“The Ice Age of the JWST ERA: Mapping the Frozen Voids of the Galaxy”

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OU Astrochemistry

The Open University

Observations: Alison Craigon; Jennifer Noble; Aleksi Suutarinen; Tim Kendall; George Pagomenous

MD work: Pavel Elkind; James Miller; John McCann, Pierre Guisquiere

Experiments: Jennifer Noble; Catherine Hill; Natalia Pascual; Sabrina Gaertner; Anita Dawes; Vincent Deguin; Olivier Auriacombe; Pierre Guisquiere

AstrobiologyOU UK SPACE AGENCY Science & Technology Facilities Council cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY esa MARIE CURIE ACTIONS SEVENTH FRAMEWORK PROGRAMME LASSIE UKRI Research England

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Dr Stefan Anderson (Trondheim) Prof Gunar Nyman (Gothenberg)
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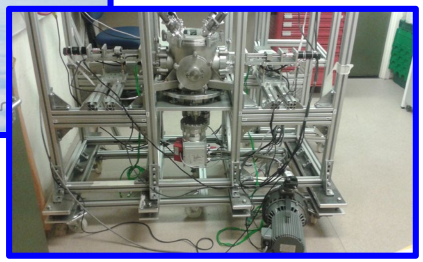
Prof. Dinko Chakarov (Chalmers)
Prof. Martin McCoustra (Herriot Watt)
Telespazio Vega UK; Lockheed Martin; Dynamic Analytical Imaging Ltd

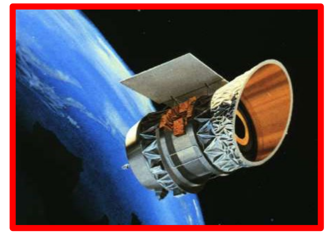
Fraser Group @ OU..



Parabolic Flight
- ice aggregation

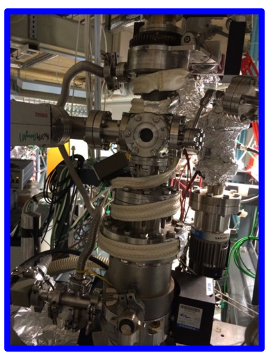
Ground or Space IR / Sub-mm Observations

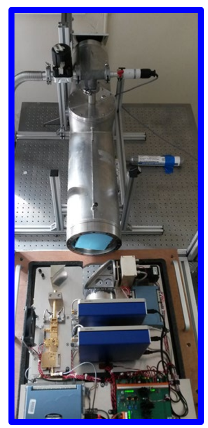
- ice & gas in star-forming regions
- Plumes of Enceladus & Europa



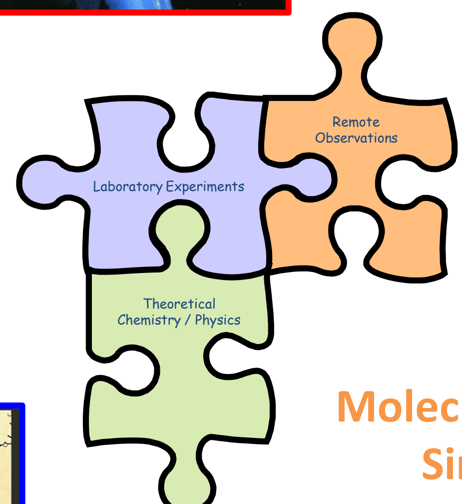
ALMA in the LAB
THz DES
- THz ice / gas spectra
- (non)-thermal ice desorption

UHV / HV Surface Science
- physical & chemical ice properties
- dust-ice interactions





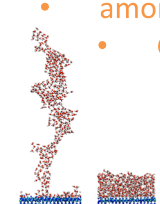
Laboratory Experiments



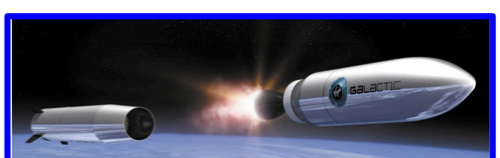
NIMROD (ISIS)
- ice structure
- ice sintering

Molecular Dynamics Simulations

- amorphous ice structure
- Growth kinetics

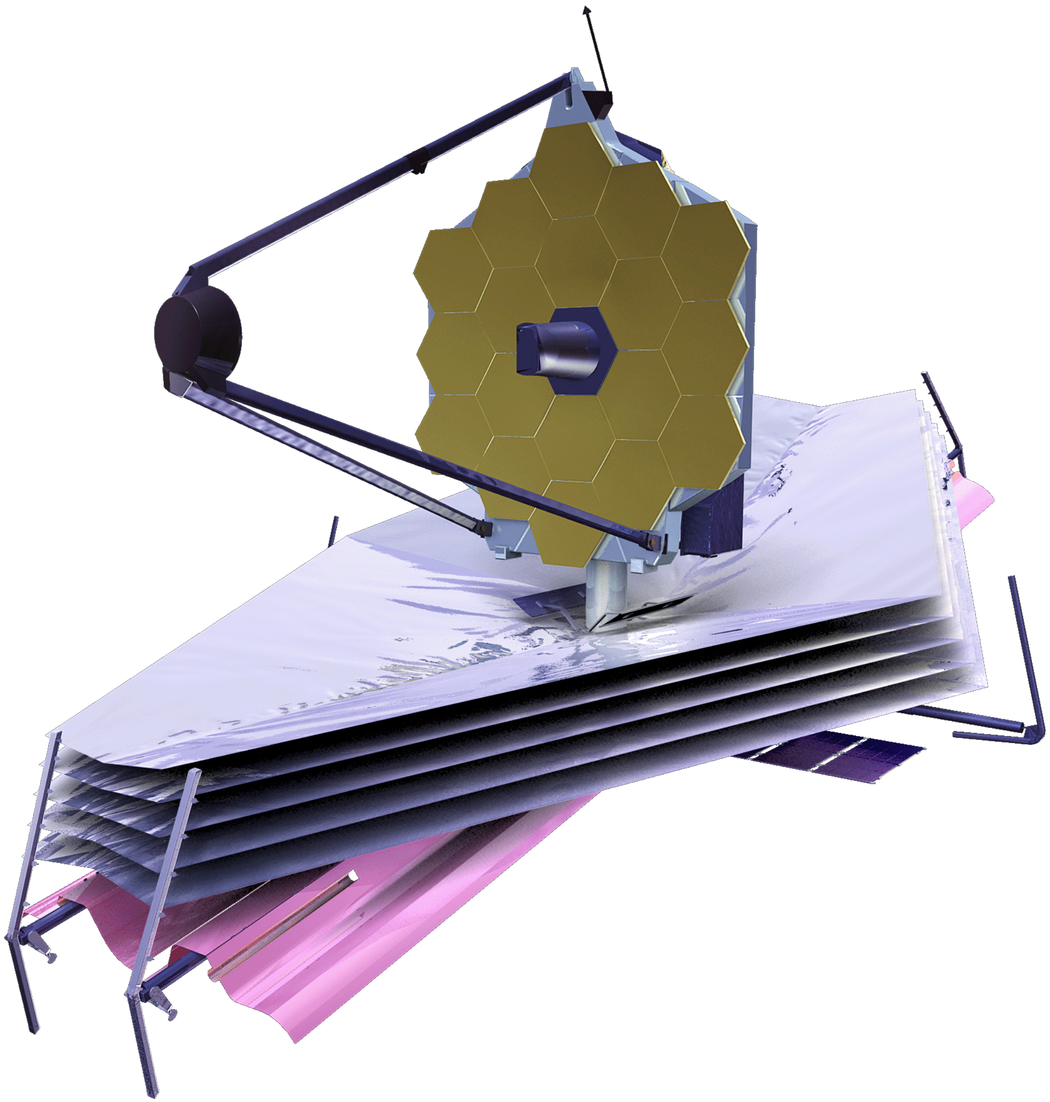


Sub-Orbital Flights



60 sec adventures in microgravity

JWST ERA – huge advantages
“our ice machine” (+ warm gas)



Parallel observing

Spectral Coverage

Resolution

Sensitivity

JWST ERS Programmes (13)

exciting “new science” / demonstrate JWST technical & scientific capabilities / community products / worldwide team reach

3/4 instruments = NIRSPEC NIRCAM MIRI

Pre-stellar / protostellar / disks / clouds
Galactic Star Formation

Why ice?


MATTHEW McCONAUGHEY
ANNE HATHAWAY
JESSICA CHASTAIN
AND MICHAEL CAINE
THE END OF EARTH WILL NOT BE THE END OF US.
FROM THE DIRECTOR OF THE DARK KNIGHT TRILOGY AND INCEPTION
INTERSTELLAR
COMING SOON


A FILM BY CHRISTOPHER NOLAN
INTERSTELLAR
IN CINEMAS NOVEMBER 7

The "Universal" Water Cycle

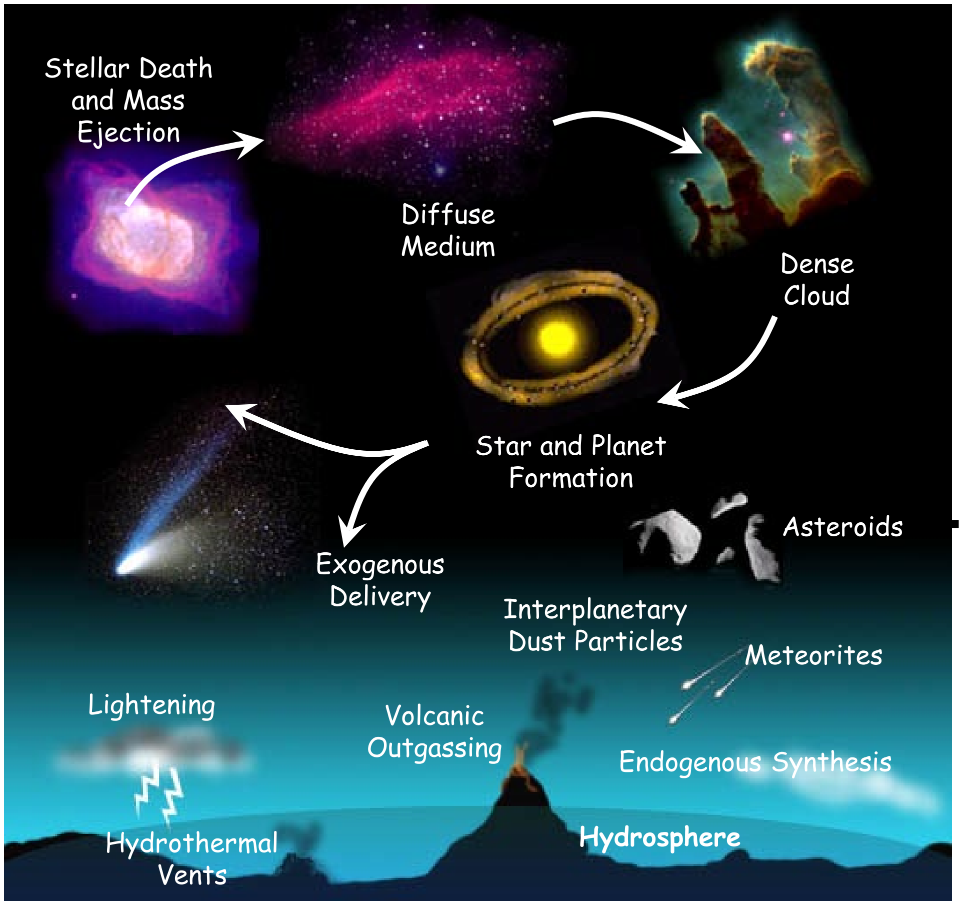


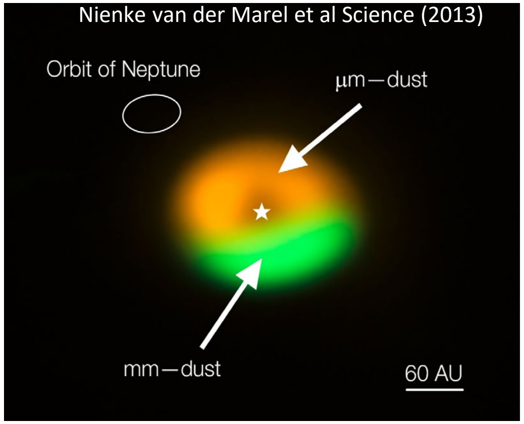
Image adapted from Stars 'R' Us material

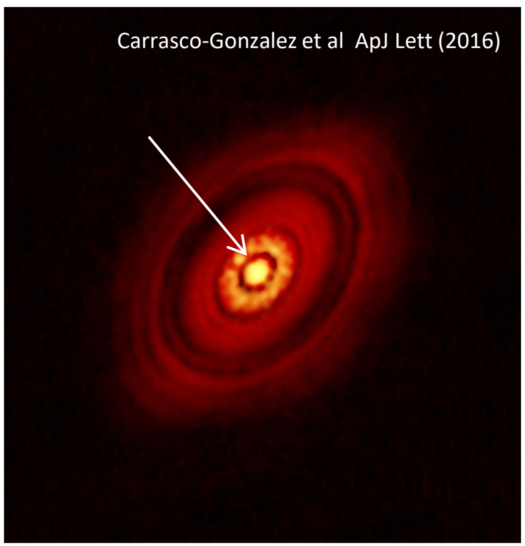
Water in ISM =
SOLID / GAS Ø ONLY

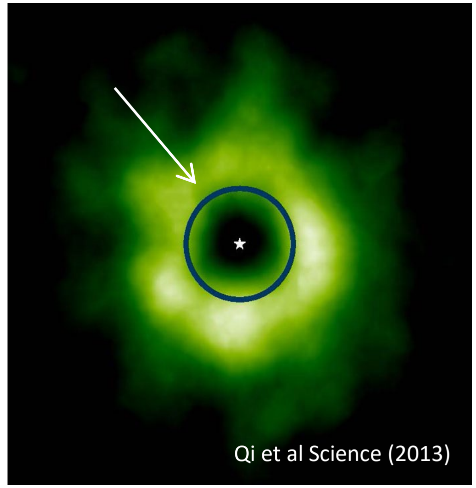
Planetary systems =
Water can vitally ALSO exist in liquid Ø which provides the environment for biological, geological & atmospheric evolution.

Timely & Topical

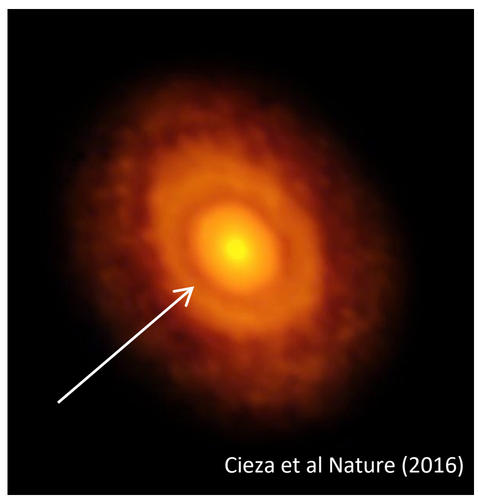
dust traps, clumping
size differentiation



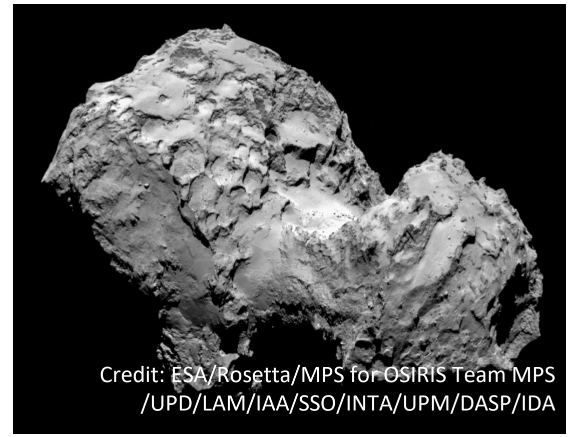




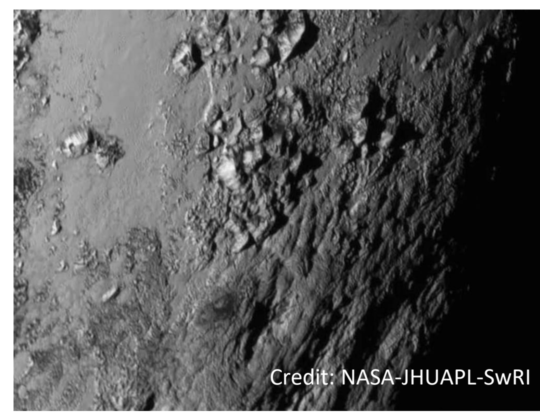
"Snow Lines"
in Disks



Comet(s) formed from
low-density fluffy grains



Icy regolith proliferates
on KBO surfaces (Pluto)



IMPACT of "cold"
solid–state "stuff"
on astrophysics
Pre-stellar clouds
Proto-planetary disks
(Exo) Comets & 'ice-teroids'
(Exo)planets & moons
Extra-galactic SF

"Ethanol"
(or other alcohols
i.e methanol)
COMS
Life?
1st COMS z= ?

Bottom Line

From observations we want to know

How much ice?

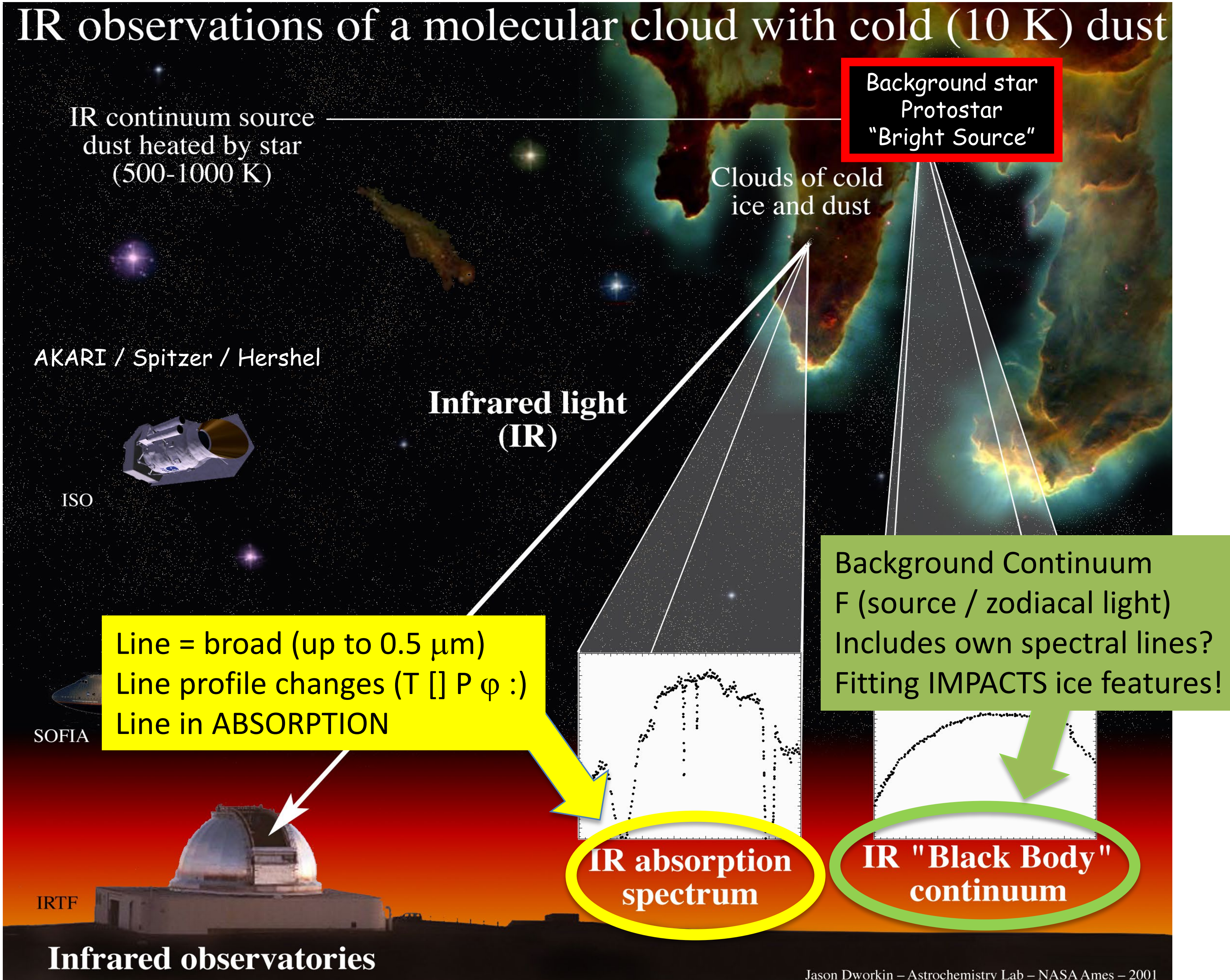
What type of ice?

Where is it?

= understand role of ice in star / planet formation
= understand synergy between gas and solid state
= understand chemical complexity (origins of life)

The Open University

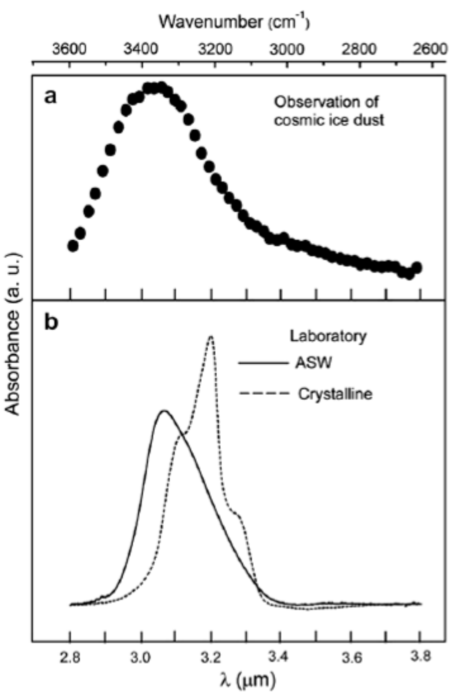
Observing / Mapping ISM Ices

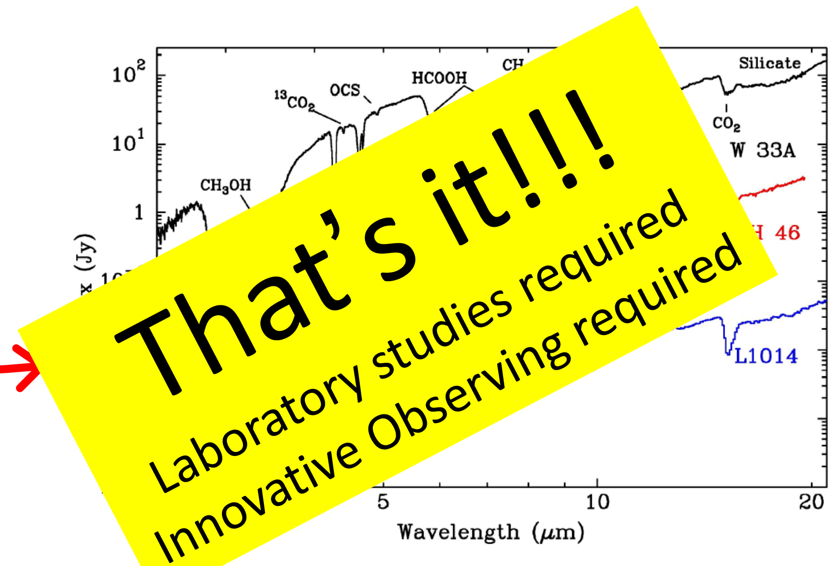

IR observations of a molecular cloud with cold (10 K) dust
Background star
Protostar
"Bright Source"
IR continuum source
dust heated by star
(500-1000 K)
Clouds of cold
ice and dust
AKARI / Spitzer / Hershel
Infrared light
(IR)
ISO
Background Continuum
F (source / zodiacal light)
Includes own spectral lines?
Fitting IMPACTS ice features!
Line = broad (up to 0.5 μm)
Line profile changes (T [] P φ :)
Line in ABSORPTION
SOFIA
IRTF
IR absorption spectrum
IR "Black Body" continuum
Infrared observatories
Jason Dworkin – Astrochemistry Lab – NASA Ames – 2001

Observational Reality Check

Solid-State Condensed Molecular Phases detected in NIR / MIR spectroscopy

Watanabe & Kouchi (2008) P&SS





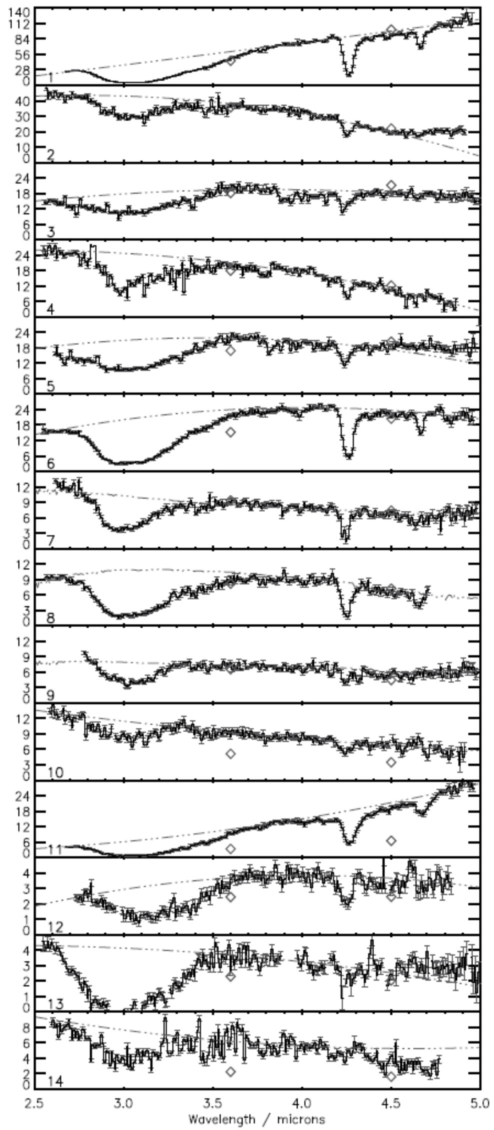
...n Dishoeck et al., Pacific-Chem Proceedings (2006)

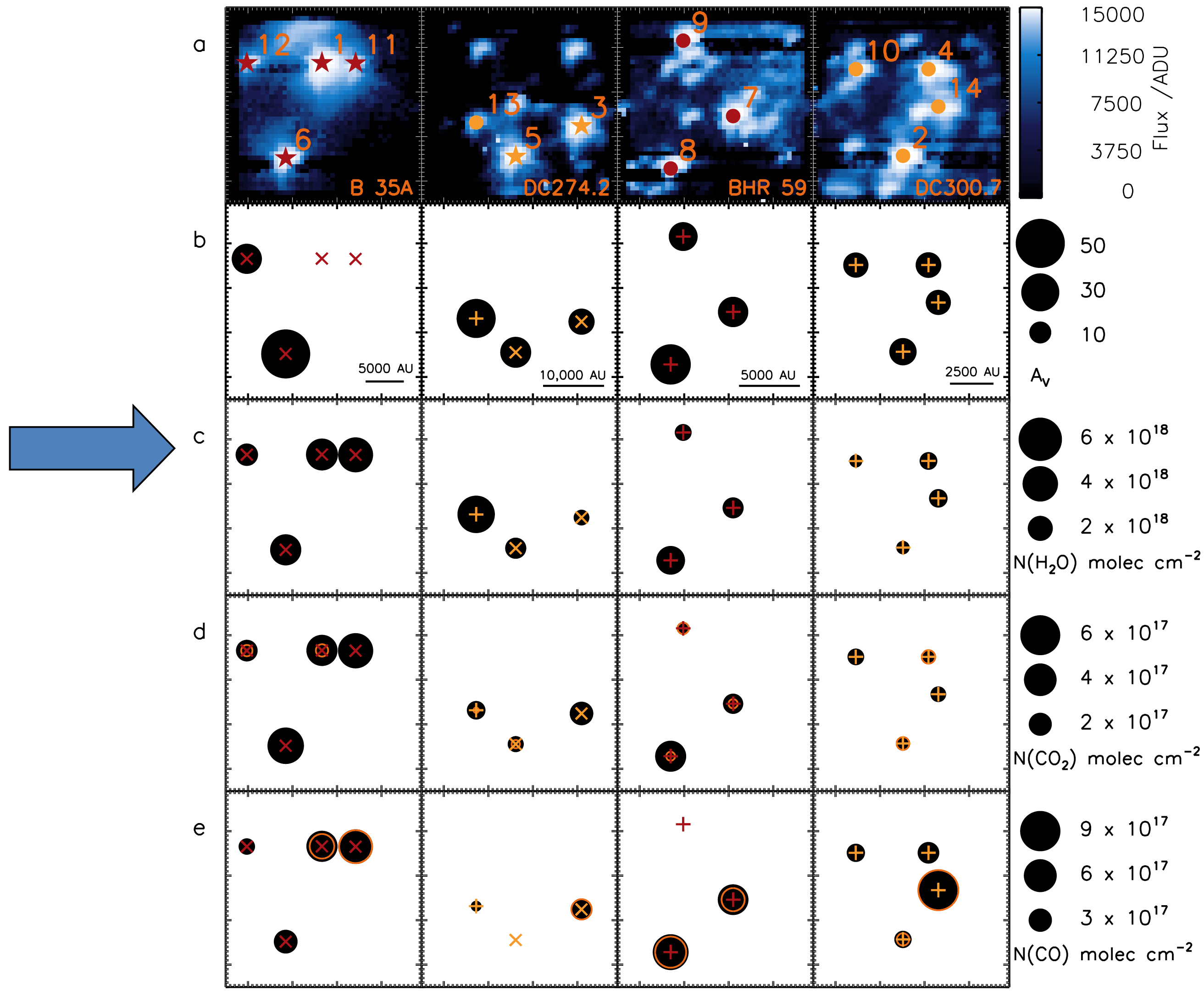
Analysis shows H_2O is most abundant molecular solid

Ice = major molecular reservoir in ISM

Band profile clearly identifies H_2O phase as AMORPHOUS

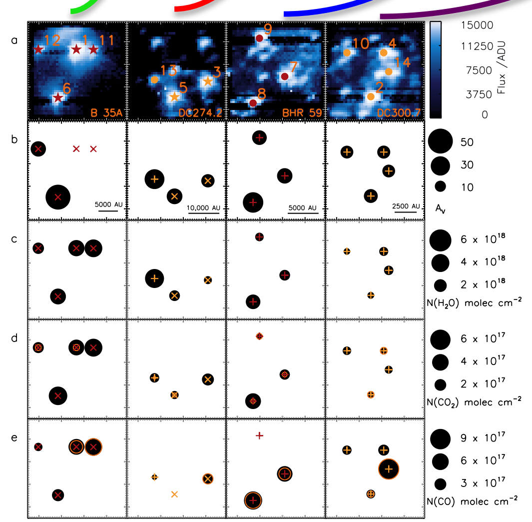
Are Statistics Best? Mapping

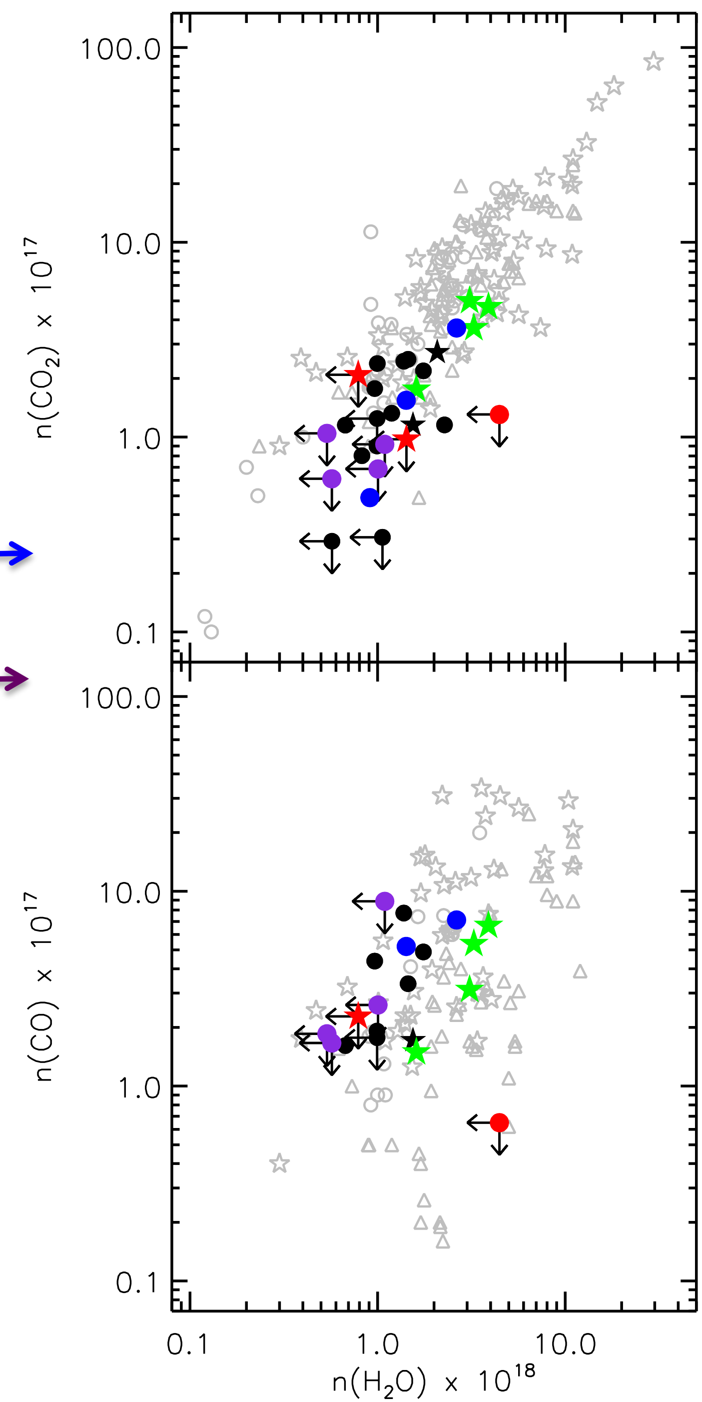




Noble et al (2013)
Noble et al MNRAS (2017)

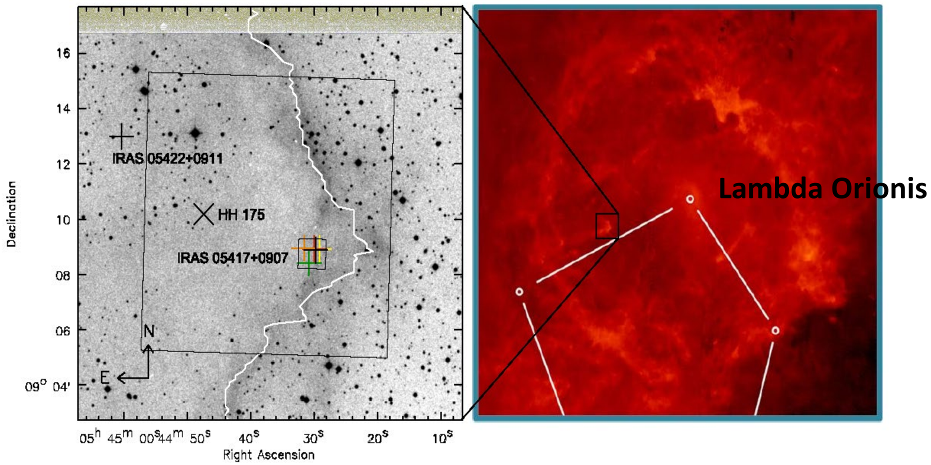
Scatter & “More = More”

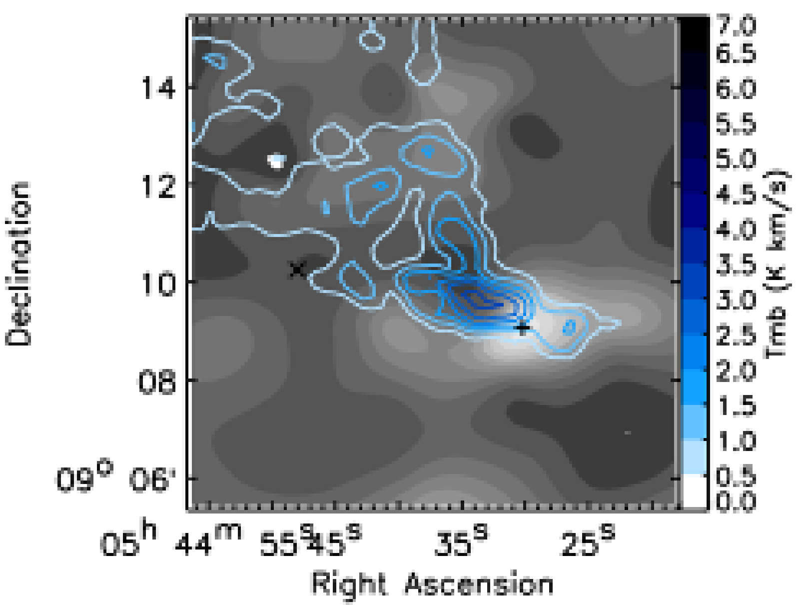


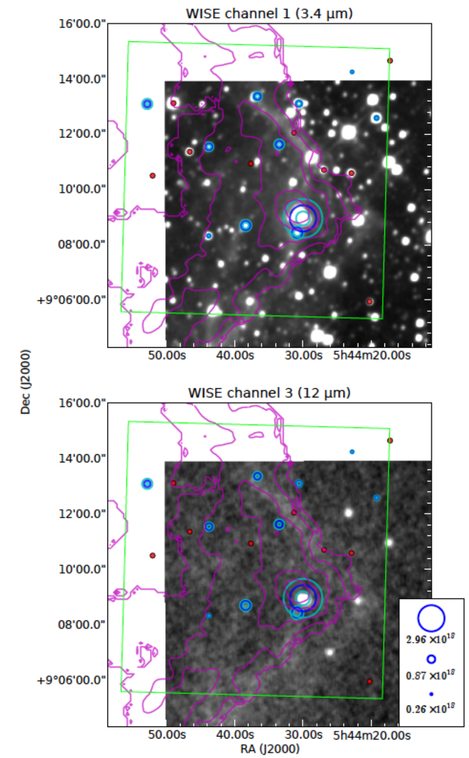


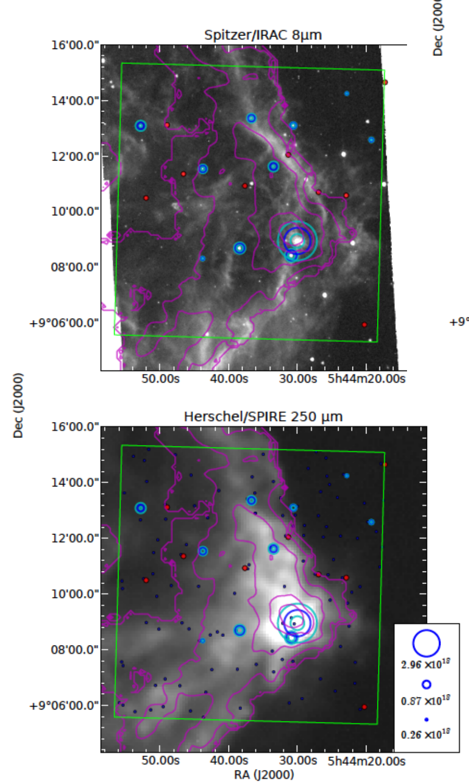
Noble et al (2013)
Noble et al MNRAS (2017)

eg 1 – B35a (CO & CO_2 ice maps)



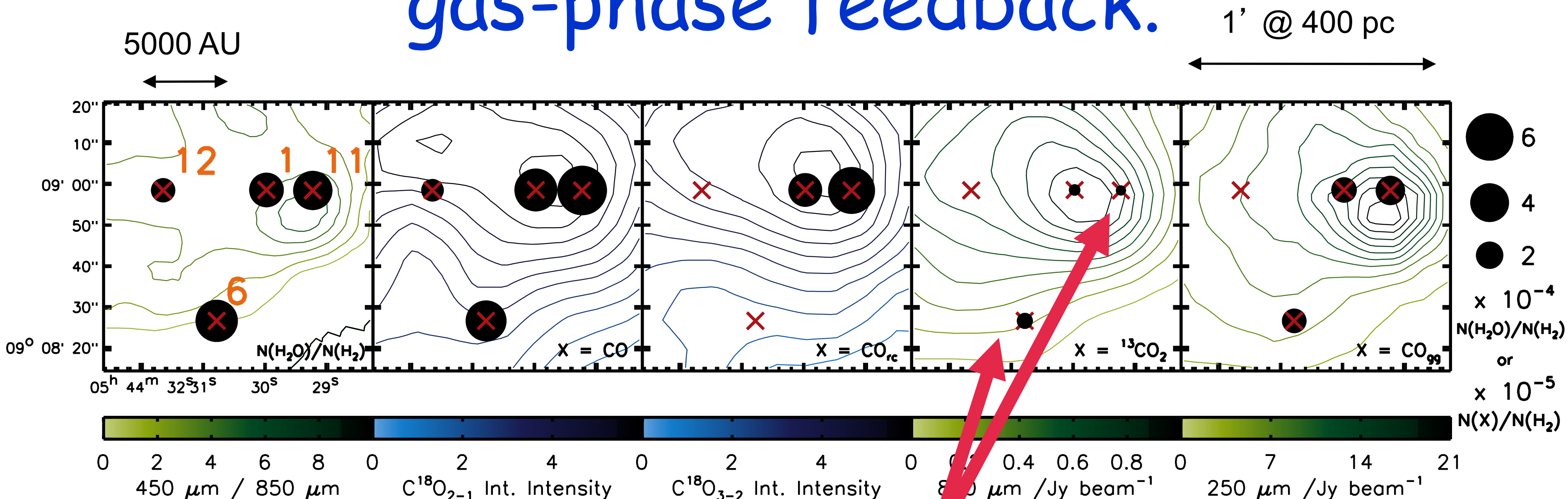


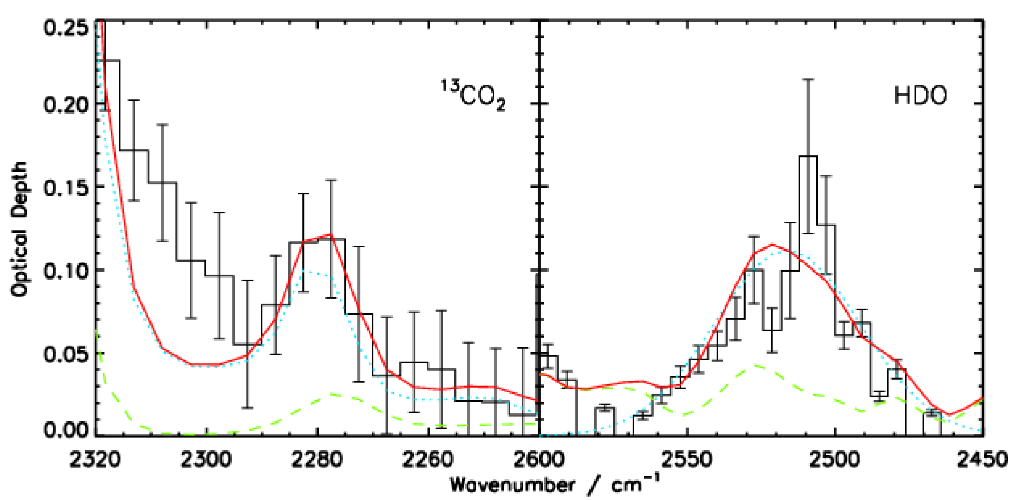




Suutarinnen in prep;
Craigon et al in prep;
Noble et al (2013) ApJ ;
Noble et al MNRAS (2017);

Ice central to chemistry and gas-phase feedback.



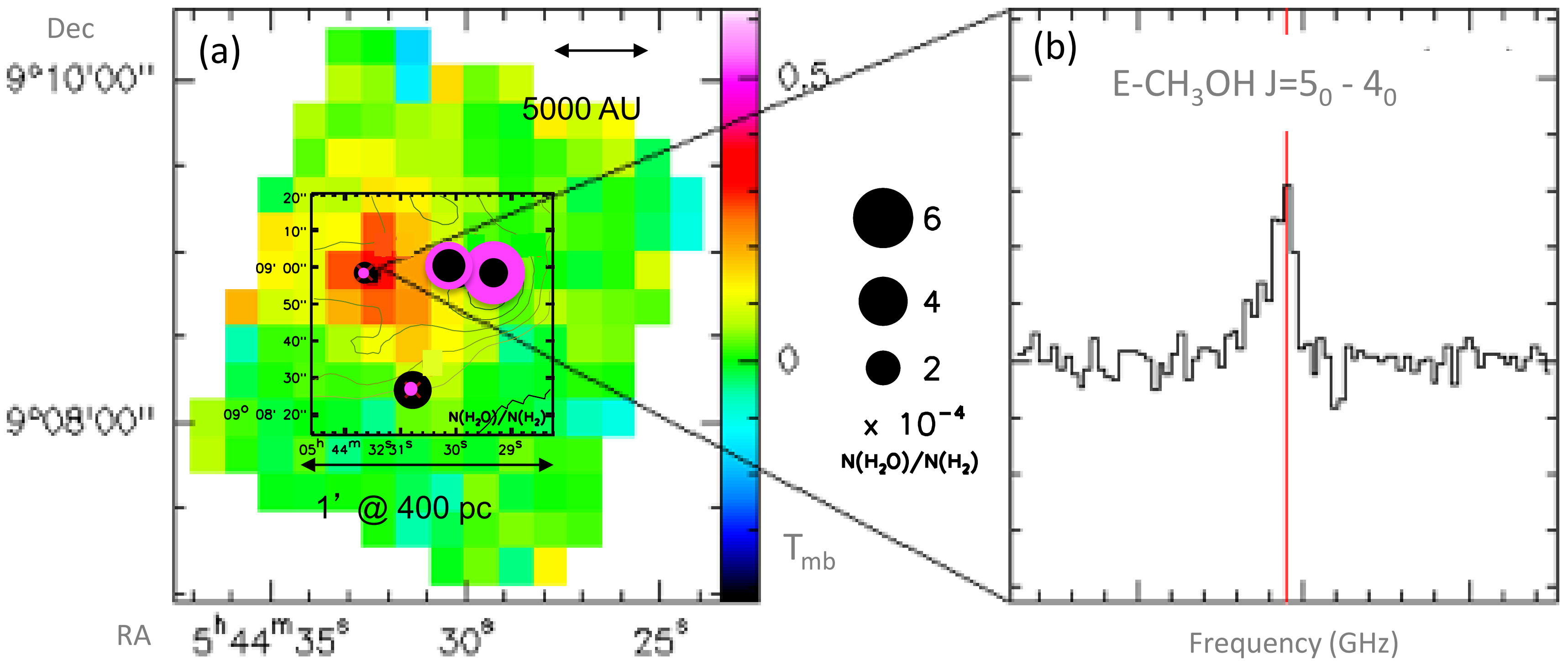


HDO / H_2O = 2 – 4 %

[HDO] = $8.6\times10^{17} – 1.7\times10^{17}$ cm^{-2}

Fraser et al (2019) in prep
Noble et al MNRAS (2017)

First (look) CH_3OH gas-ice maps… AKARI + SMA + APEX



- CH_3OH gas and ice seem anti-correlated again (phew!)
- Huge variability over a small distance – why???
- Still some CH_3OH ice where CH_3OH gas peaks

(does this hint to dual COMS chemistry formation routes?)

→ Potential tests of COMS formation

in prep (2019) Perotti, Fraser, Jorgensen, Kristensen

Eg 2 – SVS 4
(1st H2O ice-maps)

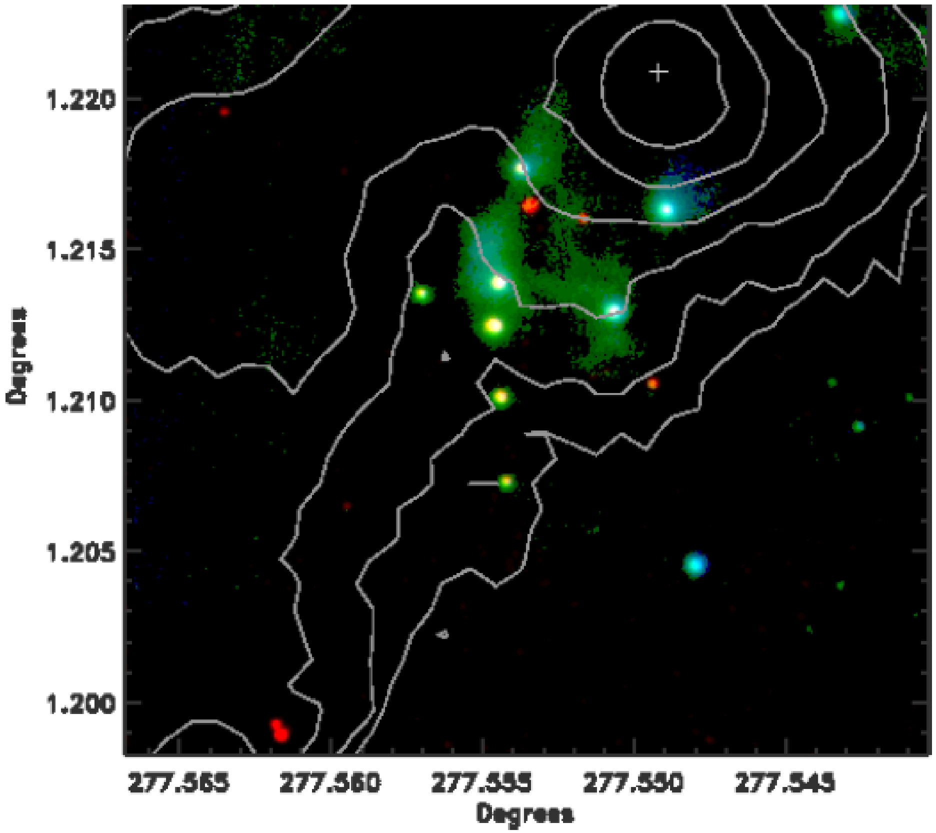
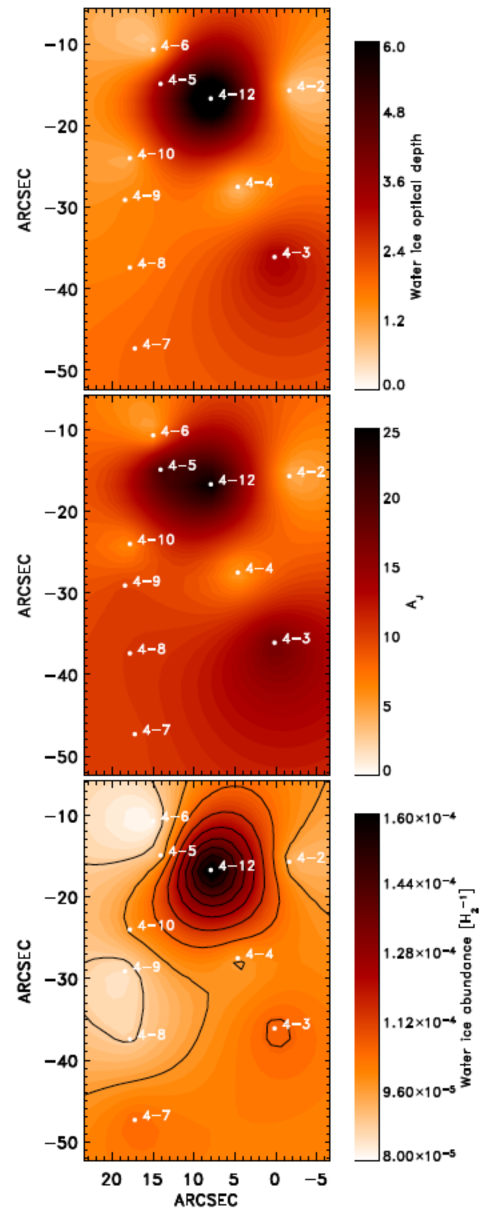


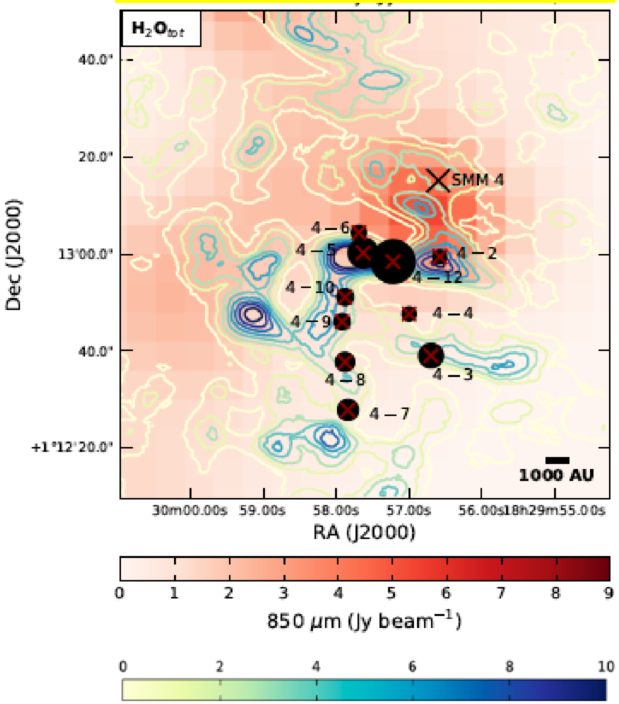
Fig. 1. *J*, *H*, 4 μm colour composite of SVS 4. The contours show the 850 μm SCUBA map by Davis et al. (1999). The cross indicates the central position of SMM 4.



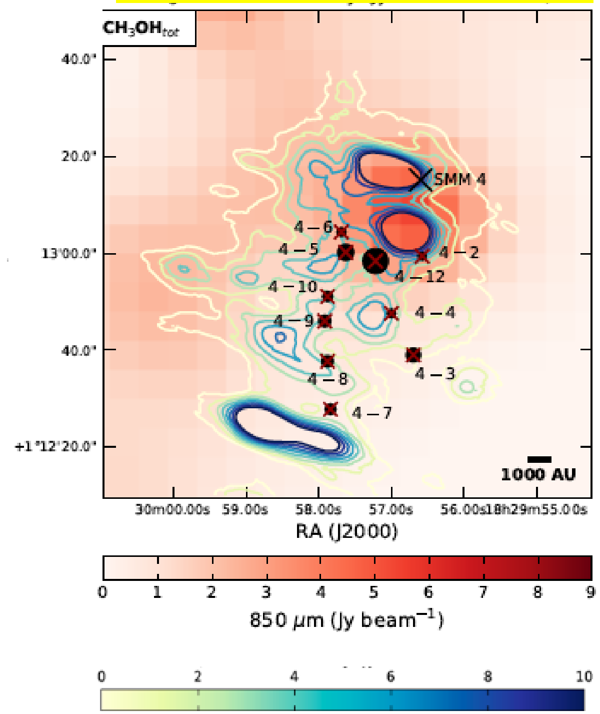
Pontoppidan et al (2004) ApJ

SVS4 ice maps

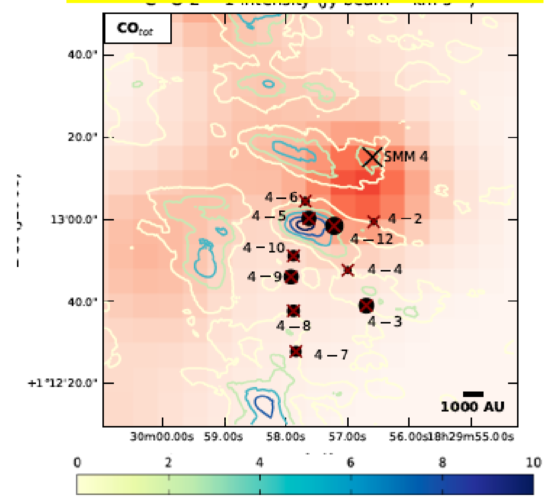
^{13}CO - cloud extent vs H_2O ice



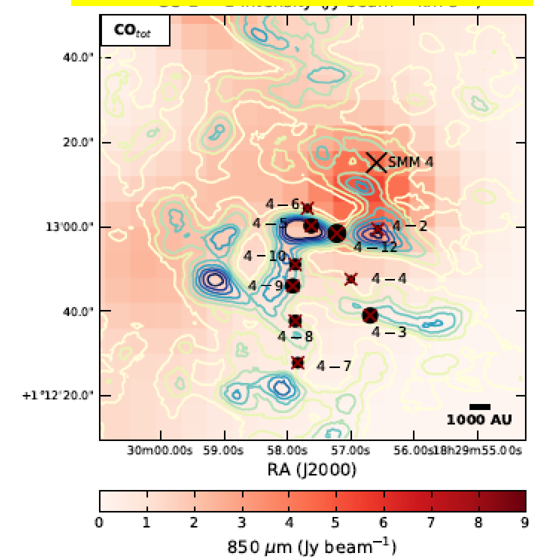
CH_3OH gas vs ice



$C^{18}O$ – densest cores



^{13}CO - cloud extent



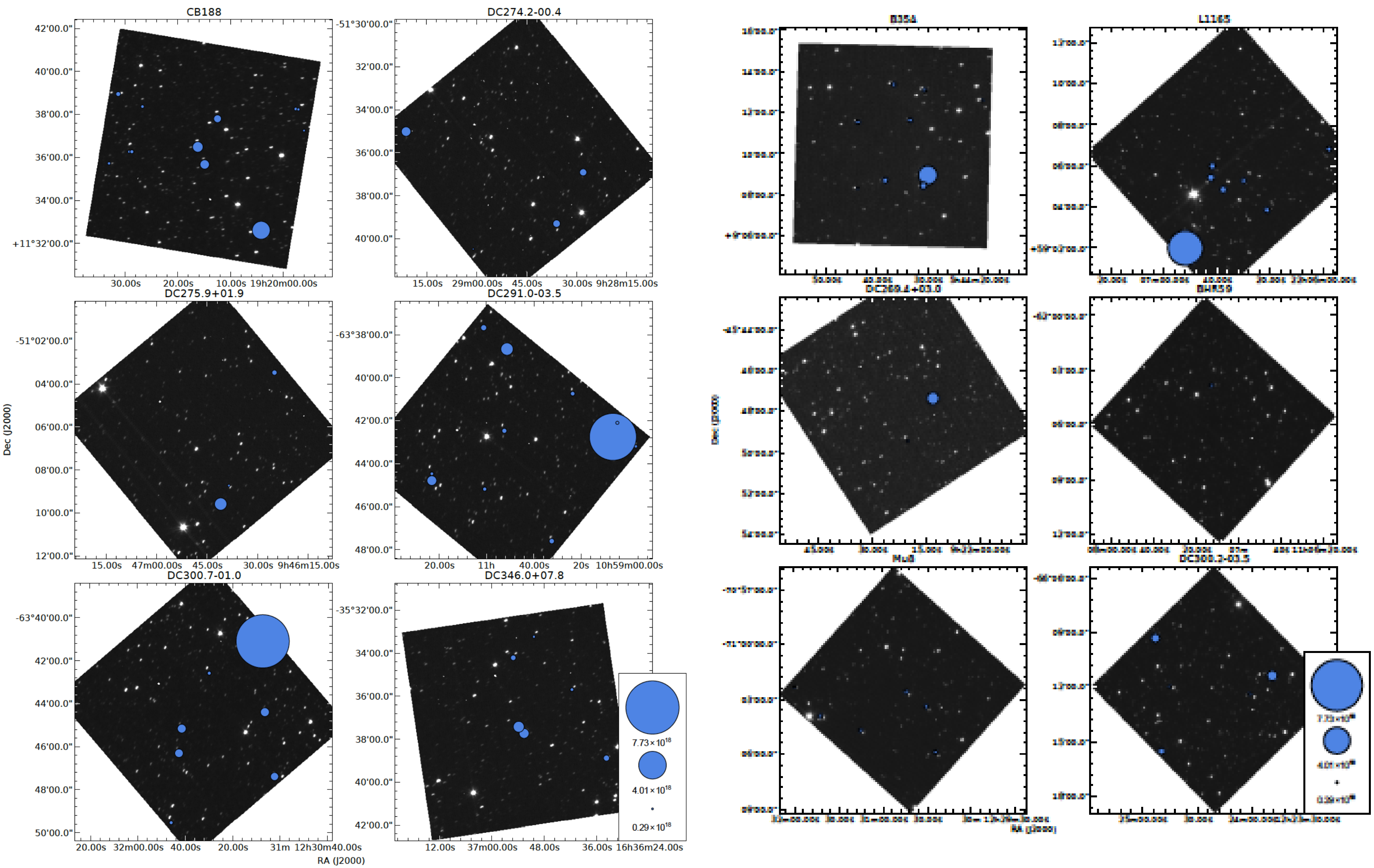
- Can't predict how much (H_2O) ice from gas maps ☹
- Can't predict how much (H_2O) ice from dust maps ☹
- Huge variability over a small distance – why???

- CH_3OH gas and ice seem anti-correlated (phew!)

in prep (2019) Perotti, Fraser, Jorgensen, Kristensen et al

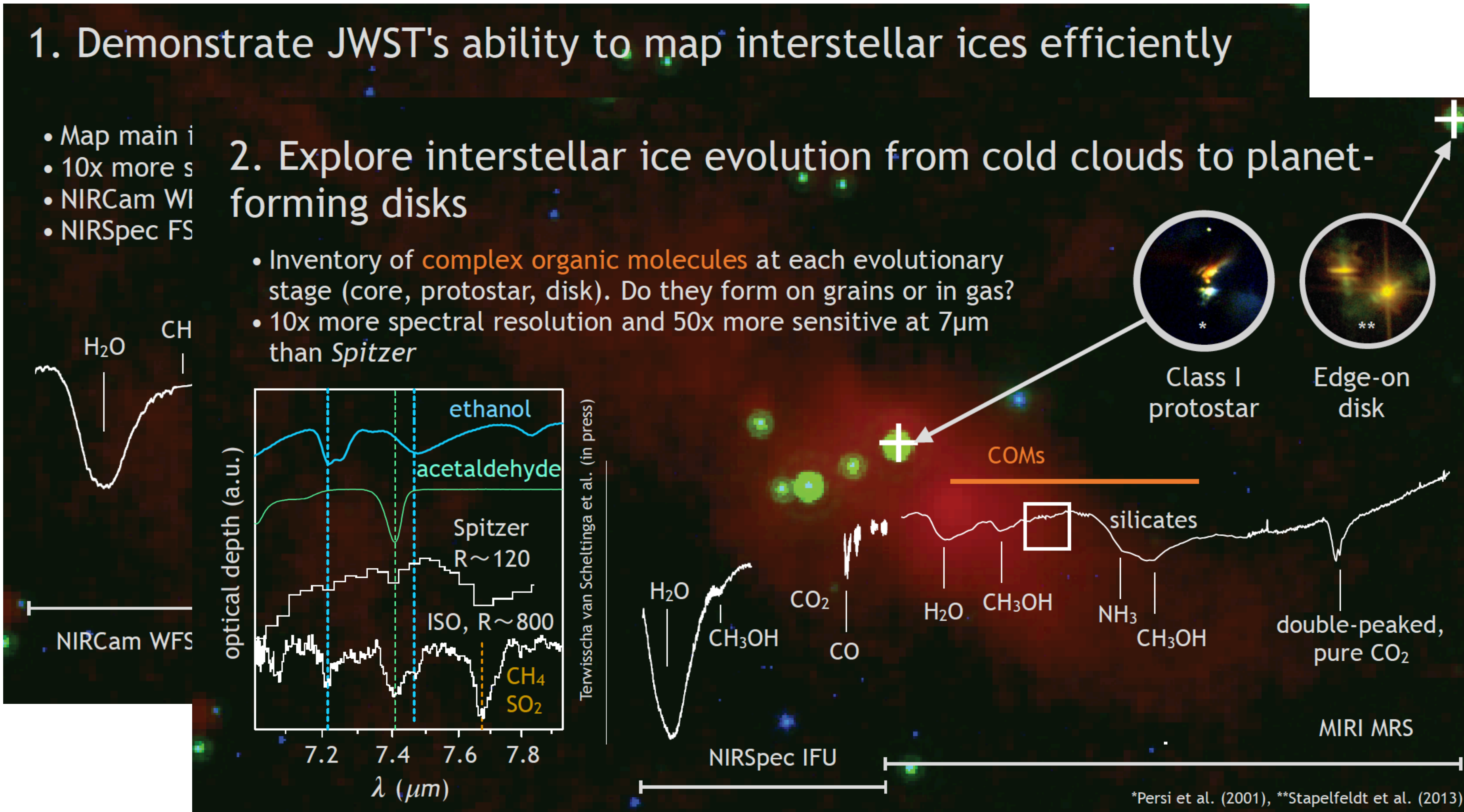
Prospects – JWST ERA

Ice mapping pre-stellar cores

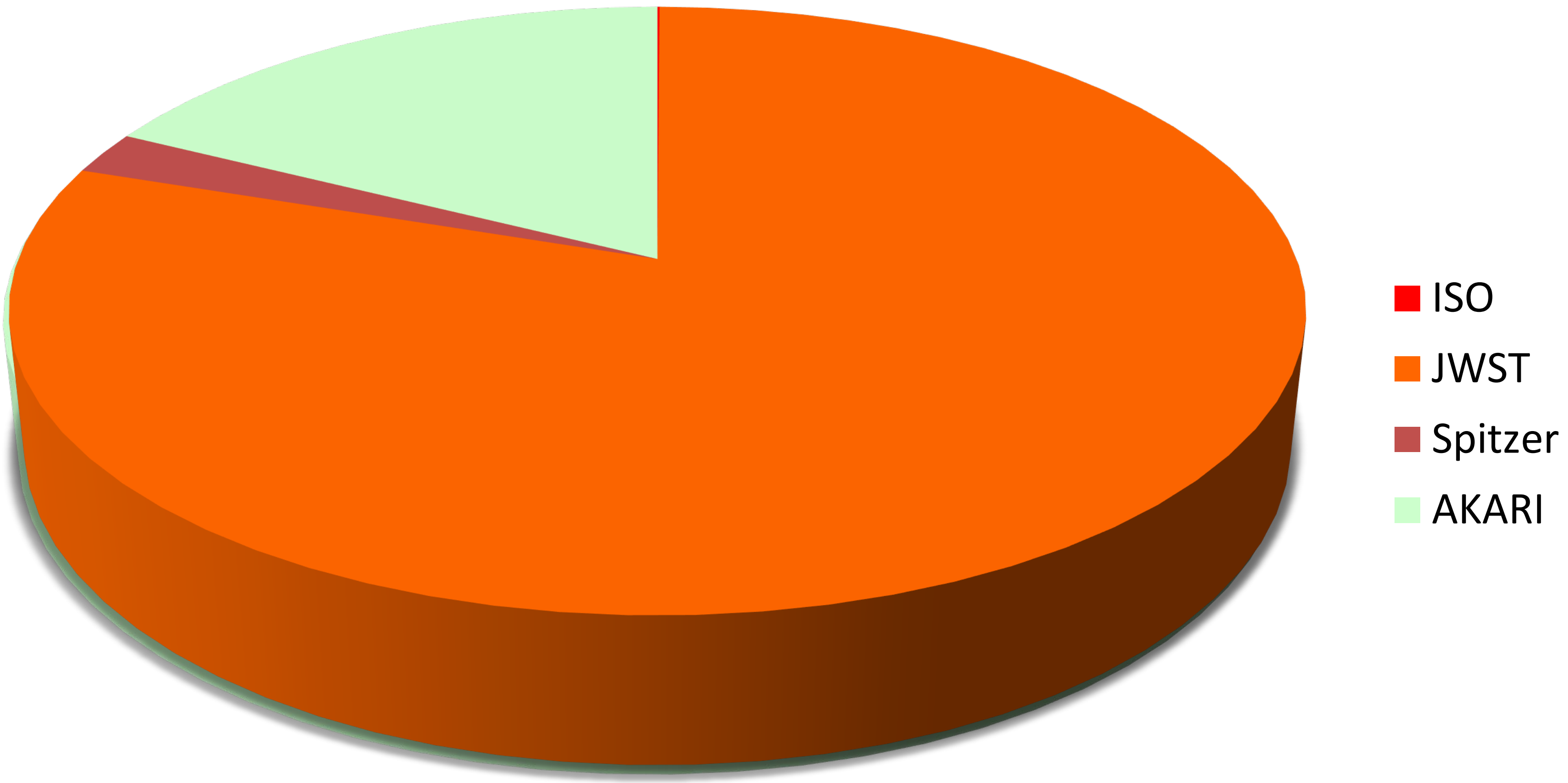


Suutarinnen et al (2019) in prep

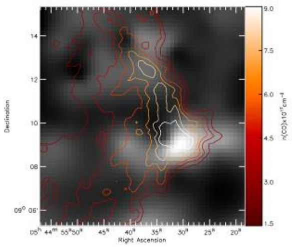

The IceAge ERS program
Community astrochemistry in the era of JWST

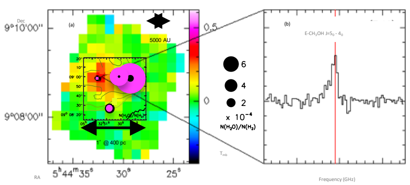

1. Demonstrate JWST's ability to map interstellar ices efficiently
• Map main i
• 10x more s
• NIRCam WI
• NIRSpec FS
H2O
CH
NIRCam WFS
2. Explore interstellar ice evolution from cold clouds to planet-forming disks
• Inventory of complex organic molecules at each evolutionary stage (core, protostar, disk). Do they form on grains or in gas?
• 10x more spectral resolution and 50x more sensitive at 7μm than Spitzer
ethanol
acetaldehyde
Spitzer R~120
ISO, R~800
CH4
SO2
optical depth (a.u.)
7.2
7.4
7.6
7.8
λ (μm)
Terwisscha van Scheltinga et al. (in press)
*
**
Class I protostar
Edge-on disk
COMs
silicates
H2O
CH3OH
CO2
CO
H2O
CH3OH
NH3
CH3OH
double-peaked, pure CO2
NIRSpec IFU
MIRI MRS
*Persi et al. (2001), **Stapelfeldt et al. (2013)

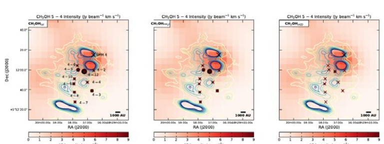
No. of Observed Background Stars with Ice

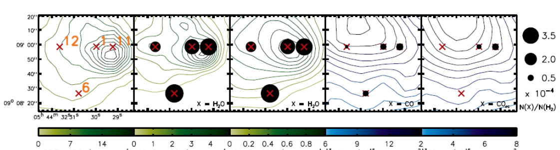


Ice Mapping Conclusions









- Ice abundance doesn't trace dust / T / gas density ☹
- Ice components reveal chemistry, and can ONLY be constrained by combining accurate lab data with observations (unique solutions)
- Even on a small scale (< 1000 AU) ice abundances vary (a lot)
- Local physical conditions affect ice desorption – gas chemistry – cooling & feedback mechanisms in SFR
- Its not entirely clear that there really is an "onset extinction" to ice formation
- abundance on spatial scale = complexity of LOCAL astrophysics
- Ice beyond gas / dust edges of clouds?

The answers await JWST… 2021+…..