The Synergy between VLBI and Gaia astrometry

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Ross Burns (JIVE)
& Bessel team

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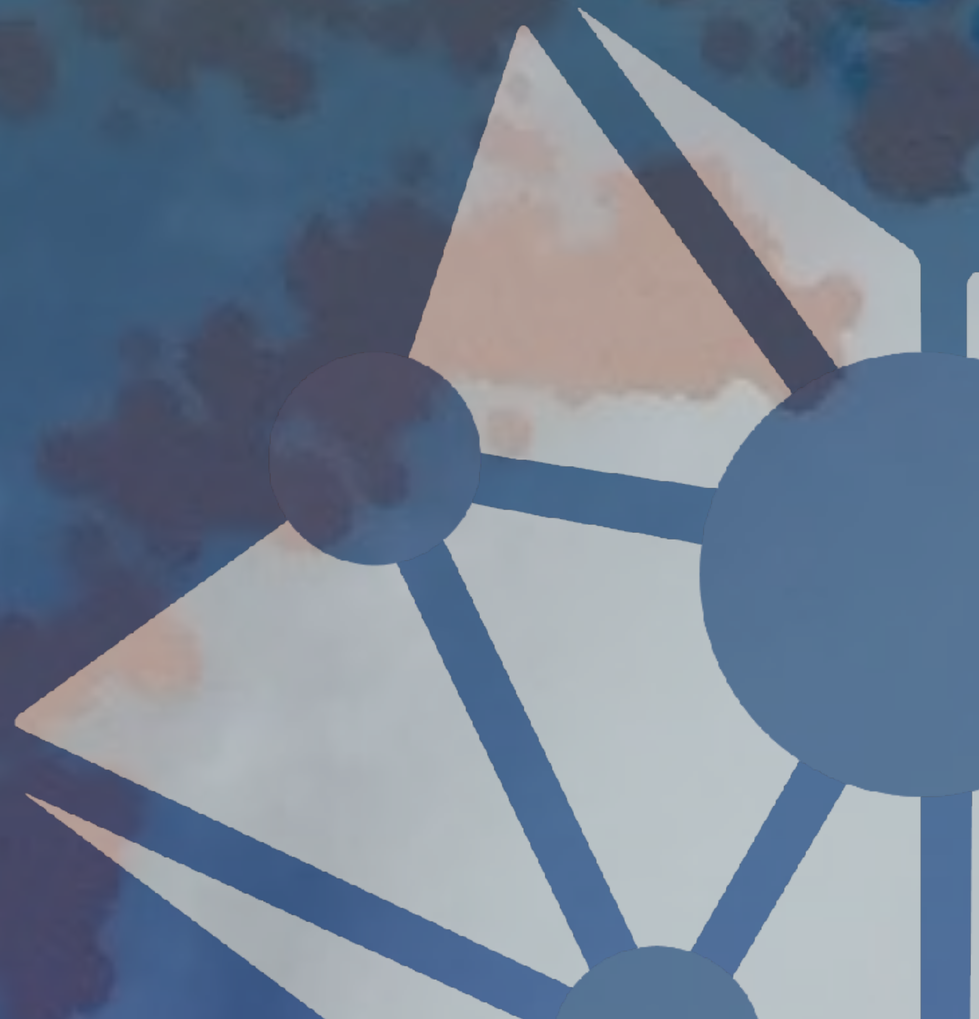
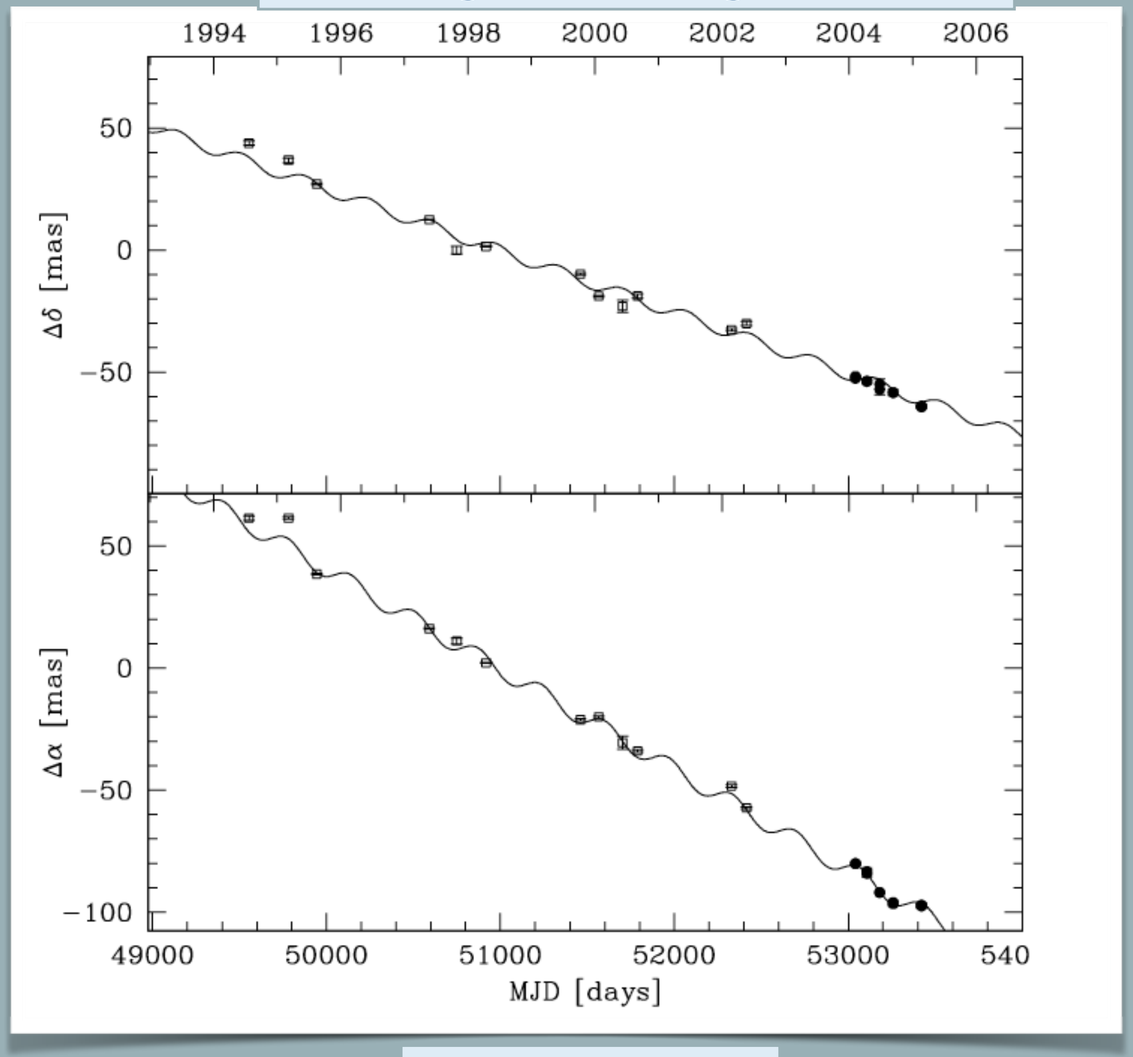
Ylva Pihlström (UNM)
Mike Rich (UCLA)
& BAaDE team



Synergy VLBI & Gaia

Vlemmings & van Langevelde 2007



π=3.67±0.27mas

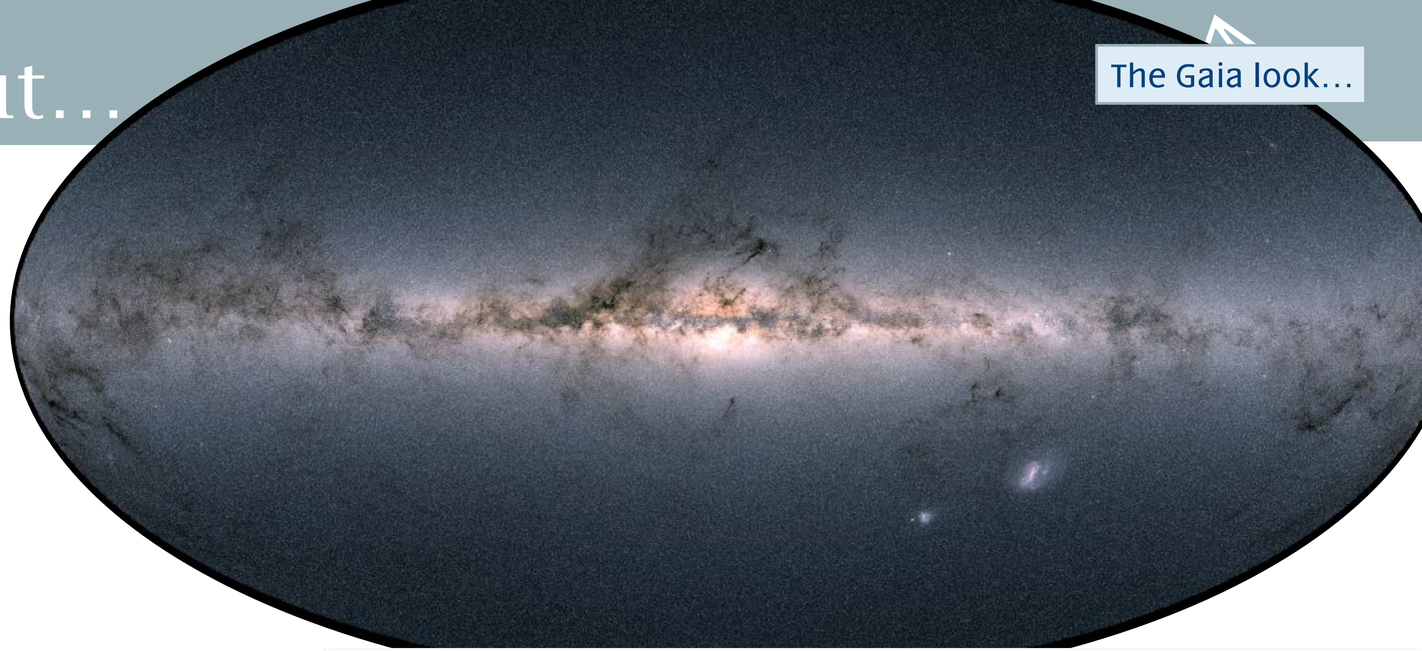
- Advocating the value of VLBI astrometry
  - of Galactic maser sources
- Now Gaia has delivered

- Complementary in many aspects
  - Distances to individual objects
    - Pinpointing central object in molecular environment
  - Studying stellar populations
  - Detailed structure of the Galaxy
    - Spiral arms, embedded HMSF regions
    - Bulge & Bar, even through optical extinction
  - Kinematic parameters of the Galaxy
    - Size
    - Rotation curve

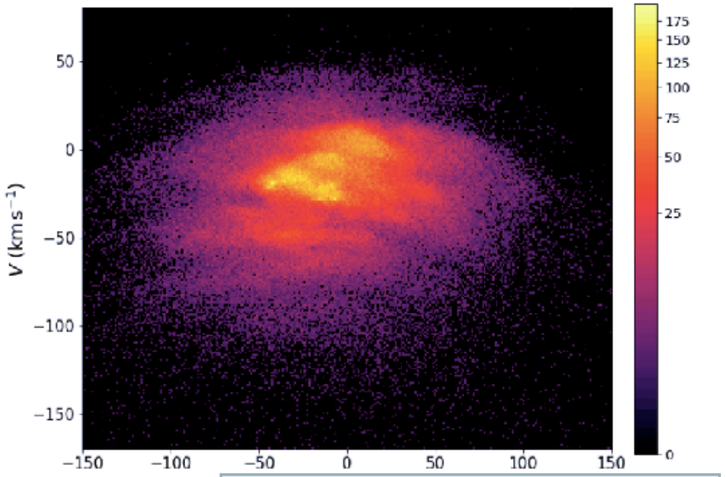
For Gaia - ICRF comparison:
Jacobs talk, Charlot poster

Overwhelming Gaia output…

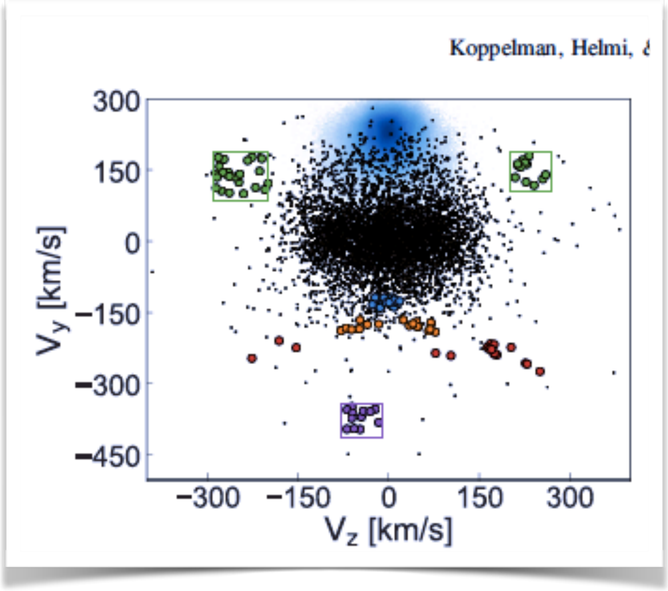
The Gaia look…

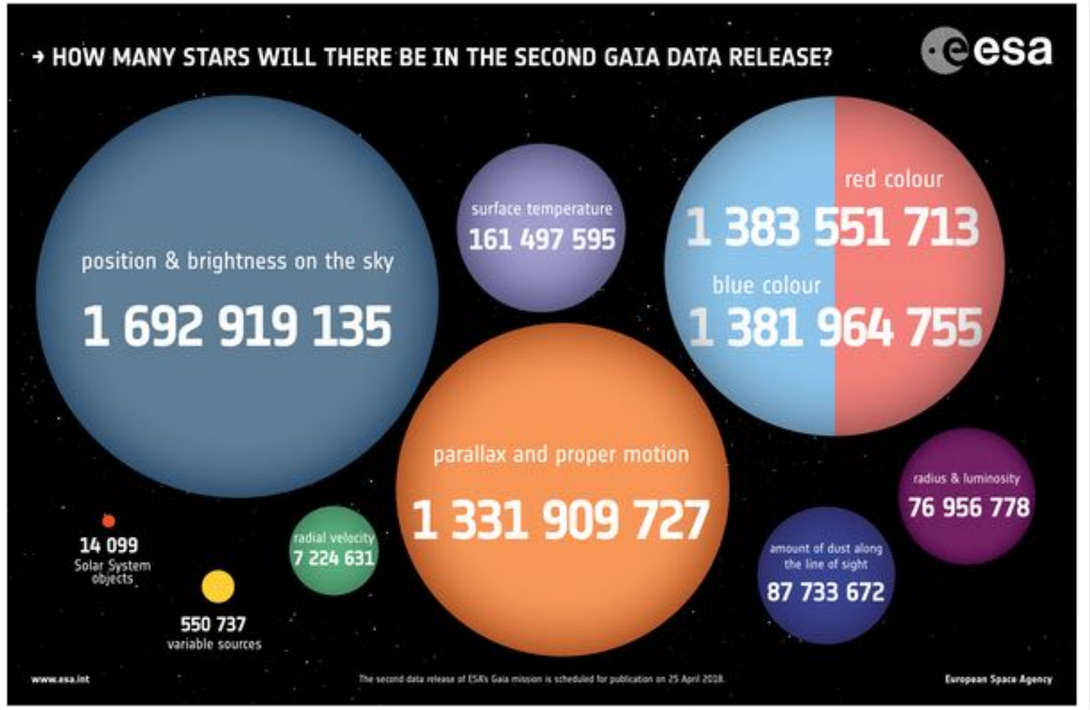


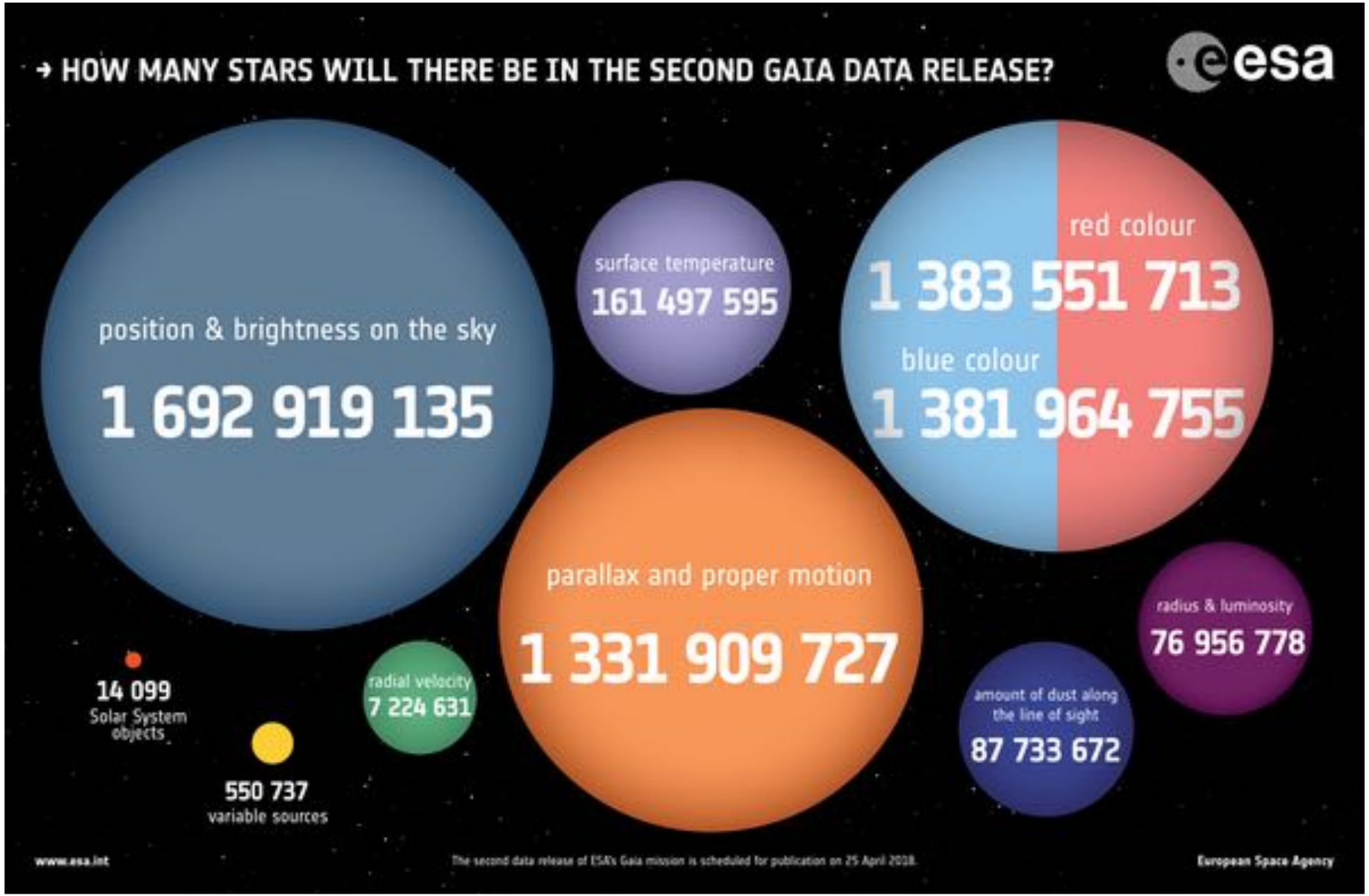
- Focus on Galaxy construction
  - Bears on structure formation in the Universe
  - Can we deduce recent and ongoing mergers?
  - What is the (spiral) type of our Galaxy
  - Its star formation rate and its history
- Understand stellar populations
  - Kinematics, distribution, age, metallicity

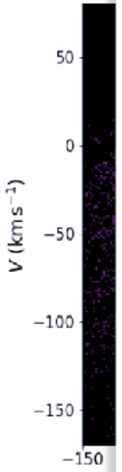


Phase space cut, Katz et al. 2018

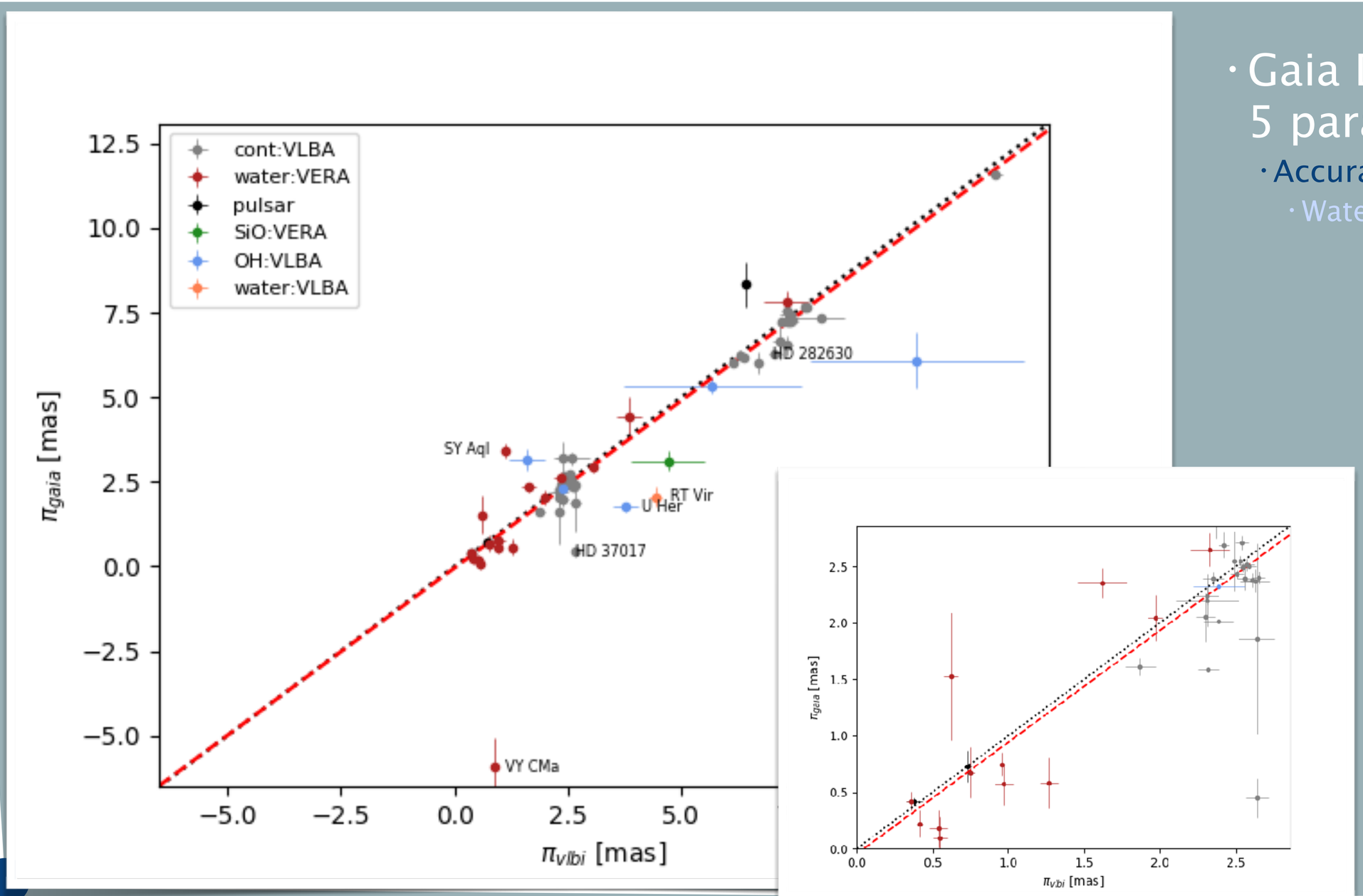





→ HOW MANY STARS WILL THERE BE IN THE SECOND GAIA DATA RELEASE?
esa
position & brightness on the sky
1 692 919 135
surface temperature
161 497 595
red colour
1 383 551 713
blue colour
1 381 964 755
parallax and proper motion
1 331 909 727
radius & luminosity
76 956 778
amount of dust along the line of sight
87 733 672
radial velocity
7 224 631
14 099
Solar System objects
550 737
variable sources
www.esa.int
The second data release of ESA's Gaia mission is scheduled for publication on 25 April 2018.
European Space Agency


50
0
−50
−100
−150
−150
V (km s⁻¹)

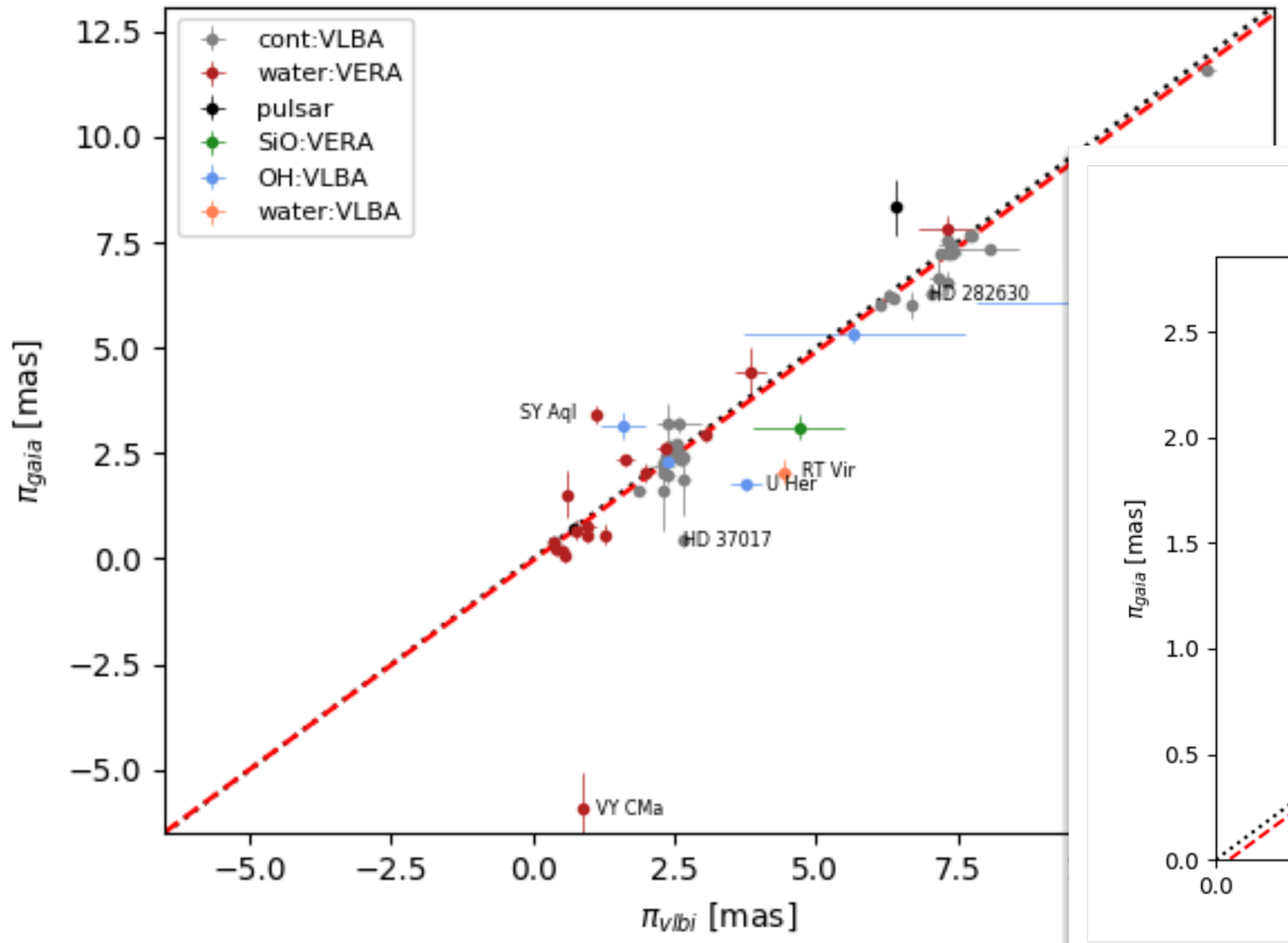
Gaia vs VLBI parallaxes



- Gaia DR2:
  5 parameter solution
  - Accuracies can be comparable
    - Water masers still win

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
- Jennings et al. 2018

Gaia vs VLBI parallaxes



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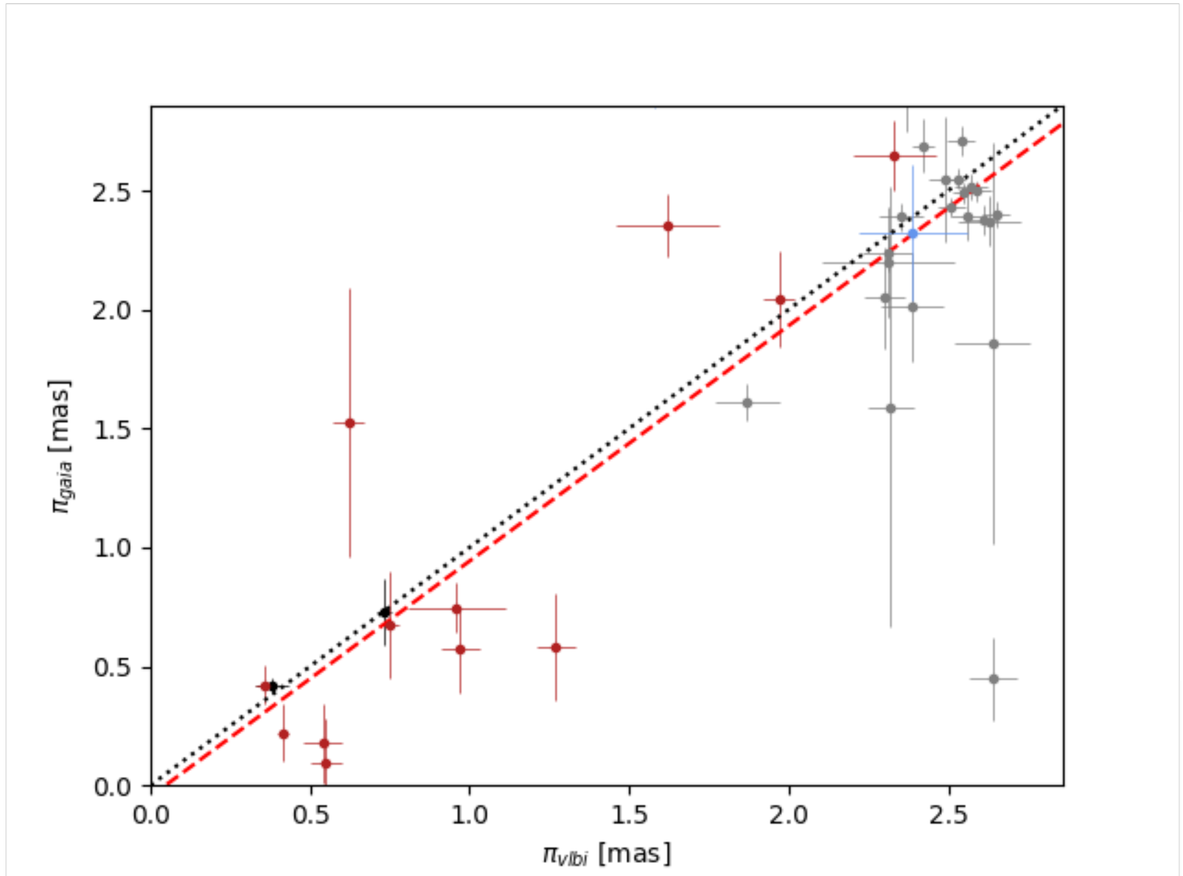
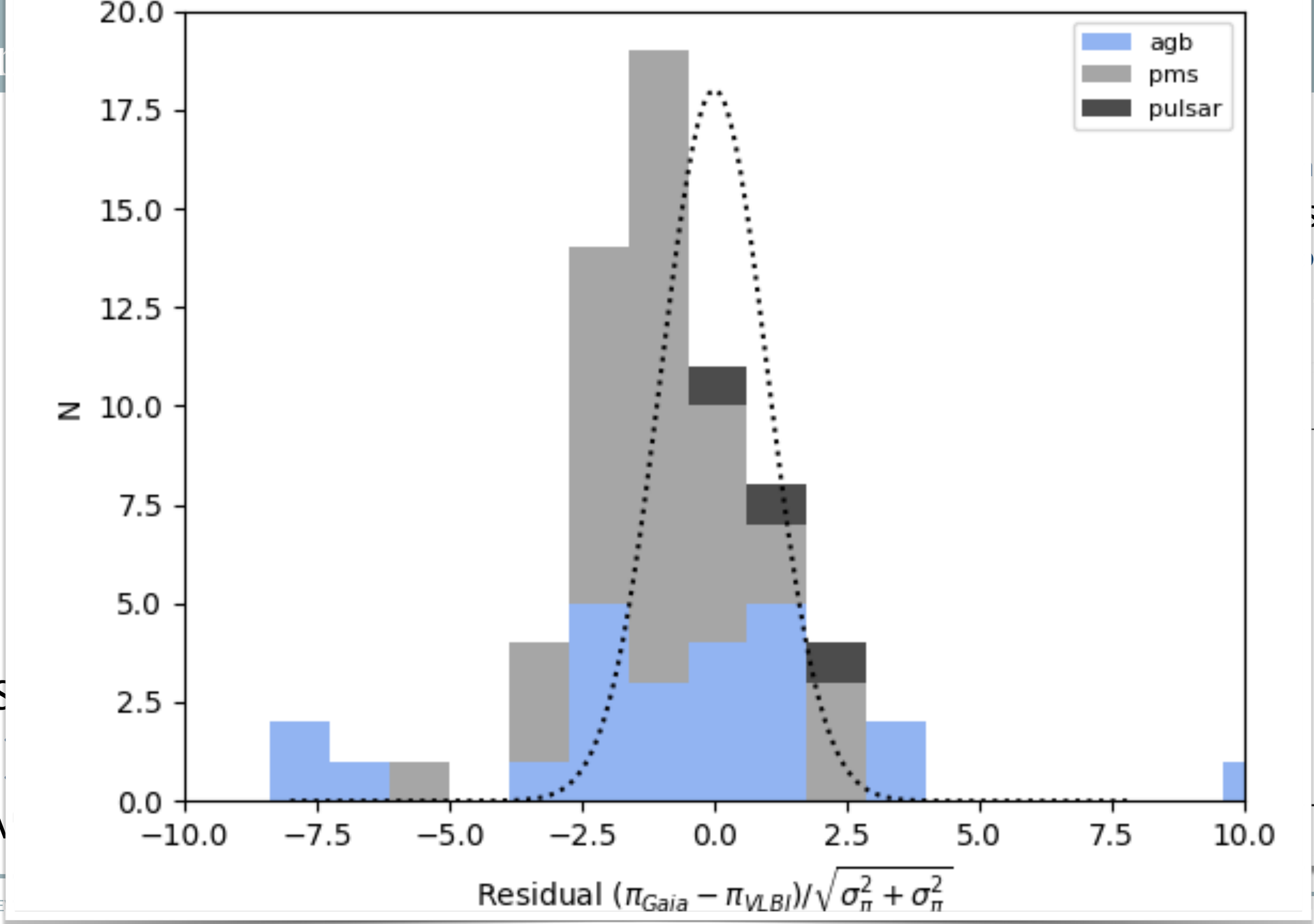
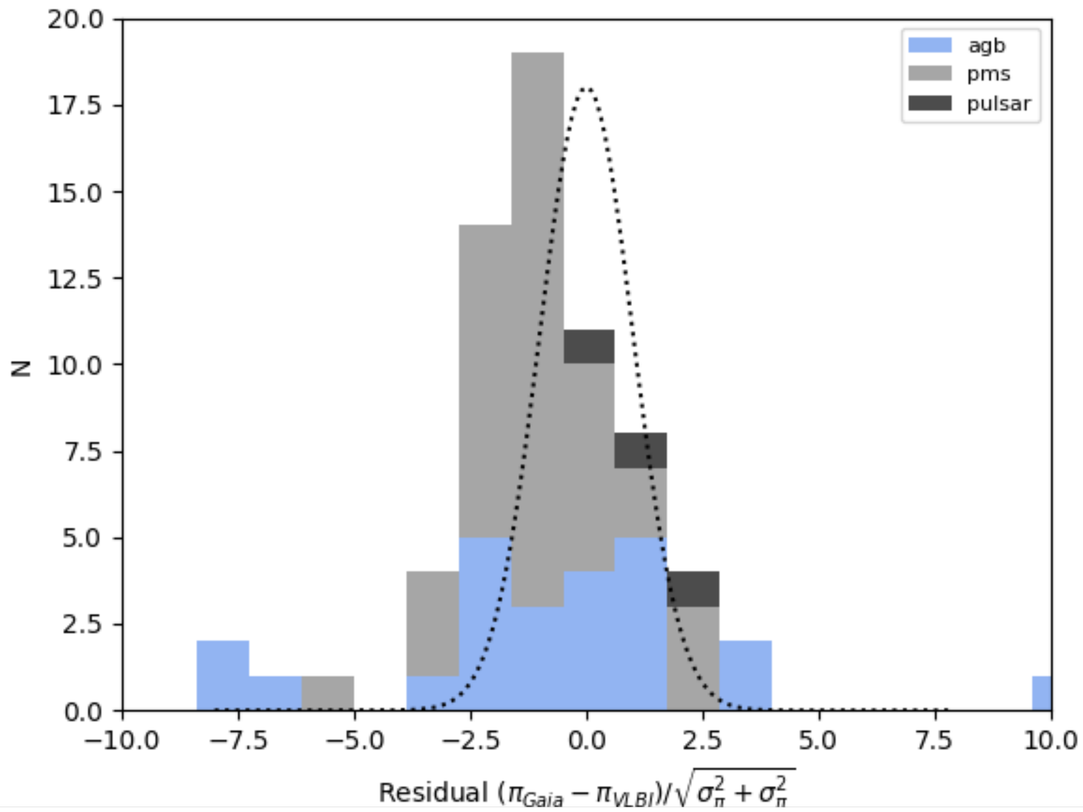


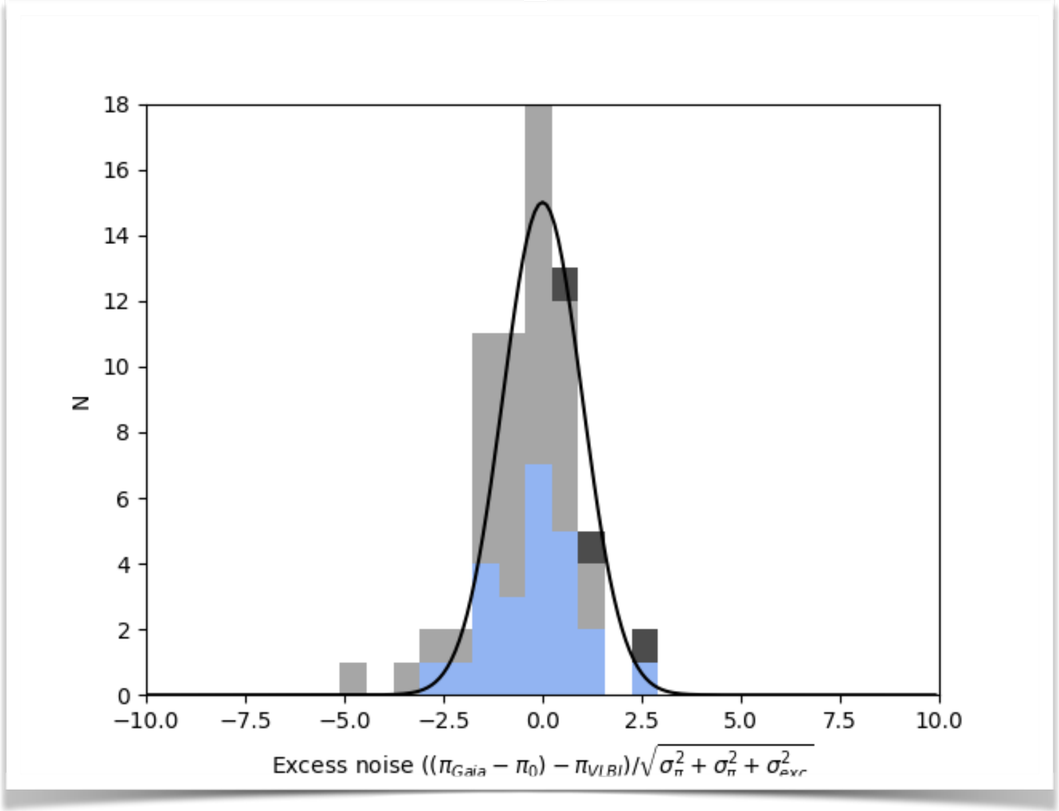

agb
pms
pulsar
N
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0
Residual $(\pi_{Gaia} - \pi_{VLBI})/\sqrt{\sigma_\pi^2 + \sigma_\pi^2}$

Understanding the differences



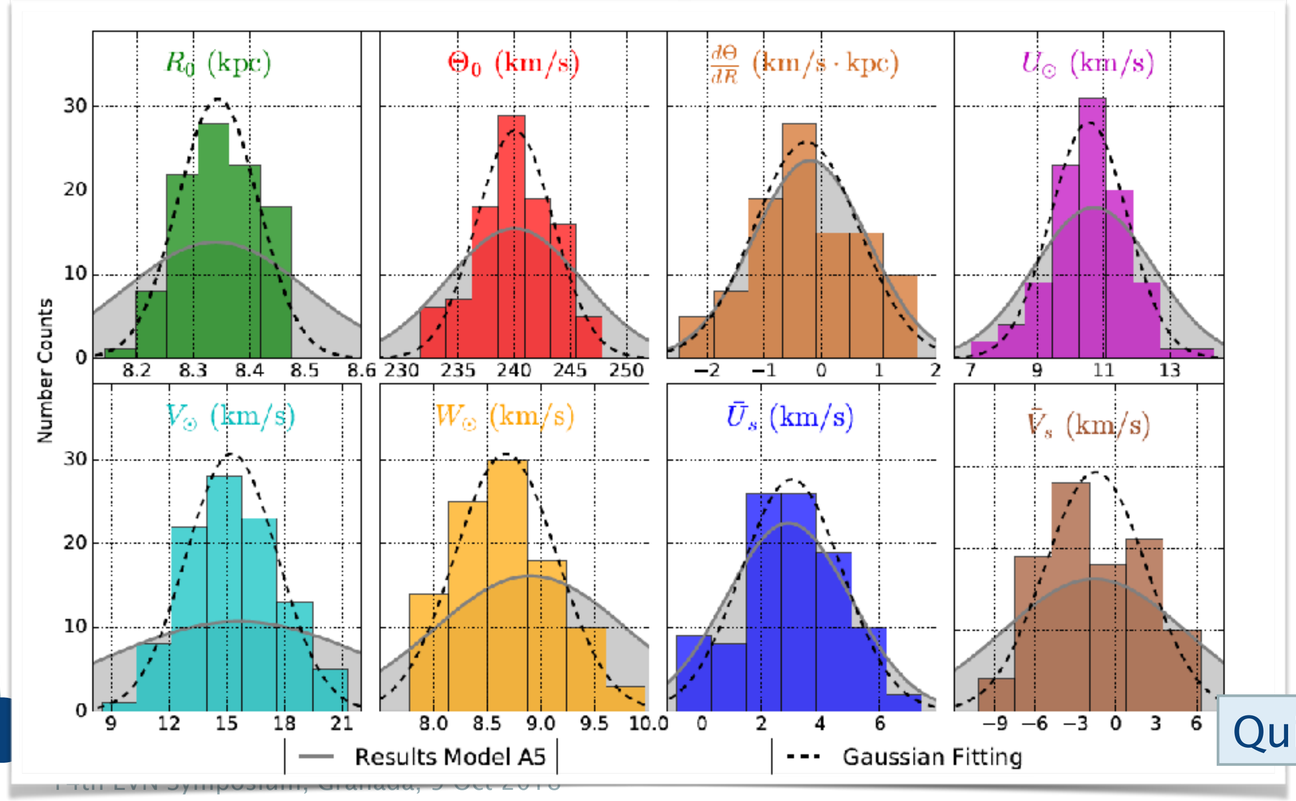
- Statistics seem OK when:
  - Shifting by parallax offset
  - And adding the excess noise
- VLBI parallaxes still valuable

- Gaia zero point offset
  - Quite large when determined from this sample
- Giants have large Gaia residuals
  - Structure and (colour) variability of photosphere
  - Convection related variability (Chiavassa et al. 2018)
- Some stars too bright…

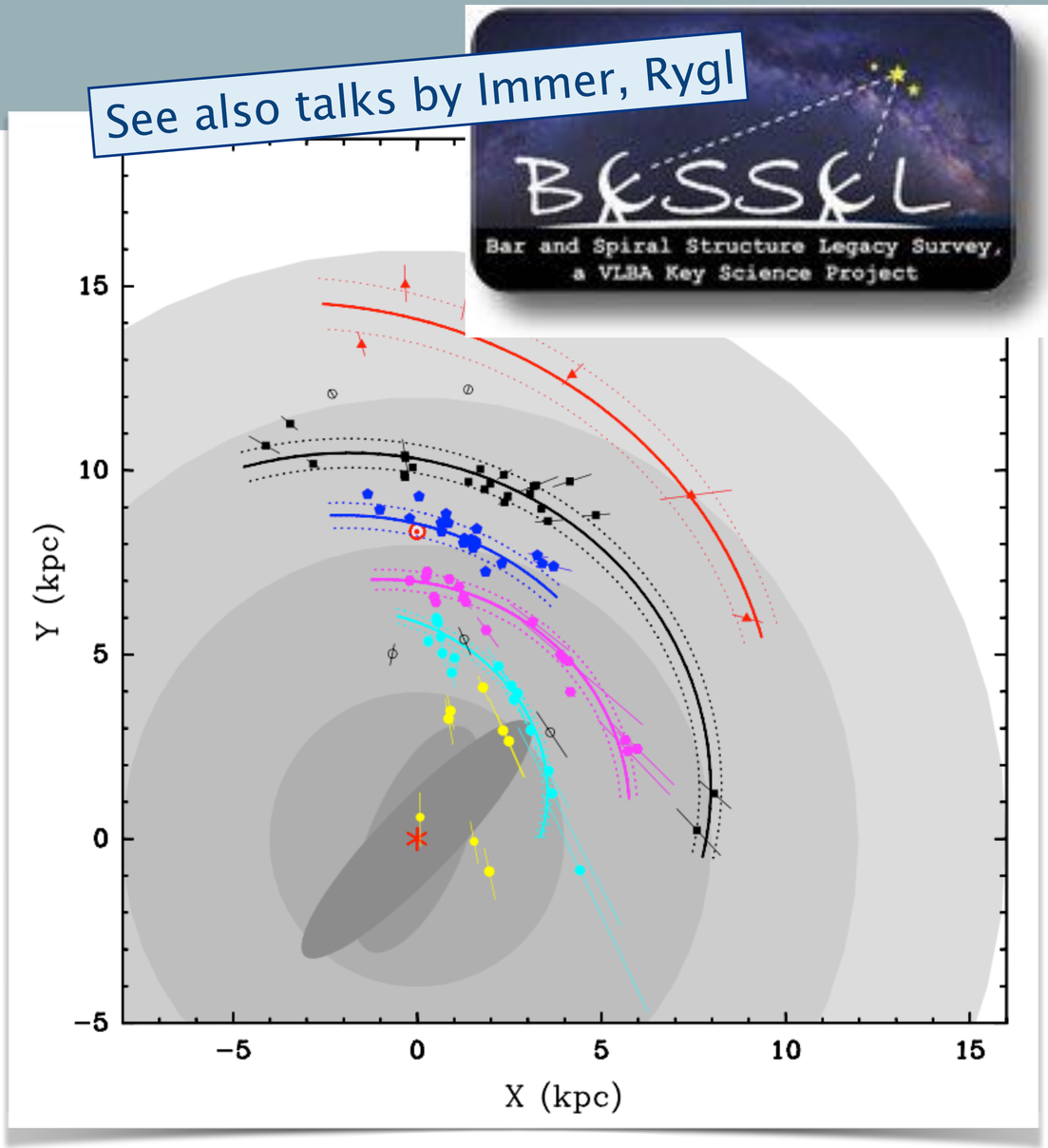


BeSSeL survey

- Progress to improve coverage
  - > 100 new targets
  - Largely with VLBA 6.7 GHz
- Best way to measure MW parameters
  - Demonstrated to bias-free
- Unique for localising spiral arms



See also talks by Immer, Rygl



Quiroga-Nunez et al., 2017

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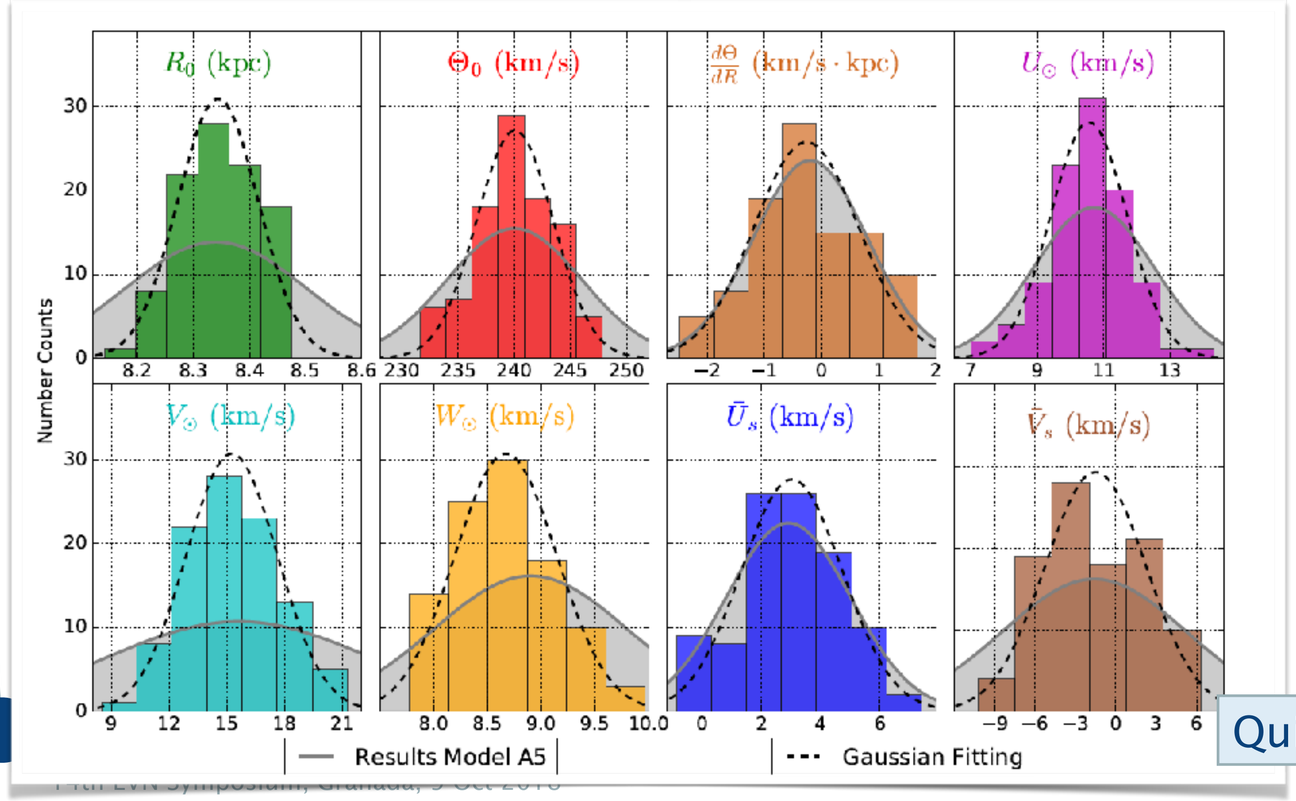

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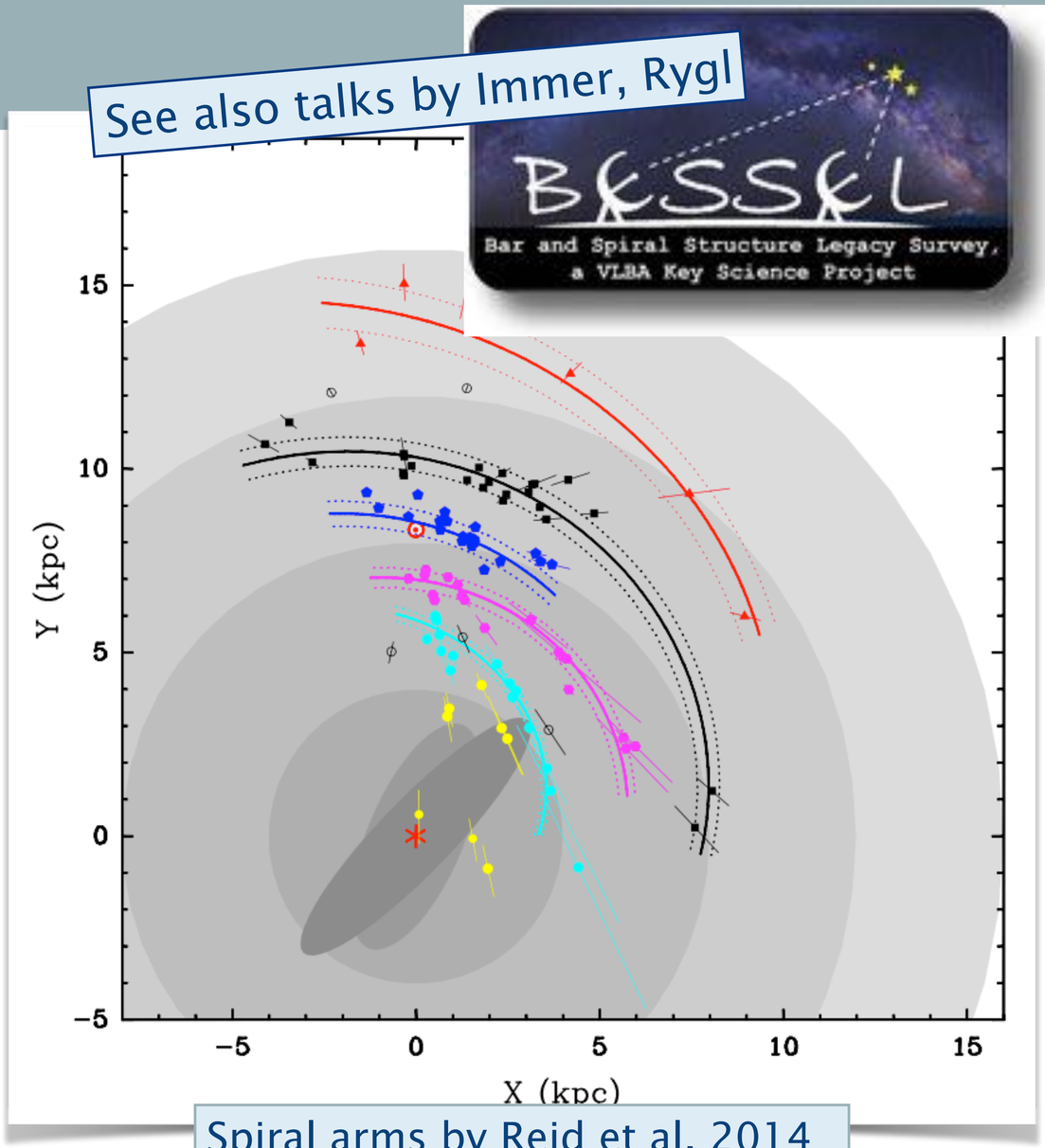
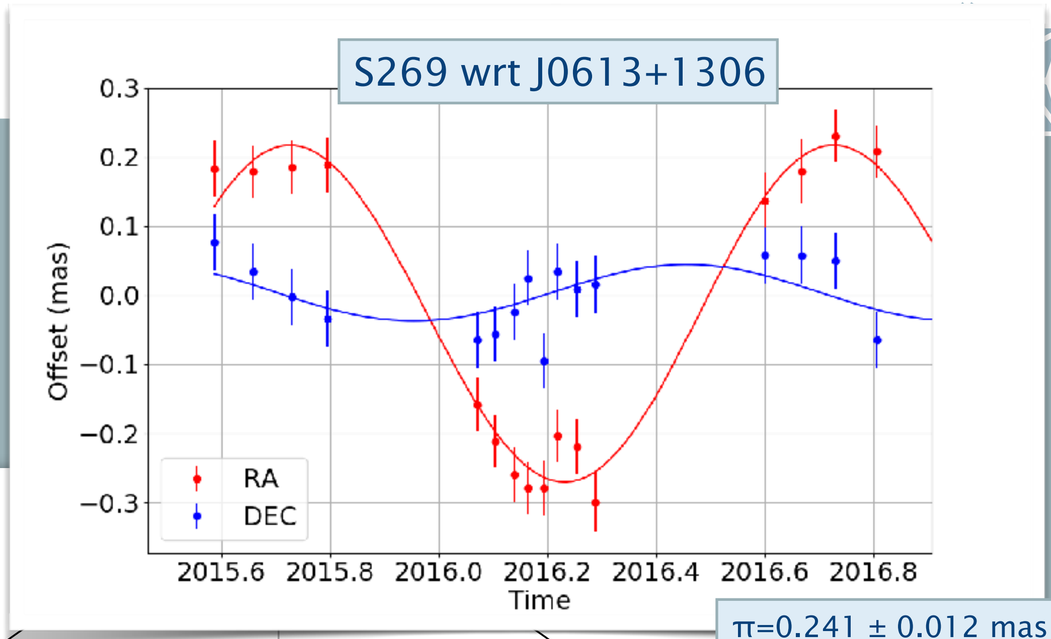


Spiral arms by Reid et al. 2014

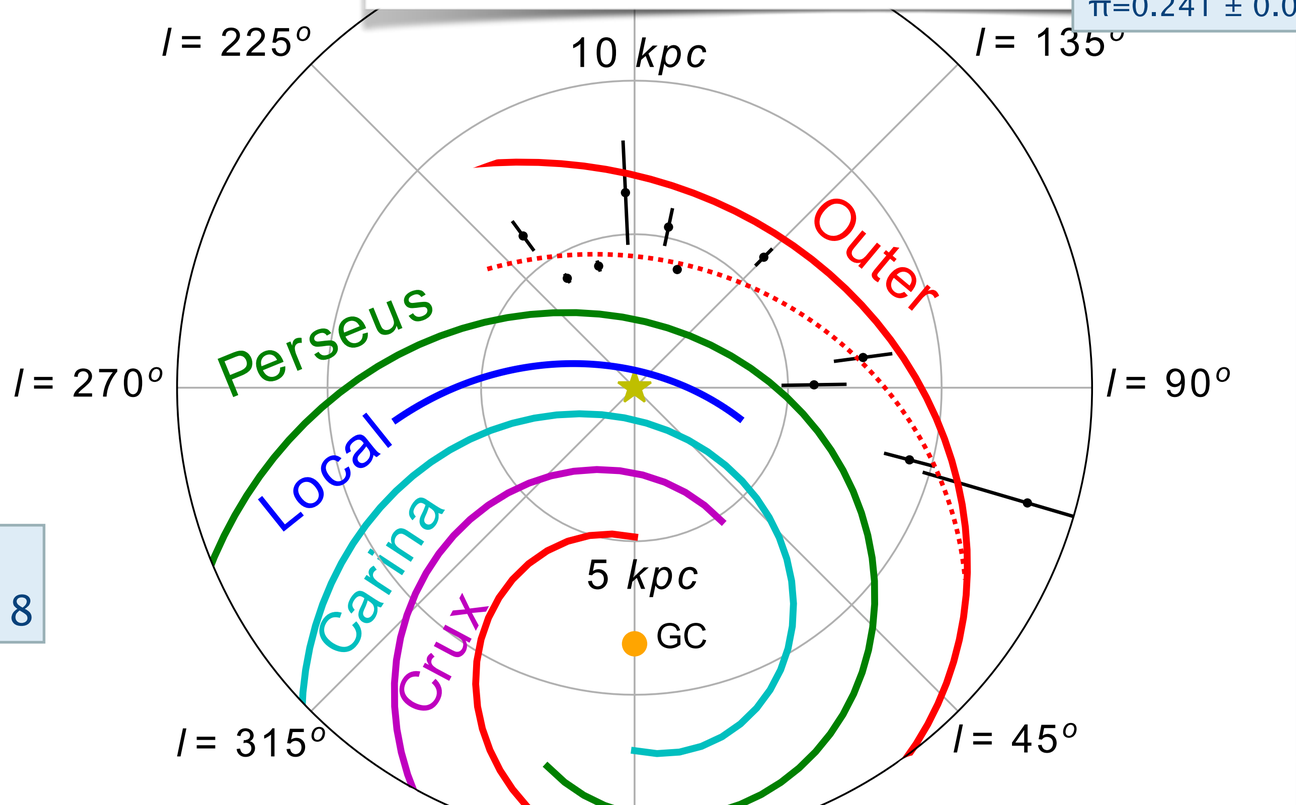
Quiroga-Nunez et al., 2017

BeSSeL source S269

- Recent result with VLBA
  - Previous VERA results controversial
  - Now 12 VLBA epochs and better image fidelity
- Confirming the closer distance
  - Is it in the Outer arm?
  - Is the Outer arm closer than previously thought?



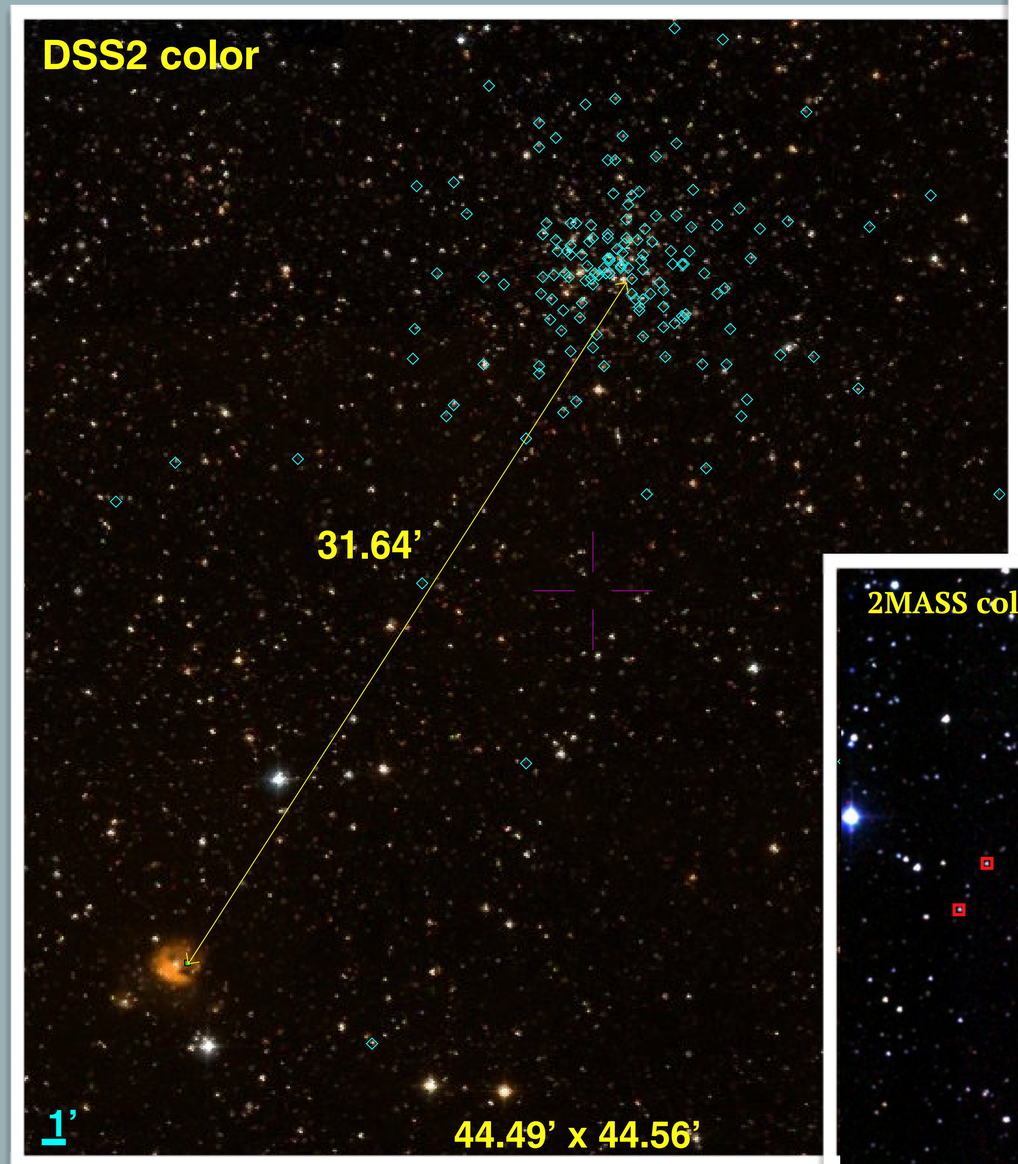
π=0.241 ± 0.012 mas

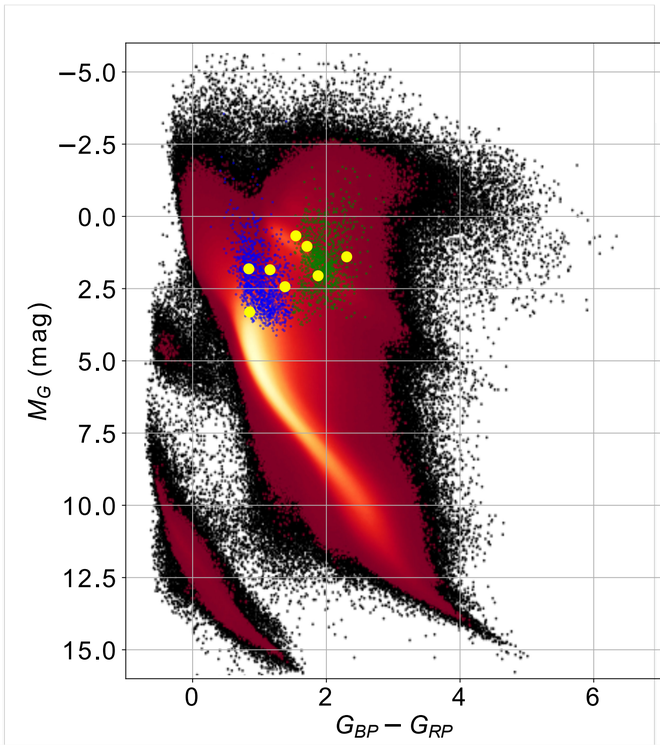


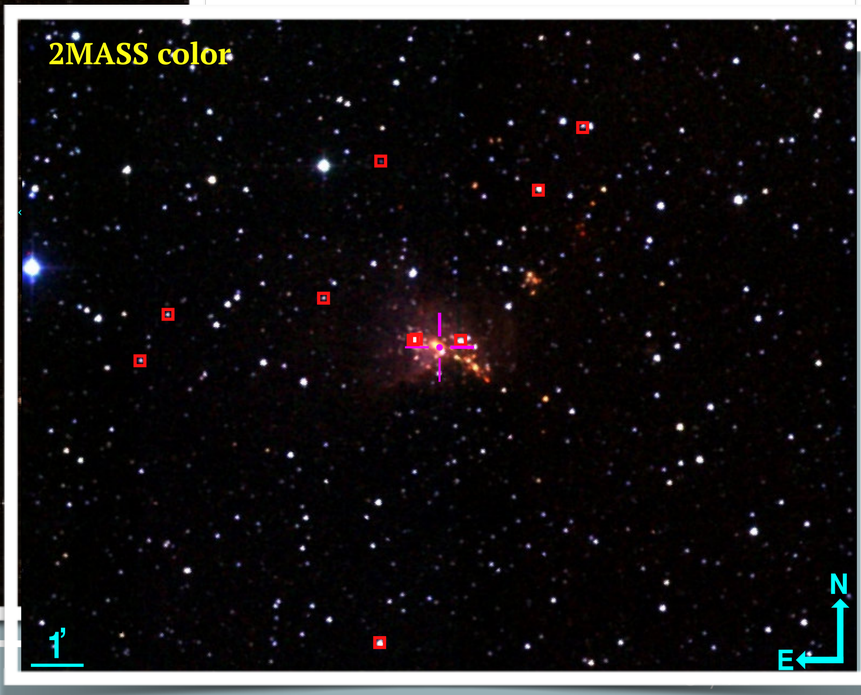
water masers in S269
Quiroga Nunez et al 2018

Associated young stars?

- Next to S269 is NGC 2194
  - Similar distance
  - PM not inconsistent
    - maser motions measured
  - Separated from core of cluster
- But in principle associated stars are expected
  - Can be used to refine distances
  - Maybe even ages

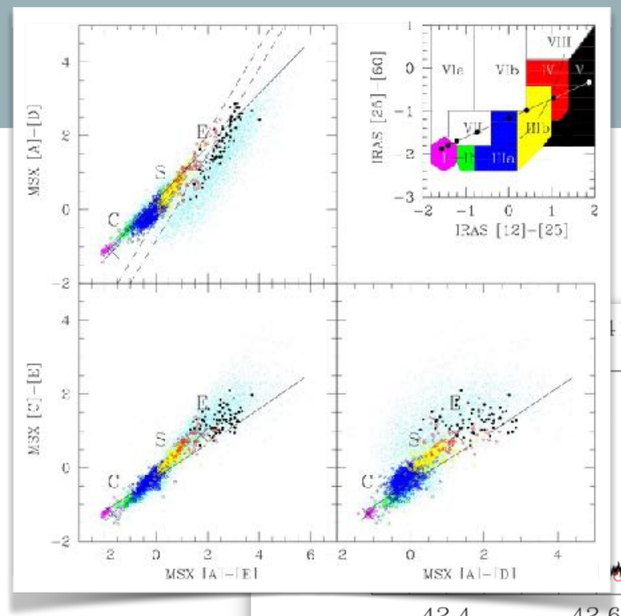


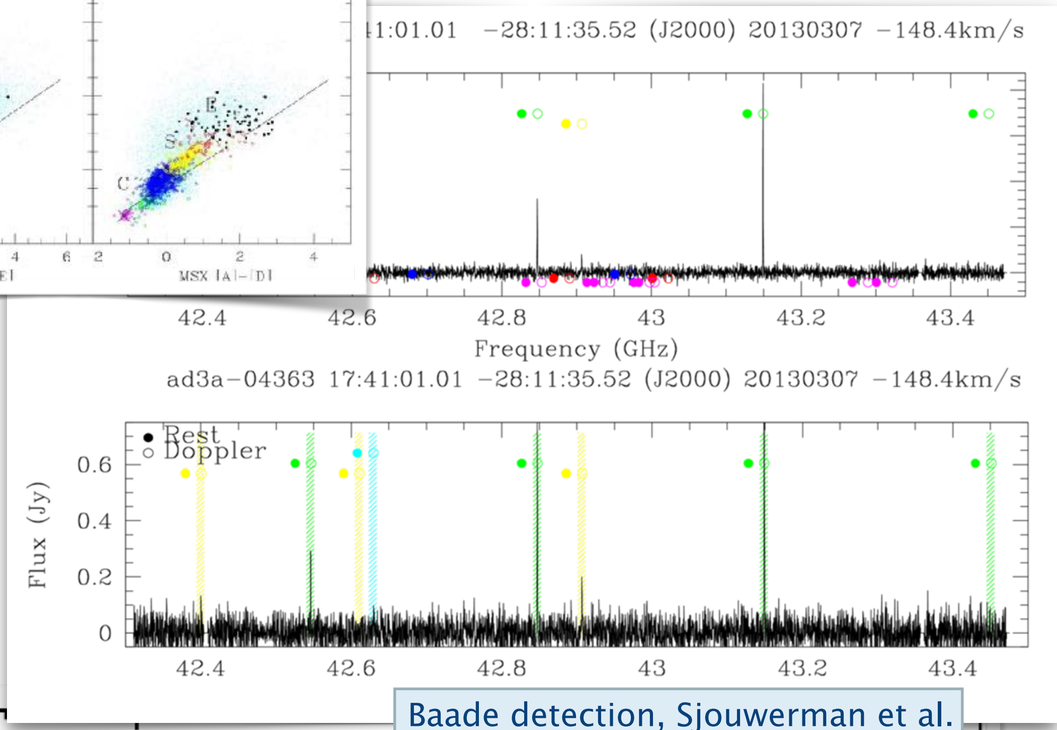




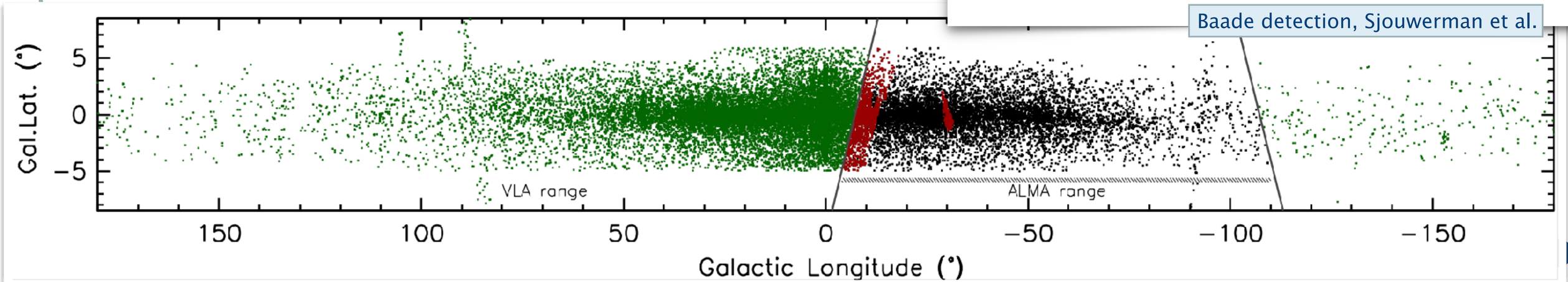
BAaDE project

- Bulge Asymmetries and Dynamic Evolution
  - Going for Mira stars with SiO masers
  - IR selection based on MSX
- Concentrated on |b| < 5º
  - No optical data, but kinematics of bar
- 30,000 targets
  - VLA 19.000 observations complete
    - Very fast detection experiment
    - No time for phase calibration
  - ALMA ongoing



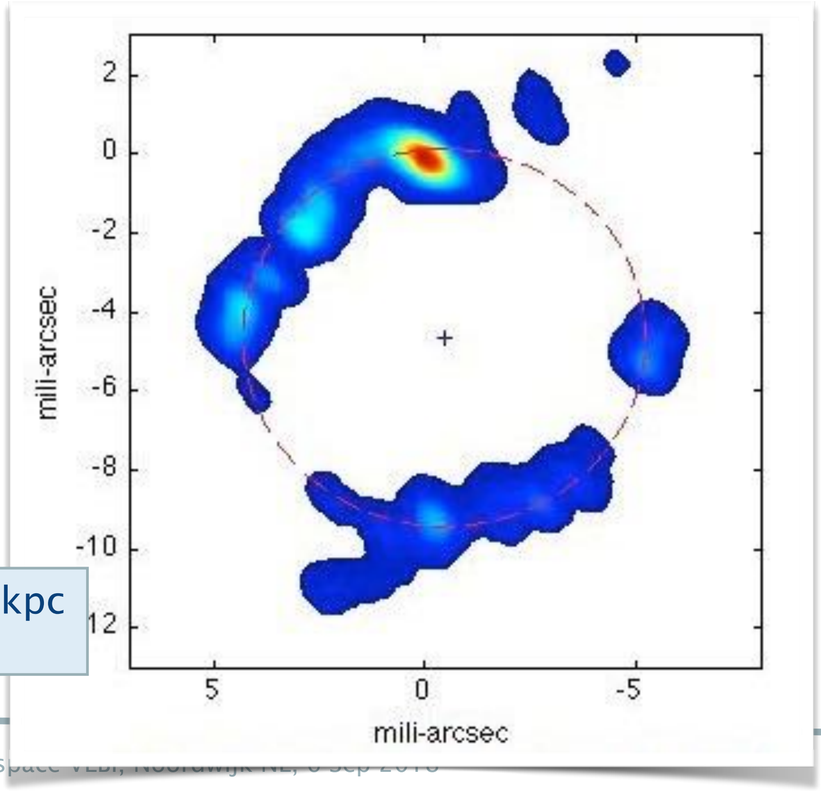


Baade detection, Sjouwerman et al.



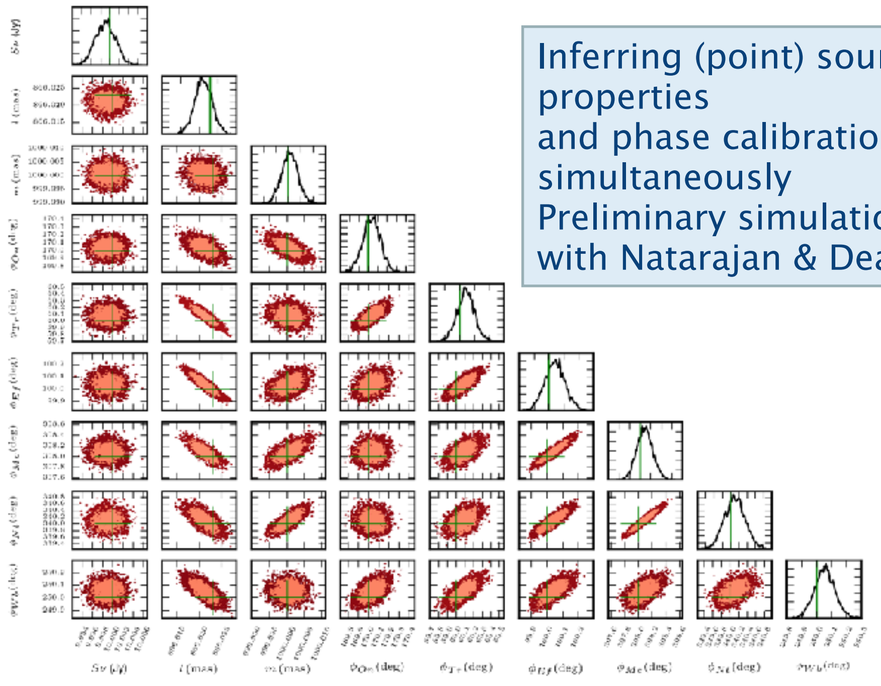
So, you want to do SiO astrometry?

- Current practice of cross-calibration
  - Coherence time short
  - Calibrators weak and few
  - Region of interest is central Galaxy, low dec
  - A-priori positions poor
  - SiO masers close to stars and variable
- Do 100–200 stars in the bar?



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

- Addressing these limitations:
  - Test observations with various parameters
  - Calibrator surveys
  - Explore non-imaging astrometry
  - Consider K/Q cross calibration?

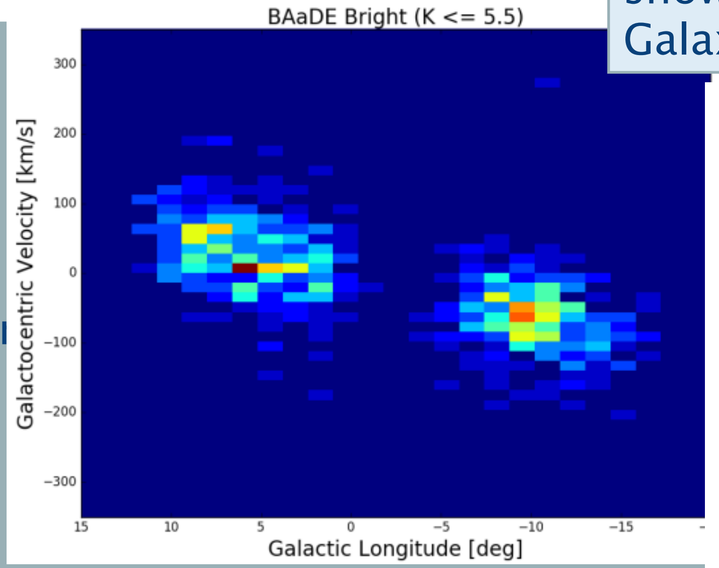


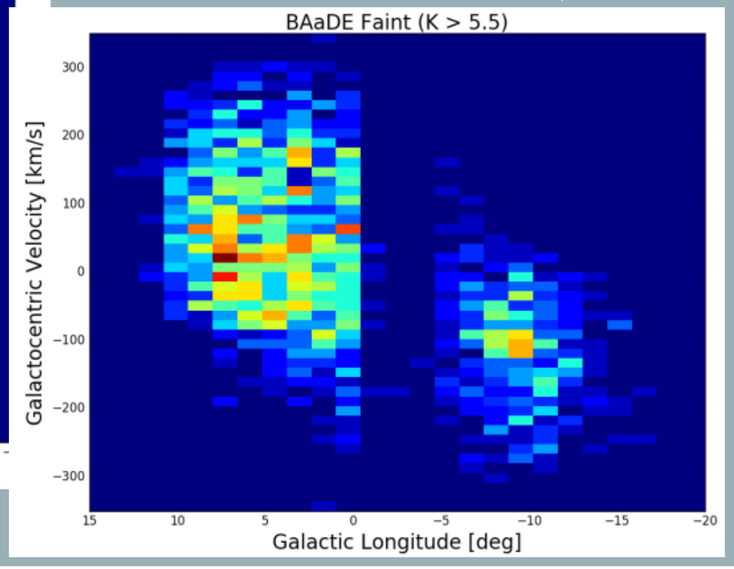
Inferring (point) source properties
and phase calibration simultaneously
Preliminary simulations with Natarajan & Deane

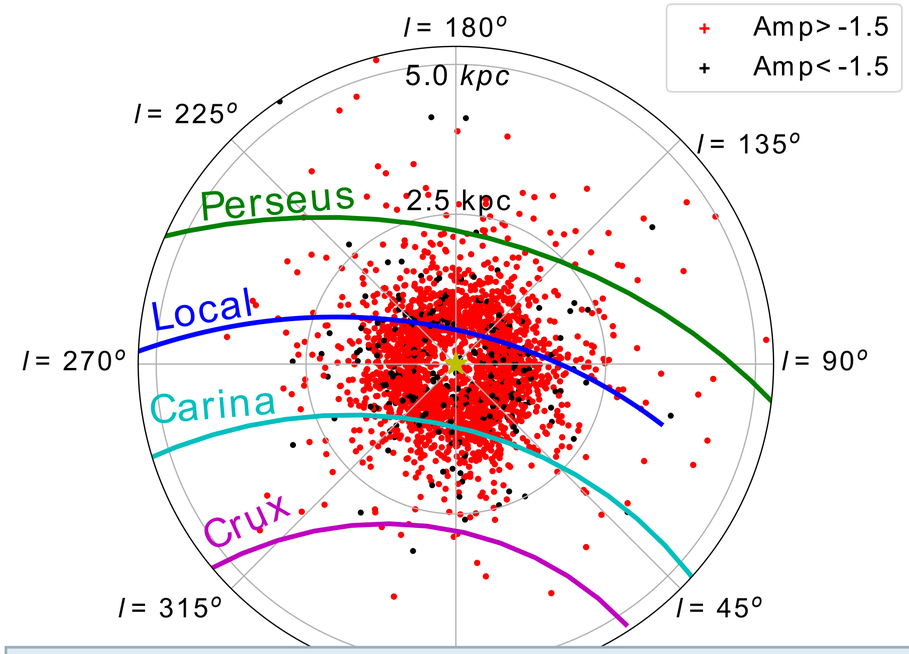
View on inner Galaxy

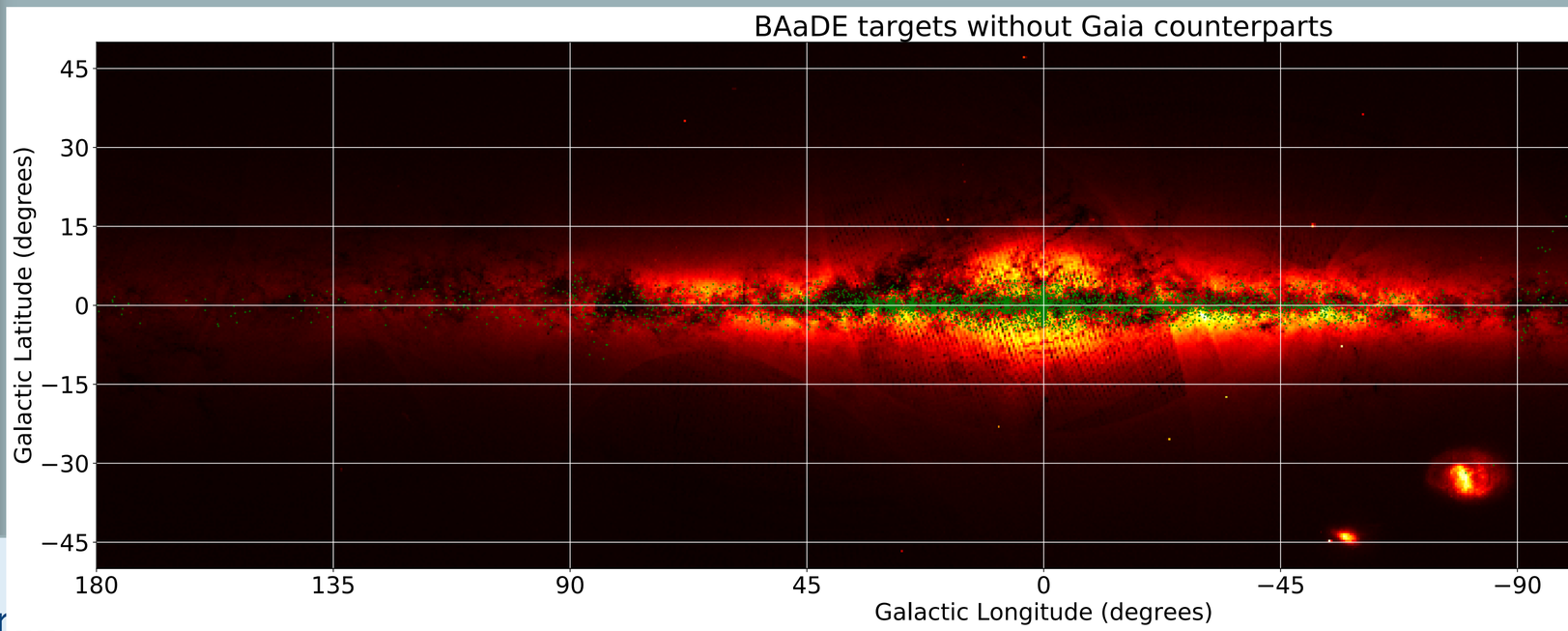
- BAaDE samples disk and bar
  - Kinematics & population analysis
- Cannot be reached by Gaia
  - But overlap Gaia - BAaDE sample can constrai

l-v diagram of preliminary sample shows 2 stellar populations in inner Galaxy. Trapp et al. 2018 ApJ



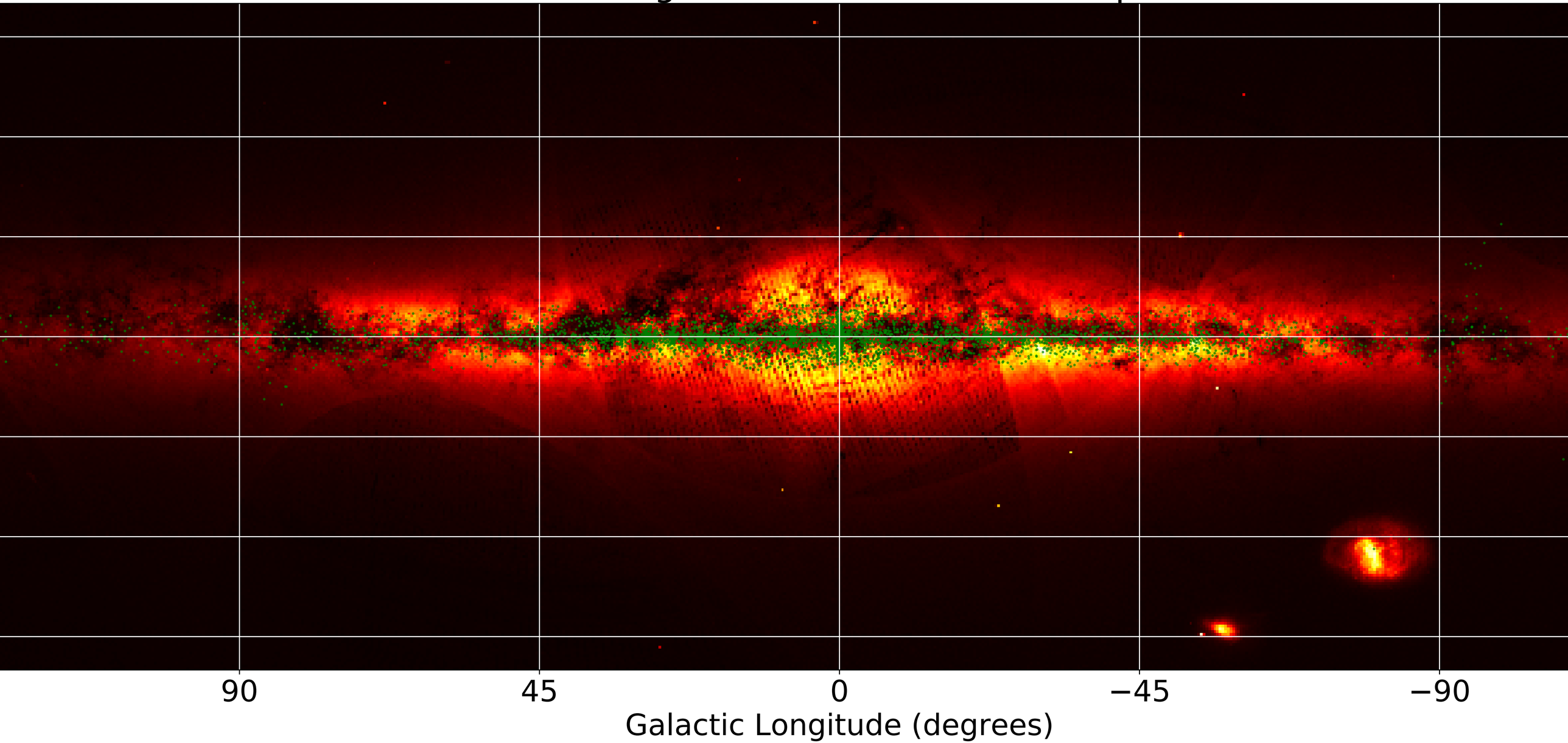






SiO maser candidates identified in Gaia DR2 with accurate distances Quiroga-Nunez in prep

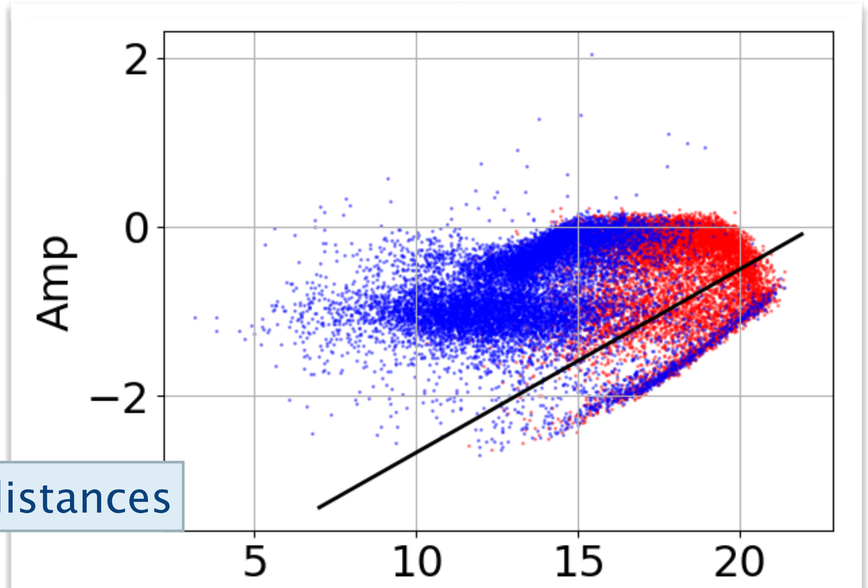
BAaDE targets without Gaia counterparts



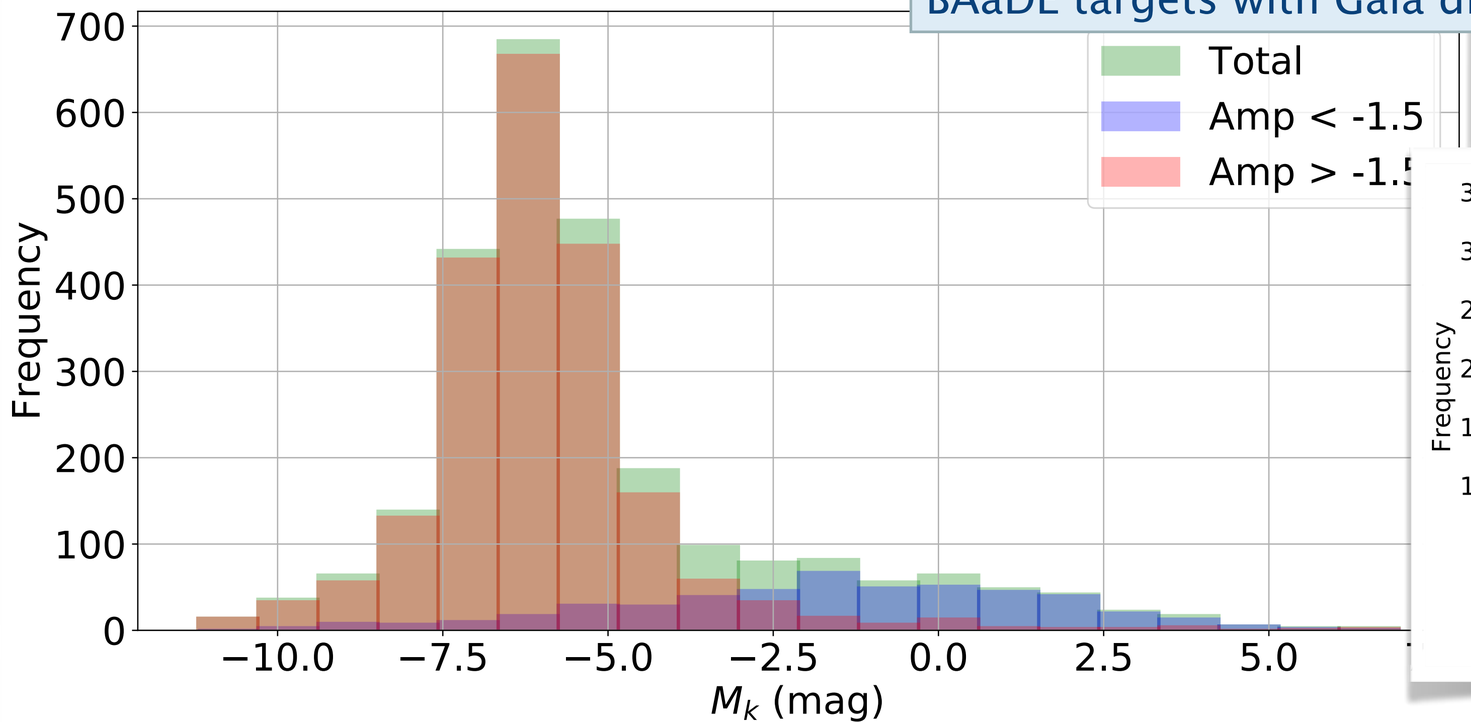
SiO maser candidates identified in Gaia DR2
with accurate distances Quiroga-Nunez in prep

Work in progress: characterising population

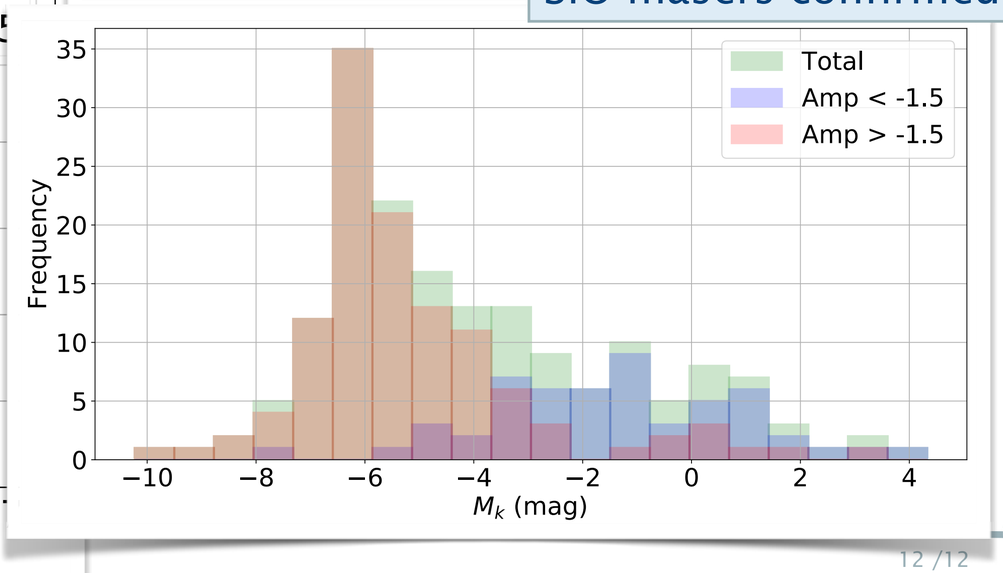
- From 28,000 targets
  - 20,000 have 2Mass, Gaia counterpart
    - But must include some false positives
  - 2,554 have $\sigma_\pi/\pi < 0.2$
  - Of which 172 have SiO masers detected
- So far consistent with LPV AGB stars
  - As expected
  - Towards progenitor mass and age



BAaDE targets with Gaia distances



SiO masers confirmed

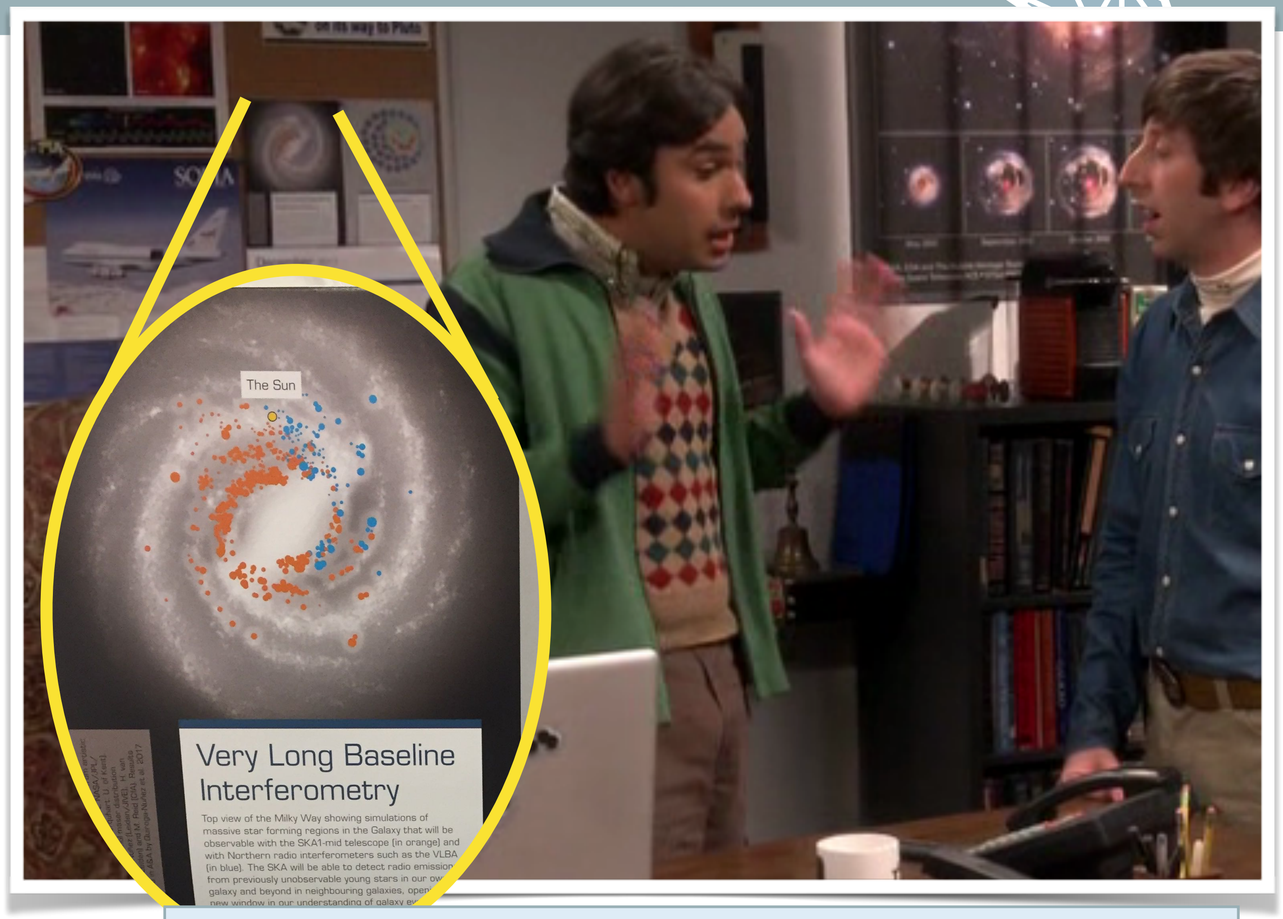


Future

- New telescopes can improve VLBI:

- High mass star forming regions
  - Southern hemisphere campaigns (AuScope)
  - African VLBI Network developments
    - Refurbished communication dishes
  - SKA1-Mid will have VLBI capabilities
    - And receiver (band 5) for methanol (and water)
    - Major improvements in SNR and calibrator coverage

- Evolved stars
  - VERA important for water masers
  - Simultaneous water and SiO masers on Korean telescopes
  - SiO masers on VLBA to be tested
    - progress with mm VLBI
    - may be targets for ngVLA long baselines



BeSSeL simulations featured on the SKA calendar on display in dr. Koothrappali's office (Quiroga-Nunez et al., 2017)

Credit to Luis-Henry Quiroga-Nuñez

Synergy VLBI — Gaia

- previous VLBI astrometry OK
  - Gaia errors not trivial for AGB stars
- VLBI measuring spiral structure
  - And overall MW parameters
- May reach inner Galaxy kinematics
  - Gaia valuable for characterising population
- AVN & SKA will contribute