

# Emission lines from galaxies in the Epoch of Reionization

Simona Gallerani

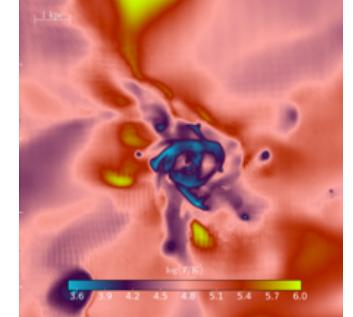
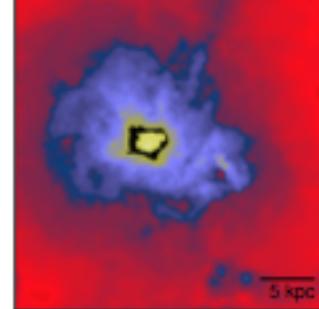
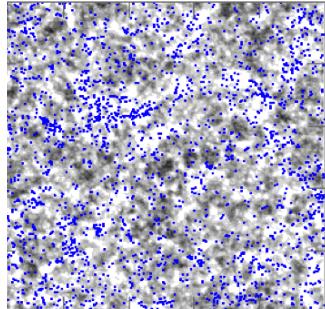
Emanuele Sobacchi, Andrea Ferrara, Livia Vallini,  
Andrea Pallottini, Carlotta Gruppioni, Andrei Mesinger



SCUOLA  
NORMALE  
SUPERIORE

Monte Mario, Roma, SPICA workshop, 5<sup>th</sup> April 2016





# Emission lines from galaxies in the Epoch of Reionization



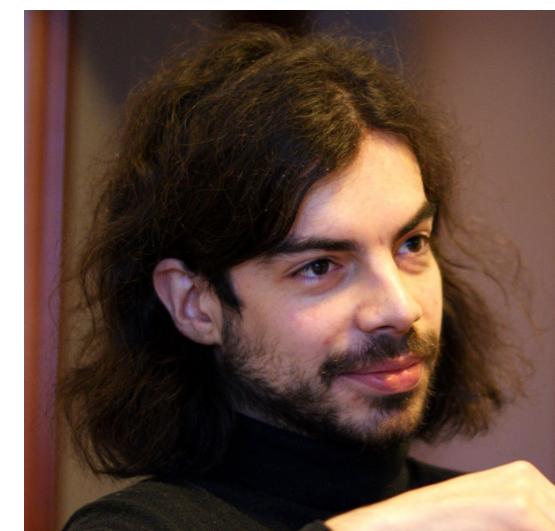
**Emanuele Sobacchi**

Scuola Normale



**Livia Vallini**

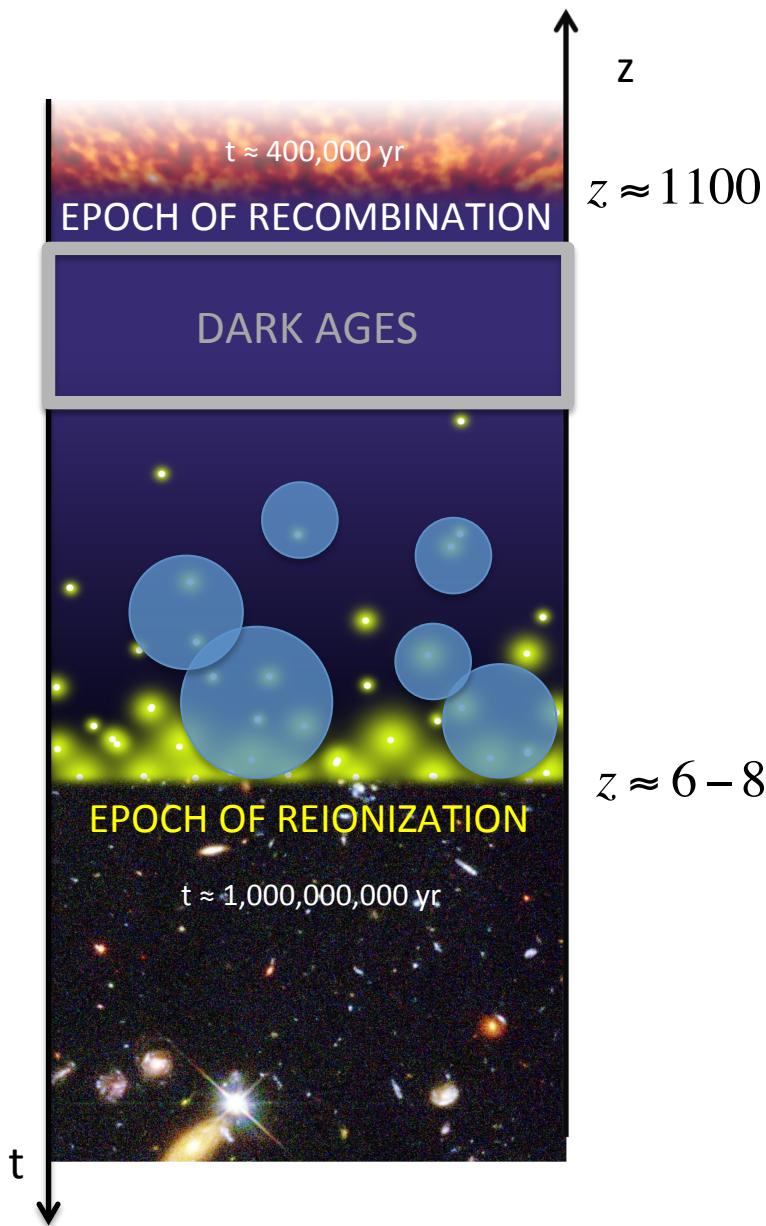
Bologna University



**Andrea Pallottini**

Cambridge University

# Open questions from the dark ages of the Universe



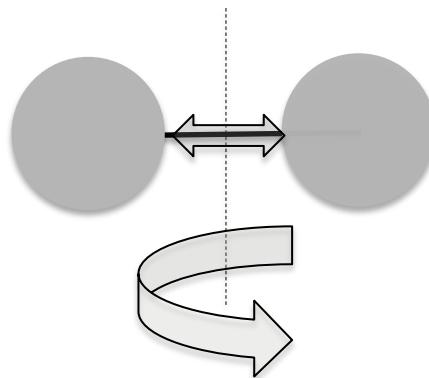
What are the properties of first galaxies?

When did they form?

**Can SPICA help us  
answering these question?**

# MIR emission from the first objects

Roto-Vibrational lines from H<sub>2</sub>



Combes & Pfenninger (1998);  
Timmersmann et al. (1996);  
Turner et al. (1977)

| $\Lambda^{(1)} \text{ [\mu m]}$ | $T_{ex}^{(2)} \text{ [K]}$ | $A^{(3)} \text{ [s}^{-1}]$ |
|---------------------------------|----------------------------|----------------------------|
| 28.0                            | 512                        | $2.94 \times 10^{-11}$     |
| 17.0                            | 1015                       | $4.76 \times 10^{-10}$     |
| 9.7                             | 2503                       | $9.84 \times 10^{-9}$      |
| 6.9                             | 4586                       | $5.88 \times 10^{-8}$      |
| 2.12                            | 6953                       | $3.47 \times 10^{-7}$      |

$$2 \text{ } \mu\text{m} < \lambda_{\text{em}} < 30 \text{ } \mu\text{m}$$

$$z \approx 6$$

$$14 \text{ } \mu\text{m} < \lambda_{\text{obs}} < 210 \text{ } \mu\text{m}$$

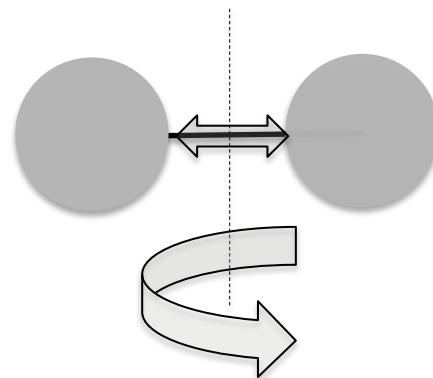
Are these lines detectable  
with SPICA/SAFARI?



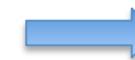
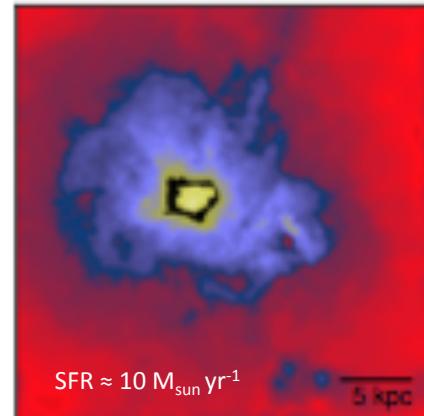
$$34 \text{ } \mu\text{m} < \lambda_{\text{obs}} < 210 \text{ } \mu\text{m}$$

# MIR emission from high-z molecular hydrogen

Roto-Vibrational lines from H<sub>2</sub>



Galaxy simulations



$$L_{H_2} \approx \left( \frac{M_{H_2}}{10^5 M_{sun}} \right) L_{sun}$$

+  
RT calculations with  
CLOUDY

(Vallini et al. in prep., 2015, 2013)

$$M_{halo} \geq 10^{15} M_{sun} !$$



SPICA detection limit  
 $7 \times 10^{-17} \text{ erg s}^{-1} \text{cm}^{-2}$

$$\begin{array}{c} \updownarrow \\ z \approx 6 \end{array}$$

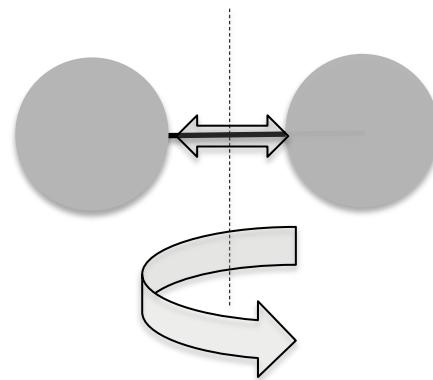
$$L_{threshold} = 6 \times 10^9 L_{sun}$$

(1 hr observing time)

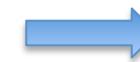
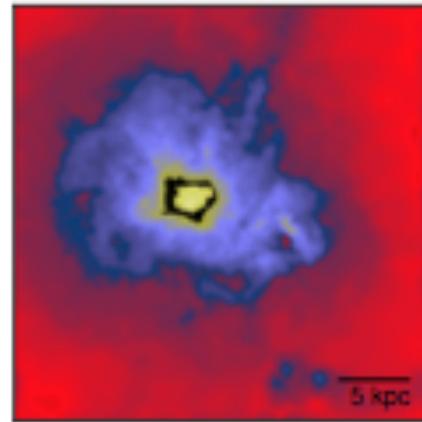
Only extremely rare objects  
can be detected with IR roto-vibrational lines from H<sub>2</sub>

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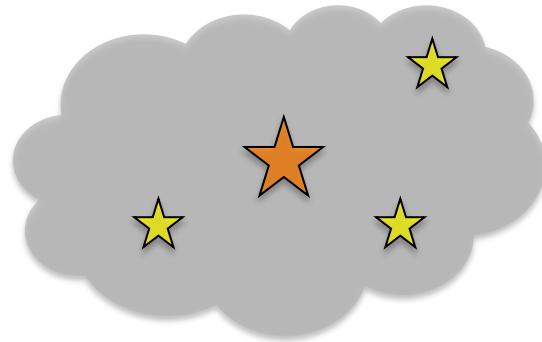
$$L_{threshold} = 6 \times 10^9 L_{sun}$$

(1 hr observing time)

But...

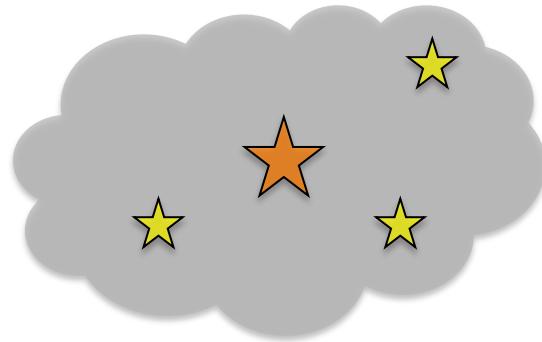
Supernova feedback not included in these calculations

# MIR emission from shock-heated H<sub>2</sub>

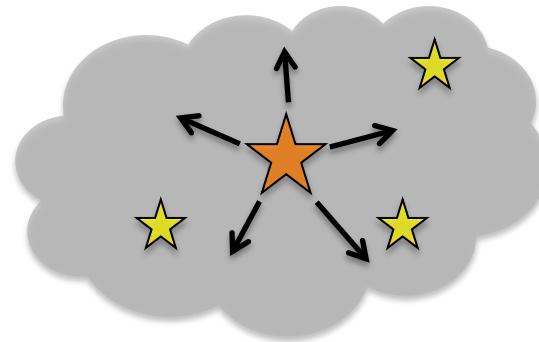


Massive stars form and evolve  
in the high density regions  
of high-z galaxies

# MIR emission from shock-heated H<sub>2</sub>

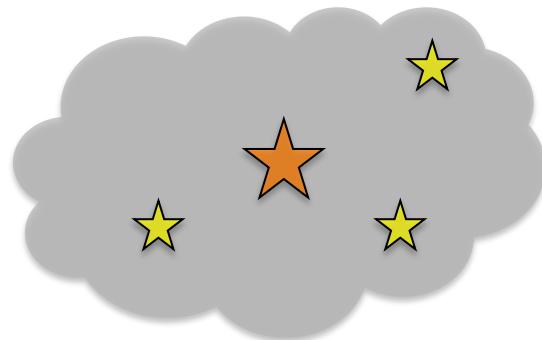


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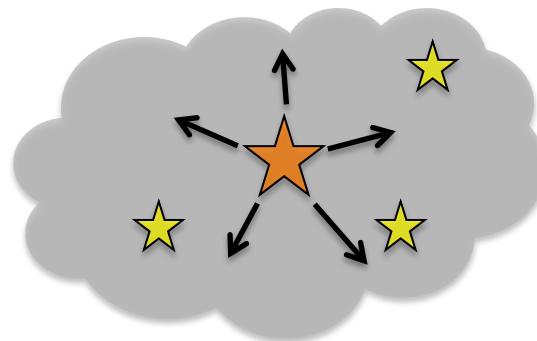


Shocks  
of the galactic gas  
due to SN explosions

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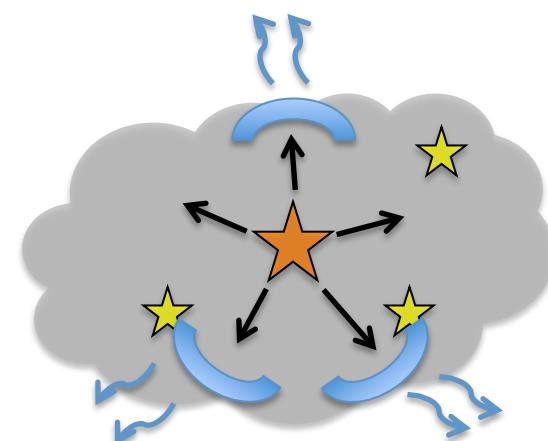


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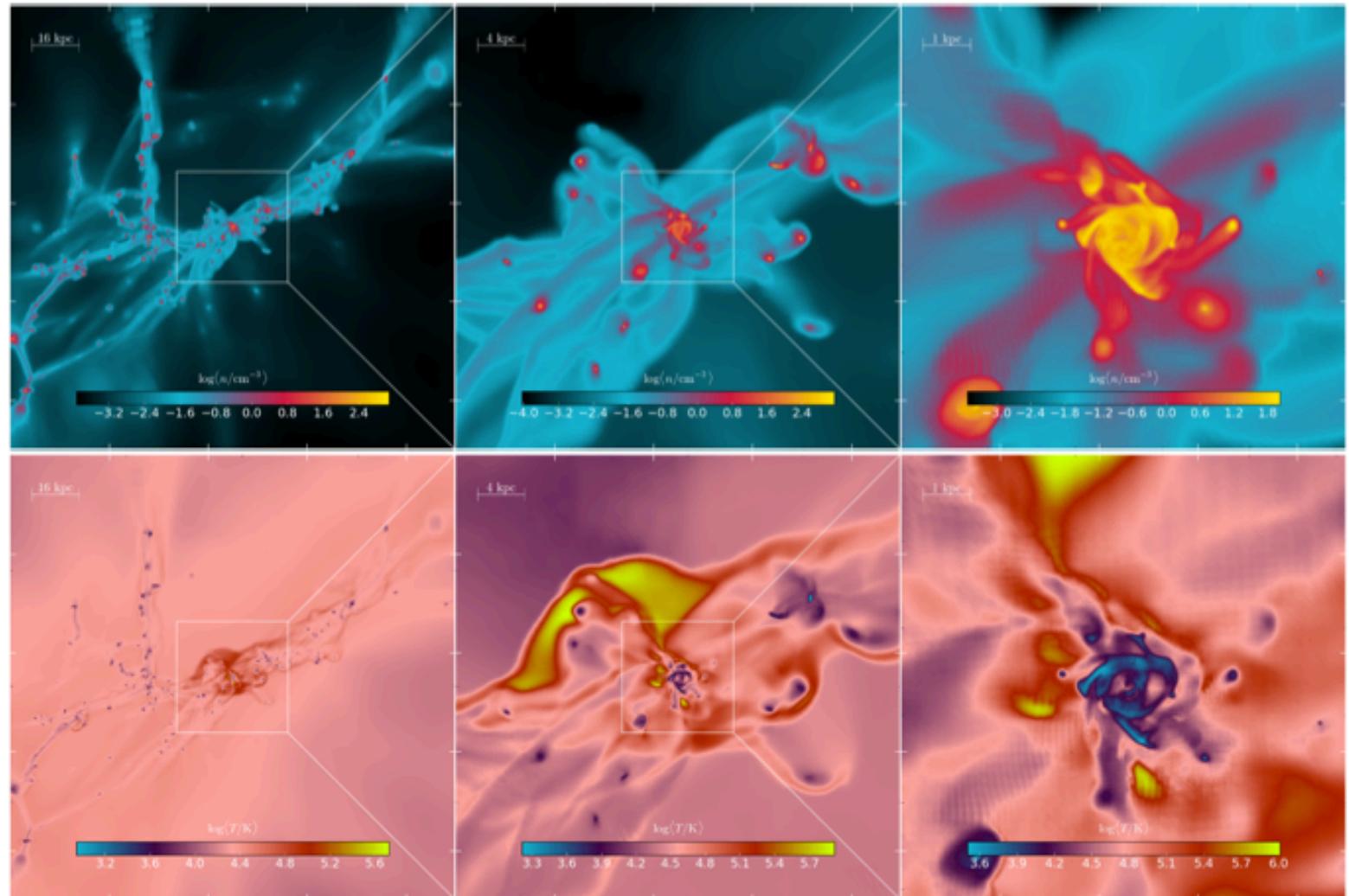


Shocks  
of the galactic gas  
due to SN explosions

H<sub>2</sub> is efficiently formed  
in cooling gas behind shocks  
produced during the blowaway (Ferrara 1998)



# Zoom-in simulations of high-z ( $\approx 7$ ) galaxies

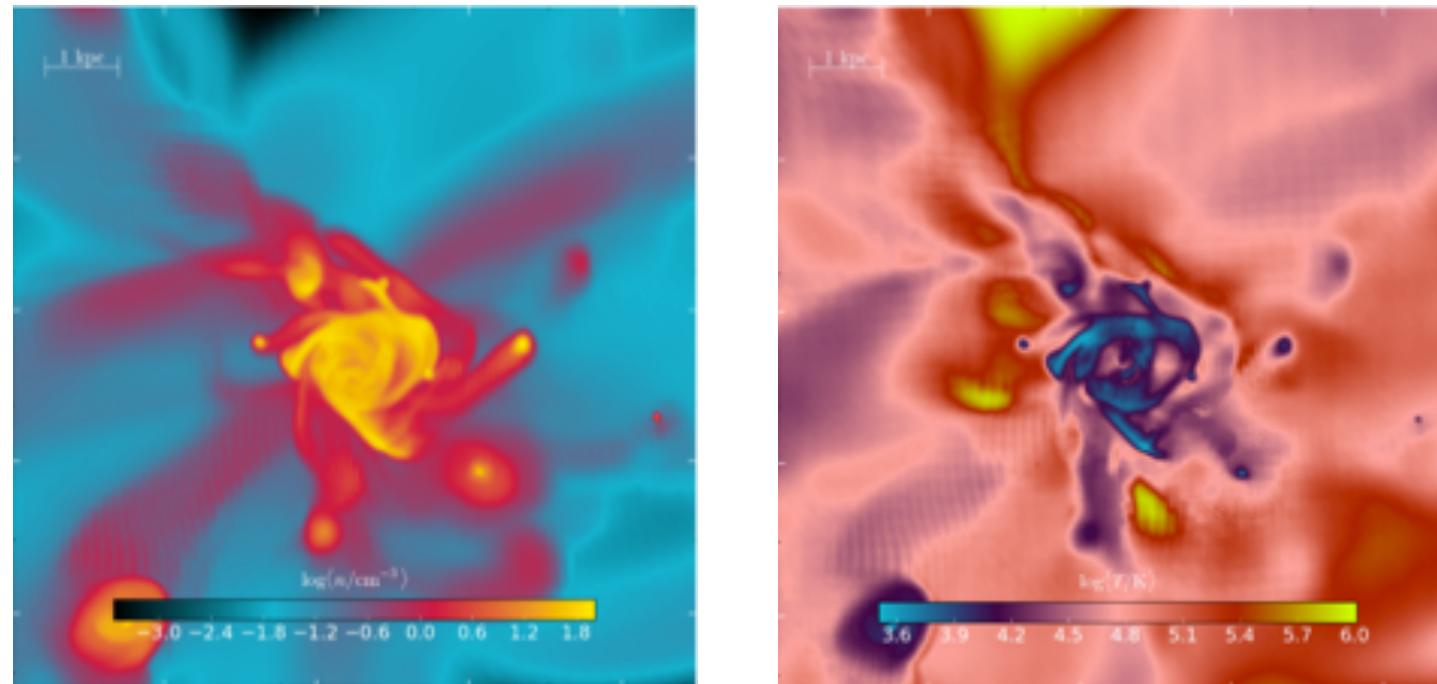


Density  
Temperature

Full treatment of SuperNova feedback

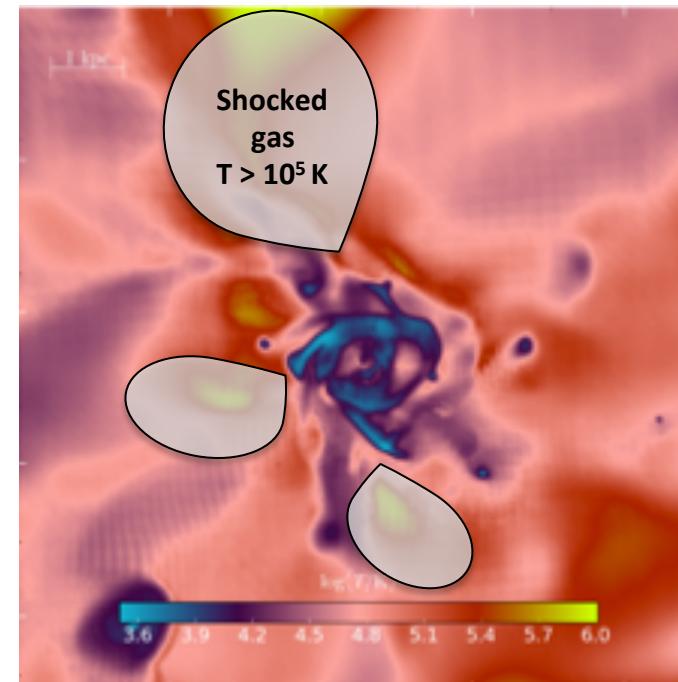
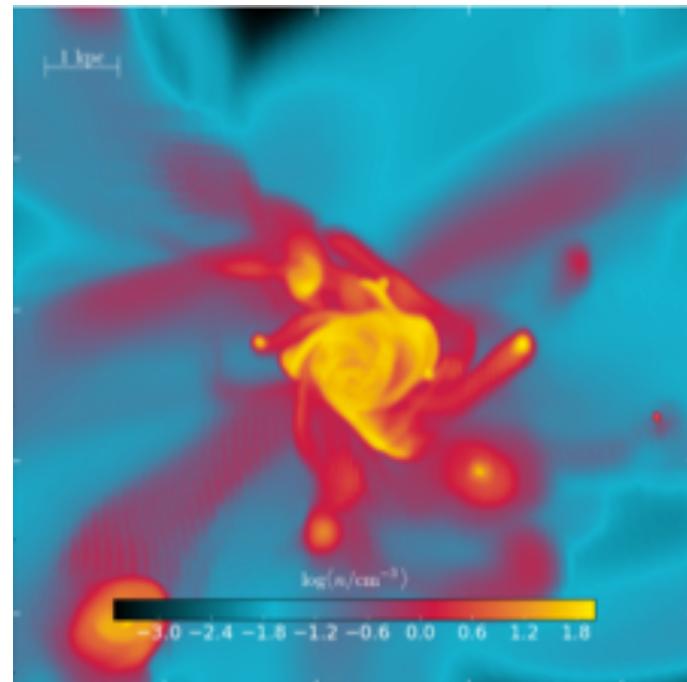
Pallottini et al., in preparation, 2015, 2014

# MIR emission from shock-heated H<sub>2</sub>



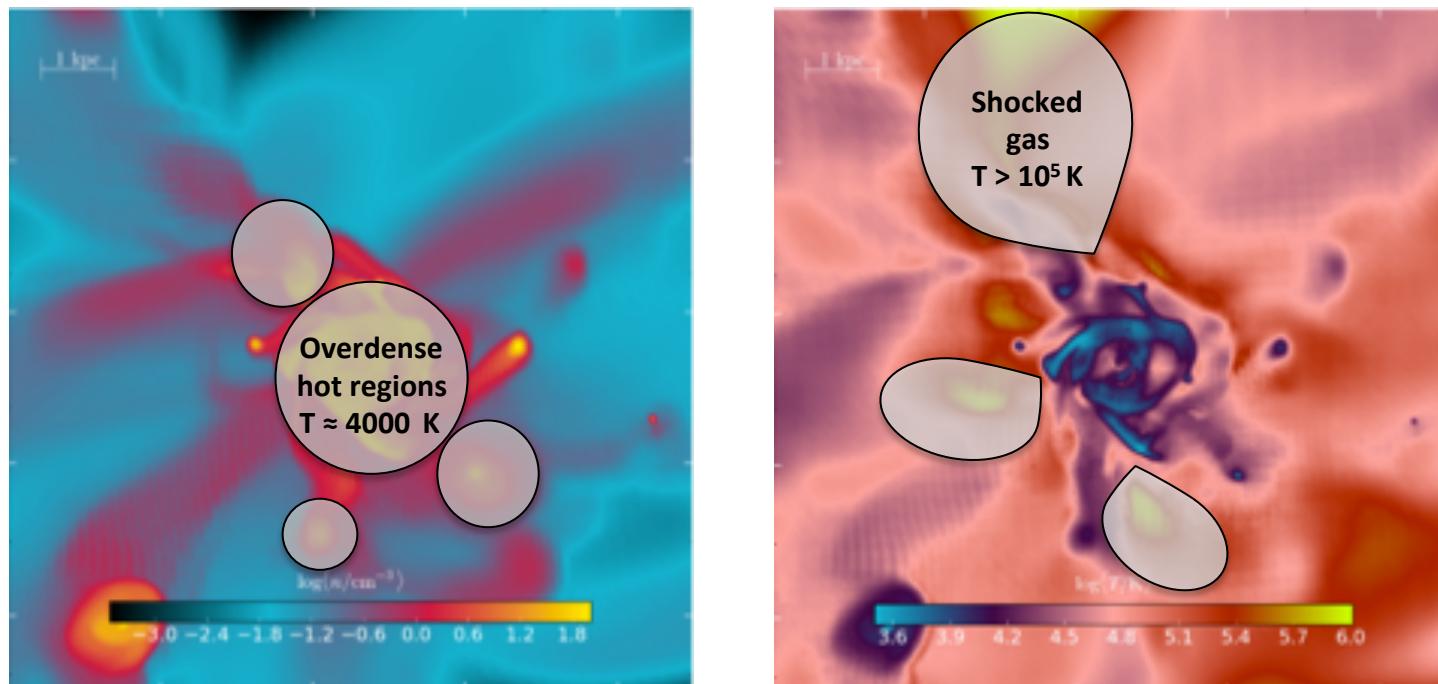
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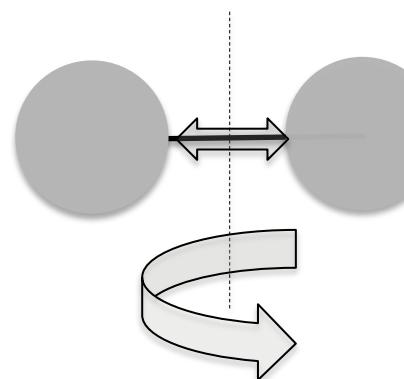
# MIR emission from shock-heated H<sub>2</sub>



Pallottini et al., in preparation, 2015, 2014

# MIR emission from shock-heated H<sub>2</sub>

Roto-Vibrational lines from H<sub>2</sub>

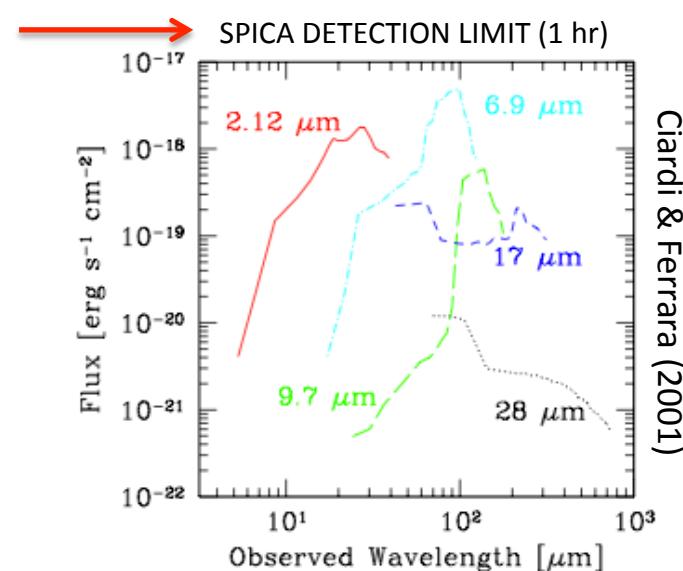


$$\text{Flux}_{\text{H}_2} \approx 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$$

$$\text{Flux}_{\text{H}_2} \propto M_{\text{halo}}$$



$$M_{\text{halo}} \approx 10^8 - 10^9 M_{\odot}$$



$$M_{\text{halo}} \approx 10^{10} - 10^{11} M_{\odot}$$

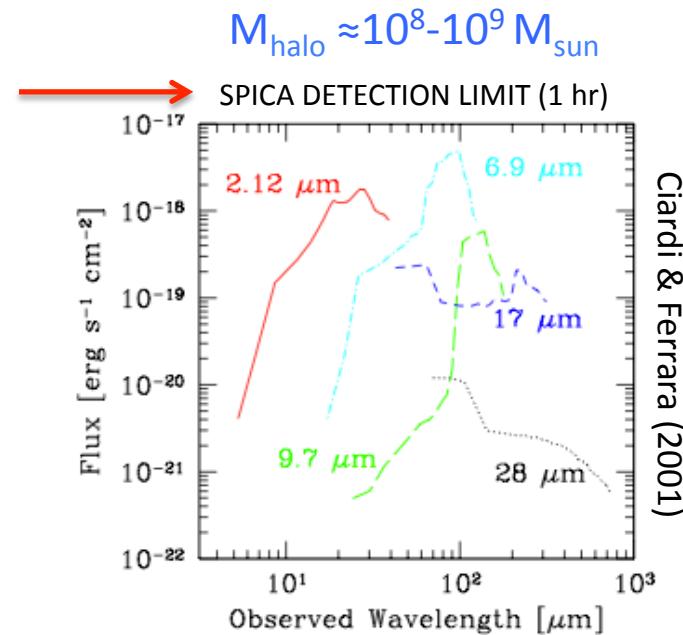
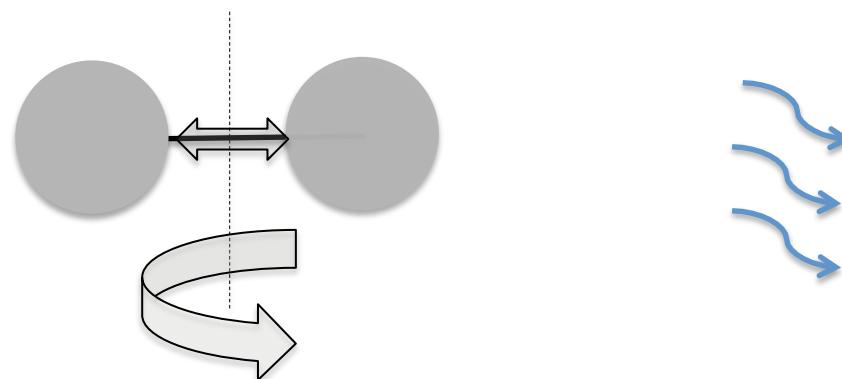
$$\text{Flux}_{\text{H}_2} \approx 10^{-17} - 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$$

1-2.5 hour are required to detect with SPICA

Roto-Vibrational lines from H<sub>2</sub> in z≈7 galaxies with M<sub>halo</sub> ≈ 10<sup>10</sup>-10<sup>11</sup> M<sub>sun</sub>

# MIR emission from shock-heated H<sub>2</sub>

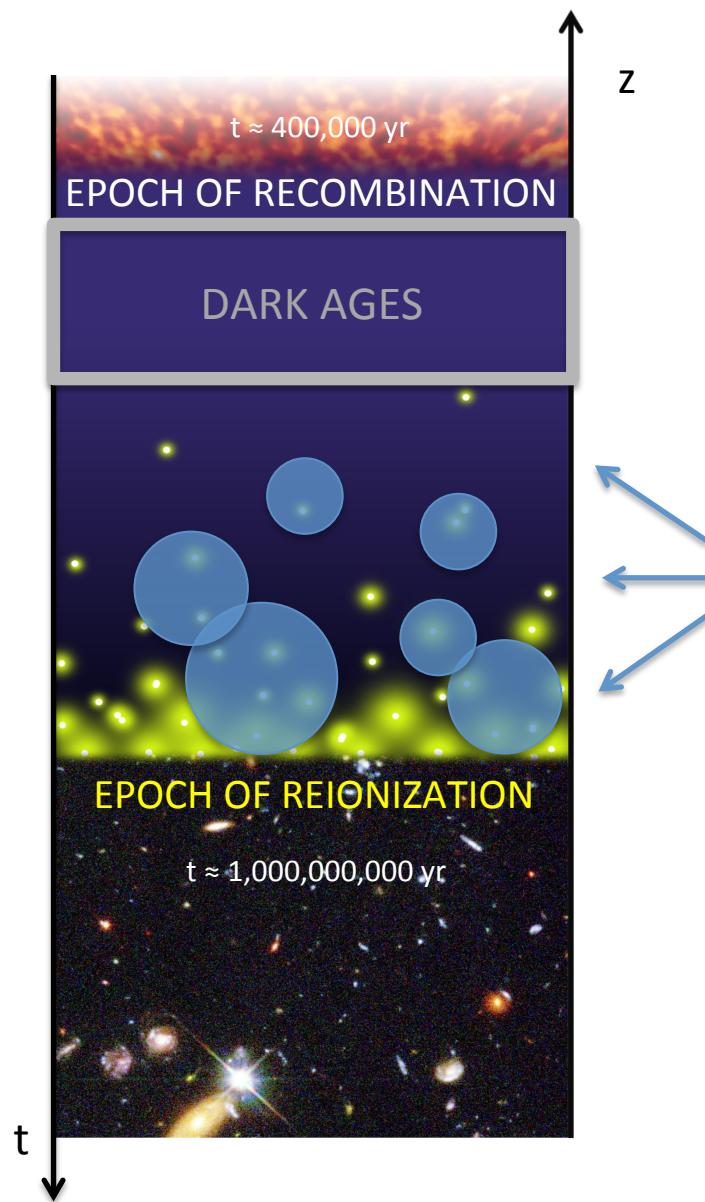
Roto-Vibrational lines from H<sub>2</sub>



Detecting H<sub>2</sub> in  $10^{10} - 10^{11} M_{\odot}$  galaxies at high redshift...

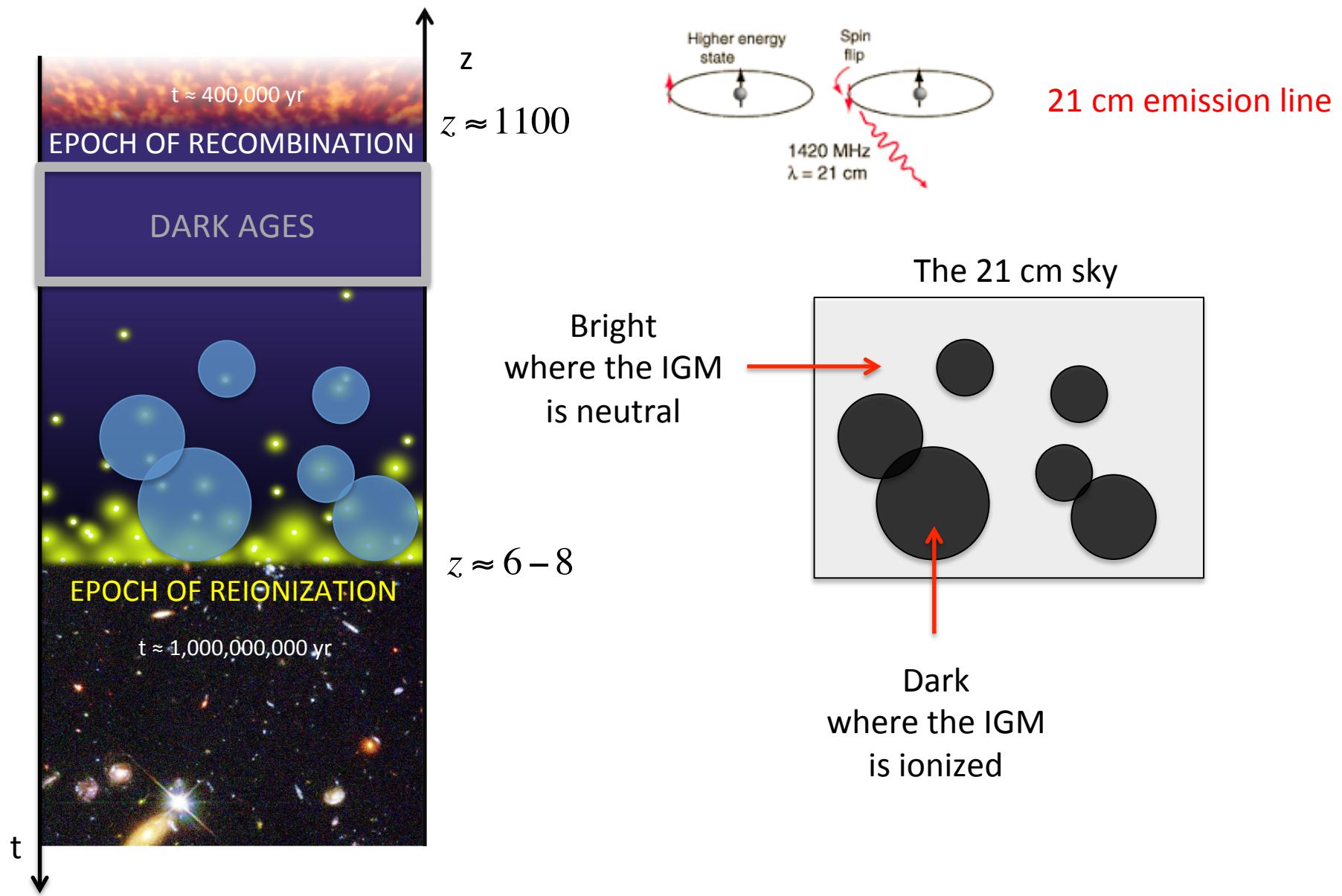
- Follow up observations
- Searching for new sources? Where should we point our telescope?

# Morphology of cosmic reionization



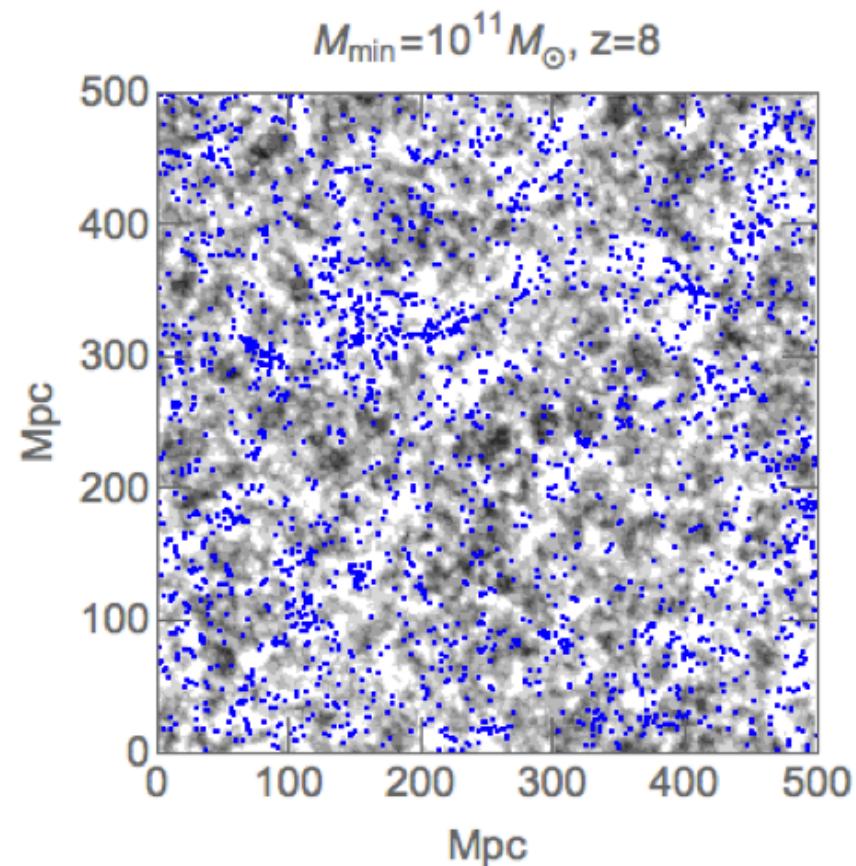
Ionized bubbles  
driven by ionizing photons  
form the first luminous objects

# Morphology of cosmic reionization



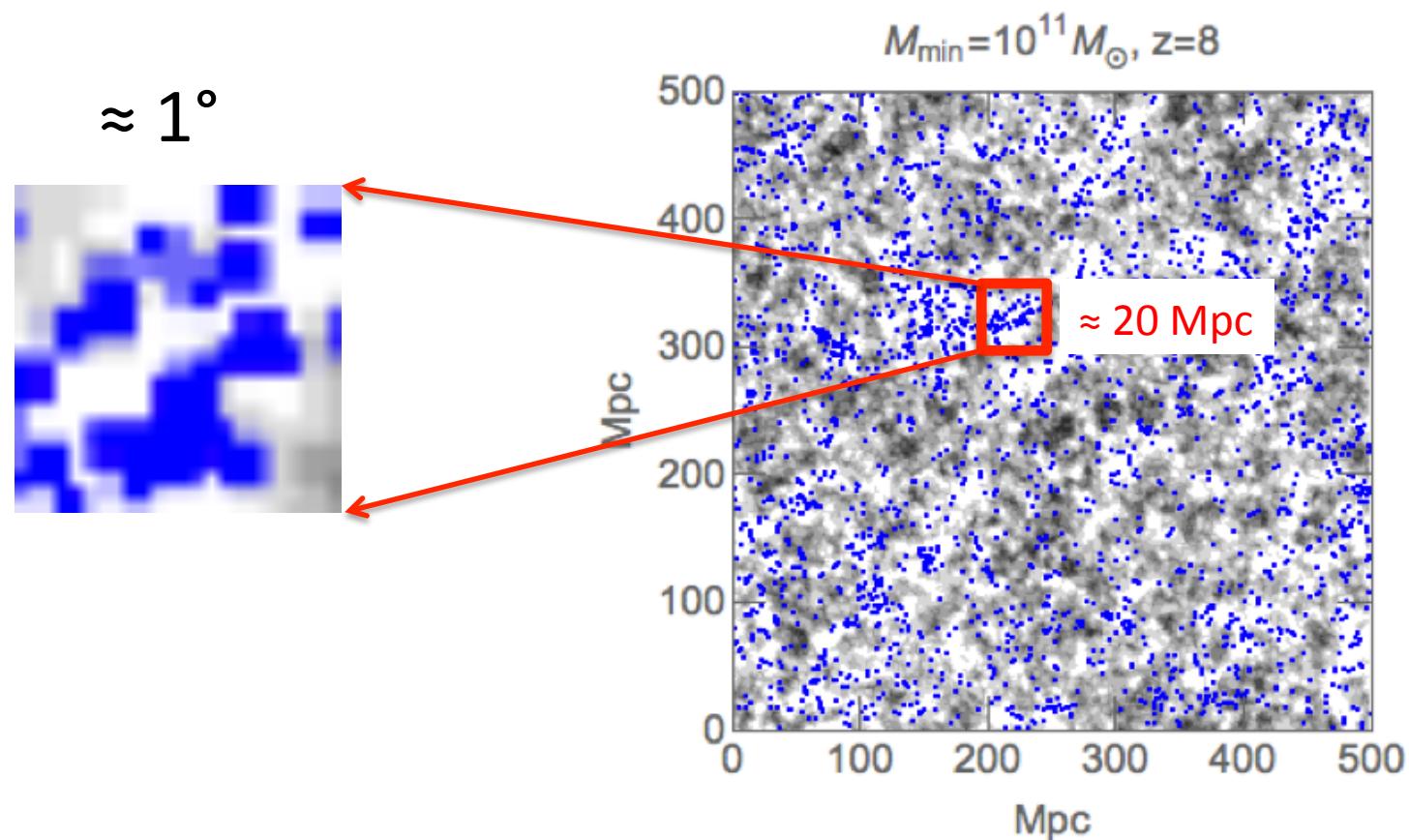
# THE SPICA-SKA SYNERGY

We can look for the highest redshift sources in the ionized bubbles, namely in the dark part of the 21 cm maps



Sobacchi et al. in prep., Sobacchi et al. (2016)  
21CMFAST by Mesinger et al. (2011)

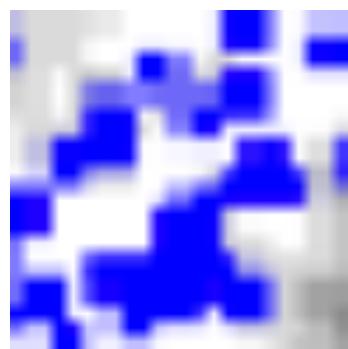
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# THE SPICA-SKA SYNERGY

$\approx 1^\circ$

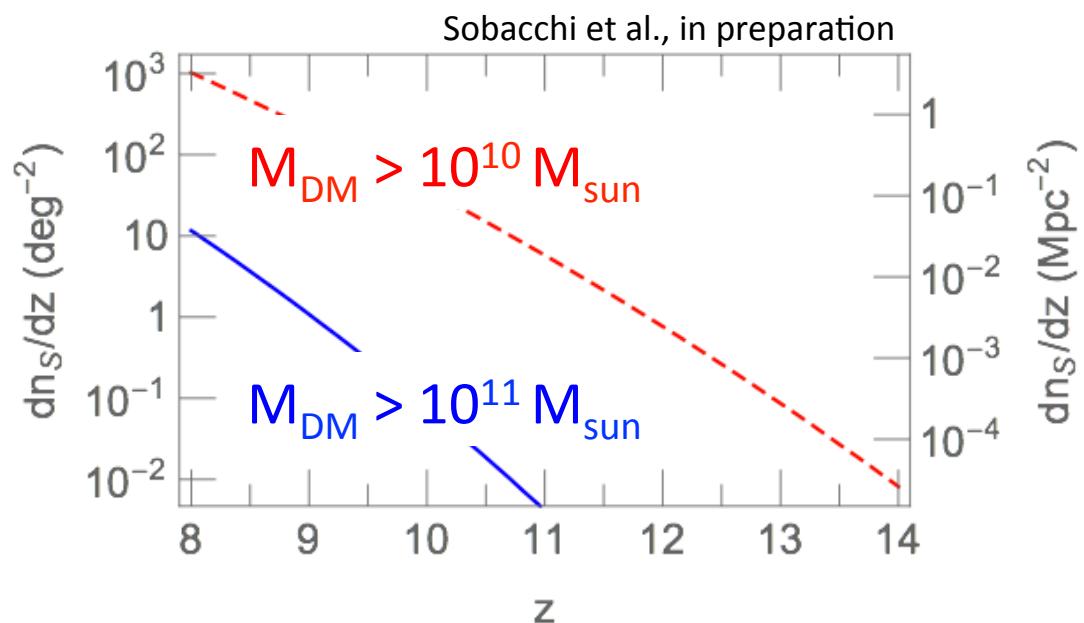


$\approx 10$  galaxies

(1 hr observing time)

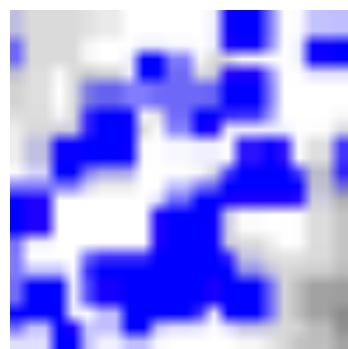
$\approx 1000$  galaxies

(2.5 hr observing time)

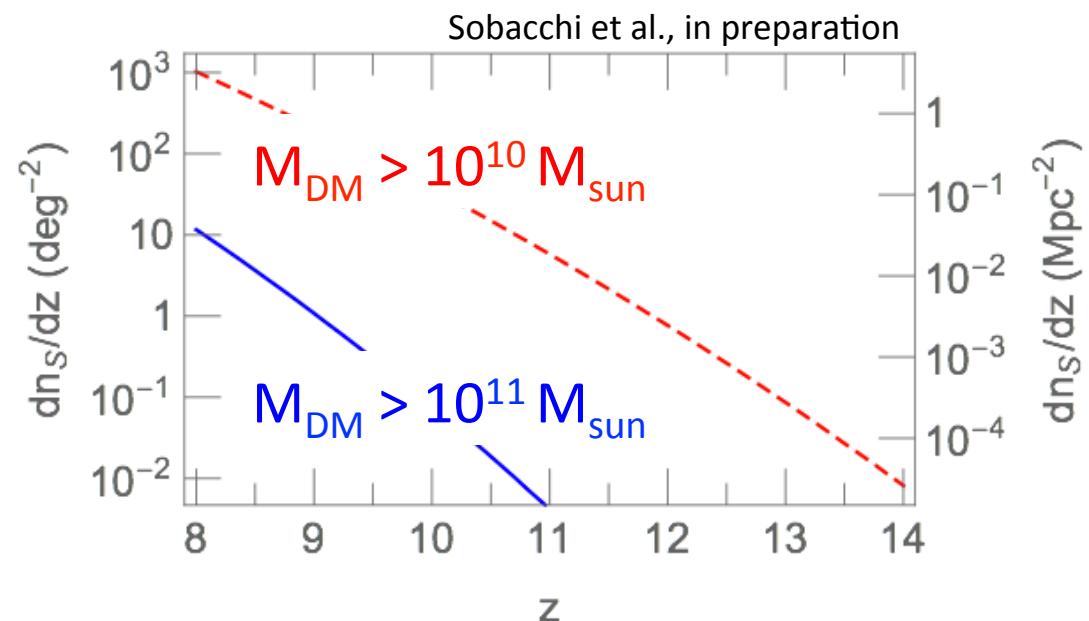


# THE SPICA-SKA SYNERGY

$\approx 1^\circ$

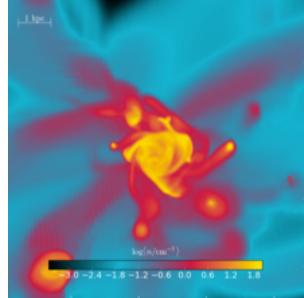


$\approx 10$  galaxies  
(1 hr observing time)  
 $\approx 1000$  galaxies  
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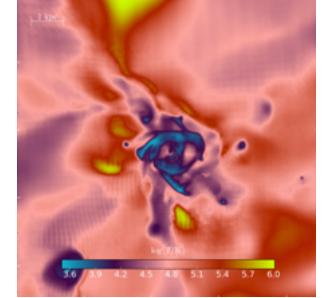


But...  
SPICA/SAFARI  
is a pointing spectrometer

Too many pointings are required!



# CONCLUSIONS



- Galaxies in the **epoch of reionization** can be detected through (shock-heated) **molecular hydrogen** with **SPICA**
- SPICA can **follow-up high-z** (candidate) galaxies detected at different wavelengths in 1-2.5 hr
- SPICA can provide information on **the molecular gas** and **SFR** of galaxies in the EoR

