Deep extragalactic survey with Tsukuba 10m THz telescope

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Outline

- Continuum imaging survey
  - Introduction
  - Sensitivity estimate
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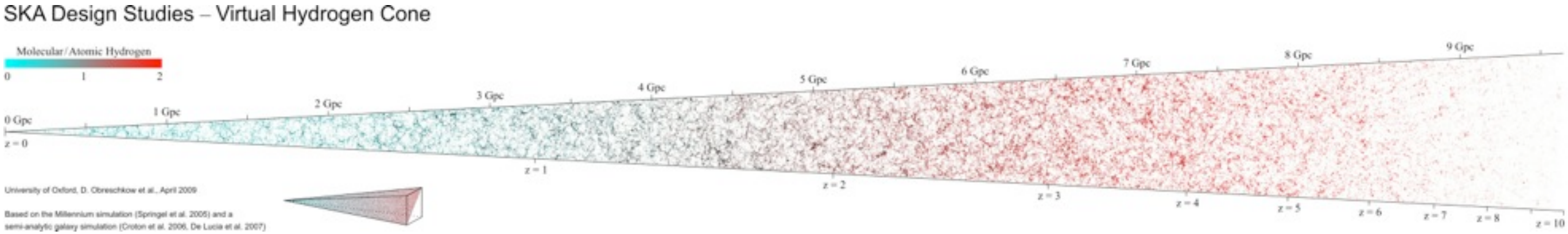
  - Summary and requirements
- Mid-z SF galaxies seen in FIR fine structure lines
  - Introduction
  - [OIII]/[CII] survey
  - Sensitivity estimate

前提

- **10m 望遠鏡のサイエンスに特化します**
  - どこに discovery space があるか？→ **まずは feasibility study をしたい**
  - **GLT/CCAT との住み分け？ (Hirashita et al. 2015, arxiv:1511.00839)**
- 30m 望遠鏡のサイエンスについては、関連する大口径望遠鏡 (LST) の検討資料をご覧ください
  - WS on “Large Aperture Millimeter/Submillimeter Telescope in the ALMA Era”
    - LSTWS2011: http://www.ioa.s.u-tokyo.ac.jp/~ytamura/WS/WS2011
    - LSTWS2012: http://www.ioa.s.u-tokyo.ac.jp/~kkohno/ALMA/index.php?Workshop120929
    - LSTWS2015: http://www.ioa.s.u-tokyo.ac.jp/~ytamura/WS/LSTWS2015
  - New Trends in Radio Astronomy in the ALMA Era: The 30th Anniversary of Nobeyama (2012)
    - http://www.nro.nao.ac.jp/~nro30/html/Symposium2012
  - 宇電懇シンポジウム
    - 田村 (2012) http://www.ioa.s.u-tokyo.ac.jp/~ytamura/Wiki/?plugin=attach&pcmd=open&file=ytamura_asteII_121222.pdf&refer=ASTE
    - 川辺 (2015) http://alma-intweb.mtk.nao.ac.jp/~udencon/symp/symp2014/symp2014-kawabe.pdf
    - 田村 (2015) http://alma-intweb.mtk.nao.ac.jp/~udencon/symp/symp2014/symp2014-tamura1.pdf
  - 野辺山ユーザーズミーティング
    - 田村 (2011) http://www.ioa.s.u-tokyo.ac.jp/~ytamura/Wiki/?plugin=attach&pcmd=open&file=ytamura_ct_110728.pdf&refer=ASTE
    - 川辺, 河野, 田村他 (2012) http://www.ioa.s.u-tokyo.ac.jp/~ytamura/Wiki/?plugin=attach&pcmd=open&file=ytamura_asteII_120726.pdf&refer=ASTE
    - 河野 (2013) http://www.nro.nao.ac.jp/~nroum/html/data/25b/NROUM-LargeTelescope-Kohno130725-toLOC.pdf
  - ASTE/ALMA Future Development Workshop
    - 田村 (2013) http://alma-intweb.mtk.nao.ac.jp/~diono/meetings/EA_Development_Meeting/Program_files/Tamura.pdf
    - 河野 (2014) http://alma-intweb.mtk.nao.ac.jp/~diono/meetings/ASTE_ALMA_2014/astealma-devws-kohno140618.pdf
    - 田村 (2014) http://alma-intweb.mtk.nao.ac.jp/~diono/meetings/ASTE_ALMA_2014/ytamura_astews_140617.pdf
    - 遠藤 (2014) http://alma-intweb.mtk.nao.ac.jp/~diono/meetings/ASTE_ALMA_2014/endo_aste_ws_dist.pdf

Viewgraph from LSTWS 2015



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

CSFH Cosmic Star-formation History

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

EoR Epoch of Reionization

Search for earliest “hidden” galaxies, first generation galaxies

Evolution of Galaxies

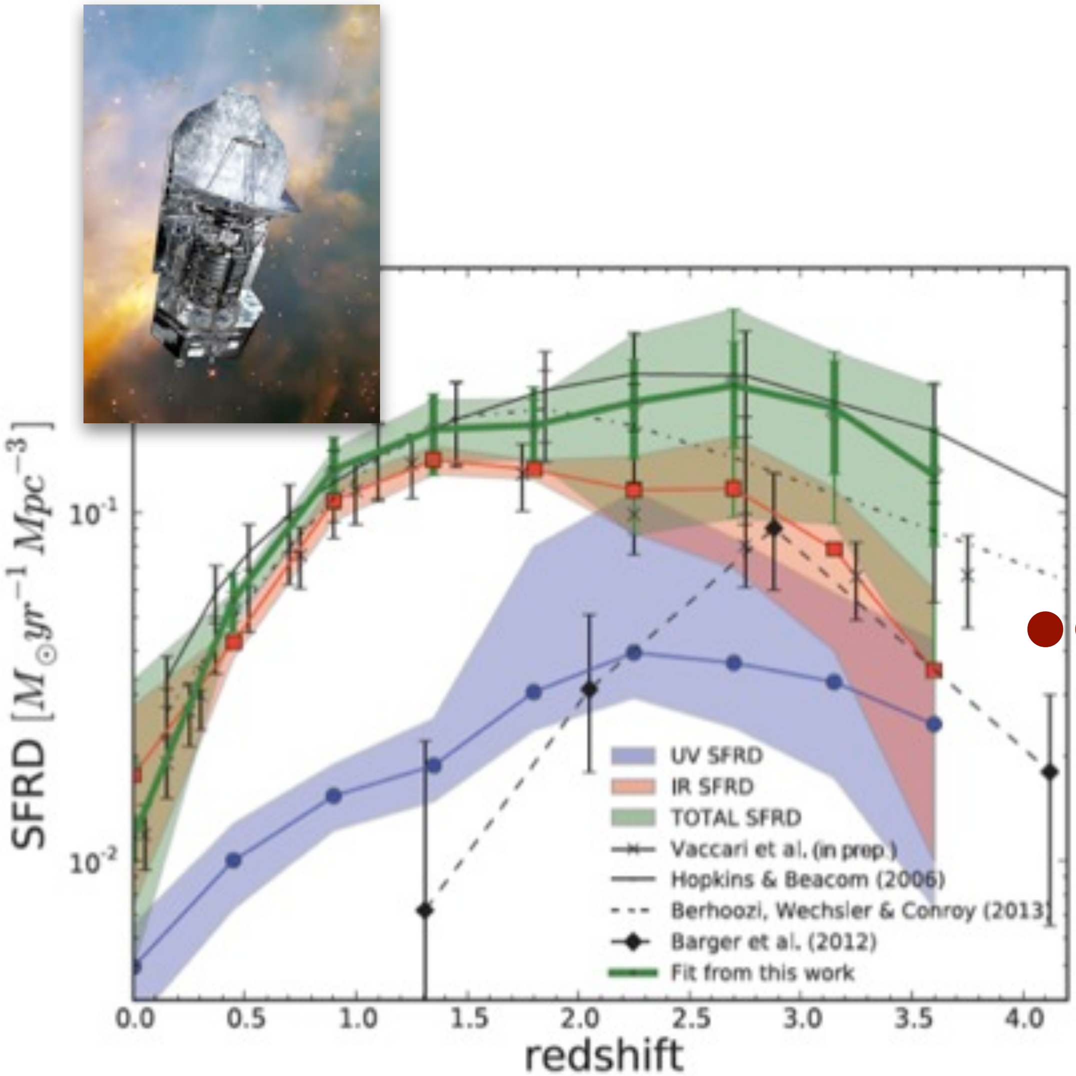
Cosmic evolution of galaxies proved through properties of interstellar medium

… and serendipitous discoveries

Line emitters, transient and variables, …

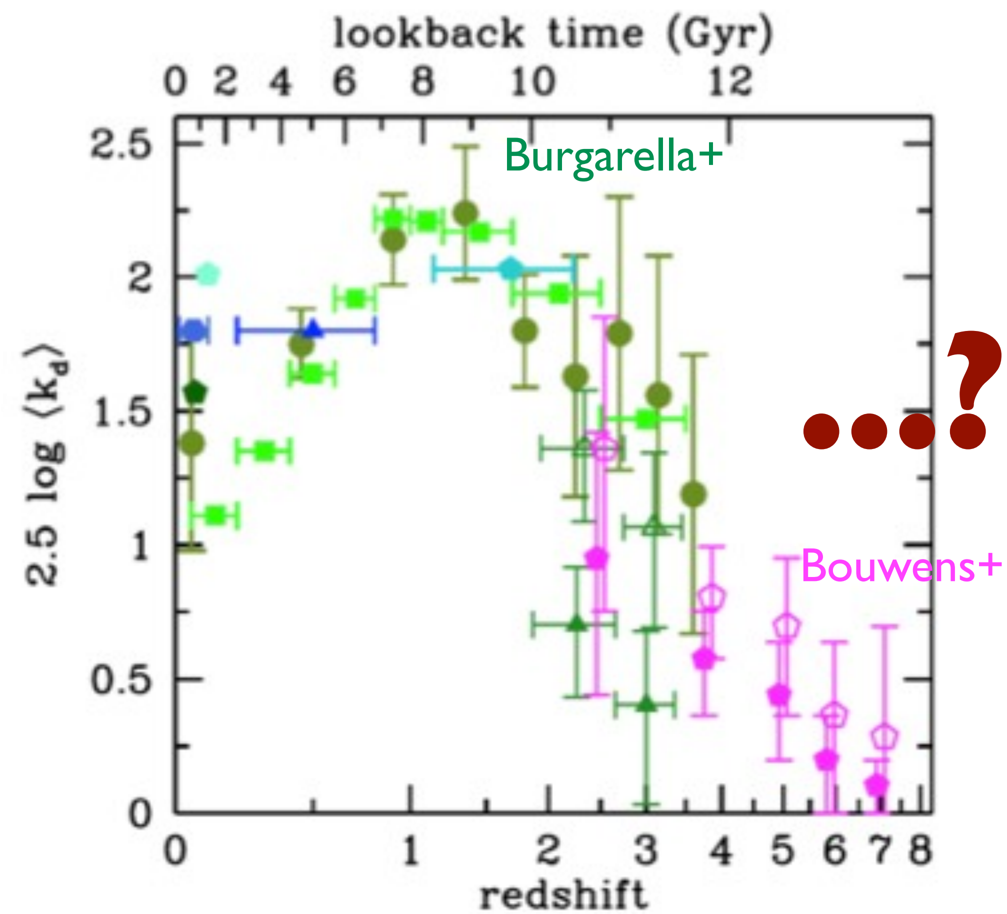
Continuum imaging survey

Cosmic star formation history: Roles of dusty galaxy population



...?

Burgarella et al. 2013



...?

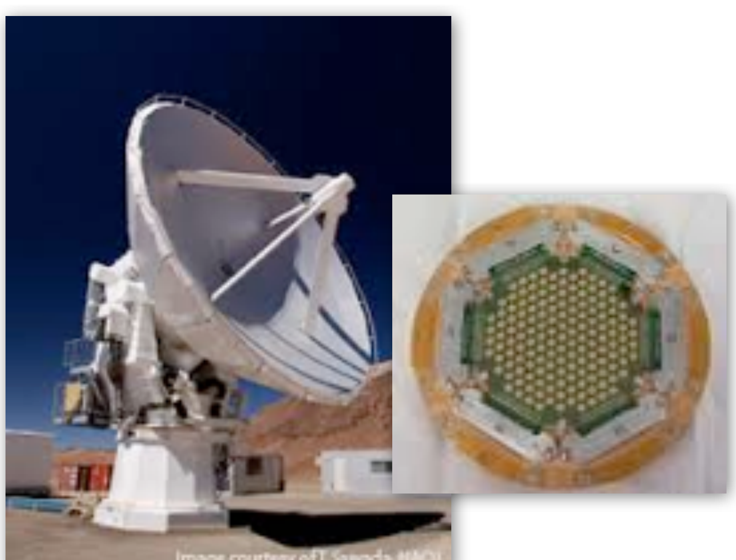
Madau & Dickinson 2014

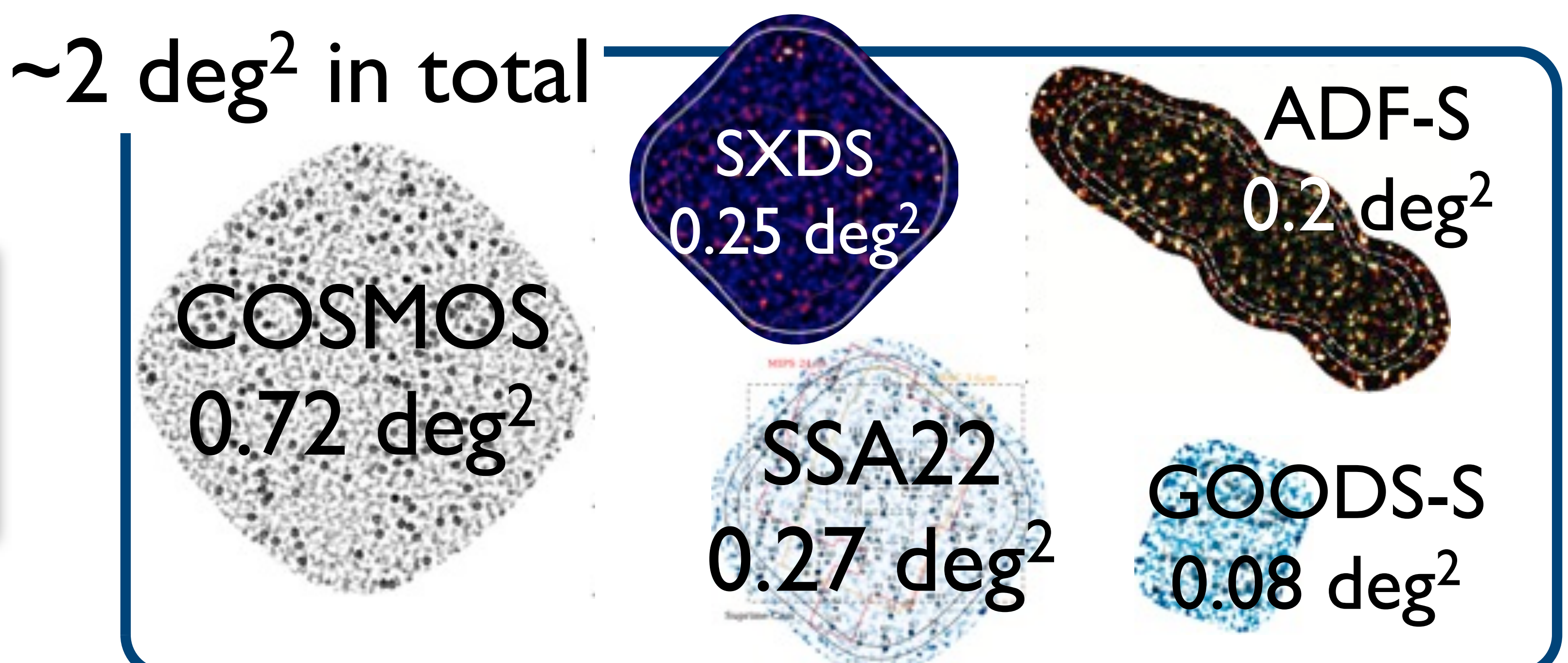
- Cosmic SFR density (SFRD) peaks at z = 1-3.
- What is the role of dusty galaxies at z > 4?
- Cosmic evolution of extinction.
- What is the role of dust in z > 4 galaxies?

cosmic "obscured" star-formation through the cosmic time is still unknown.

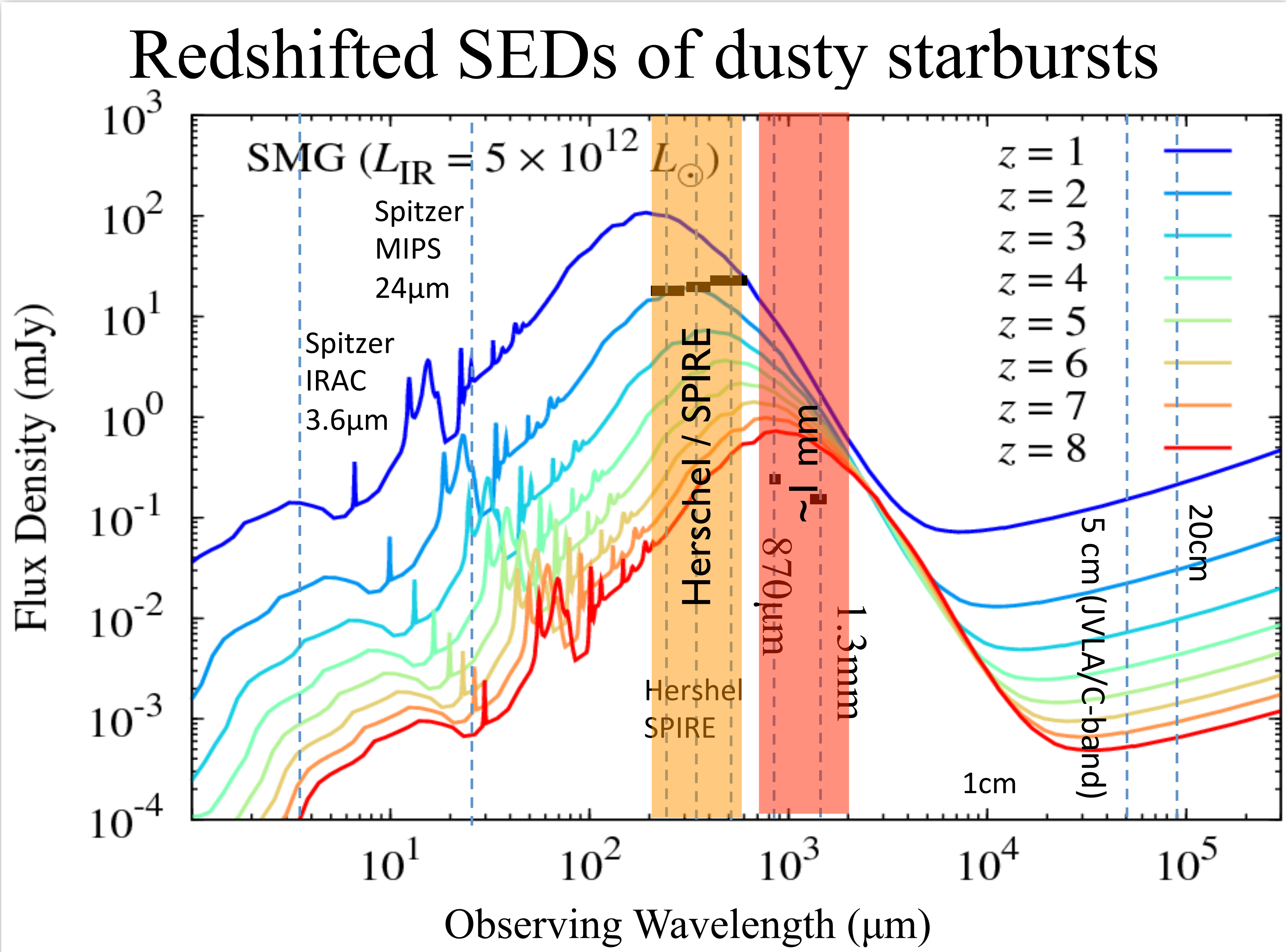
AzTEC/ASTE 1.1-mm Survey

- AzTEC 1.1mm camera (Wilson et al. 2008) on ASTE, in 2007/2008.
- 2 deg^2, $\sigma \sim$ 0.5–1 mJy/B, ~1400 SMGs, ~20 papers published (-2014 Aug.)
  - **1.1 mm number counts** (Hatsukade+10; Scott+12), **clustering** (Hatsukade+, in prep.), **relation with LSSs** (Tamura+09; Aretxaga+11; Umehata+14, Umehata+15)
  - Case studies: **lensed SMGs** (Wilson+08; Ikarashi+11; Takekoshi+13; Tamura+15), **SMGs w/ X-ray sources (proto-QSOs)** (Tamura+10; Humphyley+11; Johnson+13)
  - **Photo-z's, redshift distribution** (Yun+12; Umehata+14; Ikarashi+15)
- ALMA follow-up observations on-going (Ikarashi+, Umehata+, Kohno+, Suzuki+ for Cy1; Hatsukade+, Umehata+, Kohno+, Lee+ for Cy2; many for Cy 3)





THz to ~1mm color (photo-z with dust SEDs)



Viewgraph prepared by Kohno-san

Sensitivity: Calculation

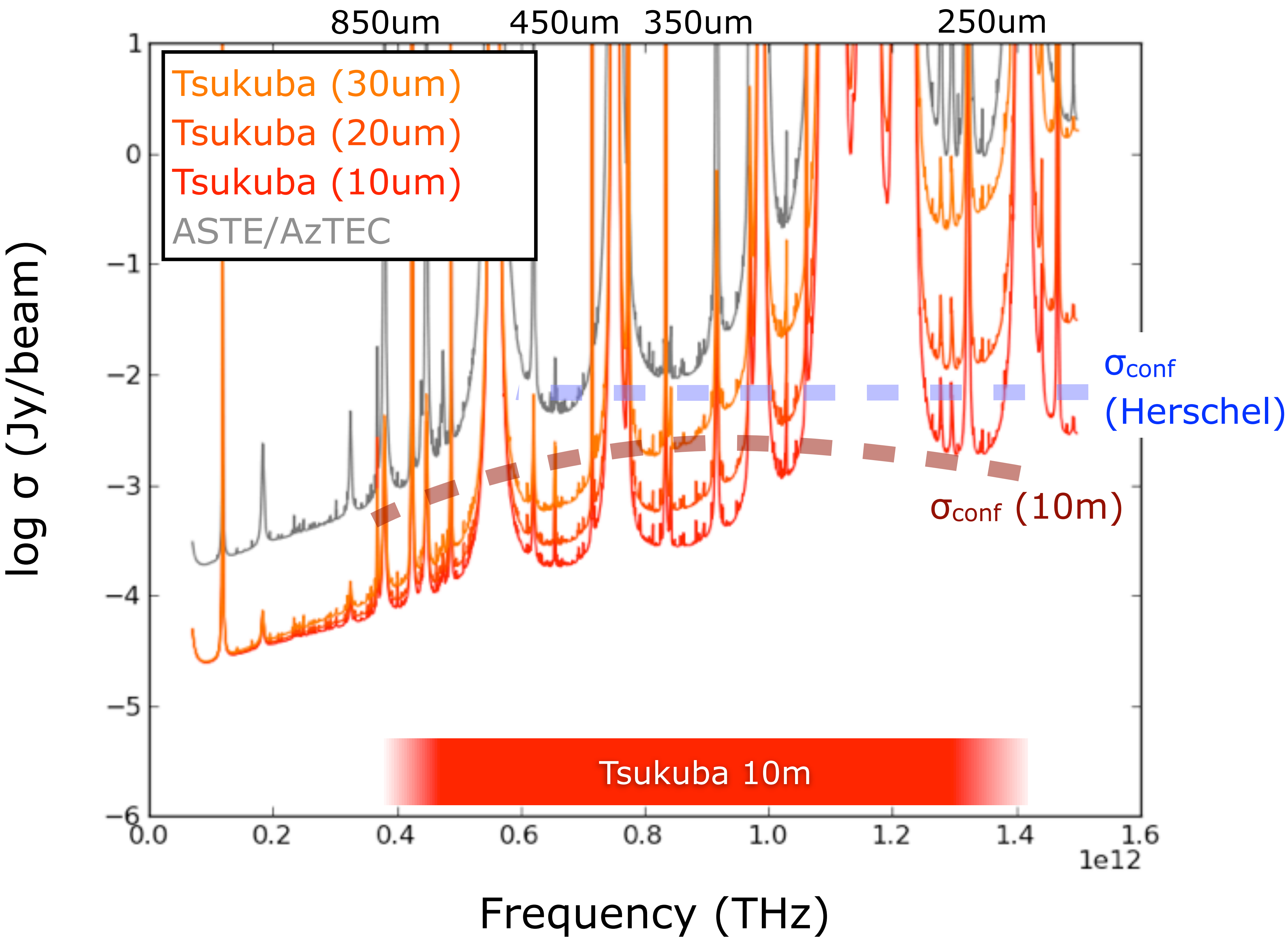
- We consider -
  - 1) Ab-initio noise estimate to account for MKID and optical efficiencies (Endo+2016, de Visser+2014);
  - 2) Ruze formula to account for primary aperture efficiency;
  - 3) Atmospheric model to account for atmospheric transmission and photon noise at the Antarctic and Chajnantor (Paine +2012);
  - 4) Optimally filtered image with an appropriate beam size at an arbitrary observing frequency to mimic the actual map-making procedure which maximizes the point source sensitivity.

- The estimates are consistent with those prepared by Nakai-san/Kuno-san and actually observed with ASTE/AzTEC.

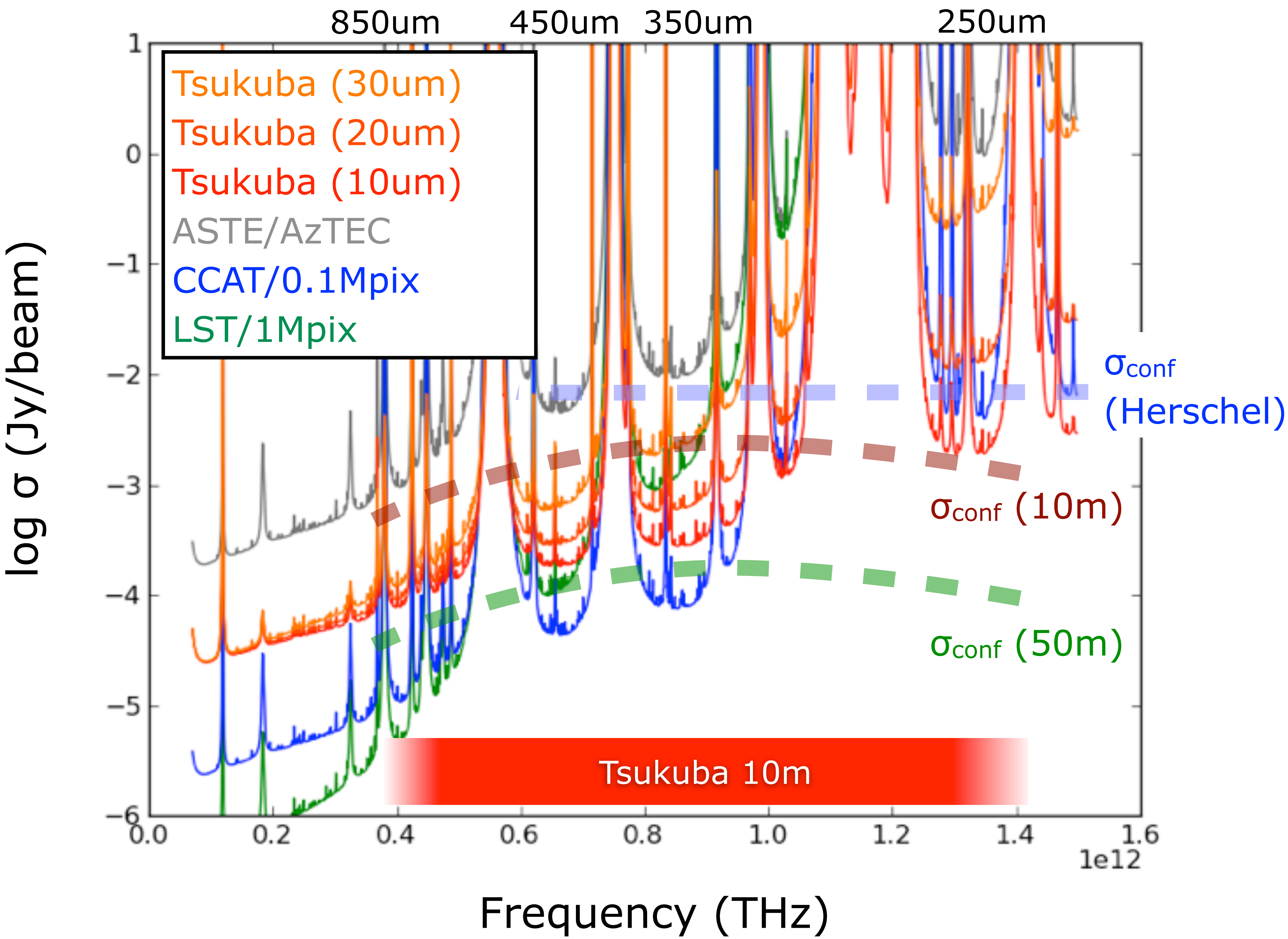
Sensitivity: Assumptions

- **Tsukuba 10-m Telescope**
  - Surface error = 10, **20**, 30 micron
  - N_pix = 6000 pixels (350 um)
  - R = 12 (ΔB = 80 GHz @1 THz)
  - Antarctic: PWV = 140 um, T_atm = 200 K
- **Other telescopes (for reference)**
  - ASTE/AzTEC: D=10m, surface=20 um, Npix=100 pix
  - CCAT: D=25m, surface=15um, Npix=0.1 Mpix
  - LST: D=50m, surface=45um, Npix=1 Mpix
  - R = 12 (ΔB = 80 GHz @1 THz)
  - Chajnantor: PWV = 600 um, T_atm = 273 K
- **Fiducial model survey**
  - Area = 1 sq-deg
  - t_on-source = 1000 hr

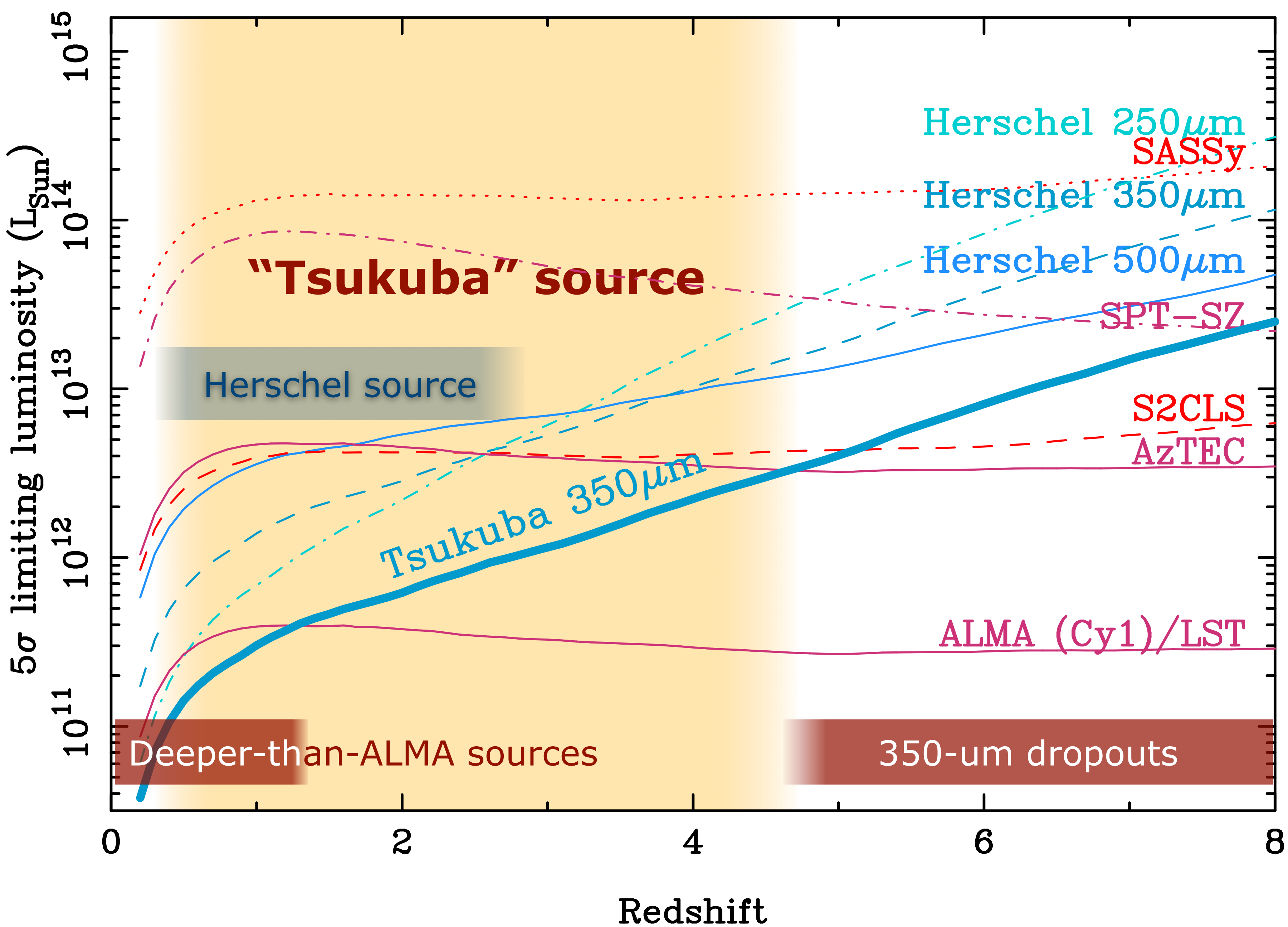
Sensitivity: 1 sq-deg survey



Sensitivity: 1 sq-deg survey



Sensitivity: Limiting IR luminosity



Brief comment on science cases

- **1. Connecting "single-dish selected" and "ALMA detected" populations at z ~ 1–4**
  - (i) Cross-calibration of Herschel results
    - Confusion is always bad for extragalactic studies.
    - Resolving Herschel sources at deeper limit will drastically change of the statistical aspect of Herschel results (just like ALMA has changed the picture we obtained with SCUBA/AzTEC).
    - Number counts, cosmic SFR density, counterpart identifications, etc.
  - (ii) Statistical studies of "sub-mJy" sources
    - ALMA FoV is too small.
    - Multi-λ understanding of more "normal" galaxies that are responsible for cosmic SF.

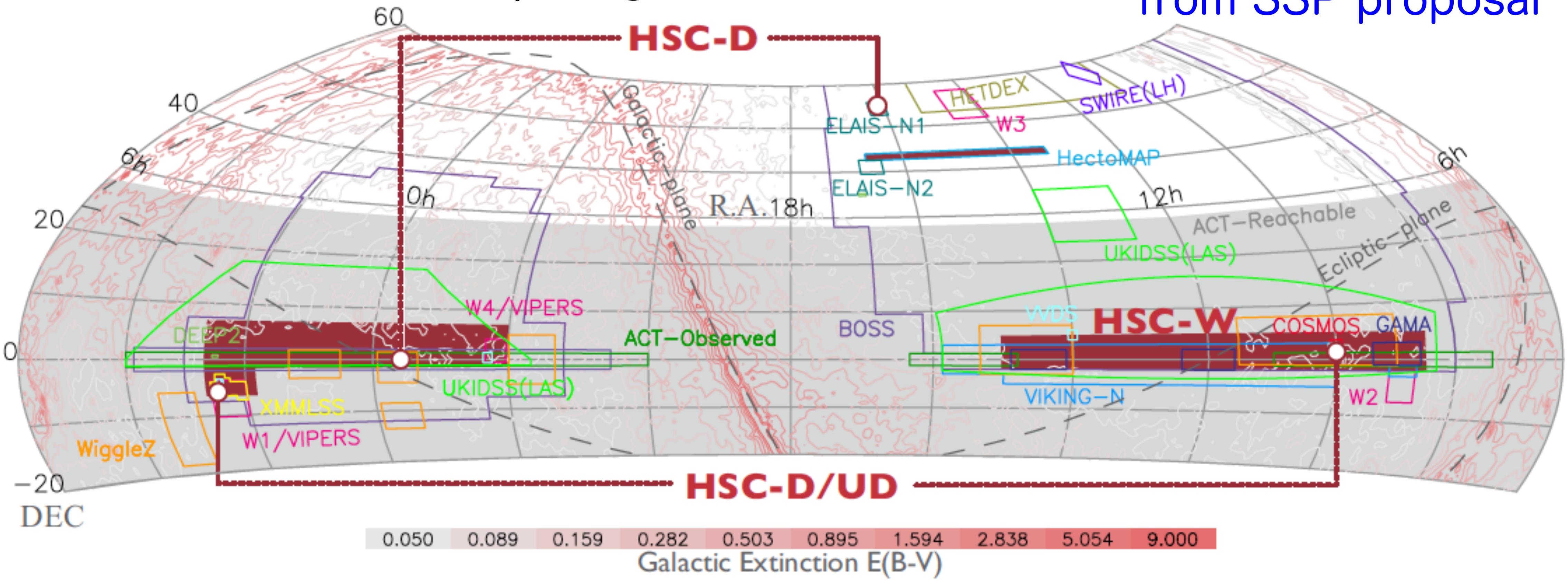
- **2. Extracting THz-dropouts to explore the z > 5 population of SMGs**

Summary (continuum imaging survey)

- **Science goals**
  - extend the Herschel results out to $z \sim 5$ (cf. Herschel $z < 3$) and cover the era of the cosmic high-noon.
  - high-z ($z > 5$) sources will be extracted by combining ~1mm results, which is more efficient than Herschel/SPIRE bands.
- **Sensitivity**
  - will reach confusion limit (σ_{conf}(350um) ~ 1 mJy) in reasonable amount of time (~1000 hr).
  - It is essential to have (1) kilo-pix array cameras and (2) transparent sky in THz bands.
- **Requirements / Recommendations**
  - Multi-color photometry
  - Surface error < 20 um to surpass Herschel and CCAT (Atacama, 5000m) at 1.3 THz
  - Low EL angles to access the equator $\delta \sim 0°$ (or at least GOODS-South at $\delta = -35°$)
  - Tight coordination with SPICA (e.g. SEP/ADF-South)

SSP-HSC survey regions

from SSP proposal



Three-layer survey (wedding-cake-style)

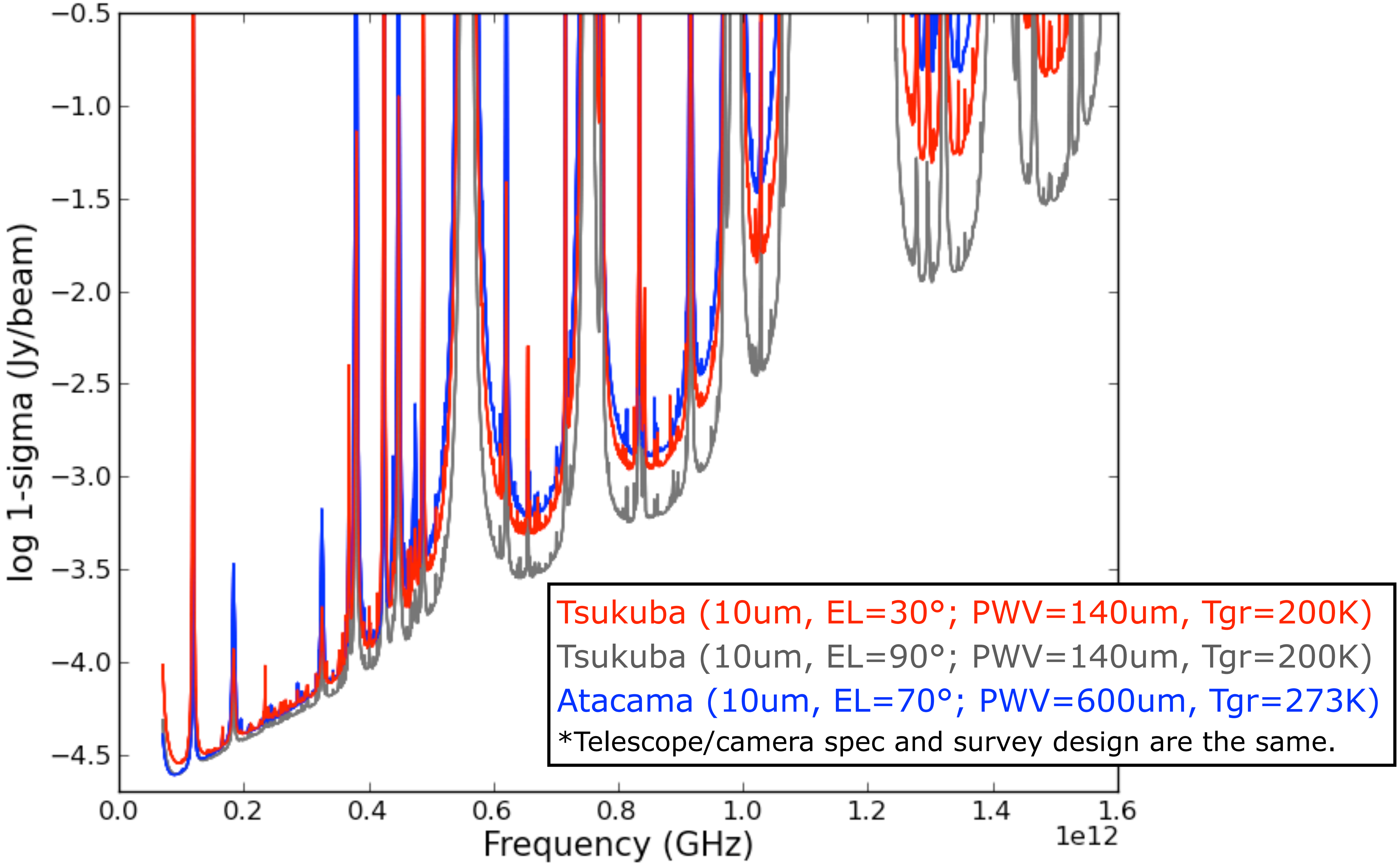
Wide: Fall (~640 deg^2), Spring (~680 deg^2), North (~55 deg^2)
~1400 deg^2 in total

Deep: ~7 deg^2 (4 FoVs) x 4 regions = ~28 deg^2 in total
around COSMOS, SXDS, ELAIS-N1, & DEEP2-3

Ultradeep: ~1.75 deg^2 (1 FoV) x 2 regions = ~3.5 deg^2 in total
around COSMOS & SXDS

Viewgraph prepared by Nagao-san

Antarctic vs. Atacama



Mid-z SF galaxies
seen in FIR fine structure (FS) lines

of detections FS lines is growing…

References

[CII]157 detections
- Maiolino+2005 (SDSS1148)
- Iono+2006 (BR1202)

- Maiolino+2009 (BRI0952)
- Walter+2009 (SDSS1148)

- Hailey_Dunsheath+2010 (MIPS1428)
- Ivison+2010 (Eyelash*)
- Stacey+2010 (z~1)
- Wagg+2010 (BRI1335)

- Cox+2011 (SDP141)
- De Breuck+2011 (LESS0332)
- Valtchanov+2011 (SDP81*)

- Carilli+2012 (BR1202)
- Gallerani+2012 (BRI0952)
- Maiolino+2012 (SDSS1148)
- Salome+2012 (BR1202)
- Swinbank+2012 (ALESS SMGs)
- Venemans+2012 (ULAS1120)
- Wagg+2012 (BR1202, LAEs)

- Carniani+2013 (BR1202)
- Rawle+2013 (HLS0918)
- Riechers+2013 (FLS3)
- Wang+2013 (z~6 QSOs, deficit, Mdyn, LF)
- Willott+2013 (J2329)

- De Breuck+2014 (LESS0332)
- Decarli+2014 (BR1202)
- Ferkinhoff+2014 (SDP11)
- Riechers+2014 (Az3, LBG)
- Williams+2014 (BR1202, LAEs)

[NII]205 detections
- Bradford+2011 (APM08279)
- Combes+2012 (HLS0918)
- Decarli+2012 (APM08279, MM18423)
- Nagao+2012 (LESS0332)
- Decarli+2014 (BR1202)

[NII]122 detections
- Ferkinhoff+2011 (SMM02399, Cloverleaf)

[OIII]88 detections
- Ferkinhoff+2010 (APM08279)
- Valtchanov+2011 (SDP81*)

[OIII]52 detections
- Sturm+2010 (MIPS1428*)

[OI]63 detections
- Sturm+2010 (MIPS1428*)
- Ferkinhoff+2014 (SDP11*)

@ Simple interpretation
[CII]/FIR deficit
[CII] as SF tracer
- de Looze+2011*

[CII] morphology and dynamics
[CII]/CO PDR analysis
[CII] luminosity function
- Swinbank+2012
- Wang+2011

@ Photoionization / PDR analysis
[NII]/[CII] metallicity, PDR-HII
- Nagao+2012
- Decarli+2014

[OIII]/[NII] UV hardness
- Ferkinhoff+2010
- Ferkinhoff+2011

*) Herschel results

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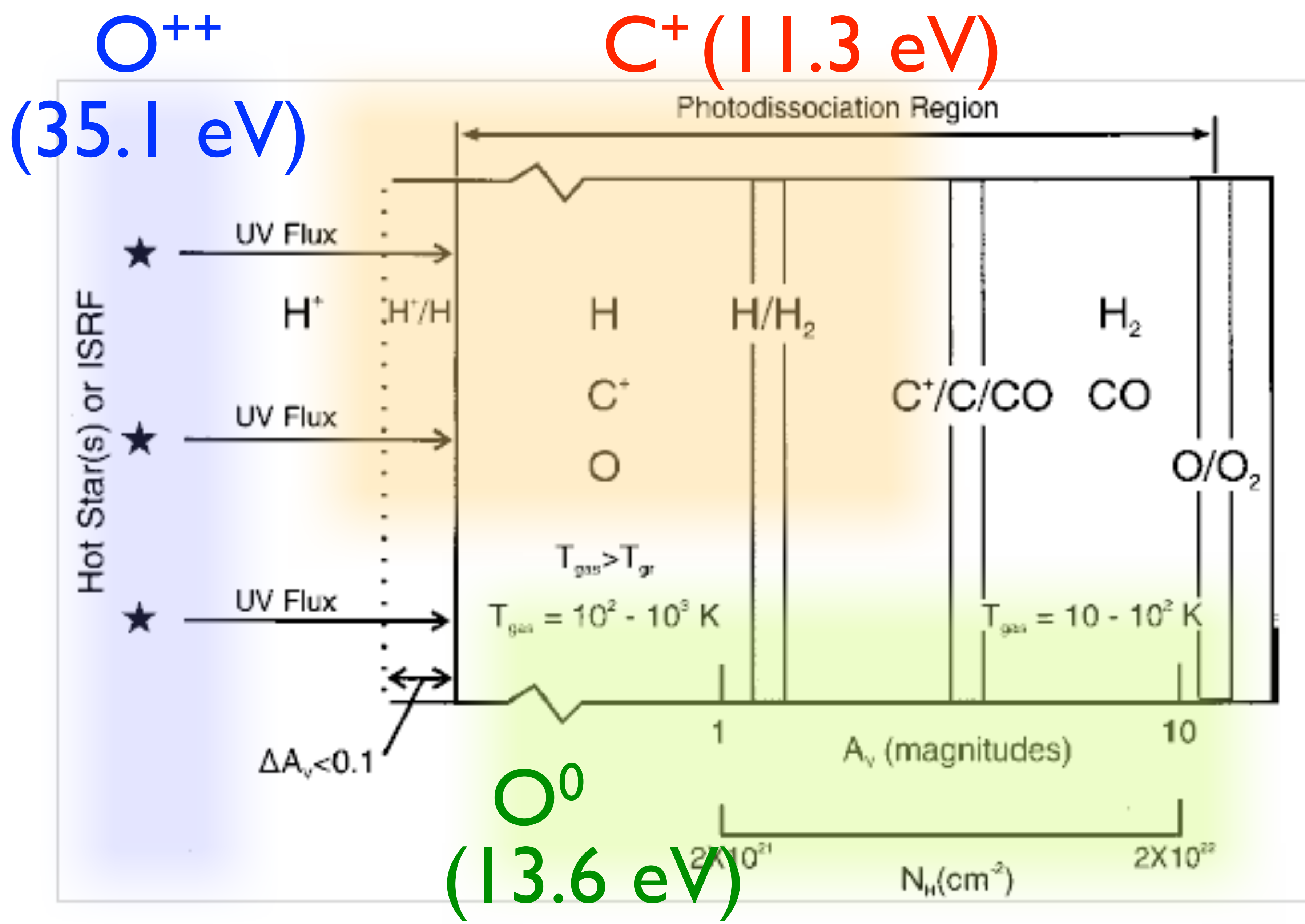
Viewgraph from ALMA WS 系外微細構造線勉強会 2014（田村）

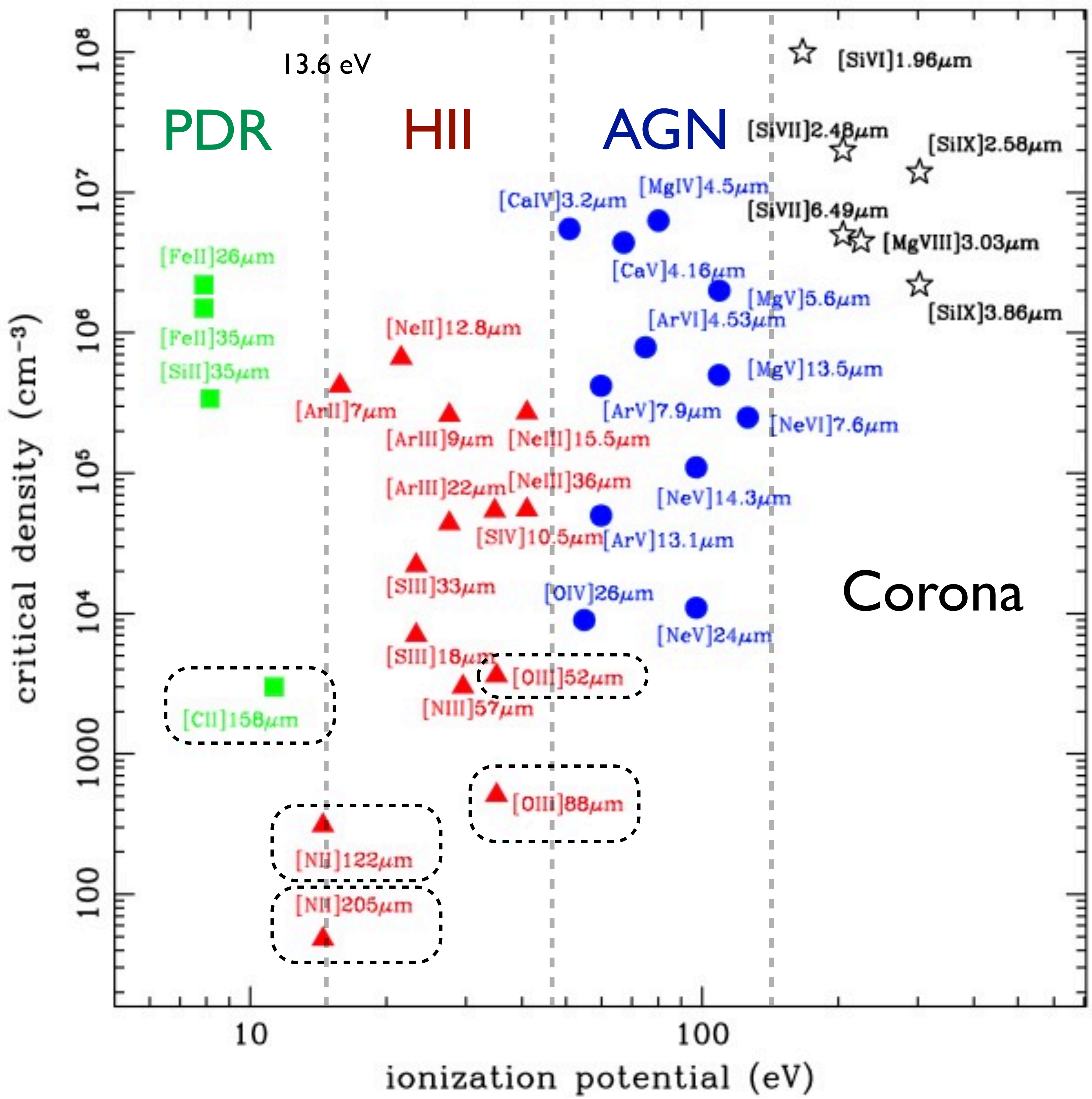
Photodissociation region



Tielens & Hollenbach 2005, Phys. Rev.

9

Viewgraph from ALMA WS 系外微細構造線勉強会 2014（田村）



Spinoglio+2012

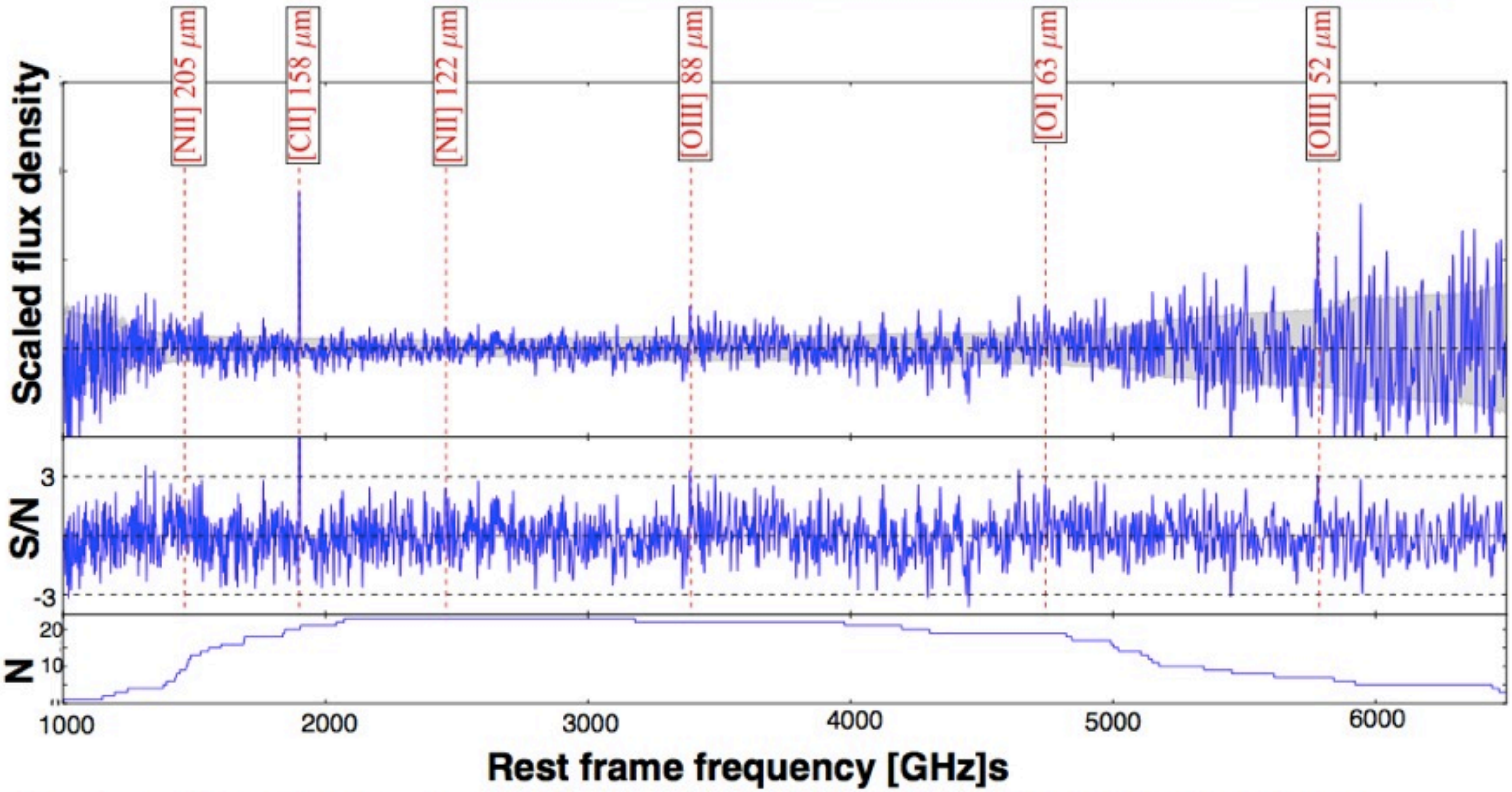
20

SMG stacks

Results

S/N >5 は [CII] だけ
[CII] で規格化した微細構造輝線の 3σ upper limit

[OI] 63	[OIII] 52	[OIII] 88	[NII] 122	[NII] 205
0.36	0.85	0.27	0.19	0.27

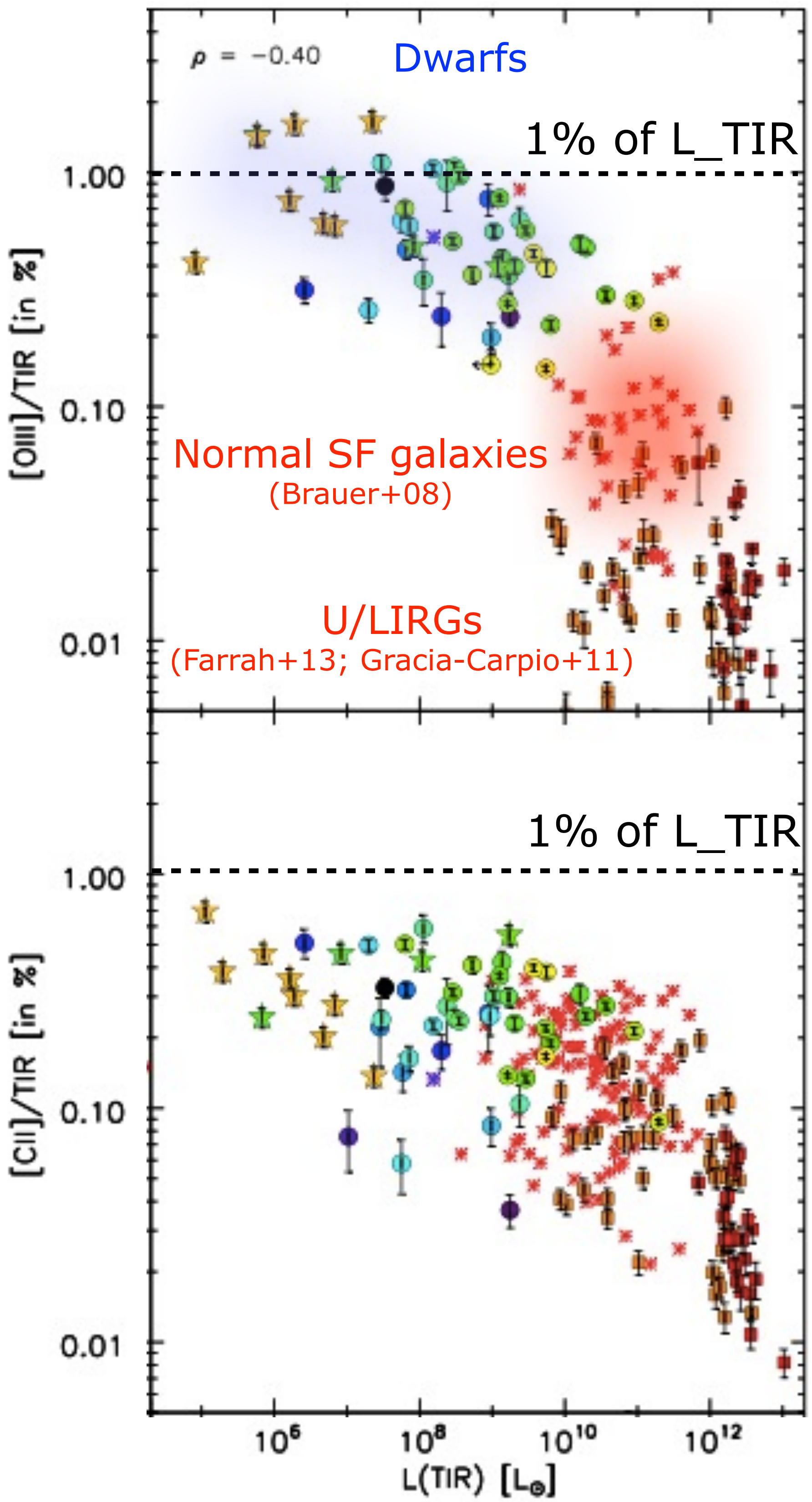


Herschel 宇宙望遠鏡分光データの stacking 解析によるサブミリ波銀河の物理化学状態の制限 (X37b)

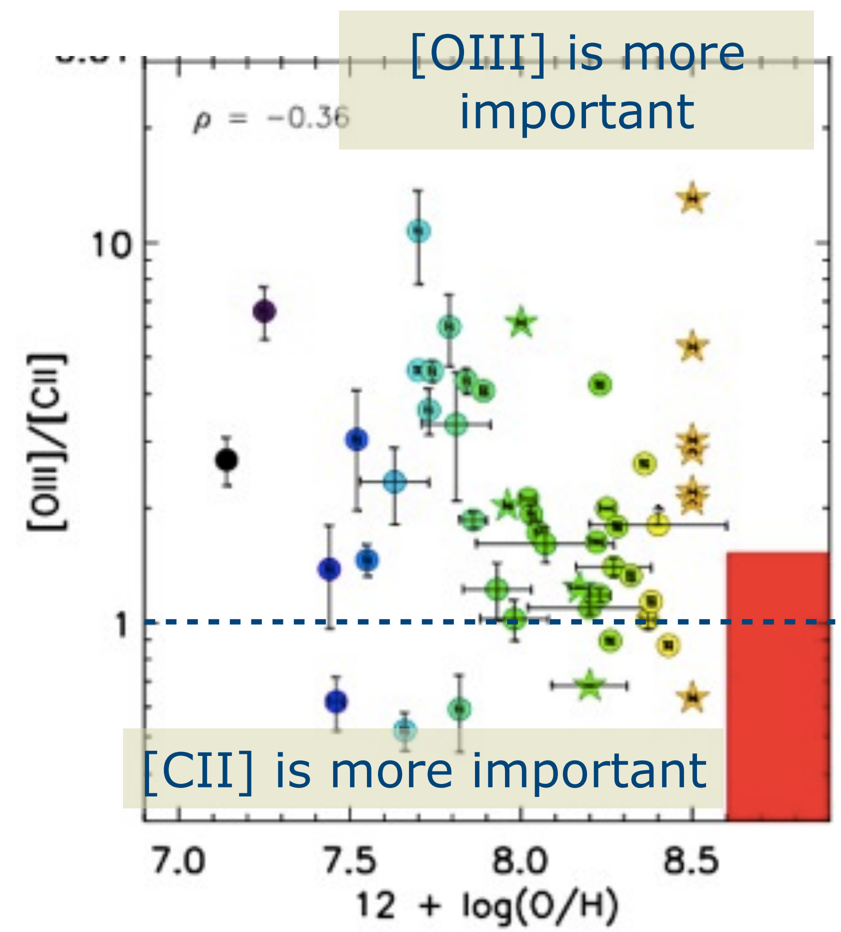
山口, 田村ほか (2015) 日本天文学会秋季年会

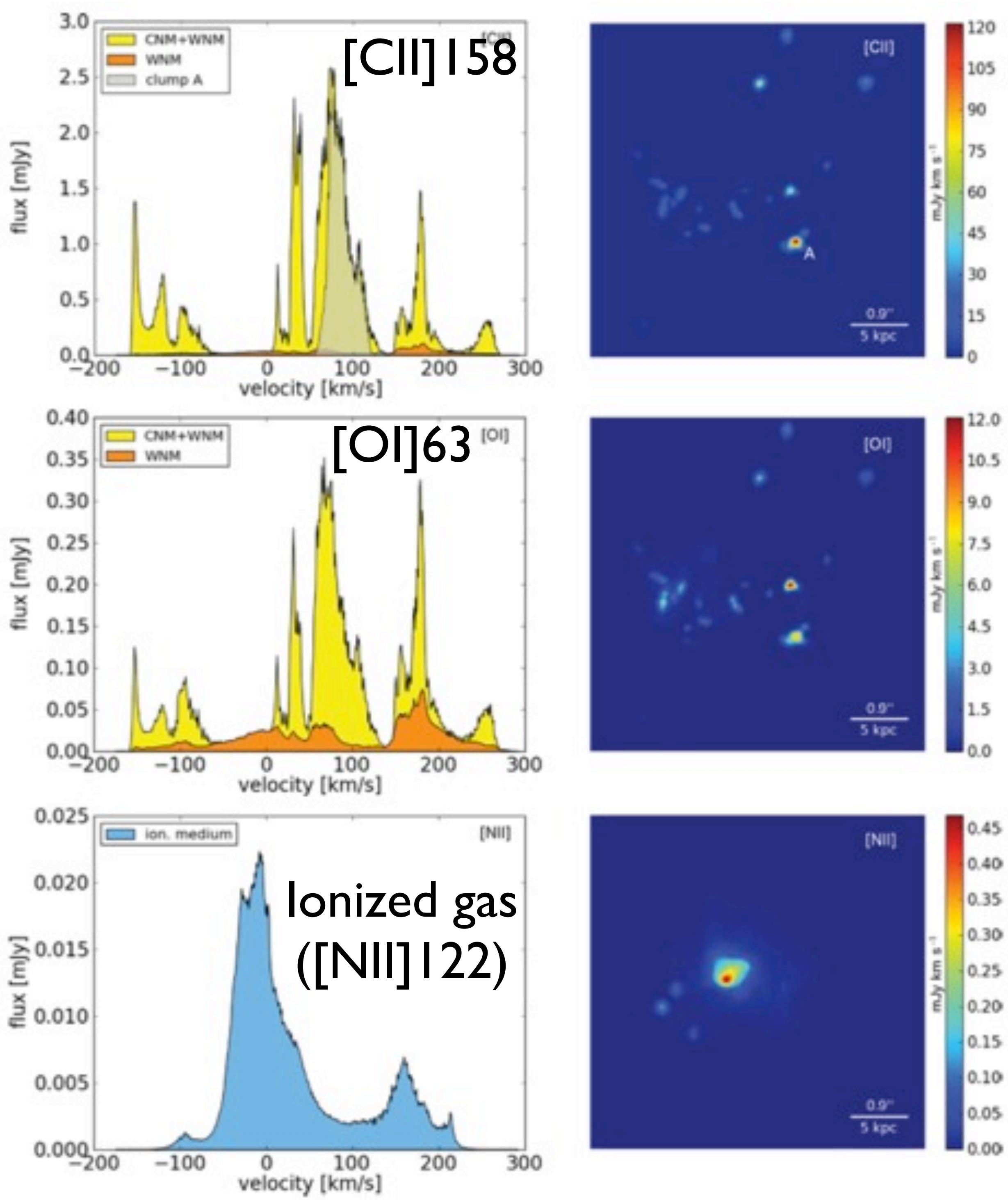
Herschel Dwarf Galaxy Survey

Cormier+2015

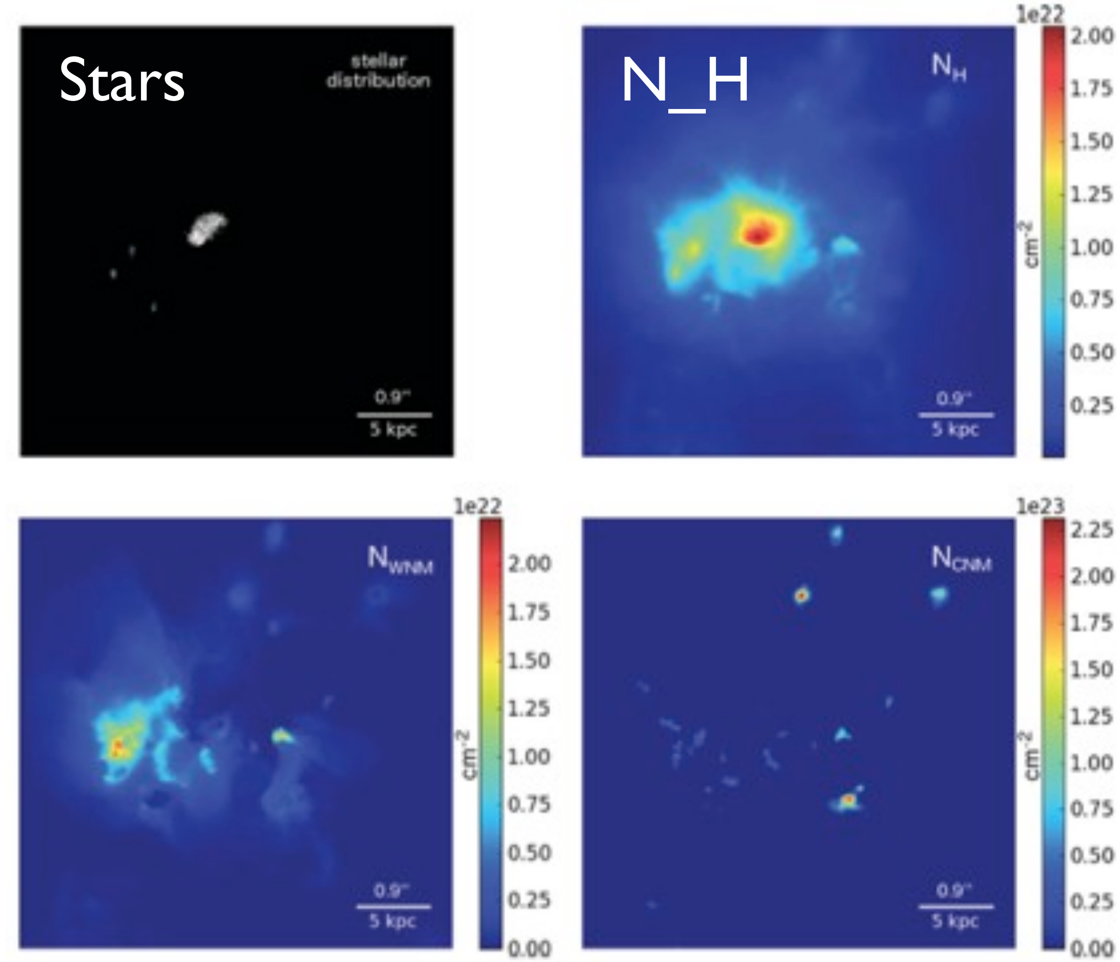


- ❖ Local dwarfs (i.e. low metallicity SF galaxies) as low-z analogs of typical SF galaxies at high redshift.
- ❖ [OIII]88 is the brightest
  - ❖ L_[OIII]88 / L_[CII]158 > 1 (up to ~10).
- ❖ High ionization state and/or "truncated" PDRs (matter-bounded Stromgren sphere)?





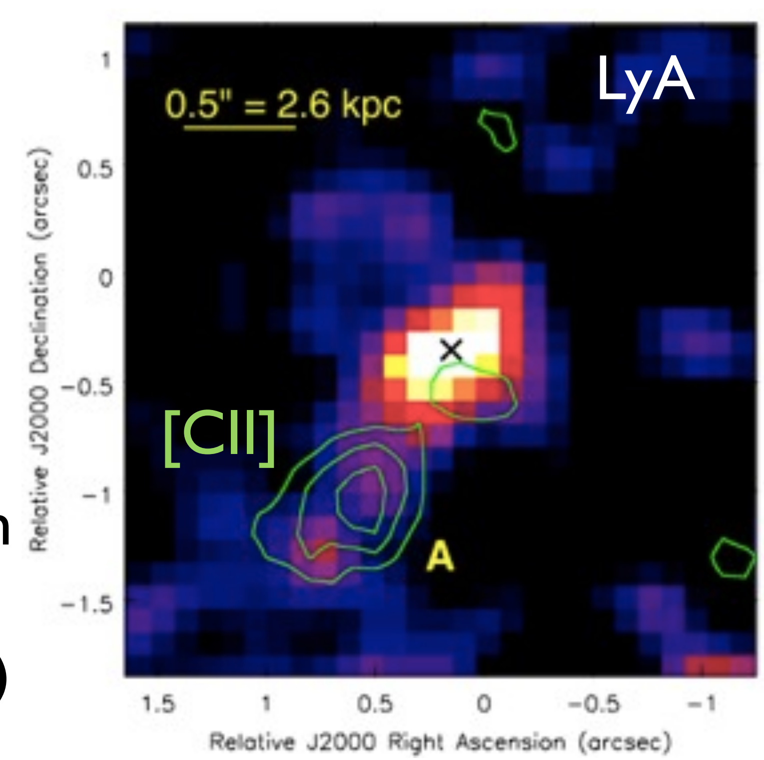
Vallini+2013



N_WNM
1cm^{-3}, 5000K

N_CNM
50cm^{-3}, 250K

z = 7.1 LAE with
ALMA/[CII]
(Maiolino+2015)

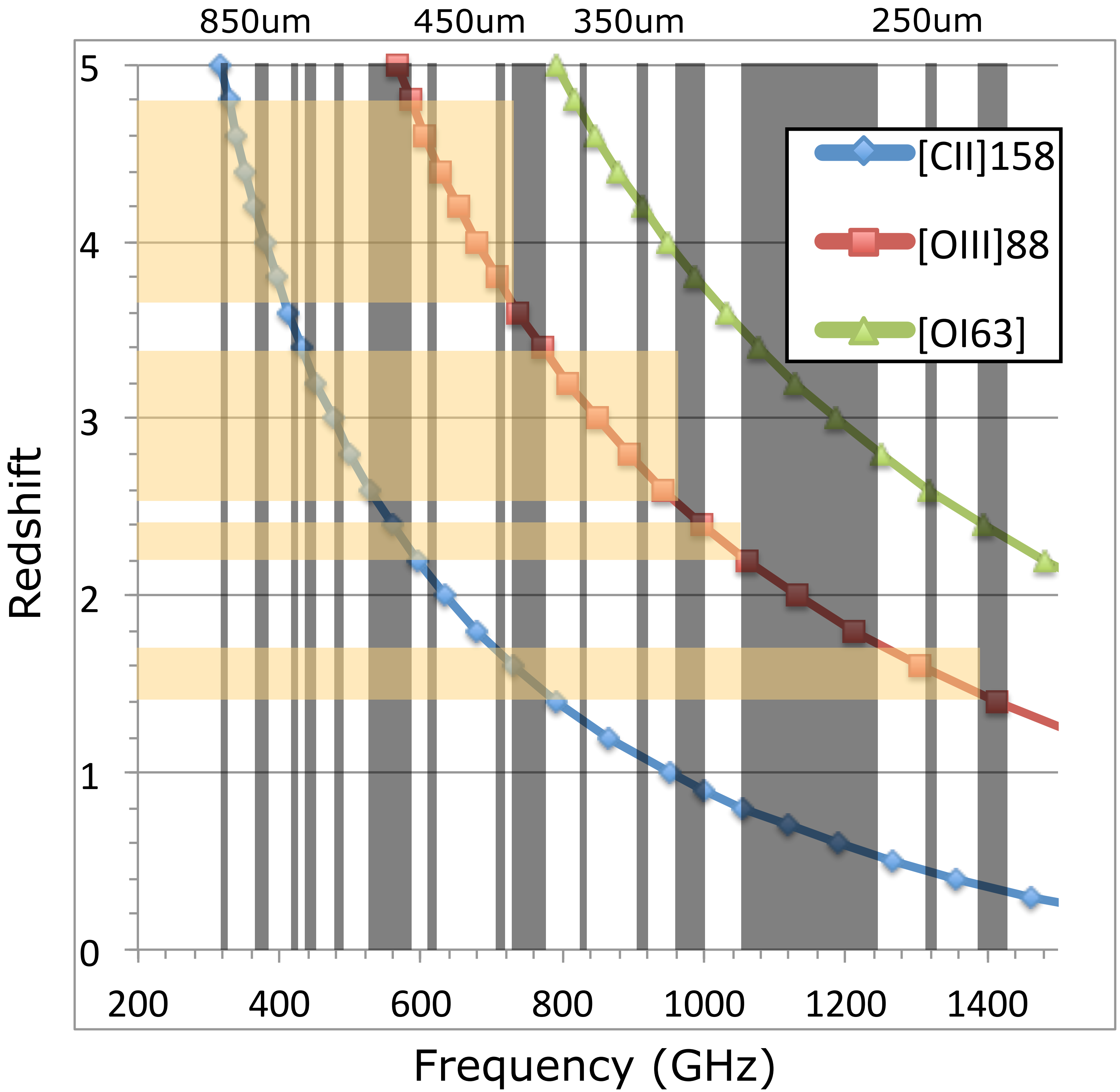


[OIII]88/[CII]158 Survey

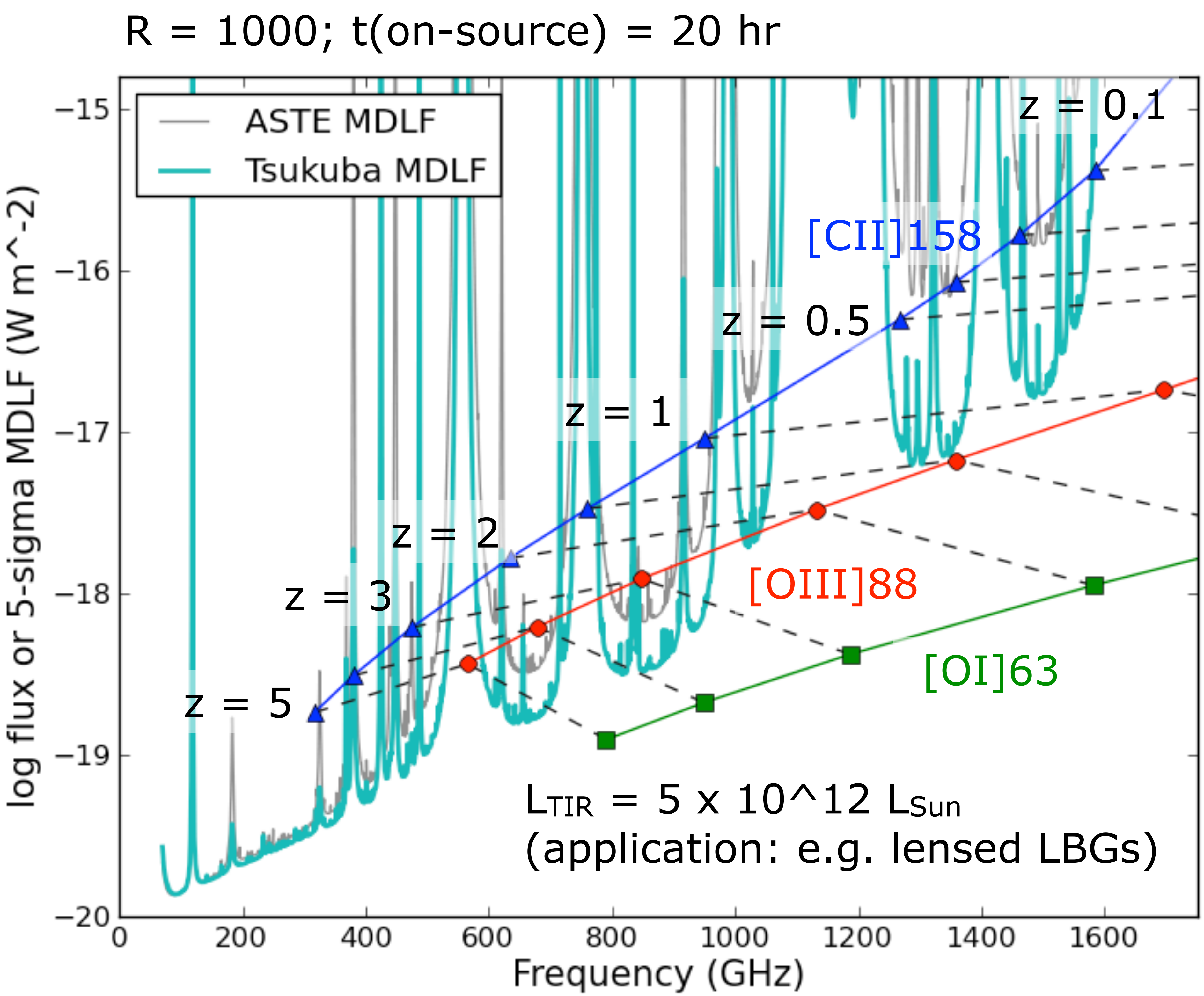
- **Window to "primordial" galaxies in the early universe**
  - will help us answer the fundamental (and longstanding) question: Did $z > 6$ SF galaxies (e.g. LAEs) generate FUV photons enough to fully re-ionize the Universe?
  - THz telescopes are not very good at doing $z > 6$, but lower-redshift calibration should be extremely important for opening low-metallicity universe at mid-z (e.g. primordial pocket) and "calibrating $z > 6$ results" as well.

- **However, [OIII] observations are very limited to only two… (Ferkinhoff+2010)**

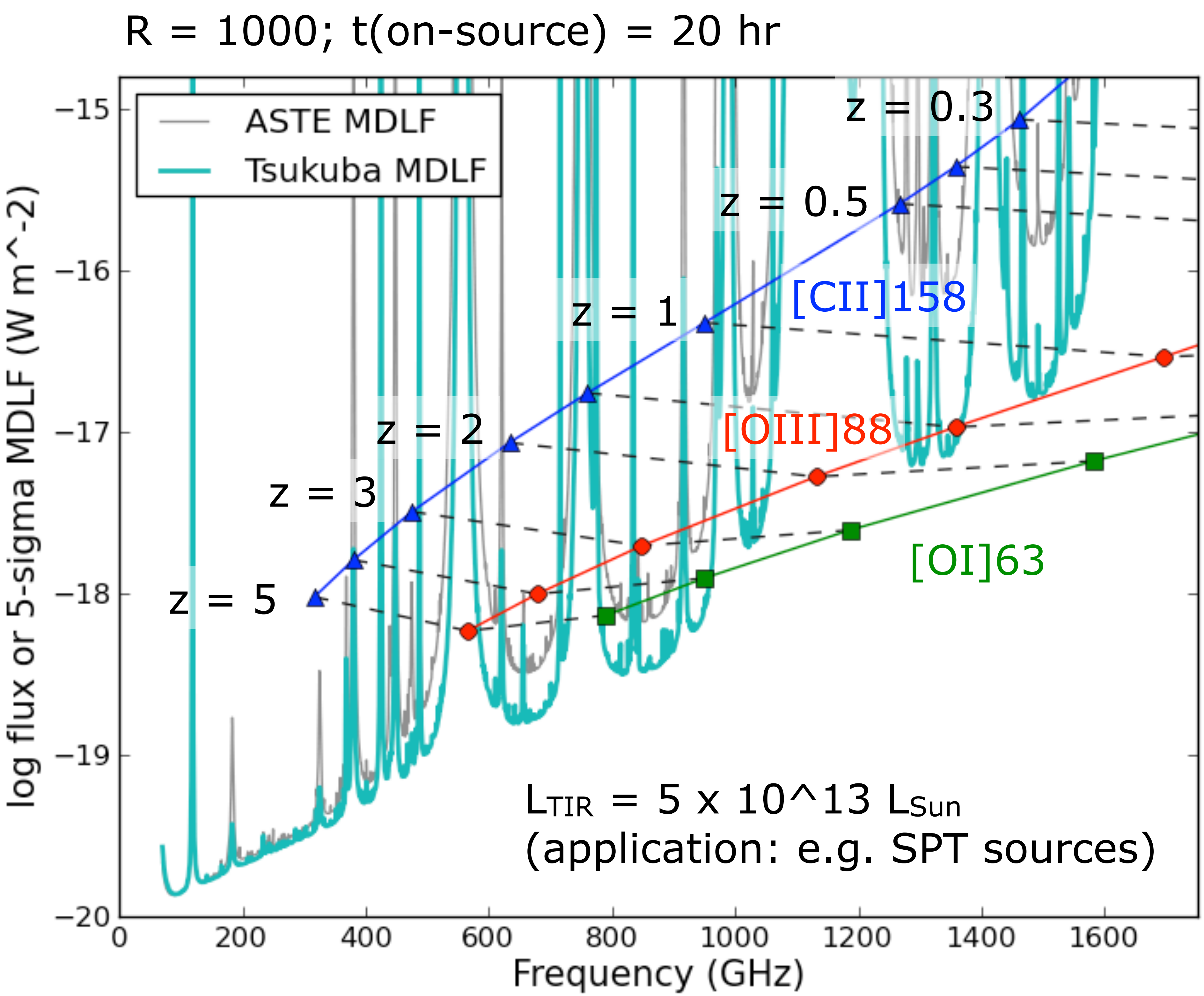
Sensitivity



Sensitivity: Low-*Z* galaxies



Sensitivity: *Z*_Sun galaxies



Summary (FS lines)

- **Science goals**
  - Observations of mid-z SF galaxies in FS lines of [OIII]88 and [CII]158 will
- **Sensitivities**
  - The 10m will detect both [OIII]88 and [CII]158 in
    - (1) *lensed* SMGs with ~Z_Sun (Lir ~ 5e13 L_Sun)
    - (2) *lensed* UV-selected galaxies with sub-Z_Sun (Lir ~ 5e12 L_Sun) at 1 < z < 4.
- **Requirements / Recommendation**
  - Surface error < 20 um to surpass Herschel and CCAT (Atacama, 5000m) at 1.5 THz
  - Transparent sky at > 1 THz
  - You can start even with ASTE/DESHIMA, which offers a good opportunity to prepare good science cases with Tsukuba 10m THz telescope.
  - Tight coordination with SPICA