rate density

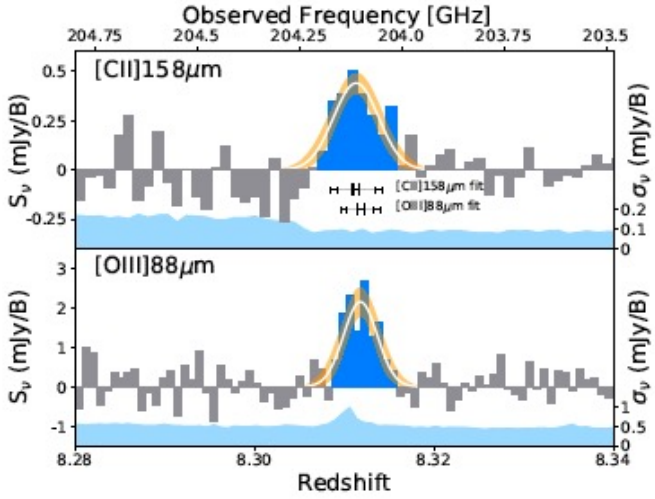
NRAO

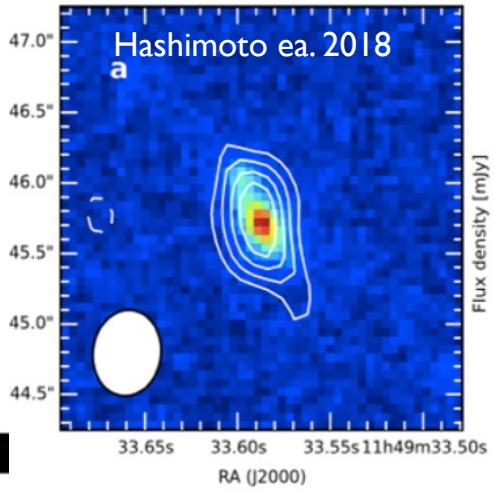
ALMA opens a new window on the first galaxies

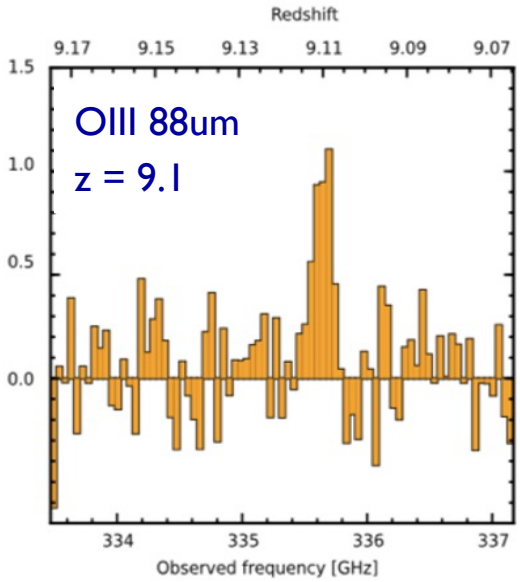
Atomic Fine Structure Lines to z > 9







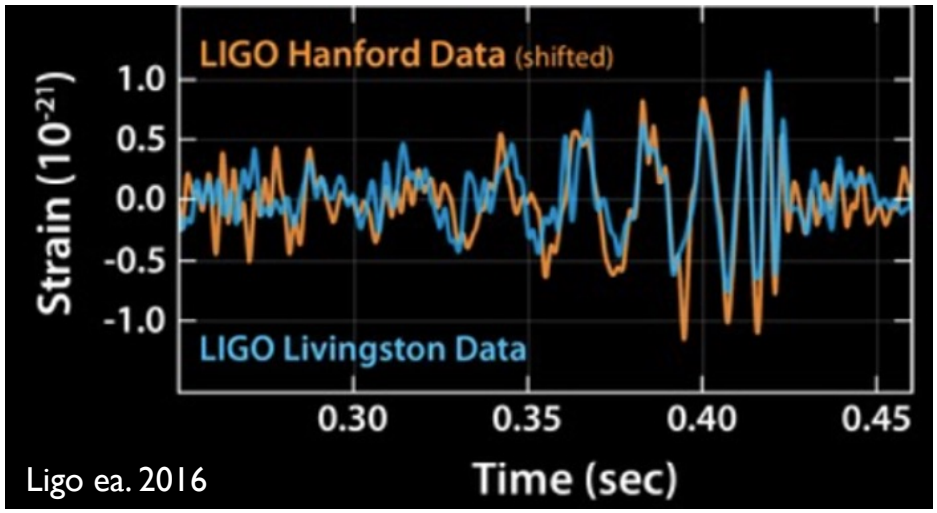


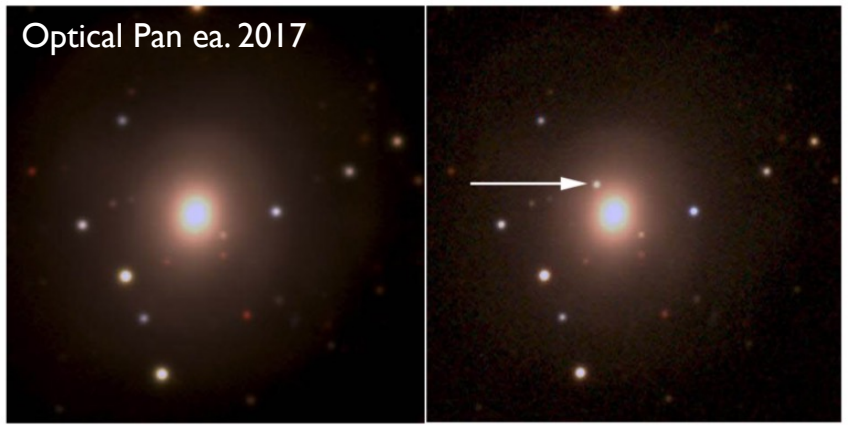


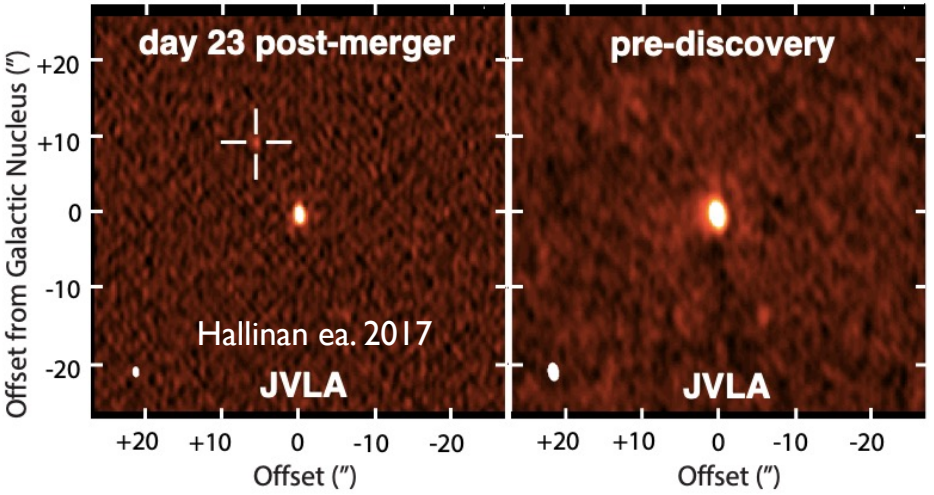
- *Dynamics of 1st galaxies to 1 kpc*
- *ISM conditions*
- *New redshift machine for 1st galaxies*

New messengers, New Physics

New Windows on the Dynamic Universe



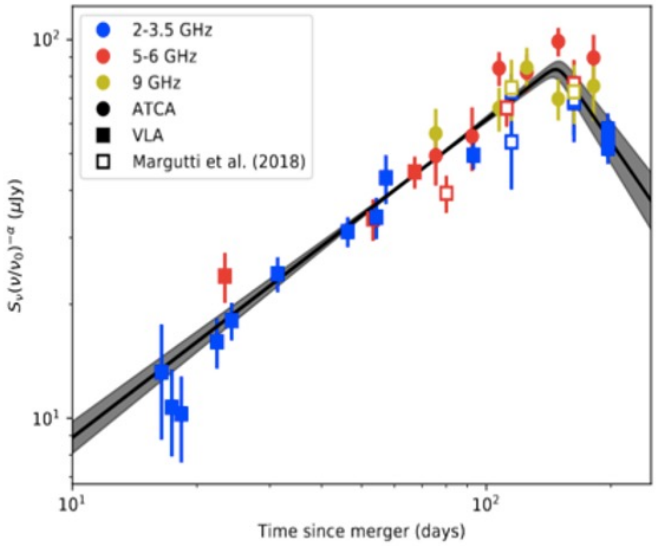


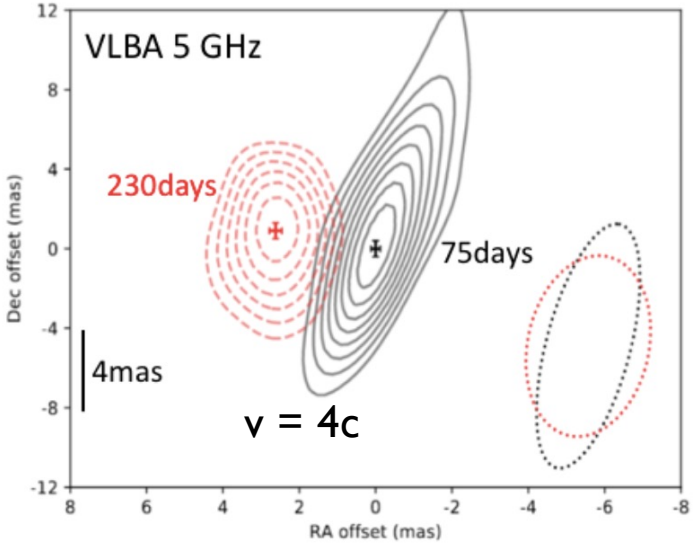


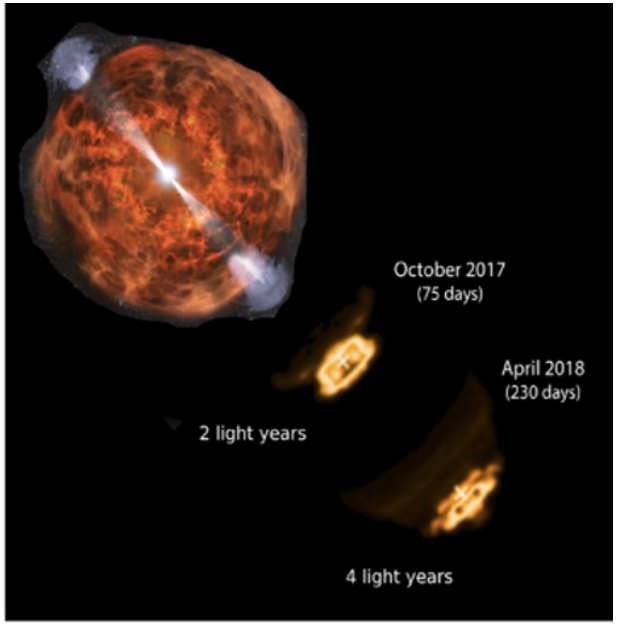
Gravitational Waves Sources: The VLA was key in the multi-wavelength campaign that discovered the EM counter-part to the merging binary ~ 30 $M_\odot$ black-holes, identified with a galaxy at z = 0.093.

NRAO

Smothered, then emerging, relativistic jet model for merging binary black hole







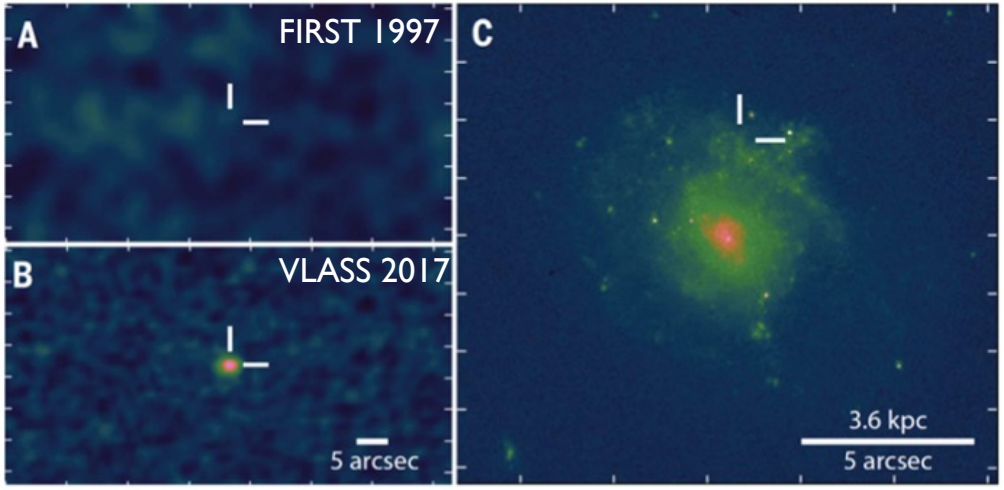
The radio light curve of GW170817 and VLBA imaging of the emerging relativistic jet from the merging binary black hole system. Right: schematic model for the EM counterpart to GW source: a wide angle jet which is trapped by the explosion debris (Dobie ea. 2018; Mooley ea. 2018).

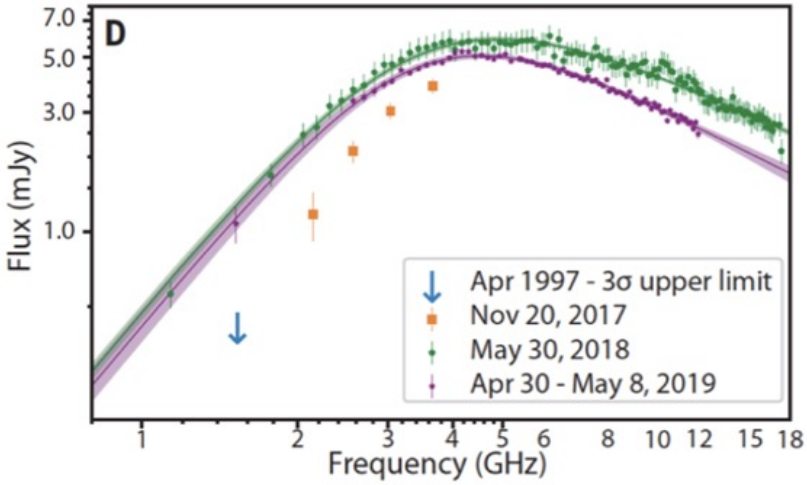
NRAO

VLASS: the radio transient factory

2500 explosive transients per epoch

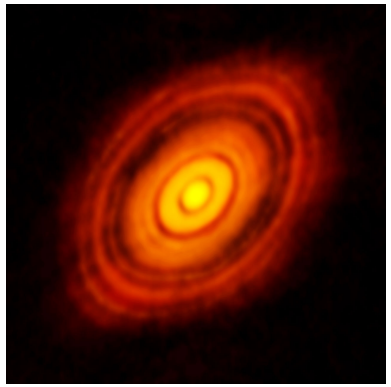
- VLASS transient VT 1210+4956: not detected in FIRST, but appears in VLASS
- Identified with dwarf galaxy at z = 0.035
- Radio spectrum => synchrotron self-absorption model
- Likely merger-driven core collapse supernova (Dong et al. 2021).

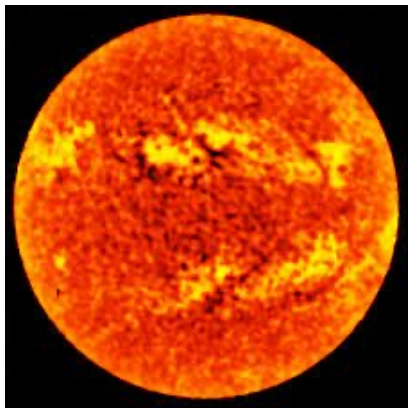


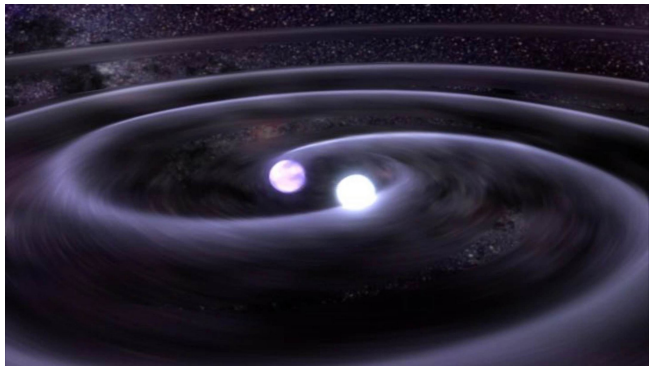


In 1983, I lived in a Universe where:

- The only planets were in the Solar system
- PP 'disks' were point sources
- The most distant galaxy was 3c295 at z=0.5
- The existence of Black Holes was hotly contested
- Gravitational waves were an even vaguer prediction
- Physical cosmology bordered on metaphysics
- The sky was considered (mostly) static and immutable







NRAO