On the Search for High-Redshift H_2 emission from the Dark Ages

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Outline

Part I-- Overview of H_2 Formation in Early universe

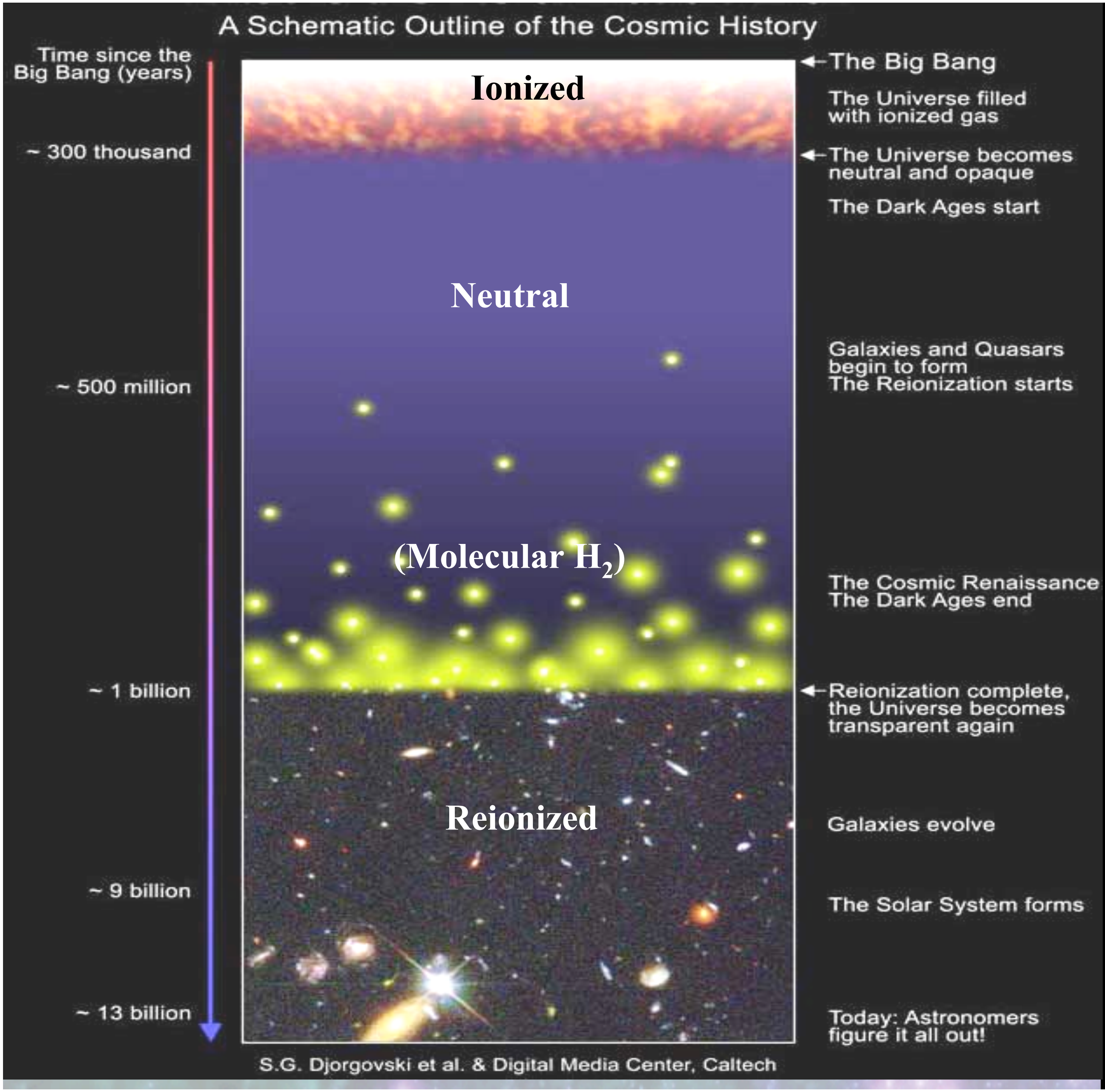
Part II-- Shocked Gas in the Local Universe:

Is Turbulent Feedback important in the Dark Ages?
(Question for the theorists at this meeting)

Part III-- Choice of Observational Scales?

Avoiding foreground galaxies versus sensitivity to possible "large scale" turbulent structure

History of Baryons in the Universe

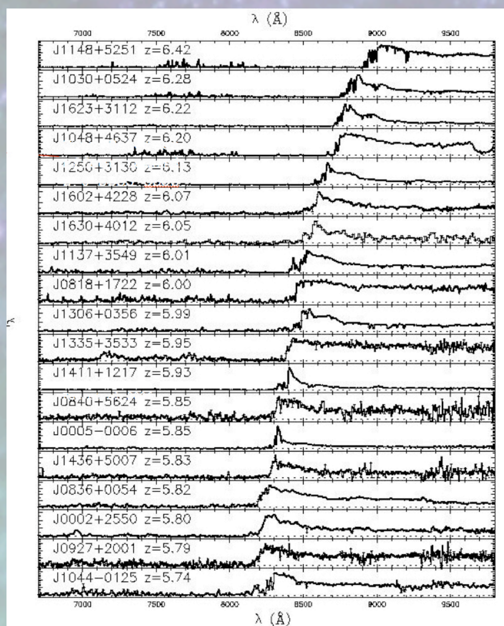


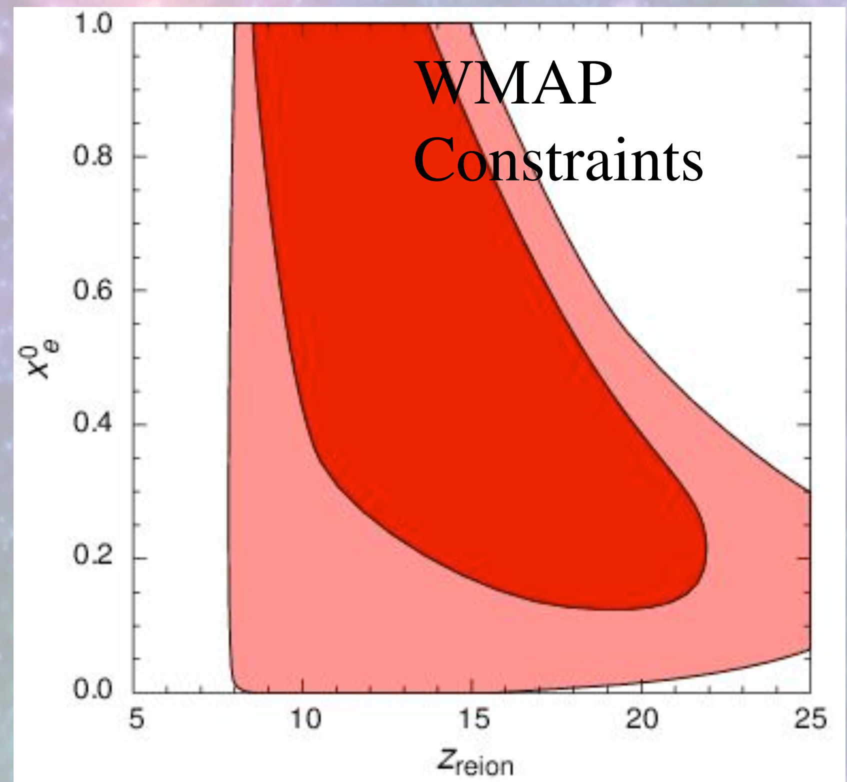
Re-ionization Epoch 6 < z < 15?

Page + 06; Spergel 06

Fan et al 2006

Gunn-Peterson Effect toward z~6 SDSS QSOs



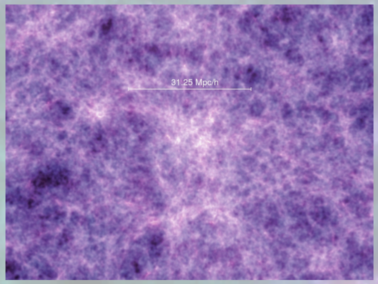


Strong evidence for an increasingly neutral medium beyond z > 6)

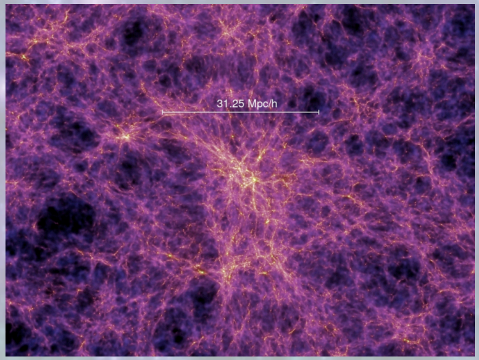
Shull & Venkatesan 07

Primordial H_2/H fraction too low for spontaneous collapse of gas $\sim 10^{-6}$

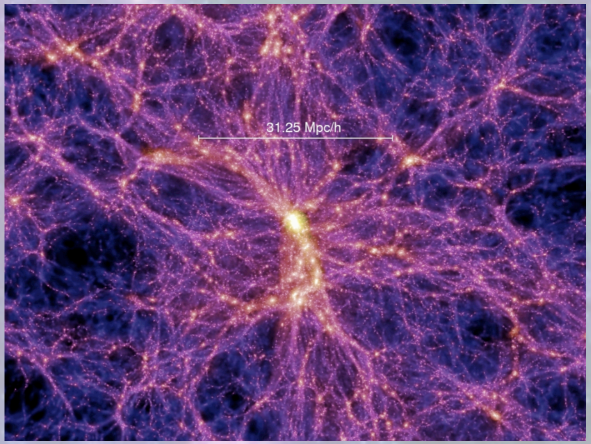
FATE of Sub-galactic clouds therefore depends on rapid growth of H_2 via gas phase reactions in the early universe--probably after the gas has settled into DM haloes (see nice recent review by Piero Madau (2007)) *arXiv:0706.0123*



Z=18



Z=6



Z~0

To make the first stars will require a molecular hydrogen phase.

Two main ways to make H_2 (e. g. Saslow & Zipoy 1967; Peebles & Dicke 1968, Lepp & Shull 1984)

H^- pure gas route (important at higher z -there are others at even high)

$H + H^- = H_2 + e^-$ H^- abundance depends critically on the electron abundance. rate $R_g = k_1 n_h^2 \varepsilon_e$ where $\varepsilon_e = n_e/n_h$

Note: rate for equation above not well known-yet crucial (Glover et al. 2006)

Below T =200K, cooling by HD and LiH important

Formation on grains (dust route--important when $z < 15$ $T_{cmb} < 50K$)

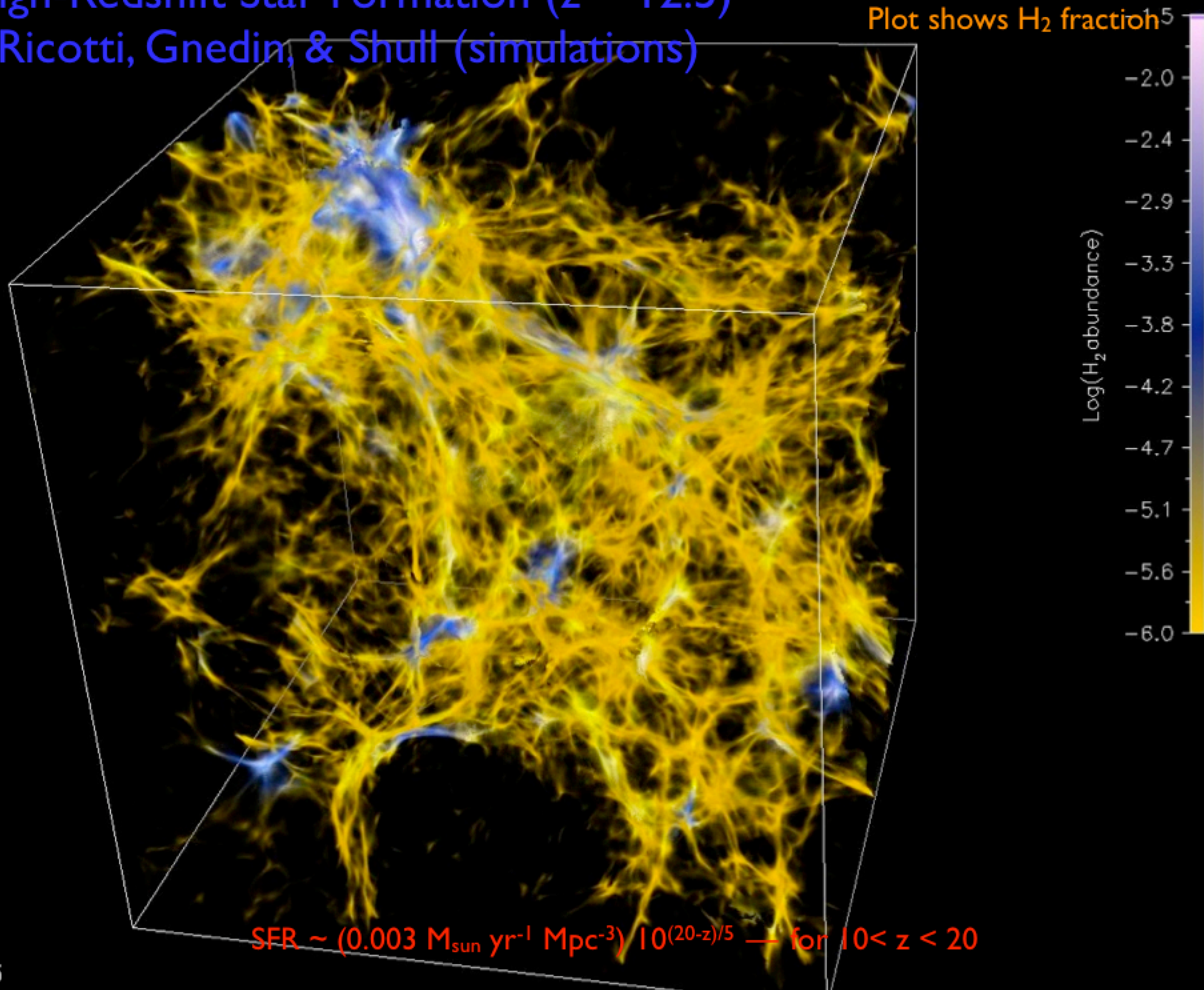
$R_d = 1/2\, n(H) v_H\, (n_d \sigma_d) \varepsilon_{H2} S_H$ (Tielens & Hollenbach 1985)

$= k_2\, \varepsilon_{H2} S_H\, n(H) \varepsilon_d n_h$ where ε_d=dust/gas ratio

(e. g. Cazaux & Spaans 2004)

High-Redshift Star Formation (z = 12.5)

Ricotti, Gnedin, & Shull (simulations)



SFR ~ $(0.003\ M_{sun}\ yr^{-1}\ Mpc^{-3})\ 10^{(20-z)/5}$ — for $10 < z < 20$

Feedback is important?

Yoshida et al. (2007) 3-d cosmology with heat/cool

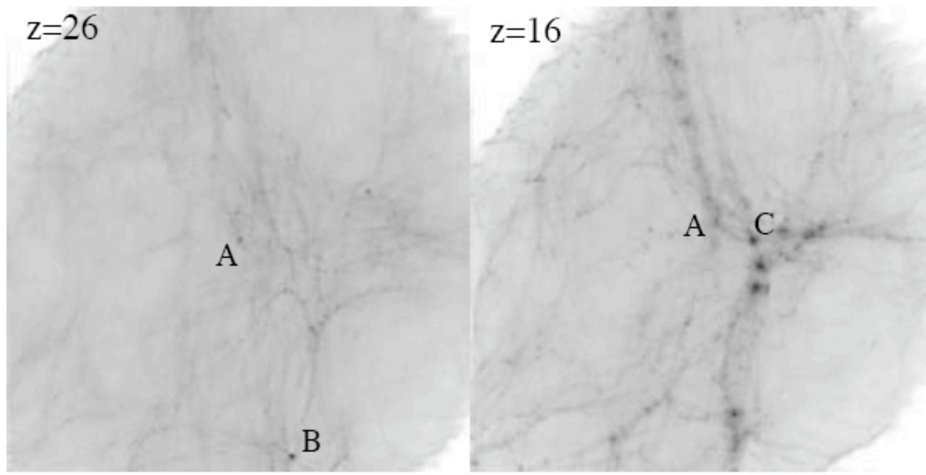


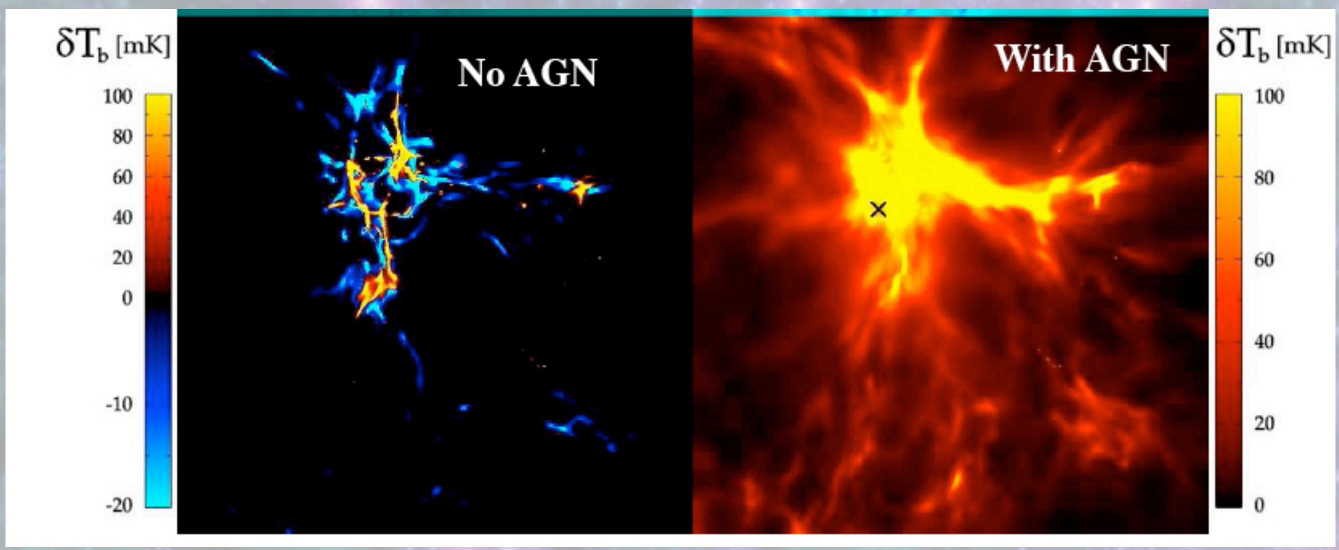
Fig. 9.— Underlying dark matter density field at $z = 26$ when the first star is formed (left), and at $z = 16$ when the second-generation star(s) are formed (right), showing a significant evolution in ~ 100 Myrs. The main halo is marked by A. Halo B is a nearby massive halo, whose evolution is studied in section 5.1. The descendant of Halo A is indicated in the right panel, where there is another halo (C) close to it. Halo C hosts the second generation star-forming gas cloud which was formed from an ionized gas.

This simulation shows that gas filaments are significantly perturbed by the first stars at very hi-z, and do not follow and clump exclusively on DM halos, nor the most massive by z =16. The models of Mike Shull also underline the importance of smaller halos as the sites of the first cloud collapses.

Material falling back into smaller halos, supernova and other processes (the accretion itself) could drive shocks through the gas? How might infall perturb the collapse within halos? AGN feedback ?

This is a caution that our knowledge of the early universe is still very uncertain. We know the H_2 formation depends on dust fraction, ionization and the form of feedback! Its complicated!

Enhancers : Mini AGN
Will they warm the medium and increase dramatically the electron density?

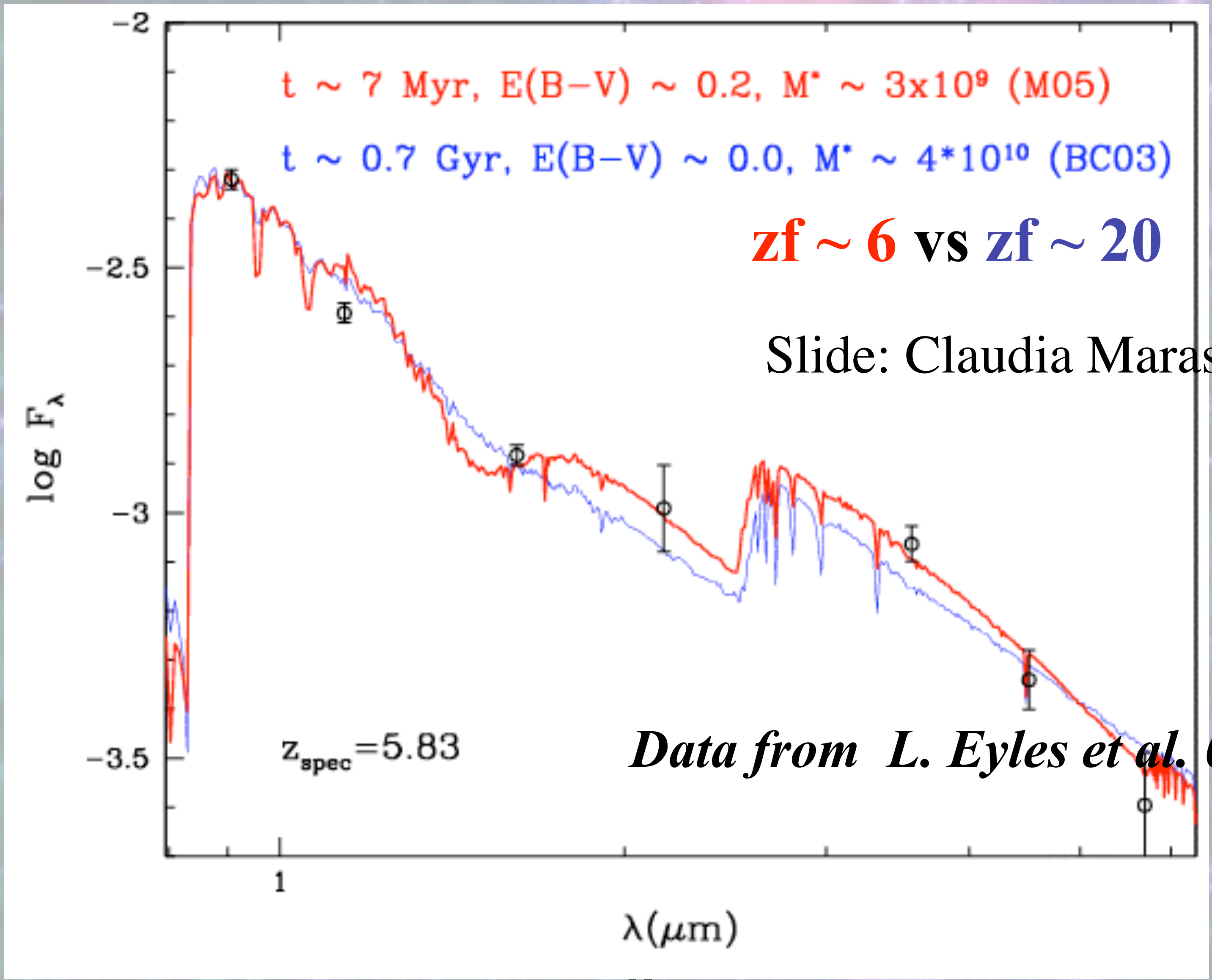


Kuhlen, Madau & Montgomery (2006)

This could dramatically increase the H_2 formation rate through The H- route. (there are other effects which can destroy H-, e. g.)

Stellar Populations are seen at Hi-z

When they formed is a subject of debate



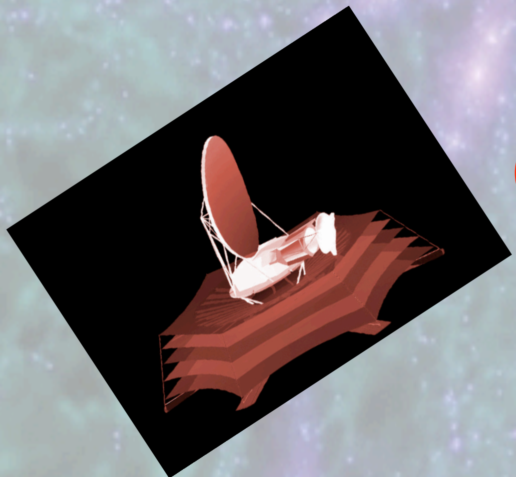
Slide: Claudia Maraston '08

Data from L. Eyles et al. 05

Can we detect H_2 emission from protoclouds at high-z?

Wavelength range for key rotational line puts detection in FIR-SPACE MISSION

0-0 S(3) 9.66um	z = 6-15	68-154 μm	Strongest
0-0 S(1) 17.08um	z = 6-15	119-272 μm	X_{gal} lines
0-0 S(0) 28um	z = 6-15	196-448 μm	



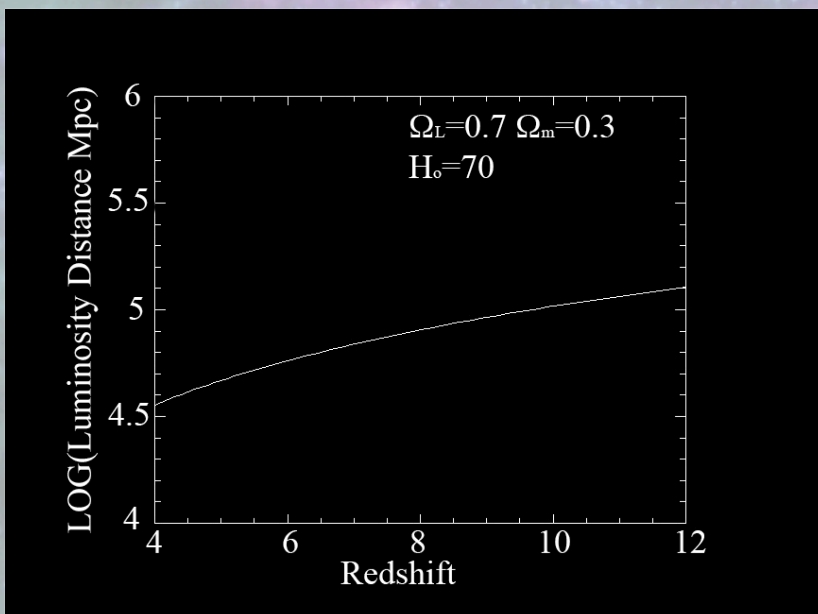
Note: ALMA will be blind to these unless significant emission at z > 15

Fiducial Luminosity

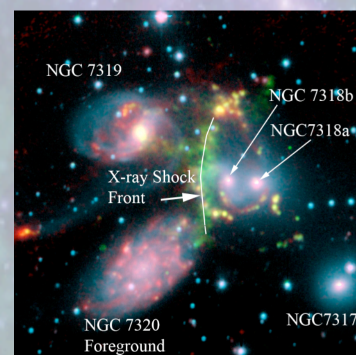
L41= 10^{41} ergs/s ~ $10^{-10}/[38*\pi*(D_L)^2]$ W/m^2

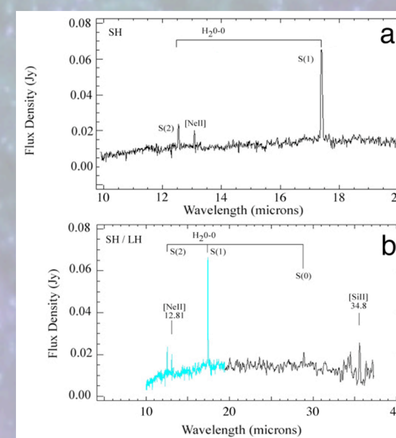
Where D_L is the luminosity distance. For ΛCDM

Ω_L=0.7, Ω_m=0.3, H_o=70

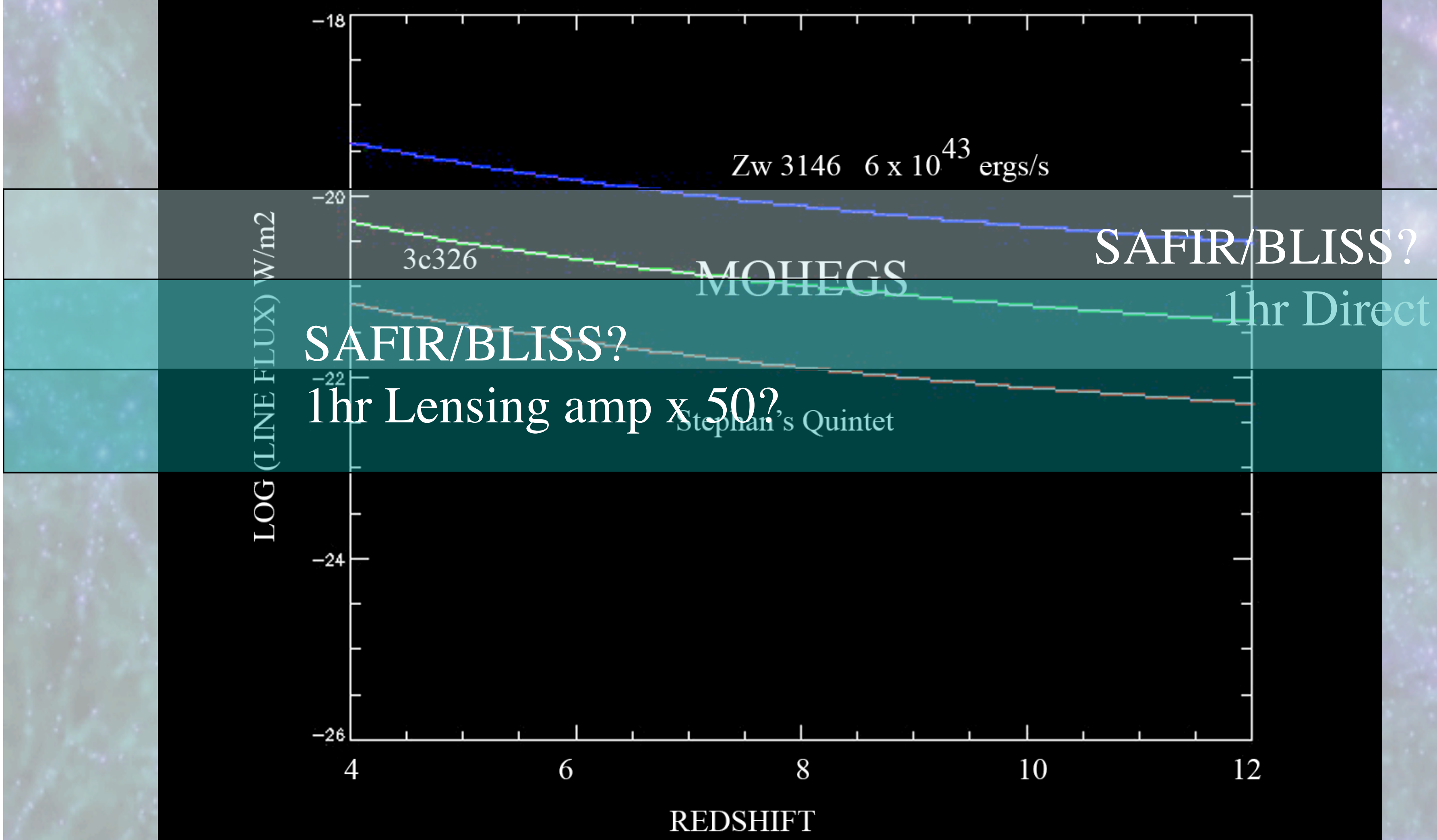


L41 = Luminosity of H_2 in Stephan's Quintet!





REDSHIFTING THE MOHEGS

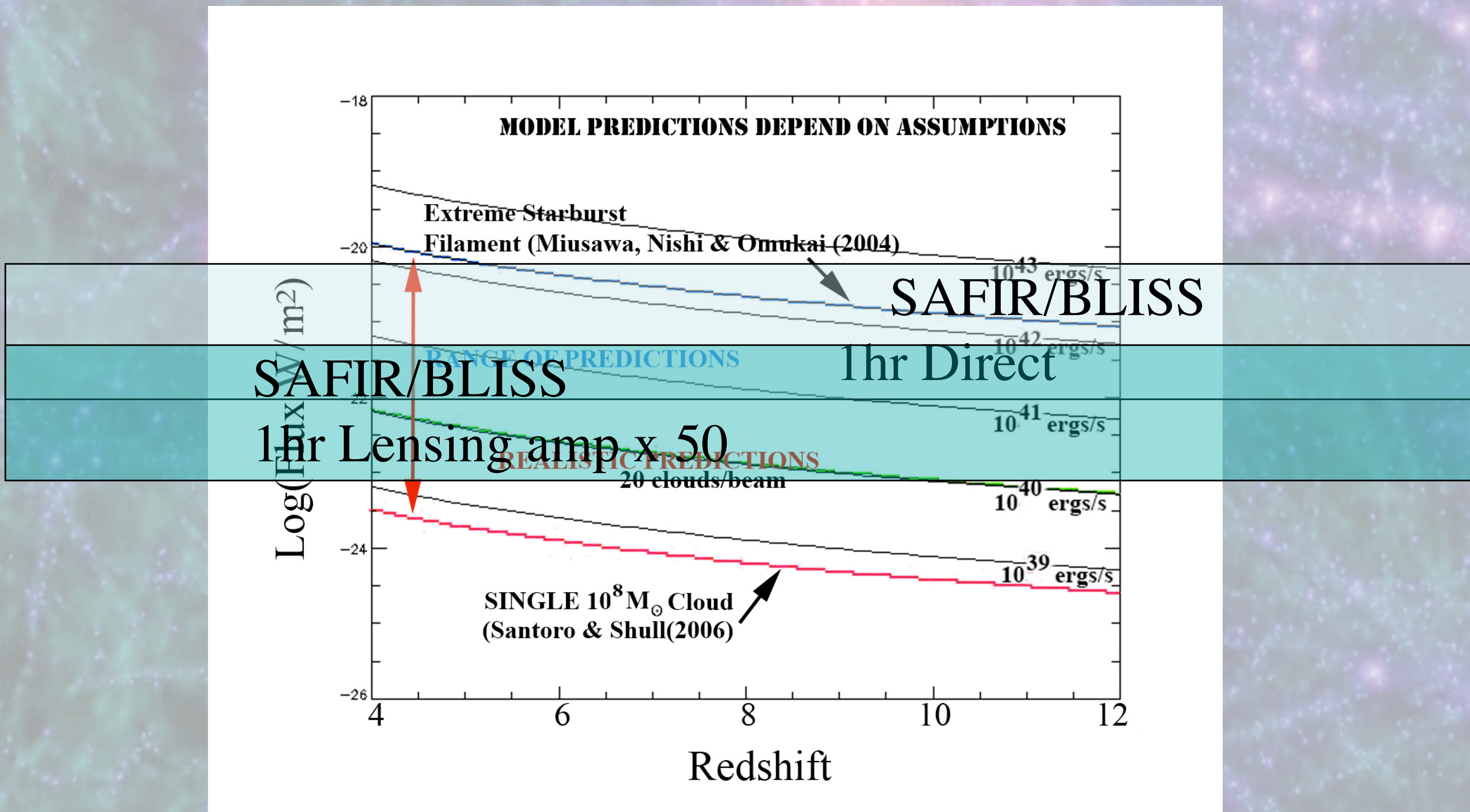


Santoro & Shull (2006)
Primordial Clouds-Condense into clumps of 10^8 M_{sun}

Recent prediction suggest that gas fragments into clumps with scale governed by the prompt metals from first SN which soon dominate the cooling:
(scale set line cooling timescale <= adiabatic free-fall time)

Detailed prediction suggest in each clump
L([OI]) ~ 1 to 10 x L41 ergs/s (detectable with ALMA?)
L([CII])~ 1 to 10 x L41 ergs/s (“ “)
L([H2]) ~ 1/200 L41 ergs/s for T = 200-1000K gas
This material has already accumulated into DM halos and may be quite inhomogenious. Sizes are < 1kpc.
NEED LOTS OF CLUMPS TO DETECT H_2 Directly!

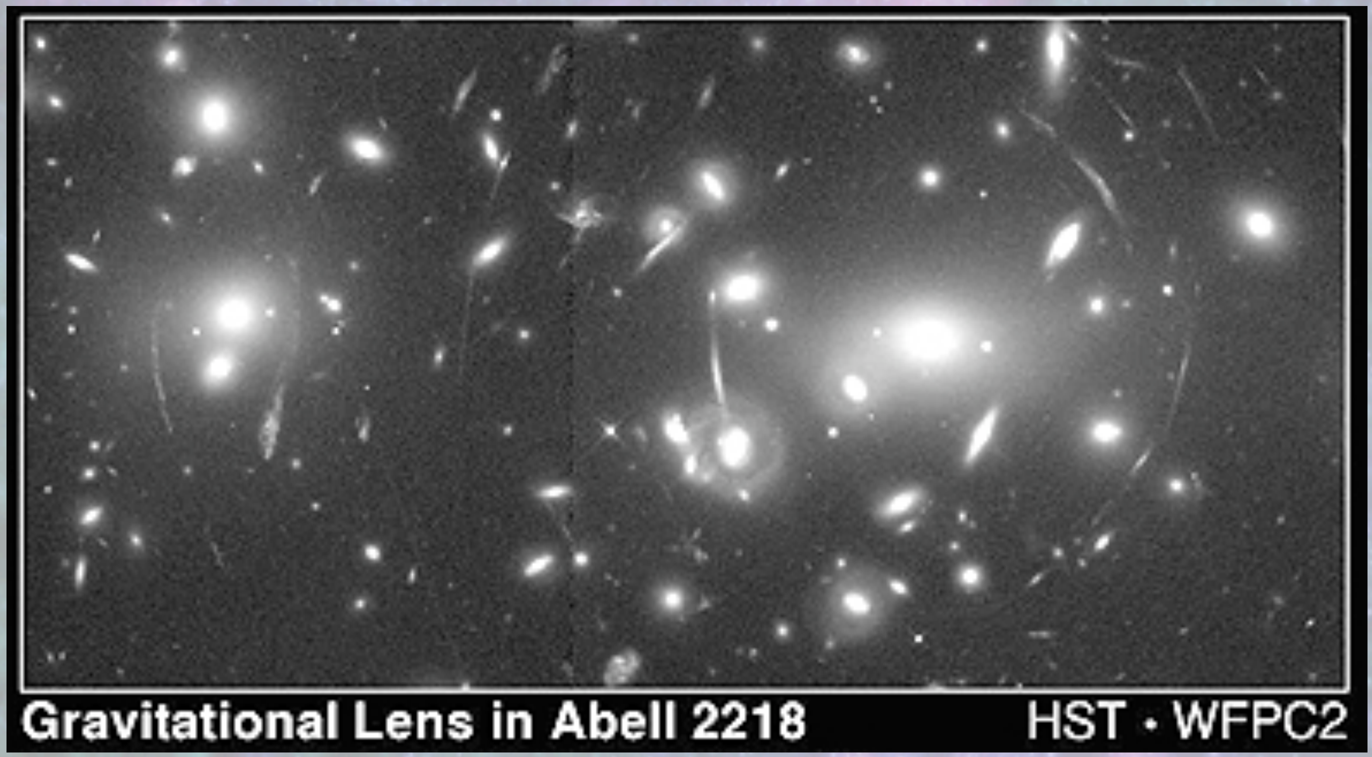
Huge range in model predictions



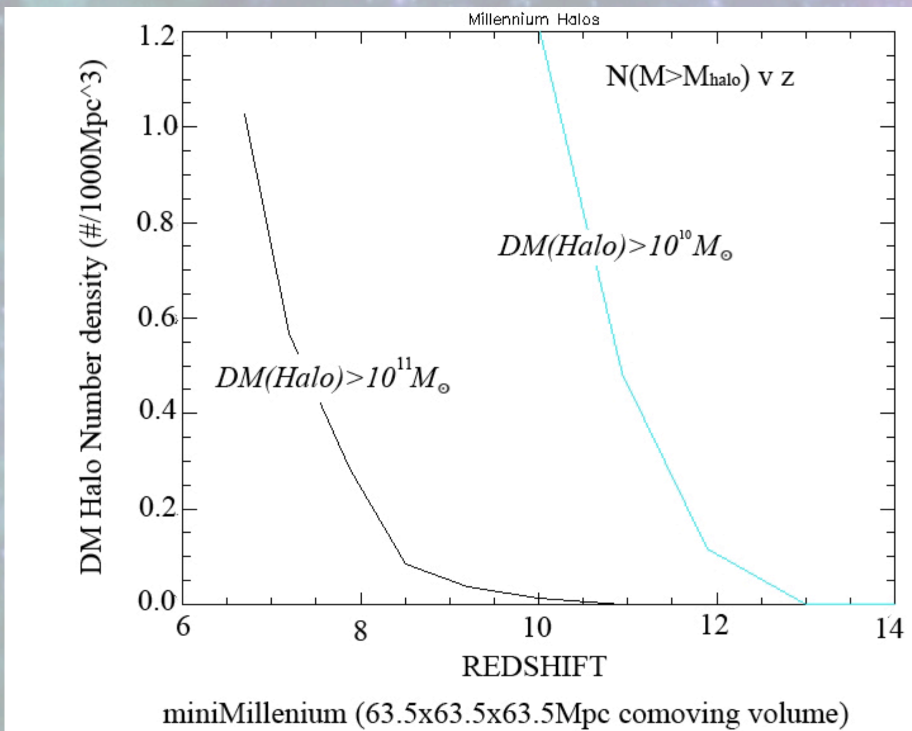
Amplification is needed

Can we use a lensing cluster to image the high z H_2?

Can give amplification factors of 20-100



What is the likelihood we will hit an interesting "clump"?



If we survey to main caustics of 10 major lensing systems we will explore 1000 Mpc^3. (assuming we map with a 10 arcsec swath around each cluster--amplifying < kpc scale structure at z=10 ~Typical scale from models of clumps)

From Millennium Simulation we expect ~ one 10^{11}Msun halo and several hundred DM halos at z = 7, but the number drops rapidly with redshift. (At z = 10, expect only a few 10^{10} M_{sun} in 1000 $Mpcs^3$. But how does gas and DM relate?

Observational Perspective- Why Shocks might be important

Are we underestimating the expected signal strength? Could

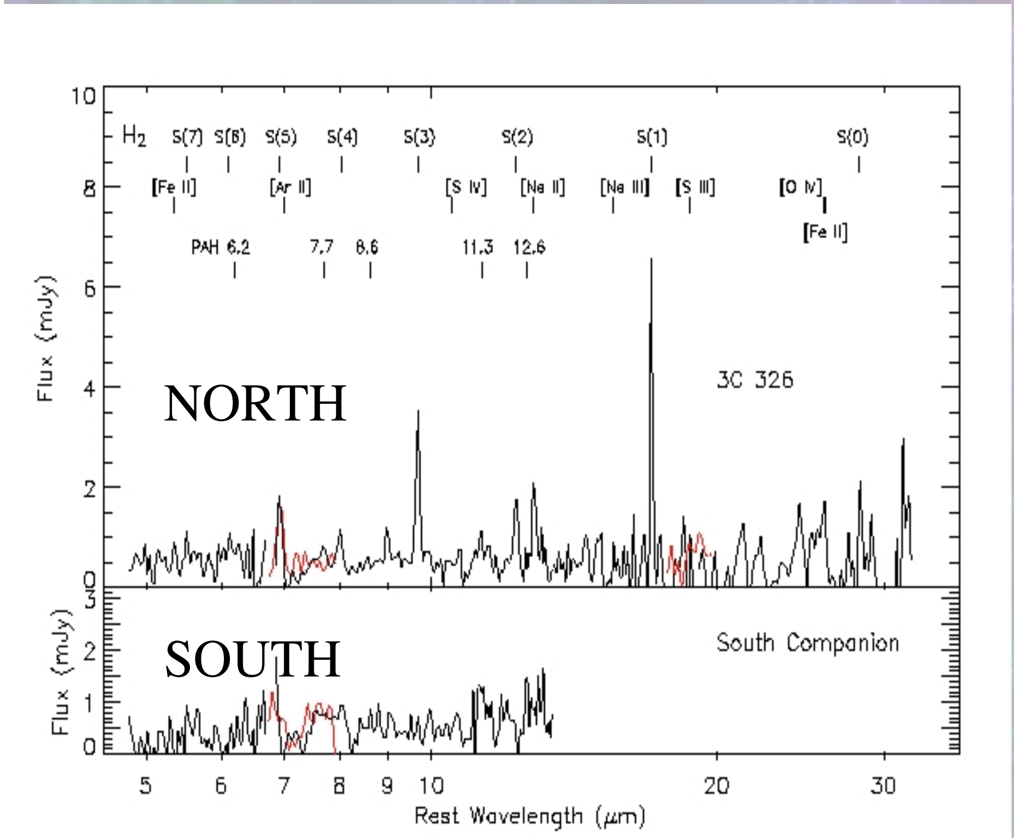
shocks also enhance the emission?

Stephan's Quintet (1*L41) , 3C326 (8*L41) and Zwicky 3146 Egami et al. 2006 (60*L41!)

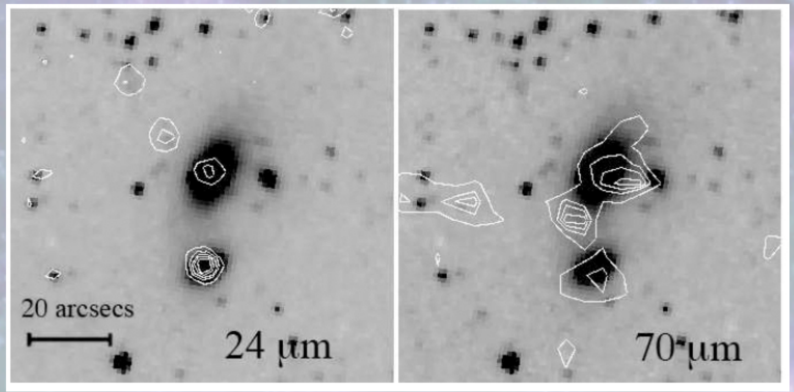
3C 326 — H_2 Dominated Spectrum

THE MOST EXTREME MOHEG SO FAR

[Ogle, Antonnuci, Appleton & Whysong, ApJ (2007), 668, 699]



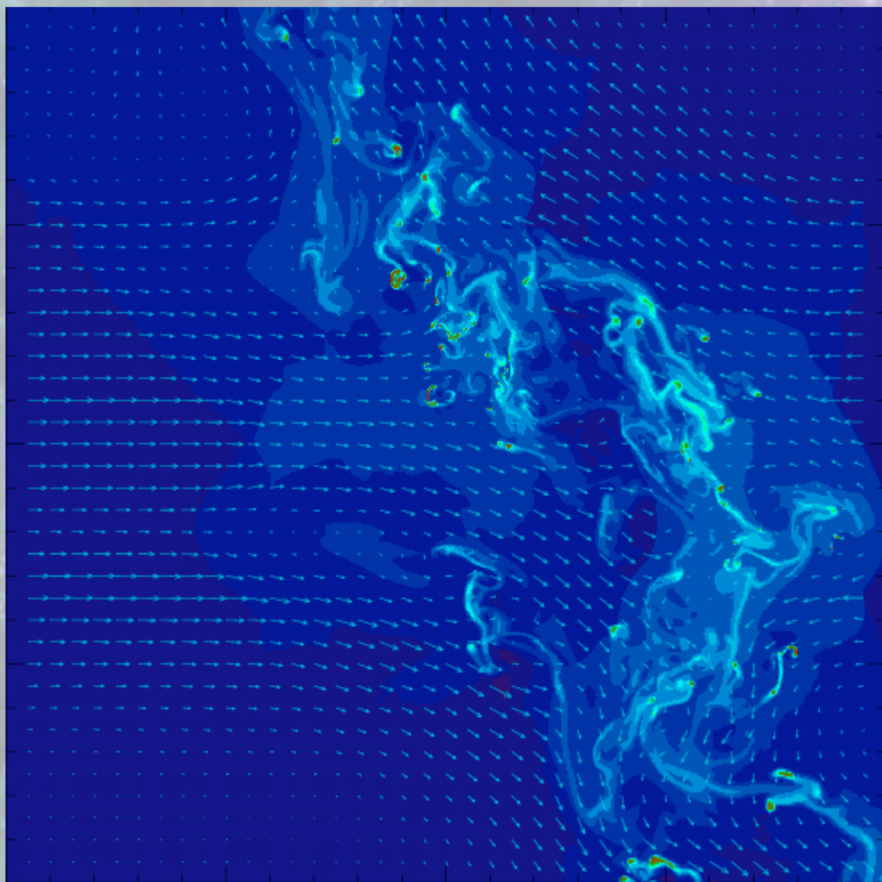
- Galaxy and AGN continua are weak $L(H_2)= 8 \times 10^{41}$ erg/s (S(0)-S(7))
- $L(H_2)/L(IR_{(7\text{-}1000um)})= 17\%$
- $M(H_2)$warm = $1.1 \times 10^9\ M_{sun}$



Accretion onto northern galaxy may power H_2 luminosity

Spitzer IRS, SL and LL

The Importance of Turbulence in the High-z gas?

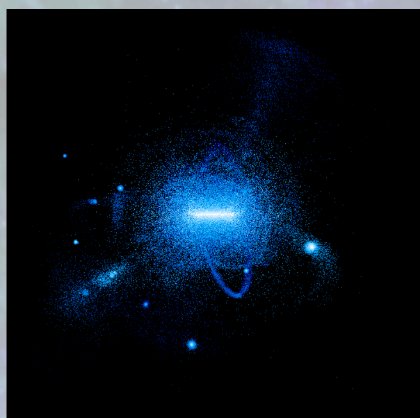


Sources of Turbulence?

1) Collisions between halos
2) SN Shocks and Winds from
   1st massive stars?
1) Accretion flows between
   CDM Halos?
1) AGN Winds

WILL TURBULENCE ENHANCE THE SIGNAL LIKE THE MOHEGs?

How different is SQ from the merging of cloudy halos in early universe?

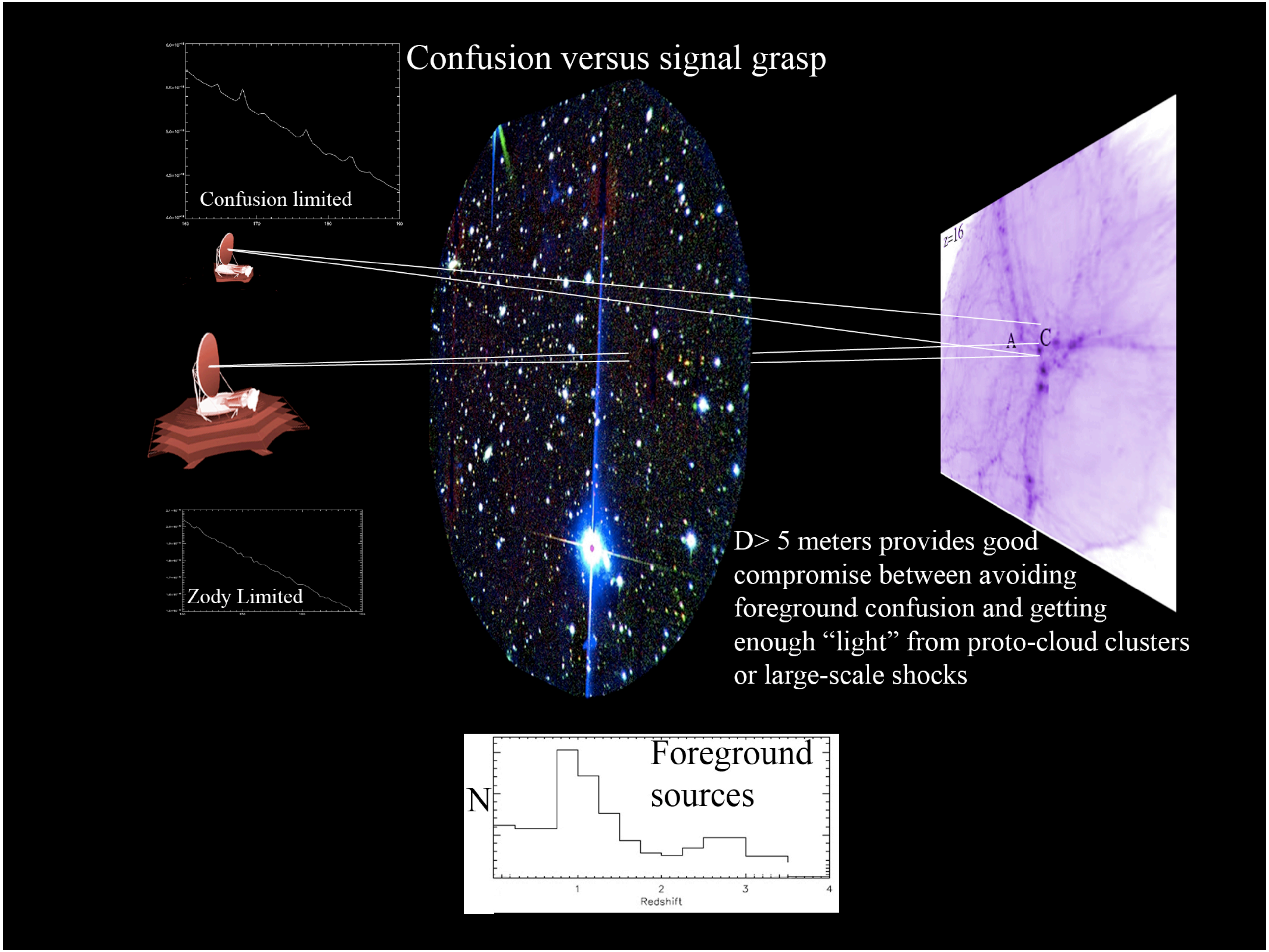


In Stephan's quintet
We see large H2 power
in rotational lines from
ggiant shock. If
DM haloes merge could
They do something similar?

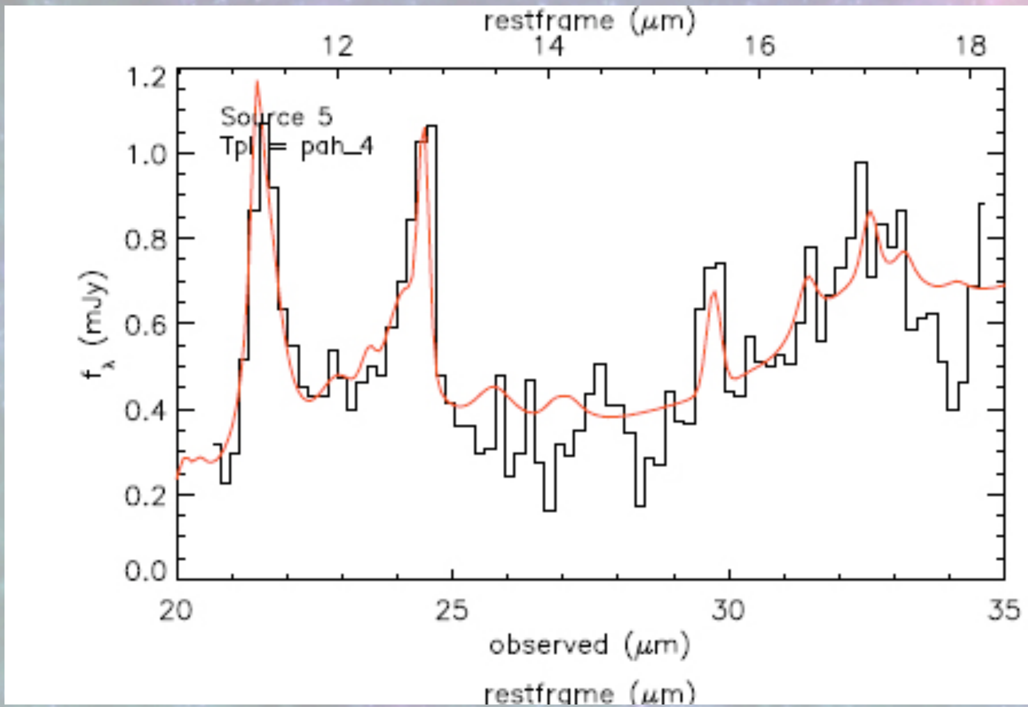
Limitations

Detectors/Spectrometers: Concepts like M. Bradford's WaFIR-spectrometer and extremely low-noise bolometers.
Promising: Ultimately we need detectors that can get down to the natural background of the Zody night sky ~ 10^{-21} W/m^2, for spectroscopy R~ 1000. Current detectors are not yet capable of this.
Spectral Confusion: To avoid foreground contamination of the primordial signature by low luminosity galaxies will require large apertures (say D = 5 meters FWHM <= 8 arcsecs at z = 10, 8 arcsec ~ 35 kpc). This might be well matched to accretion flows and or large-scale turbulent structures where many compact H_2 clouds may lie in beam. Interferometers may provide too much resolution.

Simulations indicate that for aperture D > 4-5 meters spectral contamination is not severe unless the L_{bol}> 5 x 10^9 L_{sun} galaxies have z distribution that is very different from the population that dominated the CIR background (next 3 slides if time)

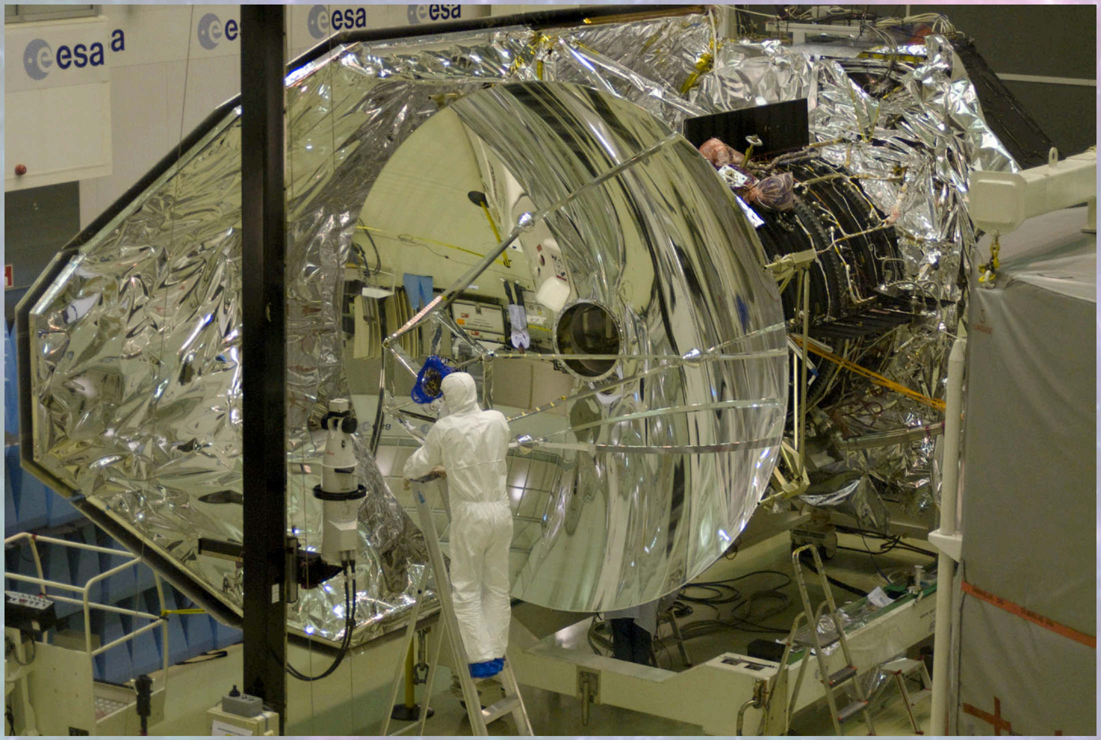

Confusion versus signal grasp
Confusion limited
Zody Limited
z=16
A
C
D> 5 meters provides good compromise between avoiding foreground confusion and getting enough "light" from proto-cloud clusters or large-scale shocks
N
Foreground sources
1
2
3
4
Redshift

Not much constraint on low-luminosity sources at z = 1



Ultradeep IRS survey
HDF Good field
6hrs/pixel 2 x 2 arcmin
Bertincount et al. (2008)
These objects are quite
low luminosity and
A large fraction look
Like Star-forming galaxies

Herschel will help us



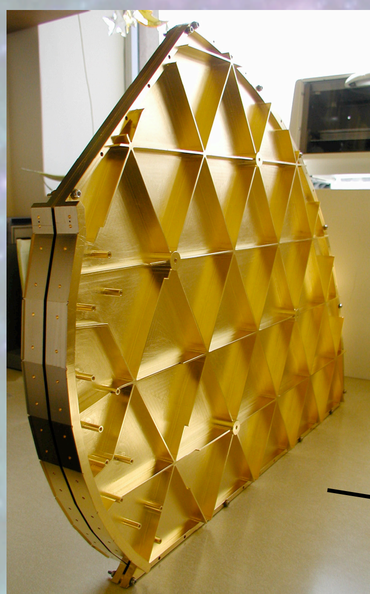
Nearby galaxy
Spectroscopy
(Kingfish et al)

Long-wave
Number counts
And low-lum
galaxies

Innovative spectrometer designs will be needed to image areas of sky containing H_2 hotspots.

Ideally would need many pixels on the sky and thousands of pixels in the dispersion direction : could get away with R=600 (500km/s), 60-400 microns

NOTE 5 arcsecs = 21kpc at z =10



Matt Bradford's Z-Spec instrument

(Bradford et al. 2004)

Ideally would need some form of Integral Field Unit to feed a large-format FIR/Submm spectrometer w chopper

BLISS?

Conclusions

•**High-z rotational H_2 at $6 < z < 15$ can only be observed in Far-IR with a large aperture cooled telescope. Technical challenges large but scientific benefits would be enormous!** A large cooled telescope with imaging spectroscopic (R~1000) would be needed to beat confusion and yet keep a large beam (~5-8 arcsecs at 200μm) needed to detect collections of primordial faint objects at $6 < z < 10$.

• Models of H_2 emission from first and second generation single molecular clouds yield fluxes that are close to or below the limit of Detection for most realistic current models. However new discoveries (MOHEGs) in the local universe suggest that turbulence can amplify the H_2 signal. **Are such processes possible at Hi-z? (Accretion and A GN driven?) If so they will be readily detectable to z = 10.**

•Use of lensing clusters may allow **primordial cloud complexes to be amplified by factors of 10** or more (into detectible range?). Also helps to beat confusion noise.