大型サブミリ波望遠鏡による
重力波源追観測の可能性

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Ryohei Kawabe, Kotaro Kohno, Tai Oshima and LST WG

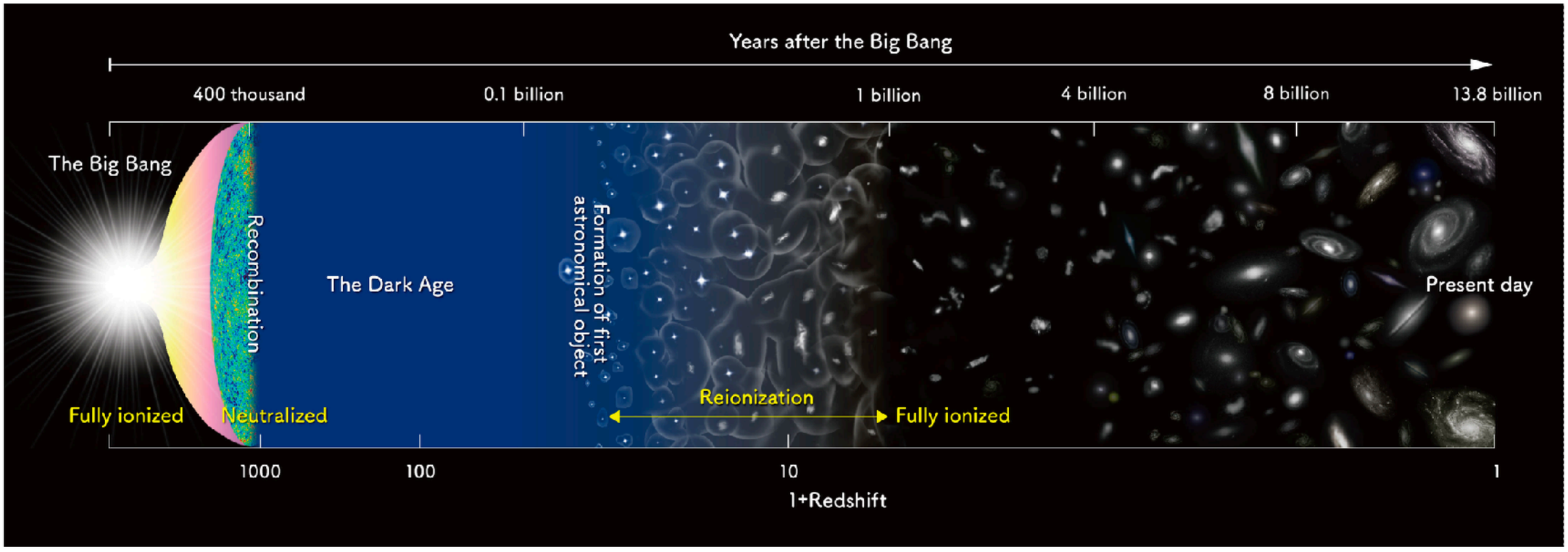
The 17th DECIGO Workshop
Nagoya University, 1-2 November 2018

Outline

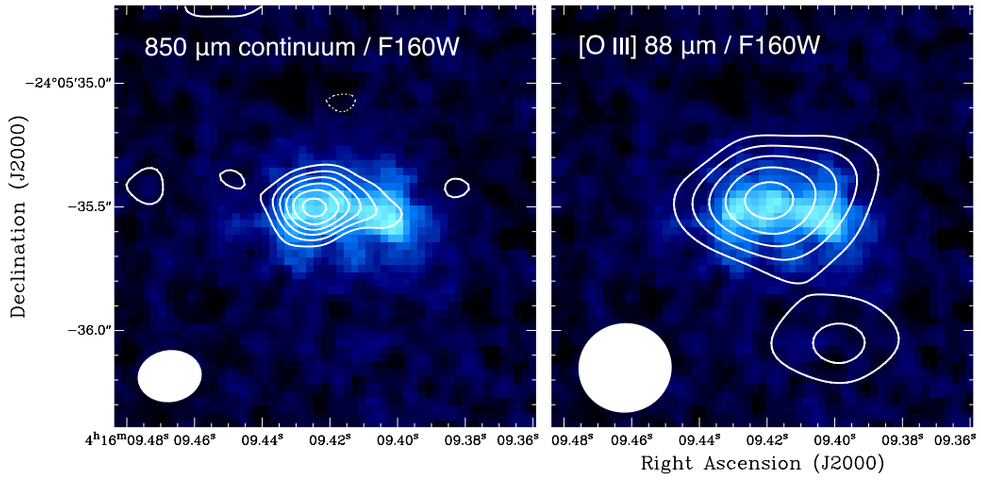
- Introduction
  - What is the parameter space to go with single dish (SD) telescopes?
  - How a SD telescope complements current facilities (ALMA)
- Large Submillimeter Telescope (LST): Imaging-spectroscopic surveyor
  - Possible science cases
- Submm transients
  - How will a submm SD telescope complement multi-messenger followups of (B-)DECIGO GW sources?
  - Just show the expected sensitivity
- Summary

ALMA

Frontiers in Submm Cosmology



[OIII]/dust detection at z = 8.312



Tamura et al. (2018), submitted

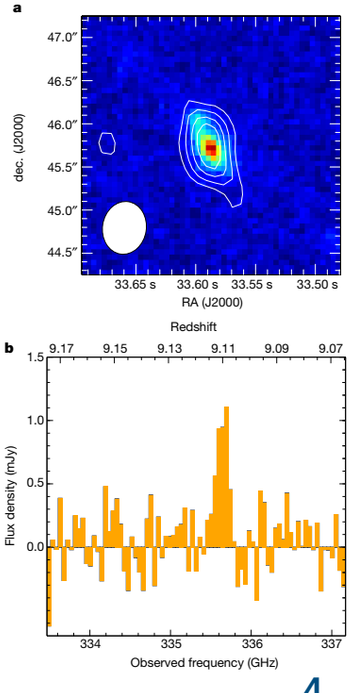
World redshift record (z = 9.110) with ALMA!

LETTER

https://doi.org/10.1038/s41586-018-0117-z

The onset of star formation 250 million years after the Big Bang

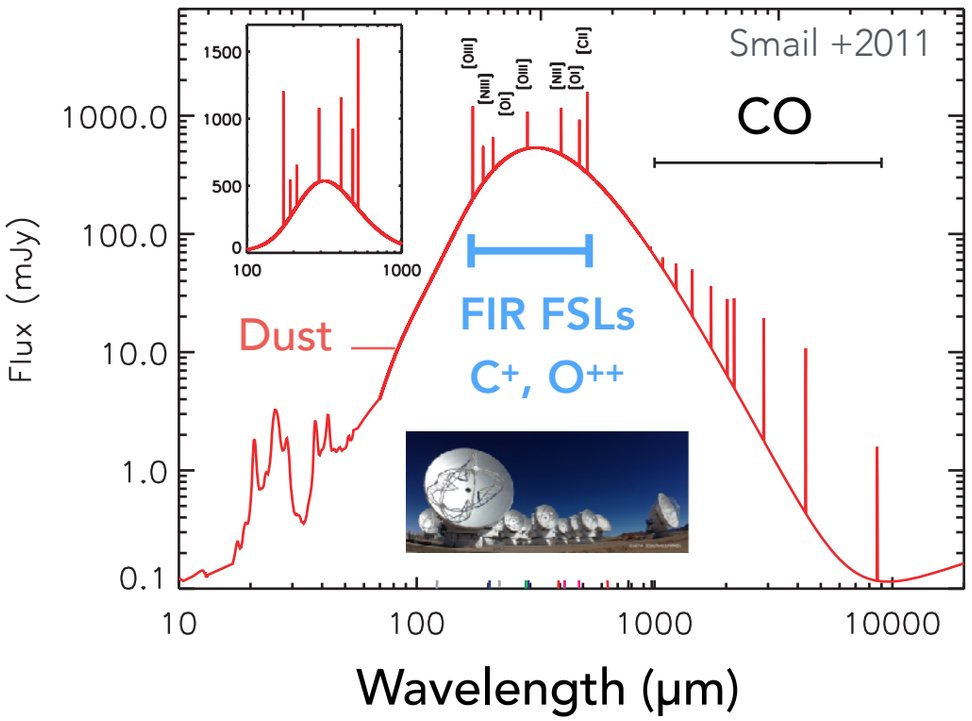
Takuya Hashimoto[1,2*], Nicolas Laporte[3,4], Ken Mawatari[1], Richard S. Ellis[3], Akio K. Inoue[1], Erik Zackrisson[5], Guido Roberts-Borsani[3], Wei Zheng[6], Yoichi Tamura[7], Franz E. Bauer[8,9,10], Thomas Fletcher[3], Yuichi Harikane[11,12], Bunyo Hatsukade[13], Natsuki H. Hayatsu[12,14], Yuichi Matsuda[2,15], Hiroshi Matsuo[2,15], Takashi Okamoto[16], Masami Ouchi[11,17], Roser Pelló[4], Claes-Erik Rydberg[18], Ikkoh Shimizu[19], Yoshiaki Taniguchi[20,21], Hideki Umehata[13,20,21] & Naoki Yoshida[12,17]

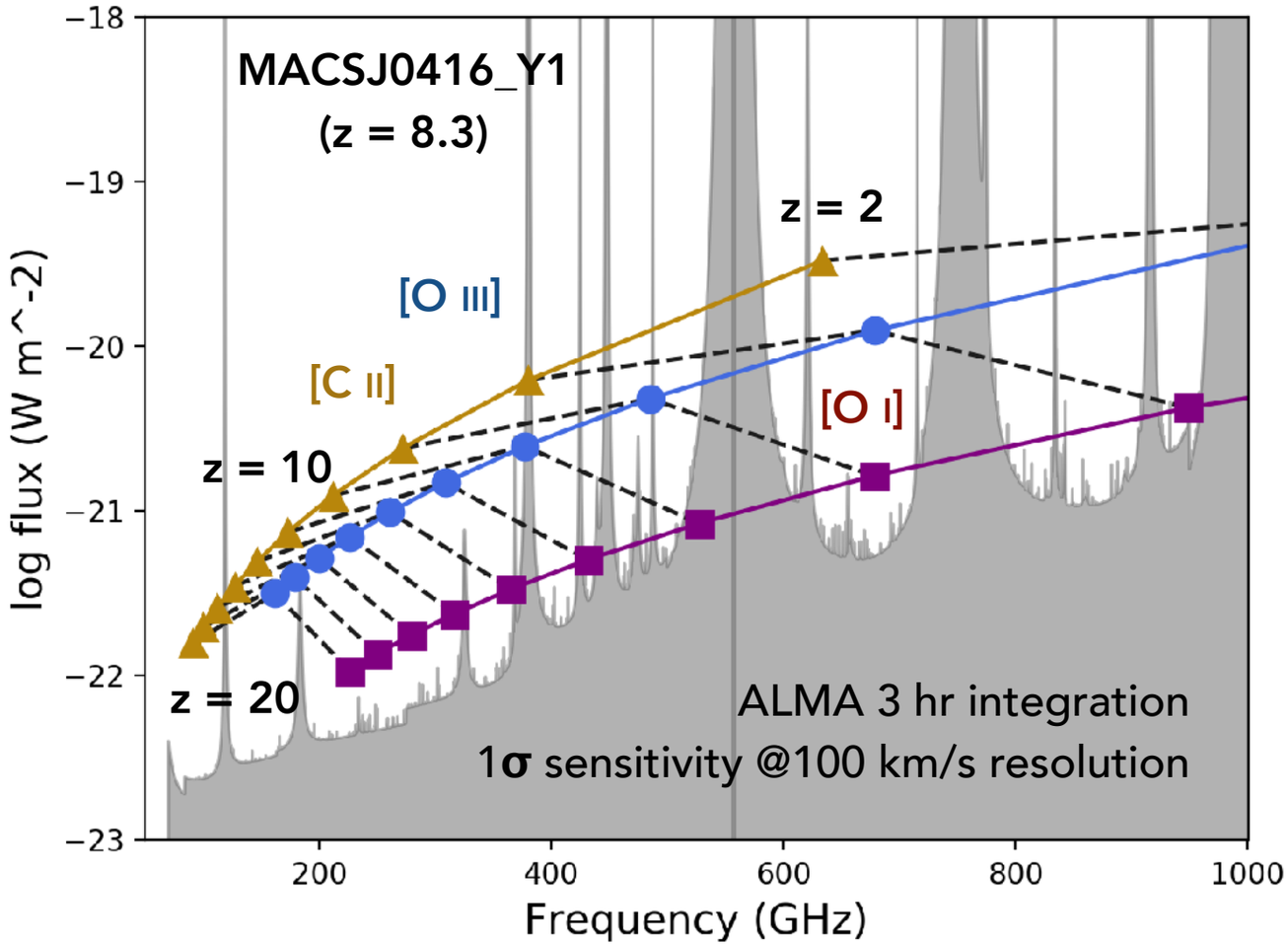


Hashimoto, YT et al. (2018) Nature

Far-Infrared Fine-Structure Lines

- Brightest lines in the FIR: [C II] 158um, [O III] 88um, [O I] 63um
- Probe physical properties of ISM (ionization state, metallicity)
- Reach z = 20. Competitive with JWST/NIRSpec C III]1909A

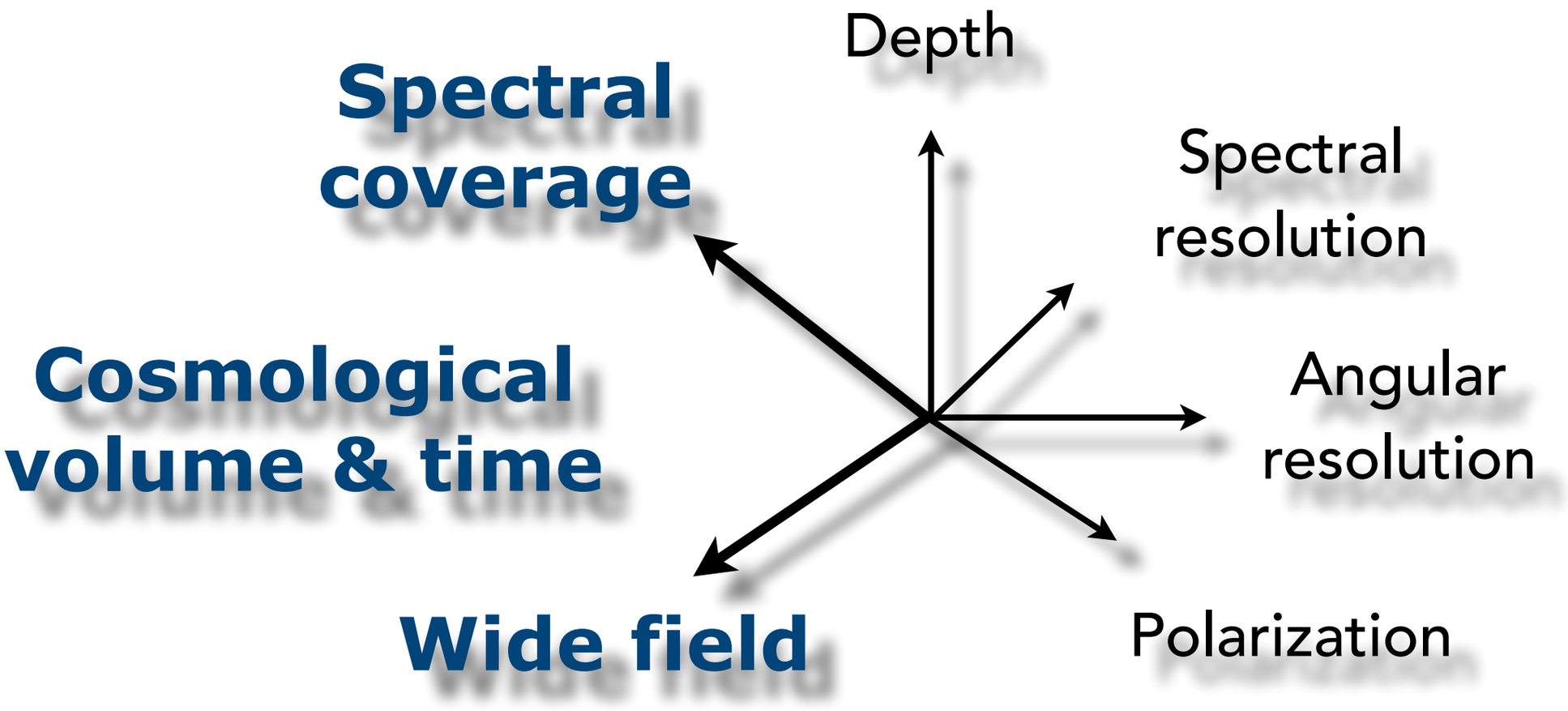




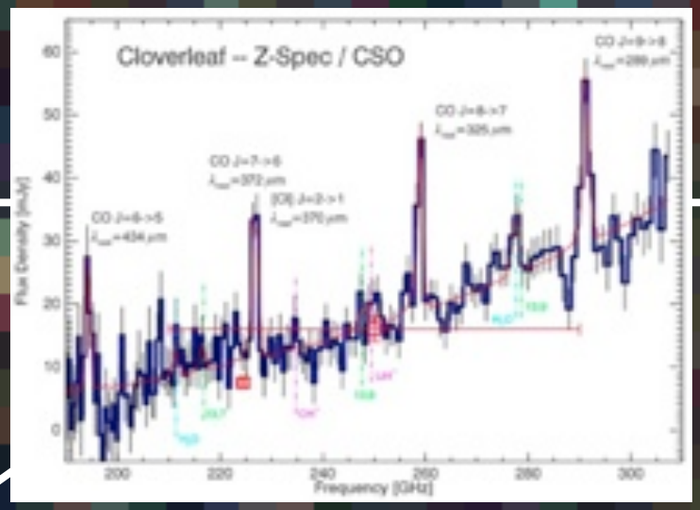
Redshift Record

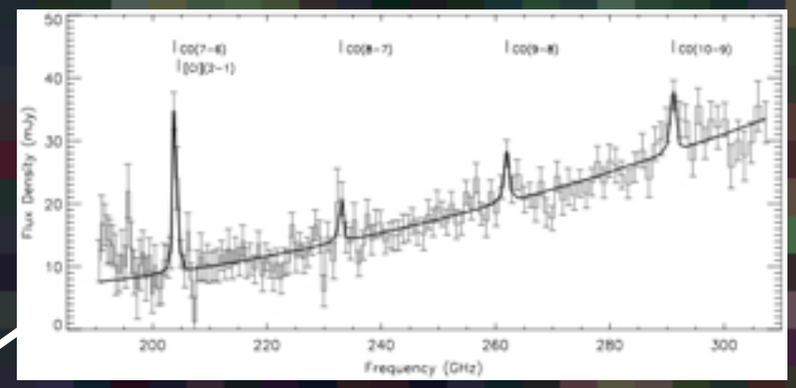
#	Redshift	Object	References	Telescope/Line
1	9.110	MACS J1149-JD	**Hashimoto, YT+ (2018)***	**ALMA/[OIII]**
2	8.683	EGSY-2008532660	Zitrin+ (2015)*	Keck/Lyα
3	8.38	A2744_YD4	Laporte+ (2017)	**ALMA/[OIII]**
4	8.312	MACS0416_Y1	**Tamura+ (2018)**	**ALMA/[OIII]**
5	7.664	z7_GSD_3811	Song+ (2016)	Keck/Lyα
6	7.640	MACS1423-z7p64	Hoag+ (2017)	HST/Lyα & **ALMA/[CII]**
7	7.541	ULAS J1342+0928	Banados+(2017)	Magellan/Lyα
8	7.508	z8-GND-5296	Finkelstein+ (2013)*	Keck/Lyα
9	7.452	GS2_1406	Larson+ (2017)	HST/Lyα
10	7.212	SXDF-NB1006-2	Shibuya+(2012) **Inoue, YT+ (2016)***	Subaru+Keck/Lya **ALMA/[OIII]**

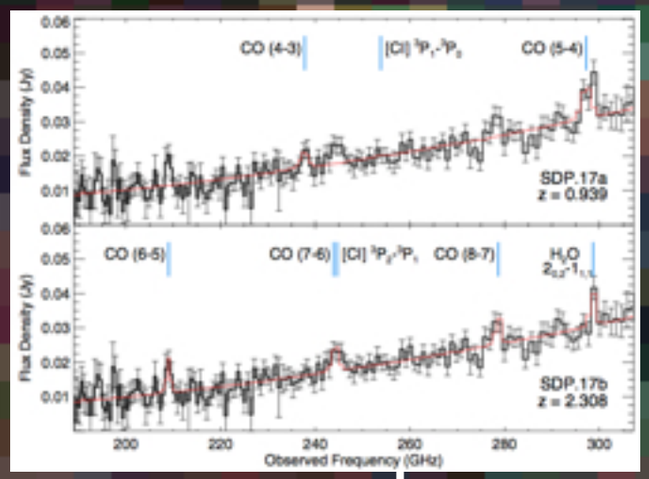
New discovery space?

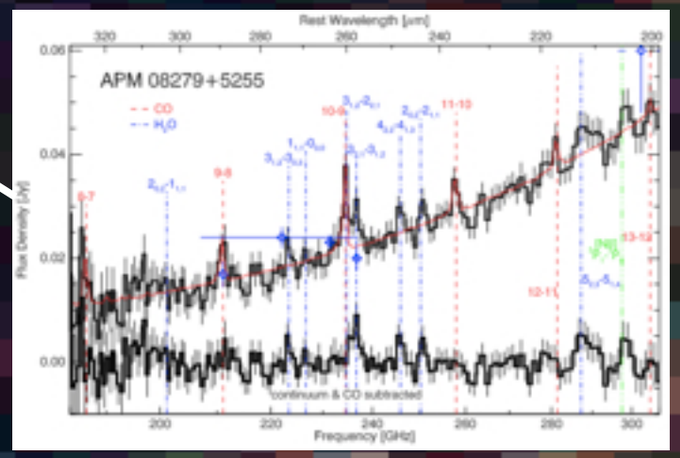


HerMES Lockman Hole
© HerMES / ESA





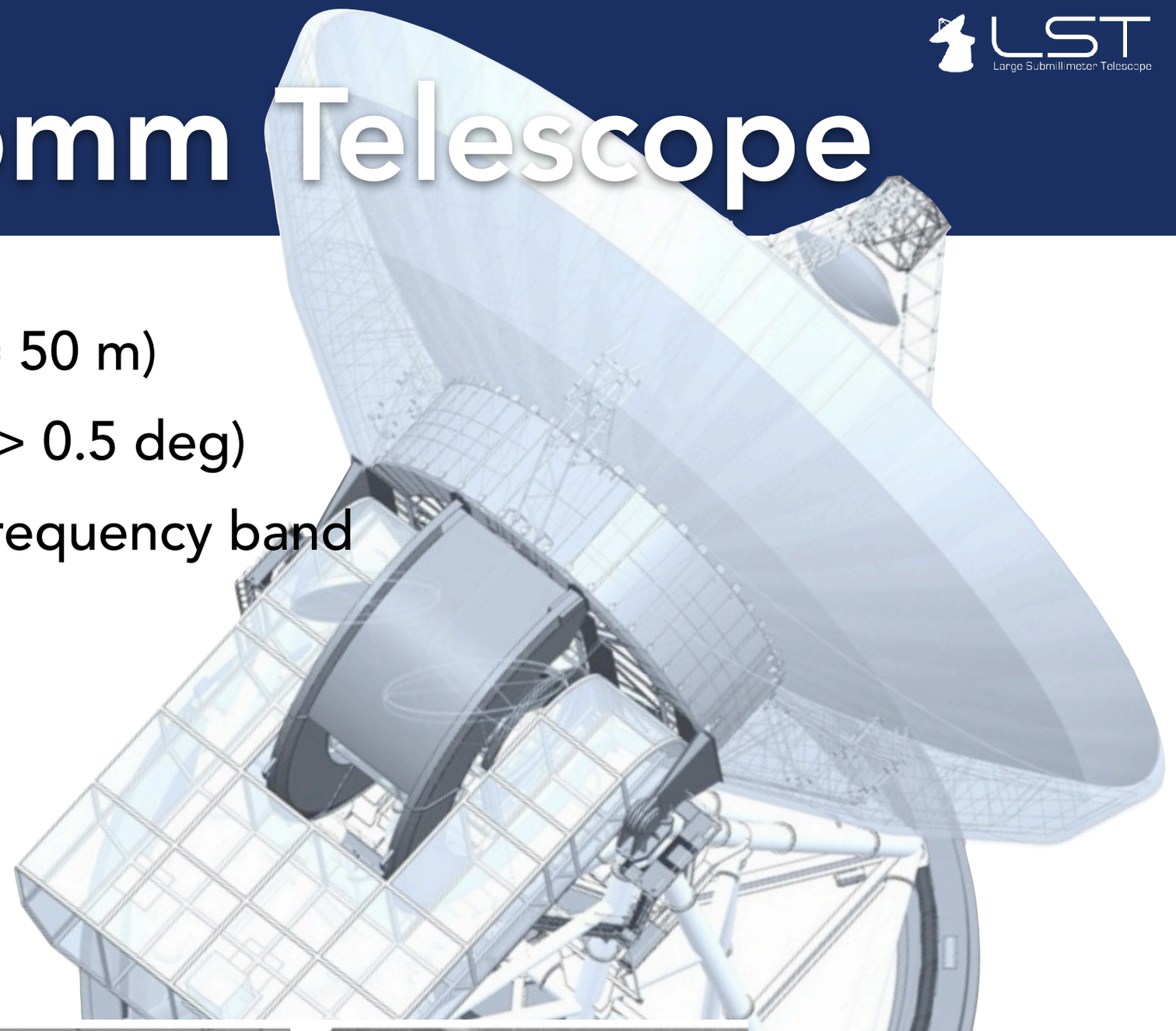




Large Submm Telescope

LST
Large Submillimeter Telescope

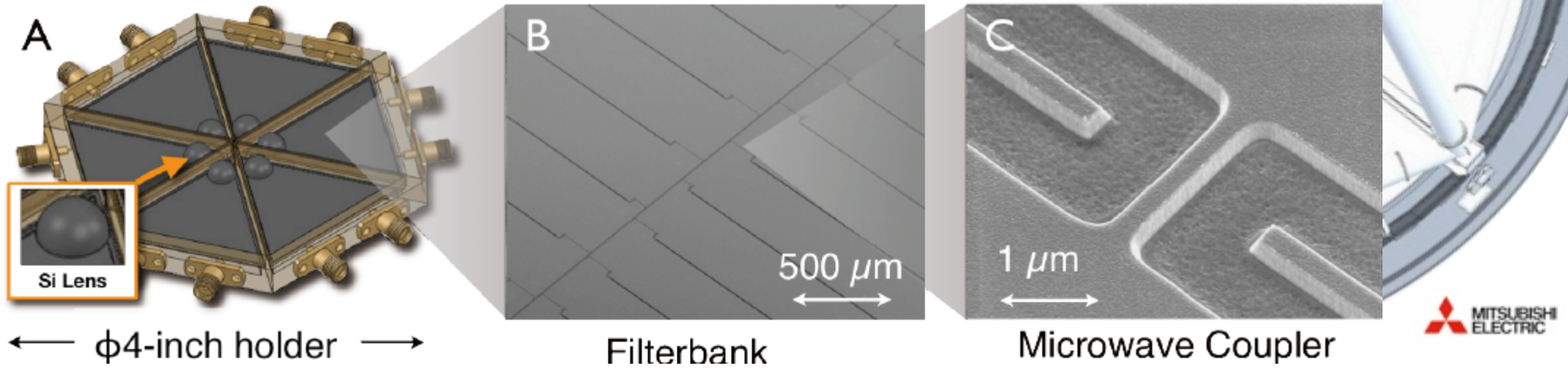
- Large aperture (D = 50 m)
- Wide field of view (> 0.5 deg)
- Long-submm/mm frequency band
- Survey-oriented



DESHIMA

Deep **S**pectroscopic **Hi**gh-z **Ma**pper

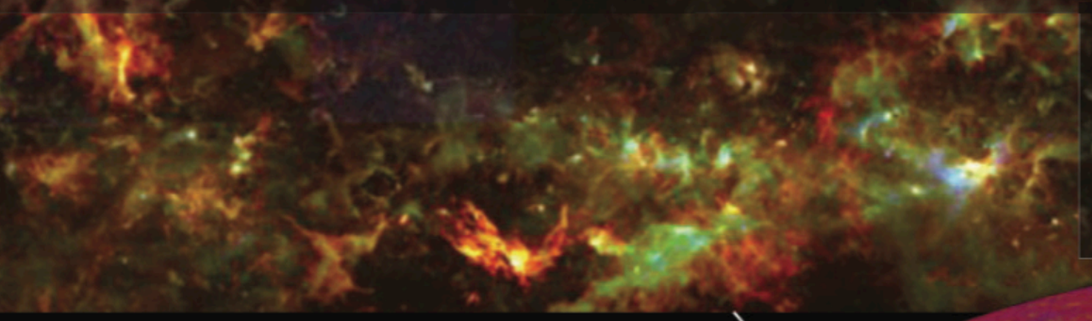
(Endo et al. 2011)



LST

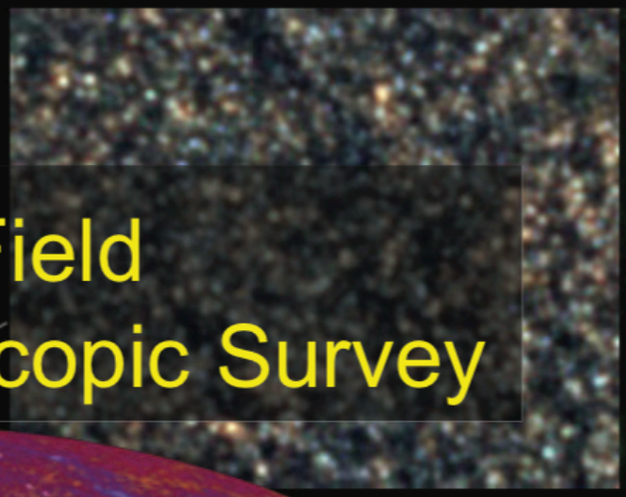
LARGE SUBMILLIMETER TELESCOPE

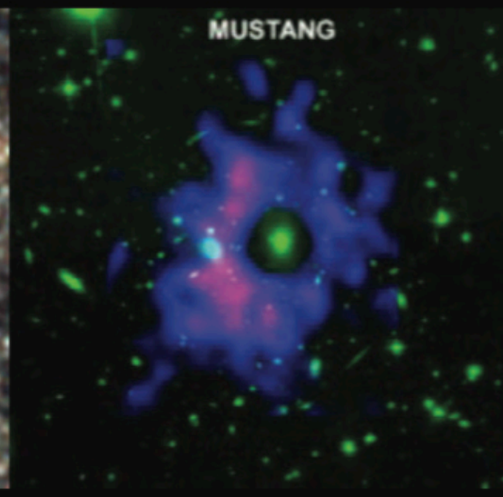
Develop new discovery space complementary to ALMA



- Wide-Field Spectroscopic Survey

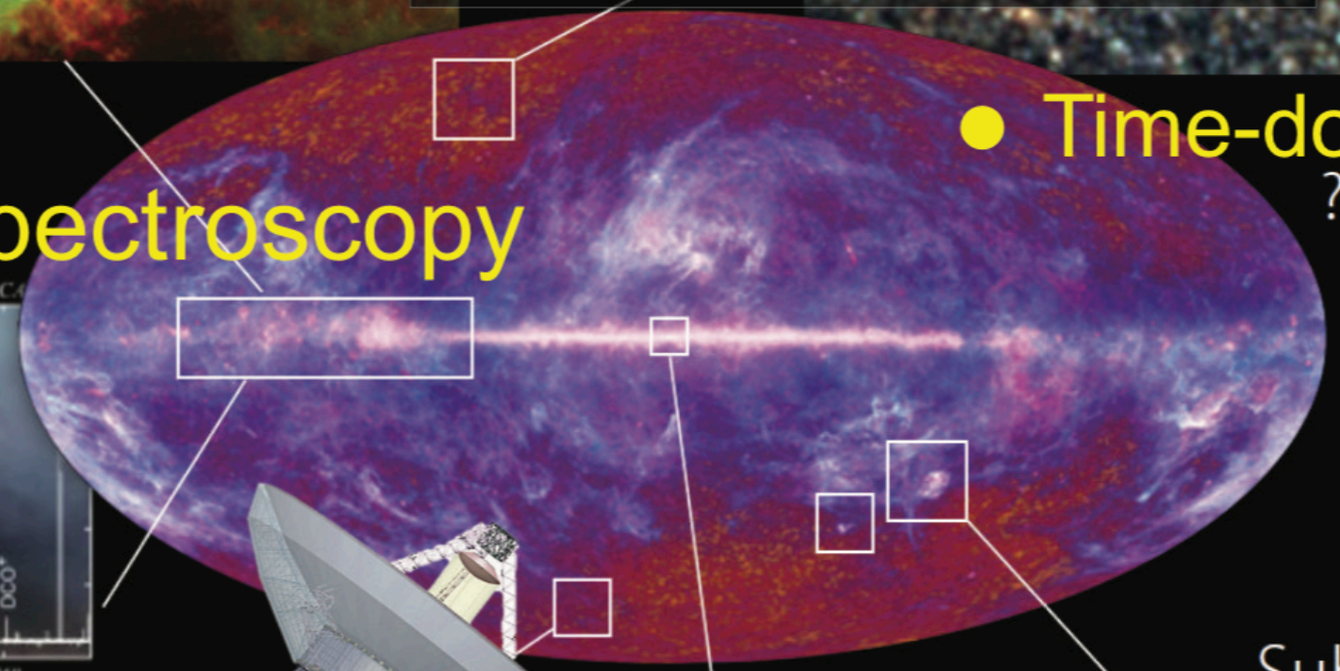
Distant Galaxies and Clusters





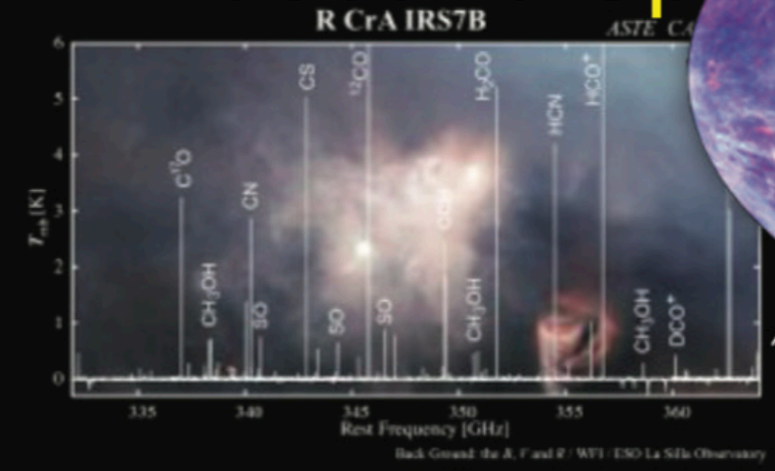
Galactic Plane

- Wideband Spectroscopy



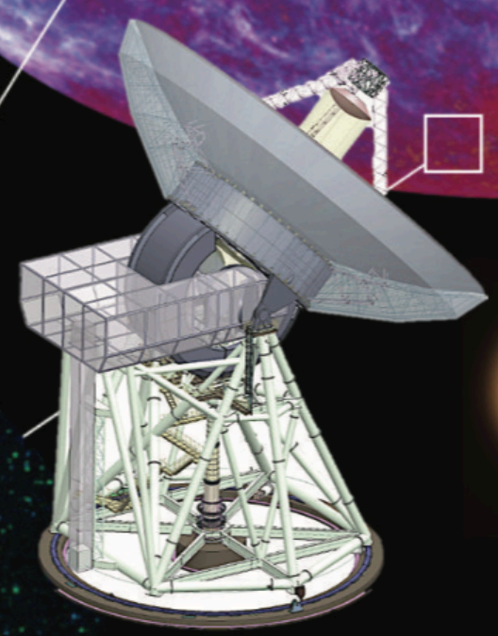
- Time-domain Science

?



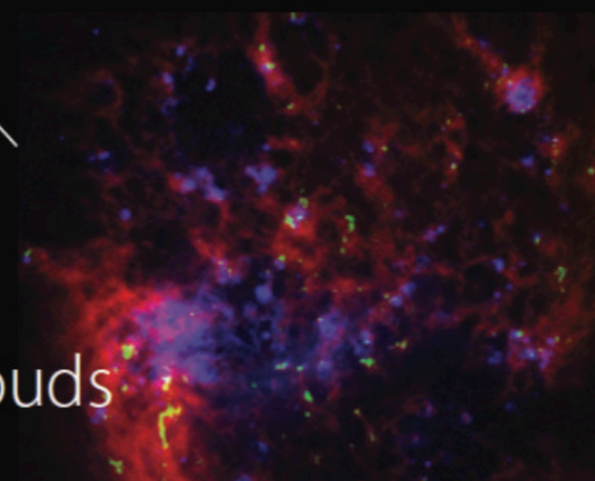
Astrochemistry

Submm Transients



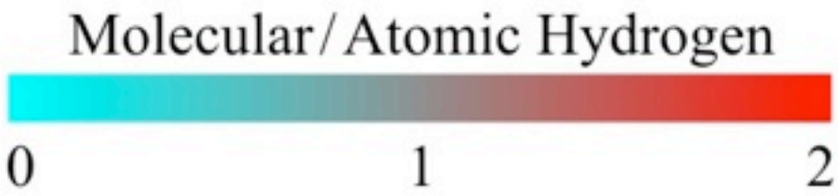
VLBI

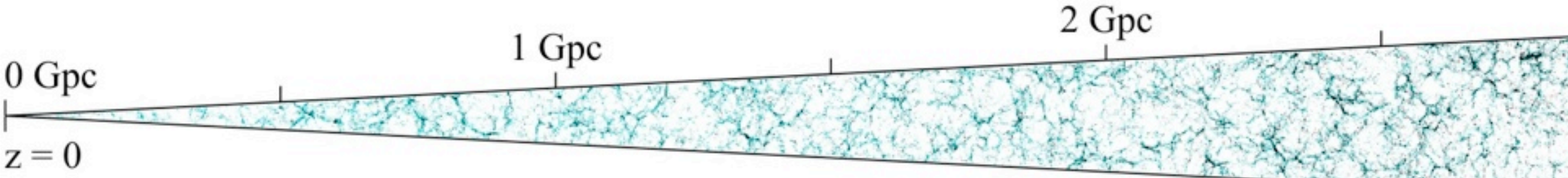
Nearby Galaxies



Magellanic Clouds

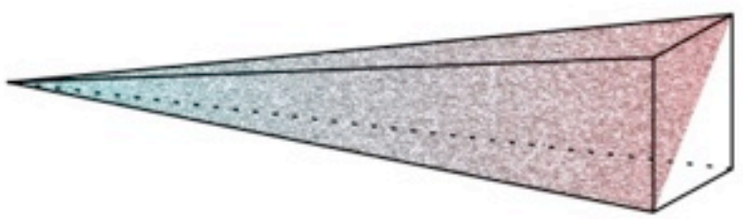
SKA Design Studies – Virtual Hydrogen Cone

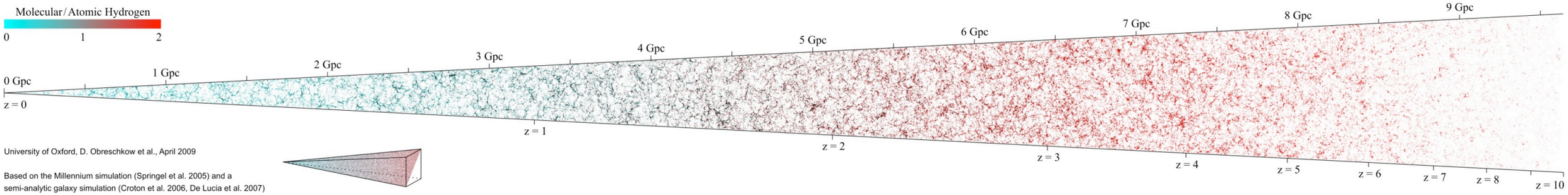




University of Oxford, D. Obreschkow et al., April 2009

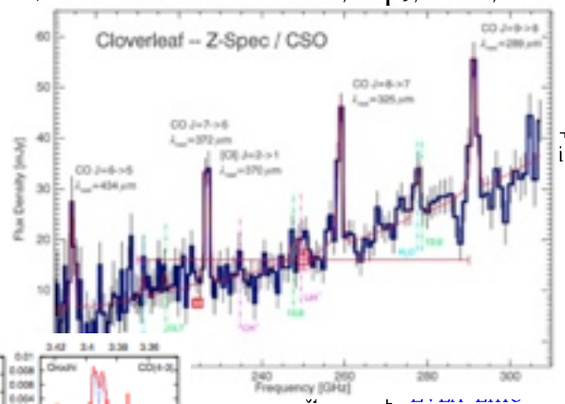
Based on the Millennium simulation (Springel et al. 2005) and a semi-analytic galaxy simulation (Croton et al. 2006, De Lucia et al. 2007)



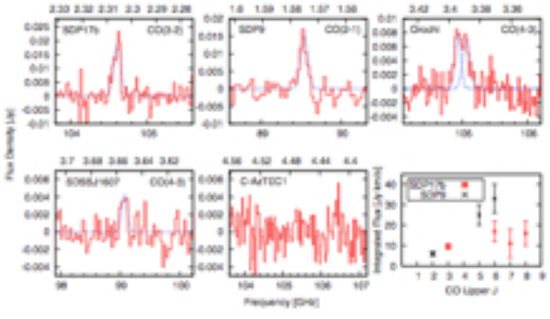


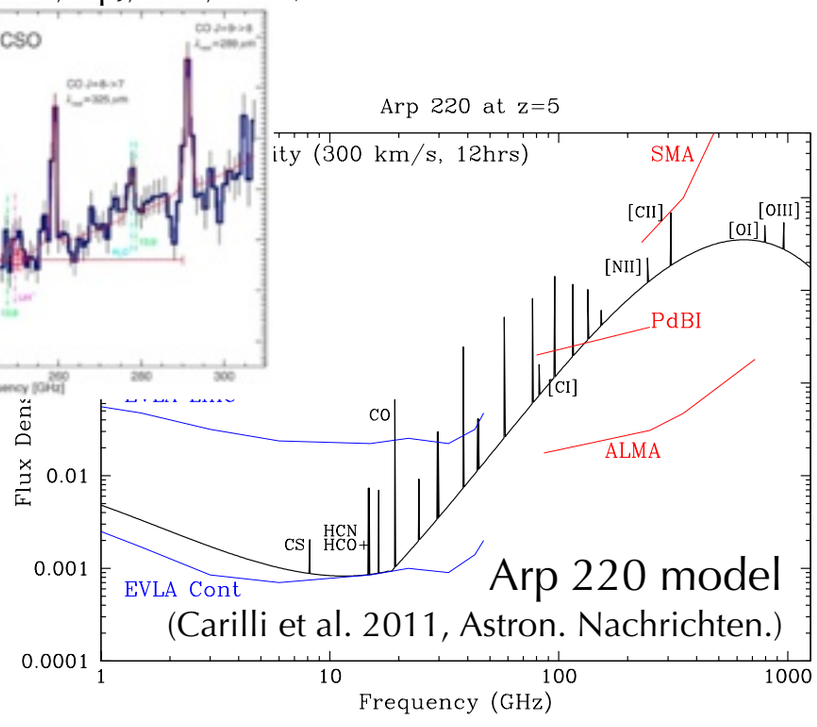
CO/[CII] Tomography

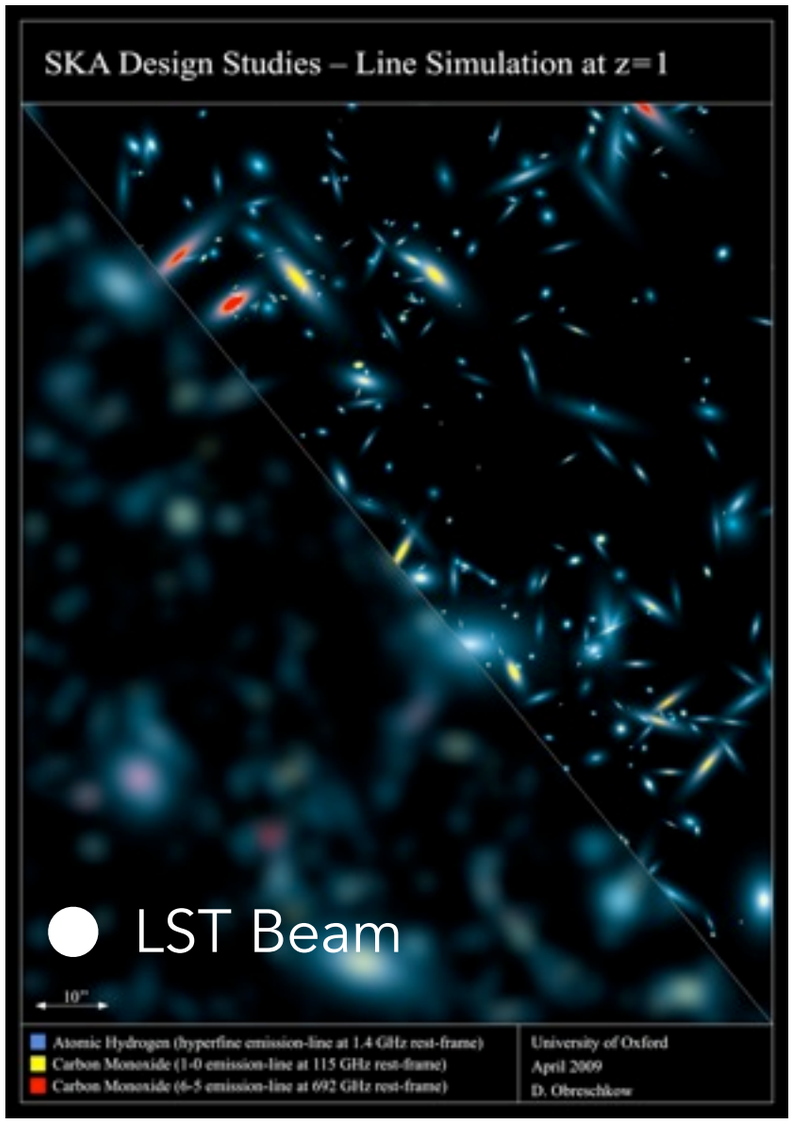
Cloverleaf QSO at z=2.6
(Bradford et al. 2009, ApJ, 705, 112.)



CO in SMGs w/ NRO45m
(Iono et al. 2012, PASJ)

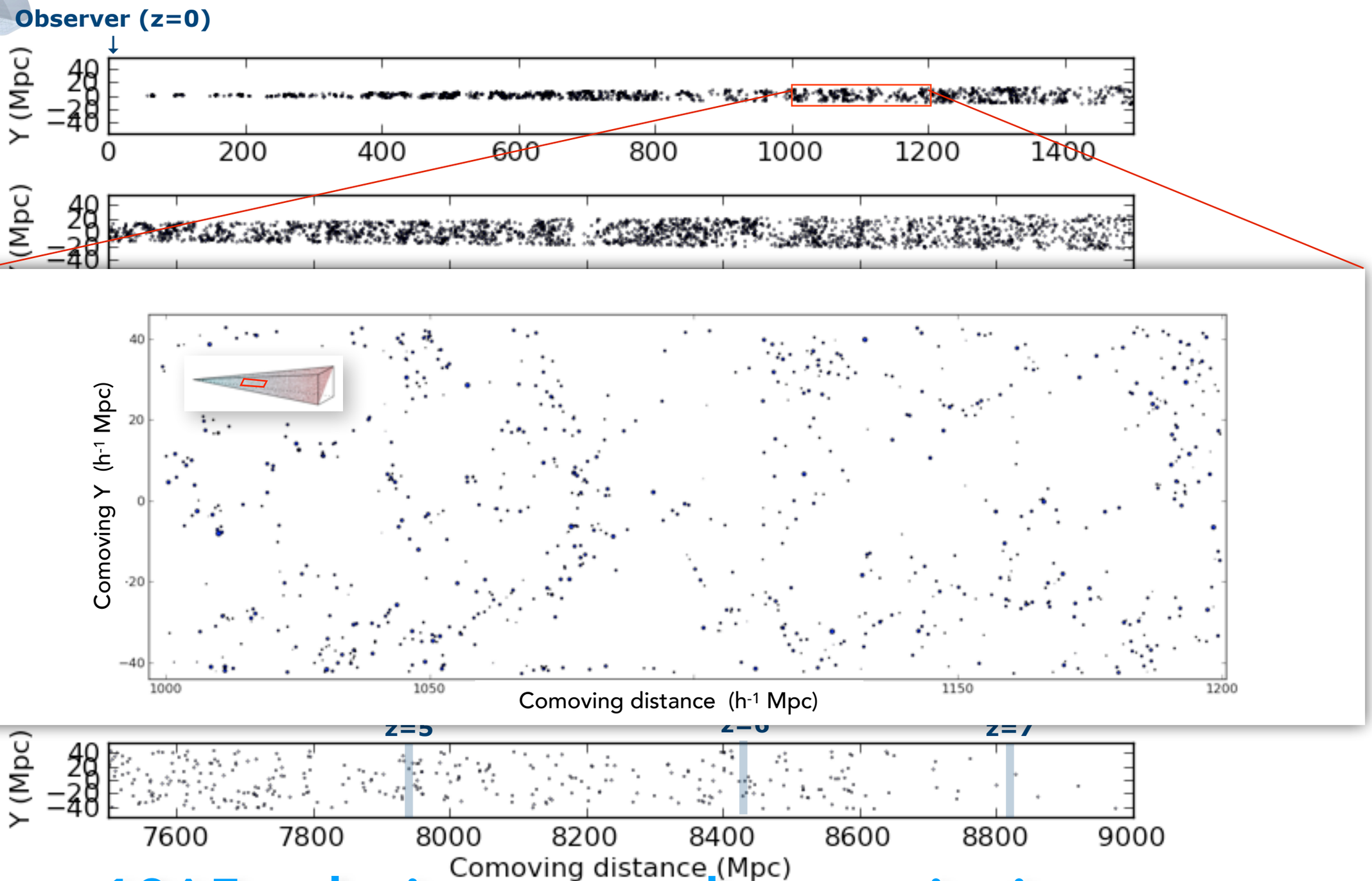






CO/[CII]: representative emission lines in mm-FIR.
Benefit from negative k-correction of CO ladder and FIR lines.
Overcome the confusion problems.

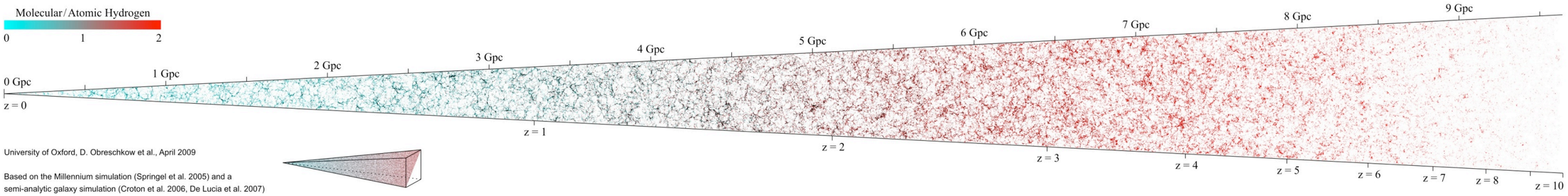
Light cone from the LST 2-deg² Survey



10^5 galaxies across the cosmic time

10^3 galaxies in the epoch of reionization

SKA Design Studies – Virtual Hydrogen Cone



CO/[CII] Tomography

RSD Redshift Space Distortion

Verify GR by estimating the growth rate of structure, dark energy problem

LSS Cosmic Large-Scale Structure

Investigate the correlation between dark and baryonic matters from clustering analysis, dark matter problem

EoR Epoch of Reionization

Search for earliest “hidden” galaxies, first generation galaxies

CSFH Cosmic Star-formation History

Investigate mass/luminosity function of molecular gas as a function of redshift, “hidden” history of baryonic matter

Evolution of Galaxies

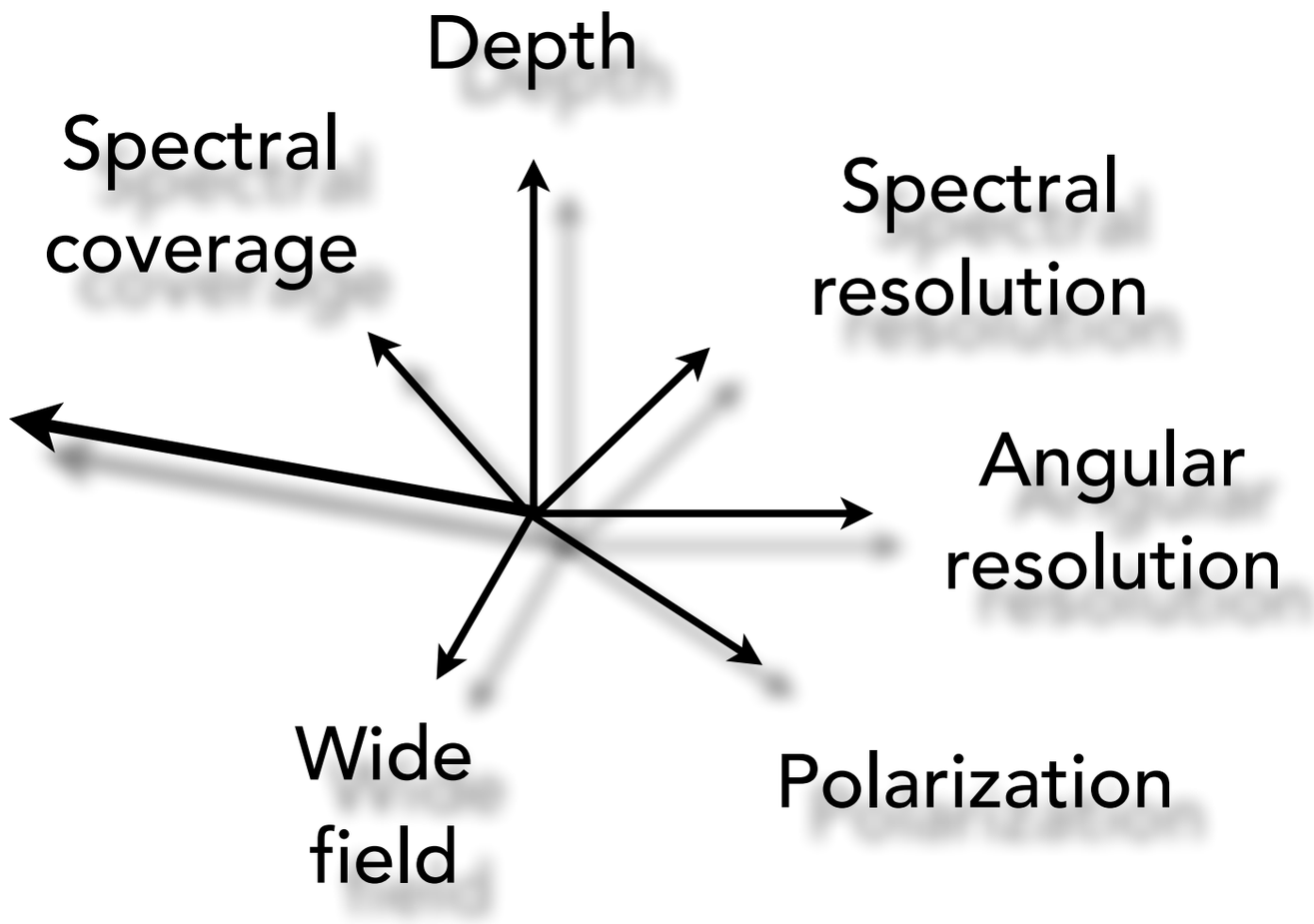
Cosmic evolution of galaxies proved through properties of interstellar medium

… and serendipitous discoveries

Line emitters, transient and variables, …

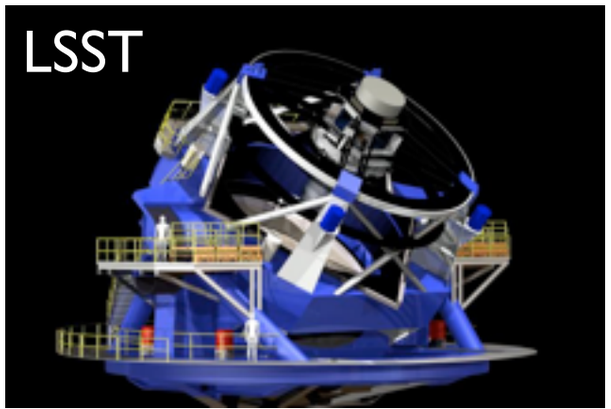
New discovery space?

Time domain

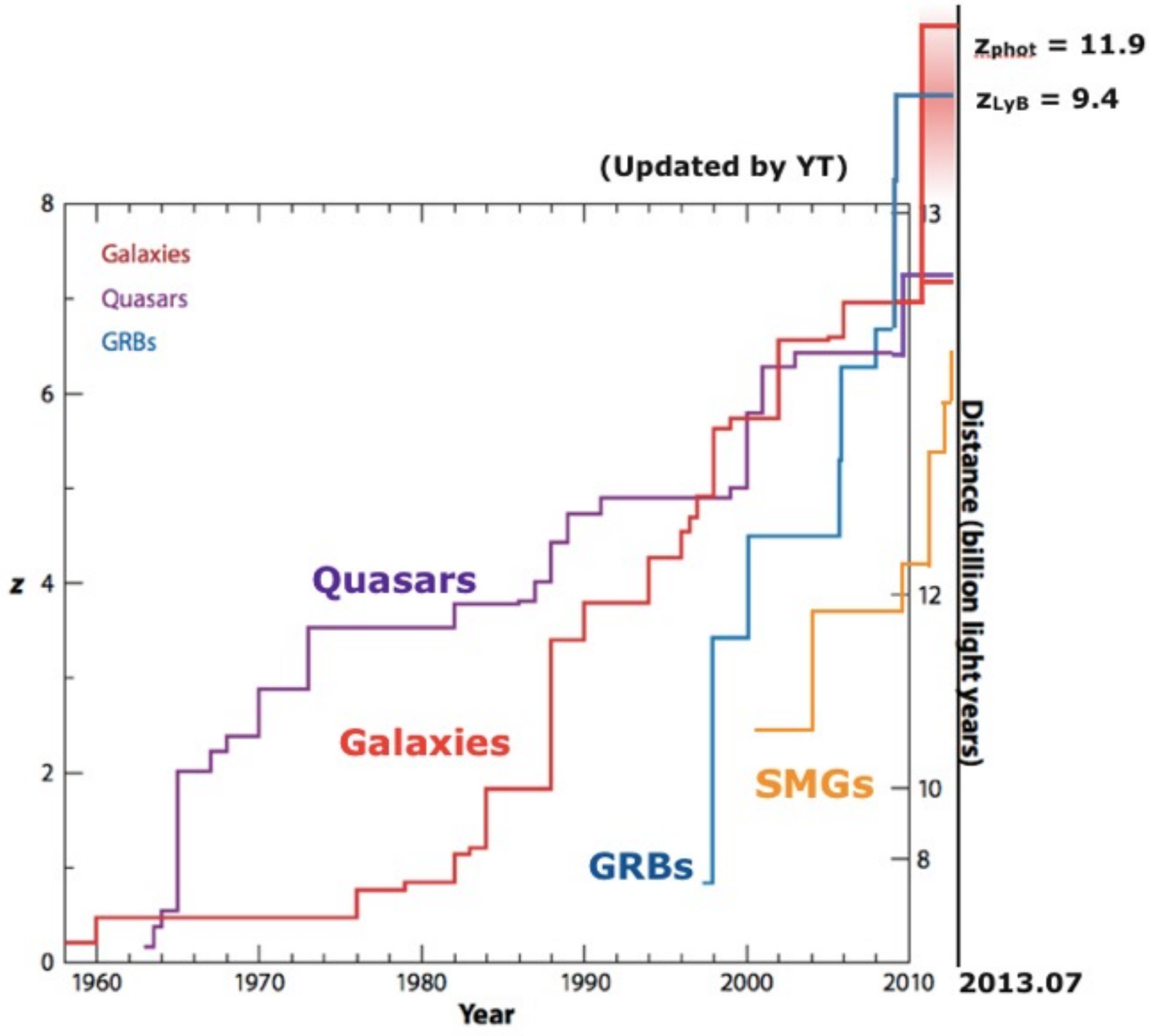


What is Time domain astronomy?

- Many facilities in 2020's for transient/variable searches
  - LSST will detect *a million of transients per night*.
  - Gravitational wave (GW) telescopes (VIRGO, LIGO, KAGRA) will *detect* GW sources, which require multi-messenger follow-up observations.
- Long duration ***γ-ray bursts (GRBs)*** trace the SF history
  - collapse of massive stars; E(iso) ~ 10^52–10^54 erg
  - can be observed even at a cosmological distance
  - occur a few times per day
  - ***Excellent tracer of cosmic star formation history***



Redshift record



Why GRBs in sub/mm?

(see also Hatsukade, YT+2014, Nature, 510, 247)

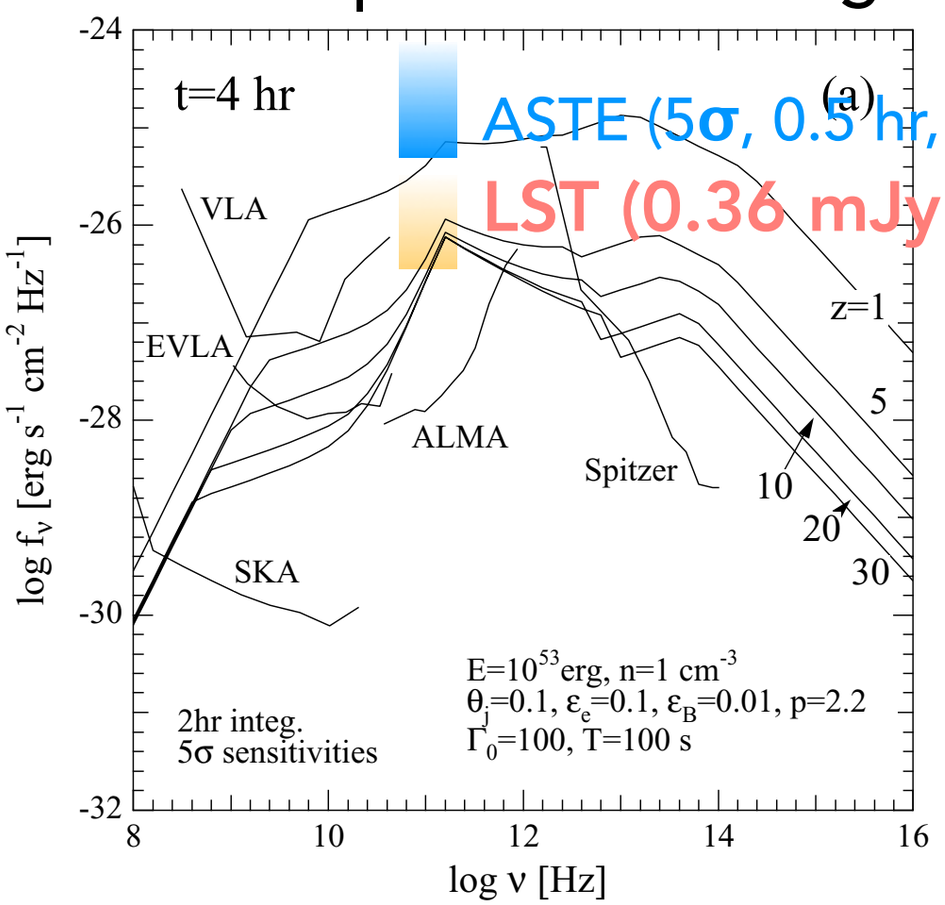
← Complementary tracer →
of cosmic star formation

“Submm flare” from GRB reverse shocks

- Earliest afterglows from reverse shocks (< 4 hr) peak at ~300 GHz, and bright (~1 mJy) even at z > 10 (Inoue+2007)
  - similar to dusty star-forming galaxies
  - Bright compared to a typical galaxy at z > 5 (~10 uJy)
- But, short-lived... → Deep and wide image in one shot

1 mJy →

1 uJy →

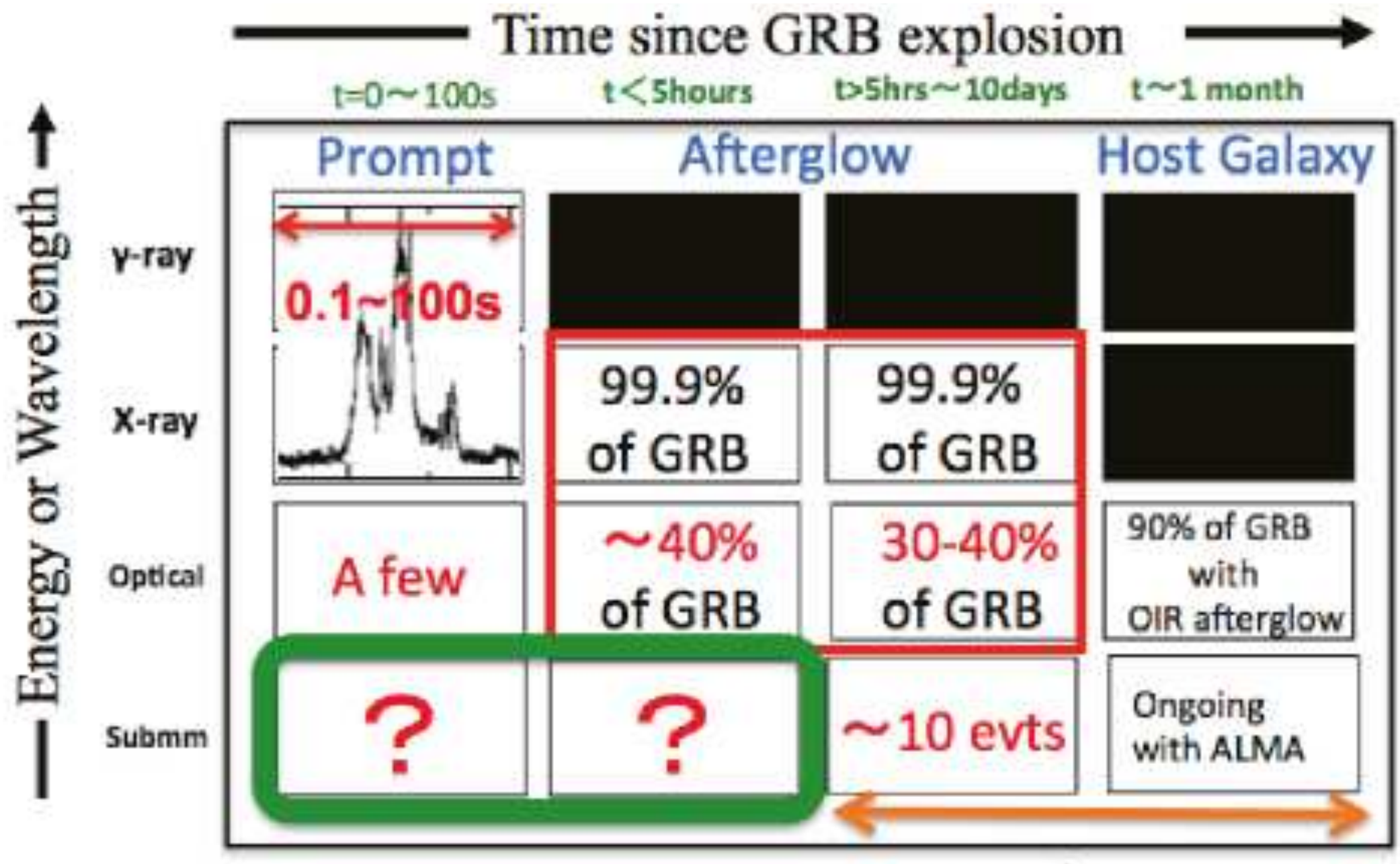


ASTE (5σ, 0.5 hr, confusion limited)

LST (0.36 mJy at 1.1mm, 5σ)

Predicted SED of GRB afterglow at z = 1–30 4hr after the burst

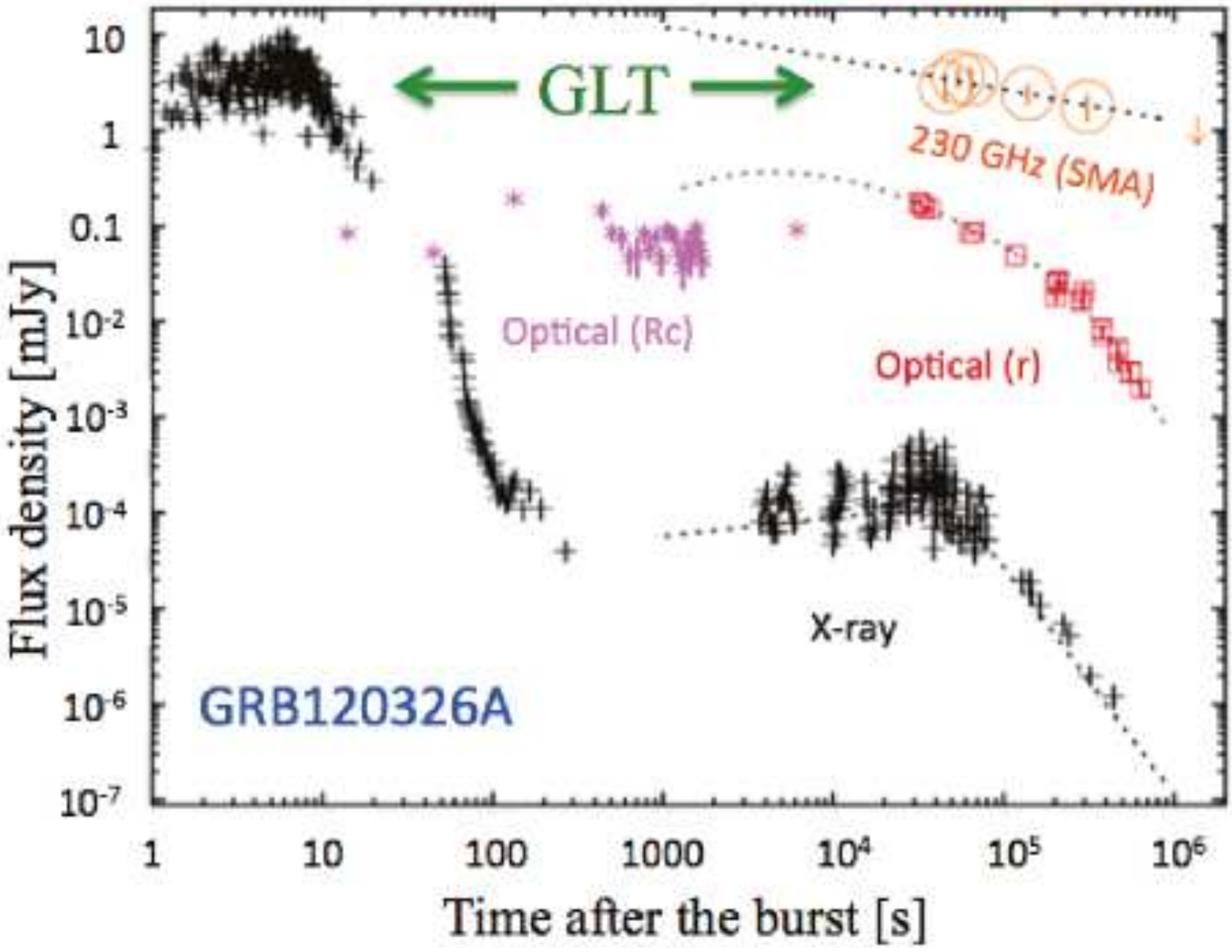
(Inoue+2007, MN, 380, 1715)



New singledish

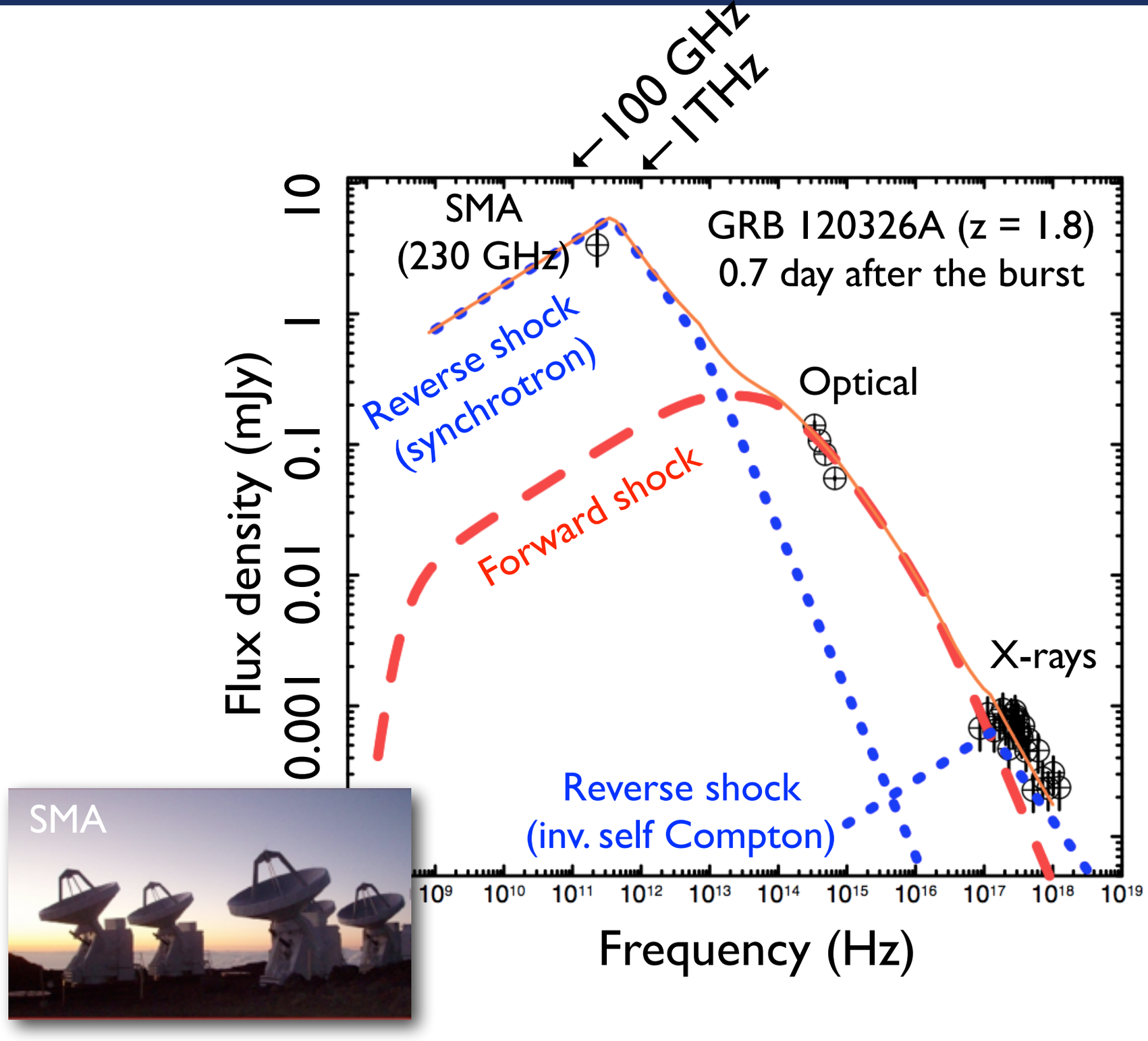
ALMA (submm interferometry)

Urata+2015


GLT
230 GHz (SMA)
Optical (Rc)
Optical (r)
X-ray
GRB120326A
Flux density [mJy]
Time after the burst [s]
10
1
0.1
10-2
10-3
10-4
10-5
10-6
10-7
1
10
100
1000
10^4
10^5
10^6

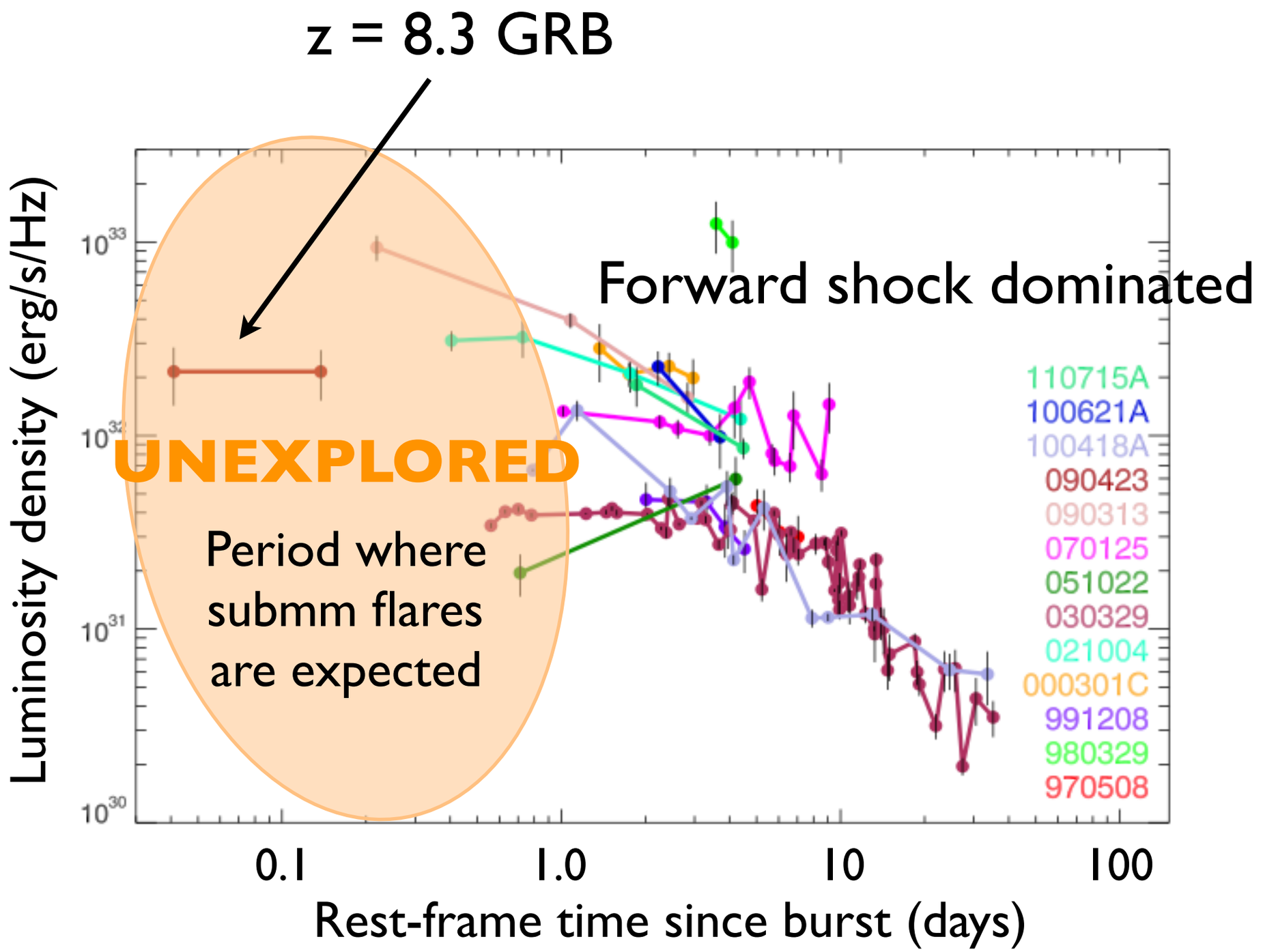
Urata+2015

SMA detection of submm flare

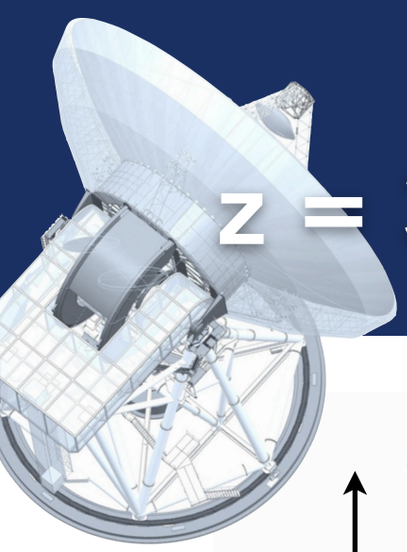


Urata+2014

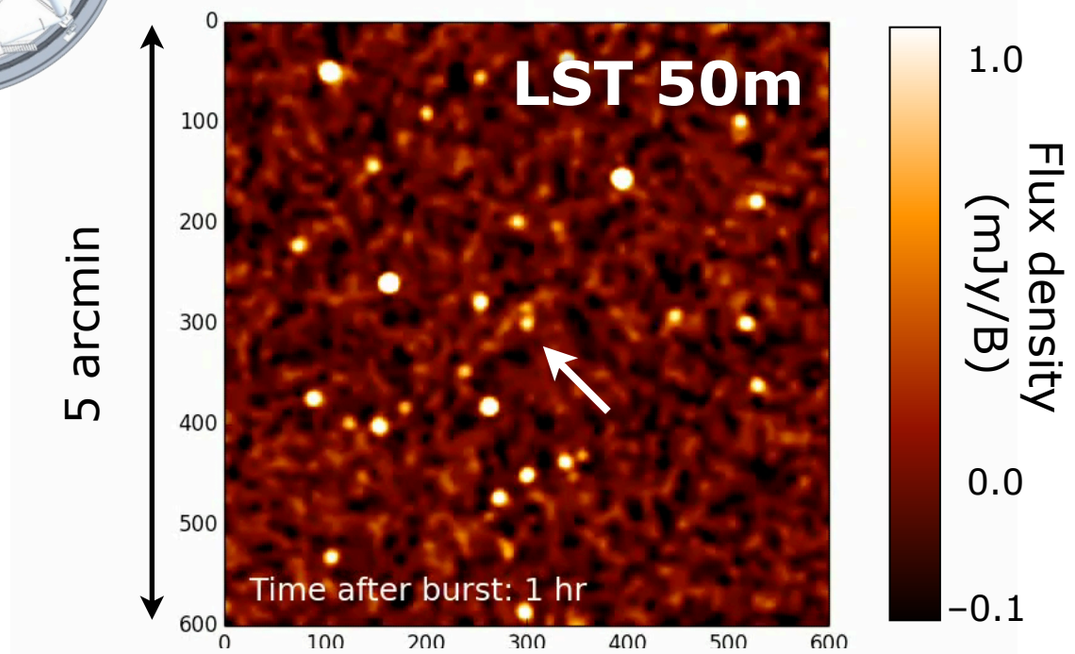
Sub/mm GRB studies to date

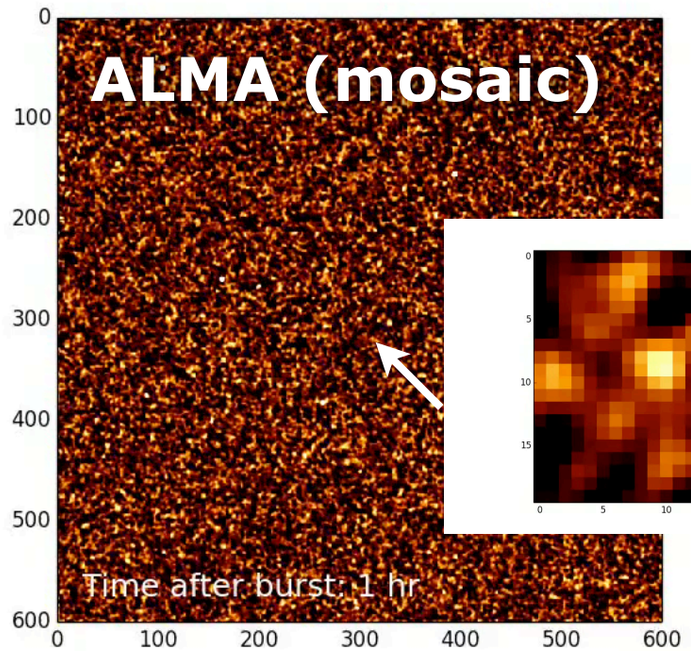


de Ugarte Postigo et al. (2012)

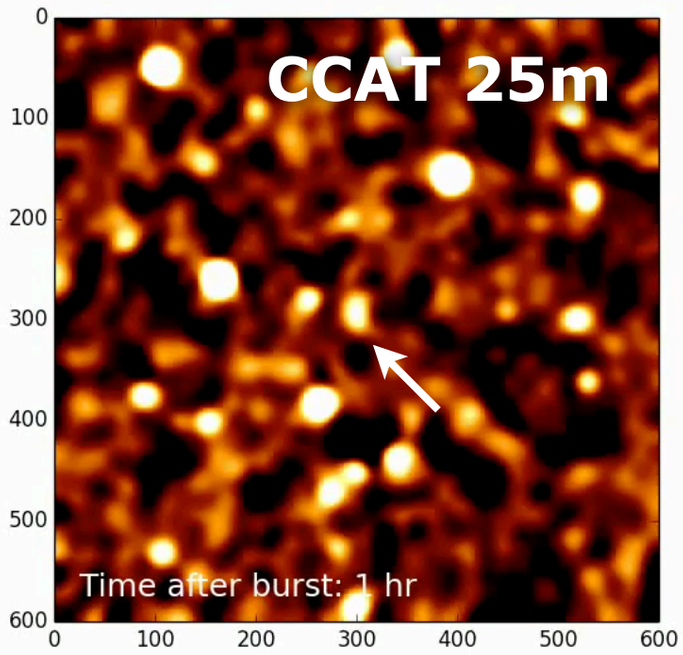


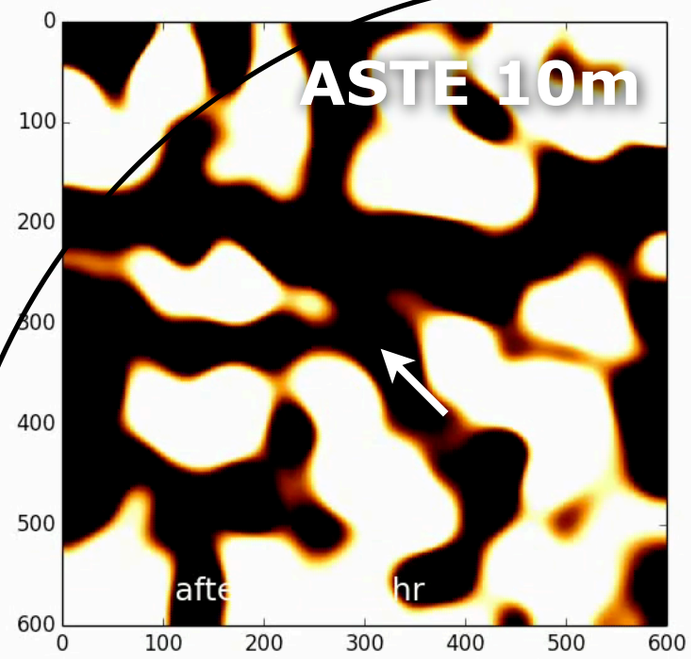
z = 30 GRB afterglow (1-12hr, 300GHz)





ALMA FoV (Band 7)

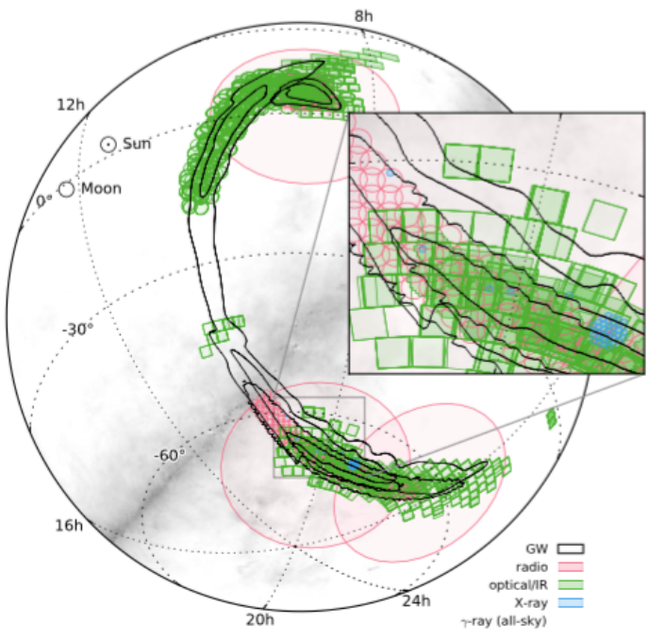




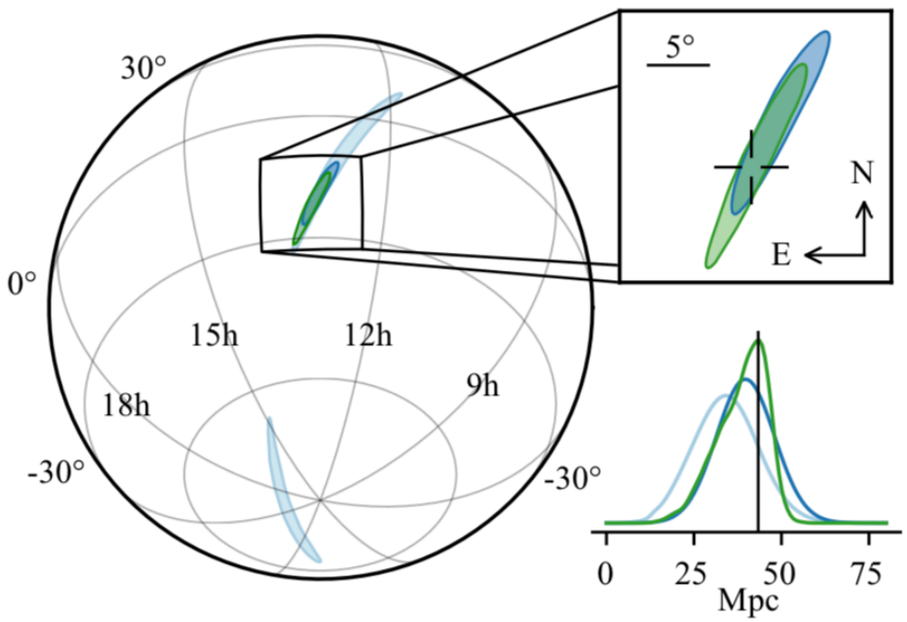
Swift/BAT error circle

EM followups of GW sources

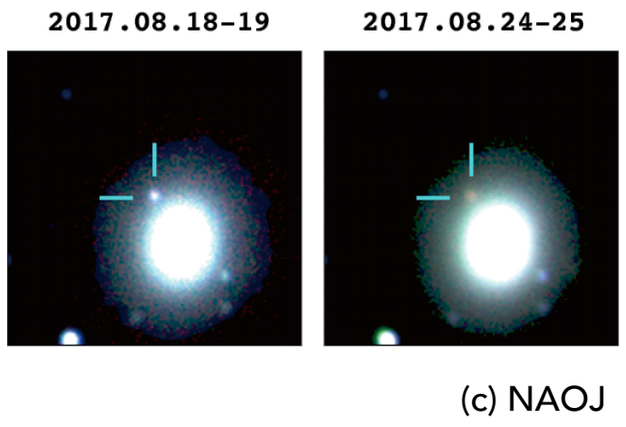
- The first GW source GW150914 had an error circle of hundreds of sq-degrees.
- The first NS-NS merger GW170817 has been localized.
- During the course of EM followups, a lot of transients were discovered.
- Potential transients in submm: GRB orphan afterglows?



Abott+16



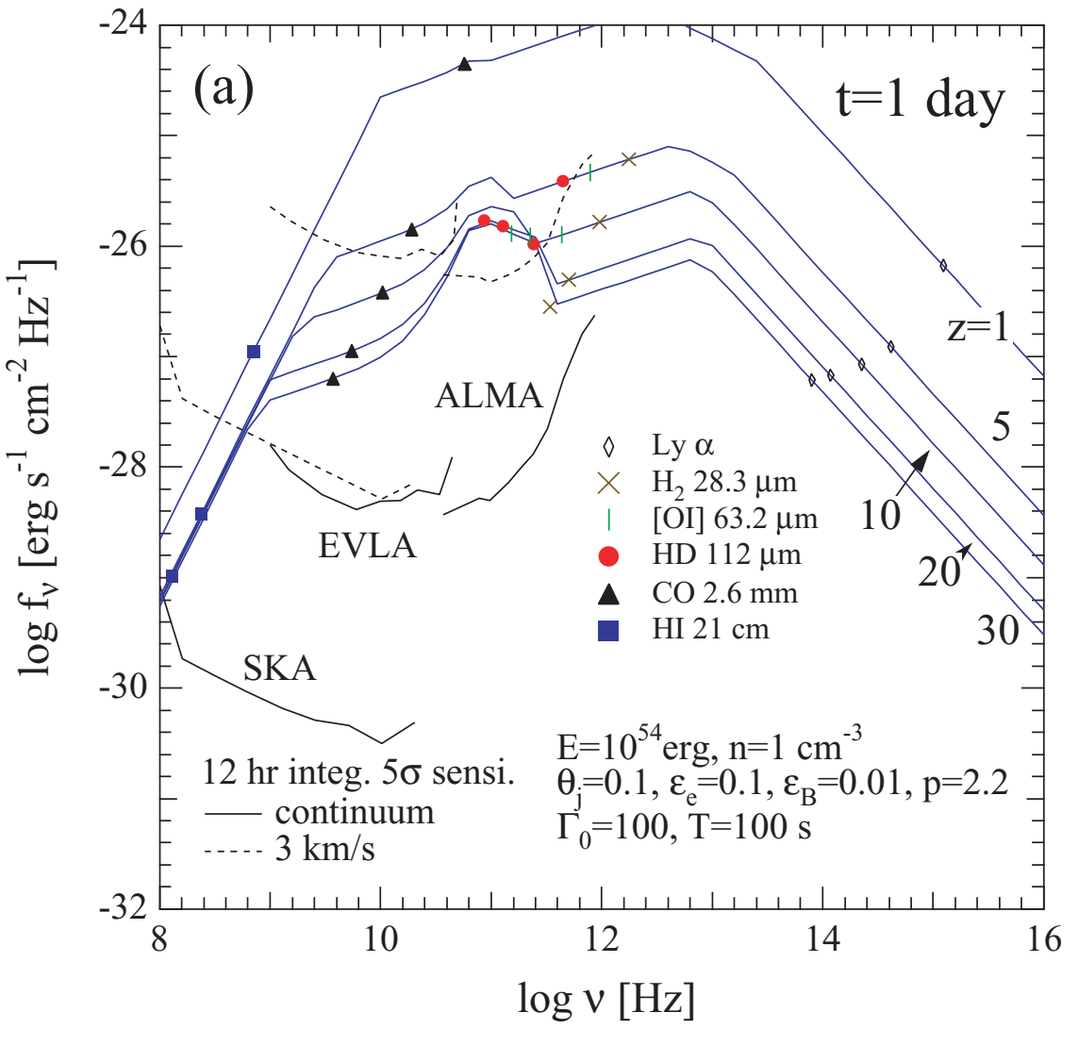
LVC+17



(c) NAOJ

If a prediction with 1'Φ error circle...

- ALMA/SKA/ngVLA + future large SD telescope (e.g., LST) will detect the interstellar/circumstellar media *in absorption*.
- Submm/radio facilities will detect the host galaxies, even if the environment is dusty!



(Inoue+2007, MN, 380, 1715)

Summary

- **LST for Extragalactic "CO/[CII] Tomography"**
  - will aim to open a new discovery space complementary to what current/planed telescopes, such as ALMA, SPICA, and Subaru/TMT are exploring/will explore.
  - will provide a basic dataset useful for extragalactic/ cosmological studies ("**Submm version of SDSS**").

- **Time-domain science in the sub/mm**
  - Wide-field SD telescopes should be powerful for time-domain science
  - Multi-messenger followups of (B-)DECIGO GW EM counterparts