The Way of Water: H_2O emission in a DSFG at z≈3.1

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The plot

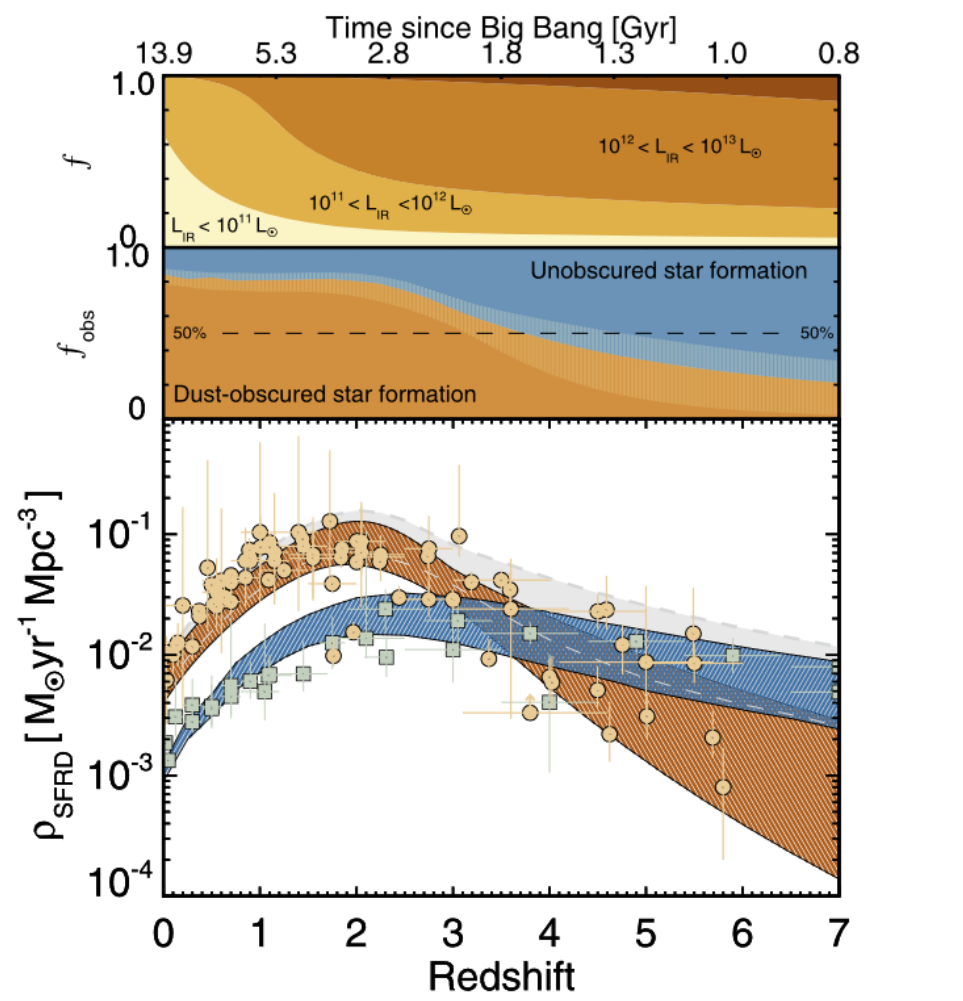
ALMA high-resolution ($\lesssim$ 0.3 arcsec) observations of water emission lines in the strongly lensed HATLAS J113526: optically invisible, bright in the submm, extreme SFR $\approx$ 1700 $M_{\odot}$ yr^{-1} (using a Salpeter IMF).

Highest resolution ever reached in H_20 at high-z .

Reference paper, "*The Way of Water: ALMA resolves H_2O emission lines in a strongly lensed dusty star-forming galaxy at z ≈3.1",* Perrotta+ 2023, *ApJ in press*

Work based on archival ALMA public data: ADS/JAO.ALMA\#2018.1.00861.S

Prologue: why are DSFGs important?



Zavala+ 2021, Casey+2021

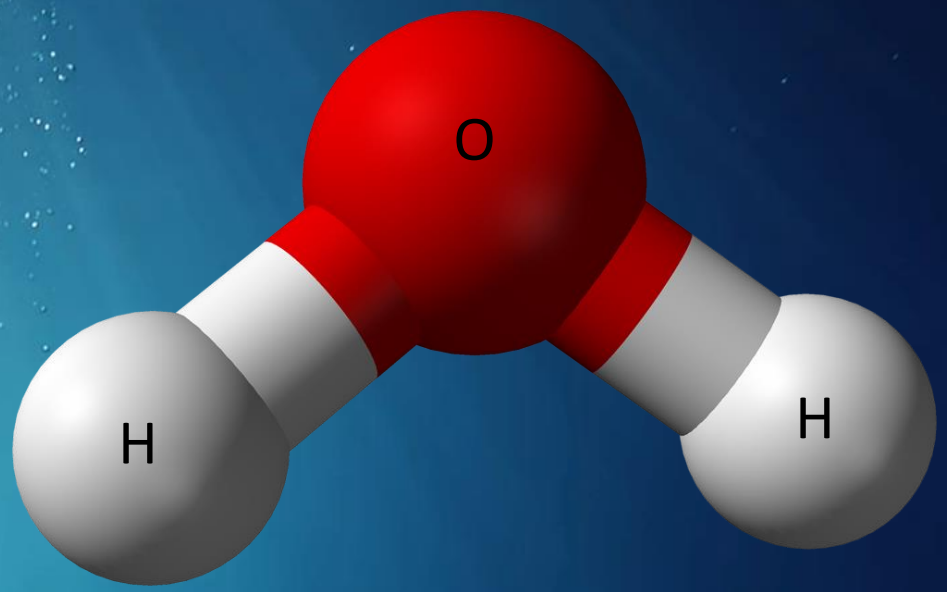
Obscured SF peaks at z ≈ 2-2.5, but has dominated the cosmic history of star formation for the past ~12 billion years, back to z ~ 4.

For z>2, mainly DSFG with $L_{IR} > 10^{12} L_\odot$, i.e. star-formation rates of thousands of $M_\odot$ /yr : most intense starbursts in the Universe.

A sub-sample of DSFGs are known to harbor heavily dust-enshrouded supermassive black holes.

Unique laboratory for investigating the physics of star formation and the chemistry of ISM in extreme environments.

The leading actor: H_20



- Near-prolate asymmetric-top molecule:

$I_c \approx I_b > I_a$

- High dipole moment (1.85 Debye,

w.r.t. 0.1 D of CO)

- High energy level-spacing (light hydride)

⇨

- Strongly coupled with the FIR radiation field from dust: tracer of regions where dust is strongly irradiated → compact warm SF regions
- Critical density decreased due to «trapping» of the resonant photons, e.g. n_{crit} 10^9 cm $^{-3}$ $n_{c\ eff}$ 10^5 cm $^{-3}$.

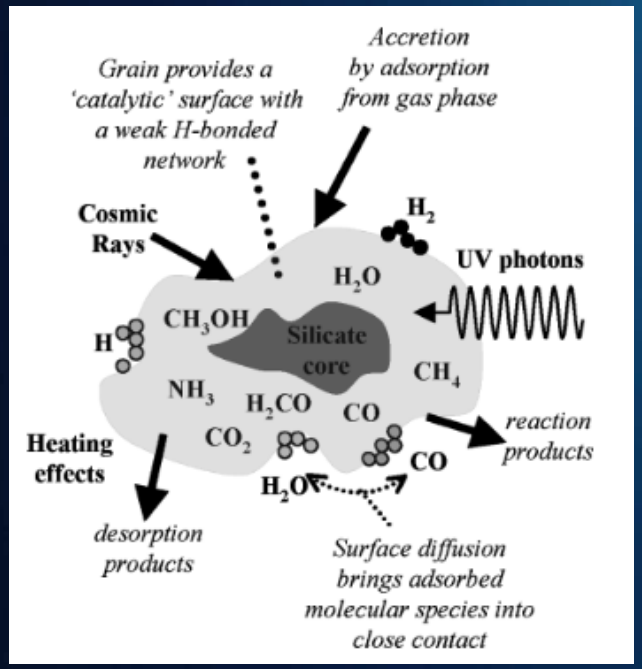
The supporting actor: Dust

1- Catalizer for water formation (in solid form) in dense, cold clouds;

2- Ice storage, until cloud collapse to protostars when temperature gradients releases H_2O in the gas phase;

3- Absorption of UV light, released as IR-FIR, radiatively exciting rotational lines of water and other molecules (via IR and FIR pumping) according to the selection rules.

1)



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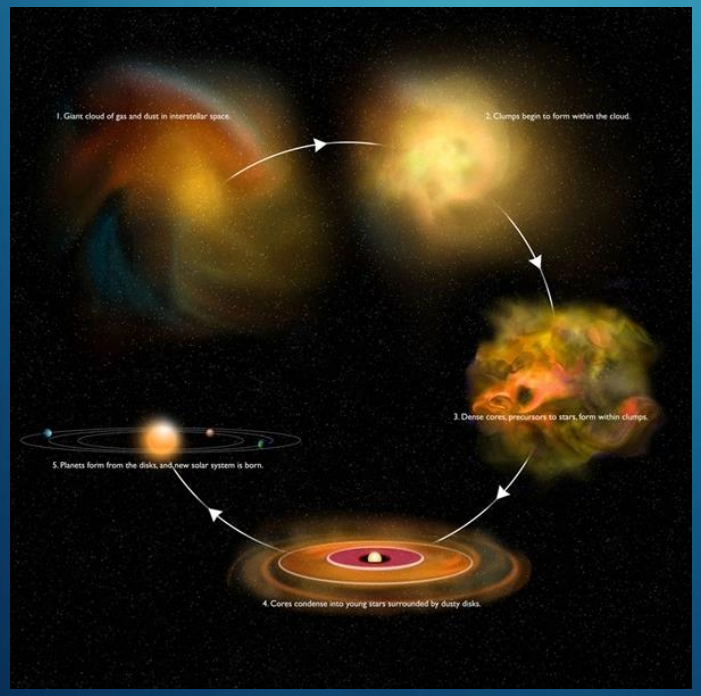

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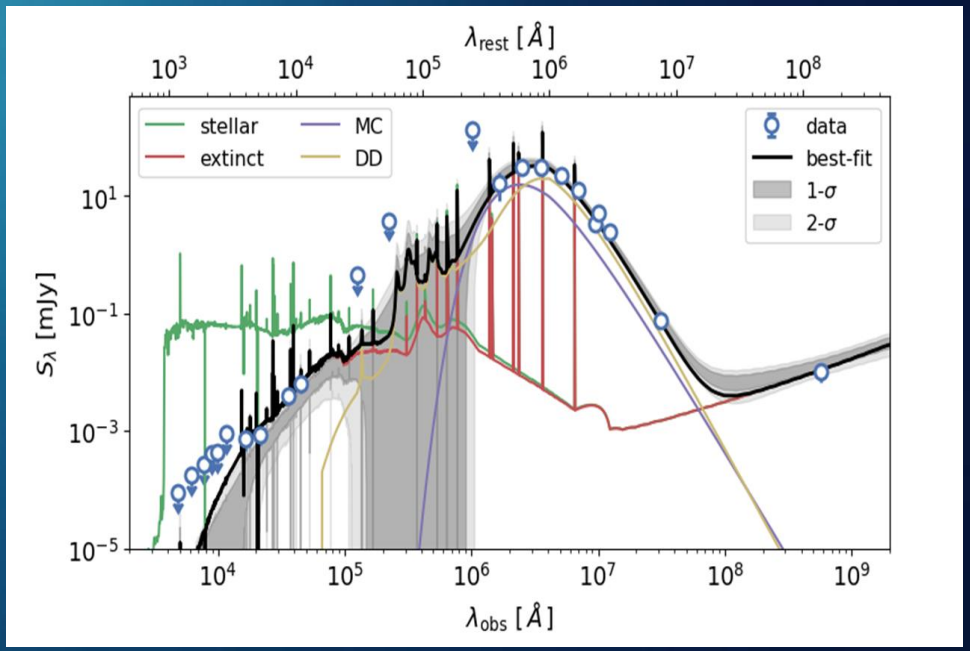


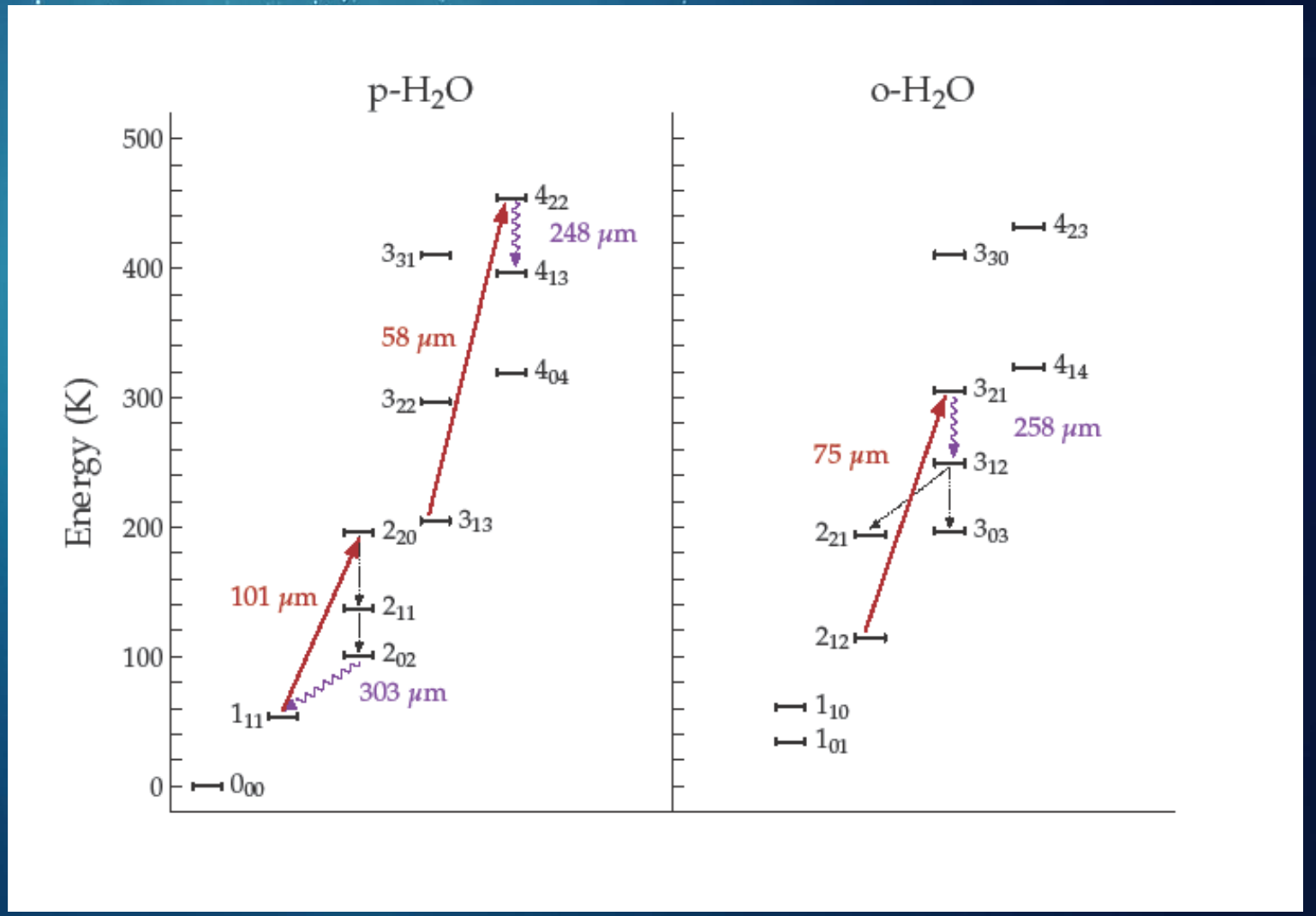
Images Credits: Fraser+ , *The Rev of Sci. Instr.*· May 2002; Bill Saxton, NRAO/AUI/NSF; T. Ronconi+, 2023.

The “makeup”: H_2O excitation/ spectroscopy

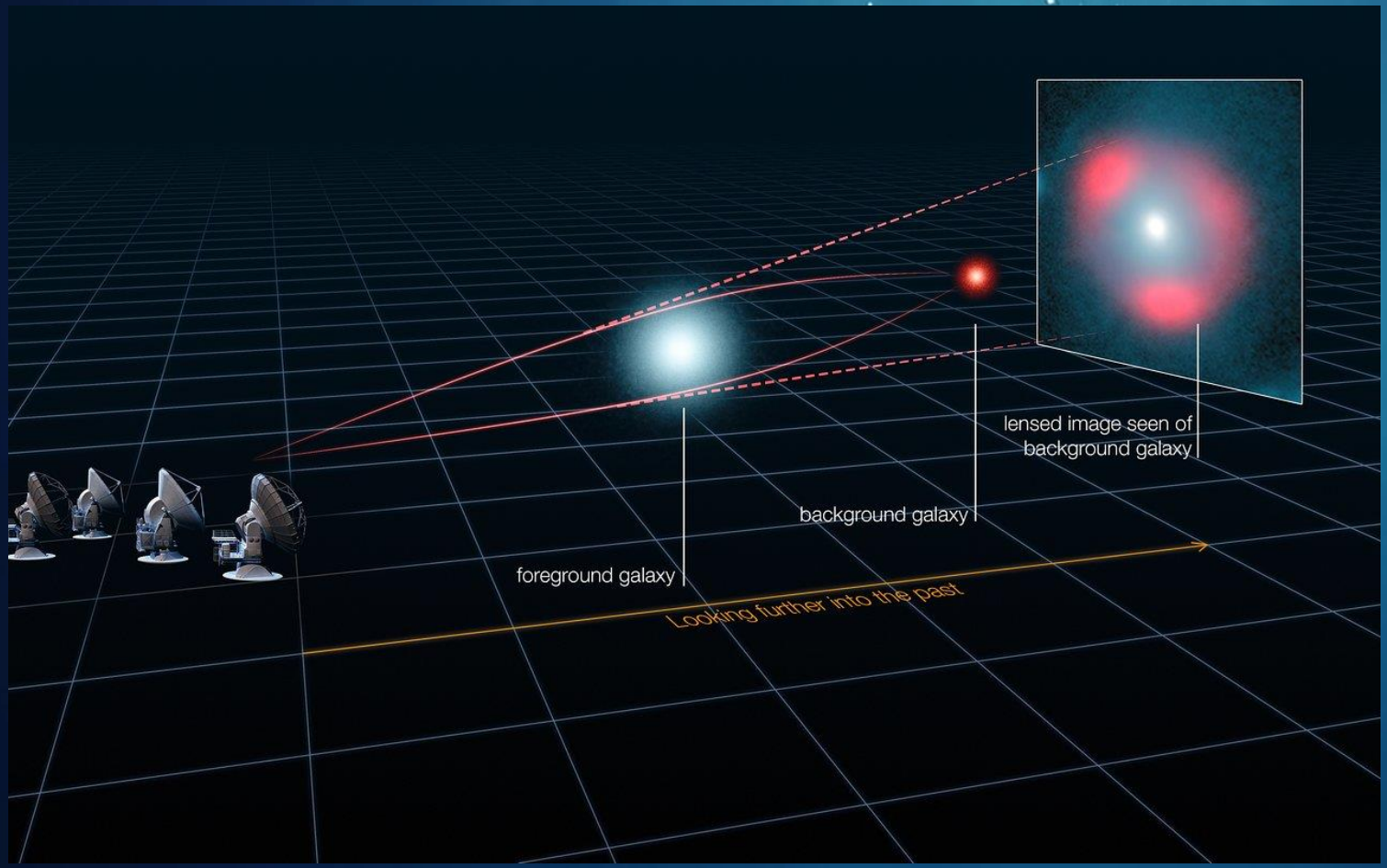
Besides collisional excitation, FIR pumping populates levels which decay through a cascade process emitting submm photons.

Transition	ν_{rest} [GHz]	E_{upper} [K]
p-H_2O 2_{02}-1_{11}	987.927	100.8
o-H_2O 3_{21}-3_{12}	1162.912	305.2
p-H_2O 4_{22}-4_{13}	1207.639	454.3

Para (antiparallel H protons spins) and ortho (parallel H spins) do not mix.

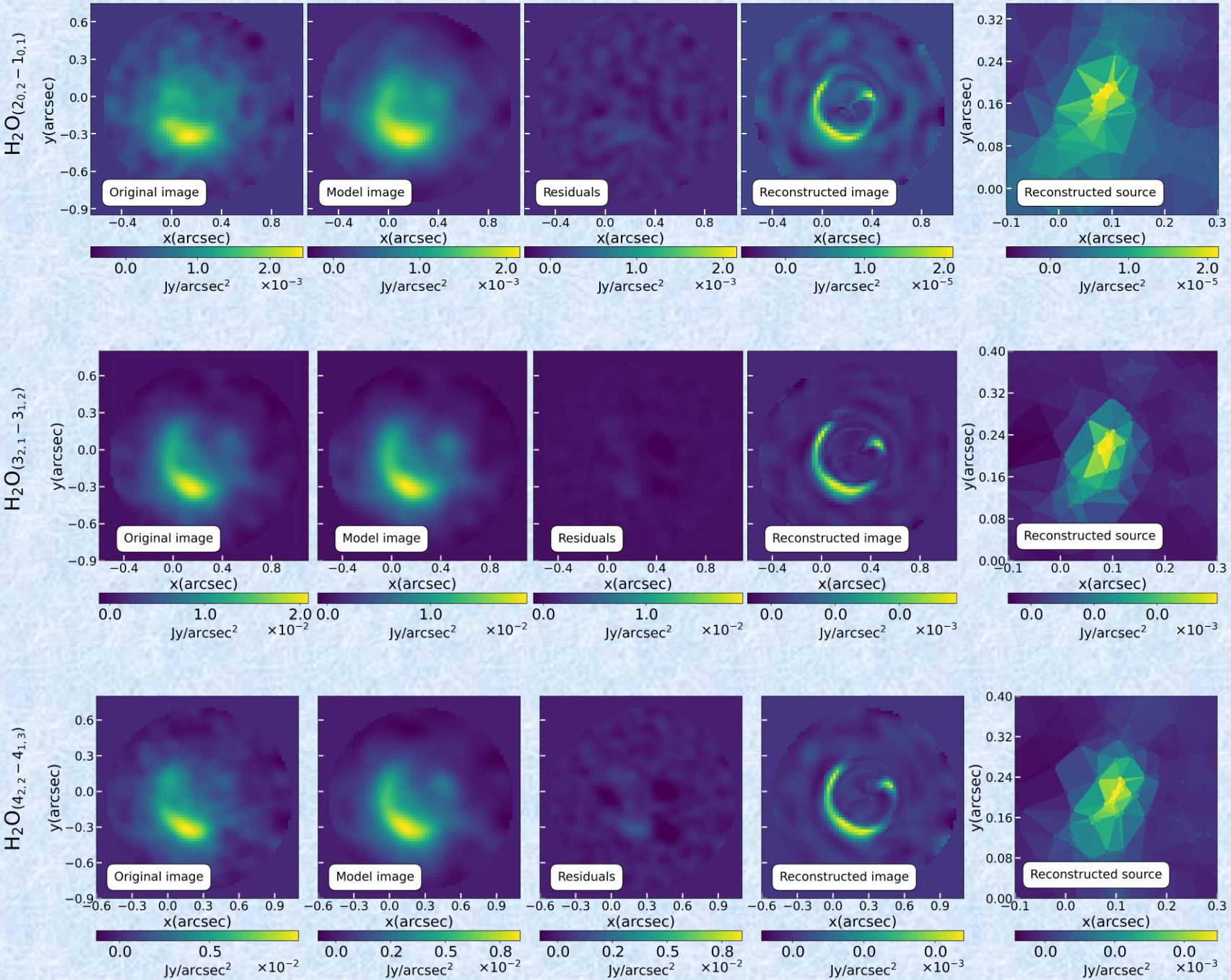


Academy Award winner for Best Visual Effects: Gravitational Lensing



Credits :ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.

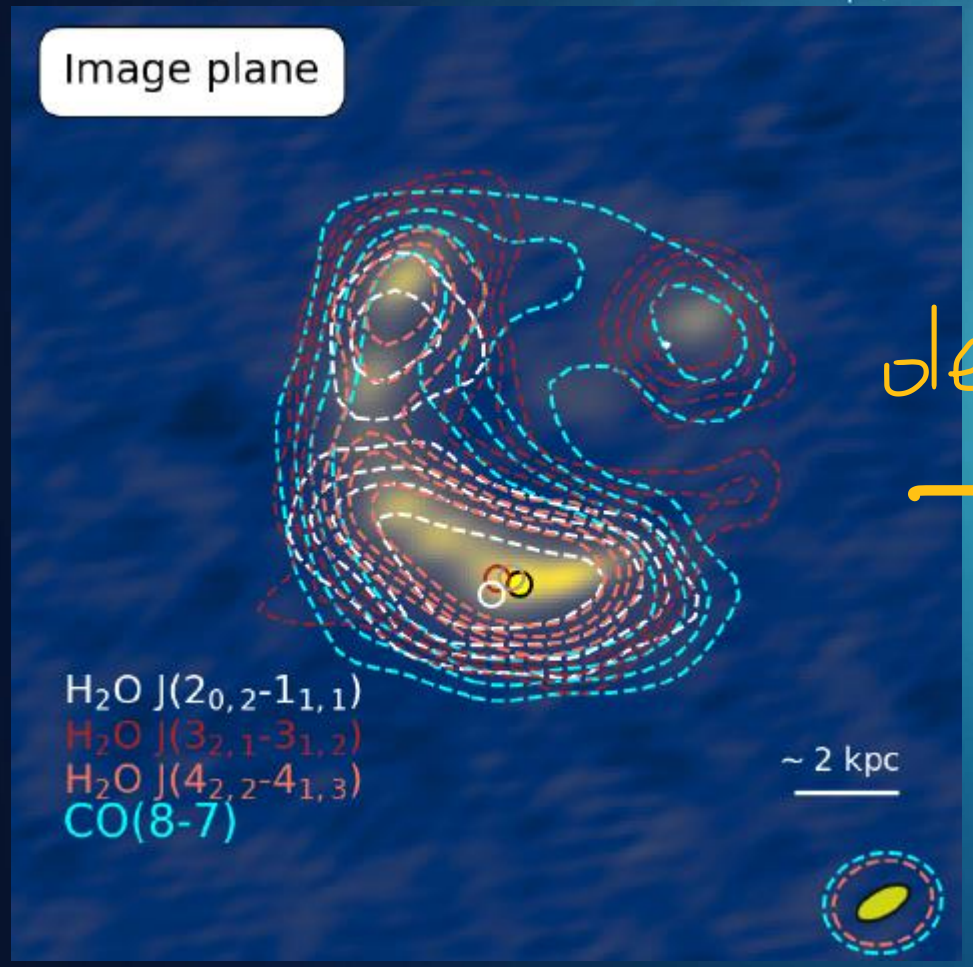
- Magnification factors for J113526 water lines of the order 7-12 in flux densities;
- Stretched angular scales → target source resolved up to few hundreds pcs.



Columns:
-ALMA dirty image
-Best-fit lensed model dirty image
-residuals
-image plane's model
- reconstructed source plane (using Singular Isothermal Ellipsoid lens model, see Giulietti+2022)

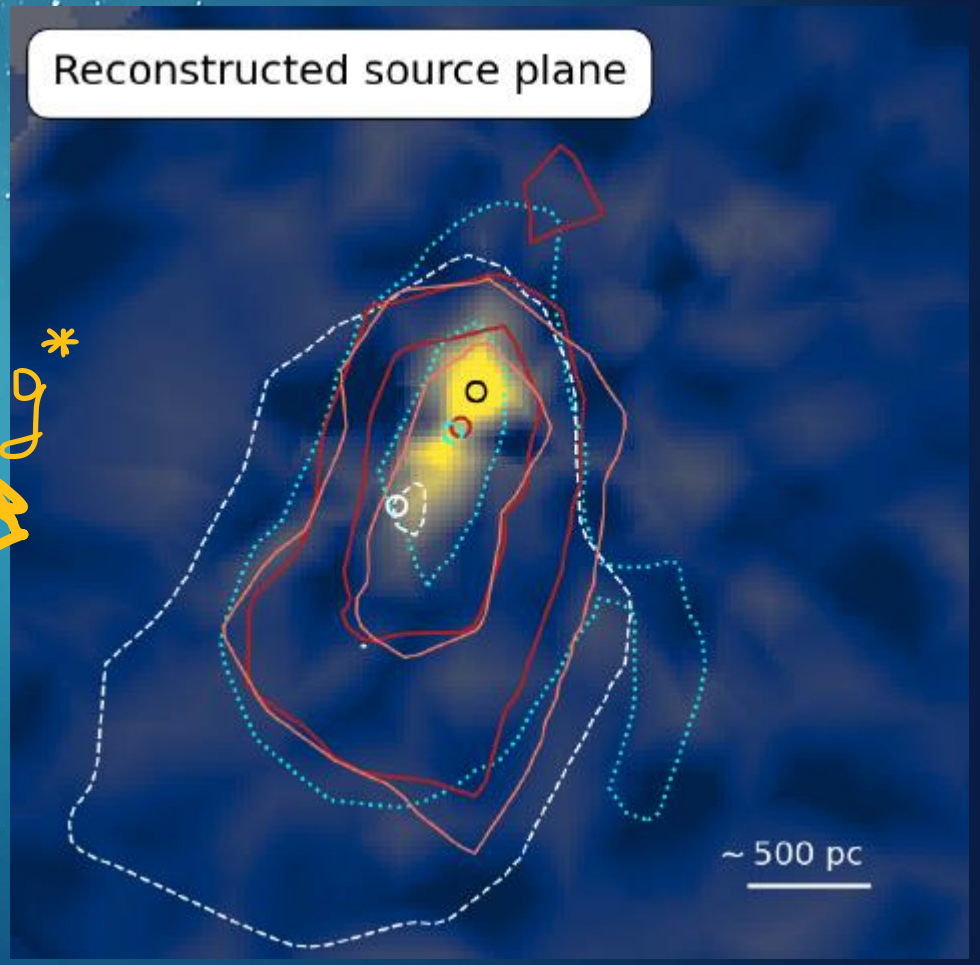
Brightness scale

Imaging analysis



5, 7, 9, 12 σ contours

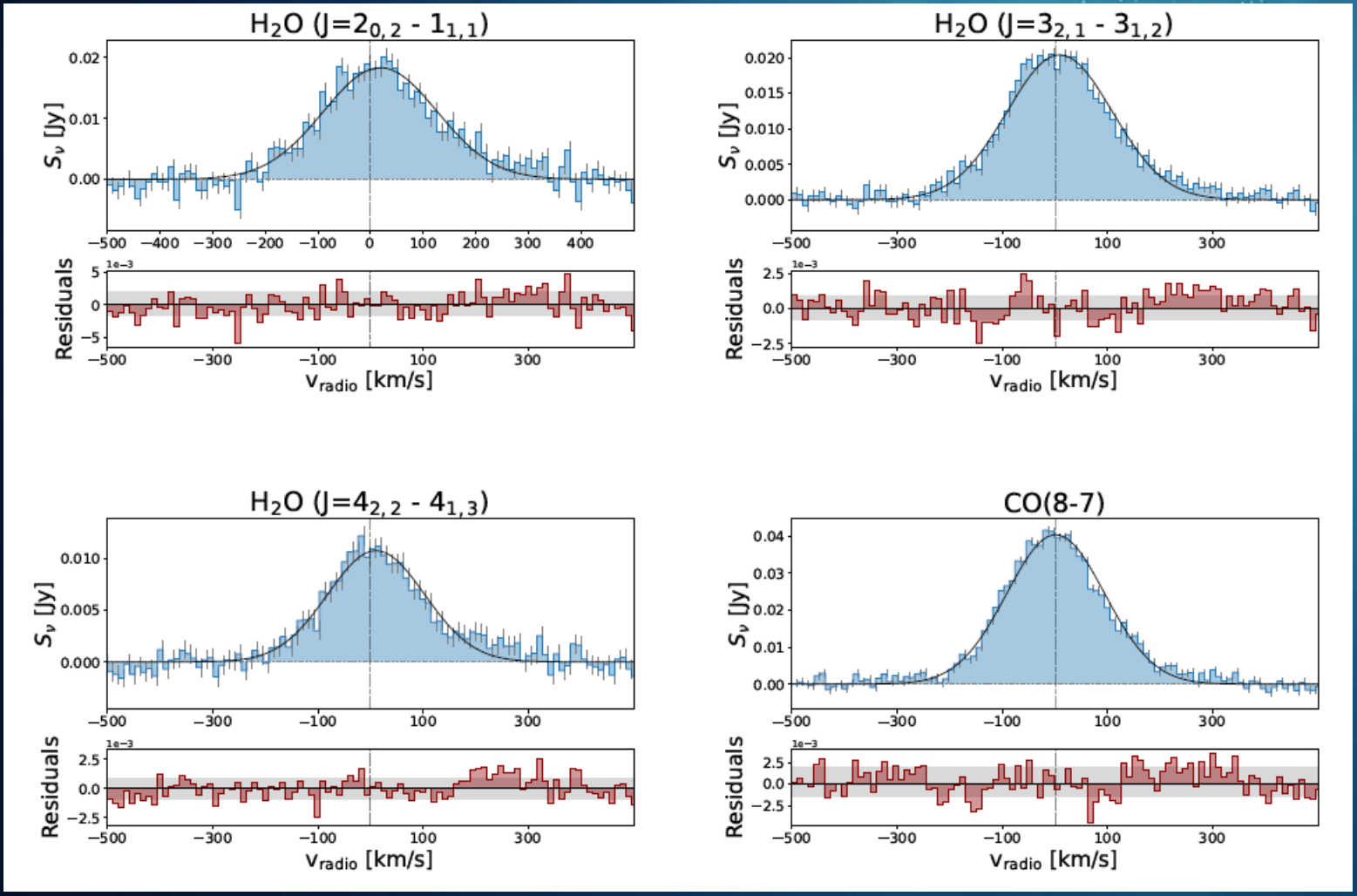
ole-lensing*



3, 11 σ

Central nucleus traced by mid and hig lines!

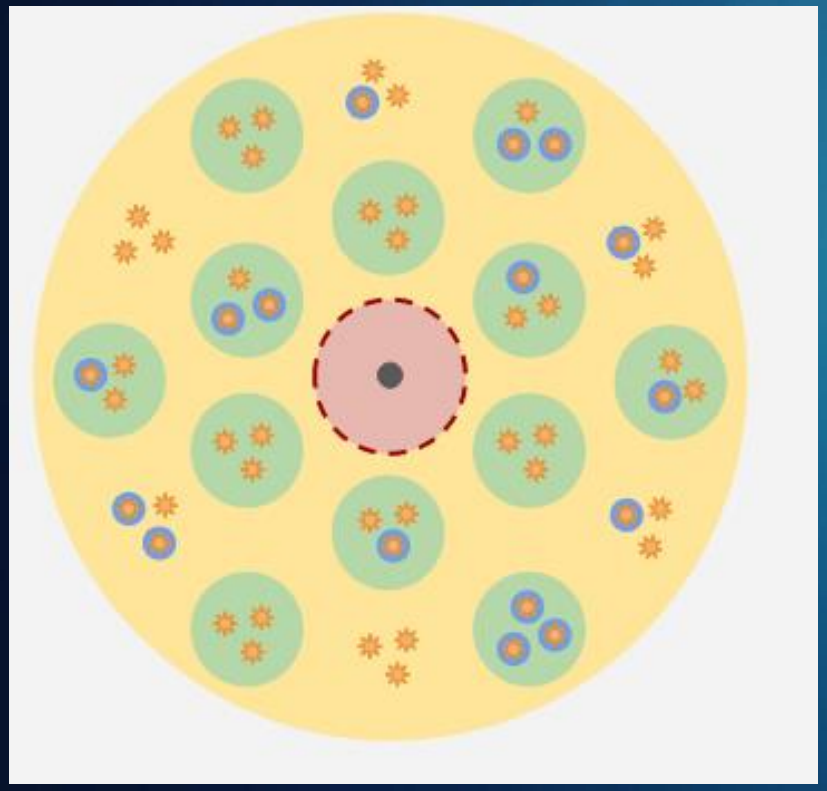
Emission lines



No evidence for rotation or outflows of the central nucleus (confirming results from CII analysis, Giulietti+2022).

High-level CO lines and H_20 lines arising from a compact, warm-gas and warm-dust region.

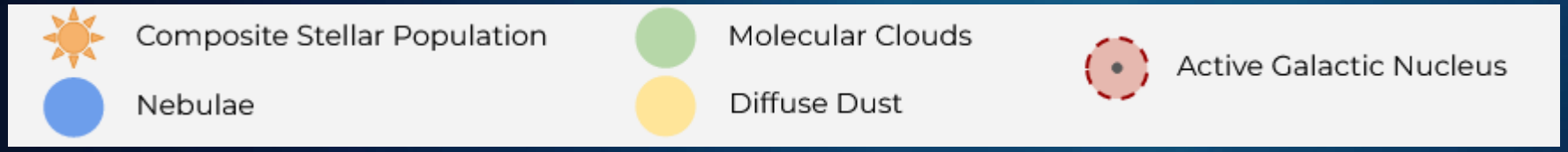
The big puzzle of high-z astrochemistry/spectroscopy



For the Astro-chemist, there is no such thing as a “galaxy”, but only “molecular building blocks” with their own physical properties. High-z galaxies only allow the analysis of an “average” signal. Key word: SIMPLIFY.

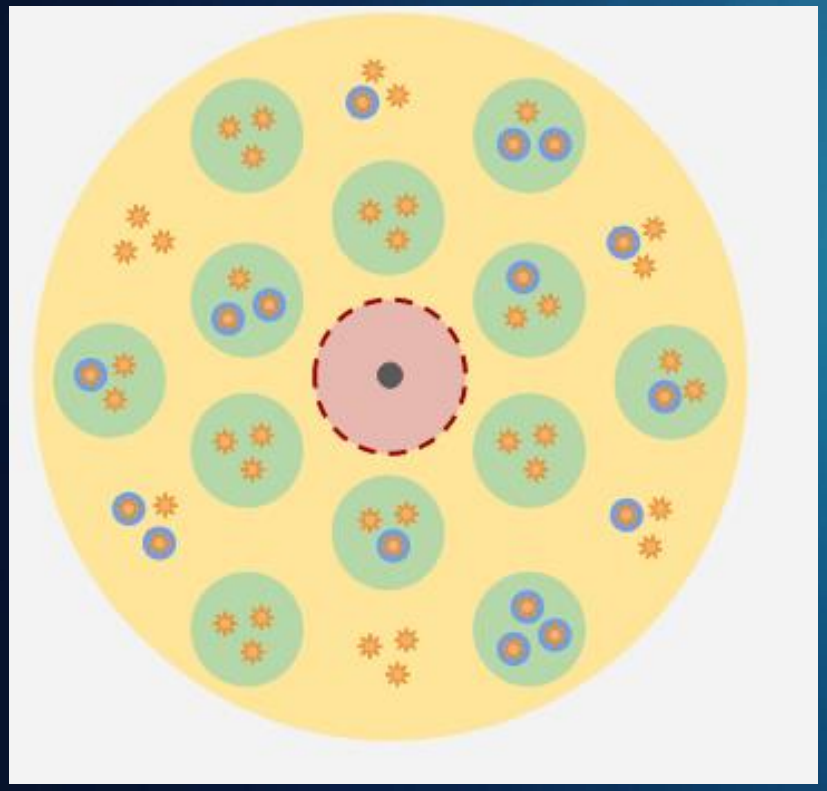
Modeling: how much molecular gas resides in DSFGs, and how is it distributed? (Rybak+2022, Ronconi+2023)

Stacking techniques may help to get the “average” ISM (Spilker+2014;Torsello M., in prep.)



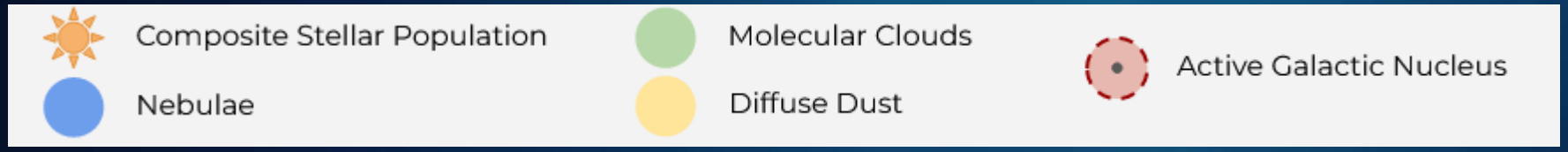
Courtesy Ronconi T.

The big puzzle of high-z astrochemistry/spectroscopy



J113526 has a central, compact zone where water transitions are ignited, as well as emission from CO(8-7) transition.

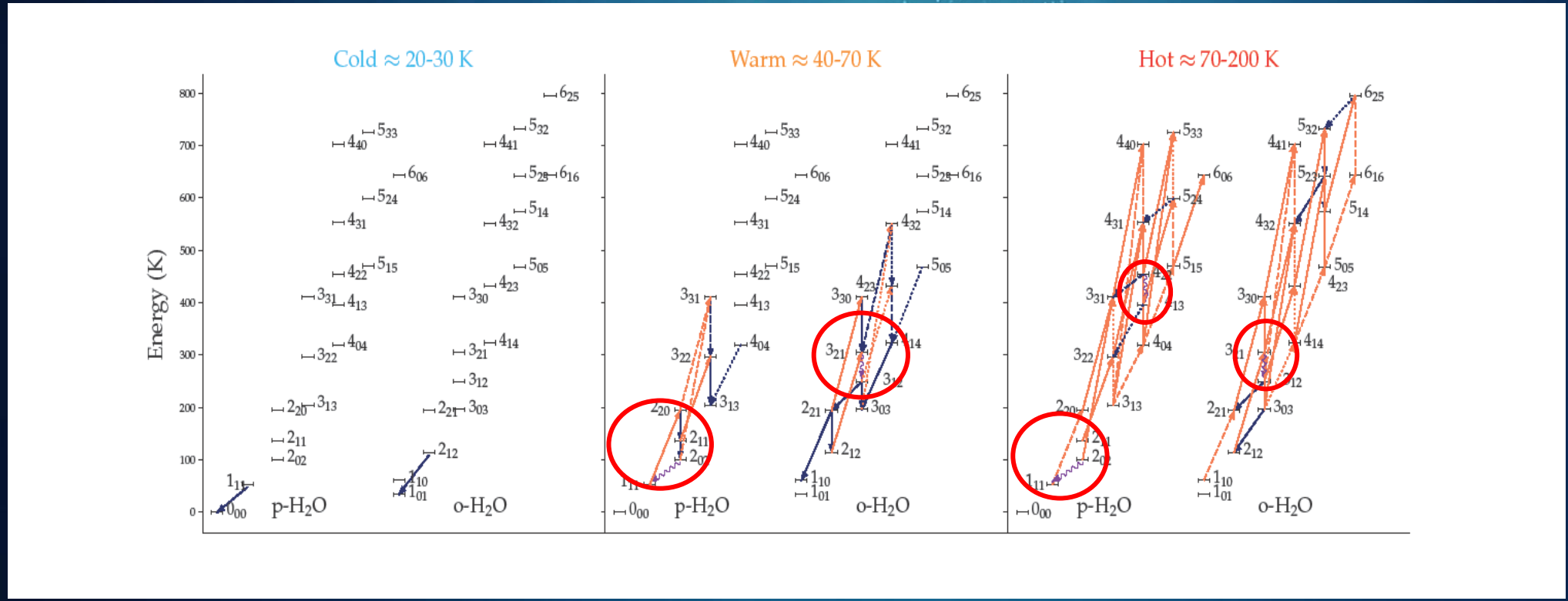
Liu+ 2017: a galaxy is modeled with different ISM "components". Each component is an ensemble of molecular clumps with identical physical properties.
T_{ex} and level populations in a clump depends on the physical conditions of the dust and of the gas itself.
Typical values for a warm gas component: T_K =50 K, $n(H)=10^5\ cm^{-3}$, $X(H_20)=10^{-5}$



Courtesy Ronconi T.

Denouement: ISM in J113526

Credits: Liu+ 2017, ApJ 846, 5.



Radiative transfer solution needed to get the ISM average parameters.

Hot component, Tdust ~ 70 K, n(H)~ 10^5 cm^{-3} and Tgas ~ 50 K embedded in a diffuse dust component Tdust ~ 40 K

Star formation traced by water lines

Assuming Salpeter IMF, $SFR[M_{Sun}\ yr^{-1}] \approx 1.47 \times 10^{-10} L_{IR}\ [L_{Sun}]$. $L_{IR} \leftrightarrow L_{H2O}$

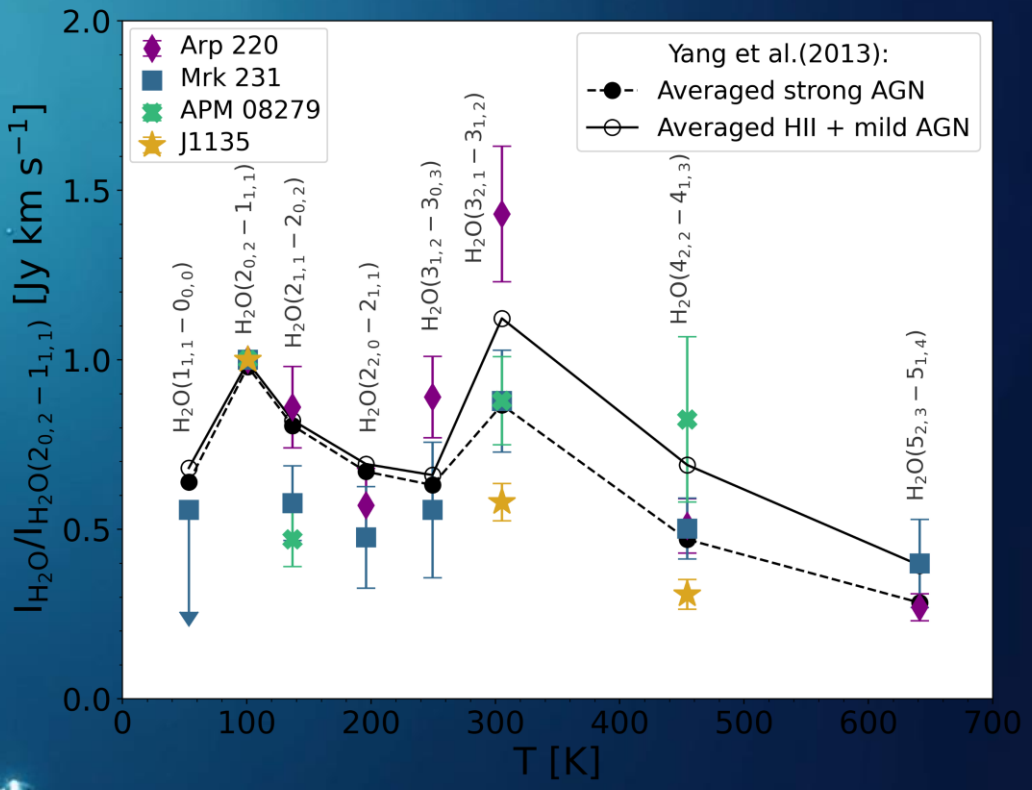
Caveats: L_{IR} can be enhanced by non-SF mechanisms; L_{IR}/L_{H2O} may be biased by collision contribution ⟶

More reliable to trace SF through the purely FIR-pumped water lines (e.g. 4_{22}-4_{13}).

Starburst vs AGN tracers?

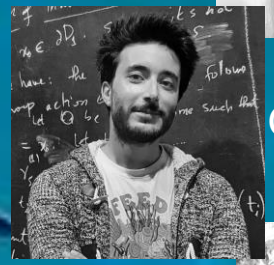
High/medium H_20 lines of J1135 analogous to the sample containing a mild AGN.

Comparison with Yang+ 2013 (for two samples taken from the NASA/IPAC Extragalactic Database), Mrk 231 (Gonzalez-Alfonso+ 2010), Arp 220 (Rangwala+2011), and the lensed QSO APM08279+5255 (vanderWerf+2011) show that AGN may have little impact on water excitation.



End credits

Marika Giulietti



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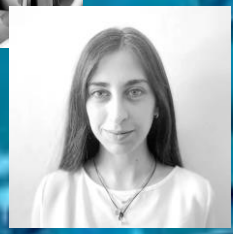

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