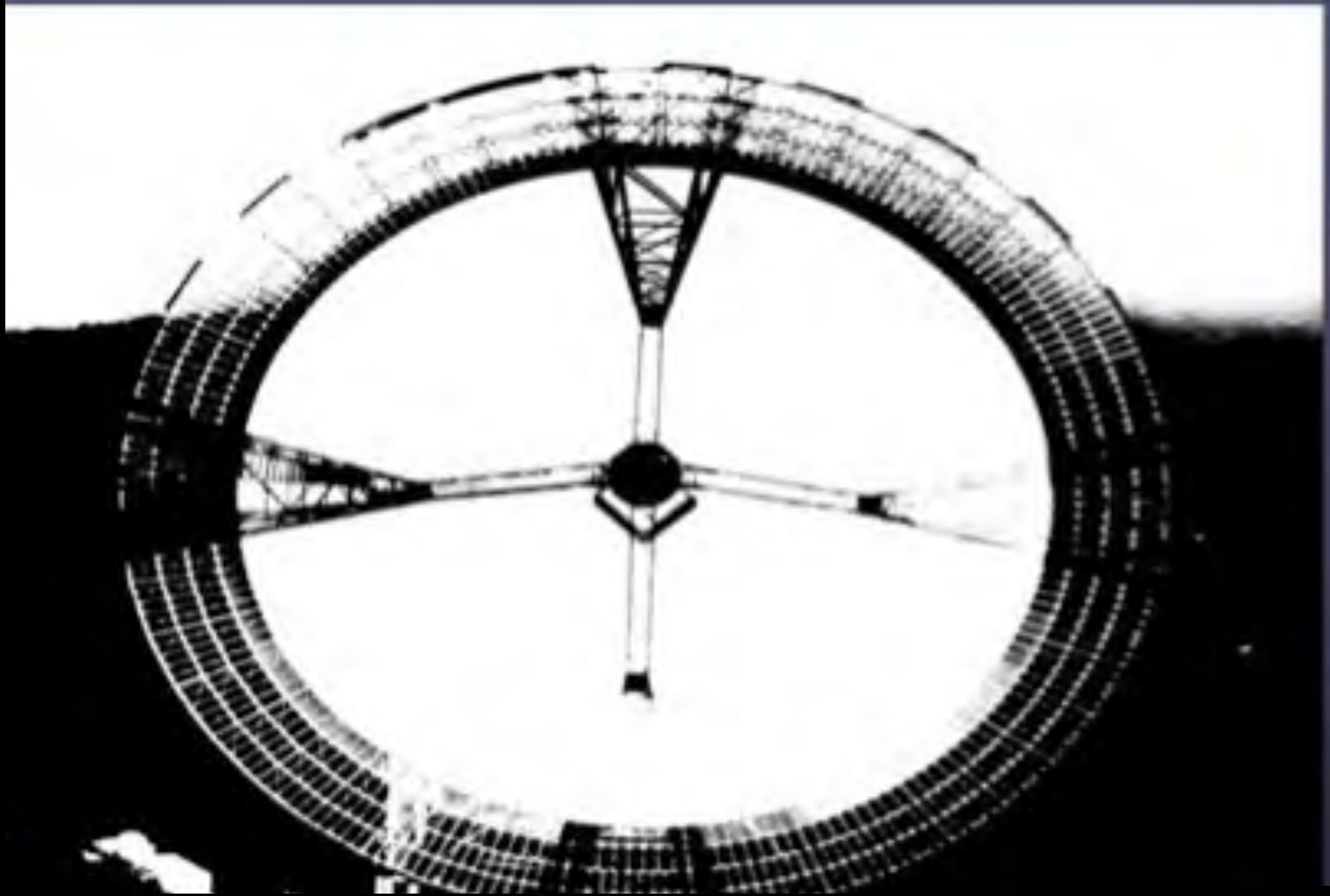
A Survey of GBT Science

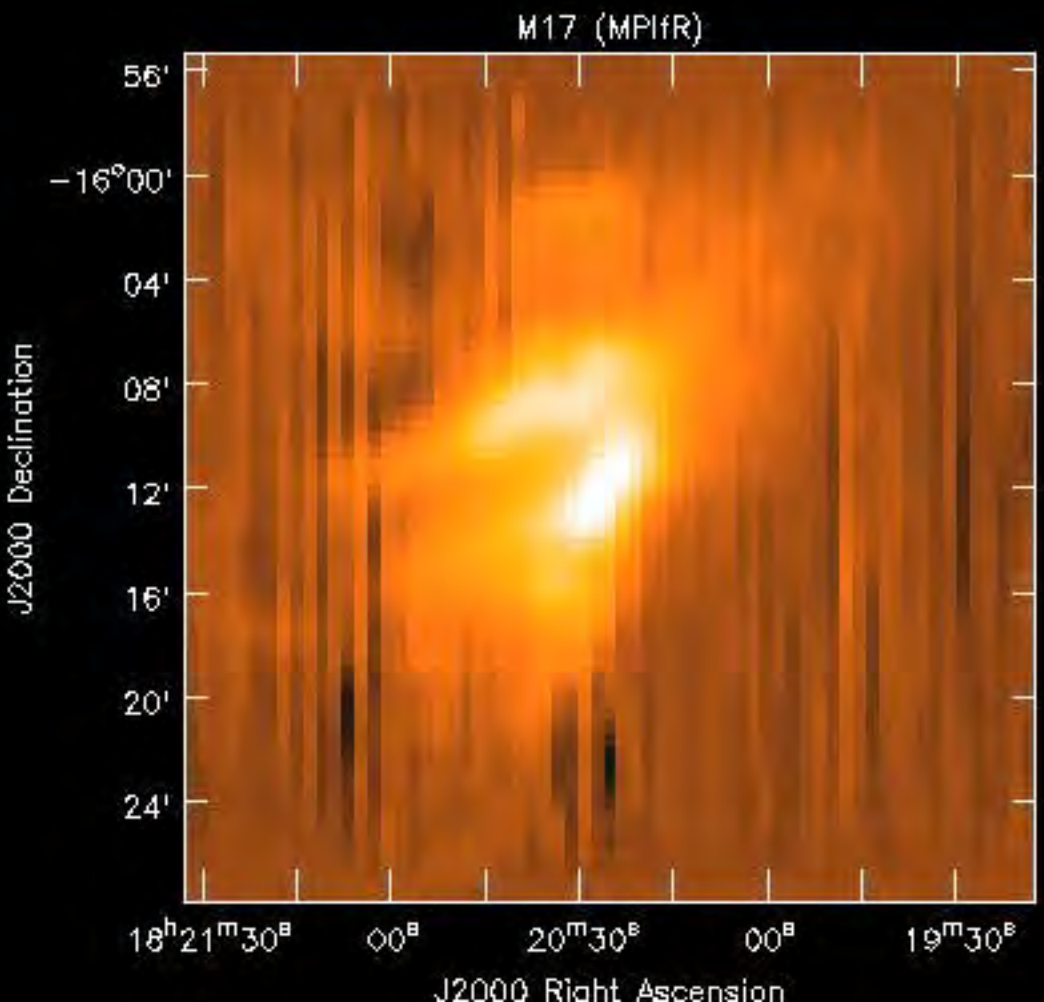
Felix J. Lockman
Green Bank Observatory, Green Bank, WV

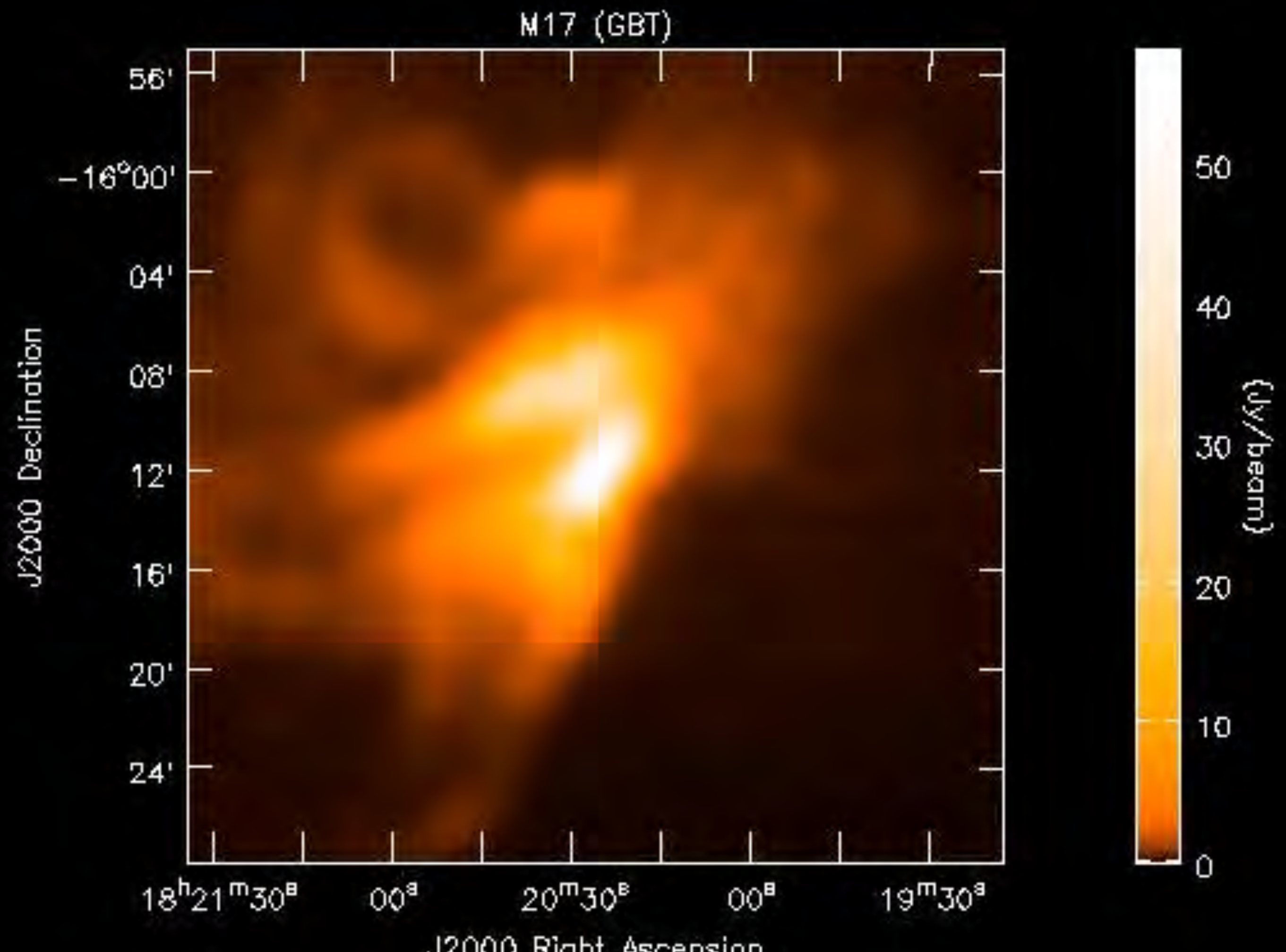
GBT Surveys Workshop — November 13, 2018

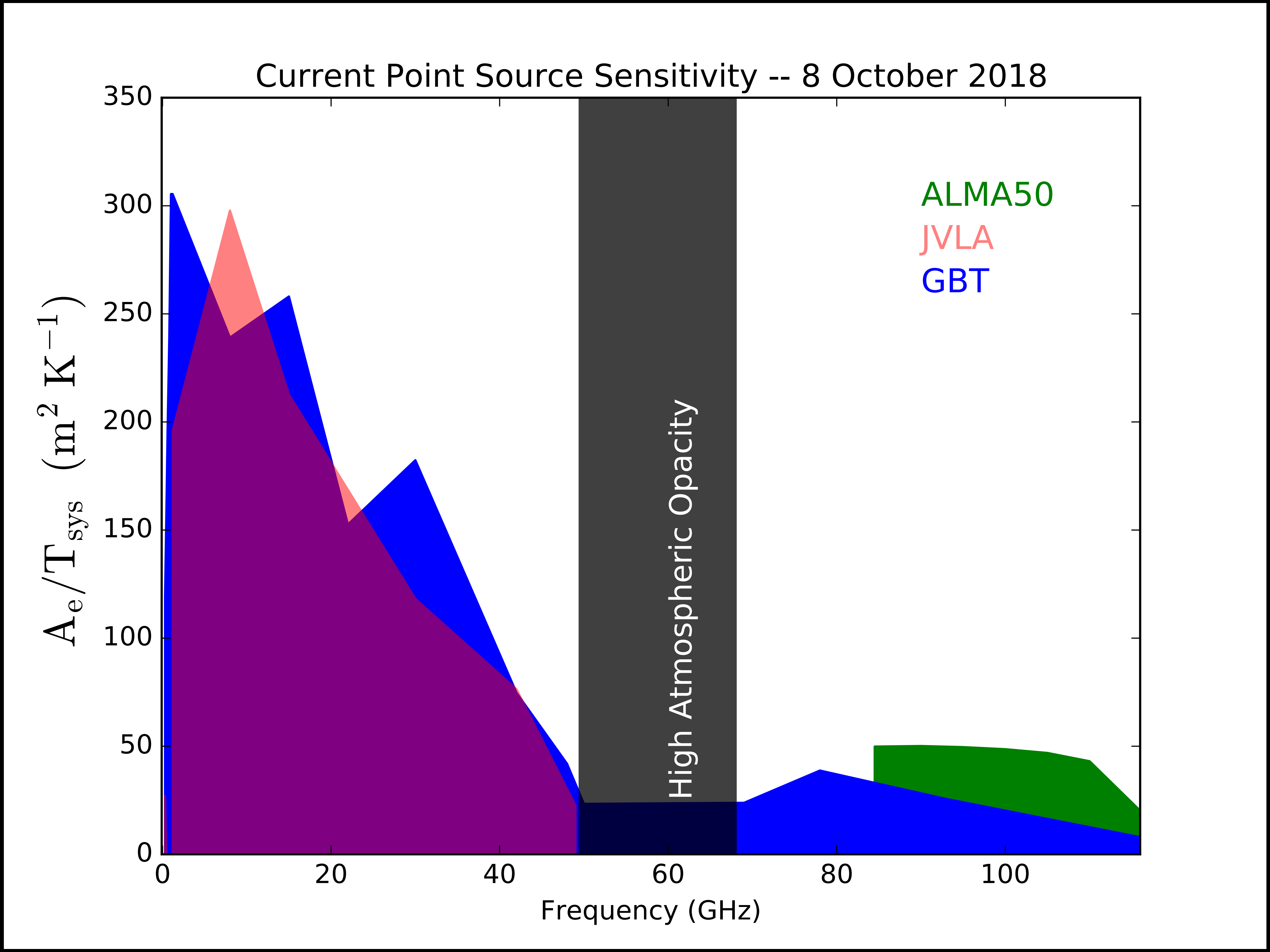

National Radio Quiet Zone
Appalachian Mountains
Washington D.C.
GREEN BANK OBSERVATORY

Unblocked Optics for High Dynamic Range

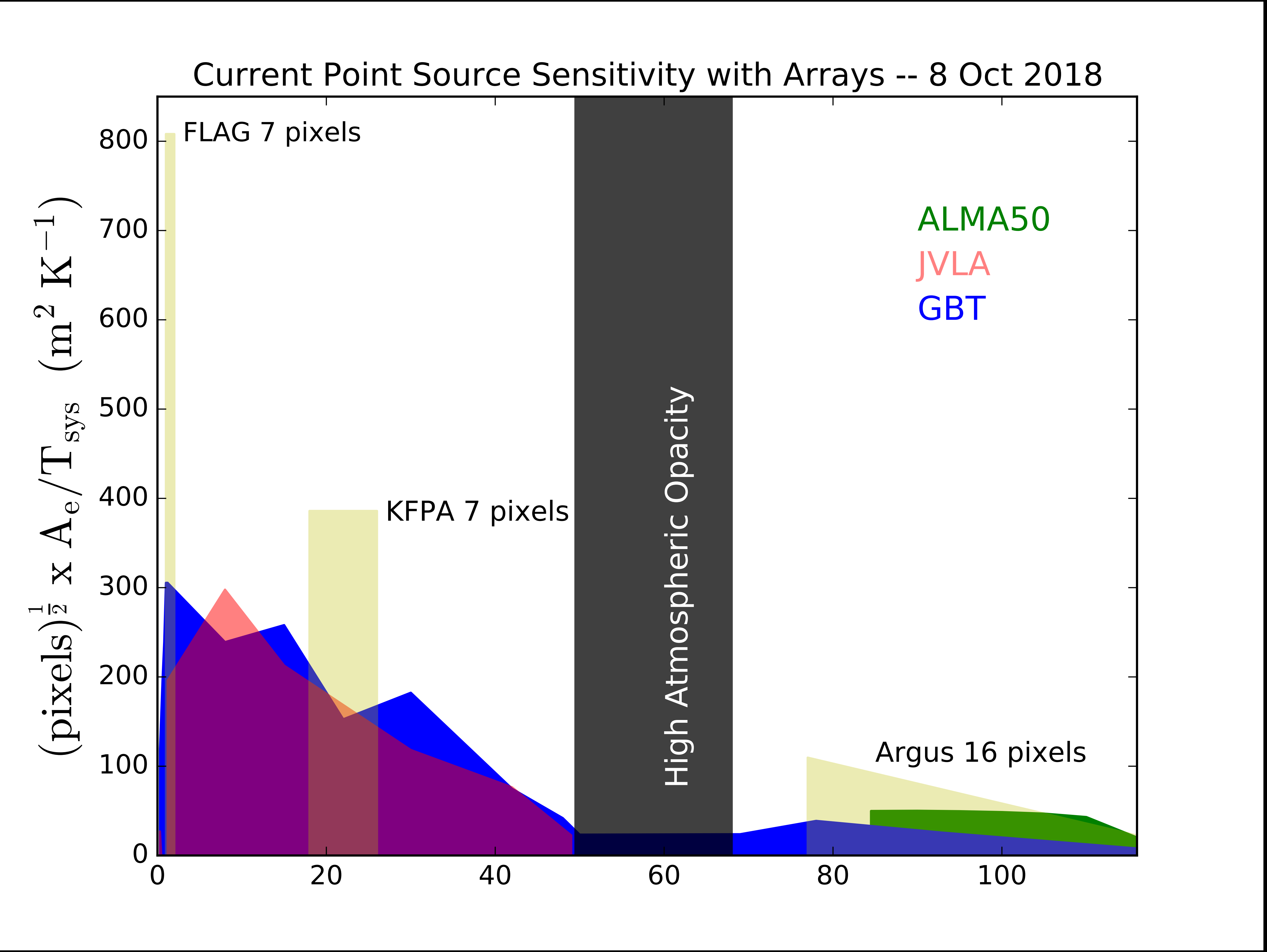








Current Point Source Sensitivity -- 8 October 2018
A_e/T_{sys} $(m^2\ K^{-1})$
0
50
100
150
200
250
300
350
0
20
40
60
80
100
Frequency (GHz)
High Atmospheric Opacity
ALMA50
JVLA
GBT


Current Point Source Sensitivity with Arrays -- 8 Oct 2018
$(\mathrm{pixels})^{\frac{1}{2}}$ x $\mathrm{A_e/T_{sys}}$ $(\mathrm{m^2\,K^{-1}})$
0
100
200
300
400
500
600
700
800
0
20
40
60
80
100
FLAG 7 pixels
KFPA 7 pixels
High Atmospheric Opacity
Argus 16 pixels
ALMA50
JVLA
GBT

FLAG 21cm – 7 beams

FLAG 2018

The Astronomical Journal, 155:202 (18pp), 2018 May

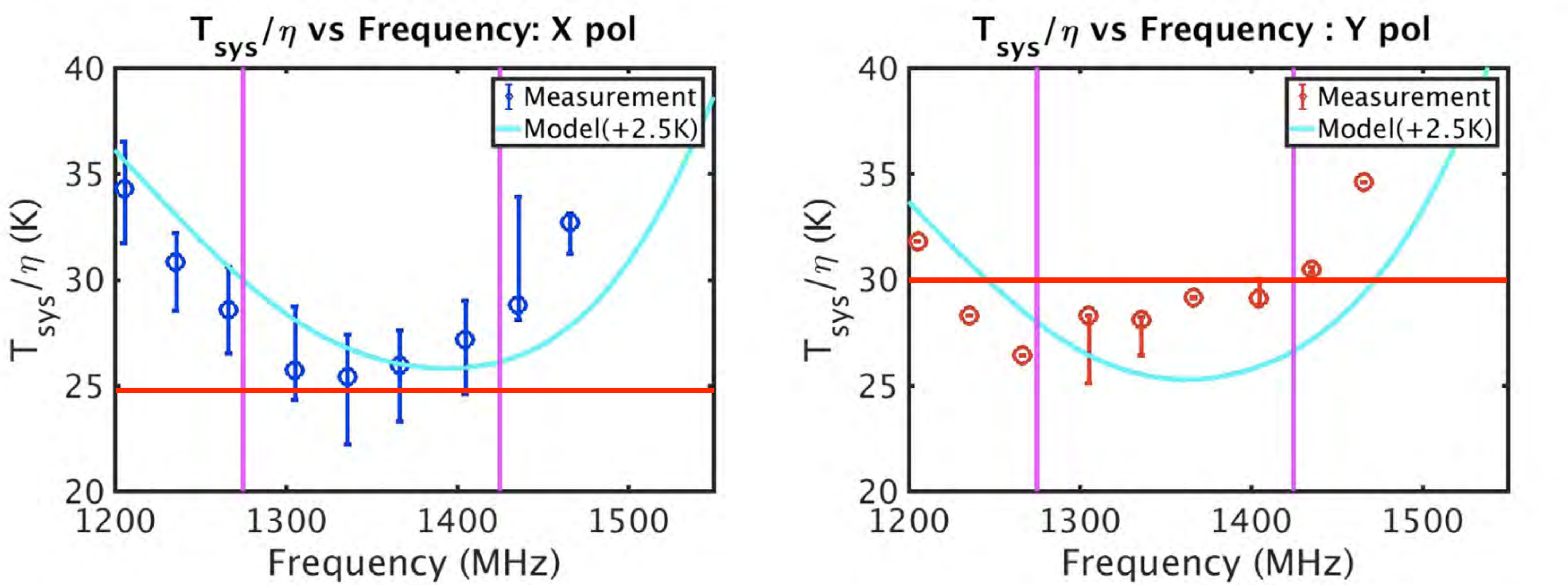


Figure 14. The PAF model prediction (solid line) along with the median measured $T_{\rm sys}/\eta$ with their peak-to-peak variations for the *X* (left) and *Y* (right) polarizations. The data points shown in Figure 9 are used to compute the median $T_{\rm sys}/\eta$. The median is computed from the set of measurements in a frequency interval of ~1.5 MHz. The model assumes lossless PAF; hence, the system temperature in the model is increased by 2.5 K to take into account the losses ahead of the LNA (see Figure 3(b)).

At 1.4 GHz for aperture efficiency 0.7, Tsys = 19 K, 21 K

Roshi et al. 2018, AJ, 155, 202

The GBT User Community

Observers: 1,300 in 2013-2017
Observers: 601 in 2017
30% “new”

The GBT is as oversubscribed as the JVLA

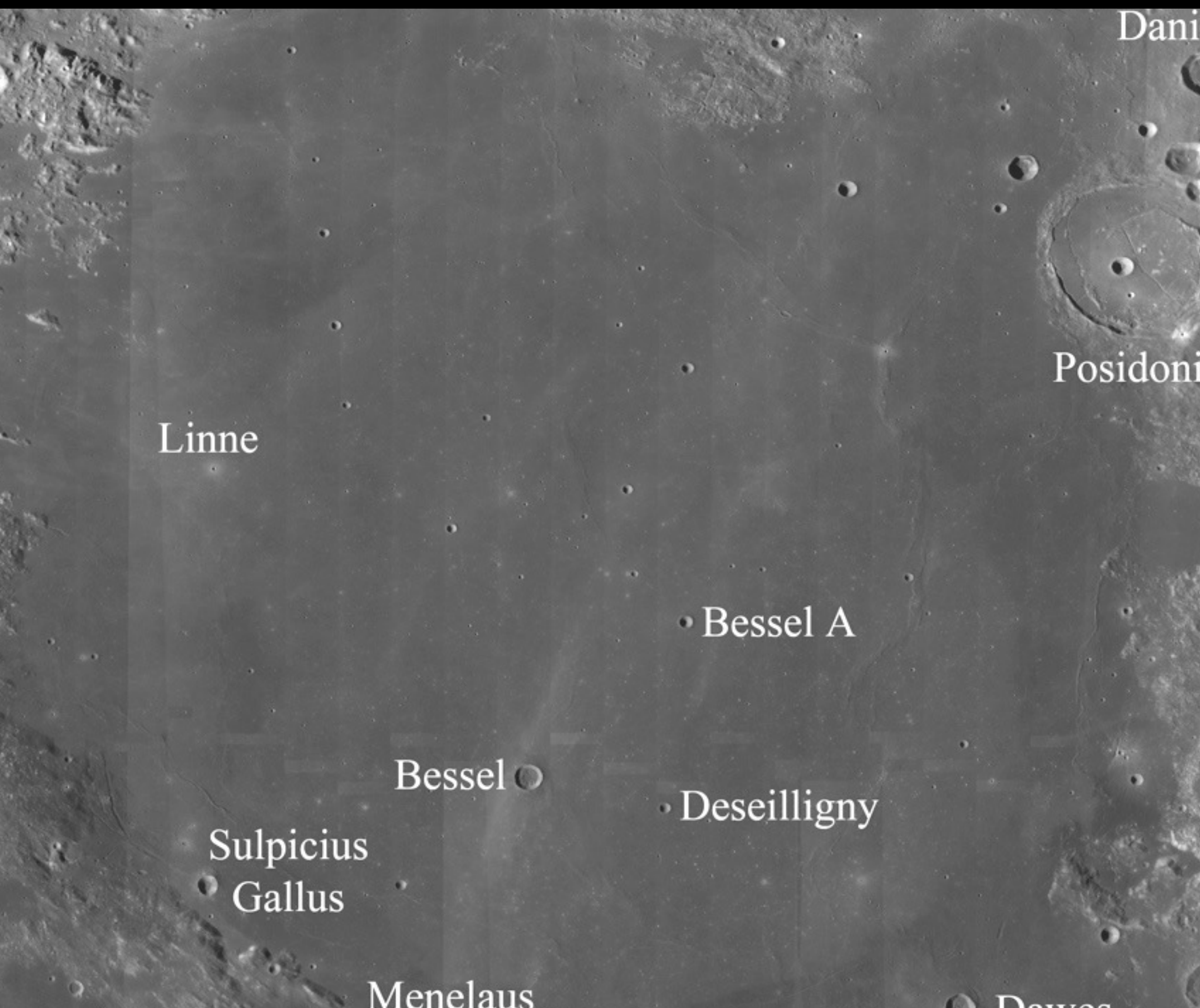
GBT Usage	2010-2012 6540 hours	2016-2107 6813 hours
Spectroscopy	3,464 53%	3,832 56%
Pulsars	1,920 29%	2,212 32%
VLBI	754 12%	414 6%
Continuum	352 5%	298 4%
Radar	50 1%	58 1%

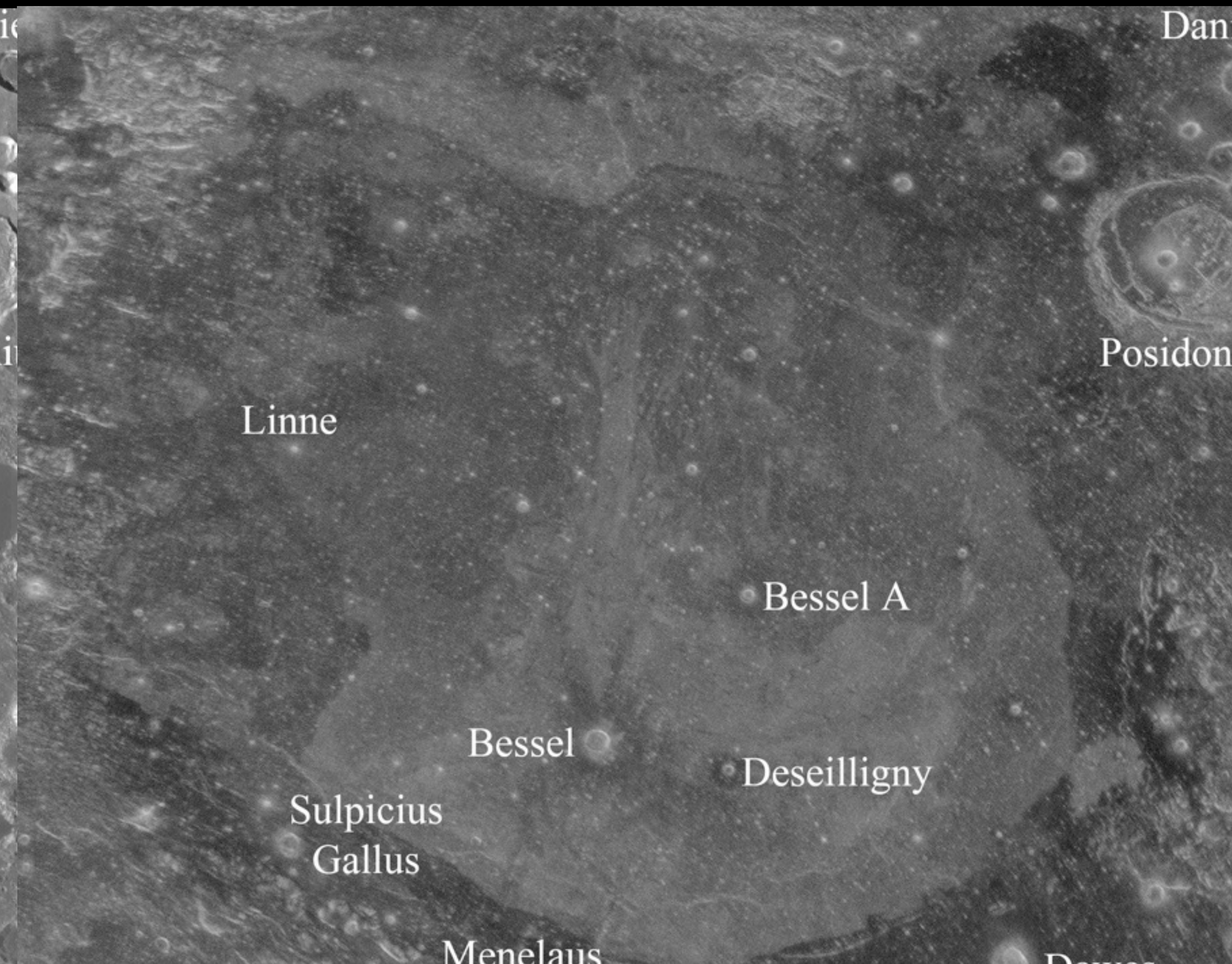
Topics of most-cited GBT publications

(October 2018)

- Pulsars and compact objects
- Gravity and General Relativity
- Galactic Hydrogen surveys
- Interstellar Chemistry
- The internal structure of Mercury
- Star formation & pre-stellar objects
- Studies of a binary black hole
- Hydrogen content of galaxies
- Star formation in highly redshifted galaxies
- Anisotropies in the cosmic Infrared background

Bi-static radar studies with Arecibo



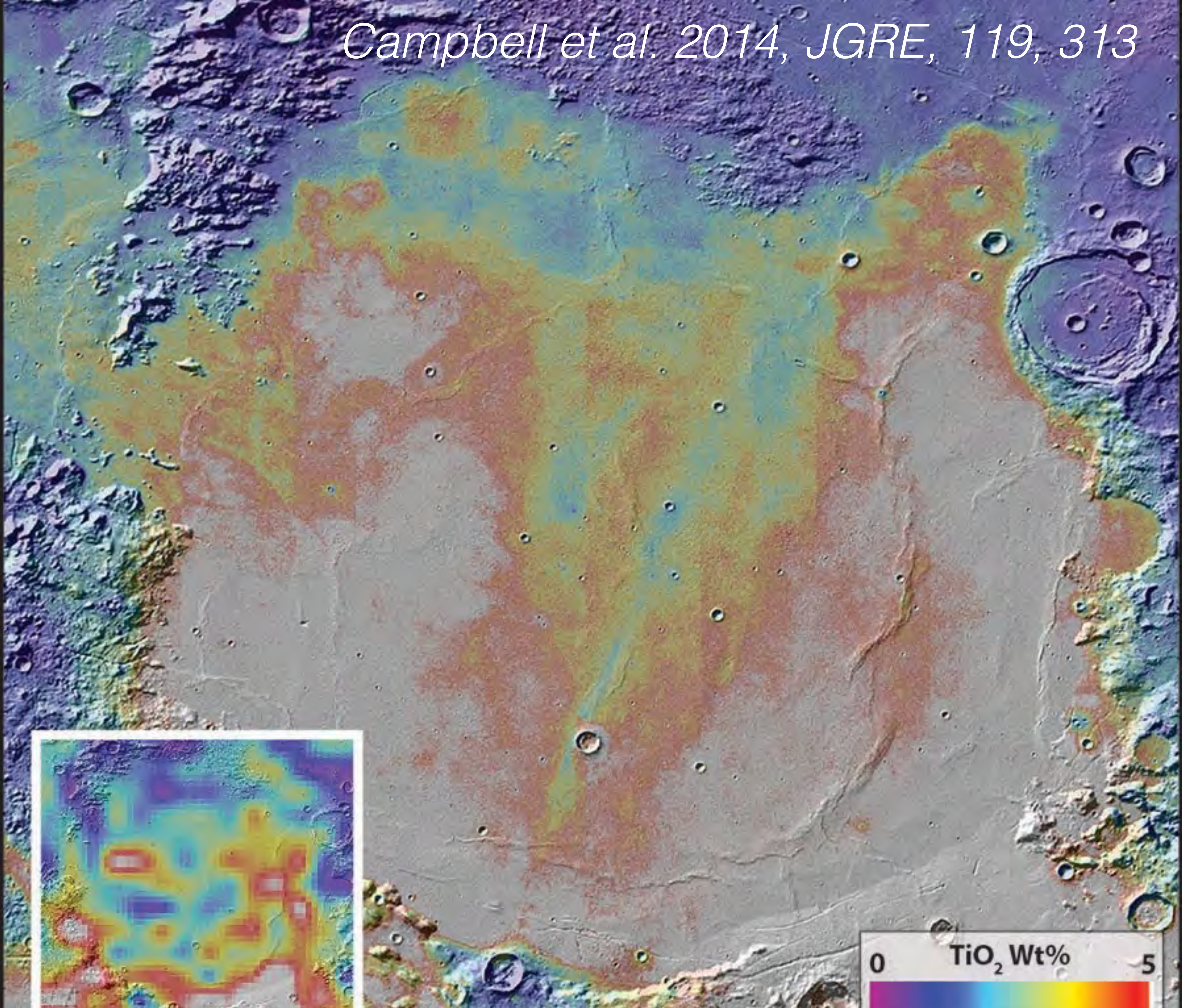


OPTICAL

70cm RADAR

Campbell et al. 2014, JGRE, 119, 313

TiO_2



Secondary crater-initiated debris flow on the Moon

K.S. Martin-Wells[a,*], D.B. Campbell[b], B.A. Campbell[c], L.M. Carter[d], Q. Fox[a]

[a] Franklin & Marshall College, 422 Hackman Physical Sciences Laboratories Building, 415 Harrisburg Avenue, Lancaster, PA, 17603, USA
[b] Cornell University, 502 Space Sciences Building, Ithaca, NY, 14853, USA
[c] Center for Earth and Planetary Studies, National Air and Space Museum, 600 Independence Ave SW, Washington, D.C., 20560, USA
[d] NASA Goddard Space Flight Center, Mail Code 698, Greenbelt, MD, 20771, USA

2017, Icarus

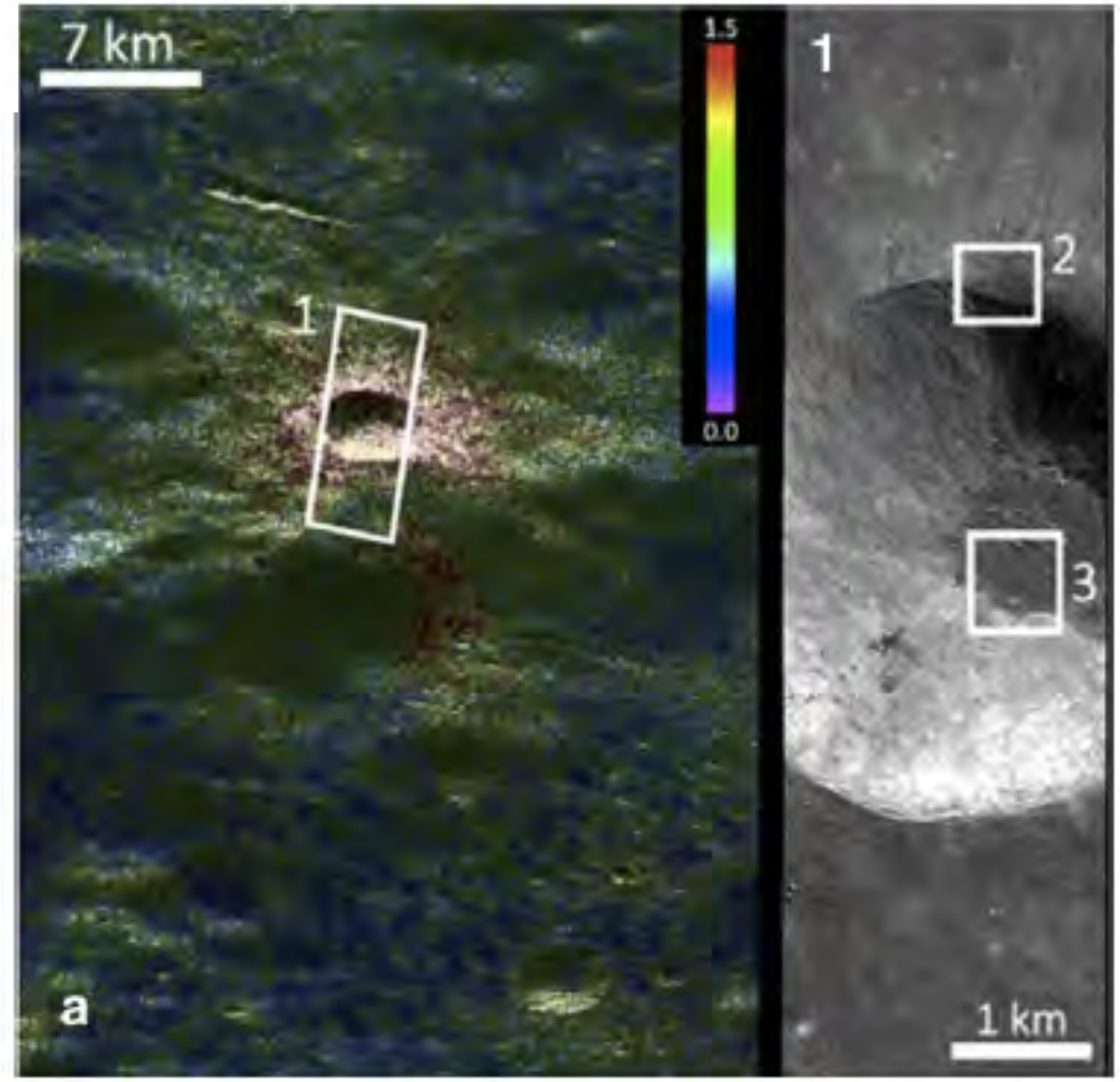
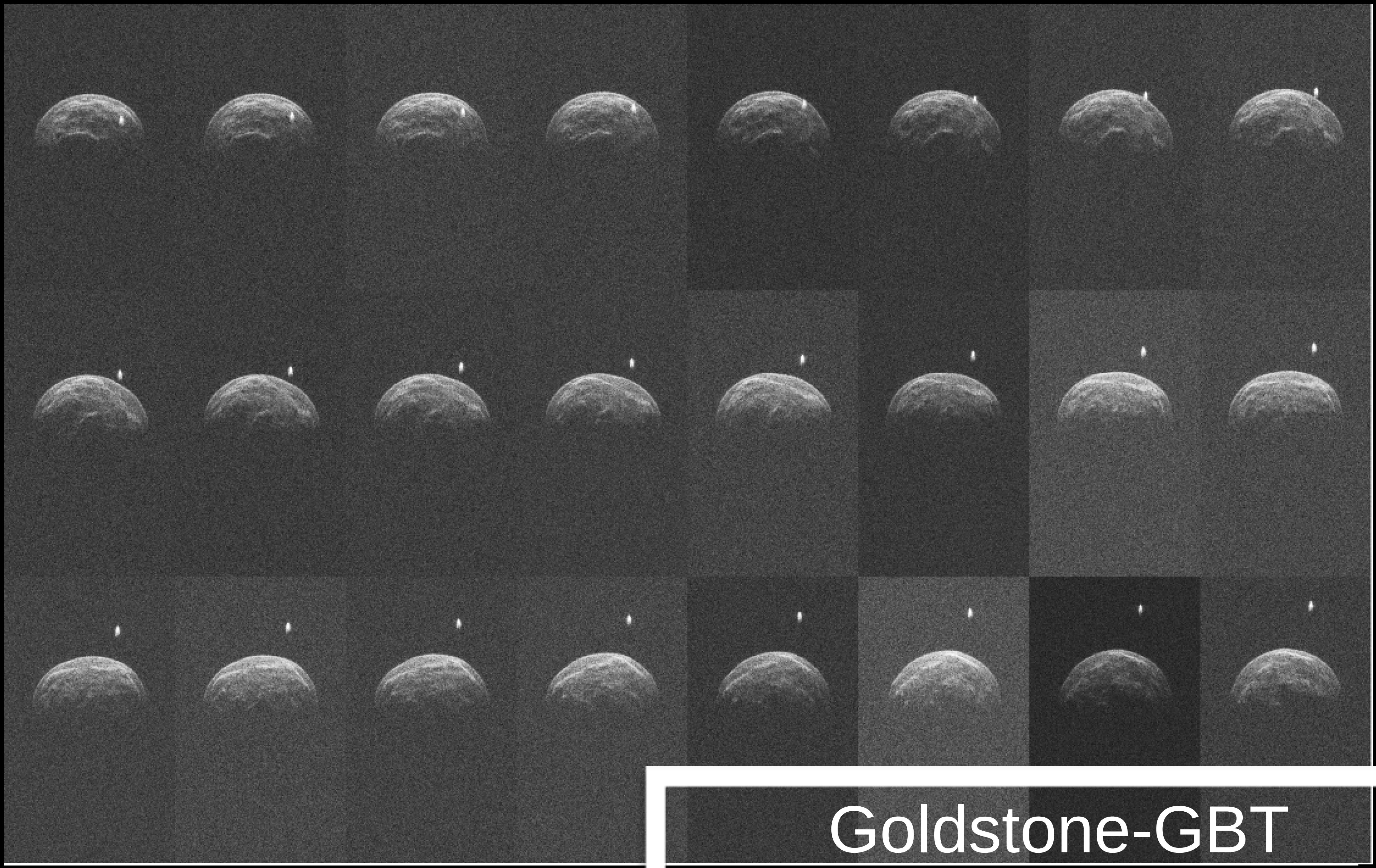


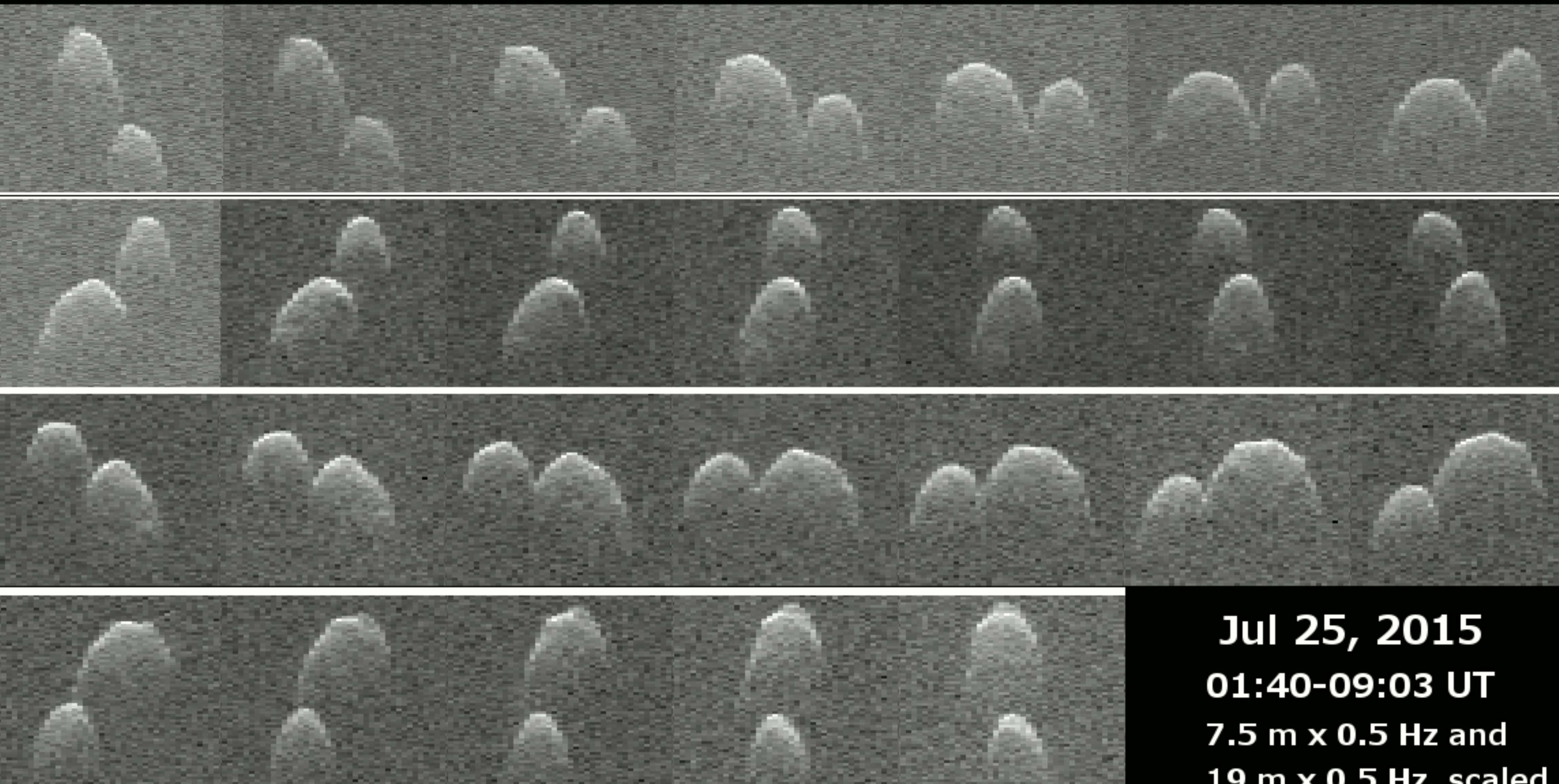
Fig. 2. **(a)** Arecibo-GBT 13-cm radar CPR product with coverage of Control Region 2. For all radar CPR images presented in this work, CPR products are overlaid on polarized ("opposite sense") products of the same region. Color scale bars in CPR products indicate CPR values. Control craters in this work exhibited radar CPR enhancements concentrated in disks around the crater planforms, extending no more than a few crater radii from the impacts. The 13-cm signatures extend to greater distances from the crater than the 70-cm signatures. Radar CPR enhancement "tails," like those in Fig. 5, were not observed at control craters. Note that the CPR enhancement associated with the primary crater in Control Region 2 is roughly azimuthally symmetric around the crater rim.
(1) Control Region 2 (NAC product M142239567). Insets 2 and 3 are shown in more detail in Fig. 3. Note the sharp change in local slope along the crater rim. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

GBT bi-static radar of near earth objects



Goldstone-GBT
27 Jan 2015
Asteroid 2004BL86
with small companion

(85989) 1999 JD6

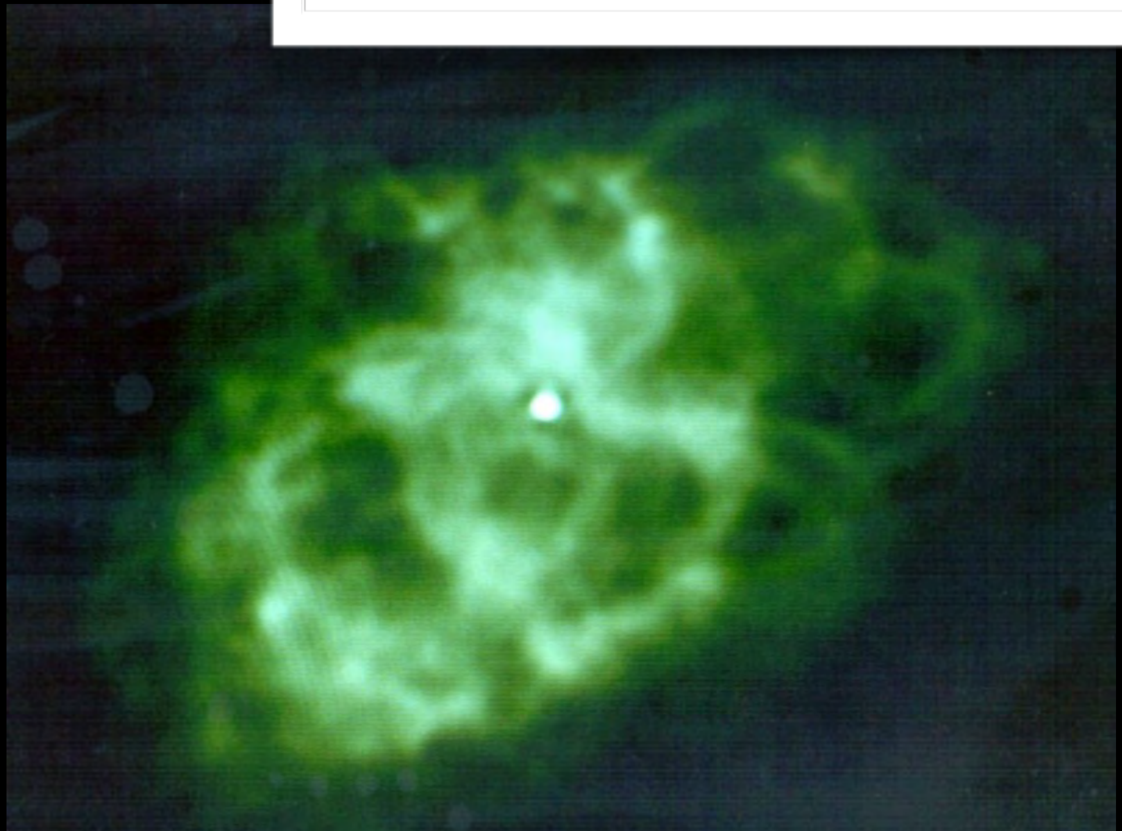


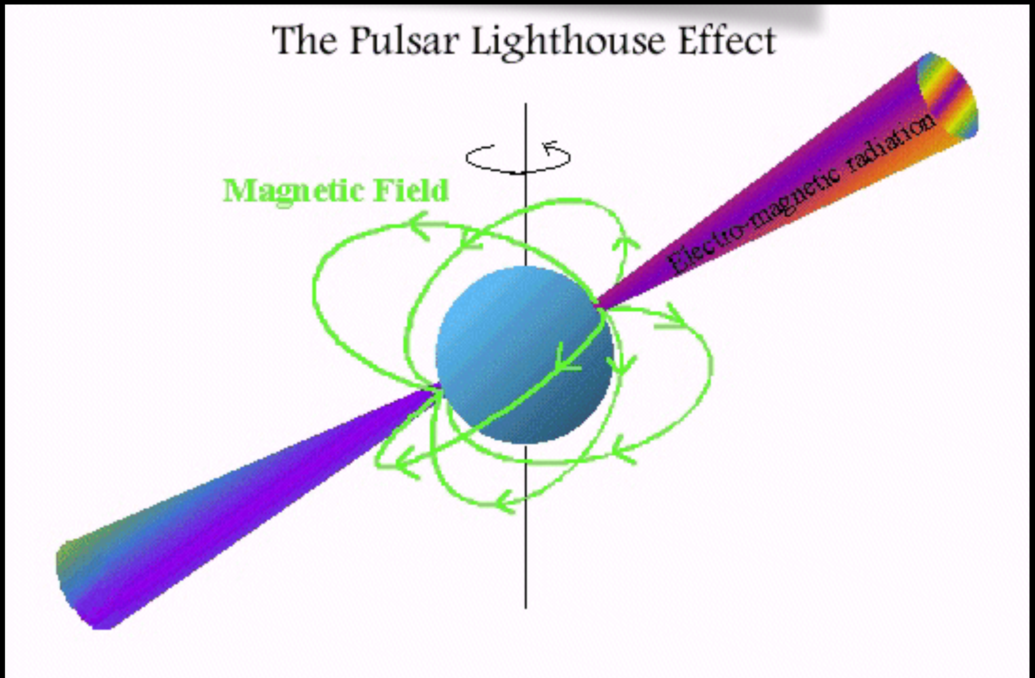
Goldstone-GBT bistatic radar images

~18x the distance to the Moon

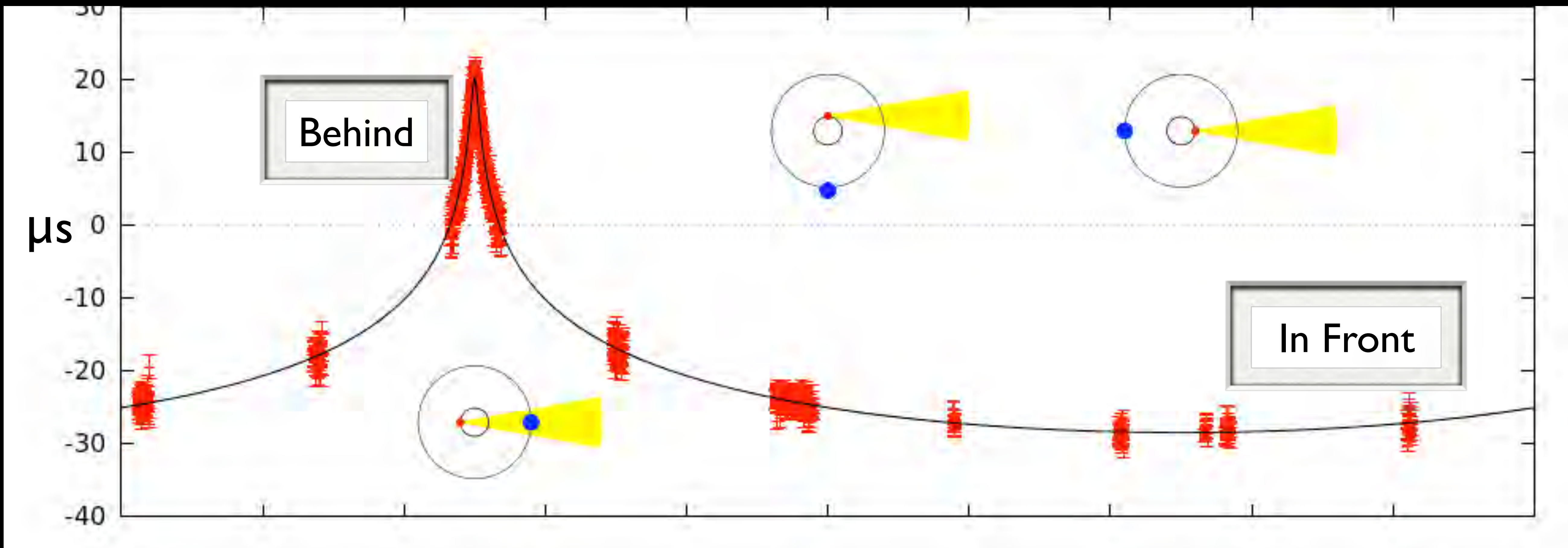
GBT -- The Premier Pulsar Telescope

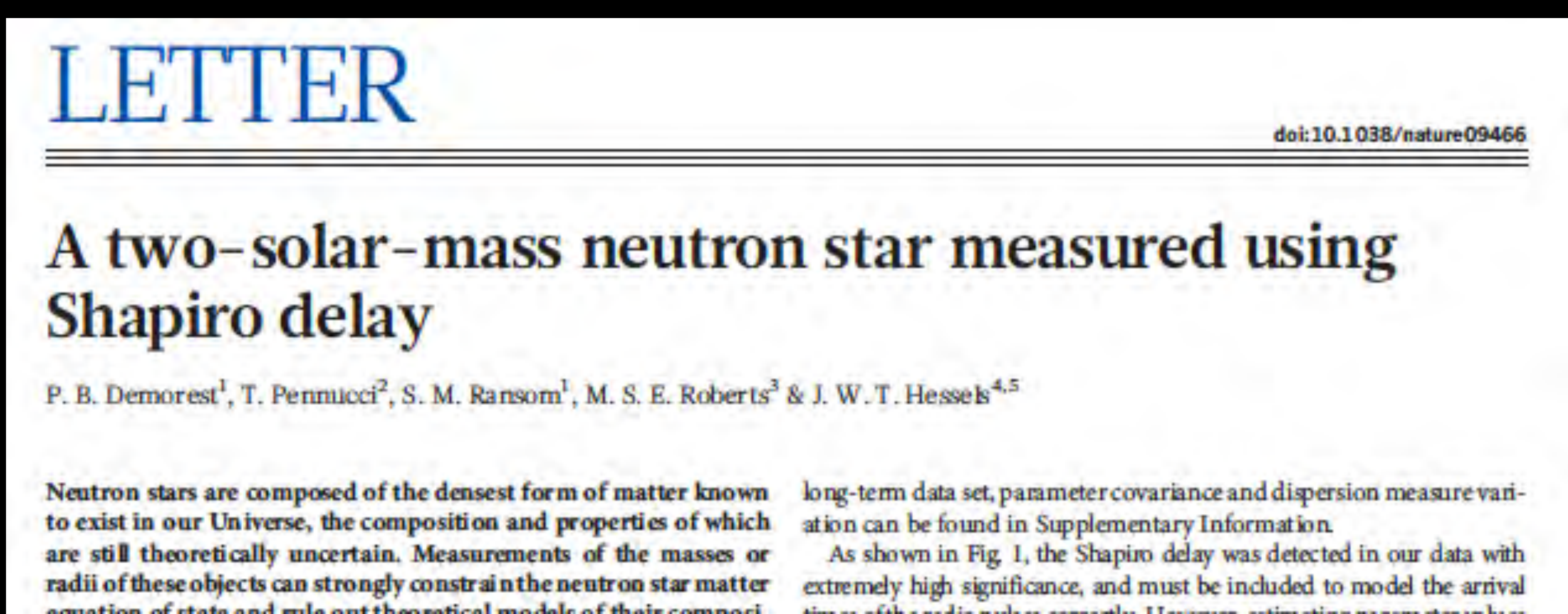
- Fastest Pulsar
- Most Massive Pulsar
- Pulsars in Globular Clusters
- Tests of General Relativity
- Relativistic Spin Precession
- Pulsar in a three-body system
- Coolest/oldest white dwarf star





The Shapiro Delay in Pulsars





LETTER

doi:10.1038/nature09466

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Neutron stars are composed of the densest form of matter known to exist in our Universe, the composition and properties of which are still theoretically uncertain. Measurements of the masses or radii of these objects can strongly constrain the neutron star matter

long-term data set, parameter covariance and dispersion measure variation can be found in Supplementary Information.

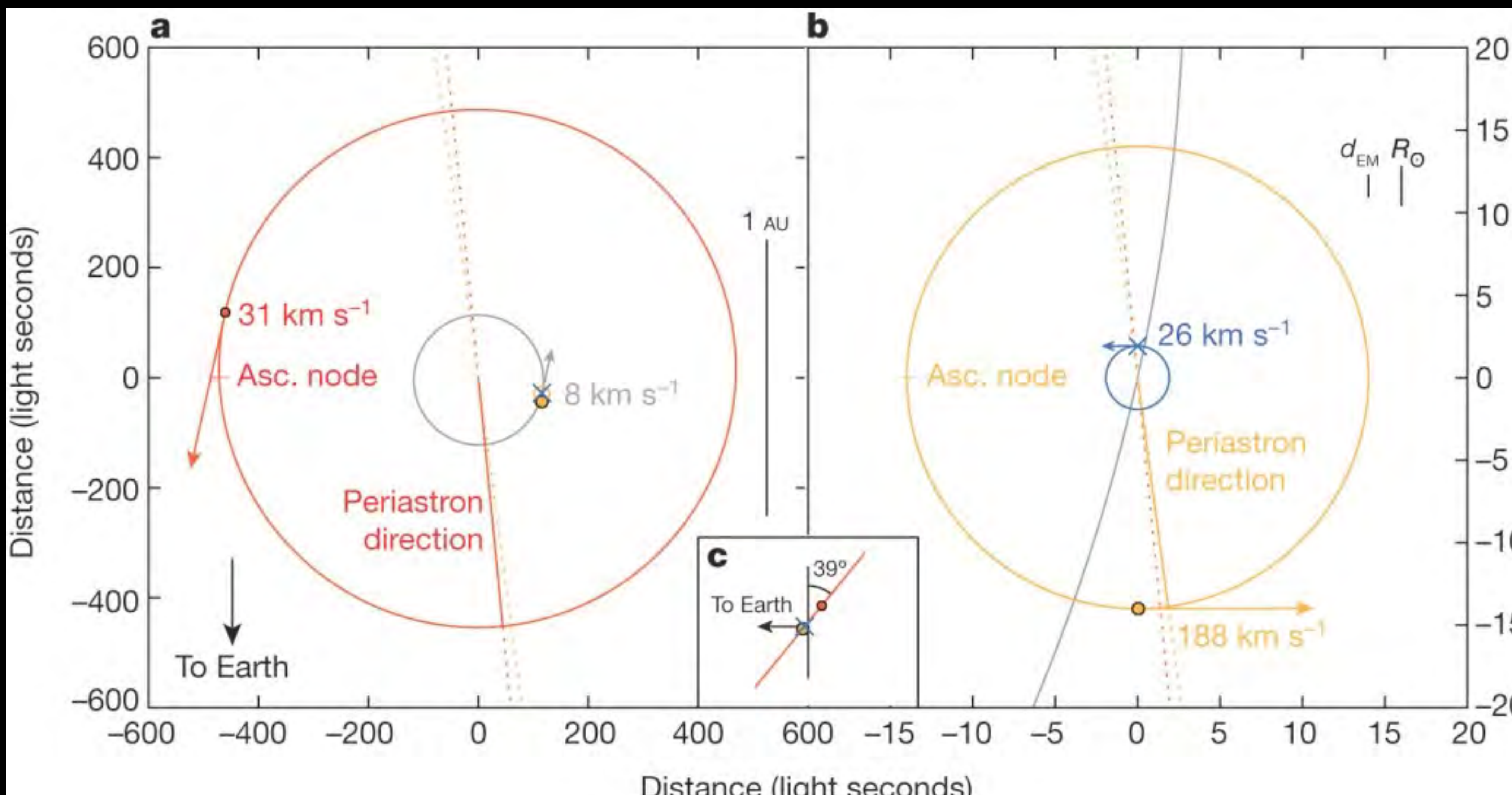
As shown in Fig. 1, the Shapiro delay was detected in our data with extremely high significance, and must be included to model the arrival

LETTER

doi:10.1038/nature12917

A millisecond pulsar in a stellar triple system

S. M. Ransom[1], I. H. Stairs[2], A. M. Archibald[3,4], J. W. T. Hessels[3,5], D. L. Kaplan[6,7], M. H. van Kerkwijk[8], J. Boyles[9,10], A. T. Deller[3], S. Chatterjee[11], A. Schechtman-Rook[7], A. Berndsen[2], R. S. Lynch[4], D. R. Lorimer[9], C. Karako-Argaman[4], V. M. Kaspi[4], V. I. Kondratiev[3,12], M. A. McLaughlin[9], J. van Leeuwen[3,5], R. Rosen[1,9], M. S. E. Roberts[13,14] & K. Stovall[15,16]



$$F = ma = GmM/r^2 \quad ???$$

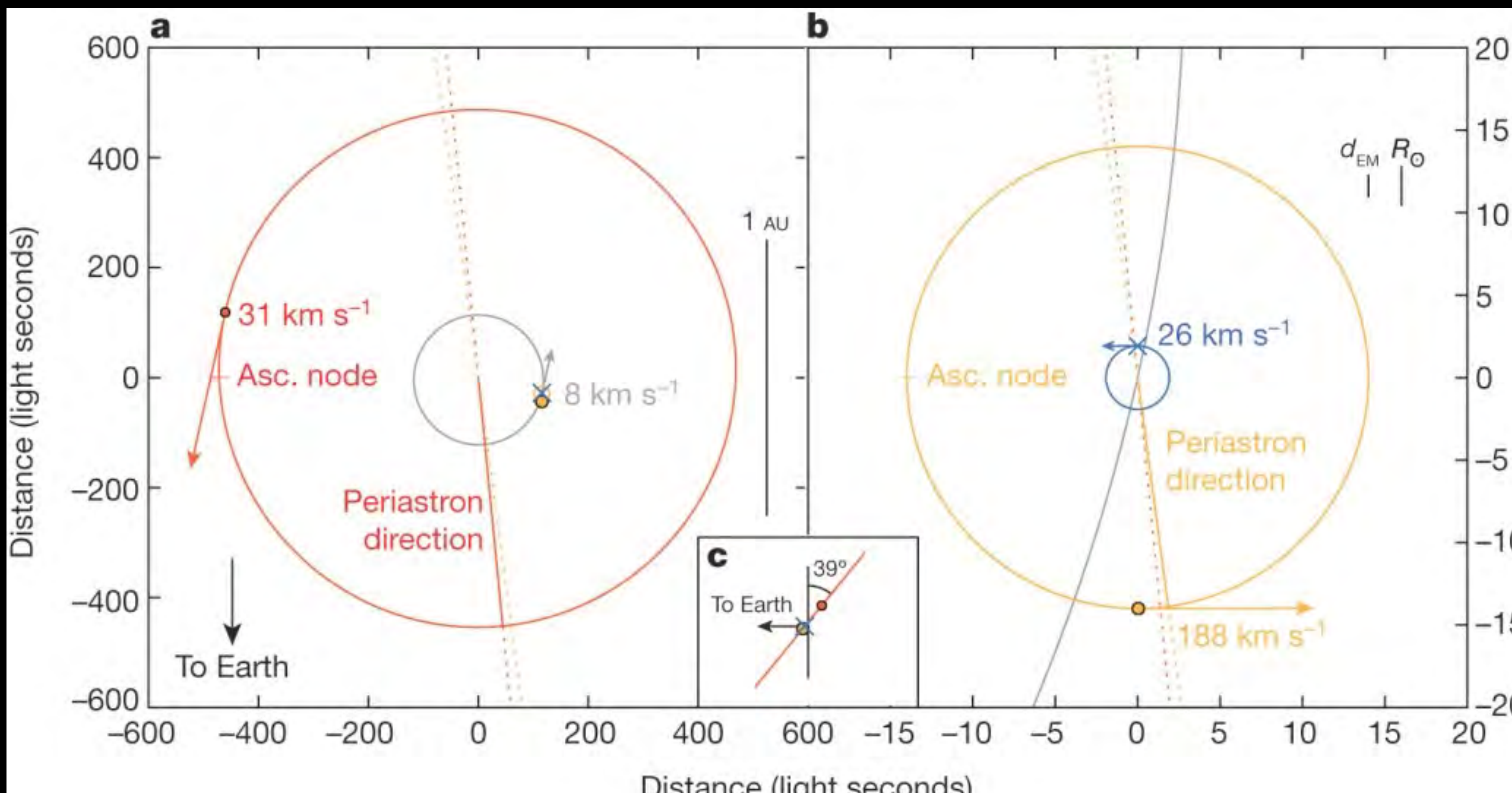
LETTER

2018

https://doi.org/10.1038/s41586-018-0265-1

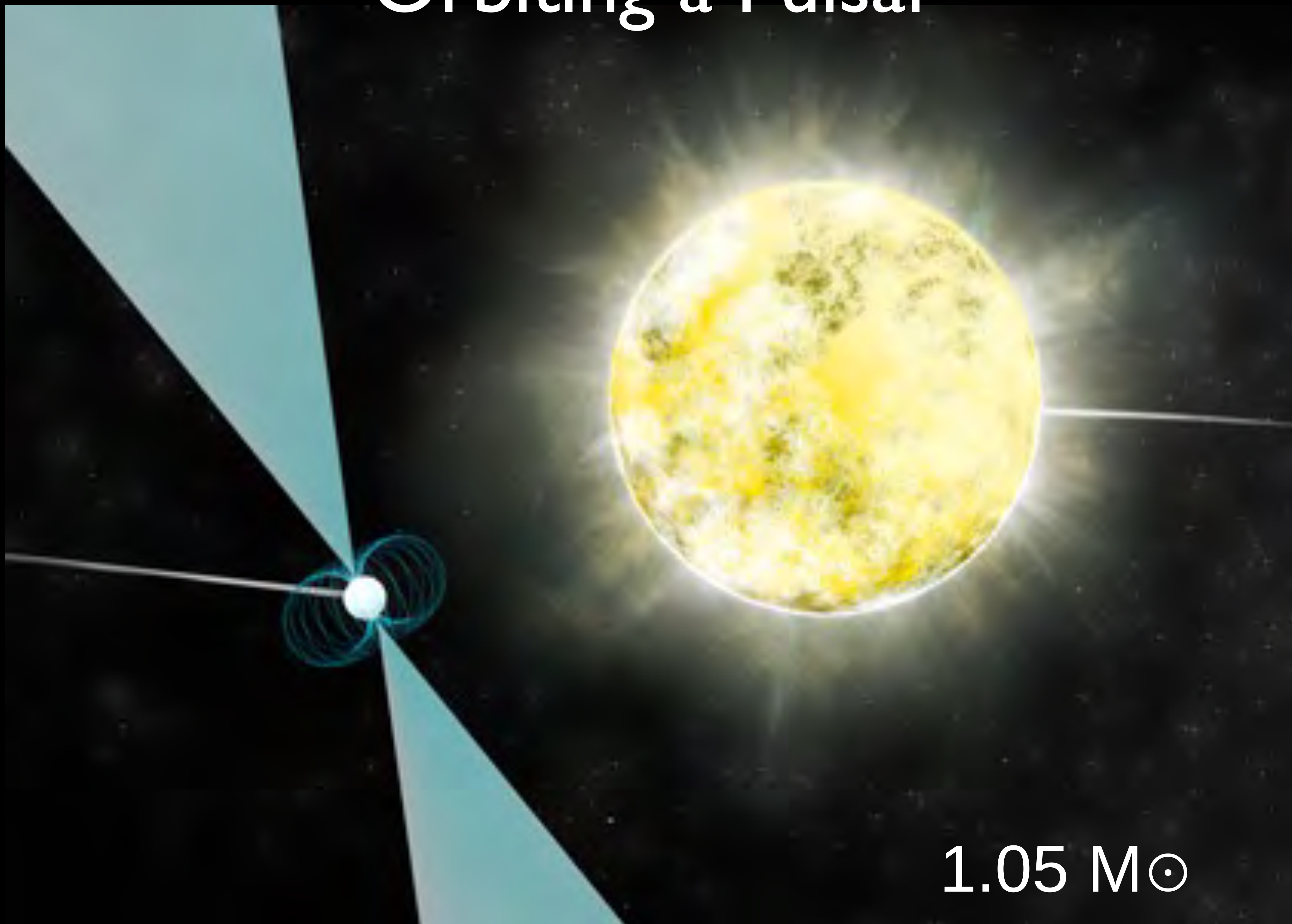
Universality of free fall from the orbital motion of a pulsar in a stellar triple system

Anne M. Archibald[1,2]*, Nina V. Gusinskaia[1], Jason W. T. Hessels[1,2], Adam T. Deller[3,4], David L. Kaplan[5], Duncan R. Lorimer[6,7], Ryan S. Lynch[7,8], Scott M. Ransom[9] & Ingrid H. Stairs[10]



$$F = ma = GmM/r^2 \quad \pm 2.6\times10^{-6}$$

A Solid Carbon “Diamond” Star Orbiting a Pulsar

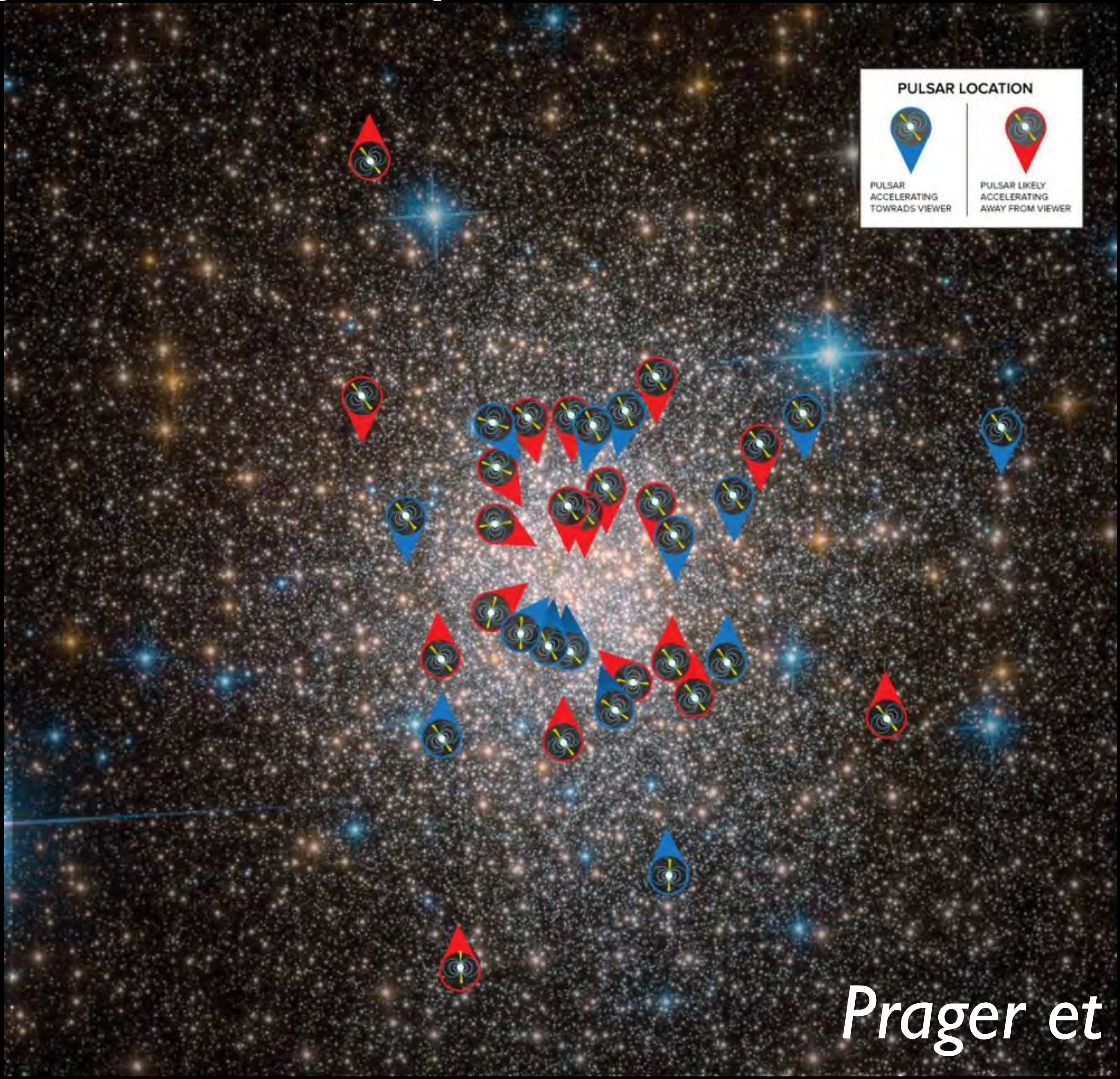


$1.05\ M_\odot$

$T_{eff} < 3\ 000$ K

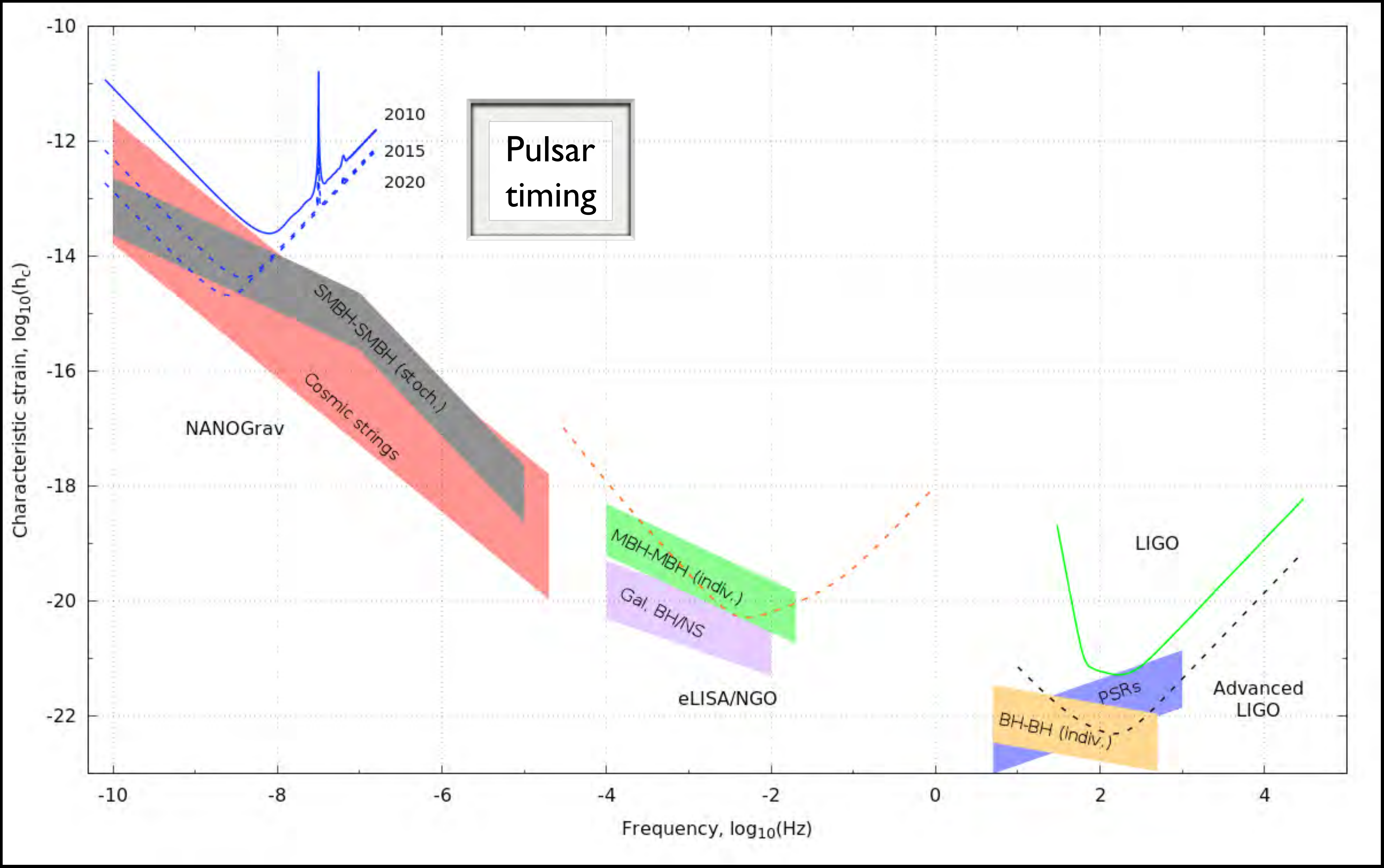
Kaplan et al. (2014)

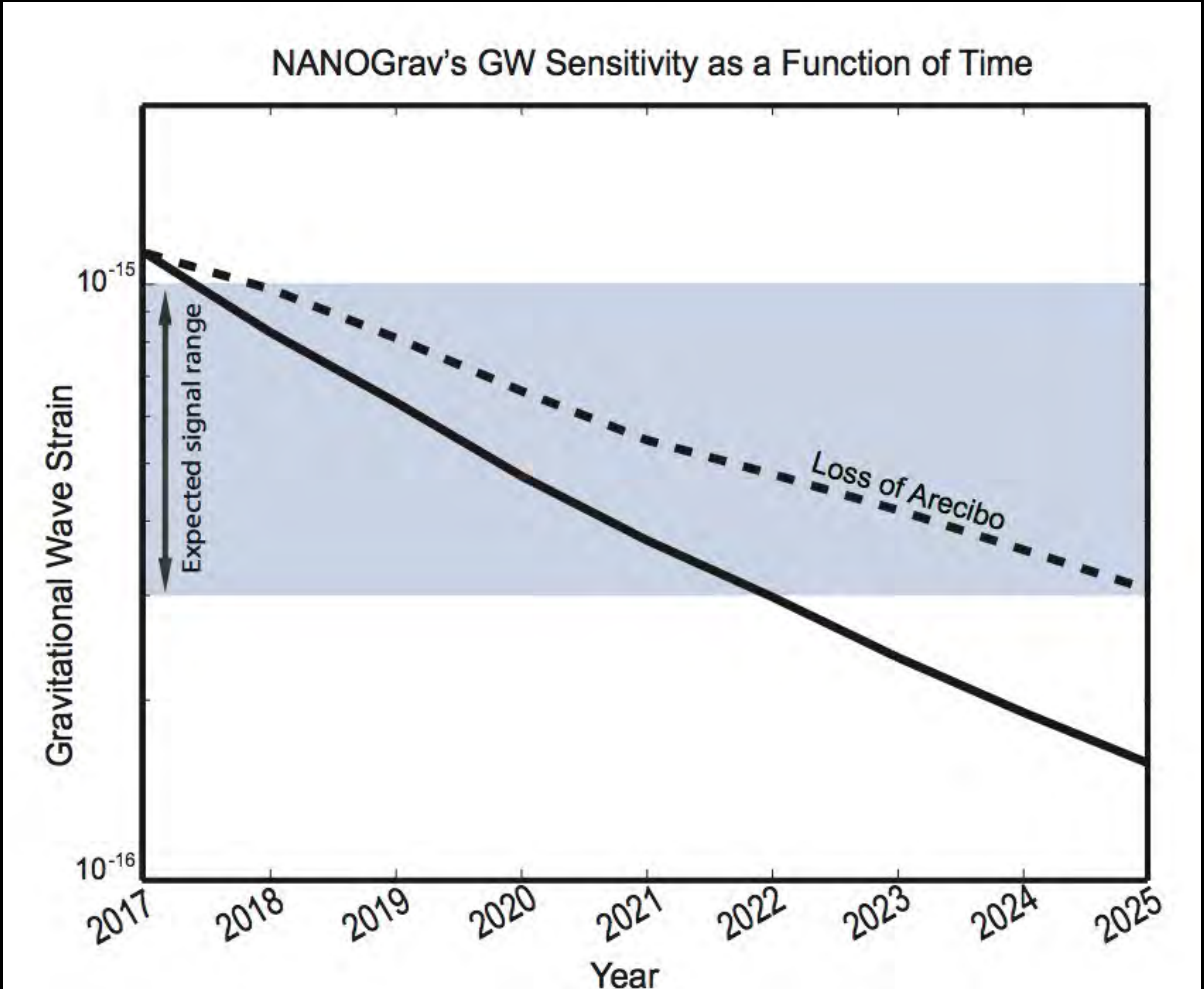
Acceleration of pulsars maps the gravitational potential of Terzan 5



Prager et al. 2017

Predicted Power in Gravitational Radiation



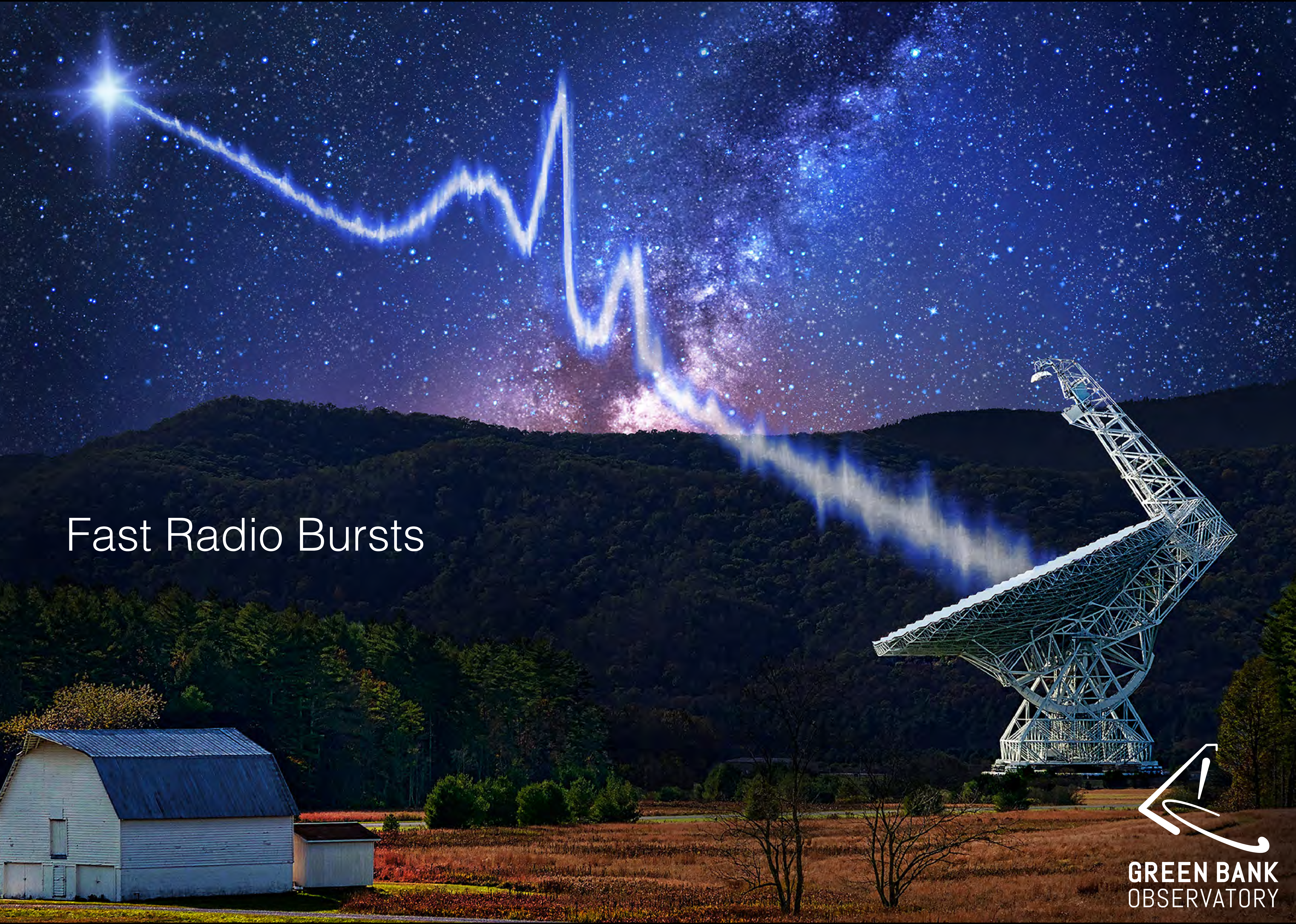


NANOGrav's GW Sensitivity as a Function of Time
Gravitational Wave Strain
10^{-15}
10^{-16}
Expected signal range
Loss of Arecibo
2017
2018
2019
2020
2021
2022
2023
2024
2025
Year

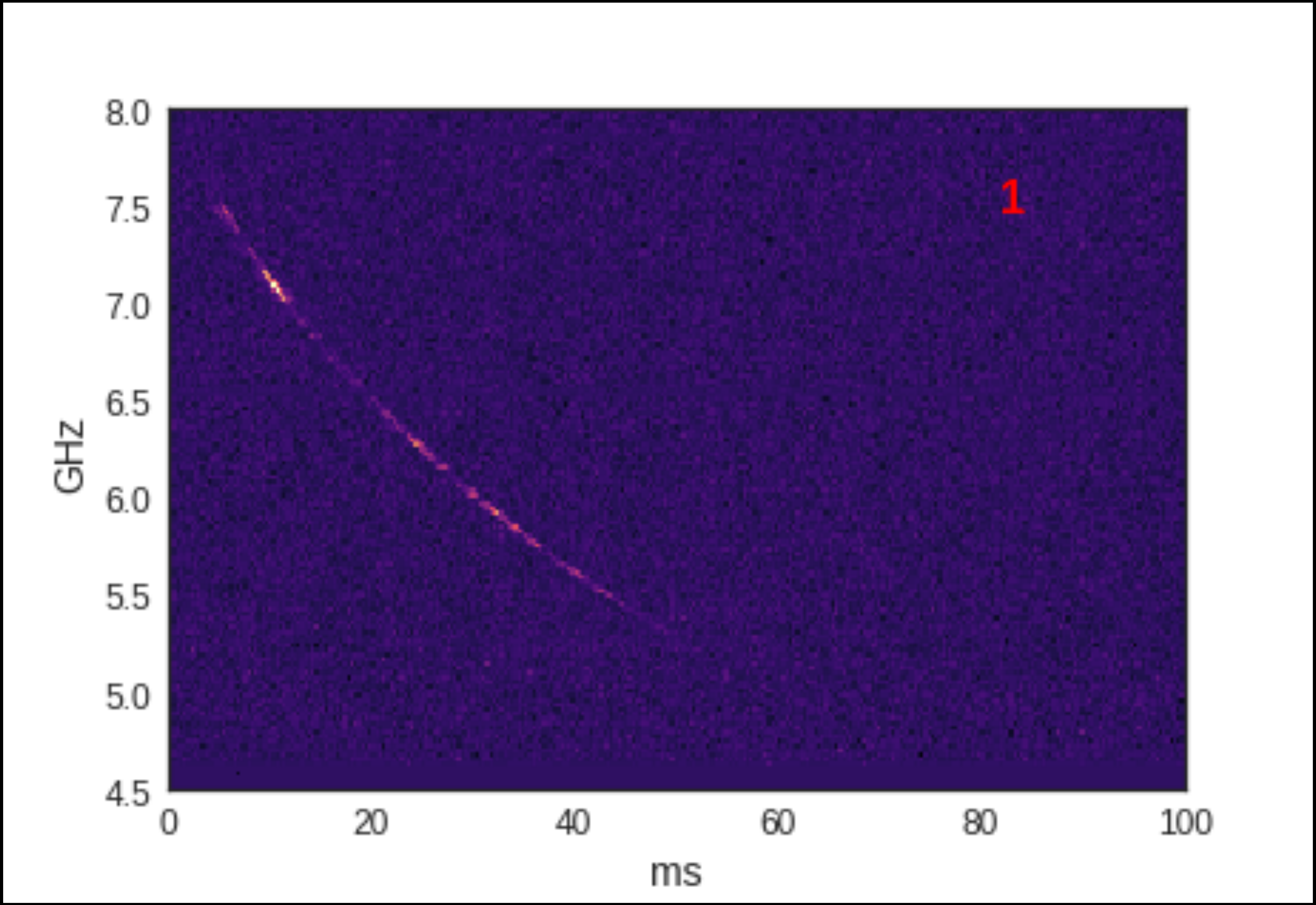
THE NANOGRAV NINE-YEAR DATA SET: EXCESS NOISE IN MILLISECOND PULSAR ARRIVAL TIMES

M. T. Lam[1,2,3], J. M. Cordes[3], S. Chatterjee[3], Z. Arzoumanian[4], K. Crowter[5], P. B. Demorest[6], T. Dolch[7], J. A Ellis[8,21], R. D. Ferdman[9,10], E. Fonseca[5], M. E. Gonzalez[5,11], G. Jones[12], M. L. Jones[1,2], L. Levin[13], D. R. Madison[14], M. A. McLaughlin[1,2], D. J. Nice[15], T. T. Pennucci[1,2,12], S. M. Ransom[14], R. M. Shannon[16,17], X. Siemens[18], I. H. Stairs[5], K. Stovall[6,19], J. K. Swiggum[18], and W. W. Zhu[20]

"… it is likely that some component of our achromatic noise is due to gravitational waves… (2017)"


Fast Radio Bursts
GREEN BANK
OBSERVATORY

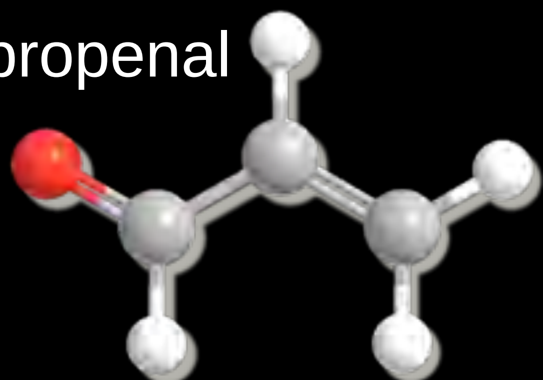
Fast Radio Bursts

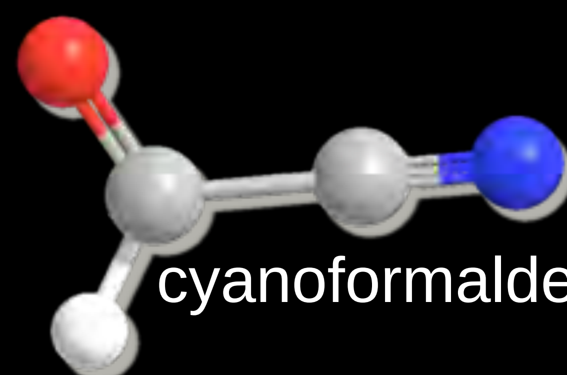


Zhang et al 2018

Interstellar Chemistry

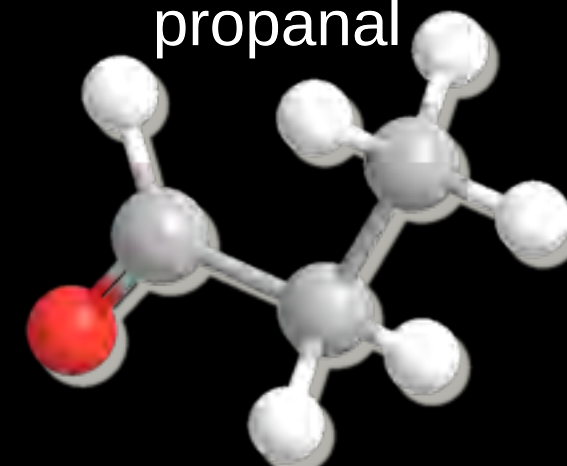
propenal

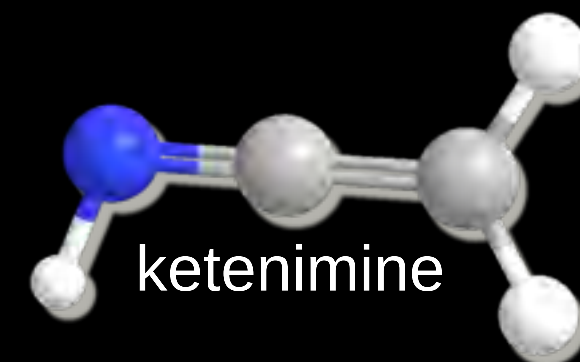




cyanoformaldehyde

propanal

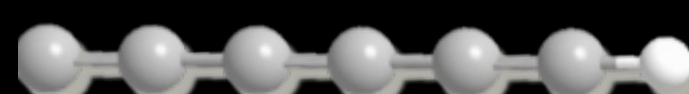




ketenimine

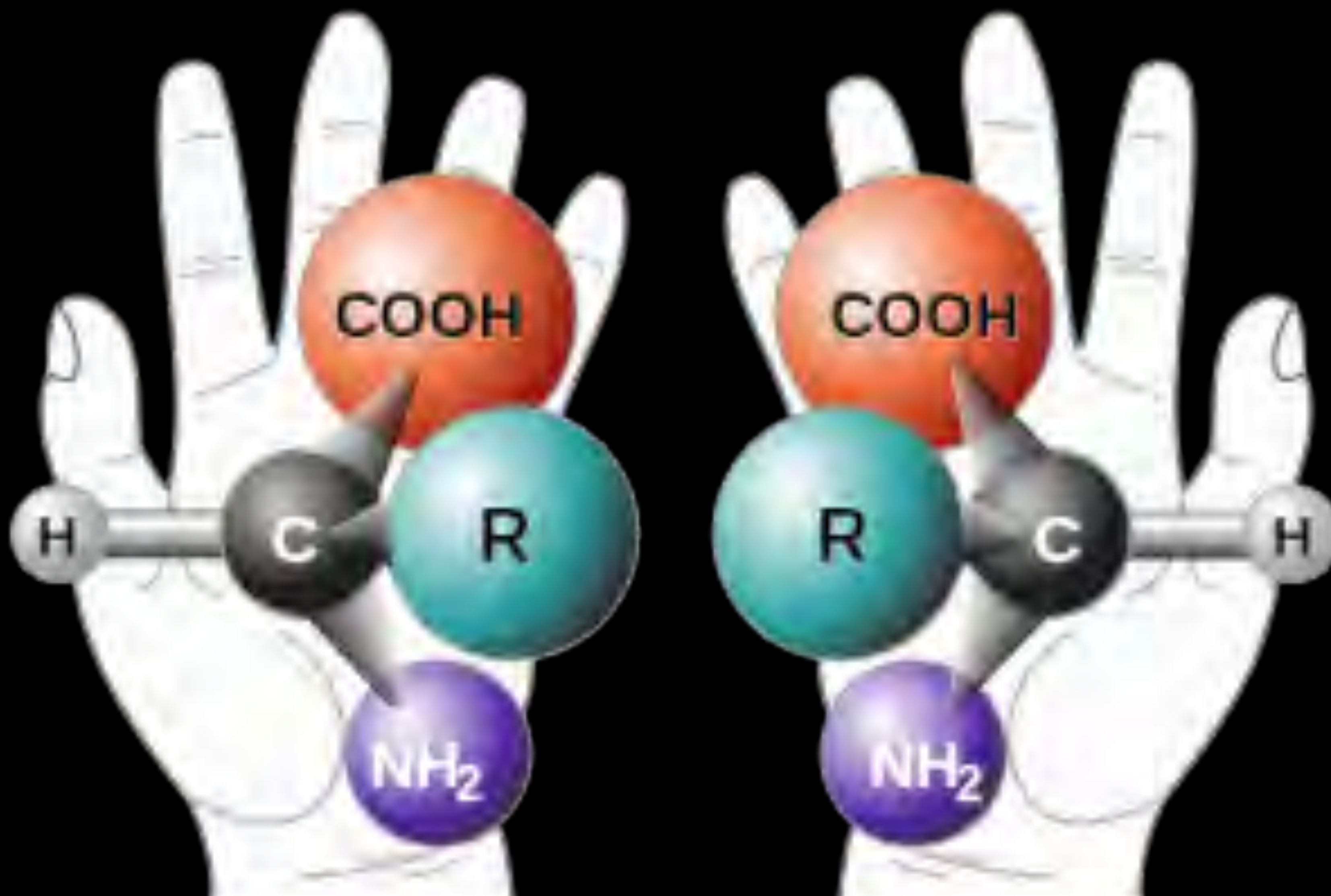
Some of the 20+ New GBT Molecule Detections

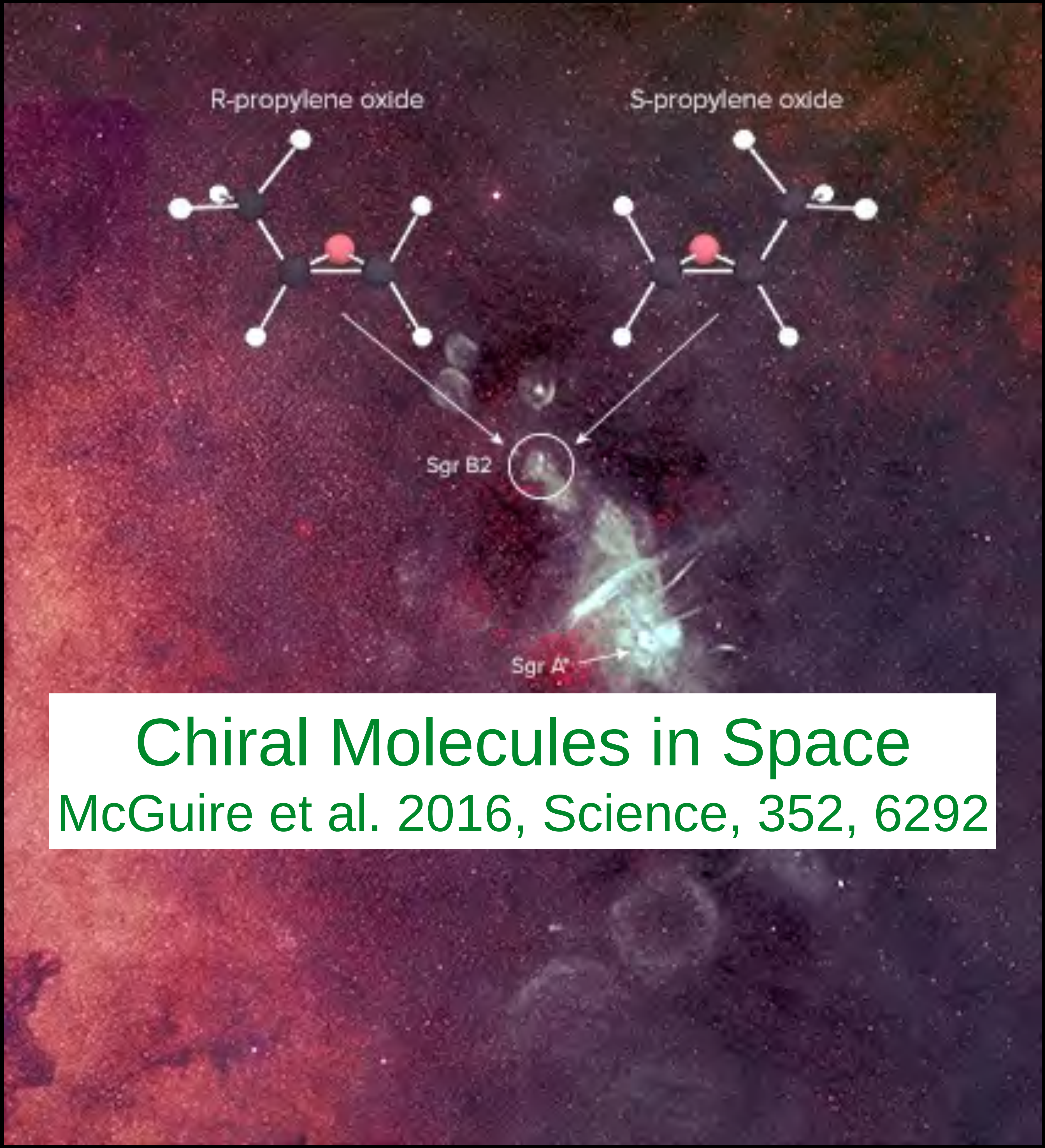
C_6 H-



McCarthy et al. 2006, ApJ, 652, L141

A Chiral molecule





Chiral Molecules in Space

McGuire et al. 2016, Science, 352, 6292

The Chemistry of Interstellar Space

The Astrophysical Journal Letters, 843:L28 (5pp), 2017 July 10

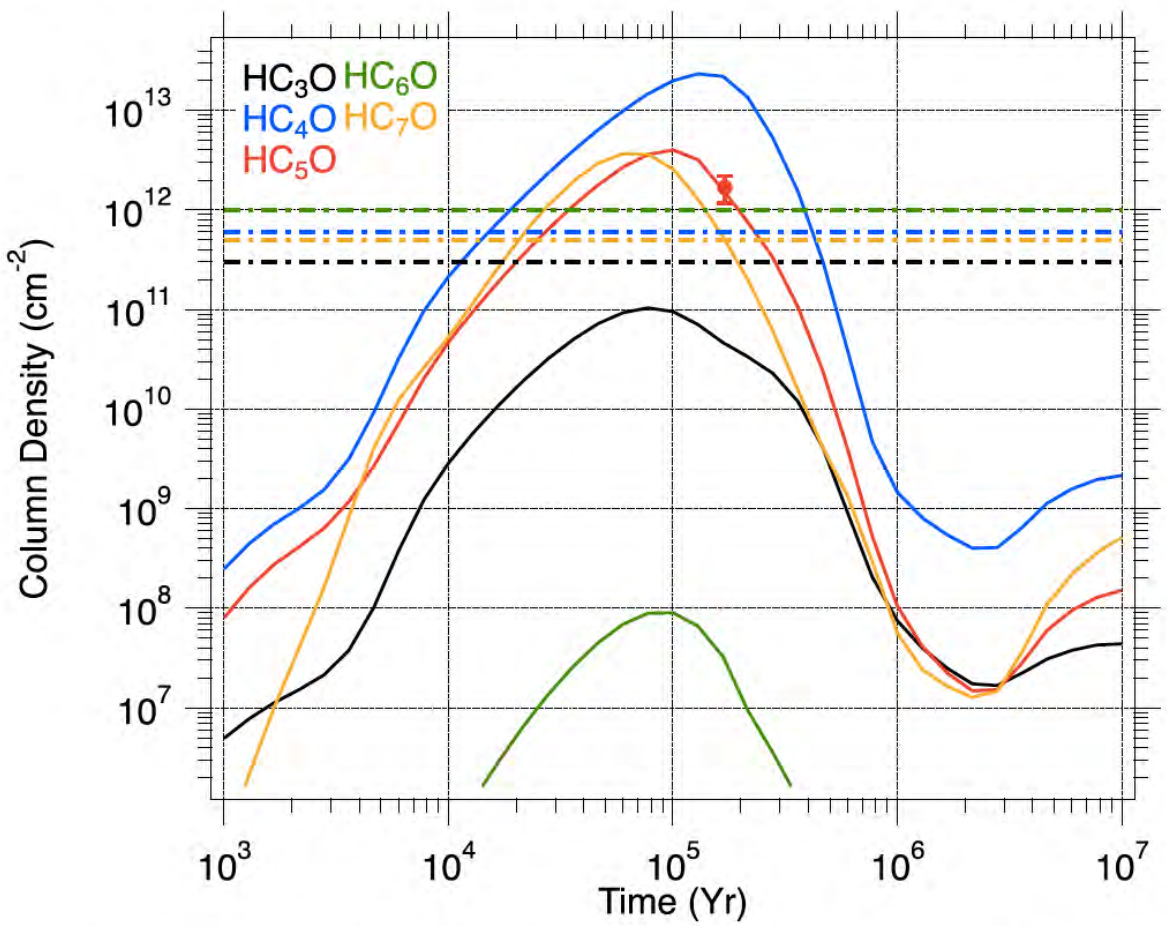
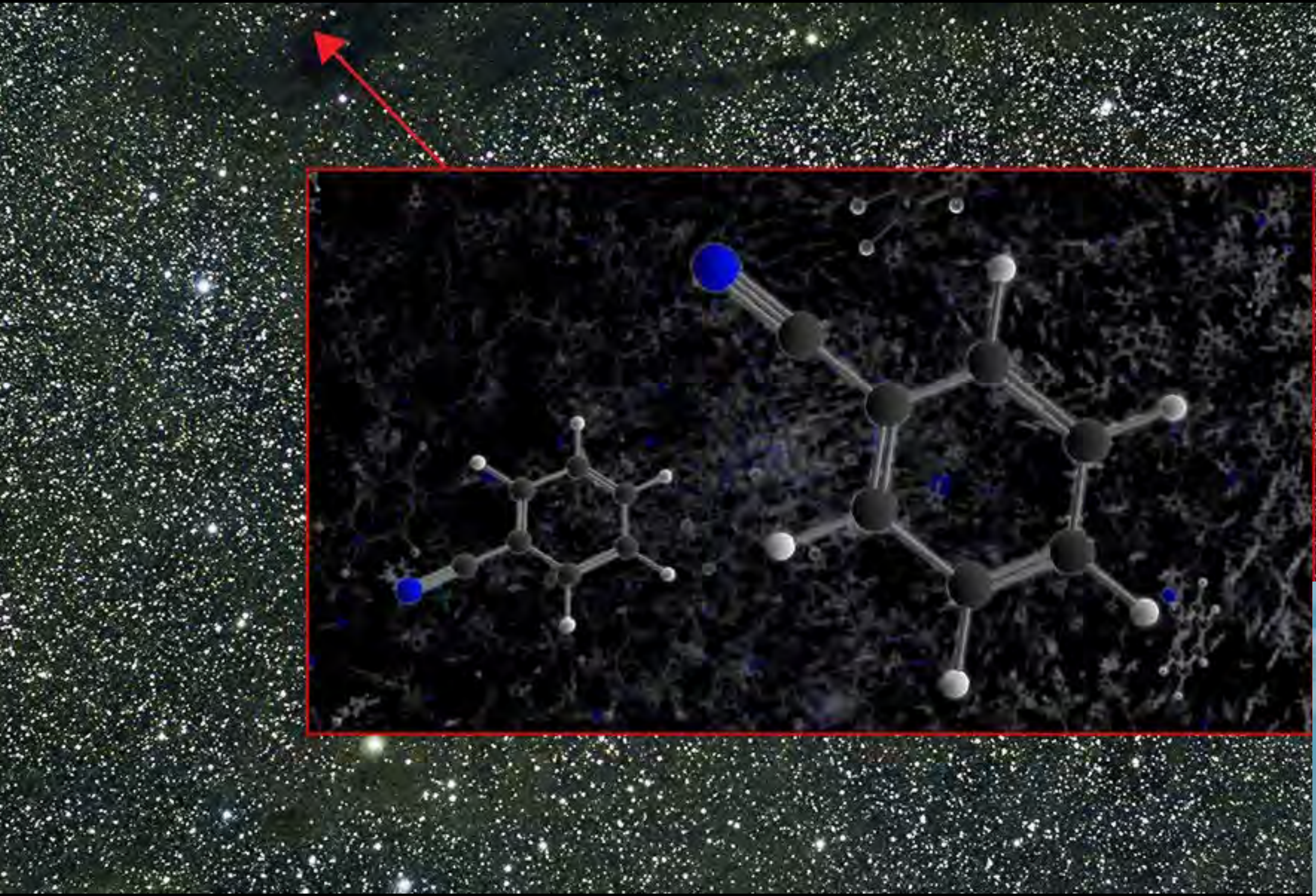


Figure 3. Results of the model of the HC_nO radicals discussed in Section 5.3. Gas-phase column densities predicted by the model as a function of time are shown as solid lines. Upper limits established by observation are shown as dashed lines. The observed column density of HC_5O at the best-fit cloud age ($\sim 2 \times 10^5$ years) is indicated with a red dot. An estimated error of 30% is shown based on assumed flux calibration accuracy.

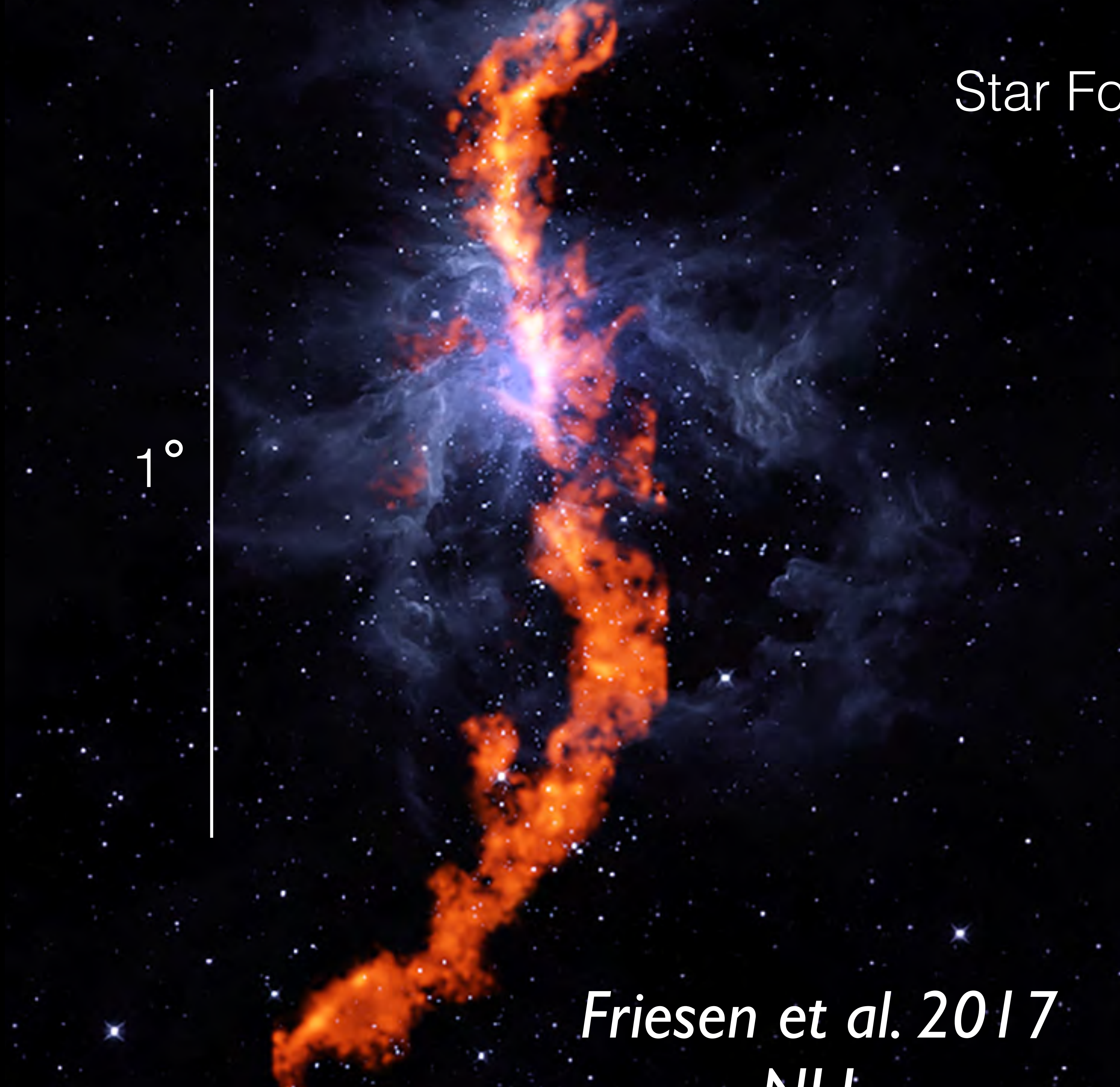
McGuire et al 2017 Detection of HC_5O

Benzonitrile

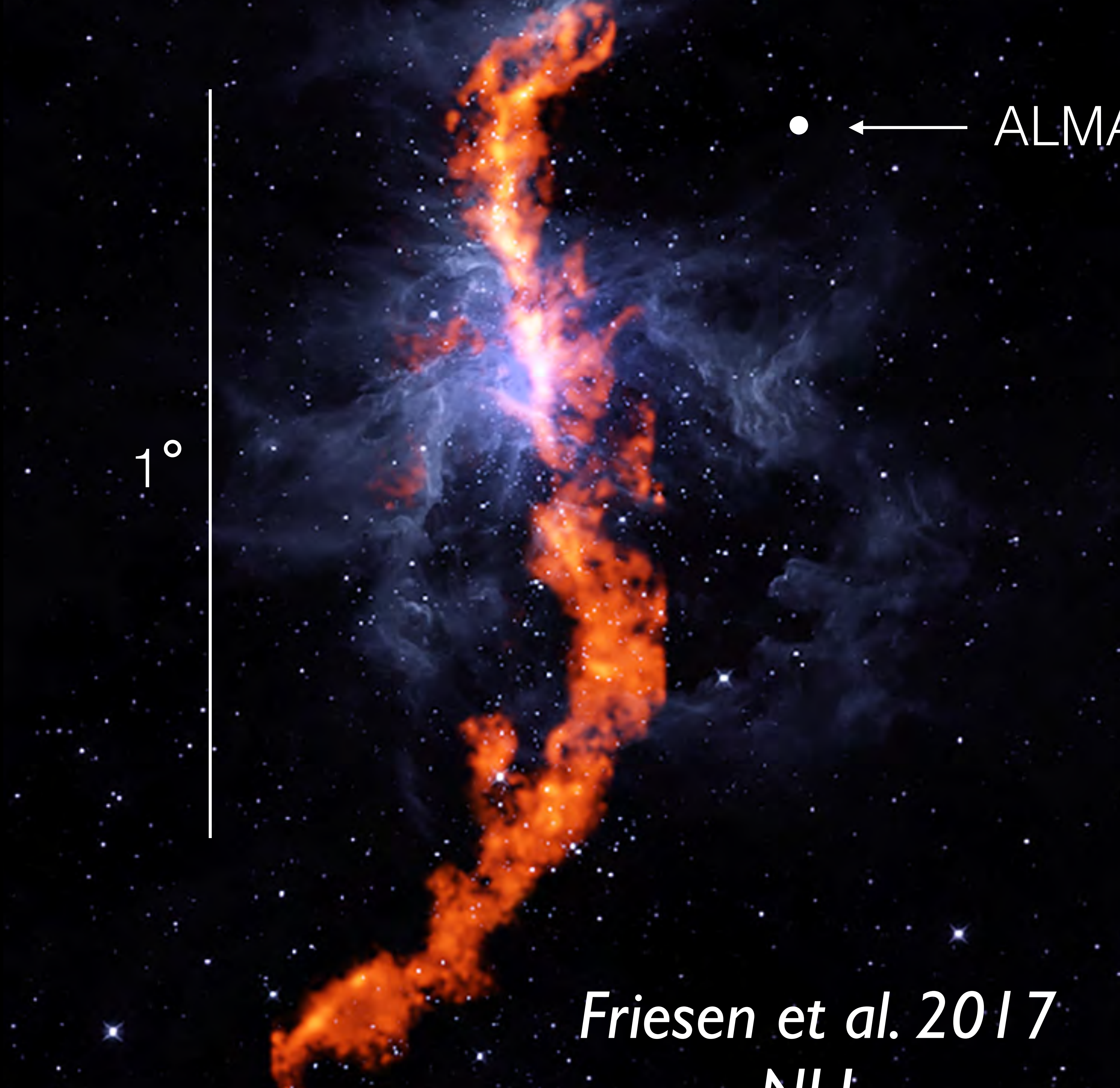


McGuire et al. 2018, Science, 359, 202

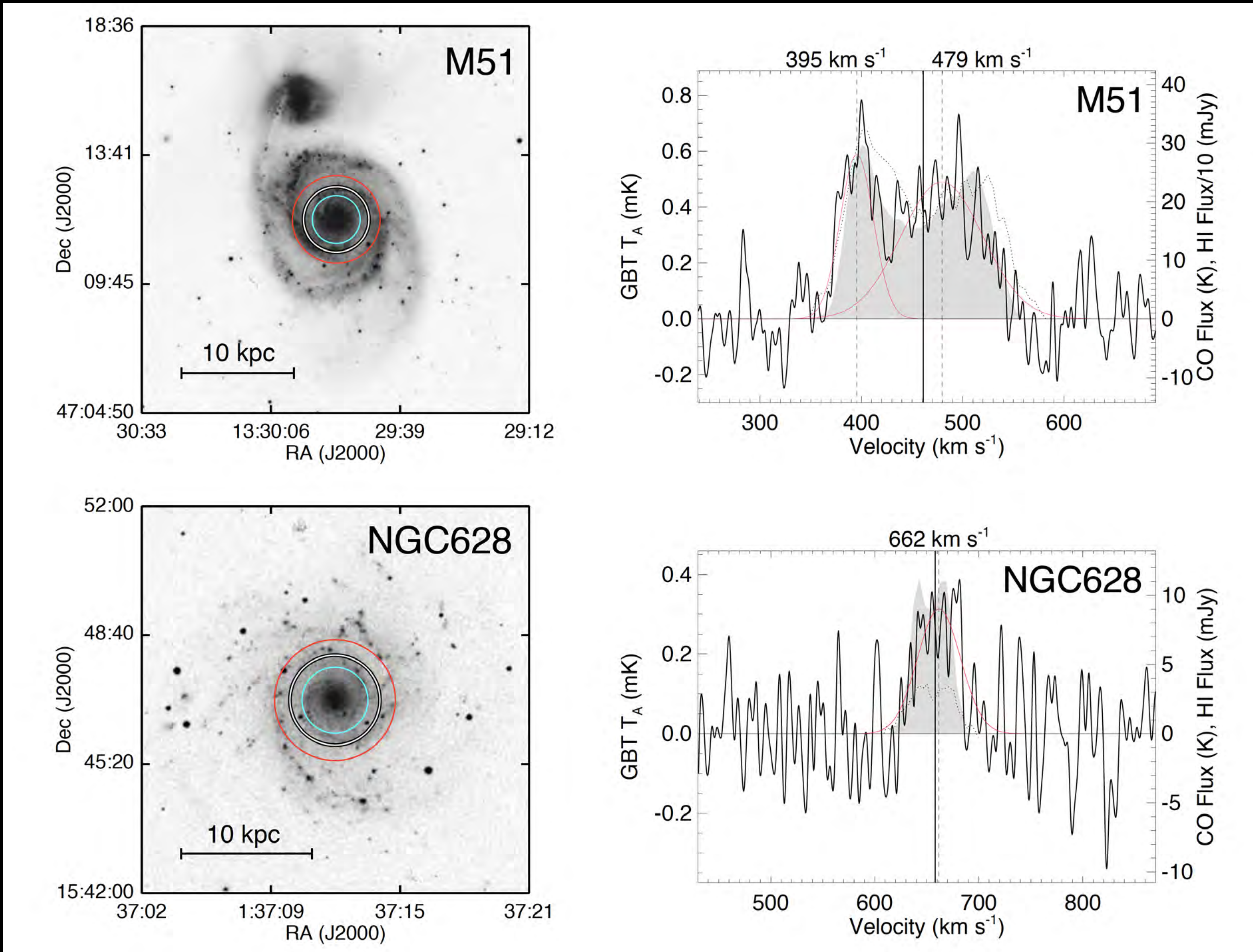
Star Formation



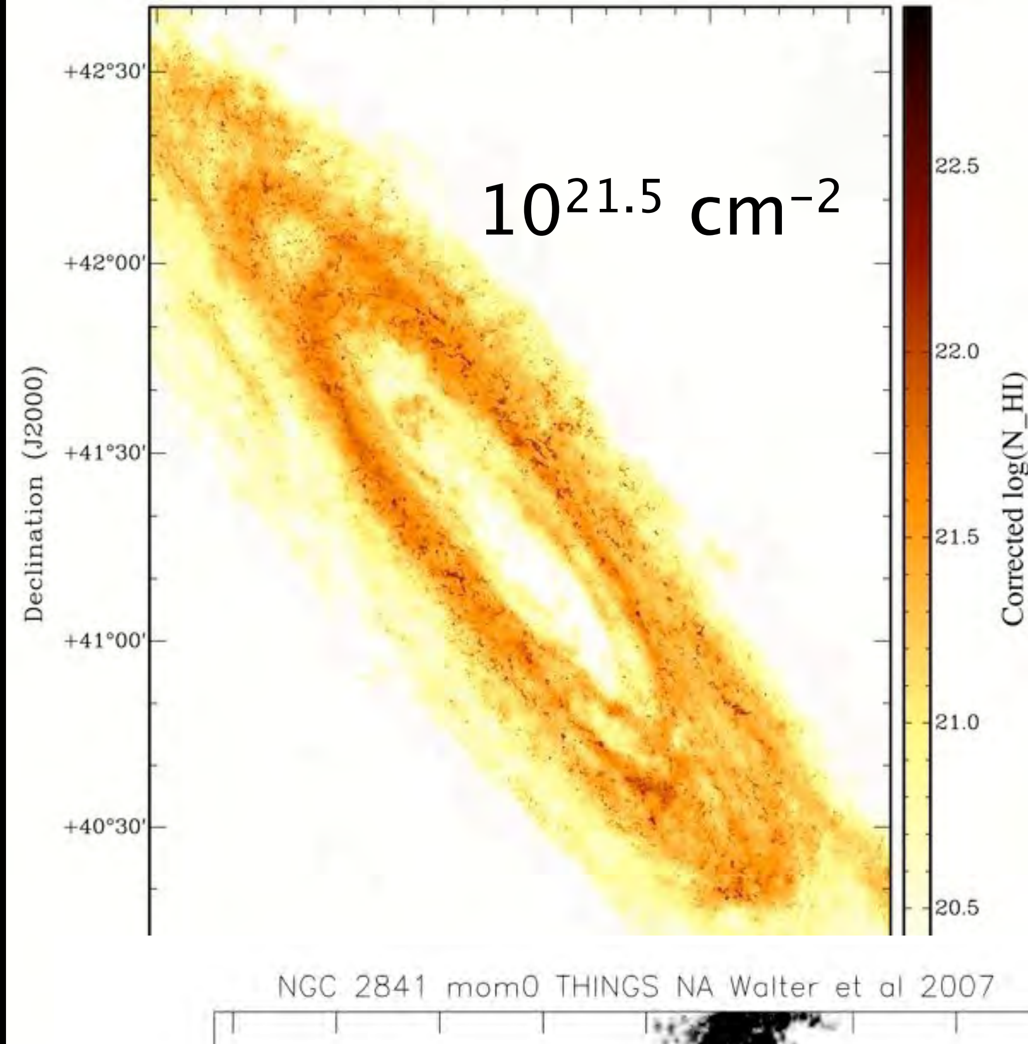
Friesen et al. 2017
NH_3

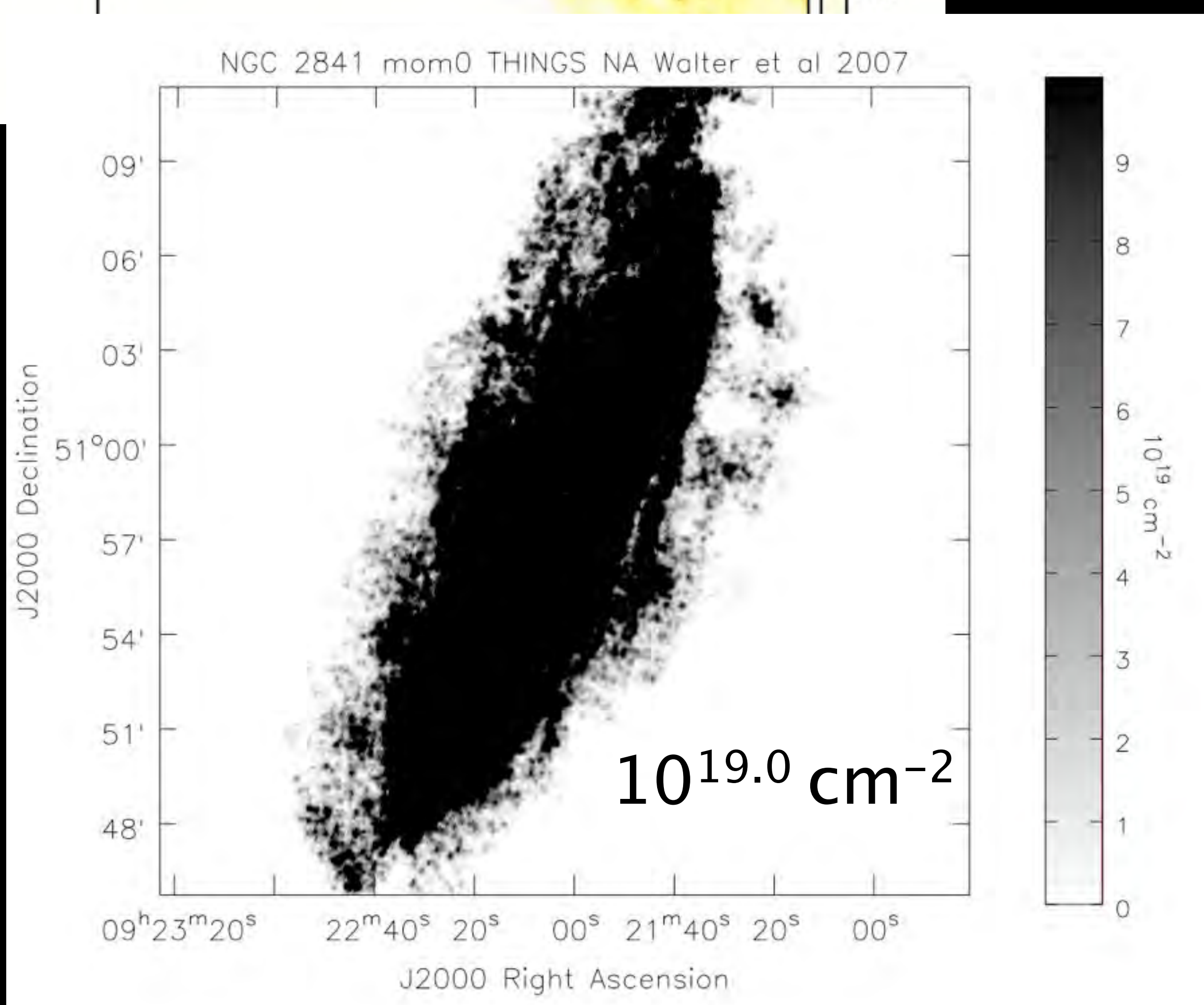


Friesen et al. 2017
NH_3



Luisi et al. 2018 sigma=0.1 mK





THINGS VLA Survey

Walter et al. 2008

30″ 3σ=$10^{19.5}$

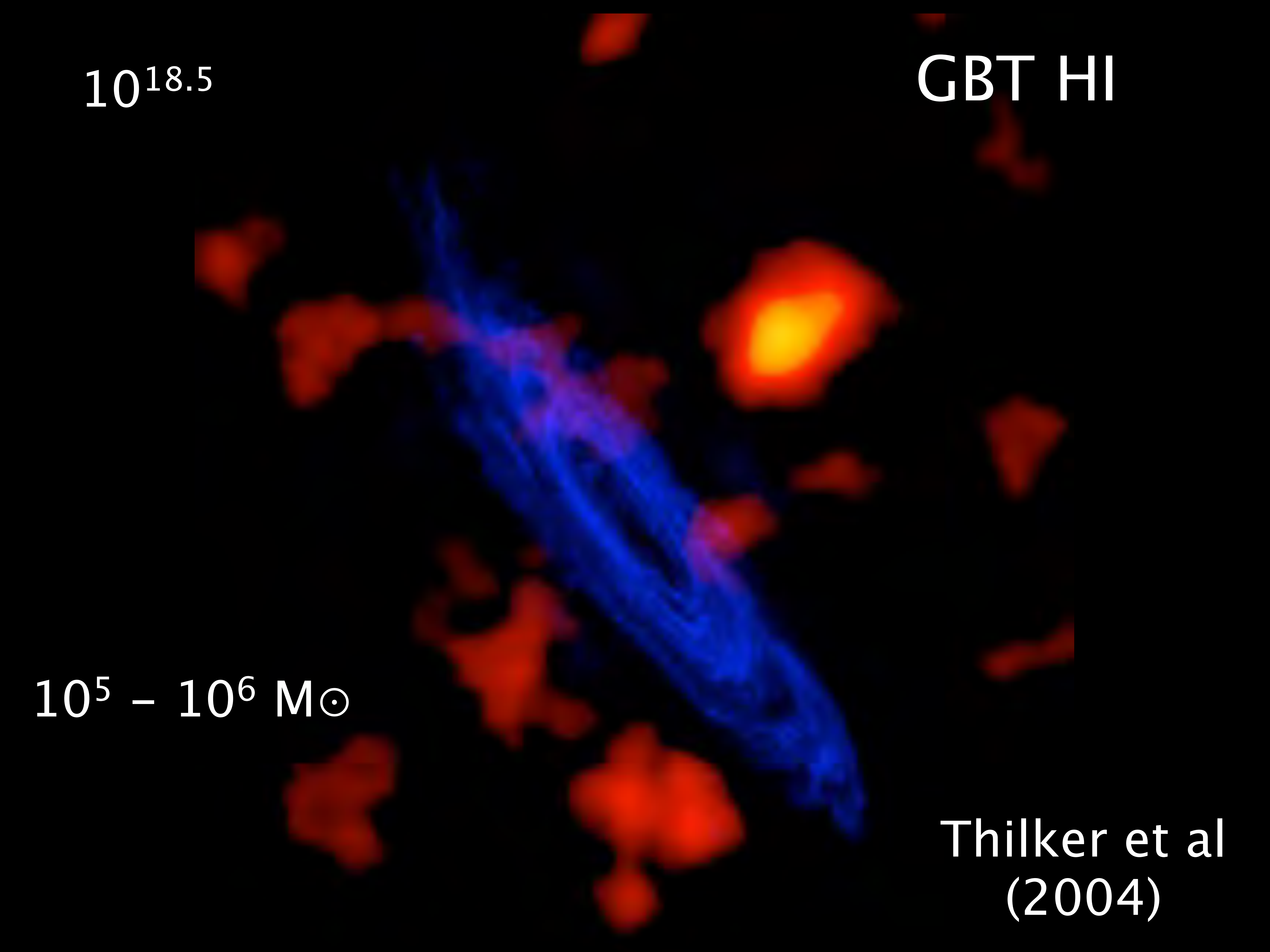
6″ 3σ=$10^{20.5}$

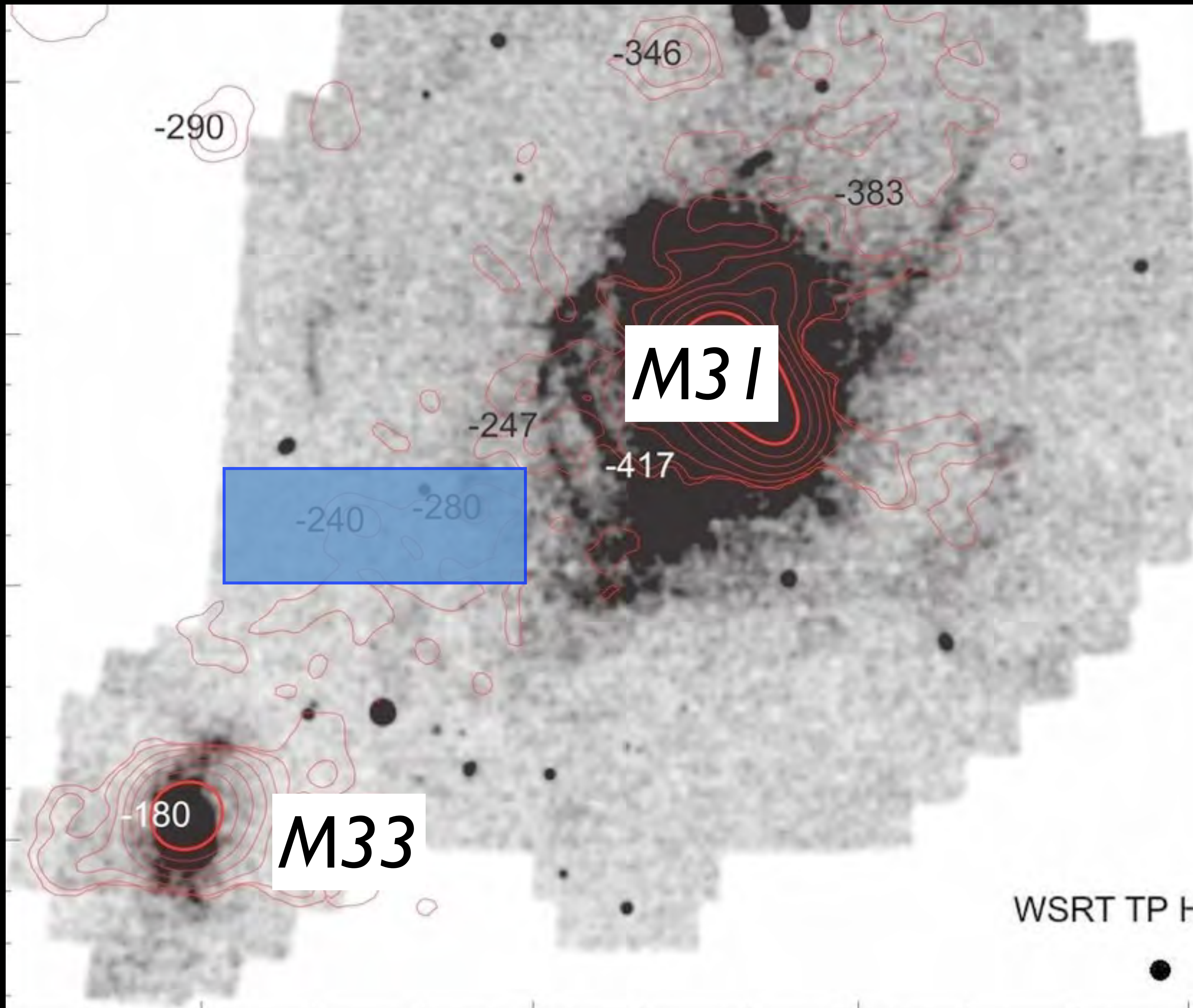
HALOGAS WSRT Survey

Heald et al. 2011

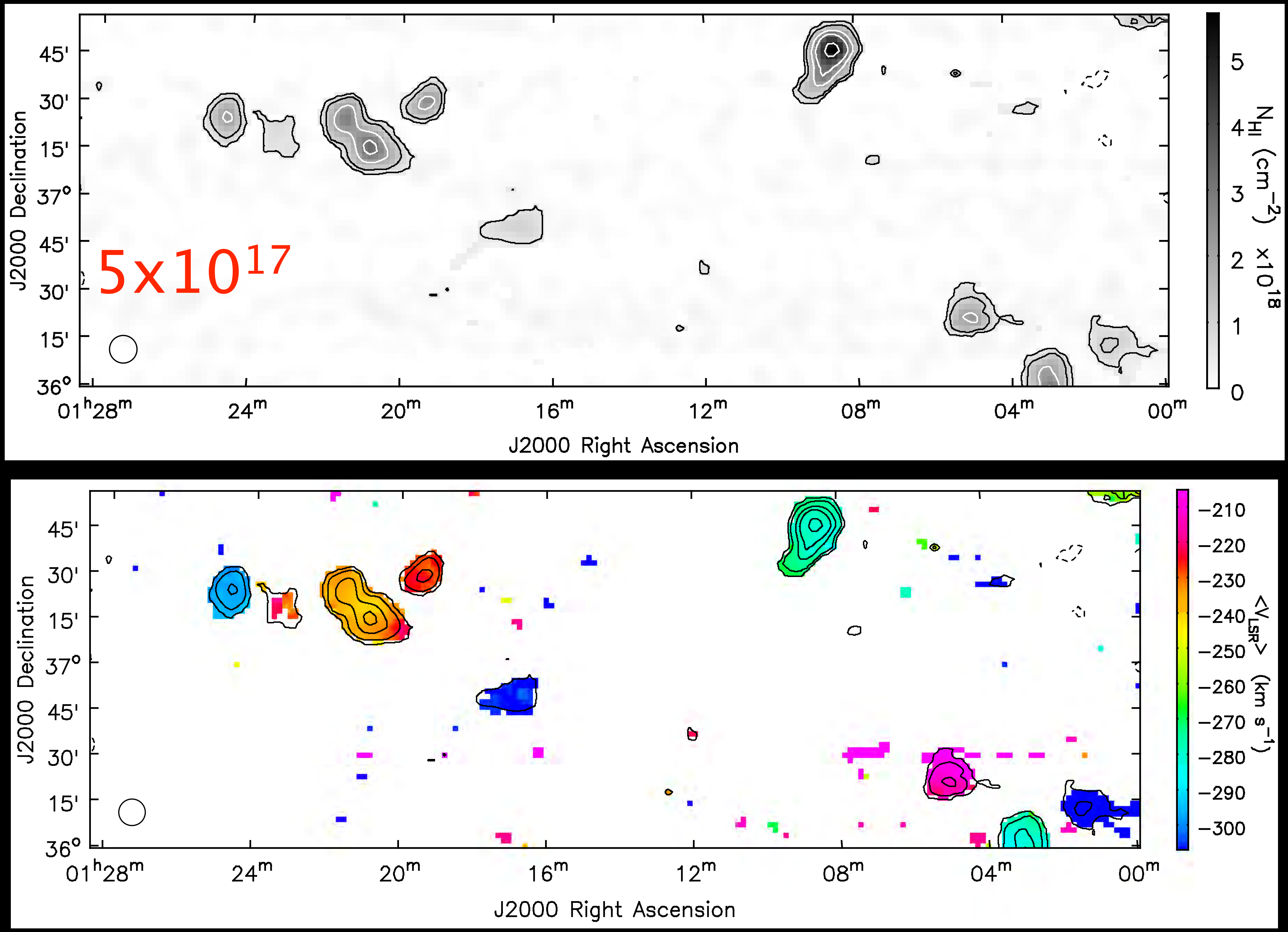
15″ to N_{HI} limit ~$10^{19.0}$

120 hours per galaxy


$10^{18.5}$
GBT HI
$10^5 - 10^6$ M⊙
Thilker et al
(2004)


-346
-290
-383
M31
-247
-417
-240
-280
-180
M33
WSRT TP H

M31-M33 Clouds



Wolfe et al. 2013, Nature, 497, 224; 2016, ApJ, 816, 81

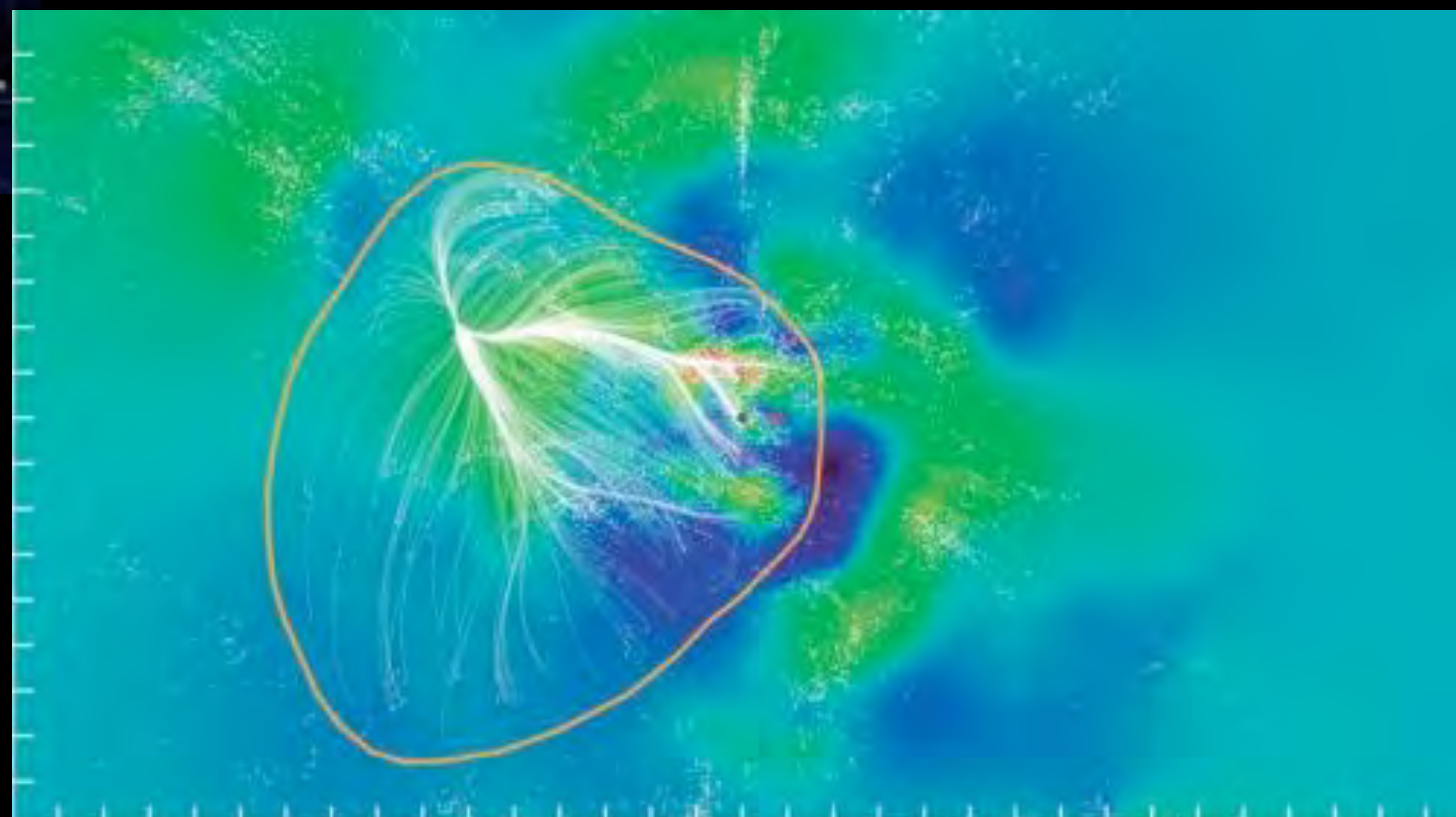
No Hydrogen in the Milky Way's Dwarf Galaxies

GBT results from Spekkens et al. 2014

Galaxy	L ($L_\odot$)	M_{HI} ($M_\odot$)
Segue I	340	<11
UMa II	41,000	<74
Bootes II	1,000	<38
Coma Ber	3,700	<62
Ursa Mi	280,000	<63
Draco	280,000	<133
Spitzer Cloud		400
Hydra II		<200*

GBT Hydrogen measurements show the structure of the local Universe

(Tully et al. 2014)



GBT+MUSTANG-2 vs ALMA: Sensitivity, Capabilities at 3.3mm (90 GHz)

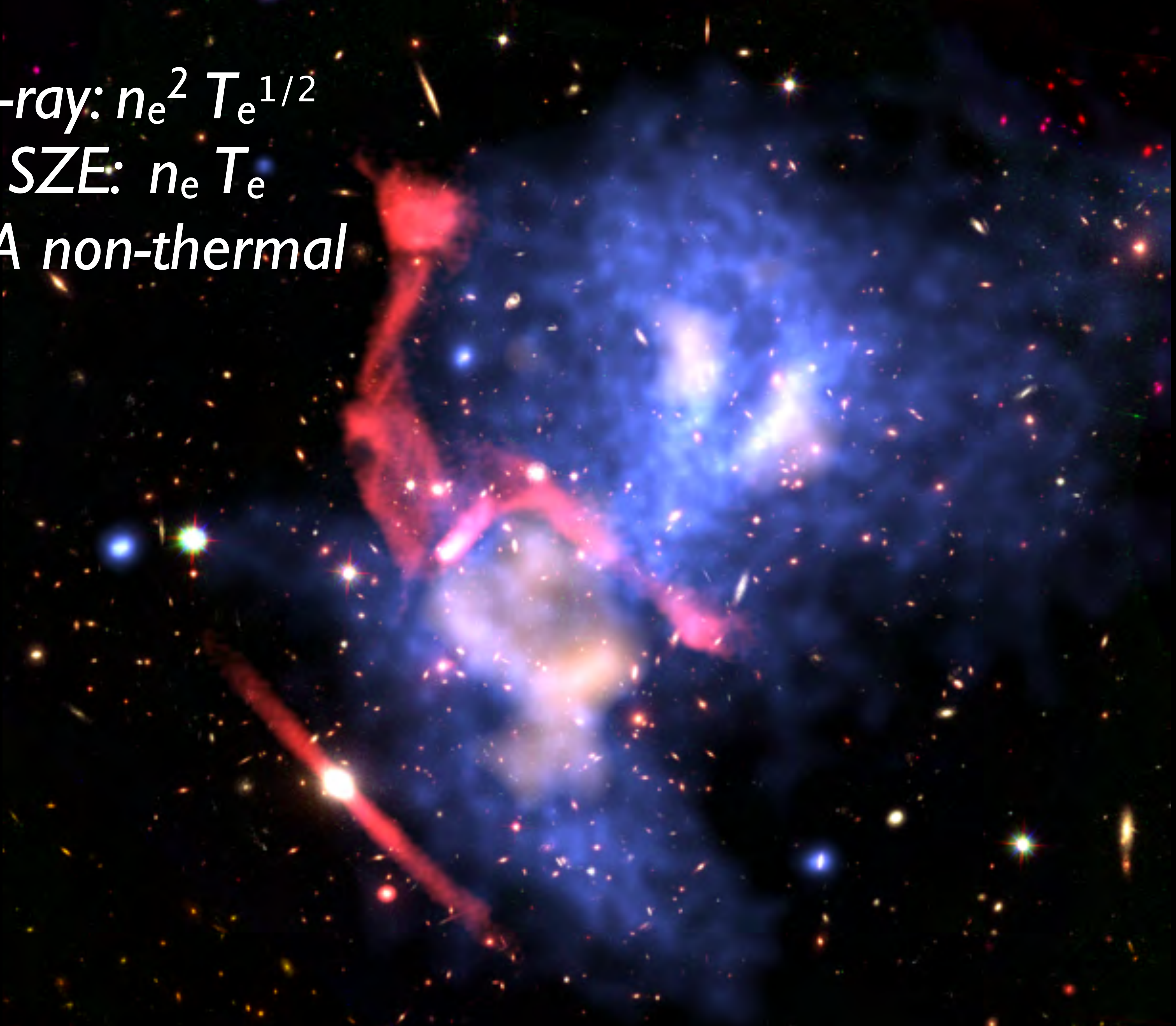
	Spectral Channels	Integration time	Largest Spatial Scale
MUSTANG-2	1	1h	4'
ALMA (12m)	10s of 1,000s	1.5h	32"
ALMA (12m+7m)	"	12h	74"
ALMA (12m+7m+TP)	"	19h	4'+… ???

Time to get to 56 uJy/bm RMS on D=6' area.

All capabilities except ALMA total power (single dish) continuum are real & demonstrated.

ALMA & MUSTANG-2 observing overheads are similar

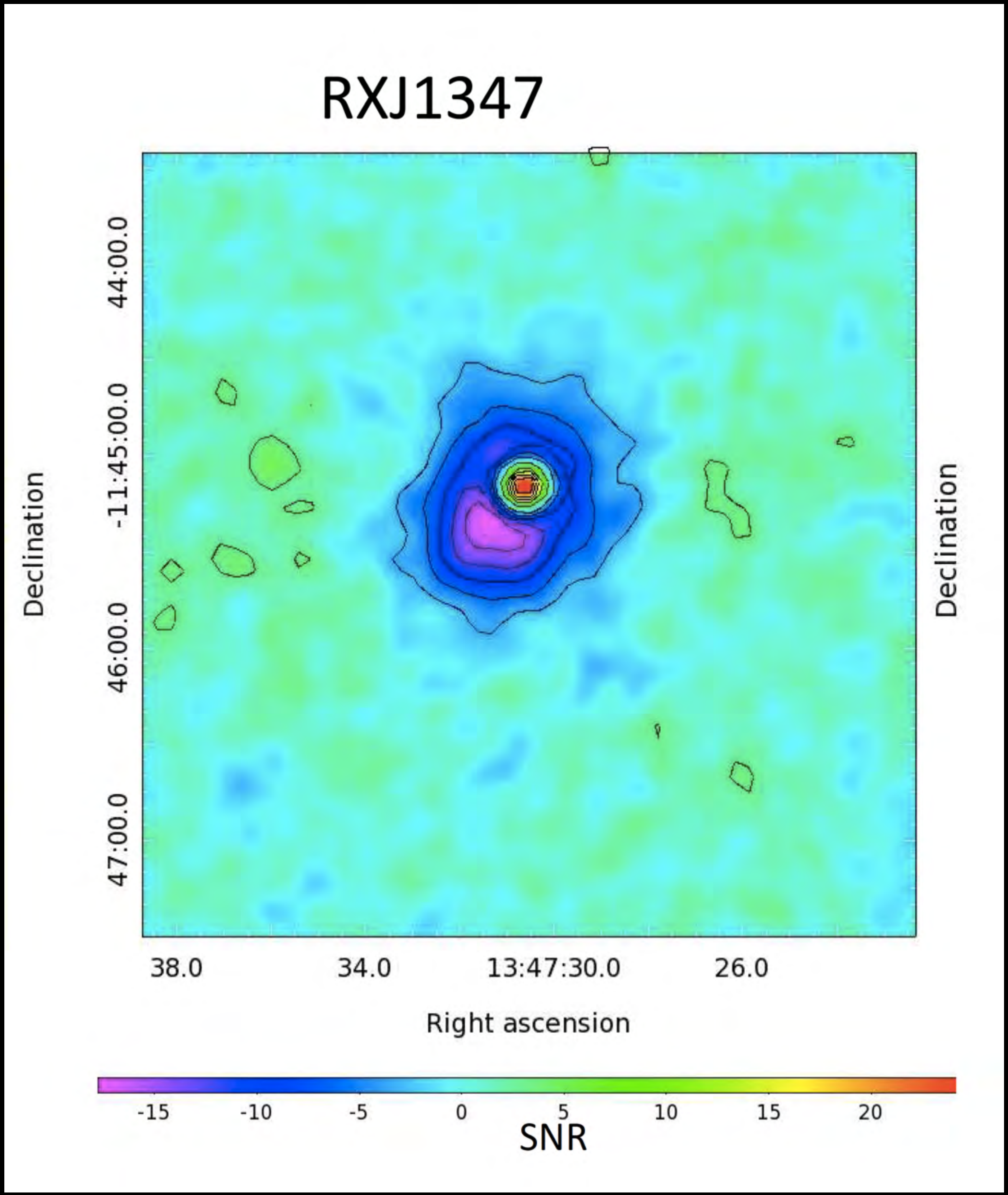
GBT High-Resolution 3mm SZE in a Cluster



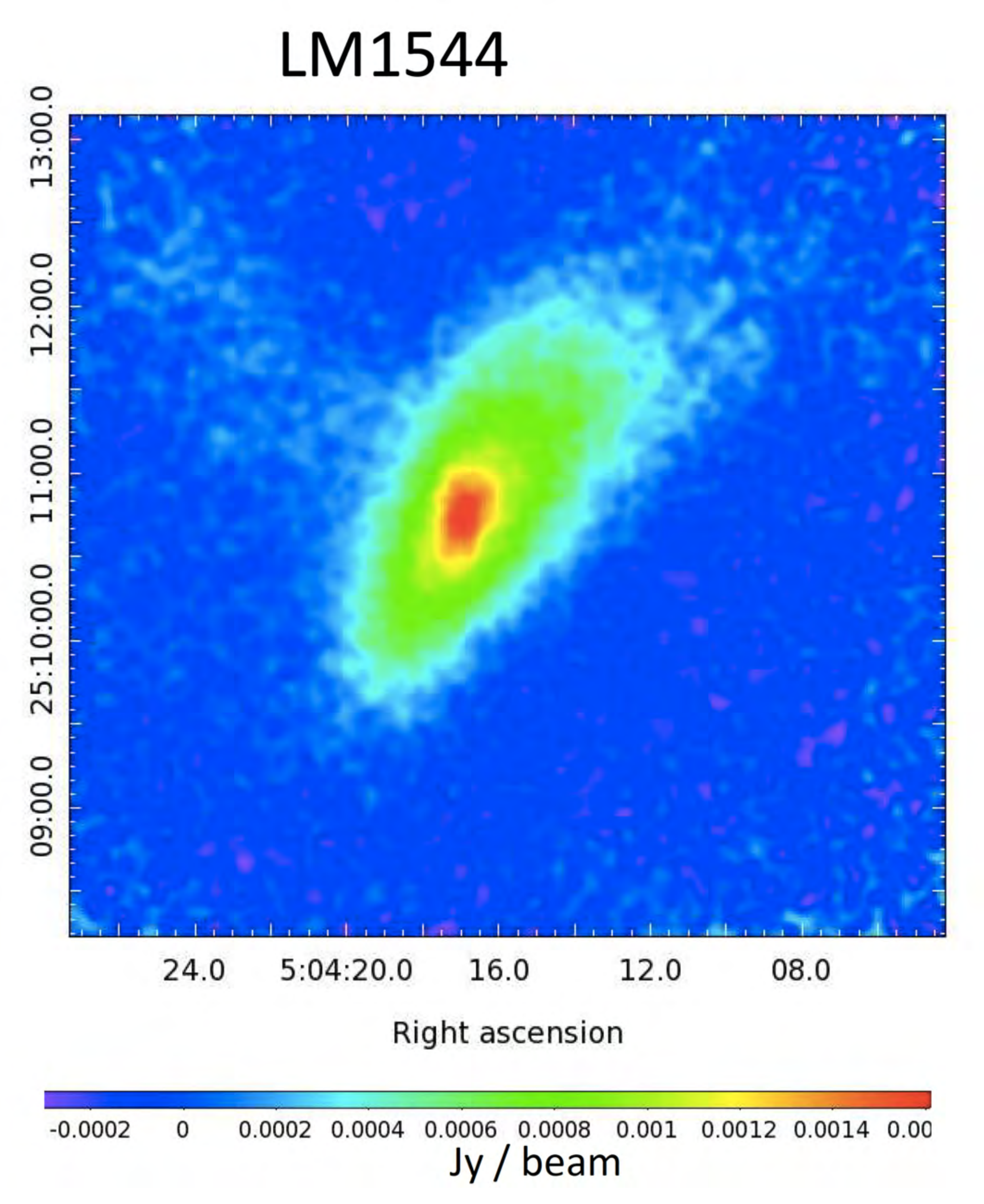
X-ray: $n_e^2\ T_e^{1/2}$

SZE: $n_e\ T_e$

VLA non-thermal



RXJ1347 Cluster — SZE detected at 15 sigma in 2 hours
Dicker et al 2018 (in press)



LM1544 — Pre-stellar core
Dicker et al 2018 (in press)

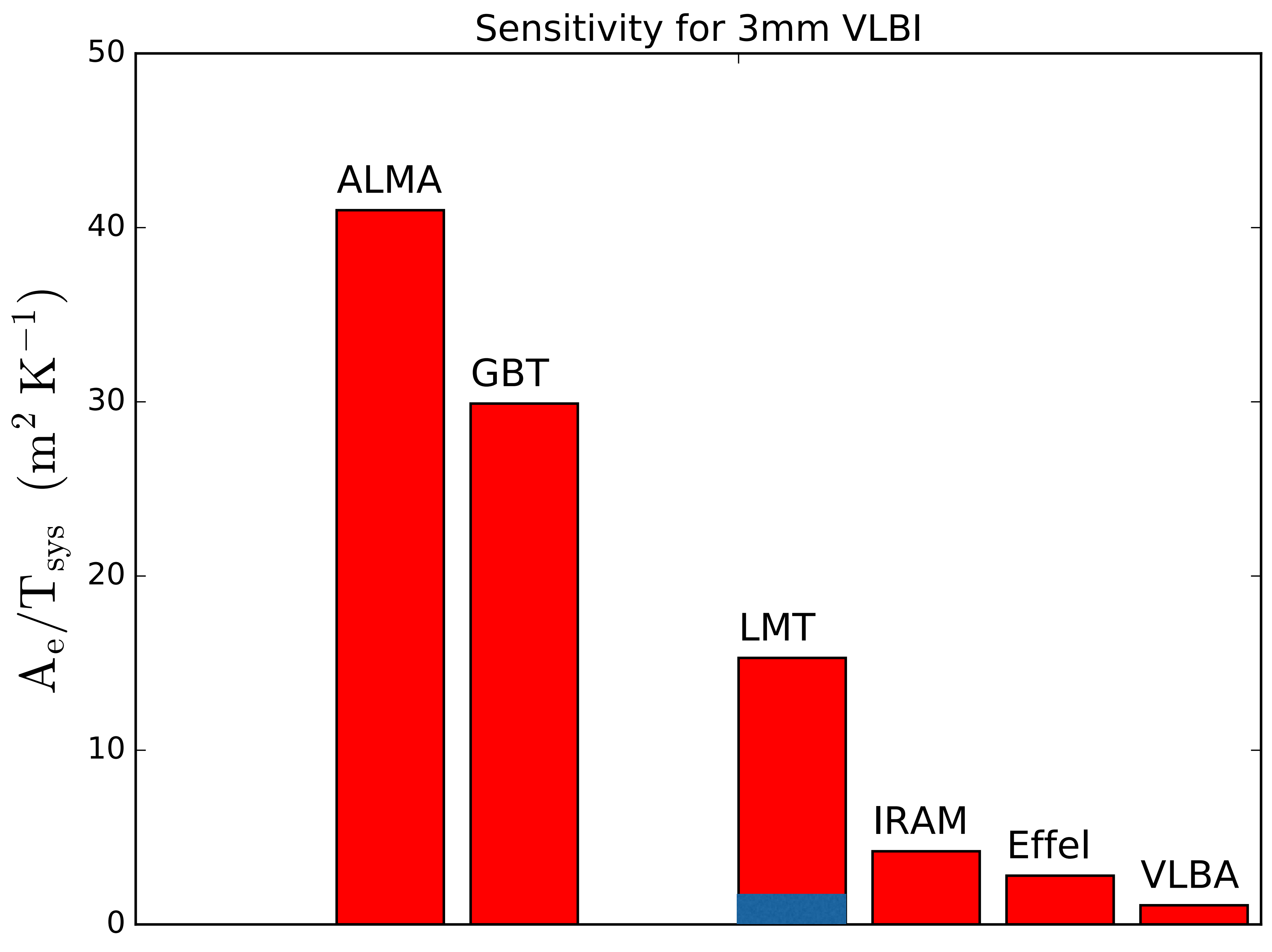
H_2O Masers in Disks Around Black Holes

Zhao et al. 2018, ApJ, 854, 124

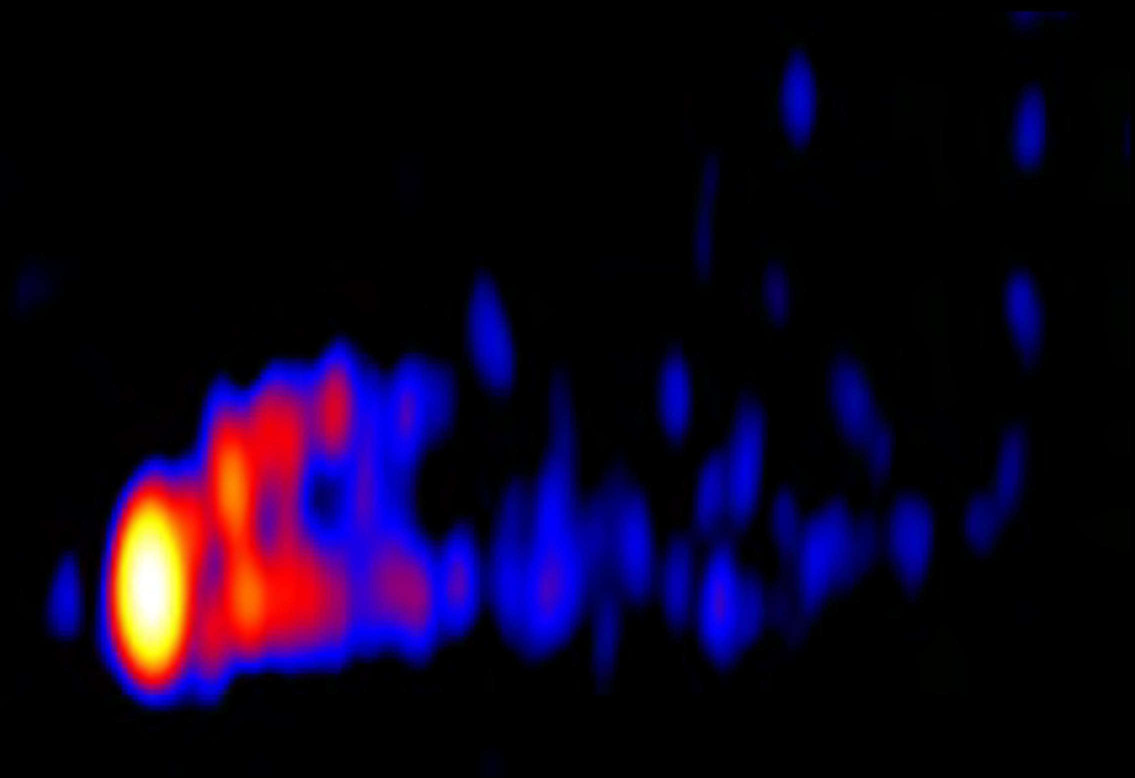
Gao et al. 2017 ApJ, 834, 52

Discovered by the GBT
Monitored by the GBT
Imaged by the VLBA + GBT

3mm VLBI
GBT 18B Oversubscription = 5.3x

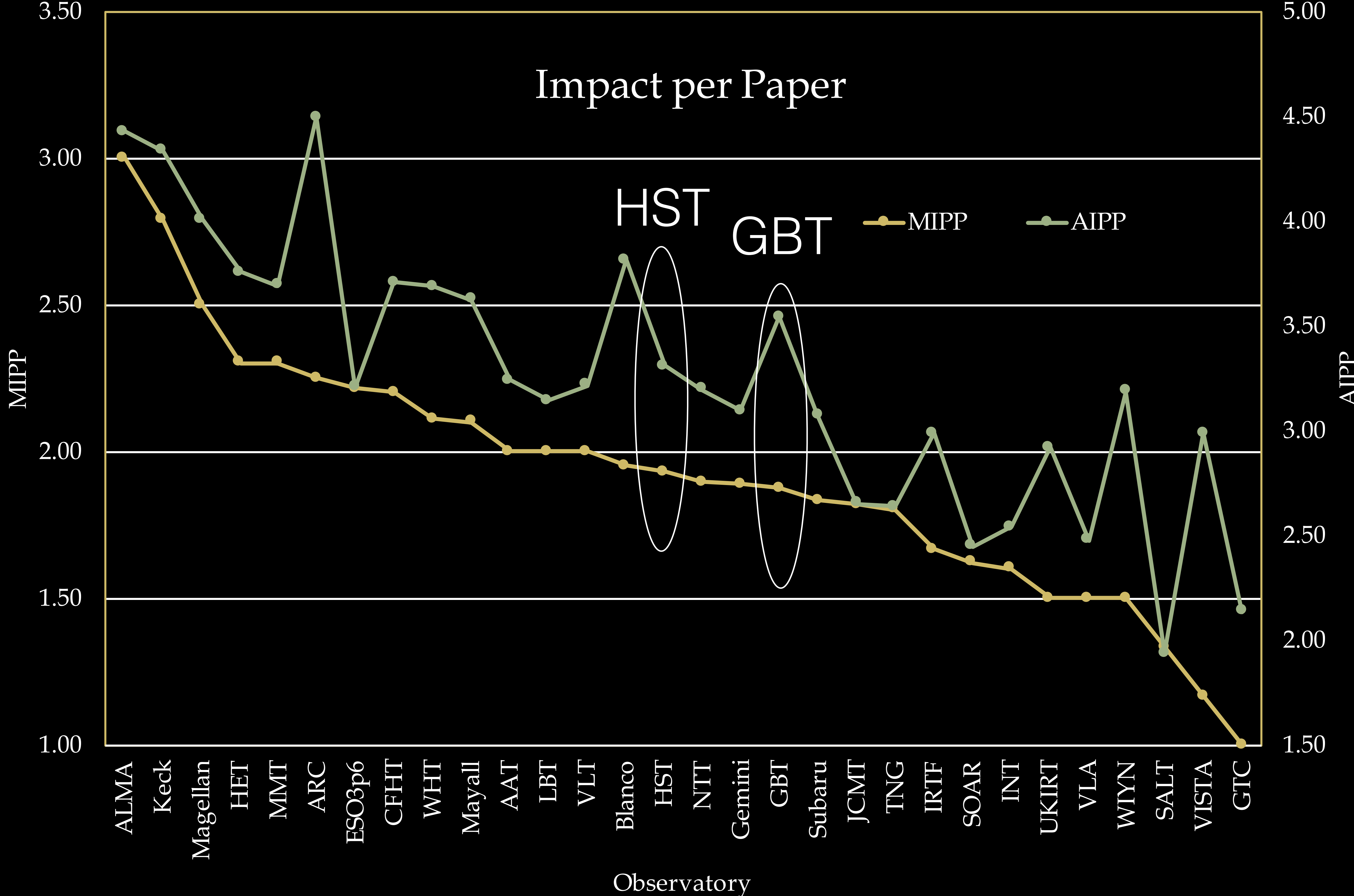


M87 3mm VLBI Jet



The M87 jet at an angular resolution of 0.25x0.08 mas in 3mm VLBI (Hada et al 2016)

2012 - 2016



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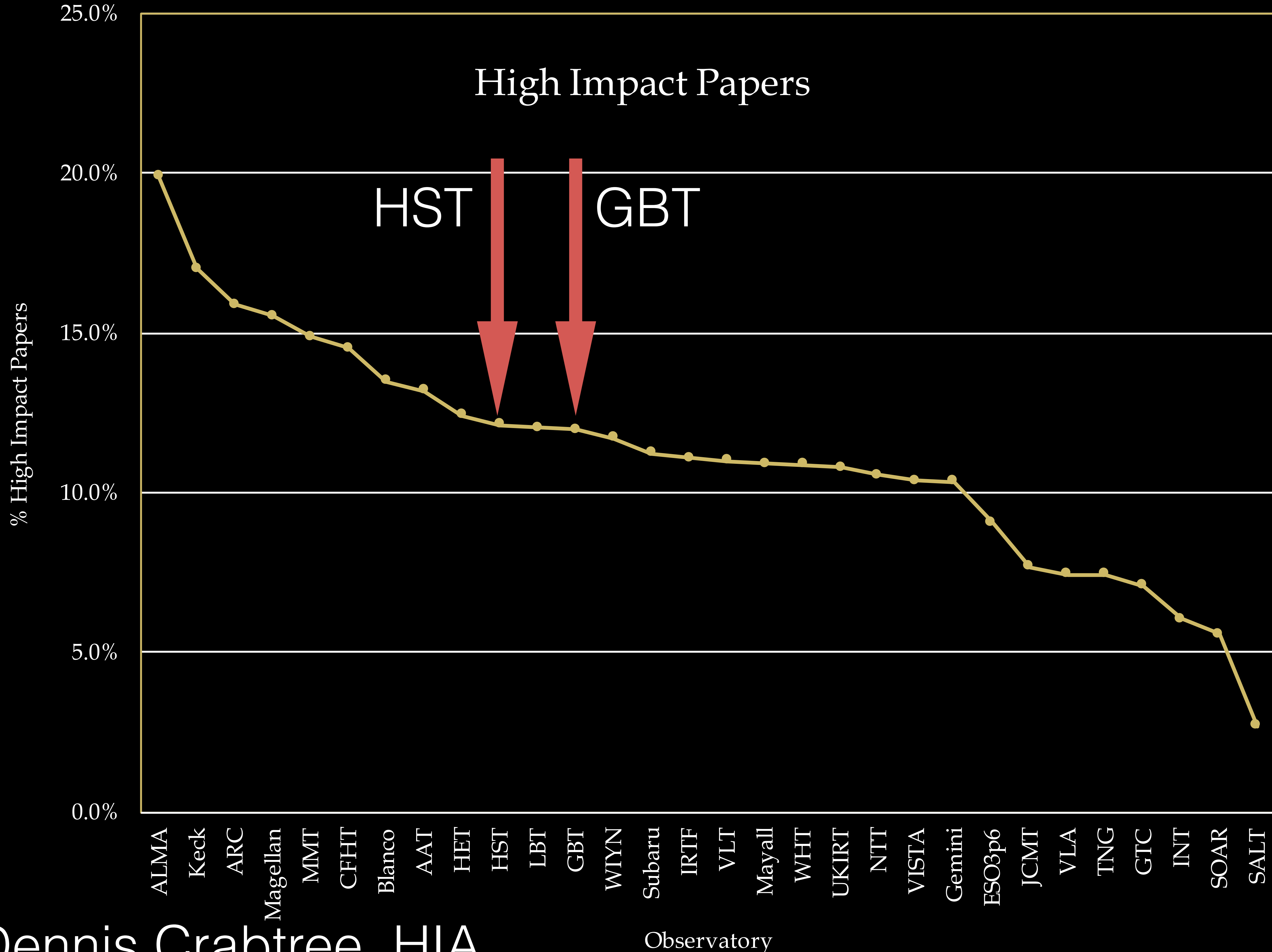
2012 - 2016



Dennis Crabtree, HIA

Extra Large Proposals: Expression of Interest

5 for GBT only
1 for GBT with VLA
4 for VLA with GBT

Every GBT receiver except 3mm spectroscopy was requested

Divestiture

GBT Usage	2010-2012 6540 hours	2016-2107 6813 hours
Spectroscopy	3,464 53%	3,832 56%
Pulsars	1,920 29%	2,212 32%
VLBI	754 12%	414 6%
Continuum	352 5%	298 4%
Radar	50 1%	58 1%

Not Open Skies

GBT Usage	2010-2012 6540 hours	2016-2107 6813 hours
Spectroscopy	3,464 53%	~1,930 ~28% ~1,900 ~28%
Pulsars	1,920 29%	1,932 28% 280 4%
VLBI	754 12%	~300 ~4% ~100 ~2%
Continuum	352 5%	298 4%
Radar	50 1%	58 1%