# Fundamental Physics
# Cosmology
## Relics of the Early Universe

Frank Bertoldi

Bonn University

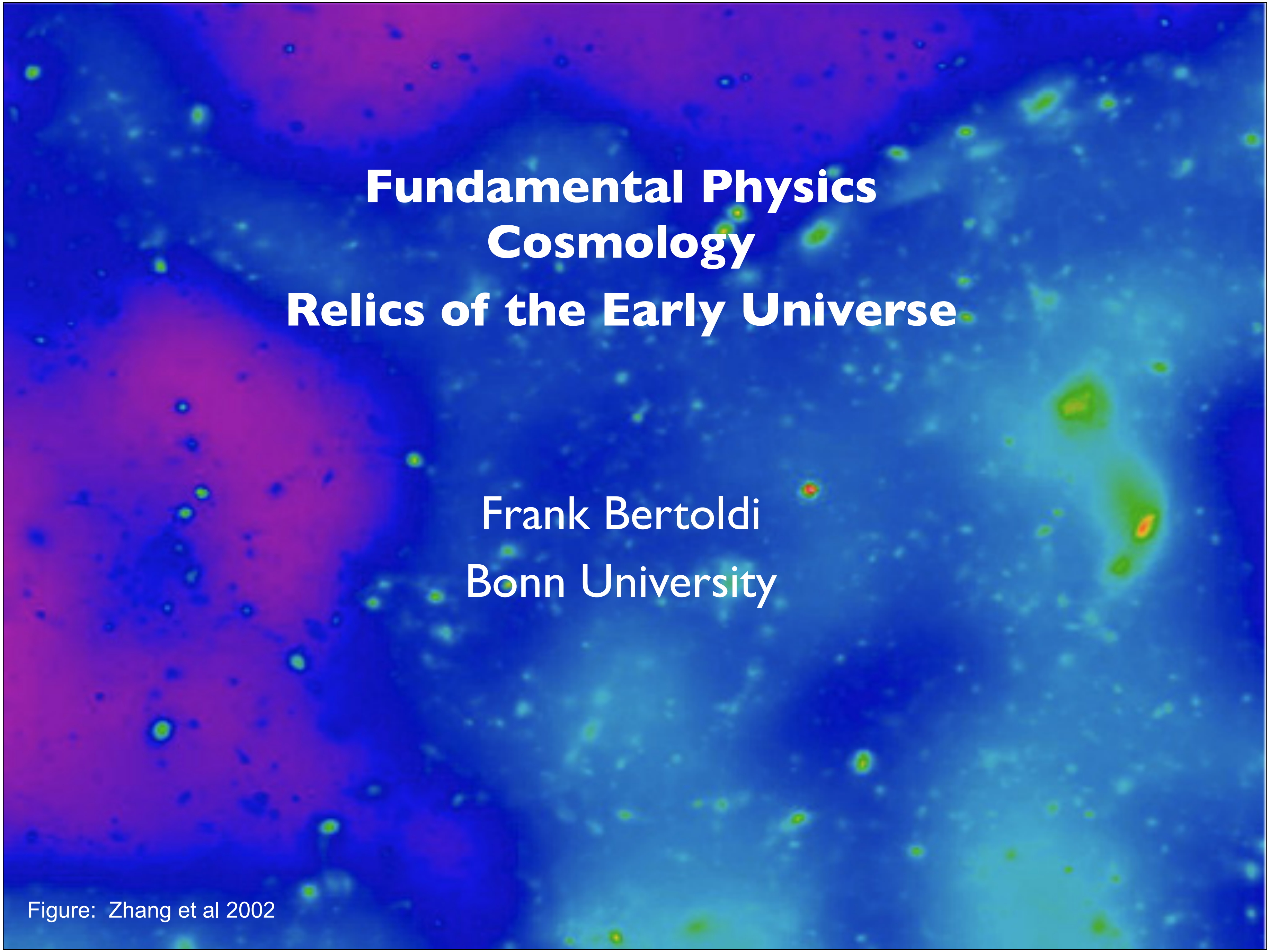
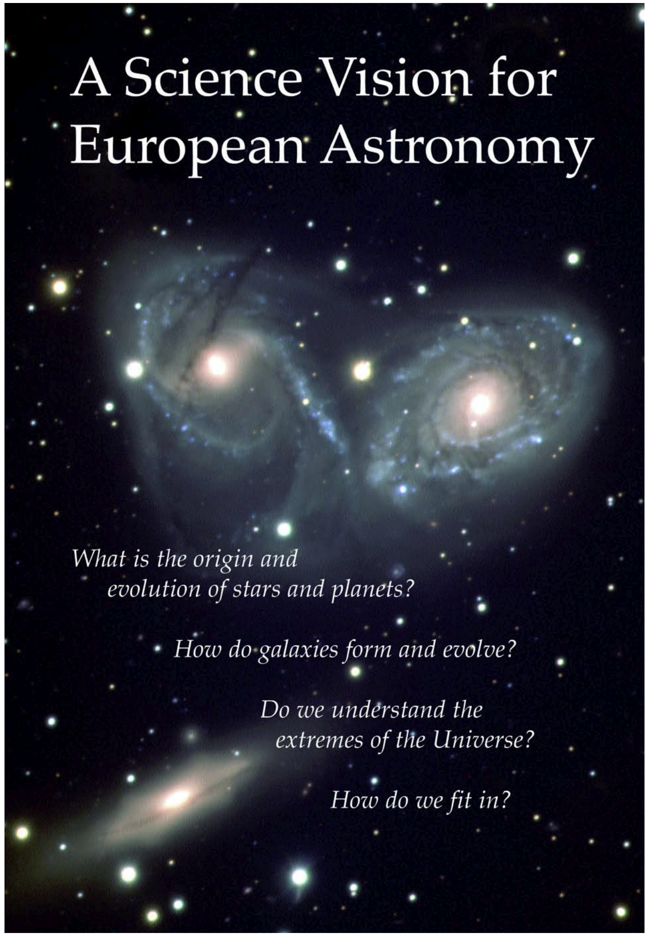


Figure:  Zhang et al 2002



A Science Vision for
European Astronomy

*What is the origin and
evolution of stars and planets?*

*How do galaxies form and evolve?*

*Do we understand the
extremes of the Universe?*

*How do we fit in?*

## Do we understand the extremes of the Universe?

### How did the Universe begin?

- gravity waves:
  - CMB B-mode polarization
  - LISA
  - Pulsar timing (SKA)

### What is dark matter and dark energy?

- CMB polarization
- gravitational lensing / cosmic shear (optical/radio imaging)
- BAO, LSS, clusters (large scale imaging)
- SNIa (NIR)

### Can we observe strong gravity in action?

- gravity waves from tight double NS or BH: pulsar timing
- Shapiro time delay
- black holes:
  - mergers, event horizon imaging, Fe X-ray monitoring

### How do supernovae and gamma-ray bursts work?

- monitor explosions at all wavelengths, incl neutrinos

### How do black hole accretion, jets and outflows operate?

- high-res. & survey radio, X/gamma monitoring

### What do we learn from energetic radiation and particles?

- Cherenkov arrays to TeV, air shower detectors

## How do galaxies form and evolve?

### How did the Universe emerge from its Dark Ages?

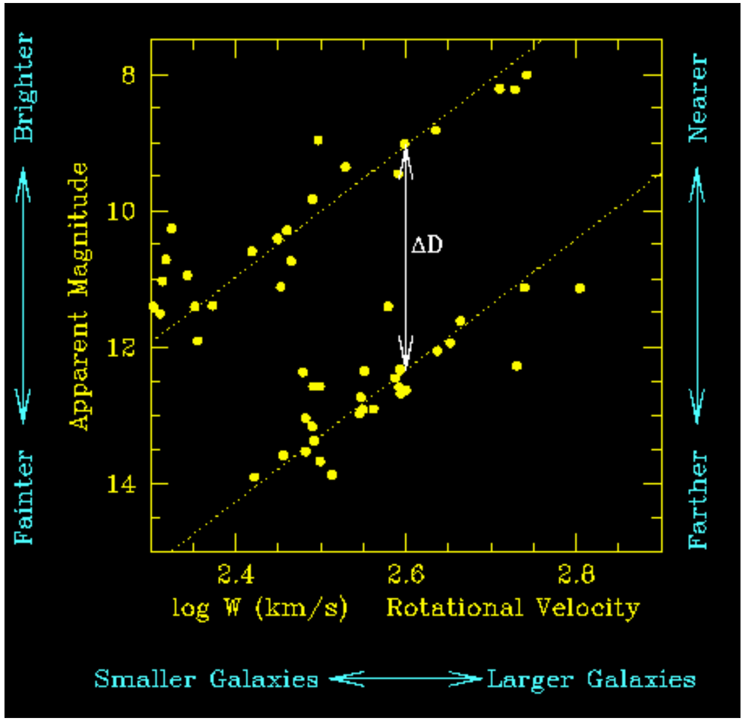
### How did the structure of the cosmic web evolve?

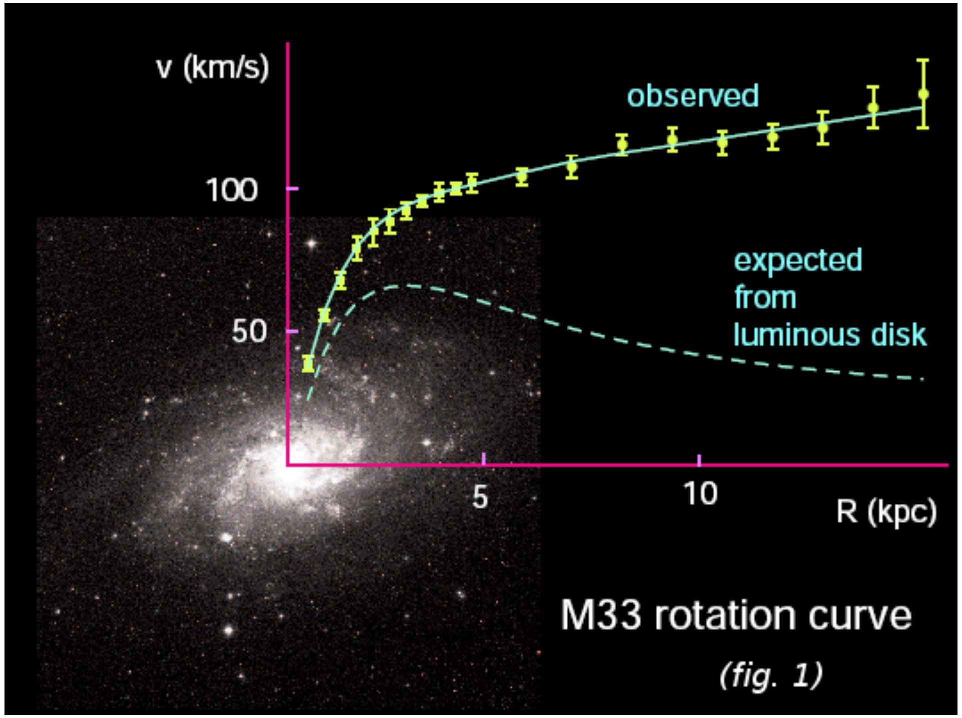
# Selected ALMA science

- Dark matter:  rotation curves
- Absorption lines
  - mass, abundances, fundamental constants
- Star formation during the Epoch of Reionization
  - continuum, lines, GRBs
- Sunyaev-Zel'dovich Effect
  - dark energy, cosmology, cluster physics
- CMB polarization

# Molecular line widths / shapes

- Rotation curves: Dark Matter distribution in Galaxies
- CO Tully-Fisher relation: cf. HI, less sensitive to broadening by galaxy interactions.





M33 rotation curve

*(fig. 1)*

# Absorption lines

More sensitive to cold gas along l.o.s.
with ALMA 100 times more background sources
explore:

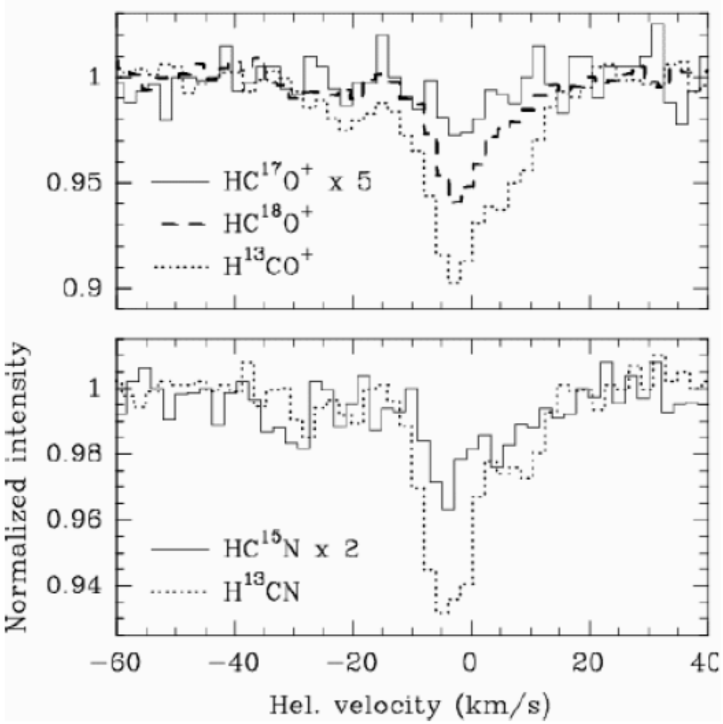
- abundances & chemistry as function of z
- $T_{CMB}(z)$
- Hubble constant through time delay btw two lensed images
- variation of fundamental constants:
  - fine structure constant
  - $m_e/m_p$
  - proton gyromagnetic ratio

  (Kaluza-Klein, Superstrings, compactified extra-dimensions)

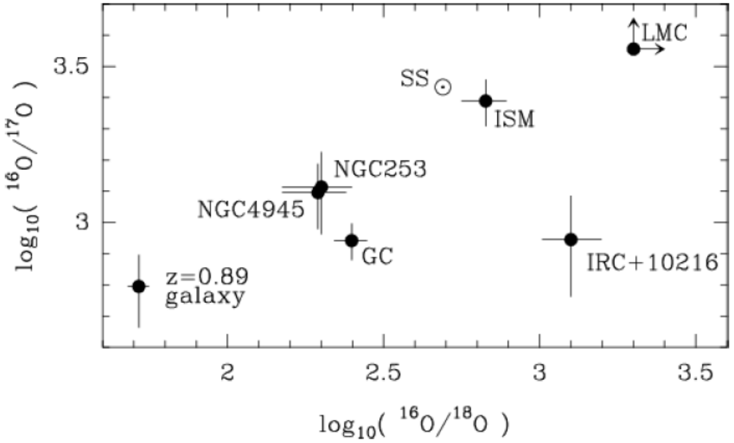
  Doublets/multiplets: O($10^{-5}$)

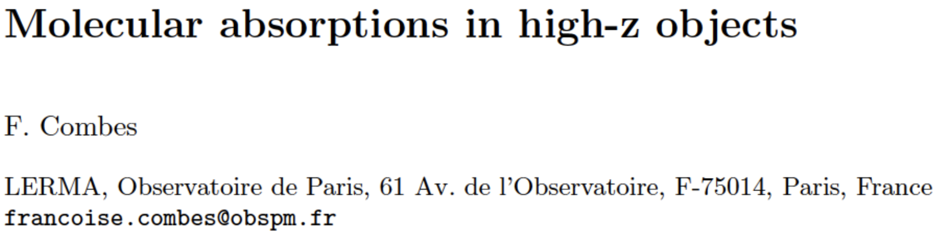
  Radio <u>advantage</u>: high spec. res., cold narrow lines

  <u>Problem</u>: kinematical bias



PKS 1830-211





# Molecular absorptions in high-z objects

F. Combes

LERMA, Observatoire de Paris, 61 Av. de l'Observatoire, F-75014, Paris, France
`francoise.combes@obspm.fr`

Large IRAM program:
150 sources with >0.15 Jy @3mm
+ all strongly lensed systems

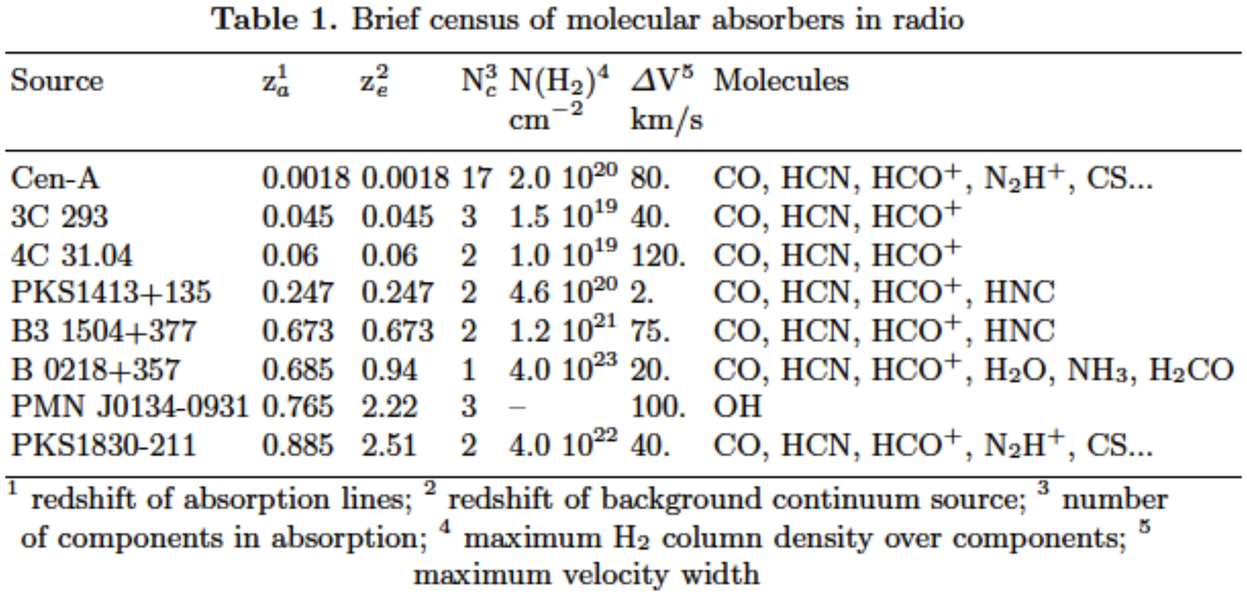
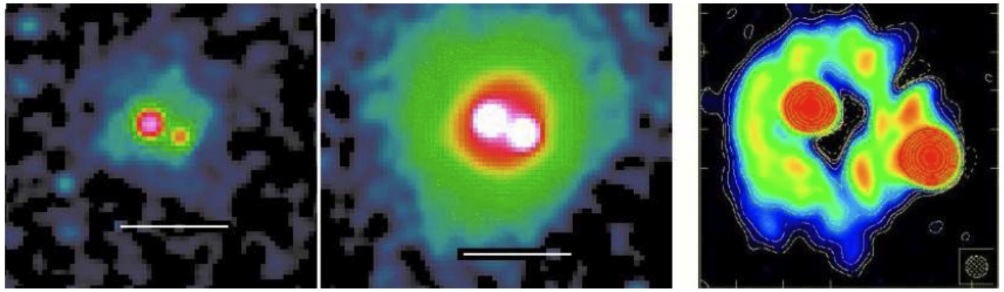


**Table 1.** Brief census of molecular absorbers in radio

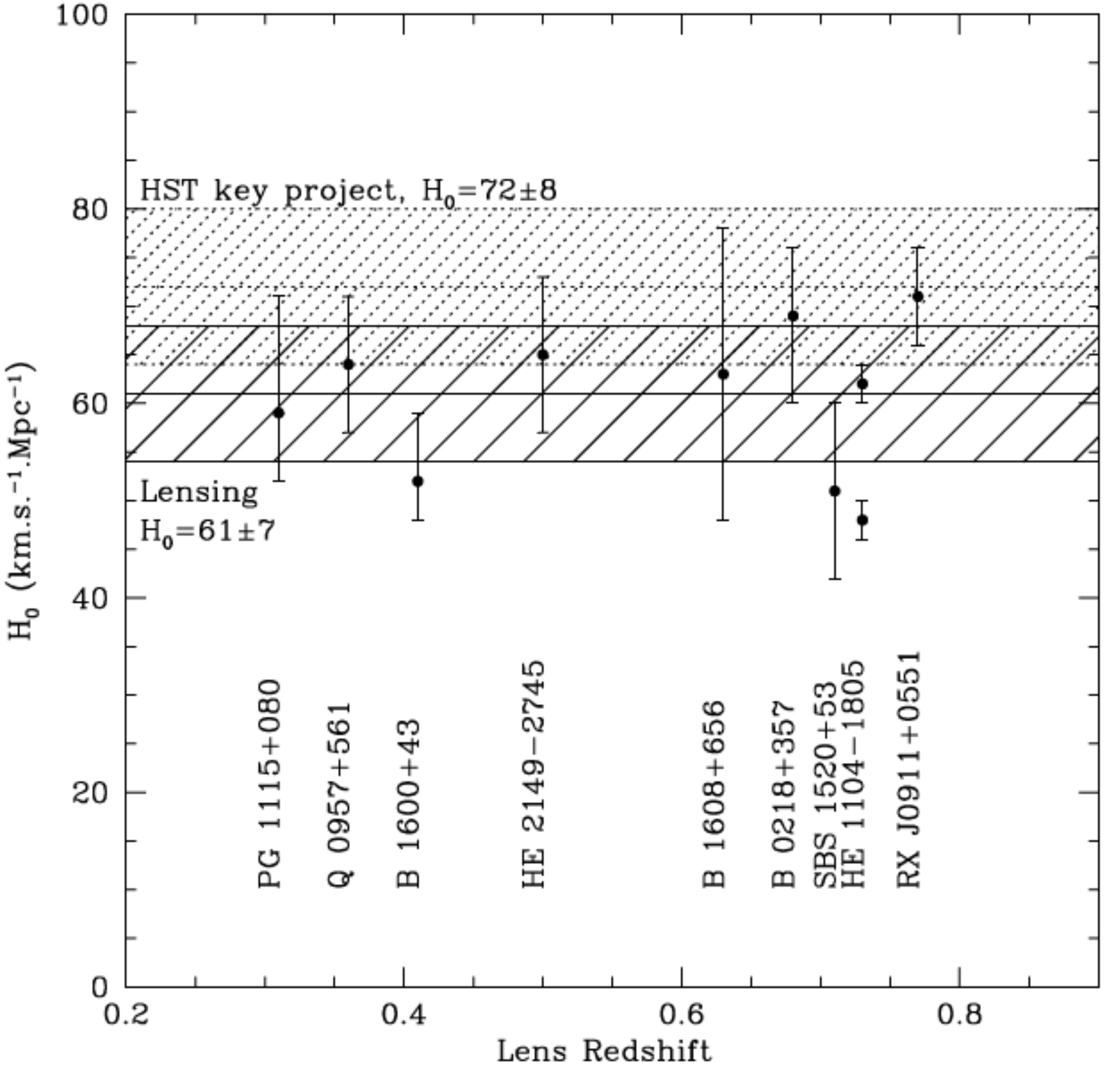
| Source | $z_a^1$ | $z_e^2$ | $N_c^3$ | $N(H_2)^4$ cm$^{-2}$ | $\Delta V^5$ km/s | Molecules |
|---|---|---|---|---|---|---|
| Cen-A | 0.0018 | 0.0018 | 17 | $2.0\ 10^{20}$ | 80. | CO, HCN, $HCO^+$, $N_2H^+$, CS... |
| 3C 293 | 0.045 | 0.045 | 3 | $1.5\ 10^{19}$ | 40. | CO, HCN, $HCO^+$ |
| 4C 31.04 | 0.06 | 0.06 | 2 | $1.0\ 10^{19}$ | 120. | CO, HCN, $HCO^+$ |
| PKS1413+135 | 0.247 | 0.247 | 2 | $4.6\ 10^{20}$ | 2. | CO, HCN, $HCO^+$, HNC |
| B3 1504+377 | 0.673 | 0.673 | 2 | $1.2\ 10^{21}$ | 75. | CO, HCN, $HCO^+$, HNC |
| B 0218+357 | 0.685 | 0.94 | 1 | $4.0\ 10^{23}$ | 20. | CO, HCN, $HCO^+$, $H_2O$, $NH_3$, $H_2CO$ |
| PMN J0134-0931 | 0.765 | 2.22 | 3 | – | 100. | OH |
| PKS1830-211 | 0.885 | 2.51 | 2 | $4.0\ 10^{22}$ | 40. | CO, HCN, $HCO^+$, $N_2H^+$, CS... |

[1] redshift of absorption lines; [2] redshift of background continuum source; [3] number of components in absorption; [4] maximum $H_2$ column density over components; [5] maximum velocity width

Sensitive searches for: $O_2$, $H_2O$, LiH (3e-12), $NH_3$, $H_0$=70 km/s/Mpc



B0218+357



[ Courbin (2003), *astro-ph/0304497* ]

# Probing General Relativity

C.Will 2006

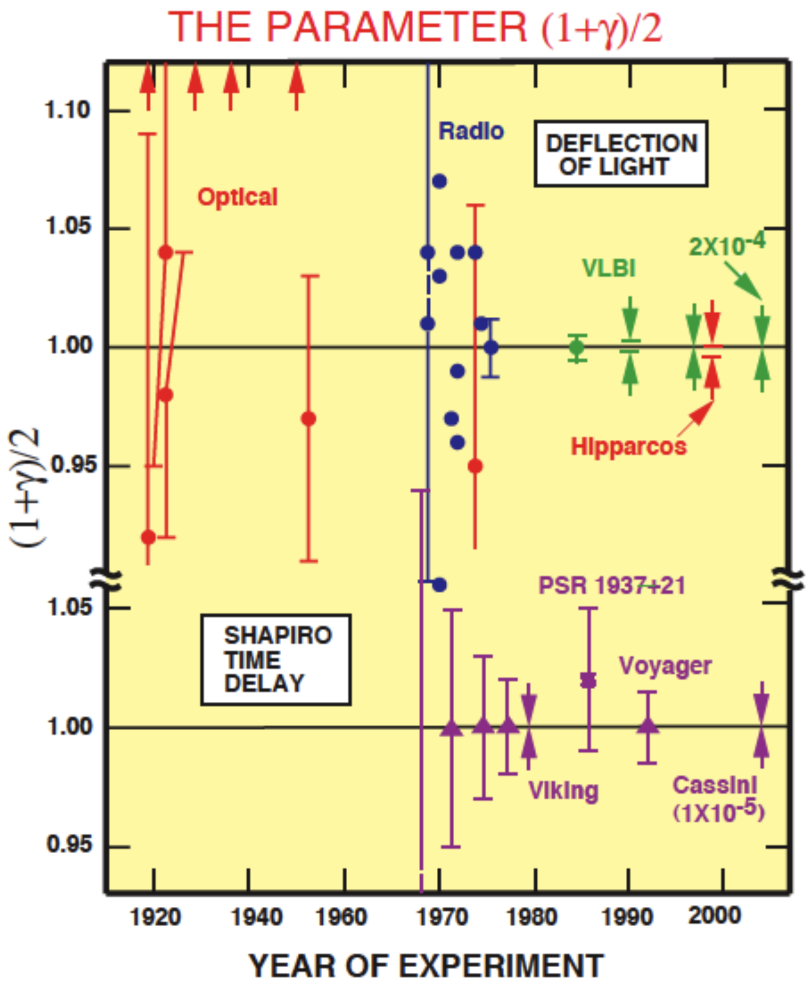
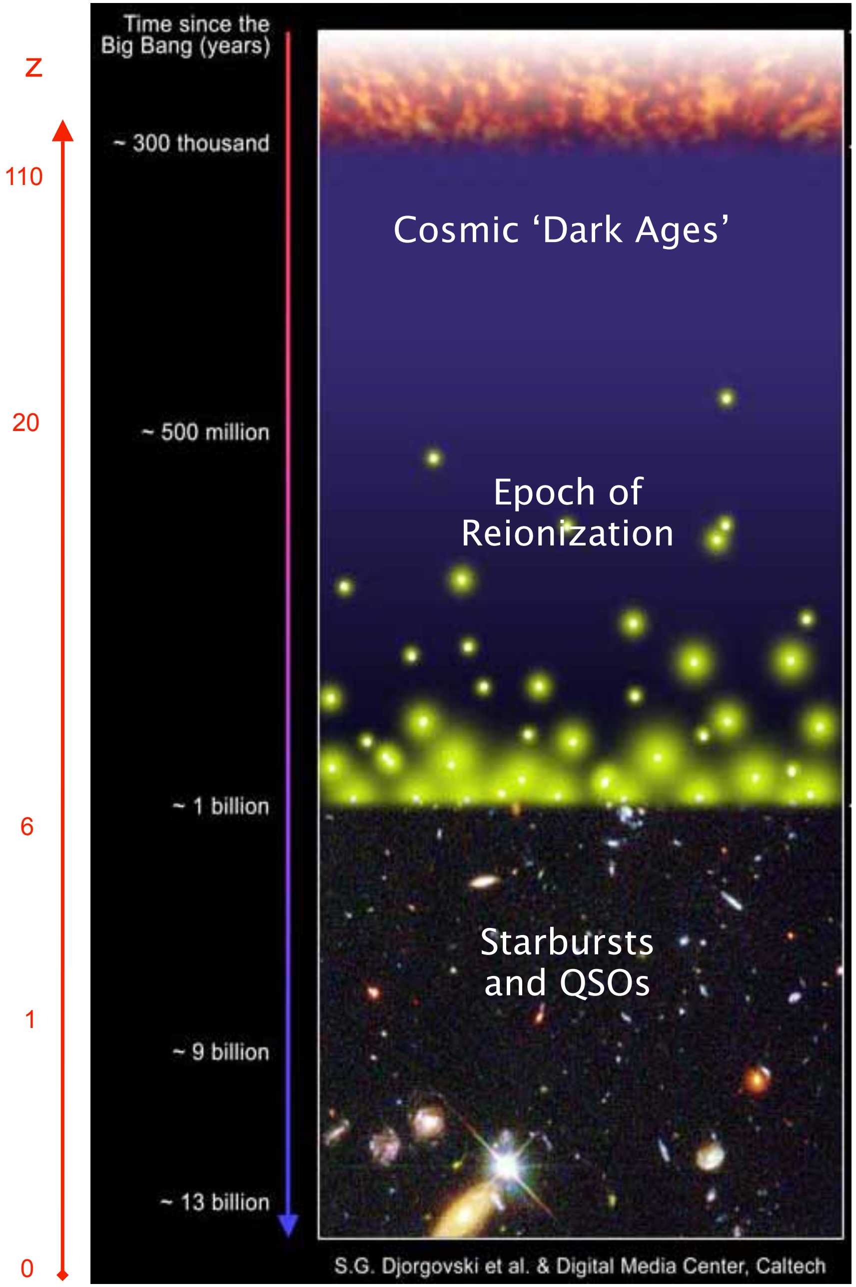


Figure 5: *Measurements of the coefficient* $(1+\gamma)/2$ *from light deflection and time delay measurements. Its GR value is unity. The arrows at the top denote anomalously large values from early eclipse expeditions. The Shapiro time-delay measurements using the Cassini spacecraft yielded an agreement with GR to* $10^{-3}$ *percent, and VLBI light deflection measurements have reached 0.02 percent. Hipparcos denotes the optical astrometry satellite, which reached 0.1 percent.*

# for ALMA:

- ➡ line survey of known absorbers
- ➡ search for new absorbers, $S_{3mm}$>50 mJy

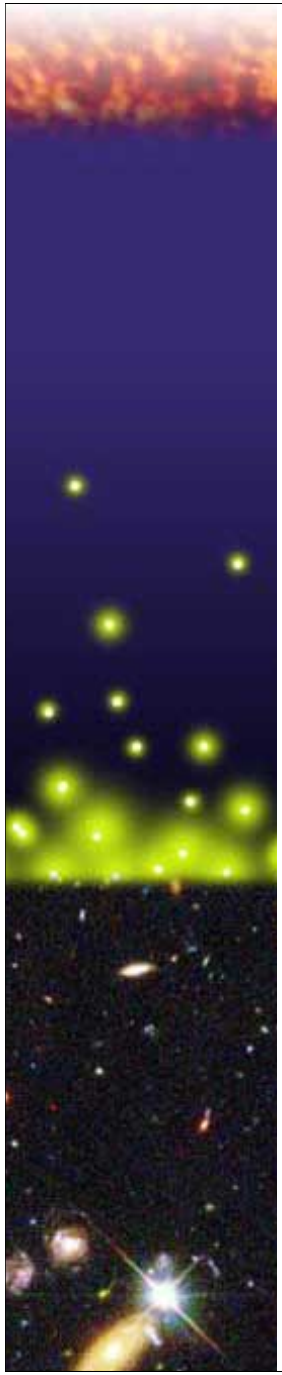


S.G. Djorgovski et al. & Digital Media Center, Caltech

# Epoch of Reionization

- CMB polarization suggests ionization to z=11±3 (Page ’06)
- complex process, variance in space & time (Fan ’06)
- Gunn-Peterson absorption at z>6

  ➠ optically obscure



# Studies of z>7 Sources: Why care?

sources responsible for reionization

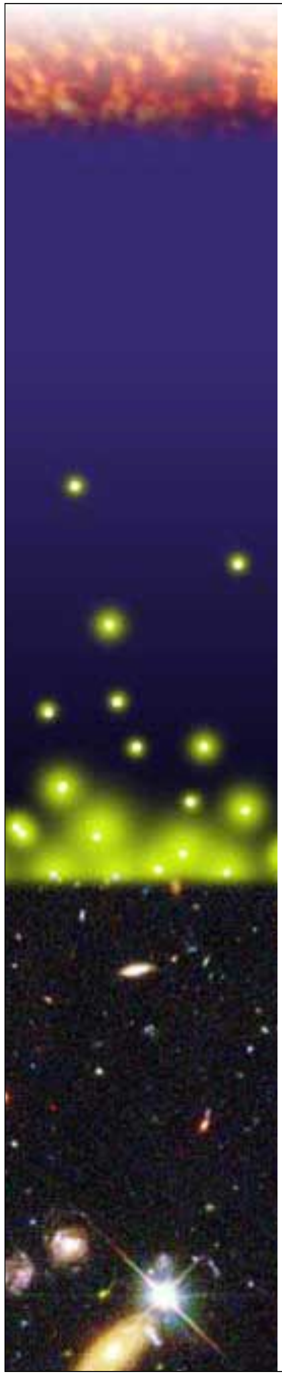
| | | |
|---|---|---|
| constrain: | SFR | (contribution to reionization) |
| | $M_{gas}$ | (fuel for SF & evol. state) |
| | $M_{dyn}$ | (hierarchical models, M-$\sigma$) |

probe the state of the IGM!

galaxies now detected to z=7 (780 Myr after Big Bang)

we ***know*** that they must have formed stars at z>7

z=7 ⇨ z=10: 300 Myr



# z>7 Sources: How to find them?

**broad band searches**:

SDSS: ~dozen z~6 QSOs [7000 sq.deg.] [Fan et al. 06]

QSO record holder: J1148+5251 at z=6.42

UKIDDS/VISTA

PanSTARRS

**narrow band searches**:

Ly$\alpha$ emitters: - z~6.6, [~30, 1/4 sq.deg.] - SFR~30 $M_{sun}$/yr [Taniguchi et al. 05]

- z=5.7 in COSMOS [Muraya et al. 07]

Carilli et al. '07: radio (100) & mm (10) stacking

- z=6.98 [Iye et al. 06]
- z=8.8 non-det. [Cuby et al. 06]

H$\alpha$ emitter: z~9.8 w/ IRS/Spitzer [Lacy et al. 06]

**GRBs**

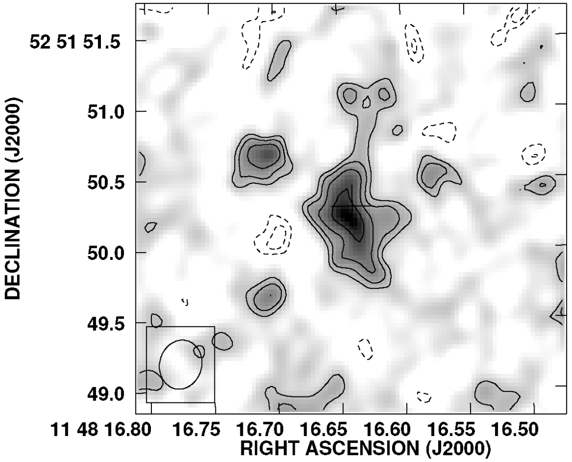
'Just' a matter of time until z>7 sources are detected

**ALMA** (FOV: 1') will not be a survey machine

# z>7 Sources: What can ALMA do?

## Spectral lines

| | |
|---|---|
| $M_{gas}$ | - fuel for SF, evolutionary state |
| morphology | - sizes, merger vs. disks vs. ? |
| $M_{dyn}$ | - hierarchical model, M-σ |

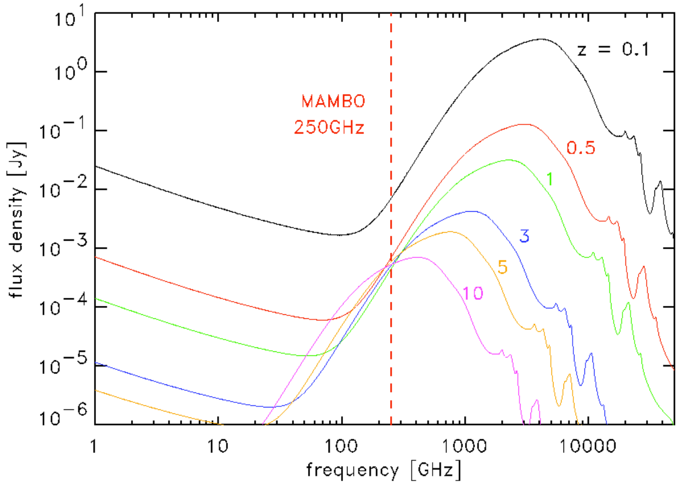


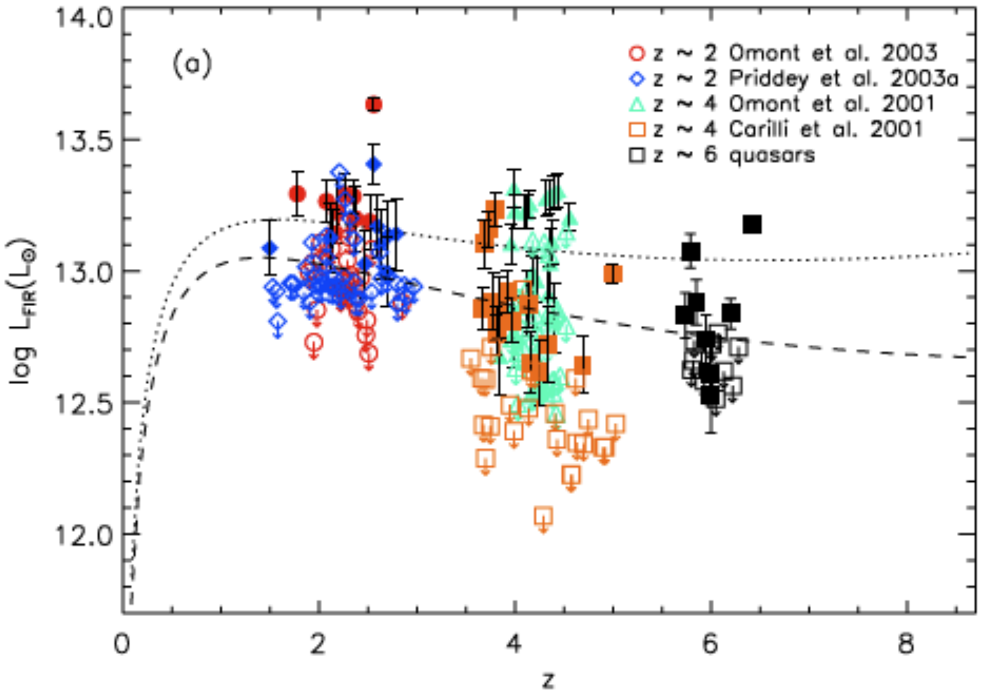
CO @ z=6.4

Line of choice so far @ high z: CO

Not because it's best tracer…

…but because it is easiest to observe



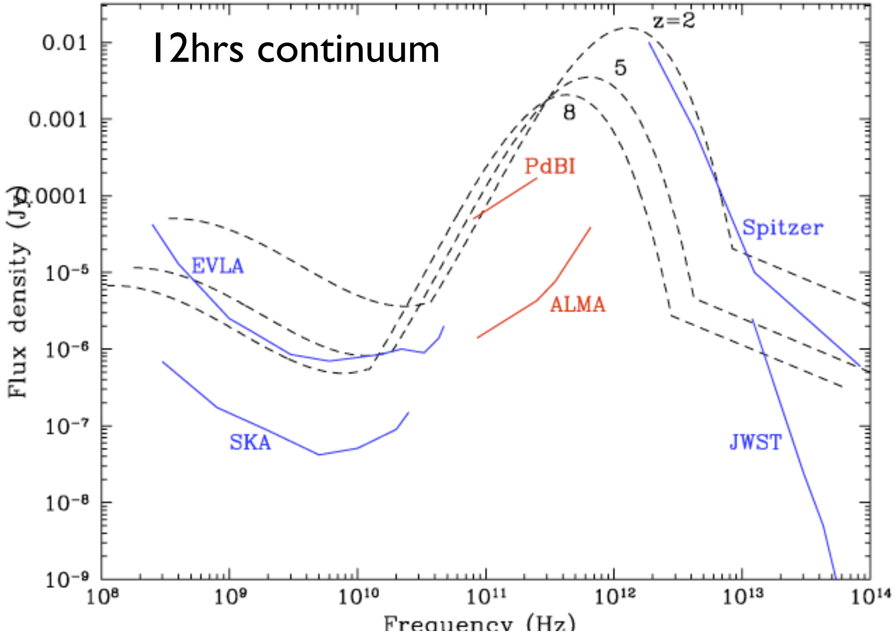


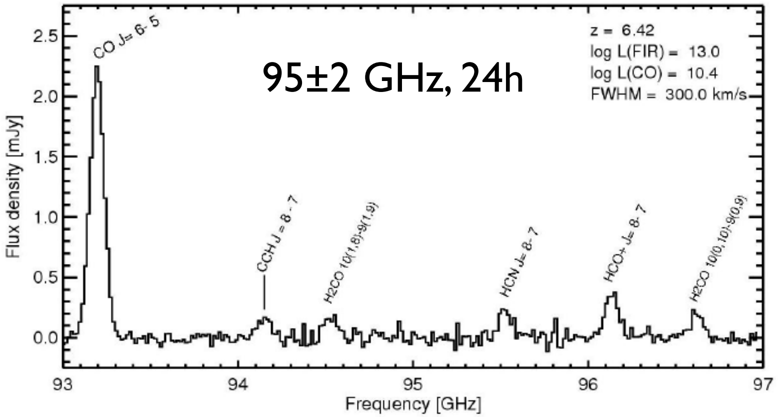
Detailed studies only on extreme objects

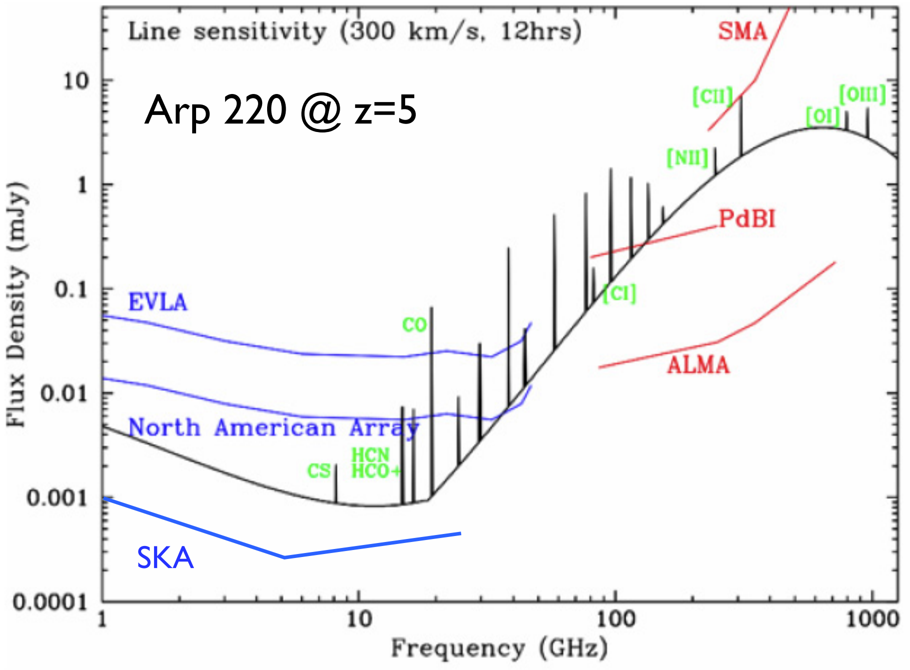
ALMA will detect J1148 in 1 sec
normal SF galaxies in hours:
20 $\mu$Jy , 10 $M_{sun}$/yr

Lines:
CO, HCN, HCO+, H2O, ...
CII 158
CI 370, 609
OI 63, 145
OIII 52, 88
NII 205
NIII 57

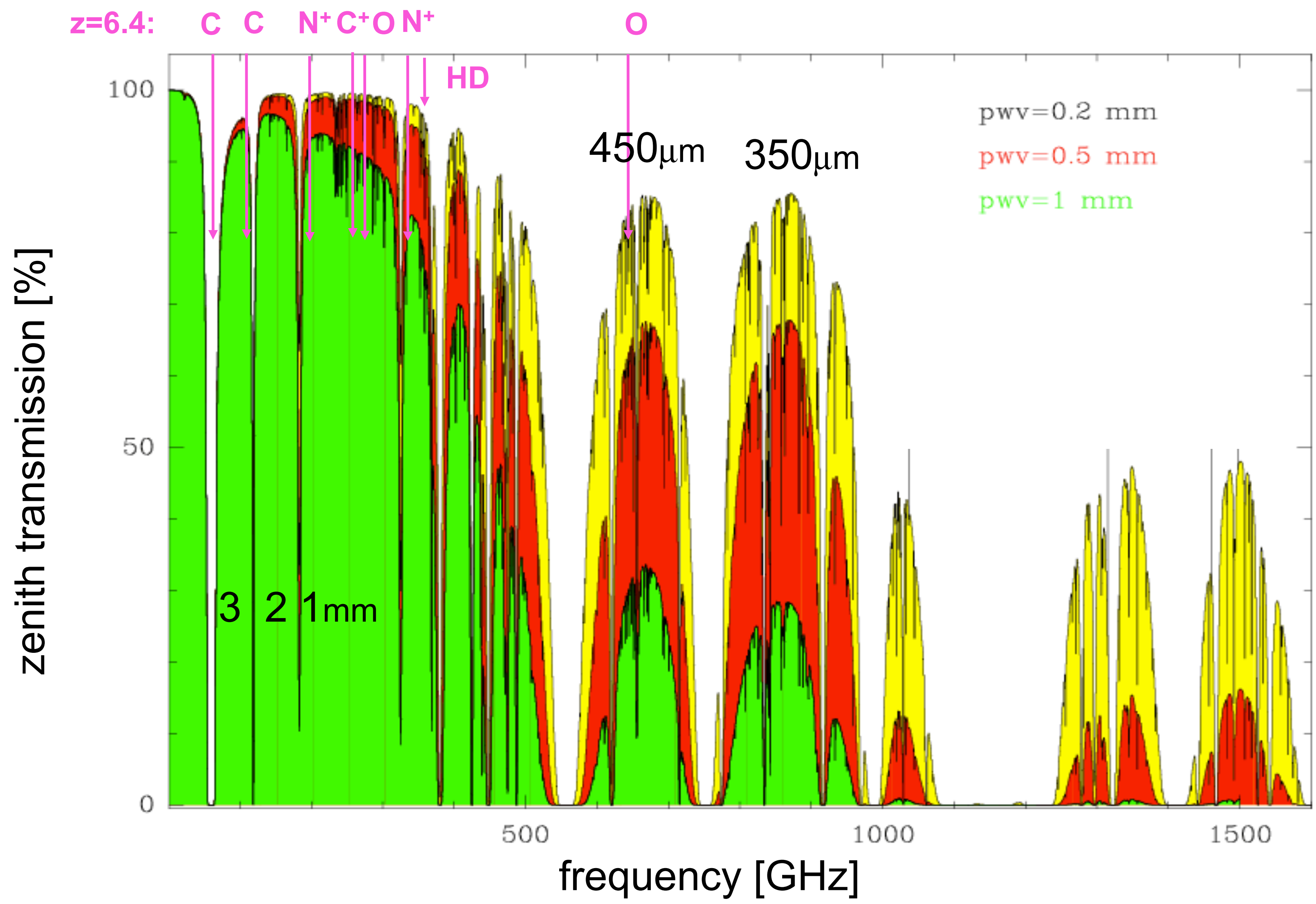
Note: $C^+$ line obs. not sensitivity-limited!


12hrs continuum


95±2 GHz, 24h

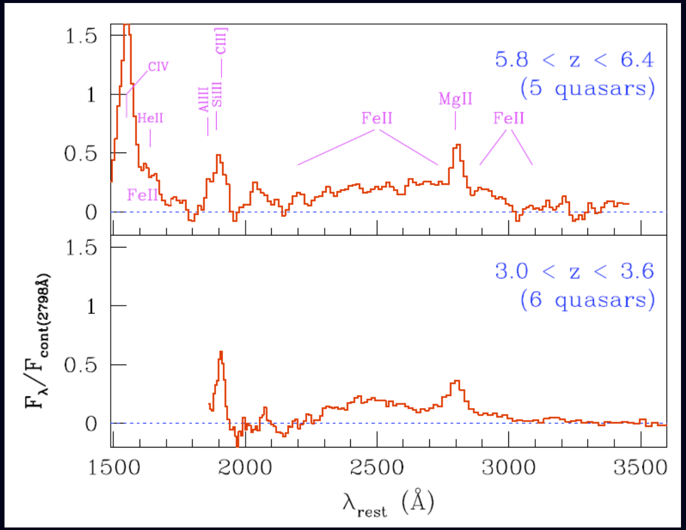

Arp 220 @ z=5

# Far-IR Cooling lines at high z shifted into observable windows



# No Metallicity Evolution at high z

The alpha-element (O, Mg, Si, Ca, and Ti) abundance of a star is an indicator of the star's enrichment history. Type II supernovae create large amounts of the alpha elements with respect to iron, while Type Ia supernovae do not.



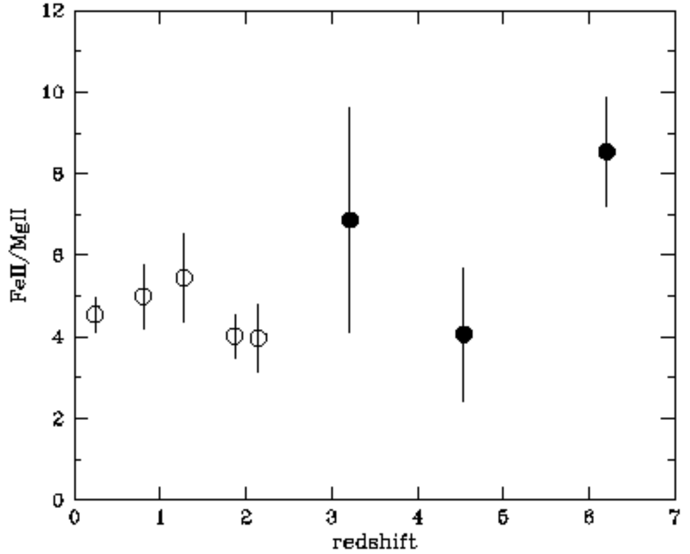
At z>5 age of Universe comparable time for stellar processes to enrich ISM

Fe, C mostly enriched by SN Ia and AGB stars: need 1 Gyr to evolve.

But FeII-multiplet 2600 Å bump suggests super-solar abundance!

FeII / MgII 2798 suggests no evolution of Fe to α-element (produced on shorter time by SNII)

similar for C N Si



Maiolino ea.

However, broad lines arise from small regions.

But CO (thick), [CII]158μm (thin) show strong C enrichment on kpc-scale

Recent models account for strong enrichment of Fe C N Si on 100 Myr

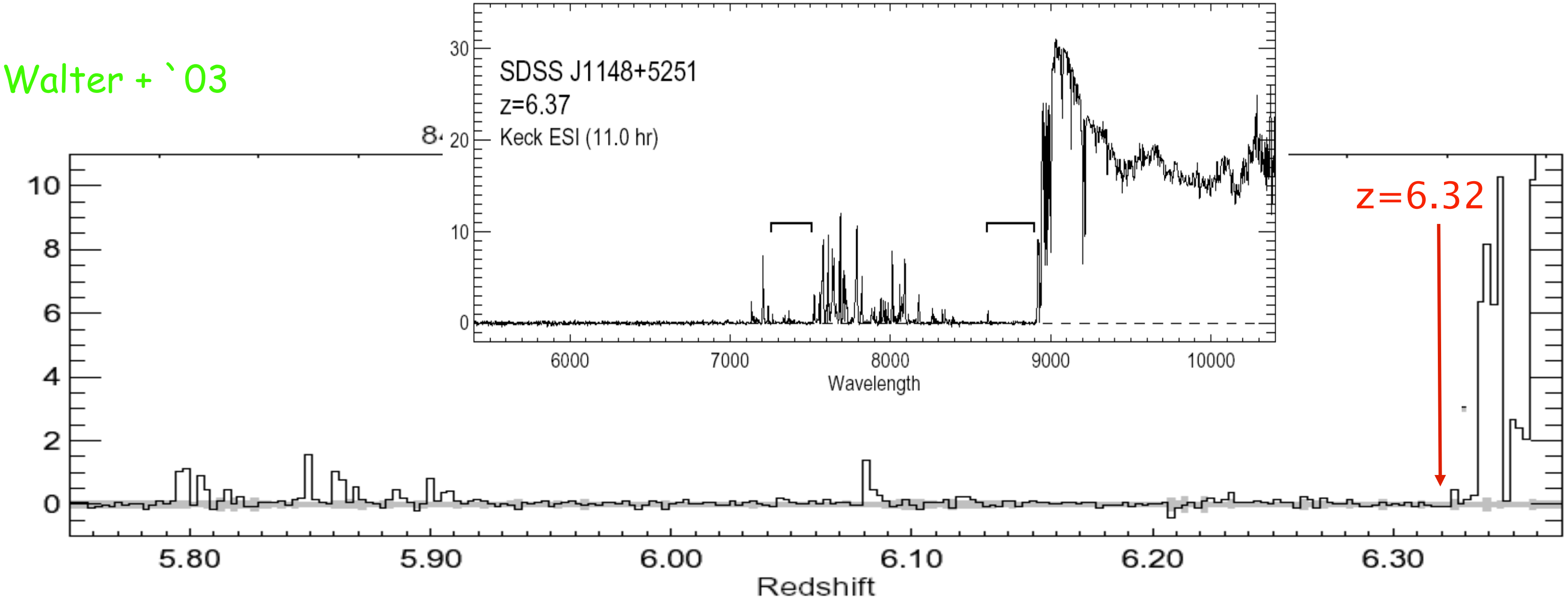
„fast“ SNIa can enrich ISM on <100Myr (Mannucci et al. 2005, 2006)

# Watching Reionization

Proximity effect:   Ly $\alpha$ emission from $6.32 < z < 6.419$  (CO)

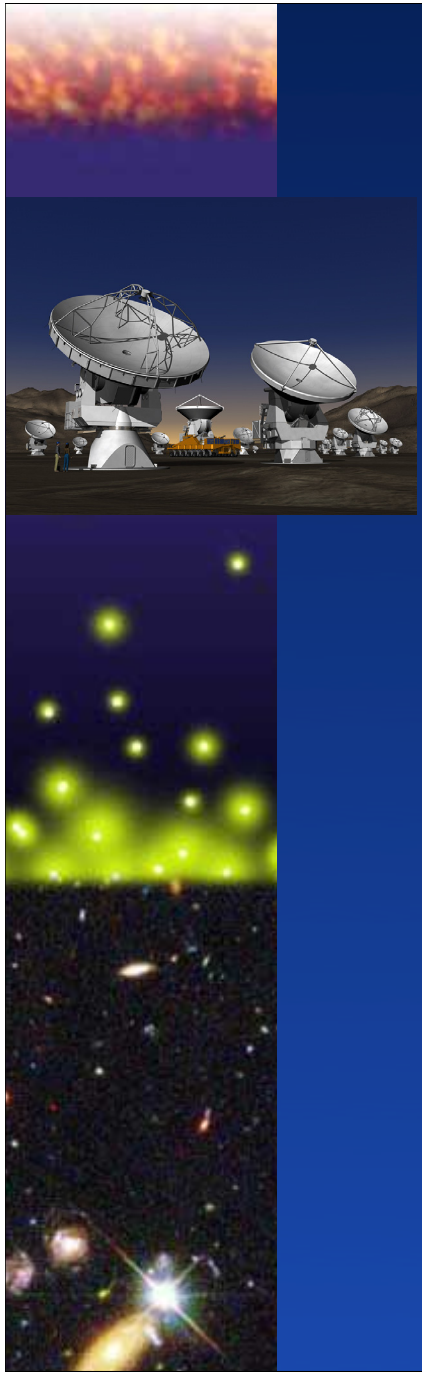
Ionized sphere around QSO:  R= 4.7 Mpc
J1148 contributes to reionization

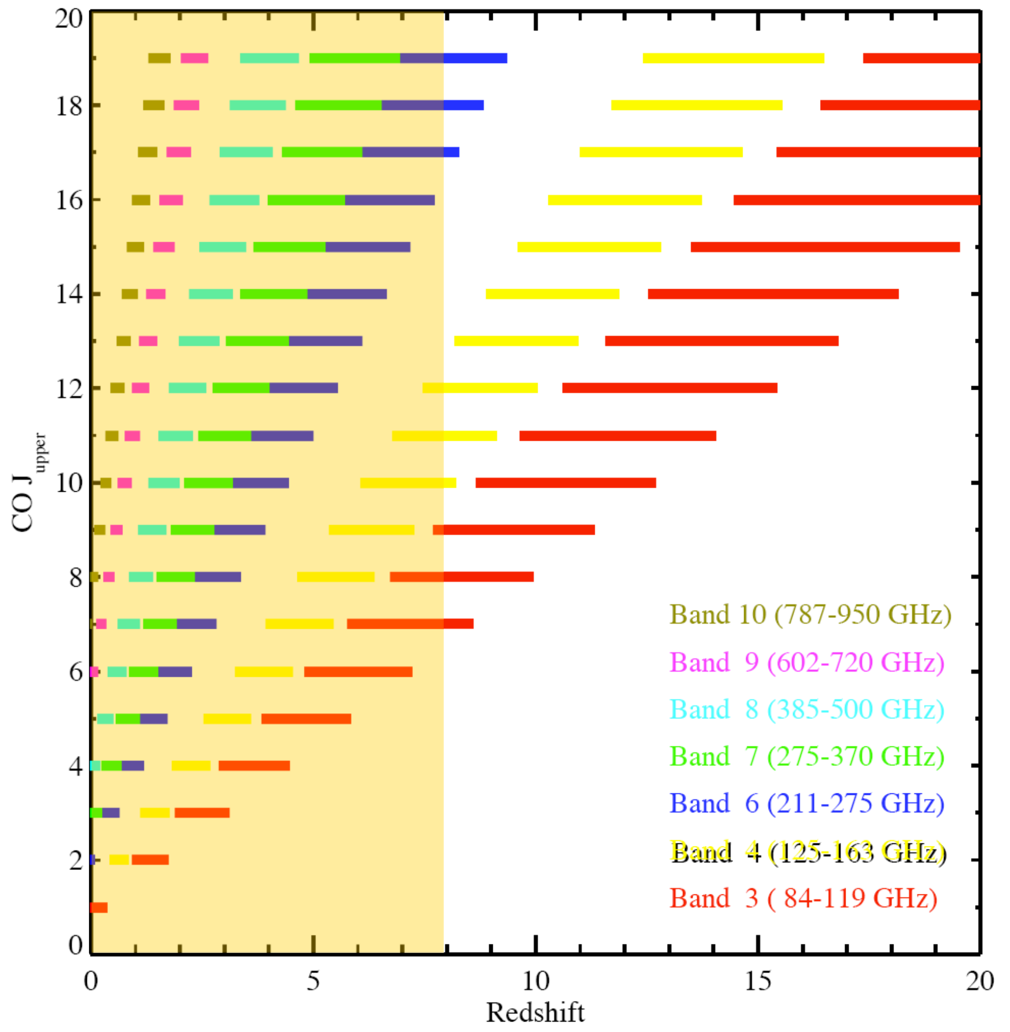
age of sphere:  $10^7$ years, similar formation timescale of BH



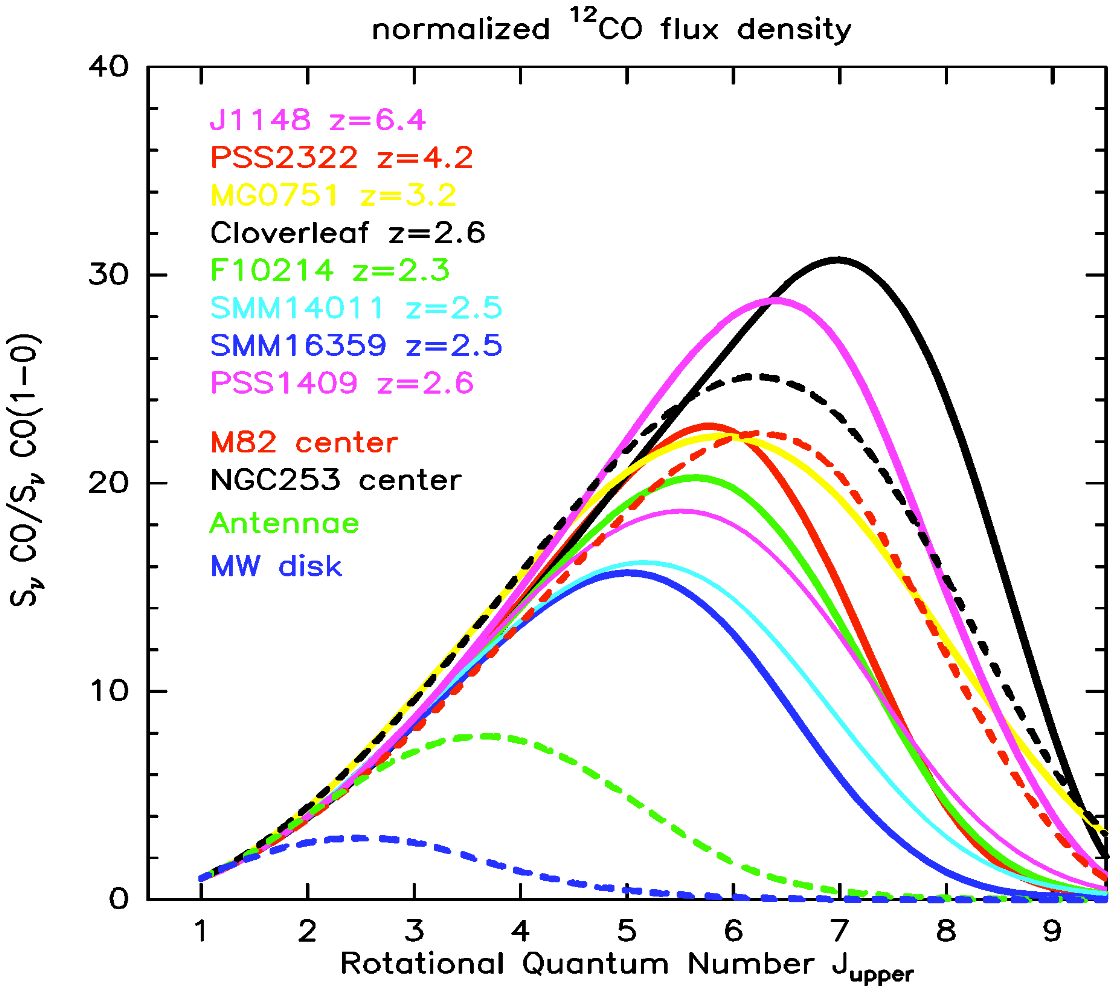
Walter + `03

# z>8 Sources: ALMA CO discovery space

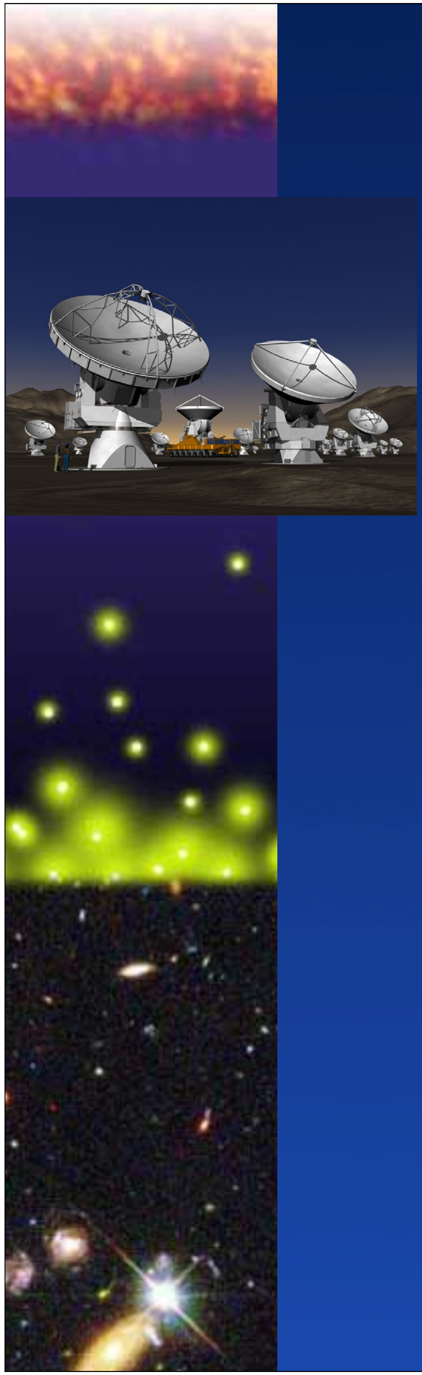


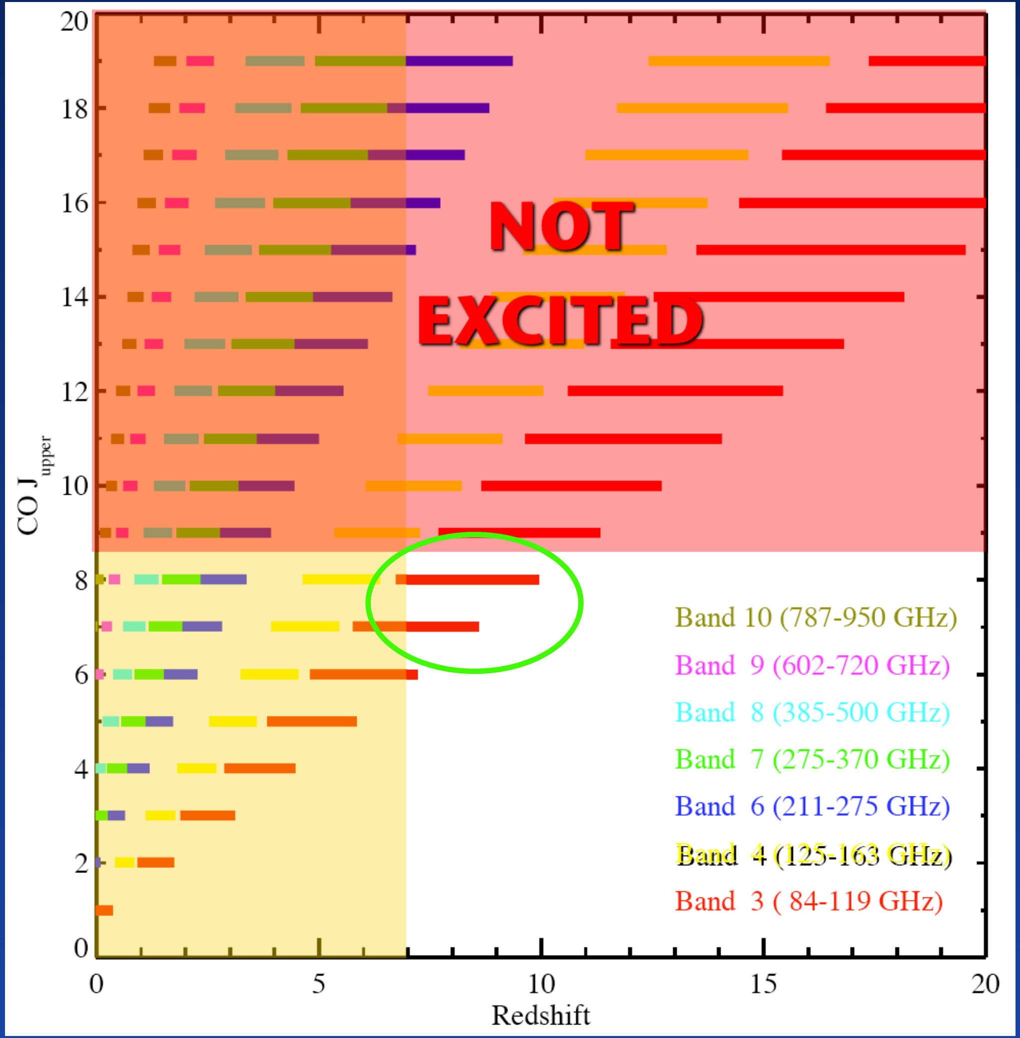


i.e., for z~10, need to observe CO J>8
but is gas actually excited?

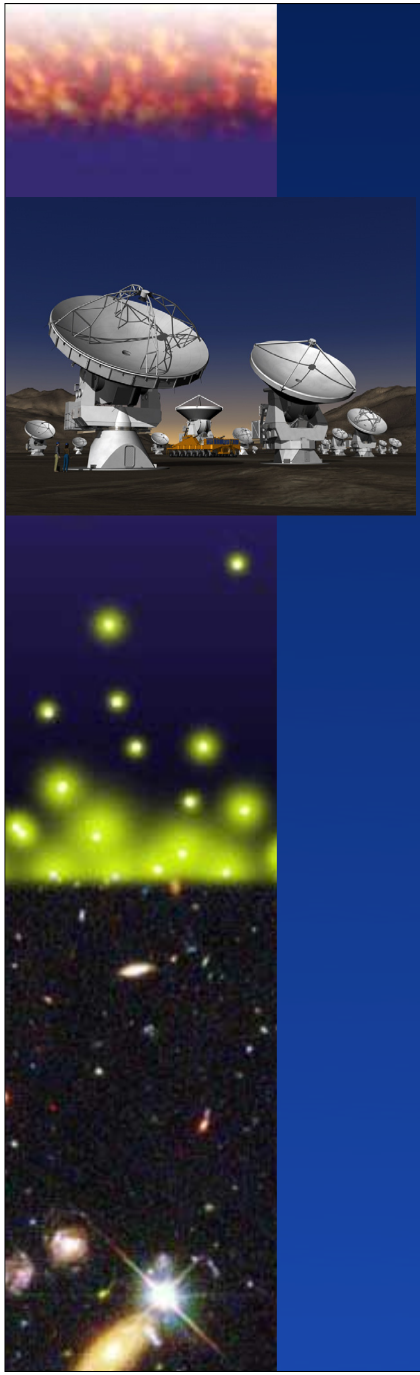

normalized $^{12}$CO flux density
J1148 z=6.4
PSS2322 z=4.2
MG0751 z=3.2
Cloverleaf z=2.6
F10214 z=2.3
SMM14011 z=2.5
SMM16359 z=2.5
PSS1409 z=2.6
M82 center
NGC253 center
Antennae
MW disk
$S_\nu$ CO/$S_\nu$ CO(1–0)
0
10
20
30
40
1
2
3
4
5
6
7
8
9
Rotational Quantum Number $J_{upper}$

# z>7 Sources: ALMA CO discovery space

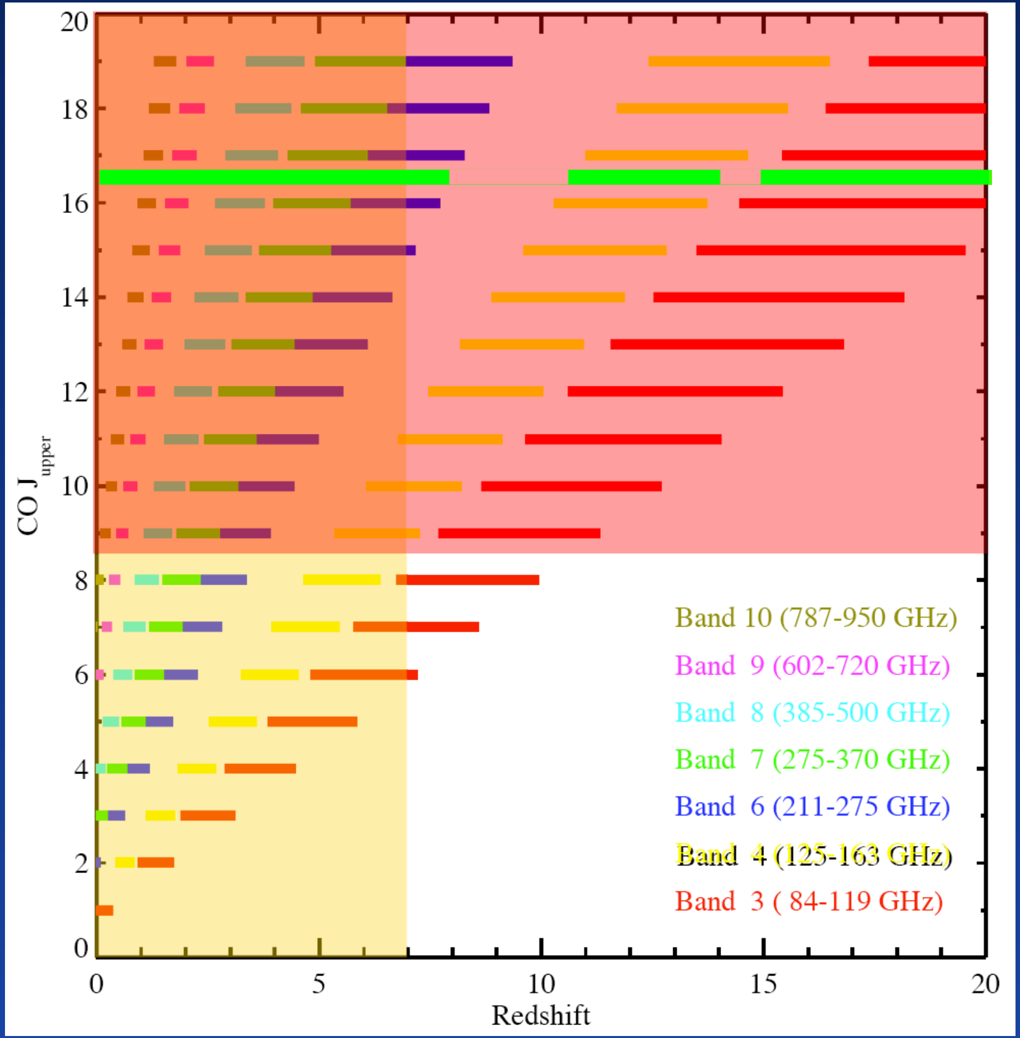




Bummer! ALMA CO discovery space small!

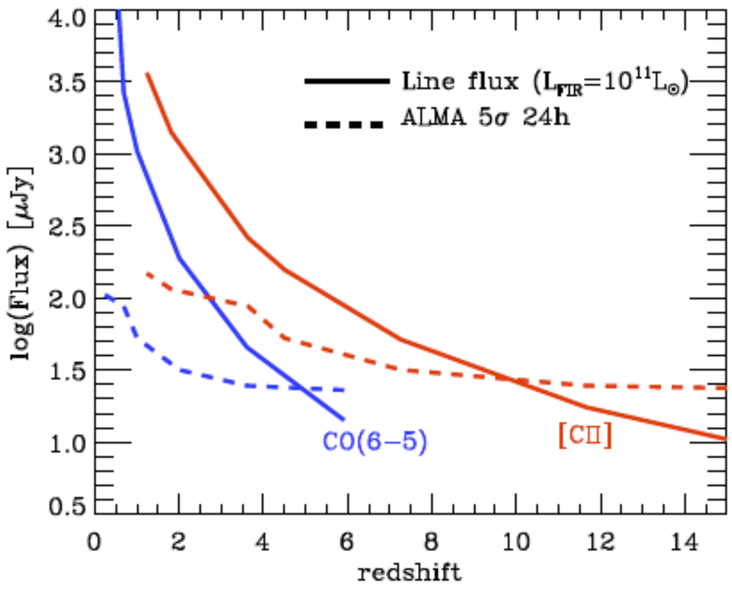


# [CII] line



Bummer! Gap in coverage from z=8-10.5

Need band 5 for many antennas



R. Maiolino

ALMA observations of the [CII] line will play a fundamental role in studying the youngest galaxies in the Epoch of Cosmic Reionization at z>7. Given the expected line strengths it should be possible to resolve these galaxies in the [CII] line emission on kpc scales. Such measurements would not only constrain the sizes but would also help to derive the dynamical masses in these early starforming systems. Given the typical CO excitation in starforming galaxies (i.e. drop in excitation around the J∼6 transitions), ALMA will likely act as a [CII]– rather than a CO–machine for objects at these extreme redshifts.

# Resolution is Key

goal: resolve CO emission spatially/kinematically
compare to optical/NIR spectral imaging
dynamical masses!

1” ~ 7.5kpc [8.5 kpc @ z=2, 5.8 kpc @ z=6]

➡ need ~0.15” resolution to get 1 kpc resolution

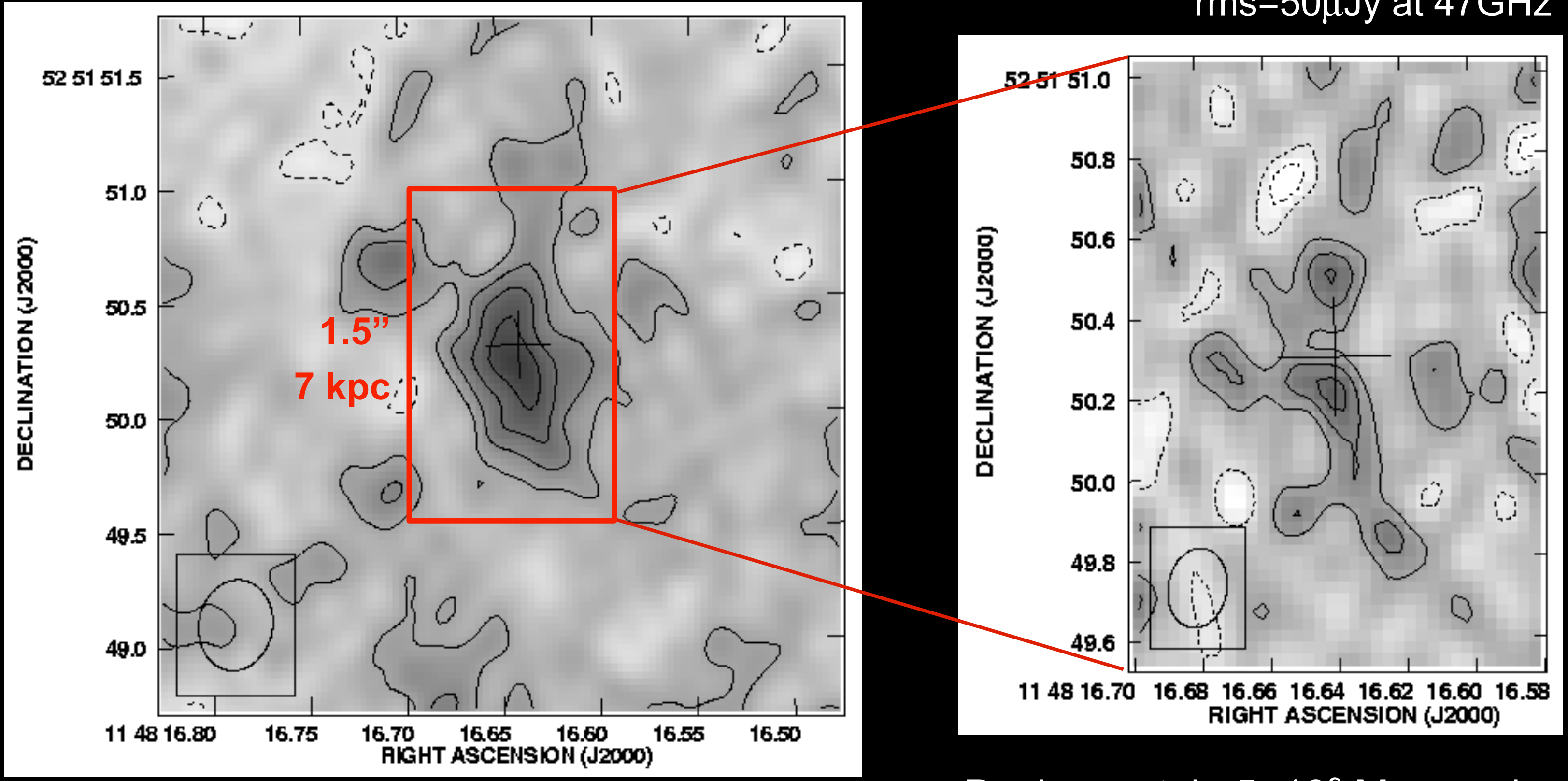
z=6.5 CO(7–6): 100 GHz (band 3): 4 km baselines
z=2.5 CO(3–2): 100 GHz (band 3): 4 km baselines
CO(6–5): 230 GHz (band 6): 1.8 km baselines

➡ high–res (0.15”) CO studies at high z need long baselines

currently only doable with VLA!

# Resolved CO(3-2) at redshift 6.42

rms=50µJy at 47GHz



Half of emission extended.

Stretch to NW: tidal feature ?

$T_B$ = 3 K = Milky Way

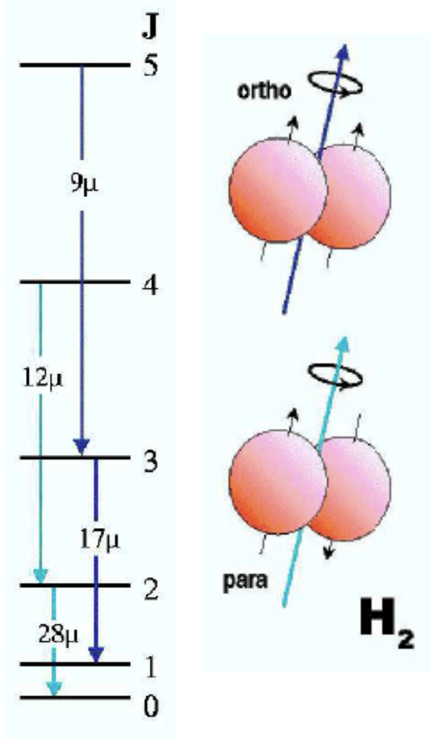
Peaks contain $5\times10^9$ $M_{sun}$ each

Separation = 0.3” = 1.7 kpc

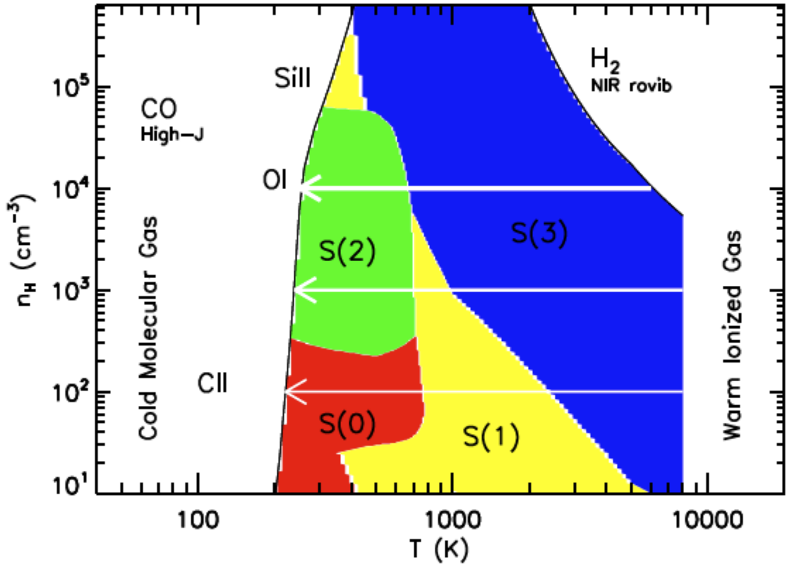
$T_B$ = 20K = $T_B$ (starburst)

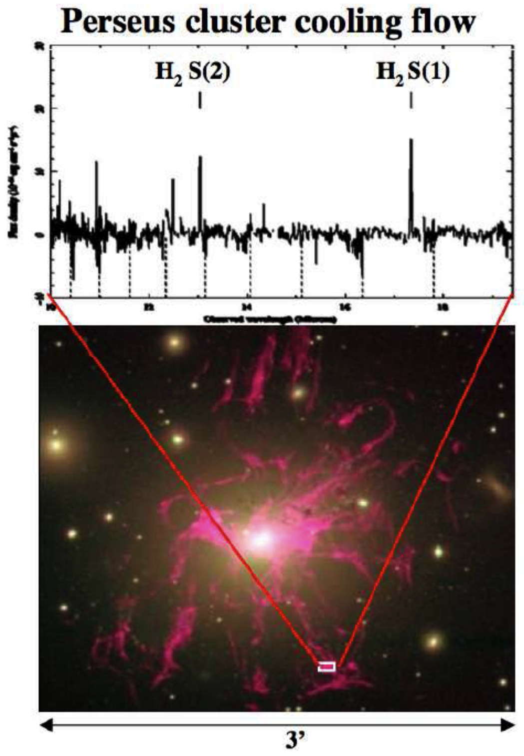
Merging galaxies or dissociation by QSO?

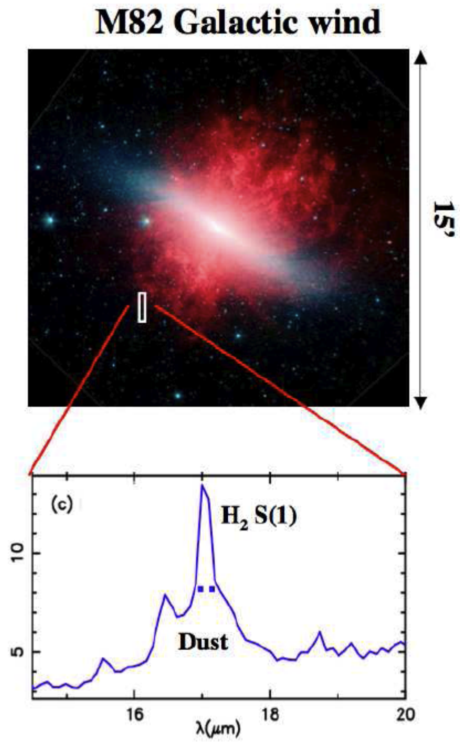
Walter, Carilli, Bertoldi, et al. 2004



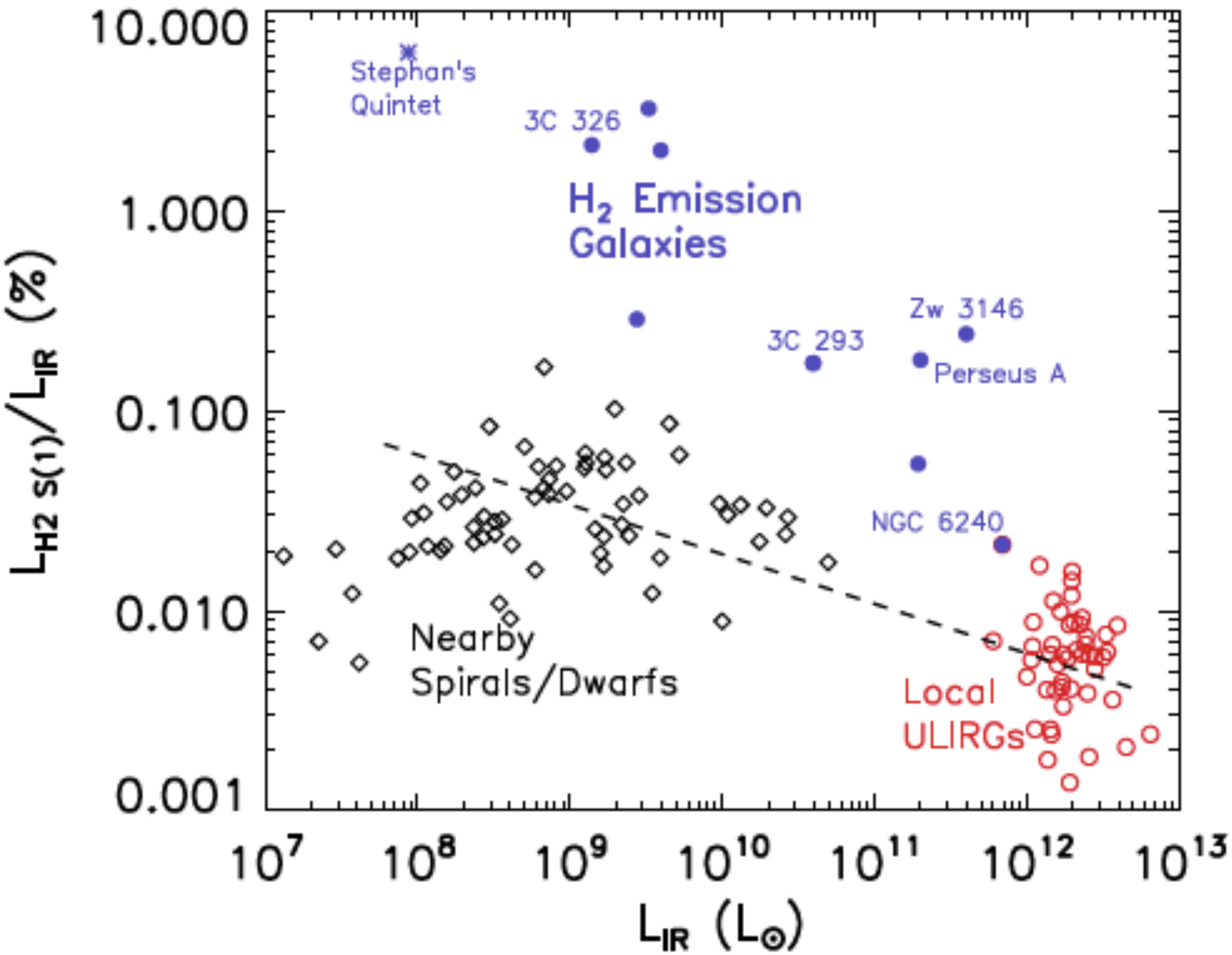
Boulanger et al. 2008







- $H_2$ prominent coolant in transition regions
- star forming region PDRs
- intergalactic medium
- Early Universe


Stephan's Quintet
3C 326
$H_2$ Emission Galaxies
Zw 3146
3C 293
Perseus A
NGC 6240
Nearby Spirals/Dwarfs
Local ULIRGs
$L_{H2\,S(1)}/L_{IR}$ (%)
$L_{IR}$ ($L_\odot$)
10.000
1.000
0.100
0.010
0.001
$10^7$
$10^8$
$10^9$
$10^{10}$
$10^{11}$
$10^{12}$
$10^{13}$

# $H_2$ with ALMA Band 10,11

0-0 S(0) 28.2 $\mu$m, 10.1239 GHz

z= 5.5-6.0,  6.3-7.1

0-0 S(1) 17.0 $\mu$m, 17.5988 THz

z= 10.2-11.2

Here 0-0 S(0) at 831-903 GHz

(Band 10:  787-950 GHz)

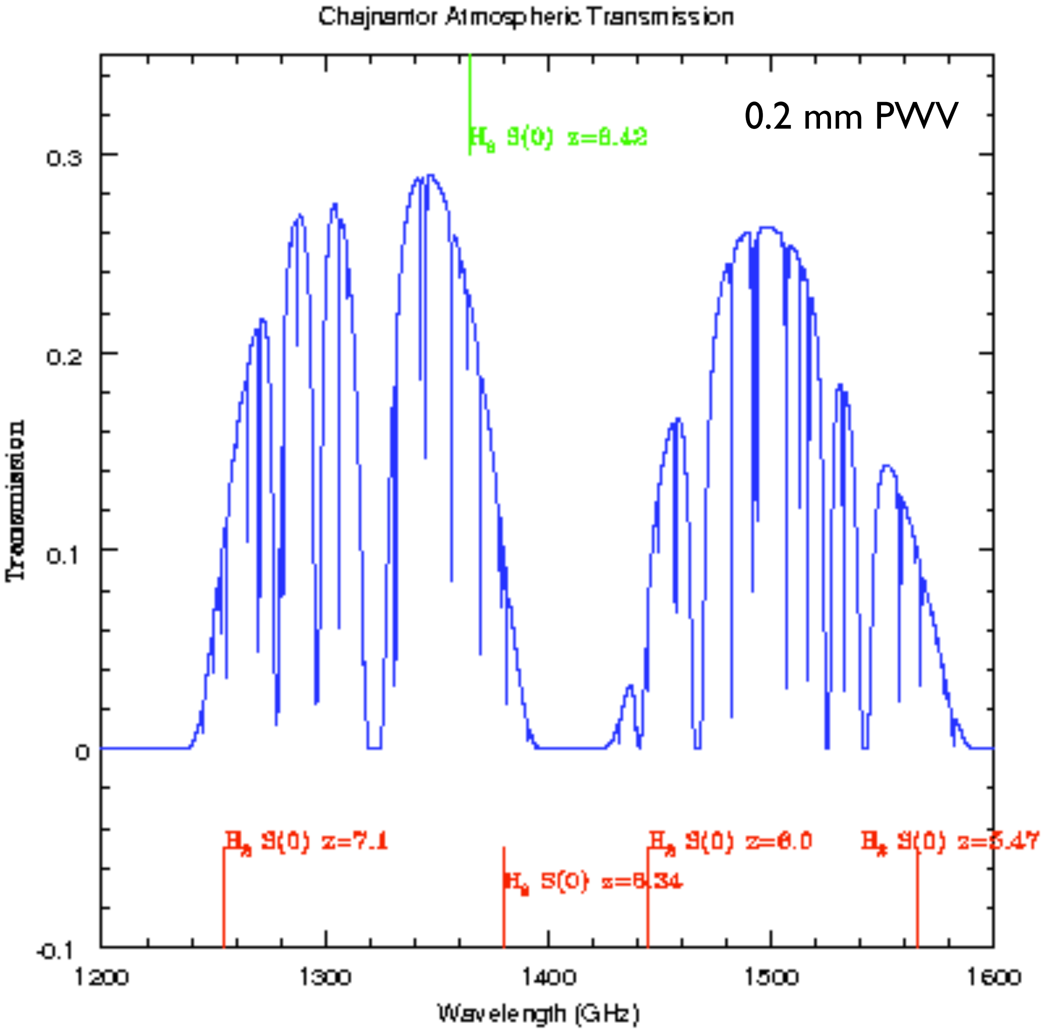
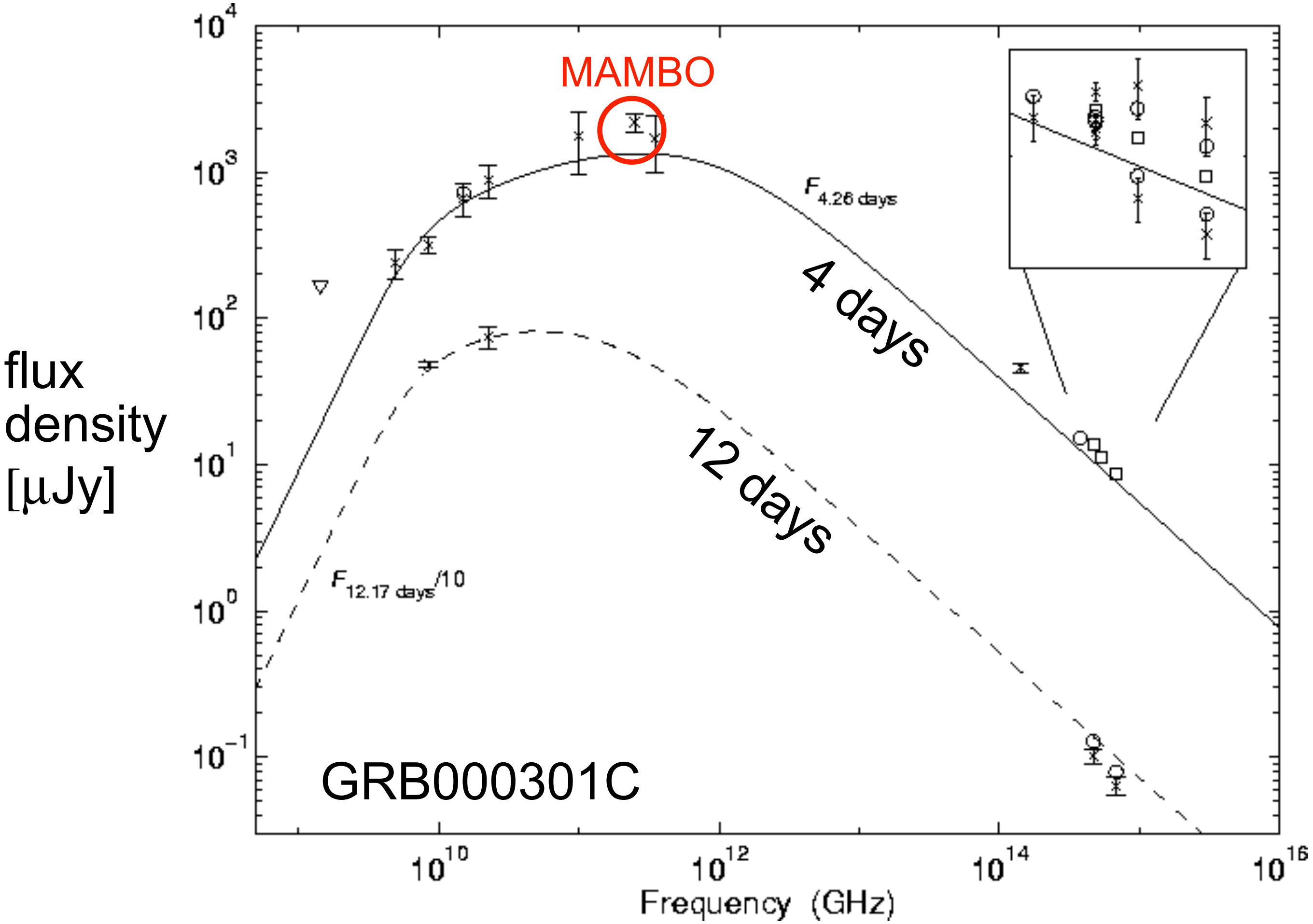


Figure from Al Wooten

# Gamma Ray Burst Afterglows

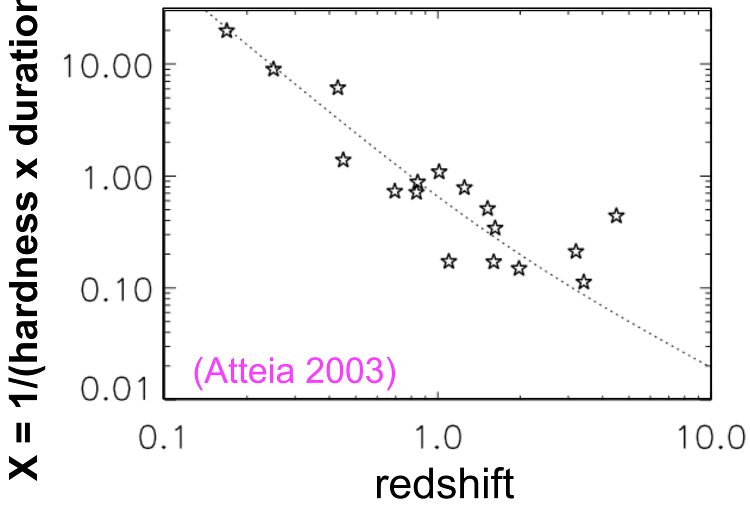
Yet only a hand full of mm detections, from GRB 991208 to 090313



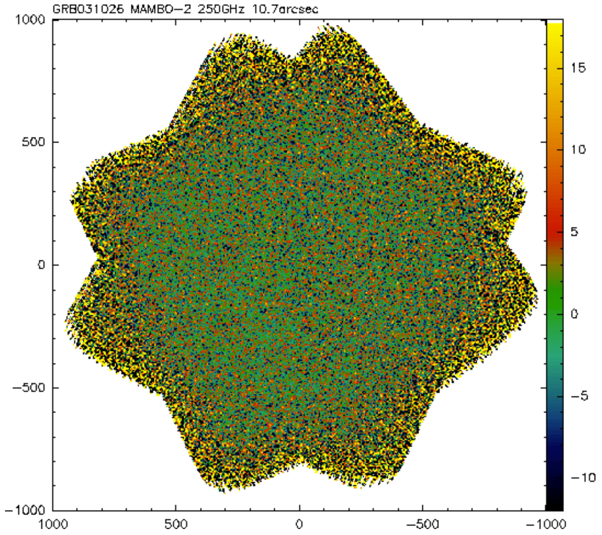
# GRBs in EoR

Possibly half of all GRB at z>5 !
But afterglow would not show in the optical due to Ly-forest, so try in mm or X-ray.

Empirical correlation

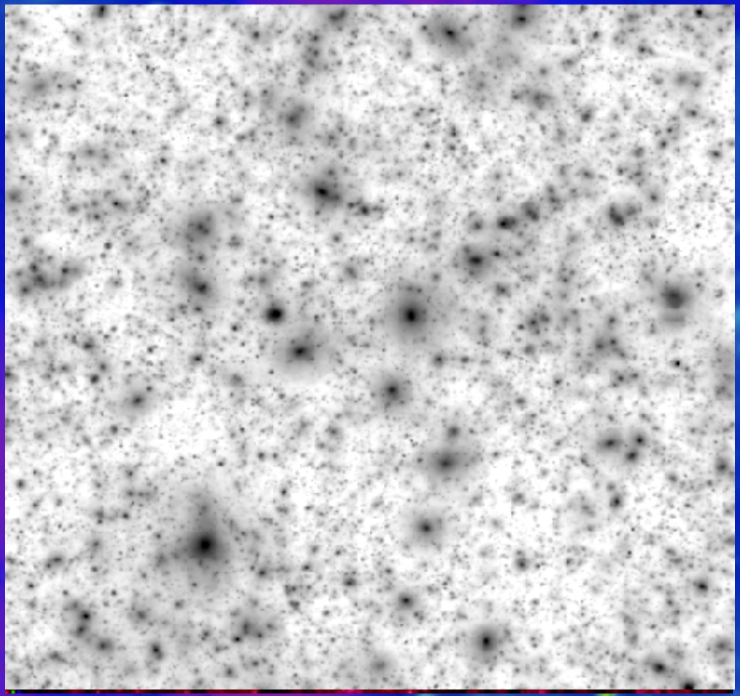


(Atteia 2003)

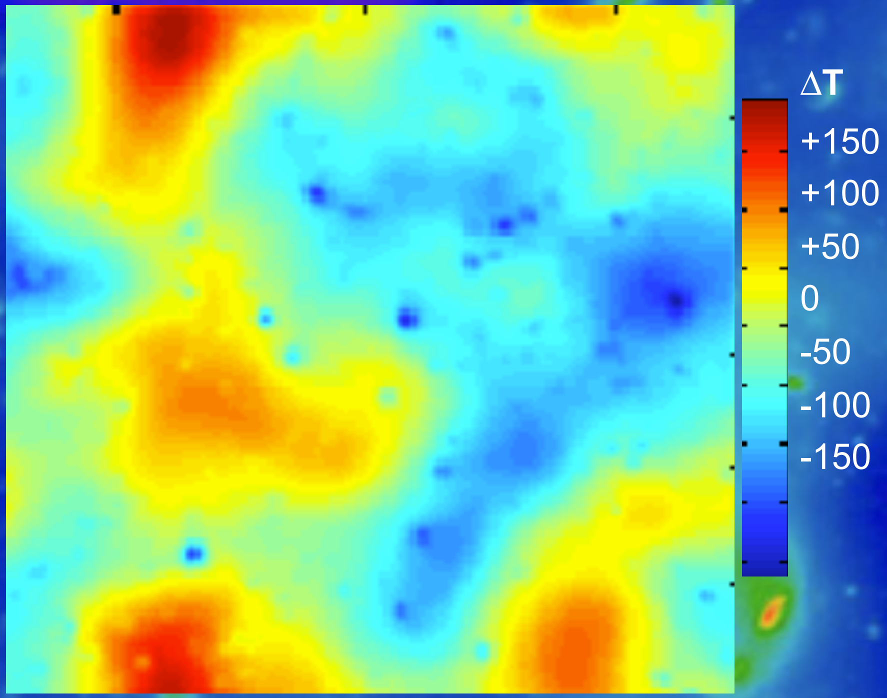


GRB 031026: a dark GRB at z=14 ?
MAMBO 5 mJy rms over 300 arcmin$^2$ in 4 h

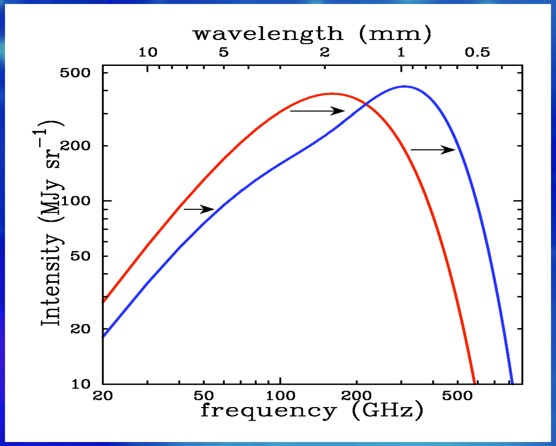
## SZ Effect

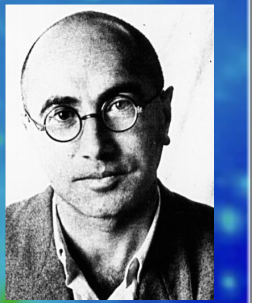


## SZ plus CMB
@1’ resolution



Simulations by M. White





# Sunyaev-Zel’dovich Effect

First detection with Ryle telescope (Jones 1992)
Now >100 clusters with BIMA, OVRO, IRAM, JCMT
APEX, ACBAR, CSO, SPT, ...

Detection depends on mass, independent of z.

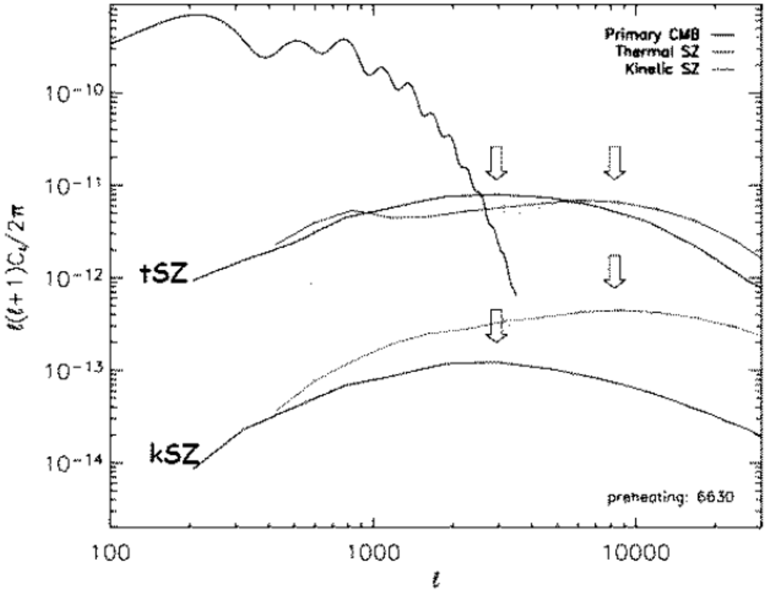
ALMA not a survey instrument but will be able to:

- map high-z clusters
- detect rotation
- cluster based Hubble diagram: Dark Energy e.o.s. w(z)
- From counts(z): $\Omega_m$ , $\sigma_8$
- $T_{CMB}$(z)

Cluster physics:

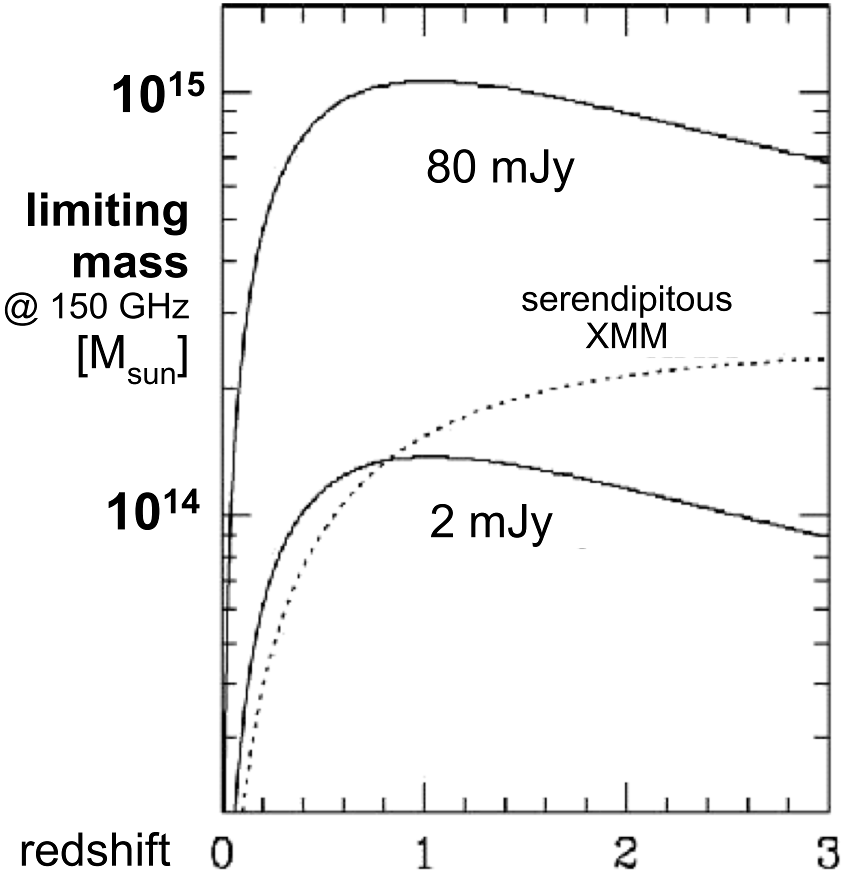
- map hot gas: shocks, cooling lows, cold fronts, $T_e$,
- determine radial velocity through kSZ
- baryon fraction,
- M-T relation

Anisotropy power as function of scale



Detection depends on mass, independent of z

# Limiting Mass of SZE Surveys



well understood selection function

$$D_a^{-2} \propto (1+z)^4/z^2$$
$$T \propto (1+z)$$

**study**:

growth of structure

individual clusters

# ALMA is not a survey instrument

## leave that to other single dish telescopes:

APEX-SZ

Atacama Cosmology Telescope

South Pole Telescope

- Discovery of hundreds of galaxy clusters by mapping 100 to 4000 sqd to ~50 μK detection limit.
- constrain cosmological parameters, e.g. $\sigma_8$ and Dark Energy parameter w.
- study development of galaxy clusters and galaxies in clusters.
- Study CMB secondary anisotropies, Ostriker-Vishniac effect, quadratic Doppler effect, high-z SNR, patchy reionization, etc.

Ostriker-Vishniak (1986) effect:
probes 10kpc ionized clouds velocity in e.o.r.
arcsec scale anisotropy 30 $\mu$K

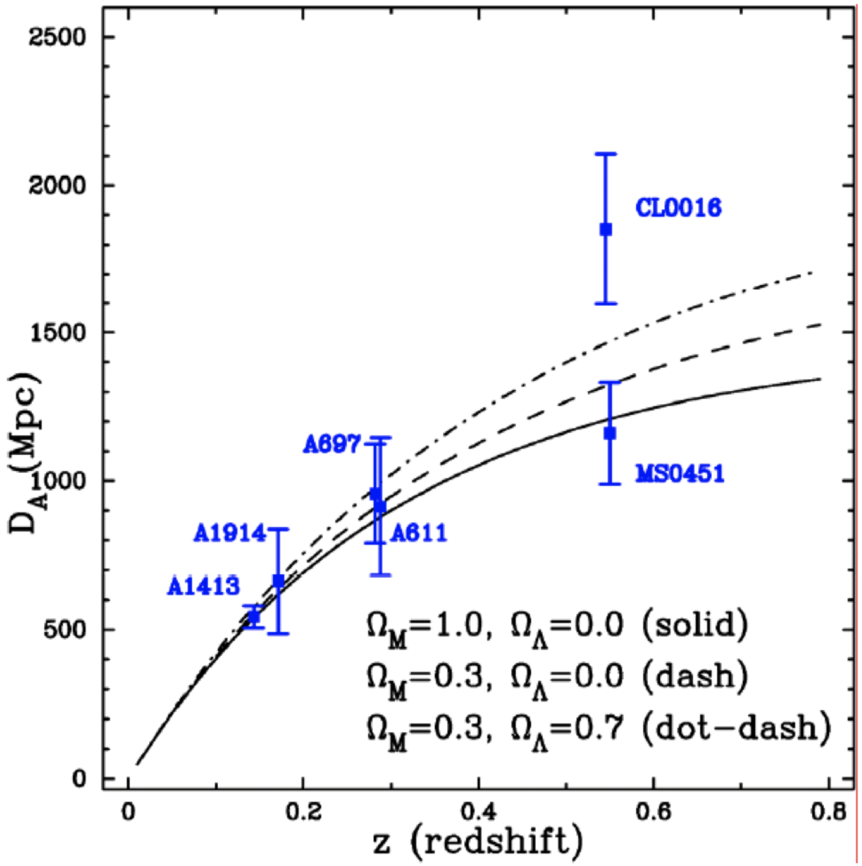
# Current Cluster Radio Detections

- About 100 cluster detections
  - high significance (> $10\sigma$) detections
  - multi-telescope confirmations
  - interferometer maps, structures usually from X-rays, more recent from APEX
- Spectral measurements still rudimentary
  - no kinematic effect detections
- Commencing blind surveys
  - SPT first confirmed detections Staniszewski et al. 2009

## By ALMA Early Science (Mark Birkinshaw, Orsay 2005)

- About 1000 cluster radio detections
  - Most from Planck: low-*z* *(also X-ray & optical)*
  - 10% from high-resolution SZ surveys (SPT, ACT ...)
- About 100 images with > 100 resolution elements
  - Mostly interferometric, tailored arrays, 10 arcsec FWHM
  - Some bolometric maps, 15 arcsec FWHM
- About 50 integrated spectral measurements
  - Still confusion limited
  - Still problems with absolute calibration

# cluster based Hubble diagram: Dark Energy e.o.s. w(z)

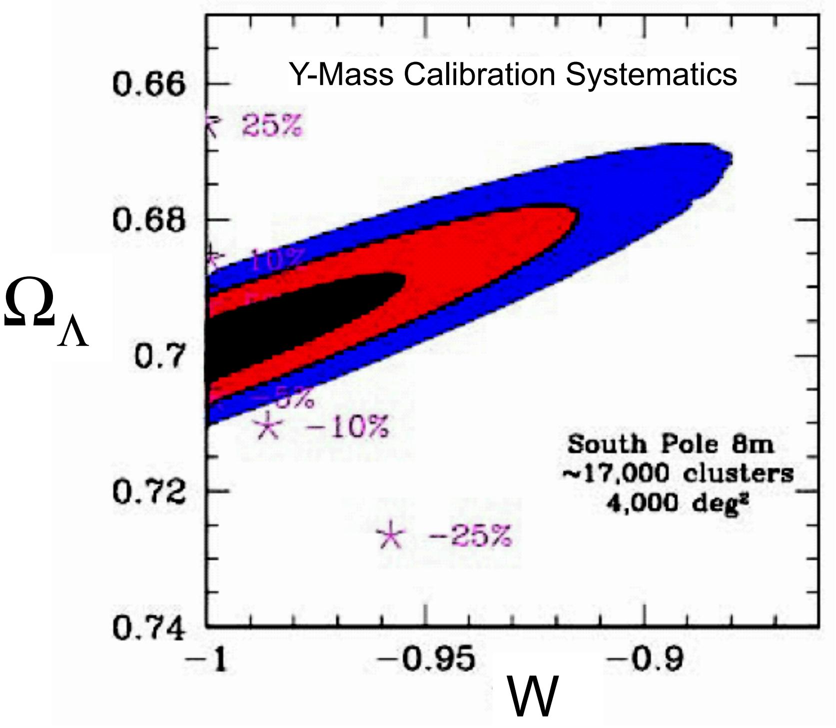


# For Cosmology, first resolve systematic mass bias

Controlling systematic errors on mass is prime concern !

Need multi-wavelength follow-up.

Figure by Joe Mohr



# Problem of Mass-Observable Relation

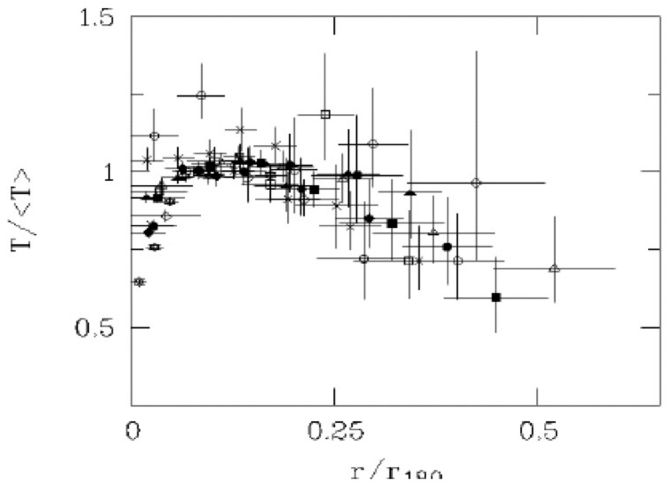
unresolved SZ / X obs. yield total Comptonization / luminosity, and with a mean spectroscopic $T_{gas}$ → gas mass, entropy.

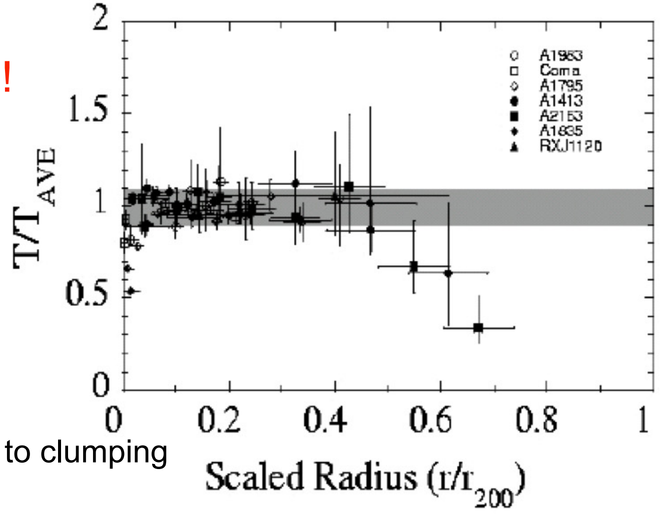
Problems:

- ✦ **gas not isothermal**: unclear what „mean“ temperature means: rely on simulations
- ✦ clusters have **no clear boundaries**, dep. on accretion shock. No clear total flux.
- ✦ **Non-gravitational physics**: AGN, SF, cooling, shocks

Require resolved observations, at least of subsample!

De Grandi & Molendi, ApJ 567 (2002) 1



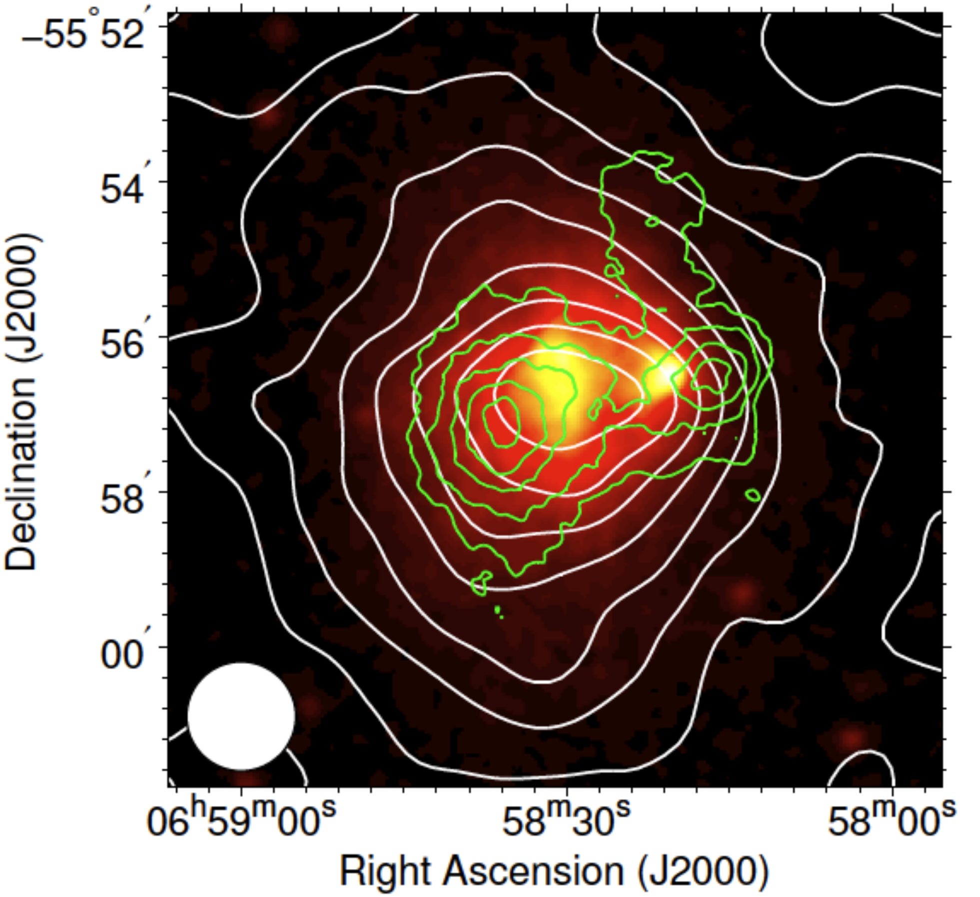


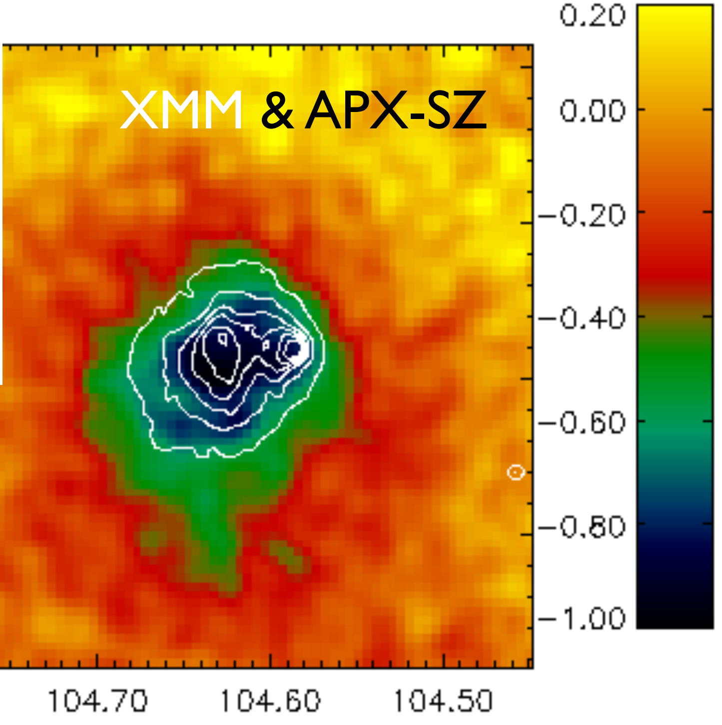
Arnaud et al, astro-ph/0312398

Deprojection: SZ (nT) sensitive on heating/cooling, X($n^2T^{1/2}$) sensitive to clumping

# Bullet Cluster

Halverson et al. 2009



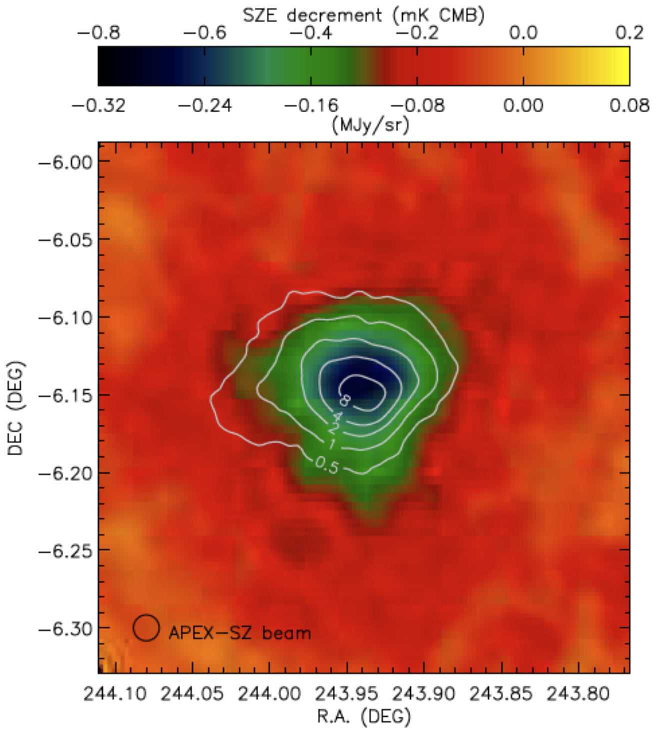


The SZE map in white contours, overlaid on an X-ray map from XMM observations. Green contours show the weak lensing surface mass density reconstruction from Clowe et al. (2006). The SZE contour interval is 100 $\mu K_{CMB}$.

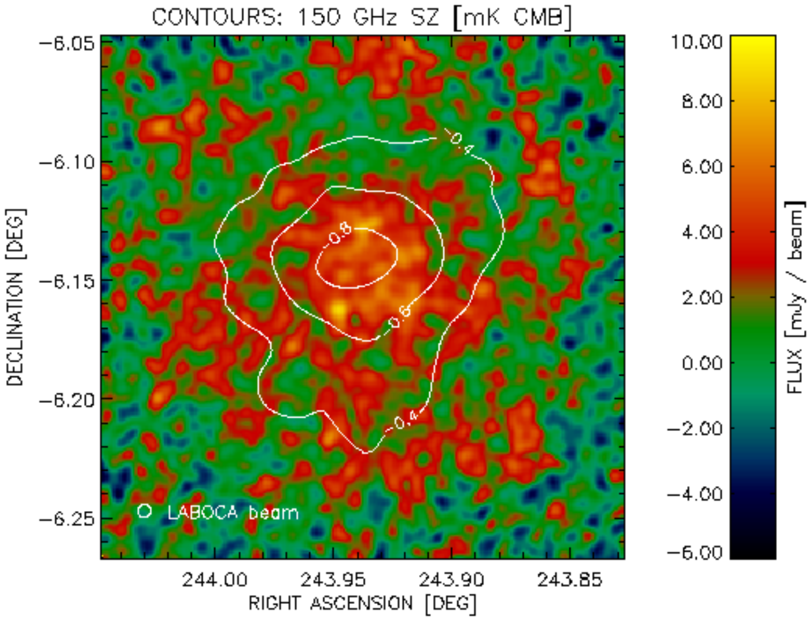
# APEX resolved cluster observations

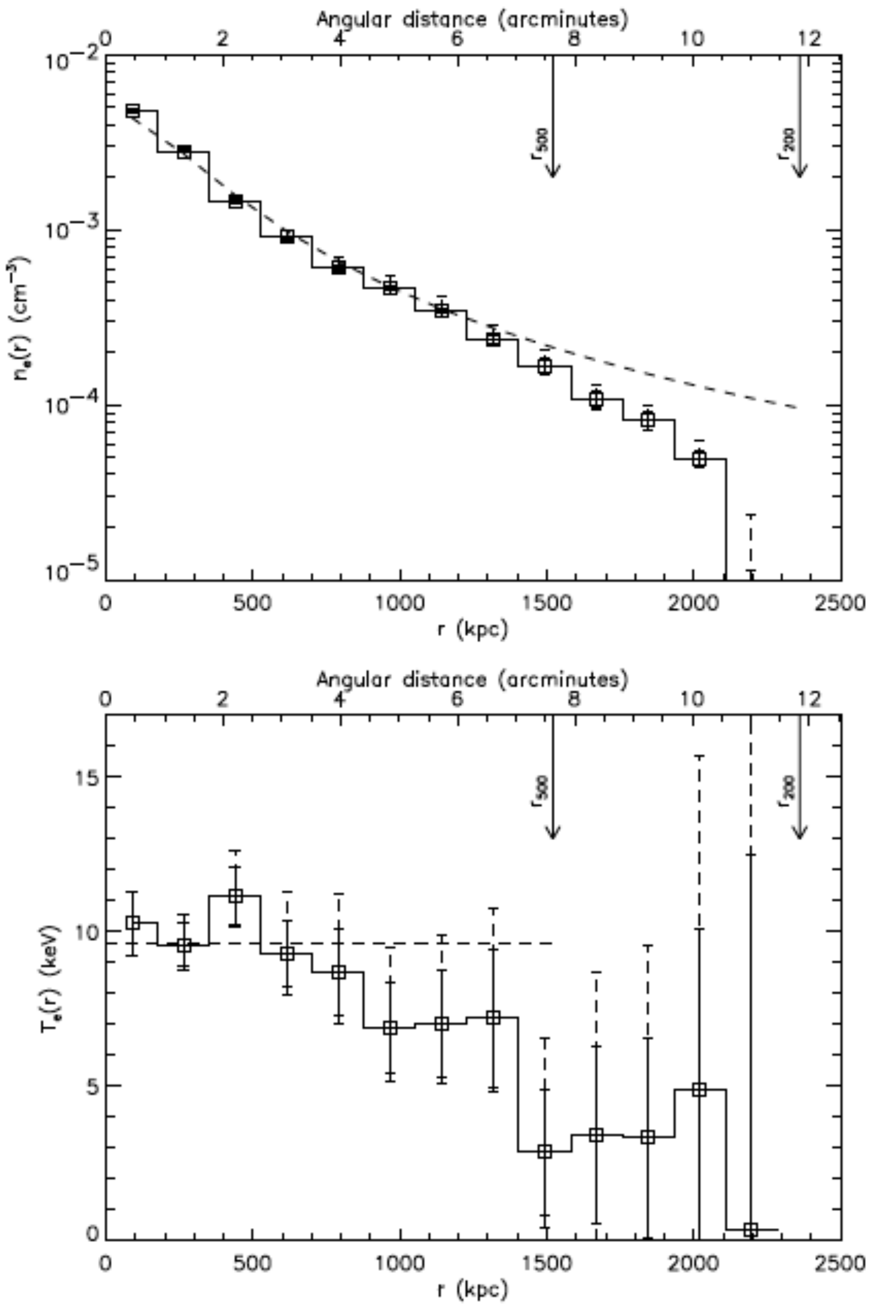
Abell 2164 (Nord et al. astro-ph)

APEX-SZ 150GHz @1', contours: XMM

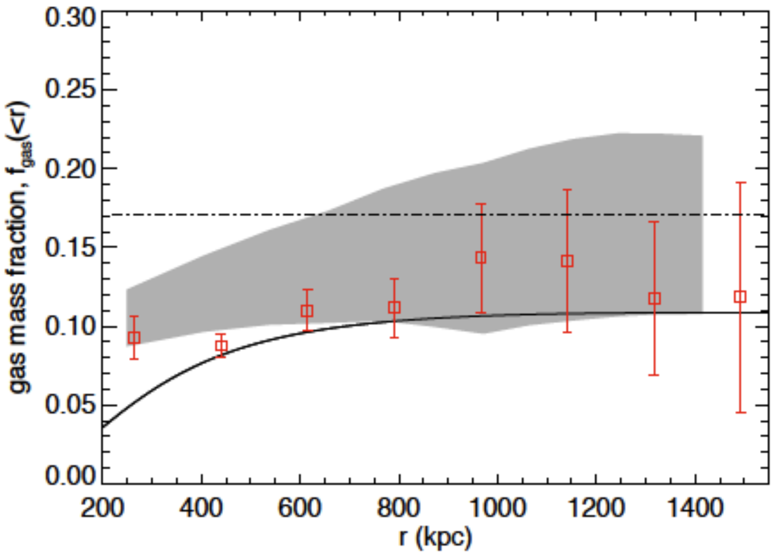


LABOCA 350GHz @20", contour 150GHz





De-projected density & temperature profiles



**Gas mass fraction** measurement from APEX-SZ data. The solid line is the result of isothermal beta-fit, the red points from non-parametric deprojection. The horizontal dot-dashed line represents the cosmic baryon fraction from WMAP 5-yr data.

# Relativistic Temperatures

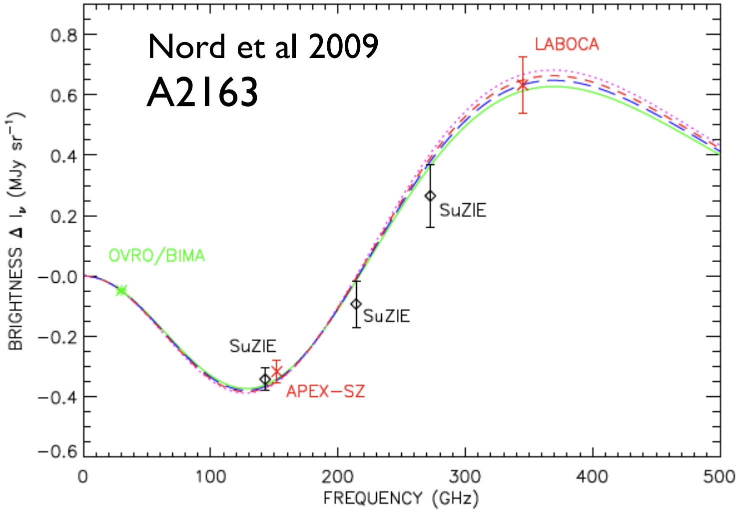
(Rephaeli, 1995; Challinor & Lasenby 1998; Sazonov & Sunyaev, 1998; Itoh et al., 1998)

→ corrections to the lowest order signals

→ especially important at high frequencies

→ 10-20% deviations

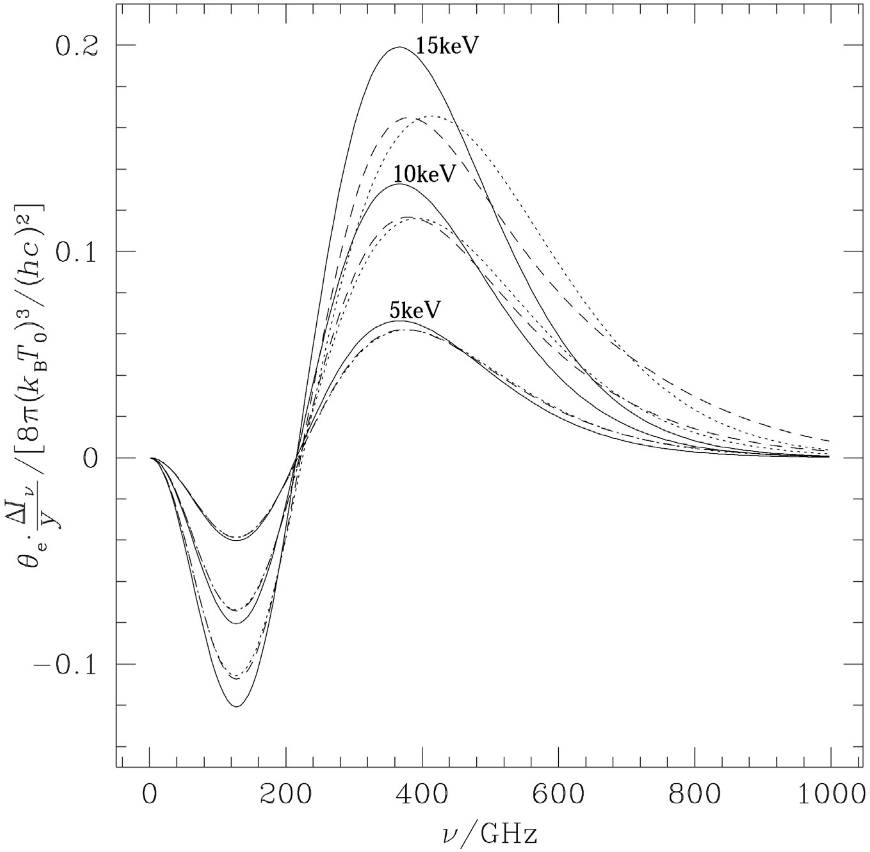
→ possiblility to measure the electron temperature
only with the CMB (strong frequency dependence)



Nord et al 2009

A2163

**Fig. 9.** SZE spectrum of Abell 2163 (points) and best-fit models using different priors on the ICM temperature: 8 keV (solid line), 10 keV (long-dashed line), 12 keV (short-dashed line) and 14 keV (dotted line).

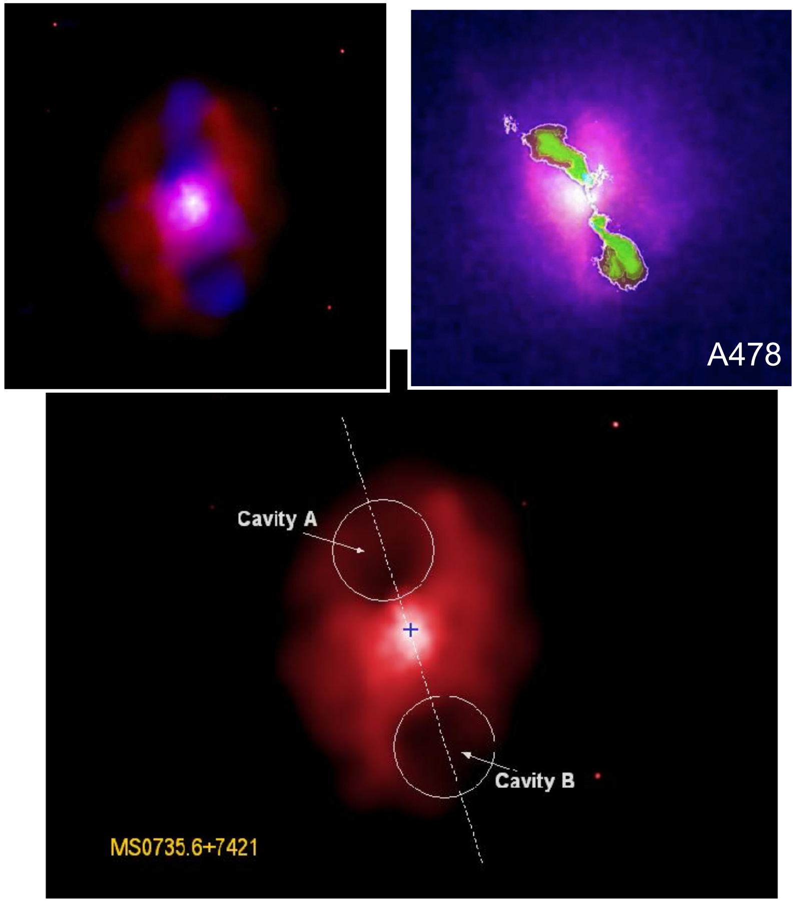


# Interesting physics: AGN-driven bubbles

Relativistic particles create there own type of SZ signal.
Radio bubbles filled with relativistic particles “contaminate” the SZ signal even when their synchrotron radio emission is too weak at lower wavelength to be detectable.

Interesting in its own right:
what provides pressure?
Jet driving agent: hadronic, leptonic?

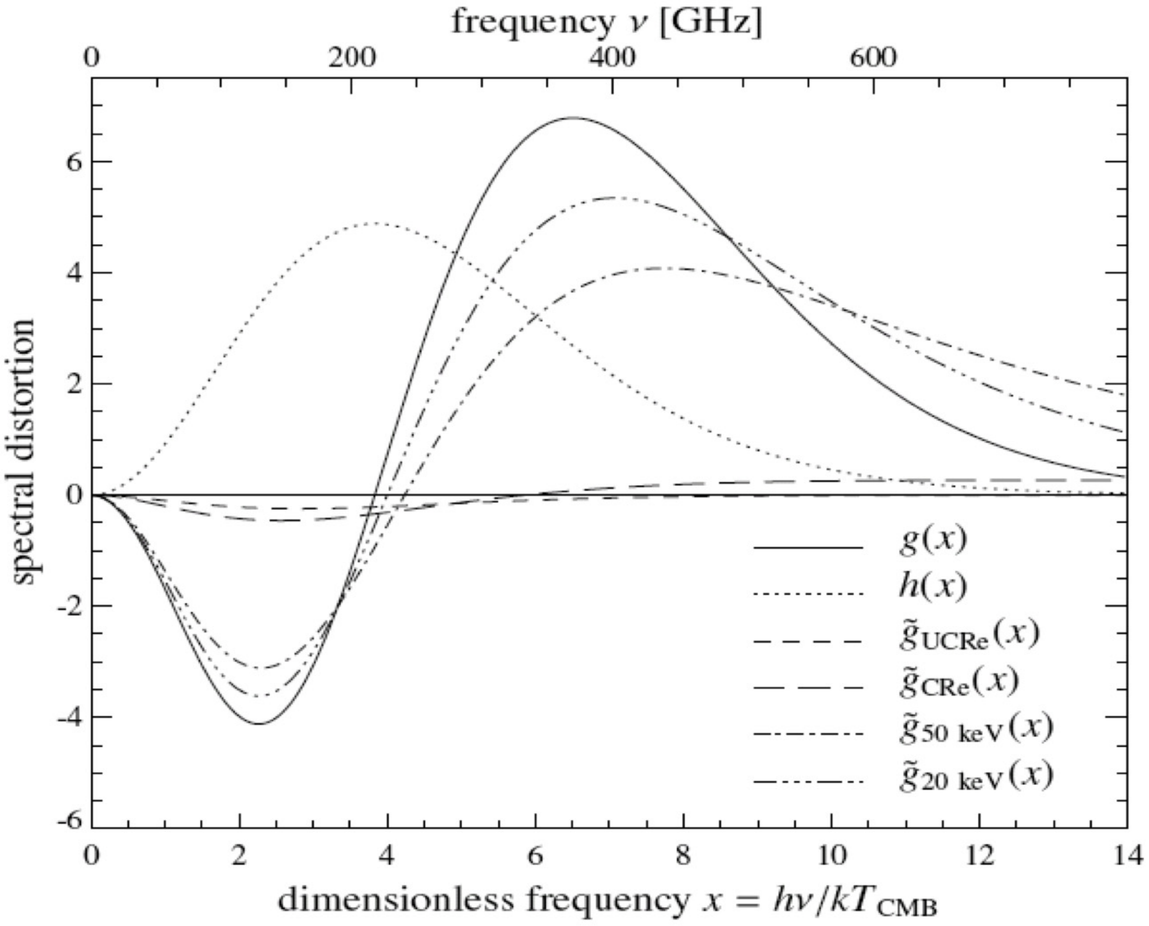
Hot dilute gas does not emit X-rays.
SZ observations measure $P_e$



Chandra image of a cluster with radio cavities filled by synchrotron emission, probably originating from central AGN outburst (Colafrancesco et al. 2005).

# AGN-driven bubbles: effect on SZ spectrum

Relativisitic e p B
vs. thermal e
???

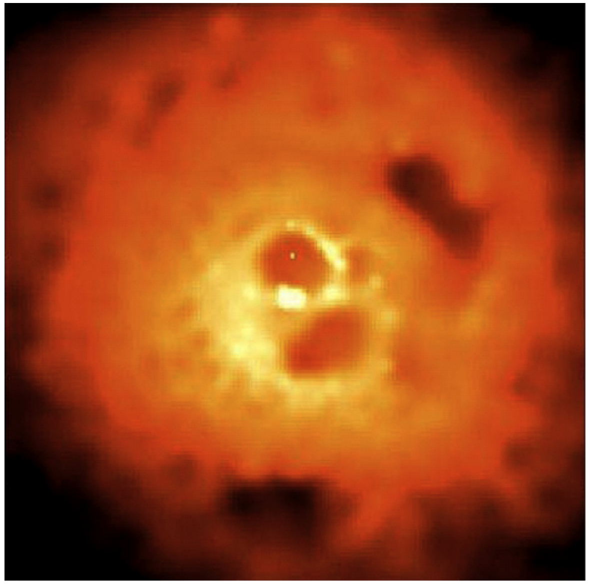


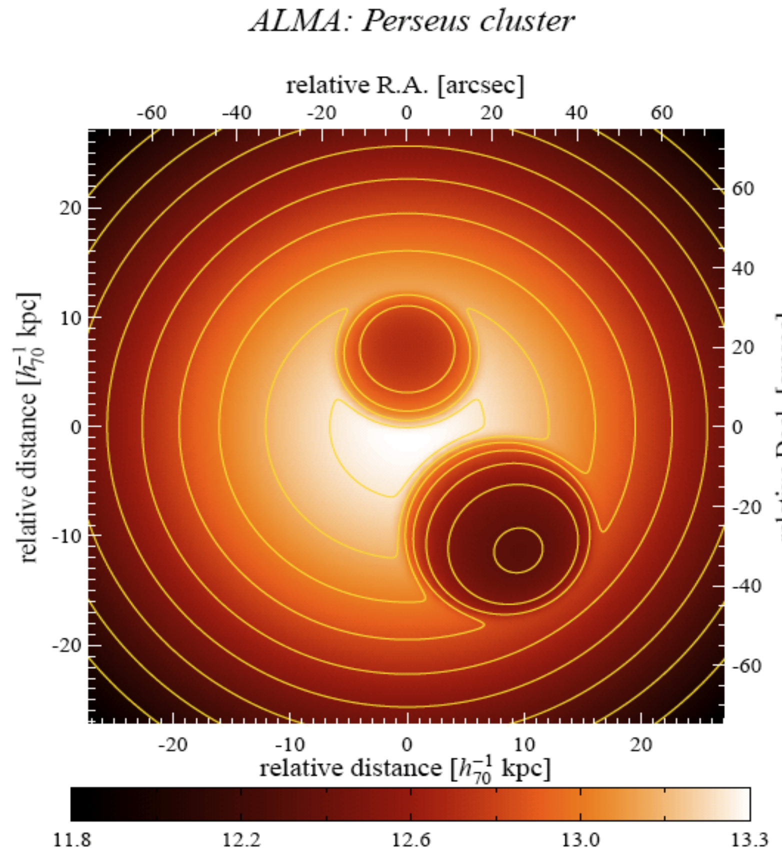
**Predicted SZ spectrum for several models of bubble gas**

Blue line: (invisible) thermal SZ from hot gas.
Black lines: emission of bubble for different parameters (cut-off on relativistic particla momentum).
Red lines: corresponding total.

In extreme case, strong, detectable non-thermal emission.
At 220 GHz (SZ zero point) only bubbles appear in the images.

# Imaging Bubbles with ALMA





ALMA band 4 (144GHz):
FoV 36´´, FWHM 3´´

| Telescope: cluster | $I_A$ [mJy amin$^{-2}$] | $I_B$ [mJy amin$^{-2}$] | exposure [hours] |
|---|---|---|---|
| ALMA: Perseus | 13.25 | 12.70 | 5.1 |
| ALMA: Abell 2052 | 3.930 | 3.698 | 38 |
| GBT: Perseus | 11.31 | 10.85 | 2.1 |
| GBT: Abell 2052 | 3.272 | 3.138 | 31 |

# Large & small scale motion of the ICM

- Mergers in the cosmological context

should excite large & small scale motion of the ICM !

(off-axis mergers)

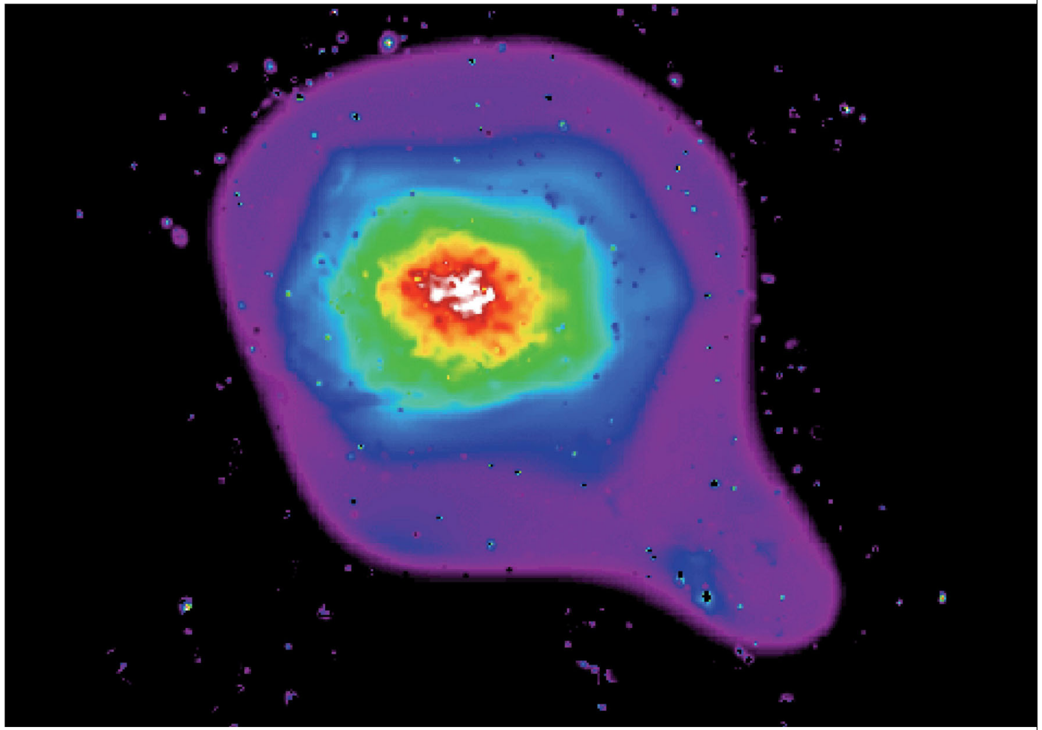
- Coma Cluster (XMM)

(Schuecker et al., 2004)

→ turbulent motions on scales ~20-145 kpc (2“ at z=1) (core radius 420 kpc)

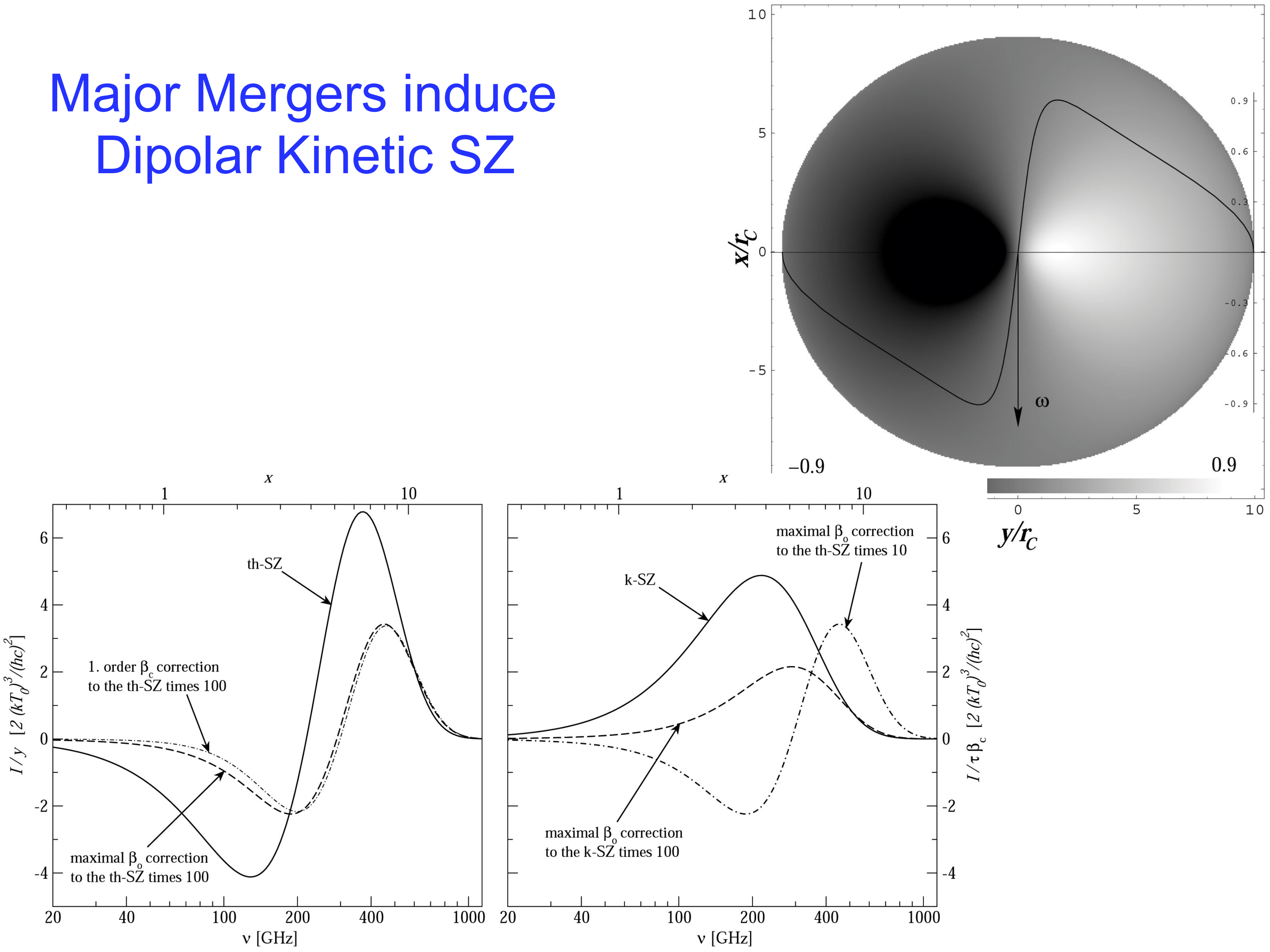
→ turbulence on larger scales is possible!

- Turbulent cascades
  - from large to small scales
  - viscosity
  - plasma instabilities
  - magnetic fields
  - transition between k-SZ & th-SZ



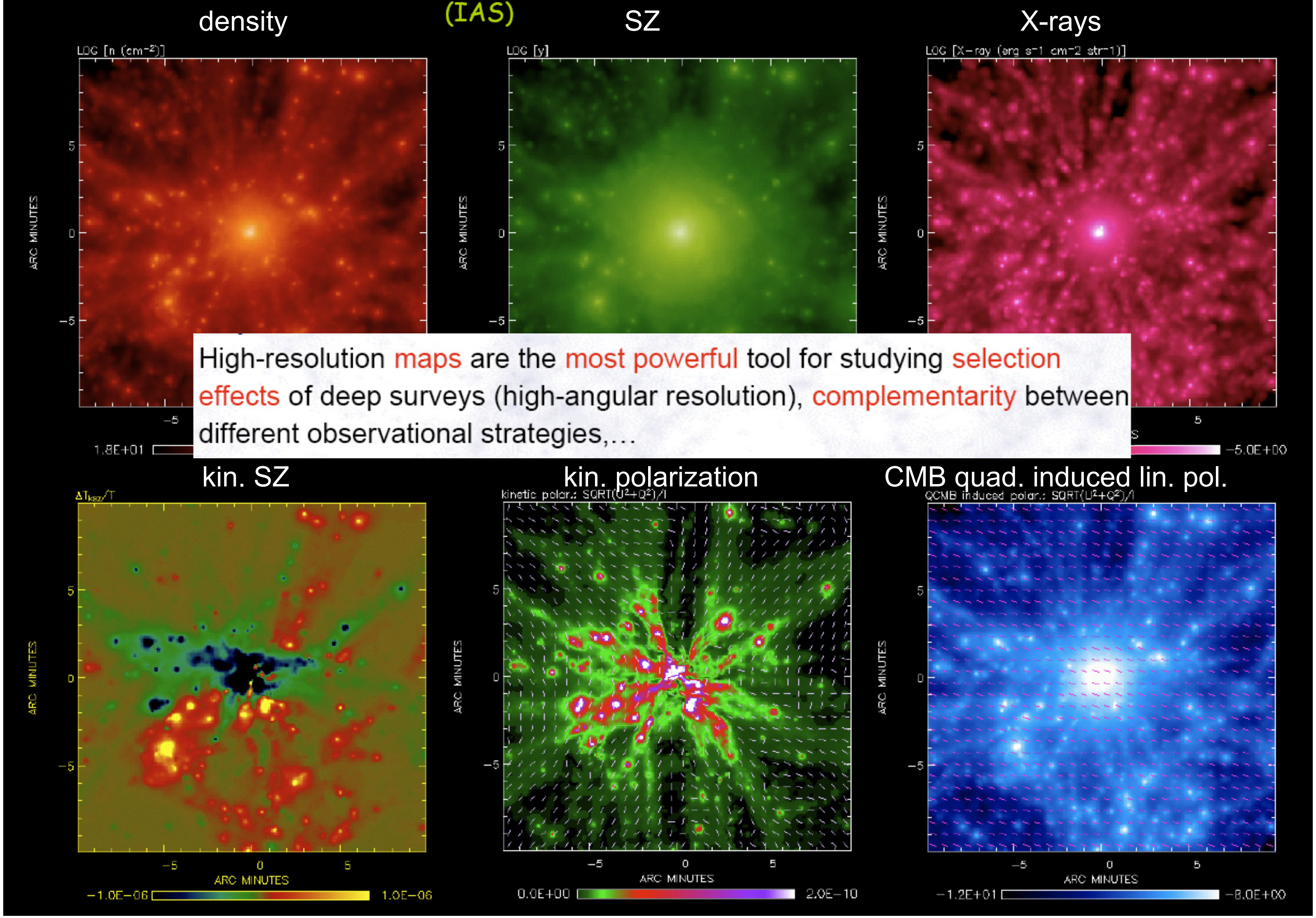
Schuecker et al., 2004

# Major Mergers induce Dipolar Kinetic SZ



Antonio da Silva

(IAS)

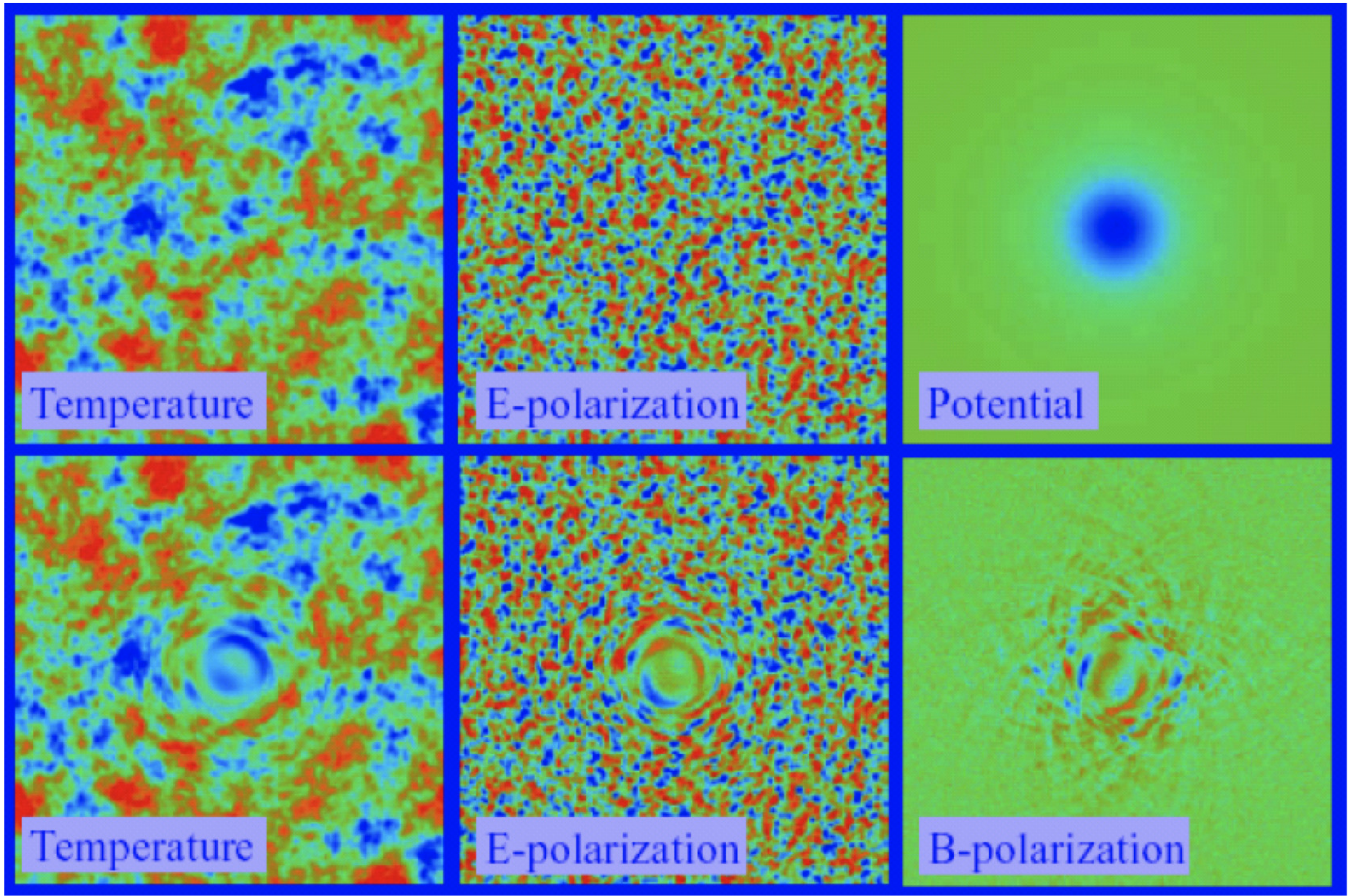


High-resolution maps are the most powerful tool for studying selection effects of deep surveys (high-angular resolution), complementarity between different observational strategies,…

# Interferometers can measure polarization on μK scale!

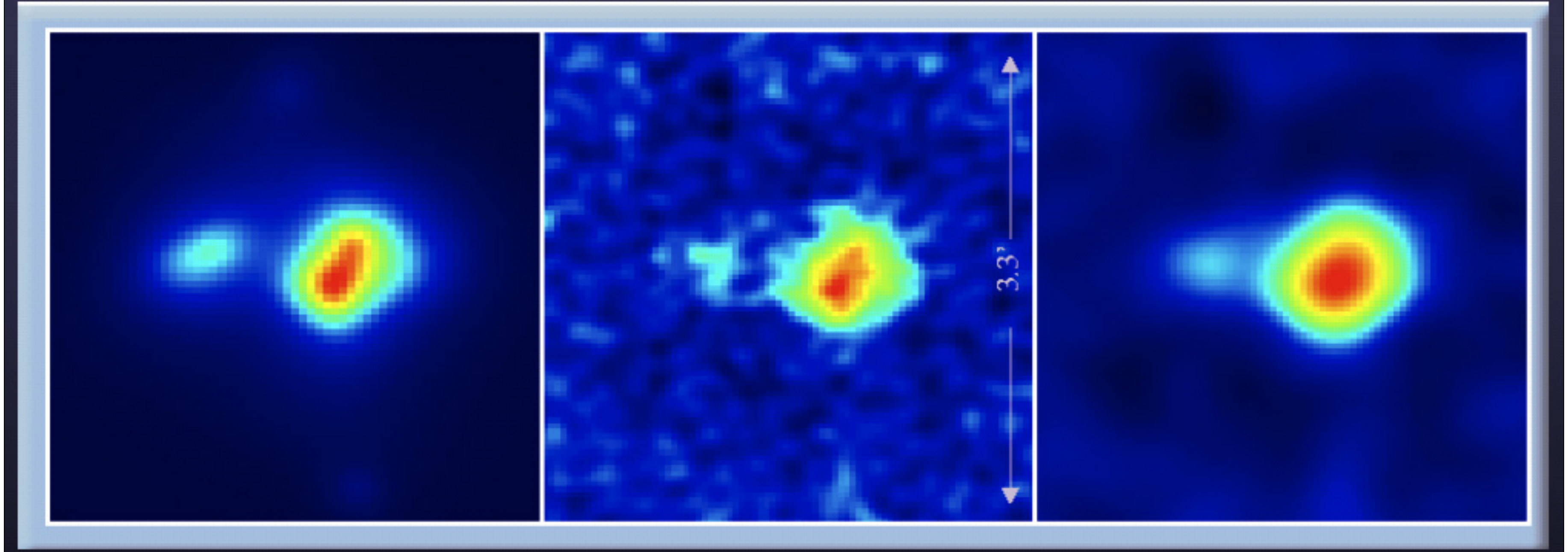
Note: clusters will lens CMB polarization signal

might prove interesting for probing nearby cluster potentials



Hu & Okamoto 2001

# Imaging the SZE with ALMA Band 1



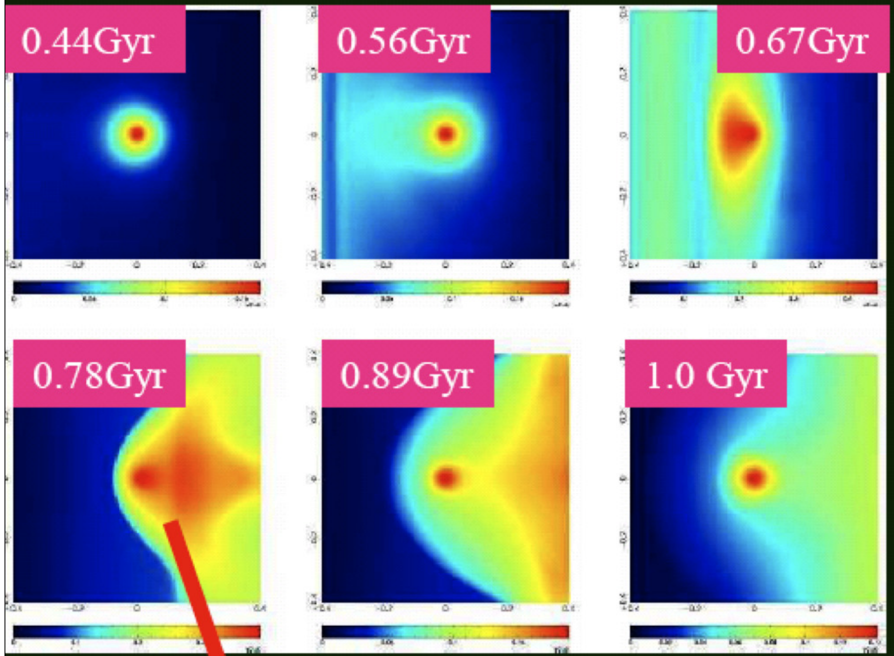
ALMA observes SZE

| SZE simulation (left) | 4 hours ALMA (center) | after 4kλ taper (right) |
|---|---|---|
| 2.5 × $10^{14}$ Msun *z*=1 | 34 GHz in compact config. | equiv. 22" FWHM |
| ~5σ SZA survey detection | 1.5 μJy (14 μK) 9.7" beam | 2.8 μJy (2.7 μK) |

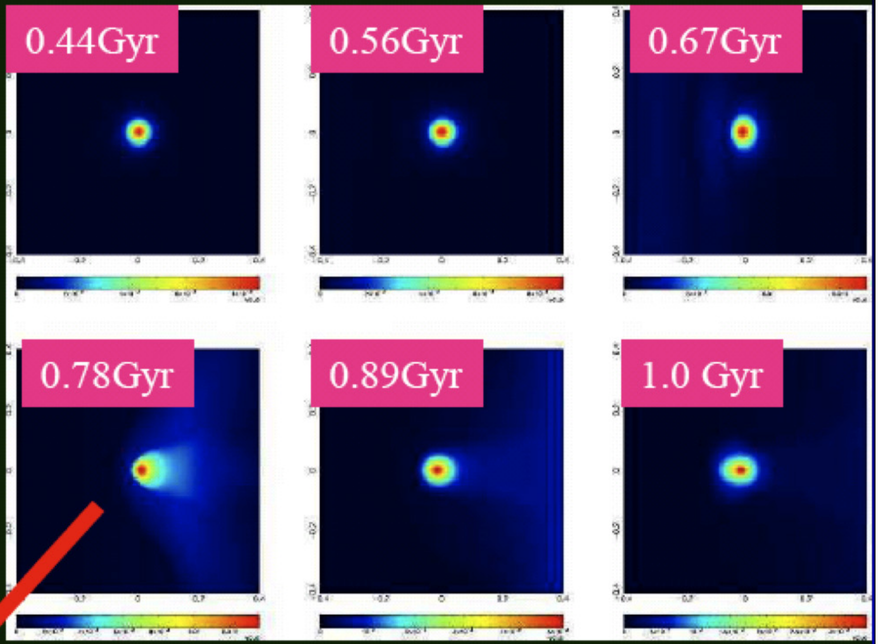
ALMA will provide images of high redshift clusters identified in surveys from other instruments like AMI, SZA, SPT, APEX-SZ, ACT

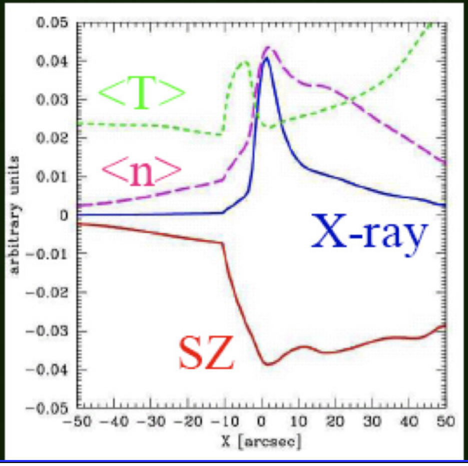
# Simulations of sub-cluster mergers (Takizawa 2005)

$I_{SZ} \propto \int n_e T_e \, dl$



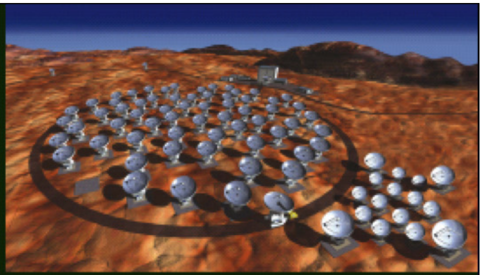
$I_X \propto \int n_e^2 T_e^{1/2} \, dl$

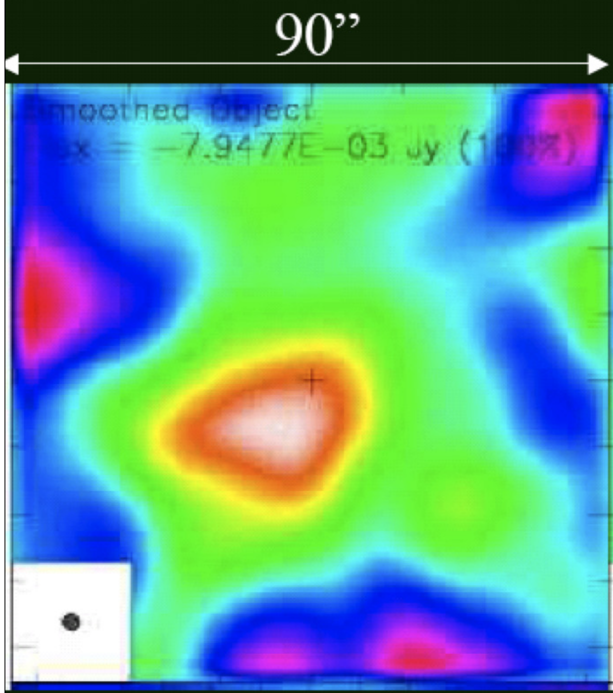




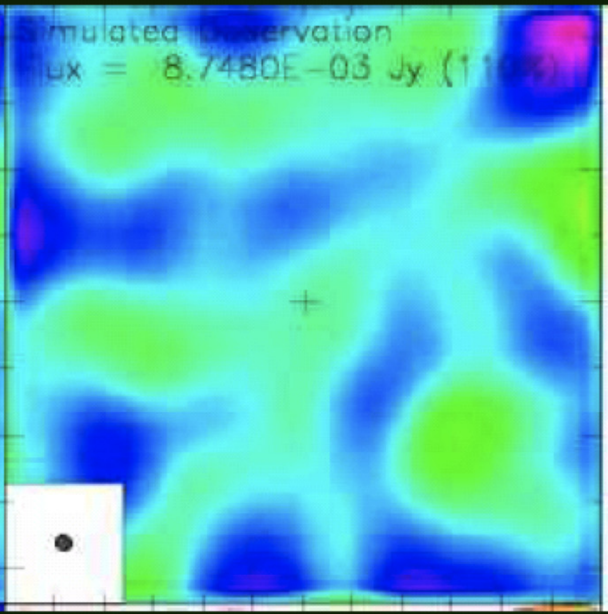
SZE image is highly disturbed, while X-ray remains compact.
⇒ better tracer of shock front

# Feasibility simulations for ALMA by GILDAS (Tsutsumi et al. 2005)



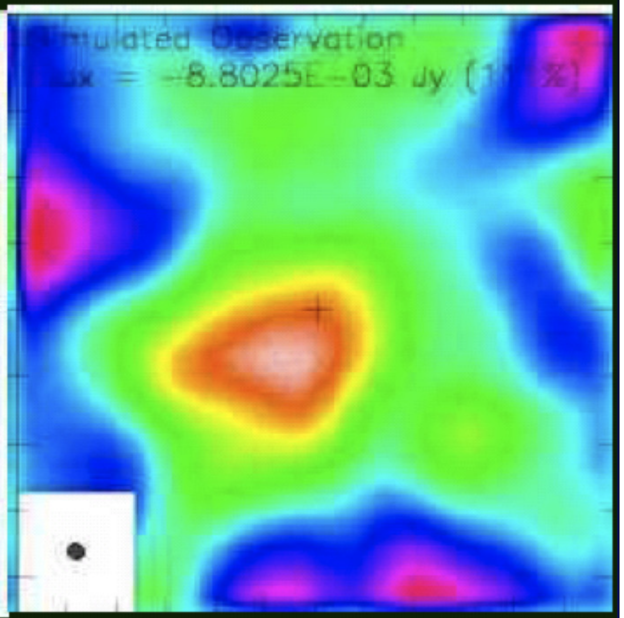


INPUT based on
150GHz data (13”FWHM)
of RX J147.5-1145



ALMA 64 arrays
longest baseline 150m
13 mosaics, 18 min

(Band 4)



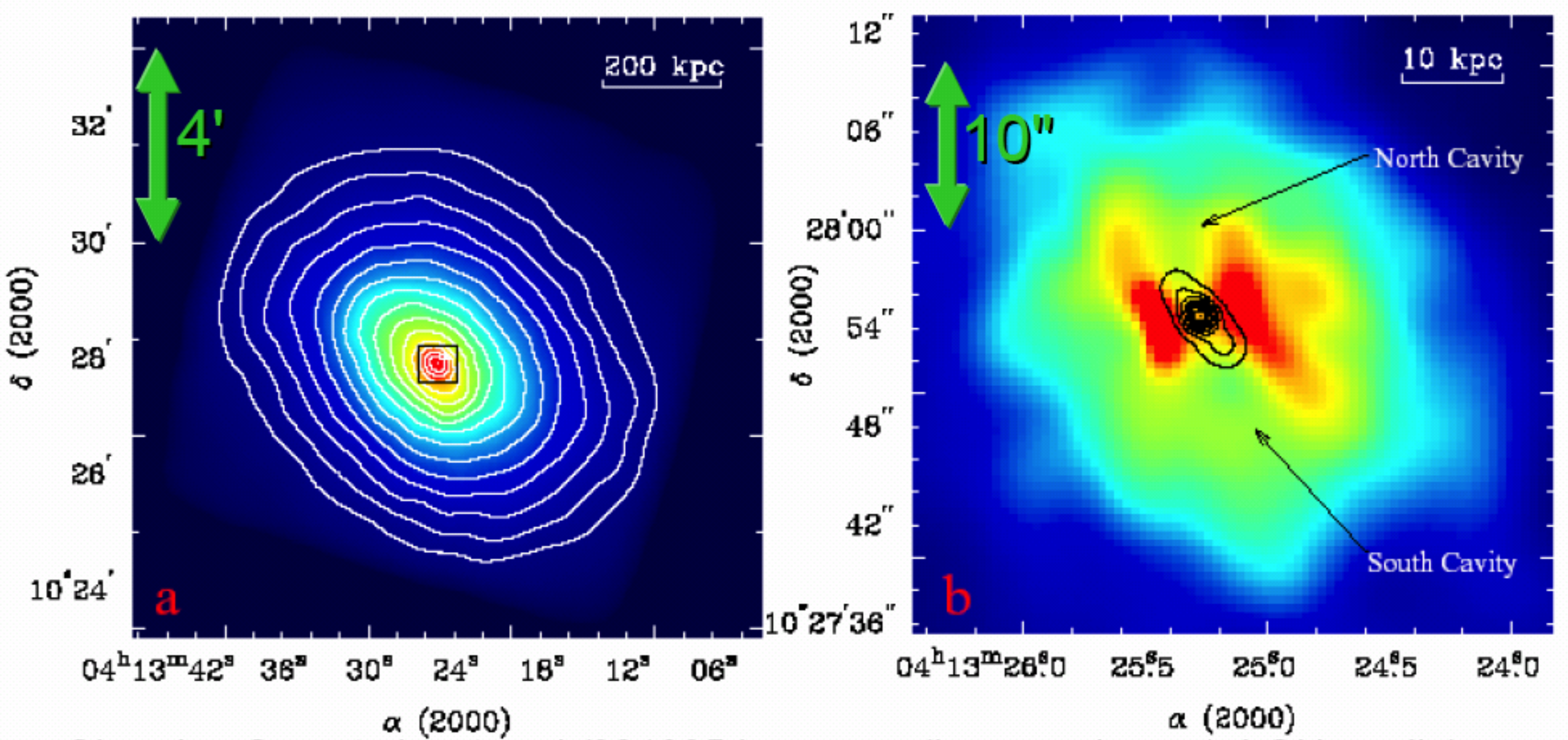
with ACA
longest baseline 30m
13 mosaics, 72 min

$1\sigma$=0.03 mJy/beam
peak = -0.22 mJy/beam
FWHM=2.4”

ACA improves image fidelity: opens ALMA for SZ !

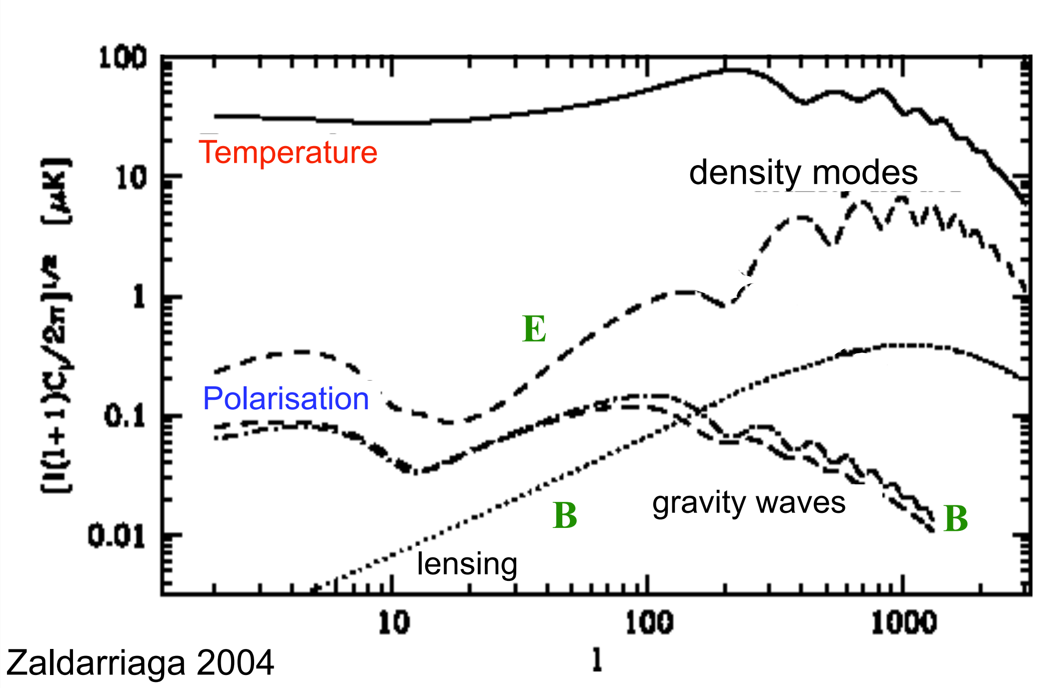
# Case for ALMA Band 3 (100 GHz)

Abell 478: relaxed cooling flow cluster at z=0.09, X-ray cavities
Need high-resolution SZ-observations with X-ray to determine Pressure

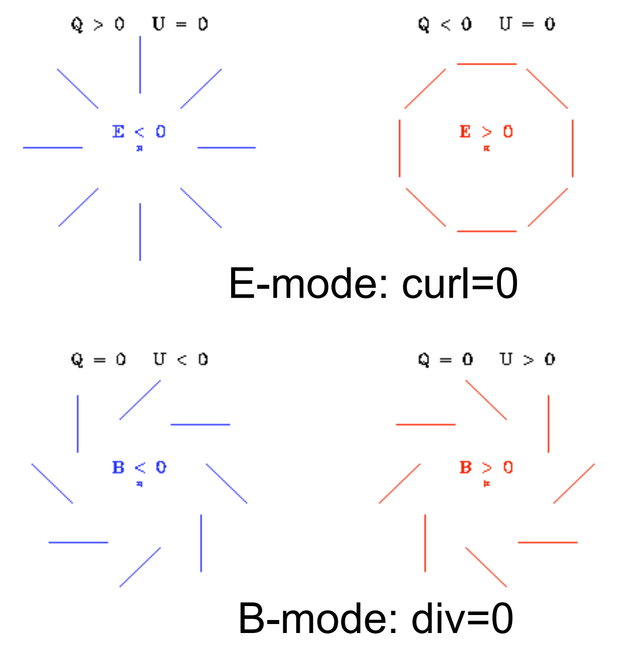


*Chandra: Sun et al. astro-ph/0210054* *(inner region + 1.4 GHz radio)*

# CMB Polarisation



Zaldarriaga 2004



Divide polarization into modes that reflect scalar / vector character of the density field

B-Mode reflects tearing of space-time during Inflation @ $10^{-35}$ sek :
Current uncertatinty ~$10^{24}$

# Dark-energy constraints with ALMA polarization measurements

## Synergies with CMB experiments

**Paola Andreani · Carlo Baccigalupi**

**Abstract** The Cosmic Microwave Background (CMB) physics can be used to constrain the dark energy dynamics: B modes of the polarization of the diffuse CMB emission as well as the polarized signal towards clusters of galaxies are sensitive to the Hubble expansion rate and thus the dark energy abundance in the early stage of cosmic acceleration. The first effect is sourced by gravitational lensing of large scale cosmic structures, the second is due to scattering of the primary CMB temperature anisotropy quadrupole by free electrons in cluster plasma. We are investigating the capabilities of ALMA to detect these effects and constrain the high-redshift dark energy abundance through measurements of sub-arcminute CMB anisotropies.