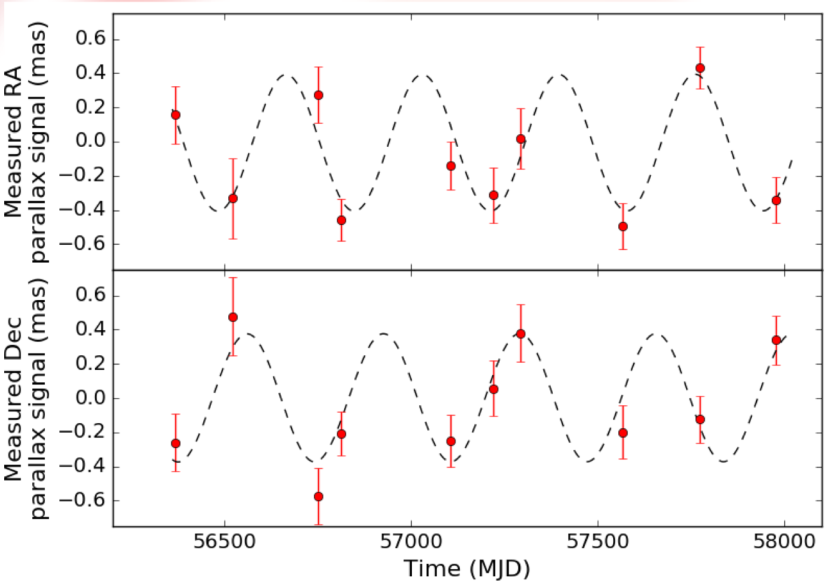


International Centre for Radio Astronomy Research

Astrometry of compact objects

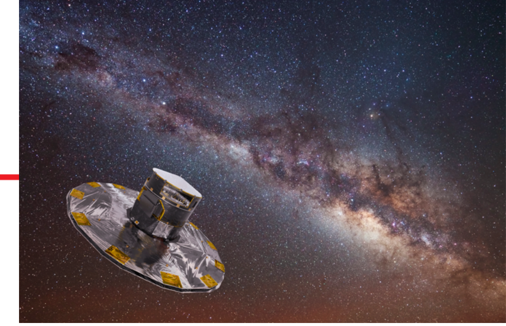
James Miller-Jones

ICRAR – Curtin University

Curtin University

The University of Western Australia

Why astrometry?

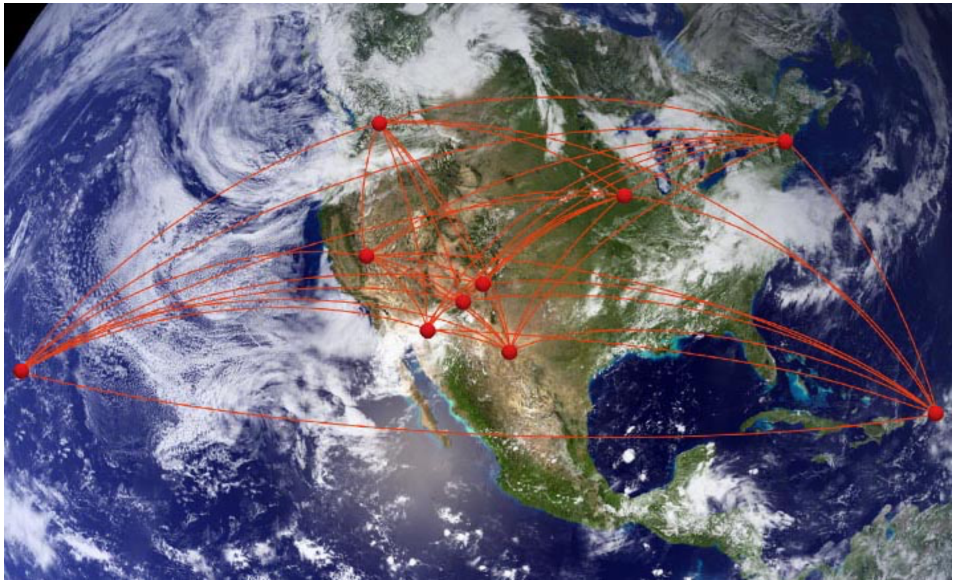


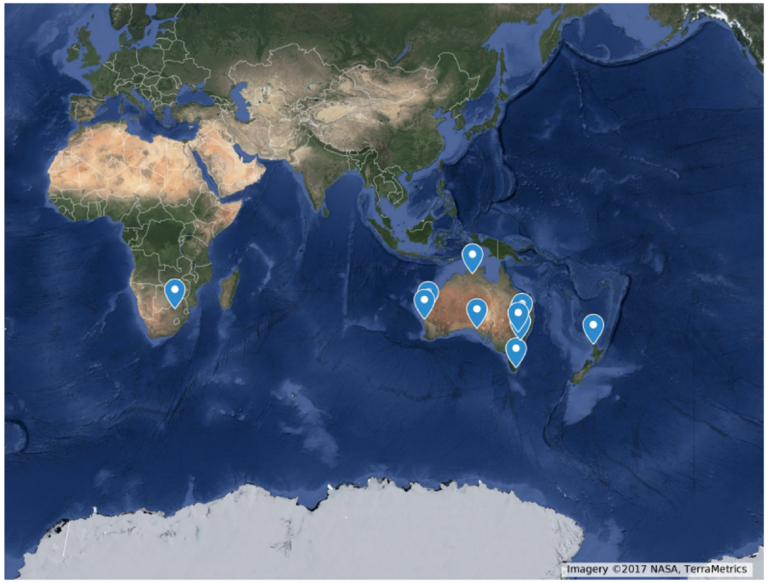
Fundamental physical parameters

- XRB jets and pulsars are unresolved astrometric targets

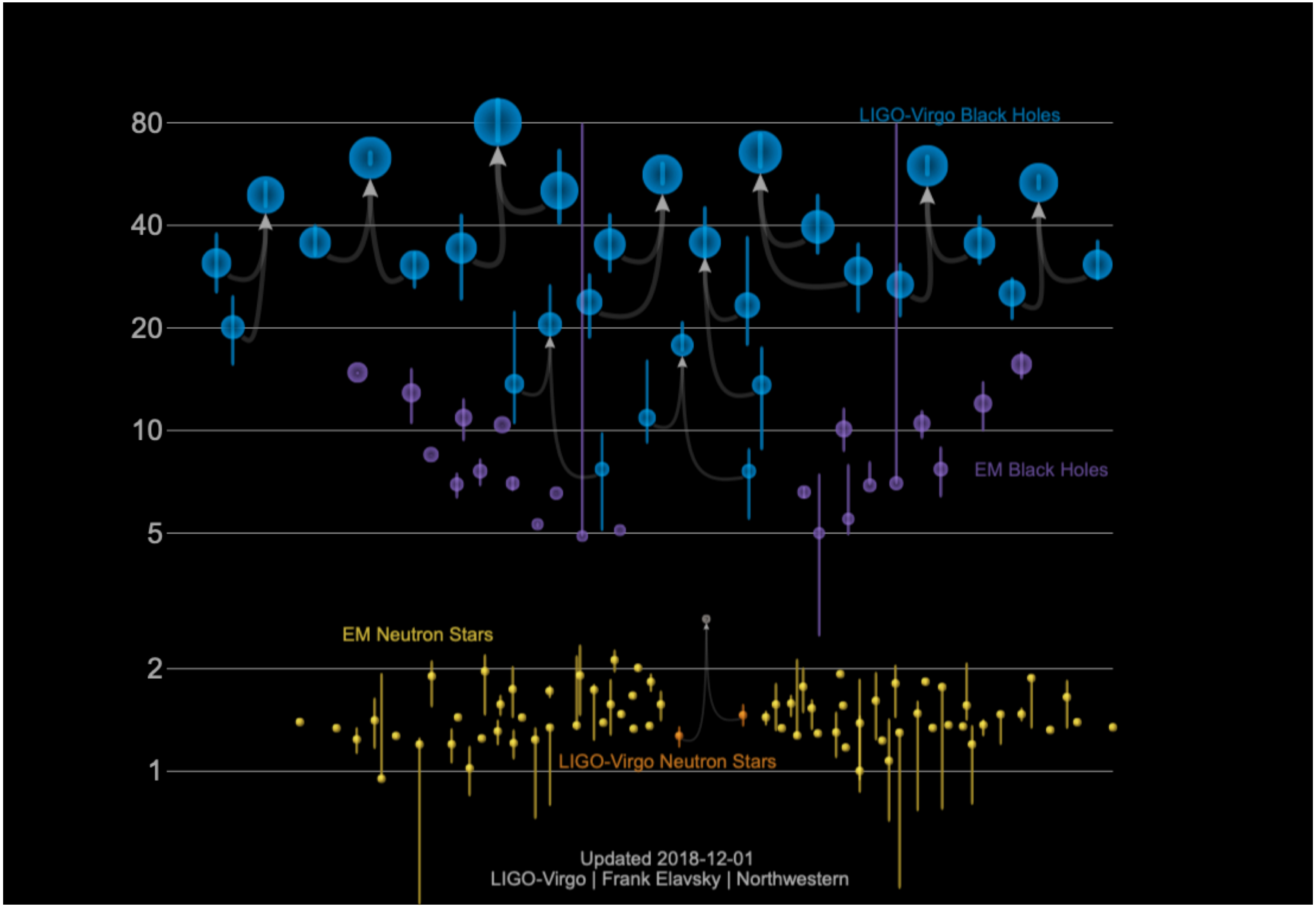
Easier ↓ Harder

  - *Proper motion*: Natal kicks and formation mechanisms
  - *Parallax*: Model-independent distances
  - *Residuals*: Jet size scales
  - *Orbital motion*: Component masses





Key science questions

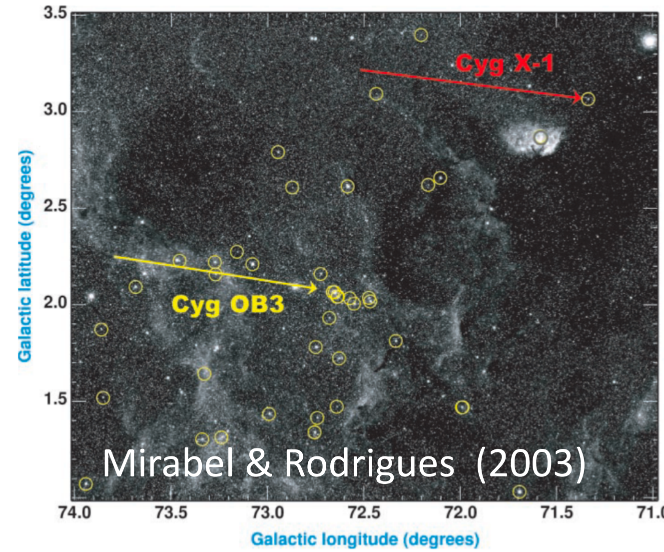


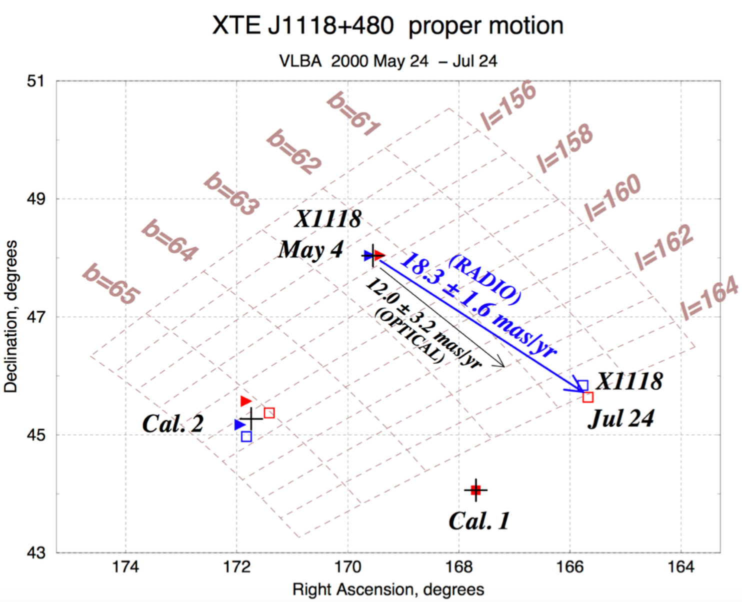
Natal kicks and black hole formation

Supernova or direct collapse?

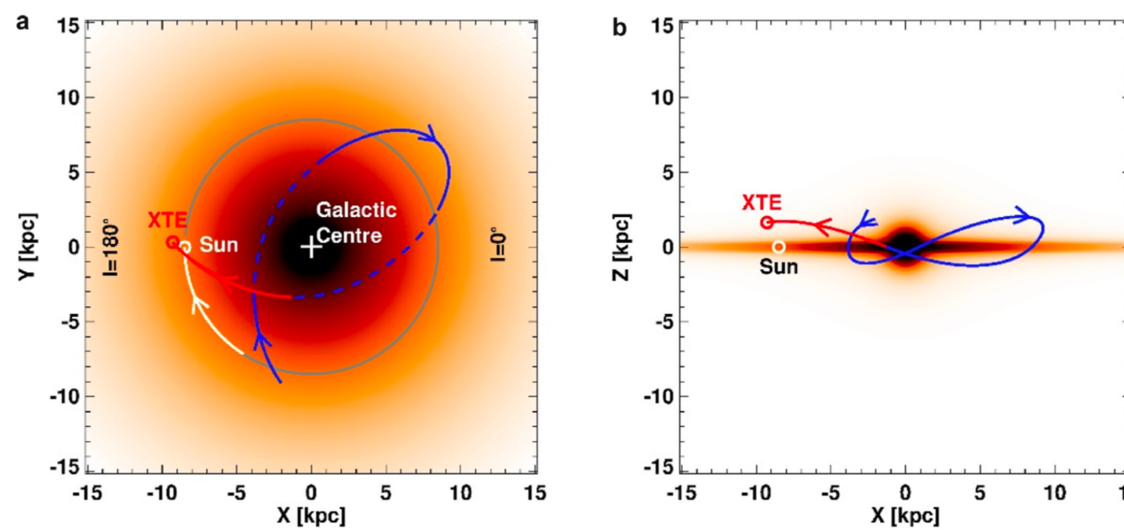
Recoil or asymmetric kicks?

- Full 3D space velocity
  - Proper motions (astrometry)
  - Radial velocities (OIR spectra)
  - Distances (parallax)





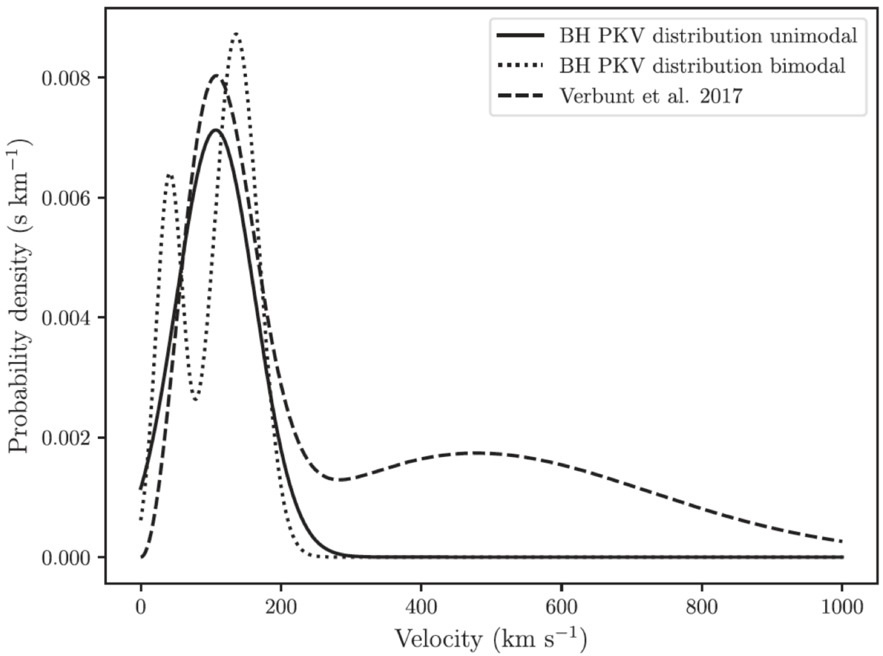
Mirabel et al. (2001)



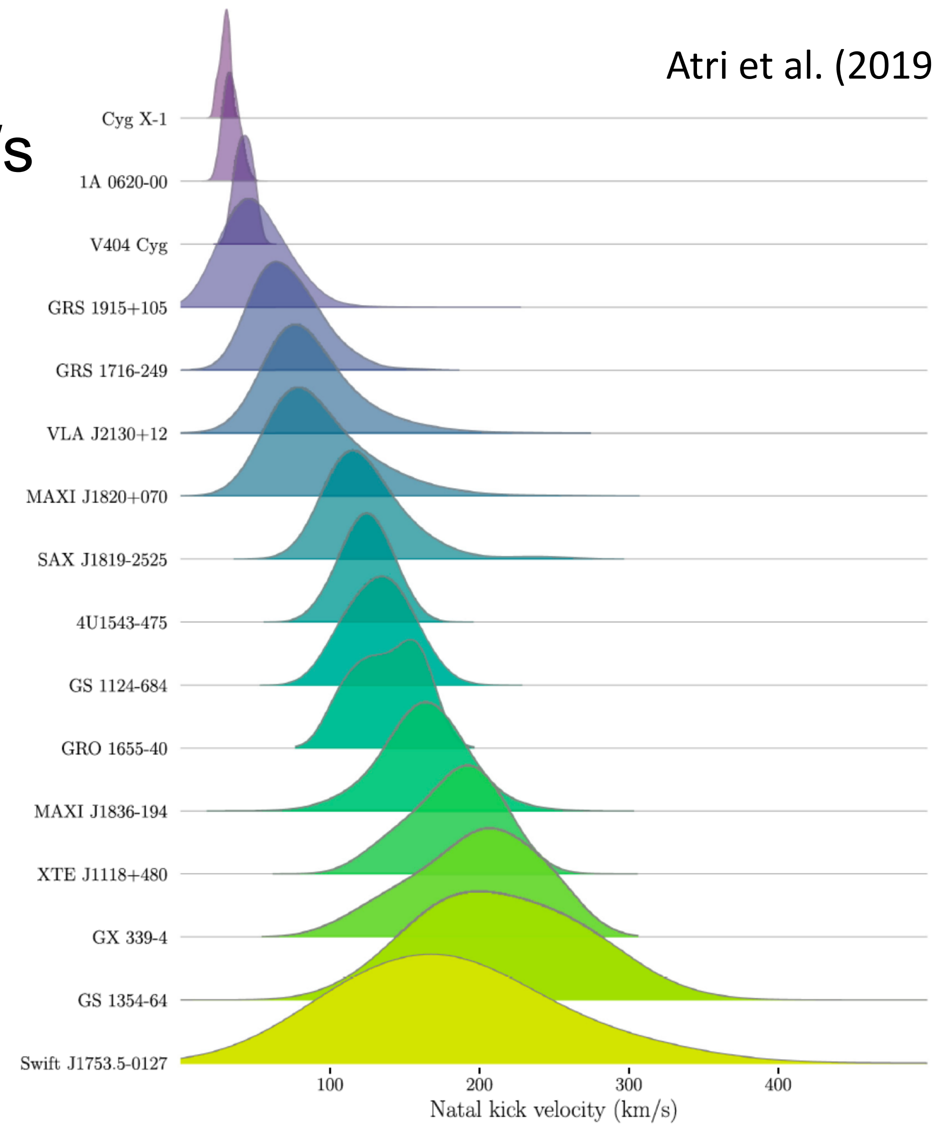
Natal kicks and black hole formation

Kick distribution PDFs

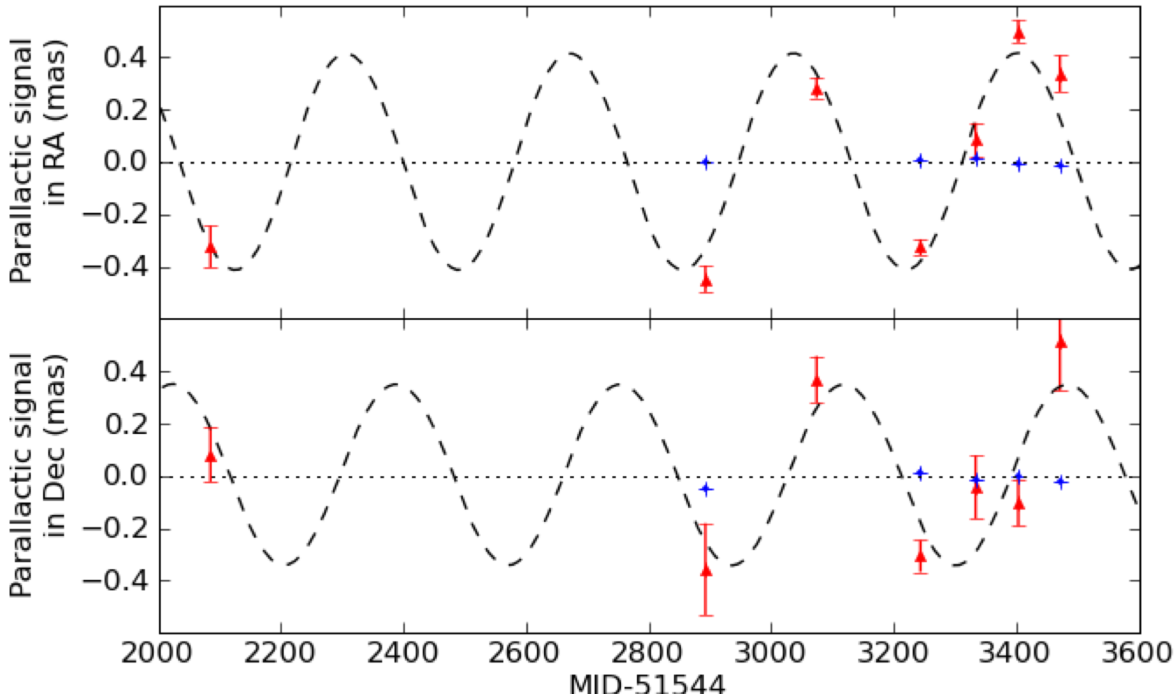
- 16 BHXRBs, <v>=107 km/s
- Globular cluster ejection
- Field binary disruption
- Merger sites
- Spin alignments

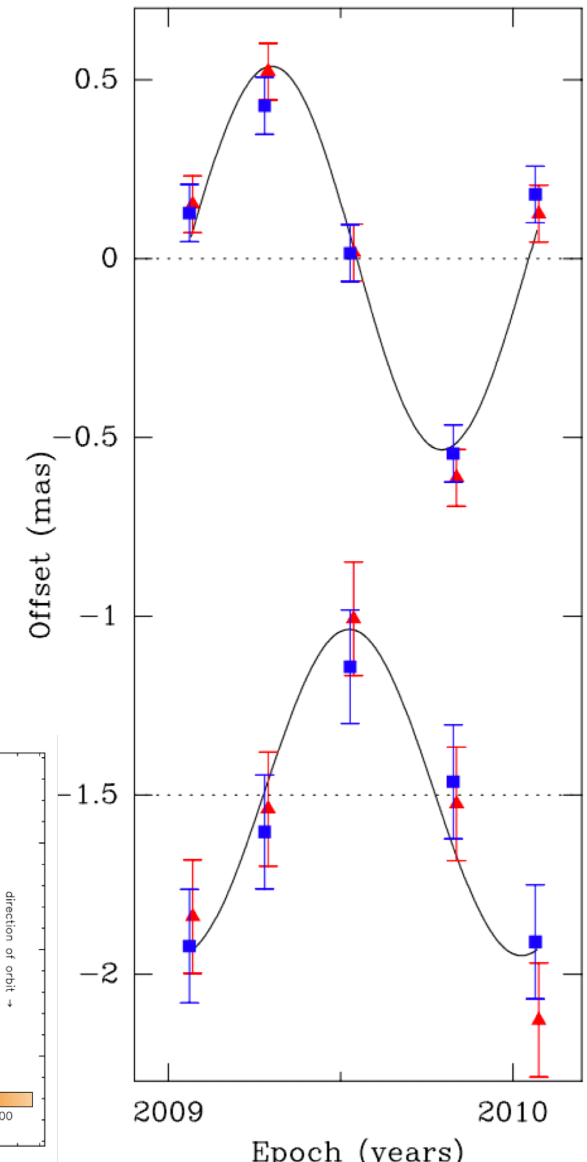


Atri et al. (2019)

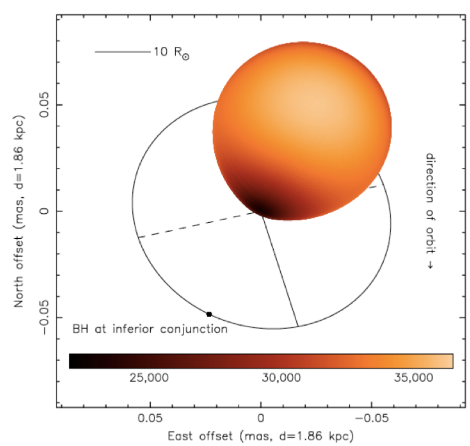


Parallax: model-independent distances





V404 Cygni: 2.39 ± 0.14 kpc
Miller-Jones et al. (2009)

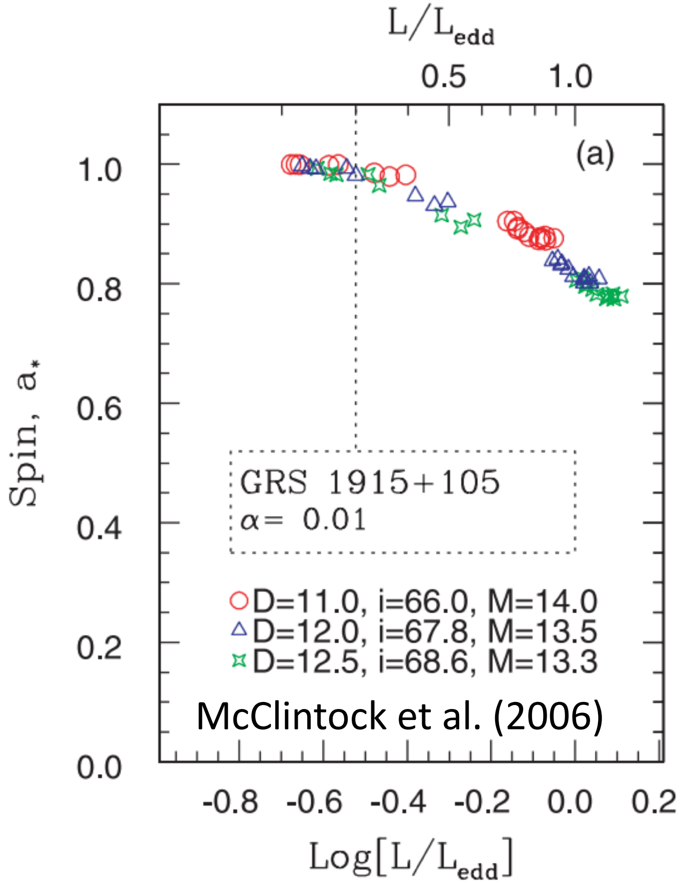


Cyg X-1: 1.86 ± 0.12 kpc
Reid et al. (2011)

Solve for system parameters
Orosz et al. (2011)

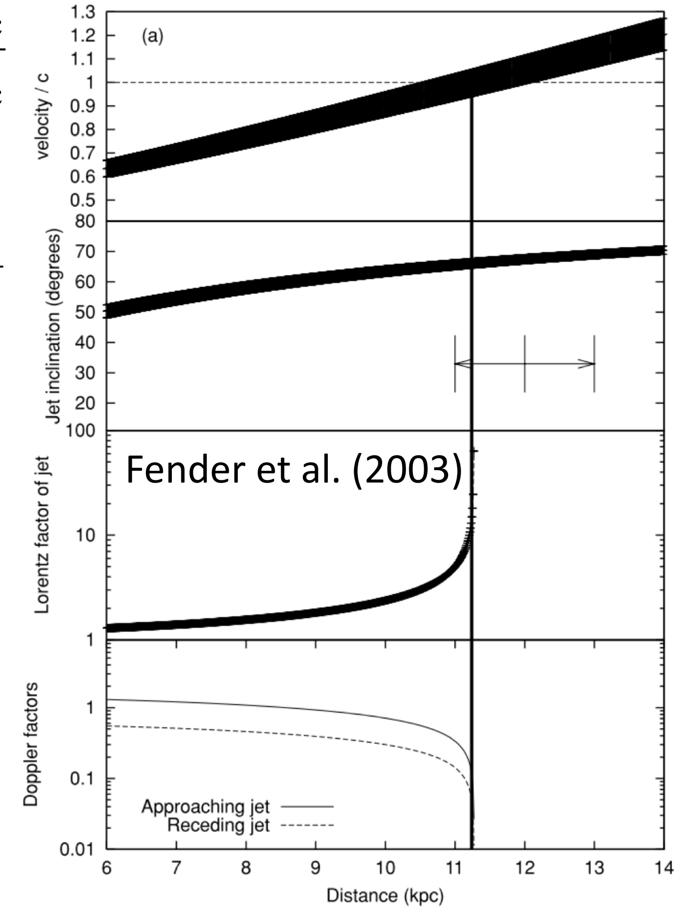
Accurate system parameters

Distances help constrain spins, masses, jet speeds



$$\beta \cos i = \frac{\mu_{\rm app} - \mu_{\rm rec}}{\mu_{\rm app} + \mu_{\rm rec}}$$

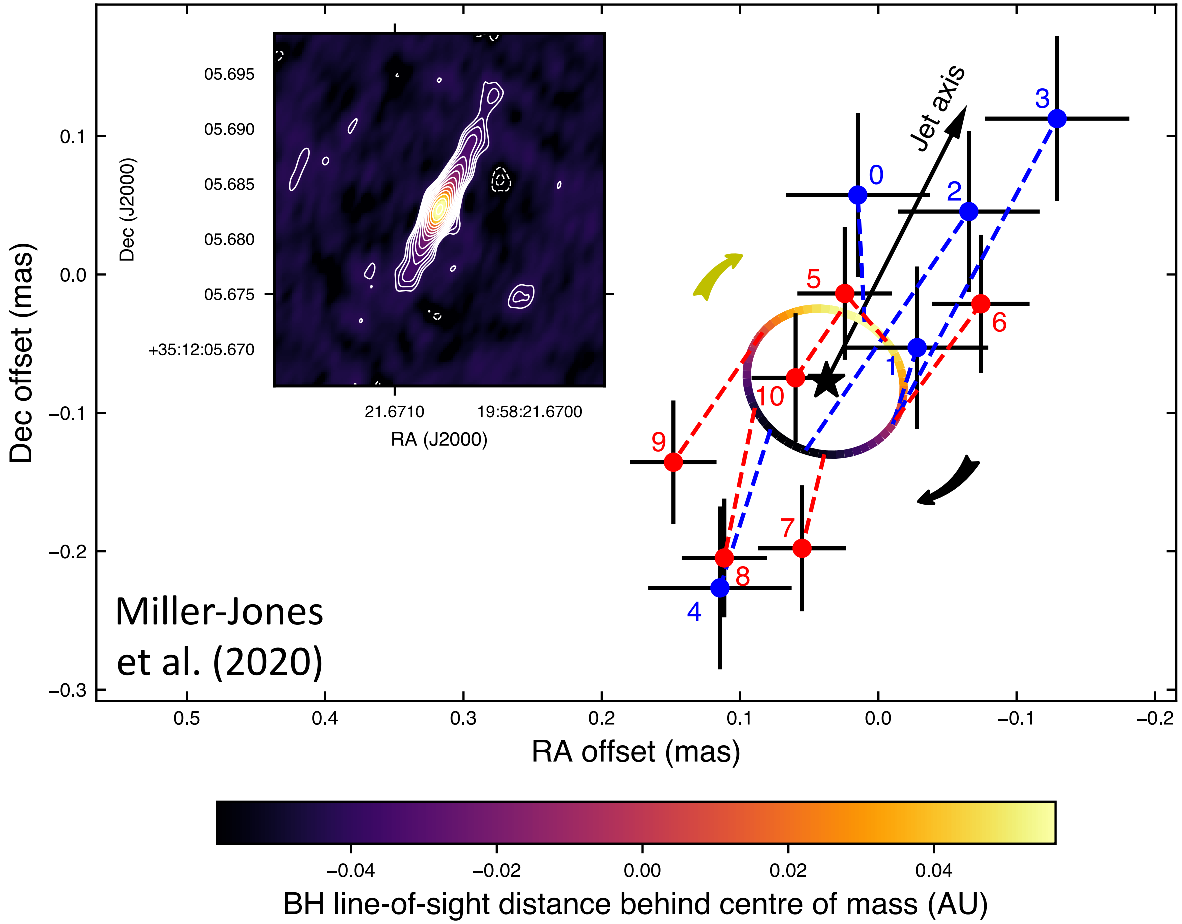
$$\tan i = \frac{2d}{c} \frac{\mu_{\rm app}\mu_{\rm rec}}{\mu_{\rm app} - \mu_{\rm rec}}$$



Measuring orbital motion

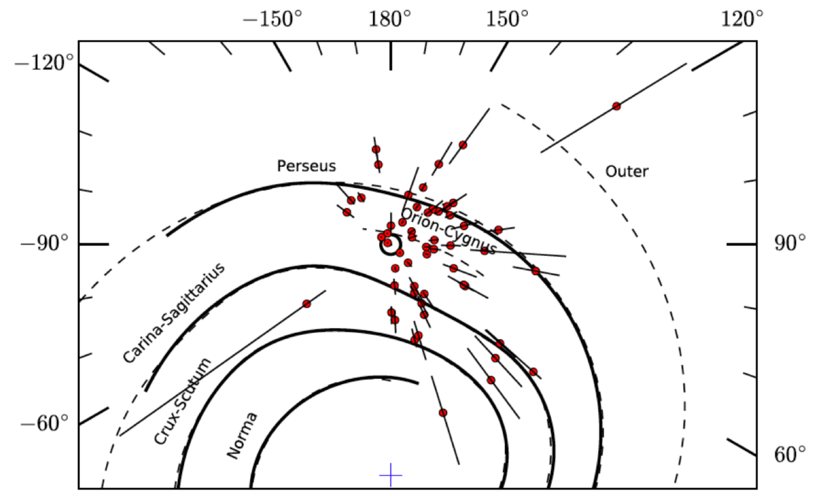
Scatter up and down the jet axis can affect signal

Accounting for this revises the parallax and black hole mass

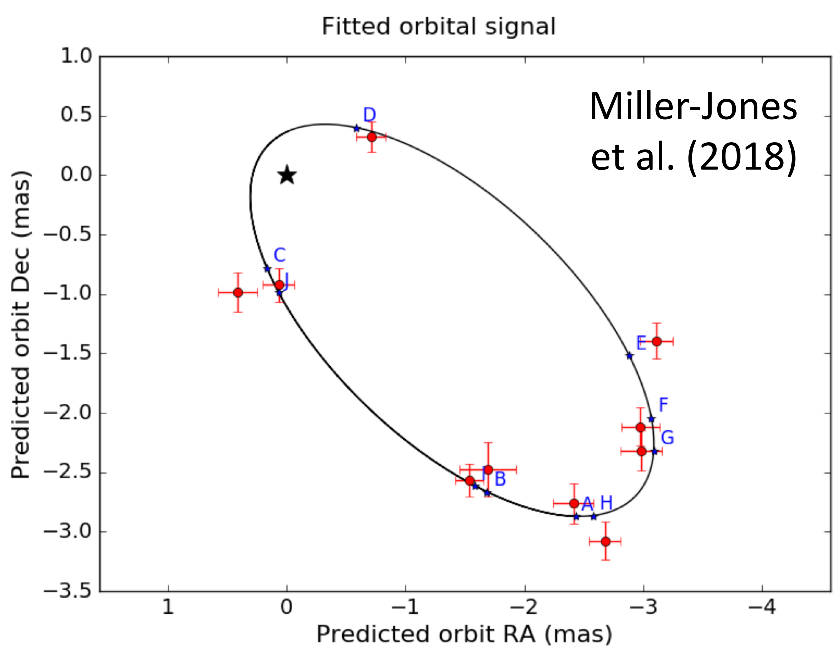


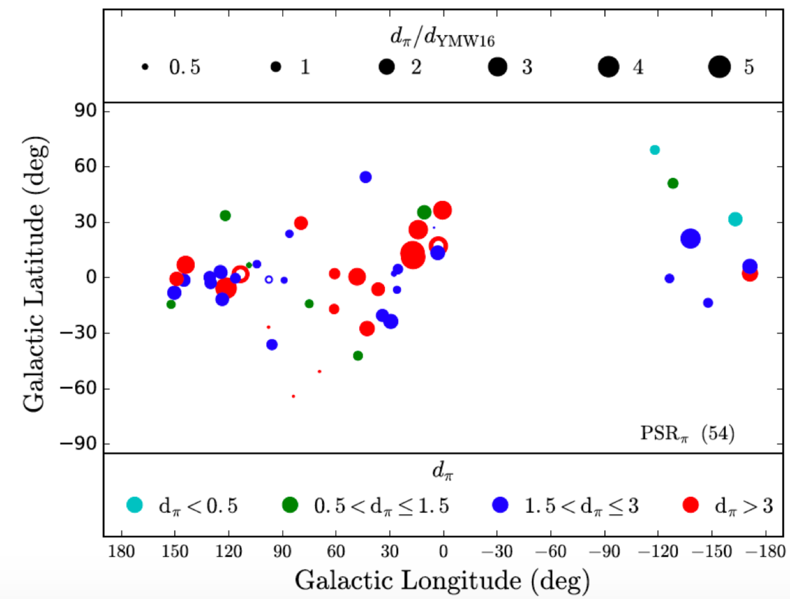
Pulsar astrometry

- Electron density models
- Pulsar kick distributions
- Efficiency of γ-ray production
- Systematics for PTAs
- Accurate NS masses (VLBI + Gaia)

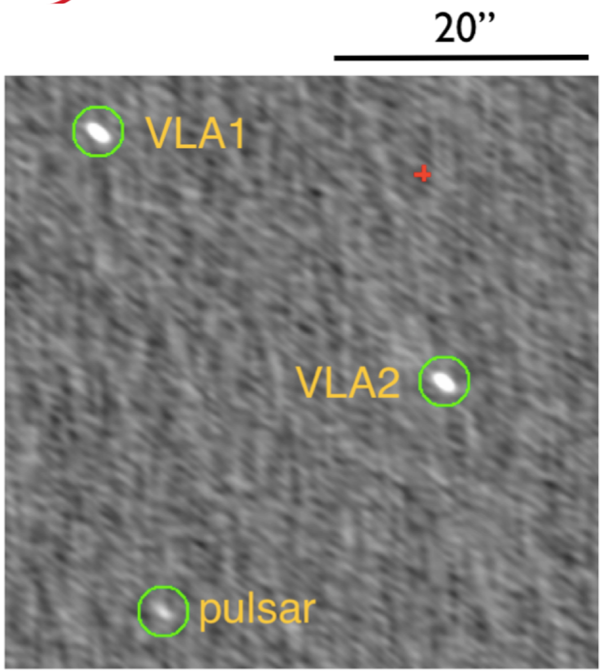


Deller et al. (2019)



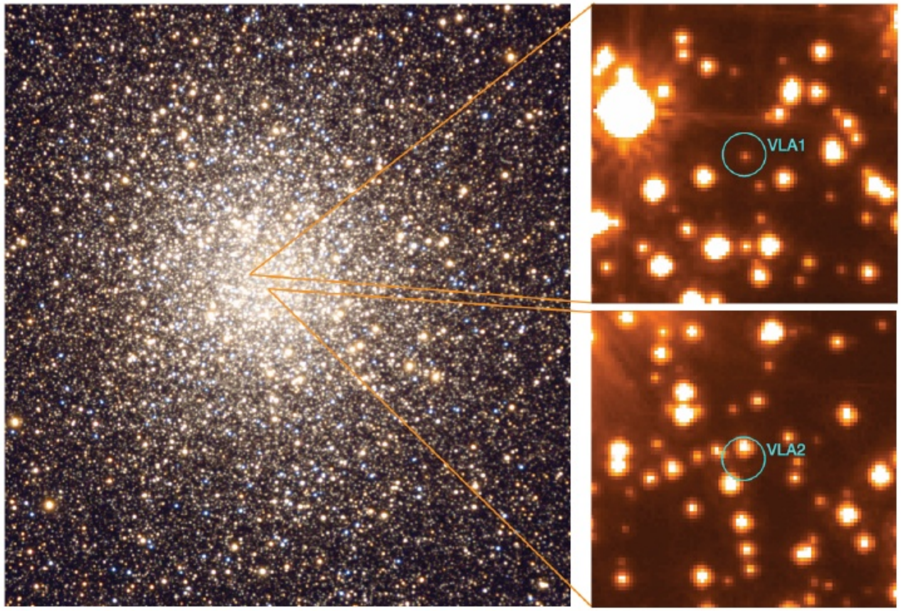


Black holes in globular clusters?

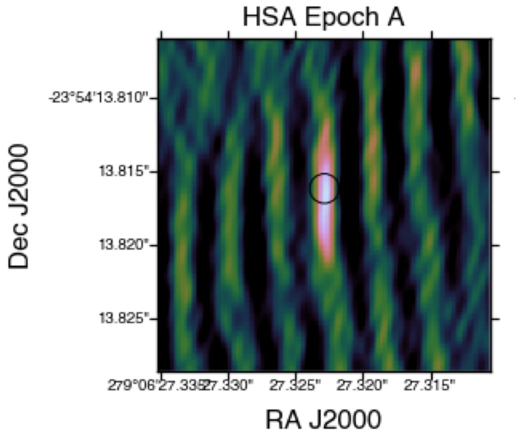


Strader et al. (2012)

M22



VLBI astrometry can measure proper motions to confirm cluster membership

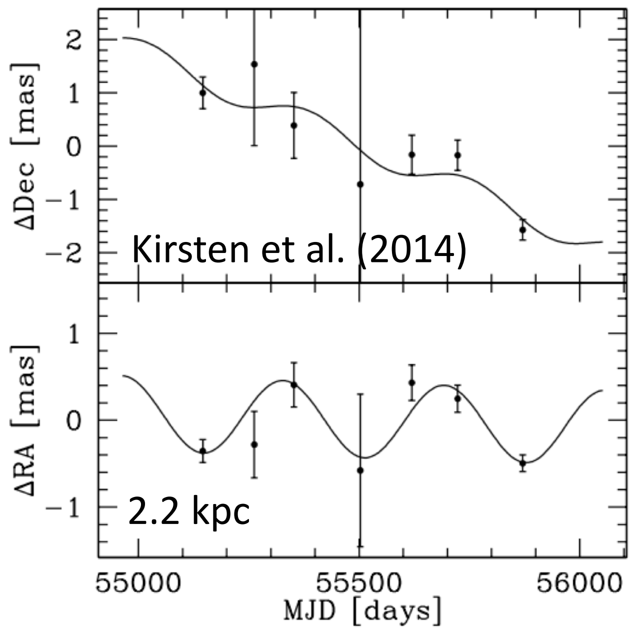


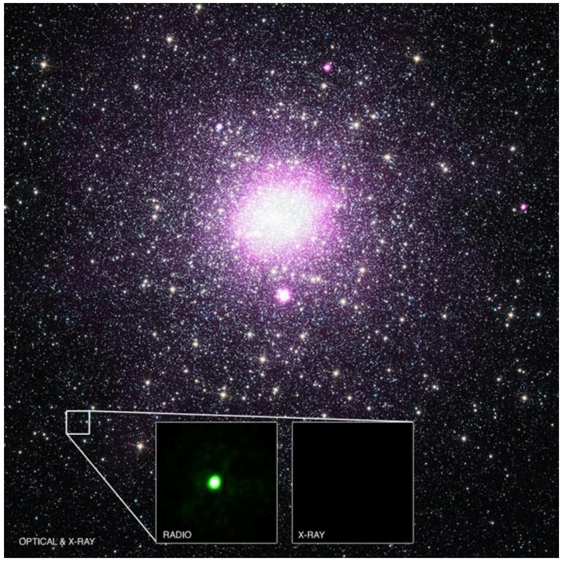
Finding new Galactic compact objects

M15 foreground

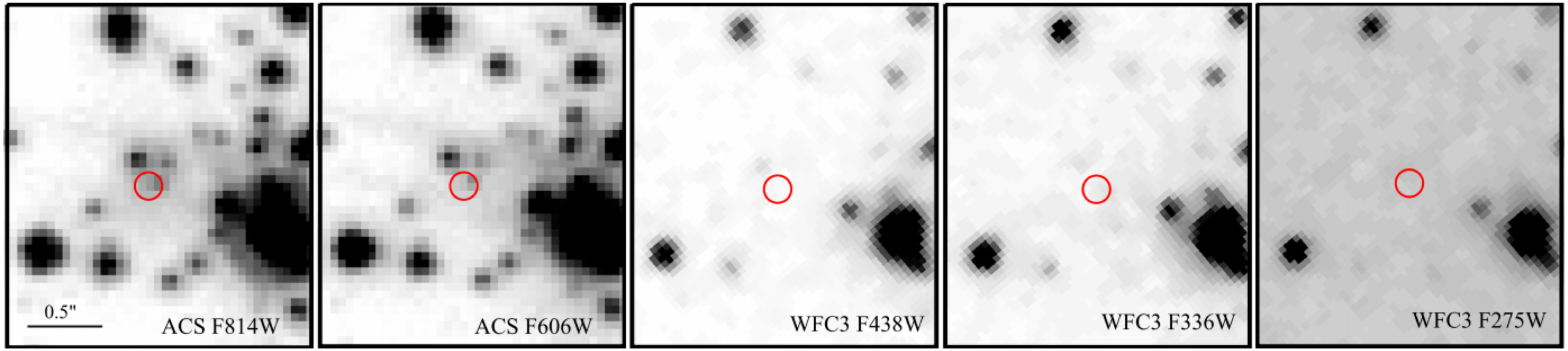
- Radio-bright
- Red optical counterpart

- Quiescent XRB?
- Implies large population
- $2.6 \times 10^4 - 1.7 \times 10^8$





B Tetarenko et al. (2018)

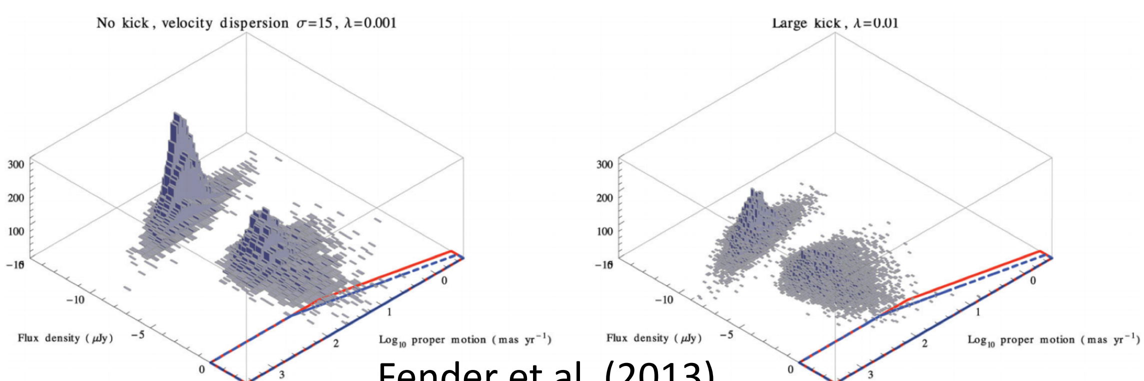


A sensitive radio survey

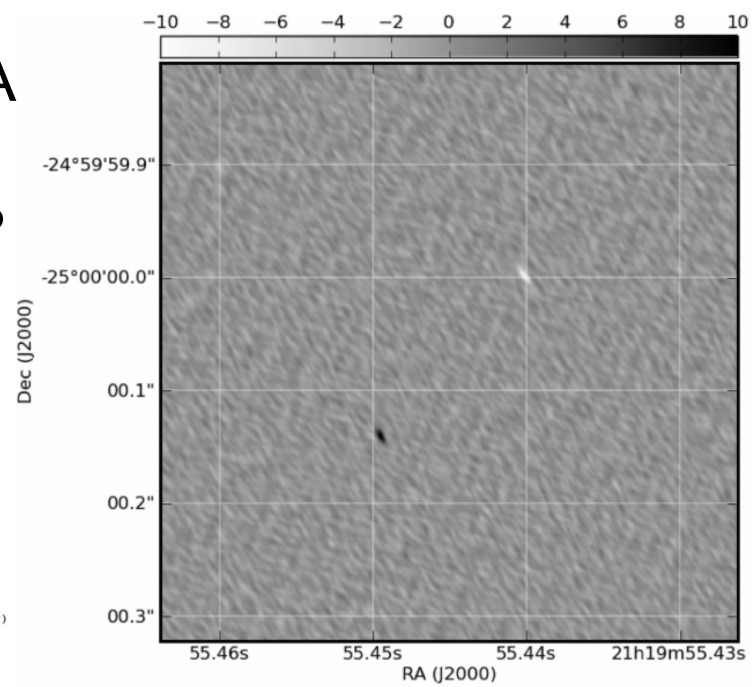
Current population of BH XRBs is X-ray selected

- ~20 dynamically confirmed, ~60 candidates
- Biased towards longer orbital periods
- Simulations predict a few thousand in the Galaxy
- 10 deg^2 ngVLA survey of the Bulge should detect 1% of all short-period black hole XRBs
  - Proper motions from 2 yr of ngVLA

    Maccarone et al. (2019)
- Also BHs accreting from the ISM?



Fender et al. (2013)



Future ngVLA science

ngVLA will address a range of science questions:

- Black hole formation mechanism
  - Supernova or direct collapse?
  - Natal kick distribution
  - Impacts BBH formation scenarios and merger sites
- Black hole mass distribution
  - Minimum BH mass; is there a mass gap? SN mechanisms
  - Maximum BH mass; stellar wind mass loss rates
- Black hole population
  - Constrains common envelope efficiency
- Neutron star masses
  - Equation of state
- Accurate system parameters
  - Jet velocities, size scales
- Globular cluster populations
  - Cluster dynamics, evolution, BBH mergers