Maser astrometry, Galactic structure

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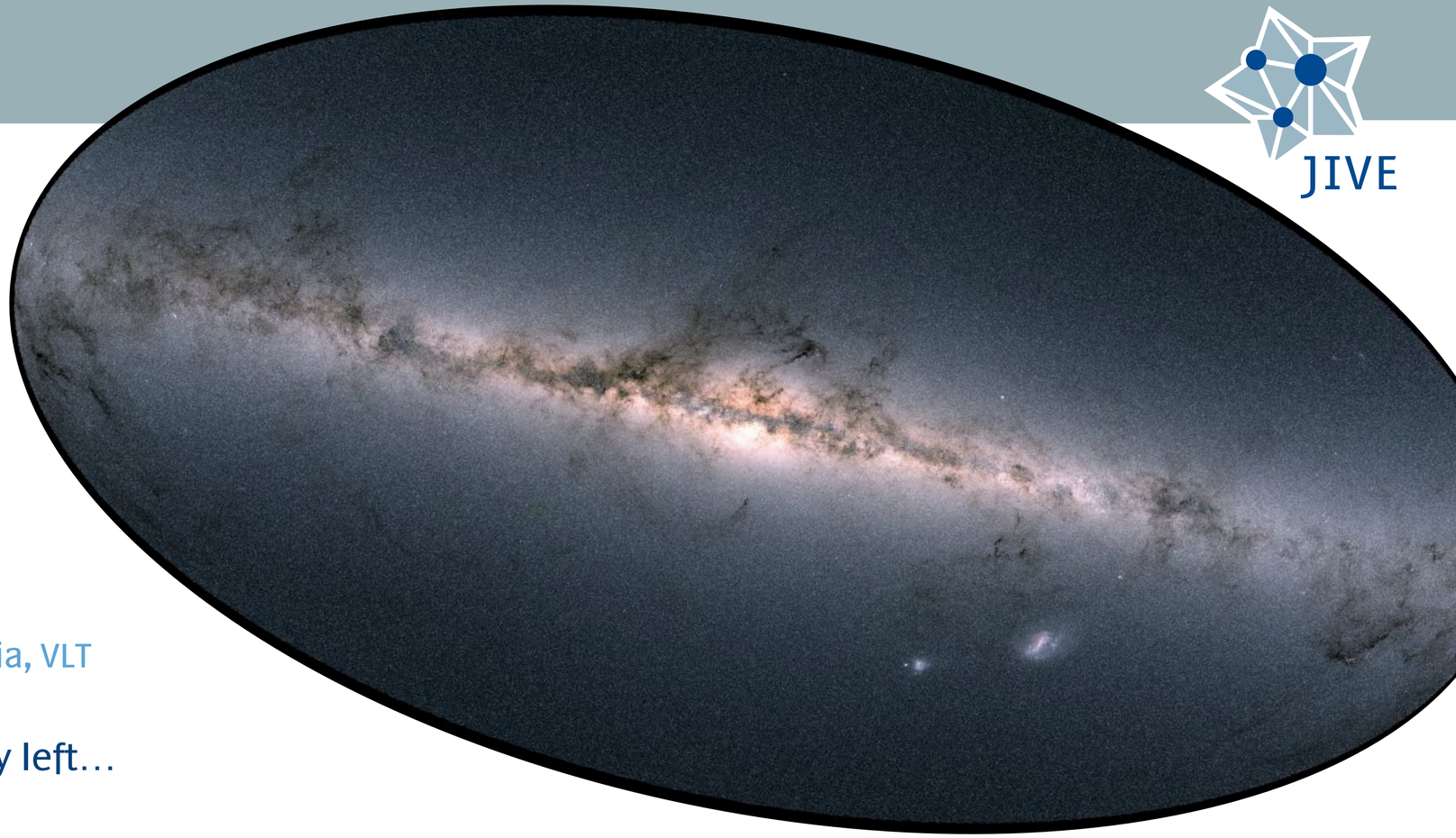
Background

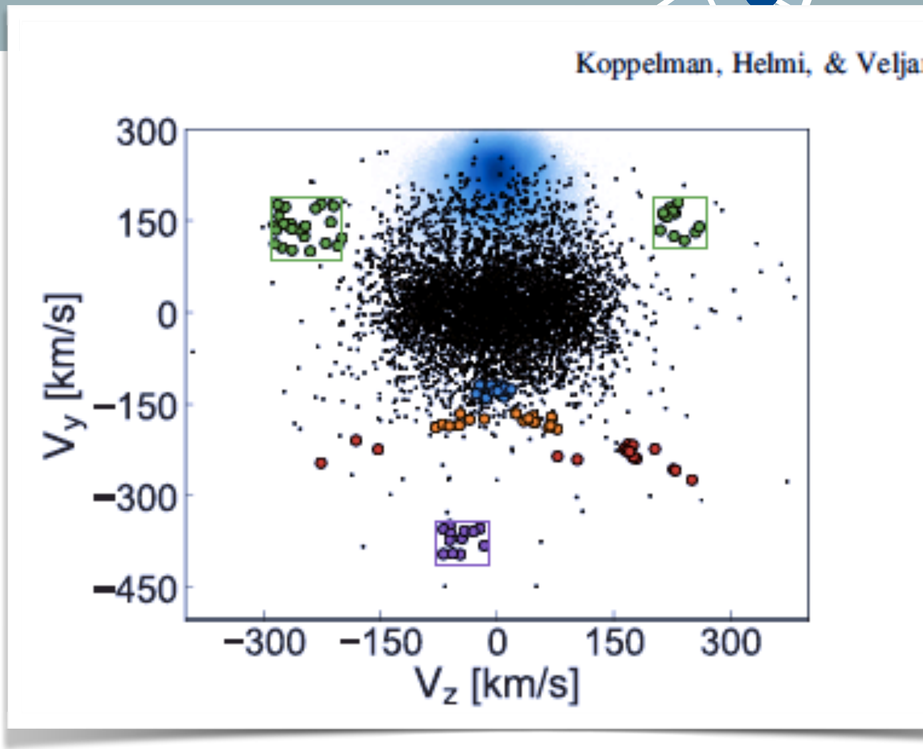
- Based on a talk for SKA-NL
  - Sorry if not very quantitative
  - Busy (in a new way) semester…
- Also reporting from the NL
  - Keen interest in Galaxy formation
  - And origins of stars, planets, life
    - But most of that focuses on ALMA, Gaia, VLT
    - Not much Galactic at ASTRON
  - 2/5 NL representatives on SWG Galaxy left…
- Also on
  - SADT consortium
  - CoL SWG
  - VLBI WG
- This talk:
  - Radio continuum…Evolved stars… HMSF regions…



The Gaia look…

Main interest

- How did the Galaxy form and how does it evolve?
  - Bears on structure formation in the Universe
  - Can we deduce recent and ongoing mergers?
    - Maybe a major merger in the past?
  - What is the (spiral) type of our Galaxy
    - And size, total mass, dark matter?
  - Its star formation rate and its history

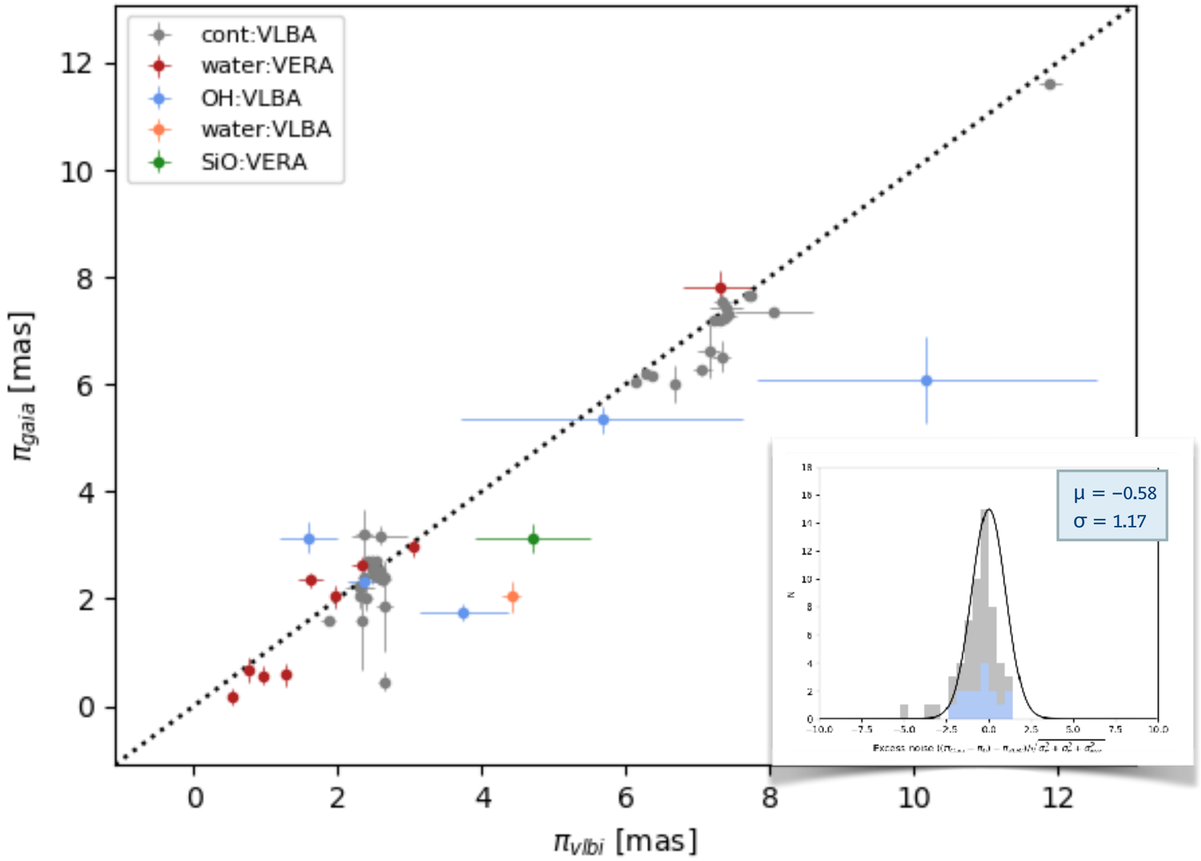


- The Galaxy is close and —but— we are in the middle of it…
  - Both in space and time
  - Still a unique view on stellar populations and their distribution

- Make progress by understanding the stellar populations
  - Including the ones being born and the dying
  - Masses, luminosities, ages, metallicities
  - And their distribution: galacto-centric radius, scale height, orbits
    - In particular: spiral arms, Galactic bar, bulge, Galactic Centre, outer Galaxy

In the age of Gaia?

- In many case in synergy with Gaia
  - Although Gaia catalogue has 1.3E9 entries and VLBI only 2E2…
  - Not a subset of Gaia sample
- Gaia will revolutionise samples
  - Of PMS stars
  - And evolved stars
- Gaia poses new question on the assembly of Galaxy
  - Recent and past mergers…
  - Stellar populations and kinematic structures
- Gaia confirmation of the hard work put into VLBI astrometry

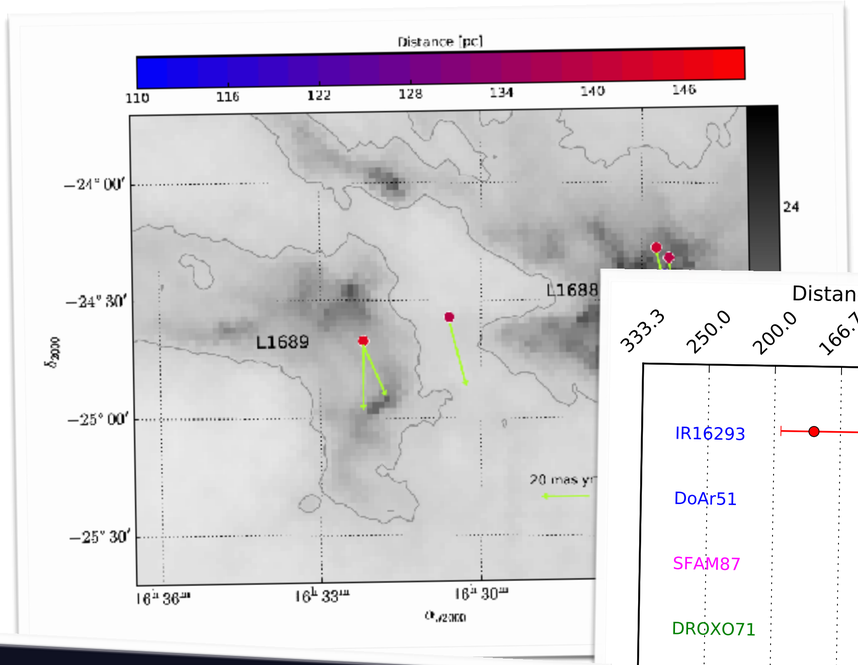


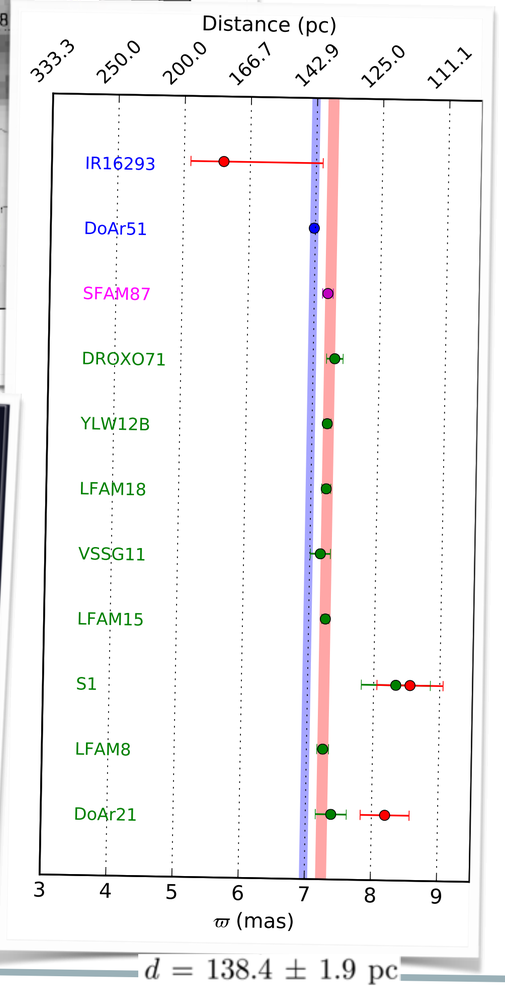
From many sources, including Loinard et al, Vlemmings & van Langevelde 2007, Kamezaki et al. 2016, Nakagawa et al. 2014, Kamezaki et al. 2012, Nyu et al 2011, Min et al. 2014, Nakagawa et al. 2008, Vlemmings et al 2004, Zhang et al. 2017, Nagakawa et al. 2016

Astrometry of (non-thermal) stars

Results on Ophiucus, Ortiz-Leon et al 2017a,b

- Many pre-main sequence stars active radio emitters
  - Can map depth of molecular clouds
  - History/gradient of star-formation
- Synergy with CoL
  - Grain growth vs
  - Ionisation, HII regions
  - Magnetic, non-thermal activity, binaries





$$d = 138.4 \pm 1.9 \text{ pc}$$

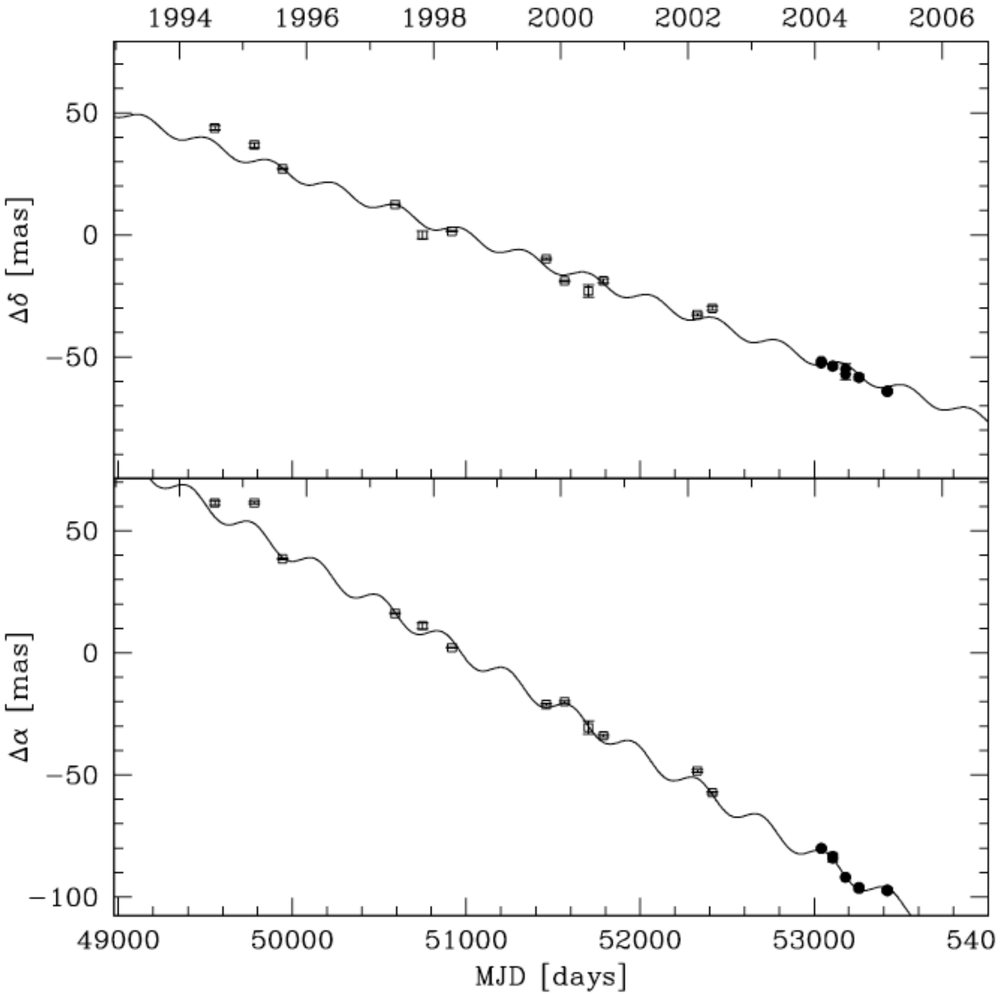
Evolved stars

- Mira-like AGB stars with circumstellar shells
  - Have (optical &) IR counterparts
    - OH, H_2O and SiO masers
  - Probe the (relaxed) stellar content

- But astrometry at relevant distances?
  - Probably requires coverage of the 43GHz
  - If not with SKA?
    - ALMA (band 1 or 86 GHz in band 2)
    - ngVLA (also include long baselines)

- Probably not with OH masers
  - Although still of interest for studying mass-loss etc.
    - Maybe excited OH
- Maybe some H_2O masers at 22GHz
- SiO masers are of interest
  - But not for SKA1

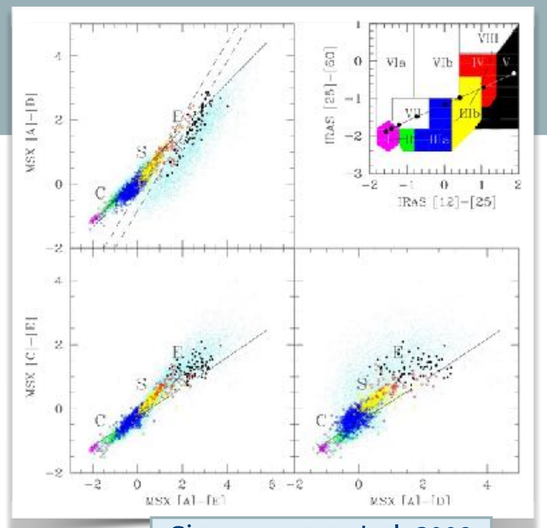
Vlemmings & van Langevelde 2007



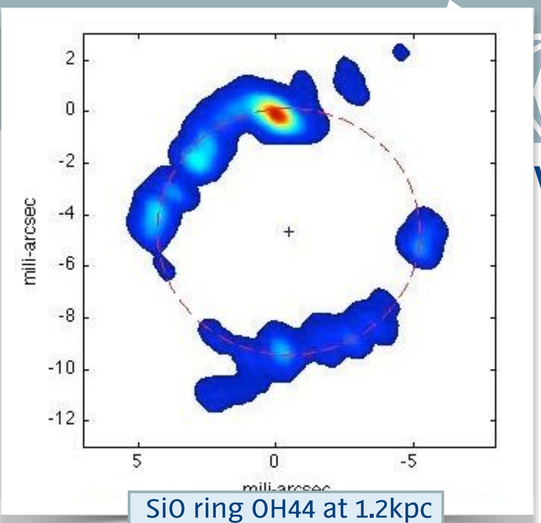
π=3.67±0.27mas

BAaDE project

- Going for Mira stars with SiO masers
  - even if they appear in varying rings
- IR selection based on MSX
- Can search multiple maser lines
  - also lines for Carbon-rich stars
  - most sources display more than one line: very reliable velocities
- Concentrated on |b| < 5º
  - No optical data, but kinematics of bar
- 28.000 targets
  - VLA 19.000 observations complete
    - Very fast detection experiment
    - No time for phase calibration
  - ALMA ongoing

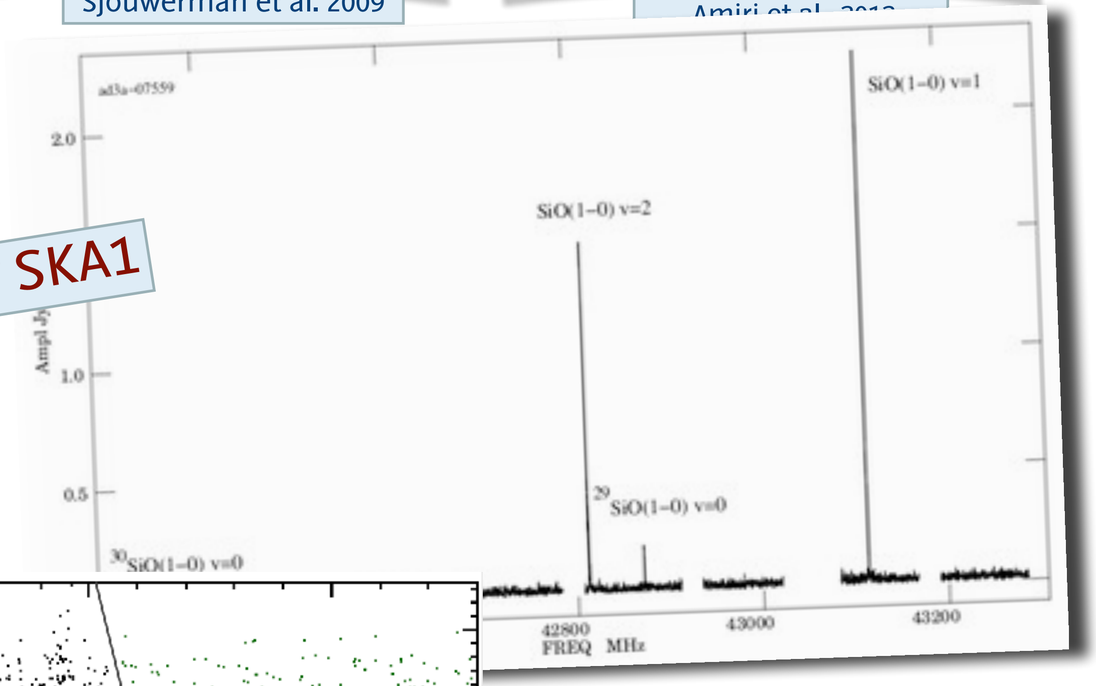


Sjouwerman et al. 2009

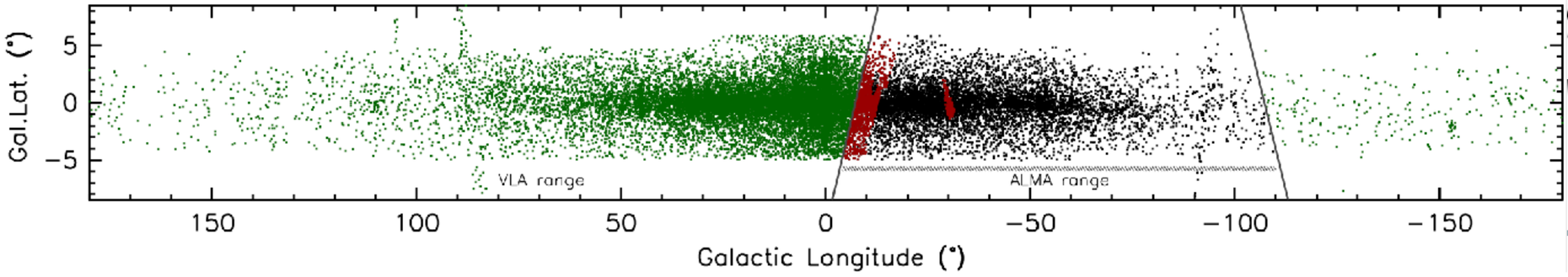


SiO ring OH44 at 1.2kpc
Amiri et al., 2012

Not covered by SKA1



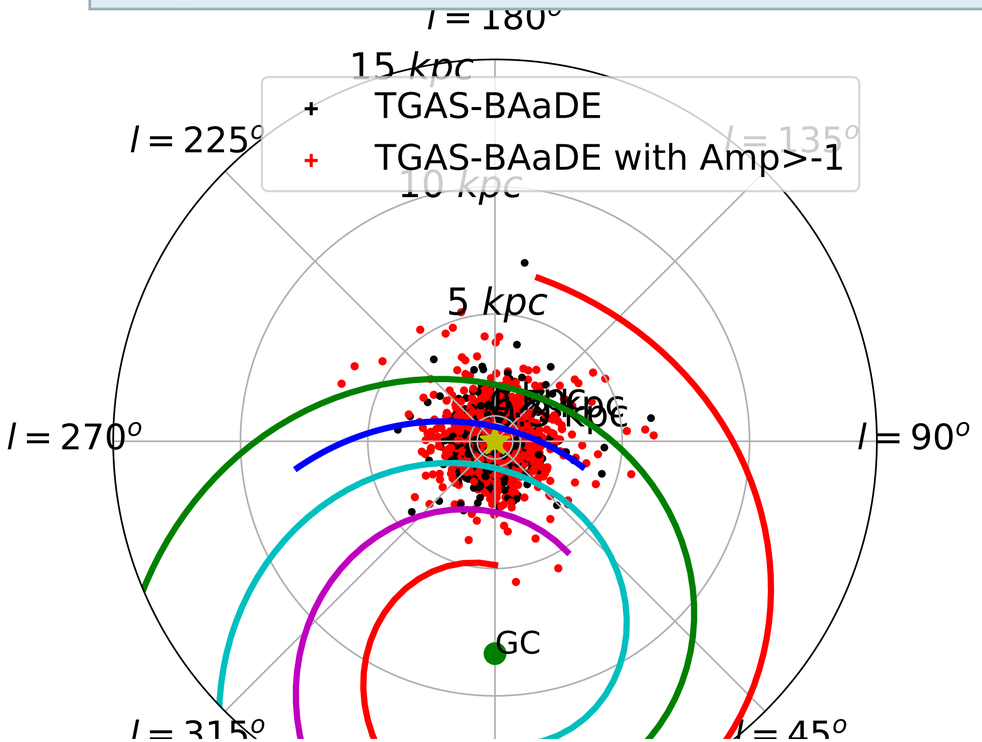
Baade detection, Sjouwerman et al.



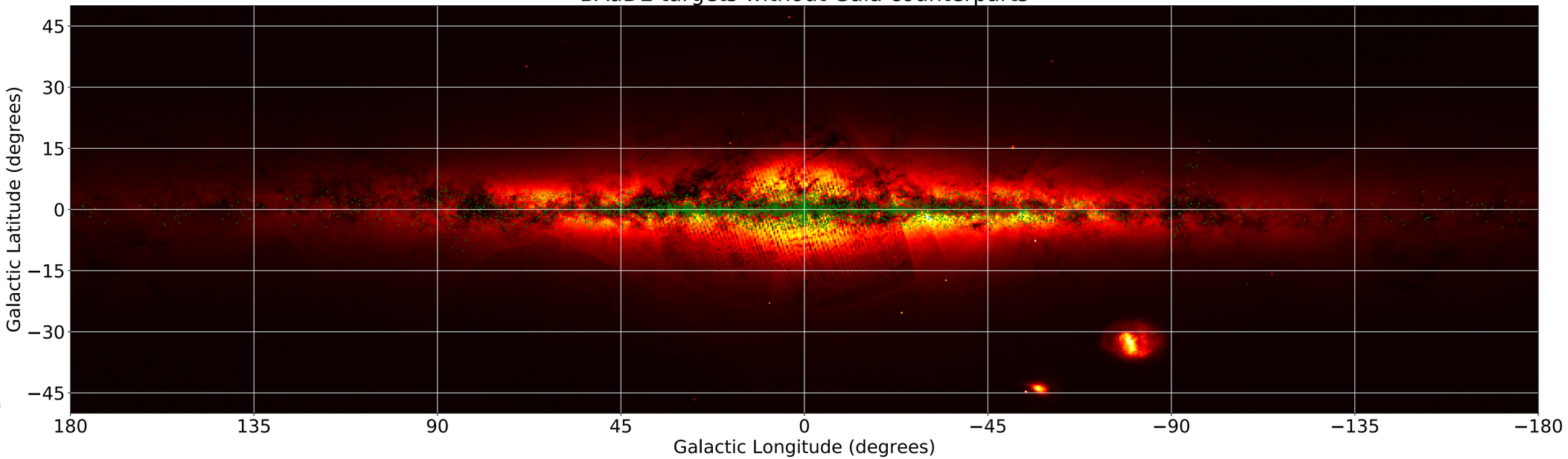
Comparison with Gaia

- Interesting to understand sample
  - M_{bol}, Colours, even Periods eventually
- But limited to the Galactic foreground
  - Interstellar extinction
  - Sources very red by own dust shells

SiO maser candidates identified in Gaia DR2 with accurate distances
Quiroga-Nunez in preparation

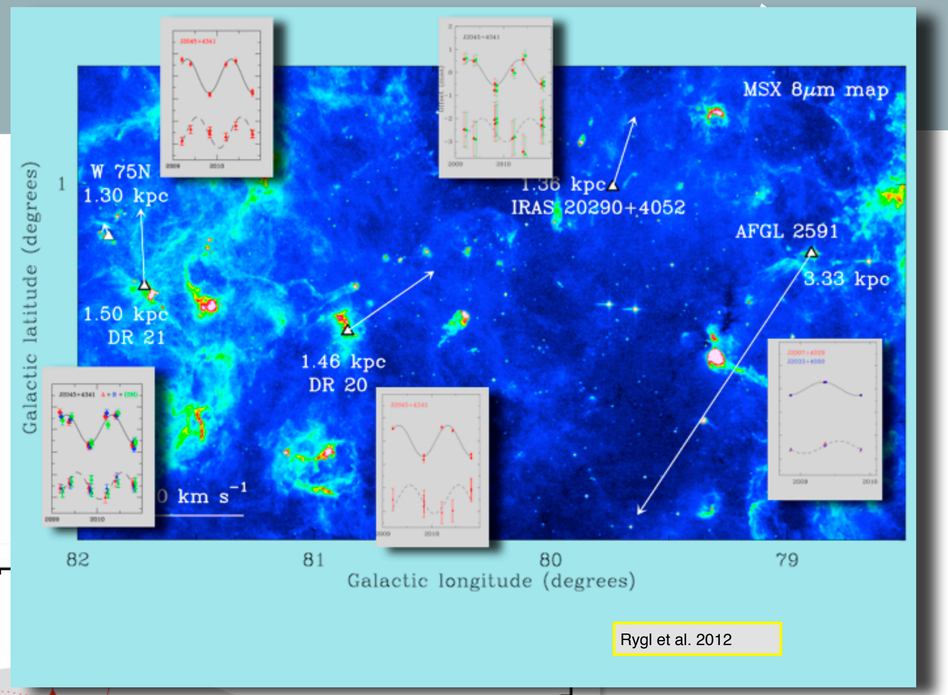


BAaDE targets without Gaia counterparts

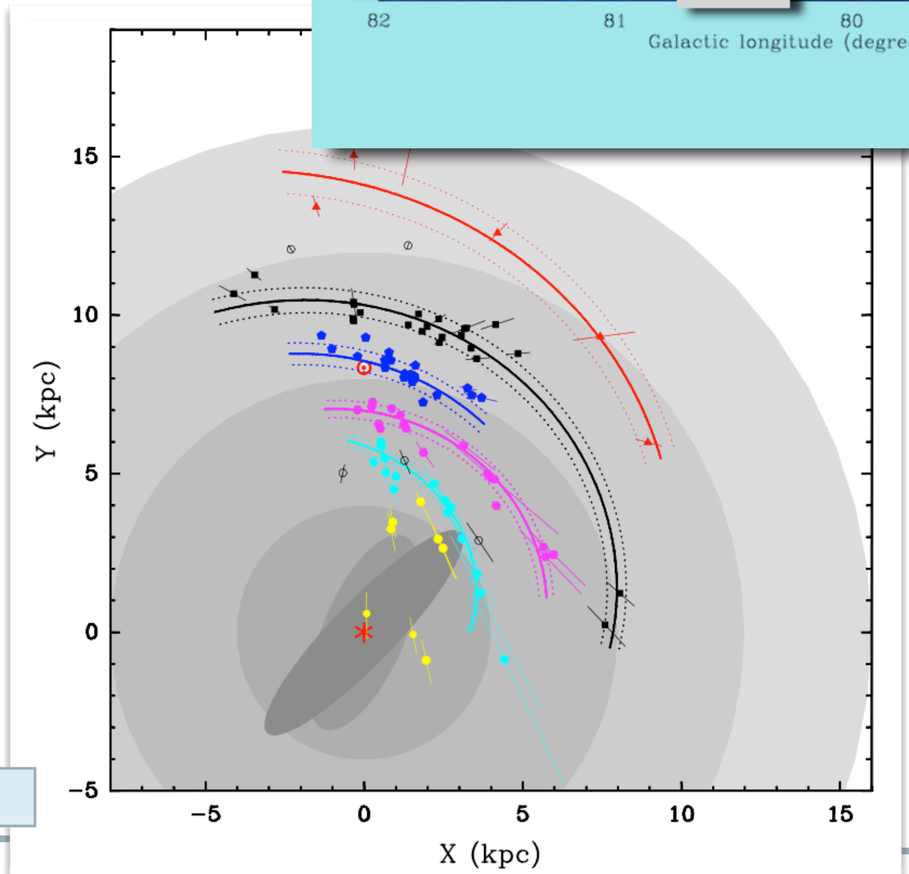


High mass star formation

- Most promising targets for VLBI@SKA
- Ideal for measuring size of Galaxy
  - Distance scale & rotation curve
    - Full Galaxy not accessible to Gaia
  - BeSSel project
    - 6.7, 12 GHz CH_3OH
    - 22 GHz H_2O masers
- Distance to individual HMSF regions
- And location of the Spiral arms
  - Classification of Milky Way
  - Induced star formation?
- Now mostly limited to Northern Sky
  - Checked against biases
  - But inner Galaxy largely unexplored



Rygl et al. 2012



Reid et al. 2014

Bessel project progressing

- Refining spiral structure
- Including 6.7 GHz on the VLBA
  - Harder to get accurate distances
    - Less resolution
    - More ionosphere

water masers in S269
Quiroga Nunez et al 2018

- First results from Southern Hemisphere

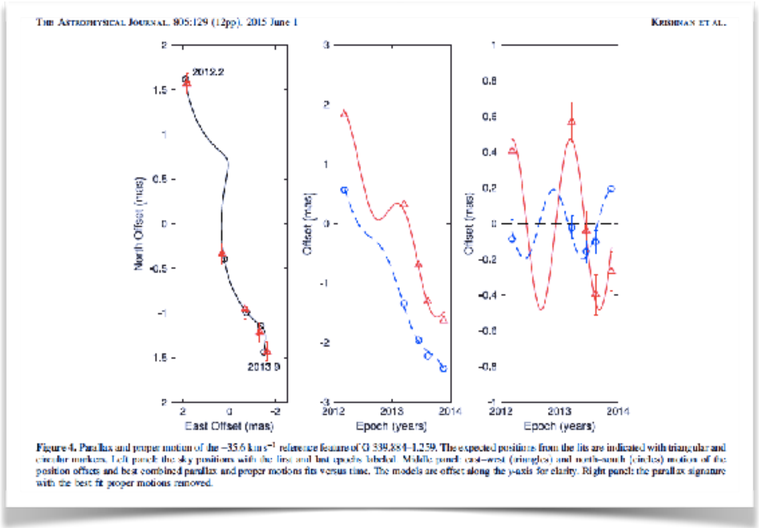


Figure 4. Parallax and proper motion of the −35.6 km s^{-1} reference feature of G 339.884−1.259. The expected positions from the fits are indicated with triangular and circular markers. Left panel: the sky positions with the first and last epochs labeled. Middle panel: east–west (triangles) and north–south (circles) motion of the position offsets and best combined parallax and proper motions fits versus time. The models are offset along the y-axis for clarity. Right panel: the parallax signature with the best fit proper motions removed.

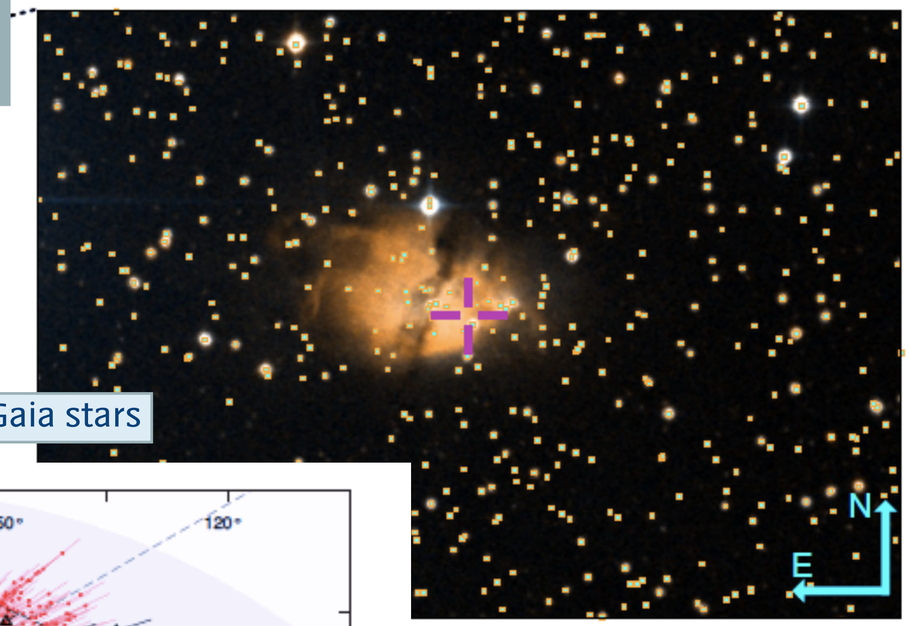
Krishnan et al., 2015

Under Embargo

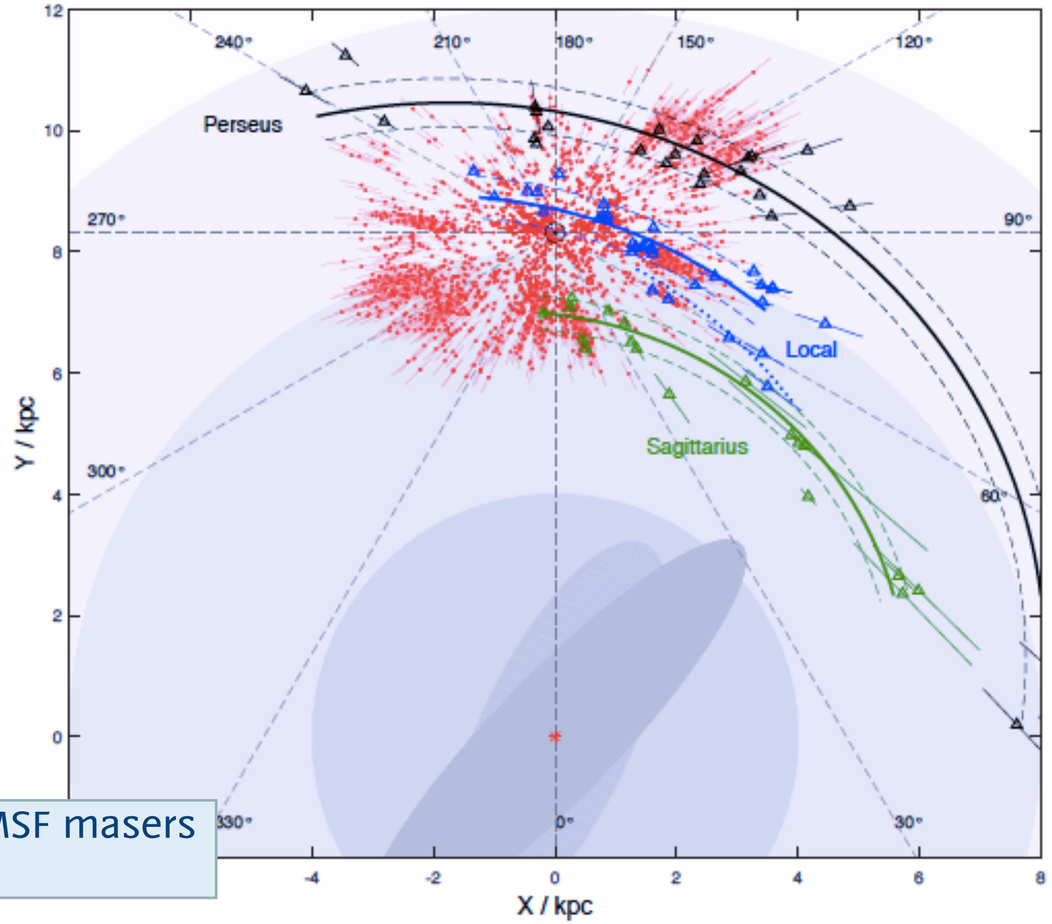
Reid et al., 2019

Synergy with Gaia

- Maybe also possible here
  - Looking for ‘cluster companions’
- Comparison on structure
- And Galaxy properties



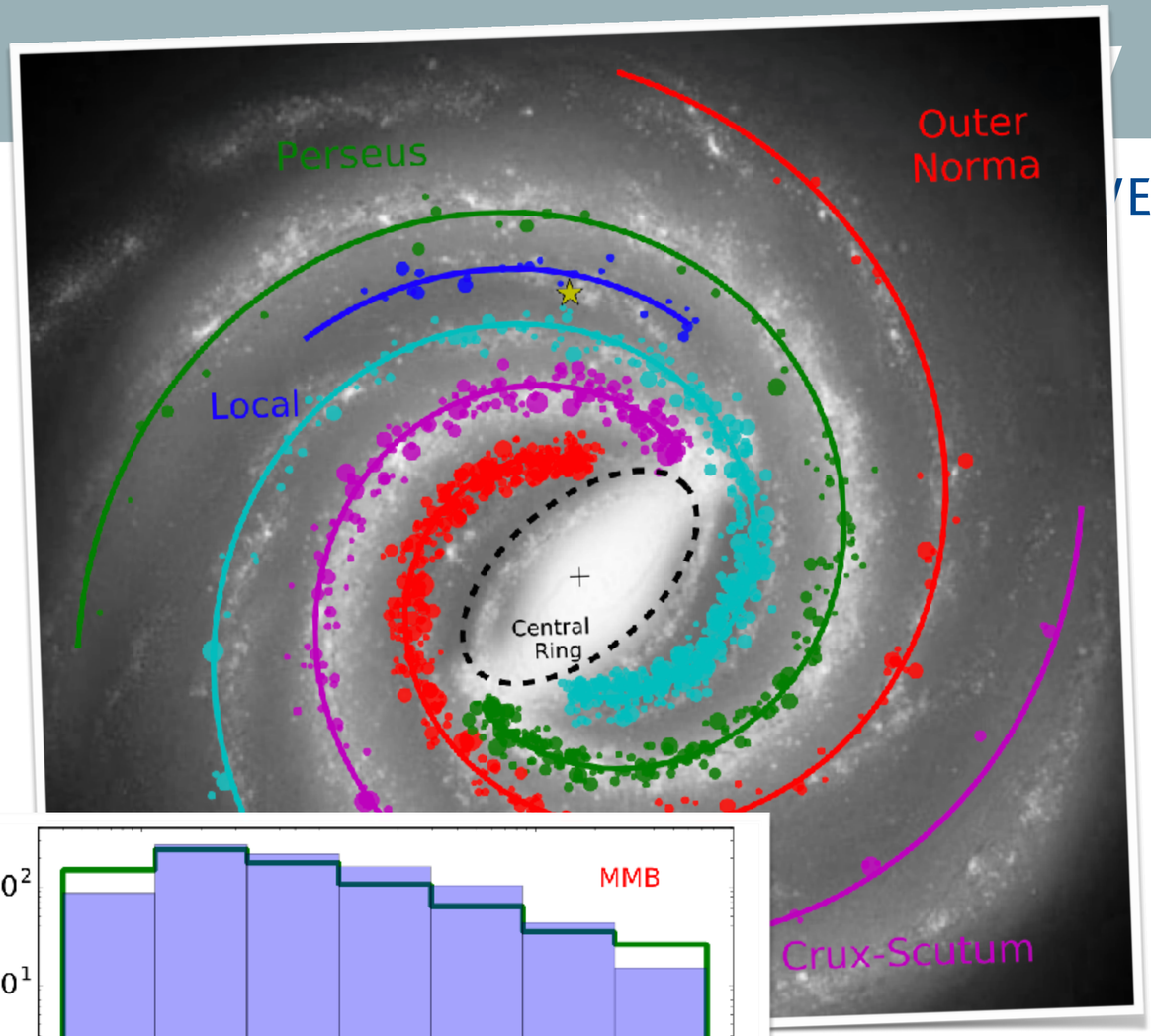
S269 field with Gaia stars

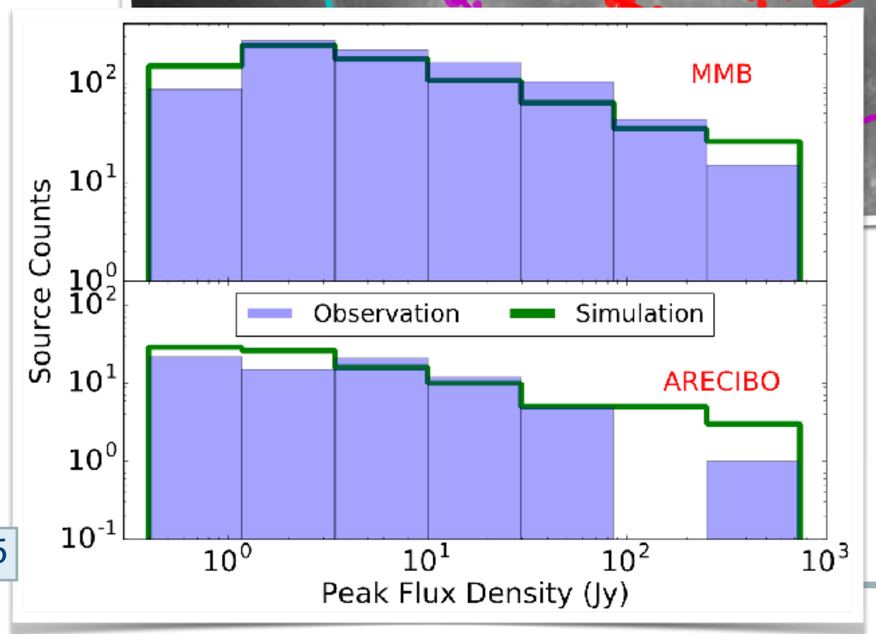


Gaia O stars & HMSF masers
Xu et al., 2018

Did simulations

- Created thousands of Monte Carlo galaxies
  - Populated with random 6.7 GHz masers
    - Outside the central ring
  - Following spiral structure
  - Galactic rotation and velocity ellipses
  - Scale length for young, massive stars
  - Z-height of thin disk
- Fitted the resulted luminosity function
  - Against MMB survey (and Arecibo)
- Derive maser populations with fluxes
  - Can simulate VLBI astrometry accuracies
  - Produce predictions on error budgets





Quiroga Nunez et al., 2016

Main goal: check against biases

- Are the Galaxy parameter estimates robust?
  - Selecting bright masers for astrometry
  - From Northern hemisphere
  - Could result in biases for basic parameters
- No such effect found
  - Reid 2014 errors are conservative
  - Not easy to separate solar motion and Galactic rotation

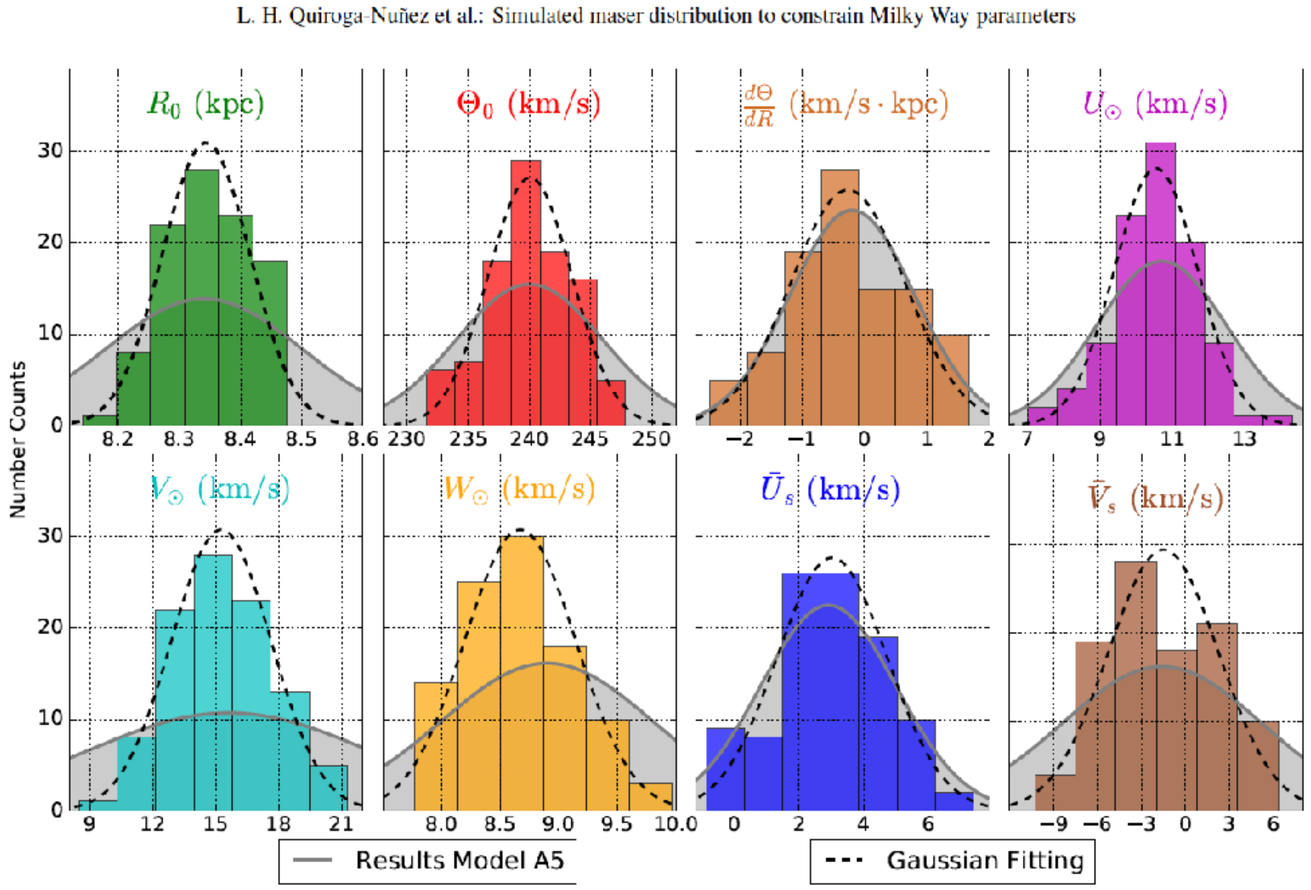
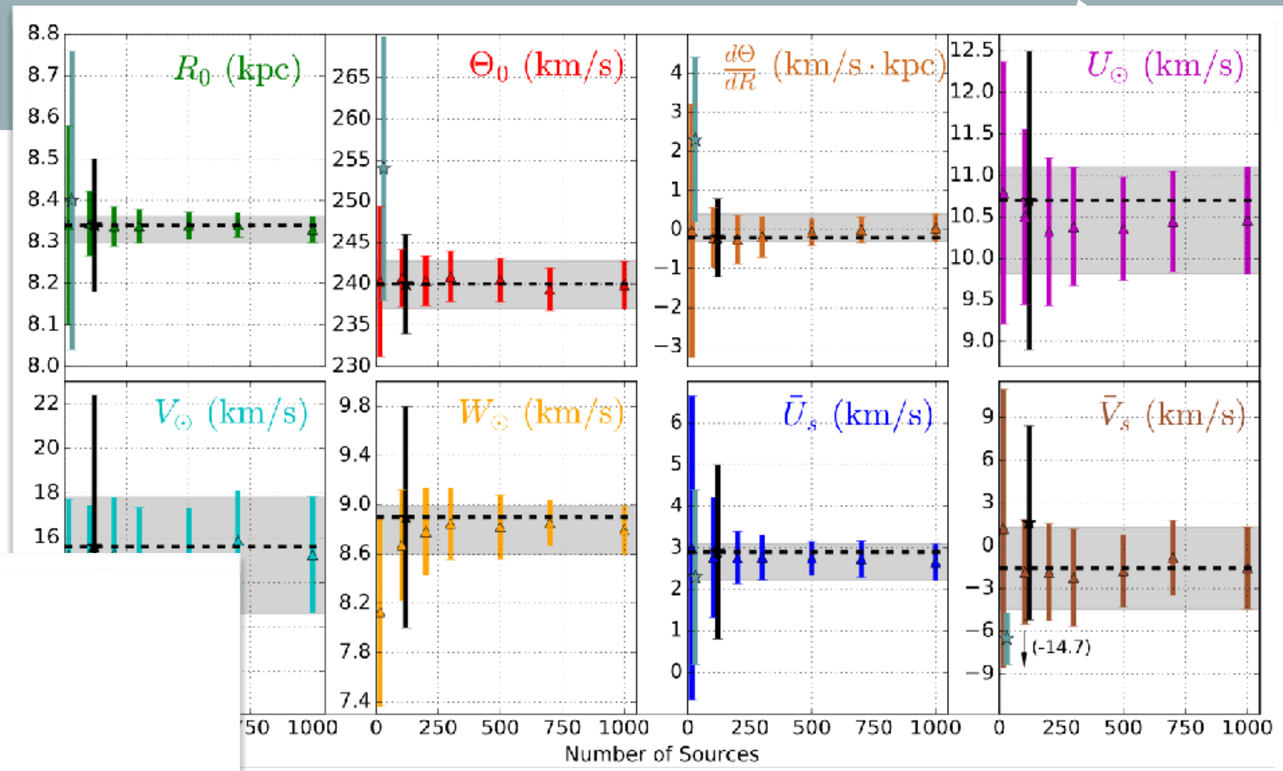


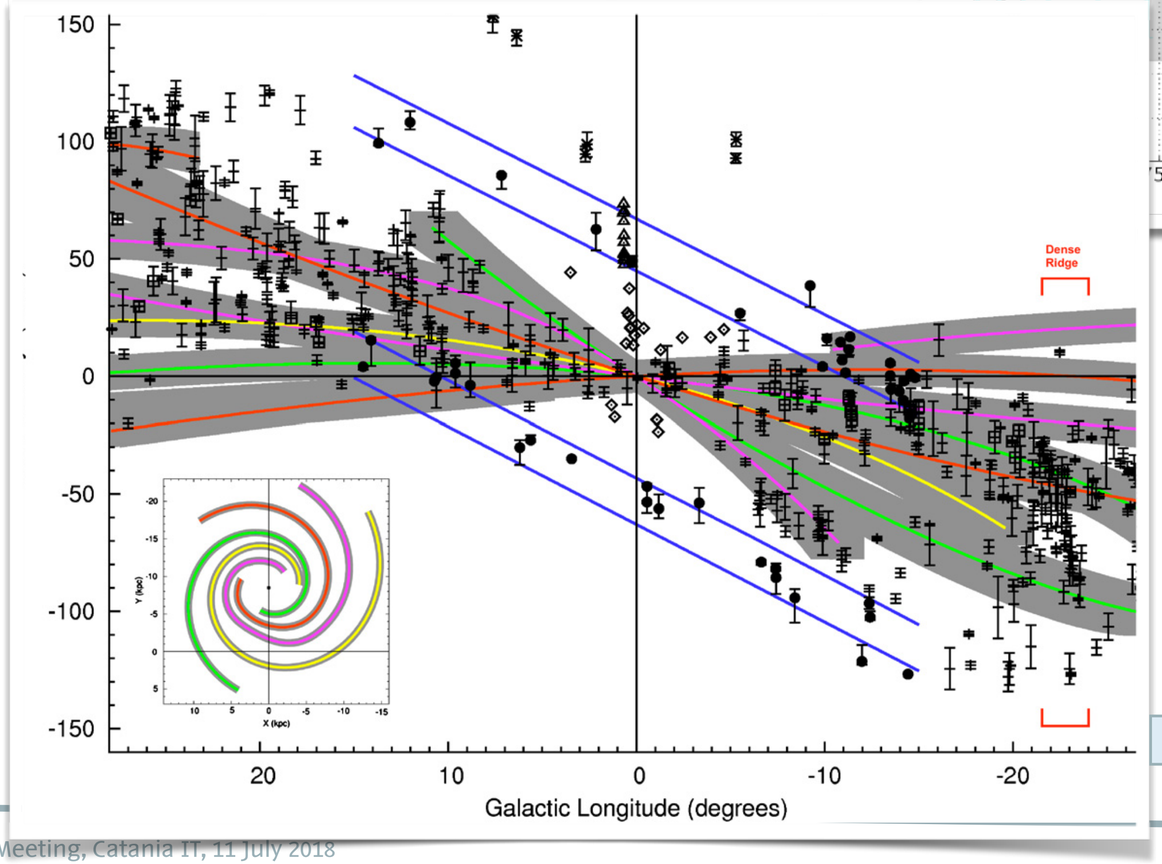
Fig. 7. Galactic parameters distributions found for 100 simulated galaxies mimicking the BeSSeL data sample selection (Sect. 3.2). The values listed in Table 4 correspond to the fitting made to the histograms and shown as black dashed lines. Bayesian fitting results for the A5 model reported in Reid et al. (2014) are shown as gray regions.

Future

- Can predict improvements on Galactic parameters
  - Main science is actually on spiral structure
  - Notably for inner Galaxy, bar & molecular ring



Theoretical improvement with Southern VLBI on basic Galactic parameters



Green et al., 2011

What is needed

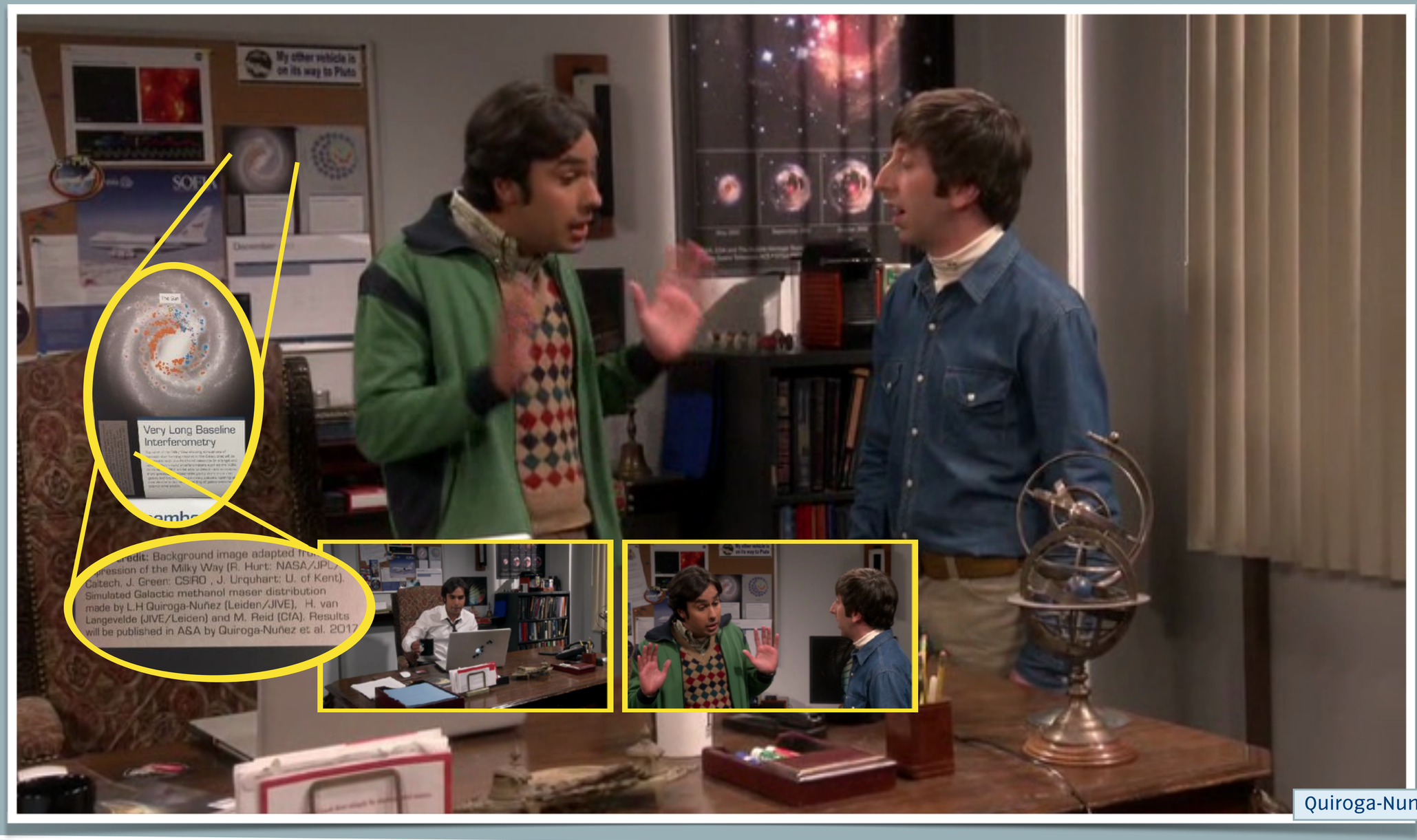
- There are maybe 1000 targets at 6.7 GHz
  - A fair fraction at 12 GHz
  - Not sure if survey with Mid is required for this
  - They all require 4-6 epochs of 0.5 hour
  - Impact on the science is predicted in Quiroga-Nunez et al. 2017
    - Additional value in individual distances

- But what is the scarcest resource here?
  - SKA mid time, possibly
  - VLBI network time maybe
    - Also in demand for pulsar VLBI and more
  - VLBI network consumables, the sad reality
  - VLBI processing, can be addressed
  - VLBI user time…

- Depend thus on operational model for VLBI
  - How and what VLBI time can be applied for
  - Subject of WP in JUMPING JIVE project

- Maybe not the most urgent SKA science, but the case with best exposure

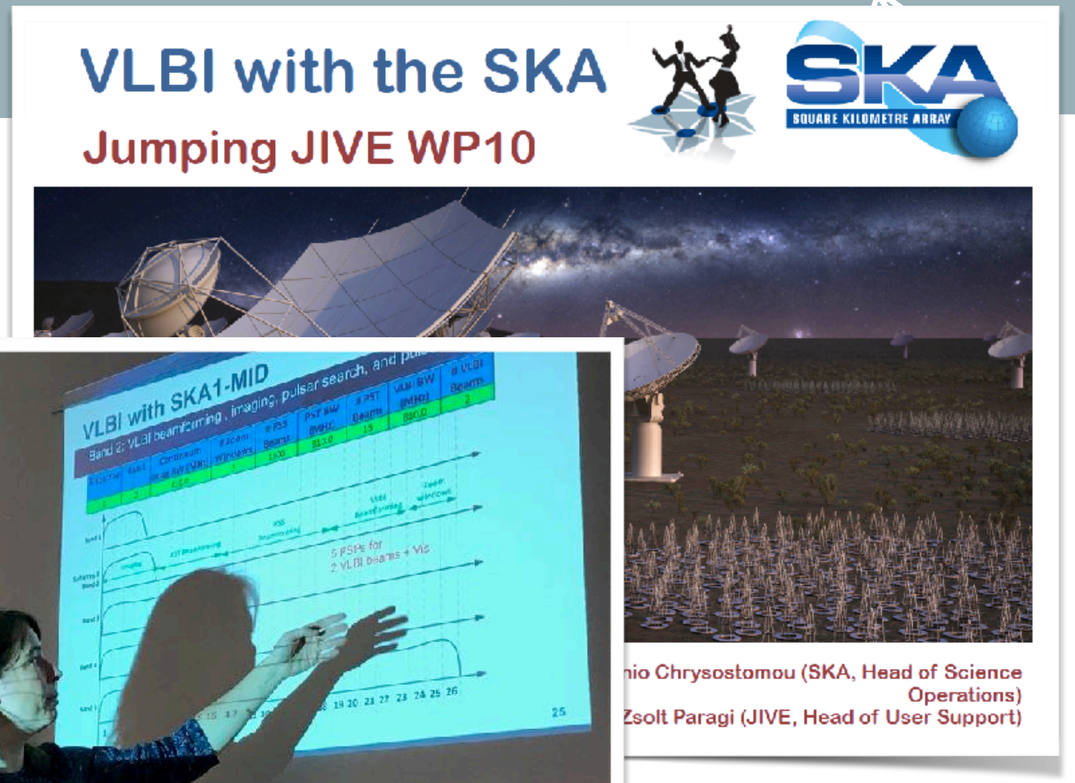
Simulations got some exposure...

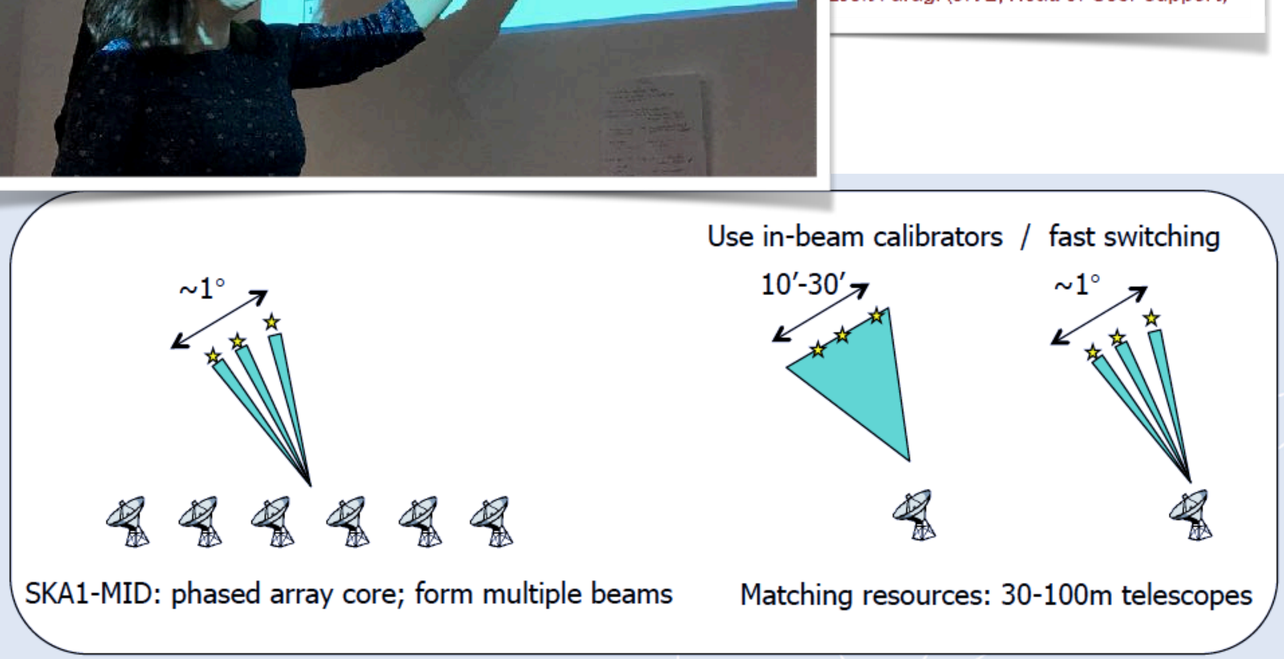


Quiroga-Nunez et al., 2017

VLBI@SKA

- Supported by JUMPING JIVE WP10
- Contributing VLBI domain specialist
  - Cristina Garcia-Miro started 1 August 2017
  - Technical definition with different drivers
    - Pulsar astrometry needed for timing
    - Localising transients
    - HI absorption to characterise redshifted galaxies
    - Star formation history across Universe
- VLBI as part of KSPs
- Early commissioning?
- Also support for the AVN
  - African VLBI Network





Wrap up

- VLBI astrometry needs:
  - Band 5 receivers
    - Preferably 5a in core that can be phased up
    - 5b: 12 GHz (and even 22GHz) would be nice
  - VLBI capabilities
    - Other African and Souther hemisphere VLBI elements
    - Multiple beams on the sky for in-beam calibrators
    - Compatible bands for wide band calibration

- Operational model
  - How, where to apply for rest of array
    - Some lessons learned from VLBI@ALMA
  - Allocate VLBI time at SKA in KSP
    - Not many options for commensal observing