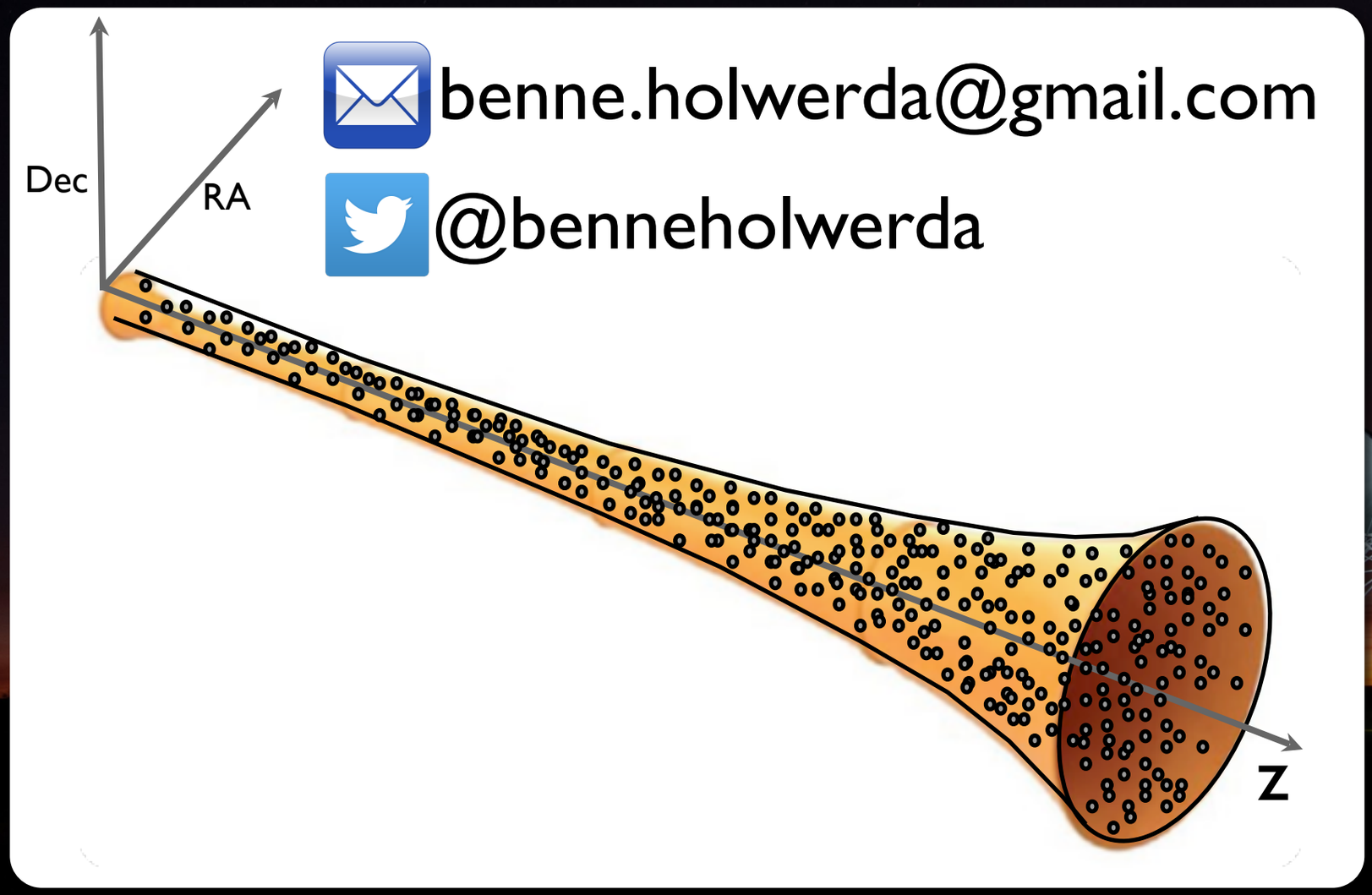
LADUMA

Looking at the Distant Universe with the MeerKAT Array



B.W. Holwerda[1], S.-L. Blyth[2] & A. J. Baker[3]

1)University of Louisville
2) Astrophysics, Cosmology and Gravity Centre (ACGC), University of Cape Town
3) Rutgers, the State University of New Jersey

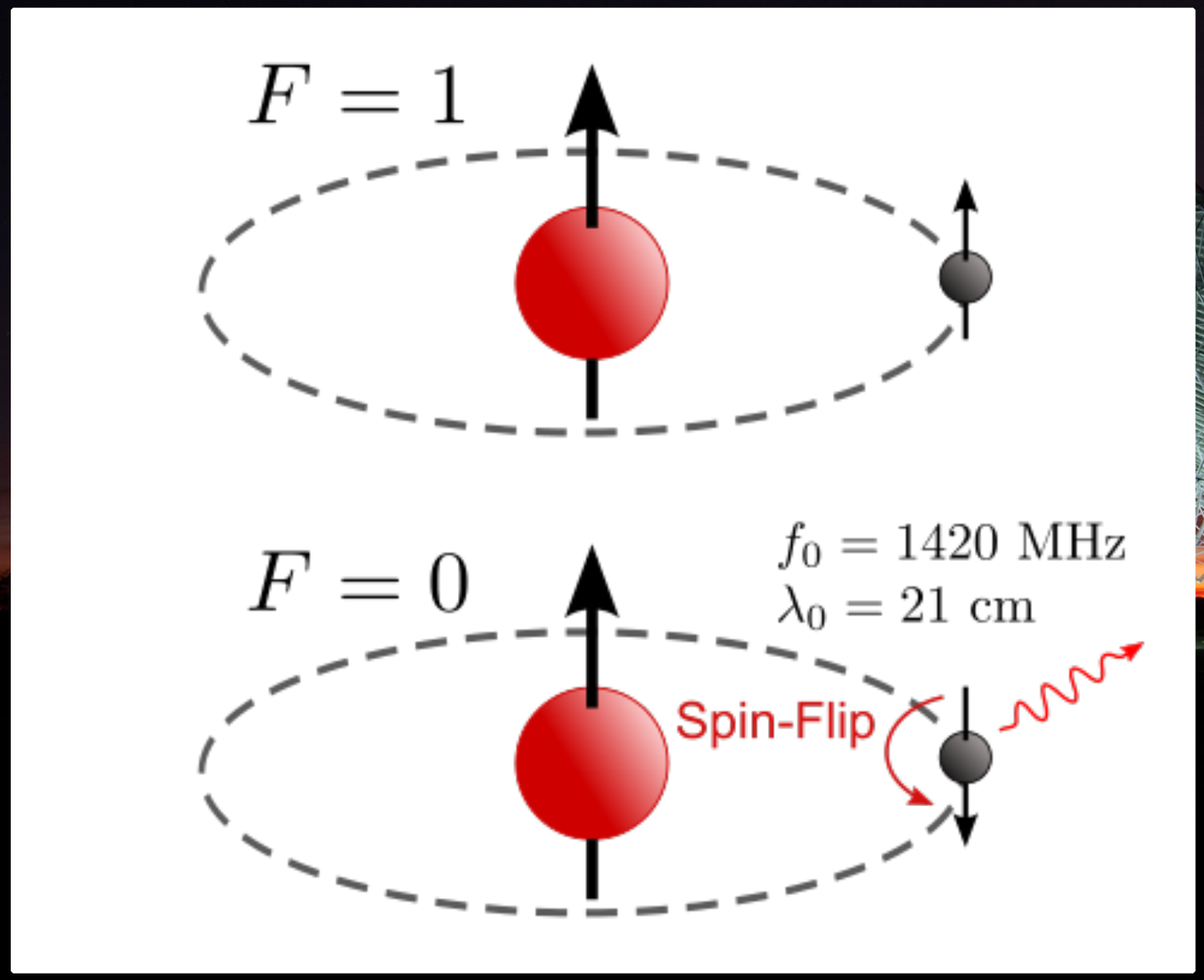
LADUMA Team

MeerKAT TAC rating: Priority1
Awarded 5000 hours for a single pointing.

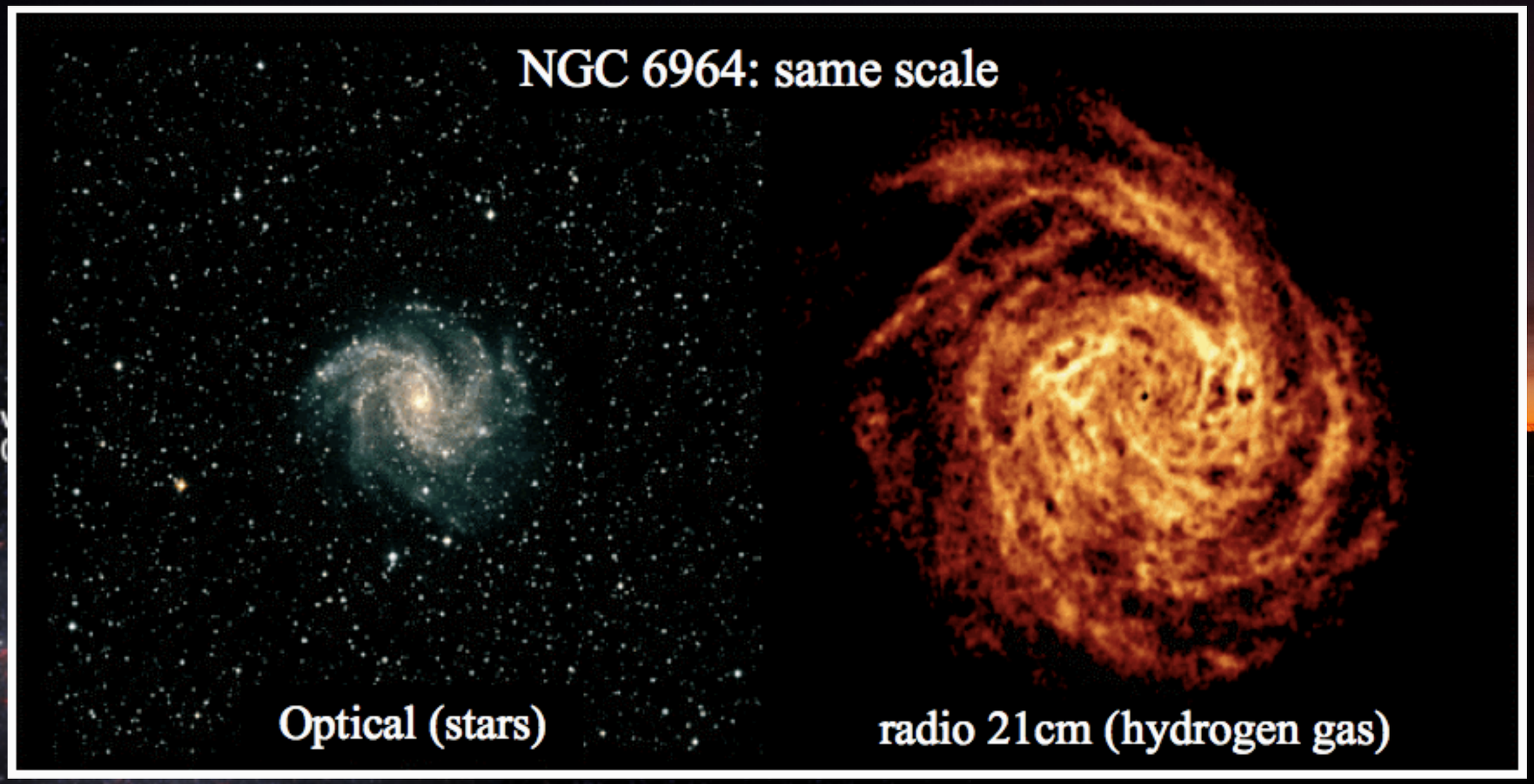
PIs: S.-L. Blyth, B. W. Holwerda, A. J. Baker,

co-Is: B. Bassett, M. Bershady, A. Bouchard, F.H. Briggs, B. Catinella, L. Chemin, S. Crawford, C. Cress, D. Cunnama, J. Darling, R. Davé, R. Deane, E. de Blok, E. Elson, A. Faltenbacher, S. February, X. Fernàndez B. Frank, E. Gawiser, E. Giovannoli, T. Henning, K. Hess, I. Heywood, J. Hughes, M. Jarvis, R. Johnston, S. Kannappan, N. Katz, D. Kereš, H-R. Klöckner, R.Kraan-Korteweg, P. Lah, M. Lehnert, A. Leroy, N. Maddox, S. Makhathini, G. Meurer, M. Meyer, K. Moodley, R. Morganti, D. Obreschkow, S.-H. Oh, T. Oosterloo, D.J. Pisano, A. Popping, G. Popping, S. Ravindranath, E. Schinnerer, A. Schröder, K. Sheth, O. Smirnov, M. Smith, R. Somerville, R. Srianand, L. Staveley-Smith, I. Stewart, M. Vaccari, P. Väisänen, K.van der Heyden, W. van Driel, M. Verheijen, F. Walter, E. Wilcots, T. Williams, P. Woudt, M. Zwaan, J. Zwart

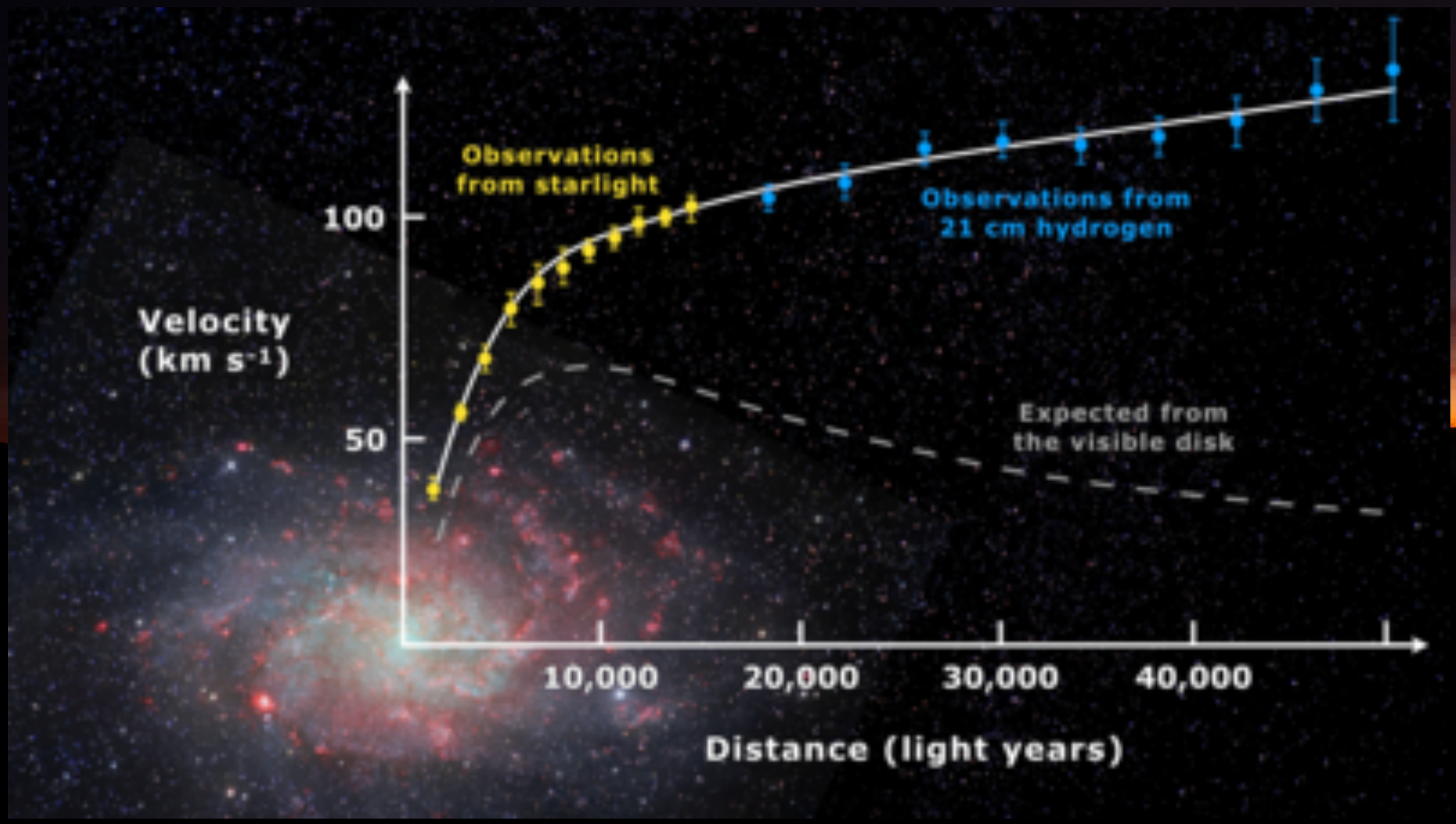
21cm Hydrogen



21cm Information on Galaxy



21cm Information on Galaxy



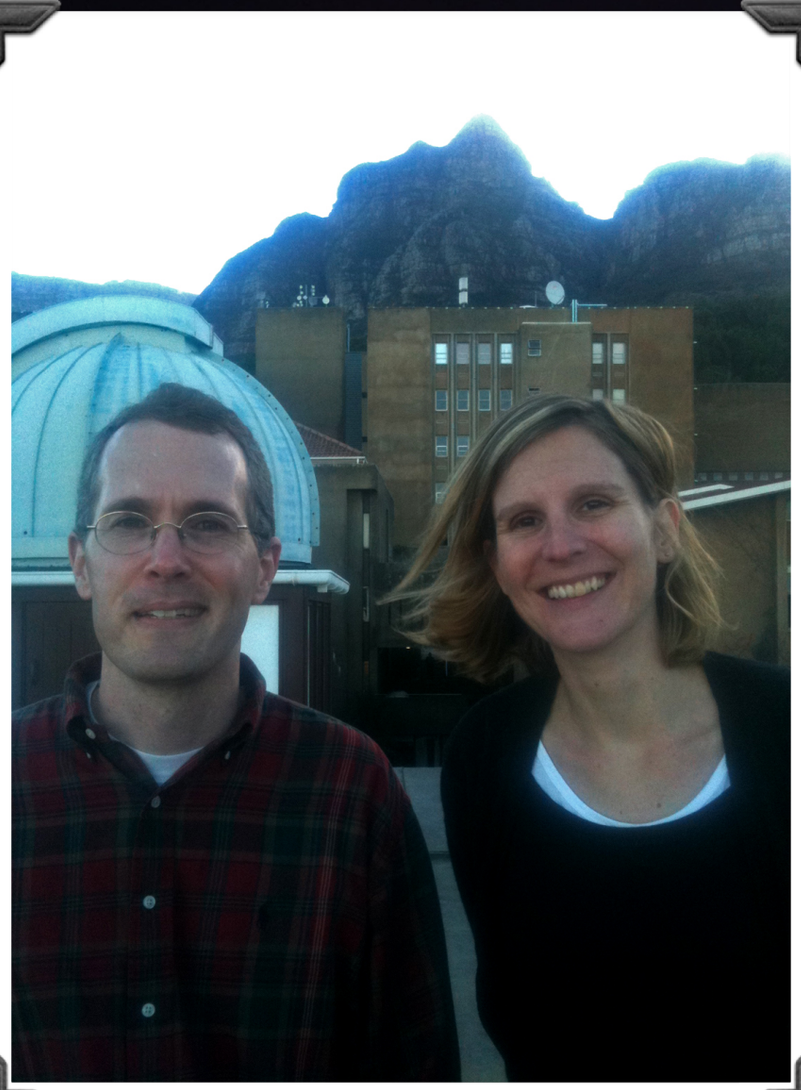
The Team

Active Team

- PIs meet every week over Skype.
- working on:
  - Outreach activities
  - Ancillary data.
  - Promotion of survey, Meerkat & SKA.

PI tag...

Blyth & Holwerda



Baker & Blyth

Baker & Holwerda

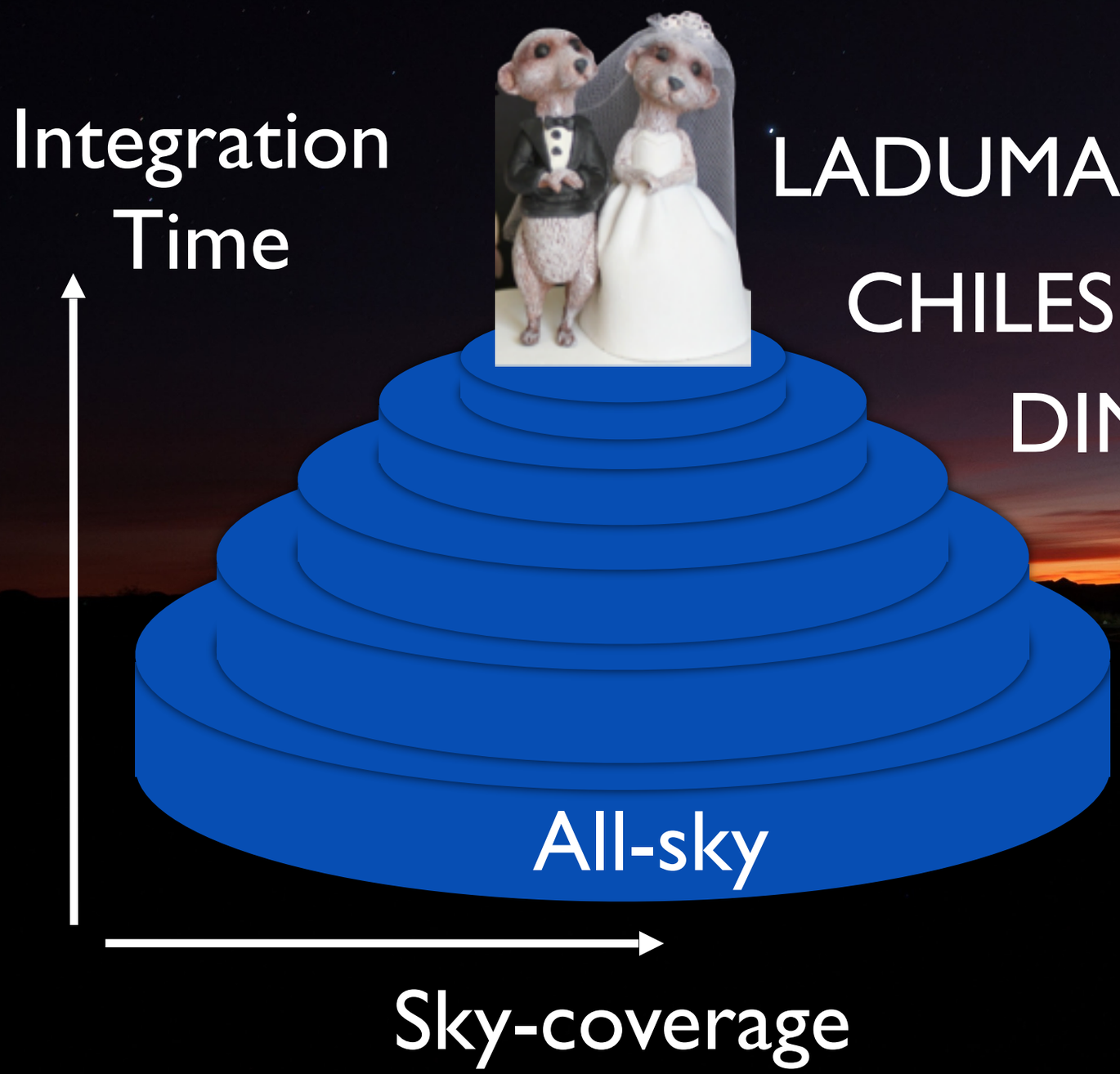
This has happened only once before...

PHISCC at ASTRON (photo: Lister Stavely-Smith)

B. W. Holwerda (UofL) - INAF - 22 Dec 2020

Potjie Project

Tiered Cake of Surveys



LADUMA (MeerKAT)

CHILES (EVLA)

DINGO (ASKAP)

Medium-Deep Survey (APERTIF)

Wallaby + WNSHS (ASKAP, APERTIF)

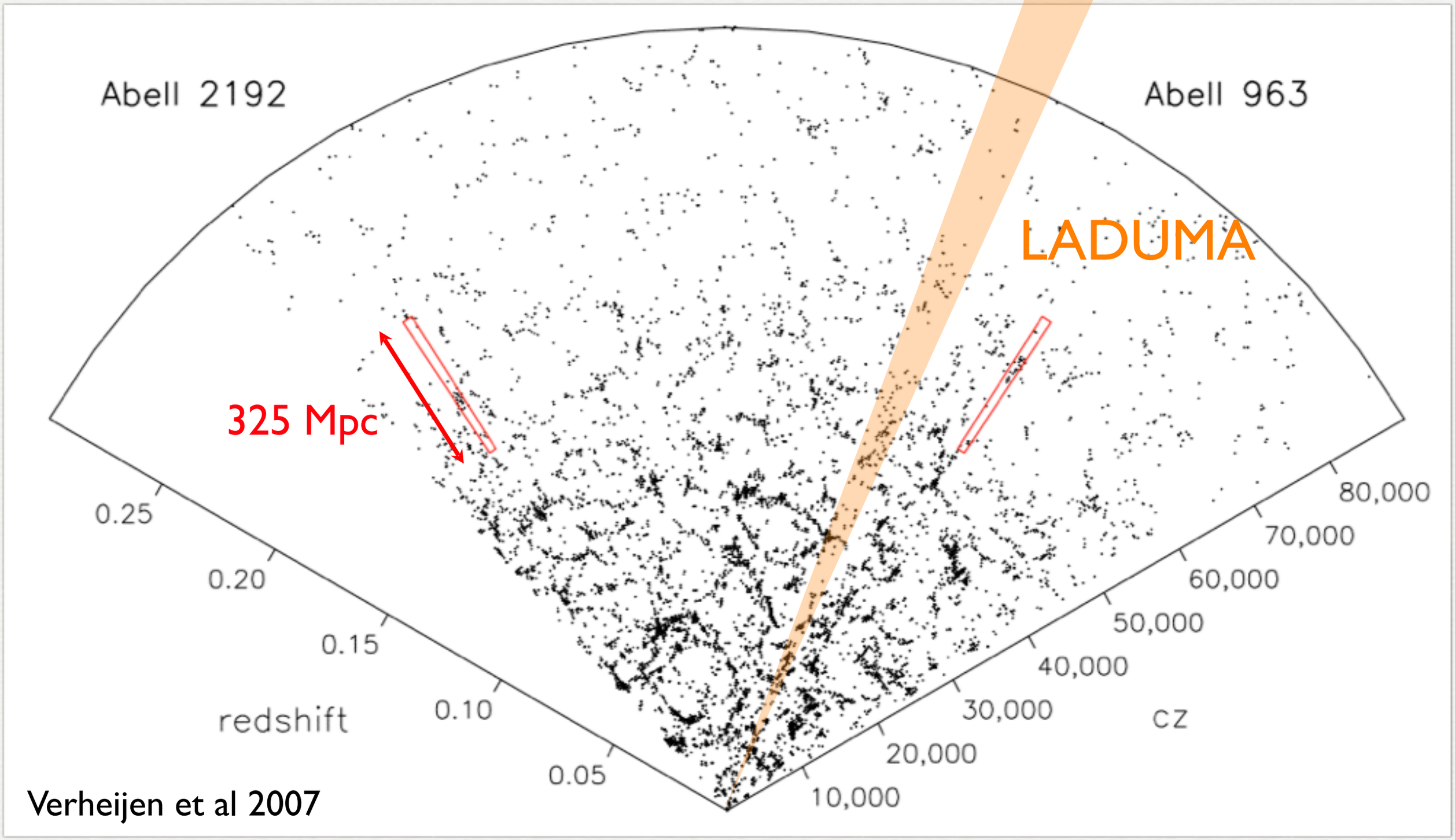
Main Questions

- How does the (baryonic) Tully-Fisher relation evolve with redshift?
- How does the HI mass function (HIMF) vary with redshift and environment?
- How does the cosmic HI density (Ω_{HI}) evolve with redshift?
- How do galaxies' HI masses depend on their stellar and/or host halo masses, environment, and redshifts?

The Science Case

- Essentials unchanged since the proposal in 2009.
- Updated and adapted to new instrumentation realities.
- Keeping a “living document” between the PIs that will be the basis for the Survey Description Paper (May 2016).

Single Deep Field

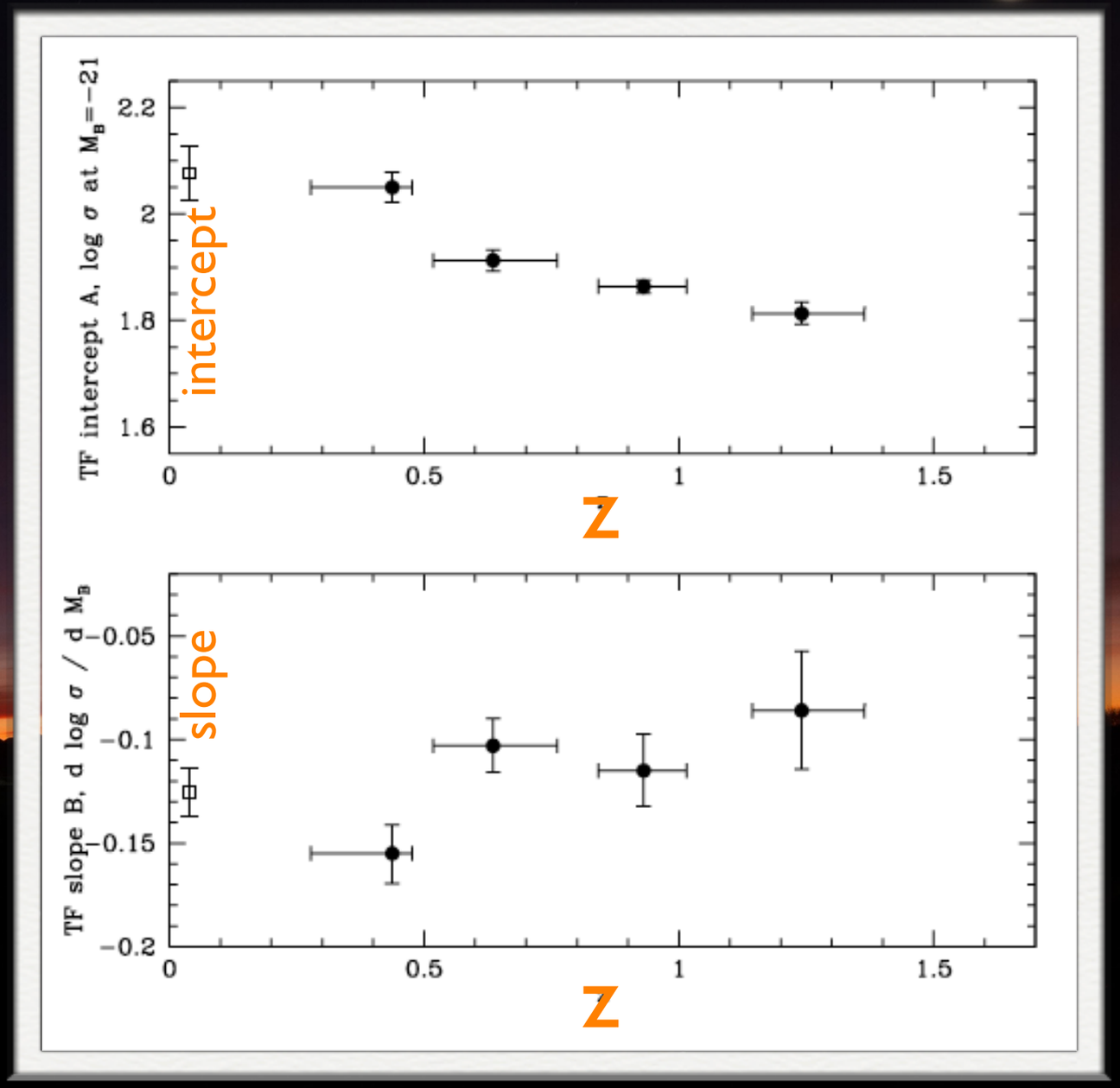


Verheijen et al 2007

SDSS redshift space

Baryonic Tully-Fisher Relation

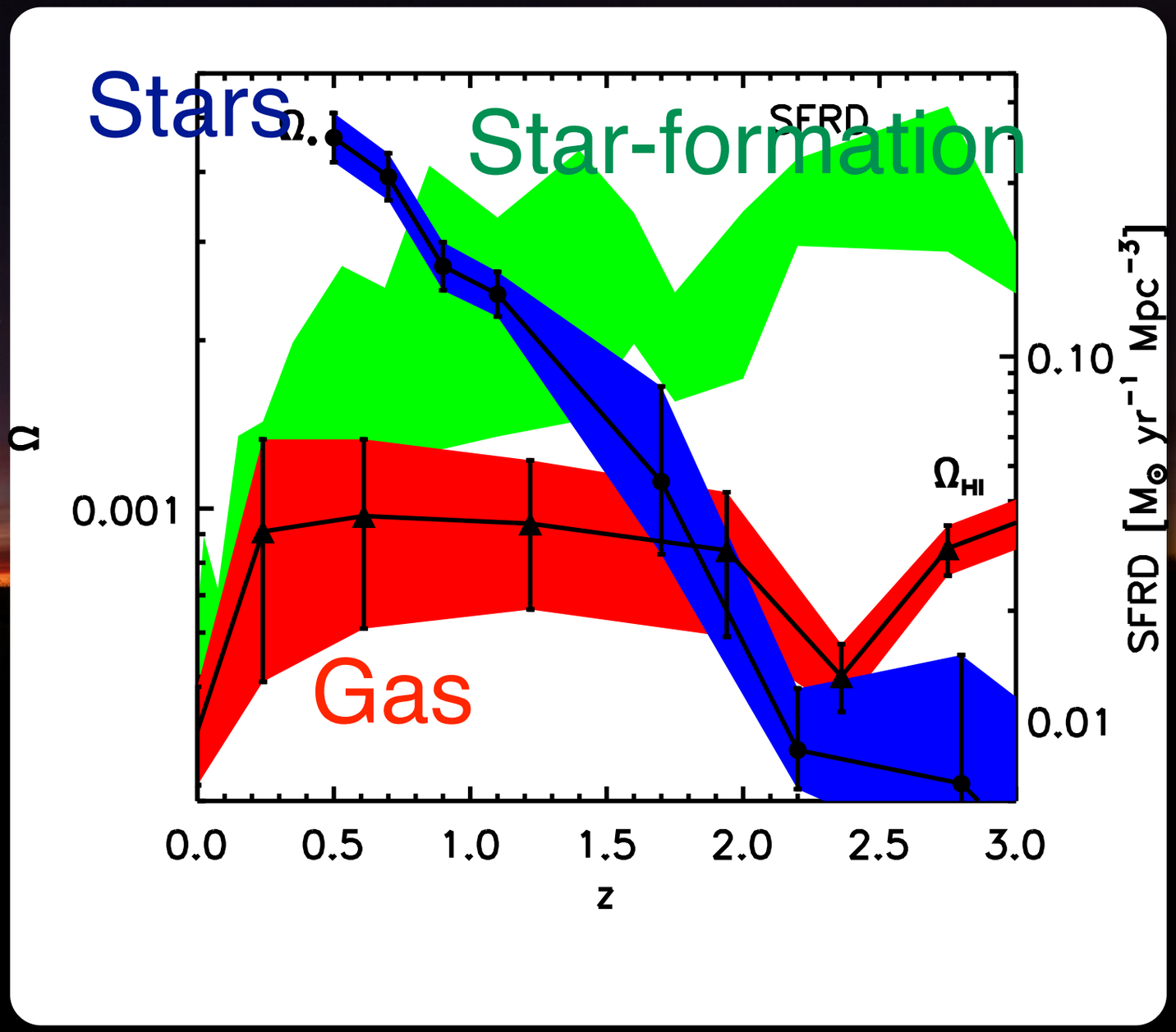
- Galaxies rotate since z>1
- Stellar mass TFR shows evolution for 0<z<1.3
- Halpha does not trace well into the halo
- Unknown how the Baryonic TFR evolves over cosmic time.
- LADUMA will observe 1000s of HI profiles.



Weiner et al. (2006)

Fueling Star-formation

- Star-formation declines, slow then fast.
- Stellar mass increases
- Gas supply constant?

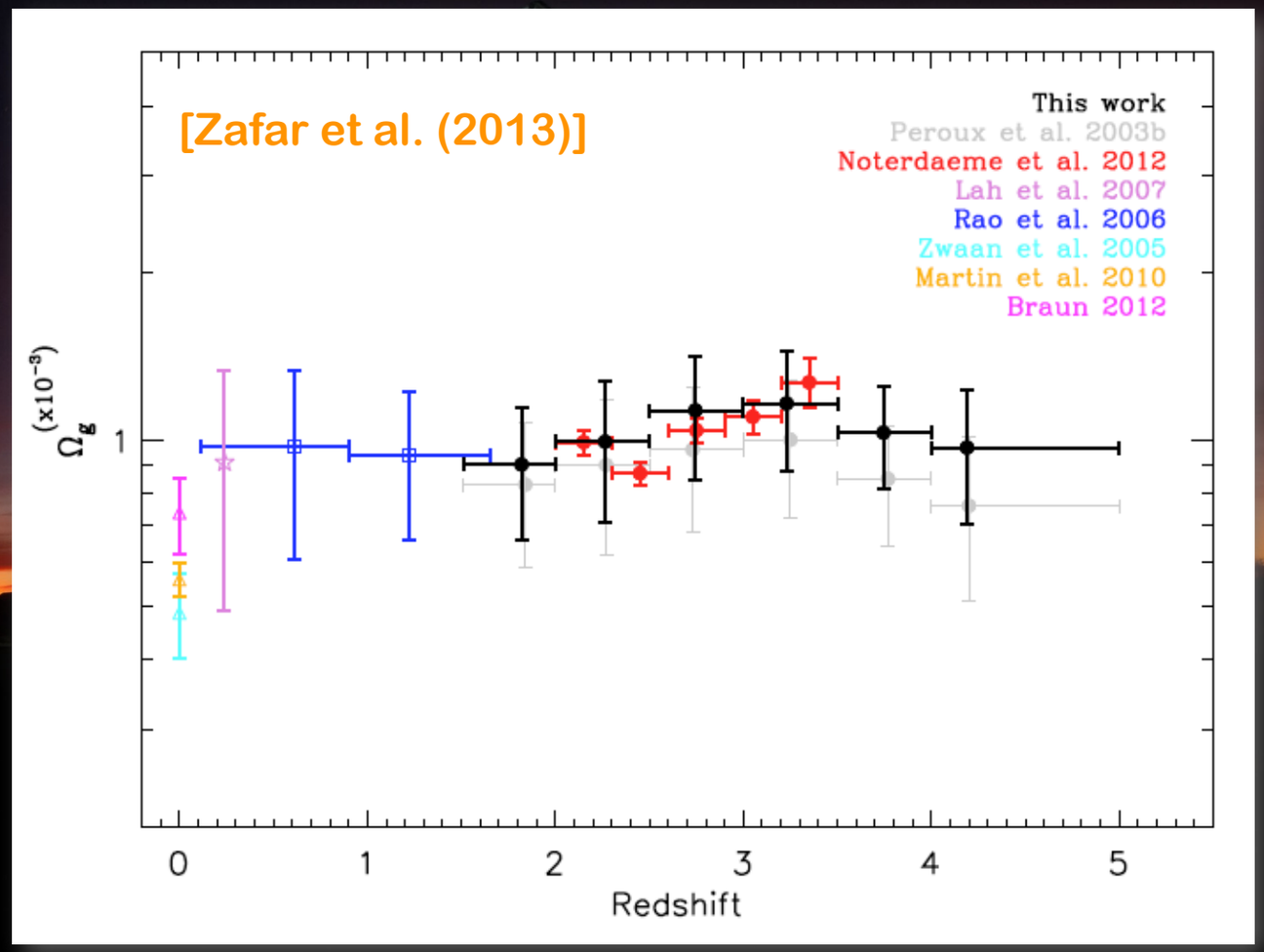


Putman+ 2009

Science: Cosmic HI Density (Ω_{HI})

What is the average amount of HI at different z?

Ω_{HI} vs. z



- **What is the trend for 0.2< z <0.6 where SFR is decreasing?**
- **How will HI measurements compare to Lyα and MgII absorber results at high z?**

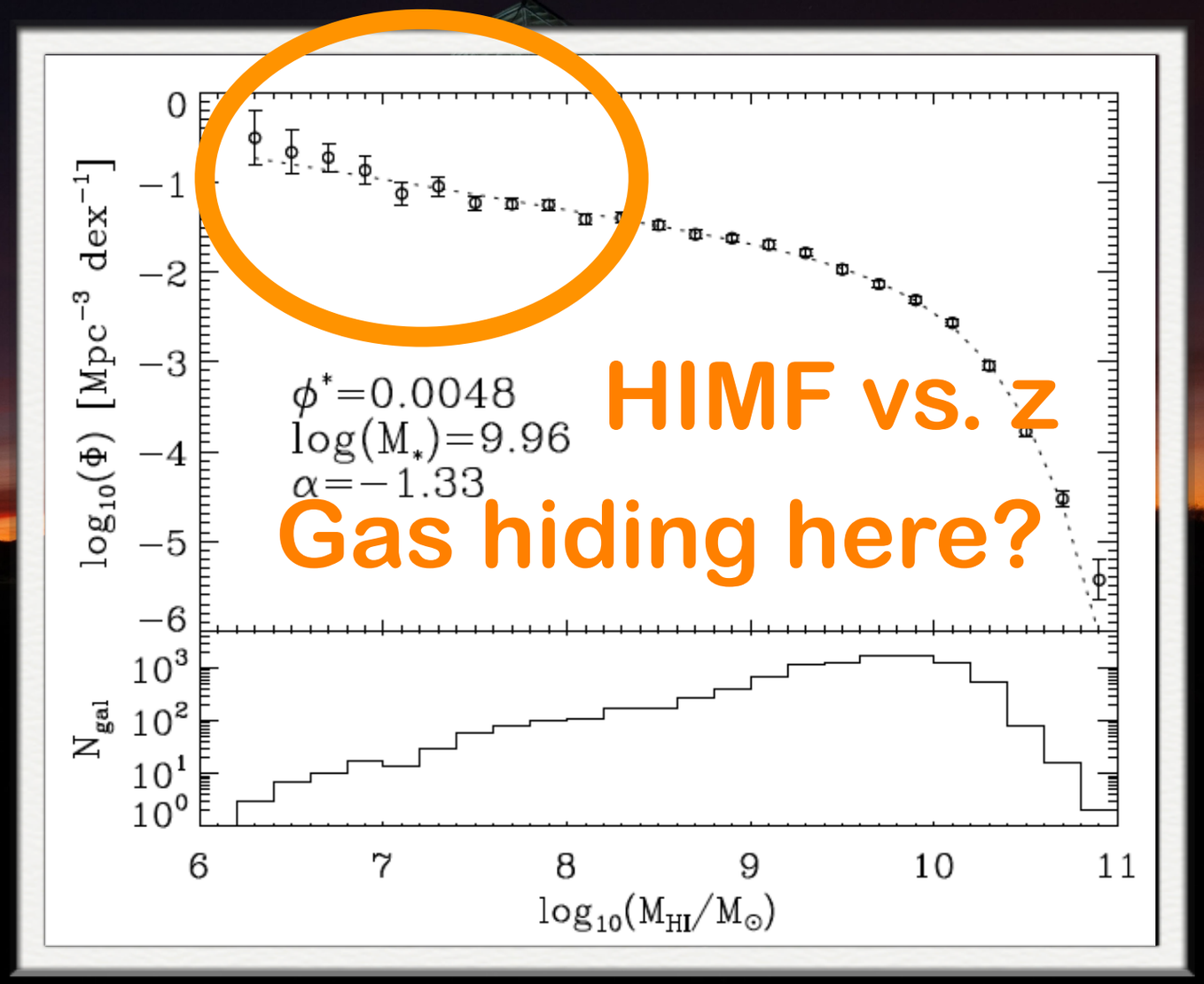
Science: HI Mass Function

To study galaxy evolution over cosmic time, we need to understand where & how much HI exists...

How is HI distributed within galaxies?

- How do M^*_{HI}, α & normalization vary?
- Help to constrain hierarchical galaxy formation models
- Differences with environment?

HIMF vs. z



Martin et al. (2010)

(measured for z<0.06)

LADUMA Science Questions

- How does the (baryonic) Tully-Fisher relation evolve with redshift?
- How does the HI mass function (HIMF) vary with redshift and environment?
- How does the cosmic HI density (Ω_{HI}) evolve with redshift?
- How do galaxies' HI masses depend on their stellar and/or host halo masses, environment, and redshifts?

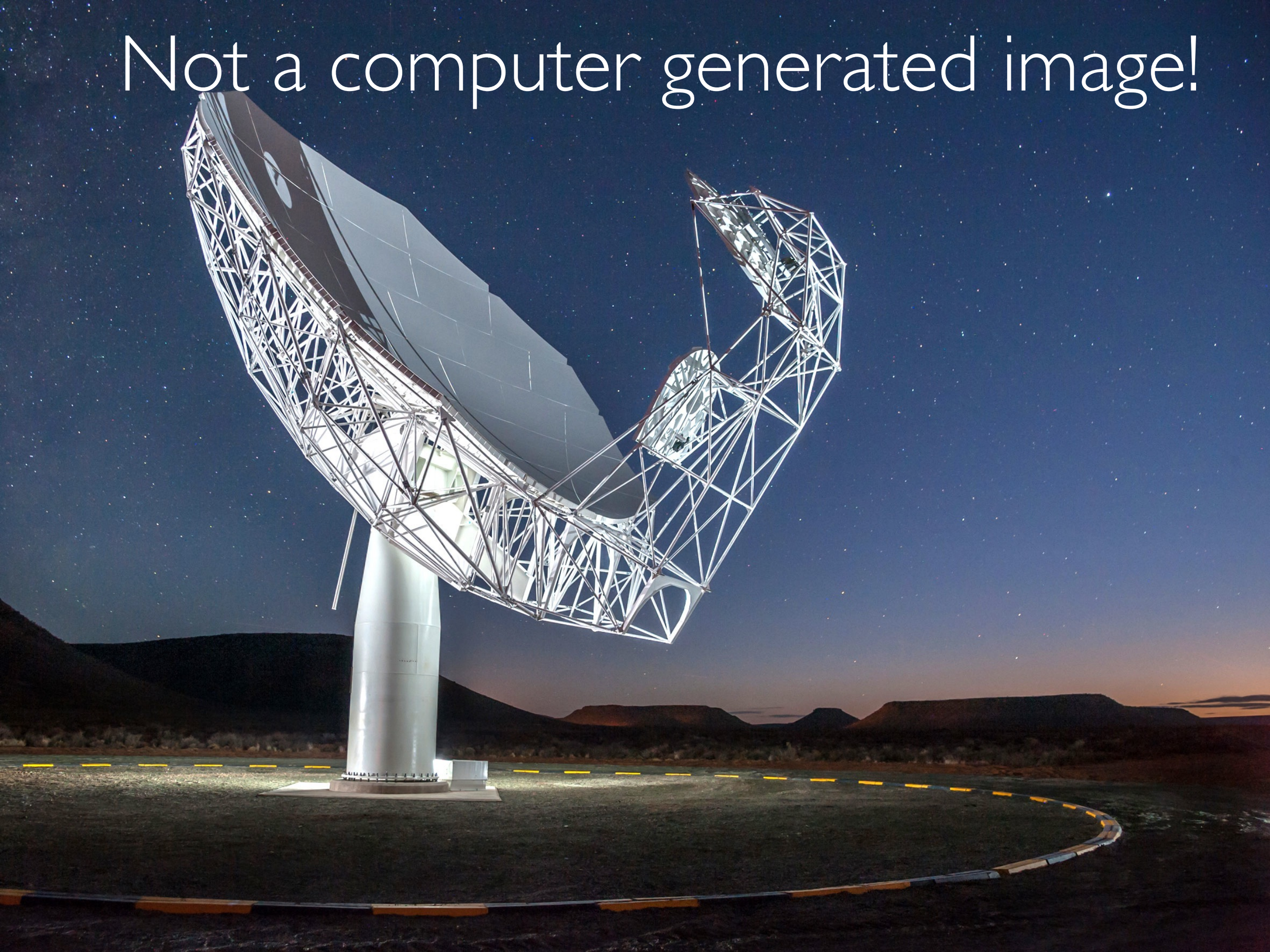
Bonus Science

- An OH maser survey!
- A closer look at any specific high-z galaxy population of interest:
  - DLA's
  - gas content of ellipticals
  - "dark" HI galaxies.
  - etc etc.
- Comparisons between HI absorption & emission.
- Merger statistics from close pairs.

Need spectroscopic redshifts + multiwavelength data!

MeerKAT

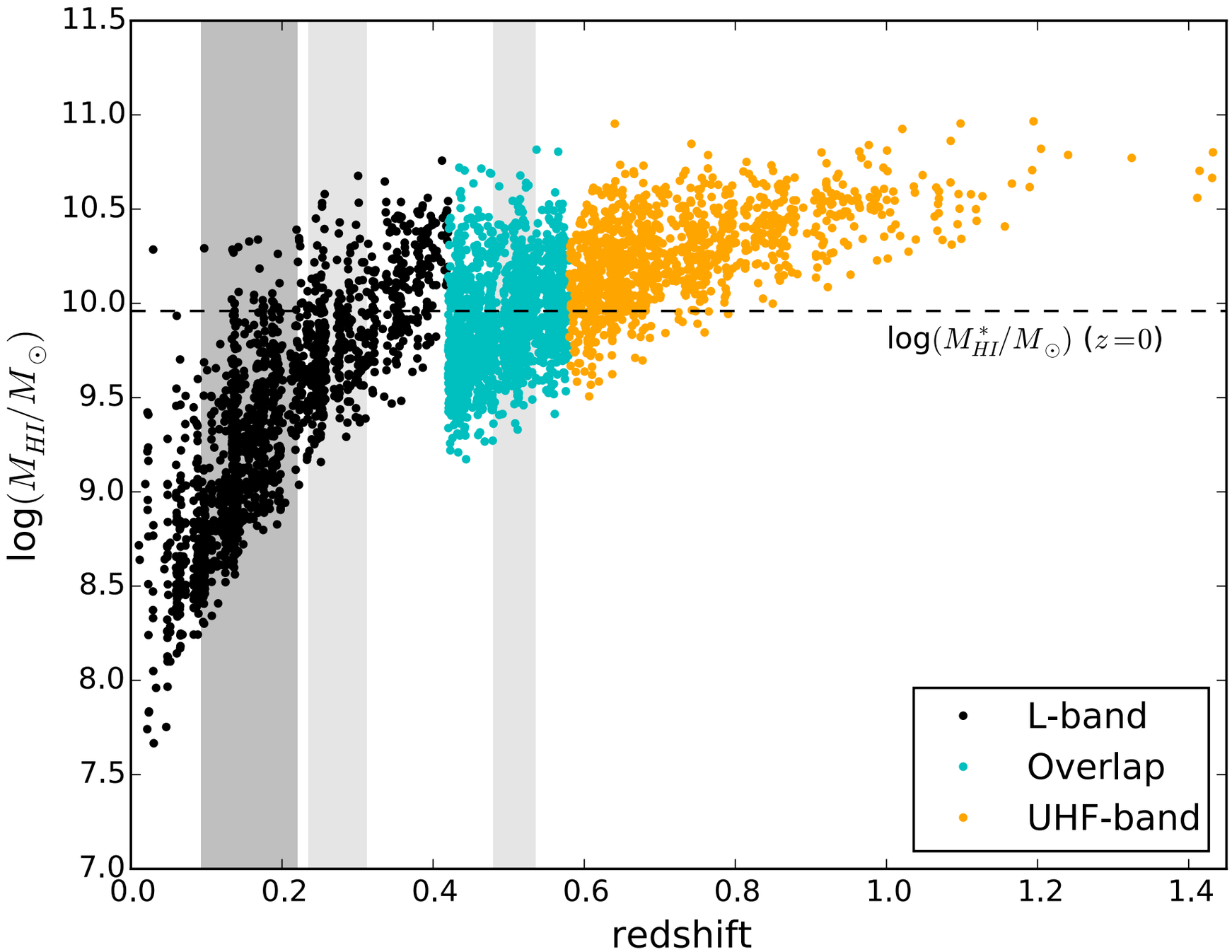
Not a computer generated image!



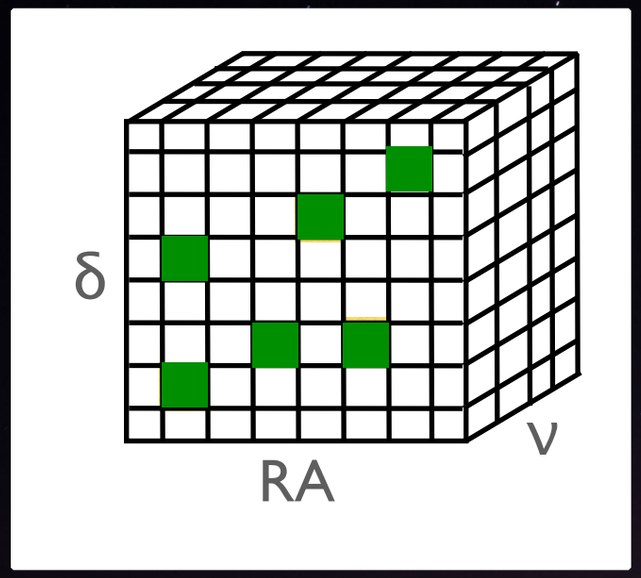
First Observations

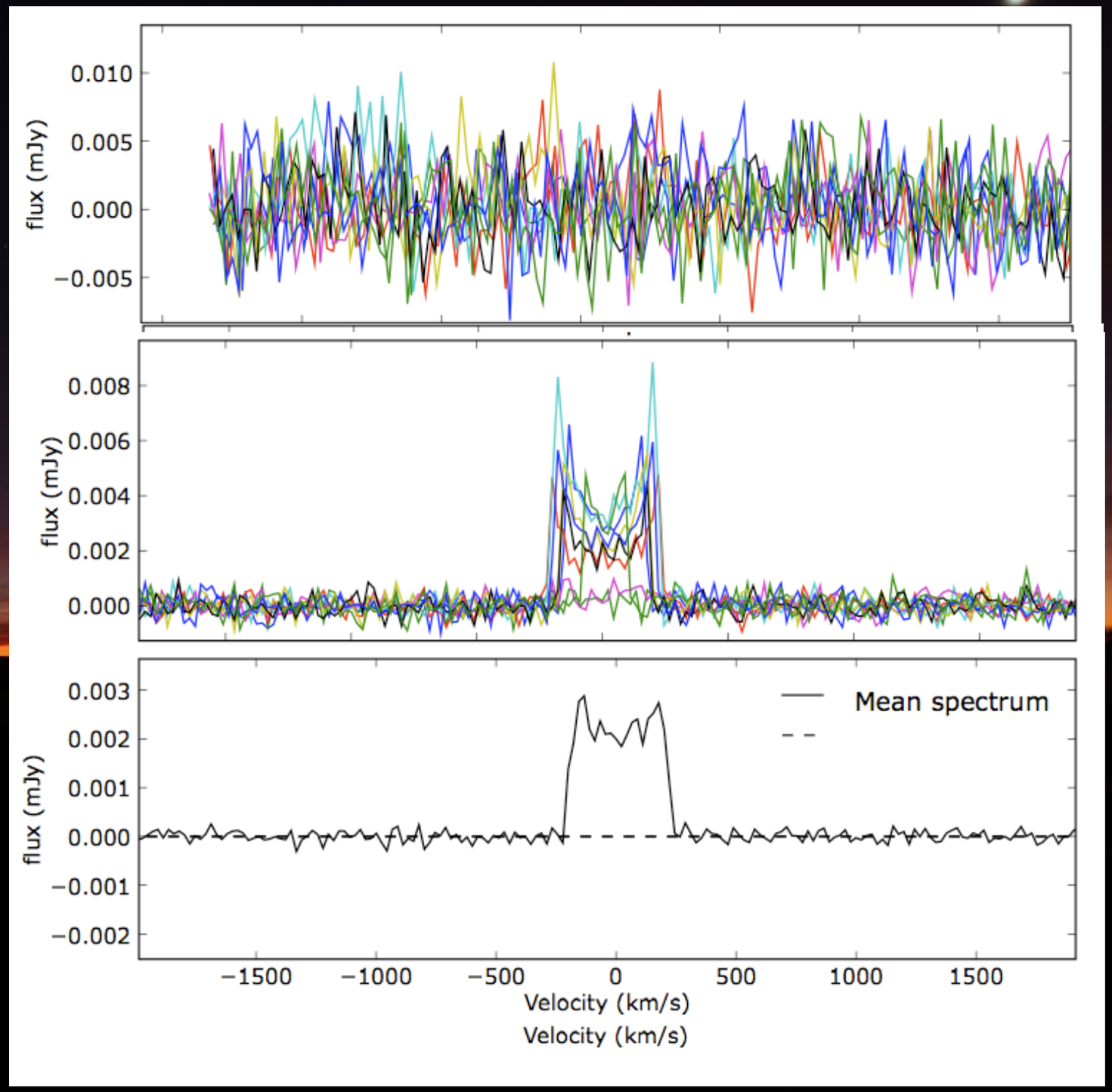
- L-band tracks completed
- First two UFH tracks completed
- First HI detections and continuum.

Direct Detections



HI Line Stacking



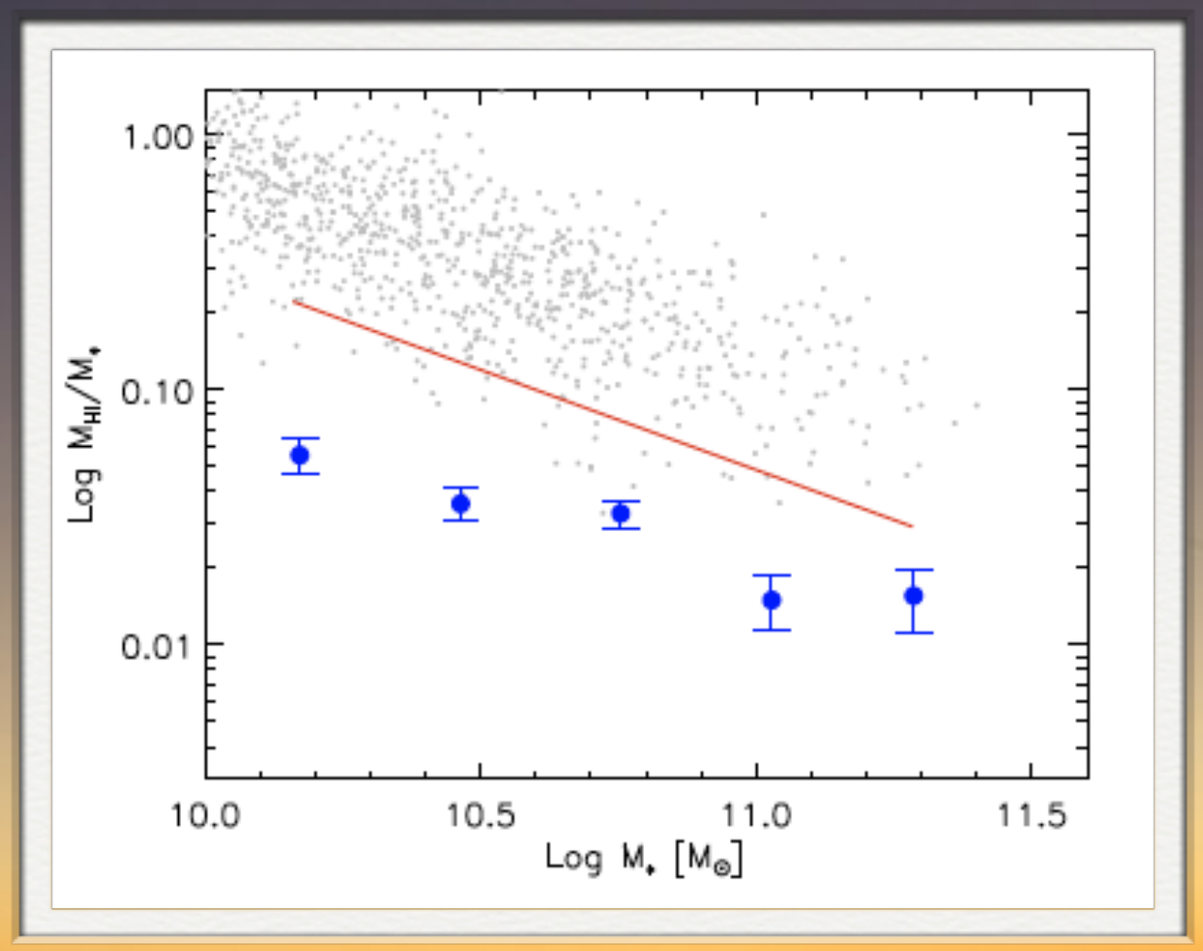


- **STEP 1:** extract spectra using known positions and redshifts.
- **STEP 2:** shift all spectra to common frame.
- **STEP 3:** Co-add spectra
- **STEP 3A:** More = better.
- See J. Healy's talk tomorrow!

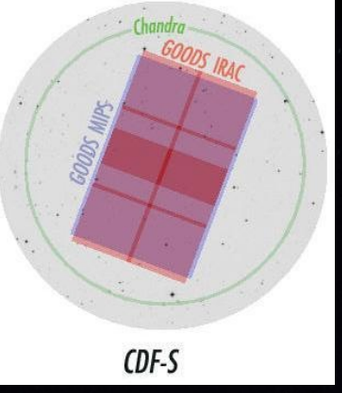
Applications of HI stacking

- Stacking has enabled investigation of subsets of ALFALFA galaxies based on type

Fabello et al. 2010



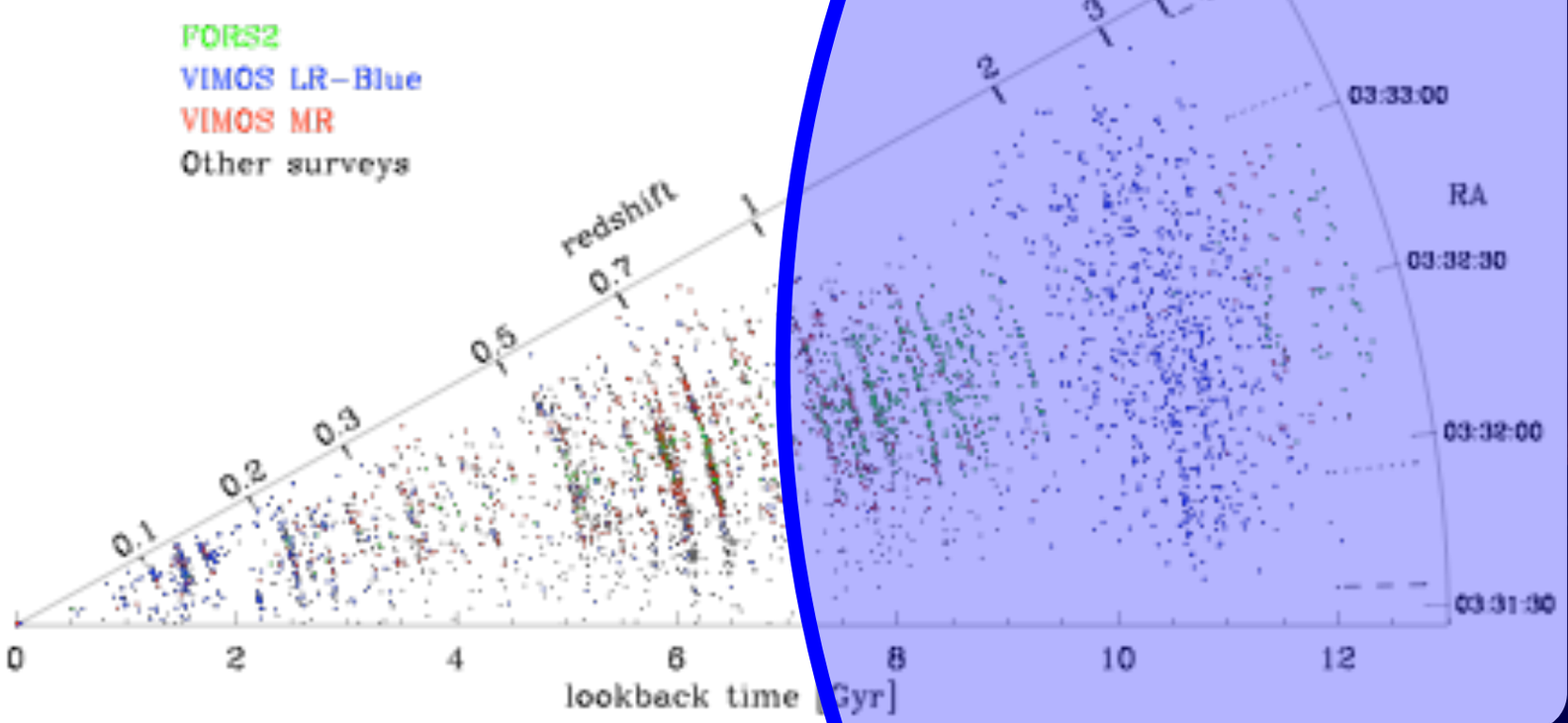
- Bulge-dominated galaxies have a lower HI gas fraction at a given stellar mass than the average (Fabello et al. 2010)

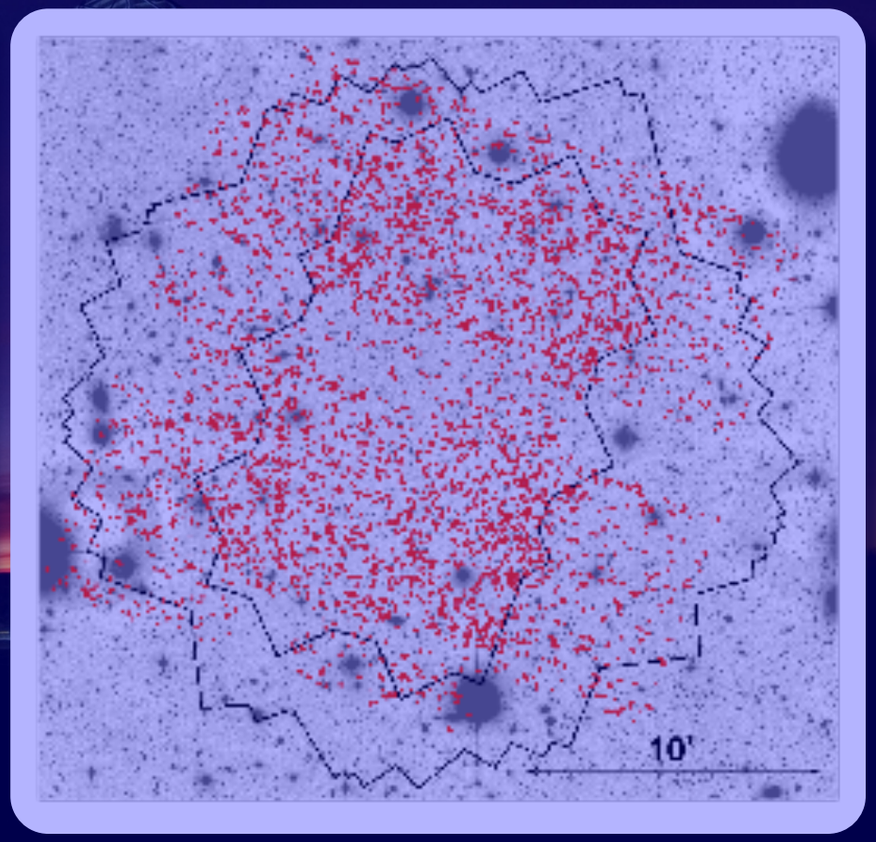


VLT coverage

MeerKAT FOV at z~1.4

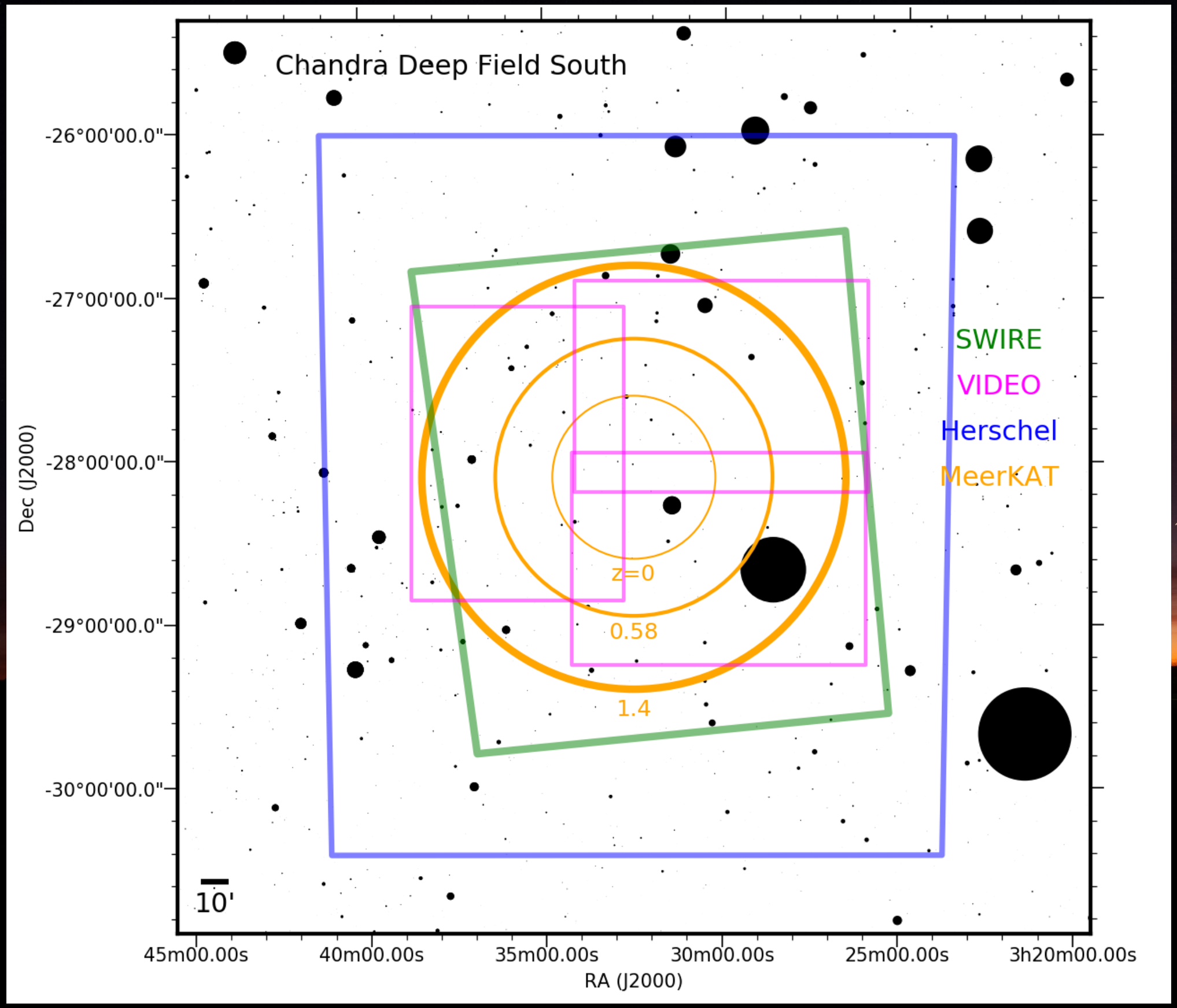
Balestra et al. 2010 A&A 512, A12





Multi-Wavelength

Blind HI Survey



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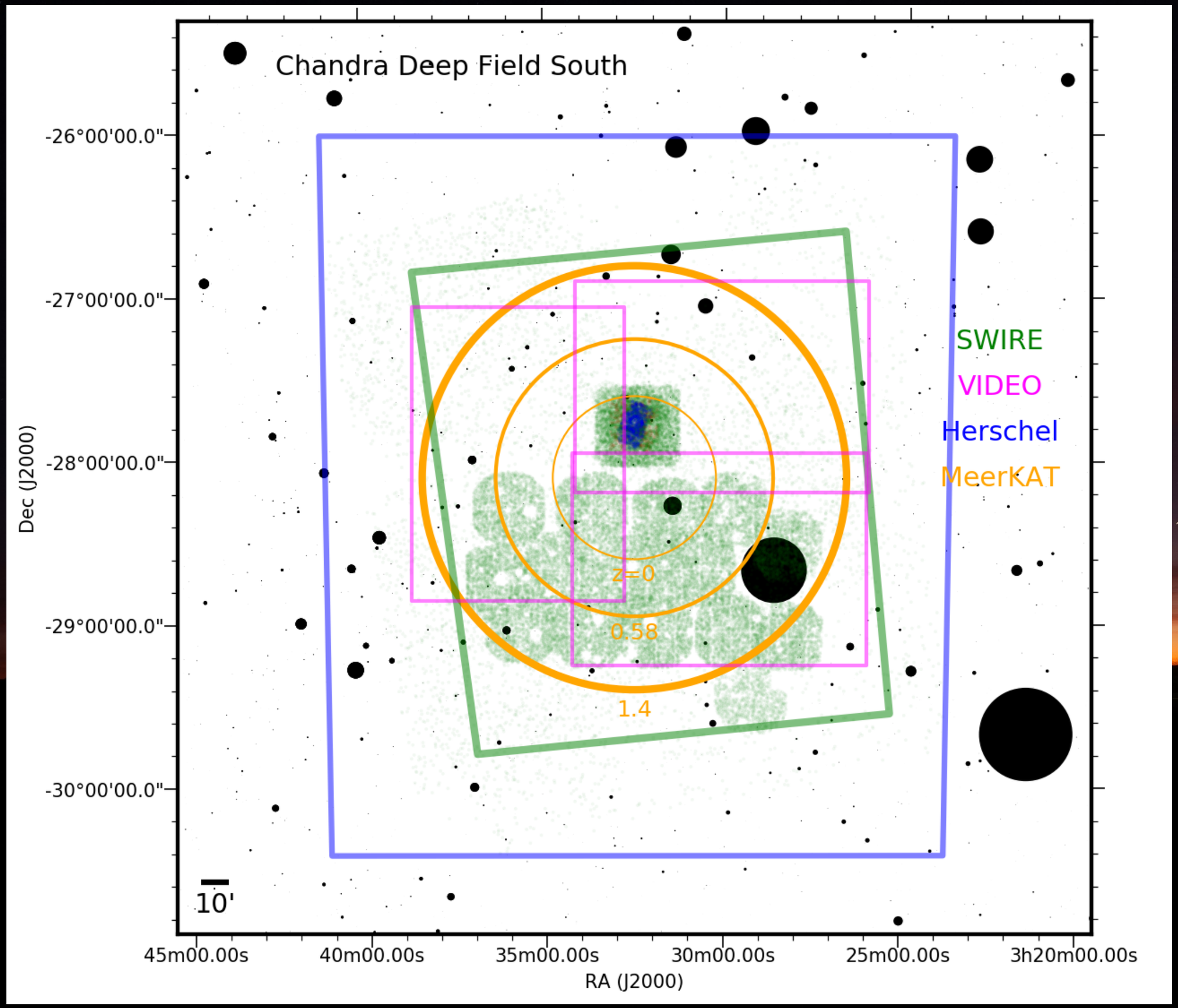

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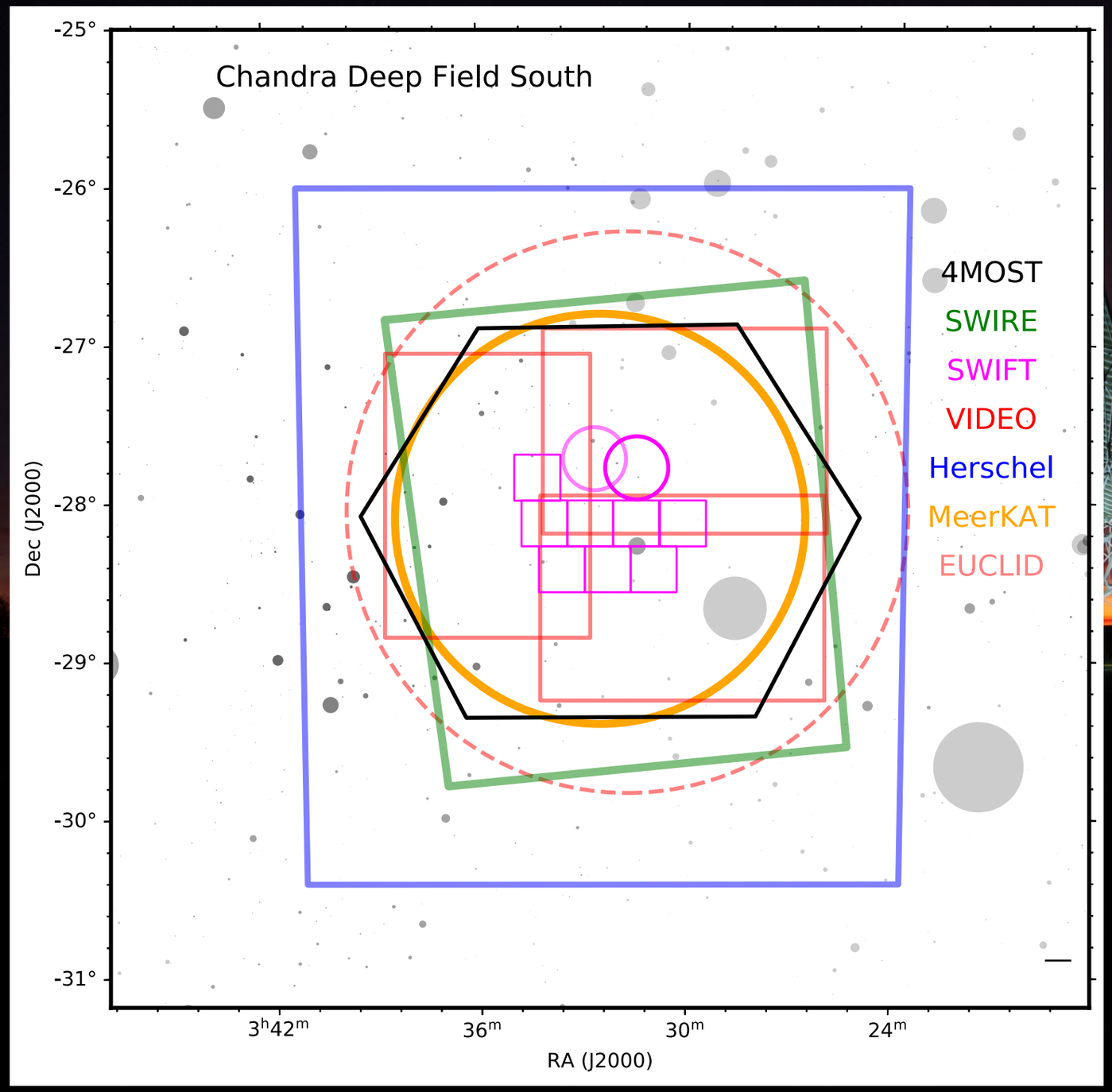
Euclid and SWIFT



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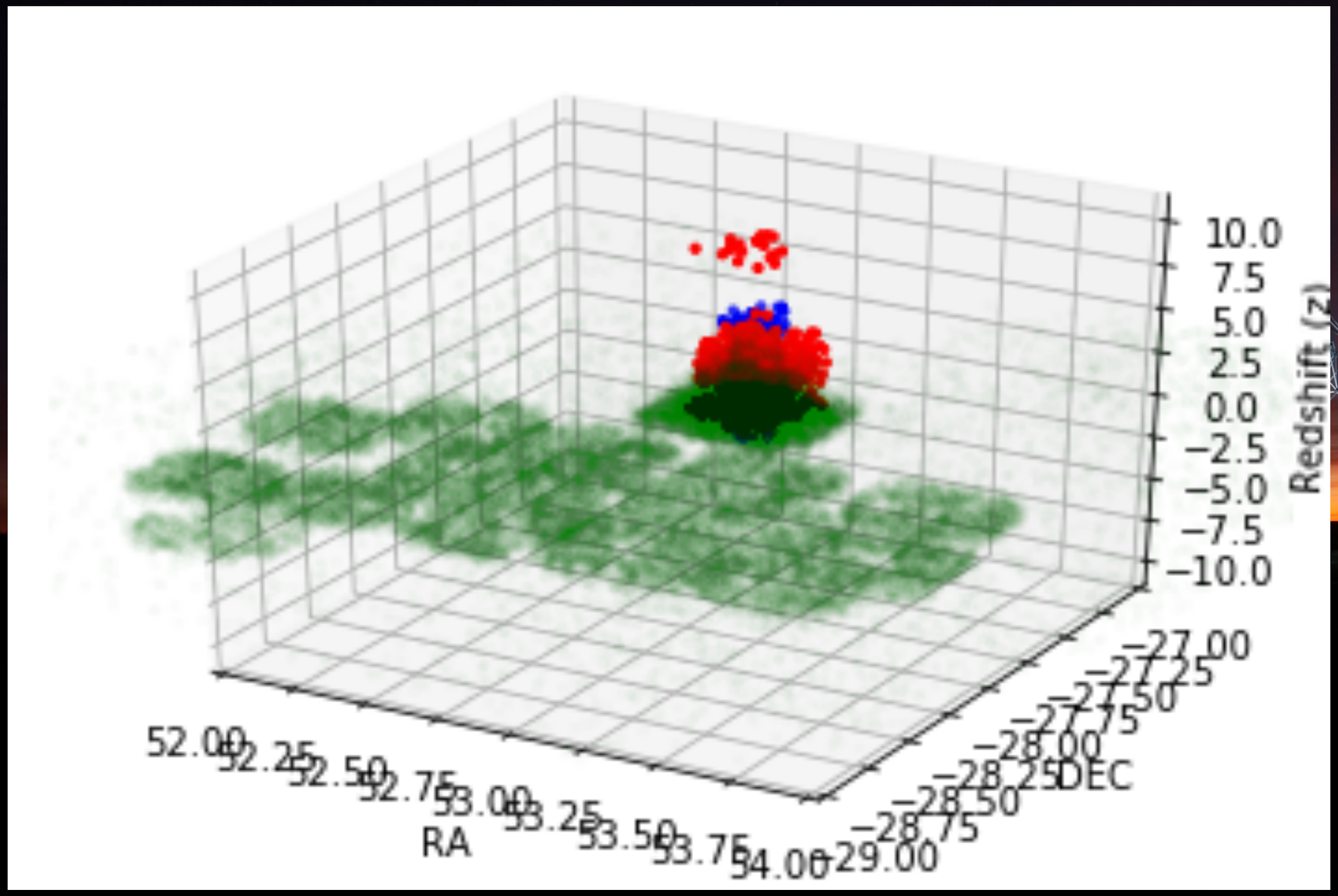
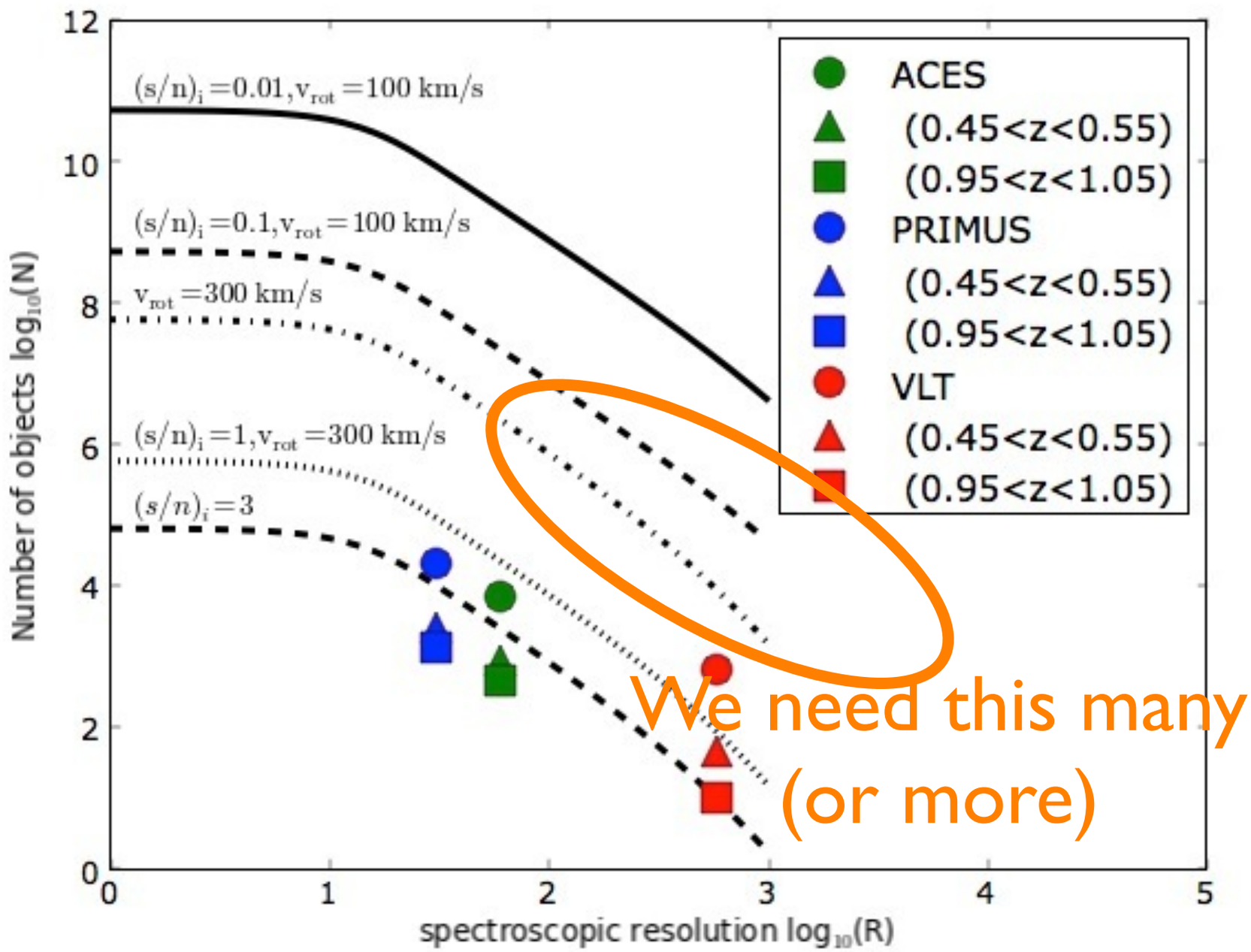
Treasure Trove of Redshifts



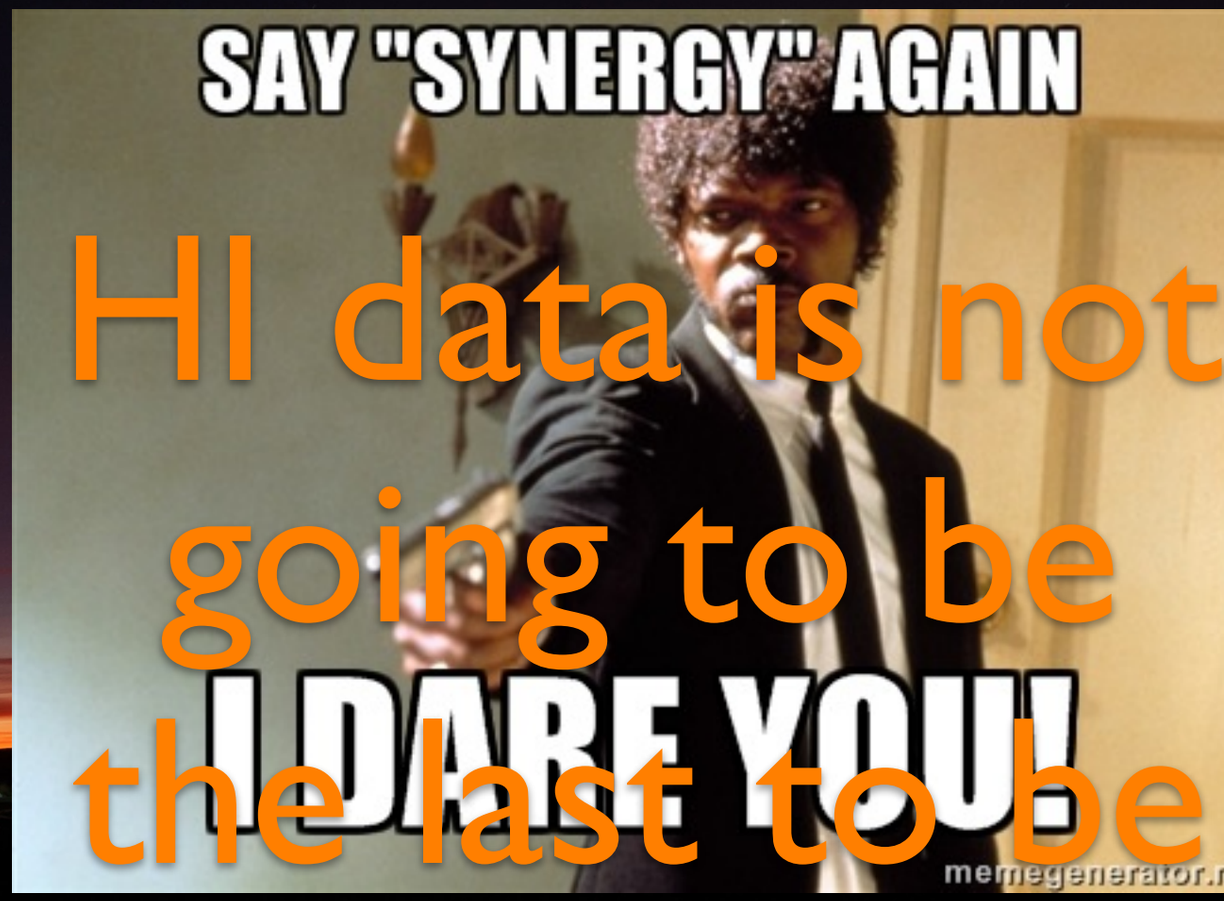
How many redshifts do we need?



We need this many (or more)

Synergies

- LSST - deep Tully-Fischer
- HST/WFIRST/EUCLID - morphologies
- 4MOST - anything that requires stacking HI
- VLT/MUSE - environment
- SALT - SF characteristics
- JWST - SF/M*
- ALMA - full ISM tally



HI data is not going to be the last to be observed!

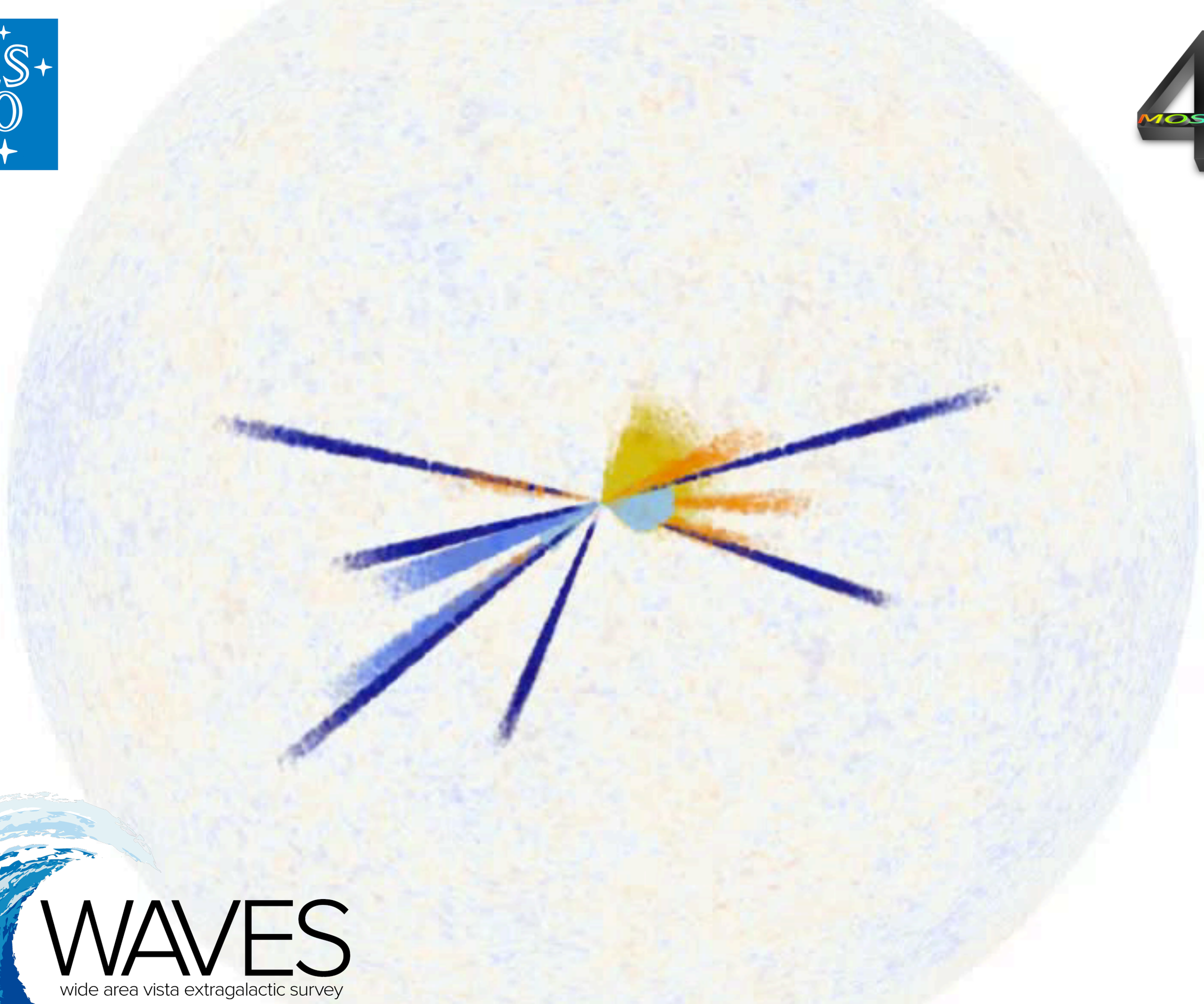
Our Ancillary Data

The LADUMA team has submitted 6 survey proposals (spectroscopic, imaging).

- NOAO proposal for deep U-band imaging over 2 deg^2.
- SALT commissioning proposal of 20 hours (8 x 30min exposures) on GOODS-S. *Ongoing*
- AAT already targeted CDFS for several programs. Dedicated NASA time for LADUMA spectroscopic redshifts (2 successful programs).
  - Props to GAMA team for technical help!!
  - 3500 redshifts

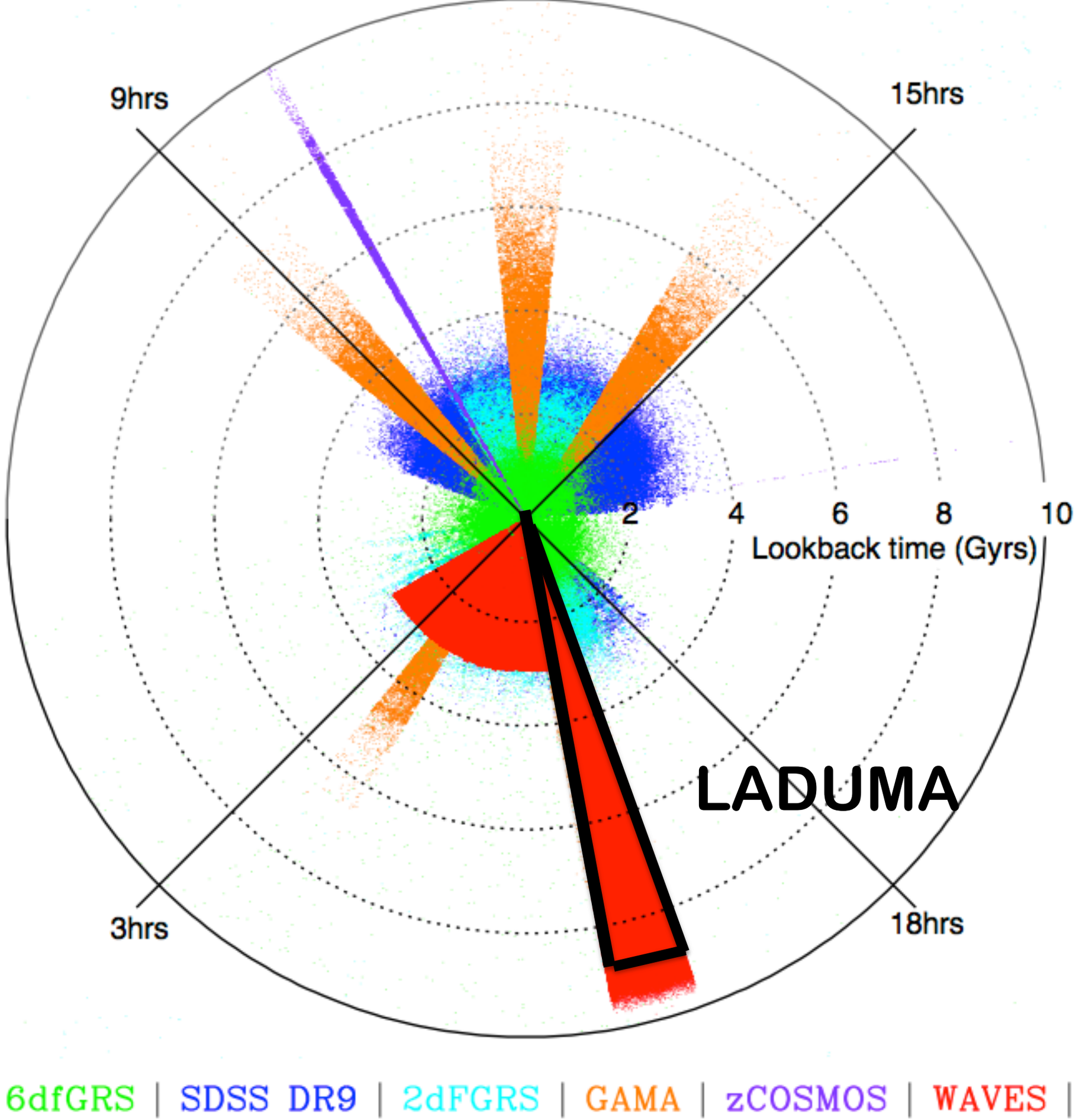
ENTER THE WAVE(S)

- 4MOST wide and deep spectroscopic surveysL
- WAVES
- ORCHIDSS
- MOONS infrared redshift survey.

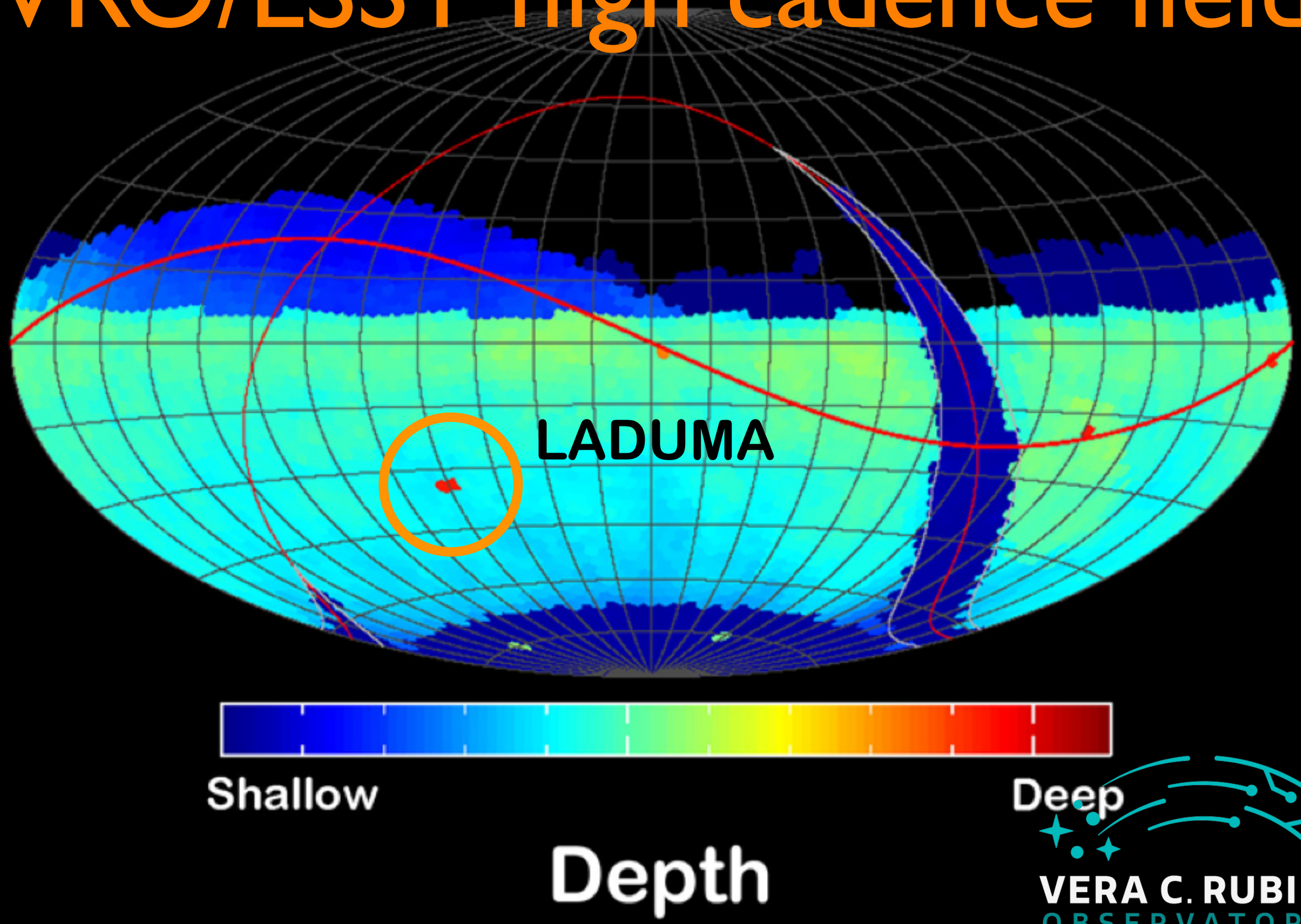


WAVES

wide area vista extragalactic survey

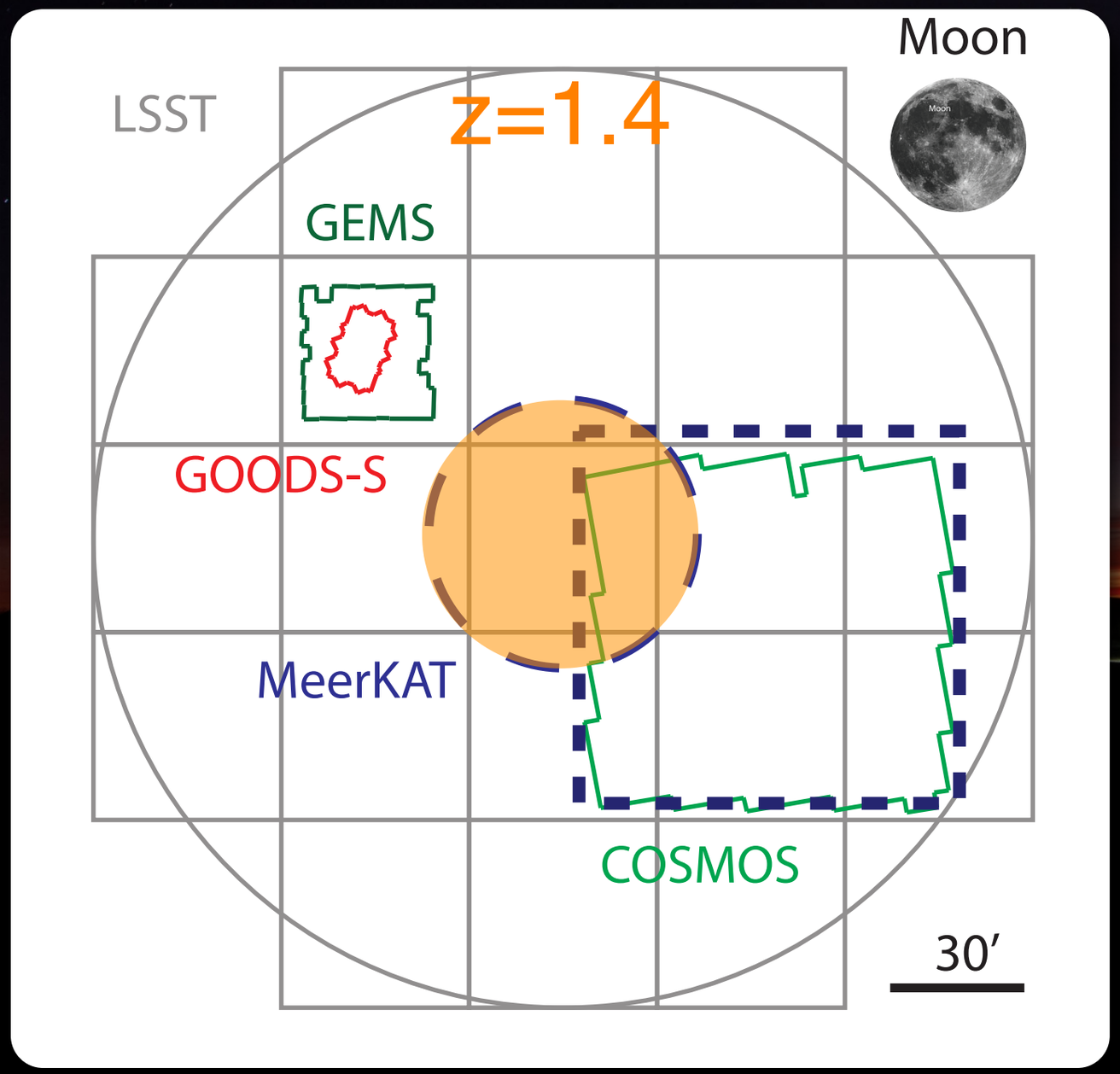

9hrs
15hrs
3hrs
18hrs
2
4
6
8
10
Lookback time (Gyrs)
LADUMA
| 6dfGRS | SDSS DR9 | 2dFGRS | GAMA | zCOSMOS | WAVES |

VRO/LSST high cadence field

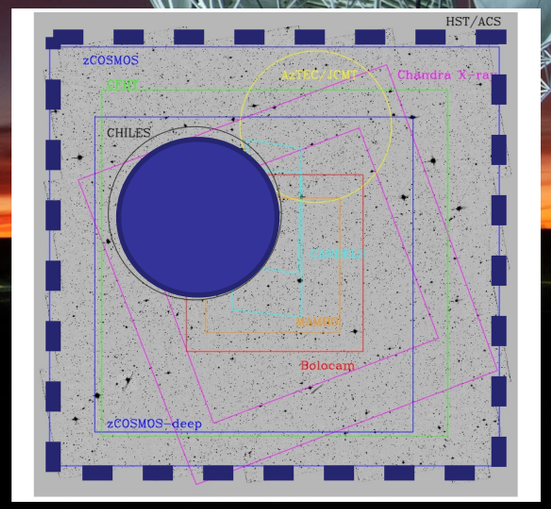


VERA C. RUBIN
OBSERVATORY

CDF-S / COSMOS



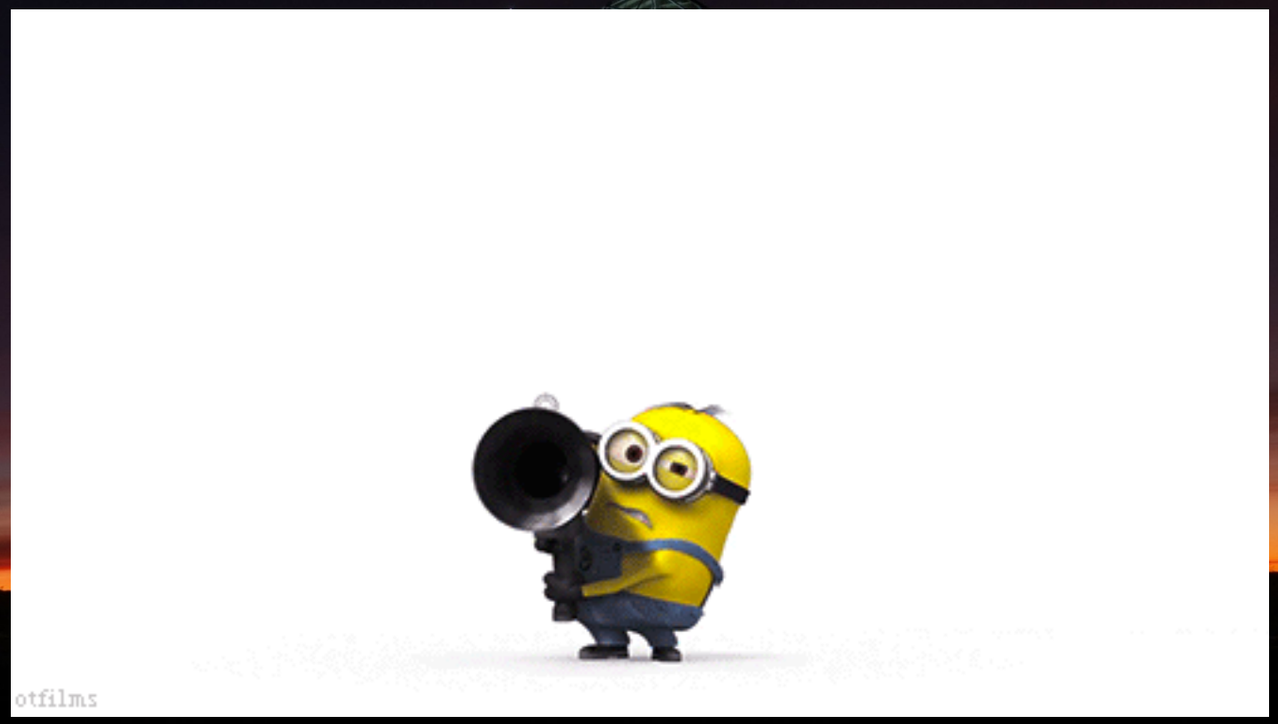
CHILES
COSMOS HI Large Extragalactic Survey



Category	Chandra Deep Field	COSMOS
Spectral coverage	30% in the medium deep field VVDS	70% zCOSMOS, G10 area of GAMA ✔
Spectral Resolution	4MOST deep field	R=600
Deep	MUSE	10-12k redshifts over 1.0 sq. deg., $I_{AB} < 24.0$
HST	WFIRST/EUCLID	F814W (I) only
GALEX	deepest available ✔	$< 26\ M_{AB}$
X-ray	second deepest anywhere with Chandra, deepest in southern hemisphere (940 ks) ✔	XMM - 1.4 megaseconds Chandra - 200 ksec, mosaiced
Radio	Some continuum with ATCA, 20 cm with VLA	Continuum with VLA, some line observations with GMRT, CHILES
Optical	VRO deep field SpARCS z-band to 24.2 (AB)	Subaru B (27.4), V (27.2), r+ (26.9), i+ (26.9), z+ (25.6) CFHT-LS u*,g*,r*,i*,z*
NIR	VIDEO Z,Y,J,H,K to 25.7,24.6,24.5,24.0,23.5 (AB) ✔ JHK (ISAAC & SOFI)	JH (CFHT-LS)
Spitzer	very deep IRAC & MIPS ✔ SWIRE fields	sCOSMOS, uniform coverage
Herschel	deepest available,SERVS ✔	HERSCHEL-HERMES field

Cosmic Variance

- Two separate fields > 1 big one
- CHILES on COSMOS, LADUMA on CDFS



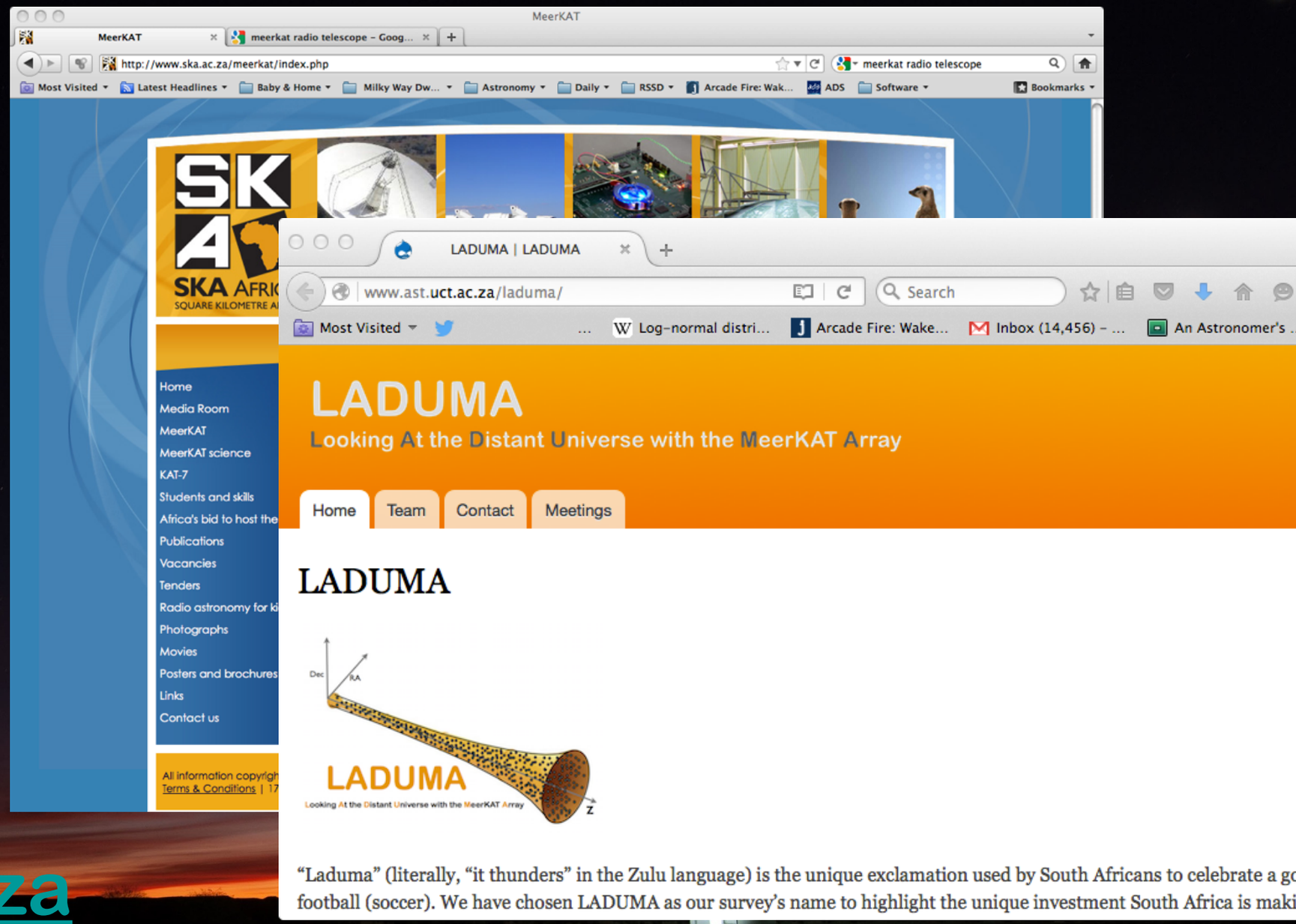
Two shots much better than one.

Out h Effort

Take-Home

- Single deep stare to detect HI; a blind HI and multi-wavelength survey.
- Line stacking and direct detections.
- Science:
  - How does the (baryonic) **Tully-Fisher** relation evolve with redshift?
  - How does the **HI mass function** (HIMF) vary with redshift and environment?
  - How does the **cosmic HI density** (Ω_{HI}) evolve with redshift?
  - How do **galaxies' HI masses** depend on their stellar and/or host halo masses, environment, and redshifts?
- Data will be public! Legacy HI cube till SKA fires up.

Thank you!



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- www.ska.ac.za/meerkat
- http://www.ast.uct.ac.za/LADUMA/
- https://www.facebook.com/MeerKATLaduma